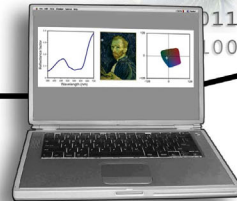


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**Technical Report
April, 2002**

**Colorimetric Characterization of a Computer-
Controlled (SGI) CRT Display**

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Characterization of an SGI CRT Monitor

Abstract

*A Silicon Graphics CRT monitor was characterized so that multispectral images could be accurately displayed in future research. After several preliminary sets of measurements, an optimal monitor set-up was established. A “contrast” setting of 100% and a “brightness” setting of 20% were used. Three analytical models were evaluated, along with corrections for flare. As expected, the GOG and GOGO models performed much better than the simple gamma model, however, all were acceptable. The GOG model was inverted and chosen to display multispectral images in future research. ΔE^*_{94} was chosen to evaluate all three models. The GOG model resulted in an average ΔE^*_{94} of 0.5 for both the ramp and validation data used in this characterization.*

Introduction

Images on cathode ray tube (CRT) monitors must be accurate, especially when being used for the purposes of experimental research. CRTs can be characterized using a small amount of data if certain techniques are known. There are two stages to such a method. First, a (3 x 3) primary matrix of tristimulus values at red, green, and blue channels at their peaks can be used to relate tristimulus values and radiometric scalars. Next, tristimulus values can be estimated using a non-linear gamma term. Usually, other parameters, in addition to the simple gamma term, are added into the model. However, some software uses the simple gamma model in profile connection spaces. The tristimulus estimations can be compared to actual measured values to check the accuracy of a model.

Careful characterizations of CRT displays are important if such a device is to be used to its fullest capability. Flare can be especially harmful to results if not taken into account in the model. Three main types of flare exist.² These are external flare, which comes from reflections on the monitor from ambient room light, internal flare, which comes from internal scattering, and a second type of internal flare, which comes from output from other channels at the same pixel location. All of these types of flare can be accounted for in the CRT model if there are enough parameters. In addition, external flare can be accounted for by subtracting the tristimulus values of a measured black patch, with room lights off, from all other measured tristimulus values.

Another issue is channel independence.¹ If pure red (255,0,0) is being displayed, it is assumed that there is no green or blue actually being emitted. However, the total output for the sum of red, green, and blue channels is usually higher than that of a peak white.³ This can be checked with a channel independence test. A peak white can be displayed and measured, and then compared to the calculated peak white to get a color difference. This color difference will be low if the channels are greatly independent. The dependence will be most obvious at higher luminances. Therefore a color difference metric between the measured and calculated whites shows the extreme case of channel dependence for that particular monitor and set-up.

Experimental

Equipment. A Silicon Graphics color graphic display monitor was characterized. After some preliminary experiments, the “contrast” was set to 100% and the “brightness” to 20%. This was considered an optimal set-up for this particular monitor. An LMT C1210 Colormeter with a separate detector head was used to find the tristimulus values of the calibration target patches. All equipment was warmed up and calibrated as necessary. A white patch on this monitor with this set-up had a luminance of 72.1 cd/m². This was measured using an LMT L1009 handheld photometer.

Software. B. Nordgrin wrote the software that controlled the calibration target patches in C language. G. Johnson later modified it. The software allows the user to specify red, green, and blue digital counts to be displayed on a black background. MATLAB was used to write the inverted model so that an image could be displayed.

Lighting. Measurements were taken in a completely darkened room. Any flare resulting from the monitor itself was corrected for in the models.

Procedure. An eleven-step ramp from 0-255 digital counts at approximately equal increments was created. This ramp data was used for red, green, and blue channels, as well as combined to create a neutral ramp. The ramp data, as well as a 5 x 5 x 5 factorial validation data set, were displayed on the monitor and their tristimulus values were obtained using the LMT Colormeter. See Appendix 1 for the raw data.

A (3 x 3) tristimulus primary matrix was created from the measured colorimetric data at the maximum and minimum digital counts for each channel. RGB scalars were calculated using equation 1.0. Flare was accounted for by subtracting the tristimulus values at 0,0,0 digital counts (black) from all other data.

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} X_{r,\max} - X_{black} & X_{g,\max} - X_{black} & X_{b,\max} - X_{black} \\ Y_{r,\max} - Y_{black} & Y_{g,\max} - Y_{black} & Y_{b,\max} - Y_{black} \\ Z_{r,\max} - Z_{black} & Z_{g,\max} - Z_{black} & Z_{b,\max} - Z_{black} \end{bmatrix} \begin{bmatrix} X - X_{black} \\ Y - Y_{black} \\ Z - Z_{black} \end{bmatrix} \quad (1.0)$$

Three models were evaluated. The simple gamma model is as follows, with similar equations for $G_{estimate}$ and $B_{estimate}$:

$$R_{estimate} = \left(\frac{dc_r}{dc_{r,max}} \right)^{gamma_r} \quad (2.0)$$

The GOG (gain-offset-gamma) model is shown in equation 3.0, again with similar equations for $G_{estimate}$ and $B_{estimate}$:

$$R_{estimate} = \left(gain_r \left(\frac{dc_r}{dc_{r,max}} \right) + offset_r \right)^{gamma_r} \quad (3.0)$$

The offset term can be described as $(1 - gain)$. It is important that the offset term be negative in order to avoid the need for more complex models, as in Katoh, *et al.*^{4,5} In other words, the gain value must be greater than 1.0.

The GOGO model is the GOG model with the addition of an extra offset term, which often accounts for flare when it is not otherwise accounted for. The GOGO model is shown in equation 4.0.

$$R_{estimate} = \left(gain_r \left(\frac{dc_r}{dc_{r,max}} \right) + offset_r \right)^{gamma_r} + offset2_r \quad (4.0)$$

The values for gamma were estimated using a root mean square minimization between the measured and estimated values. In this case, Excel's Solver function was used. Equation 5.0 shows the root mean square calculation for the red channel.

$$RMS_r = \sqrt{\frac{\sum (R_{measured} - R_{estimated})^2}{numMeasurements_r}} \quad (5.0)$$

Tristimulus values for the combined signals were calculated using equation 6.0.

$$\begin{bmatrix} X_{estimated} \\ Y_{estimated} \\ Z_{estimated} \end{bmatrix} = \begin{bmatrix} X_{r,max} & X_{g,max} & X_{b,max} \\ Y_{r,max} & Y_{g,max} & Y_{b,max} \\ Z_{r,max} & Z_{g,max} & Z_{b,max} \end{bmatrix} \begin{bmatrix} R_{estimated} \\ G_{estimated} \\ B_{estimated} \end{bmatrix} + \begin{bmatrix} X_{black} \\ Y_{black} \\ Z_{black} \end{bmatrix} \quad (6.0)$$

These estimated tristimulus values were used to calculate CIELAB values after flare was added back in. The X_n , Y_n , and Z_n parameters used in the CIELAB equations were defined as the monitors tristimulus values at 255,255,255 digital counts (white on the monitor). CIELAB values were also calculated for the measured tristimulus values. Color differences between the measured and estimated values were calculated using ΔE^*_{94} .

The validation data were used to check how well each model performed. CIELAB values for the measured validation data were calculated. Next, each model was implemented to find the RGB scalars and equation 6.0 was used to find tristimulus values. CIELAB values were calculated for each model, as well as ΔE^*_{94} .

Results & Discussion

Chromaticities were plotted to check if the monitor primaries were stable. Primaries are considered stable if their chromaticities do not change as digital counts change. Figures 1 and 2 show the primary's chromaticities without and with a flare correction, respectively. Correcting for flare does improve the stability of the primaries for all three channels.

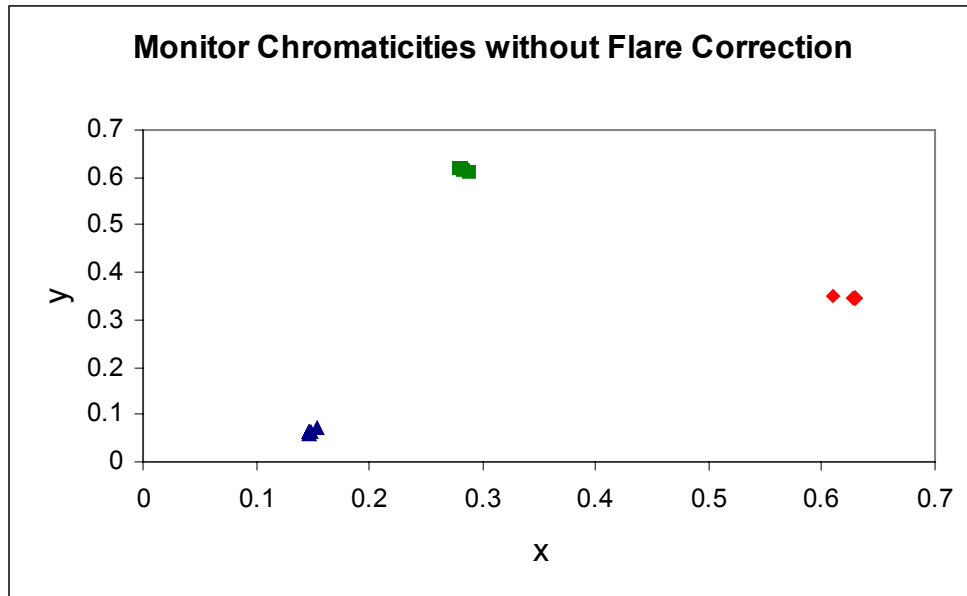


Figure 1. Chromaticities of measured monitor with no flare correction.

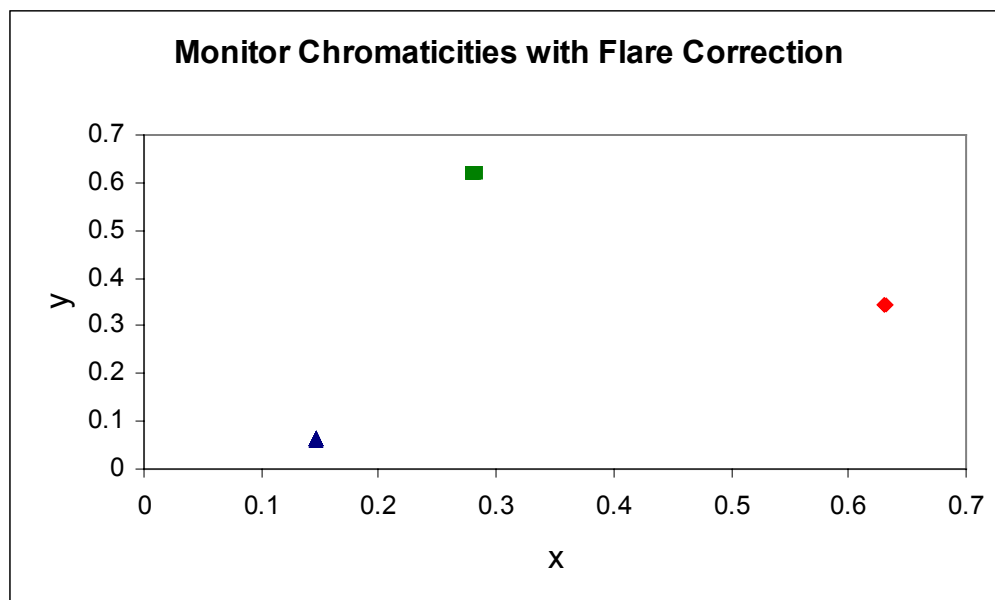


Figure 2. Chromaticities of measured monitor with flare correction.

The actual flare values that were subtracted from the monitor's measured tristimulus values are shown in Table 1. As previously mentioned, these values were found by measuring the tristimulus values for a black patch on the monitor (0,0,0 digital counts). There is more flare in

the red and green channels. This probably results because these two channels are higher in luminance.

Table I. Flare values subtracted from monitor's tristimulus values.

X	Y	Z
0.017	0.018	0.007

Table II shows the primary tristimulus matrix for this particular monitor set-up. These were the tristimulus values of the maximum digital counts for each primary ramp minus the black tristimulus values. They were used as the 3 x 3 matrix in equation 1.0.

Table II. Primary tristimulus matrix for this particular monitor set-up.

	R	G	B
X	20.16	16.85	13.56
Y	11.04	37.45	5.62
Z	0.82	6.20	73.35

The parameters for each model are shown in Table III. A flare correction was used for all models.

Table III. Model parameters for this particular monitor set-up. Red, green, and blue channel parameters are shown, respectively, for each model.

model	gain	gamma	offset
simple gamma		1.57	
		1.52	
		1.50	
GOG	1.10	1.41	
	1.06	1.38	
	1.10	1.35	
GOGO	1.08	1.42	0.00
	1.07	1.39	0.00
	1.08	1.36	0.01

Figure 3 shows the residual errors for this particular monitor set-up. Note that zero is in the center of the y-axis scale. There seems to be an overall downward trend in the residual errors for the simple gamma model. This trend is corrected for in the GOG and GOGO models.

Although all of the models have very small residual errors, they are slightly higher in the blue channel. In addition, the residual errors are larger for the simple gamma model. Note the interesting characteristic shown by these plots. At a normalized digital count of 0.588, there is a change in the direction of the residual errors for all three channels in all three models.

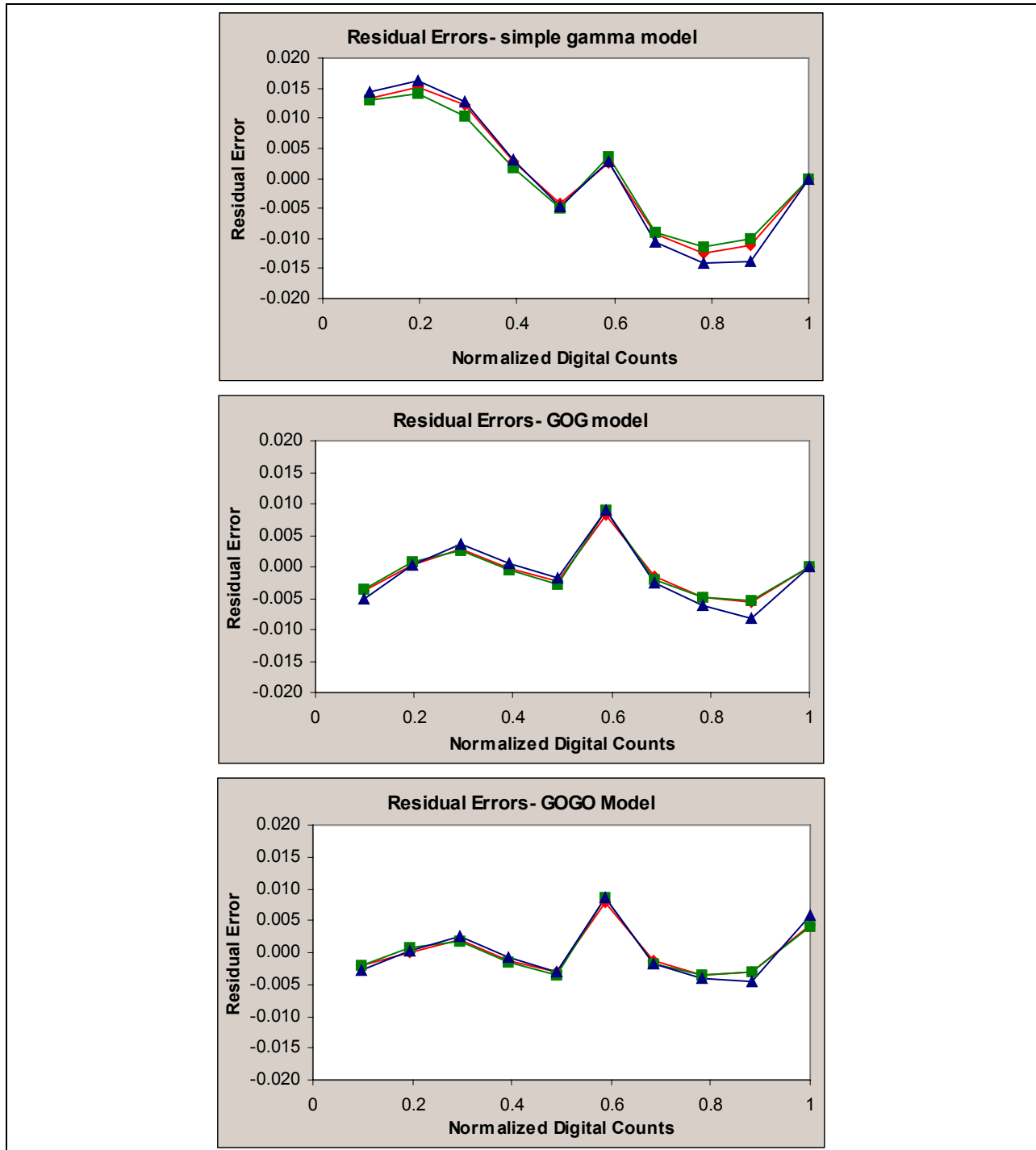


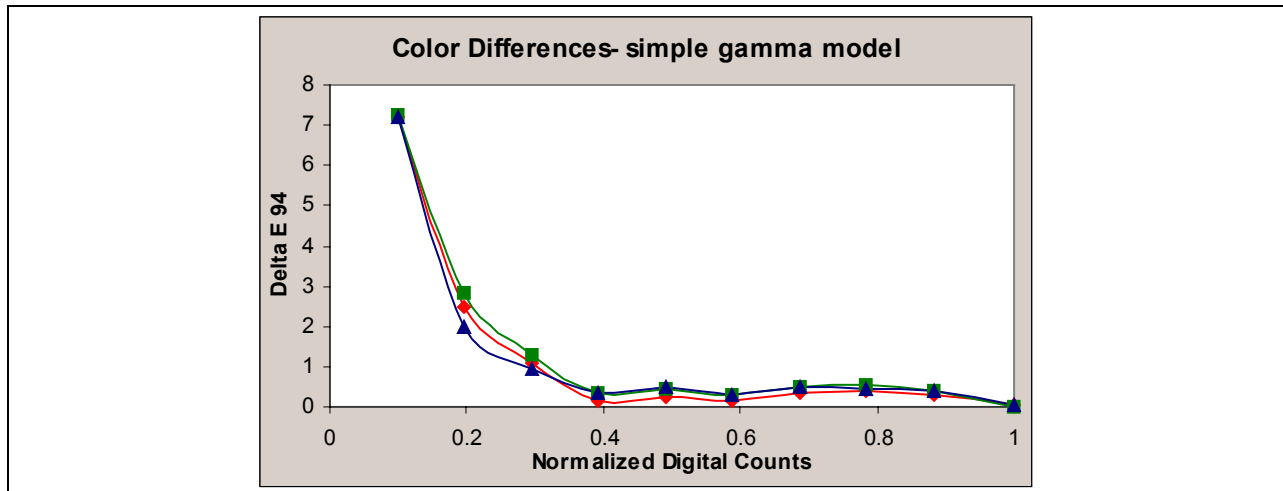
Figure 3. Residual errors for this monitor set-up for all three models.

Table IV shows the maximum and average ΔE^*_{94} color differences for this monitor set-up. The simple gamma model has the highest maximum and average color differences, while the GOGO model has the lowest.

Table IV. Color differences (ΔE^*_{94}) for each model from the measured values using this monitor set-up.

model	average	maximum
simple gamma	1.1	7.2
GOG	0.5	3.1
GOGO	0.4	1.8

Figure 4 shows ΔE^*_{94} values versus normalized digital counts for each model. The simple gamma model has much higher ΔE^*_{94} values than the GOG and GOGO models. In addition, there seems to be an overall trend of having higher color differences at lower digital counts. This could be a result of noise being introduced at lower digital counts in either the instrument or in the monitor itself. However, this effect quickly drops off as the normalized digital count reaches 0.2.



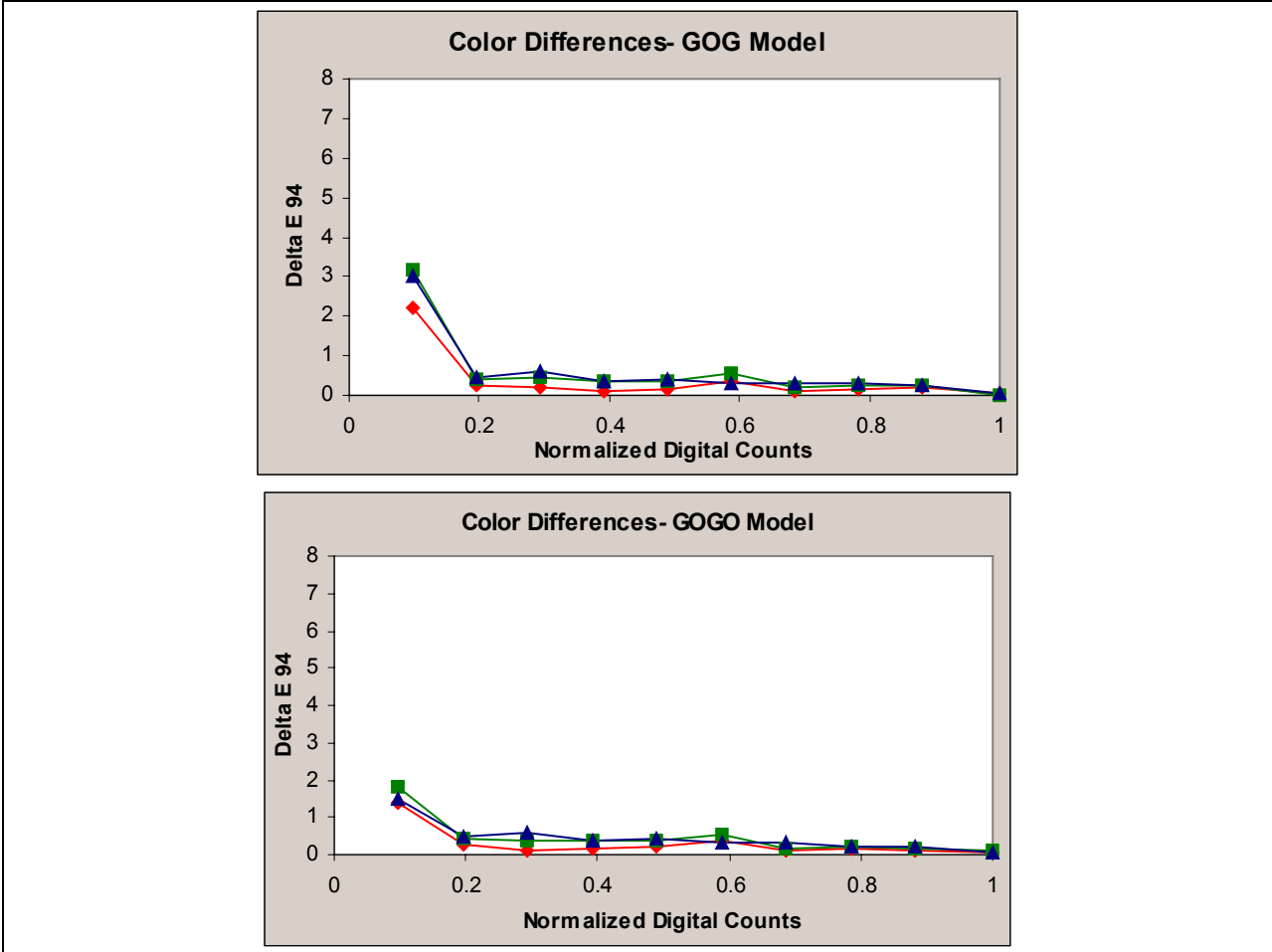


Figure 4. ΔE^*_{94} color differences for this monitor set-up.

Table V shows the maximum and average ΔE^*_{94} color differences for the validation data. Again, the simple gamma model has the highest maximum and average color differences. However, the GOGO model does not much lower values here. Instead, they are about the same as those of the GOG model.

Table V. Color differences (ΔE^*_{94}) for the validation data for each model from the measured values.

model	average	maximum
simple gamma	1.0	6.2
GOG	0.5	6.5
GOGO	0.5	6.4

Figure 5 shows ΔE^*_{94} values versus normalized digital counts for each model for the validation data set. The simple gamma model has higher ΔE^*_{94} values than the GOG and GOGO models, however, almost all color differences are under 2.0. For one color patch in the validation set, there is a much larger ΔE^*_{94} value. Table V showed this as the maximum ΔE^*_{94} value for each model. The reason for the large difference for this patch is unknown. A visual analysis of the data for this patch shows no obvious reason for the high values at this point. Therefore, it may have been an error in the measurements.

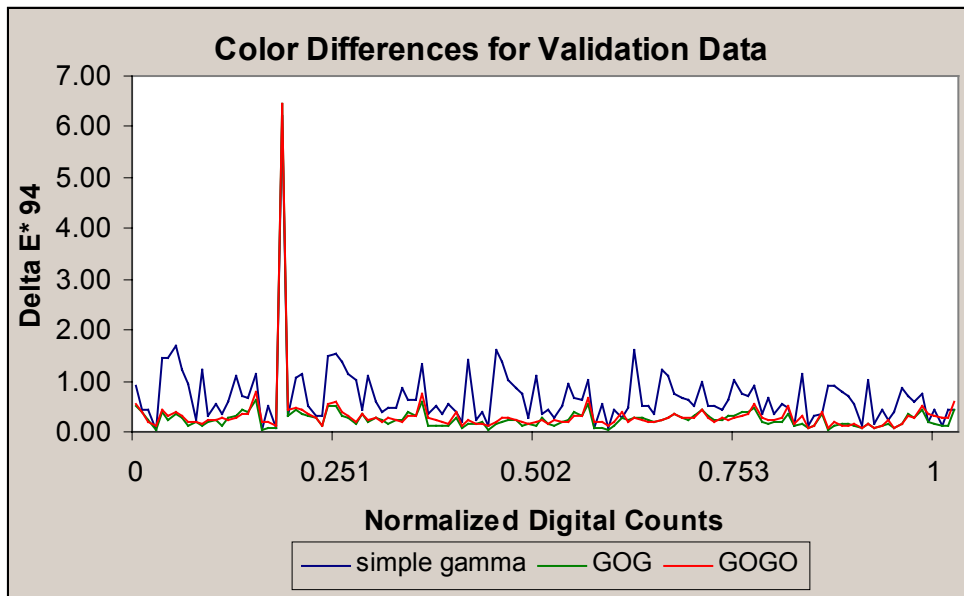


Figure 5. ΔE^*_{94} color differences for the validation data.

Figure 6 shows frequencies ΔE^*_{94} values. The histogram shows similar results to Table V and Figure 5. There are higher color differences and fewer small color differences for the simple gamma model. There is a higher frequency of small color difference values for the GOG and GOGO models. Again, this histogram shows that each model has one outlier in the color difference data.

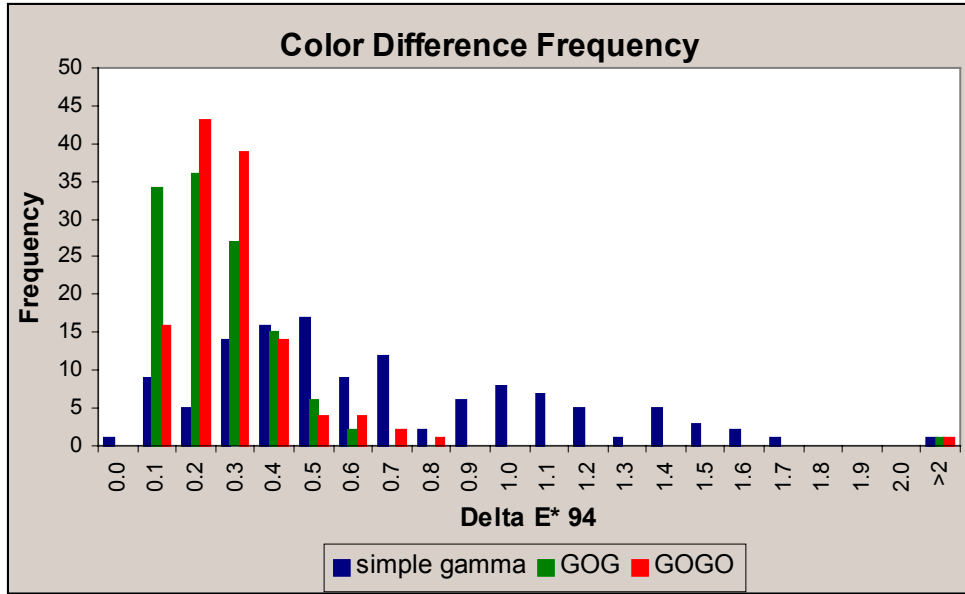


Figure 6. Frequency of ΔE^*_{94} color differences for the validation data for each model.

Channel independence was briefly evaluated. Table VI shows the measured and calculated peak white chromaticities. The color difference between these whites is only 0.42 ΔE^*_{94} , indicating good channel independence.

Table VI. Peak white chromaticities.

	x	y
measured	0.274	0.293
calculated	0.273	0.292

Conclusions

An SGI display CRT monitor was characterized using a predetermined set-up. The “contrast” was set to 100% and the “brightness” was set to 20%. Three models were evaluated. These were the simple gamma model, the gain-offset-gamma (GOG) model, and the gain-offset-gamma-offset (GOGO) model. The GOG and GOGO models performed the best, as expected.

The simple gamma model works quite well, despite its simplicity, and could be used when quick, rough methods of monitor characterization are needed with acceptable results. Color difference metrics show that a simple gamma model and a (3 x 3) primary tristimulus matrix can often achieve color differences of less than the visible threshold for most observers. However, simple gamma models do not seem appropriate for serious characterization of CRT monitors. They create added trends, which shows that they do not well describe the monitor.

The GOG model was used because of its reduction in model parameters from the GOGO model without a significant drop in accuracy. The average ΔE^*_{94} value for the validation data set was 0.5. The maximum color difference value excluding the outlier of the validation set was 0.6 ΔE^*_{94} . The model was inverted and written in MATLAB, where the final images will be displayed.

References

1. Berns, Roy S., *Methods for Characterizing CRT Displays*, Displays, 16: 173-182 (1996).
2. Berns, Roy S. & Katoh, Naoya, *The Digital to Radiometric Transfer Function for Computer Controlled CRT Displays*, CIE Expert Symposium '97 on Colour Standards for Imaging Technology, 34-37 (1997).
3. Deguchi, Tatsuya & Katoh, Naoya, *The Effect of User Controls on CRT Monitor Characteristics*, Sony Corporation.
4. Katoh, Naoya; Deguchi, Tatsuya; & Berns, Roy, *An Accurate Characterization of CRT Monitor (I) Verification of Past Studies and Clarifications of Gamma*, Optical Review, 8: 305-314 (2001).
5. Katoh, Naoya; Deguchi, Tatsuya; & Berns, Roy, *An Accurate Characterization of CRT Monitor (II) Proposal for an Extension to CIE Method and Its Verification*, Optical Review, 8: 397-408 (2001).

Appendix 1.

Raw target data, including red, green, blue, and gray ramps, as well as a validation data set.

R	G	B		0	0.502	0.753	0.502	0.753	1
	0	0	0	0	0.502	1	0.502	1	0
	0.098	0.098	0.098	0	0.753	0	0.502	1	0.251
	0.196	0.196	0.196	0	0.753	0.251	0.502	1	0.502
	0.294	0.294	0.294	0	0.753	0.502	0.502	1	0.753
	0.392	0.392	0.392	0	0.753	0.753	0.502	1	1
	0.49	0.49	0.49	0	0.753	1	0.753	0	0
	0.588	0.588	0.588	0	1	0	0.753	0	0.251
	0.686	0.686	0.686	0	1	0.251	0.753	0	0.502
	0.784	0.784	0.784	0	1	0.502	0.753	0	0.753
	0.882	0.882	0.882	0	1	0.753	0.753	0	1
	1	1	1	0	1	1	0.753	0.251	0
	0.098	0	0	0.251	0	0	0.753	0.251	0.251
	0.196	0	0	0.251	0	0.251	0.753	0.251	0.502
	0.294	0	0	0.251	0	0.502	0.753	0.251	0.753
	0.392	0	0	0.251	0	0.753	0.753	0.251	1
	0.49	0	0	0.251	0	1	0.753	0.502	0
	0.588	0	0	0.251	0.251	0	0.753	0.502	0.251
	0.686	0	0	0.251	0.251	0.251	0.753	0.502	0.502
	0.784	0	0	0.251	0.251	0.502	0.753	0.502	0.753
	0.882	0	0	0.251	0.251	0.753	0.753	0.502	1
	1	0	0	0.251	0.251	1	0.753	0.753	0
	0	0.098	0	0.251	0.502	0	0.753	0.753	0.251
	0	0.196	0	0.251	0.502	0.251	0.753	0.753	0.502
	0	0.294	0	0.251	0.502	0.502	0.753	0.753	0.753
	0	0.392	0	0.251	0.502	0.753	0.753	0.753	1
	0	0.49	0	0.251	0.502	1	0.753	1	0
	0	0.588	0	0.251	0.753	0	0.753	1	0.251
	0	0.686	0	0.251	0.753	0.251	0.753	1	0.502
	0	0.784	0	0.251	0.753	0.502	0.753	1	0.753
	0	0.882	0	0.251	0.753	0.753	0.753	1	1
	0	1	0	0.251	0.753	1	1	0	0
	0	0	0	0.251	1	0	1	0	0.251
	0	0	0.098	0.251	1	0.251	1	0	0.502
	0	0	0.196	0.251	1	0.502	1	0	0.753
	0	0	0.294	0.251	1	0.753	1	0	1
	0	0	0.392	0.251	1	1	1	0.251	0
	0	0	0.49	0.502	0	0	1	0.251	0.251
	0	0	0.588	0.502	0	0.251	1	0.251	0.502
	0	0	0.686	0.502	0	0.502	1	0.251	0.753
	0	0	0.784	0.502	0	0.753	1	0.251	1
	0	0	0.882	0.502	0	1	1	0.502	0
	0	0	1	0.502	0.251	0	1	0.502	0.251
	0	0	0	0.502	0.251	0.251	1	0.502	0.502
	0	0	0.251	0.502	0.251	0.502	1	0.502	0.753
	0	0	0.502	0.502	0.251	0.753	1	0.502	1
	0	0	0.753	0.502	0.251	1	1	0.753	0
	0	0	1	0.502	0.502	0	1	0.753	0.251
	0	0.251	0	0.502	0.502	0.251	1	0.753	0.502
	0	0.251	0.251	0.502	0.502	0.502	1	0.753	0.753
	0	0.251	0.502	0.502	0.502	0.753	1	0.753	1
	0	0.251	0.753	0.502	0.502	1	1	1	0
	0	0.251	1	0.502	0.753	0	1	1	0.251
	0	0.502	0	0.502	0.753	0.251	1	1	0.502
	0	0.502	0.251	0.502	0.753	0.502	1	1	0.753
	0	0.502	0.502	0.502	0.753	0.753	1	1	1