x·rite White Paper

Display Calibration Devices: Methods, Accuracy, and Cost

Introduction

There are many solutions on the market for calibrating your display. All of these products are made up of two parts: software and a device to measure color. To properly calibrate and profile a display you need to take some measurements, and those measurements need to be as accurate as possible. When purchasing a solution for display calibration the measurement device itself is the most important factor. Without accurate measurement the very best software will produce poor results.

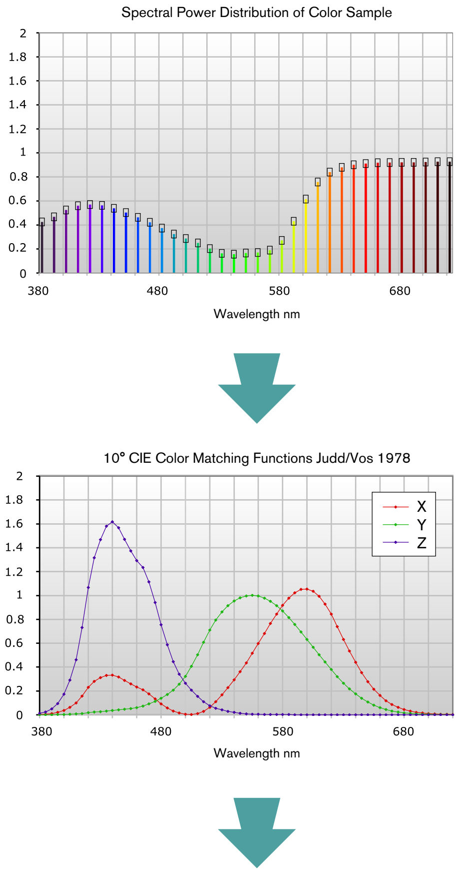
Manufacturers make all kinds of marketing claims that tout the advantage of one solution over another. If you examine a box or brochure for these products you will see long lists of features and claims. Very few of these claims are actually relevant to the real accuracy of the system. In this article we will examine what we need to measure, and what type of device will give the best measurements for a reasonable price. Two major classes of color measurement devices are used for display calibration; the spectroradiometer and the colorimeter. In this article we will examine the strengths and weaknesses of each.

What are we trying to measure? The simple answer is color, however, color is never simple. To properly calibrate and profile a display system we need to take measurements that allow us to model the complete range of color a display can produce. This range of color is often called the displays "gamut." It is important to note that a display's gamut is three-dimensional. It ranges from the brightest white, out to the pure red, green, and blue primaries, and down to black. The dark colors are just as important as white, however they are much more difficult to measure accurately.

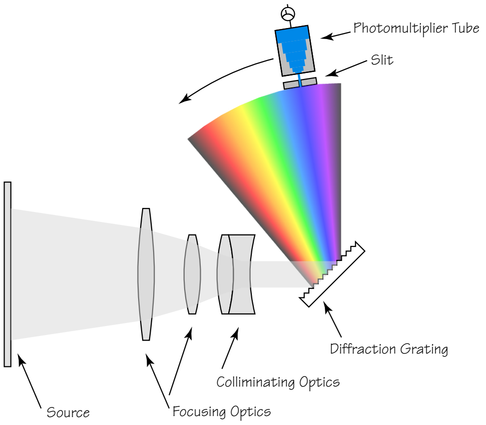
The Basics

A properly calibrated display will always display the same color for any given set of RGB values. To achieve this result we must measure color accurately everywhere within the gamut of the display. This is not a simple, straightforward task. It's relatively easy to construct a device that can measure the color of white accurately. It's harder to construct a device with great accuracy at the red, green and blue primaries. It is an order of magnitude harder yet to measure black and very dark colors with that same accuracy.

To understand this problem we need to understand how we define a "color" scientifically. Color in our mind is a perception created when light strikes the three types of cone receptors in the eye. Each of these receptors is sensitive to different wavelengths of light. When light with the proper wavelengths reaches a receptor it becomes "excited" and sends a proportional signal. We see different colors based on the ratio of these three signals.



A ***Spectral Power Distribution Curve*** *(SPD) from a spectroradiometer is converted to XYZ using the Color Matching functions. In this example the SPD has 32 Bands. Each band has it's own amount of error due to the signal-to-noise ratio of the detector (boxes at top of each bar.) In a bright color like the one shown here this error is not as significant. In a dark color (when each bar is much shorter) the error becomes a large portion of each band.*



***Lower cost spectroradiometers** use an array of photodetectors (usually photodiodes.) These detectors do not have the signal-to-noise ratio of the photomultiplier in the lab grade unit. The array also has gaps between each detector. The device can't see a change in the spectrum near these gaps.*

Not everyone sees color exactly the same way and many people have deficiencies in one or more receptors. In order to measure color we need a fixed, unchanging standard to define it. To create the standard, scientists conducted tests on human subjects to measure the response of the cone receptors. A large amount of data was collected, anomalous subject data was removed and an average dataset created. You may have heard the term "standard observer," this refers to that dataset.

From the Standard Observer dataset scientists created a set of theoretical curves that describe the color response of human vision. These three curves are referred to collectively as the "tri-stimulus response curves" and given the names X, Y and Z.

To measure a color we need to determine the signal (value) that would be produced by the theoretical receptors X, Y and Z. If we know the values for XYZ we know the exact color in a scientific reproducible way.

There is more than one way to achieve this, and each method has different advantages and disadvantages as well as various implementations. In this paper we will focus on the two methods that are widely used for display calibration. These are the spectroradiometer and the colorimeter. Take notice of the fact I am using the term "spectroradiometer" not "spectrophotometer." A spectrophotometer measures reflectance and is used on surfaces or printed materials. A spectroradiometer measures radiation such as that from an emissive display like a CRT or an LCD.

The Spectroradiometer:

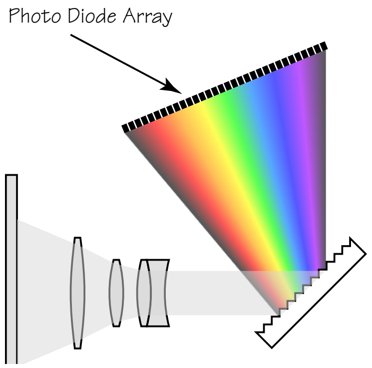
A spectroradiometer is a device that measures the energy level along the visible spectrum. The output of a spectroradiometer may be displayed as a graph of energy vs. wavelength. This graph is called a Spectral Power Distribution (SPD) curve. Using simple mathematics we can compare each of the X, Y, Z response curves to the SPD and obtain a set of tri-stimulus values. There are three primary factors that determine the accuracy of a spectroradiometric measurement.

Spectral Bandwidth — An SPD is a bar graph running from 400 to 700 nm. The spectral bandwidth tells you how many bars are in the graph. The smaller the bandwidth the more bars and thus the more accurate the curve.

Resolution — How big is a discrete energy step. Another way to think about this, how many values can be reported between no energy and the maximum energy of the sensor. Manufacturers often report this in terms of bits – however due to the signal-to-noise ratio, you may not be able to use all your bits.

Signal-to-Noise Ratio — All sensors have noise; cosmic radiation, IR, EM and other factors cause the output of a sensor to fluctuate. The ratio of this fluctuation to the signal being measured is the S/N ratio. With a high signal (bright white) the signal-to-noise ratio will be very high and your resolution will be excellent. When you are measuring a very low signal such as a very dark color the noise can obliterate the signal and produce a less accurate measurement. As we will see this is a very important factor. In a spectroradiometer the original source is being broken down into very small pieces this reduces the available signal for each measurement.

The 1nm Metrology Lab Spectroradiometer ($40,000-$100,000)



*The **Lab Grade Spectroradiometer** is very expensive,slow, and very accurate.*

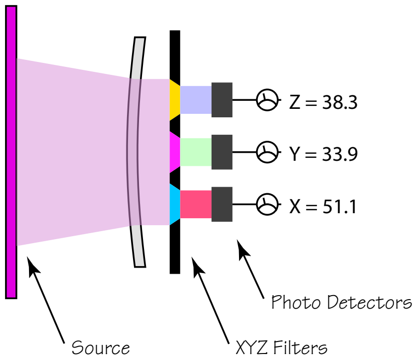
If budget and time are not factors you care about, this is the very best way to measure any emissive color. I am often confronted by persons who attempt to convince me that a spectral device is the best way to measure a display's color. If this is the device they are referring to, they're right, however at a reasonable price point for the purpose of calibration they are wrong. The lab grade spectroradiometer is a simple device, extremely accurate, very slow and the individual parts are quite expensive. Incoming light is focused and colliminated. This beam strikes a diffraction grating which splits the light into its component wavelengths. A special sensor called a Photomultiplier Tube with a tiny slit in front is moved through the path of the spectrum one step at a time. At each position the energy of that portion of the spectrum is measured. To get the best measurement, we want to break up the spectrum into 1nm steps from 380-700 nm. That's 320 individual steps; at each one we must pause and take a measurement. If the sample is dark we may need to spend an entire second on each step to get an accurate reading. That's over 5 min to take one measurement! The accuracy of this device comes from it's incredible signal-to-noise ratio. Some high-end photomultiplier tubes can detect individual photons, the smallest quanta of light possible. They also can be tuned so they only respond to the visible wavelengths of light. This means stray radiation and heat (IR) do not create noise in the sensor. These devices are not useful for calibrating displays, they are however, very useful for calibrating other devices and creating a reference standard against which we can measure accuracy.

There are other kinds of spectroradiometer at much lower price points from $40,000 down to around $1000. Mostly these devices do not move a sensor through the spectrum; instead these devices use an array of sensors that span it. They use semiconductor based light sensors, most often photo-diode arrays. The device can sample each portion of the spectrum simultaneously. This means a much faster measurement, rarely longer than a second for the whole measurement. There are many engineering challenges that make this device more complex and expensive to attain high accuracy.

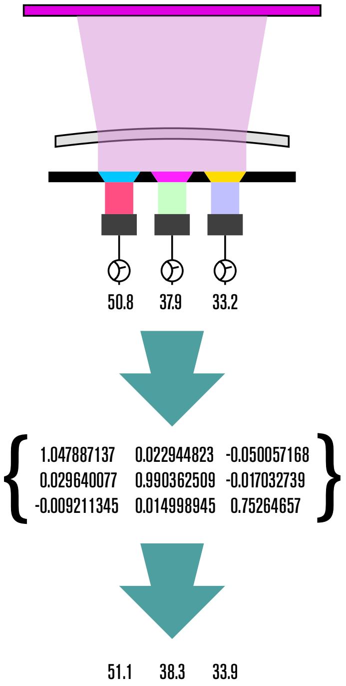
These devices have a bandwidth from around 5nm to 20nm. The space that must be present between each sensor creates a sampling error (some devices use two overlapping sensor sets.) The semiconductor light sensors used by these less expensive devices are all much more sensitive to noise. This is important to understand. When you are dividing your sample light source into 64 bands many of those bands are going to have very low energy levels. If your source is dark to start with, those individual bands will be minuscule. That means the signal-to-noise ratio will be very low and accuracy will be reduced.

All of the complex problems posed by the array-based spectroradiometer can be overcome. It simply takes more money. Diode arrays can cost $10 up to $1000. If you use overlapping $1000 arrays that's even better. If you use better amplifiers, and implement cooling systems for the array, the signal-to-noise ratio can be improved. Better optics can gather more light and align it better into the array. I know of no device that better exemplifies the term "you get what you pay for."

For a job like measuring a white light source a low end spectral device may be excellent. If you are adjusting the grey tracking of an LCD display, the error of the device



The ***XYZ Colorimeter*** *is very simple and inexpensive. It has three detectors one each for X,Y and Z. These detectors are much larger and therefore have much better signal-to-noise ratios. The direct result is X,Y,Z data of high accuracy. The large sensors mean that low light levels produce a stronger signal. Because, the light from each sensor is from many spectral bands not just one, the total energy is even greater creating even better signal-to-noise ratios.*



When a colorimeter is calibrated to the source primaries of a display with a calibration matrix. The accuracy of the colorimeter on that type of display is greatly increased. The worst case accuracy of this type of purpose built colorimeter can not be matched with a spectroradiometer anywhere near the price. In fact you would have to spend 100 times as much to achieve this accuracy with a spectroradiometer.

on the darker patches may be far greater than the adjustment accuracy of the display. My experience has shown that to accurately calibrate a display with a spectroradiometer you need to spend at least $10,000 on the device. When I develop a calibration system I use a $25,000 device as my reference. That device is about twice as accurate as the smallest adjustment I can make to the display system.

XYZ Colorimeters

There is a much simpler device for measuring color: the Colorimeter. Our eye sees color with just three sensors. As discussed above, we have a theoretical model of these sensors, so if we can simulate these theoretical receptors we have a device that will produce XYZ data directly. To create this device all we have to do is place filters that simulate the XYZ response curves in front of three separate sensors. No complex lenses or moving parts are required. The sensor elements themselves can have a much larger surface area (100X or more) so even though we use inexpensive semiconductor sensors our signal-to-noise ratio goes way up.

The only difficulty with the production of an XYZ colorimeter is the filters. The XYZ response curves are complex. In order to create these complex filters, many separate filters must be stacked together to achieve the final curves. The filters achieved are never perfect matches to the XYZ curves. However they don't need to be. By calibrating a colorimeter at the factory against reference sources, a mathematical correction called a "calibration matrix" is stored in the colorimeter. This corrects the minor errors that are introduced by inaccuracies of the filters. This does not create a device that can measure "any" color with perfect accuracy. Instead a colorimeter of this type will produce very accurate results from most sources. Certain sources that have very narrow bandwidths like lasers will not be as accurate.

The cost of a very good, lab grade colorimeter may be in the $1000-$5000 range. However a device like this can measure most sources as well as the $40,000 spectroradiometer. More importantly, it will surpass the performance of the $1,000-40,000 spectroradiometers when measuring dark colors. The signal-to-noise ratio of the final XYZ values will be much higher for the colorimeter due to its increased sensor surface area, and the total amount of energy being measured per sensor. Unless you need to measure the color of a laser, a colorimeter will almost always provide a better measurement for much less money.

The Pseudo XYZ or RGB Colorimeter

In all the cases above we have been discussing expensive instruments that are designed to measure "any" light source. In the unique case of display calibration we often know exactly what kinds of spectra we are going to measure. As an example, let's say we know we are going to measure a Sony CRT. All Sony CRTs use the same three phosphors (one red, one green and one blue) known collectively as the P-22 phosphor set. Variation of the spectra from these phosphors is slight. If we use these spectra at the factory when we calibrate our colorimeter, the colorimeter will have incredible accuracy measuring a Sony display, far better than any spectroradiometer at 10X the price.

An interesting advantage of this kind of "purpose built" colorimeter is it does not need to have filters that are near perfect XYZ simulators. All you need are simple RGB filters that can discriminate very well between the three primary phosphors. If you know the source primaries you are going to measure, you can build a very accurate device for an extremely small amount of money. I have worked with colorimeters that cost less than $100 to build that rival the accuracy of a $20,000 spectroradiometer when used on the display they were designed for. That same spectroradiometer could not provide any measurement of black on the display. The $100 colorimeter could measure black with a high degree of accuracy.

In many cases we need a more universal device one that can measure any CRT or LCD display on the market. A universal device will not always know the exact primaries of the display to be measured. However, we can design a colorimeter that will provide a high level of accuracy for all displays. I like to call this type of colorimeter the pseudo XYZ colorimeter. The idea here is to create a filter set that is a “pretty good” match to the XYZ curves. The difference between “near perfect” and “pretty good” is a lot of money. The raw result from this colorimeter will be much better than an RGB colorimeter for an unknown device. We can again increase that accuracy with calibration.

There are 3 major CRT phosphor sets and they are all similar. If you build a calibration matrix for one of them on a pseudo xyz colorimeter it will do an excellent job on all of them. LCDs however need their own matrix. The primaries used by LCDs are very different. Some new LCD technologies in the future will require a third matrix to be stored in the colorimeter.

The differences in the primaries of these various displays is what allows the colorimeter to determine which display it is measuring and then select the appropriate calibration matrix automatically.

In conclusion

A laboratory spectroradiometer is an invaluable instrument when you need to measure an unknown light source. Nothing is more accurate or more expensive. When your color measurement task involves a source of known characteristics, a “purpose built” colorimeter will provide greater accuracy at a much lower cost. The colorimeter is always the superior solution if you need to measure the full gamut of such a device with speed and accuracy.

About the author – Karl Lang—*product creator, scientist, artist and engineer—has worked to bring a long history of products and technologies to market. You may recognize some of them: The Radius System 100, Thunder Color, PressView, Artica, and The ColorMatch System. Recently Karl was the architect for the Sony Artisan Color Reference System.*