Digital imaging colorimeter for fast measurement of chromaticity coordinate and luminance uniformity of displays

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ABSTRACT

Color and luminance uniformity testing of displays is often limited to fewer than ten measurement points on the display surface due to the length of time necessary to make a single point measurement. A CCD-based digital imaging tristimulus colorimeter has been developed which is capable of measuring luminance and chromaticity coordinates at over one million spatial locations in several seconds. The Four-Color Method of colorimeter calibration, recently proposed by NIST, has been employed and found to be superior to single point calibration using Illuminant A. Color and luminance uniformity of a CRT and LCD display were measured using the new digital imaging tristimulus colorimeter and a diode array spectrometer. The data show that chromaticity coordinate and luminance measurements using the CCD-based imaging tristimulus colorimeter compare favorably with the point measurements obtained using a diode array spectrometer over the color gamut of a CRT and LCD display.

Keywords: Photometry, colorimetry, video photometer, colorimeter, CCD, display testing, luminance uniformity.

1. INTRODUCTION

The application of charge coupled device (CCD) technology in the fields of photometry and colorimetry has been acknowledged by the National Institute of Standards and Technology as one of the most interesting development efforts for spectral radiometry and photometry in the coming years [1]. The benefits to industry due to the detector array approach of CCD photometry and colorimetry are multifarious and substantial. Testing of display systems routinely involves the use of luminance meters and colorimeters, which employ a single detector and are therefore classified as 'spot photometers' or 'spot colorimeters'. The advantage of using a CCD array detector is chiefly that the number of detectors for a single measurement can be very large (in excess of $1x10^6$). So, rather than taking many separate spot measurements of a display device sequentially, having to move the spot detector for each measurement point, CCD photometry and colorimetry measurement systems are able to image the entire display onto many detectors at once thereby capturing many thousands or millions of points in several seconds. In addition to the substantial savings in time for measuring multiple test points on a display, the CCD photometer and colorimeter offers the capability of measuring more data points than would otherwise be possible in a reasonable amount of time during the engineering and quality assurance phase of display system design and production.

2. THE CCD PHOTOMETER / COLORIMETER SYSTEM

We have developed a CCD photometer / colorimeter system capable of employing a variety of CCDs ranging from 512 x 512 pixels to 3072 x 2048 pixels in resolution. The ProMetric® Color CCD Light and Color Measurement system consists of a 16-bit CCD camera and windows-based software for camera control and data analysis. A schematic diagram and photograph of the ProMetric® Color CCD Light and Color Measurement System is shown in Figure 1.

In this system, light from a display device under test enters the imaging lens, passes through a lens aperture, through a color filter in a computer-controlled filter wheel, and through a mechanical shutter before being imaged onto the CCD array. This particular system utilized a 512x512 pixel CCD and a 2-stage Peltier cooling system using two back-to-back thermo-electric coolers (TECs) to control the temperature of the CCD array. The cooling of the CCD allows us to operate the CCD at 16-bits analog to digital conversion with approximately 2 bits of noise (i.e. 4 grayscale units of noise out of a possible 65,536 maximum dynamic range). A 16-bit CCD implies that up to 2^{16} or 65,536 grayscale levels of dynamic range are available to characterize the amount of light incident on each pixel.

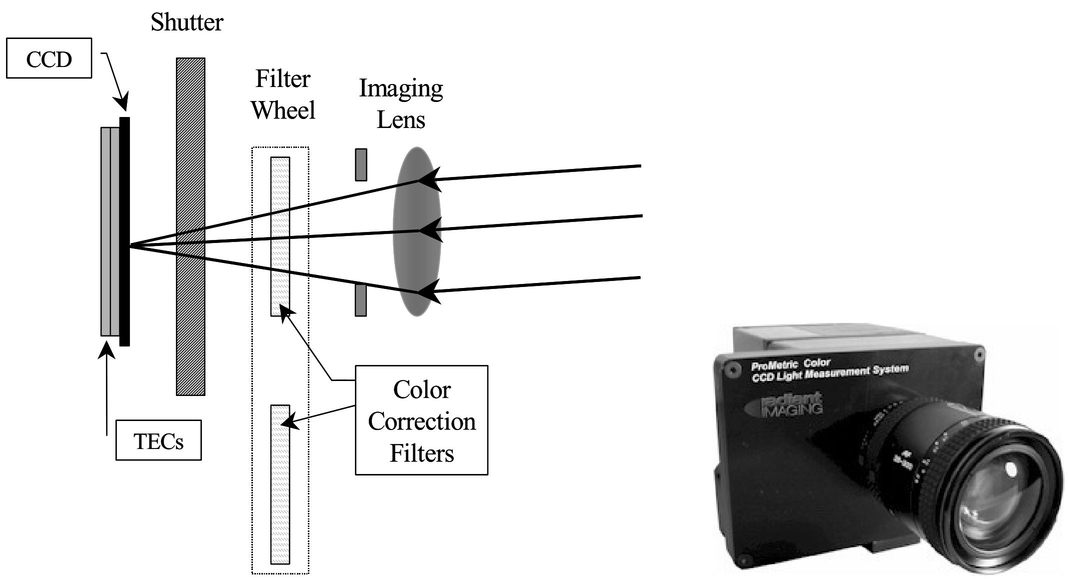


Figure 1. Schematic and photograph of the CCD Photometer and Colorimeter Digital Camera

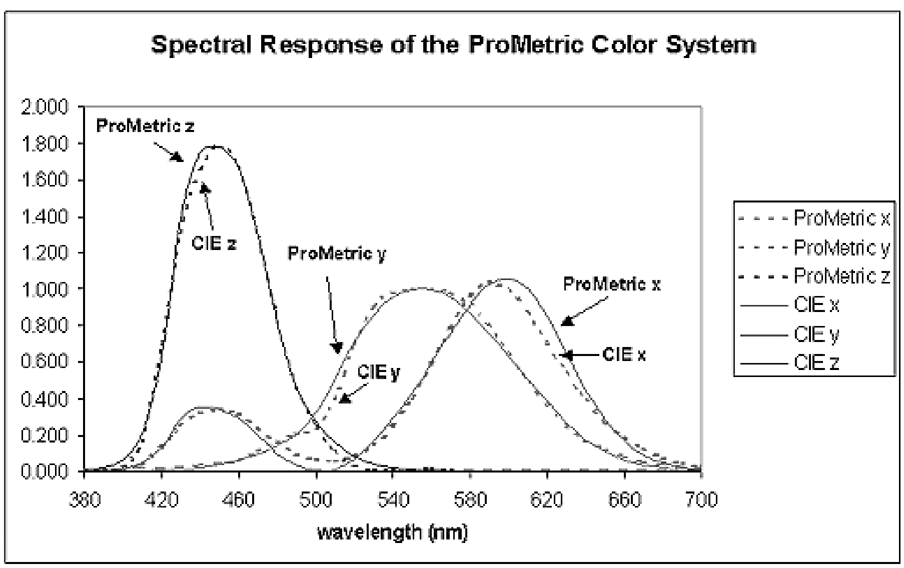


Figure 2. The spectral response of the ProMetric® Color System

There are three filters contained within the computer-controlled filter wheel. The spectral transmittance of these filters was specifically designed to match the spectral transmission characteristics of the imaging lens and CCD of the system so that the combined lens-filter-CCD spectral response would be as close as possible to the CIE 1931 2 degree observer color matching functions. The spectral response of our system along with the CIE color matching functions is shown in Figure 2. The computer-controlled camera records three images of a display under test using the three filters sequentially. Once the system has been properly calibrated, the luminance value and CIE 1931 chromaticity coordinates may then be determined from each pixel within the image using the computer software.

3. CALIBRATION

As with any photometer or tristimulus colorimeter, the CCD system must be properly calibrated to yield measurements in units of luminance and CIE chromaticity coordinates. In addition to normal calibration procedures for a single detector instrument, the fact that the CCD system is an imaging system requires special consideration for luminance calibration. In order to calibrate the CCD system, the illuminance incident on the CCD must be "flat fielded" so that the response of the CCD pixels accurately represents the luminance of a device under test. In Figure 3, a uniform luminance light source is located at the object plane of an imaging lens and a CCD is located at the image plane. This diagram is useful for calculating the illuminance E at an image plane due to a uniform luminance source having luminance L. As we shall see, the illuminance E due to the uniform luminance light source is not constant and therefore the CCD response must be corrected.

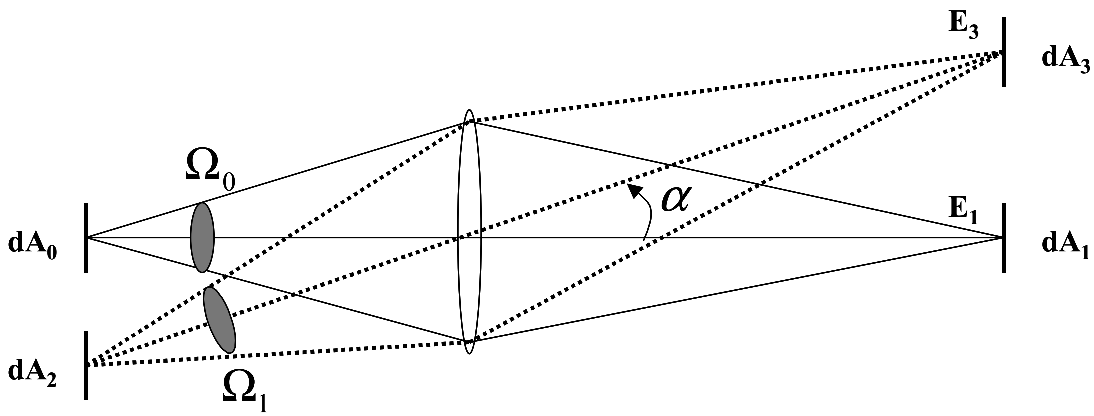


Figure 3. Diagram for calculating illuminance at an image plane due to a uniform luminance source.

Both infinitesimal emitting areas dA_0 and dA_2 are Lambertian emitting sources with luminance L_0. The illuminance at dA_1 is due to the flux emitted from dA_0 and collected by the imaging lens which focuses that flux onto the surface dA_1. Similarly, the illuminance on dA_3 is due to the flux emitted from dA_2 and collected by the imaging lens which focuses that flux onto the surface dA_3. For a perfectly transmitting and perfectly corrected lens, the on-axis illuminance E_1 due to the Lambertian emitting surface of area dA_0 is given by:

(1) $$E_1 = L_o \frac{dA_0}{dA_1} \Omega_0 .$$ (*see for example [6,7]*)

However, the same illuminance is not present at dA_3 since the total amount of flux collected from dA_2 by the imaging lens is smaller due to the smaller solid angle subtended by the imaging lens Ω_1 and due to the fact that the illuminance on dA_3 is spread over a larger area than the on-axis case (since the angle of incidence is not normal to the surface at dA_3). The off-axis illuminance E_3 due to the Lambertian emitting surface with area dA_2 is given by:

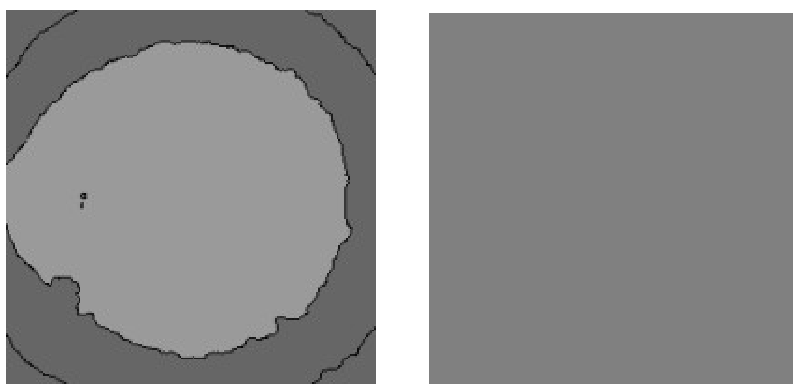
(2) $$E_3 = \frac{L_0 dA_2 \Omega_1 \cos\alpha}{dA_3 / \cos\alpha} = \frac{L_0 dA_2 \Omega_1 \cos^2\alpha}{dA_3} = L_0 \frac{dA_2}{dA_3} \Omega_0 \cos^4\alpha .$$

It can be seen from equation (2) that even in the case of a perfectly corrected optical system with a perfectly transmitting lens, the illuminance on the image plane is not constant for a constant luminance source, but falls off as the fourth power of the cosine of the field angle. For a real camera, the illuminance distribution on the image plane is further affected by absorption of the imaging lens glass and filters as well as vignetting, internal reflections, scattered light, lens distortion and lens aberrations. In order to account for all of these potential sources of error, the CCD must be empirically corrected (flat fielded) during the calibration procedure.

The CCD system was calibrated for luminance units by using a uniform luminance light source. The CCD camera was placed a distance of 1.0 meters away from the uniform luminance light source and a calibration image acquired. A software algorithm was developed which calculated a pixel by pixel correction matrix K, for the CCD. Since the 512 x 512 matrix of CCD pixel grayscale values M and the 512 x 512 matrix of luminance values L of the uniform luminance calibration source are known, K may be calculated from equation (3).

$$M \cdot K = L \quad (3)$$

The matrix of constant luminance values L was determined by using a NIST traceable luminance meter to measure the luminance at the center and normal to the uniform luminance surface of our calibration source. The correction matrix K was then calculated and stored as a luminance calibration file. Figure 4 shows the resultant iso-illuminance plots from the CCD of the uniform luminance light source with and without the correction matrix applied. Once the CCD was successfully flat fielded, the luminance values of the Diode Array Spectrometer (DAS) and the CCD system were then scaled, for the sake of comparison, by using a measurement from a NIST traceable spot luminance meter of the display under test.



without correction matrix   with correction matrix

FIGURE 4. Iso-illuminance distributions on the CCD with and without the correction matrix applied.

The color calibration of the system was performed in two ways. First, the CCD system was calibrated using a NIST traceable Illuminant A light source. The CCD camera captured images of the illuminant A light source using the red, green, and blue filters and the known chromaticity coordinates along with the ratio of X1/X2 were entered into the ProMetric® software.

The second method of color calibration employed was the Four-Color Matrix Method for correction of tristimulus colorimeters developed by NIST [3,4] specifically for display testing. The Four-Color Matrix Method calculation of Ohno and Hardis [3] was programmed into the ProMetric® software. The algorithm requires that the camera capture images of a color display with red, green, blue and white colors displayed on the screen. The colors emitted from the display under test were measured using a DAS and the resultant chromaticity values for each color were entered into the ProMetric® software. The software calculated a color correction matrix via the method of Ohno and Hardis [3]. This 3 x 3 color correction matrix was then multiplied by the original 3 x 3 illuminant A calibration matrix and the resultant matrix used to calculate chromaticity coordinates of the display under test. This procedure was used for both the CRT and LCD display since the effectiveness of the 4-Color Matrix Method depends on the spectral characteristics of the colors [3].

It is worth noting that the best way to calibrate a CRT monitor using the 4-Color Matrix Method is to use a monochrome tube with only 1 color phosphor present for the calibration images of red, green, and blue. This would require four separate monochrome tubes for the calibration procedure. Philips has developed a specific tube called a Mondrian tube which simplifies the calibration procedure by requiring only one tube. The special Mondrian tube is constructed such that in each quadrant of the tube only one basic phosphor is present. As basic colors, Philips used red, green, blue and a specific white. The tube has the advantage that the chromaticity in each segment is not influenced by internal reflections because only one phosphor is present at each quadrant. In order to avoid extreme levels of luminance, the normally used shadow-mask is still present although not being necessary for color selection but only for luminance control. This tube allows for one calibration image to be captured and can greatly simplify the color calibration procedure for CRT tubes.

4. EXPERIMENTAL SET-UP

Both a CRT monitor and LCD monitor were tested for luminance uniformity and CIE chromaticity coordinates. The ProMetric® system was positioned a distance of 156 inches away from the surface of the CRT and a distance of 200 inches from the LCD as shown in Figure 5. The CRT under test was a DELL Ultrascan M990 computer monitor. The active matrix LCD under test was the display of a Compaq Armada 6500 laptop computer.

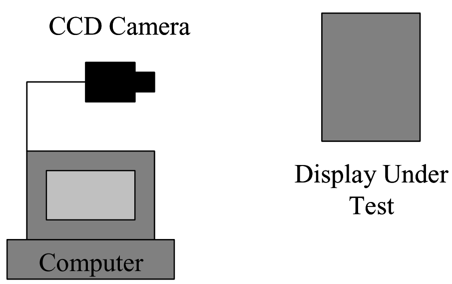


Figure 5. Experimental set-up for testing display devices using a CCD Light and Color Measurement System.

Three experiments were performed with the CRT and LCD display device. First, luminance uniformity of the CRT and LCD displays, each with a white screen, was measured following the procedures of VESA Display Measurement Standard version 1.0 section 306 [5] using the nine test points shown in Figure 6. Second, the chromaticity coordinates at the center of the CRT and LCD screens were measured using test patterns from the VESA Flat Panel Display Measurement Standard version 1.0 using the Illuminant A color calibration and then with the 4-Color Matrix Method calibrations. The test patterns for the chromaticity data included full-screen color slides in PowerPoint format for White, Blue, Red, Green, Cyan, Magenta and Yellow. The relative color outputs of the test patterns are shown in Table 1.

Color	Red	Green	Blue
Black	0	0	0
Red	255	0	0
Green	0	255	0
Blue	0	0	255
Cyan	0	255	255
Magenta	255	0	255
Yellow	255	255	0
White	255	255	255

Table 1. Relative outputs of displays for colors tested

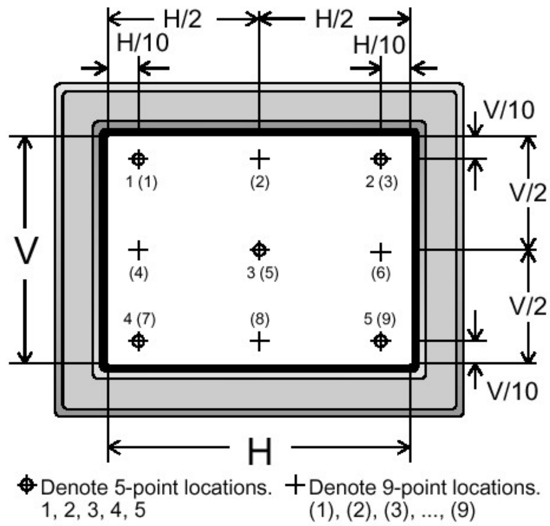


Figure 6. The nine points measured for luminance uniformity. [5]

5. RESULTS

Iso-luminance diagrams of the white screen under test for the CRT and LCD displays are shown in Figures 7 and 8 respectively. The results for the CRT and LCD display uniformity measurements are shown below in Tables 2 and 3 respectively. The data show an average percent difference between the DAS and the ProMetric® CCD Light and Color Measurement system of 2% for the luminance values of the CRT and 1% for the LCD display.

Iso-plot diagrams of the x and y chromaticity coordinate of the white screen under test for the CRT and LCD displays are shown in Figures 9 through 12. The results for CIE 1931 chromaticity coordinate (x,y) measurements with the DAS and the ProMetric® CCD Light and Color Measurement System calibrated to illuminant A are shown below in Tables 4 and 6 for the CRT and LCD display respectively. The average (x,y) chromaticity coordinate difference between the DAS and the ProMetric® system with Illuminant A calibration for the CRT was (0.014, 0.012) with a standard deviation of (0.011, 0.011) and for the LCD display, (0.017, 0.021) with a standard deviation of (0.010, 0.020).

The results for CIE 1931 chromaticity coordinate (x,y) measurements with a DAS and a ProMetric® CCD Light and Color Measurement System calibrated using the Four-Color Matrix Method of color calibration show a marked improvement over the results with Illuminant A calibration. This data is shown in Tables 5 and 7. The average (x,y) chromaticity coordinate difference between the DAS and the ProMetric® system for the CRT was (0.003, 0.003) with a standard deviation of (0.002, 0.002) and for the LCD display, (0.001, 0.002) with a standard deviation of (0.002, 0.003).

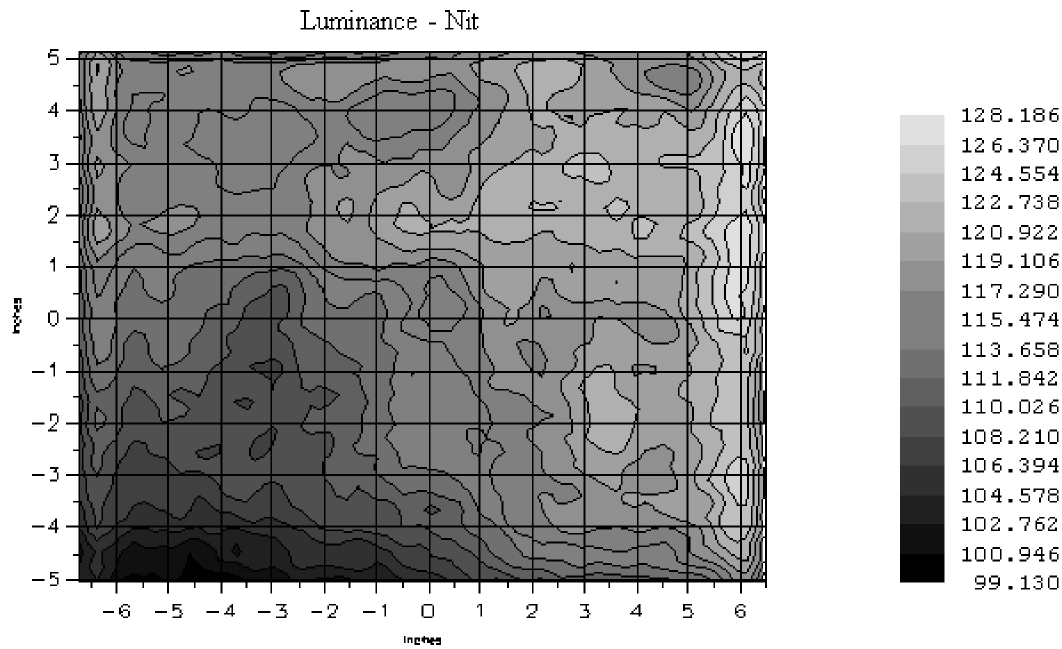


Figure 7. Iso-Luminance plot of the luminance of a white CRT screen taken with a CCD Light and Color Measurement System.

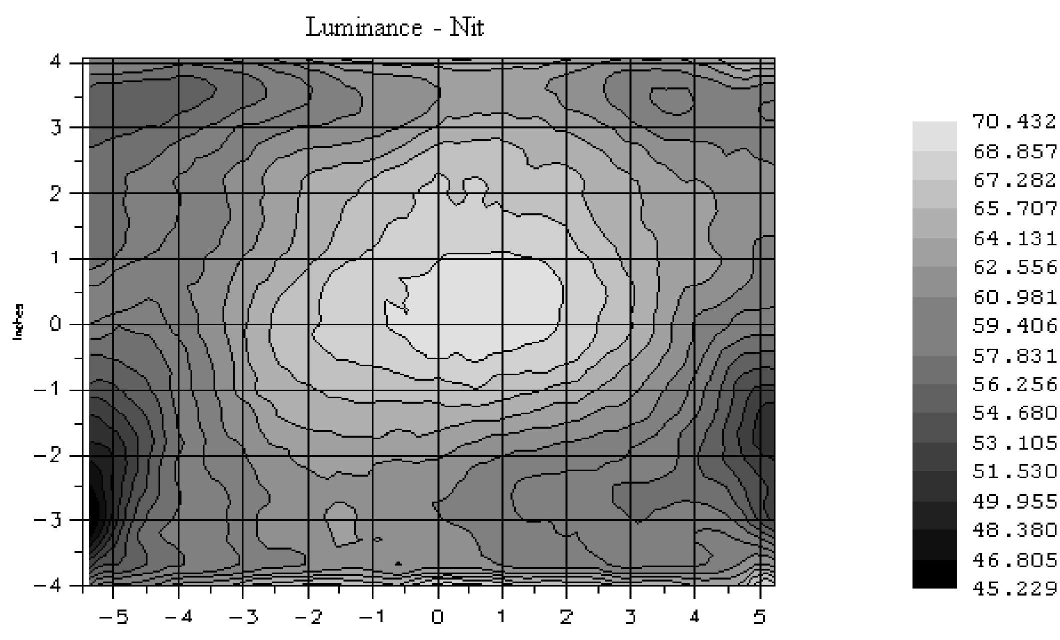


Figure 8. Iso-Luminance plot of the luminance of a white LCD screen taken with a CCD Light and Color Measurement System.

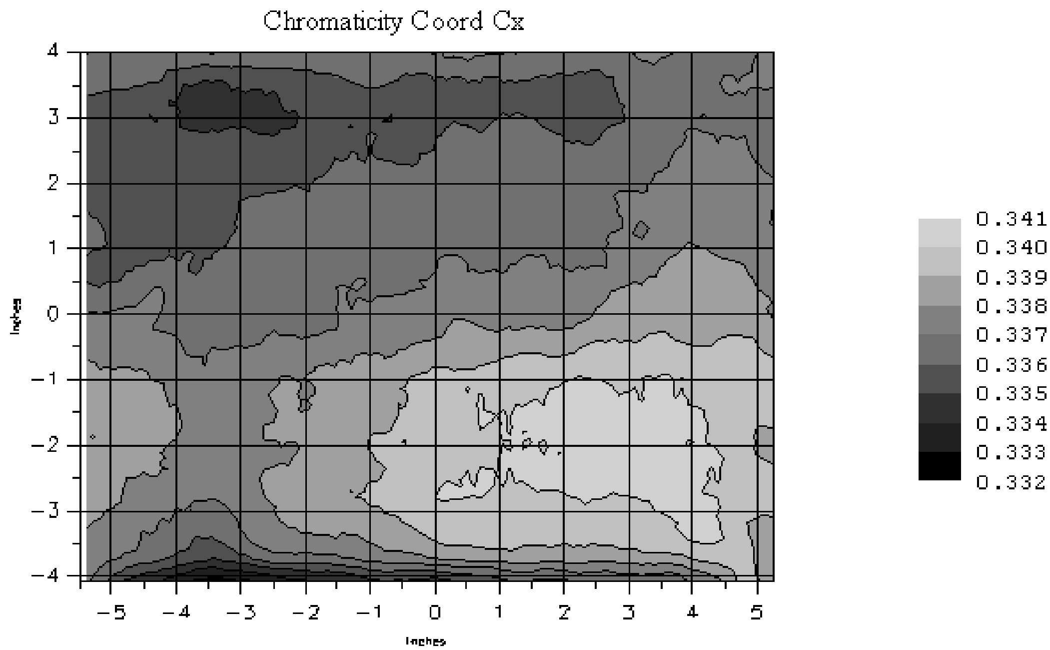


Figure 9. Iso-plot of the x chromaticity coordinate of a white CRT screen taken with a CCD Light and Color Measurement System.

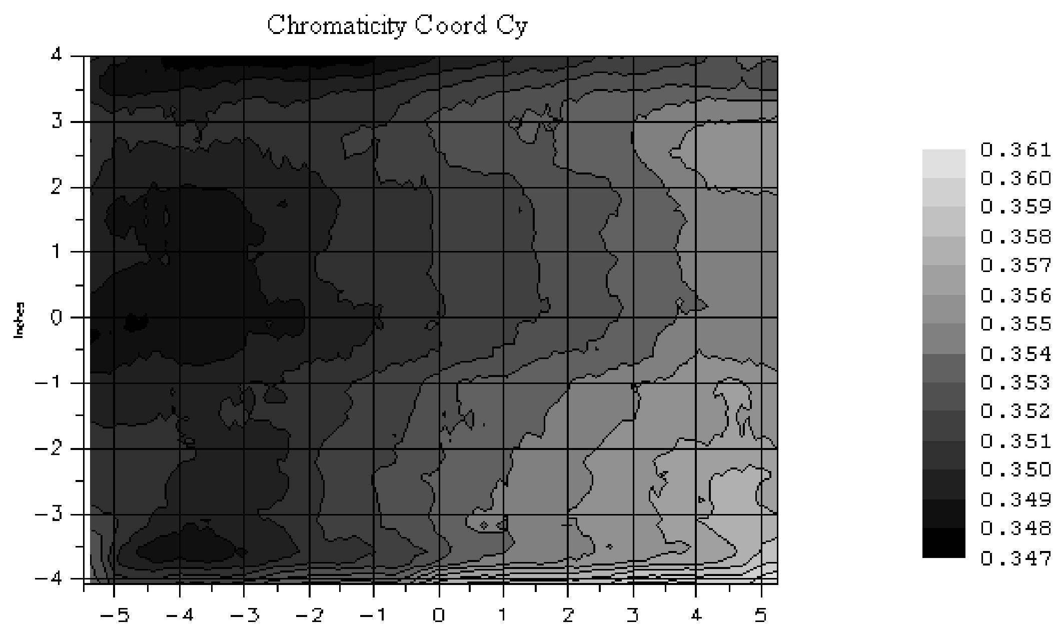


Figure 10. Iso-plot of the y chromaticity coordinate of a white CRT screen taken with a CCD Light and Color Measurement System.

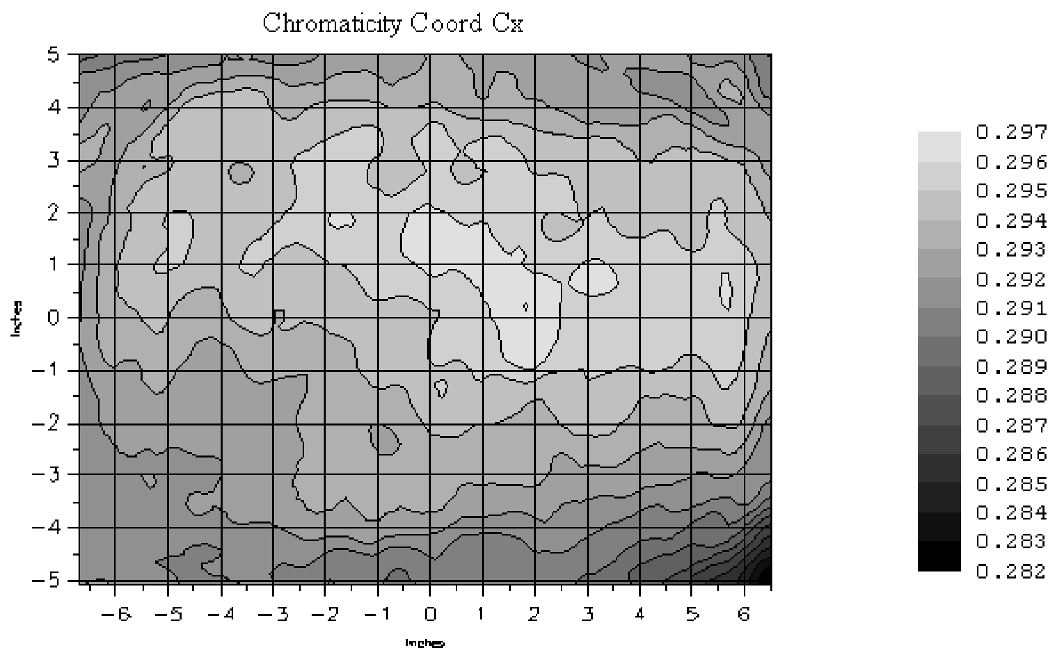


Figure 11. Iso-plot of the x chromaticity coordinate of a white LCD display screen taken with a CCD Light and Color Measurement System.

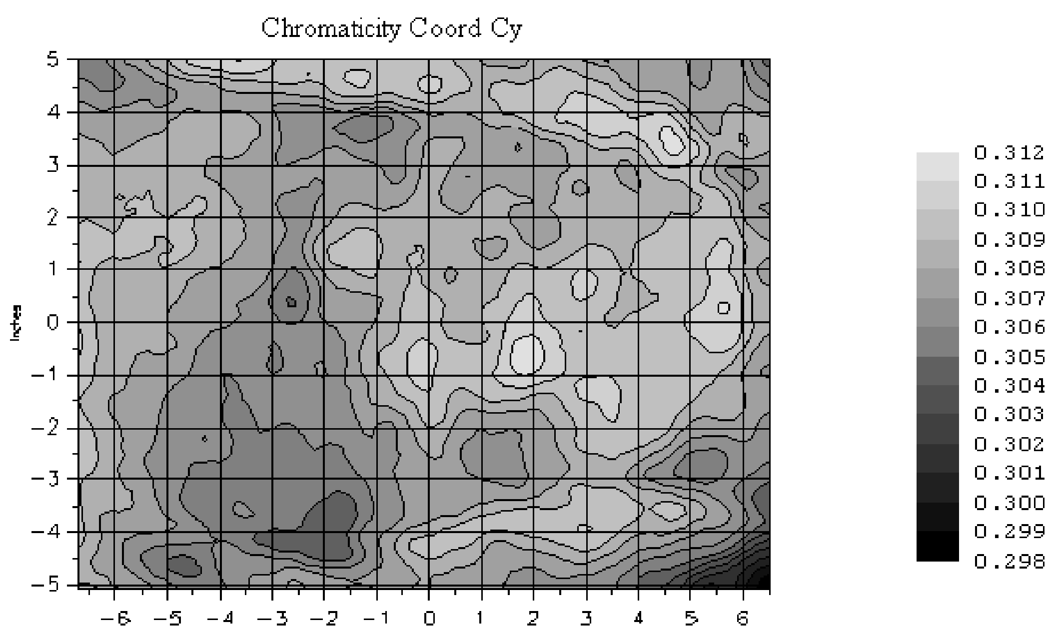


Figure 12. Iso-plot of the y chromaticity coordinate of a white LCD display screen taken with a CCD Light and Color Measurement System.

CRT Point	DAS (nit)	ProMetric® (nit)	Percent Difference
1	118	122	3%
2	118	122	3%
3	120	124	3%
4	118	118	0%
5	122	122	0%
6	126	128	2%
7	111	110	1%
8	112	115	3%
9	118	123	4%

Table 2. Luminance uniformity measurements of a white CRT screen made with a Diode Array Spectrometer and a ProMetric® Color CCD Light and Color Measurement System.

LCD Point	DAS (nit)	ProMetric® (nit)	Percent Difference
1	56	55	1%
2	63	63	0%
3	60	60	0%
4	59	59	0%
5	69	69	0%
6	60	61	2%
7	57	57	1%
8	61	61	2%
9	60	59	1%

Table 3. Luminance uniformity measurements of a white LCD screen made with a Diode Array Spectrometer and a ProMetric® Color CCD Light and Color Measurement System.

CRT Color	DAS (x)	DAS (y)	ProMetric® w/ Illuminant A Calibration (x)	ProMetric® w/ Illuminant A Calibration (y)	|Delta x|	|Delta y|	Vector Δxy
White	0.293	0.307	0.282	0.307	0.011	0.000	0.011
Blue	0.161	0.080	0.125	0.057	0.036	0.023	0.043
Cyan	0.215	0.302	0.202	0.301	0.013	0.001	0.013
Green	0.293	0.583	0.295	0.605	0.002	0.022	0.022
Magenta	0.299	0.158	0.285	0.157	0.014	0.001	0.014
Red	0.590	0.335	0.607	0.358	0.017	0.023	0.029
Yellow	0.406	0.500	0.411	0.513	0.005	0.013	0.014

Table 4. Chromaticity coordinates of a CRT measured with a Diode Array Spectrometer and a ProMetric® Color CCD Light and Color Measurement System with Illuminant A calibration.

CRT Color	DAS (x)	DAS (y)	ProMetric® w/ 4-Color Calibration (x)	ProMetric® w/ 4-Color Calibration (y)	|Delta x|	|Delta y|	Vector Δxy
White	0.293	0.307	0.295	0.309	0.002	0.002	0.003
Blue	0.161	0.080	0.162	0.081	0.001	0.001	0.001
Cyan	0.215	0.302	0.220	0.302	0.005	0.000	0.005
Green	0.293	0.583	0.295	0.581	0.002	0.002	0.003
Magenta	0.299	0.158	0.296	0.162	0.003	0.004	0.005
Red	0.590	0.335	0.589	0.338	0.001	0.003	0.003
Yellow	0.406	0.500	0.402	0.492	0.005	0.008	0.009

Table 5. Chromaticity coordinates of a CRT measured with a Diode Array Spectrometer and a ProMetric® Color CCD Light and Color Measurement System with 4-Color Matrix Method calibration.

LCD Color	DAS (x)	DAS (y)	ProMetric® w/ Illuminant A Calibration (x)	ProMetric® w/ Illuminant A Calibration (y)	|Delta x|	|Delta y|	Vector Δxy
White	0.338	0.354	0.315	0.354	0.023	0.000	0.023
Blue	0.170	0.139	0.133	0.093	0.037	0.046	0.059
Cyan	0.250	0.357	0.224	0.350	0.026	0.007	0.027
Green	0.322	0.529	0.306	0.582	0.016	0.053	0.055
Magenta	0.335	0.220	0.306	0.201	0.029	0.019	0.035
Red	0.566	0.340	0.578	0.370	0.012	0.030	0.032
Yellow	0.429	0.462	0.419	0.497	0.010	0.035	0.036

Table 6. Chromaticity coordinates of a LCD Display measured with a Diode Array Spectrometer and a ProMetric® Color CCD Light and Color Measurement System with Illuminant A calibration.

LCD Color	DAS (x)	DAS (y)	ProMetric® w/ 4-Color Calibration (x)	ProMetric® w/ 4-Color Calibration (x)	|Delta x|	|Delta y|	Vector Δxy
White	0.338	0.354	0.338	0.351	0.000	0.003	0.003
Blue	0.170	0.139	0.168	0.136	0.002	0.003	0.004
Cyan	0.250	0.357	0.254	0.354	0.004	0.003	0.005
Green	0.322	0.529	0.323	0.532	0.001	0.003	0.003
Magenta	0.335	0.220	0.334	0.221	0.001	0.001	0.001
Red	0.566	0.340	0.567	0.340	0.001	0.000	0.001
Yellow	0.429	0.462	0.425	0.454	0.004	0.008	0.009

Table 7. Chromaticity coordinates of a LCD Display measured with a Diode Array Spectrometer and a ProMetric® Color CCD Light and Color Measurement System with 4-Color Matrix Method calibration.

6. CONCLUSIONS

We have shown that a CCD-based digital imaging photometer and colorimeter is capable of measuring thousands of data points containing luminance and CIE chromaticity data for both CRT and LCD displays. The data agrees well with similar measurements made with a Diode Array Spectrometer. In addition, the time required to capture data for over 250,000 data points has been substantially reduced from that of conventional single point detector techniques.

Quantitative comparison of luminance values measured using a Diode Array Spectrometer and a CCD-based digital imaging photometer and colorimeter were found to agree to within an average percent error of 2% for luminance uniformity tests of a CRT and to within 1% for luminance uniformity tests of a LCD display.

When using the 4-Color Matrix Method of colorimeter calibration recommended by NIST, the CCD-based digital imaging colorimeter showed substantial improvement in color measurement accuracy over a calibration method using only Illuminant A. The CIE x and y chromaticity coordinates for the CCD-based digital imaging colorimeter using the 4-Color Matrix Method of colorimeter calibration were shown to agree with DAS measurements to within an average of 0.003 for a CRT and 0.002 for a LCD display.

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