FOUR-COLOR MATRIX METHOD

By Edward F. Kelley, Ph.D., KELTEK, LLC.

Many of us use colorimeters to attempt to make measurements of the colors presented on electronic displays. These colorimeters often consist of three or four filtered photodiodes that in proper combination provide chromaticity values (x, y) and the luminance L for the CIE 1931 color space.[i] The resulting color measurement of CIE 1931 chromaticity coordinates and luminance provides a basis for calculating the color as expressed in the other CIE color spaces, such as (u', v'), L; CIELAB (a^*,b^*, L^*); and CIELUV (u^*, v^*, L^*). The intention of these colorimeters is that the filtered photodiodes provide the spectral responsivities of the color-matching functions $\bar{x}$, $\bar{y}$, $\bar{z}$ for the 1931 CIE color space.

Often colorimeters are calibrated using a spectrally broadband CIE Illuminant A source of light having a correlated color temperature (CCT) of 2856 K. This incandescent tungsten-halogen spectrum covers the visible spectrum with much more red than blue and violet. Depending upon the quality of the filter-photodiode combinations, colorimeters can perform well with broadband colors such as paints under broadband illumination such as sunlight.

However, because of the difficulty in exactly creating the required colored filters, deviations from the desired color-matching-function responsivities can occur that will result in large errors in color and luminance measurements whenever the spectra of the colors are no longer broadband. This happens with many display technologies, such as light-emitting diodes (LEDs), mercury spectra (as used in some projectors), cathode-ray tubes (CRTs), and cold-cathode-fluorescent (CCFL) backlit liquid crystal displays (LCDs). With different display technologies exhibiting very different spectra, it can be difficult to compare colors and luminances with accuracy, and chromaticity-coordinate uncertainties of 0.01 and luminance uncertainties of 10 % readily occur. We would prefer uncertainties that are a factor of ten smaller.

Fortunately there exists a method to correct the measurement results from a colorimeter to provide accurate chromaticity coordinates and luminances for each different spectrum from each different display technology. It is known as the four-color matrix method (FCMM).[ii,iii] A calibrated reference spectroradiometer measures the red (R), green (G), blue (B), and white (W) colors of a certain display technology and provides the chromaticity coordinates and luminances for each color: (x_R, y_R), L_R; (x_G, y_G), L_G; (x_B, y_B), L_B; (x_W, y_W), L_W. The colorimeter also measures the same display obtaining its set of resulting colors: (x'_R, y'_R), L'_R; (x'_G, y'_G), L'_G; (x'_B, y'_B), L'_B; (x'_W, y'_W), L'_W. From these measurements, a matrix is developed that will transform the colorimeter results as close as possible into the results obtained by the spectroradiometer. That same matrix can then be used to transform any other color measured by the colorimeter on that same display into accurate chromaticity coordinates and luminance values. This method is so successful that the National Institute of Standards and Technology (NIST) has developed a calibration facility based upon the FCMM.[iv] Yes, it is *that* accurate!

To use a colorimeter for display measurements, a new matrix must be determined for each spectrum type encountered using the FCMM. A matrix developed for one type of display will not necessarily work on another display of a different technology because the spectra are different. For example, we would not expect that a matrix developed for a LCD would be appropriate for a LED display. Because the filter-photodiode combinations for each colorimeter may be a little different than another of the same brand and model, a set of matrices needs to be developed for each colorimeter and for each display technology. Similarly, because of possible variations in the spectra within any single display technology, we could be tempted to develop a matrix for each display within a single technology. However, provided the variations are relatively small, such a splintering of the process is usually not necessary. Whether a new matrix is needed depends upon how the spectra of the RGB colors change from display to display and technology to technology.

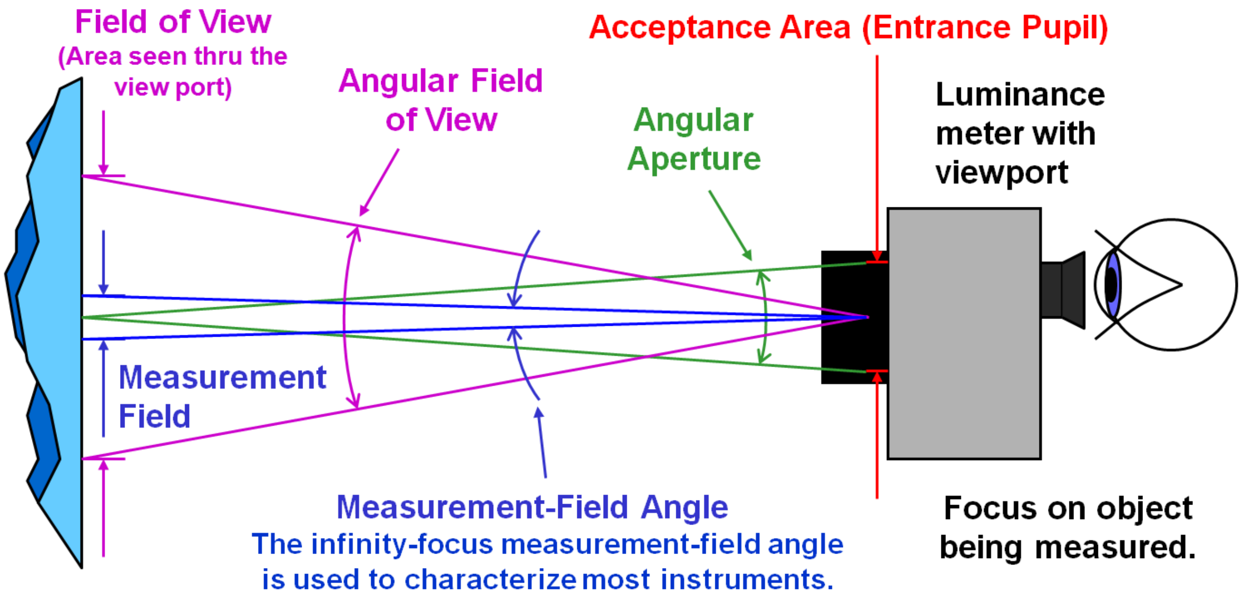
A factor that can possibly be a problem is cross talk. When measuring the different RGB colors, we would want to be sure that the colors are as pure as possible and represent the intended colors. If a video board is defective, if the cable is of poor quality, or if the display is somehow defective so that a little of one of the other colors is slightly mixed into the color being measured because of cross talk or other problems, then the color we think we are measuring is being corrupted by contributions from other subpixels. An inspection of each RGB color with a powerful magnifying glass should reveal any such problems as cross talk. It is not a likely problem, but it is a good idea to be aware of the possibility so that we don't blame an entire display technology for the problems with a single display, our video generator, or bad cabling.

Another problem is warmup. How long should the display be turned on before the colors are measured? This will depend upon the display technology, and it is wise to make such an assessment for each technology to be measured. Often people use a 15 min or 20 min warmup time, but that is usually *not* adequate for the accuracies we are trying to obtain with the FCMM. Warmup times of an hour or even two hours may be required before a display reaches a stability that will guarantee that the colors and luminances don't change relative to one another during the time while the set of measurement results are obtained. Also, in case the display has a "memory" it might be wise to give it a little time before measuring a new color—these are things that can be determined by experimentation.

Because of the inherent accuracy of this FCMM, alignment of the colorimeter and spectroradiometer with the normal of the display surface can be critical. This is particularly important for displays that have significant viewing-angle changes of their properties. Depending upon the technology, it can be beneficial to assure alignment of the measurement system to a small fraction of a degree. Related to this viewing-angle sensitivity is the subtense of the detector. If the angular aperture is too large or if the measurement field is too large, then it may be collecting light from too wide an area whereby viewing-angle deviations can influence the measurement. Similarly, for screens that are influenced by mechanical pressure such as many LCDs, contact colorimeters that place too much force on the surface can influence the measurement. If such contact devices are used, it can be important to assure that they are touching the screen lightly enough to avoid any changes in the measurement results from mechanical contact. Additionally, any stray light entering the colorimeter from the surround must be eliminated.

Once all these factors are considered, the four-color matrix method for correcting colorimeters can provide us with very impressive results.

Nomenclature Summary of View-Port Photometer



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http://keltekresearch.com/index.html

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[i] (Commission Internationale de l'Eclairage [International Commission on Illumination]). An excellent short review of the CIE color-space developments is available: Y. Ohno, "CIE Fundamentals for Color Measurements," Proc. IS&T NIP16 International Conference on Digital Printing Technologies, Oct. 15-20, 2000, Vancouver, Canada (2000), pp. 540-545 (http://physics.nist.gov/Divisions/Div844/facilities/photo/Publications/OhnoNIP16-2000.pdf).

[ii] Y. Ohno and J. Hardis, "Four-Color Matrix Method for Correction of Tristimulus Colorimeters," Proc. IS&T Fifth Color Imaging Conference, 301-305 (1997) (http://physics.nist.gov/Divisions/Div844/facilities/photo/Publications/IST97.pdf).

[iii] Y. Ohno and S. Brown, "Four-Color Matrix Method for Correction of Tristimulus Colorimeters - Part 2," Proc. IS&T Sixth Color Imaging Conference, 65-68 (1998) (http://physics.nist.gov/Divisions/Div844/facilities/photo/Publications/IST98_2.pdf).

[iv] S. Brown and Y. Ohno, "NIST Calibration Facility for Display Colorimeters," Proc. IS&T/SPIE 11th International Symposium, Electronic Imaging '99, San Jose (1999) (http://physics.nist.gov/Divisions/Div844/facilities/photo/Publications/SPIE_Imaging_99.pdf).