Model Based Color Tolerances

Nathan Moroney
Hewlett-Packard Laboratories
Palo Alto, California, USA

Abstract

Mathematical models have been successfully used in a number of areas related to digital color imaging. In general the focus has been on using models to characterize the color reproduction properties of a device or to embody specific aspects of color perception. However, models can also be used to estimate color tolerances. This paper demonstrates how a simplified CIE gain, offset and gamma or GOG model for the CRT and CIECAM97s can be used to determine hardware and viewing condition tolerances for an sRGB monitor. Error curves and surfaces are derived for the gamma, offset and phosphor chromaticities. Similarly, error curves and surfaces are computed for luminance of the adapting field, adopted white point and the surround.

Introduction

There are a number of aspects to establishing digital color fidelity tests.[1] This is due, in part, to the fact that there are system and component considerations for establishing color reproduction tolerances. The performance metrics are also an issue and will vary based on component testing and overall system testing. For example, the color consistency for a device can be expressed in terms of colorimetric error statistics.[2] On the other hand, system color reproduction is more complex and may encompass multiple objectives such as image reproduction versus accurate spot colors or reproduction versus matching.[3] The focus of this paper is the determination of color tolerances for a given device using some form of a model. Historically, there has been limited information about color tolerances and usually these tolerances have been based on expert consensus, psychophysical experimentation[4] or measurement databases.[5,6] However, this paper describes how the hardware and viewing conditions for sRGB[7] can be toleranced using a simplified CIE GOG model[8] and CIECAM97s[9] respectively. The tolerances included in this paper are only initial estimates and require additional refinement. Therefore, the focus will be on the methodology and not the specific tolerances.

A model is a parameterized and abstract representation of some real world phenomenon. Models can be used for both prediction and to gain a better understanding of the underlying principles. Some models can be inverted and a useful model will have a high degree of accuracy and will avoid known shortcomings, such as Farm-Gate Contraction.[10] On the left of Figure 1, a general flowchart is shown for a forward model. In this case n parameters, P_1, …, P_n, are used by a function F(x) to compute y given x. In the middle of this figure, the model is inverted to compute x given y. On the right of Figure 1, the change in P_i or ΔP_i can be compared to the resulting change in the output or Δy. This approach can be used to derive color tolerances for the parameters in a given model.

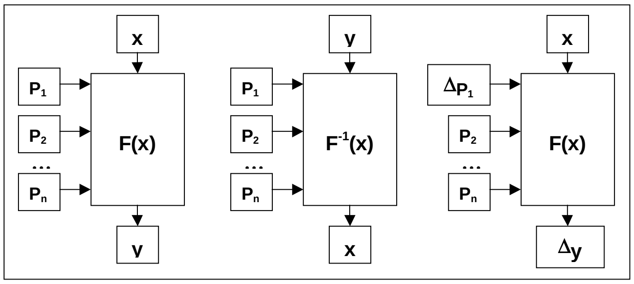

Figure 1. From left to right, flowchart examples of forward, inverse and parameter toleranced models. The values P_i correspond to model parameters.

Methodology

In order to understand how a change in a model parameter will impact the output, a fixed set of input values must be used. In this case, a 9 by 9 by 9 uniform sampling of 729 points in sRGB space was used as input data. The arithmetic mean and the maximum color differences were used as the error statistics. The CIELAB color space was used to assess changes in gamma, offset and phosphor chromaticity. The CIECAM97s color space was used to understand the influence of the white point, luminance of the adapting field and the surround.

The CIELAB color space was used instead of ΔE^*_{94} because of the utility of plotting three-dimensional color difference vectors. Previous research[11] has also provided rough estimates for perceptibility limits for average CIELAB color differences. In this paper, an average ΔE^*_{ab} of 3 is used as a limit and it is straightforward to use other limit values. Error surface tolerances were estimated by those parameter values that formed a box that neither inscribed nor circumscribed the color difference loci. Specifically, the values listed in Table 1 are the lower-left and upper-right corners of a rectangle that is neither completely inside nor outside of the limit value. An alternative approach is to compute the major and minor axes of the tolerance ellipse.

This analysis differs from recent work in color error propagation[12,13] in that no attempt is made to model the error in closed form. Instead error statistics are computed between two populations. Note that the accuracy of this analysis will be limited by the accuracy of the models but does not include any measurement error.[14] Finally, the parameters are examined one or two at a time in order to reduce the complexity of the analysis. However, this approach does not reveal any interactions between the parameters. Additional research is required to understand potential parameter interactions. Finally, this analysis focuses on color differences as the key consideration for the tolerances although it will be useful to consider other factors, such as uniformity,[15] gamut volume and other factors, when developing tolerances for products.

Hardware Tolerances

The CIE GOG model provides a powerful tool for characterizing and calibrating CRTs.[16,17] This model consists of gain, offset and gamma parameters and a 3 by 3 matrix. This model must actually be further reduced before actual hardware components are exposed. For example, the CIE GOG model is based on a "simple gamma"[18] that is actually a function of beam current, grid voltage, and the video card. In this paper the CIE GOG model is used as a first step to getting the hardware tolerances and the basic process can be reduced until specific components are isolated.

For compactness, the CIE GOG model can be reduced to two parameters based on the assumption that the maximum device value for one of the channels should yield the corresponding primary tristimulus values. Specifically, given that

$$1 = ((Gain \cdot 1) + Offset)^{\gamma} \qquad (1)$$

A two term model that is a function of only gamma and offset can then be derived as follows:

$$y = (x - (Offset \cdot x) + Offset)^{\gamma} \qquad (2)$$

This allows a two-dimensional error surface to be computed for various offset and gamma values. Using the three-term GOG model would have required more sophisticated three-dimensional visualization or multiple two-dimensional projections. The error surface is shown in Figure 2. In all cases, the reference is the sRGB specification. The x-axis is the offset and the y-axis is the gamma. The z-axis, coming out of the page, is the average ΔE*ab. Regions where the average color difference is 0 to 3, 3 to 6 and greater than 6 are coded white, light gray and dark gray, respectively. The color difference ellipses have a diagonal orientation and are roughly centered on 0.05 offset and 2.4 gamma.

The chromaticities of the phosphors can be assessed in a similar manner. The nominal sRGB value can then be systematically modified to create an error surface in 1931 chromaticity space. Figures 3 through 6 show these error surfaces for the red, green and blue phosphors. The abscissa is the x chromaticity and the ordinate is the y chromaticity. The surface is average ΔE*ab and is shaded according to the format used in Figure 2.

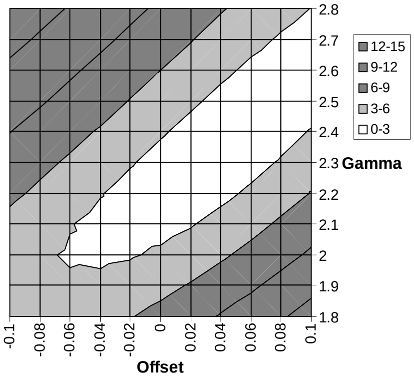

Figure 2. Average ΔE$_{ab}$ error versus offset and gamma.*

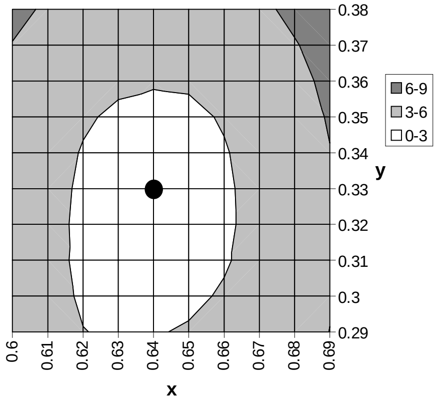

*Figure 3. Average ΔE*ab surface for the red sRGB phosphor, shown as a black dot at 0.64, 0.33, in 1931 chromaticities.*

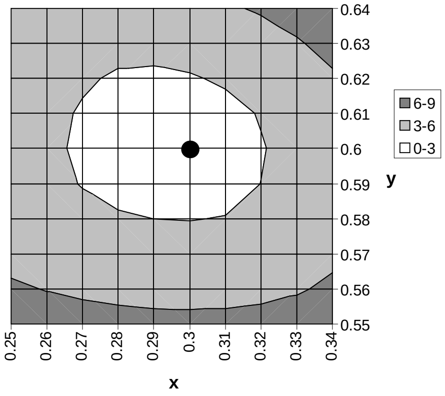

*Figure 4. Average ΔE*ab surface for the green sRGB phosphor, shown as a black dot at 0.3, 0.6, in 1931 chromaticities.*

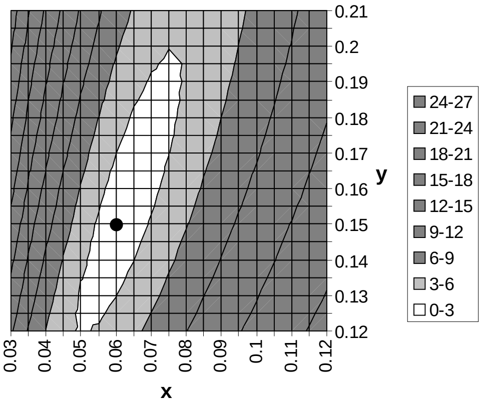

*Figure 5. Average ΔE*ab surface for the blue sRGB phosphor, shown as a black dot at 0.06, 0.15, in 1931 chromaticities.*

Relative to the red and green phosphors, the blue tolerance ellipse is significantly elongated. In fact the surface had to be generated at a higher sampling rate in order to accurately render the shape of the ellipse. In none of the cases are the color difference loci symmetric. This asymmetry can impact the nominal values used during manufacturing. Furthermore, it may be more time consuming and difficult to determine these types of asymmetries using psychophysics or manufacturing databases.

Viewing Conditions

The viewing conditions associated with the sRGB standard can be assessed using CIECAM97s. This section assesses the impact of the white point, luminance of the adapting field and surround. Given that it is not clear how to apply the background luminance or Y_b using pixel-based transformations, this value will be set to 20 for all calculations.

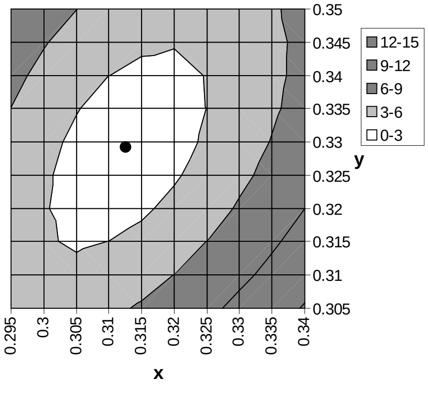

Figure 6. The CIECAM97s average color difference for the adopted white point in 1931 chromaticity space. The white point, shown as a black dot, is 0.3127, 0.3290 or D65.

The exact adapted white point for sRGB is still under investigation[19] but using D65 an error surface can be computed for the chromaticities of the adapted white point. This is shown in Figure 6, where the format of the figure is the same as previous error surfaces except that the color differences are computed in CIECAM97s instead of CIELAB.

The sRGB standard specifies an ambient illuminance of 64 lux, while Annex D specifies a typical office illumination of 350 lux. These values can be converted to the luminance of the adapting field or L_A by dividing by 5π. The resulting error curves for both illumination levels are shown in Figure 7. The x-axis is L_a or ambient illuminance divided by 5^{π} and the y-axis is the average CIECAM97s color difference. Lastly, the difference between using dim and dark surround for sRGB is an average ΔE^*_{c97} of 7.8 and maximum of 12.9. Given that the CIECAM97s surround is categorical, the surround settings must be exact.

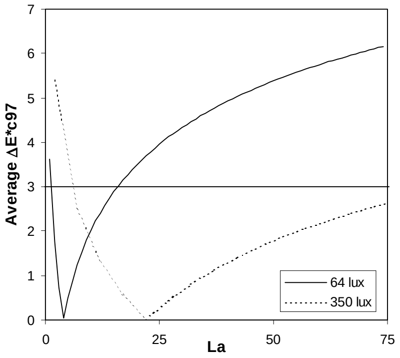

Figure 7. The CIECAM97s average color difference versus the luminance of the adapting field at 64 and 350 lux.

Table 1. Model based tolerances for sRGB.

Parameter	Low	High
Simple Gamma	2.1	2.4
Offset	-0.02	0.04
Red x	0.62	0.66
Red y	0.29	0.35
Green x	0.27	0.32
Green y	0.58	0.28
Blue x	0.055	0.065
Blue y	0.135	0.17
White x	0.300	0.325
White y	0.315	0.340
L_A at 64 lux	1.5	15
L_A at 350 lux	5	85
Surround	Exact	Exact

Conclusions

Modeling is an important tool for digital color imaging and has been widely applied to problems of device characterization and color vision. However an accurate and well-formulated model can also be used to estimate tolerances for the associated parameters. A two-term version of the CIE GOG model for the CRT was used to estimate sRGB gamma, offset and phosphor tolerances.

CIECAM97s was used to derive approximate tolerances for the sRGB viewing conditions. All of the tolerances were asymmetric to some degree and a summary of the results is listed in Table 1. It is interesting to note that a recent experiment estimates that over 60% of monitors have a gamma between 2.0 and 2.5.[20] The basic technique of model based tolerancing can be refined and extended to other models and to compare the relative importance of the model parameters. For example this approach could be applied to a printer model or could be used to rank order the parameters relative to measurement uncertainty or manufacturing variability.

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