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# Standard Guide for
# Modeling the Colorimetric Properties of a Visual Display Unit[1]

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## INTRODUCTION

This guide provides directions and mathematical models for deriving the relationship between digital settings in a computer-controlled visual display unit and the resulting photometric and colorimetric output of the display unit. The accurate determination of this relationship is critical to the goal of accurate, device-independent color simulation on a visual display unit.

## 1. Scope

1.1 This guide is intended for use in establishing the operating characteristics of a visual display unit (VDU), such as a cathode ray tube (CRT). Those characteristics define the relationship between the digital information supplied by a computer, which defines an image, and the resulting spectral radiant exitance and CIE tristimulus values. The mathematical description of this relationship can be used to provide a nearby device-independent model for the accurate display of color and colored images on the VDU. The CIE tristimulus values referred to here are those calculated from the CIE 1931 2° standard colorimetric (photopic) observer.

1.2 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

## 2. Referenced Documents

2.1 *ASTM Standards:*

E 284 Terminology of Appearance[2]

E 1336 Test Method for Obtaining Colorimetric Data from a Visual Display Unit by Spectroradiometry[2]

E 1455 Practice for Obtaining Colorimetric Data from a Visual Display Unit Using Tristimulus Colorimeters[2]

## 3. Terminology

3.1 Definitions of appearance terms in Terminology E 284 are applicable to this guide.

3.2 *Acronyms:*

3.2.1 *CRT*, *n*—an abbreviation for the term cathode ray tube, a device for projecting a stream of electrons onto a phosphor-coated screen in such a way as to display characters and graphics.

3.2.2 *DAC*, *n*—an abbreviation for the term digital to analog converter, a device for accepting a digital computer bit pattern and translating it into an analog voltage of a prescribed value.

3.2.3 *LUT*, *n*—an abbreviation for the term look up table, a process in which input and output values are mapped in an *n*-dimensional table such that, for a given input value, the appropriate output value is "looked-up" from the table.

3.2.4 *VDU*, *n*—an abbreviation for the term visual display unit, a device interfaced to a computer for displaying text and graphics.

3.2.4.1 *Discussion*—A CRT is one type of VDU.

## 4. Summary of Guide

4.1 Every color stimulus generated on a VDU is realized by the linear (additive) superposition of the spectral power distribution of three primaries. Test Method E 1336 describes how to measure the spectral power distributions and reduce them to CIE tristimulus values. Practice E 1455 describes how to measure the CIE tristimulus values of the primaries directly. An exact characterization of the VDU would require measurement of the spectral power distribution at all possible combinations of primary settings. Modern, computer-controlled VDUs will provide 256 or more levels of each of the three primaries. This results in more than 16 777 000 unique settings, which is far too many combinations to be measured practically (see Note 1). Instead, a characteristic function relating the radiant output of the screen to the digital inputs from the computer must be derived. Procedures are outlined for deriving a characteristic function for a computer-controlled

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[1] This guide is under the jurisdiction of ASTM Committee E12 on Color and Appearance and is the direct responsibility of Subcommittee E12.06 on Appearance of Displays .

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[2] *Annual Book of ASTM Standards*, Vol 06.01.

VDU, using a minimum number of spectral radiometric measurements while maintaining near optimum accuracy. Examples of deriving and testing such models are given in Appendix X1.

NOTE 1—Different primary settings do not necessarily produce perceptibly different colors. For VDUs with a large number (for example, 16 777 000) of different primary settings, the number of perceptibly different colors will be less than the number of primary settings.

## 5. Significance and Use

5.1 The color displayed on a VDU is an important aspect of the reproduction of colored images. The VDU is often used as the design, edit, and approval medium. Images are placed into the computer by some sort of capture device, such as a camera or scanner, modified by the computer operator, and sent on to a printer or color separation generator, or even to a paint dispenser or textile dyer. The color of the final product is to have some well-defined relationship to the original. The most common medium for establishing the relationship between input, edit, and output color (device-independent color space) is the CIE tristimulus space. This guide identifies the procedures for deriving a model that relates the digital computer settings of a VDU to the CIE tristimulus values of the colored light emitted by the primaries.

## 6. Models

6.1 The models are based on eight basic assumptions. First, at each pixel location on the VDU, the radiant exitance (emitted light per unit area) attributable to one primary type (red, green, or blue) is invariant with the radiant exitances of the other primary types. Second, the radiance exitance at one spatial location is invariant with the radiant exitance at other spatial locations. Third, the relative spectral radiant exitance of a primary is invariant with excitation level. Fourth, there is no inter-reflection of light between pixel locations. Fifth, the output of the digital-to-analog conversion process is linear. Sixth, there is no ambient glare (flare) from the screen into the observer's eyes. Seventh, the refresh rate of the image is rapid enough to produce temporal fusion (no noticeable flicker) for the normal observer. Eighth, the pixel pitch is fine enough to produce spatial fusion for the normal observer. Each of the eight basic assumptions should be tested and either verified, noted, or corrected before deriving a characteristic model.

6.1.1 Assumption 1, independence of the primaries, is tested by measuring the radiometric output at several levels, as described by Cowen and Rowell.[3] If the departures are small, they may be neglected or a LUT correction applied. If the departures are significant and maximum reproduction accuracy is required, only a full table look-up method can be used to create the RGB to XYZ transform.

6.1.2 Assumption 2, spatial invariance, can be tested by measuring the center of a dark display and then repeating the measurements with pixels near the edge of the display illuminated fully. The display may have to be considered unusable for critical applications if this assumption is not met. The amount of spectral variance will be a function of both position and intensity of both the area of interest and the integrated area of pollution. While such models can be derived, they may be too complex to justify their use.

6.1.3 Assumption 3, level invariance, is tested by measuring the chromaticity of a primary at several different levels. It should be noted that care must be taken to maintain the signal to noise value of the color measuring instrument as the luminance of the primary is reduced. As the signal level of a colorimeter approaches the optical/electrical zero, the apparent chromaticity approaches that of neutral black.

6.1.4 Assumption 4, absence of inter-reflections, is often violated on CRT-type displays without high efficiency antireflection (HEA) antirelection coatings on the face plate gloss. This is detected in the same manner as spatial invariance. Again, models for this can be derived, but the complexity may not be worth the effort.

6.1.5 Assumption 5, linearity of the DAC, can be tested with a calibrated, high-precision oscilloscope. A doubling of the digital counts should produce a doubling of the output signal. It should be noted that RS-170 voltage levels are from −0.286 V to +0.714 V with the range from 0 V to 0.714 V being used for signal level and 0 V to −0.286 V being used for synchronization during the blanking interval on a CRT-type display. Other types of visual display units may have their own unique voltage ranges as well. In general, the setting of the drive voltage requires the simultaneous alignment of many operational parameters, the specification of which are beyond the scope of this guide. It is assumed that the signal generator and the receiver are adjusted to be within their unique operational specifications before the linearity test is performed.

6.1.6 Assumption 6, ambient glare, can be tested with a telephometer, measuring the luminance and chroma of each primary in a dark and ambient environment. If the two readings differ by an unacceptable amount, either the display must be outfitted with light shields or its operation restricted to a dark environment.

6.1.7 Assumption 7, flicker rate, is a function of the display electronics and display type. Chromatic flicker ceases at frequencies above 30 Hz. Brightness flicker ceases for most people above 60 Hz, although some people continue to experience the sensation of flicker up to 70 Hz. Most modern graphics displays operate at refresh rates above 60 Hz. Broadcast displays may operate at rates as low as 30 Hz. Low-rate display electronics interfaced to a high-rate display may result in an unacceptable appearance.

6.1.8 Assumption 8, pixel density, is a characteristic of the display and a function of the application. A low-density display may be adequate for displaying solid patches of color but not for detailed drawings or renderings.

6.2 Examples of using the LUT method are also given in this guide for completeness. There are three possible approaches to modeling the relationship between the digital counts and the VDU tristimulus values. The first requires the user to adjust the video gain and offset manually such that the black level and the offset cancel each other. The second method tries to approximate the gain and offset by trial and error. The

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[3] Cowan, W. B., and Rowell, N., "On the Gun Independence and Phosphor Constancy of Colour Video Monitors," *Color Research and Application*, Vol 11, 1986, pp. S35–S38.

third method, the one used most commonly commercially, ignores the physical origins of the signals and collects measurements of the VDU output at a large number of points, sampling each primary channel between the minimum and maximum counts. The unmeasured data values are determined by interpolation, and a LUT is formed such that all possible combinations of primary settings can be found in the table. The recommended procedure in this guide conforms most closely to the second method, using statistical methods to determine the optimum parametric values for the gain, offset, and gamma of each primary while requiring the smallest number of calibration patches. This, then, linearizes the output of the system, and a linear transformation is applied to convert the linear RGB primary values to CIE tristimulus values.

6.3 The model parameters for the red primary are related to the operational variables as follows:

$$M_{\lambda,r} = M_{\lambda,r,max}\left[k_{g,r}\left(\frac{d_r}{2^N - 1}\right) + k_{o,r}\right]^{\gamma} \tag{1}$$

where:

$M_{\lambda,r}$ = the spectral exitance of the (r)ed primary,

$M_{\lambda,r,max}$ = the maximum spectral exitance of the (r)ed primary,

$d_r$ = the digital setting of the (r)ed primary,

$2^N - 1$ = the number of digital states generated by the display driver,

$k_{g,r}$ = the system (g)ain coefficient for the (r)ed primary,

$k_{o,r}$ = the system (o)ffset coefficient for the (r)ed primary, and

$\gamma$ = the system gamma coefficient.

6.3.1 Similar expressions can be derived for the green and blue primaries. Following the procedures given in Test Method E 1336, the spectroradiometer will measure the spectral radiance ($L_\lambda$) of an extended diffuse source, such as a VDU. The spectral radiance is related to the spectral exitance as follows:

$$L_\lambda = \frac{M_\lambda}{\pi} \tag{2}$$

6.3.2 The radiance for each primary can be described as follows:

$$L_{\lambda,r} = RL_{\lambda,r,max},\ L_{\lambda,g} = GL_{\lambda,g,max},\ L_{\lambda,b} = BL_{\lambda,b,max}$$

The scalars *R*, *G*, and *B* can be thought of as the display tristimulus values. From Test Method E 1336, we obtain the relationship between the measured spectral radiance and the CIE tristimulus values, in luminance units as follows:

$$\begin{aligned} X_r &= 683\int_{360}^{830} L_{\lambda,r}\ \overline{x_\lambda} d\lambda = 683\int_{360}^{830} L_{\lambda,r,max}\ \bar{x}_\lambda d\lambda \\ Y_r &= 683\int_{360}^{830} L_{\lambda,r}\ \bar{y}_\lambda d\lambda = 683R\int_{360}^{830} L_{\lambda,r,max}\ \bar{y}_\lambda d\lambda \\ Z_r &= 683\int_{360}^{830} L_{\lambda,r}\ \bar{z}_\lambda d\lambda = 683R\int_{360}^{830} L_{\lambda,r,max}\ \bar{z}_\lambda d\lambda \end{aligned} \tag{3}$$

6.3.3 The linear superposition of the red, green, and blue tristimulus values yield the following:

$$\begin{aligned} X &= 683\int_{360}^{830} (L_{\lambda,r} + L_{\lambda,g} + L_{\lambda,b})\ \bar{x}_\lambda d\lambda \\ &= RX_{r,max} + GX_{g,max} + BX_{b,max} \\ Y &= 683\int_{360}^{830} (L_{\lambda,r} + L_{\lambda,g} + L_{\lambda,b})\ \bar{y}_\lambda d\lambda \\ &= RY_{r,max} + GY_{g,max} + BY_{b,max} \\ Z &= 683\int_{360}^{830} (L_{\lambda,r} + L_{\lambda,g} + L_{\lambda,b})\ \bar{z}_\lambda d\lambda \\ &= RZ_{r,max} + GZ_{g,max} + BZ_{b,max} \end{aligned} \tag{4}$$

In matrix notation, these equations can be reduced to the following:

$$\begin{matrix} [X] & & [X_{r,max} & X_{g,max} & X_{b,max}] & [R] \\ [Y] & = & [Y_{r,max} & Y_{g,max} & Y_{b,max}] & \cdot [G] \\ [Z] & & [Z_{r,max} & Z_{g,max} & Z_{b,max}] & [B] \end{matrix} \tag{5}$$

where *R*, *G*, and *B* are defined as follows:

$$\begin{aligned} R &= \left[k_{g,r}\left(\frac{d_r}{2^n-1}\right)+k_{o,r}\right]^{\gamma} \text{for } \left(k_{g,r}\left(\frac{d_r}{2^n-1}\right) + k_{o,r}\right) \\ &\geq 0 \\ &= 0 \qquad \text{for} \qquad < 0 \\ G &= \left[k_{g,g}\left(\frac{d_g}{2^n-1}\right)+k_{o,g}\right]^{\gamma} \text{for } \left(k_{g,g}\left(\frac{d_g}{2^n-1}\right) + k_{o,g}\right) \\ &\geq 0 \\ &= 0 \qquad \text{for} \qquad < 0 \\ B &= \left[k_{g,b}\left(\frac{d_b}{2^n-1}\right)+k_{o,b}\right]^{\gamma} \text{for } \left(k_{g,b}\left(\frac{d_b}{2^n-1}\right) + k_{o,b}\right) \\ &\geq 0 \\ &= 0 \qquad \text{for} \qquad < 0 \end{aligned} \tag{6}$$

Being linear, these equations are invertable. Thus the inverse is given, in matrix notation, as follows:

$$\begin{matrix} R & = & X_{r,max} & X_{g,max} & X_{b,max} & X \\ G & = & Y_{r,max} & Y_{g,max} & Y_{b,max} & Y \\ B & = & Z_{r,max} & Z_{g,max} & Z_{b,max} & Z \end{matrix} \tag{7}$$

and in like manner,

$$\begin{aligned} d_r &= \left(\frac{2^n - 1}{k_{g,r}}\right)(R^{\frac{1}{\gamma_r}} - - k_{o,r}) \quad \text{for} \quad 0 \leq R \leq 1 \\ d_g &= \left(\frac{2^n - 1}{k_{g,g}}\right)(R^{\frac{1}{\gamma_g}} - k_{o,g}) \quad \text{for} \quad 0 \leq G \leq 1 \\ d_b &= \left(\frac{2^n - 1}{k_{g,b}}\right)(B^{\frac{1}{\gamma_b}} - k_{o,b}) \quad \text{for} \quad 0 \leq B \leq 1 \end{aligned} \tag{8}$$

## 7. Procedure

7.1 *Analytical Method*:

7.1.1 Once the display unit is warmed up and stabilized, it is necessary to display the test patches over a constant neutral background of approximately 18 % of the maximum luminance. Measure the color of the patches following the procedures contained in Test Method E 1336 or Practice E 1455. The calculated or measured tristimulus values are used to estimate the optimum set of values for the model parameters and the coefficients of the *XYZ* to *RGB* conversion matrix. The patches should be as small as practical and distributed in a square or hexagonal pattern. Readings from each of the patches will be averaged together to constitute a measurement. Display the following sets of patches and measure with at least five neutral patches, ($d_r = d_g = d_b$) with DAC settings of 32, 96, 128, 192, and 255, the three primaries at maximum DAC setting (255 for eight-bit display drivers). An alternate set of patches would be eight to sixteen patches (16, 32, 48, 64, 80, 96,112, 128, 144, 160, 176, 192, 208, 224, 240, and255for each primary. This series maps the gamma curves directly but does not allow modeling of any small levels of a lack of primary independence.

7.1.2 The three sets of calculated tristimulus values for the primaries form the values of the conversion matrix, columnwise as described in (Eq 5), in the following form are as follows:

$$\begin{matrix} X \\ Y \\ Z \end{matrix} = \begin{matrix} X_r & X_g & X_b \\ Y_r & Y_g & Y_b \\ Z_r & Z_g & Z_b \end{matrix} \quad \begin{matrix} R \\ G \\ B \end{matrix} \tag{9}$$

This treats *RGB* as the normalized monitor tristimulus values. The values for $k_g$, $k_o$, and $\gamma$ are determined from (Eq 6) in Section 6 by non-linear regression of the following:

$$R = \left[k_{g,r}\left(\frac{\text{DAC}}{255}\right) + k_{o,r}\right]^{\gamma} \tag{10}$$

$$G = \left[k_{g,g}\left(\frac{\text{DAC}}{255}\right) + k_{o,g}\right]^{\gamma}$$

$$B = \left[k_{g,b}\left(\frac{\text{DAC}}{255}\right) + k_{o,b}\right]^{\gamma}$$

*RGB*, the normalized monitor tristimulus values, are calculated from the inverse of the *XYZ* to *RGB* matrix given by (Eq 7). That completes the model. Given any set of DAC values, the model will predict the *XYZ* for that setting, and given any *XYZ* values, the model will predict the DAC values required to produce that color.

7.2 *Look-up Table Method*:

7.2.1 Once the display unit is warmed up and stabilized, it is necessary to display the test patterns over a constant neutral background with a luminancy of approximately 18 % of the maximum display luminance. The number of patches to be displayed and kept in the LUT depends on the method of interpolation and accuracy required. Hung[4] gives the following guidelines for selecting a LUT for an eight-bit (256 levels per primary) system. Luts of 64 by 64 by 64 (262 144 colors) are considered adequate for simple 3-D interpolation. This is one-fourth of the total number of levels possible in an eight-bit system. One must resort to more sophisticated interpolation schemes to reduce the number of levels further, such as trilinear (cubic) or tetrahedral interpolation and more sophisticated subdivision of the signal space, such as tetrahedral division instead of cubic division. The procedures in the next section describe the application of tetrahedral interpolation on a tetrahedral subdivision of *RGB* space.

7.2.2 A tetrahedral subdivision of a cubic space divides the space along the cube diagonals, forming planes of triangles. This has the added advantage that tetrahedra in *RGB* space can be related linearly to tetrahedra in the *XYZ* space and vice versa, allowing easy backward transformations, a feature not observed in cubic subdivision. Given a tetrahedron composed of four points, as shown in Fig. 1, enclosing a selected point, the interpolation is performed as follows:

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[4] Hung, Po-Chieh, "Colorimetric Calibration in Electronic Imaging Devices Using a Look-Up-Table Model and Interpolation," *Journal of Electronic Imaging*, Vol 2, No. 1, 1993, pp. 53–61.

$$x_p = x_1 - x_0\ x_2 - x_0\ x_3 - x_0 \quad r_1 - r_0\ r_2 - r_0 \quad r_3 - r_0 \quad r_p - r_0 \quad x_0 \tag{11}$$

$$y_p = y_1 - y_0\ y_2 - y_0\ y_3 - y_0 \cdot g_1 - g_0\ g_2 - g_0 \quad g_3 - g_0 \cdot g_p - g_0 + y_0$$

$$z_p = z_1 - z_0\ z_2 - z_0\ z_3 - z_0 \quad b_1 - b_0\ b_2 - b_0 \quad b_3 - b_0 \quad b_p - b_0 \quad z_0$$

and

(12)

$$rp = r1 - r0\ r2 - r0 \quad r3 - r0 \quad x1 - x0\ x2 - x0 \quad x3 - x0 \quad xp - x0 \quad r0$$

$$gp = g1 - g0\ g2 - g0\ g3 - g0 \cdot y1 - y0\ y2 - y0 \quad y3 - y0 \cdot yp - y0 + g0$$

$$bp = b1 - b0\ b2 - b0\ b3 - b0 \quad z1 - z0\ z2 - z0 \quad z3 - z0 \quad zp - z0 \quad b0$$

To test whether a point $p$ lies within the tetrahedron defined by the four points (subscript 0, 1, 2, 3), use the following equation:

$$a = x_1 - x_0 \quad x_2 - x_0 \quad x_3 - x_0 \quad x_p - x_0 \tag{13}$$

$$b = y_1 - y_0 \quad y_2 - y_0 \quad y_3 - y_0 \cdot y_p - y_0$$

$$c = z_1 - z_0 \quad z_2 - z_0 \quad z_3 - z_0 \quad z_p - z_0$$

Point $p$ is included in the tetrahedron if $a > 0$, $b > 0$, $c > 0$ and $a + b + c < 1$. Using tetrahedral subdivision and interpolation, the 64 by 64 by 64 grid can be reduced to 17 by 17 by 17 with a maximum theoretical error of 1.7 $\Delta E_{uv}$ and to 9 by 9 by 9 with a maximum theoretical error of 6.2 $\Delta E_{uv}$.

## 8. Application

**TABLE 1 Correlated Color Temperature of Three White Points**

| °K | *x* | *y* |
|---|---|---|
| 5000 | 0.346 | 0.359 |
| 6500 | 0.313 | 0.329 |
| 9000 | 0.285 | 0.300 |

8.1 Before beginning the measurements, the monitor should be positioned away from external electric and magnetic fields and degaussed with an external degaussing coil. The nested gain (brightness) should be set so that a full-field white has a luminance just below the highest luminance attainable. The nested offset (contrast) should be set so that the display appears black when the digital counts are set to 20. The image size, convergence, and focus should be verified according to the manufacturer's recommendations.

8.2 The color balance should be set to provide the desired white point. This involves adjustment of the individual gain and offset of each primary (sometimes termed sub-brightness and sub-contrast) so that the chromaticity of the display for $d_r = d_g = d_b$ matches that of the desired white point. Some commonly used white points have correlated color temperatures and chromaticities, indicated in Table 1. White points with color temperatures of 6500°K or above are recommended in the literature. The monitor should be turned on and allowed to warm up for 40 to 60 min before making any measurements.

## 9. Precision and Bias

9.1 Reports in the literature[5,6] indicate that this method of modeling results in predicted colors with an average color difference from the actual patch of less than 0.5 CIELAB unit and a maximum color difference of 1.0 CIELAB unit (see Appendix X1 for details). The actual precision and bias have yet to be determined.

## 10. Keywords

10.1 cathode ray tubes (CRTs); colorimetry; computer graphics; displays; video monitors; visual display units

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[5] Berns, R. S., Motta, R. J., Gorzynski, M. E., "CRT Colorimetry, Part I: Theory and Practice," *Color Research and Application*, Vol 18, 1993, pp. 299–314.

[6] Berns, R. S., Gorzynski, M. E., Motta, R. J., "CRT Colorimetry Part II: Methodology," *Color Research and Application*, Vol 18, 1993, pp. 315–325.

# APPENDIX

### (Nonmandatory Information)

## X1. NUMERICAL EXAMPLES

X1.1 An example of the characterization and modeling of a CRT-type display unit is given here. The data are from papers by Berns, Motta, and Gorzynski.[5,6] The monitor used here was set up as described in Section 7 and characterized according to the steps outlined in Section 8 using methods similar to those in Test Method E 1336 or Practice E 1455. The maximum luminance was approximately 45 cd/m$^2$. The measured tristimulus values of the three primaries are given in Table X1.1.

X1.1.1 These data are used to generate the *RGB* to *XYZ* transformation matrix for normalized *RGB*. The DAC values are divided by 255 to yield $R = G = B = 1$, and the matrix elements are inserted according to (Eq 5).

**TABLE X1.1 Tristimulus Values of the CRT Primaries**

| | $d_r$ | $d_g$ | $d_b$ | *X* | *Y* | *Z* |
|---|---|---|---|---|---|---|
| Red | 255 | 0 | 0 | 21.77 | 11.97 | 1.158 |
| Green | 0 | 255 | 0 | 12.58 | 27.61 | 5.723 |
| Blue | 0 | 0 | 255 | 6.622 | 3.507 | 34.30 |

$$\begin{array}{ccccccc} X & = & 21.77 & 12.58 & 6.622 & & R \\ Y & = & 11.97 & 27.61 & 3.507 & & G \\ Z & = & 1.158 & 5.723 & 34.30 & & B \end{array} \tag{X1.1}$$

X1.1.2 Five neutral patches were displayed and measured next. Table X1.2 gives the color data for those measurements.

X1.1.3 Using the matrix transformation derived in (Eq X1.1), the *XYZ* values given in Table X1.2 are transformed to *RGB* values and are given in Table X1.3.

X1.1.4 The data given in Table X1.3 are used to estimate values for the gain, offset, and gamma parameters using non-linear regression and the models given in (Eq 6). The

**TABLE X1.2 Tristimulus Values of Five Neutral Patches**

| | $d_r$ | $d_g$ | $d_b$ | $X$ | $Y$ | $Z$ |
|---|---|---|---|---|---|---|
| 1 | 30 | 30 | 30 | 0.113 | 0.100 | 0.079 |
| 2 | 90 | 90 | 90 | 2.699 | 2.746 | 2.342 |
| 3 | 128 | 128 | 128 | 6.976 | 7.250 | 6.493 |
| 4 | 190 | 190 | 190 | 19.21 | 20.21 | 18.77 |
| 5 | 255 | 255 | 255 | 40.56 | 42.66 | 40.46 |

**TABLE X1.3 Transformed RGB Tristimulus Values of Five Neutral Patches**

| | $d_r$ | $d_g$ | $d_b$ | $R$ | $G$ | $B$ |
|---|---|---|---|---|---|---|
| 1 | 30 | 30 | 30 | 0.004 | 0.002 | 0.002 |
| 2 | 90 | 90 | 90 | 0.072 | 0.061 | 0.056 |
| 3 | 128 | 128 | 128 | 0.177 | 0.166 | 0.156 |
| 4 | 190 | 190 | 190 | 0.474 | 0.469 | 0.453 |
| 5 | 255 | 255 | 255 | 0.993 | 0.990 | 0.981 |

**TABLE X1.4 Estimates of Gain, Offset, and Gamma for the CRT Model**

| Channel | Gain, $k_g$ | Offset, $k_0$ | Gamma, $\gamma$ |
|---|---|---|---|
| Red | 1.004 | − 0.004 | 2.500 |
| Green | 1.066 | − 0.066 | 2.363 |
| Blue | 1.058 | − 0.058 | 2.462 |

results are given in Table X1.4.

X1.1.5 The final table, Table X1.5, indicates the colorimetric results for predictions using the model just derived. The results are stated in terms of the CIELAB color differences between the predicted and measured tristimulus values. As can be seen, the results are quite good.

**TABLE X1.5 CIELAB Color Differences Between Model Predictions and Instrumental Measurements for the Example CRT**

| | $d_r$ | $d_g$ | $d_b$ | $\Delta E^*_{ab}$ |
|---|---|---|---|---|
| Red | 60 | 0 | 0 | 2.1 |
| | 128 | 0 | 0 | 0.7 |
| | 255 | 0 | 0 | 0.1 |
| Green | 0 | 60 | 0 | 2.4 |
| | 0 | 128 | 0 | 0.6 |
| | 0 | 255 | 0 | 0.0 |
| Blue | 0 | 0 | 60 | 2.0 |
| | 0 | 0 | 128 | 0.6 |
| | 0 | 0 | 255 | 0.1 |
| Neutral | 30 | 30 | 30 | 1.5 |
| | 90 | 90 | 90 | 0.6 |
| | 128 | 128 | 128 | 0.4 |
| | 190 | 190 | 190 | 0.5 |
| | 255 | 255 | 255 | 0.7 |
| Average | | | | 0.88 |

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