Reconsideration of CRT Monitor Characteristics

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Introduction

Recently, CRT monitor's characteristics are drawing people's attention once again in the color imaging field, since it is the most popularly used color imaging device, today. By the ICC specification,[1] the monitor's characteristics can be described by the chromaticity and the tone curve of each channel. This idea is based on the research by Berns, et al.,[2] which later became a CIE technical report: CIE 122-1996[3] and ASTM designation: E 1682-96.[4] These models are based on some fundamental assumptions. However, in real situations, its characteristics deviate from the theoretical values. IEC has issued IEC/CD 61966-3,[5] which describes a measurement procedure for the basic characteristics and the instability of the device. Hewlett-Packard and Microsoft has proposed the sRGB Color Space,[6] which is based on the "standard" CRT monitor characteristics. It is now proposed to IEC as NP 61966-2.1.[7] Other recent standards related to CRT monitor characteristics are VESA's EDID 2.0[8] which incorporated CIE's tone curve and sRGB color space in the specification, and ISO/FDIS 9241 Part 7[9] and Part 8[10] which is defining ergonomic requirements for displayed colors.

Historically, CRT characteristics were investigated in the 1910's by Child[11] and Langmuir[12] and later in the 1950's by Oliver,[13] but not much research has been done until recently, as of colorimetric characterization. In this paper, four basic characteristics of the CRT monitor are reconsidered, i.e., 1) Tone Curve Characteristics, 2) Phosphor and Additive Color Mixture, 3) Gamut, and 4) Viewing Flare.

1. Tone Curve Characteristics

The term "gamma" is frequently used for the CRT monitor's tone curve characteristics of each channel. Here, the transfer function is represented as "Γ" and the exponent of the transfer function is represented as "γ". The overall transfer characteristics of the CRT monitor between the input signal data: "*dc*" and the output luminance: "*Y*" can be represented closely by the power law as in the equation for the simple model below. This "γ" is called "simple gamma" in this paper, hereafter. Most people use this simple gamma as the monitor's overall gamma, which could sometimes be very misleading.[14] The characteristics of the CRT monitor are more complex and can be expressed as a combination of several parts' characteristics. The overall characteristics can be expressed as follows;

$$\begin{aligned} \text{Display\_}\Gamma &= \text{Monitor\_}\Gamma \times \text{VideoCard\_}\Gamma \\ &= (\text{CRT\_}\Gamma \times \text{Set\_}\Gamma) \times \text{VideoCard\_}\Gamma \\ &= \{(\text{Phosphor\_}\Gamma \times \text{Gun\_}\Gamma) \times \text{Set\_}\Gamma\} \times \text{VideoCard\_}\Gamma \end{aligned}$$

where;

$$\text{Monitor\_}\Gamma = \text{CRT\_}\Gamma \times \text{Set\_}\Gamma$$
$$\text{CRT\_}\Gamma = \text{Phosphor\_}\Gamma \times \text{Gun\_}\Gamma$$

Display_Γ:	Digital data: *dc* vs. Luminance: *Y*
VideoCard_Γ:	Digital data: *dc* vs. Analogue data: V_{in}
Monitor_Γ:	Analogue data: V_{in} vs. Luminance: *Y*
Set_Γ:	Analogue data: V_{in} vs. Grid Voltage: E_d
CRT_Γ:	Grid Voltage: E_d vs. Luminance: *Y*
Gun_Γ:	Grid Voltage: E_d vs. Beam Current: I_k
Phosphor_Γ:	Beam Current: I_k vs. Luminance: *Y*

Several models have been proposed to represent these characteristics. Below are some of the proposed equations to represent the CRT monitor's characteristics. "*X*" in the following equations represents input value: "$dc/(2^n - 1)$." Other complex methods are also proposed.[15,16,17] Here, the following four equations that are used in the recent standards are compared.

1: Simple model
$Y = aX^{\gamma}$

2: CIE model (Publ. 122-1996)
$Y = (aX + b)^{\gamma}$

3: IEC new model (CD 61966-3 ver. 2.x or 3.x)
$Y = (aX + b)^{\gamma} + c$

4: IEC old model (WD 61966-3 ver. 1.x)
$Y = aX^{\gamma} + b$

First, VideoCard_Γ is usually a linear transformation with no gain or offset terms and can be ignored in most cases. Second, Set_Γ is controlled by the factory adjustment or user can change the settings by the user controls such as contrast or brightness knobs, which can be expressed as a linear transformation with gain and offset terms (i.e., $aV_{in} + b$).

The Child-Langmuir law states that the current density reaching the anode from a thermionic cathode: "j_k" follows a 3/2 power law for a vacuum tubes.

$$j_k \propto E_d^{3/2}$$

This applies to current density: "j_k", not total current: "I_k". From this law, Bessho has derived the total current: "I_k"[18];

$$I_k \propto E_d^{5/2}$$

which implies that Gun_Γ can well be represented as a power law and its exponent: "γ" is theoretically 5/2 or 2.5. However, in real situation for the CRT, Gun_Γ deviates from the theoretical value.

Lastly, Phosphor_Γ describes phosphor's saturation characteristics of luminance versus beam current. In a certain range of luminance (under 100 cd/m^2). Phosphor_Γ could also be closely represented by the power law and its exponent: "γ" is somewhere around 0.9. This makes CRT_Γ close to 2.2, which is the product of Gun_Γ and Phosphor_Γ. Broadcast monitors assume perfect setting with term "*b*" being zero, thus its overall gamma is set to 2.2, which is compatible with the sRGB specification. On the other hand, computer displays have higher value of simple gamma around 2.5. This is due to a slightly negative "*b*" term, to compensate for the light surround in the office. However, Phosphor_Γ depends on phosphor's chemical component, thus it duffers from channel to channel. Also, Phosphor_Γ heavily depends on other settings such as electron beam focus, display refresh rate, and screen size, etc. It should also be noted that the saturation characteristics' power law fails at higher luminance range.

By following each part's characteristics, the CIE model (#2) should closely represent the monitor's overall characteristics. As stated in CIE 122-1966, user settings such as contrast or brightness knob will change the "*a*" and "*b* " terms in the models above. But the "γ" should stay the same since it is an intrinsic characteristic of the CRT (i.e., gun and phosphor). In other words, "*a* " and "*b*" are dependent on user settings but "γ" should be independent of such settings. The above models at nine different settings of contrast and brightness are compared. Figures 1 a) to c) show the average of "γ : gamma", "*a* : *gain*" and "b : offset" of different settings on the left, and their standard deviation on the right. The experimental results indicated that both model #2 and #3's standard deviation of gamma was smaller than other models, thus these models are appropriate from this point of view.

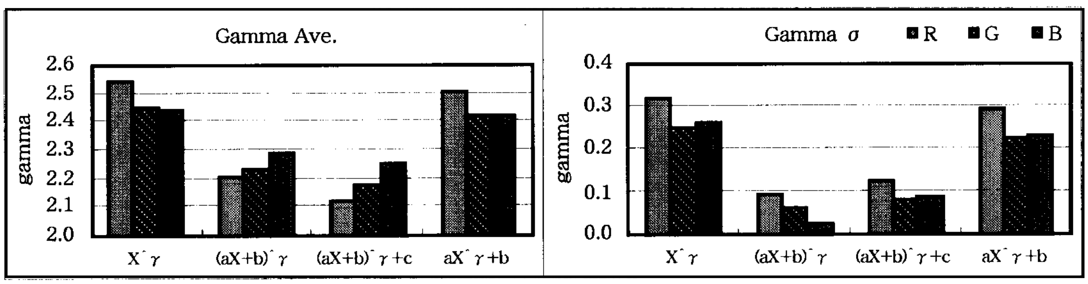

Figure 1a. Model Comparison for Gamma at Various Settings

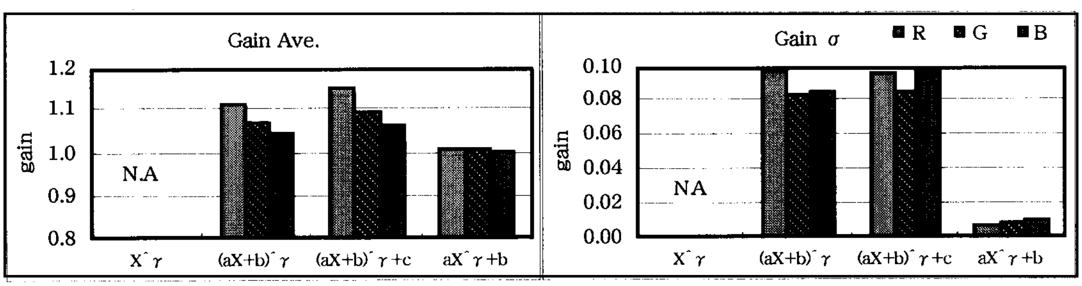

Figure 1b. Model Comparison for Gain at Various Settings

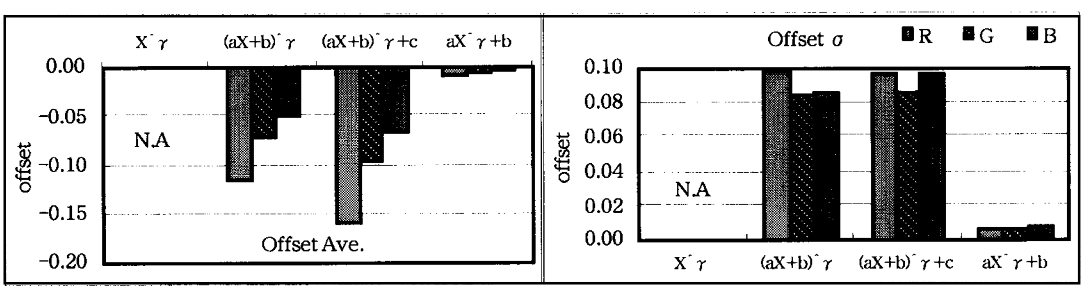

Figure 1c. Model Comparison for Offset at Various Settings

Next, the model prediction error was investigated and its result is shown in Figure 2. Non-linear regression technique was applied for all the models. (Note that in IEC document, linear regression technique in log-log space is recommended, which results in poor precision.) Again, model #2 and #3 performs better than other models and model #1 performs worst. The difference between model #2 and#3 is the term "*c*". This term could be used to represent a flare, which will later be discussed in section 4. However, if the measurement is performed in the darkened room with black background, as stated in the IEC document, there should be no internal or external flare. Therefore, a s experimental results indicated, model #2 and #3 are not significantly different, and term "c" is not significant term.

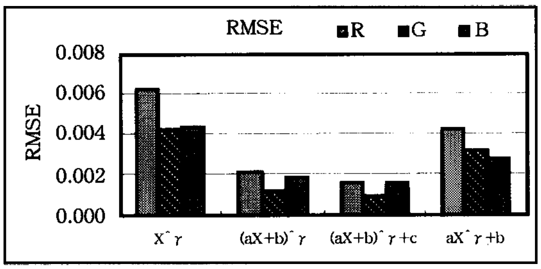

Figure 2. Model Comparison for RMS. Error

2. Phosphors and Additive Color Mixture

There have been several specifications for CRT phosphor chromaticities,[19] e.g., ITU-R,[20] EBU[21] and SMPTE.[22] However, these specifications are slightly different from phosphors used for CRT monitors on the market today (e.g., Sony-P22). Table 1 shows the specifications for the different sets of phosphors and Figures 3 shows their gamuts.

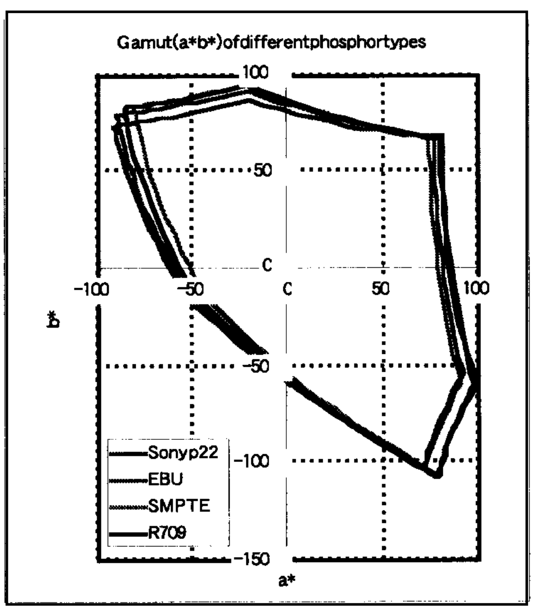

*Figure 3. Gamut in a*b* Coordinate*

Table 1. Specifications for RGB Phosphors

Spec		Red	Green	Blue	White	
I T U-R	x	0.640	0.300	0.150	D65	0.3127
BT.709-2	y	0.330	0.600	0.060	(6504K)	0.3290
EBU	x	0.64	0.29	0.15	D65	0.313
Tech.3213	y	0.33	0.60	0.06	(6504K)	0.329
SMPTE	x	0.630	0.310	0.155	D65	0.3127
Rpl45-1987	y	0.340	0.595	0.070	(6504K)	0.3290
(Sony)	x	0.625	0.280	0.155	D93	0.2831
(P22)	y	0.340	0.595	0.070		0.2971

The color differences of the Macbeth ColorChecker® displayed with different set of phosphors were calculated and are shown i n Table 2. The average color differences of twenty-four colors are listed in the upper half of the table and standard deviations are in the lower half.

Table 2. Color Differences with Different Sets of Phosphors

std_dev\d_E*ab	ITU-R	EBU	SMPTE	Sony-P22
ITU-R	—	0.836	1.719	2.208
EBU	0.631	—	2.374	1.638
SMPTE	1.316	1.833	—	2.518
Sony_P22	1.648	1.319	1.946	—

CRT monitors are self-luminous displays and produce colors by the mixture of red , green and blue phosphors which can be expressed reasonably well by the color additivity rule. The relationship between the tristimulus values and the linearized RGB can be expressed as a 3 × 3 matrix as follows:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = M_{Ideal} \cdot \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

where;

$$M_{Ideal} = \begin{bmatrix} X_{R,\max} & X_{G,\max} & X_{B,\max} \\ Y_{R,\max} & Y_{G,\max} & Y_{B,\max} \\ Z_{R,\max} & Z_{G,\max} & Z_{B,\max} \end{bmatrix}.$$

However, the measured values of maximum white is usually less than the sum of maximum red, green and blue signals. This is due to interactions between the channels. Interactions are caused by several reasons; e.g., 1) internal scattered electrons, 2) electron beam's mislanding, 3) phosphors' cross contamination, 4) insufficient power supply. When the interactions among the channels are not negligible, the relationship between linearized RGB and XYZ could be described better by the equation from linear regression from several displayed colors. Here, an interaction matrix (3 × 3 or 3 × 8) is introduced.

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = M_{Ideal} \cdot M_{Interaction(3\times 3)} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = M_{Ideal} \cdot M_{Interaction(3\times 8)} \begin{bmatrix} 1 \\ R \\ G \\ B \\ RG \\ GB \\ BR \\ RGB \end{bmatrix}$$

Some people have used square terms: "R^2, G^2, B^2" for this compensation.[23,17] These terms are physically meaningless, because they are for the compensating non-linearity of single channel, which should have been corrected by the tone curves. The cross terms: "*RG, GB, BR, RGB*" are for the interdependence among the channels and the offset term: "1" is for the flare. There are several ways to obtain this transformation matrix between the linearized RGB and reproduced colors' tristimulus values: XYZ.

1: measure maximum red, green and blue signals
2: obtain a 3 × 3 matrix by linear regression
3: obtain a 3 × 8 matrix by linear regression

Table. 3. Results with Different Characterization

std_dev\d_E*ab	Setting A	Setting B	Setting C	Setting D
RGB max	1.35 ± 1.21	1.55 ± 1.00	1.40 ± 0.78	5.74 ± 2.50
3 × 3 Regression	1.33 ± 1.12	1.76 ± 0.98	1.09 ± 0.46	3.30 ± 1.60
3 × 8 Reresssion	1.36 ± 1.25	1.51 ± 1.15	1.21 ± 1.06	0.73 ± 0.25

Table 3 is the comparison of characterization results by these techniques. Color differences and their standard deviations were calculated for four different settings. For the normal settings (A to C), characterization results did not depend on the choice of techniques and acceptable results were obtained even with technique #1. However, for the extreme setting (D) with maximum brightness and contrast, the characterization results were heavily dependent on the choice of techniques. For such an extreme setting, technique #3 could be used.

3. Gamut

The volume of the CRT monitor's gamut was calculated and compared with those of printing/photography. The total volume of the CRT monitor's gamut in CIELAB space is much larger than those of printing/photography. However, it does not cover all the color of the printing/photography.

As seen in Figure 4 (a), the CRT monitor's gamut is larger at the red, green and blue primaries, but not in the cyan or yellow region. Figure 4 (b) shows the gamut of the monitor with different white point settings in the a*b* coordinate. (It was assumed that the human visual system adapts to the maximum white for each case.)

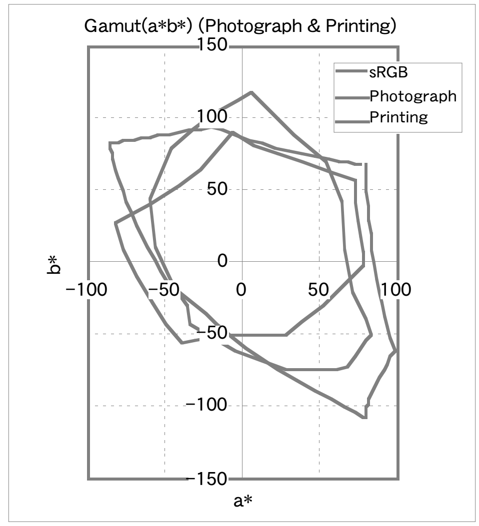

Figure 4a. Gamut of Different Media

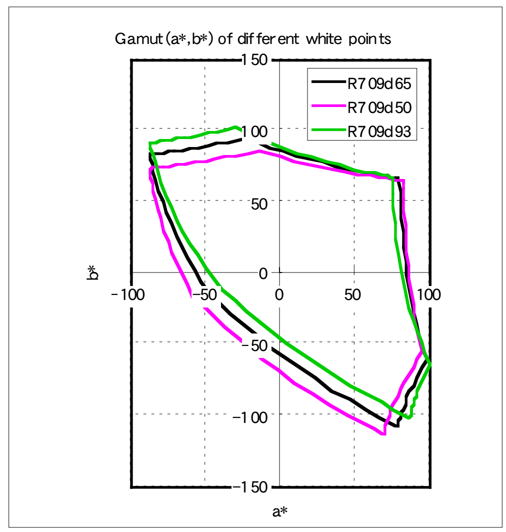

Figure 4b. Gamut at Different White Points

When color management across different media is considered, it is probable that colors that are out of the CRT monitor's gamut will be transferred, stored, or processed in some RGB color space. (Note that some kind of gamut mapping is necessary to display these colors on the monitor.) One way to extend this gamut for the RGB color space is to make head/foot-room for encoding. In ITU-R Rec. 601,[24] it is defined as;

$$D'_{RGB} = INT\,[(219V' + 16) + 0.5]$$

In ITU-R BT. 1200,[25] for extended colour gamut;

$$D'_{RGB} = INT\,[(160V' + 48) + 0.5]$$

In sRGB, it is defined as;

$$R_{8bit} = [(WDC - KDC) \times R'_{sRGB}] + KDC$$
$$G_{8bit} = [(WDC - KDC) \times G'_{sRGB}] + KDC$$
$$B_{8bit} = [(WDC - KDC) \times B'_{sRGB}] + KDC$$

where WDC is the white level and KDC represents the black level, which is not defined in the specification at this moment. We have investigated how the virtual gamut can be extended by making head/foot-room.

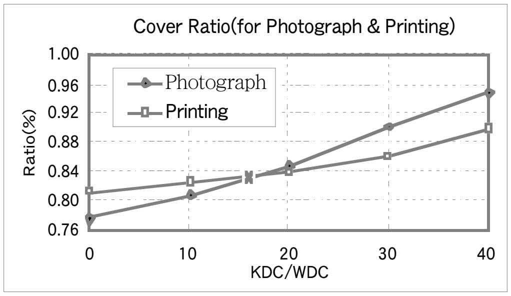

Figure 5a. Cover Ratio for Photograph & Printing

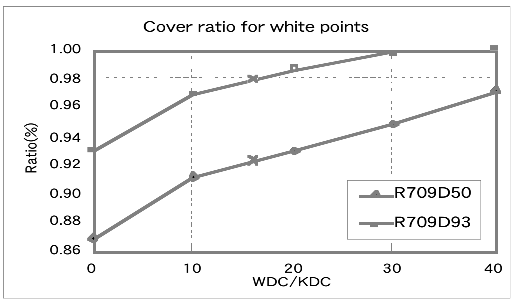

Figure 5b. Cover Ratio for Different White Point

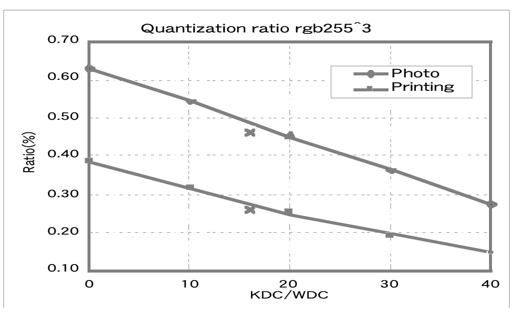

Figure 6a. Quantization Efficiency for Photograph & Printing

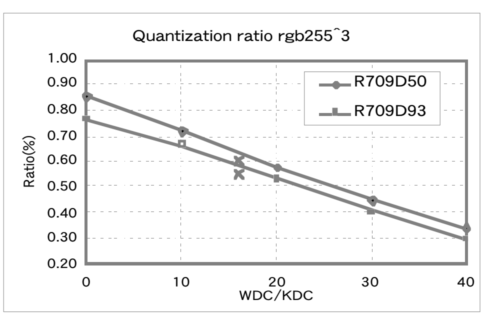

Figure 6b. Quantization Efficiency for Different White Point

First, the "cover ratio" was investigated which is defined as the proportion of the target gamut volume covered by the monitor's gamut with the head/foot-room. As readily expected, the cover ratio increases with the head/foot-room in CIELAB units. (The symbol "x" in the figures indicates the Rec. 601).

However, by making the gamut larger with head/foot-room, quantization becomes less efficient. Therefore, the "quantization efficiency" was next investigated which can be defined as the proportion of 24 bit colors in RGB space which will be included by the target gamut. It is also readily expected that the quantization efficiency decreases with head/foot-room.

Lastly, the "expansion efficiency" was examined which is defined as the proportion of the expanded RGB colors in either headroom or footroom, which are included in the target gamut. It can be seen in Figure 7 that the expansion has certain effects on covering target gamut until 10 to 20. But with larger head/foot-room, it would not have much effect on the cover ratio and rather makes quantization less effective.

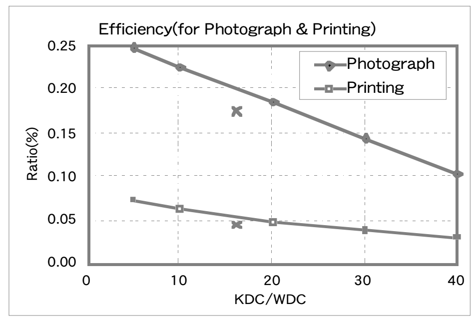

Figure 7a. Expansion Efficiency for Photograph & Printing

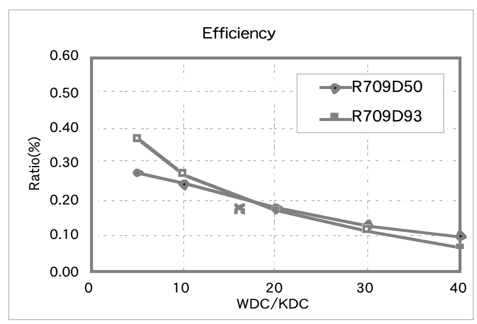

Figure 7b. Expansion Efficiency for Different White Point

4. Viewing Flare

In the CIE 122-1996, terms for internal flare and external flare are added to the colors produced by the phosphors.

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{\text{CRT}} = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{\text{Phosphor}} + \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{\text{Internal Flare}} + \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{\text{External Flare}}$$

Internal flare is caused by the internal reflection in the CRT glass, when phosphor around the measurement point is emitting some amount of light. This reflection depends on neighboring pixels, thus it should theoretically be compensated on pixel-by-pixel basis.

Color appearance on a CRT monitor is very much affected by the ambient lighting, since the human visual system changes its sensitivity according to the surroundings.[26,27] However, colors reproduced by the phosphors are also physically affected by the ambient light.[28] When ambient light is present, the CRT screen reflects some of the ambient light and this reflection is added to the colors produced by the phosphors as above. And the external flare could be expressed as;

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{\text{External Flare}} = R_{bk} \cdot \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{\text{Ambient}} = R_{bk} \cdot \frac{M}{\pi} \cdot \frac{1}{y_{\text{Ambient}}} \cdot \begin{bmatrix} x_{\text{Ambient}} \\ y_{\text{Ambient}} \\ 1 - x_{\text{Ambient}} - y_{\text{Ambient}} \end{bmatrix}$$

where "R_{bk}" is the reflection ratio of the CRT screen (usually 3 to 5 %). Alternatively, it can be expressed with illuminance: M (lux) if we assume Lambertian reflection. In sRGB, both an encoding viewing environment and a typical viewing environment are defined. The encoding ambient illuminant is D50 (0.3457, 0.3585) and its luminance level is 64 lux. The encoding viewing flare is 1.0%. Here, we get;

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{\text{External Flare}} = \begin{bmatrix} 0.1964 \\ 0.2037 \\ 0.1681 \end{bmatrix}$$

The typical ambient illuminant is also D50 and its luminance level is 200 lux. The typical viewing flare is 5.0%. Then,

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{\text{External Flare}} = \begin{bmatrix} 3.0694 \\ 3.1831 \\ 2.7236 \end{bmatrix}$$

is obtained. It is readily expected that the CRT monitor's gamut in the typical viewing environment is reduced by the ambient illumination. And in the normal office environment, illuminance is usually more than 200 lux, usually 500 to 1000 lux. Figure 8 shows the gamut volume of the CRT monitor at different illuminance. Figure 9 (a) and (b) shows the gamut shape in a*b* and L*C* coordinates, respectively. ITU-R BT. 709 phosphors were used and viewing flare is assumed to be 5.0% with ambient illumination by an F6 illuminant. As seen from the figures, the gamut of the CRT monitor is greatly reduced by the reflection of the ambient illumination. The gamut is reduced not only in the direction of the lightness axis but also in the direction of chroma.

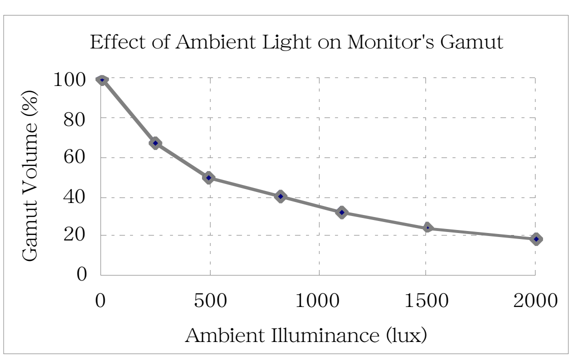

Figure 8. Gamut Volume of a Monitor under Ambient Lighting

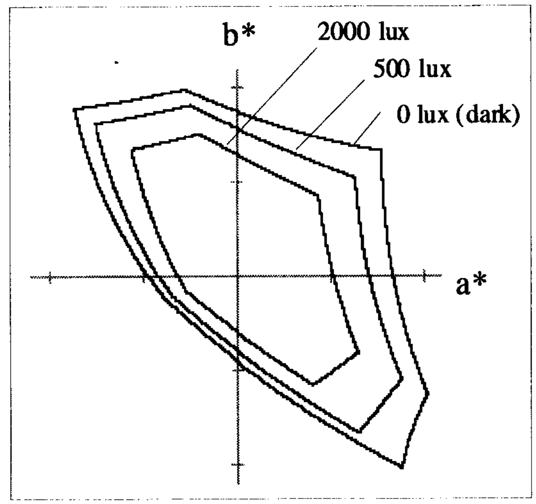

*Figure 9a. Gamut under Ambient Lighting in a*b* coordinate*

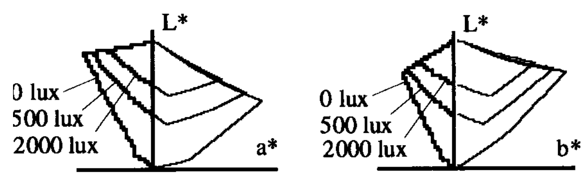

*Figure 9b. Gamut under Ambient Lighting in L*C* coordinate*

5. Other Problems

As mentioned in earlier sections, properly calibrated CRT monitors could be characterized well by the tone curves of each channel and the additive color mixture matrix. However, this needs some further assumptions for both temporal and spatial stability. These instability measurements are described in IEC 61966-3.

CRT monitors are very unstable at start-up, and they should be warmed up for more than thirty minutes or one hour for accurate color reprodction. After that, CRT monitors are rather stable for the middle-term (i.e., hours or days). As for the long-term (i.e., months or years) stability, glass browning or phosphor aging start to occur, which will affect the CRT monitor characteristics.

CRT monitors are not stable with respect to the screen position. The luminance at the corner of the CRT screen is much darker than that of the center. However, the component of the color difference is mostly the lightness, not chroma or hue. Therefore, color constancy holds for the human visual system to a certain degree.

Summary

Some of the basic calorimetric characteristics of the CRT monitor were examined. These characteristics are closely related to each other. It was found that; 1) CIE model works well for the tone curve characteristics when the CRT monitors are properly calibrated, 2) sRGB's standard monitor characteristics represent reasonably well for the current broadcast monitors, 3) the monitor's gamut is much larger than that of photography and printing, but it does not cover all of the photograph and printing's gamut even with the head/foot room, 4) the monitor's gamut is greatly reduced with the reflection of the ambient illumination. The CRT monitors are rather easy device for the calorimetric characterization, if they were calibrated properly. However, some compensation is necessary if the monitor's characteristics deviates from the ideal set-ups or if it were seen under light illumination.

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