Color accurate monitors: Basic features and comparison of four monitors

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Abstract — Color accurate monitors are high resolution, luminance-controlled displays with very large color gamut. They have internal controls to match specific color standards (e.g., sRGB, Adobe-RGB, REC-709) and well-defined gamma functions (mostly $\gamma = 2.2$, but others such as Equal Probability of Detection, Digital Imaging and Communications in Medicine). Usually, they come with external tools for automatic calibration (like Chroma 5 or Spider) and for communicating with the host computer through USB port, and with software to control the calibration process. Most of them allow a calibration to a specific customer selected color gamut, besides the precalibrated standards, but limit the gray levels calibration to a gamma type function (typically $\gamma = 2.2$). Their unique properties, challenges, and applications will be discussed. A comparison between the properties of four monitors and optical test results of their parameters is presented.

Keywords *— color accurate monitors, calibrated monitors.*

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1 Introduction

Displays are used for many applications. In this paper, we will focus on applications that require accurate color rendition, such as those used in the printing industry or those used to edit digital films. All these applications require a close match to colors in predefined color space and expect the accuracy to be maintained across time, across network of monitors, and in all color combinations and gray levels. In these regards (requirements and constraints), they are similar to medical displays. We will discuss some of the challenges and calibration tools.

2 Applications and requirements

2.1 Applications

Applications of color accurate monitors include the following: printing and advertising industries; graphic art; photography; films industry – editing movies (on films or digital); computer animation; medical (color sensitive) – for example, endoscopy, skin photographs (dermatology), etc.; art – to present picture or for creation of new art; geospatial – aerial images, color-coded images, satellite images of vegetation, etc.; painting – color mixing for preparing paint samples in everyday applications (e.g., house paints); and more.

2.2 Requirements

In all these applications, we need to meet the following:

(1) Color Gamut – standard [e.g., sRGB, Adobe, REC-709;)];
(2) "Gamma" – controlled gray levels, to meet luminance separation and proper color mixing in intermediate levels;
(3) White balance – defined white color that meets a color standard, CCT number, or user selected;
(4) Luminance – controlled level, defined by a standard, by the ambient lighting conditions, or both; and
(5) Stability – over long time (minimize need for calibration).

Looking at these requirements, we see a strong similarity to medical displays. They also require accurate gray levels, well-defined luminance control, and stability over time. This should guarantee the doctors proper diagnosis at any time or location. Medical displays follow the TG18 standards, with controlled luminance and defined gray level scheme [Digital Imaging and Communications in Medicine (DICOM) Grayscale Standard Display Function (GSDF) 3.14].[1–3] At this time, there are no specifications for color medical displays although there is active work in this area.[4]

One major concern with color accurate monitors is their match to a specific color standard. To meet several color gamuts, they usually start with a very wide gamut, typically above 100% National Television System Committee (NTSC). To achieve this, most monitors use backlights with discrete LEDs (red, green, and blue) and color rich filters within the active matrix liquid crystal displays. Both cavity with multiple LEDs and edge lit light guides are used. A cold cathode fluorescent lamp backlight is rarely used.

Starting with a wide color gamut ("native colors") and using color conversion matrices will make the monitors meet each of the color standards. The desired standard triangle should be enclosed within the native colors gamut. The process will be further discussed below.

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The color standards to be met are several. Here are some of the standards: NTSC, sRGB, Adobe RGB, REC 709, SMPTE-C, SMPTE-431-2 (D-Cinema), and EBU. They are shown in Fig. 1 in the International Commission on Illumination (CIE) x-y space. Each standard was developed for specific applications. Each includes a color target gamut under typical viewing conditions and gray level scheme, to control the color mixes at different tones. For example, the sRGB (IEC 61966-2-1)[14] was developed by HP and Microsoft for use on monitors, printers, and the Internet. The goal is to maintain the image visibility of information recorded by cameras, in typical viewing and ambient lighting conditions.[5,6]

Some color accurate monitors have preset calibrations for commonly used standards and addressed from the on-screen display menu. Out of the four monitors that we tested, only two had preset standards from the menu (with internal calibration). The other two allowed the standards, but requested an external calibration process or confirmation. More details are included in the latter text.

The monitors are addressed with standard graphical cards, and the conversion from the natural primary colors of the monitor to the required standard is performed through internal matrix multiplications. Lookup tables are set to maintain the white balance within a tight tolerance for all gray levels, whereas the luminance matches the gamma function.

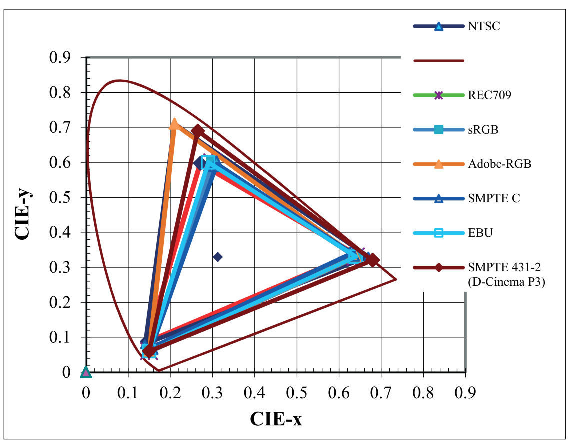

FIGURE 1 — Typical gamut standards used in color displays.

3 Calibration and typical measurements

As mentioned, all color accurate monitors allow a few predefined standards with an internal on-screen display selection and external user-selected colors.

3.1 Calibration tools

External calibration is performed through a contact photometer, close to the center of the display. The photometer is based on silicon sensors and has one detector for each primary color and calibrated color filters. Typical photometers are: "Chroma 5", "i1" (made by X-Rite, Grand Rapids, MI, USA)[7], and "Spyder 3" (made by ColorVision) or newer Spyder versions (by Datacolor, Lawrenceville, NJ, USA).[8] All these photometers use USB communication. The connection is through the back of the monitor, where some information is locally stored. The control and procedure software resides in the host computer; this includes the screen interface for the calibration process.

3.2 Calibration process

The calibration process is described schematically in Fig. 2. The process includes the generation of the color matrix conversion, sometimes called color space conversion (CSC). The calculation of this matrix needs to have linear gray levels. Therefore, the first step in the process is to generate linear gray levels. A lookup table (LUT) denoted as LUT1 in Fig. 2 is calculated in a method described in the latter text. For the calculation of the conversion matrix (CSC), we first need to measure the native primary colors of the display (native RGB). We have the following matrix relation:

(1) [Target matrix] = [CSC] [native RGB]

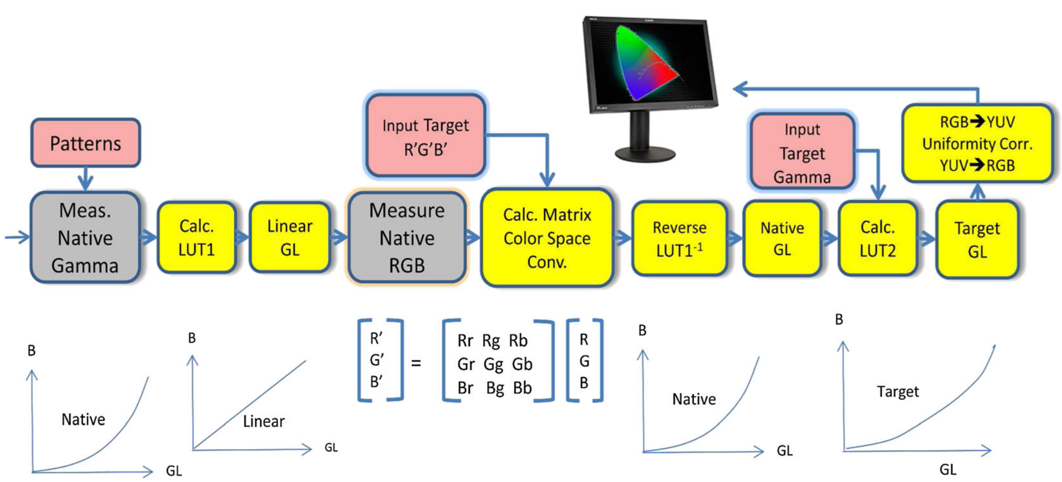

FIGURE 2 — Calibration process (schematic).

Therefore:

(2) [CSC] = [Target matrix] [native RGB]$^{-1}$

Once the color space conversion matrix is calculated, the primary colors are converted (R′G′B′).[9]

Now, we have to change the gray levels scheme to the target gray levels. This is carried out in two steps: (1) linear to native scale; and (2) native to the target gray levels. The last step is a uniformity correction. A nonuniformity map is stored and multiplied at each location. It is easier to do the correction in the YUV space; therefore, there is a double conversion from RGB to YUV and back (after the uniformity correction). The signals are now fed into the display peripheral electronics.

3.3 Gray levels control (lookup tables)

To generate a special gray level scheme, we need first to measure the native curve of the monitor (lookup table = 1) and find the transformation to the desired curve. Figure 3 shows a native curve of a panel, and a target curve (EPD – Equal Probability of Detection). Both curves are presented in 8-bit gray levels (256 gray levels). The native curve is normalized to the maximum luminance of the target curve.

In generating the lookup table (LUT), both curves (native and target) have to be normalized to full white (maximum luminance). The second step is to interpolate the curves to higher resolution. Typically the curves will be measured with 256 (8-bit) levels. The interpolation will increase the target, for example, to 10 bits and the native curve to 12 bits or higher (depending on the electronics chip used). Once this is performed, the LUT can be made by matching the closest numbers from one column to the other. This process is shown graphically in Fig. 3. You start from a given level on the target curve, move horizontally until you hit the native curve, then go vertically to the scale to read the closest matching gray level number. This is demonstrated in Fig. 3 by arrows for two cases.

In principle, the process has to be performed separately for each primary color. Having the same lookup table for all three primary colors, makes for a good estimate. For gamma = 2.2 this process is already stored in color accurate monitors. Figure 4 shows an example of measured gamma 2.2 and its target. The target gray levels curve is "Gray Level", which is the Gamma 2.2 defined by the sRGB specifications.[5,6] Note that this Gray Level curve is actually an average of 2.2, in most of the curve, but becomes linear near the black. The calculated exponent curve of gamma using 2.2 in the exponent is denoted in the Fig. 4 as "Gamma 2.2" (dashed curve). The measured curve is denoted by "Lum-Gry" (black color).

In Fig. 5, we compare the EPD curve with the DICOM curve used in medical imaging[1–3] and the exponential curve with Gamma = 2.2. As can be seen, the EPD curve is very similar to the DICOM curve, but with narrower gray level range.

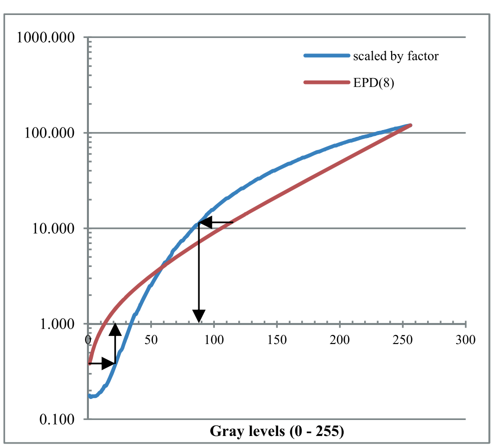

FIGURE 3 — Generating a lookup table: monitor native curve (scaled by a factor) and target curve (EPD – Equal Probability of Detection).

3.4 Basic specifications

The commercial color-accurate monitors that we tested are: Lacie-724 (24″ by Lacie, S.A.S. Massy Cedex, France),[10] ColorEdge CG243W (24.1″ by Eizo, Nanao Corp., Nanao, Japan),[11] LG W2420R (24″ by LG, South Korea),[12] and

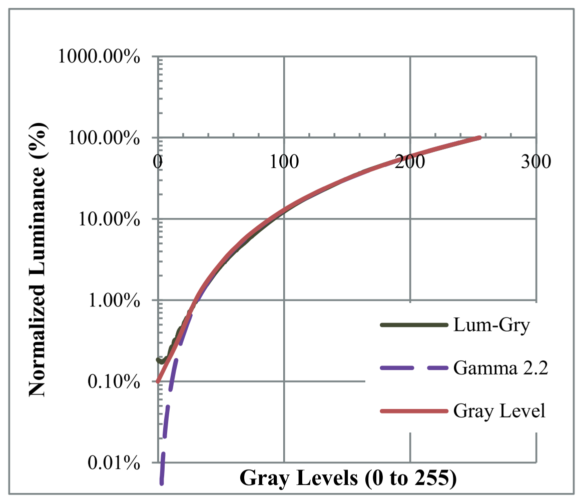

FIGURE 4 — Gamma = 2.2; Lum-Gry (measured); Gamma 2.2 (exponent 2.2 behavior); Gray Level (target – sRGB).

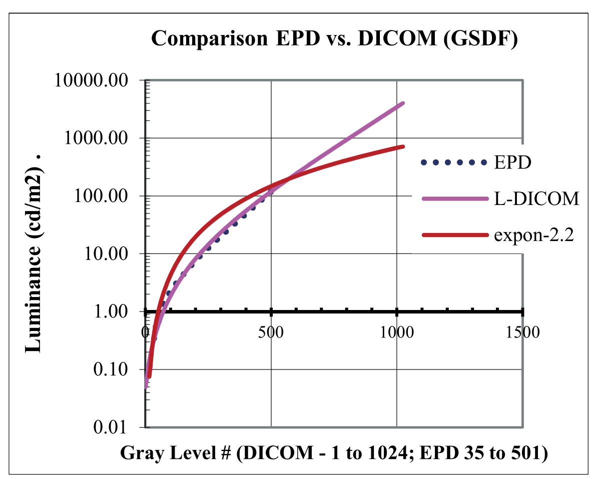

FIGURE 5 — Comparison of Equal Probability of Detection (EPD), L-DICOM, and exponential 2.2 gray levels curves.

TABLE 1 — Color gamut (%NTSC) for the four monitors in CIE *x*-*y* or CIE *u*′-*v*′ spaces.

	Eizo (%)	Lacie (%)	LG (%)	Planar (%)
%NTSC (CIE *x*–*y*)	108	112	113	109
%NTSC (CIE *u*′–*v*′)	125	125	138	132

PX2491W (24″ by Planar Systems, Beaverton, OR, USA).[13] Most are IPS - In-Plane-Switching mode, except Lacie (sPVA - super-patterned vertical alignment), and are somewhat similar in performance and features. The Planar display was intended to be assembled for a stereo-mirror pair, but at this point in time this part of the project is not completed. The HP DreamColor LP2480zx, (HP, Palo Alto, CA, USA) professional display 24″ is discontinued and not tested. The basic specifications are summarized in Table 2.

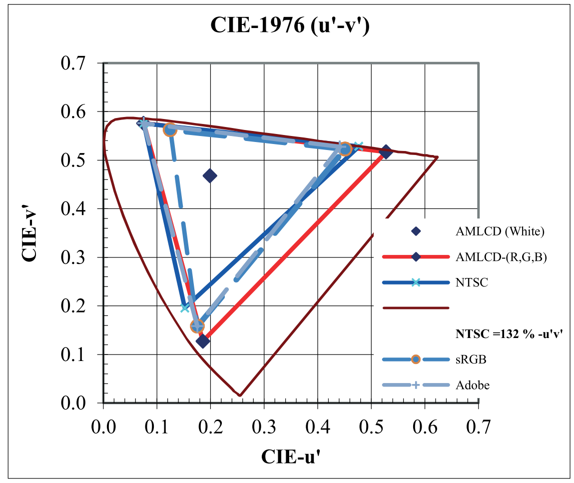

FIGURE 6 — Color gamut of the native display [active matrix liquid crystal displays-RGB] versus National Television System Committee, sRGB, and Adobe standards.

3.5 Optical tests

We tested the monitors previously mentioned and compared their characteristics. Table 1 summarizes the color gamut for the "user" (native) colors.

In Fig. 6, we see the plot of the native primary colors for the Planar monitor (curve: AMLCD – R, G, B). It shows that the triangle is bigger than the sRGB (dashed gray), Adobe RGB (dashed light blue), and NTSC (dark blue) curves. With proper CSC matrices, we can achieve all required colors for each standard. Only the blue of the NTSC is out of the native color gamut, just barely. When calculating the CSC matrix, we might have negative numbers, which should be put as zeros for first approximation. However, most recent applications no longer use NTSC.

The angular contrast ratio of two of the monitors is shown in Fig. 7 (in polar coordinates). The top is for the Lacie monitor and the bottom for the LG monitor. Both plots show very nice contrasts over wide viewing angles both horizontally and vertically, as well as diagonally. The best contrast is found close to normal viewing angle (the scale is red).

All these displays have very good gray level separation over angles. Figure 8 shows a vertical (top) and horizontal (bottom) luminance levels at steps of 31 levels for the Lacie monitor in native mode.

In color accurate monitors, it is essential that the colors will converge to a single white point as a function of gray levels, and that the white point will not shift much ($C^*ab < 5$). In Fig. 9, we see the colors measured at each gray level. The white (Gry) points shift very little (in the center). This plot is for Planar's monitor in the PLNR mode, which has primary colors similar

TABLE 2 — typical features of color accurate monitors.

Basic specifications Producer	Eizo[11]	Lacie[10]	LG[12]	Planar[13]
Model	ColorEdge CG245W	Lacie 724	W2420R	PX2491W
Screen				
Screen size	24.1 in.	24.0 in.	24.0 in.	24.0 in.
Technology/LC structure	TFT-active matrix/IPS	TFT-active matrix/S-PVA	TFT-active matrix/IPS	TFT-active matrix/IPS
Screen resolution	1920 × 1200	1920 × 1200	1920 × 1200	1920 × 1200
Dot pitch (mm)	0.27	0.27	0.27	0.27
Brightness (cd/m^2)	270	250	250	270
Contrast (typ)	850	1000	1000	1000
View angle (CR = 10)	178°H/178°V	178°H/178°V	178°H/178°V	178°H/178°V
Response time	5 ms (Avg)	6 ms/16 ms	6 ms/6 ms	6 ms
Colors/calibration				
Color temperature	Adobe RGB, sRGB, Rec709, EBU, SMPTE-C, DCI	Most standards (by external calibration)	6500 K, user calibration	6500 K (sRGB, Adobe, PLNR, more), user
Color depth (bits)	8 bits	8 bits (lookup = 14)	10 bits	10 bits
Gamma (γ)	2.2	2.2	2.2	2.2, EPD, native
Internal stored standards	—	—	sRGB, Adobe RGB, User	sRGB, Adobe RGB, PLNR (sRGB/EPD), native
External calibration	Yes	Yes	Yes	Yes
Interfaces	DVI-I	DVI-I, DVD-D	DVI-I, DVI-D	DVI-I, DVI-D, RGB, HDMI (1920 × 1080)
USB ports	×2	×2	×4	×4
Backlight	R/G/B LEDs	CCFL (?)	R/G/B LEDs	R/G/B LEDs

LC structure, local committee structure; TFT, thin film transistors; CCFL, cold cathode fluorescent lamp.

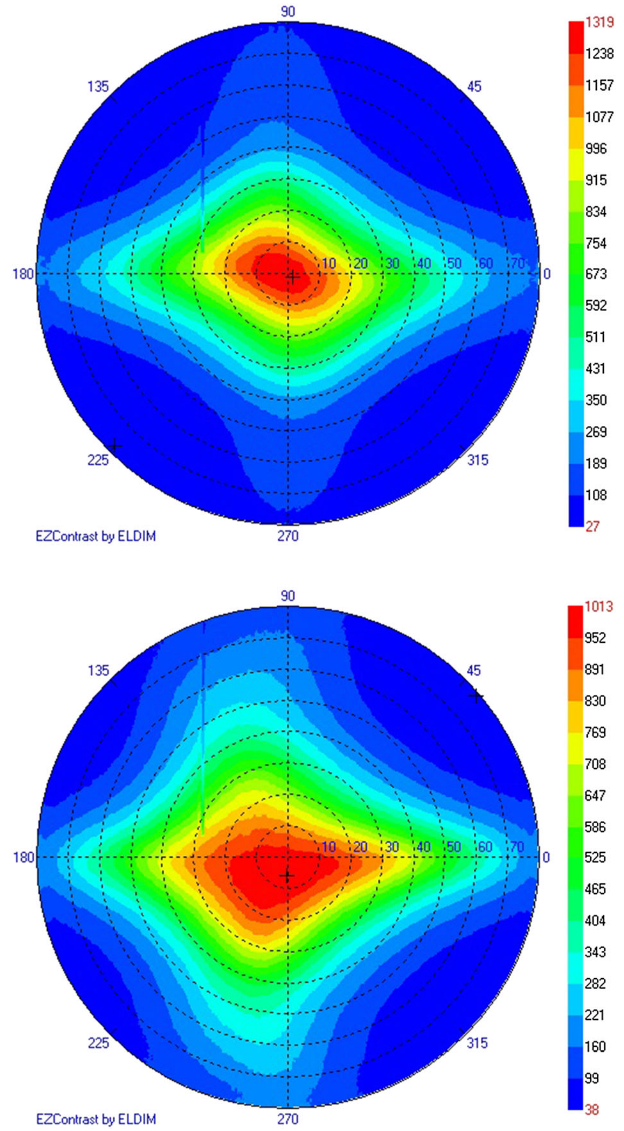

FIGURE 7 — Angular contrast ratio of two of the monitors: (a) Lacie (top); and (b) LG (bottom).

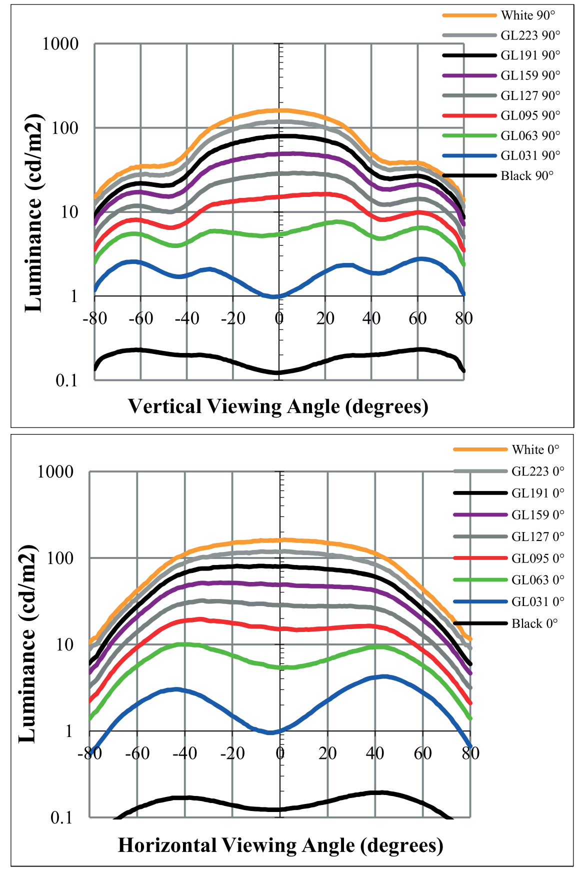

FIGURE 8 — Luminance versus gray levels (steps 31) for Lacie monitor (top-vertical, bottom-horizontal).

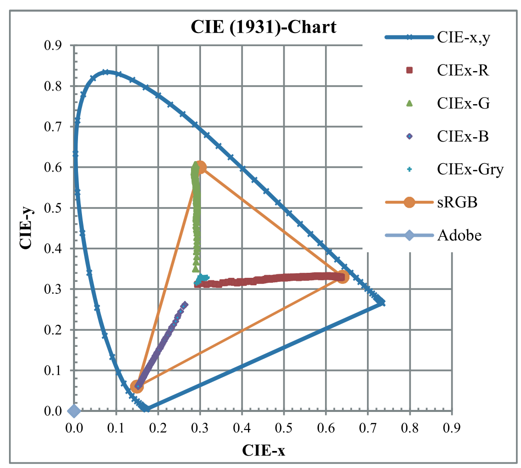

FIGURE 9 — Colors at gray levels in Planar monitor (PLNR mode – sRGB with gamma = EPD – Equal Probability of Detection curve).

to the sRGB mode, whereas the gray levels follow the EPD curve. As you can see, the colors of intermediate gray levels nearly form a straight line from full color towards black. This is an indication that the color mixes in mid-gray levels are properly adjusted. This requires two things: (1) a match in the gray levels of the primary colors in mid-levels; and (2) that the color conversion matrix is properly calculated.

A similar way to present the color coordinates at gray levels is in Fig. 10. In this plot, the CIE x-coordinate and y-coordinate are plotted on the vertical scale, coded with the proper colors. We would like these curves to be as horizontal as possible. They converge to the black CIE (x, y) point. A straight line for both x and y curves (CIEx-Gry, CIEy-Gry) means minimum shift in white color balance over gray levels.

In Fig. 11, we see the measured gray levels (Lum-Gry) in comparison with the target EPD curve (EPD2). It might take several iterations to find the optimum lookup table and meet the criteria of $\delta L^* < 2.5$ between measured and target curves.

3.6 Conclusion

Color monitors have the following features:

(1) Internal (precalibration) or external tools to match specific color standards. This generates conversion matrices that are used on the fly for each input.

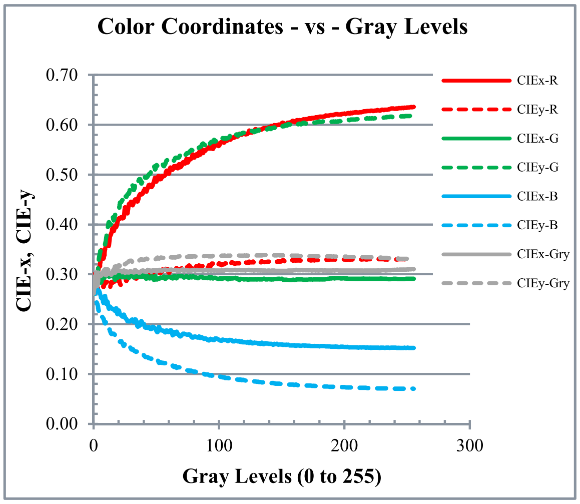

FIGURE 10 — Color coordinates at gray levels (for primary colors and gray; CIE-x in solid lines, CIE-y in dashed line).

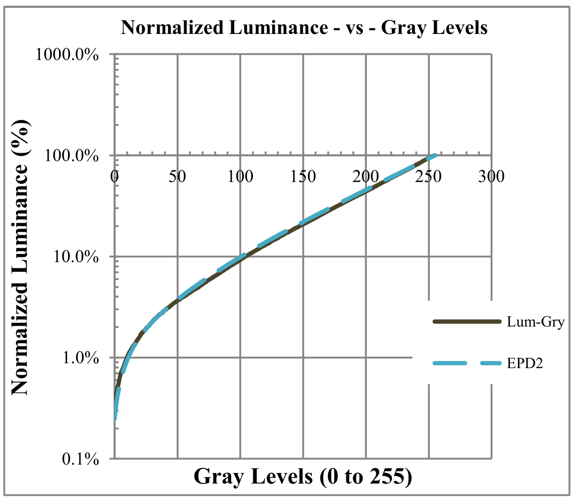

FIGURE 11 — Gray levels match to the target gamma (EPD2 curve) in Planar's monitor, PLNR mode.

(2) Gray level lookup tables that are responsible for meeting specific "gamma" (commonly $\gamma = 2.2$), proper white balance, and colors mix.

(3) Luminance control – this topic was not discussed previously. However, because the vision system has different capabilities at brightness levels, it is important to maintain certain luminance levels once the calibration is performed.

In the case of RGB LED backlights, it also helps to maintain white balance by adjusting each LED strip (R, G, or B) separately and by making sure that the backlight color balancing is proper.

4 Summary

Color accurate monitors have very demanding features. They are high-resolution panels (typically WUXGA) with very saturated colors (>100% NTSC). This is usually achieved with an RGB LED backlight and saturated colors within the panel. Most monitors use IPS mode to guarantee color mixing and gray levels separation over wide viewing angles.

We showed some measurements of this characteristic. The monitors have backlight luminance control to maintain white balance of the backlight and overall luminance at full white and gray levels. The monitors have preset calibrated color standards and external calibration means (and software) with photometers (packs) connected through USB. Most of the time the gamma is 2.2, but developers can generate modes with special gamma curves.

The applications that use these monitors include the printing industry, graphics art, photography, film, medical imaging, art generation, and geospatial, among others.

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13 PX2491W, Planar web: www.planar.com
14 A copy of the IEC official sRGB specification (IEC 61966-2-1:1999) are available for purchase on www.iec.ch

Adi Abileah is the chief scientist at the Technology Group, Planar Systems, Beaverton, Oregon. His main activity is related to development of active matrix liquid crystal displays (AMLCD), physics and optics of the displays of several technologies, and backlights and enhancement techniques. Adi has BS in Physics from the Technion (Israel Institute of Technology) and MS in Plasma Physics from the Hebrew University, Jerusalem. And a 2-year research work at the university on high power CO_2 lasers. He developed soil mechanics density sensors at the Negev Institute. His first industry job was in medical imaging (Nuclear Medicine) at Elscint, Israel. He was the head of the Electro-Optics Group at Elbit for several years, and then the manager of EL-OP north branch R&D center in Haifa, Israel. On 1987, he joined OIS – Optical Imaging Systems in Michigan where he became the manager of the optics group and responsible for all related topics in the development of AMLCDs. During this period, he became expert in the optics of AMLCDs, testing techniques, and liquid crystals physics. He served at OIS until the company closed at 1998 and then joined Planar. Adi has 33 US patents, mostly related to displays, backlights, 3-D stereo and in-cell optical sensors. He presented many technical papers at SID, SPIE, and OSA conferences, and gave several seminars at SID. In 2005, he received the Fellow Award of SID. In 2010, he got the SID President Recognition Award. In 2007, he became the director of the Pacific Northwest chapter of SID. He co-chaired and was program chair of ADEAC conferences (2005/2006). He was program chair of LatinDisplay/IDRC in the last couple of years (2010/2011). Adi is an Associate Editor for JSID 3-D displays and chairing the 3-D stereo subcommittee of ICDM standards. He just started to be the chair of the Applications subcommittee for the SID conferences and papers selection.