1998

Colorimetric characterization of the Apple studio display (Flat panel LCD)

Mark Fairchild

David Wyble

Recommended Citation
Munsell Color Science Laboratory Technical Report (1998)

Munsell Color Science Laboratory Technical Report

Colorimetric Characterization of the Apple Studio Display (Flat Panel LCD)

Mark D. Fairchild and David R. Wyble

July, 1998

Munsell Color Science Laboratory
Center for Imaging Science
Rochester Institute of Technology
54 Lomb Memorial Drive
Rochester, NY 14623-5604
mdf@cis.rit.edu

Abstract

The colorimetric characterization of a flat-panel LCD monitor, the Apple Studio Display, using traditional CRT characterization techniques was evaluated. The results showed that the display performed up to the manufacturer's specifications in terms of luminance and contrast. However, the traditional CRT gain-offset-gamma (GOG) model for characterization was inadequate and a model with one-dimensional lookup tables followed by a 3x3 matrix was developed. The LUT model performed excellently with average CIE94 color differences between measured and predicted colors of approximately 1.0.

Acknowledgements: This research was supported by the Munsell Color Science Laboratory, the NSF-NYS/IUCRC and NYSSTF CAT Center for Electronic Imaging Systems, and LMT.

Contents

Introduction

Flat-panel LCD-based monitors are quickly becoming a common peripheral for desktop personal computers and workstations. Such displays potentially offer greater luminance, higher contrast ratios, greater sharpness, and better spatial uniformity than CRT displays. The objectives of this research were to examine a typical desktop LCD monitor and determine if its performance with respect to colorimetric characterization is sufficient to consider such a display for stimulus presentation in psychophysical experiments. The approach was to evaluate the basic colorimetric performance of the display and determine if the traditional techniques that have been successfully applied to CRT displays are also applicable to LCD systems. The traditional CRT techniques have been summarized by Berns[1] and can be described as application of the gain-offset-gamma (GOG) model to characterize the electro-optical transfer functions of the display and a 3x3 linear transform to go from RGB to CIE XYZ tristimulus values. The monitor evaluated was a commercial product available from Apple Computer, Inc., the Apple Studio Display.

Specifications, Configuration, & Setup

The Apple Studio Display became available in the summer of 1998 at a retail price of $1999 and an educational price of $1749. Its pricing and capabilities place it squarely in competition with high-quality CRT displays. It is also one of the few displays available that is capable of reproducing full 24-bit color. Some of the manufacturer's technical specifications of the display include:

- 15.1" Diagonal Viewable Image Size,
- Thin-Film Transistor Active-Matrix LCD,
- 120° Hor. and 90° Vert. Viewing Angles,
- 200 cd / m^2 Peak Luminance,
- 200:1 Contrast Ratio,
- 1024x768 Pixels,
- 24-Bit Color Resolution,
- Digital White-Point Control,
- Multisync to 13 Video Configurations,
- NTSC Video Inputs (Composite and S-Video),
- 7.6 Pounds.

More detailed information can be found at <www.apple.com>.

For this evaluation, the monitor was set up using its default internal D65 white point, maximum brightness setting, automatic white- and black-point settings, 1024x768 at 75 Hz. video timing, and full 24-bit color resolution. The display was driven using the built-in video controller of an Apple Power Macintosh 8600/200 computer. The video LUTs of the video controller were set to a nominal gamma of 1.8 (Macintosh Standard) using the "Knoll Gamma" software to avoid any idiosyncrasies with the standard Macintosh system LUTs.[1]

With the exception of the warmup evaluations, all measurements were made after approximately 30 minutes of warmup time for the display. Colorimetric measurements were made using an LMT C1200 Colormeter. Luminance measurements were made using an LMT L1009 Photometer. Spectral radiance and additional luminance measurements were made using a PhotoResearch PR-704 spectroradiometer. The large number of colorimetric measurements were facilitated using the Matlab driven IEEE interface between the Macintosh and the LMT 1200 that was developed within MCSL. All colorimetric coordinates were determined using the CIE 1931 Standard Colorimetric Observer (2°). Unless otherwise specified, all measurements were performed on a large central uniform square patch (approximately 400x400 pixels) with the remainder of the display filled with a medium gray background represented by RGB digital counts of (128,128,128).

Spectral Characteristics

The spectral radiance characteristics of the display are illustrated in Figs. 1-3. Figure 1 shows the spectral radiance distribution for a white. This figure illustrates the basic characteristics of the fluorescent back-light utilized in this display. It is clear that the fluorescent source has what could be described as a three-narrow-band distribution that maximizes emission in three relatively narrow regions of the spectrum. This would clearly be an optimal choice for maximizing both color-gamut volume and efficiency. The peak spectral radiance of the white point is about 0.018 W/m^2sr.

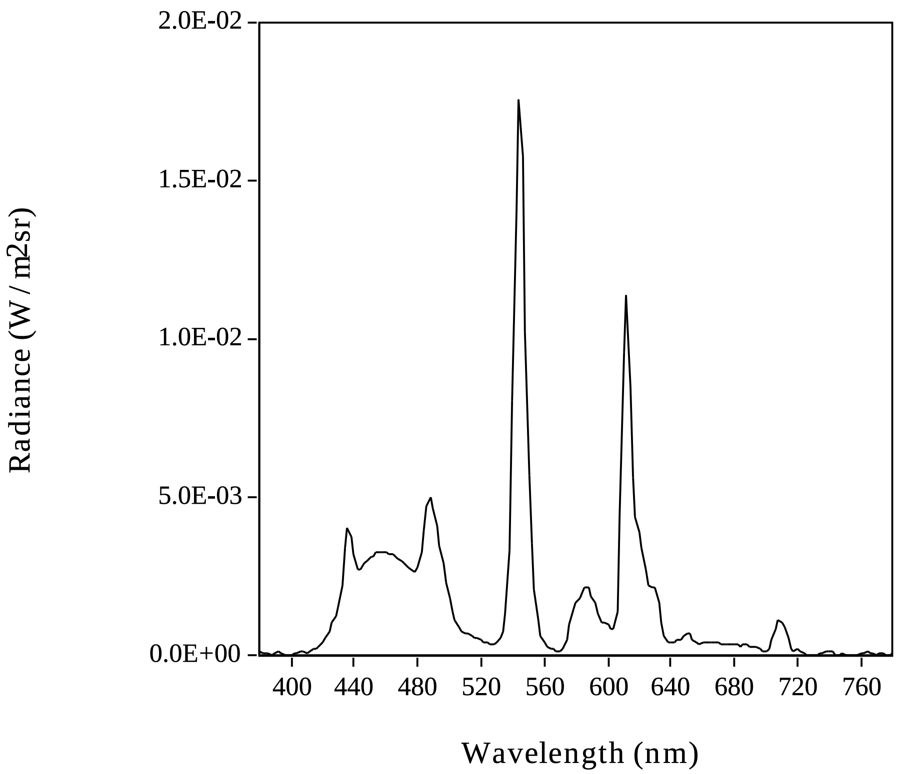

Figure 1. Spectral radiance distribution of the monitor white.

Figure 2 shows the spectral distribution of black on the display. As with all displays, the displayed black does not have spectral radiance values of zero. The spectral distribution of the black is similar to that of the white, with a bit more energy (relatively) emitted in the blue region of the spectrum. The non-zero black radiances are the result of inter-reflection from the gray background on the display (minimal) and a minimal amount of energy that always "leaks" through the LCD filters. Note that the peak spectral radiance of the black is approximately 0.00007 W / m^2sr, or about 0.4 percent of the white.

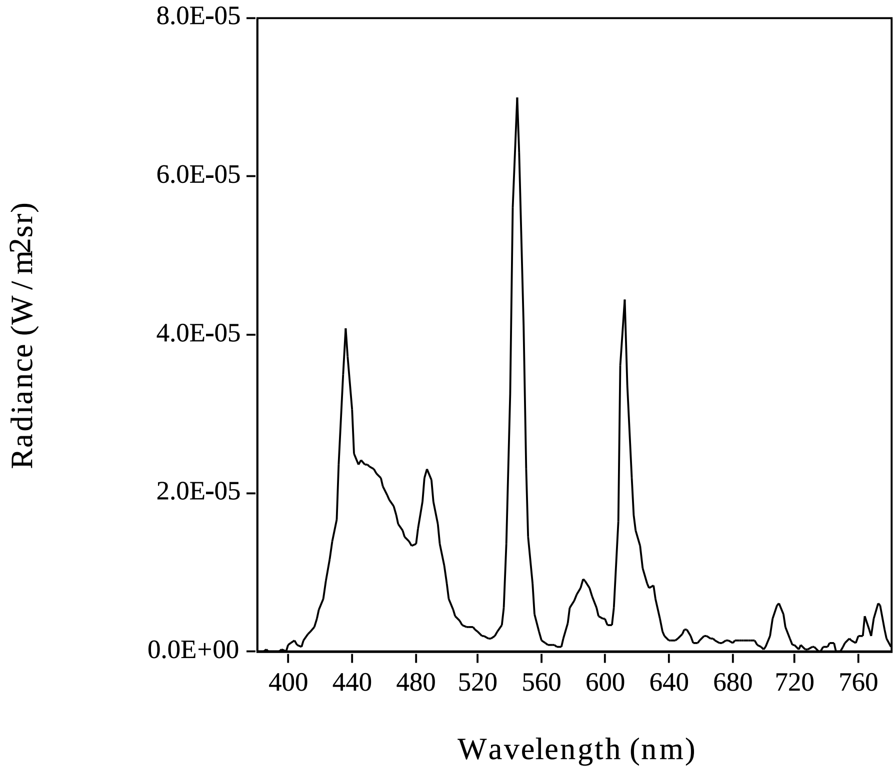

Figure 2. Spectral radiance distribution of the monitor black.

Figure 3 illustrates the spectral radiance distributions of the separate RGB primaries of the display. This illustrates the efficient combination of the broad-band RGB filters of the LCD and the narrow-band emissions of the fluorescent back light.

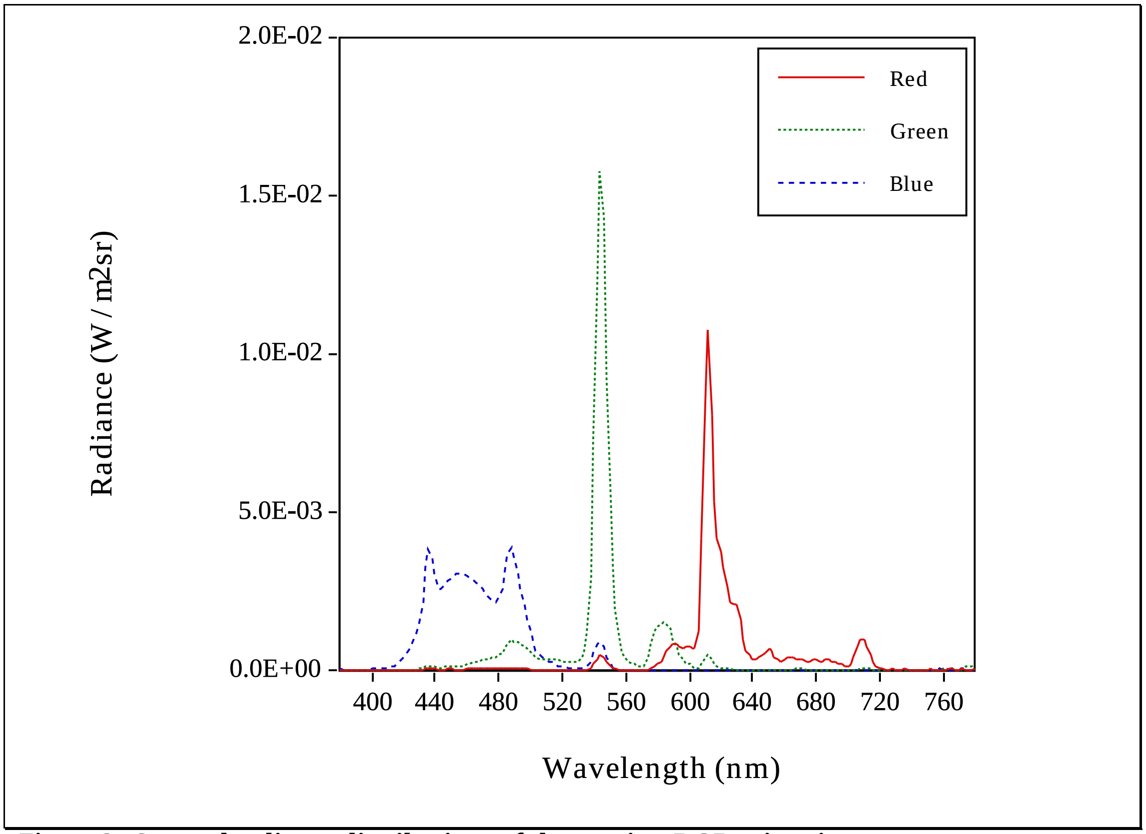

Figure 3. Spectral radiance distributions of the monitor RGB primaries.

Warmup

Since normal fluorescent tubes require significant warmup time in order to reach stable output (on the order of 15 - 30 minutes), it was expected that an LCD monitor with a fluorescent back light might exhibit similar warmup characteristics. To evaluate this, a series of measurements were made in which the displayed and measured color was alternated between a medium gray (100,100,100) and a full white (255,255,255) every two minutes with a tristimulus measurement being made in the middle of each interval. These measurements began from a cold start (initial power-up of the monitor) for a total of four hours.

Figure 4 illustrates the CIE XYZ tristimulus values of the display white over the 4-hour warmup period. The results show characteristics similar to those of a typical fluorescent lamp. The output levels increase quickly early on and then reach a very stable level after about 45 minutes. These data can be completely attributed to the warmup of the fluorescent back light.

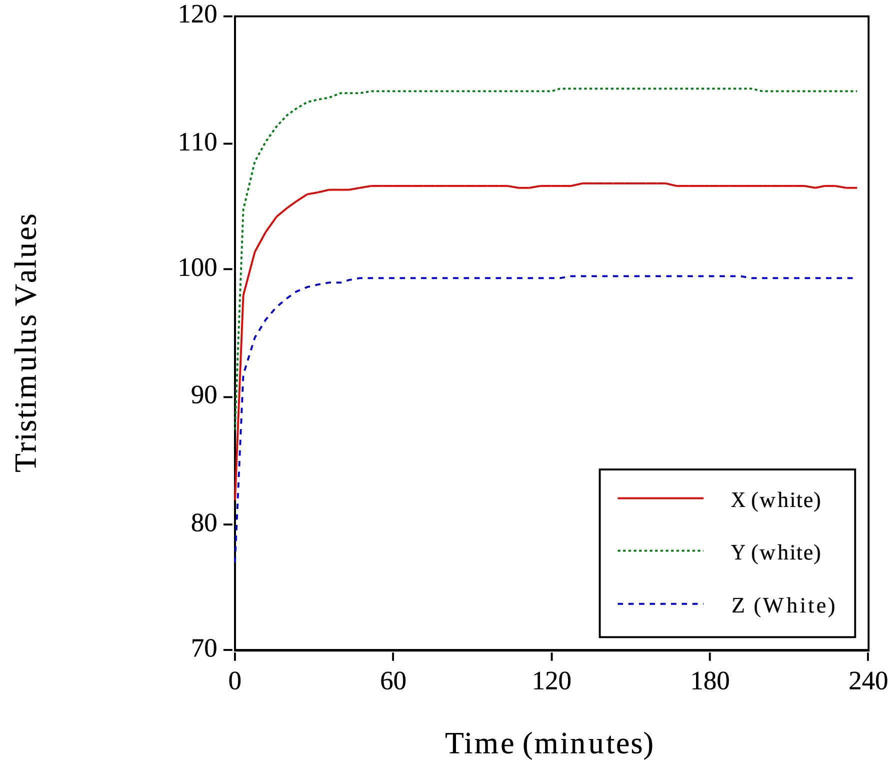

Figure 4. Tristimulus values over a 4-hour warmup period for the monitor white.

Unfortunately, the story is not so simple for the gray patch as illustrated in Fig. 5. Again, the output levels for the gray patch increase significantly at the beginning and this can be attributed to the back-light warm-up described above. However, after about 15 minutes the output for the gray patch actually starts to decrease and never reaches a completely stable level for the full 4-hour evaluation. This decrease in the output for a middle gray combined with the increase/stability of the output for the white indicates that the contrast of the display is actually changing over the 4-hour warmup period. Such a change can only be attributed to changes in the properties of the LCD itself. Perhaps the monitor is reaching thermal equilibrium and the transmission characteristics of the LCD change as a function of temperature.

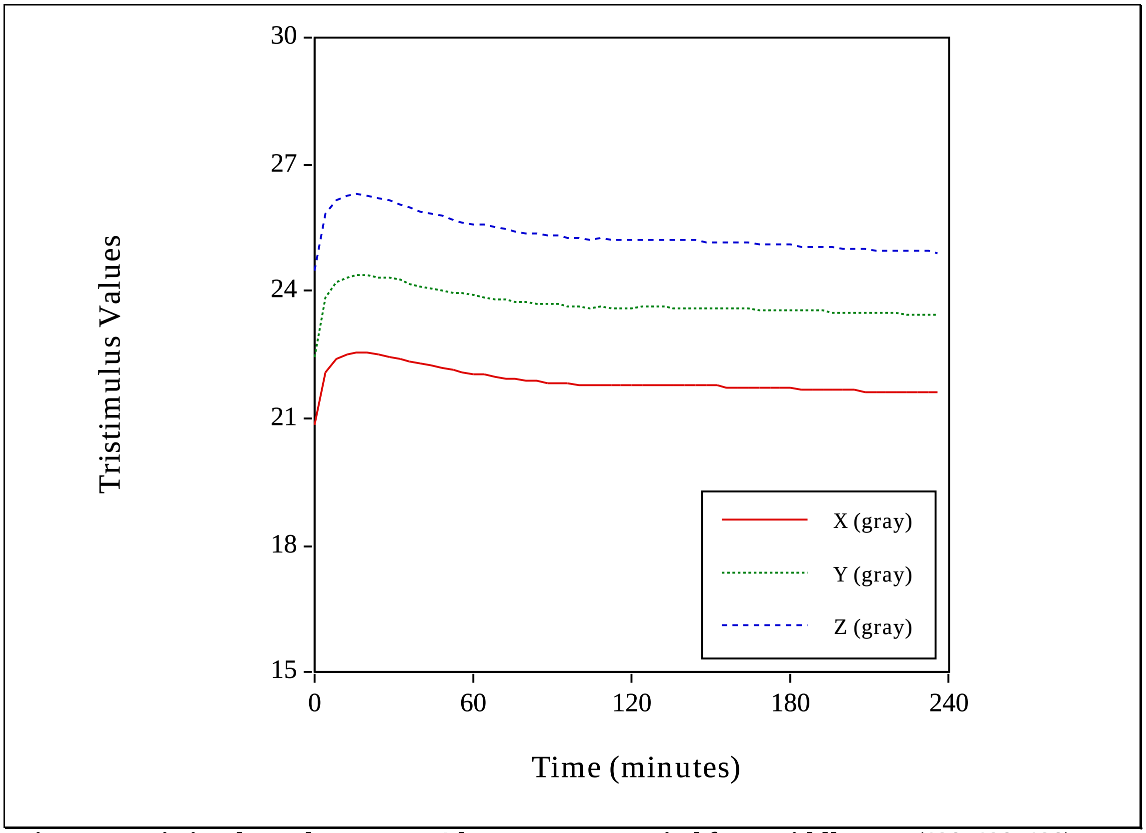

Figure 5. Tristimulus values over a 4-hour warmup period for a middle gray (128, 128, 128).

The unusual warmup characteristics of the LCD, combined with its lack of stability over the 4-hour warmup period, create a fundamental limitation to the accuracy with which the display can be characterized and its usefulness in critical research applications. Despite this rather severe limitation, the colorimetric characterization of the display under typical user conditions was completed in order to determine the level of accuracy obtainable.

Spatial Independence

Spatial independence refers to the impact (or lack thereof) that a color displayed on one area of the monitor has on another color. Clearly, a monitor with poor spatial independence cannot produce reliable color stimuli since the colors displayed on another area of the screen will impact the colorimetry of a test stimulus. To evaluate the spatial independence of the LCD monitor a series of color stimuli were defined. These included black (0,0,0), gray (128,128,128), white (255,255,255), two reds {(128,0,0),(255,0,0)}, two greens {(0,128,0),(0,255,0)}, and two blues {(0,0,128),(0,0,255)}. Each of the nine color stimuli was measured on nine different backgrounds made up of the same nine colors for a total of 81 colorimetric measurements. The data were converted to CIELAB coordinates using the measured tristimulus values of the monitor white on a white background as the CIELAB reference white. Since the spatial dependencies in the data were minimal, they are summarized using mean color-difference from the mean (MCDM) metrics calculated in terms of CIE94 color differences. For each color, the mean CIELAB coordinates across the 9 backgrounds were calculated and then the color differences between this mean and each of the nine measurements were calculated and averaged to produce the MCDMs listed in table I. Overall the average MCDM was 0.20 indicating that there is very little spatial dependency for this display. There was little systematic tendency in the results for either a dependency on stimulus color or background color. The middle column of table II shows the MCDMs for the various stimuli averaged across background while the third column provides the same values averaged across stimulus color for a single background. The spatial independence of the display is very good and not a limiting factor in its colorimetric characterization.

Table I. MCDMs (CIE94 color differences) for spatial independence measurements.

Color	MCDM *(across Backgrounds)*	MCDM *(across Stimuli)*
Black	0.11	0.16
Gray	0.27	0.13
White	0.34	0.23
Red1	0.14	0.16
Red2	0.12	0.25
Green1	0.15	0.16
Green2	0.48	0.29
Blue1	0.14	0.18
Blue2	0.04	0.22

Luminance & Contrast

The luminance of the RGB primaries and monitor white and black were measured both with the LMT photometer and calculated from the PhotoResearch-PR704-measured spectral radiance data. The results are summarized in table II below.

Table II. Measured luminances (cd/m^2) of various color stimuli and the sum of the RGB primary luminances.

Color	LMT (cd/m^2)	PR704 (cd/m^2)
R (255,0,0)	46	52
G (0,255,0)	119	130
B (0,0,255)	20	35
W (255,255,255)	188	220
K (0,0,0)	0.7	0.9
R+G+B	185	217

The results in table II indicate the sorry state of affairs with respect to the accuracy to photometric measurements. Both instruments are believed to be in reasonable (or at least typical) calibration states. However their agreement on luminance measurements is quite poor. The values from the two instruments are approximately linearly related with the PR704 values exceeding the LMT values by approximately 15 percent. The peak white of the display is approximately 200 cd/m^2 on average thus corroborating the manufacturer's claimed luminance. This also exceeds the output of typical CRT displays by approximately a factor of three. The contrast of the display (ratio of white to black) is approximately 250:1 on average and therefore significantly exceeding both the manufacturer's claims and the capability of typical CRT displays.

The additivity of the display can be evaluated by comparing the sum the measured luminances for RGB displayed individually with the measured luminance for the display white. This sum is presented in the final row of table II. The additivity of the display is quite good (on par with typical CRT displays) with the summed luminance of the primaries within about 1.5% of the white-point luminance.

Chromaticity Constancy of Primaries

Some researchers have been concerned that the chromaticity of the primaries in an LCD display vary with display level. If this were the case, then a simple 3x3 matrix transform could not be used to convert RGB tristimulus values to CIE XYZ tristimulus values. This question was examined by measuring RGB ramps on the display in which each of the three primaries was stepped in digital count from 0 to 255 in increments of 5. Thus 52 levels of emission were measured for each of the three primaries. These data were then converted to chromaticity coordinates and are plotted in Fig. 6

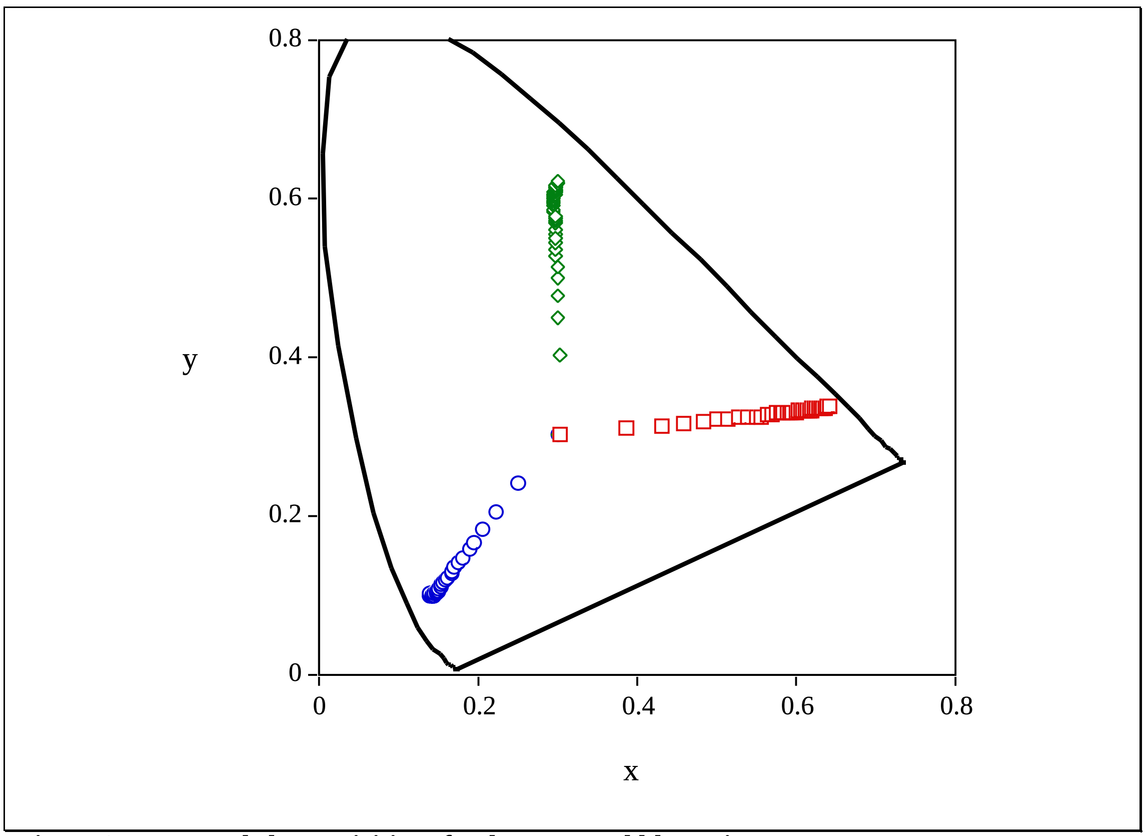

Figure 6. Measured chromaticities of red, green, and blue primary ramps.

It is clear from Fig. 6 that the primary chromaticities do indeed vary with display level. Upon further examination of the data it becomes clear that as the displayed level approaches zero, the primary chromaticity approaches that of the measured display black. (This is seen in Fig. 6 by the convergence of all of the primary chromaticities to a single point in the center of the diagram.) Thus, the shift in primary chromaticities might be modeled as if an additive flare were present in all of the measurements. This flare would have minimal effect on the full-on primaries (digital count of 255) and a maximum effect on the full-off primaries (digital count of 0). Of course, in this LCD display (measured in a completely darkened room) the cause of this "flare" is not reflected light off the display face, probably very little due to inter-reflection flare, but mostly due to light "leaking" through the LCD when it is set to black. To examine this hypothesis, the tristimulus data for the primary ramps were first corrected by subtracting out the tristimulus values for the black measurement. After this

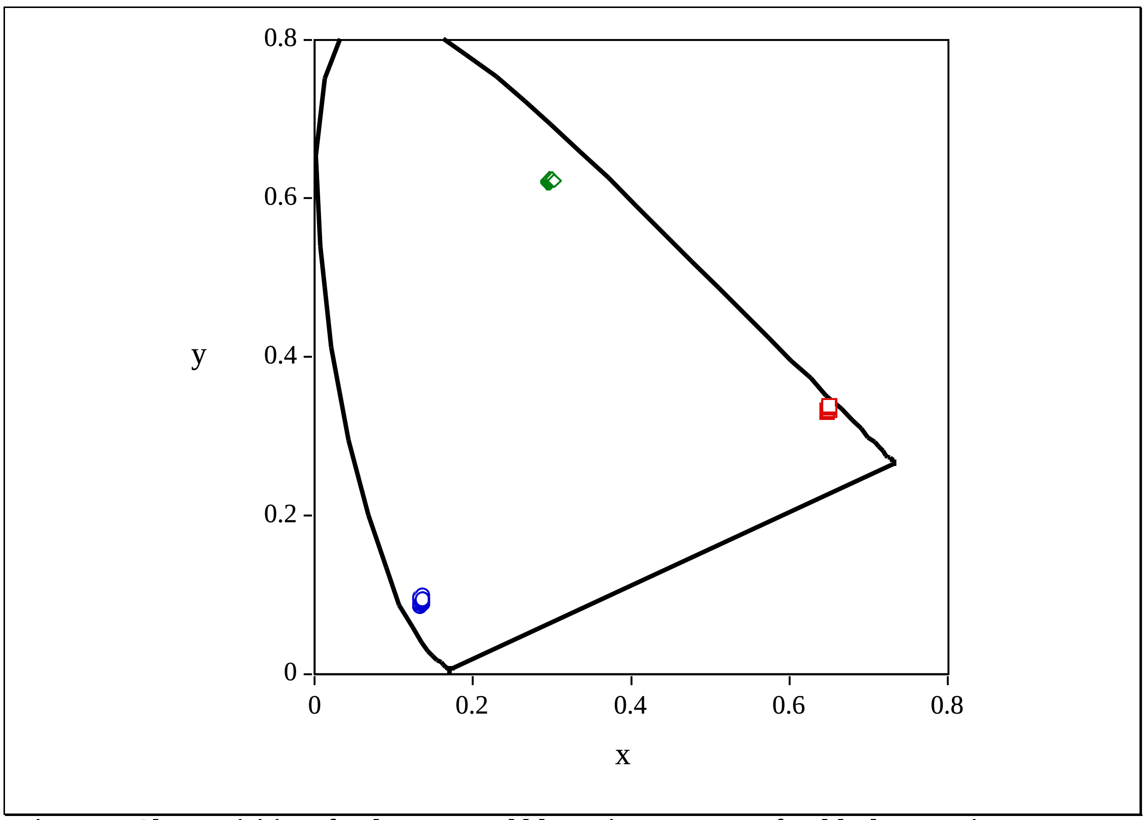

Figure 7. Chromaticities of red, green, and blue primary ramps after black correction.

black correction chromaticity coordinates were again calculated for the 52-level RGB ramps and these are plotted in Fig. 7.

It is clear in Fig. 7 that the display exhibits primary constancy and the 3x3 matrix transform model can be used to convert from RGB to XYZ tristimulus values as long as additivity is also preserved. The figure also illustrates that, contrary to common belief, the chromaticities of the primaries in an LCD can be quite highly saturated and very similar to those found in CRT displays.

Additivity

In addition to the luminance additivity described above, the additivity of the display for all three tristimulus values was examined by comparing the tristimulus values for the display white with the summed tristimulus values of the full-on red, green, and blue primaries. All values were black corrected as described in the section on chromaticity constancy of primaries. The results are summarized in table III.

Table III. Measured tristimulus values (arbitrary units) of white and the sum of individual RGB primary measurements.

Value	White	Sum (R+G+B)	Difference
X	105.8	104.6	1.1%
Y	112.8	110.5	2.0%
Z	99.4	99.2	0.2%

It is clear that additivity is preserved along the three colorimetric dimensions as well as it is on the luminance alone (better than 2%). The precise physical cause of this slight lack of additivity in an LCD is unclear (Although a drain on the power supply driving the LCD panel itself could be imagined to cause this problem. The magnitude of the voltages involved would just be much smaller than those in a CRT.) The degree of additivity illustrated in table III seems sufficient to justify a 3x3 primary transform matrix. It should also be noted that the white-point chromaticity differs significantly from the nominal default of

D65. The measured white-point was a correlated color temperature of about 6000K.

Primary Transform Matrix & Inverse

The primary transform matrix for the colorimetric characterization of this display was derived from the direct colorimetric measurements of the three full-on primaries after black correction. The matrix and it's inverse are given in Eqs. 1 and 2.

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 55.2 & 33.5 & 15.9 \\ 28.8 & 70.2 & 11.5 \\ 1.0 & 8.4 & 89.8 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 0.02396 & -0.01109 & -0.002821 \\ -0.009936 & 0.01907 & -0.0006826 \\ 0.0006627 & -0.001660 & 0.01123 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \tag{2}$$

These matrices were used in all of the model testing described in the following sections.

Electro-Optical Transfer Function

The electro-optical transfer function is used to describe the relationship between the signal used to drive a given display channel and the luminance produced by that channel. For CRT displays, this function is sometimes referred to as "gamma" and it is the aspect of the display characterization described by the gain-offset-gamma (GOG) portion of the traditional CRT-characterization model.[1] The GOG model properly describes the physics and circuitry of a CRT display and has therefore performed exceptionally well in their characterization. There is no *a priori* reason to believe that the same function would be appropriate to describe the electro-optical transfer functions of an LCD monitor. In fact, Glasser,[2] has shown that the transfer function for an LCD is very different from that of a CRT. A plot from Glasser's chapter illustrating this point is reproduced in Fig. 8.

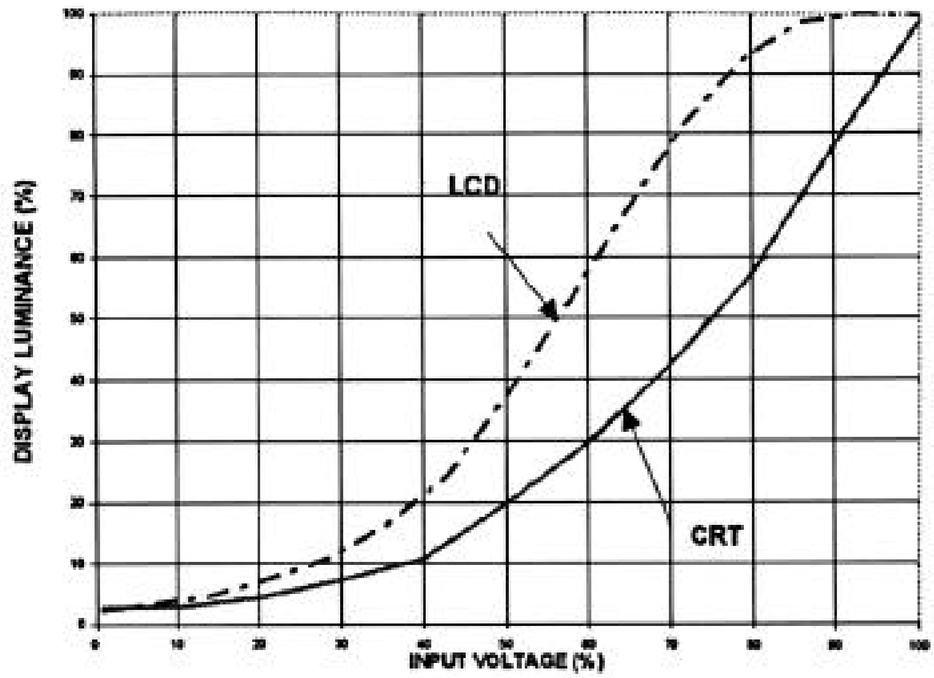

Figure 8. Typical electro-optical response functions for a CRT and LCD (from Glasser[2]).

While the raw physical performance of an LCD differs from that of a CRT, it is reasonable to expect that the digital drive circuitry for a general-purpose LCD monitor would be designed to mimic a CRT's behavior such that the images presented to users appear similar to those they have come to expect from CRTs driven by computer video outputs or NTSC video. Since the Apple display is designed to accept either type of input (and is an entirely digital display at the lowest levels), it is reasonable to expect some kind of circuitry to mimic a CRT's performance.

Figures 9-11 illustrate the measured electro-optical transfer functions for the red, green, and blue channels respectively. These data were obtained using Berns' technique[1] by measuring the tristimulus values of a gray ramp at 52 levels (0 to 255 in increments of 5) and using the matrix given in the previous section to transform from CIE XYZ (after black correction) to RGB scalars.

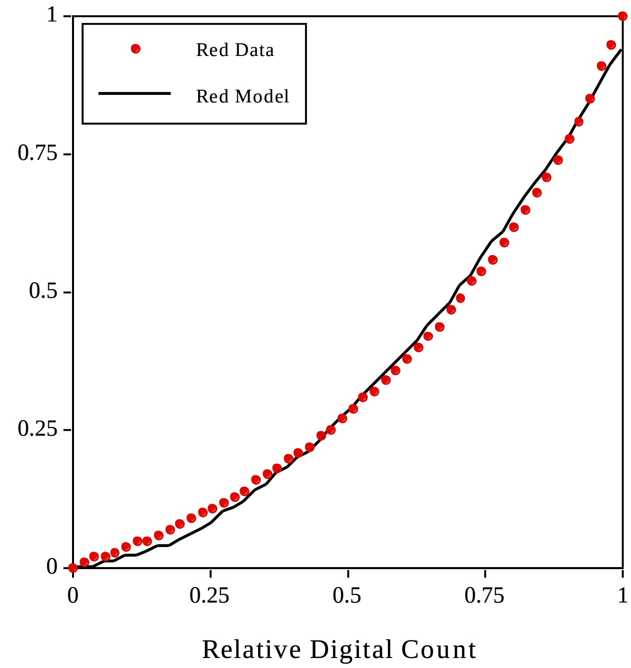

Figure 9. Measured data and fitted GOG model for the red-channel electro-optical transfer function.

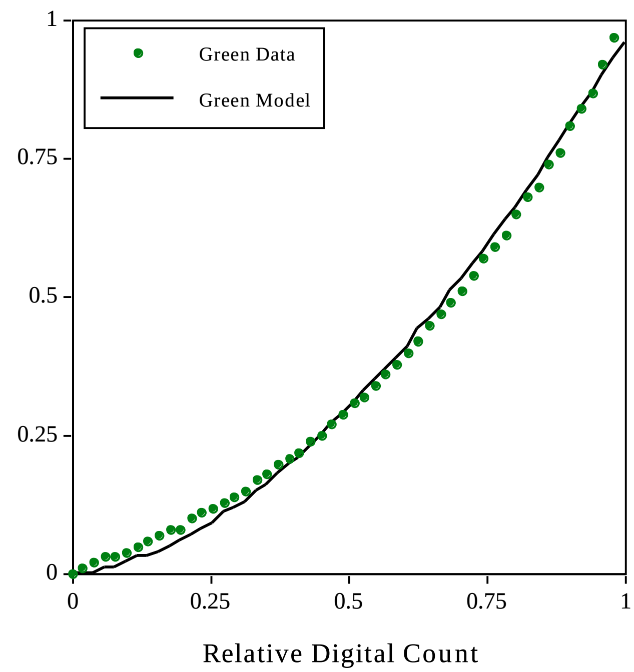

Figure 10. Measured data and fitted GOG model for the green-channel electro-optical transfer function.

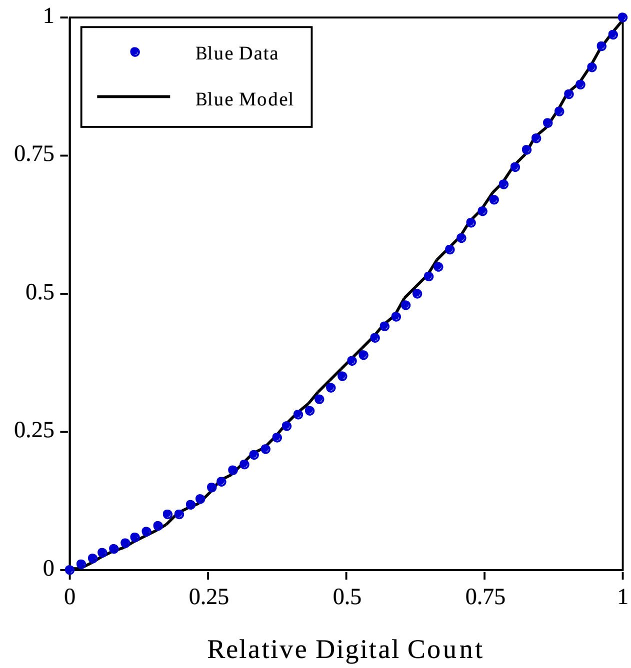

Figure 11. Measured data and fitted GOG model for the blue-channel electro-optical transfer function.

The data in Figs. 9-11 clearly show that the display's digital circuitry and (perhaps, but not likely) the display-driver software are designed such that the electro-optical transfer function of the LCD mimics the typical response of a CRT.

The solid lines are the best fitting GOG models for each of the three functions. Since all measured tristimulus values were first black corrected, no offset term was used in the GOG model. After this correction, all offsets are, by definition, zero. Thus the fitted GOG model took on the form given in Eq. 3.

$$\text{RadiometricScalar} = (gain \times \text{DigitalCount})^{gamma} \quad (3)$$

Table IV contains the fitted gain and gamma parameters along with the R^2 goodness-of-fit metric. The simplex nonlinear fitting function of SYSTAT was used to generate the function fits.

Table IV. Fitted GOG-model parameters and R^2 values.

Channel	*gain*	*gamma*	R^2
R	0.965	1.758	0.998
G	0.978	1.697	0.998
B	0.996	1.434	1.000

Judging from Figs. 9-11 and the R^2 values in table III, it appears that the GOG model describes the electro-optical transfer properties of the LCD monitor quite well. (It should also be noted that the functions are quite close to the nominal Macintosh gamma of 1.8.) However, closer examination of Figs. 9-11 reveals that there are some potentially important systematic errors in the model fits, particularly for the red and green channels. The fitted functions are too low for low digital counts and too high for higher digital counts. This is further illustrated in Fig. 12, which shows the residual error of the three model fits.

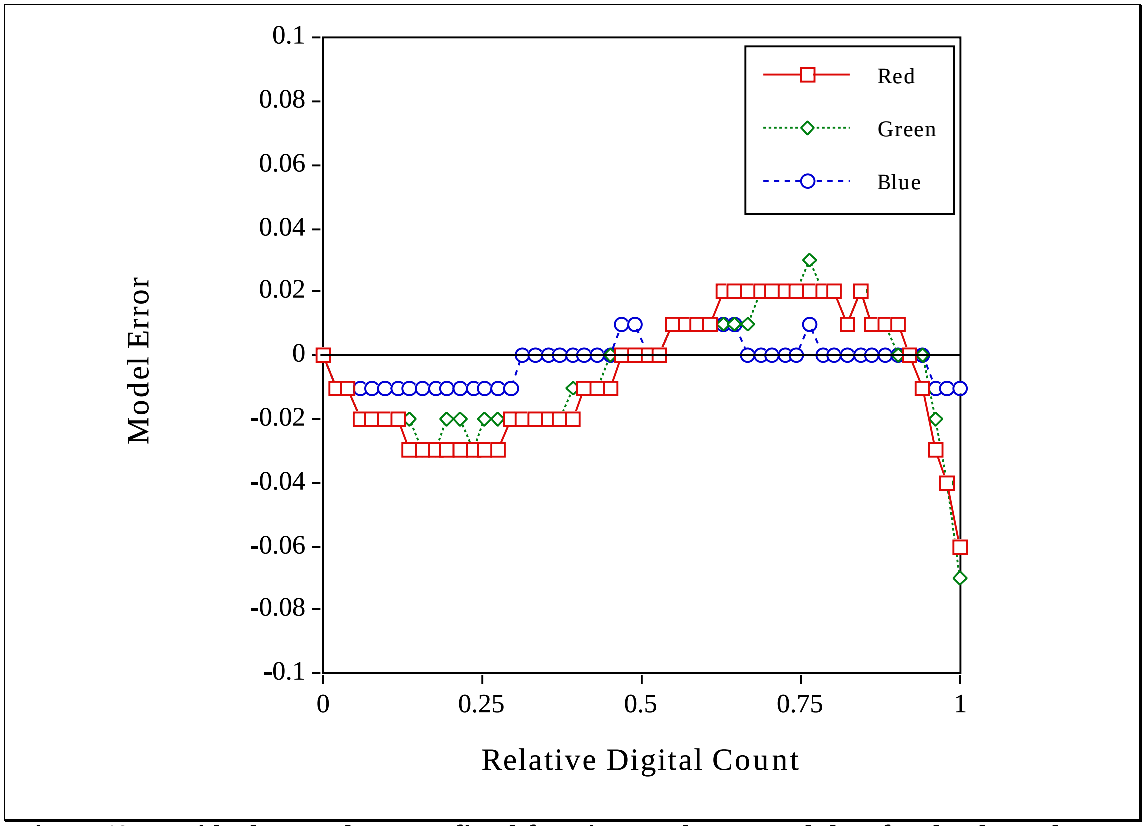

Figure 12. Residual errors between fitted functions and measured data for the three electro-optical transfer functions.

Again, the error illustrated in Fig. 12 appears quite small (generally less than 2% of the full scale) and it might be assumed that this would have a small impact on the colorimetric characterization. However, these small absolute errors can become very large relative errors for dark colors and thus result in large chromaticity differences between the predicted and measured chromaticities of dark colors. The relative errors for the three model fits are illustrated as percentages in Fig. 13.

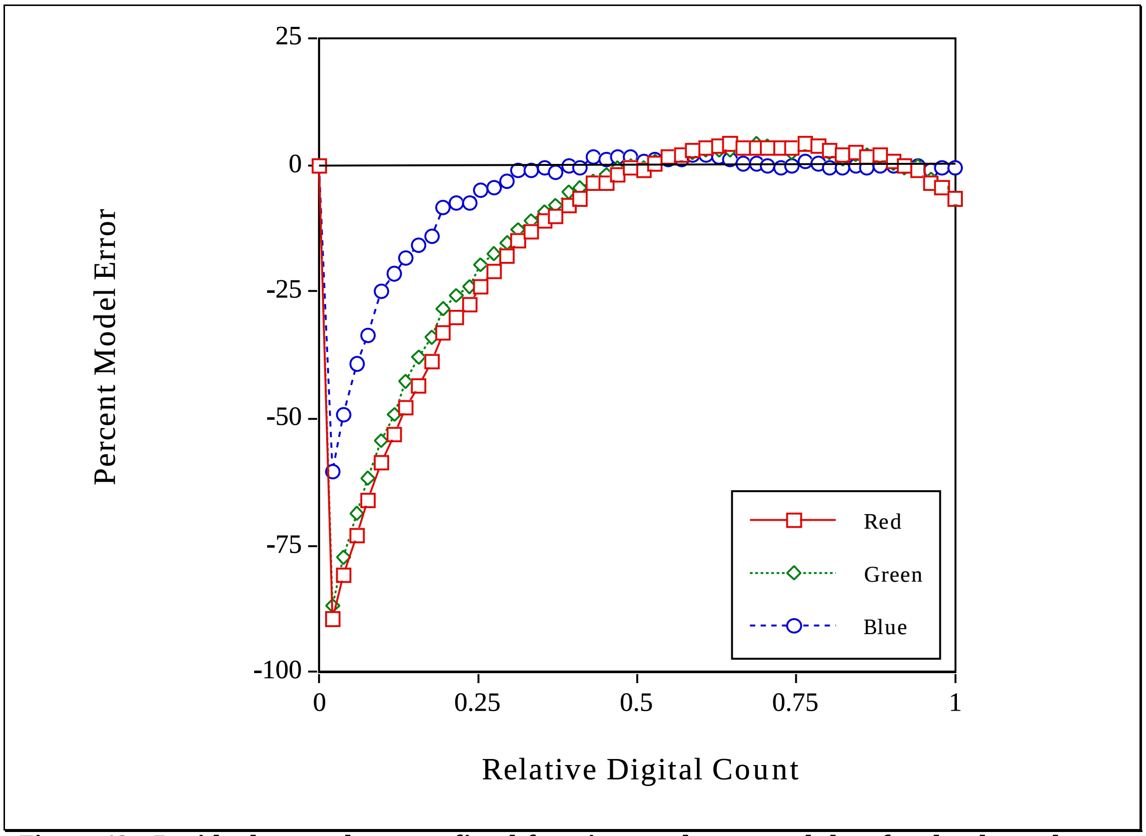

Figure 13. Residual errors between fitted functions and measured data for the three electro-optical transfer functions expressed as percentages.

As Fig. 13 illustrates, the relative errors for the GOG-model fits can reach nearly 100%. This translates almost directly into colorimetric (specifically, chromaticity) errors in the overall display characterization reviewed below.

Once the magnitude of these errors was understood in terms of colorimetric performance, a second model was constructed to test the hypothesis that most of the characterization error was due to the poor fits of the GOG model to the electro-optical transfer characteristics of the display rather than any problems with the 3x3 matrix due to a lack of additivity. This model consisted of three one-dimensional lookup tables (LUTs) used to describe the three electro-optical transfer functions and the same 3x3 matrix for the primary transformation. The three LUTs were constructed via linear interpolation on the 52-level radiometric scalar data shown in Figs. 9-11.

Overall Model Performance

Given two models for the colorimetric characterization of this display, (the GOG model and the LUT model, both utilizing the same 3x3 matrix), the next step was to evaluate the overall colorimetric performance of these characterization techniques. This was accomplished by measuring a set of 100 color stimuli that were generated using random combination of RGB digital values. The digital values were then used to predict the CIE tristimulus values for each of these 100 colors and the predictions were compared with the actual measurements. The data are summarized in terms of CIE94 color differences and the CIELAB coordinates were calculated using the measured tristimulus values of the monitor white as the reference white. The performance of these two models for the 100 random colors is summarized statistically in table V and illustrated in the histograms of Fig. 14.

Table V. Summary statistics of model performance. CIE94 color differences between model predictions and measurements for 100 randomly generated colors.

Statistic	GOG Model	LUT Model
Mean	2.13	1.02
Minimum	0.50	0.07
Maximum	8.06	2.88

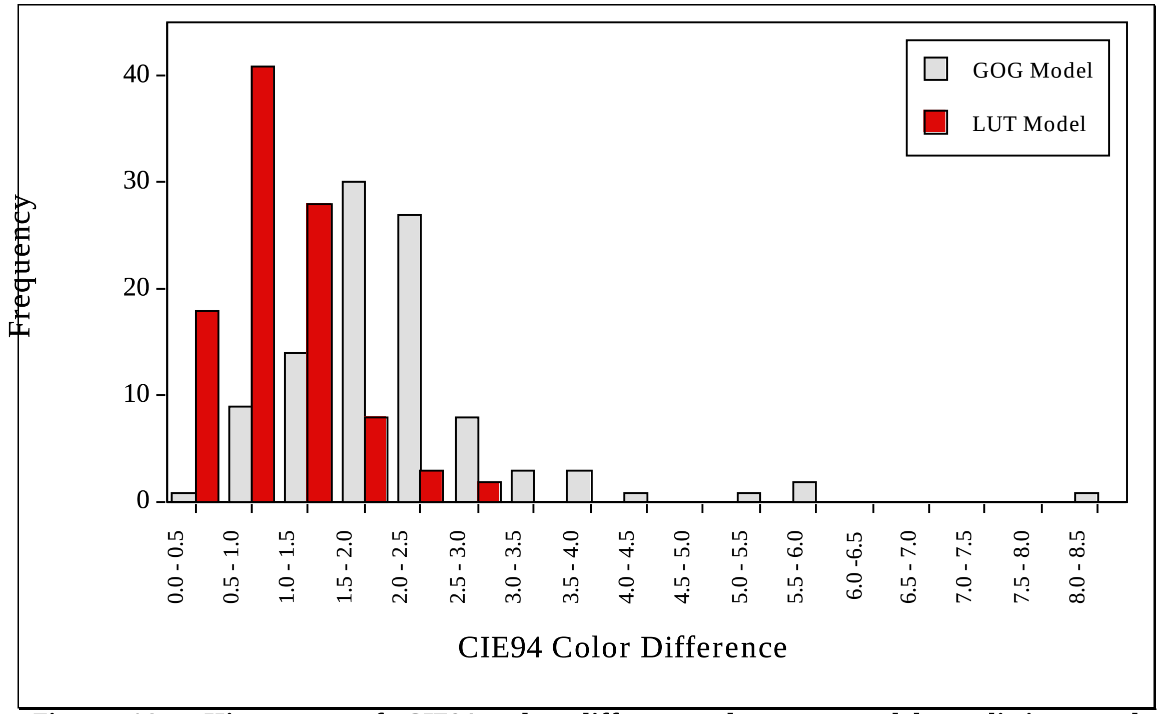

Figure 14. Histograms of CIE94 color differences between model predictions and measurements for 100 randomly generated colors using both the GOG and LUT models.

Overall, the GOG model produced predictions with an average CIE94 color difference of about 2.0. This is significantly worse than typical CRT characterizations and inadequate for research purposes. The LUT model corrected much of the error resulting in an average CIE94 color difference performance of about 1.0. This is similar to the performance expected with a typical CRT display, but still worse than could be obtained with a high-quality CRT.[1]

Conclusions

This research evaluated the use of traditional CRT colorimetric characterization strategies as applied to a flat-panel LCD monitor. The results indicate that the performance of the monitor meets the manufacturers specifications for greater luminance and contrast than typical CRT monitors. However, the traditional GOG model was inadequate for the colorimetric characterization of the display for research purposes. The accuracy of the GOG characterization is probably adequate for most desktop color applications and color management systems. When the GOG functions are replaced with simple one-dimensional LUTs to characterize the display's electro-optical transfer functions, the characterization performance is excellent. The LUT model's performance is probably adequate for research that involved comparisons between images on the display, but still not quite good enough for research involving cross-media comparisons or color discrimination judgements.

One aspect of the display that was not evaluated was the angular dependency of the displayed colors. This is a classic problem with LCDs that has received much attention. This particular display has exceptional angular performance. While it has been criticized in popular reviews as "useless for real color work" due to "color inaccuracy",[3] this criticism is not justified based on the results of this project. The display is useful within the manufacturer's specifications (120° horizontal, 90° vertical) and the color changes are indiscriminable for small head movements. For research purposes it might be necessary to fix the observers' head position using a chin rest, but no further restraints would be required. Also, the results of this work illustrate that the color accuracy of the display is quite high with a careful characterization.

References

1. R.S. Berns, Methods for Characterizing CRT Displays, *Displays* **16,** 173-182 (1996).
2. J. Glasser, Principles of Display Measurement and Calibration, Chapter 14 in *Display Systems: Design and Applications,* L.W. MacDonald and A.C. Lowe, Eds., John Wiley & Sons, Chichester (1997).
3. R. Myslewski, Reviews: Studio Display: Limitations Mar Stylish Monitor, *Macworld* **August,** 50 (1998)