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ACCURATE CHROMATICITY MEASUREMENTS OF LIGHTING COMPONENTS

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By
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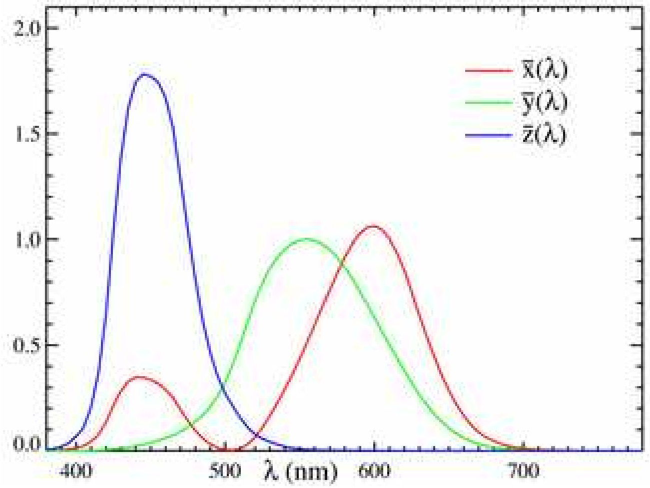
Introduction

The evaluation of a lighting component to industry or military specifications requires the precision measurement of parameters such as chromaticity (color), luminance (brightness) and spectral distribution. This paper describes various measurement technologies, industry standard representations for chromaticity and the inherent benefits and limitations of each.

Visual Perception of Chromaticity and Luminance

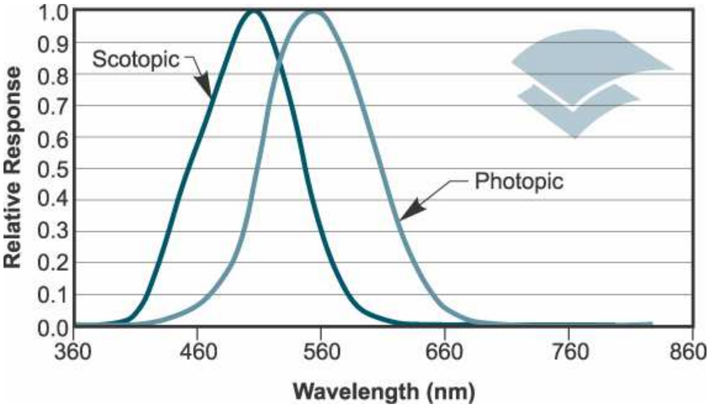
The visual parameters most often specified for a lighting component are chromaticity and luminance. In order to quantify these parameters, a measurement instrument must be able to accurately gather the spectral radiance of the lighting component and then interpret the spectral radiance as perceived by the human eye.

The human eye perceives chromaticity and luminance based upon a biochemical response to red, green and blue light, known as the Tristimulus values X, Y and Z respectively. The most common color specifications involve measurement to the 1931 CIE 2 Degree Standard Observer with the x-bar(λ), y-bar(λ) and z-bar(λ) spectral response characteristics as shown in Figure 1. Note the secondary red Tristimulus response in the blue region.



1931 CIE 2 Degree Standard Observer Tristimulus Curves
Figure 1

The perception of Photopic luminance is defined by the Y Tristimulus response and is valid for all lighting conditions except very low levels. At very low illuminance levels, the perception of luminance follows the Scotopic response curve. There is no color perception in Scotopic vision and the response curve is shifted toward the blue compared to the Photopic response. A comparison of the Photopic and Scotopic response curves is shown in Figure 2. Mesopic vision occurs at intermediate illuminance levels and is an undefined combination of the two curves. Since few industry standard measurements are based upon either the Scotopic or Mesopic response, they are discussed here solely for reference.



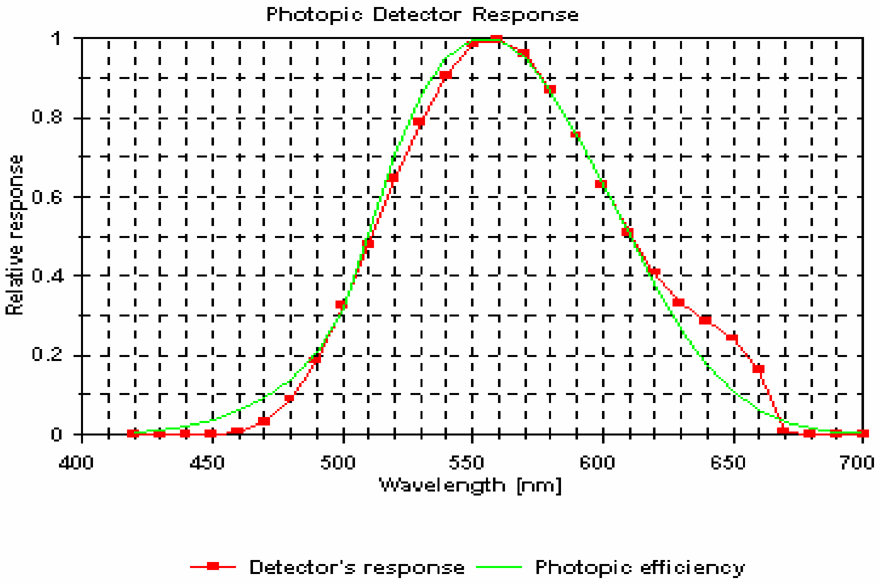
Differences in the Photopic and Scotopic Response
<u>Figure 2</u>

Using Filter-Based Instruments to Measure Chromaticity and Luminance

Most photometers and colorimeters use filters that attempt to match the x-bar(λ), y-bar(λ) and z-bar(λ) response curves and thus measure the Tristimulus values directly. Most inexpensive instruments omit the secondary x-bar(λ) response in the blue region of the spectrum. More expensive filter instruments include an additional x/b filter to correct for the secondary red response in the blue region. An example of a high quality filter photometer commonly used for military and aerospace lighting component measurement is shown in Figure 3.

Photo Research 1980A Photometer
<u>Figure 3</u>

The precision of all filter-based instruments depends upon the care taken by the instrument manufacturer to match the filter transmittance characteristics to the spectral response characteristics of the instrument detector and the 1931 CIE x-bar(λ), y-bar(λ) and z-bar(λ) spectral response functions. To illustrate the problems in precisely matching the CIE Tristimulus curves, the Photopic response curve of a commercially available detector is shown in Figure 4. Note that while the overall curve match appears good, there are several wavelength areas in the Photopic response where there is substantial error. This is particularly evident in the deep blue and red portion of the spectrum where the error is more than 2:1. If the spectral radiance of a lighting component has significant energy in these inaccurate spectral response regions, the luminance measurement error would be high.



Photopic Response Characteristics of a Commercially Available Detector
Figure 4

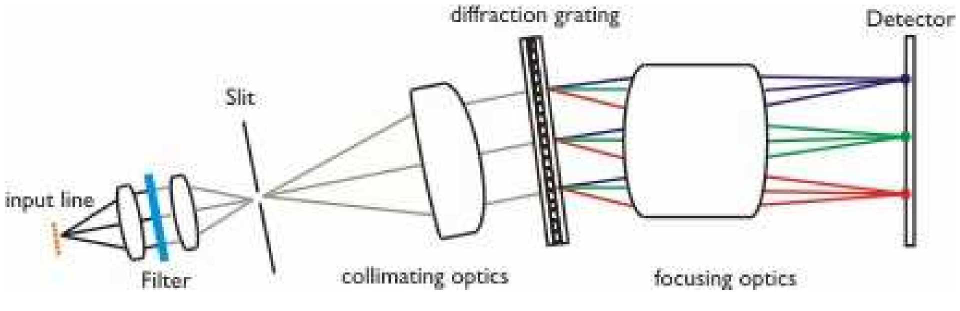
Because of the difficulty in precisely matching the instrument filters to the Tristimulus response, the accuracy of the instrument is usually specified when measuring a broad spectrum incandescent light source such as an Illuminant A. While a high quality filter instrument can produce adequate uncorrected measurements on broad spectrum incandescent white light sources, nearly all fail to produce acceptable uncorrected accuracy when measuring monochromatic light sources such as LED, Plasma or AMLCD displays. This is because it is nearly impossible to precisely match a filter and detector to the CIE Tristimulus response curves at all wavelengths simultaneously.

To achieve greater precision, it is common to apply correction factors to the measured Tristimulus values to correct for filter irregularities in the instrument. These correction factors are only valid, however, if the spectral radiance characteristics of a lighting component are well known. For example, correction factors for an incandescent red display will almost never be the same as those for a LED red display. This is because the spectral radiance distribution of an incandescent red display is much broader and inaccuracies in the instrument filter will be spread over a larger number of wavelengths. The narrower LED spectral radiance distribution will be spread over a smaller number of wavelengths and the inaccuracies in the instrument filter will be accentuated and register a greater error.

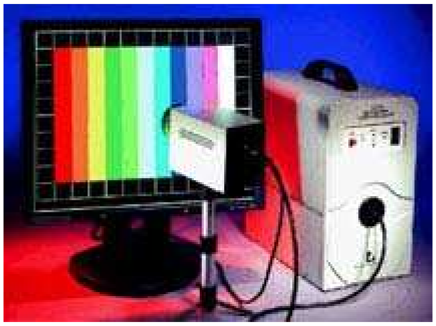
The Spectroradiometer- a More Precise Method of Measurement

If the spectral radiance characteristics of a lighting component were collected wavelength by wavelength, the CIE Tristimulus values could be applied mathematically with much greater precision. Such a device is known as a spectroradiometer. All spectroradiometers contain slits that determine the spectral bandwidth of the instrument, a diffraction grating to disperse the light by wavelength and a detector for quantifying the wavelength dispersed light.

The most common spectroradiometer technology available for chromaticity and luminance measurement is the multichannel type. A typical multichannel spectroradiometer uses a photodiode detector array to collect the entire spectrum simultaneously and has a configuration similar to that shown in Figure 5. Because all of the wavelengths in the visible spectrum are collected simultaneously, it is possible to collect accurate spectral radiance data in only a few seconds. A commercially available multichannel spectroradiometer is shown in Figure 6. Such an instrument is capable of accurately measuring a wide variety of light sources including incandescent, LED, Plasma, AMLCD and CRT.



Multichannel Spectroradiometer Internal Configuration
Figure 5



Optronic Laboratories OL-770DMS Multichannel Spectroradiometer
Figure 6

Once the raw spectral radiance data is collected using the spectroradiometer, it must be normalized to correct for detector, grating and optics non-linearity. This procedure involves multiplying each collected spectral radiance data point by a unique correction factor generated during instrument calibration to a known radiance standard. After spectral radiance collection and normalization, the data will now be in calibrated spectral radiance energy units and the CIE Tristimulus values can be calculated using the mathematical procedure shown in Figure 7. These calculations are normally performed without the need for user intervention either within the instrument itself or by the controlling software operating on a desktop computer.

$$X = \int_{380}^{780} I(\lambda)\,\overline{x}(\lambda)\,d\lambda \qquad Y = \int_{380}^{780} I(\lambda)\,\overline{y}(\lambda)\,d\lambda \qquad Z = \int_{380}^{780} I(\lambda)\,\overline{z}(\lambda)\,d\lambda$$

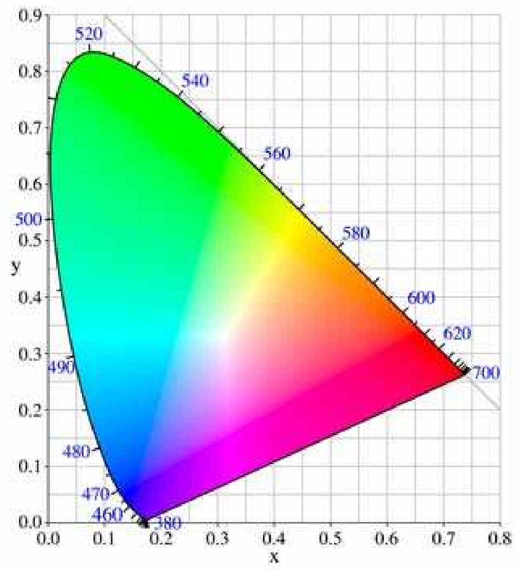
Where:

I (λ) = Spectral radiance of the lighting component
x-bar(λ), y-bar(λ), z-bar(λ) = 1931 CIE 2 Degree Standard Observer response
d(λ) = wavelength collection interval

Calculation of 1931 CIE Tristimulus Values from Spectral Radiance
Figure 7

Making the Tristimulus Data Meaningful

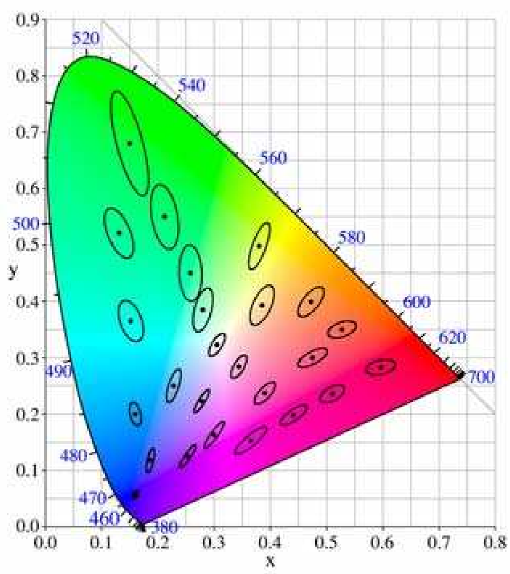
In order to make the Tristimulus values meaningful in an industry standard coordinate system, the Tristimulus values are usually modified to an x and y coordinate system and then plotted on the 1931 CIE XYZ color space for comparison to specification limits. Luminance of the lighting component is the Y integral calculated in the procedure above. The 1931 CIE XYZ color space and the Tristimulus equations for x and y are shown in Figure 8.



x = X/(X+Y+Z)
y = Y/(X+Y+Z)

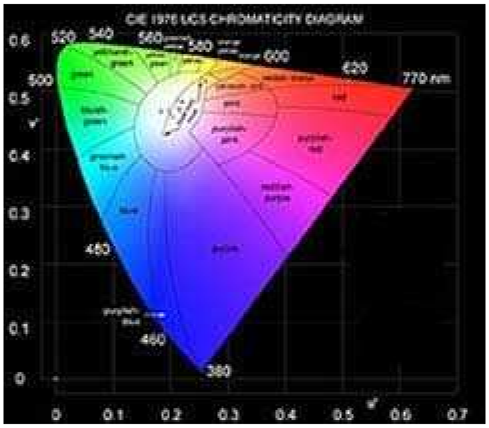
1931 CIE (2 Degree) XYZ Color Space
Figure 8

Even though the CIE 1931 XYZ color space has been an industry standard for many years, one of its weaknesses is plotting uniform appearing colors and how to specify these colors. Uniform appearing colors within the CIE 1931 XYZ color space are not mathematically uniform and tend to be highly elliptical rather than circular as shown in the MacAdam Ellipse drawing in Figure 9. Note how the dimensions of the ellipse vary with position within the CIE color space.



MacAdam Ellipses within the 1931 CIE Color Space
Figure 9

To correct this problem, the CIE LUV color space was adopted in 1976 and is shown in Figure 10. This system, also known as the Uniform Chromaticity Scale or UCS, allows uniform appearing colors to appear more circular. Although the CIE 1931 XYZ color space is still an industry standard, some military specifications such as MIL-STD-3009 have adopted the UCS color space because a simple circular distance calculation can be performed to determine conformity to specification limits. Transferring CIE x and y coordinates to UCS u' and v' coordinates is a simple mathematical procedure shown in Figure 11.



1976 LUV (UCS) Color Space
<u>Figure 10</u>

$$u' = \frac{4x}{-2x + 12y + 3} \qquad v' = \frac{9y}{-2x + 12y + 3}$$

1931 CIE XYZ Color Space to 1976 LUV Color Space Conversion
<u>Figure 11</u>

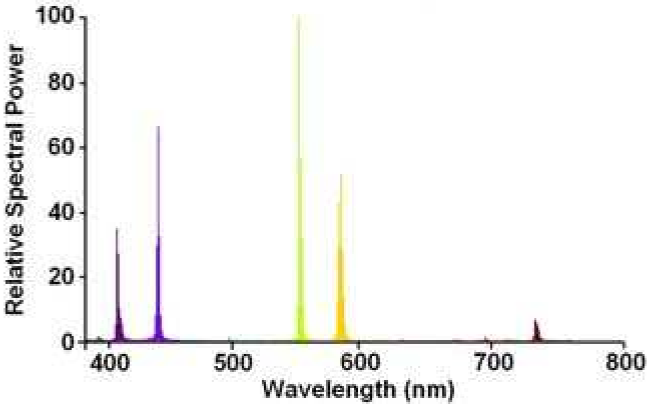
While the computational requirements a spectroradiometer are more intensive than using a simple filter photometer or colorimeter, manufacturers have now included these computations within system software and are performed completely transparent to the instrument operator. Most software now includes features that display final chromaticity and luminance results directly on the computer screen in either the CIE XYZ or LUV color space and automatically compared to specification limits.

Selection of a Spectroradiometer

There are numerous fast scanning spectroradiometers available capable of collecting spectral radiance data over the 380-780 nanometer range. In selecting a spectroradiometer, it is important that the instrument be sensitive enough for the intended application, stable and collect enough data points across the visible spectrum to provide an adequate degree of precision. Since photodiode arrays are highly sensitive to temperature, units that are either temperature compensated or cooled by a thermoelectric cooler are preferred over instruments without these features. Stability and sensitivity are both enhanced by detector cooling because noise and slight shifts in spectral response characteristics that degrade instrument performance are both reduced. For maximum sensitivity and accuracy, the photodiode array should have the capability of long integration times with at least 256 detector elements. More than 256 detector elements will allow a more accurate determination of wavelength but at the expense of sensitivity due to the smaller detector area. Less than 256 elements will usually reduce cost and improve sensitivity but degrade wavelength accuracy.

Spectroradiometer Calibration

Calibration of a spectroradiometer requires two standard light sources, one for wavelength calibration and the other for radiance calibration. The wavelength standard is usually a gas discharge lamp with known spectral lines. A typical mercury gas discharge spectrum is shown in Figure 12. Major peaks in the mercury spectrum occur at 404.6nm, 435.8nm, 546.1nm and two closely spaced lines at 576.9nm and 579.1nm.



Mercury Gas Discharge Spectrum
Figure 12

Calibration for the purpose of normalizing detector response requires a broad spectrum light source with known spectral radiance characteristics, usually an Illuminant A. Commercial Illuminant A spectral radiance standards contain an incandescent lamp, an integrating sphere, are driven with a constant current power source and contain a photoelectric sensor for regulating the luminous output. Once the apparent spectral radiance of the Illuminant A is read by the spectroradiometer, this data is mathematically compared by the calibration software to the true spectral radiance and correction factors by wavelength are calculated. This calibration data is then stored within the spectroradiometer and used to normalize all data collected by the instrument.

In addition to manufacturer performed calibration services, many manufacturers of multichannel spectroradiometers now offer calibration software for users that wish to perform these procedures themselves if suitable calibration standards are available. This can be particularly useful and cost effective if the user owns or maintains a number of spectroradiometers that all must be periodically calibrated.

Conclusion

The measurement of chromaticity and luminance using a filter based instrument requires knowledge of both the spectral radiance characteristics of the lighting component under test and the spectral response characteristics of the instrument in order to achieve accurate results. A multichannel spectroradiometer can perform very accurate measurements of both chromaticity and luminance over a wide variety of light sources including incandescent, LED, Plasma, AMLCD and CRT without correction factors. Even though the computation requirements for a multichannel spectroradiometer are more intensive than a filter based instrument, modern systems now include these computations within system software requiring little or no operator intervention. The final chromaticity and luminance results are then displayed directly on the computer screen in either the CIE XYZ or LUV color space and automatically compared to specification limits.