

Color measurement and calibration of professional display devices

Abstract:

With the advance of display technologies using LED light sources, the problems of color consistency, accuracy and calibration become again important. This white paper shows that the use of tristimulus color sensors is not satisfactory for such displays: a spectrometer is needed to insure accurate color representation and calibration.

1 Introduction and use cases

In many professional applications that use displays, *color uniformity, calibration and stability* are of prime importance.

For example the *video walls* for digital signage or control room applications have to be uniform in order to convey the information properly. If the 'tiles', or 'cubes' forming a video wall are not uniform, this will interfere with the intended content shown on the wall, resulting in anything ranging from operator annoyance to wrong (and possibly critical) interpretation of data. Also a display wall with bad uniformity has a bad 'PR value' – since everybody expects the wall to be uniform, if this is not the case it will make some eyebrows frown.

Making the different tiles uniform is so called '*relative calibration*', or '*display consistency*'.

In other professional applications not only the display consistency, but also the actual color representation must be as correct as possible. This is the so-called '*absolute calibration*'. One example is a *broadcast reference monitor* used in quality checks and as a general picture reference in a broadcast studio. Further on, the display walls used in *studio backdrop* applications should not only be uniform ('relative calibration'), but also must be calibrated to an absolute target matching the studio lights. In an adjacent industry, a *post-production* studio must be sure that the creative color grading done on the display must look the same as when printed on film (without actually doing this, which saves them costs).

In the *medical imaging* world, the displays used in life-critical applications must show a correct grey scale and color – in order to convey the proper x-ray, scan or other medical information. Wrong picture interpretation can be catastrophic for the patient.

Whatever the use case for display (wall) uniformity and accuracy, it is highly desirable that these color parameters are stable with time. A display that is not stable must be recalibrated at regular intervals, or in the strictest cases before every use. This of course adds to the cost of maintenance, and is intrusive which in some cases (24/7 usage) is not allowed at all.

It becomes obvious that in these applications careful and correct color measurement is a necessity – and professionals in these areas are pretty much aware of this.



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2 A new factor in the equation – LED illumination

The professional display world has functioned well so far with the existing display technologies and color measurement equipment. What has changed so we have to open this topic again?

The answer is – LED ('Light Emitting Diode'). It is an inorganic, solid-state light source. The LCD displays use more and more LED backlights instead of CCFL lamps (LED-based TV sets are even outselling the traditional CCFL ones, even at a high premium¹). The first DLP projectors using LED illumination have also hit the market in 2009, and hopes are high that the 'green', environmental-friendly LED will replace the UHP mercury lamps soon. It is important thus to look back at the basics and see what challenges this new LED technology brings in terms of color calibration of displays.

2.1 Brightness and lifetime

It is widely known that LEDs have a larger lifetime than UHP counterparts in projection. The light output of the lamps is taken as the main parameter when lifetime is considered^{2,3}. Where an UHP lamp could live 10,000 hours on average and actually could burst at any time, LED backlights and CCFL lamps:

- a) Have a rated lifetime of 40-50,000 hours (to half brightness).
- b) Don't usually fail in a 'catastrophic' manner – they will live even after the rated lifetime, although they might not be usable because the brightness might be too low.

2.2 Color performance with aging

It is less widely known that the *color performance* of LED illumination is actually *more susceptible* to temperature changes, driving current and aging than traditional displays. While the CCFL and UHP illumination, as well as the CRT phosphors mainly *decrease in brightness* and change *chromaticity* only slightly (UHP, CCFL) or not at all (CRT), with LED the colors *both* decrease in brightness *and* considerably change the chromaticity⁴.

To shed some more light on this, we will take a look at the light spectra of different display light sources (Fig. 1). A spectrum is a function of light intensity from the wavelength. A comparison of the lamp and LED technology is given in two graphs, for LCD (comparing CCFL with LED) and DLP (comparing UHP with LED). The lamp spectra are given in blue thick lines, the LED spectra in dashed magenta lines. The intensity is in arbitrary units.

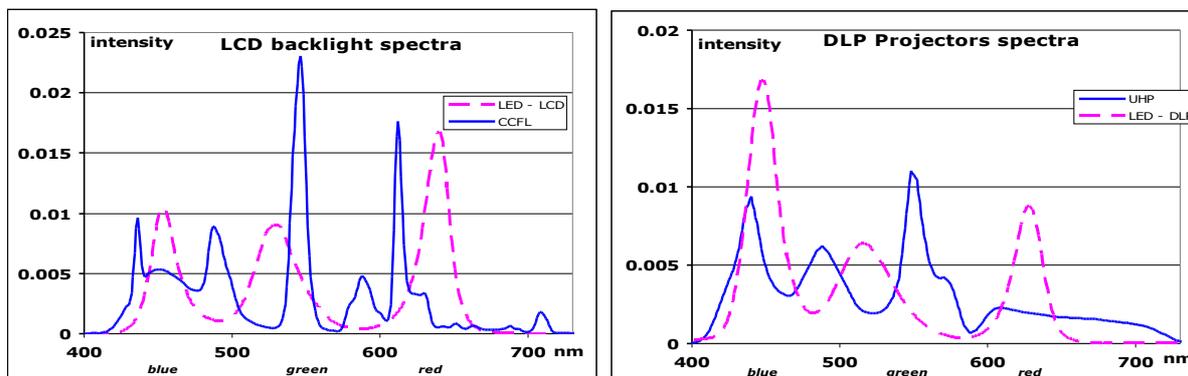


Fig 1. Left: Comparison of CCFL and LED spectra for an LCD.

Fig 1. Right: Comparison of UHP and LED spectra for an DLP projector.

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CRT:

The CRT contains red, green and blue phosphors that emit light when a guided electron beam hits them. These phosphors do not change color with time, but do decrease in brightness along usage, which results in both a darker display. Because different phosphors can decrease brightness with a different pace, the white balance will also be offset with time. So the main challenge in CRTs was to maintain the color temperature (white balance).

Lamp (CCFL or UHP):

With aging or increasing temperature, the different lamp spectral peaks decrease in intensity. Their peak wavelength and peak width also shift, however the brightness decrease of the primaries is predominant so for practical purposes we can neglect the chromaticity change.

LED:

The LED spectrum has a different behavior than both phosphors and lamps. With aging and/or higher temperature, the LED spectral peaks: a) lower; b) widen; and c) shift to different wavelengths, all at the same time. The lowering is connected to decreasing brightness. But the shift and widening means that the color also changes in chromaticity. Moreover, the only way to control brightness of an LED is with changing the current through it. But a different current means a different local temperature, so this again changes the spectrum. The end result of LED aging is thus: lower brightness, offset white balance, and changed chromaticity of primary colors and all other colors in between.

The next figure proves that the peak wavelength shifts with LED (junction) temperature⁴. We see that for every 10 °C, the peak wavelength shifts by about 2 nm. This shift looks minor, but in fact it can contribute to a very visible shift in the perceived color.

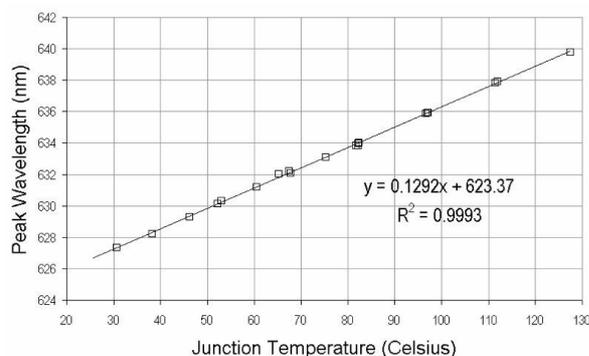


Fig 2. The LED peak wavelength shifts with temperature

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2.3 Example

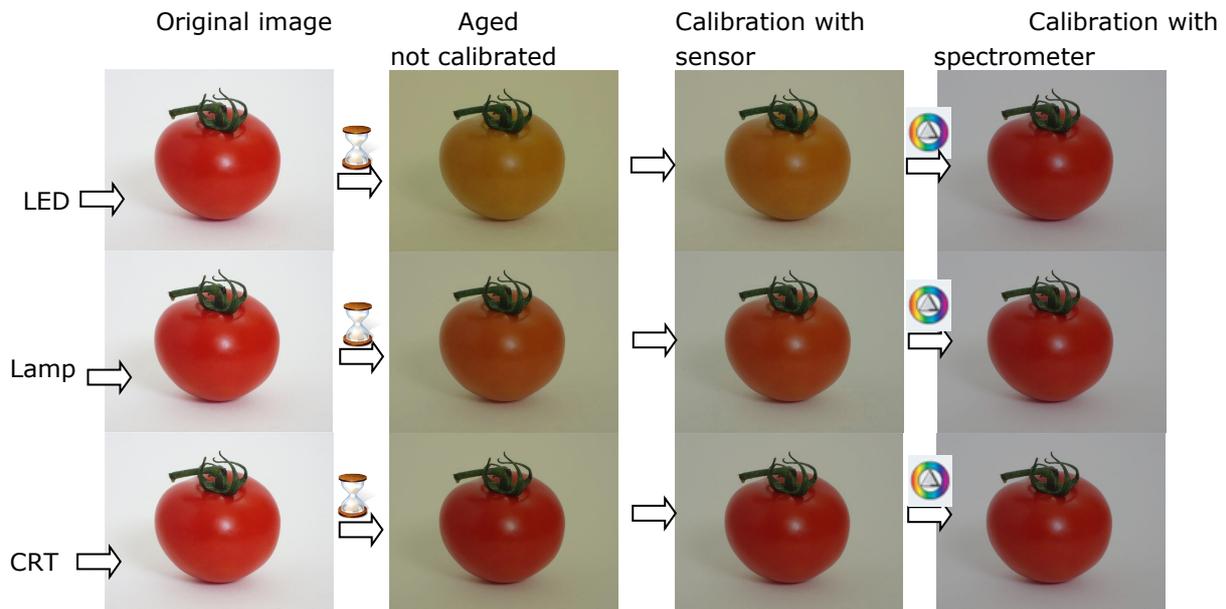


Fig 3. Effect of aging on LED, Lamp or CRT before (middle) and after (right) white point calibration.

Left – original image

The original image (on the left), would be seen on a new and freshly calibrated display.

Middle – aged display, no white balance compensation

In all displays, the brightness goes down with aging. What is different, is the amount of color change. In an LED-based display, the primary colors change (the tomato actually looks less ripe in spite of the aging...). Also the white balance becomes more yellowish because the blue LED has a fastest brightness decrease.

For a lamp-based display both the white point and the chromaticity shift, but less than in LEDs, resulting in a red color that is more like the original one.

For a CRT (third row), the white balance can change and the brightness goes down, but the chromaticity doesn't change.

Right – aged display, with white balance compensation

In order to correct the white balance shift, most professional displays use a monochrome sensor that measures the brightness of the primary colors, and it doesn't measure color at all. The white point is then calculated based on the assumed primary chromaticities. Only a few displays actually use a color sensor. As it will become clear in the next chapter, these color sensors are at best good enough for measuring the brightness of the primary colors and of brightness and chromaticity of white. Using the color sensor, the neutral white balance can be restored, but the actual shift in colors is more difficult to be measured. The pictures on the right show what happens if such a correction is done. The white background becomes neutral white (although dimmer). However the colors are still wrong in the case of a lamp-based display, and even more so in the LED-based display.

There is nothing we can do about the decreasing brightness of a lamp, LED or CRT phosphors. But surely we would at least like to keep the white balance *and* the colors the same. Is this possible? The answer is yes. We just need the correct measuring equipment.

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3 Color measurement

The idea behind *meaningful* color measurement is to represent color in terms that humans understand. Light by its physical nature is made up of electromagnetic waves with different wavelengths and intensities. So the ultimate light measurement is in terms of a spectrum. However such a spectrum doesn't tell us if a color is brown, yellow, purple, white, blue, turquoise, green etc.

So we need a simpler way to represent color. Therefore we examine the human visual system. The human eye has 3 different types of receptors that are responsible for (roughly) the blue, green and red light region. Each receptor detects the total intensity of the light within its region, so in approximation each receptor acts as a color filter, and we get an impression of the color by mixing three different lights. The responses of these 'filters' for an average human observer have been measured and standardized. They are called Color Matching Functions (CMFs) (Fig. 4) and have been standardized by the CIE committee already in 1931⁵.

Based on the above discussion, there are three ways to measure color.

The ultimate way is to use a spectrometer. Measure the spectrum, apply the standardized CMFs, and obtain a color measurement in terms of three meaningful parameters. This is the most accurate measurement.

Another (and cheaper) way is to make a device that uses filters with exactly the same characteristic as the CMFs, measure the luminance of each filtered portion, and obtain a set of 3 parameters. This is the principle of tristimulus color sensors.

The last way, having the highest degree of abstraction and approximation, is to measure the integral brightness of the primary colors. This method doesn't produce any color data, but knowing the spectrum in advance, and assuming it doesn't change a lot, could yield an approximation of the chromaticity as well. Let's go into more detail of each of the three measurement methods.

3.1 Monochrome sensor

The simplest method in measuring display devices is to measure the brightness of the primary colors using a monochrome light sensor. For example for a DLP projector using a lamp and a color wheel, such sensor would in turn measure the brightness of the R, G and B light transmitted through the color wheel. In case of a LED engine the monochrome sensor (or 3 sensors, depending on the construction) would measure the intensity of the R, G and B LED light. The assumption made here is that the color filter characteristics as well as the light spectrum of the source are known in advance and do not change. But if the spectrum doesn't change, we don't need to measure it and correct it real time, do we? As shown above, the spectrum actually changes with time and temperature quite significantly. Since the monochrome sensor measures the total intensity of the light with disregard to the shape and shift of the spectrum, such a sensor can barely correct the color temperature of white, let alone the chromaticity of the primaries. In conclusion, a monochrome sensor cannot be used to guarantee a visually uniform display wall as well as a high-accuracy direct-view display.

3.2 Tristimulus sensor

The basic assumption of a tristimulus sensor is that its color filters have exactly the same characteristics as the CMFs. However this is impossible with the state-of-the-art of the color filter technology today. At best the color sensor filters follow the *trend* of the CMFs, but they still *deviate* substantially (Fig.4 shows the response of a typical tristimulus sensor compared with the CMFs).

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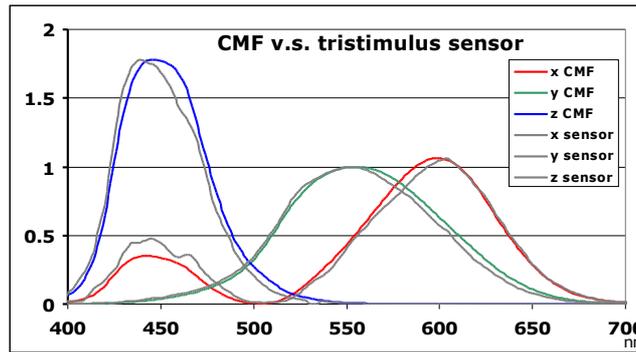


Fig.4 Deviation of a tristimulus sensor from the color matching functions

This deviation directly means that we must be careful with interpreting the measurement results from such a sensor, as they have a considerable error compared to a spectrometer. Furthermore, because this deviation is not the same for all wavelengths, the measurement result and error will depend on the *type of the light spectrum*: the position of the peak wavelength, the width of the peaks, and even on the *changes* in the spectrum of the same light source.

Now, it is possible to *minimize* this error by calibrating a color sensor upfront to a given display device (spectrum). This is done by color sensor manufactures. The difference between the readings of a spectrometer and a color sensor is stored in the color sensor, and is used as a correction factor in subsequent color sensor measurements. This approach will never deliver exact results, but in practice it can give acceptable results as long as the display spectrum is not much different from the spectrum that has been used to calibrate the sensor. It is only applicable to small changes in the spectrum shape.

Tristimulus sensor and CRTs:

The CRT makes light using emitting phosphors with a fixed chromaticity. What changes is the intensity (brightness) of the phosphors. A tristimulus sensor that has been calibrated upfront for use with CRTs needs just to detect the change in brightness of the phosphors. Then it is easy to calculate the gain corrections for the three (r, g, b) electron guns, and to obtain a correct white balance. So for CRT displays, a tristimulus sensor does the calibration job quite well.

Tristimulus sensor and lamp-based displays:

In case of a lamp illumination, the spectrum has a lot of peaks, but they do not shift much. The peaks mostly tend to drop in brightness. A tristimulus sensor can detect a drop in brightness of each primary, and so making the white point stable is not such a problem. The absolute measurement might be prone to an error, but relatively (between different displays, or compared to a previous measurement), the white point will be quite consistent. So for lamp-based displays, regarding the costs and benefits, the tristimulus color sensor does an acceptable job.

Tristimulus sensor and LED-based displays:

The spectrum of the solid state LEDs does all the funny things with aging: the peaks widen, lower and shift, causing both brightness and chromaticity changes. Different LEDs will still age differently. In order to stabilize brightness, the current must be changed, again influencing the

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spectrum. Absolute LED color measurement with a tristimulus sensor is thus impossible, but even relative display wall calibration is a challenge because the cubes all have different spectra.

3.3 Spectrometer

So the tristimulus sensor is good for some displays (CRT), good enough for other (lamps), and not good at all for LEDs. Another option is to use a *spectrometer*. It analyzes the incoming light: it uses a prism or diffraction grating to make a 'rainbow' – split the light into wavelengths. This light then shines on a CCD or CMOS array containing of many sensors. Each sensor reads out the intensity of a narrow wavelength interval, and thus an accurate measurement of the spectral distribution is obtained. From this spectrum, using colorimetric calculations with theoretical values, a set of three RGB or XYZ values is obtained with the highest accuracy possible. As the incoming light is not pre-filtered like in a color sensor, any change of the light spectrum will be correctly measured. So even if the LED spectrum changes intensity, shifts in wavelength, widens the peaks, or at different LED batches (old and new), the spectrometer will catch any minute difference and will give accurate measurements at all times.

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3.4 Examples

DLP display wall with LED illumination calibrated with a tristimulus sensor

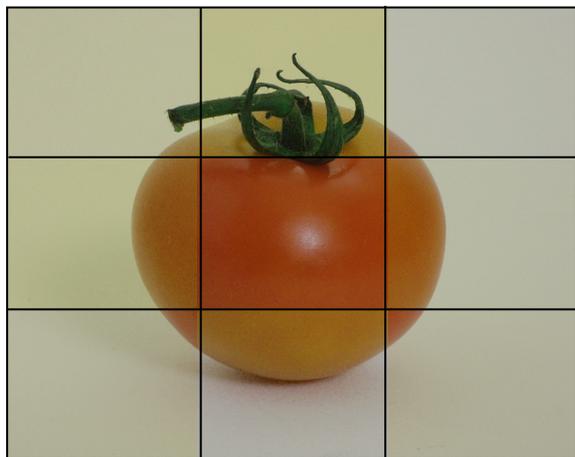


Fig.5 What color does a tomato have? A possible result of an aged 3x3 display wall with LED illumination if it is not calibrated by a spectrometer

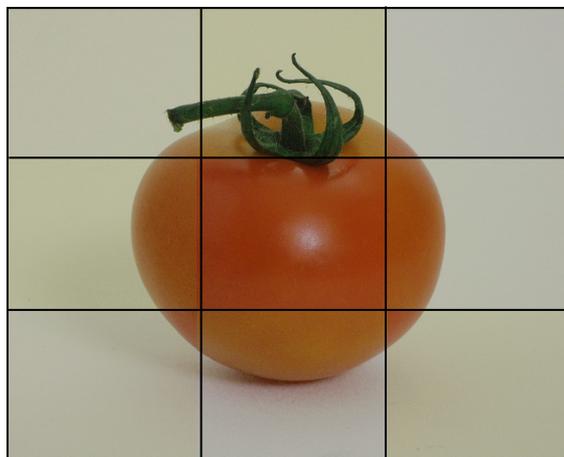


Fig.6 Even when providing some sort of white balance, a tristimulus sensor cannot catch the fine chromaticity changes. The display wall will still not be uniform if it is not calibrated by a spectrometer.

DLP Display wall with LED illumination calibrated with a spectrometer

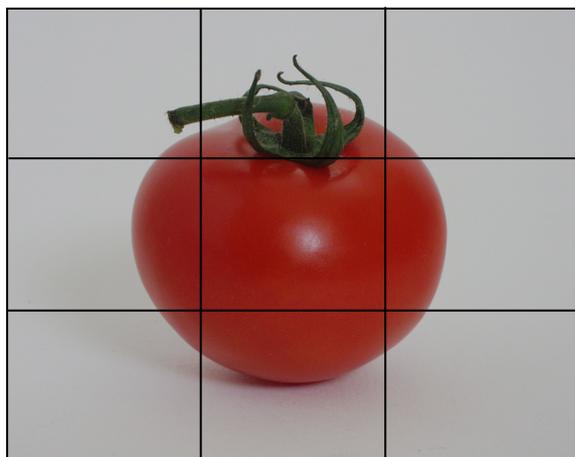


Fig.7 Even though the brightness of the display wall decreases with time, (internal) spectrometer calibration ensures that colors remain true and uniform across the wall.

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4 Conclusion

The advance of the solid state LEDs as light source for displays is now a fact. However LED behaves quite differently from the 'traditional' UHP or CCFL light sources. A detailed understanding of this behavior shows that LEDs are more instable with time, temperature and driving current, so extra precaution in calibration and measurement is needed. While for CCFL and UHP a simple tristimulus color sensor could yield satisfactory results, to accurately measure and calibrate LEDs a real spectrometer is necessary. Barco has understood this challenge, and so far is the only manufacturer in the world utilizing a spectrometer in its product lines based on LED illumination.

One example is the RHDM – a line of grade-1, reference displays for broadcast and post-production. Another example is the OL – our latest line of DLP rear-projection, seamless video wall cubes. Both products contain an embedded spectrometer that tracks the LED spectrum real-time, and takes care of continuous autocalibration both in relative sense (display wall cubes between each other) and in absolute sense (accurate colors by a broadcast standard). The final result is a stable product that requires little or no maintenance at all.

5 References

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⁵ http://en.wikipedia.org/wiki/CIE_1931_color_space