Emissive Color Measurement: Measuring Chromaticity and Color Temperature of White LEDs
by Miriam Mowat, Applications Scientist

Accurate measurement of emissive color is an important application of spectroscopy. LED manufacturers use color measurement for binning their products (i.e., sorting by performance and other criteria) to ensure product consistency and quality. Display manufacturers use emissive color measurements to calibrate the color of display screens. Emissive measurements of LEDs are also useful in horticulture (1), where LEDs are part of plant research and greenhouse lighting; and in biomedical applications, such as the work conducted by NASA on the use of LEDs for stimulation of cell growth (2).

In this application note we will compare emissive color measurements of a NIST (National Institute of Standards and Technology) calibrated white LED from two Ocean Optics spectrometers: the compact STS microspectrometer and the new Flame spectrometer. Flame is the next generation of miniature spectrometers from Ocean Optics, delivering high thermal stability and low unit to unit variation while offering interchangeable slits and simple device connectors.

We compared the STS and Flame spectrometers on three primary measurement criteria: speed, accuracy and repeatability.

Color Measurement
Defining the color of something is tricky at best. The way human eyes perceive color is not trivial to replicate. In the 20th century, several methods for defining color were developed. The coordinate system CIE XYZ 1931 is often used, with X and Z referring to chromaticity (hue) and Y referring to luminance (intensity). Figure 1 shows the CIE 1931 X and Y color space.

An alternative coordinate system, CIE L*a*b*, is also commonly used, with L* referring to lightness (intensity), a* to red/green chromaticity and b* to yellow/blue chromaticity. For this note, x and y have been used, as they are the parameters defined in the NIST traceable calibration of the LEDs. These parameters can be derived from the CIE 1931 system such that \( x = \frac{X}{X+Y+Z} \) and \( y = \frac{Y}{X+Y+Z} \).

Also, correlated color temperature (CCT) and dominant wavelength were measured for comparison to the calibrated values of the LED. These are commonly used characteristics to define the output of LEDs and are derived from the x and y values. In particular, CCT is important for lighting applications as it defines the appearance of the light’s color.
When measuring the emissive color of LEDs, it is necessary to define the accepted distance between measurements in xy color space for LEDs of the same color. A method for categorizing different colors was developed by David MacAdam in the mid-20th century. He defined ellipses containing a region in xy space within which an average person cannot visually distinguish different colors. This region can be extended to define areas of the CIE 1931 color space chromaticity diagram into which LEDs can be binned. A MacAdam ellipse can be thought of as the standard deviation in xy space at which color difference becomes perceptible.

ANSI (American National Standards Institute) C78-377A sets the standard of a 4-step MacAdam ellipse for CFL (compact fluorescent lamp) and halogen manufacture (3). Each step represents an area where any point on the ellipse will be one standard deviation away from the center point; for example, 4-step means four standard deviations away.

A common standard among LED manufacturers defines the acceptable boundary as a 7-step MacAdam ellipse for most commercial applications. The binning of LEDs is done by defining bins corresponding with 7-step MacAdam ellipses, as shown in Figure 2.
Figure 2: Diagram of how 7-step MacAdam ellipses are used to define LED bins on the CIE 1931 Chromaticity Diagram (3).

This diagram can be used as a guideline to help define how close the measurements need to be in order to bin LEDs into groups of the same color. As just one LED is measured for this application note, it is reasonable to expect the results to lie within one of these bins despite differences in the setups used.

**Emissive Color Measurement Setup**

An absolute emissive color measurement can be accomplished in a few steps:

1. Define your experimental setup
2. Make an absolute irradiance calibration of the setup using a calibrated light source
3. Measure the emissive color of the LEDs

For our measurements, an integrating sphere (FOIS-1) was attached to the spectrometer via a 400 µm fiber patch chord. A calibrated halogen light source, configured for use with an integrating sphere (HL-3P-INT-CAL), was used to calibrate the setup for absolute irradiance.

**Results: Measurement Speed**

Figure 3 presents the spectrum of a NIST calibrated white LED as measured by the STS and Flame spectrometers, each calibrated for absolute irradiance. Both spectrometers had a 100 um slit, and all measurements were taken with 50 averages and a boxcar of 5 applied. The integration times required to get an equivalent signal to noise ratio were different for the two spectrometers, with the Flame at 20 ms and the STS at 300 ms.
Figure 3: The spectrum of a white LED as measured by the Flame and STS spectrometers. The integration time was optimized for each spectrometer to achieve similar signal strength. The results demonstrate higher throughput performance for the Flame, indicating that much faster measurements can be taken.

This difference in integration time shows an advantage in sensitivity for the Flame compared with the STS. Flame can measure in 20 ms what it takes the STS to measure in 300 ms – a 15x advantage. This allows Flame to make rapid measurements for applications where speed is paramount, such as testing and quality control in production environments. Ocean Optics also offers the high throughput Torus and Maya LSL spectrometers for even faster measurements.

Although Flame is a small instrument, STS does have a size advantage. If the spectrometer needs to be integrated into another device, the compact size of the STS – just 40 mm x 42 mm x 24 mm – may make it the better option for some applications. Small footprint, handheld instruments can be used almost anywhere including research labs, process environments, testing and inspection sites and agricultural settings.

Results: Absolute Accuracy

Now that we know the Flame can get the same signal to noise performance at a fraction of the integration time as the STS, it is important to know if this has an effect on the consistency of results. Can such rapid measurements be taken without sacrificing accuracy and repeatability?

To test this, 80 measurements were taken in four groups of 20 with a new background dark reference in-between each set. This way the data contained both the variation present in the system as well as any variation in repeatability due to changes in the dark. CCT, dominant wavelength and x and y values were recorded and a graph was plotted of x and y to show the extent of the
measurement variation (Figure 4). This graph shows the clustering of the measured x and y color parameters for each of the spectrometers, as well as the calibrated values of the NIST LED.

![Clustering of repeated measurements of a white LED using the Flame and the STS](image)

**Figure 4:** Measurements of xy values of a white LED. Results from repeated measurements from each spectrometer are displayed and compared with the position of the NIST calibration values. Flame appears to have greater accuracy than the STS as its results are closer to the NIST values.

The results from the Flame lie closer to the true calibrated value provided in the NIST data. Table 1 shows a comparison of the average result from each spectrometer with the NIST calibration values. In each case the data from the Flame is closer to the calibration values. This suggests that the Flame provides a setup that is close to that used in the NIST method to define the calibrated values.

**Table 1.** Flame and STS Emissive Color Measurement Accuracy Compared with NIST Values

<table>
<thead>
<tr>
<th></th>
<th>x</th>
<th>% error</th>
<th>y</th>
<th>% error</th>
<th>Dominant λ (nm)</th>
<th>% error</th>
<th>CCT (K)</th>
<th>% error</th>
</tr>
</thead>
<tbody>
<tr>
<td>NIST values</td>
<td>0.2850</td>
<td>--</td>
<td>0.2747</td>
<td>--</td>
<td>462.7</td>
<td>--</td>
<td>10349</td>
<td>--</td>
</tr>
<tr>
<td>Flame</td>
<td>0.2924</td>
<td>2.5%</td>
<td>0.2809</td>
<td>2.3%</td>
<td>447.2</td>
<td>3.2%</td>
<td>9089</td>
<td>12%</td>
</tr>
<tr>
<td>STS</td>
<td>0.2953</td>
<td>3.6%</td>
<td>0.2853</td>
<td>3.8%</td>
<td>439.9</td>
<td>6.4%</td>
<td>8596</td>
<td>17%</td>
</tr>
</tbody>
</table>
Although the results for each spectrometer appear to be well clustered, there is a clear discrepancy between the measured values and the NIST values. This absolute but repeatable difference between the results is most likely due to the differences in the Flame and STS setups compared with the setup used in obtaining the NIST values, in the calibration of the spectrometers and with the radiometrically calibrated light source.

However, since this error is persistent and repeatable, removing it via a correction would be possible. In fact, this is a major reason to use a NIST calibrated LED and power supply, as they allow users to correct for system to system variation and for variance in the lamp calibrations used. This is why the repeatability of the system is perhaps the most important indicator of performance, as we will discuss later.

When using the LED binning method described above as a guideline for the acceptable spread of results, we observe that the variation in accuracy in our testing is low. Both the STS and the Flame give results that lie within a 7-step MacAdam ellipse (Table 2). Although the results for STS and Flame do not account for differences in the equipment and calibration used for the NIST results, they do demonstrate the very high accuracy of Ocean Optics spectrometers for LED color binning.

In Table 2, the distance between the Flame and STS measured values and the values given by the NIST calibration is calculated as shown. This difference is then divided by the estimated MacAdam ellipse for the region to give the number of MacAdam steps within which the Flame and STS values lie.

Table 2. Flame and STS Emissive Color Accuracy Results by MacAdam Steps

<table>
<thead>
<tr>
<th></th>
<th>Distance from NIST calibration values (= \sqrt{dx^2 + dy^2})</th>
<th>MacAdam Steps calculated from ellipse estimate for this region</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flame</td>
<td>0.00965</td>
<td>3.92</td>
</tr>
<tr>
<td>STS</td>
<td>0.01478</td>
<td>6.00</td>
</tr>
</tbody>
</table>

Table 2 values were calculated using an estimated MacAdam ellipse centered on the NIST calibration values. The ellipse parameters used were \(a = 0.0024\), \(b = 0.0005\) where \(a\) is the semi-major axis, and \(b\) is the semi-minor axis. The distance from the center point was calculated for the results from the Flame and the STS, and then was divided by these MacAdam ellipse parameters. This shows that the results for the Flame are within a 4-step MacAdam ellipse, and the results from the STS are within a 6-step MacAdam ellipse.
Figure 5: Plot of xy space showing the defined bins for white LEDs. Our LED is a cool white LED and lies in the area with the highest color temperature. The source of plot at left is a technical article by LED manufacturer Cree, Inc. (4).

Figure 5 shows that our graph roughly overlays on to a 7-step bin. This is without correcting for errors in the calibration, so we can expect that with such a correction the results would be even better.

Results: Repeatability
As we have seen, we are able to achieve good absolute accuracy with Flame and STS, but what about the repeatability of measurements?

The repeatability for both instruments is within the ability of human eyes to distinguish a difference. From Figure 5, the cluster of results for each spectrometer shows a small spread, implying good repeatability; Figure 6 shows clustering of results for Flame in close-up. Also, the data in the table below shows the standard deviations from each spectrometer. This gives an idea of the variation of each of the parameters.

<table>
<thead>
<tr>
<th></th>
<th>x</th>
<th>y</th>
<th>dominant λ</th>
<th>CCT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flame</td>
<td>5.55E-17</td>
<td>2.47E-05</td>
<td>0.054138</td>
<td>1.312791</td>
</tr>
<tr>
<td>STS</td>
<td>7.71E-05</td>
<td>1E-04</td>
<td>0.432337</td>
<td>11.34189</td>
</tr>
</tbody>
</table>

These show that the results from the Flame have a lower standard deviation than that of the STS, for all parameters. This suggests that the Flame achieves better repeatability.
This spread also can be defined in relation to a MacAdam ellipse. The results from each spectrometer fall inside a single 1-step MacAdam ellipse. This means that the measurements for both spectrometers can be relied upon to find color differences below the limit of human perception, once the system has been calibrated for setup and other zeroing errors.

In Table 3, the measured deviation shows an estimate for the size of each set of results. This is then divided by the estimated MacAdam ellipse for this region. For both spectrometers, the results are easily within one MacAdam step.

Table 3. Flame and STS Emissive Color Measurement Repeatability by MacAdam Steps

<table>
<thead>
<tr>
<th>Deviation $= \sqrt{dx^2 + dy^2}$</th>
<th>MacAdam Steps calculated from ellipse estimate for this region</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flame 0.00002</td>
<td>0.01</td>
</tr>
<tr>
<td>STS 0.00013</td>
<td>0.05</td>
</tr>
</tbody>
</table>

**Summary: How Flame and STS Stack Up**

In this head to head comparison between the Flame and STS spectrometer for emissive color measurement of LEDs, we have observed that Flame’s greater sensitivity enables it to be used for rapid measurements. Flame can achieve the same signal to noise performance as the STS in a fraction of the time -- an advantage in applications where speed is of primary importance. Torus and Maya LSL are other high throughput spectrometer options for fast measurements.

In addition, the STS and the Flame have good absolute accuracy when measurements are compared to a NIST calibrated LED. The absolute emissive color results using off the shelf Ocean Optics equipment fell within a 7-step MacAdam ellipse, a definition used by many LED manufacturers to define the extent of a single “bin” for LED color. This was without any correction applied to account for the differences in equipment between the NIST setup and the STS and Flame setups.

Each spectrometer also demonstrated its repeatability, in both cases less than 1 MacAdam ellipse. The Flame had lower standard deviation in its measurements, with the color temperature standard deviation being about 0.1 of that for the STS. Repeatability is a key parameter, as much of the absolute error can be calibrated out as persistent system error. Repeatability means users will get nearly the same result every time they use the same equipment. This demonstrates the power of spectroscopy to reliably detect small changes in color between LEDs, below the limit of human perception.

Different spectrometers allow you to match the performance to your application needs (Table 4). The Flame spectrometer offers a good balance of compact size and strong performance. The STS, while not quite so accurate or repeatable, still offers a useful combination of small size and great value.

Table 4. Comparison of Flame and STS Spectrometers for Key Criteria
Color is a difficult thing to measure at the best of times as it is not an absolute value. The use of spectroscopy allows you to define it objectively. Ocean Optics off the shelf spectrometers, light sources, accessories and software provide powerful tools for accurate measurement of emissive color.

**Works Cited**


