Improved Display Color Measurements with the WP214 Imaging Spectral Colorimeter

Chad Greene, Tim Moggridge, Paul Prior
Westboro Photonics, Ottawa, Canada

Abstract
An innovative imaging colorimeter measurement system which corrects tristimulus images by referencing an integrated spot spectroradiometer is introduced. Improvements offered to the display test industry by the new measurement system over current colorimeter designs are verified by measurements with comparable instruments and the analysis of a modern mobile display.

Author Keywords
Uniformity; Color; Luminance; Chromaticity; Viewing Angle; Tristimulus Filter; Spectroradiometer; Colorimeter; Spectrometer.

1. Introduction
Traditional colorimeter instruments utilize a set of tristimulus filters in front of a detector to provide a color measurement of a scene. Whether the detector is a small photodiode, PMT, or an imaging CCD, the measurement accuracy is critically dependent upon how well the instrument matches the CIE tristimulus functions.

Common approaches to the construction and correction of an imaging colorimeter may include:

1. characterizing the spectral responsivity of the entire optical instrument such that the design of the tristimulus filter set can be optimized;

2. reducing the fitting errors of the tristimulus filters by one, or both of the following:
   a. increasing the number of unique glass layers in the absorbing filter stack;
   b. adopting costly thin-film deposition techniques;

3. placing the tristimulus filters in a collimated section of the instrument to reduce angle of incidence and filter path length differences;

4. mathematical post-processing of the measurements to create a vector correction in tristimulus space, or by using the four-color matrix method for correction [1, 2], both of which reference the tristimulus values from a spectroradiometer.

This paper reviews the advancements produced, and limitations remaining, when the aforementioned color accuracy improvement strategies are employed within imaging colorimeter systems. Additionally, a new class of imaging colorimeter, referred to as the WP214, references an integrated spot spectroradiometer, and is evaluated through display color accuracy tests. The color accuracy capabilities of this instrument are revealed through comparison measurements of a modern mobile display when measured by an external reference spectroradiometer, the Instrument Systems CAS140CT-151 with a telescope optical probe, and typical high resolution imaging colorimeters, the WP640 and WP690. The imaging colorimeters used the common colorimeter construction approaches 1 and 2, and the WP640 utilized the measurement processing approach 4. The WP214 instrument utilized all four approaches listed earlier.

2. WP214 Imaging Spectral Colorimeter
The WP214 imaging spectral colorimeter combines an integrated imaging tristimulus colorimeter, spectroradiometer, beam collimating optics, and interchangeable lens options into a single portable system (see Figure 1). Through the use of a beam splitter, the imaging colorimeter1 and spot spectroradiometer simultaneously measure the same scene. A

1 The WP214 integrated colorimeter produces an image with 0.5 Megapixels resolution.
tristimulus correction is then derived from the spectral measurement data and applied to all tristimulus measurement pixels of the imaging colorimeter.

Since the WP214 measurement system simultaneously leverages imaging colorimeter and spectroradiometer technologies, its color measurement performance was evaluated against both types of systems.

The test configuration and methodology for each type of measurement scenario are detailed below.

**On-Axis Lu’v’**

The display under test (DUT) was fixtured on a mechanical stage which allowed it to be translated in a plane perpendicular to the optical axis of each measurement system. The imaging field-of-view (FOV) for each instrument, defined by a calibrated lens and working distance configuration (see Table 1), was selected such that any off-axis spot measurements (herein areas of interest, or AOIs) of the DUT would reside within a narrow cone angle (see Figure 2).

### 3. Test Configuration & Methodology

Three types of measurement instruments were used to acquire two types of measurements of the display under test (DUT): on-axis Lu’v’, and Lxy as a function of angle of observation (known herein as viewing angle measurements).

All measurement instruments used to acquire the data were calibrated against the same absolute spectral radiance standard, thus minimizing uncertainty in the calibration traceability chain.

During the on-axis Lu’v’ measurement scenario, each measurement system acquired a set of color measurements of the DUT when it was configured to completely display RGB white (255, 255, 255), red (255, 0, 0), green (0, 255, 0), and blue (0, 0, 255). While the measurement programme was identical for the viewing angle measurement scenario, only color measurements of the DUT set to white (255, 255, 255) are presented here.

---

**Table 1.** Lens selections and calibrated working distances (WD) for each system used to measure the DUT. System configurations used for the viewing angle measurements are denoted (VA).

<table>
<thead>
<tr>
<th>Measurement System</th>
<th>Lens²</th>
<th>WD [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOP100 + CAS140CT</td>
<td>50mm</td>
<td>100</td>
</tr>
<tr>
<td>WP214-2D</td>
<td>50mm</td>
<td>100</td>
</tr>
<tr>
<td>WP640</td>
<td>28mm</td>
<td>25</td>
</tr>
<tr>
<td>WP214-Conometer (VA)</td>
<td>Conometer</td>
<td>1</td>
</tr>
<tr>
<td>WP690 (VA)</td>
<td>24mm</td>
<td>100</td>
</tr>
</tbody>
</table>

---

² All lenses were Nikon Nikkor, with the exception of the Conometer lens.
The reference spectroradiometer acquired on-axis measurements of the DUT for each of the color settings at each of the AOI positions shown in Figure 2. The WP214 and WP640 each acquired on-axis measurements aligned to the center AOI for each of the DUT color settings. WP214 color measurement statistics derived from the remaining four AOIs were taken off-axis at an angle of 1.5°.

Color measurements acquired by the WP640 were reported with and without the application of the “Four-Color Matrix Method for Correction of Tristimulus Colorimeters” [1, 2], which utilized the tristimulus statistics acquired by the reference spectroradiometer as inputs.

Viewing Angle Lxy:

The DUT was fixtured on a modified mechanical stage which allowed it to rotate about an axis located within the plane of the display. The field of view for the WP690 imaging colorimeter (see Table 1) was selected such that a large number of imager pixels would cover the full DUT. Due to the change in measurement perspective as the DUT was rotated, the number of WP690 pixels used to measure the DUT ranged from 305,000 to 45,000 pixels, at 0° and 80° orientations, respectively.

Similarly, the FOV of the reference spectroradiometer (see Table 1) was chosen such that its sampling spot would contain a large number of DUT pixels. The number of DUT pixels contained in the reference spectroradiometer sampling spot ranged from 3100 pixels at 0° to 71,000 pixels at 80°.

Due to the large imaging FOV of the WP214-Conometer, its working distance (see Table 1) was selected such that its entire FOV was filled by the largest number of DUT pixels. Thus the diameter of the FOV of the WP214-Conometer covered approximately 720 DUT display pixels.

Throughout all measurements, the same DUT pixel was used as the alignment reference location for all three measurement systems. This ensured that the sampling areas of each system were always centered on the same DUT pixel location.

Finally, unlike the WP640, the WP690 measurements were not color corrected to the reference spectroradiometer. The reason for this was that independent comparisons of the viewing angle measurement performance of the WP214-Conometer and WP690 versus the reference spectroradiometer were desired.

4. Results

The on-axis display color measurement performance of the WP214 and WP640 instruments was evaluated through a 1976 CIE \( (u',v') \) chromaticity (CIELUV) residual analysis with the reference spectroradiometer. The mean chromaticity difference statistic, \( \Delta u'v' \), between the WP214 and reference spectroradiometer was determined for each AOI and display color setting, where \( \Delta u'v' \) is defined as:

\[
\Delta u',v' = \sqrt{(u'_{\text{ref}} - u'_{\text{sys}})^2 + (v'_{\text{ref}} - v'_{\text{sys}})^2}
\]  

and the subscripts \( \text{ref} \) and \( \text{sys} \) correspond to the reference spectroradiometer and WP214 respectively. The same statistical analysis was performed for the WP640 compared to the reference spectroradiometer, but for the on-axis measurements only.

Figure 3 shows the on-axis measurement results of \( \Delta u'v' \) for the WP214 (blue squares) and WP640 (red circles) as compared to the reference spectroradiometer for each of the four DUT color settings. The WP214 data also includes range bars which indicate the variation of \( \Delta u'v' \) for the off-axis AOIs shown in Figure 2.

Since the WP214 integrated spectroradiometer is used to correct the WP214 integrated colorimeter, the accuracy of the WP214 is limited by the accuracy of the spectroradiometer. A comparison of spectra acquired by the WP214 integrated spectroradiometer and the reference spectroradiometer is shown for a white display setting in Figure 4.

Figures 5 - 8 show the CIELUV chromaticity coordinates for on-axis spot measurements by each of the measurement systems for display settings of white, red, green, and blue respectively.
Figure 3. Δu’v’ values for the WP214 (blue squares) and color-corrected WP640 (red circles) for the white and primary color display settings.

Figure 4. Spectra acquired by the WP214 integrated (dashed red curve), and reference (solid green curve) spectroradiometers for a white DUT setting.

Figure 5. CIELUV on-axis color measurements acquired by the non–color-corrected WP640 (●), color-corrected WP640 (○), WP214 (■), and reference spectroradiometer (□), for a white DUT setting.

Without the application of the color correction, typical on-axis color residuals for the WP640 ranged from Δu’v’ ~ 0.0051 to 0.0426, with the worst correlation to the reference spectroradiometer occurring for a red DUT setting (see Figure 6). When the color correction was applied to the WP640 measurements, the typical on-axis color residuals were reduced to Δu’v’ ~ 0.0007 to 0.0023 (see Figure 3).

Red

Figure 6. CIELUV on-axis color measurements acquired by the non–color-corrected WP640 (●), color-corrected WP640 (○), WP214 (■), and reference spectroradiometer (□), for a red DUT setting.

Green

Figure 7. CIELUV on-axis color measurements acquired by the non–color-corrected WP640 (●), color-corrected WP640 (○), WP214 (■), and reference spectroradiometer (□), for a green DUT setting.

Blue

Figure 8. CIELUV on-axis color measurements acquired by the non–color-corrected WP640 (●), color-corrected WP640 (○), WP214 (■), and reference spectroradiometer (□), for a blue DUT setting.
The display under test viewing angle measurements acquired by the WP214-Conometer, WP690, and reference spectroradiometer, were analysed in CIE 1931 XYZ (Lxy) space. The WP690 and reference spectroradiometer sampled the DUT as it was rotated in 10° increments about an axis within the plane of the display. The technology utilized by the WP214-Conometer allowed it to acquire viewing angle measurements in all directions\textsuperscript{3}, simultaneously, thus providing higher resolution viewing angle information about the display under test. Horizontal viewing angle cross sections\textsuperscript{4} were compiled from the Lxy measurements from each measurement instrument, and are shown in Figures 9 - 11.

The imaging pixel areas covering the full measured display under test (which varied in size as discussed in §3) were taken to be the sampling areas for the WP690 Lxy viewing angle measurements. The sample mean of each of these areas was recorded and plotted as the black dots in Figures 9 - 11, which also have error bars representing the standard deviations of the sampling areas. The spot measurements acquired by the reference spectroradiometer are plotted as the solid red curve, and the solid blue curve in Figures 9 - 11 represents the horizontal viewing angle cross section extracted from the Lxy measurements acquired by the WP214-Conometer.

Three measurement post-processing actions were applied to the WP214-Conometer results, leading to the final horizontal cross sections of Lxy:

(a) Moiré present in the original measurement data was minimized or removed via the application of a band rejection filter in the spatial frequency domain;

(b) The “thickness” of the horizontal cross section was 10 imager pixels, leading to averaging of the cross section data in the direction perpendicular to the horizontal cross section;

(c) Application of a boxcar smoothing filter 5 pixels in length along the direction of the horizontal cross section.

\textsuperscript{3} The angular resolution of the WP214-Conometer was approximately 0.3° in (Φ, θ).

\textsuperscript{4} Horizontal viewing angle cross sections were compiled from 17 sampling areas representing polar coordinates of (Φ,θ) = [ (180°,80°), (180°,70°), …, (180°,10°), (0°,0°), (0°,10°), … (0°,70°), (0°,80°) ].

There was remarkable agreement across the DUT viewing angle measurements acquired by the three independent measurement systems, as indicated by the shapes, amplitudes, and offsets of the curves shown in Figures 9 - 11. As shown in Figure 9, the on-axis luminance amplitude measured by the reference spectroradiometer was 6% higher than the values measured by the WP214-Conometer and WP690. However, for angles greater than 10° off-axis, all three systems agreed to within 5%.
The shapes of the horizontal cross sections in chromaticity x or y viewing angle spaces (see Figures 10 and 11) demonstrated less agreement than those in the luminance viewing angle space. The general trends agreed, however there were many inflections and peaks present in the WP214-Conometer horizontal cross sections which were not apparent in the reference spectroradiometer, nor in the WP690 horizontal cross sections.

This is most likely attributed to the lack of sampling resolution utilized in the reference spectroradiometer and WP690 viewing angle measurements, each of which acquired Lxy measurements of the DUT in 10° increments. In contrast, after accounting for the statistical impact of the boxcar smoothing filter, the sampling resolution of the WP214-Conometer was effectively six times larger, enabling it to detect smaller scale patterns in the viewing angle properties of the display under test. As such, the maximum deviation between the WP214-Conometer and the reference spectroradiometer was no more than 0.009 and 0.01 for chromaticity x and y horizontal cross sections, respectively.

5. Discussion
The on-axis and viewing angle color differences observed between the measurements acquired by the WP214 imaging spectral colorimeter, WP640 and WP690 imaging colorimeters, and the reference spectroradiometer, for each of the DUT color settings, may have been influenced by:
(a) DUT instabilities which varied over time and as a function of temperature;
(b) moiré effects within the WP640 and WP214-Conometer measurements;
(c) varied path lengths for light rays transmitted through the tristimulus filters on-axis versus through wider angles;
(d) additional stray light within the WP214 integrated spectroradiometer.

Each of these effects is discussed in further detail below.

(a) DUT Instabilities.
The display under test was an LED-backlit high-resolution LCD mobile phone display which was set to the maximum brightness level. The stability of its optical output was uncertain as it may have changed due to the use of multiple test patterns, thermal drift, or possibly the state of the battery charge.

Since each system measured the display in sequence, there was a time difference, for example, between when the WP214 imaged the DUT, and when the reference spectroradiometer inspected the DUT. Thus any luminance and color differences observed between each of the measurement systems may have been influenced by the DUT instabilities.

(b) Moiré Effects.
In this study, moiré is a re-sampling phenomenon resulting from using a discretized imaging device (i.e. a CCD) to measure a discretized luminous source (i.e. the DUT). With respect to the imaging tests described herein, any moiré patterns produced were strongly dependent upon:
- DUT pixel size and spatial arrangement;
- Imager pixel size and spatial arrangement;
- Separation distance between the DUT and measurement system;
• Rotation angle between the DUT and measurement system.

Several techniques exist for the prevention and/or removal of moiré in 2D measurements including:
• de-focusing of the imaging system;
• the introduction of a rotation angle or optimal working distance between the imaging system and the DUT potentially minimizing the production of spatial sampling harmonics;
• the application of spatial filtering to the measurement data;
• the application of a band rejection filter in the spatial frequency domain.

The lower resolution WP214 had no apparent moiré patterns present in its measurement data when it was used to acquire on-axis measurements of the DUT. However, when the WP214-Conometer was used to acquire viewing angle measurements of the DUT, moiré patterns were visible and removed using a band rejection filter in frequency space.

The higher resolution WP640 had clearly visible moiré patterns in its color measurement data (see Figure 12). As a result of the measurement spot size (56 pixels diameter; see Figure 2) being much larger than the spatial period of the moiré patterns, a simple 15 pixel diameter mean filter was applied to the measurements to smooth over any moiré patterns present.

The even higher resolution WP690 viewing angle measurements did not suffer from the presence of moiré patterns. This is explainable due to the presence of a rotation angle between the plane of the CCD inside of the WP690 and the plane of the display under test. The introduction of the perspective geometry (tilted angle of observation) reduced the likelihood of generating spatial harmonics which would have manifested themselves as moiré patterns within the measurement data.

(c) Varied Path Lengths for Light Rays.

The tristimulus filters found in the WP214, WP640, and WP690 filter wheels are laminated layers of glass of different refractive indices and spectral transmissions. A filter is typically 5 – 7mm thick and 25 to 31mm in diameter – large enough to transmit all of the desired light from the lens system to the CCD sensor area. The WP214 assembly is designed such that the filters are sequentially placed within the collimated space of the instrument boresight. In this way the optical path for each ray of light through any tristimulus filter is nearly normal.

The WP640 and WP690 imaging colorimeters do not have a collimated light space between the lens and the sensor. Light rays focused onto the corner of the sensor will have traversed a longer path length through a tristimulus filter than those focused onto the center of the sensor. Thus the tristimulus filtering will vary for different points on the sensor. A method to spatially apply the four-color matrix method for correction has yet to be devised, hence only on-axis measurements from the WP640 were color-corrected.
(d) WP214 Stray Light.

The removal of stray light in a spectrometer system is a common problem for which many hardware and software solutions have been developed [3, 4].

Figure 4 shows logarithmically-scaled spectra acquired by the WP214 and the reference spectroradiometer with the DUT set to white. At both the blue and red ends of the spectrum from the WP214, there is an upturn in the measurement as compared to the reference spectroradiometer. These upturns are due to stray light found within the spectrometer of the WP214. The stray light adds chromaticity error, but this correlation was determined to be $\Delta u'v' \sim 0.0013,$ based upon the average of the four on-axis display color measurements (see Figure 3).

6. Conclusions and Future Work

The WP214 demonstrated a color correlation better than $\Delta u'v' \sim 0.0035$ for both on- and off-axis measurements (non-viewing angle). The on-axis measurements correlated within $\Delta u'v' \sim 0.0025,$ and were mostly better than the four-color corrected WP640 imaging colorimeter.

All three measurement instruments were in agreement to within 6% for the luminance viewing angle measurements of the display under test set to white. The largest deviation in the chromaticity viewing angle measurements between the WP214-Conometer and the reference spectroradiometer was less than 0.01. The maximum deviation of the WP690 from the reference spectroradiometer was less than 0.008 for all chromaticity measurements.

Future work may involve:

1. Acquiring a better understanding of the precision and accuracy of all instruments used in these tests. This would be done by measuring temperature stabilized LED sources of various colors rather than a mobile phone display;
2. Determining the impact on $\Delta u'v'$ by various levels of stray light and establishing tolerance limits;
3. Developing a software-based correction to detect and remove stray light;
4. Innovating the “Four-Color Matrix Method for Correction of Tristimulus Colorimeters” to be spatially, and/or angularly dependent.

7. References


