Munsell Color Science Laboratory Technical Report

Colorimetric Characterization of Three Computer Displays (LCD and CRT)

Jason E. Gibson and Mark D. Fairchild

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Abstract

The colorimetric characterization of two flat-panel LCD displays, an SGI 1600SW and an IBM prototype, was evaluated and compared to that of a flat-screen CRT display, the Sony GDM-F500. The results showed that both the SGI and the Sony displays could be characterized using the traditional gain-offset-gamma (GOG) model. Some improvement for the SGI display was gained by using three 1D LUTs in place of the gamma correction step. The prototype IBM display however exhibited a significant failure of additivity and could not be characterized as well as the other displays at this time.

Munsell Color Science Laboratory
Center for Imaging Science
Rochester Institute of Technology
54 Lomb Memorial Drive
Rochester, NY 14623-5604 USA

1 Introduction

1.1 Background

The basic procedure for characterizing a color CRT display using the gain-offset-gamma (GOG) model is given in [Berns 1996, Berns 93a, 93b]. In the basic implementation a fitted nonlinear function is first used to convert normalized digital counts $\{d_r, d_g, d_b\}$ into linear scalars {R,G,B}. These scalars are then linearly combined via a 3x3 matrix and the internal flare added in. In some cases three 1D LUTs can be substituted for the nonlinear transfer functions.

1.2 Measurement Conditions

Colorimetric measurements were made using an LMT C1200 Colorimeter which gives readings in arbitrary units. Luminance measurements in cd/m^2 were made using an LMT L1009 Photometer with a 1° aperture. Spectral Radiance measurements and additional luminance and spectral measurements were made using a Photo Research PR704 spectroradiometer. All colorimetric coordinates were determined using the CIE 1931 Standard Colorimetric Observer (2°). Colorimetric errors are evaluated in terms of ΔE^*_{94} color differences with the standard parametric factors.

Unless otherwise noted, all measurements were performed on a central 3.5" uniform square patch with the remainder of the display filled with a medium gray background represented by RGB digital counts of (128,128,128). This was done to simulate the load placed on the display during normal usage.

As with all LCD displays, the appearance of both the SGI and IBM displays is angular dependent. To ensure a consistent evaluation of each display, all measurements were made at a 0° incident angle.

2 Display Specifications, Configuration, and Setup

This section details each of the three monitors tested. A table at the end of this section is provided for easy comparison of the major technical specifications of each display.

2.1 Sony GDM-F500

During this analysis this display was driven by an Apple Macintosh G3 computer at a resolution of 1280x1024 @80Hz. The white point was set at 6500K using the monitor's built-in controls. Because most CRTs are sensitive to magnetic field variations, all measurements were taken without moving the display. The onboard degaussing feature was used several times before beginning measurements. Apple's ColorSync software was set in a generic RGB mode during all phases of testing.

2.1.1 Product Features

The GDM-F500 is Sony's flagship model display for CAD and graphic professionals. This virtually flat 21" CRT uses the FD Trinitron® tube. Other enhancements include:

- HiDensity™ Electron Gun which allows for a tight 0.22 mm aperture grille pitch.
- Enhanced Elliptical Correction System™ technology which uses additional focusing elements to correct for the elliptical beam shape distortions near the edges of the screen.
- GeoLock Plus™ circuitry which automatically senses and neutralizes electromagnetic fields thereby reducing image color distortion commonly noticeable on large CRTs.

1.1.2 Further Information

More information about this display can be found on Sony's web site: http://www.ita.sel.sony.com/products/displays/fseries/gdmf500.html.

White papers containing more details on the various technologies used in this, and other Sony displays can be found at: http://www.ita.sel.sony.com/products/displays/displaytech.html.

In this section:

1.2 Silicon Graphics 1600SW Flat Panel Monitor

The 1600SW display was driven by a SGI Visual Workstation 320. The SGI ColorLock™ sensor and software was used to calibrate the display to the sRGB setting (D65 white point, gamma of 2.2) prior to making measurements.

1.1.1 Product Features

The 1600SW is an active matrix digital LCD, flat panel display with a SXGA-wide (1600 x 1024) format. Product features include:

- Adjustable white balance via software and dynamic backlight adjustment. Accurate to within 25K.
- ColorLock™ system which uses factory characterization data stored within the onboard memory of each monitor and a specially designed photopic sensor to self-correct the panel.

1.1.2 Display Defects

As with most LCD panels on the market today, defects are common due to high manufacturing costs. The most common defects are weak pixels and ones that are stuck in one state which appear as unchanging bright or dark spots depending on the display mode (normal bright vs. normal dark).

Silicon Graphics allows no more that 5 green defects per monitor, with no more than a total of 8 bright defects of all colors combined. On the particular display used in this study (SN 92000350N), there are two noticeable "on" red pixels near the edge of the screen.

1.1.3 Viewing Angle

One of the major issues facing the designers of LCD displays is viewing angle. The pixels of an LCD display do not emit light (as in a CRT) but rather obtain it from a backlight source and transmit it along their molecular axes. Since the twisted-nematic liquid crystals exhibit birefringence, changes in viewing angle lead to changes in appearance.

SGI defines the viewing angle of their displays to be the range of angles giving acceptable contrast ratios and linear gray scales. This display claims a viewing angle of 120° horizontal, +45°/-55° vertical. From casual observation of the display, these values seems to be correct.

1.1.4 Further Information

More information can be found on SGI's web site at: www.sgi.com/peripherals/flatpanel

A well written introduction to LCD display technologies, as well as the specific advances made in the SGI display can be found at: www.sgi.com/peripherals/flatpanel/whitepapers.html

In this section:

1.3 IBM

The IBM prototype display called Roentgen is a 200ppi digital active matrix TFTLCD display with a QSXGA (2560 x 2048) format. To avoid the need for special high-end adapter, the screen is controlled by four separate SXGA display adapters each driving one quarter of the screen.

1.1.1 Display Defects

As with the SGI display, several defects are present in the IBM display. Being a prototype however, they are more widespread, and varied. Although every effort was taken to minimize their impact, many of them were unavoidable in the measurement area. Such defects would not be present in a final product.

Shot Boundaries – Ten regularly spaced vertical bands appear across the width of this unit, each one corresponds to a single exposure in the photolithography process used in manufacturing the panel. Slight miss-alignment of the edges cause a mach banding effect, emphasizing their appearance, especially on light backgrounds. These can be eliminated using better alignment control.

White Blobs – Several small white blobs are visible on the screen which are caused by a disruption in the cell block creating an interference condition. These can be eliminated or screened out in manufacturing.

Black Blobs – A noticeable black blob caused by contamination on the back polarizer is also present.

Line Defects – Since LCD displays are essentially accessed in a row/column format, any missed connection in the 1.6 miles of specially formulated thin-film copper wire can cause an entire row or column of pixels to be unaddressable. A white line also appears in several locations due to weak gate lines. IBM has developed technologies to minimize these defects in the prototype unit.

Horizontal Smudges – One area on the display has a smudged appearance on the front glass due to residual chemicals left from hand buffing the polyamide layer which aligns the liquid crystals.

Uneven Illumination – For the prototype display, an off-the-shelf back light system was used since the increased resolution was the primary focus. A customized back light unit as is used in the SGI display will improve both the intensity and uniformity of the back light in production units.

1.1.2 Viewing Angle

The viewing angle of the IBM display very limited. Even small shifts in viewing position alter the appearance of the image. This is because no effort has been made to minimize the angular dependency in this prototype. A commercial version of the display would require much improvement in this area.

1.1.3 Further Information

Information about Roentgen can be found at:

www.research.ibm.com/news/detail/factsheet200.html or in [Bassak 1998].

In this section:

1.4 Summary Comparison

The table below lists the key features of each display for comparison.

Table 2-1Summary Comparison of Display Physical Characteristics

	Sony GDM-F500	SGI 1600SW	IBM Roentgen
Viewing Size	19.8” Diagonal	17.3” Diagonal	16.3” Diagonal
Resolution	~ 72 ppi	110 ppi	200 ppi
Pixel Pitch	0.22 mm	0.231 mm	0.126 mm
Number of Pixels	1280H x 1024V @80Hz	1600H x 1024V	2560H x 2048V
Bits per channel	8	8	6
Luminance	56 cd/m^2 (427:1 contrast)	161 cd/m^2 (276:1)	153 cd/m^2 (205:1)
Weight	70.5 lbs.	16 lbs.	< 20 lbs.

Please note the following points:

- In this comparison, viewing size is defined as the diagonal size of the viewable area of the display.
- The number of pixels figure for the Sony CRT is the setting used for this evaluation, it is capable of many other configurations.
- Luminance measurements were made on a central 3.5" square surrounded by mid gray.

2 Spectral Characteristics

A useful property when characterizing a display is that of stable primaries. To examine the spectral stability of the display's primaries, a series of four logarithmically spaced patches {35,81,145,255} was displayed for each primary and measured with the PR704. A five step ramp, including black, was also measured. If the primaries were spectrally stable, the normalized plots of each ramp shown in the figures below would appear as a single curve.

During the measurement process, every effort was made to keep the PR704 perpendicular to the display to minimize angular effects. At the distances used for measurement, the 0.5° circular aperture spanned approximately 20 pixels on the display.

While the PR704 provided data from 380–780nm at 2nm intervals, only the range from 400-700nm was evaluated in this section. If the tristimulus values used in subsequent stages were to be calculated from this data it is suggested that the range be extended to at least 720nm to capture the red phosphor emission near 710nm [Berns 1993b]. Issues such as the tradeoff between bandpass and sampling increment must also be addressed. Since a very accurate colorimeter, the LMT C1200, was available which gives tristimulus values directly, these spectral measurements were made primarily for illustrative purposes.

2.1 Sony

The spectral radiance characteristics of the Sony display are shown in the figures below. Figure 2-1 shows the spectral radiance distribution of the white. Figure 2-2 shows the corresponding plot for the displays black. Plots of the normalized ramps are show in

Figure 2-3 – Figure 2-6 below. In these figures the solid line represents the full on primary {level 255}, and the broken lines the intermediate levels.

Figure 2-1Sony Display White Radiance

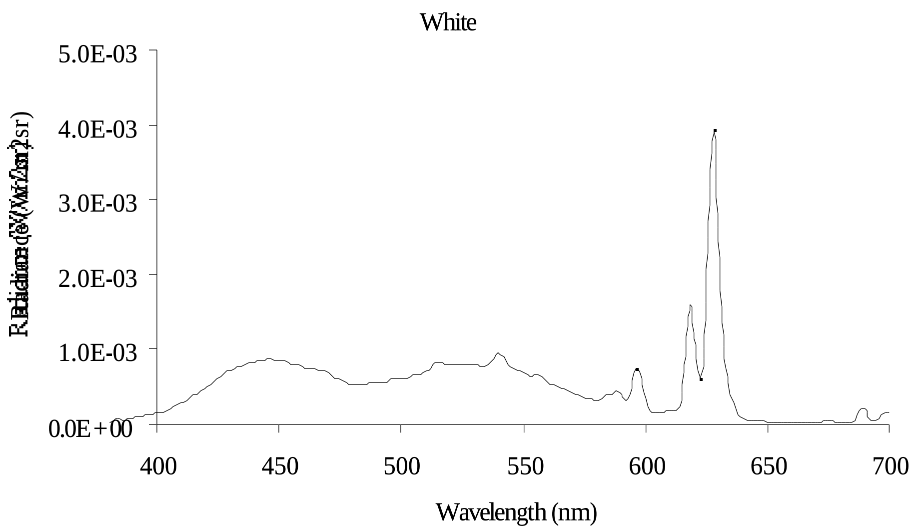


Figure 2-2Sony Display Black Radiance

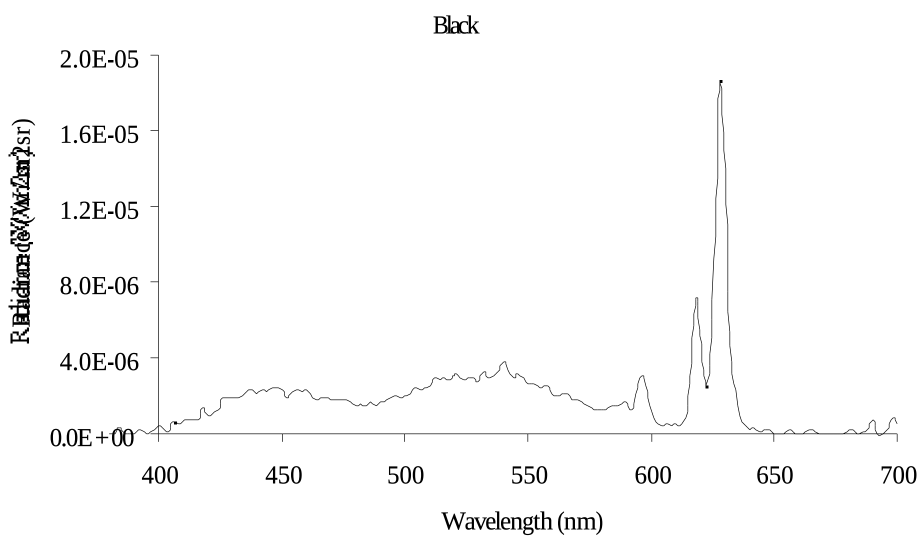


Figure 2-3Normalized Gray Ramp

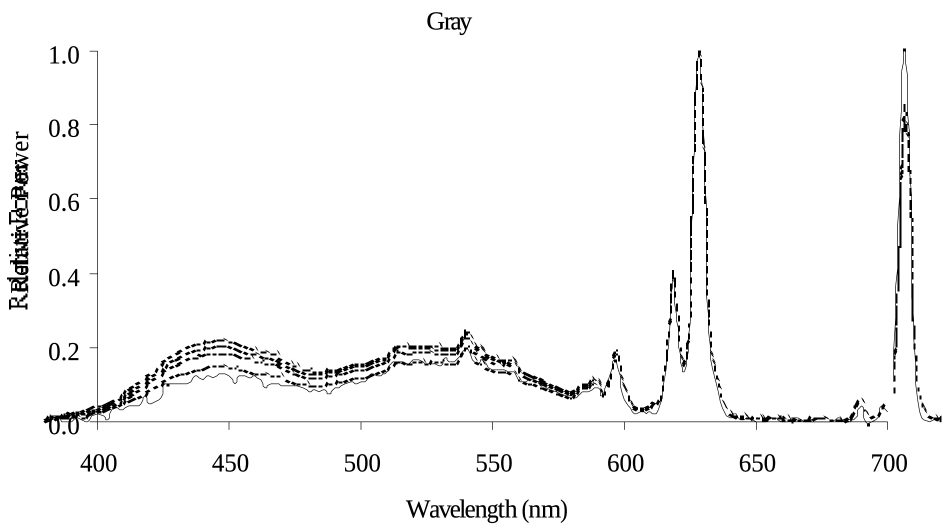


Figure 2-4Normalized Red Ramp

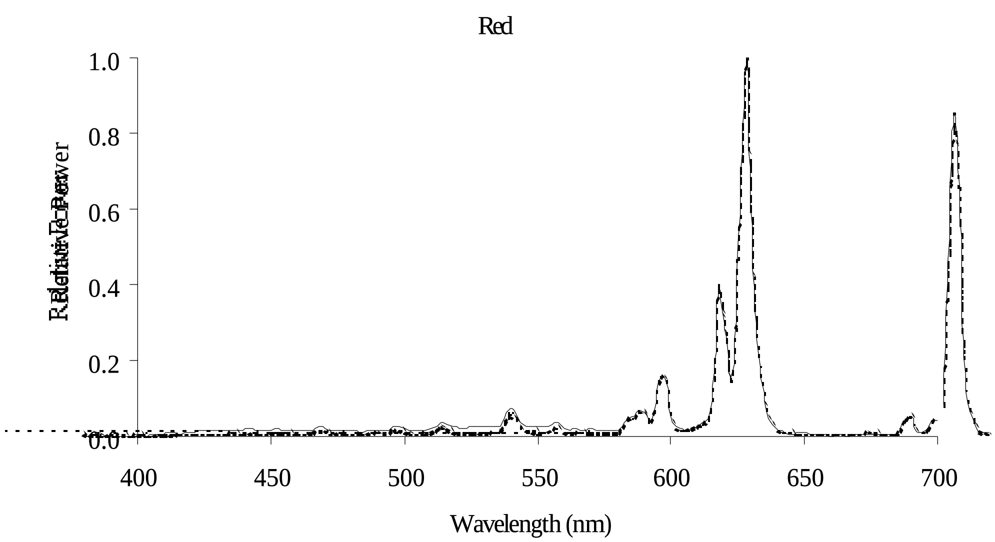


Figure 2-5Normalized Green Ramp

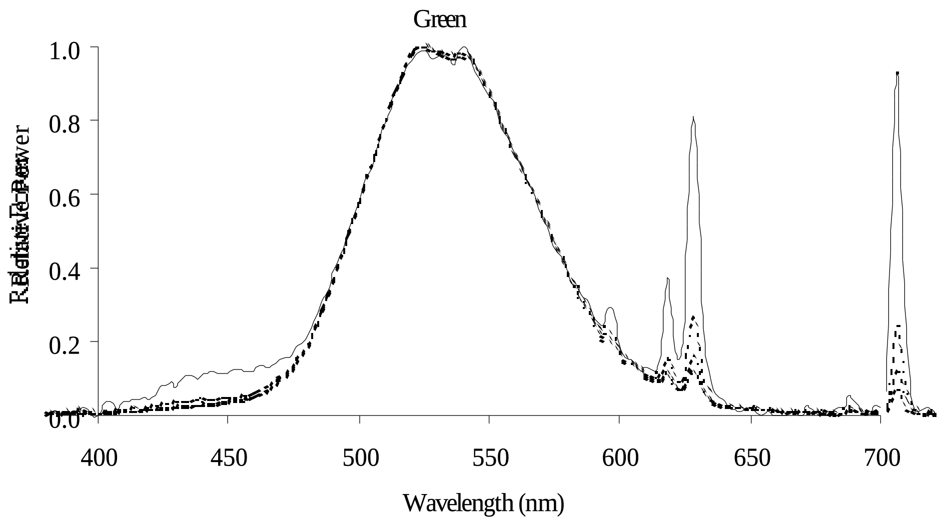
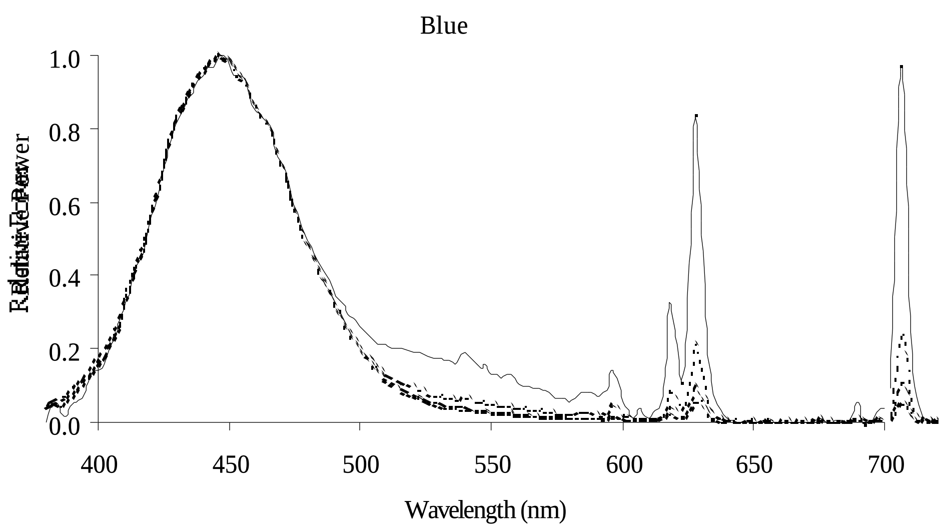


Figure 2-6Normalized Blue Ramp



Based on the figures above, it would appear that the Sony display exhibits reasonable spectral stability as to be expected from a good quality CRT. From spectral measurements such as these, the purity of each channel can be readily evaluated. For example, the strong peak near 630nm from the rare-earth elements used in the red phosphor is visible in both the green and blue channels.

2.2 SGI

The corresponding measurements for the SGI display are given below. The white, shown in Figure 2-7, is characteristic of the fluorescent backlight utilized in this display. The non-zero radiance for the black state, Figure 2-8 (compare to Figure 2-2), is common for LCD displays as the polarizes are unable to fully extinguish the backlight and a small amount leaks through.

Figure 2-7SGI Display White Radiance

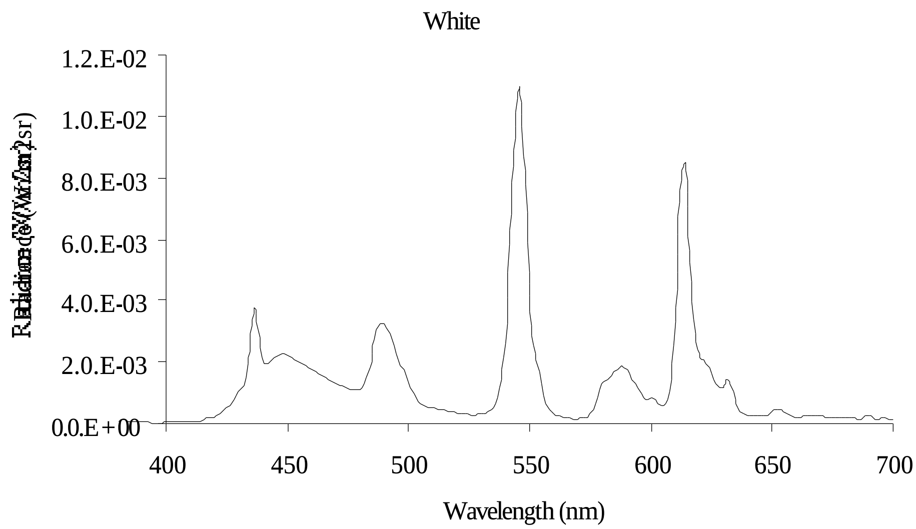


Figure 2-8SGI Display Black Radiance

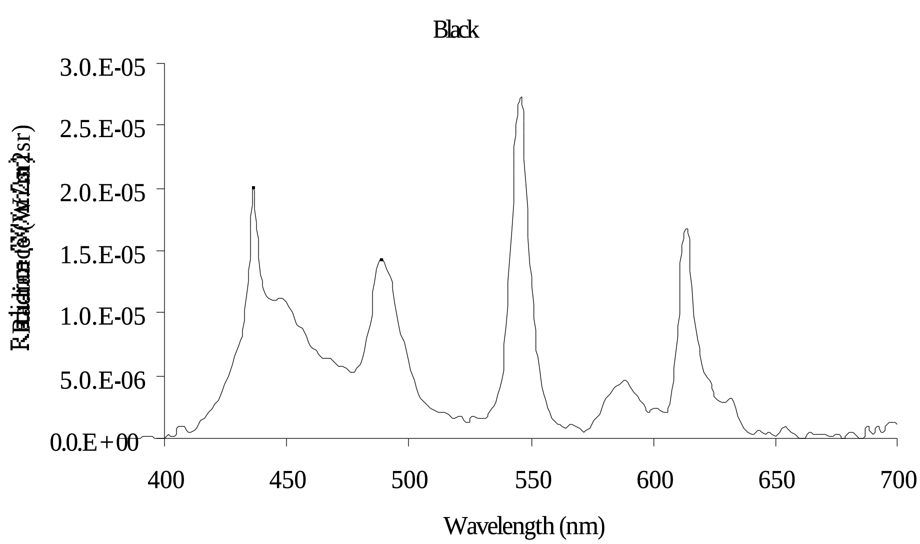


Figure 2-9Normalized Gray Ramp

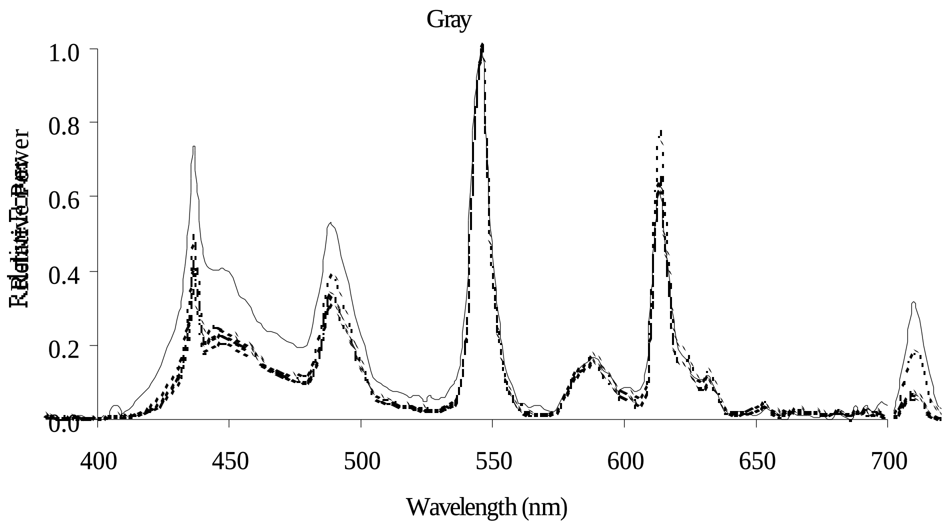


Figure 2-10Normalized Red Ramp

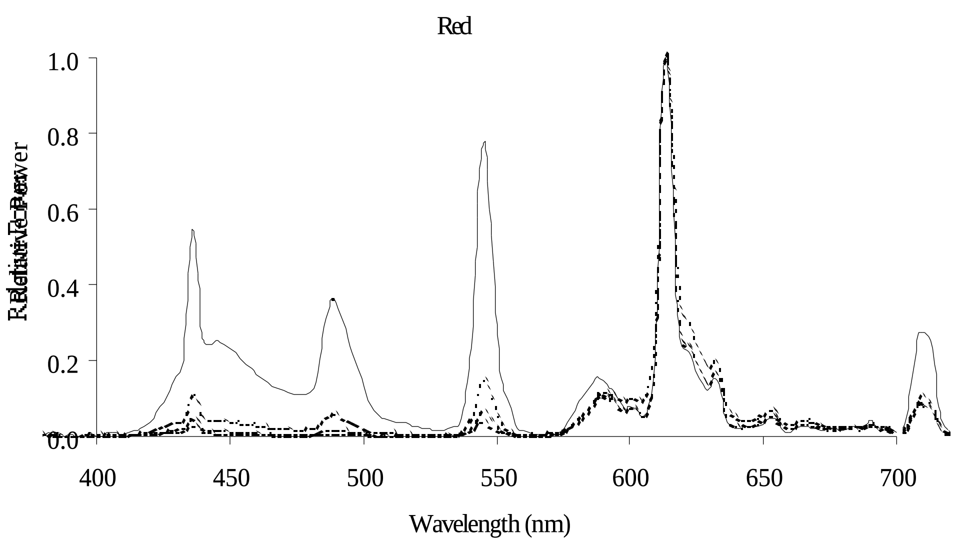


Figure 2-11Normalized Green Ramp

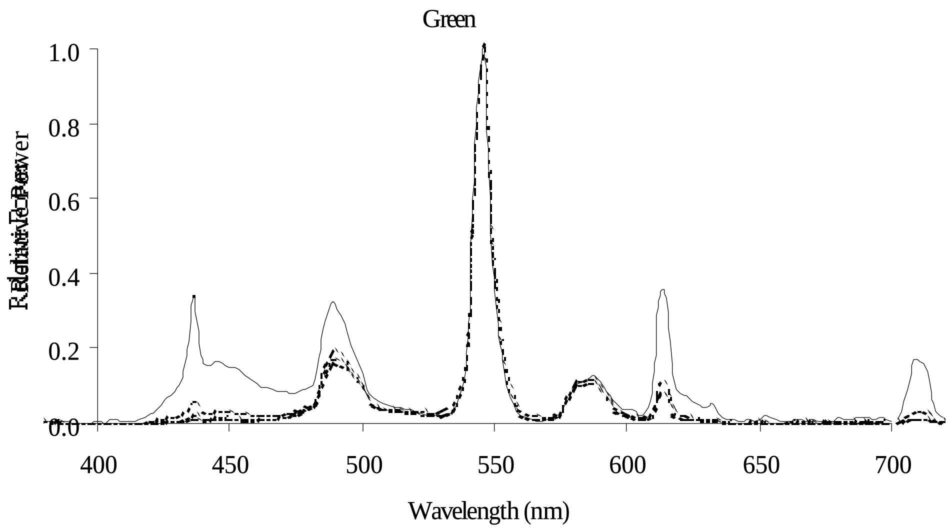
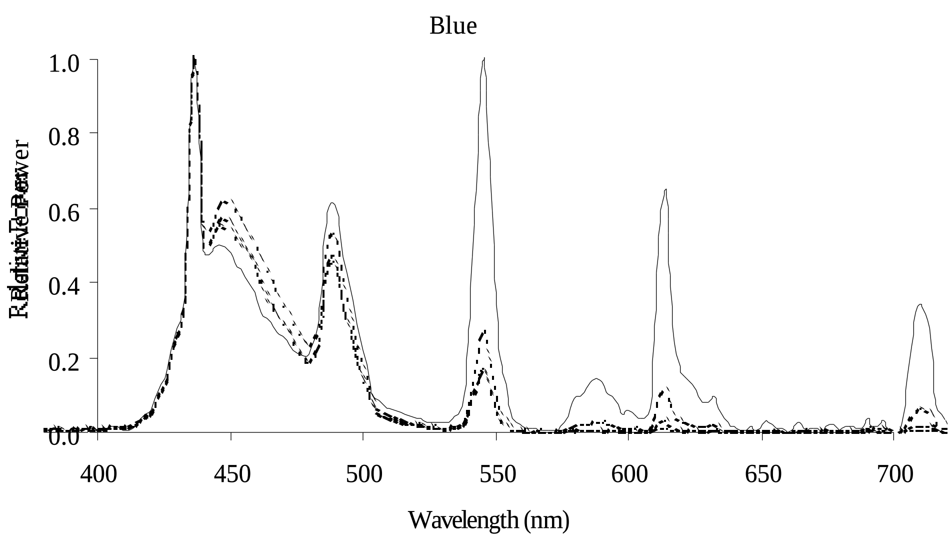


Figure 2-12Normalized Blue Ramp



The normalized plots of each channel appear to have greater variability than was seen in the Sony monitor, especially in the blue. Furthermore, the characteristics of the fluorescent backlight are visible in all three channels.

2.3 IBM

Measurements on the IBM display follow. Again, the characteristics of the fluorescent backlight are clearly visible from the white shown in Figure 2-13.

Figure 2-13IBM Display White Radiance

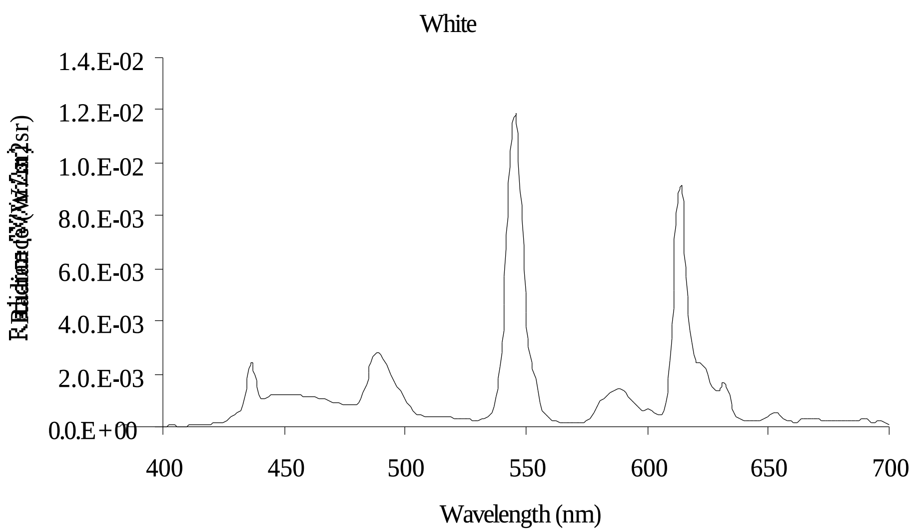


Figure 2-14IBM Display Black Radiance

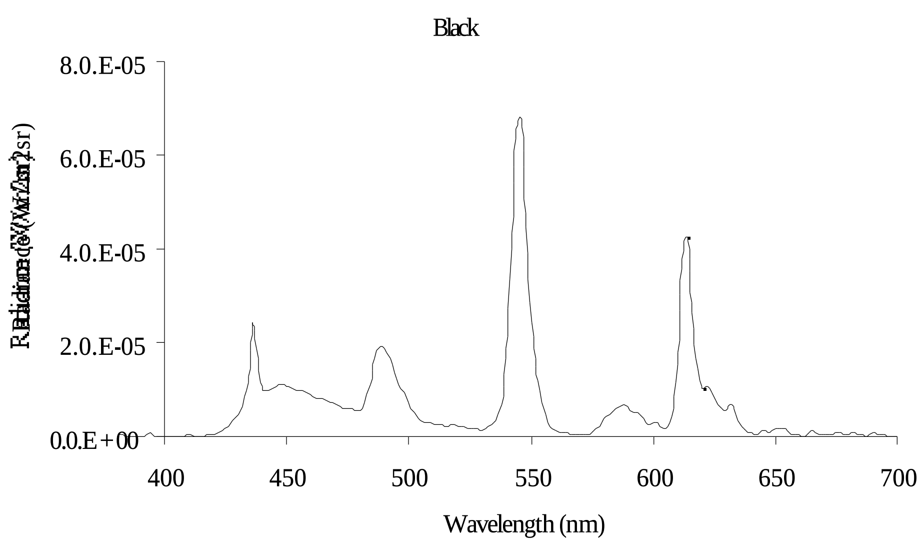


Figure 2-15Normalized Gray Ramp

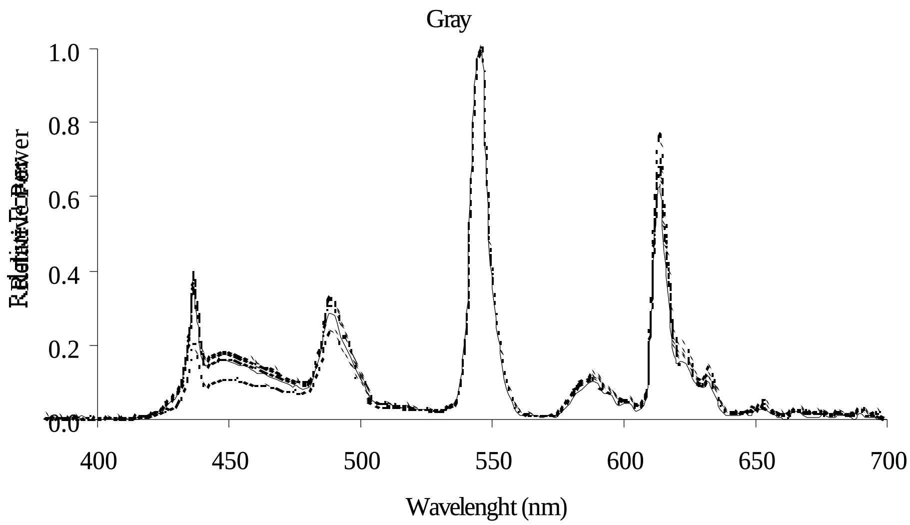


Figure 2-16Normalized Red Ramp

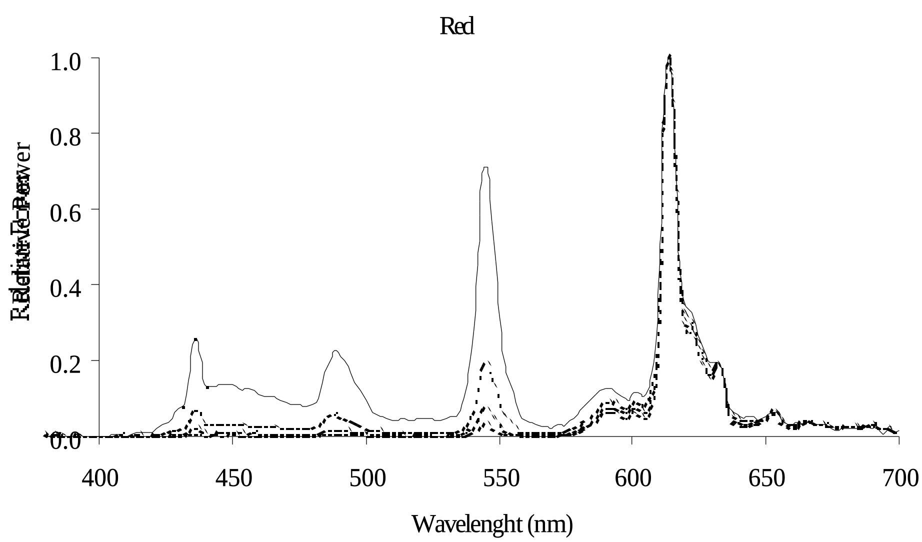


Figure 2-17Normalized Green Ramp

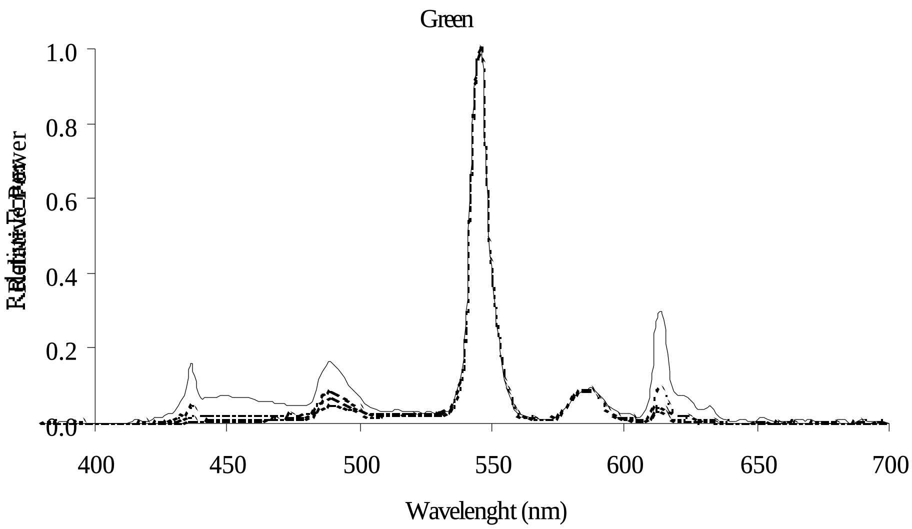
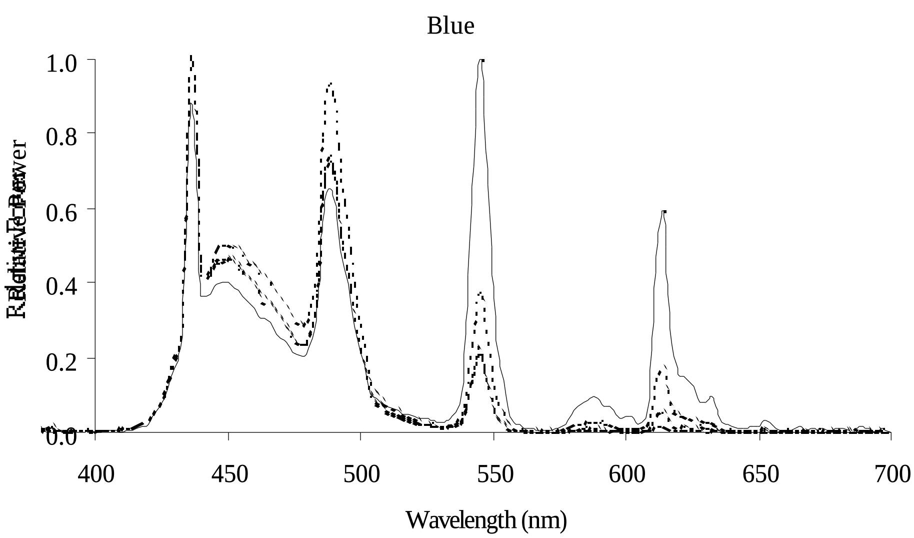


Figure 2-18Normalized Blue Ramp



2.4 Summary Comparison

2.4.1 Peak Spectral Radiance

Table 2-1 compares the peak spectral radiance output of each display for white, black, and the primaries. The two LCD displays have higher peak radiance in all three channels than the conventional display, due in part to the use of the narrow-band fluorescent backlights.

Table 2-1Peak Spectral Radiance Values for Each Display

Peak Radiance (W/m^2sr)E-03	Sony	SGI	IBM
White Point	3.94	10.9	12.0
Black	0.02	0.03	0.07
Red	3.83	5.5	8.2
Green	0.75	8.8	11.0
Blue	0.83	3.4	2.4

2.4.2 Spectral Variability.

To summarize the observed deviations from stability, coefficients of variation ($CV = \sigma/\mu$) were computed. That is, at each wavelength (400–700nm, 2nm), the standard deviation and average of all four (or five) normalized measurements at that wavelength was computed and the ratio taken. The average of all 151 CVs for each ramp is shown in Table 2-2. By normalizing the standard deviation with the mean, CVs are directly comparable across changes of magnitude.

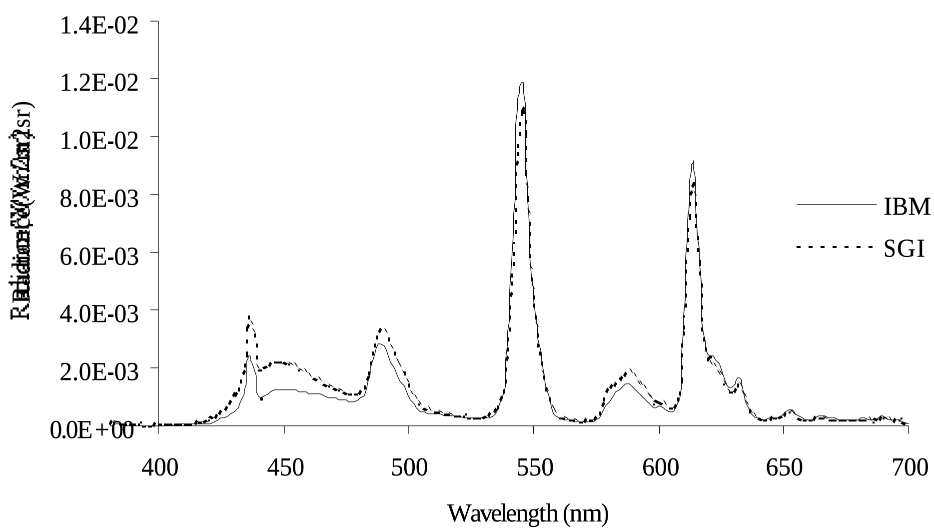
Table 2-2Spectral variability-Average CV over wavelength

	Sony	SGI	IBM
Gray	0.20	0.34	0.19
Red	0.35	0.81	0.84
Green	0.32	0.72	0.69
Blue	0.57	0.72	0.63

2.4.3 LCD backlight Comparison

Examining Figure 2-19, it appears that the SGI and IBM display use a similar fluorescent back light, with the SGI display having slightly more output in the blue end of the spectrum. Since the IBM display is a prototype unit designed for testing the new LCD, a standard back light was used. It is possible with some optimization of the backlight and filters used that the IBM display could be improved.

Figure 2-19Backlight Comparison of IBM and SGI displays



3 Temporal Stability

Both CRT and LCD displays require time to reach a steady state from a cold start. While no specific warm-up tests were run for the displays evaluated in this report, the characteristics observed by Fairchild [1998] can reasonably be expected for the LCD displays. To ensure that the display had reached a steady state, each display was left for over four hours before beginning measurements.

Since the measurement process involved several repeat presentation of each primary over the course of several hours, a post hoc evaluation of the temporal stability can be preformed. Table 3-1 below shows the ΔE^*_{94} mean color difference from the mean (MCDM) for each primary. The time span for these measurements is over three and a half hours for each display.

Table 3-1Temporal Stability of each Display

	Sony	SGI	IBM
Red	0.13	0.06	0.05
Green	0.14	0.05	0.04
Blue	0.08	0.04	0.03

The results indicate that the two LCD panels were very stable over the time of measurement and therefore were given adequate warm-up time prior to starting. The slightly larger variability seen on the CRT is not surprising and is small enough to be of little concern.

4 Spatial Independence

Spatial independence refers to the impact that a color displayed on one area of the monitor has on a color in another area. Characterizing a display that does not exhibit this property is difficult if not impossible. To test the spatial independence of each display, a series of nine color stimuli were measured on nine different background made up of the same nine colors for a total of 81 colorimetric measurements [Fairchild 1998]. The CIELAB coordinates of each stimulus were then computed using the average value of white on gray as the CIELAB reference white. The data are summarized in Table 4-1 for each display using mean color-difference from the mean (MCDM) metrics in terms of CIE94 color differences. The MCDMs were calculated both across background (i.e. how did the nine different backgrounds affect each of the foreground colors), and across stimuli (i.e. how much did the nine different foreground colors change on a given background). The data in this section were not flare corrected since only changes are compared.

Table 4-1MCDMs for Spatial Independence Measurements

	Sony		SGI		IBM	
Color	Background	Stimuli	Background	Stimuli	Background	Stimuli
Black {0}	0.76	1.67	0.10	0.03	0.15	0.13
Gray{128}	0.18	0.53	0.07	0.26	0.15	0.48
White {255}	1.68	0.44	0.14	0.07	0.17	0.25
Red {128}	0.42	0.64	0.08	0.05	0.23	0.23
Red {255}	0.52	0.32	0.06	0.04	0.22	0.13
Green {128}	0.53	0.32	0.09	0.12	0.19	0.31
Green {255}	0.44	0.26	0.05	0.03	0.28	0.12
Blue {128}	0.63	0.92	0.08	0.07	0.19	0.14
Blue {255}	0.38	0.43	0.06	0.05	0.27	0.06

The overall MCDM for the SGI display was 0.08, 0.21 for the IBM, and 0.62 for the Sony display. Given that each pixel in an active-matrix TFT-LCD is physically distinct from it's neighbors, good spatial independence was expected. In a conventional CRT, a single scanning electron beam is used to address each pixel of a given color and they often suffer from poor spatial independence.

5 Luminance & Contrast

Using the LMT L1009 photometer, the luminance of each primary, black, and white was measured. The contrast of the display was then calculated by taking the ratio of the white to the black. Results are summarized in the tables bellow. The targets were displayed as both full-screen colors, Table 5-1, and as 3.5" squares with gray surround, Table 5-2, for comparison. The large difference in values point to the need for carefully defining the measurement conditions before stating results.

Table 5-1Measured Luminance and Contrast–Full Screen

Color	Sony (cd/m^2)	SGI (cd/m^2)	IBM (cd/m^2)
Red	15.47	44.5	38.3
Green	36.0	110.3	93.9
Blue	3.51	13.81	11.92
White	55.8	167.8	150.7
Black	0.004	0.541	0.665
Contrast (W/K)	13950:1	310:1	227:1

Table 5-2Measured Luminance and Contrast–3.5" Square with Gray Surround

Color	Sony (cd/m^2)	SGI (cd/m^2)	IBM (cd/m^2)
Red	15.70	42.9	38.4
Green	39.3	106.4	94.5
Blue	3.96	13.34	12.19
White	55.9	161.5	152.7
Black	0.131	0.584	0.745
Contrast (W/K)	427:1	276:1	205:1

Comparing the two tables above, it can be seen that the two LCD panels maintained their black level, and therefore contrast as the target size was reduced. Given the nature of the LCD display, it is expected that this would hold even for very small targets. In comparison, the CRT had an extremely large contrast with a full screen measurement, but a more moderate contrast when the target was reduced in size. Reducing the target size further would cause still more reduction in contrast.

5.1 Sony

The full screen luminance of the Sony monitor is more than a factor of two lower than either of the two LCD displays tested but is typical of most good quality CRT displays. The full screen contrast ratio however was quite high for the Sony display. When properly setup, little to no light is emitted from the black state on a CRT.

5.2 SGI

The SGI monitor has the highest luminance output of the thee monitors tested in this report. While not as high luminance as the Apple Studio display measured by Fairchild [1998] which measured 188 cd/m^2, the SGI's contrast ratio was considerably higher (310:1 vs. 250:1) indicating a darker black level. The measured contrast ratio is on par with the manufactures claim of 350:1. To achieve this SGI uses two techniques. First, a negative birefringence compensation film is placed after the liquid crystal cell to compensate for the positive birefringence introduced by the liquid crystal giving a greater extinction level. Second, thick color filters are used to maintain high saturation levels in the primary color subpixels thus minimizing the impact of any stray leakage from adjacent pixels.

5.3 IBM

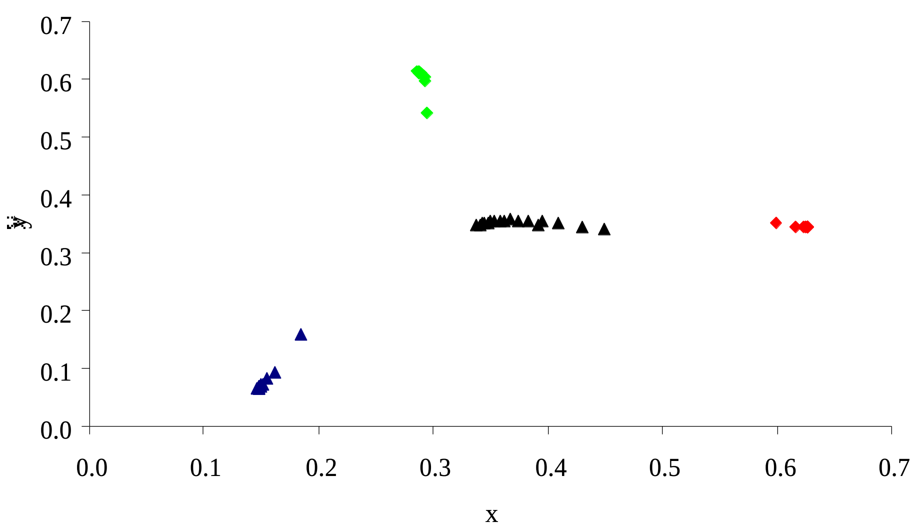
The weaker performance of the IBM display is most likely due to it's prototype nature and will be likely be improved upon in the commercial version.

6 Chromaticity Constancy of Primaries

The gain-offset-gamma (GOG) model for characterizing displays uses a two stage process. First, three 1D-LUT's are used to transform the incoming digital counts into linear scalars. Second, the linear scalars are multiplied by a 3x3 primary mixing-matrix. Thus the estimated signal is a scaled version of the full strength primaries. For this process to work, the chromaticity coordinates of each level must remain constant. To test this assumption, a series of 16 logarithmically spaced steps in red, green, blue were measured along with a 17 log-step gray ramp. As discussed by Fairchild [1998], the black level flare has been removed from each measurement before computing the chromaticities. Results for each display are given below.

6.1 Sony

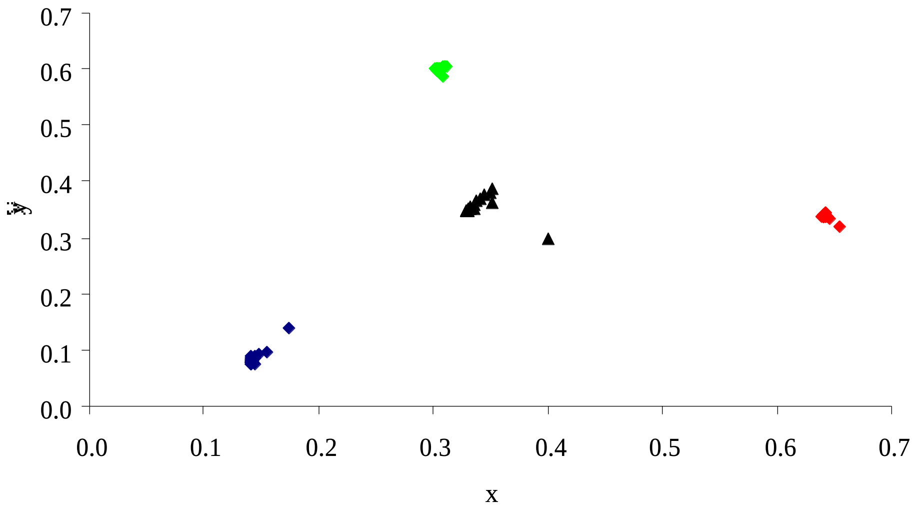
Figure 6-1Chromaticity of Red, Green, Blue Primaries and Neutrals



The primary constancy of the Sony display appears adequate, as is expected of a high quality CRT. The tendency of each primary towards the white point may indicate that some residual flare was not accounted for. The large variation in the gray levels is due primarily to the undefined nature of chromaticity coordinates at very low tristimulus values.

6.2 SGI

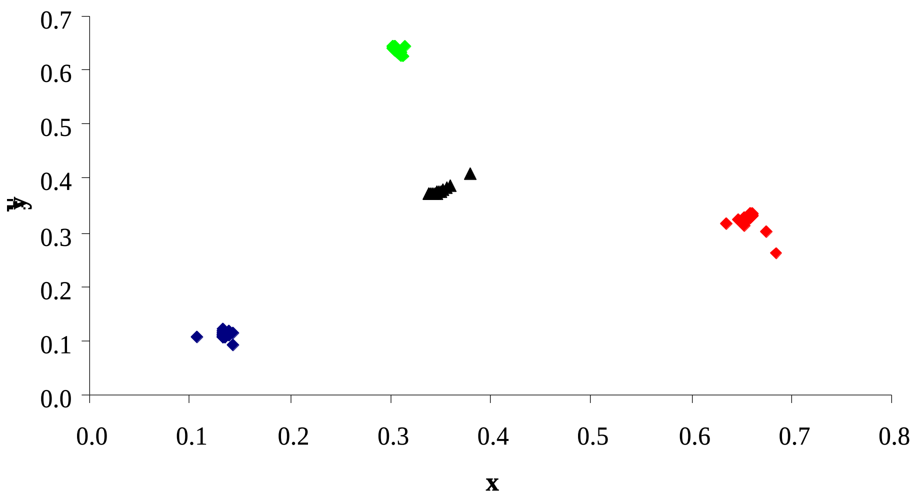
Figure 6-2Chromaticity of Red, Green, Blue Primaries and Neutrals



The SGI display appears to exhibit good consistency in the primaries and has a stable gray scale. The one outlying point in the gray ramp is the black. The tristimulus values of the black patch, after subtracting the average flare value, were slightly non zero {-0.001, -0.0008, -0.0007} and therefore produced an outlying point in chromaticity space rather than being undefined if it measured {0,0,0}. In practice these small deviations from zero are insignificant and would be removed, their inclusion here is simply illustrative.

6.3 IBM

Figure 6-3Chromaticity of Red, Green, Blue Primaries and Neutrals



6.4 Summary Comparison

To summarize the variability of each displays primaries, Table 6-1 lists the coefficient of variation in both the x and y dimensions for each primary.

Table 6-1Chromaticity Variability

Color	Sony		SGI		IBM	
	x	y	x	Y	X	Y
Red	0.01	0.00	0.01	0.01	0.01	0.02
Green	0.01	0.03	0.01	0.01	0.02	0.01
Blue	0.06	0.31	0.01	0.15	0.08	0.07
Gray	0.09	0.01	0.02	0.01	0.03	0.02

7 Additivity

The additivity of each display was evaluated in both luminance, Table 7-1, and tristimulus space, Table 7-2. Luminance values were measured with the LMT L1009 photometer at a distance such that its 1° spot size spanned approximately 20 pixels on the display. The LMTC1200 colorimeter used for tristimulus measurements has a 3" diameter aperture and is set 2.25" back from the front surface of the device by means of a matte black tube. All tristimulus values in this section were flare corrected by subtracting the average tristimulus values of the black squares measured (8 in all) from the corresponding values of each sample. Results for each display are discussed in the various sub-sections below.

Table 7-1Luminance Additivity

Color	Sony (cd/m^2)	SGI (cd/m^2)	IBM (cd/m^2)
R+G+B	54.98	168.61	144.12
White	55.8	167.8	150.7
Difference	1.5%	-0.5%	4.5%

Table 7-2 Tristimulus Additivity

	Sony			SGI			IBM		
Value	White	R+G+B	% Diff.	White	R+G+B	% Diff.	White	R+G+B	% Diff.
X	35.78	35.53	0.70%	84.83	84.82	0.01%	75.92	70.14	7.61%
Y	36.94	36.70	0.63%	87.40	87.33	0.08%	81.32	75.21	7.51%
Z	33.26	32.77	1.46%	69.02	68.96	0.09%	41.46	40.22	2.98%

7.1 Sony

The small failure of additivity for this display might well be due to a small increase in flare at the high luminance levels which is not present when estimating the flare from black alone. There may also be circuitry on board the display which increases power sent to the electron guns to compensate for their increased load. The degree of additivity is sufficient to justify the use of a 3x3 primary matrix transform.

7.2 SGI

The additivity on this display was excellent, exceeding many other displays we have tested. Given the high resolution of this display and the discrete nature of each pixel, it is not surprising that the additivity was good. The use of the 3x3 primary matrix transform is well justified.

7.3 IBM

The large differences between white and R + G + B are disturbing. A possible cause may be the strong angular dependency of this display. The LMT colorimeter was used with a very large acceptance cone and may therefore be subject to color shift errors. However, a substantial failure of additivity was also observed using various aperture sizes both with the LMT photometer and the colorimeter as shown in the table below. This issue is still under investigation.

Table 7-3 Additivity vs. Aperture Size – LMT Colorimeter

	3" Aperture			1" Aperture			0.5" Aperture		
Color	X	Y	Z	X	Y	Z	X	Y	Z
Red	37.84	19.279	0.263	3.764	1.916	0.027	0.749	0.381	0.005
Green	21.34	45.069	3.403	2.121	4.494	0.34	0.421	0.892	0.066
Blue	5.988	5.439	33.62	0.61	0.543	3.417	0.121	0.108	0.675
R + G + B	65.16	69.787	37.29	6.495	6.953	3.784	1.291	1.381	0.746
White	70.6	75.509	38.55	7.004	7.482	3.862	1.385	1.483	0.76
% Difference	7.7%	7.6%	3.3%	7.3%	7.1%	2.0%	6.8%	6.9%	1.8%

Table 7-4 Additivity vs. Aperture Size – LMT Photometer

	Aperture Size			
Color	6'	20'	1deg	3deg
Red	36.5	36.6	36.6	36.4
Green	88.8	89.0	88.8	88.2
Blue	11.6	11.60	11.58	11.54
R + G + B	136.9	137.2	136.98	136.14
White	143.3	143.5	143.3	142.4

%Difference	4.5%	4.4%	4.4%	4.4%

8 Electro-Optical Transfer Functions

8.1 Sony

Being a conventional CRT display, the standard GOG model was used to characterize the Sony display. From a 17 step, logarithmically spaced gray ramp, target RGB scalars were estimated using the inverse 3x3 mixing matrix. Then, using a simplex nonlinear estimation, a constrained GOG model was fitted using Equation 8-1. The estimated parameters are given in Table 8-1, and the resulting curves are plotted in Figure 8-1–Figure 8-3.

Equation 8-1GOG Model Constrained to Gain + Offset = 1.0

$$\cdot = \left[Gain \times \left(\frac{d_c}{255} \right) + (1 - Gain) \right]^{Gamma}$$

Where: · refers to the red, green, or blue scalar (RGB).

Table 8-1Estimated GOG Parameters for Sony Monitor

Channel	Gain	Gamma
Red	1.0025	1.6553
Green	1.0200	1.7052
Blue	1.0200	1.7581

To test the fit of this model, the training data was estimated and the ΔE^*_{94} difference computed. Average error was 0.61, with a maximum of 1.13. A test with independent data is given in §9.

Figure 8-1Measured Data and Fitted GOG model for the Red-channel

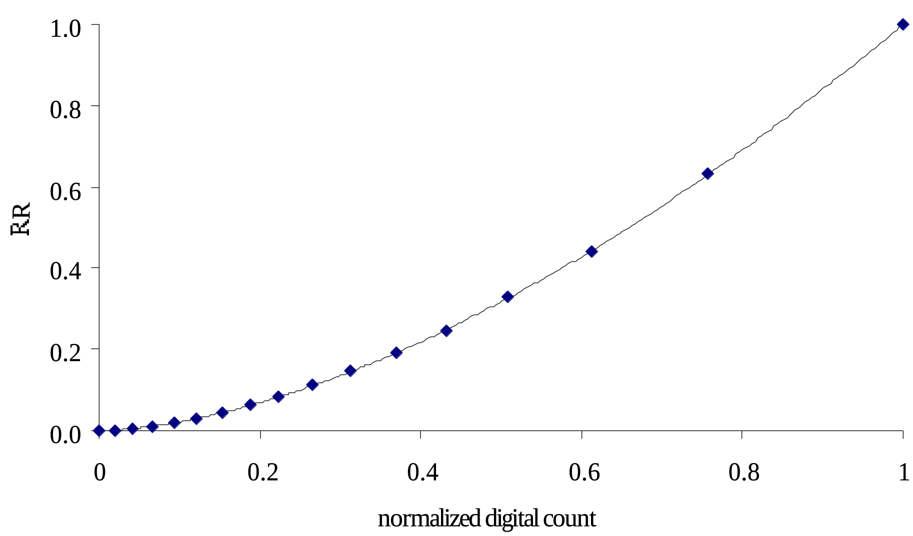


Figure 8-2Measured Data and Fitted GOG model for the Green-channel

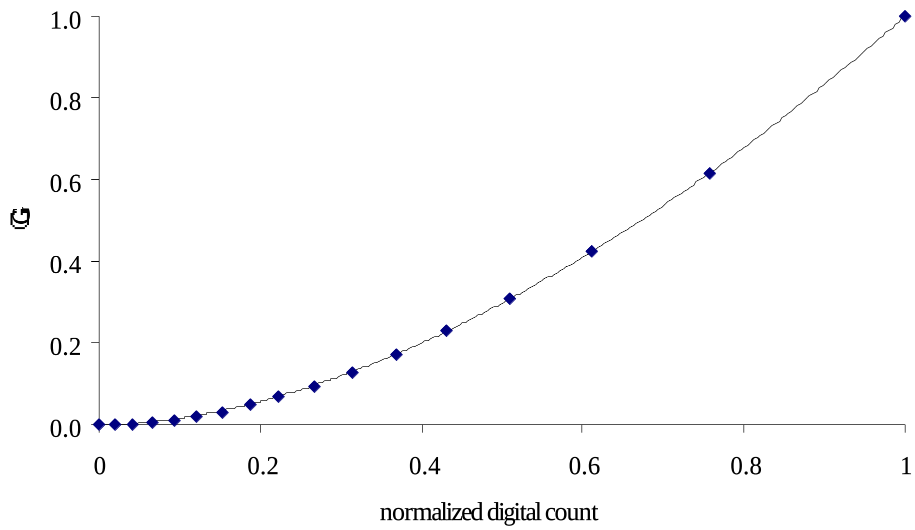
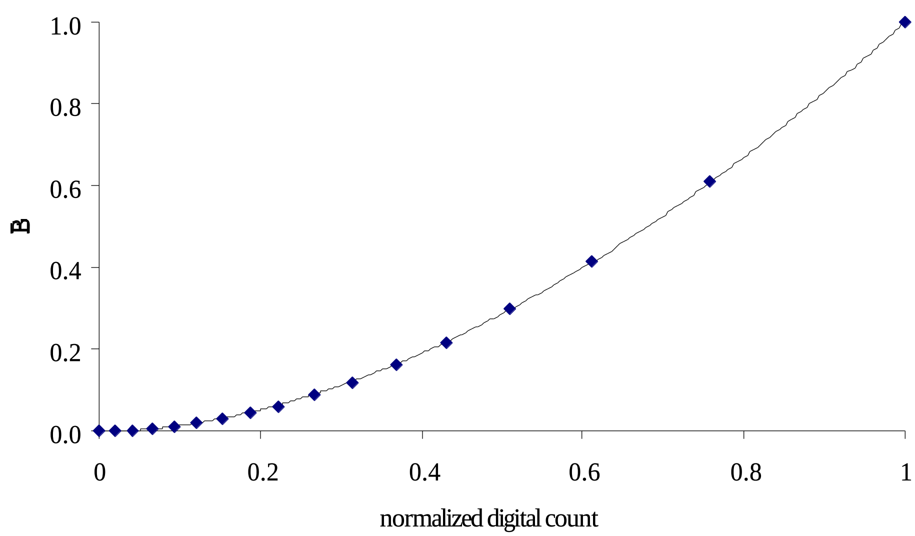


Figure 8-3Measured Data and Fitted GOG model for the Blue-channel



8.2 SGI

Both a conventional GOG model using a 17 step neutral ramp, and a cubic spline interpolation of three 52 step ramps (red, green, blue) were used in modeling the SGI display. The estimated parameters of the GOG model are shown in the table and graphs below.

Table 8-28-3Estimated GOG Parameters for SGI Display

Channel	Gain	Gamma
Red	0.6706	4.4622
Green	0.8000	3.2559
Blue	0.9507	2.2841

The low estimated gain terms indicate a poor dark state. Preferably, the gain terms should all be slightly greater than 1.0 which creates negative offsets (offset = 1.0 - gain) and ensures that no light is being emitted at the black level.

As with the Sony display, the fit of each model was evaluated by re-estimating the training data. Results for the two models tested for the SGI are shown in Table 8-4. An independent data set is evaluated in §10.

Table 8-4Redistribution Errors for SGI Models

Model	Average ΔE^*_{94}	Maximum ΔE^*_{94}	Number of Points measured
GOG	2.94	6.72	17 logarithmically spaced gray patches
LUT	0.97	2.2	52 steps each for RGB, 156 total

Figure 8-4Measured Data and Fitted GOG model for the Red-channel

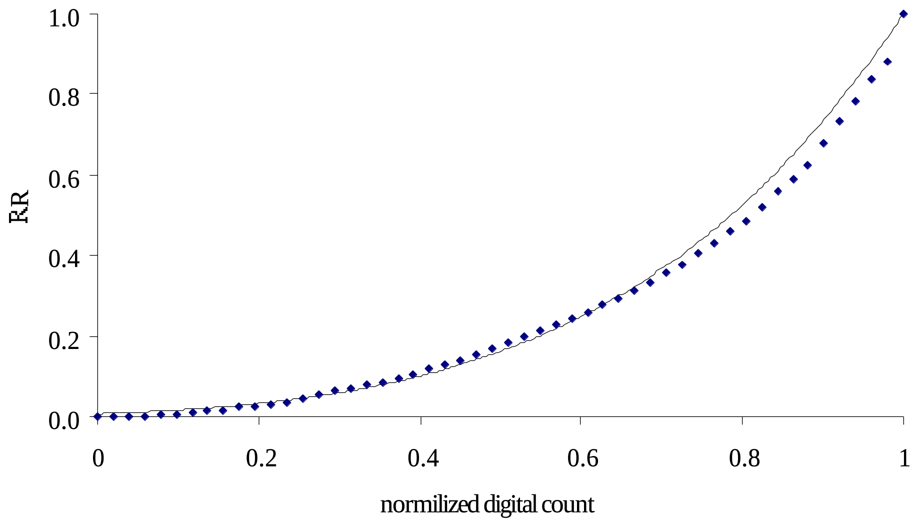


Figure 8-5Measured Data and Fitted GOG model for the Green-channel

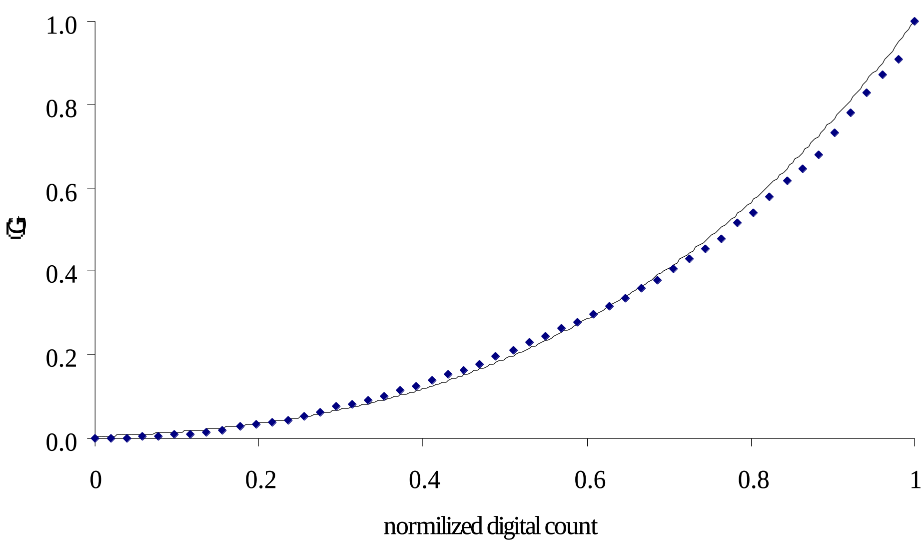
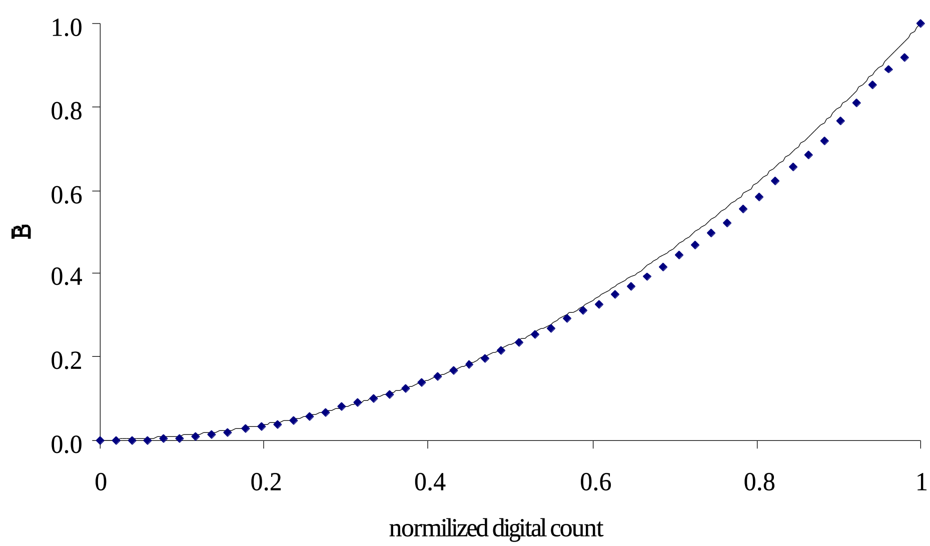


Figure 8-6Measured Data and Fitted GOG model for the Blue-channel



Although the GOG model fit the low end reasonably well, the systematic trends to overestimate the high end indicated that this model might not perform well. Therefore, a set of three 1D LUTs were created from the 52 step primary ramps using cubic-spline interpolation between the nodes. The resulting transfer curves are shown below.

Figure 8-7Measured Data and LUT for the Red-channel

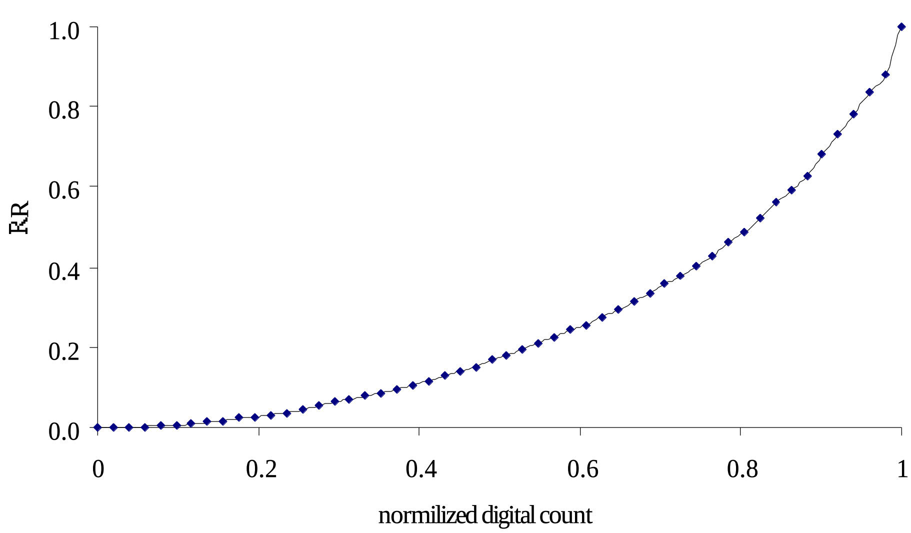


Figure 8-8Measured Data and LUT for the Green-channel

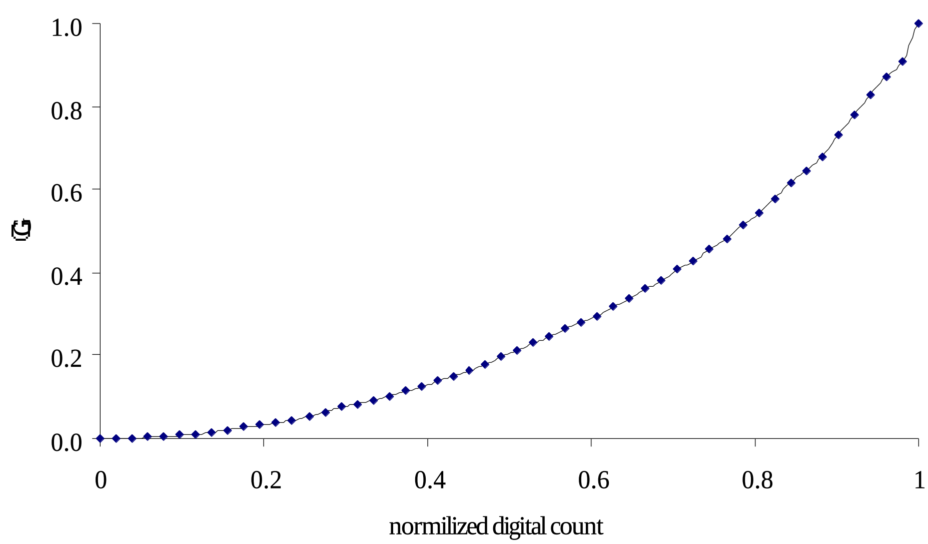
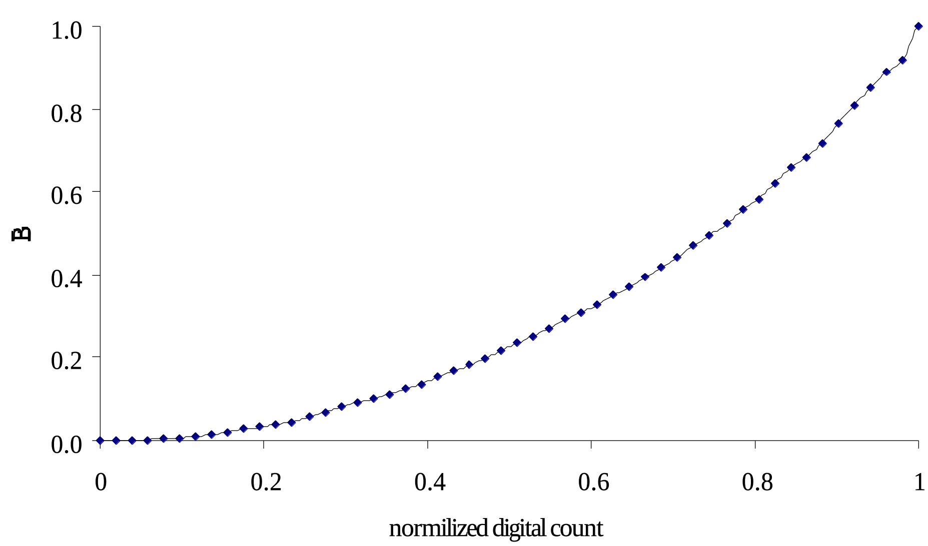


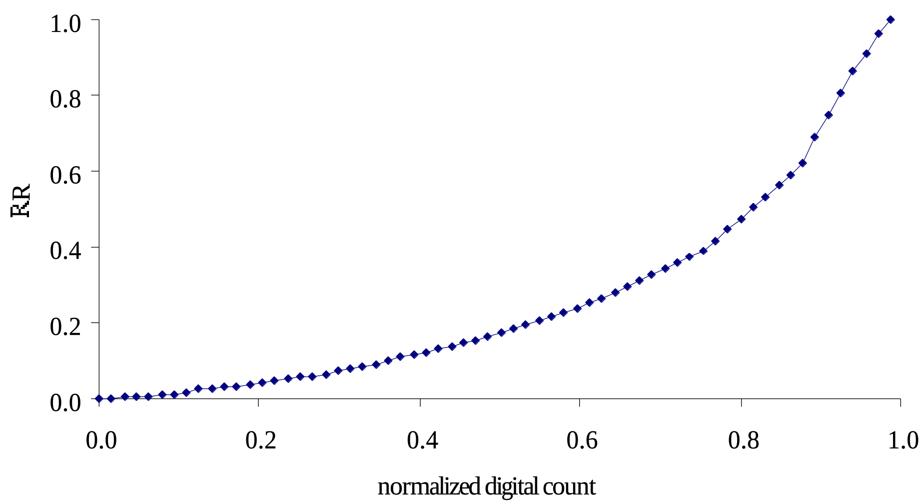
Figure 8-9Measured Data and LUT for the Blue-channel



8.3 IBM

Being a 6 bit/channel device, a direct LUT was easily built by measuring all 64 levels for each primary. Since no interpolation was needed, the lines in the figures below are for clarity only, the 64 discrete points were all that was required.

Figure 8-10Measured Data for the Red-channel



The rather jagged shape of this transfer curve, and the two below for green and blue, clearly suggest that the GOG model is inappropriate for this display.

Figure 8-11Measured Data for the Green-channel

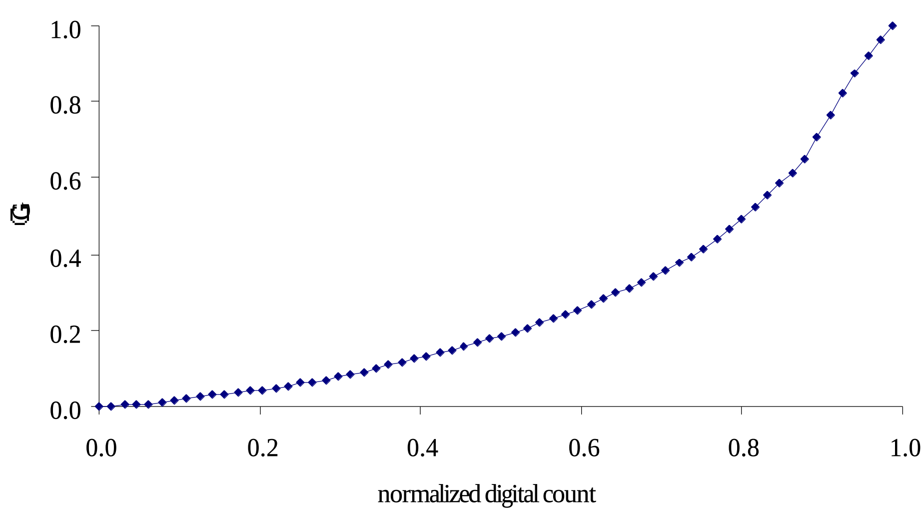
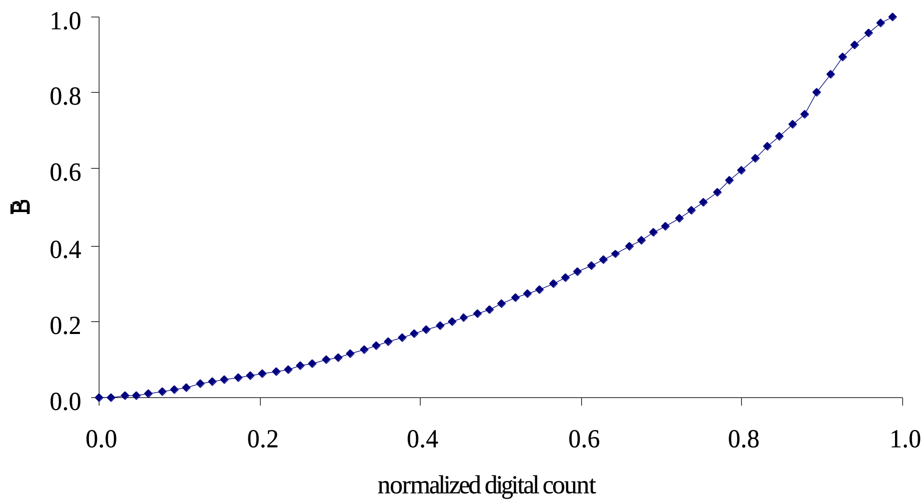


Figure 8-12Measured Data for the Blue-channel



For reasons to be discussed in the following section, two aditional models were evaluated for this display. Their relavent chrateristics are described below. The redistribution preformance of all three models is given in Table 8-5.

Peak Model In this model the 3x3 primary mixture matrix is made from the tristimulus values of the peak red, green, and blue primaries. The LUT was then built by multiplying the RGB ramps with the inverse of this matrix to obtain target scalar values.

Scaled Model To account for the lack of additivity, the columns of the above 3x3 were scaled such that the row sums were equal to the white point. The LUT was then built using the ramp data such that: $R = X/X_{max}$ of the red ramp, $G = Y/Y_{max}$ from the green ramp, and $B = Z/Z_{max}$ from the blue.

Fit Model The 3x3 mixture matrix for this model was derived from a least squares fit to 283 points. The Scaled Model LUT was used.

Table 8-5Redistribution Error for IBM Display Models

Model	Average ΔE^*94	Maximum ΔE^*94	# of Points in Model
Peak	0.58	1.74	192 step RGB ramp
Scaled	1.36	2.60	192 step RGB ramp
Fit	1.20	6.55	283 various

The poor performance of the Scaled model on the ramp data is to be expected since it was not specifically created to fit that data set. The Fit model preformed poorly on this test but was built on a more representative data set including: the full 192 step RGB ramp, two repeat measures of a smaller RGB ramp, two repeat measurements of a 17 step gray scale, and the 9 patches from the spatial independence test which were presented on gray backgrounds.

9 Model Performance and Evaluation

The performance of each model derived above was tested by measuring a 3x3x3 target and an additional 15 pre-selected random colors for a total of 42 patches. A 3x3x3 target refers to a sampling design in which three levels are chosen, {44, 128, 212} in this instance, and each of the red, green, and blue channels are varied in all 27 combinations of these levels. That is, the first patch displayed would have a RGB triplet of {44,44,44}, the next patch presented would be {44,44,128}, followed by {44,44,212}, {44,128,44},... ,{212,212,212}. The 15 pre-selected random colors were included to increase the sample size and to counter any systematic effects caused by the 3x3x3 sampling design. The results, in terms of ΔE^*_{94} between measured and predicted values are summarized in Table 9-1. The three methods listed for the IBM display refer to different models used and will be explained in §9.3.

Table 9-1 ΔE^*_{94} *Colorimetric Error for 3x3x3 Independent Data Set*

	Quartile				
Display	25%	50%	75%	Average	Maximum
Sony	0.23	0.33	0.41	0.36	1.10
SGI (GOG)	1.63	1.89	2.07	1.98	5.57
SGI (LUT)	0.83	1.05	1.23	1.01	1.81
IBM (Peak)	3.77	5.28	6.442	4.91	7.92
IBM (Scaled)	2.49	3.68	4.87	3.73	7.63
IBM (Fit)	2.81	4.40	5.26	4.06	7.34

In building the SGI-LUT and IBM models, a 17 step gray scale was measured twice as a check on repeatability. The average of these two sets forms a second independent data set to test these four models on as shown in Table 9-2 below. In the case of the Fit model, the two gray scales were included in the modeling set, so it's inclusion in the table below is for comparison only.

Table 9-2 ΔE^*_{94} *Colorimetric Error for 17 Step Gray Scale Data Set*

Model	Average	Maximum
SGI (LUT)	0.78	1.62
IBM (Peak)	2.71	8.09
IBM (Scaled)	2.07	6.23
IBM (Fit)	2.15	6.49

9.1 Sony

Overall, the model for the Sony display fit quite well as is typical of a properly set up high quality CRT. The good performance on both the redistribution test and the independent data set suggest that the model is robust and should perform well in subsequent testing.

9.2 SGI

As expected based on the systematic errors observed in the GOG model fits, the LUT based method preformed better on the SGI display. The LUT model should be adequate for most purposes and is on par to the results found by Fairchild [1998] for an Apple Studio display (average of 1.02, maximum of 2.88 on 100 independent samples). The LUT model performance on the Gray Scale data set was adequate.

9.3 IBM

Overall the IBM models performed less than satisfactory. It is hoped that, with further effort, a satisfactory and robust model can be derived.

One possible solution in cases where models fail is to use a 3D look-up-table. Given the 64 levels of each primary there are a total of 64^3 = 262,144 possible colors (as opposed to the 16.77 million combinations for an 8 bit display). Therefore a reasonable sub-sampling, (perhaps an 13x13x13 target of 2197 patches, or around 0.8% of the total), of these levels could be measured. One of the three models could be used to up-sample the data to a full 64-cubed 3D LUT. An alternate solution might be to measure several hundred more patches and add them to the data set used in the Fit model. This would require fewer measurements and may provide adequate results. Failing that, the data could still be used as part of the 13-cubed sampling. Further analysis is needed before any definite conclusions can be drawn.

The relative merits and weaknesses of each model tested are discussed in the following sections.

9.3.1 Peak Model

This model had the best redistribution performance of the three models tested. The average ΔE^*_{94} was 0.58 compared to 1.36 for the Scaled model and 1.19 for the Fit model. However, the performance on the 3x3x3 independent data set, and the gray scale data set was worse than the other two models as shown in Table 9-1 and Table 9-2.

9.3.2 Scaled Model

This model had the poorest redistribution performance of the three tested, though not totally unacceptable. The performance on the 3x3x3 independent data set, and the gray scale data set was better than either of the other two models but still higher than desired.

9.3.3 Fit Model

This model is interesting in that, while it was never the best model for any of the data sets tested, it was also never the worst. This is typical of statistical fits as they tend to evenly distribute the error. The fit on the 3x3x3 independent data set is rather high. A possible improvement to this model may be to use an appropriately weighted regression (i.e. using the Neugebauer quality factor weights [Neugebauer 1956]) since minimizing errors in XYZ does not directly minimize errors in CIELAB.

A table comparing the rankings of the three methods is given below for comparison, the average error as well as the maximum error is given in parentheses next to each model. It would appear from the overall results that the Scaled model would be the best choice to work with in further analysis.

Table 9-3Rankings of IBM Models for 3 Data Sets

Rank	Redistribution	3x3x3 + Random	17 step Gray Scale
1st	Peak (0.56, 1.74)	Scaled (3.73, 7.64)	Scaled (2.07, 6.23)
2nd	Fit (1.20, 6.55)	Fit (4.06, 7.34)	Fit (2.15, 6.55)
3rd	Scaled (1.36, 2.60)	Peak (4.91, 7.93)	Peak (2.71, 8.15)

10 Conclusions

Three displays have been evaluated and compared. The displays tested were a Sony GDM-F500 virtually-flat CRT, a SGI 1600SW flat-panel display, and a 200ppi prototype IBM flat-panel. A summary of the findings follows:

- The spectral variability of each display was evaluated and found to be quite stable.
- The temporal characteristics of all three displays was found to be adequate given the four hour warm-up time allowed.
- The spatial independence of each display was quite good. The SGI especially stood out in this regards, being among the best we have evaluated.
- The luminance and contrast of the SGI display were quite high, the IBM prototype being a close second.
- Chromatic constancy was found to be sufficient in each monitor to suggest that an additive model could work.
- The additivity both in luminance and chromaticity was then evaluated. Both the Sony and SGI display exhibited excellent performance in this regard. The IBM display was found to have a large failure of additivity (~ 7% in some cases), which may account for the poor performance of the model.
- The electro-optical transfer function of each display was fit using various methods. This fit was evaluated by estimating the same set of data used in building each model.
- The performance of each display's model(s) was evaluated using a 3x3x3 and 15 random-color independent target. The Sony and SGI were both very well modeled with maximum errors of 1.1 and 1.8 ΔE^*_{94} respectively. The IBM display was not as well modeled, the best version having maximum errors of 7.6 and an average of 3.7. Some improvements to this model have been suggested and will be evaluated in further reports.

11 References

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