A Spectrally Tunable LED Sphere Source Enables Accurate Calibration of Tristimulus Colorimeters

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ABSTRACT

The Four-Color Matrix method (FCM) was developed to improve the accuracy of chromaticity measurements of various display colors. The method is valid for each type of display having similar spectra. To develop the Four-Color correction matrix, spectral measurements of primary red, green, blue, and white colors of a display are needed. Consequently, a calibration facility should be equipped with a number of different displays. This is very inconvenient and expensive. A spectrally tunable light source (STS) that can mimic different display spectral distributions would eliminate the need for maintaining a wide variety of displays and would enable a colorimeter to be calibrated for a number of different displays using the same setup. Simulations show that an STS that can create red, green, blue and white distributions that are close to the real spectral power distribution (SPD) of a display works well with the FCM for the calibration of colorimeters.

Keywords: color, colorimeter, display, Four Color Method, light emitting diode, spectral power distribution.

1. INTRODUCTION

Colorimeters are commonly used to measure chromaticity coordinates (x, y) as well as the luminance (cd/m^2) emitted from displays. Basic protocols for these kinds of measurements are available [1]. Due to imperfect matching of the spectral responsivities of the colorimeter channels to the CIE color matching functions, measurement errors are inevitable. When the instruments measure light sources having spectra similar to the standard calibration source, many sources of errors are cancelled and the residual measurement errors will be small. Colorimeters are normally calibrated against an incandescent standard lamp operated at a color temperature of 2856 K, approximating the spectral distribution of CIE Standard Illuminant A [2]. When colorimeters measure light sources having dissimilar spectra from Illuminant A, the errors can be significant. For example, inter-instrument variations for chromaticity measurements of various colors of a display are as large as 0.01 in x, y and 10 % in Y (corresponding to ~10 ΔE^*ab) while the manufacturers' specifications (specified for Illuminant A) are 0.002 in (x, y) and 2 % in Y. Lower measurement uncertainties are needed in many applications; e.g., international standards [3, 4] require measurement uncertainty of 0.005 or less in chromaticity and 4% or less for luminance when measuring red, green, blue and white colors of cathode ray tube displays (CRT) or liquid crystal displays (LCD).

Utilizing the fact that the colored light produced by most displays is a linear superposition of the spectral power distribution of three (red, green, and blue) primaries, matrix techniques have been developed to improve the accuracy of color display measurement [1, 5, 6].

2. FOUR-COLOR MATRIX METHOD FOR CORRECTION OF TRISTIMULUS COLORIMETERS

One of the approaches used to develop the colorimeter correction matrix is the Four-Color Method (FCM) [5, 6]. With FCM, the colorimeter being corrected measures the chromaticity coordinates (x_{mR}, y_{mR}), (x_{mG}, y_{mG}), (x_{mB}, y_{mB}) of primary red, green, and blue colors and (x_{mW}, y_{mW}) of the white color emitted by display. The chromaticity coordinates (x_{rR}, y_{rR}), (x_{rG}, y_{rG}), (x_{rB}, y_{rB}), (x_{rW}, y_{rW}) of the same colors are calculated based on measurements taken by a primary reference spectroradiometer. From those chromaticity coordinates the relative tristimulus values of the

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primary colors are defined by the matrix M_{RGB} for the colorimeter measurements and by the matrix N_{RGB} for the reference spectroradiometer measurements using the following equations:

$$M_{RGB} = \begin{bmatrix} X_{mR} & X_{mG} & X_{mB} \\ Y_{mR} & Y_{mG} & Y_{mB} \\ Z_{mR} & Z_{mG} & Z_{mB} \end{bmatrix} = \begin{bmatrix} x_{mR} & x_{mG} & x_{mB} \\ y_{mR} & y_{mG} & y_{mB} \\ z_{mR} & z_{mG} & z_{mB} \end{bmatrix} \begin{bmatrix} k_{mR} & 0 & 0 \\ 0 & k_{mG} & 0 \\ 0 & 0 & k_{mB} \end{bmatrix} \tag{1}$$

where (k_{mR}, k_{mG}, k_{mB}) are the relative factors for measured luminance of each display color and $k_{mR} + k_{mG} + k_{mB} = 1$.

$$N_{RGB} = \begin{bmatrix} X_{rR} & X_{rG} & X_{rB} \\ Y_{rR} & Y_{rG} & Y_{rB} \\ Z_{rR} & Z_{rG} & Z_{rB} \end{bmatrix} = \begin{bmatrix} x_{rR} & x_{rG} & x_{rB} \\ y_{rR} & y_{rG} & y_{rB} \\ z_{rR} & z_{rG} & z_{rB} \end{bmatrix} \begin{bmatrix} k_{rR} & 0 & 0 \\ 0 & k_{rG} & 0 \\ 0 & 0 & k_{rB} \end{bmatrix} \tag{2}$$

where (k_{rR}, k_{rG}, k_{rB}) are the relative factors for luminance of each display color and $k_{rR} + k_{rG} + k_{rB} = 1$.

Based on the additivity of tristimulus values, the chromaticity coordinates (x_{mW}, y_{mW}), (x_{rW}, y_{rW}) of the white color emitted by the display can be calculated by the following relationships:

$$\begin{bmatrix} x_{mW} \\ y_{mW} \\ z_{mW} \end{bmatrix} = \begin{bmatrix} x_{mR} & x_{mG} & x_{mB} \\ y_{mR} & y_{mG} & y_{mB} \\ z_{mR} & z_{mG} & z_{mB} \end{bmatrix} \begin{bmatrix} k_{mR} \\ k_{mG} \\ k_{mB} \end{bmatrix} \tag{3}$$

$$\begin{bmatrix} x_{rW} \\ y_{rW} \\ z_{rW} \end{bmatrix} = \begin{bmatrix} x_{rR} & x_{rG} & x_{rB} \\ y_{rR} & y_{rG} & y_{rB} \\ z_{rR} & z_{rG} & z_{rB} \end{bmatrix} \begin{bmatrix} k_{rR} \\ k_{rG} \\ k_{rB} \end{bmatrix}. \tag{4}$$

The white color of the display can be made of any intensity combination of the three primary colors as far as each primary color has significant intensity. The values of the relative factors (k_{mR}, k_{mG}, k_{mB}) and (k_{rR}, k_{rG}, k_{rB}) can be obtained by solving eq. (3) and eq. (4).

$$\begin{bmatrix} k_{mR} \\ k_{mG} \\ k_{mB} \end{bmatrix} = \begin{bmatrix} x_{mR} & x_{mG} & x_{mB} \\ y_{mR} & y_{mG} & y_{mB} \\ z_{mR} & z_{mG} & z_{mB} \end{bmatrix}^{-1} \begin{bmatrix} x_{mW} \\ y_{mW} \\ z_{mW} \end{bmatrix} \tag{5}$$

$$\begin{bmatrix} k_{rR} \\ k_{rG} \\ k_{rB} \end{bmatrix} = \begin{bmatrix} x_{rR} & x_{rG} & x_{rB} \\ y_{rR} & y_{rG} & y_{rB} \\ z_{rR} & z_{rG} & z_{rB} \end{bmatrix}^{-1} \begin{bmatrix} x_{rW} \\ y_{rW} \\ z_{rW} \end{bmatrix}. \tag{6}$$

The correction matrix R is then given by:

$$R = N_{RGB} \cdot M_{RGB}^{-1}. \tag{7}$$

If the relative tristimulus values M for any colors measured by the colorimeter are given by:

$$M = \begin{bmatrix} X_m \\ Y_m \\ Z_m \end{bmatrix} = k_{FCM} \begin{bmatrix} x_m \\ y_m \\ z_m \end{bmatrix}, \tag{8}$$

where k_{FCM} is an arbitrary factor, then the relative tristimulus values M are corrected to M' by using the correction matrix R as $M' = R \cdot M$. Finally, for any color emitted by the display, corrected chromaticity values are computed from M'.

The accuracy of this method has been studied for spectral variation of displays including CRTs, LCDs and organic light-emitting diode (OLED) displays. The results show that the FCM correction matrix works well for each type of display having similar primary color spectra. After a pplication of the FCM to a colorimeter, the residual errors in measurements of a display are found to be within 0.002 in chromaticity (x, y) and a color difference of $2\Delta E^*_{ab}$. However, if the correction matrix is developed for one type of display and other types of display are measured, the error correction will not be effective. Consequently, the FCM should be developed for each type of display to be measured by the colorimeter. A calibration facility should be equipped with number of diff erent displays. This will be very inconvenient and expensive.

A spectrally tunable light source (STS) that can mimic different display spectral distributions would eliminate the need for maintaining a wide variety of different displays. The STS should create source distributions that are close to the spectral power distributions (SPDs) of the display's primary red, green, blue, and white colors.

3. DEVELOPMENT OF A TUNABLE LED-BASED COLORIMETRIC SOURCE

An STS using a conventional lamp and monochromator with a multi-element liquid crystal filter has been reported [7]. This source suffers from low flux, especially in the blue wavelength, due to the SPD of the lamp. A higher efficiency and more flexible option involves mixing the spectral flux of different color LEDs. A source able to mimic a given color, but not a given spectrum distribution has been reported [8]. An STS using a number of LEDs having different peak wavelengths has been designed at the National Institute of Standards and Technology (NIST) USA, to mimic the spectral distributions of a wide variety of light sources including displays over the spectral range from 380 nm to 780 nm.

3.1. Construction of the STS

The STS is an integrating sphere source illuminated by a la rge number of LEDs having different spectral peaks and distributions, as shown in Fig. 1. The LEDs can be driven and controlled individually with a 256 channel, computer-controlled power supply. The large number of spectral channels helps facilitate accurate ma tching of fine structure in target source SPDs. A diode array spectroradiometer and a photometer are used as monitor devices to determine the real-time radiometric/photometric output of the STS. A computer logs the output of the spectroradiometer and individually controls the drive currents of the LEDs to obtain the required target source distribution. The LEDs are mounted in 8 to 10 heads (Fig. 1 shows only 4 heads) equipped with a temperature-controlled mounting plate to cool the LEDs and stabilize their temperature.

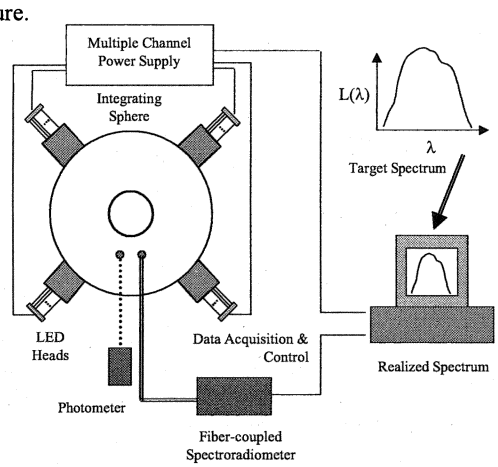

Fig. 1. Configuration of the STS de signed and being developed at NIST.

3.2. Matching Algorithm

Different SPDs emitted by display (TARGET SPDs), can be realized using an optimization algorithm, which is based on the modified gradient method [9]:

1) Make a pre-selection of initial value of power coefficient $k_i^{(0)}$, $i = 1...n$ of i-th LED

2) Calculate the j -th value of k_i :

$$k_i^{(j)} = k_i^{(j-1)} - 0.001 \frac{\partial \sum_{380}^{780} \left(\sum_{i=1}^{n} k_i^{(j-1)} S_{\mathrm{LED}_i}(\lambda) - S_{\mathrm{TARGET}}(\lambda) \right)^2}{\partial k_i^{(j-1)}}$$

3) If $\sum_{380}^{780} \left| \sum_{i=1}^{n} k_i^{(j)} S_{\mathrm{LED}_i}(\lambda) - S_{\mathrm{TARGET}}(\lambda) \right| = \sum_{380}^{780} \left| \sum_{i=1}^{n} k_i^{(j-1)} S_{\mathrm{LED}_i}(\lambda) - S_{\mathrm{TARGET}}(\lambda) \right|$

then $k^{(j)}$ is the final value of coefficient.

Based on this algorithm, a program calculates the value of the power coefficients $k^{(j)}$ for each LED. In Step 1), the initial values of the algorithm are set. They can be any po sitive numbers. In Step 2), the next values of variables k are determined in an iterative way. This means that for every k the square of the difference of the target spectrum and the spectrum built up from the LED spectra weighted by variables k is derived by variable k to be iterated further. Based on the derivative and the previous iterated value of k, the next value of k is computed as shown above. The coefficient for the step size (0.001) was determined empirically.

Variable k is strongly related to the current applied to the LED belonging to that variable. The equality is obtained from a large number of iterations where the individual LED currents (power coefficients k) are increased or decreased in small steps. The individual LED currents are obtained from that optimization. The integral-sum of the differences at each wavelength shows the quality of the realized spectral match. In Step 3), the logical condition for stopping the iteration is formulated. It can be interpreted that the algorithm stops when the values of k reach a steady-state solution.

3.3. Simulation of the STS

To give us guidelines on the number of LEDs necessary to match a display SPD for calibration purposes, simulations were conducted to evaluate the accuracies of calibrating colo rimeters CRT or LCD type of display, using LED models [10] based on a Gaussian function with spectral width (FWHM) of 20 nm. Simulations were run with 5 nm and 20 nm intervals of LED peak wavelengths in the 380 to 780 nm region. Thus, a total of 80 or 20 LEDs are used for the intervals of 5 nm or 20 nm, respectively. The resulting spectrum, the sum of all model LEDs, weighted according to the optimization given in 3.2, is referred to as an "STS model".

Figures 2 and 3 show the SPD of the STS model matched to a CRT display producing white color using model LEDs at 5 nm intervals (Fig. 2) and 20 nm intervals (Fig. 3). The figures depict the SPD of the original white display as well as that of the STS model. Figures 4 and 5 present the results for an LCD display.

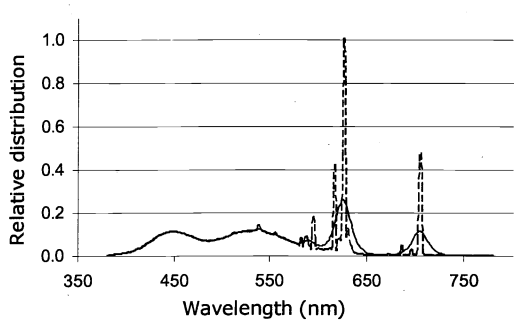

Fig. 2. SPD of a CRT (white) (dashed line) and the STS model with 5 nm LED intervals.

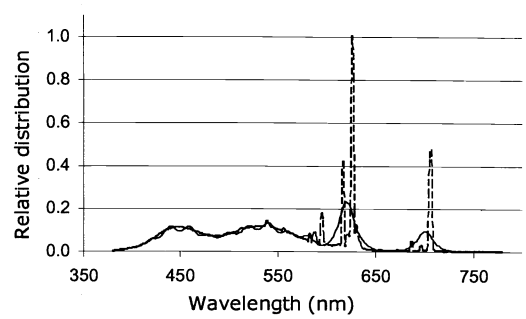

Fig. 3. SPD of a CRT (white) (dashed line) and the STS model with 20 nm LED intervals.

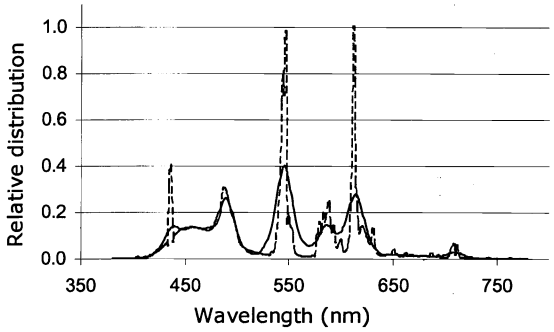

Fig. 4. SPD of an LCD white (dashed line) and the STS model with LEDs at 5 nm intervals (solid line).

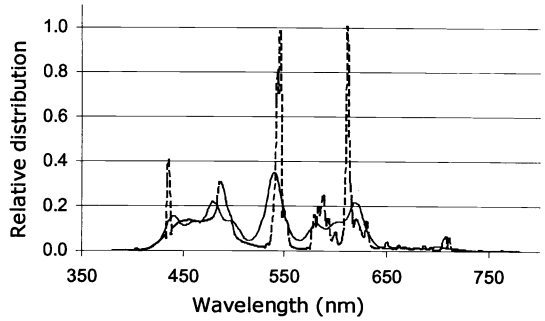

Fig. 5. SPD of an LCD white (dashed line) and the STS model with LEDs at 20 nm intervals (solid line) .

In the next investigation, a colorimeter was analyzed for its measurement accuracy when measuring different colors of CRT and LCD type displays using a calibration matrix based on measurements of the modeled STS SPDs. The measured relative spectral responsivity of a colorimeter was used in these simulations. The colorimeter was calibrated by CIE Illuminant A (Figs. 6, 7), and then the correction matrix was obtained by calculation based on the STS model (5 nm and 20 nm LED intervals) and FCM (Figs. 8, 9, 10, 11).

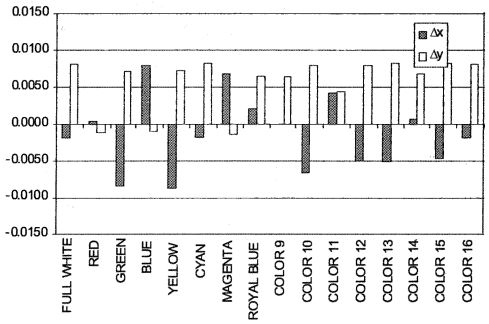

Fig. 6. Chromaticity errors when colorimeter calibrated by Illuminant A, measured colors emitted by a CRT display.

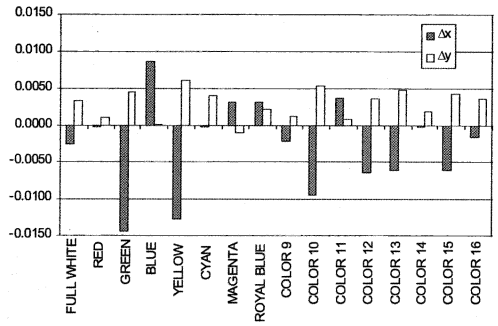

Fig. 7. Chromaticity errors when colorimeter calibrated by Illuminant A, measured colors emitted by an LCD display.

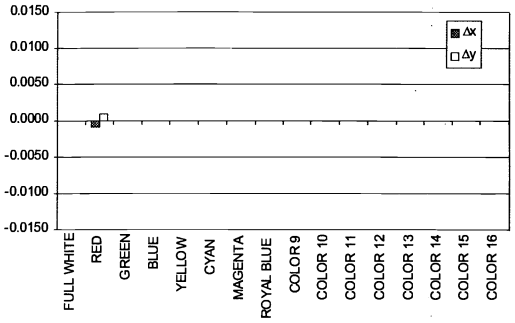

Fig. 8. Chromaticity errors when the calibration matrix for CRT type of display was obtained by using an STS source with LEDs every 20 nm.

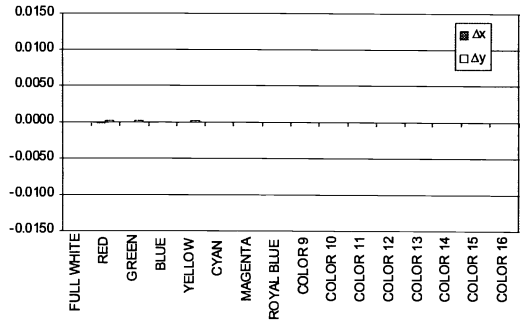

Fig. 9. Chromaticity errors when calibration matrix for CRT type of display was obtained by using STS source with LEDs every 5 nm.

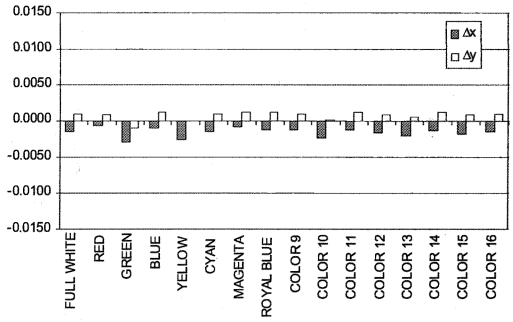

Fig. 10. Chromaticity errors when the calibration matrix for LCD type of display was obtained by using STS source with LED spaced every 20 nm.

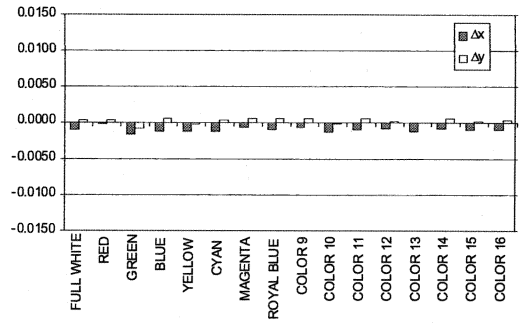

Fig. 11. Chromaticity errors when the calibration matrix for LCD type of display was obtained by using STS source with LEDs spaced every 5 nm.

3.4. LED selection and characterizations

Prior to the final design of the LED heads, a large number of LEDs were purchased and evaluated for total radiant flux, spectral power distribution, and peak wavelength. The LEDs were seasoned prior to incorporation into the source to improve their radiometric stability. After seasoning, the LEDs were characterized. The spectral power distributions were measured versus drive-current. Spectral measurements were made with a spectroradiometer between 190 nm and 800 nm. LED characteristics vary significantly depending on material composition and manufacturer. The following results show both the variability depending on the LED color and individual variations among LEDs from the same batch. Figure 12 shows the values of radiant flux [mW] for these LEDs versus their peak wavelength. The measurements were made against standard LEDs with relative expanded uncertainties (k=2) of 5 % using a 0.5 m integrating sphere. As shown in Fig. 12, the level of the radiant flux depends largely on the LED color (peak wavelength). The yellow LEDs are dim compared to blue and red LEDs. Additionally, it is difficult to find LEDs between 525 nm and 555 nm (the so-called "green hole"). A limited number of LEDs are available between 720 nm and 760 nm.

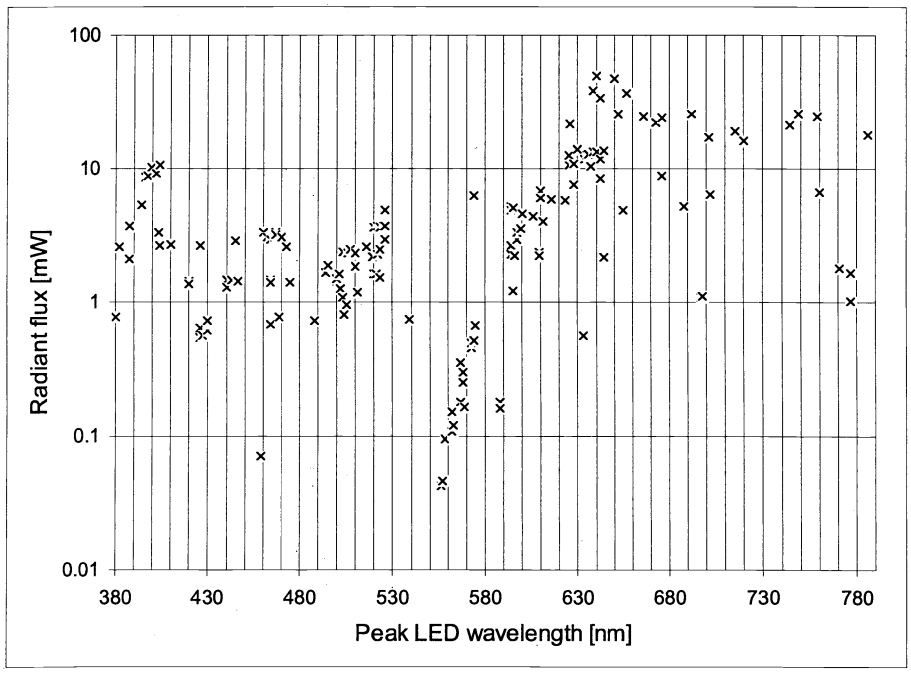

Fig. 12. Total radiant flux of the LED samples to be used in the STS plotted as a function of their peak wavelengths.

4. FOUR-COLOR MATRIX METHOD WITH STS BASED ON REAL LEDS

The STS is designed to match any spectral distribution over the range from 380 nm to 780 nm. The matching of the SPDs is realized using the optimization algorithm described in 3.2, based on measurements by a reference spectroradiometer. The optimization takes a long time due to a large number of iterations between measurements and calculations. Once the optimized condition is achieved, the drive currents of all the LEDs are recorded, and the same SPD can be reproduced by using the same sets of drive currents. The realized spectral distribution of the STS, in spite of the optimization, can be different from the target distribution due to limitations in the optimization algorithm. Additionally deviations can be caused by limitations in the availability of LEDs with the appropriate peak wavelengths, their finite spectral widths (SPD curves), as well as drifts due to temperature dependence, instability, and aging of the LEDs. When the drifts are small and slowly varying, a second optimization program (running in real time) can be used to maintain the constant SPD of the source. The average luminance of the STS, which depends on the specific spectral distribution desired, is between one hundred and several hundred $cd \cdot m^{-2}$.

The expected realizations of red, green, blue, and white SPDs to mimic real CRT display distributions are shown in Fig. 13. Due to the spectral width of LEDs, narrowband spectral features cannot be realized well. In spite of this limitation, the measurement errors can be small, as illustrated in Fig. 14.

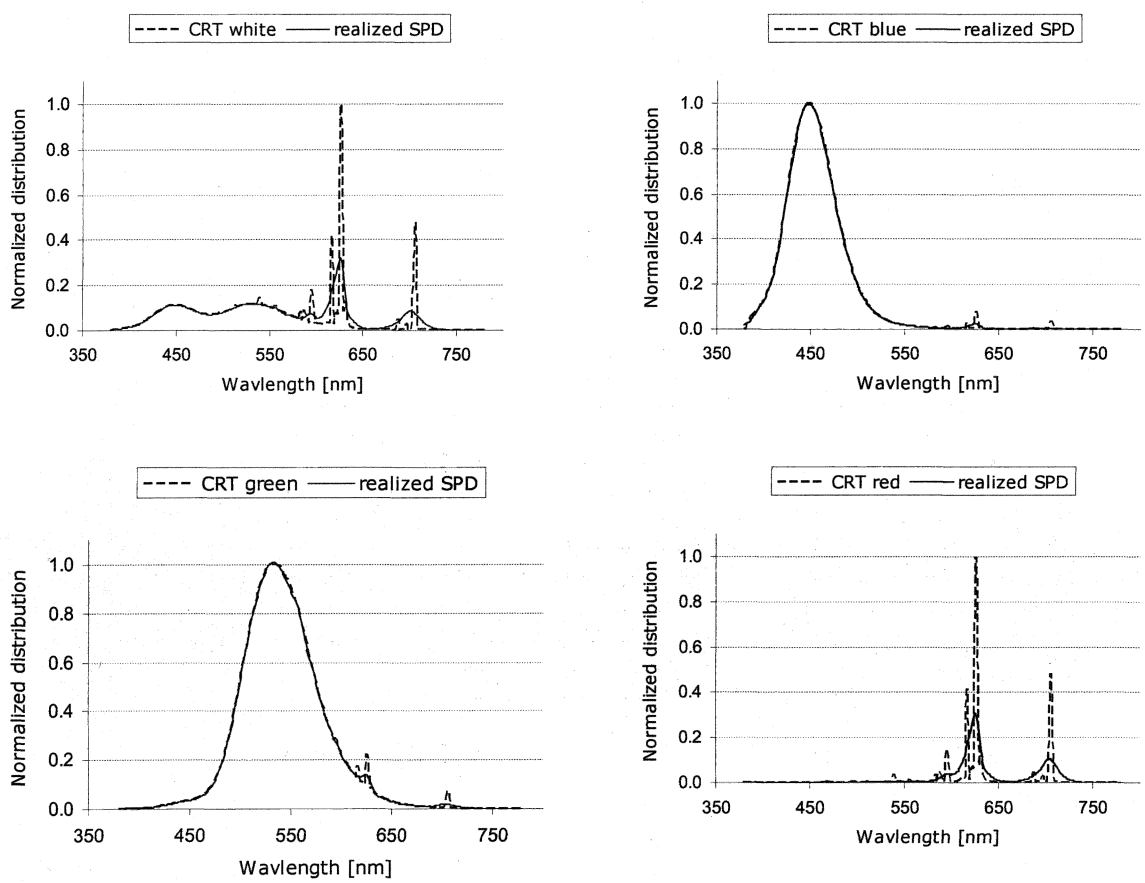

Fig. 13. Expected realizations of white, blue, red, and green SPDs emitted by CRT type display.

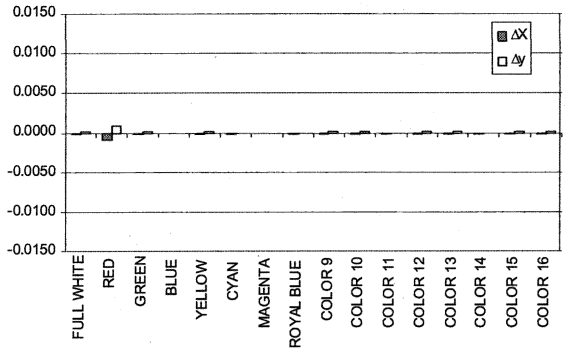

Fig. 14. Chromaticity coordinate errors when the calibration matrix was obtained by using the STS source with real LED distribu tions.

5. CONCLUSIONS

A spectrally tunable LED source (STS) has been designed and is being developed at NIST. A series of simulations have been conducted to clarify design requirements and predict th e performance of the designed tunable source. The results of the simulation for the calibration of colorimeters indicate that:

- An STS works well with the Four-Color Matrix method.
- A spectrally tunable LED source enables rapid calibration of colorimeters for various types of displays with no need for real displays.
- Utilization of the STS for calibration of display colori meters significantly simplifies calibration procedures.

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