Four-Color Matrix Method for Correction of Tristimulus Colorimeters – Part 2

Yoshi Ohno and Steven W. Brown
National Institute of Standards and Technology
Gaithersburg, Maryland

Abstract

The Four-Color Method was developed to improve the accuracy of tristimulus colorimeters for measurements of color displays. It was verified that the method works well for cathode ray tubes (CRTs). The accuracy of this method has been studied further for spectral variations of displays including CRTs, liquid crystal displays (LCDs) and organic light emitting diode (OLED) displays. A theory for additional photometric (Y) correction is also given. A simulation was conducted using data of actual tristimulus colorimeters and displays having variations in their spectral power distributions. The results show that, if the correction matrix is made with one type of display and other types of display are measured, the error correction will not be effective. If the calibration and measurement is limited to one type of display, the residual errors are found to be within 0.002 in chromaticity x, y and a color difference of 2 ΔE_{ab}. An experiment was also conducted to verify the Four-Color Method for measurements of an LCD. The errors of a colorimeter for 14 colors were reduced to within 0.002 in x, y and 1 ΔE_{ab}. It has been experimentally verified that the method works well for LCDs as well.

Introduction

Tristimulus colorimeters are commonly used to measure the chromaticity of color displays such as cathode ray tubes (CRTs) and flat panel displays (FPDs). However, due to the imperfect match of their spectral responsivities to the color matching functions, measurement errors are inevitable when the spectral power distribution of a test source is dissimilar to that of the calibration source. Tristimulus colorimeters and luminance meters are normally calibrated with CIE Illuminant A (2856 K Planckian source) which has a very different spectral power distribution from that of displays.

Matrix techniques are known to improve the accuracy of tristimulus colorimeters for color display measurements [1,2], but these methods may not work as well as expected due to measurement noise and errors. These conventional methods utilize tristimulus values, and the noise in the luminance measurement (e.g., due to display flicker and instability) affects the accuracy of the corrected chromaticity.

To improve the accuracy of the matrix technique, the Four-Color Method was developed [3]. This method is based on the (x, y) values only, and is independent of Y values, thus, in principle, eliminating errors due to luminance measurement noise. The results reported in the previous study showed much improved accuracy of the Four-Color Method over the other conventional methods. However, the results were obtained with only one CRT display, and it was not clear how this method would work if different types of displays (having different spectra) were measured. Also, the correction technique for luminance (Y) was not yet developed. In this paper, first, the theory for additional Y correction is given. Then, the accuracy of the Four-Color Method is studied further by simulation using data of several different CRTs, liquid crystal displays (LCDs), and an organic light emitting diode (OLED) display, that have significantly different spectral power distributions. Finally, an experiment was conducted, using actual colorimeters and a spectroradiometer, to test the performance of the method for 14 colors of an active matrix type LCD.

Theories – Additional *Y* Correction

The detailed theory of this method for chromaticity correction is given in the previous study [3]. In summary, a target instrument (tristimulus colorimeter) is calibrated against a reference instrument using four colors (red, green, blue, and white) of a display, and a 3 x 3 correction matrix $\boldsymbol{R}$ is obtained. In this process, only x, y chromaticity coordinates are used so that the calibration is not affected by measurement noise and errors of Y values. When the tristimulus colorimeter measures any colors of the display, corrected results are obtained by multiplying the measured tristimulus values by the $\boldsymbol{R}$-matrix.

The theory described in the previous paper did not include correction of Y values. Since the Four-Color Method utilizes chromaticity values only, the obtained $\boldsymbol{R}$-matrix has an arbitrary scale of Y and thus could not be used for Y measurement. However, by using the readings of the luminance values of the reference instrument and the target instrument for white of the display, the $\boldsymbol{R}$-matrix can be scaled for Y correction. This process is applied after the **R**-matrix is obtained as described in the previous paper [3]. The Y calibration factor k_Y is obtained as the ratio of the reference luminance value to the matrix-corrected Y value, as given by

$$k_Y = \frac{L_w}{\boldsymbol{R}_Y \ \boldsymbol{M}_w}, \tag{1}$$

where L_w is the reference luminance value of the white of a display, $\boldsymbol{R}_Y$ is the middle row of the **R**-matrix, and $\boldsymbol{M}_w$ is the tristimulus values (X, Y, Z) of white measured by the target colorimeter. The factor k_Y can also be determined by measurements of four colors (white, red, green, blue) and obtained as an average of the results with the four colors. If the instrument does not display tristimulus values, $\boldsymbol{M}_w$ is obtained from x, y, Y values by the following equation:

$$\boldsymbol{M}_w = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = Y \begin{bmatrix} x/y \\ 1 \\ (1-x-y)/y \end{bmatrix}. \tag{2}$$

The **R**-matrix is then scaled for correct luminance values Y by

$$\boldsymbol{R}' = k_Y \ \boldsymbol{R}. \tag{3}$$

By using this $\boldsymbol{R}'$-matrix, the original tristimulus values **M,** measured by the target instrument for any colors of the display, can be corrected to $\boldsymbol{M}'$ as

$$\boldsymbol{M}' = \boldsymbol{R}' \ \boldsymbol{M}. \tag{4}$$

The corrected luminance Y as well as corrected chromaticity coordinate (x, y) are computed from $\boldsymbol{M}'$.

Simulation

First, simulations were conducted to evaluate the performance of the Four-Color Method for three different types of displays: a CRT, an LCD, and an OLED display. The data of the CRT and LCD were obtained by measurement of the computer displays in our possession. The data of the OLED was obtained from the manufacturer. The spectral power distributions of the CRT and the other displays are significantly different from each other as shown in Fig. 1. The spectral responsivity data of two real tristimulus colorimeters were used as models in the simulation. Fig. 2 shows the data of Colorimeter 1; Colorimeter 2 has a similar degree of spectral match to the CIE $\bar{x}$, $\bar{y}$, $\bar{z}$ color-matching functions. The spectral mismatch evaluation term f_1' [4] ranges from 2 % to 7 % for all the channels, which are typical figures for high-grade commercial tristimulus colorimeters.

The model colorimeters (Colorimeters 1 and 2) were first calibrated against CIE Illuminant A to scale the signal from each channel. Then the $\boldsymbol{R}'$-matrix was obtained by simulating measurements of the four colors of a CRT. The intensity scales of red, green, and blue of the display were adjusted so that a mixture of these primary colors, each at 100 % intensity, created a white color of 9300 K color temperature. Then, 16 different colors were created by different intensity combinations of digital values (255, 100, 50, and 0). The values of x, y, and Y of each color as measured by the colorimeters, both before and after the $\boldsymbol{R}'$-matrix correction, as well as their true values, were calculated. Colorimeters 1 and 2 showed similar results; the results using Colorimeter 1 are described below. Figs. 3 and 4 show the results of the simulation when the colorimeter is calibrated (the matrix obtained) with a CRT and measures the three different types of displays including the CRT itself. Each bar in Fig. 3 represents the

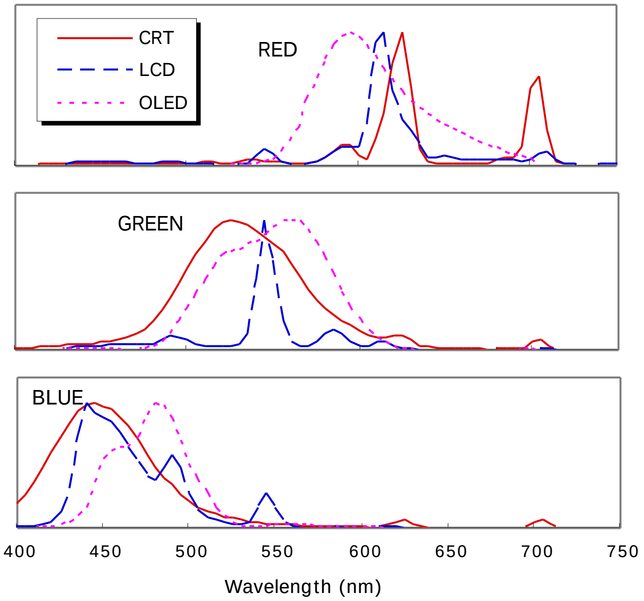

Figure 1. Spectra of the CRT, the LCD and the OLED used in the simulation

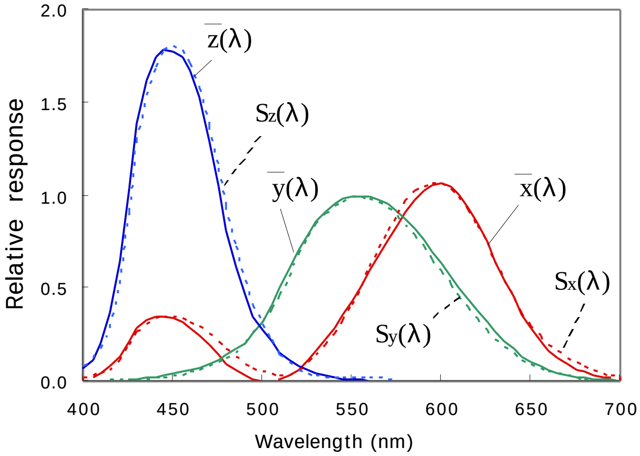

Figure 2. Spectral responsivities of Colorimeter 1.

root-mean-square (RMS) error or the maximum error in chromaticity x, y of the measured 16 colors in each condition. The results in Δx, Δy are then converted to ΔE_{ab} in Fig. 4. The CRT results (equal to zero after correction) are included to verify the computation. The LCD data show some improvement, but the correction is not sufficient if compared with the residual errors (RMS Δx, Δy of approximately 0.001) for a CRT measurement reported in the previous study. The data from the OLED show almost no improvements using the Four-Color matrix correction. The reduction of errors in Y showed a similar trend. These results indicate that the correction matrices should be obtained separately for different types of display.

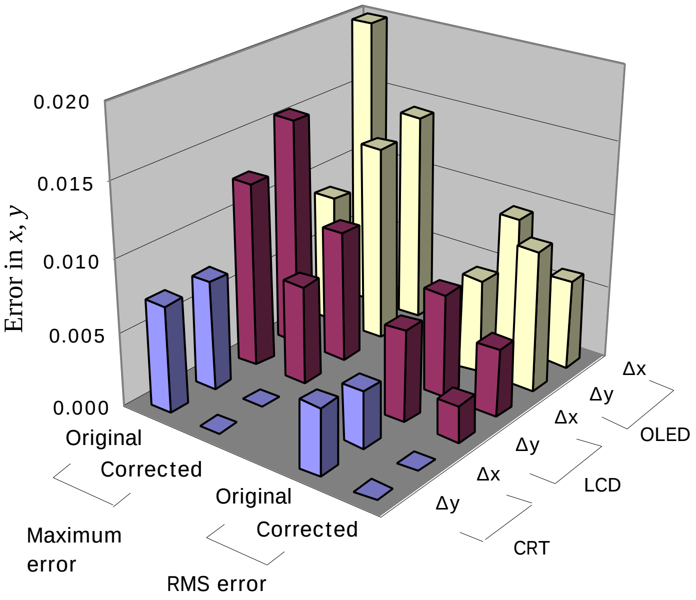

Figure 3. RMS and maximum errors in Δx, Δy of Colorimeter 1 with the matrix obtained for CRT and measuring CRT, LCD, and OLED.

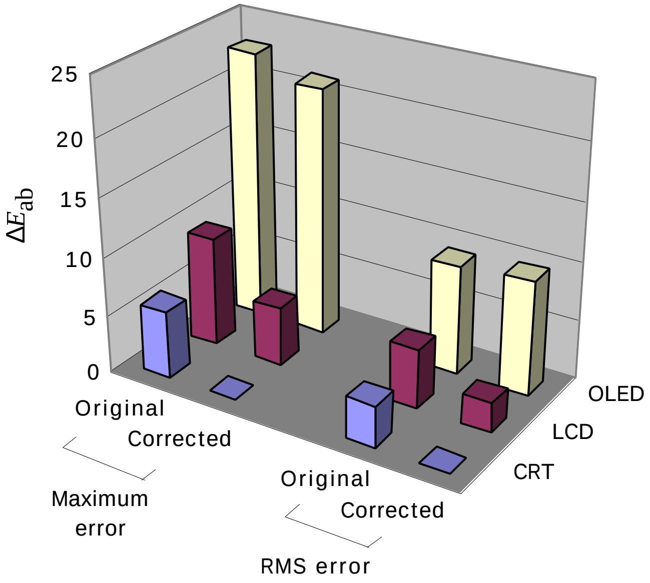

Figure 4. RMS and maximum errors in ΔE_{ab} of Colorimeter 1 with the matrix obtained for a CRT and measuring CRT, LCD, and OLED displays.

Even though the calibration and measurement are limited to one type of display, there are variations of spectra within each display type, depending on the selection of phosphors, back-lights, and color filters. Another simulation was therefore conducted to evaluate the accuracy of the Four-Color Method for such variations of spectra within one type of display. For the simulations, the spectral power distribution data of three CRTs and three LCDs from different manufacturers were chosen that show the largest differences with each other. The same colorimeter models were used in the simulation. The results for LCDs are shown in Fig. 5. The residual errors for all the 16 colors were found to be within 0.0013 in x, y, or within 1.7 ΔE_{ab}, which is satisfactory for practical use in most cases. The results for the CRTs were similar, with residual maximum errors of 0.0019 in x, y or 0.9 ΔE_{ab}. The results indicate that one matrix works with sufficient accuracies for small variations of spectra within one type of display.

Experiment

An experiment was also conducted to verify that the Four-Color Method actually works well for LCDs. It has been observed that LCD colors change with saturation levels, even when primary colors are displayed. If the spectra of the primary colors change with the saturation level, it could cause a problem for the Four-Color Method because this method assumes that the spectra of primary colors do not change. A few LCD panels were measured with a spectroradiometer for primary colors under different saturation levels. The data showed that the change of colors was caused by leakage (crosstalk) of other primary colors, and the spectral components of the real primary colors do not change.

To verify the overall accuracy of measurement for LCDs using the Four-Color Method, a measurement was conducted using an active matrix type LCD panel of 25 cm (10-inch) diagonal size. One commercial tristimulus colorimeter (Instrument A) and one diode-array type spectroradiometer (Instrument B) were used as target instruments, and another diode-array type spectro-radiometer (Instrument C) was used as a reference instrument. By measuring the four colors, the $\boldsymbol{R}'$-matrices were obtained for Instruments A and B against Instrument C. Then, additional 10 colors were measured with all the instruments. The luminance level ranged from 1.1 cd/m^2 to 63 cd/m^2 (full white). The measurements were carefully done in a dark room, with all the instruments fixed at distances of 2 m to 3 m from the display surface and within ± 4° from the perpendicular. The readings of the three instruments were taken almost simultaneously. The full screen of the display was set to each color. The data measured by Instruments A and B were then corrected by the $\boldsymbol{R}'$-matrix.

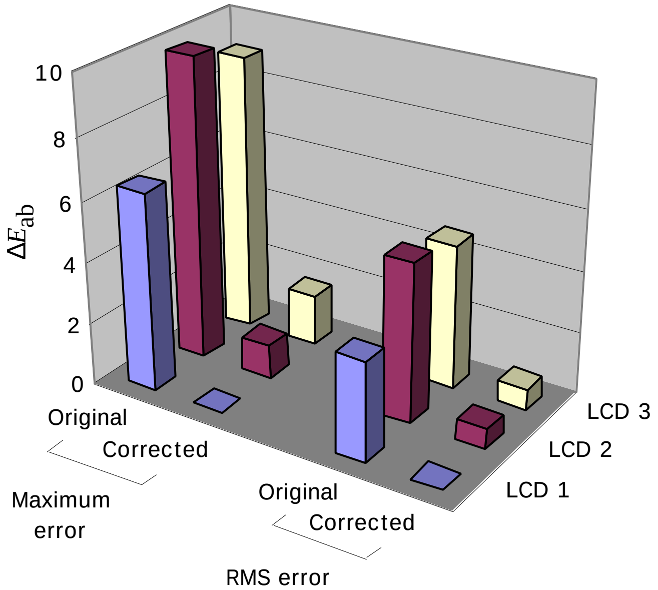

Figure 5. RMS and maximum errors in ΔE_{ab} of Colorimeter 1 with the matrix obtained for LCD 1 and measuring LCD 2 and LCD 3.

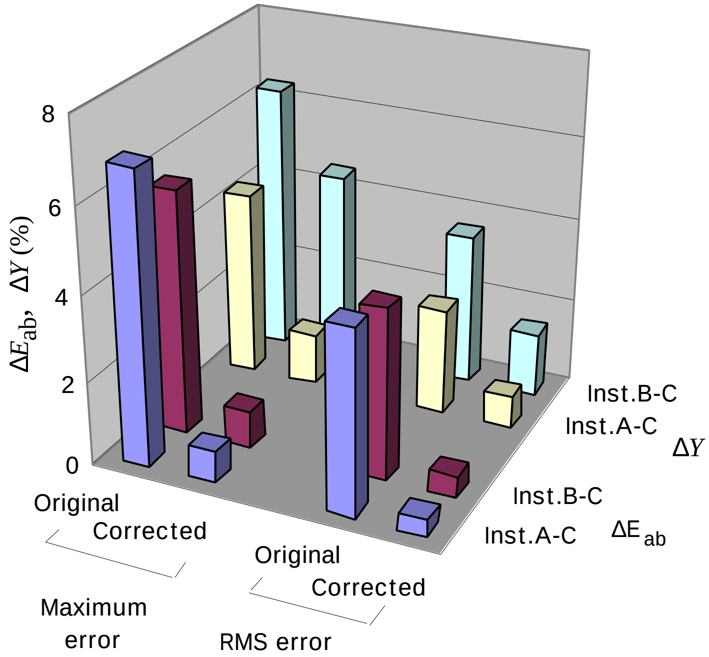

Figure 6. Results of the measurement of 14 colors of an LCD panel using instruments A, B, and C, and applying the Four-Color Method.

Fig. 6 shows the results of chromaticity differences (between the target and reference instruments) in ΔE_{ab} and luminance differences ΔY, respectively. The bars show the RMS or maximum differences for the 14 colors, before and after the matrix correction. The chromaticity errors of the target instruments (relative to the reference instrument) are reduced to within 1 ΔE_{ab} for all the colors. The RMS (maximum) differences in Δx, Δy are reduced from 0.0051, 0.0061 (0.0082, 0.0112) to 0.0004, 0.0006 (0.0008, 0.0014) for Instrument B, relative to Instrument C. The expanded uncertainty (k=2) of this comparison is estimated to be 0.001 in x, y from the repeatability of the instruments and the variation of color of the display within ± 4°. The results indicate that the Four-Color Method works well for LCDs as well as CRTs.

Conclusion

The performance of the Four-Color Method has been studied further for spectral variations of displays including CRTs, LCDs, and OLED displays. A theory for additional photometric (Y) correction is added. The simulations showed that a correction matrix should be obtained for each display type, but one matrix is effective for small variations of spectra within each type. It has also been experimentally verified that the Four-Color method works well for LCDs.

We thank Joe Velasquez and John Grangaard of the CCG, U. S. Air Force for supporting this project, Patrick Green of Planar Systems for providing the OLED data, and Ed Kelley of NIST for providing the LCD data for us.

References

1. ASTM E 1455-92, Standard Practice for Obtaining Colorimetric Data from a Visual Display Unit Using Tristimulus Colorimeters (1992).
2. ASTM E 1455-96, Standard Practice for Obtaining Colorimetric Data from a Visual Display Unit Using Tristimulus Colorimeters (1996).
3. Y. Ohno and J. Hardis, “Four-Color Matrix Method for Correction of Tristimulus Colorimeters, Proc., IS&T/SID Fifth Color Imaging Conference, 301-305, Nov. 1997.
4. CIE Publication No. 69, Methods of characterizing illuminance meters and luminance meters (1987).