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NIST Colorimetric Calibration Facility for Displays – Part 2

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Abstract
Development of a calibration facility for spectroradiometric, colorimetric, and goniometric measurements of displays, display colorimeters, and spectroradiometers has been completed at the National Institute of Standards and Technology (NIST). An overview of the facility and results of the characterization measurements are presented. The results show that the facility is capable of measuring colors of sources with an expanded uncertainty 0.001 for chromaticity (x,y) and 1˚% for luminance˚(Y). The new calibration services from NIST are designed to reduce the uncertainty of color measurements using commercial instruments to a level approaching that of the NIST reference instrument.

1. Introduction
There is an increasing need for higher-accuracy measurements of the colorimetric properties of displays. Colorimeters and spectroradiometers are commonly used to measure the chromaticity (*x, y*) and luminance (*Y*) of displays, and basic protocols for color measurement using these instruments are available [1,˚2]. However, the instruments are normally calibrated against an incandescent standard lamp, and errors for display colors (having very different spectra) tend to be much larger than manufacturers specifications (often specified only for CIE Illuminant A). For example, international standards [3,˚4] require measurement uncertainty of 0.005 or less in *x, y* chromaticity (and 4 % or less for luminance) for red, green, blue, and white (virtually all colors) of a CRT or LCD display. On the other hand, the inter-instrument variations for chromaticity measurements as large as 0.01 in *x, y* and 10 % in *Y* (corresponding to approximately 10 ˘ E^{*}_{ab}) are observed for commercial tristimulus colorimeters and diode-array spectroradiometers when measuring various colors of displays. Such measurement errors would significantly degrade the quality control of the display products and the performance of color management systems.

To address the needs for improving and certifying the measurement uncertainties of such color measuring instruments, a facility for spectroradiometric and colorimetric calibration of displays, colorimeters, and spectroradiometers has been developed at the National Institute of Standards and Technology (NIST). Since we reported the progress on this work [5,˚6], we have completed the system with significant improvements and conducted a thorough analysis of the uncertainty budget for the calibration of displays and color measuring instruments. To assess the uncertainty in color measurements with the facility, a series of test measurements have been conducted to complement the earlier computer simulations [6], and the uncertainty analysis for CRT and LCD measurements has been completed. NIST calibration services are now available for such color measuring instruments and displays.

In addition, the NIST facility is equipped with goniometric color measurement capability, and a variety of gonio-colorimetric measurements for CRT, LCD, and other flat panel displays have been performed. These data allow us to estimate the uncertainty components associated with the display orientation. The capabilities of the NIST facility will be extended to include color measurements under specified ambient light conditions for reflective and transmissive displays.

2. Instrumentation
In this facility, as shown in Figure 1, test instruments are calibrated directly against the NIST reference spectroradiometer while measuring a particular color display. The measurements are repeated for several different colors of the display, and the Four-Color correction matrix [7] is computed from the calibration results for red, green, blue, and white of the display. The correction matrix will be provided to the customer so that their test instrument readings can be corrected for any colors of the display based on the NIST calibration.

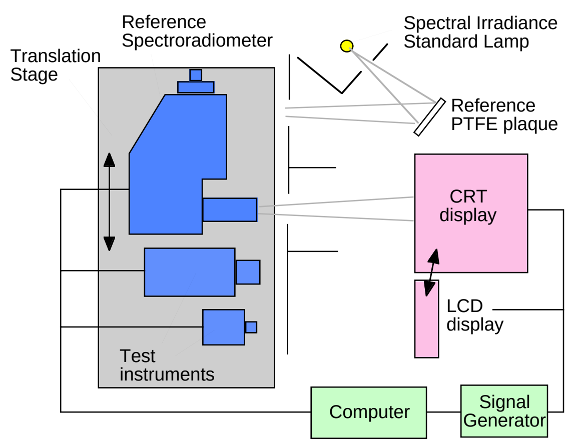

Figure 1. NIST calibration facility for display color measuring instruments.

The main component of the facility is the NIST reference spectroradiometer as shown in Figure 2. The device is a double grating, scanning monochromator equipped with imaging optics and a photomultiplier tube (PMT) for signal detection. The monochromator is configured in a subtractive mode with double holographic gratings with 1200 grooves/mm. The input optics include a reflex optic to image an area of the display onto an aperture, a relay lens to image the aperture onto the entrance slit

Expanded uncertainty with a coverage factor, *k*=2, is used throughout this paper.

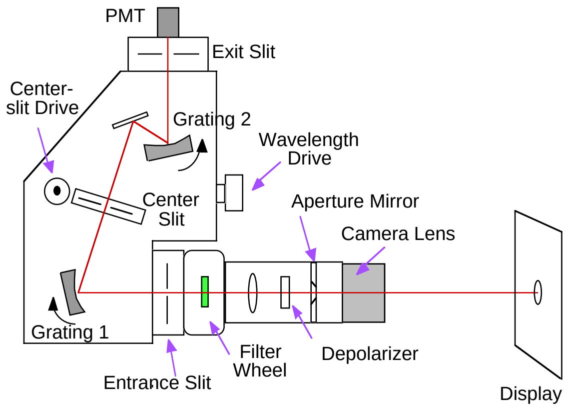

Figure 2. Configuration of the NIST reference spectroradiometer for display measurements.

of the monochromator, a depolarizer, and order-sorting filters. The depolarizer reduces the polarization sensitivity of the instrument to below 0.5 %, while the order-sorting filters eliminate higher-order diffraction effects. The monochromator center slit has been equipped with a stepper motor to control the slit width, and hence the shape and bandpass of the slit scattering function, of the instrument during a scan.

The signal at each set wavelength is detected with a PMT with a built-in current-to-voltage converter amplifier and a low-pass filter, and measured with a high-accuracy digital voltmeter. Special care is taken to avoid saturation of the PMT and the amplifier because the detector signal from displays is strongly pulsed, particularly when measuring a small area on the screen. The integration time of the voltmeter is set to a multiple of the period of the display flicker.

The entire measurement system, including a linear translator stage and an optical table, is placed in a light-tight box to minimize the ambient light. The spectroradiometer is calibrated against NIST s detector-based spectral irradiance standard lamps [8] used with a calibrated pressed polytetrafluoroethylene (PTFE) plaque [9].

Operating characteristics, including wavelength errors, spectral slit scattering function, stray light, detector linearity and temperature dependence, polarization sensitivity, and random noise have been measured; the uncertainty of each of these components is listed in Table 1. Details on the characterization of the reference spectroradiometer and uncertainty analysis are presented in the following section.

Table 1. Uncertainty components in the characterization of the reference spectroradiometer.

Parameter	Expanded Uncertainty (k=2)
Wavelength accuracy	– 0.1 nm
Bandpass variation	– 0.2 nm @ 5 nm, triangular
Stray light factor	< 2 x 10^{-6}
Polarization sensitivity	< 0.3 %
Temperature dependence	< 0.2 % after correction
Random noise	< 0.2 % of the max. value

3. Uncertainty Analysis

3.1 Spectroradiometer characterization

The uncertainty in the relative spectral radiance on the PTFE plaque, illuminated by a standard lamp and used to calibrate the spectroradiometer, is less than 0.3 %. The wavelength scale of the spectroradiometer has been calibrated by using a large number of emission lines from lasers and gas-filled lamps. A correction using a fifth order polynomial is applied to the wavelength control of the monochromator. After the correction, the expanded uncertainty of the wavelength scale of the spectroradiometer is 0.1 nm. The temperature dependence of the wavelength scale (less than 0.05 nm/K) is included in the stated uncertainty.

A triangular bandpass of 5 nm (FWHM) is used with a scanning interval of 5 nm. The slit scattering function (SSF) of the spectroradiometer is wavelength dependent, and the bandpass is not constant (~ 20 % change) over the visible region. This causes mismatches between the scanning interval and the bandpass that can lead to overestimation or underestimation of line spectra or sharp peaks in spectra. To minimize this uncertainty component, the center slit width is controlled at each set wavelength so that the bandwidth is constant to within 0.2 nm over the wavelength range from 380 nm to 780 nm.

The effect of stray light has been evaluated by various tests [6] and is found to be less than 10^{-6} in the visible wavelength region. The response of the PMT has been verified to be linear over the signal range from 10 pA to 20 nA with an uncertainty of 0.05 %. A correction factor is applied for measurements with a higher gain of the PMT than that of the calibration.

The responsivity of the PMT module is sensitive to ambient temperature. The change of PMT responsivity is also wavelength dependent, varying from -0.5 % to -4.0 % per degree C, as shown in Figure 3. Test measurements at several ambient temperatures indicate that the temperature dependence is linear at each wavelength. A correction is applied to the results to compensate for the difference between the calibration and measurement temperatures. The uncertainty due to temperature in the corrected relative radiance is less than 0.2 %.

The response of the spectroradiometer changes with the polarization status of the input flux up to 30 % if no diffuser or depolarizer is used. By using a custom-designed depolarizer [10], the maximum degree of polarization of the light incident on the PMT is 0.6 % in the 420 nm–780 nm range and 4 % in the 380 nm–420 nm range, as shown in Figure 4.

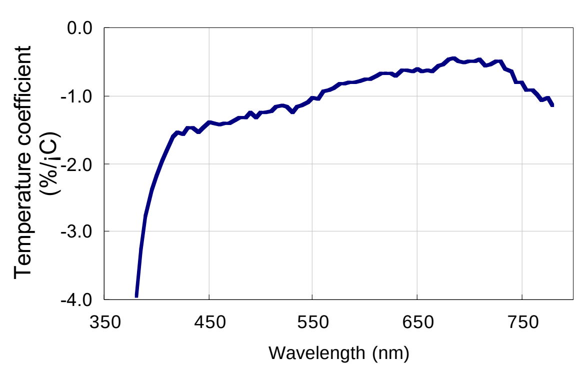

Figure 3. Temperature coefficient of the spectroradiometer response at the ambient temperature from 23°C to 25 °C.

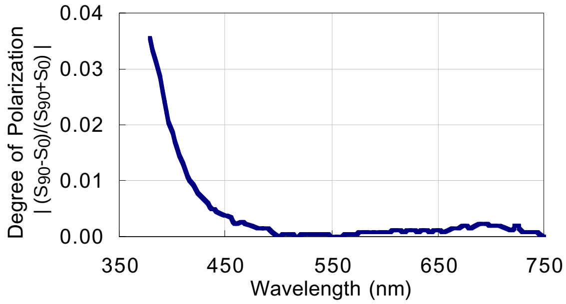

Figure 4. Polarization dependance of the spectroradiometer response.

Measurement noise can 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 the spectroradiometer itself. In this section we only consider the effect of the latter. The use of the depolarizer instead of a diffuser (to reduce polarization sensitivity) has considerably increased the signal to noise ratio of the measured spectral radiance. The relative standard deviation of a calibration of a CRT or LCD is typically less than 0.1 % of the maximum signal.

3.2 Uncertainty in display measurement

The uncertainty due to each of the components mentioned above was evaluated for the different spectral power distributions of CRT and LCD displays. Numerical methods [11, 12] and Monte Carlo simulations have been used to estimate the uncertainty in the measurement of each color of the displays.

Even with a constant bandpass, there is an effect of the bandpass on color measurements. Table 2 shows the results of a simulation of a spectroradimeter to calculate errors in chromaticity (x,y) due to a triangular bandpass of 5 nm. The results are not sensitive to variations in spectra among different models of CRT or LCD displays. Based on these results, corrections are made to all measured values, leaving a much smaller uncertainty component for the correction.

The main components contributing to the uncertainty of chromaticity (x, ˚y) values for the primary colors of an LCD device are given in Table 3. The largest component is due to the uncertainty of the wavelength scale of the spectroradiometer. This uncertainty was calculated using the numerical method [11], where a standard uncertainty component of 0.07˚nm was applied for all the wavelengths of measured data.

In Table 4, the expanded uncertainty (k=2) for the color measurements of a CRT display is given. The uncertainty of luminance, ΔY, is provided for the measurements using the working standards of the luminance unit at NIST. The different results for the two types of displays are due to the different spectral power distributions of their spectra.

3.3 Comparison measurements

To verify the uncertainty budget of the measurements and the performance of this facility, an intercomparison has been conducted within NIST. In this comparison, an integrating sphere source with a series of colored filters (red, green, and blue) was measured for spectral radiance with the spectroradiometer of this facility and with the NIST spectroradiometer at the Facility for Automated Spectral Calibrations (FASCAL) [8] that is used to

Table 2. Errors in chromaticity of CRTs and LCDs due to a 5 nm triangular bandpass of a spectroradiometer.

		White	Blue	Green	RED
CRT	ˇ x	0.0001	0.0000	0.0001	-0.0002
	ˇ y	0.0002	0.0002	-0.0004	0.0003
LCD	ˇ x	0.0000	0.0000	0.0001	-0.0003
	ˇ y	0.0003	0.0004	-0.0003	0.0003

Table 3. Uncertainty components for measurements of LCD devices pertaining to the reference spectroradiometer.

Components		White	Blue	Green	Red
Polarization effect*	$u(x)$	0.00008	0.00002	0.00004	0.00009
	$u(y)$	0.00014	0.00015	0.00010	0.00006
Temperature effect	$u(x)$	0.00010	0.00003	0.00006	0.00010
	$u(y)$	0.00015	0.00011	0.00014	0.00006
Repeatability incl. noise	$u(x)$	0.00004	0.00008	0.00009	0.00023
	$u(y)$	0.00011	0.00009	0.00026	0.00010
Wavelength scale*	$u(x)$	0.00032	0.00006	0.00022	0.00022
	$u(y)$	0.00052	0.00029	0.00052	0.00014
Effect of bandpass*	$u(x)$	0.00006	0.00006	0.00006	0.00006
	$u(y)$	0.00006	0.00006	0.00006	0.00006
Combined std. unc.	$u_c(x)$	0.00035	0.00012	0.00025	0.00035
	$u_c(y)$	0.00057	0.00036	0.00061	0.00020
Expanded uncertainty	$\boldsymbol{U(x)}$	**0.0007**	**0.0002**	**0.0005**	**0.0007**
	$\boldsymbol{U(y)}$	**0.0011**	**0.0007**	**0.0012**	**0.0004**

* After correction. Expanded uncertainty is with k=2.

Table 4. Expanded uncertainty (k=2) of color measurements of a CRT display with the reference spectroradiometer including the uncertainty of luminance unit at NIST.

CRT colors	White	Blue	Green	Red
$\boldsymbol{U(x)}$	0.0008	0.0005	0.0004	0.0007
$\boldsymbol{U(y)}$	0.0004	0.0004	0.0004	0.0004
$\boldsymbol{U(Y)}$ (%)	0.7	0.8	0.7	1.0

Table 5. The results of comparison measurements for an integrating sphere with interchangeable colored filters.

Display Spectroradiometer measurements (DSR)				
Inserted filter	No filter	Blue	Green	Red
x	0.4459	0.1700	0.2434	0.6974
y	0.4100	0.1350	0.6113	0.3023
FASCAL measurements				
x	0.4460	0.1705	0.2433	0.6970
y	0.4099	0.1348	0.6114	0.3026
Difference (DSR - FASCAL)				
Δx	-0.0001	-0.0005	0.0001	0.0004
Δy	0.0001	0.0003	-0.0001	-0.0003

maintain the official NIST spectral irradiance and radiance scale. FASCAL employs a prism-grating double monochromator with calibration traceable to a gold-point blackbody; further details are described in the reference. The comparison results are shown in Table 5, showing agreement within 0.0005 in *x, y*.

4. Goniometric color measurement

Using the goniometric color measurement capability, shifts of chromaticity and luminance as a function of viewing angle have been measured on a CRT and several different flat panel displays. Figure 5 shows the chromaticity coordinates of two recent models of LCD displays with the viewing angle varied from 0° to 80°. With increasing viewing angle, the chromaticity coordinates shifted toward the white point for LCD 1. For LCD 2, however, the colors are more constant with varied viewing angle.

Data were also taken to measure the effect of orientation of a CRT on its emitted color and luminance. When a CRT was turned horizontally in the range of 0¡ to 180¡, the luminance changed by up to 20˚% and chromaticity up to 0.002 in *x,y* for primary colors and white. Similar changes were observed when the CRT was moved sideways up to 60 cm.

These results illustrate some of the problems associated with using CRT and LCD displays as calibration standards. Consequently, colorimeters calibrated for displays are used as transfer standards for calibration services at NIST.

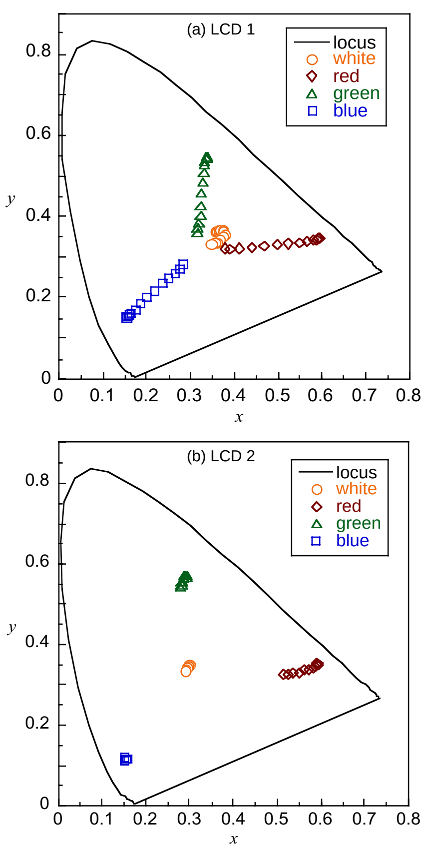

Figure 5. Goniometric measurements of the chromaticity of (a) LCD 1 and (b) LCD 2 with variable viewing angle from 0° to 80°.

5. Summary

The development of a calibration facility for spectroradiometric, colorimetric, and goniometric measurements of displays, display colorimeters, and spectroradiometers, has been completed at NIST. An overview of the facility and results of the characterization of the reference spectroradiometer and a comprehensive uncertainty analysis for measurements of CRTs and LCDs are presented. With the improvements in the calibration facility, the expanded uncertainties (k=2) of measurements for both CRTs and LCDs have been reduced to within 0.001 in *x, y* and 1˚% in ΔY —an improvement by a factor of two since our last report˚[5]. The calibration from the reference instrument is transferred to a test instrument by using a matrix correction technique, the Four-Color Method. Once calibrated against a particular display, the test instrument can make measurements of that type of display with uncertainties approaching those of the NIST reference instrument.

6. Acknowledgements

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