Technology for Grade 1 LCDs

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1 Introduction

For decades, color-critical video monitoring for broadcast and post-production applications was performed on a reference (grade 1[1]) CRT monitor, or a reference projector for cinema applications. Flat panel displays, although having clear advantages in terms of depth, longevity and insensitivity to magnetic fields, have until recently failed to produce accurate and stable pictures as required for true grade 1 monitoring. Various LCD artifacts stood in the way of accepting LCD as the next technology for color critical applications: insufficient viewing angle causing a drop in contrast, a color shift or even a color inversion; crushed dark levels and clipped highlights; over-saturated colors, skin tone errors and color cast errors; motion blurring, de-interlacing problems, jaggies, and motion judder; unstable colors and unstable brightness.

Only recently have flat panel displays started to find their way into this arena, helped by the obsolescence of the cathode ray tube (CRT), and also because flat panel technology has matured technically. Flat panels are now the viable alternative to CRTs.

This paper discusses the state-of-the-art regarding LCD technology, sheds light on its positive and negative aspects, and defends the point that if LCDs are designed into a monitor with proper care, the result can be a very acceptable reference monitor. The results of an implementation of these technologies in a real-world product are then shown and discussed.

2 Grade 1 Monitor Standards and Specifications

The last 40 years have seen the standardization of the CRT for reference or grade 1 monitoring by organizations such as the SMPTE and the EBU. Some standards or recommendations specified the complete grade 1 monitor, such as EBU Tech. 3263 that defines the colorimetry, geometry, magnetic field behavior, interference, acoustic noise, frequency response, inputs, and functionality. Other documents referred to measurement methods and colorimetry (such as SMPTE RP145, EBU 3123 etc.).

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[1] Grade 1 monitors are devices for high-grade technical quality evaluation of picture capturing, post-production, transmission and storage. These monitors must possess at least the quality properties of the equipment to be controlled.

Regarding colorimetry, a subject of prime interest in this paper, the standards have specified the required values for the white point (color temperature), primaries and uniformity, as well as allowed tolerances for these parameters. Recently, the EBU published a user requirements specification of a grade 1 flat-panel monitor (EBU Tech. 3320, [1]); the SMPTE has a committee working on a "fixed pixel matrix" reference monitor.

3 Technology choices and benefits

While it is true that many of the LCD artifacts are due to the LCD technology per se, some of them are also due to application choices. In the consumer application space, these choices are based on cost savings and a need for bright and colorful showroom displays – rather than broadcast-standard color accuracy and stability.

So, with this knowledge in hand, we can further examine the requirements for a grade 1 LCD monitor, and how technology can be used to deliver them.

3.1 LCD panel: IPS or MVA?

Based on the status of LCD technology today, the basic trade-off is between viewing angle and contrast. Technologies that optimize the viewing angle have a lower contrast ratio (CR), and vice-versa. Newer grade 1 specifications (such as EBU Tech. 3320) specify both a contrast ratio of 2000:1 and a certain viewing angle dependence of contrast and color. However, no current LCD technology can satisfy both requirements at the same time.

- VA (vertical aligned panels, in variants as MVA and SPVA) can easily achieve a very high contrast ratio of several thousands to one in the perpendicular viewing direction, but that contrast drops off very fast as the viewing angle increases.
- IPS (in-plane-switching) panels have a lower CR, but they also have very good viewing characteristics that that comply with grade 1 specifications. These include low contrast decay, and low gamma and chromaticity shifts under angle (Fig. 1b)

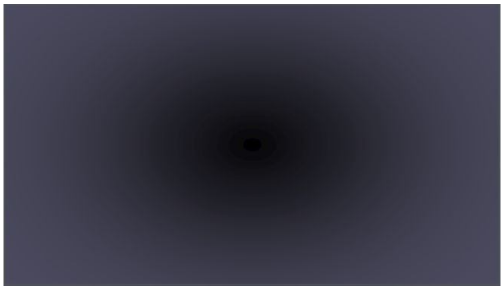

Fig.1a. VA panel as seen by an observer in front. Center contrast is higher than IPS. However off-center black becomes brighter and tinted due to viewing angle issues.

Fig.1b. IPS panel. Center contrast is lower than VA. However viewing field uniformity is much higher than VA due to better viewing angle performance.

Color professionals have a preference for both a high contrast and a good viewing angle. As nothing can be done about the viewing angle, but a lot can be done to preserve the native LCD contrast, we believe that the IPS technology is the right choice for grade 1 LCD displays. This is proven by many demonstrations of different technologies and also by the choice most manufacturers make for their highest-end broadcast LCD monitors as well as the choice of LCD panels in the medical imaging market.

3.2 Backlight: RGB-LED, White LED or CCFL[2]?

Today LED backlights seem to be preferred in TV sets, as they produce nicer looking (i.e., more saturated) colors and thinner sets. LED backlights are also considered “greener” than those with lamps containing mercury. However, there are other reasons why LED backlights are needed in a grade 1, reference LCD monitor.

Preserving Contrast and Uniformity

The only optical parameter of CCFL lamps and white LEDs that can directly be changed and controlled is the luminance. This can be changed by controlling the drive current through the lamps, or with pulse-width modulation. The native color temperature of such backlight devices is quite high (typically exceeding 10,000 K). Moreover, by changing the luminance level, the color temperature and/or color gamut can also change in an uncontrolled way. The white point and uniformity of CCFL or white LED backlit LCD monitors must therefore be regulated within the LCD panel using the RGB gains of the pixels. This however results in lower contrast and less video levels (resulting in banding). For example, when calibrating a typical LCD display with a CCFL backlight to D65, it will lose more than 30% of its luminance (and contrast), 16% of the available green level and 20% of the available red level! Even more contrast and video levels will be lost if the display is compensated for area uniformity

With RGB-LEDs, both the luminance and the white point can be set and controlled directly by the backlight. With a good design, the backlight can also be made very uniform, so only minor corrections are necessary on the LCD. This means that there is no decrease in contrast and in available video levels (also no banding). As these are crucial parameters of an LCD display, the conclusion is that at present RGB-LEDs are the best light source to ensure the correct performance of a grade 1 LCD display without sacrificing crucial parameters.

Support of different color standards

In order for one display to allow correct calibration to different worldwide standards (EBU 3213, SMPTE C, ITU-R Rec.709), the display must use wide-gamut backlights. This is also necessary in order to compensate for possible primary color shifts in the backlight due to temperature and aging effects. (see section 4.1)

The above combination of factors (achieved contrast and video level preservation, uniformity and wide gamut), makes RGB-LEDs the backlight technology of choice for grade 1 LCD monitors.

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[2] CCFL = Cold Cathode Fluorescent Lamp, i.e. first generation backlight for LCDs

4 What Else Should Be Done?

4.1 Backlight Measurement and Stabilization

The question of calibration of monitors using an RGB-LED backlight to grade 1 accuracy deserves separate attention. Two things must be considered:

a) The color probes (tristimulus sensors, colorimeters) commonly used to calibrate broadcast monitors are not accurate enough for RGB-LED spectra;

b) LEDs are much more sensitive to temperature and aging than CCFLs, so some type of internal stabilization is necessary.

a) The simplest color measurement instrument is a tristimulus sensor (a 'colorimeter'). A tristimulus color sensor splits the measured light using three color filters that approximate the human eye's color matching functions. Inside the color sensor, three luminance sensors measure the filtered light, directly resulting in three output values: X, Y, Z, or derived x, y, Y – chromaticity and luminance. However it is very difficult to make filters that exactly match the human eye sensitivity in all different wavelength regions. As long as the measured spectrum is quite wide and not peaked, (as in CRTs and CCFL-backlit monitors), the measurement error is acceptable. However, with LED spectra that are quite peaked, a tristimulus color sensor cannot produce accurate measurement results.. Even when the tristimulus sensor is calibrated to a certain LED spectrum, the LED backlight is likely to change with temperature and aging, increasing the measurement error of the tristimulus sensor (and above all making it unpredictable). Therefore in principle, a tristimulus sensor can never be good enough to correctly measure and stabilize the LED backlight to a grade 1 level. In order to perform accurate calibration to grade 1 levels, an accurate spectrometer must be used.

b) LEDs are much more sensitive to temperature and aging than CCFLs. This means that even with minor temperature changes, not only the white point, but also the primaries are likely to change visibly. Aging also plays a role, albeit on a longer time scale, making accurate measurements and real-time internal stabilization of the LED backlight a must.

Combining the above two points, it is clear that LCD monitors using RGB-LED backlights must employ internal, real-time stabilization with a highly accurate spectrometer. By performing this stabilization with an internal spectrometer, the monitor can remain calibrated for a very long period of time (at least one year, (depending on the long-term performance of the embedded spectrometer).

Implementation of this backlight technology with embedded stabilization circuitry in a product will be discussed in section 6.1.

4.2 LCD Characteristics and Corrections

The nature of LCD technology poses a set of problems for any company aspiring to make a grade 1 monitor. The most important issue is the finite contrast range of the LCD, which requires careful engineering so as not to decrease it even further. In addition, the uniformity, pixel cross-talk, native display "gamma", and the motion blur all require separate attention.

4.2.1 Panel Bit Depth

To ensure color accuracy, the native bit depth of the panel as well as the accuracy of the video processing are of paramount importance. A normal LCD panel has a bit depth of 8 bits. This means that each pixel (R, G or B) can be driven at 2^8 (255) different levels above black. With standard 'dithering' mechanisms (changing the pixel content between two states fast enough so when averaged over time an intermediate state is perceived), an additional 2 bits of accuracy can be obtained. However, 8+2 bits might not be enough to faithfully reproduce all colors, and such dithering can introduce visible artifacts (aliases) with high-frequency content.

Input signals are typically 10-bit (although they can be 8-bit video or even 12-bit XYZ for digital cinema applications). This bit depth is easily eaten up by all corrections necessary for a grade 1 monitor (uniformity, color space conversion etc). For real grade 1 accuracy, a minimum of native 10-bit panel plus a minimum of 2-bit dithering is necessary.

4.2.2 Contrast and Gamma Function

The theoretical display transfer characteristic (gamma function) is defined as a pure power law. This power function is almost horizontal at the dark levels (Fig.2). Because of the high CRT contrast, the CRT gamma curve goes close to black at low signal levels. With LCDs however, the gamma curve doesn't go to black due to the limited contrast (and remaining luminance of the black signal level).

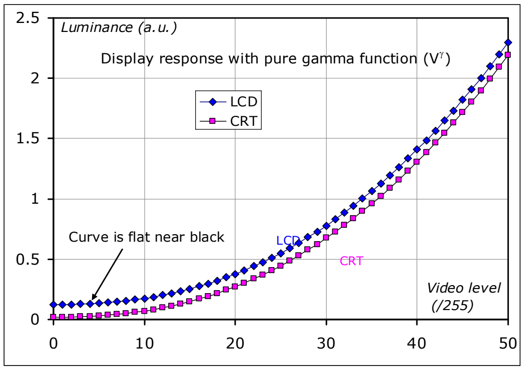

Fig.2. The ideal gamma power function is almost flat in dark levels near black. For LCDs there is a black offset.

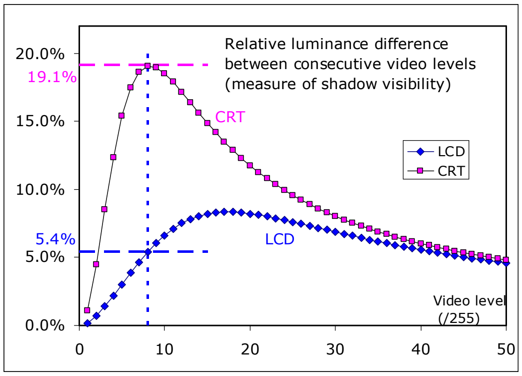

Fig.3. Because of the lower LCD contrast, the relative differences between consecutive shadow levels are much smaller, yielding less visible black detail than in CRTs.

The ability to perceive the 'shadow' details is roughly proportional to the relative (percentage) difference between them. Because of the limited LCD contrast and the comparatively large black luminance offset, the relative difference of shadow detail luminances is quite low (Fig.3).

Because of these factors, the pure power-law gamma function fails to deliver acceptable black details in LCDs, resulting in 'crushed blacks'. Knowledge of human perception, LCD physics and optics can be applied to successfully solve this problem and provide dark detail visibility without impairing the perceived display contrast.

4.2.3 Cross-talk

An LCD pixel contains a red, green and blue sub-pixel. The three sub-pixels are actually identical TFTs, but with different color filters at the top. Due to capacitive cross-talk between the pixel electrodes on a micro level, the signal on one sub-pixel influences the signal on a neighboring sub-pixel. This "influence" is called cross-talk. As a result, the color of one sub-pixel (e.g., green) will be slightly different according to whether a neighboring pixel (e.g. red and/or blue) is turned on or off. This difference, however, is large enough to change the displayed colors more than is allowed for a grade 1 monitor. Without a cross-talk correction method, an LCD display might not produce colors accurately enough to reach grade 1 standards.

4.2.4 Motion Artifacts

Motion artifacts on LCDs can be caused by motion blur and video processing. Motion blur in turn is caused by the finite liquid crystal response time and the "hold effect" (the fact that the LCD pixel retains the picture for a whole frame).

The finite response time causes blurring of fast transitions (e.g. white object moving over a black background). Instead of a sharp edge, the edge is blurred over a number of pixels that undergo transitions from black to white. However, even if the response time is zero, there will still be a perceived motion blur due to the hold effect (which is linked to human perception).

Video processing can introduce motion artifacts when 'deinterlacing'. Deinterlacing is never perfect and one can always find a sequence where the deinterlacer will produce visible errors. The idea for grade 1 monitors is not to produce a nice picture, but a correct picture. This is of course difficult if the content is interlaced. Therefore the deinterlacing shouldn't introduce additional errors, and definitely shouldn't mask, for example, field dominance errors if they are present in the signal.

There are several things that can be done to decrease the motion artifacts. All of these things are employed in the RHDM monitor described in section 6 (some of them, like the scanning backlights and black-line insertion as a user-selectable option).

- Use fast LCD panels with short response times.
- Reduce the hold effect by using scanning or pulsing backlights.
- Use a black line insertion algorithm. This method removes de-interlacing effects and increases perceptual sharpness; however the display contrast is decreased by a factor of 2.
- To ensure that grey-to-grey transitions are shorter and symmetric, speed-up and optimize the LCD response time.

5 Perceptual Factors and Matching Between Technologies

In the last few years with the advance of LED-based lighting and displays, there are more and more reports [2] that matching between LED-based displays and CRT monitors cannot be successfully done using the established CIE 1931 colorimetry.

This colorimetry was established in order to enable a simple representation of color (by three parameters only instead of a complete spectrum) by approximating the human visual system. Three color matching functions (CMF): $\bar{x}(\lambda)$, $\bar{y}(\lambda)$ and $\bar{z}(\lambda)$(mimicking the wavelength response of the three types of human visual receptors) have been experimentally derived from experiments of matching the color impression of a certain light source with a second source by changing the intensities of only three colors. By integrating the weighted spectral power distribution $I(\lambda)$ of the light source with each of the CMFs, three values (the tristimulus values *X*, *Y* and *Z*) are obtained:

$$X = \int_0^\infty I(\lambda)\bar{x}(\lambda)d\lambda \; ; \; Y = \int_0^\infty I(\lambda)\bar{y}(\lambda)d\lambda \; ; \; Z = \int_0^\infty I(\lambda)\bar{z}(\lambda)d\lambda$$

The basic characteristic of this 1931 color science is the '*metameric principle'*: if two light sources have exactly the same *X*, *Y* and *Z* coordinates, then they will *look the same* to a human observer, no matter what the spectrum of the light source is.

Today however we see that the *metameric principle is not necessarily valid* anymore when we compare LED-based display devices with a CRT.

The problem can be posed like this:

- If you match an LED-based display device to have exactly the same *X*, *Y* and *Z* as a lamp or a CRT display, then the two displays *don't look the same*.
- If you make the LED-based display device to look the same as a lamp or a CRT display, then the two display devices *don't have the same X, Y and Z values*.

It is obvious that a display that complies with the grade 1 specifications may not look the same as a CRT and vice versa. What is the real purpose of grade 1 specifications then, and how do we go about solving this problem?

According to EBU Tech.3320 [1], the grade 1 specifications define on the one hand that a monitor should look the same as a CRT, but on the other hand that the monitor must comply with color parameters and tolerances specified in terms of the CIE 1931 colorimetry. According to internal Barco experiments, the published mathematical solutions [2] that improve the CIE1931 colorimetry still do not provide a full metameric match between LED-based and CRT based displays. Therefore, in order to comply with both EBU Tech.3320 requirements, we must resort to visual matching. The tight tolerances for a grade 1 monitor are still valid independently of the metameric problem: they specify the good performance of the monitor for accurate color rendition, neutral grey scale, uniformity etc. The absolute values of the grade 1 color specifications however may be subject to recalibration when a CRT match is required.

6 Implementation

The knowledge and technology choices laid out above are implemented by Barco in the RHDM monitor line – 17’’ and 23’’ grade 1 monitors.

6.1 Implemented technology

10 bit IPS LCD panel:
In this monitor, IPS LCD technology is employed because of its good viewing angle characteristics. The LCD panel has a native bit depth of 10 bits. Using proprietary video processing and dithering algorithms, 12 (twelve) bits are added on top, resulting in a 22 bit color accuracy. The LCD frame rate is 120Hz (maximum), and is changed according to the input signal (e.g. 24p is displayed at 96 frames per second, 50i is displayed at 100 frames per second). The contrast ratio ranges from 800-1000:1 (depending on the model).

RGB-LED edge-lit backlight
The backlight is based on edge-lit RGB-LEDs, built in 6 separate ‘trays’ (horizontal light guides) with RGB-LEDs positioned on both the left and the right edges of a tray. Using this system, the backlight can be made uniform. In addition, a scanning backlight mechanism can be employed (as a user-selectable option). The wide-gamut RGB-LEDs enable the product to achieve and stabilize different color gamuts correctly (EBU 3213, Rec. 709, SMPTE C, DCI, Adobe 1998). The luminance and white point is regulated directly in the backlight with the highest accuracy.

Backlight stabilization
The backlight is stabilized in real time by using 6 light sensors (measuring the separate trays), and an integrated high-quality spectrometer (measuring the mixed white light before it is transmitted through the panel). The calibration feedback loop works in real time, so if there is any change in the backlight spectrum due to heating up or aging, it is automatically corrected.

Video processing technology
The RHDM monitor uses de-interlacing over a maximum of 2 fields, in order not to mask field inversion signal problems. The LCD is accelerated using a proprietary Barco technology. The cross-talk is removed using 3D-LUT calibration. The “dithering” to 22 bits in total is done using Barco proprietary technology.

Perceptual factors
The RHDM monitor incorporates fundamental knowledge of human perception in order to deal with the limited contrast, motion blur and colorimetry. The gamma curve in lowlights is adapted to correspond to the visibility of the shadow detail on a CRT. This solves the problem of crushed blacks due to the high black level of an LCD display. The scanning backlight decreases the perceived motion blur. The display provides an optional mode that matches it perceptually to a CRT (optionally deviating from the default CIE1931 colorimetry - see Section 5).

6.2 Results Achieved

This section presents actual measurements on an RHDM-2301 monitor in comparison to the allowed tolerances according to EBU Tech. 3320 from October 2010. The EBU document uses the CIE 1976 system (CIE L*u*v*) to express the allowed tolerances. The monitor is calibrated to 100 cd/m^2 for 100% white, Rec.709 primaries, D65 white point, gamma exponent of 2.35. The measurements were performed in a completely dark room with black walls. The instrument used was a CAS 140CT from Instruments Systems. We will take a look at the white point, grey scale tracking, uniformity, gamma curve and test colors.

White point and grey scale tracking

The theoretical and measured parameters of the display white point are given in Table 1.

White point	**Theoretical**	**Measured**
Luminance *Y*	100 cd/m^2	99.46 cd/m^2
u’	0.1978	0.1975
v’	0.4683	0.4679
*Δu*v**	1.6	0.63

Table 1. Comparison of theoretical and measured parameters of the RHDM white point. The display is well within the allowed tolerances.

The grey scale tracking is a measure of how constant the chromaticity of grey remains over the complete video range when compared to the *measured* white point. For grade 1 monitors, this tolerance is Δ*u*v**=0.5.

- Fig.4a represents the grey scale tracking (Δ*u*,* Δ*v**) as a function of the drive level. For a drive level of 100%, the deviation is 0, due to the definition of grey scale tracking. There is a high consistency (there are no visible coloration trends at different grey levels) and accuracy (the achieved grey level is much more accurate than the allowed tolerance).
- Fig.4b plots the same data in a 2D plot, losing information on the drive level dependency, but giving a better overview on the achieved grey scale tracking accuracy.

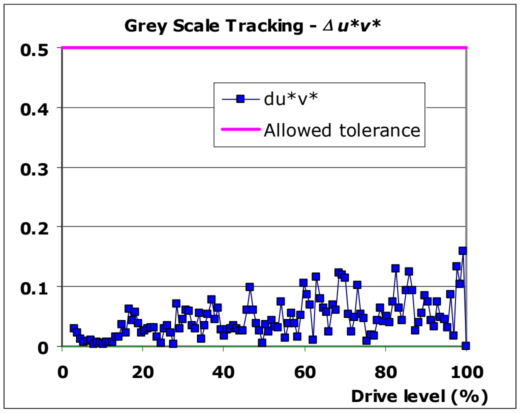

Fig.4a. Grey tracking as a function of drive level. The grey tracking is represented as the difference between the measured u* and v* from the theoretical u*, v*

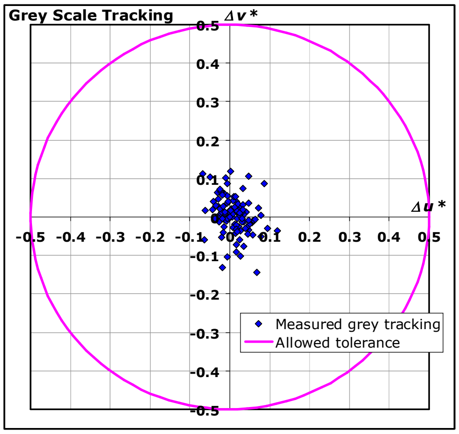

Fig.4b. Grey tracking for all drive levels on a 2D plot. The ellipse is the allowed tolerance. The RHDM is at least 2 times more accurate.

Uniformity

Display uniformity is normally defined in terms of luminance. The luminance uniformity is the ratio of the lowest and highest measured luminance on a number of defined points on the display surface. The target is to have 95% uniformity. However color uniformity in LCD displays is even more important.

- The distribution of the 13 measured points on the screen is shown in Fig. 5.
- The measured luminance (as a percent of the maximum luminance of the 13 points) is shown in Fig.6a. One can readily see that the luminance uniformity is above 98%.
- The measured chromaticities of the 13 points compared to the center (calibrated to D65, 100cd/m^2) are presented in Fig.6b. All measured points are well within the allowed uniformity tolerance of Δu^*v^*=2.6.

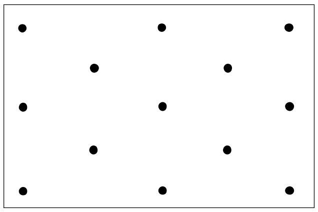

Fig.5. The distribution of the 13 measured points on screen.

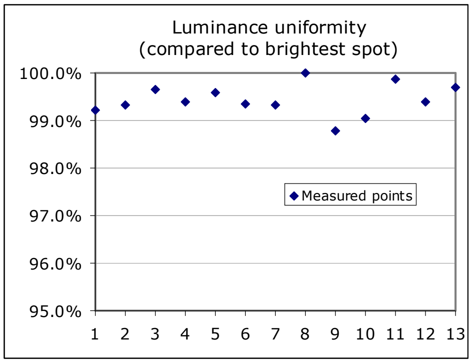

Fig.6a. 13 point luminance uniformity on a white field (D65, 100cd/m2) compared to the brightest point.

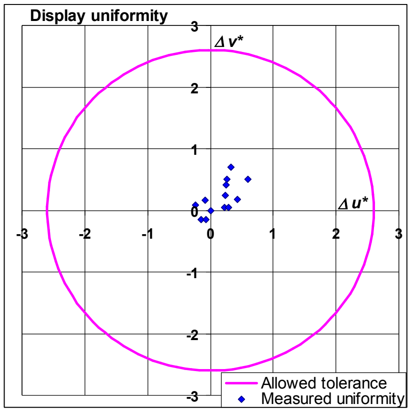

Fig.6b. 13 point color uniformity on a white field (D65) compared to the center point.

Gamma curve

The gamma curve represents the generated display luminance versus display drive level. There are two main representations of the gamma curve: the measured display luminance versus drive level, and the gamma value versus drive level.

- Fig.7a shows the measured versus the theoretical luminance as a function of the drive level. The measured curve is on top of the theoretical, with maximum 1% luminance difference, which is the normal instrument accuracy. This graph shows the correct global character of the RHDM gamma curve and its luminance accuracy.
- Fig.7b shows the gamma value as function of the drive level. The gamma value at each drive level must be constant and within allowed tolerances (±0.1). Possible interpolation errors in the

display LUT due to insufficient accuracy can result in local gamma values that are not constant. Fig.7b shows that this is not the case in the RHDM monitor.

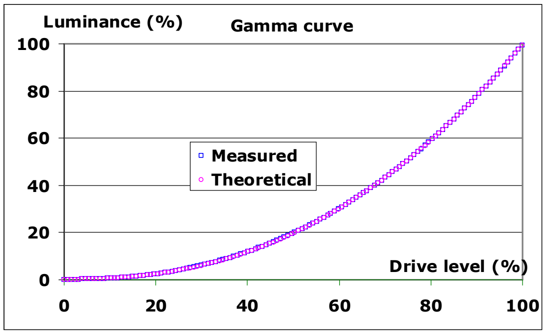

Fig.7a. The gamma curve (luminance versus drive level). The measured curve is on top of the theoretical, with maximum 1% difference (this is the instrument accuracy).

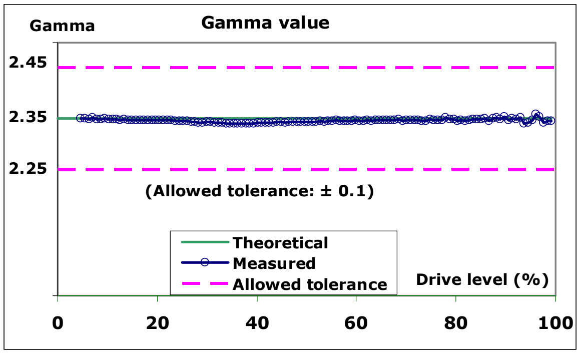

Fig.7b. The gamma value vs. drive level. The measured and theoretical curve are on top of each other. This means there are no local gamma deviations

Test colors

The test colors are the ultimate test of the monitor color accuracy. Their accuracy depends on the accuracy of the white point, gamma curve, grey scale tracking, cross-talk correction, correct video matrices, correct primaries.

In order to evaluate the color space, we used a patch of 15 test colors devised by the EBU, plus the 3 primaries. The allowed test color tolerance according to EBU 3320 Δ*u***v**=4, except for the two skin tone test colors, where the tolerance is Δ*u***v**=2.6. The measurement results represented in Fig.8 show that again, as with grey scale tracking and gamma, the RHDM under test achieved a high color accuracy.

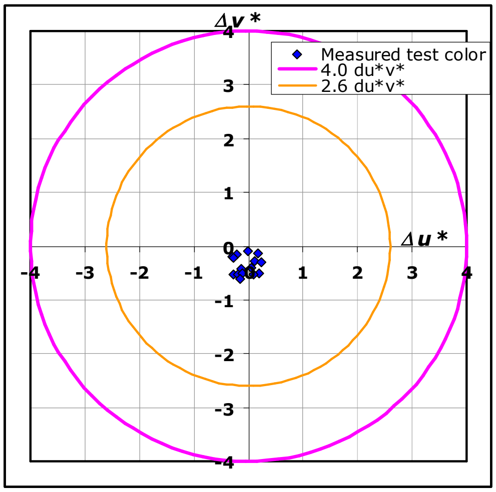

Fig.8. RHDM performance regarding different EBU test colors. For each test color, the deviation of the measured to theoretical value lies within the allowed tolerance.

7 Summary

In this paper we discussed the technology of LCD monitors, and the choices and steps necessary to solve the technology problems in order to produce an LCD grade 1 monitor.

We demonstrated that, although there are deficiencies in the LCD technology, there are also ways of solving them or at least minimizing the artifacts. The technology choices adopted are:

- Native 10 bit, IPS LCD panel (for good viewing angle and acceptable contrast);
- Edge-lit RGB-LED backlight for better uniformity, wide gamut, accurate white point and no contrast and video level loss.
- Real-time stabilization of the backlight with an embedded spectrometer in order to counter the temperature and aging effects and assure grade 1 accuracy at all time
- Cross-talk calibration in order to improve the accuracy of the intermediate colors
- Different modes and technologies for reducing motion artifacts (fast LCD panel, LCD speed-up, black line insertion mode, scanning backlight)
- Perceptual matching to CRT:
    - dark tone visibility
    - colorimetric matching (optional mode providing compensation for inadequacy of the CIE 1931 system for RGB LED measurement).

We demonstrated that the implementation of these technologies results in a LCD monitor that can comply with grade 1 specifications.

Note: This is a version of a technical paper presented at the 2010 SMPTE Technical conference.

References

[1] EBU-Tech.3320, User Requirements for Video Monitors in Television Production, October 2010, www.ebu.ch

[2] Csuti, P., Schanda, J., Colour Matching Experiments with RGB-LEDs, Color Research and Application, Volume 33, Number 2, April 2008