

# **The Calibration Conundrum: Towards Standardizing a Reference White Chromaticity for HDTV**

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**Abstract.** *High definition displays have pushed tremendous engineering and color reproduction boundaries. While they have become more widely accepted into the consumer landscape, post-production professionals often experience problematic color appearance mismatches amongst new display technologies.*

*Rendered imagery that is visually mismatched is an example of a metameric failure: a phenomenon that occurs when spectrally unique stimuli (which are intended to appear identical) are perceived differently.*

*Both a simulation and psychophysical assessment are developed in an attempt to quantify variability in color perception when using different displays. A mean visually-corresponding chromaticity offset is calculated as a replacement calibration aim. This offset is intended to satisfy a greater population of observers than existing calibration methods.*

**Keywords.** *metamerism, chromaticity, calibration, HDTV*

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## Introduction: Metamerism and Display Technologies

Human color perception boils down to a visual integration of a spectrally complex scene, which is then processed by the brain. As a result of this integration, it is possible for a variety of spectrally unique stimuli to produce identical visual responses. Spectrally variant color stimuli that are perceived identically are known as metamers [1].

With display-rendered imagery, the objective is to take advantage of the limitations of the human visual system. Using a limited subset of emissive primaries, displays render metameric matches of real scenes, effectively fooling the human visual system.

The issue of metameric failures became increasingly prevalent as the post-production industry moved away from cathode-ray tube (CRT) displays. CRT displays utilized wide-bandwidth primaries that were standardized so that a consistent stimulus was rendered for a given input voltage.

Newer high-definition display technologies utilize cold cathode fluorescent lamps (CCFLs), light emitting diodes (LEDs), organic LEDs (OLEDs), and laser primaries to render imagery. Compared to CRT illuminants, these new illuminants are spectrally unique in two ways.

First, their spectral power distributions (SPDs) are not standardized. Two or more displays with the same illuminant technology may exhibit significantly different spectral characteristics with regards to their peak wavelength and bandwidth, for example.

Secondly, the SPDs of each new display's primaries are increasingly narrower than those of CRT displays. The most extreme cases of this are laser-based systems, as their primaries are monochromatic.

Post-production professionals have performed proper calibrations on two or more of these newer high-definition displays. However, they noticed that despite identical colorimeter readings, the displays were visually mismatched. This outcome exacerbates color differences when making artistic decisions and originates from performing calibration with a simplified two-dimensional color space where points are represented using a pair of chromaticity coordinates.

## Display Calibration: Then and Now

Though illuminant technology is changing, the process of calibrating displays with three primaries remains generally the same. In short, the intensities of a display's red, green, and blue primaries are adjusted individually until they colorimetrically match a calibration target. For the display's white point, the target is usually the chromaticity of CIE Standard Illuminant D65.

CIE Standard Illuminant D65 is defined as a single SPD spanning human-visible wavelengths to represent the appearance of midday sun [2]. To obtain chromaticity coordinates of a source, it needs to be integrated with a set of color matching functions (CMFs), then normalized.

The chromaticity coordinates used to depict CIE Standard Illuminant D65, (0.3127, 0.3290), are obtained by integrating its SPD with the CIE 1931 2° CMFs. This particular set of CMFs is assumed to model human color vision. Today, many colorimeters used for calibration are built on the mathematics of the CIE 1931 2° CMFs.

Claims have been made that the CIE 1931 2° CMFs do not accurately predict color perception for a population of observers. Since 1931, many single-observer model CMFs have been developed, each claiming to more accurately predict color perception than the last. Creating additional color matching functions assumes that all observers are unique in their color perception. However, due to natural observer variability, no single mathematical model can accurately predict color for a population of observers.

Though observer variability is prevalent, this was not an issue in the phosphor-based CRT display era. The SPD of a typical CRT display (Figure 1) reveals red, green and blue primaries with wide bandwidths and noticeable overlap.

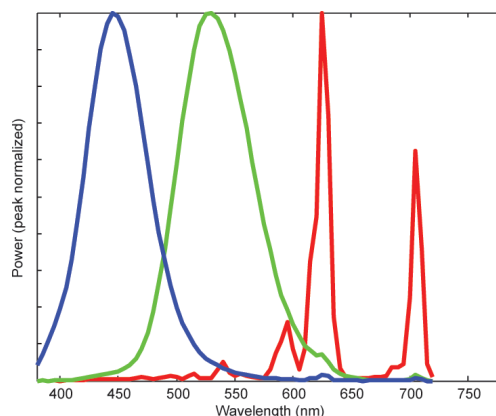


Figure 1. Spectral power distribution of a reference CRT display, color-coded according to display primary color.

Comparatively, the SPDs of professional high definition display, such as those in LED display primaries (Figure 2) or laser primaries (Figure 2) are narrower. Other displays, such as those lit with CCFL backlights (Figure 2), are spectrally distinct from CRT displays.

Though each of these displays can be tuned so that a colorimeter reports chromaticity coordinates identical to (0.3127, 0.3290), this involves adjusting the SPD of the display, which creates differences in appearances between observers with each observer integrating the signal uniquely. With the increased prevalence of new display illuminants, there has been an observed increase in variance of color perception as display primary bandwidth decreases.

## The Display Matching Simulation

Since observer variability is present, post-production facilities still seek a workaround for calibrating production displays.

Many colorimeters in use today do not account for observer variability, as they are designed solely to use the CIE 1931 2° CMFs. While this model does not account for observer variability, it can be used to measure and quantify it.

A simulation is designed which acknowledges the CIE Standard Illuminant D65 chromaticity target of (0.3127, 0.3290), and creates an offset chromaticity (unique to a given display's SPD) to visually satisfy a greater number of observers.

The simulation begins with the fully driven primary spectra of a CRT reference display, calibrated to (0.3129, 0.3290) when measured by the CIE 1931 2° CMFs. A number of additional CMFs then “view” the calibrated CRT spectra. Derived from the extremes of a diverse population of observers, each of these new CMFs represent a unique observer viewing the display.

Then, the high definition display is visually matched to the CRT reference display with respect to the new CMFs. Finally, the matched high-definition display is measured with respect to the 1931 2° CMFs. The magnitude of the difference between (0.3127, 0.3290) and the new pair of white point chromaticity coordinates is assessed.

## **The Psychophysical Display Matching Experiment**

To validate the results of the simulation, a CRT reference display, calibrated to (0.3127, 0.3290), was visually matched both to a CCFL display and LED display by 34 unique observers.

In a methods of adjustment experiment, observers were given a controller to modify the color appearance of the white point of the CCFL and LED displays using a stimulus subtending a 2° field-of-view. Based in color opponent-process theory, this controller gave observers the ability to adjust the redness, greenness, yellowness or blueness of the stimulus.

Observers were instructed to adjust the CCFL or LED displays until they believed that a visual match was achieved with the calibrated CRT reference. A colorimeter using the CIE 1931 2° CMFs was used to measure the chromaticity adjusted by the observer.

## **Results**

A significant variance in corresponding chromaticity estimates is immediately observed for both the CCFL and LED displays, most prominent when measured using an empirical assessment. Variance in the empirical assessment is to be expected when considering the presence of observer adaptation, measurement noise, and the limitations of the discrete color rendering system.

The simulated and empirical assessments of mean chromaticity offsets for the CCFL display bear only subtle resemblances with one another. Their mean chromaticity shift is transposed towards a bluish hue with varying magnitudes.

For the LED display, the simulated assessment and empirical assessment predict mean chromaticity offsets consistently with one another. While there is greater variability amongst real observers than simulated observers, variance in color difference between the mean simulated offset and mean observer offset is negligible. For both assessments, this mean offset is similar in direction and magnitude from the original chromaticity aim of (0.3127, 0.3290). The consistency in the means of both assessment methods indicate that the simulation proposed might be sufficient for determining a chromaticity offset for LED displays.

To extend this experiment to near-monochromatic primaries, a set of ITU-R BT.2020-compatible lasers were assessed using the simulation only. Compared to the results of the CCFL and LED displays, the magnitude of variability in simulated corresponding chromaticity offsets using laser primaries is significantly greater. Based on the results of the CCFL display and LED display, it

can be reasoned that an empirical assessment of a display with laser primaries would render even greater variance than its simulated assessment for the given population of observers.

Figure 2 depicts corresponding chromaticity offsets alongside the SPDs of a CCFL display, LED display, and laser primaries. The corresponding chromaticity offsets are encircled by ellipses encompassing corresponding chromaticity offsets valid for 95% of observers. Notably, the chromaticity coordinates of D65 white are also considered to be a statistically relevant part of the population.

In 2009, Sony performed a similar experiment in order to determine how to properly calibrate their reference OLED displays [3]. This followed a similar procedure as the display matching simulation. Their results suggested that using a single observer model (a modified version of the CIE 1931 2° CMFs), rather than a corresponding chromaticity offset, would render satisfactory results after empirical display assessments were made.

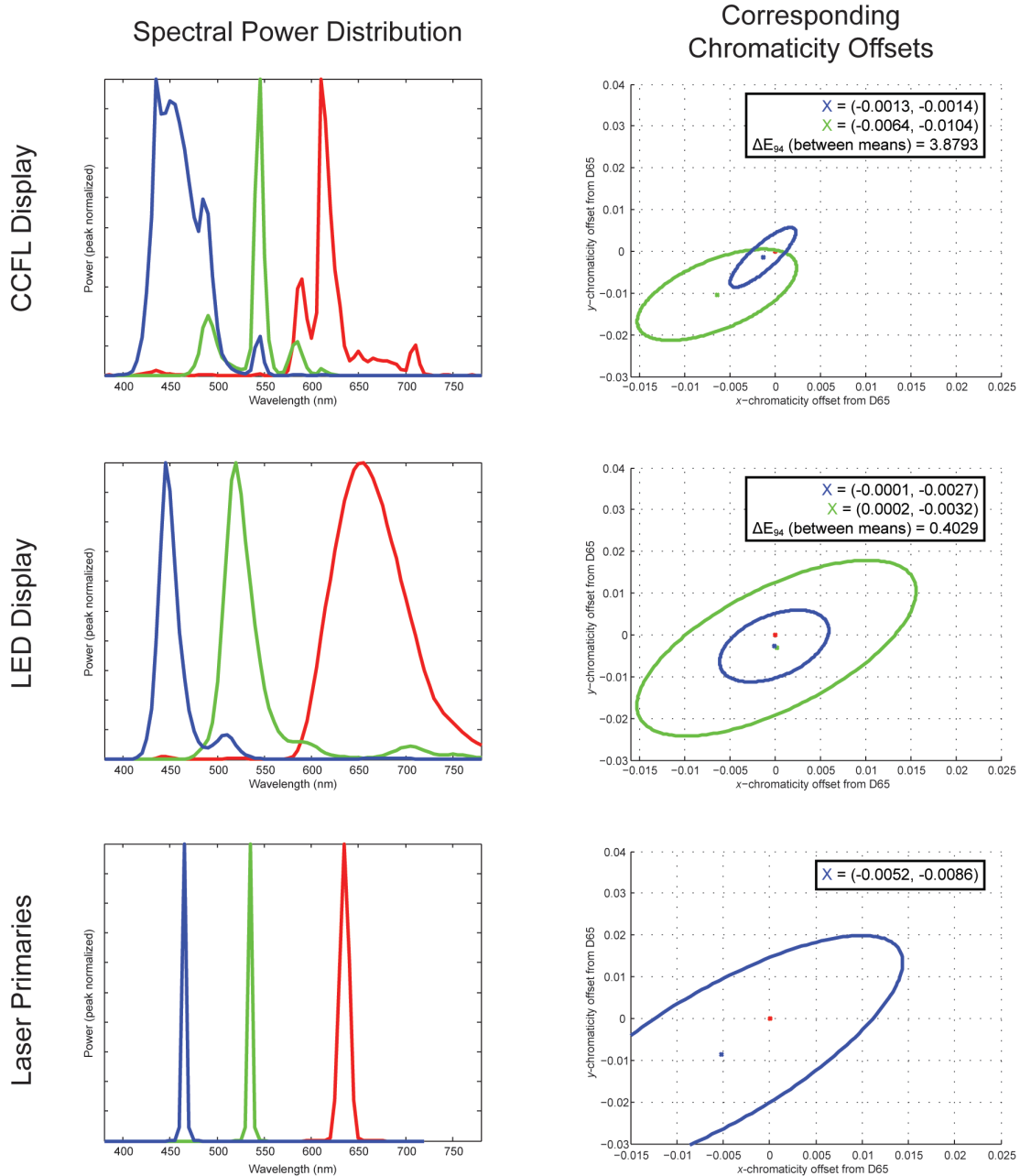


Figure 2. Spectral power distributions and corresponding chromaticity offsets for a CCFL display, LED display, and set of ITU-R BT.2020-compatible lasers. Simulated corresponding chromaticity offsets from (0.3127, 0.3290) and tolerance ellipses are illustrated in blue, empirically assessed corresponding chromaticity offsets and tolerance ellipses are in green. The chromaticity coordinates (0.3127, 0.3290) are marked in red.

## Conclusions

The results of both the simulation and empirical assessment reveal noticeable variances in observer color perception that are consistent with present research and publications investigating observer metamerism and variability.

Given the results of this experiment and the results published by Sony, it can be concluded that a simulated or empirically assessed offset can be used to modify traditional white point calibration procedures for LED and OLED displays. For CCFL displays, however, the methods proposed in this assessment may be less effective.

Observer variability differs greatly between the CCFL display and the LED display. This is consistent with the hypothesis that observer variability increases as display primary bandwidth decreases and is supported by simulation. Since observer variability is not best represented by traditional calibration methods, attention is brought to the existing standards and methodologies for calibrating displays.

The offset proposed in this assessment is designed to be integrated into production environments where display calibration is performed using a simplistic representation of colorimetry.

While the proposed method calls for a shifting of chromaticity coordinates for a more satisfactory representation of D65 white for a population of observers, it is important to reiterate that no chromaticity coordinate offset will render exact color matches for all observers. A single observer model is not wrong in its prediction of chromaticity; rather, it can be more appropriately classified as satisfactory or unsatisfactory for any single observer amongst a population.

For clarification, this simulation does not determine a best color matching function to view a display; rather, it simply provides the appropriate chromaticity coordinate offset to be used by post-production facilities utilizing colorimeters that report chromaticity with respect to the CIE 1931 2° CMFs.

## Recommendations

Given the need for a calibration standard for commercially-available, narrow bandwidth three-primary displays, and the cost of a spectroradiometer (necessary for this experiment), it is recommended for the display manufacturer to use a spectroradiometer to perform a single measurement of the fully-driven SPDs of the primaries of their displays when new primary illuminant technologies are used.

The manufacturer should then run the previously outlined simulation with a number of diverse observer models and compute a corresponding chromaticity offset with respect to the CIE 1931 2° CMFs. This offset should be recorded for each display model and delivered to consumers appropriately.

## Future Work

Displays commercially available today are manufactured with larger screen sizes than their predecessors. Further iterations of this experiment could involve an empirical evaluation where observers determine corresponding chromaticity offsets with stimuli that subtend a 10° field of

view. With such an experiment, even greater observer variability is to be expected given increased variations in color perception present in peripheral vision.

As display illuminant technologies become more advanced, display manufacturers will continue to push reproducible color gamut boundaries. One way to achieve such a gamut would involve the use of additional display primaries. Recent work by Long and Fairchild suggest the use of optimized ideal multispectral primaries for an increased likelihood of metameric image reproduction [4]. This would enable displays to render more spectrally relevant colors rendering satisfactory color reproduction.

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## References

1. Wolfe, Jeremy, Keith Kluender, and Dennis Levi. "The Perception of Color." In *Sensation & Perception*, 108-109. 2nd ed. Sunderland: Sinauer Associates, 2009.
2. "ISO 10526:1999/CIE S005-1998." International Commission on Illumination, 1998. Web. <http://www.cie.co.at/publ/abst/s005.html>.
3. Sony Corporation (2013 Feb 15). *Colour Matching Between OLED and CRT White Paper*. V1.0.
4. Long, David, and Mark Fairchild. "Optimizing Spectral Color Reproduction in Multiprimary Digital Projection."