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NIST Calibration Facility for Display Colorimeters

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ABSTRACT

A calibration facility has been developed at the National Institute of Standards and Technology (NIST) to address the need for high accuracy color measurements of displays. Calibration services tailored to display measurements are planned for colorimeters and spectroradiometers. A key component of the facility, a reference spectroradiometer, has been developed and its uncertainty for display measurements estimated using a series of computer simulations. The simulations predict that the reference spectroradiometer — corrected for wavelength error and variable bandpass — can measure any color of a cathode ray tube (CRT) or liquid crystal (LCD) display with a combined standard uncertainty of approximately 0.001 in chromaticity (x, y) and 1 % in luminance (Y). In addition, a new matrix correction technique (the Four-Color Method) has been developed as a means to transfer the calibration from the reference instrument to a test instrument. Using the Four-Color Method, the residual errors with the calibrated instrument for one type of display are reduced to within 0.001 in x,y (or ~1 ΔE^*ab) with respect to the reference instrument.

To evaluate the overall performance of the system, commercial spectroradiometers and tristimulus colorimeters were calibrated against the reference instrument, measuring both a CRT and an LCD display. The results show that calibrated target instruments can measure various colors of a particular display with a combined standard uncertainty of approximately 0.002 in x,y and 2 % in Y (~2 ΔE^*ab).

Keywords: calibration, standards, display, colorimeter, spectroradiometer, colorimetry

1. INTRODUCTION

Colorimeters and spectroradiometers are commonly used to measure the chromaticity and luminance of displays, and useful protocols for color measurement using these instruments are available [1,2]. However, the instruments are normally calibrated against an incandescent standard lamp having a broad, smoothly varying spectral power distribution, while display colors have very different spectral distributions, often incorporating narrow spectral features. As a result, chromaticity errors tend to be much larger than anticipated when these instruments are used to measure displays. For example, commercial tristimulus colorimeters and diode-array spectroradiometers can be calibrated against Illuminant A with uncertainties on the order of 0.001 in x,y and 1% in Y [3]. However, inter-instrument variations for chromaticity measurements of various colors of a display are often as large as 0.01 in x, y and 10 % in Y (corresponding to approximately 10 ΔE^*ab). Such variations are much larger than the accuracy required for many applications. For example, measurement uncertainties within 0.005 in chromaticity are recommended for CRT and LCD color measurements in international standards [4].

To address the need for higher-accuracy measurements of displays, a program has been established at NIST to develop standards and calibration services for color-measuring instruments. A central component of this program, a calibration facility, has been developed to calibrate instruments for measuring display colors [5]. In this facility, a test instrument and a reference spectroradiometer measure various colors of a particular display (e.g. a CRT or an LCD display). The chromaticity and luminance values are then compared, and the test instrument values are corrected using the Four-Color Method [6,7] to more closely approximate the reference values.

In this paper, we describe details of the reference spectroradiometer, including a comprehensive uncertainty analysis, together with recent results on the Four-Color Method.

2. CHARACTERIZATION OF THE REFERENCE SPECTRORADIOMETER

The reference spectroradiometer, shown in Fig. 1, consists of imaging optics; a double-grating, scanning monochromator for wavelength selection; and a photomultiplier tube for detection. The instrument has been characterized for stray light,

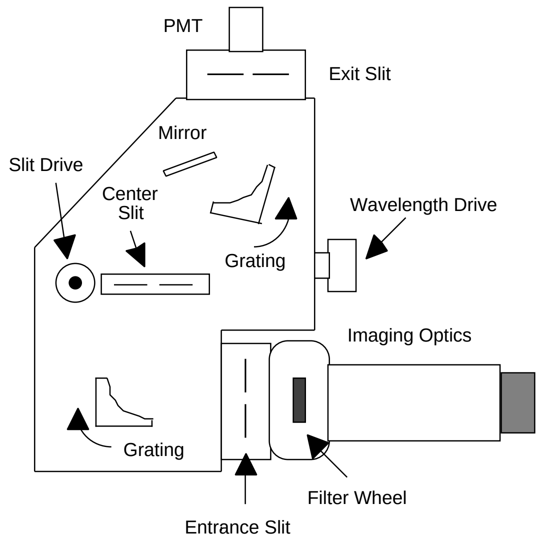

Fig. 1. Schematic diagram of the reference spectroradiometer.

wavelength error, variable bandpass, linearity, and random measurement uncertainties. These results were then incorporated into detailed simulations to estimate the uncertainty of chromaticity measurements of a CRT and an LCD display.

2.1. Wavelength accuracy

The monochromator wavelength error was measured at a number of wavelengths using a variety of gas-filled "pen" lamps and laser sources. As shown in Fig. 2, the wavelength error varies from 0.20 nm at 400 nm to 0.85 nm at 800 nm. To improve the wavelength calibration of the instrument, the data were subsequently fit to a fifth order polynomial, shown as the solid line in the figure. The resultant polynomial was then used to correct the wavelength drive of the monochromator. While the wavelength uncertainty is greatly reduced, small residual wavelength errors remain, as shown by the open circles in Fig. 2. The residual errors have a root-mean-square value of less than 0.1 nm and a maximum value of 0.1 nm.

2.2. Slit scattering function

For accurate color measurement, the slit scattering function of the monochromator should be triangular, with its bandpass matched to the scanning interval [8]. We use a 5 nm scanning interval between data points, and hence would like a triangular slit scattering function with a 5 nm full-width half-maximum (FWHM) bandpass. For a given slit width configuration, the slit scattering function is in general wavelength dependent. Fig. 3 shows the FWHM bandpass as a function of wavelength for a given slit width configuration. The bandpass varies from 6 nm at a wavelength of 400 nm to 4.5 nm at a wavelength of 800 nm. Over the same wavelength interval, the bandshape changes from trapezoidal to triangular.

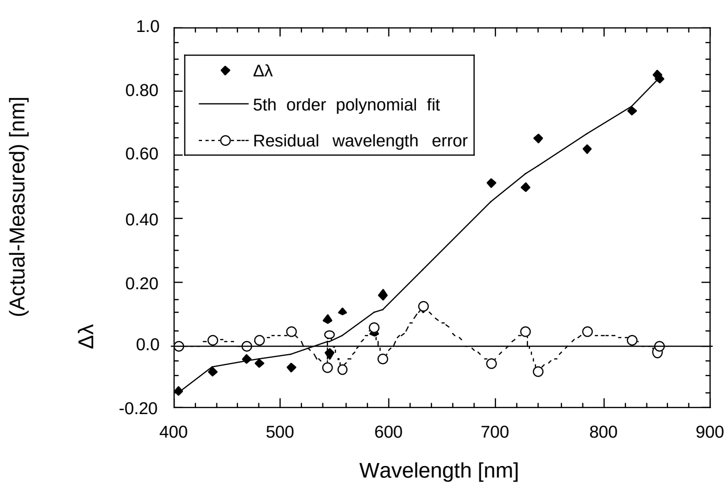

Fig. 2. Reference spectroradiometer wavelength error (solid diamonds). 5^{th} order polynomial fit to the data (solid line). Residual wavelength error (open circles).

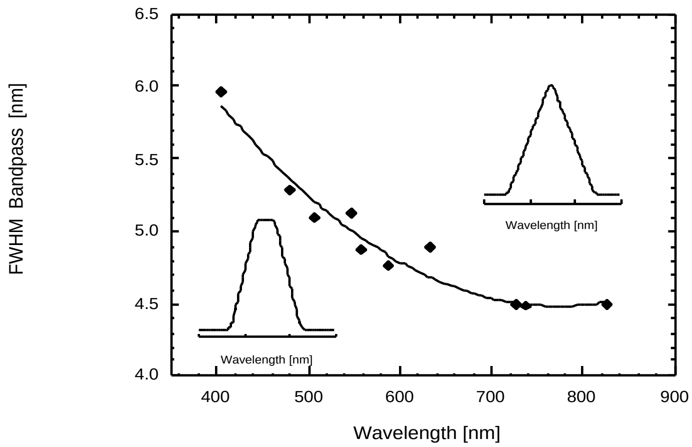

Fig. 3. Full-width, half-maximum bandpass of the spectroradiometer for entrance and exit slit settings of 1250 µm and a center slit setting of 2000 µm. (Left inset) Slit scattering function at 400 nm. (Right inset) Slit scattering function at 550 nm.

To correct the slit scattering function, the monochromator center slit is equipped with a stepper motor, enabling remote control of the slit width and consequently the slit scattering function of the instrument. By properly varying the center slit width, the slit scattering function can be adjusted to remain triangular, with a bandpass of 5 nm ± 0.1 nm over the wavelength range from 380 nm to 780 nm.

2.3. Stray light

Stray light can be a major source of error in color measurement. The stray light factor (the response of the instrument at wavelengths other than the wavelength of the input radiation, relative to the response for the input radiation) has been measured at several wavelengths using different laser lines. Narrow-band interference filters were used to eliminate background luminescence from the lasers. Neutral density filters and an integrating sphere attenuated the laser intensity, preventing saturation of the detector and enabling accurate measurements with uniform radiance.

The stray light factor was measured to be less than 10^{-6} in the visible wavelength region. An example is shown in Fig. 4 for the helium-neon (HeNe) laser wavelength (633 nm). The signal is less than 2 x 10^{-7} of the peak value when measured 15 nm (three times the bandpass) away from the HeNe laser line. Similar results were obtained at other wavelengths.

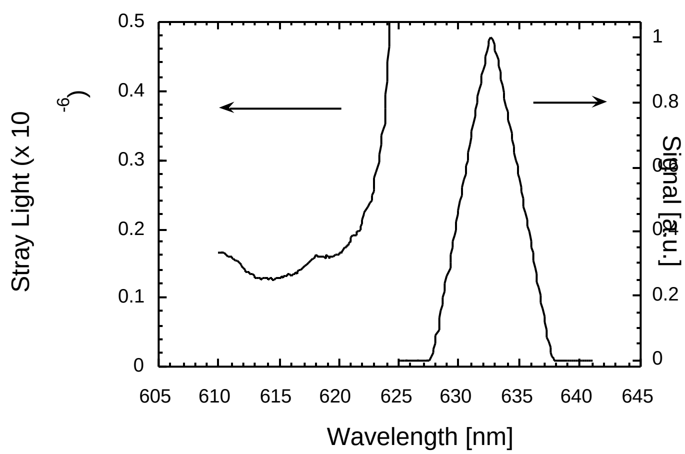

Fig. 4. Spectroradiometer stray light.

2.4. Other characteristics

The response of the instrument has been verified to be linear over the flux range of interest using the NIST Beam Conjoiner [9]. Finally, the random measurement noise, defined to be the relative standard deviation of a measurement, has been determined to be approximately 0.1 % of the maximum signal of a CRT display color (10 samples). The results of the characterizations of the spectroradiometer are summarized in Table 1.

Table 1. The reference spectroradiometer characteristics.

Parameter	Value
Wavelength Error	± 0.1 nm
Bandpass	5 nm ± 0.1 nm
Stray Light Factor	$< 10^{-6}$
Measurement Noise	0.1 % of the peak signal

3. UNCERTAINTY ANALYSIS

Detailed simulations have been done to estimate the uncertainty of display color measurements with the reference spectroradiometer. Simulations were conducted for 16 different colors of a CRT and an LCD display including primary colors and white. The primary red, green and blue spectra from the two displays used in the simulations are shown in Fig. 5. The additional 12 colors used in the simulations were obtained by mixing the primary colors in different ratios. The spectral data and the monochromator slit scattering function were prepared in 0.1 nm increments, and all calculations were carried out with 0.1 nm resolution. The simulations were repeated a minimum of 300 times for each color for statistical analysis.

In the simulations, the chromaticity values of a given spectral distribution were first calculated as true values. Errors – for example wavelength errors or random measurement uncertainties – were then introduced into the given spectrum and the chromaticity values of the new spectral distribution were calculated and compared with the true values. Sources of errors can be introduced individually into the simulation or in combination with other sources of error.

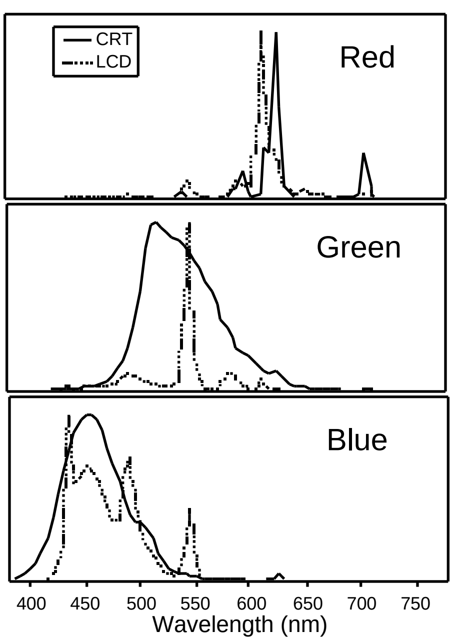

Fig. 5. Spectral power distributions of the primary red, green and blue phosphors of a CRT (solid line) and an LCD (dashed line) display used in the simulations.

Fig. 6 shows the effects of stray light on chromaticity measurements of red, green and blue CRT colors. In this simulation, the stray light factor was assumed to be constant over the entire wavelength region. The results show that, for sufficient accuracy in chromaticity measurements (<< 0.001 in x, y), the stray light factor should be less than 10^{-6}. This is easily achievable with double grating instruments such as the reference spectroradiometer, while single grating instruments often have stray light factors on the order of 10^{-4} to 10^{-5}. Care must then be taken to account for the effects of stray light or the error in chromaticity measurements can be significant.

Random measurement noise can also have a large effect on color measurement. The noise can arise from a number of sources, including instabilities in the display luminance as well as from the detector itself. Fig. 7 shows the effect of measurement noise on the resultant chromaticity values. Each data set represents the standard deviation of the chromaticity errors for a given spectral power distribution with random noise (Gaussian probability distribution) added to the monochromator output at each wavelength

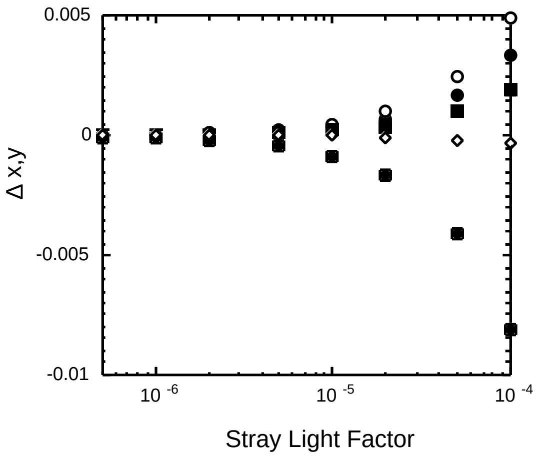

Fig. 6. Errors in chromaticity values as a function of the stray light factor for red (diamonds), green (squares) and blue (circles) CRT colors. Closed symbols refer to errors in *x*, open symbols to errors in *y*.

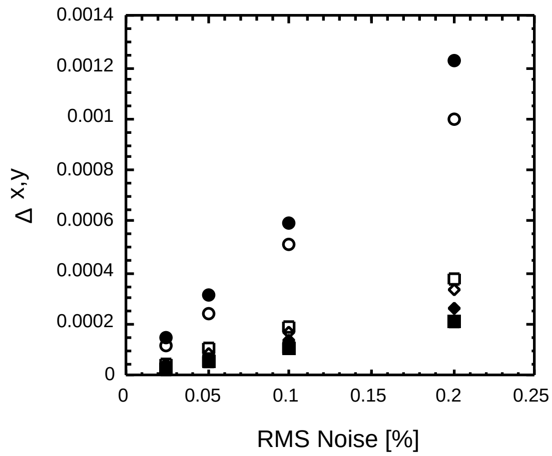

Fig. 7. Errors in chromaticity values as a function of the RMS noise (as a percentage of the maximum signal) for red (diamonds), green (squares) and blue (circles) CRT colors. Closed symbols refer to errors in *x*, open symbols to errors in *y*.

(every 5 nm). The noise is a root-mean-square value relative to the peak of the monochromator signal. As shown in the figure, measurement noise on the order of 0.2 % of the peak signal introduces an uncertainty in chromaticity values approaching 0.001.

Wavelength errors and variations in the slit scattering function also affect the accuracy of chromaticity measurements of displays, and these effects have been included in the simulations as well to estimate the total measurement uncertainty of the reference spectroradiometer.

4. TOTAL UNCERTAINTY OF THE REFERENCE SPECTRORADIOMETER

In order to estimate the total uncertainties of color measurements with the reference spectroradiometer, all the measured characteristics of the instrument (given in Table 1) were incorporated into the simulation. The results are summarized in Table 2 for the CRT and in Table 3 for the LCD display. Only the data for the primary colors and white are shown; uncertainties for the other colors were typically less than the uncertainties for the primary colors and white. For the CRT display, the uncertainty is much less than 0.001 in *x*,*y* and 1 % in *Y*, while for the LCD display, the uncertainty approaches 0.0015 in *x*,*y* and 1 % in *Y*. The different results for the two types of displays are due to the very different spectral power distributions of their respective red, green, and blue spectra. After correction for wavelength errors and slit scattering function variations, the dominant source of uncertainty in chromaticity measurements of displays is the random measurement noise.

Table 2. Combined standard uncertainty of color measurements of a CRT display with the reference spectroradiometer.

CRT colors	Δ*x*	Δ*y*	Δ*Y* (%)
White	0.0003	0.0001	0.1
Red	0.0006	0.0004	0.4
Green	0.0002	0.0002	0.1
Blue	0.0001	0.0002	0.3

Table 3. Combined standard uncertainty of color measurements of an LCD display with the reference spectroradiometer.

LCD colors	Δx	Δy	ΔY (%)
White	0.0008	0.0012	0.7
Red	0.0008	0.0005	0.8
Green	0.0007	0.0013	0.7
Blue	0.0002	0.0005	0.4

5. FOUR-COLOR METHOD

Matrix techniques are known to improve the accuracy of tristimulus colorimeters for color display measurements. These techniques all involve the derivation of a 3 by 3 correction matrix (R') that transforms a set of tristimulus values (X,Y,Z) to values that more closely approximate reference values (X_C,Y_C,Z_C):

$$\begin{bmatrix} X_C \\ Y_C \\ Z_C \end{bmatrix} = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}. \qquad (1)$$

The corrected tristimulus values are thus expressed as linear combinations of the original values X, Y, and Z.

Several different approaches have been developed to derive the correction matrix for display measurements. The American Society of Testing and Materials (ASTM) recommends a method to derive the correction matrix from measured tristimulus values of several different display colors [2]. Following this method, the correction matrix is derived in such a fashion to minimize the root-mean-square difference between measured and reference tristimulus values for several different colors of a display. The chromaticity values are then calculated from the corrected tristimulus values.

This method, however, often does not work as well as expected. The ASTM method is based on the transformation of tristimulus values, and luminance errors will affect the accuracy of the corrected chromaticity values. These luminance errors can occur due to instability of the display, flicker effects on the detector, and inter-reflections between the display surface and the instrument, among other reasons.

Measurements of chromaticity values, on the other hand, are normally more stable and reproducible than measurements of tristimulus values since they are relative measurements and many of the sources of luminance error mentioned above tend to be reduced or cancelled. To reduce effects of luminance noise on chromaticity values, a matrix correction technique, the Four-Color Method, was recently developed that reduces the difference between measured and reference chromaticity values rather than tristimulus values. Because the new method directly transforms chromaticity values, it is insensitive to luminance noise. Simulations and measurements demonstrate that the Four-Color Method avoids many of the problems associated with the earlier techniques, enabling higher accuracy color measurements of displays. Additional theoretical details and experimental results of the Four-Color Method have been previously described [5,6].

This method has been tested using a number of data sets from both CRTs and LCDs. As an example, Fig. 8 shows the errors (differences from a reference spectroradiometer) of a commercial tristimulus colorimeter and a diode-array system for 14 colors of a CRT. The differences in measured chromaticity values between the reference instrument and the commercial instruments were as large as 0.01 in x, y for the tristimulus colorimeter and 0.006 in x, y for the diode array system. Deriving the correction matrix using the Four-Color Method and applying it to the results in Fig. 8 greatly reduced the measurement errors. Figure 9 shows the residual errors of the same instruments shown in Fig. 8 (shown on the same scale) after correction by the Four-Color Method. In this case, the errors were reduced by an order of magnitude. Similar results have also been obtained for an LCD display.

The Four-Color method, or any other matrix method, assumes that the spectral shape of the three primaries is independent of the display. However, there are small variations in primary spectra between displays incorporating the same type of

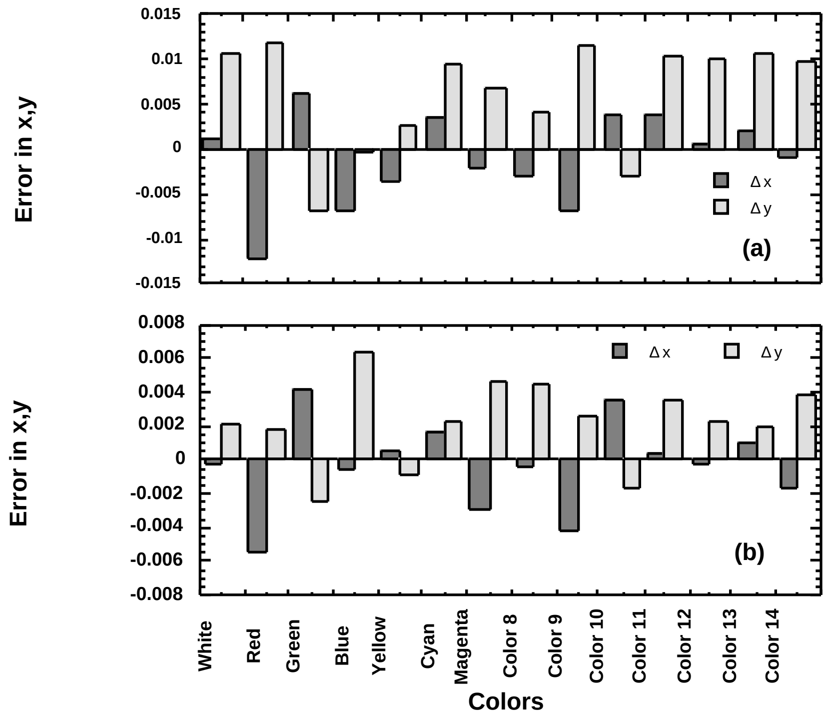

Fig. 8. Errors in chromaticity coordinates of 14 colors of a CRT display measured with (a) the tristimulus colorimeter and (b) the diode-array system.

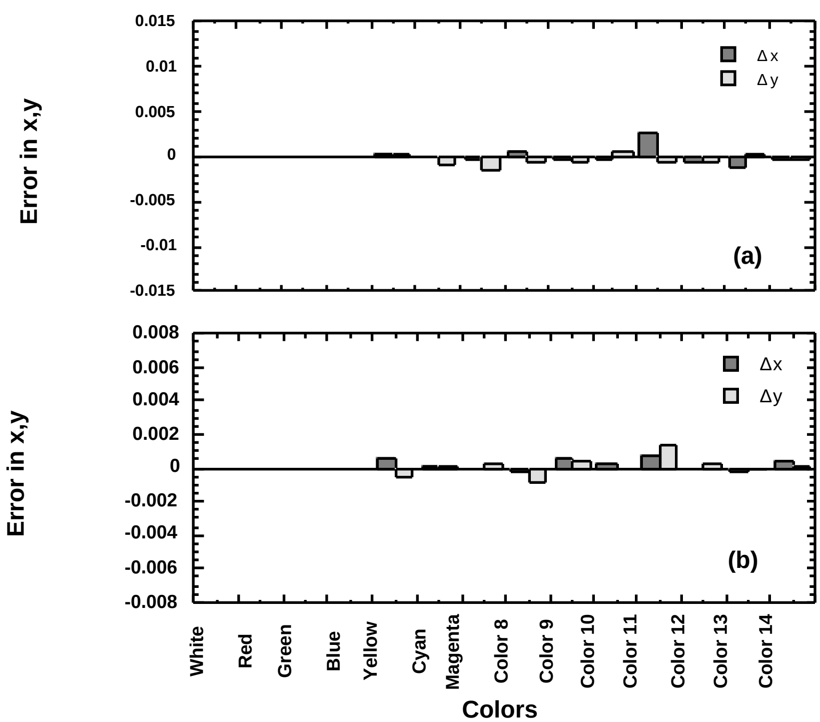

Fig. 9. Residual errors in chromaticity measurements of a CRT display after correction by the Four-Color Method for (a) the tristimulus colorimeter and (b) the diode-array system.

phosphors and, frequently, large variations between displays incorporating different types of phosphors. We therefore evaluated the ability of the Four-Color Method to correct chromaticity measurements of displays when the primary colors of the measured display had both small and large spectral variations from those of the display used during calibration. Simulations demonstrated that the Four-Color Method is not effective if the correction matrix is obtained for a CRT and the instrument measures a different type of instrument (e.g., an LCD). This means that the correction matrix should be obtained for each different type of display. However, the method works with sufficient accuracy (within 0.001 in x, y) for small spectral variations in the primary colors within the same types of displays.

6. CONCLUSIONS

A facility has been developed at NIST to calibrate color-measuring instruments for displays. A central component of the facility, the reference spectroradiometer, has been built and characterized in detail. Simulations based on measured characteristics of the spectroradiometer predict that the reference spectroradiometer can measure colors of displays with a relative combined standard uncertainty of 0.001 in chromaticity and 1 % in luminance. For calibrations, a correction matrix will be obtained using the Four-Color Method to transfer the NIST calibration to a test instrument. Using the correction matrix, the test instrument will be able to measure any colors of a display based on the NIST calibration with the smallest possible uncertainties. A more rigorous uncertainty analysis is currently in progress, including measurements of different types of displays and intercomparisons with other NIST spectroradiometers, to determine the official uncertainties for the calibrations. We expect to provide the uncertainty of calibrated instruments to be approximately 0.002 in x,y and 2 % in Y (~2 $\Delta E_{a,b}$) for a particular type of display. This NIST calibration service will be available shortly.

7. ACKNOWLEDGEMENTS

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