Color Measurement with the LSS-100P

Color is complicated. This paper provides a brief overview of color perception and measurement.

XYZ and the Eye

We can model the color perception of the eye as three band-pass filters. The ratio of the amplitudes out of these filters is how we determine the color of light. If we look at a monochromatic red light source, which has a wavelength of about 650nm, the X filter has the most output, the Y filter less, and the Z filter almost nothing. Looking at monochromatic green (510nm), the Y filter has the most output, followed by Z and X. Yellow monochromatic light (570nm) results in about equal output of the X and Y filters, and almost no output from the Z filter. As the color varies between red and green, we can use the ratio of the X and Y filter outputs to determine the color.

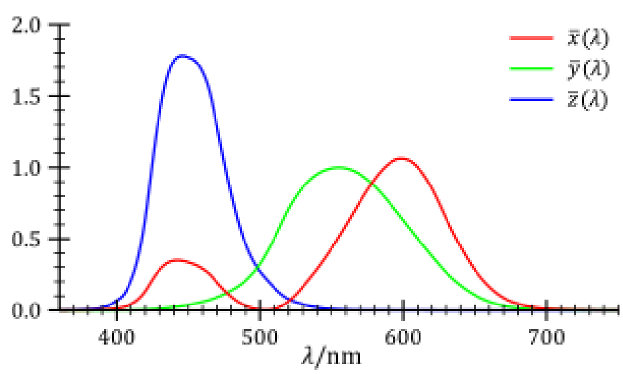

Figure 1 - XYZ Tristimulus Filters (from http://en.wikipedia.org/wiki/CIE_1931_color_space)

Monochromatic blue light has a wavelength of about 475nm. Note where that lands on the XYZ plot. Z is highest, followed by Y, then X. The "second bump" in the X filter at about 450nm is very important. Indigo monochromatic light (445nm) results in an output from the Z and X filters, but very little from Y.

Imagine we sweep a vertical line through the XYZ plot. At each wavelength, the line will intersect the X, Y, and Z curves at different levels. We use these relative levels to determine the color of monochromatic light.

Next, imagine two monochromatic sources, one at 650nm (red) and the other at 510nm (green). We can adjust the brightness of these sources such that the output of the XYZ filter is about the same as when driven with monochromatic yellow (570nm). We cannot tell the difference between a single 570nm source and a combination of 650nm and 510nm. We can use any combination of source colors to simulate a color as long as the ratios out of the XYZ filters is the same as the color we are simulating. We can combine red and green to get yellow. The eye does not know whether we are seeing two colors (red and green) or one color (yellow).

As noted before, the second bump in the X filter is very important since it allows us to combine red and blue light and have it appear to be indigo. Without the second bump, it might appear a greenish blue.

Spectrometer Based Color Measurement

A spectro-colorimeter (such as the USL PCA-100 or the Photo Research PR-655) "filters" (separates the light into separate wavelength bands using a diffraction grating) the visible spectrum into a large number of narrow bands (typically 3 to 5 nm wide). The outputs of these filters can be multiplied by constants and added to yield the same output as an optical XYZ filter set -- or the eye. This is the most accurate method of measuring color since the constants can be adjusted to precisely match the XYZ filters.

Tristimulus Color Measurement

Since the eye measures color with three filters (XYZ), we *should* be able to accurately measure color with a similar tristimulus meter. The problem is that it is very difficult to create optical filters that adjust the spectral response of a typical silicon-based photodetector to match the XYZ responses. It is considerably easier to create optical filters that result in an RGB response. Figure 2 shows the spectral response of the color sensor in the LSS-100P. Note that the RGB filter shapes are similar to the XYZ filter shapes, but have different peak wavelengths, and the red filter does not have the second bump of the X filter in the blue spectrum. Figure 3 shows the spectral response of a Minolta CS-100A tristimulus color meter. Note that it is similar to that of the LSS-100P, also missing the "second bump" of the X sensor.

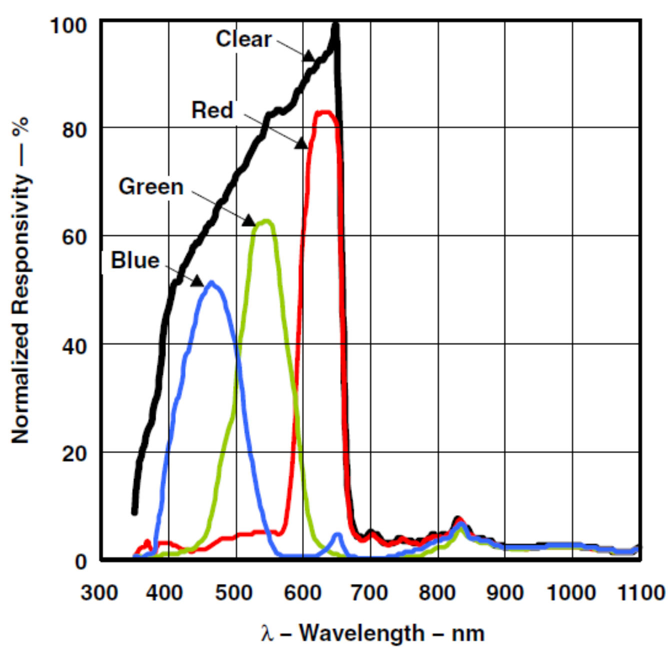

Figure 2 - LSS-100P Color Sensor Spectral Response

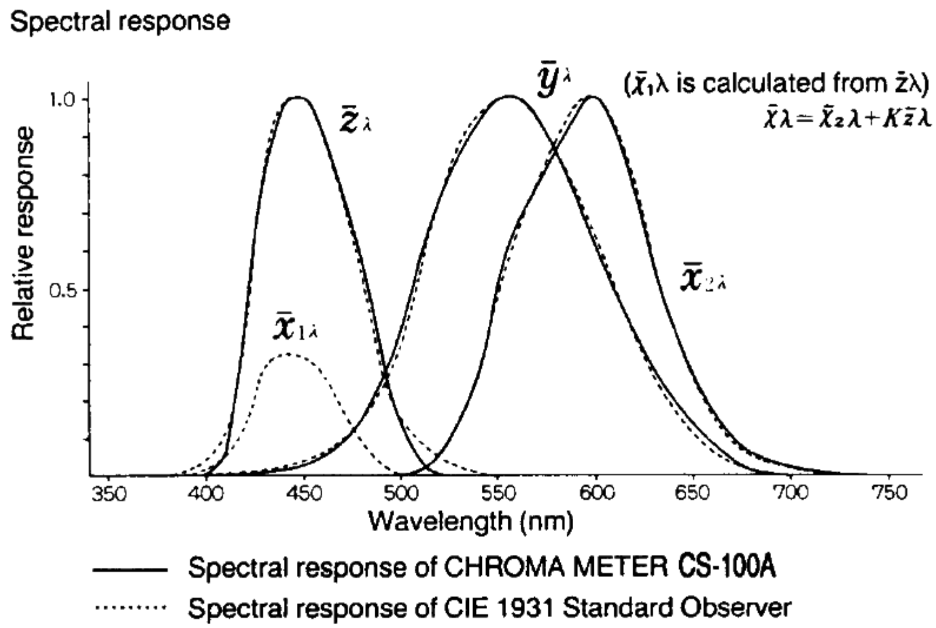

Figure 3 - Minolta CS-100A Spectral Response

RGB to XYZ Conversion

RGB-based color meters derive XYZ values by multiplying the RGB values by a color correlation matrix that is developed during device calibration. The instrument will then accurately measure colors that have similar spectra to those that were used in calibration. The LSS-100P is calibrated using red, blue, and SMPTE 431-1 white, each generated with a xenon lamp- based projector. The CS-100A is calibrated with an incandescent source at a temperature of 3111 K. The CS-100A chromaticity accuracy is rated at +/- .004 *when measuring this reference color*. As the spectra of the light being measured varies, the accuracy of the instrument varies. The LSS-100P faces the same issue (accuracy varies as spectra differing from the calibration spectra is measured), but is calibrated with a xenon source at SMPTE 431-1 white. Thus, it is most accurate at the color of interest.

Measurement Stability and Repeatability

Since the LSS-100P is used as a quality assurance instrument, stability and repeatability are of the utmost importance. Also, it is unlikely that an instrument and the projector would drift in the same direction such that incorrect color is not detected, further improving the reliability of the LSS-100P in detecting projector problems.

Long-term tests of the LSS-100P have been conducted with some of those results are shown in Figure 4. In this case, the LSS-100P was calibrated in place to agree with a PR-650. The maximum error in x or y was .003 with the vast majority of the readings agreeing with the PR-650 within .001. The PR-650 itself is rated for +/-

.0015 for x and +/-.001 for y. The stability of the LSS-100P approaches that of the much more expensive PR-650 and is well within the +/-.006 specified by SMPTE 431-1 for theaters.

Date	PR-650			LSS-100			Error			LSS Mic		dB	dB
	x	y	fL	x	y	fL	x	y	fL	94dB	114dB	Dif	Dif
5/27/2014	0.311	0.350	10	0.311	0.350	10	0.000	0.000	0.1%				
5/30/2014	0.310	0.350	9.1	0.312	0.350	9.210	0.002	0.000	1.1%				
6/6/2014	0.311	0.350	9	0.311	0.347	9.080	0.000	-0.003	0.7%				
6/13/2014	0.311	0.350	8.9	0.312	0.349	8.920	0.001	-0.001	-0.2%				
6/20/2014	0.311	0.350	8.8	0.311	0.348	8.720	0.000	-0.002	-0.9%				
6/27/2014	0.311	0.351	8.6	0.312	0.350	8.710	0.001	-0.001	0.9%				
7/3/2014	0.310	0.350	9.9	0.311	0.349	9.940	0.001	-0.001	0.2%				
7/11/2014	0.311	0.350	10	0.311	0.349	9.890	0.000	-0.001	-1.1%				
7/18/2014	0.312	0.351	8.8	0.313	0.350	8.860	0.001	-0.001	0.7%				
7/25/2014	0.312	0.351	8.9	0.313	0.351	8.750	0.001	0.000	-1.1%				
8/1/2014	0.311	0.351	9.8	0.313	0.352	9.720	0.002	0.001	-0.9%				
8/7/2014	0.312	0.351	9	0.313	0.352	8.850	0.001	0.001	-2.1%				
8/15/2014	0.312	0.351	8.9	0.313	0.350	8.710	0.001	-0.001	-1.6%				
8/22/2014	0.312	0.351	10	0.313	0.351	10.000	0.001	0.000	-1.0%				
8/29/2014	0.313	0.351	8.8	0.313	0.352	8.560	0.000	0.001	-2.2%				
9/5/2014	0.312	0.351	9.7	0.313	0.349	9.670	0.001	-0.002	-0.5%				
9/12/2014	0.312	0.351	9.7	0.313	0.351	9.590	0.001	0.000	-1.3%				
9/22/2014	0.306	0.348	9.7	0.308	0.350	9.630	0.002	0.002	-0.8%				
9/22/2014	0.306	0.348	9.7	0.308	0.350	9.680	0.002	0.002	-0.5%				
10/17/2014	0.308	0.350	9	0.309	0.351	9.000	0.001	0.001	0.3%				
12/5/2014	0.311	0.353	9.6	0.311	0.352	9.480	0.000	-0.001	-1.0%				
9/22/2015	0.309	0.351	16	0.309	0.350	17.000	0.000	-0.001	3.7%	94.1	113.6	0.1	-0.4
11/6/2015	0.321	0.332	13	0.321	0.330	13.800	0.000	-0.002	10.4%	91.7	113.6	-2.3	-0.4
12/1/2015	0.309	0.351	14	0.310	0.350	14.900	0.001	-0.001	3.5%	94.6	113.7	0.6	-0.3
1/5/2016	0.309	0.352	15	0.310	0.350	15.8	0.001	-0.002	3.9%	94.7	114.1	0.7	0.1
2/2/2016	0.310	0.352	15	0.309	0.350	15.700	-0.001	-0.002	3.3%	94.3	113.8	0.3	-0.2
3/3/2016	0.301	0.347	17	0.301	0.344	17.600	0.000	-0.003	1.1%	94.3	113.7	0.3	-0.3
4/1/2016	0.303	0.347	17	0.303	0.347	17.200	0.000	0.000	-1.1%	94.4	113.9	0.4	-0.1
5/2/2016	0.304	0.347	17	0.305	0.347	16.800	0.001	0.000	-1.2%	94.2	113.6	0.2	-0.4

Figure 4 - LSS-100P Stability Test

Luminance Measurement

The LSS-100P uses a separate detector with a photopic spectral response (corresponding to Y of XYZ). This results in accurate luminance measurements independent of the spectral content of the light (with the accuracy being determined by the accuracy of the spectral response of the optical filter). Since the LSS-100P is designed for cinema quality assurance use, and the vast majority of cinemas use xenon lamp projectors, the LSS-100P luminance is calibrated with white light (SMPTE 431-1 white) from a xenon lamp projector.

The long-term stability measurements in Figure 4 indicate a maximum deviation from the PR-650 of 2.2%. The PR-650 itself is rated for +/-2% accuracy for the luminance measurement. Note also that SMPTE 431-1 specifies a tolerance of +/-21.2% (48 cd/m^2 +/-10.248 cd/m^2). The LSS-100P stability is 10 times better than the allowed tolerance.

Summary

The most accurate color measurements are made with spectrometer-based instruments. RGB tristimulus instruments provide very similar results *if calibrated with the light spectrum to be measured.* The LSS-100P is calibrated with the same type of light source utilized in cinema and, therefore, yields more accurate results than RGB instruments calibrated with other sources