Realization and application of a detector-based tristimulus color scale at the National Institute of Standards and Technology, USA

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ABSTRACT

The recently introduced detector-based calibration method for tristimulus colorimeters has been realized. The NIST reference colorimeter has been calibrated for spectral irradiance responsivity with an uncertainty of 0.15 % (coverage factor k=2) resulting in a chromaticity uncertainty of 0.0004 (k=2) in the x and y chromaticity coordinates when a CIE Illuminant A source is measured. The color scale is realized and maintained by reference colorimeters rather than reference lamps. The color measurement uncertainty increases when sources other than Illuminant A are measured due to spectral mismatch errors of the channels. Variable reference source models have been developed so that the reference source for the colorimeter can be automatically matched to the measured test source of certain types. A model using Planckian radiation with a variable temperature has been tested and proved to be effective in eliminating the mismatch errors for incandescent lamps. Another model based on primary colors of a display has also been tested and shown to be effective.

1. INTRODUCTION

A reference tristimulus colorimeter has been developed at the National Institute of Standards and Technology (NIST) to implement the recently developed tristimulus colorimeter calibration method based on detector standards [1, 2]. The reference tristimulus colorimeter was designed such that the combined uncertainty of the color and photometric measurements is dominated by the uncertainty of the spectral responsivity calibrations. The spectral responsivities of the four colorimeter channels are closely matched to the CIE color matching functions (the f_1' values are 1.6 % for the Y and X_1, 3.6 % for the Z, and 4.1 % for the X_2 channels) to minimize additional uncertainties in color measurement. The channel spectral irradiance responsivities were determined with the lowest possible uncertainty using our laser-based facility to produce uniform monochromatic irradiance [3].

Based on the spectral irradiance responsivity of the channels, a colorimetric scale has been realized and maintained by the reference colorimeters instead of standard lamps. The detector-based color scale can be calculated for any given spectral distribution of a reference source, which can be either theoretical or real. Generally, CIE Illuminant A is used as the reference source. In this case, the uncertainty of measurement increases when sources other than Illuminant A are measured due to inherent spectral mismatch of the colorimeter channels (to the CIE functions). To avoid spectral mismatch errors, an approximate spectral distribution of the test source is needed. A need for a spectroradiometer for this purpose would negate the benefit of tristimulus colorimeters.

To solve this problem, a variable reference source model has been developed. This method, applied to certain types of source, avoids or reduces the spectral mismatch errors without knowledge of the spectral distribution of the test source. The spectral distribution of a model, used as the reference source in the colorimeter calibration equation (see below), is adjusted based on the color temperature or tristimulus values of the test source as measured by the colorimeter. A model using Planckian radiation at a variable temperature has been tested and shown to be effective for the measurement of incandescent lamps. A model based on the spectral distribution of each primary color of a liquid crystal display (LCD) has also been tested and shown to be effective for display color measurements.

2. DETECTOR-BASED CALIBRATION OF TRISTIMULUS COLORIMETERS

The spectral irradiance responsivities of the four colorimeter channels were determined on the new NIST facility for Spectral Irradiance and Radiance Responsivity Calibrations using Uniform Sources (SIRCUS) [3]. The measurement is traceable to an absolute cryogenic radiometer that maintains the NIST primary unit for optical power.

The continuously tunable output from several different tunable lasers was consecutively introduced into a small integrating sphere to produce uniform, monochromatic irradiance [3] at the reference planes of the tristimulus colorimeter and the reference trap detector. The spectral irradiance responsivity scale from the trap detector was transferred to the channels of the tristimulus colorimeter using the detector substitution method. The colorimeter signal gain was 10^8 V/A for all channels. The results are shown in Fig. 1; cubic-spline fits were applied for interpolation between the laser-measured data points.

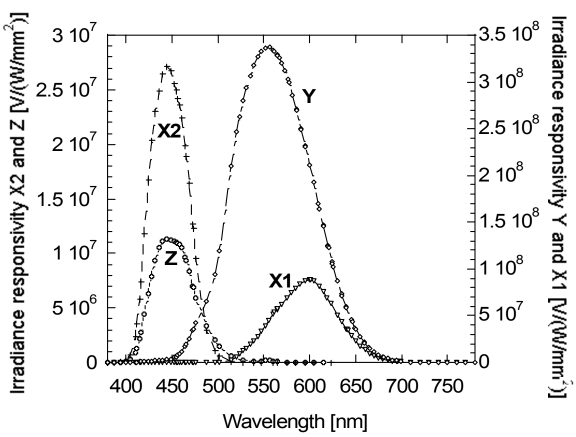

Figure 1: SIRCUS measured spectral irradiance responsivities of the reference tristimulus meter.

The responsivity transfer in the uniform monochromatic irradiance makes the calibration and application beam geometries equal. Furthermore, the uncertainty components caused by the changing internal reflectance patterns in the colorimeter (between calibration and applications) and spatial non-uniformities of the channel responsivities are reduced compared to lamp-monochromator-based calibrations. The relative combined expanded uncertainty (k=2) of the spectral irradiance responsivity transfer to the colorimeter was 0.15 %.

The low responsivity uncertainty made it possible to accurately calibrate the colorimeter channels for responsivity to tristimulus values. The channel broad-band (spectrally integrated) calibration factors have been calculated [2]:

$$k_{X1} = \frac{X_1}{I_{X1}} = \frac{K_m \int_\lambda E(\lambda)\bar{x}_1(\lambda)d\lambda}{\int_\lambda E(\lambda)s_{X1}(\lambda)d\lambda} \qquad k_{X2} = \frac{X_2}{I_{X2}} = \frac{K_m \int_\lambda E(\lambda)\bar{x}_2(\lambda)d\lambda}{\int_\lambda E(\lambda)s_{X2}(\lambda)d\lambda}$$

$$k_Y = \frac{Y}{I_Y} = \frac{K_m \int_\lambda E(\lambda)V(\lambda)d\lambda}{\int_\lambda E(\lambda)s_Y(\lambda)d\lambda} \qquad k_Z = \frac{Z}{I_Z} = \frac{K_m \int_\lambda E(\lambda)\bar{z}(\lambda)d\lambda}{\int_\lambda E(\lambda)s_Z(\lambda)d\lambda} \tag{1}$$

where $E(\lambda)$ is the relative spectral distribution of the reference source, $\bar{x}_1(\lambda)$, $\bar{x}_2(\lambda)$, $V(\lambda)$, and $\bar{z}(\lambda)$ are the CIE color matching functions, K_m is the maximum spectral luminous efficacy, 683 lm/W, $s_{X1}(\lambda)$, $s_{X2}(\lambda)$, $s_Y(\lambda)$, and $s_Z(\lambda)$ are the channel spectral irradiance responsivities, and λ is the wavelength. Both the responsivity measurements and the integrals were made between 360 nm and 1000 nm (the responsivity limit of silicon detectors). The calibration factors obtained for CIE Illuminant A are: $k_Y = 2.036$ lx/V, $k_{X1} = 8.359$, $k_{X2} = 8.769$, and $k_Z = 108.96$. The tristimulus values of test light sources were determined using these calibration factors:

$$X' = X_1' + X_2', \text{ where } X_1' = k_{X1} I_{X1}' \text{ and } X_2' = k_{X2} I_{X2}',\ Y' = k_Y I_Y', \text{ and } Z' = k_Z I_Z' \tag{2}$$

where I_{X1}', I_{X2}', I_Y', and I_Z' are the output signals of the channels for a given test source.

The 0.15 % responsivity uncertainty propagates to the tristimulus values of the measured test sources and result in uncertainties in the x, y chromaticity coordinates of 0.0004 when a CIE Illuminant A source is measured.

3. VARIABLE REFERENCE SOURCE MODEL

The low uncertainty of spectral responsivity measurements and the small spectral mismatch of the channel responsivities to the CIE color matching functions makes it possible to provide an accurate color scale to a tungsten lamp realizing CIE Illuminant A. However, when sources other than Illuminant A are measured, spectral mismatch errors are inevitable even with well-matched channel spectral responsivities. With the developed NIST colorimeter, the chromaticity errors for Planckian radiation from 2300 K to 3200 K are within 0.001. The errors for light sources other than tungsten lamps are estimated to be within 0.003 in *x, y*.

An advantage of the detector-based calibration method is that the calibration factors of the colorimeter can be determined for any spectral distribution including theoretical models. The error will be significantly reduced if an approximate spectral distribution of the test source is used as $E(\lambda)$ in Eqs. (1). However, use of a spectroradiometer for this purpose will negate the benefit of tristimulus colorimeters. An attempt has been made to use spectral distribution models to reduce or eliminate spectral mismatch errors with no prior information of the spectrum of the test source.

A model using Planckian radiation with a variable temperature T [K] has been introduced and tested. $E(\lambda)$ in Eqs. (1) is given by

$$E(\lambda) = k\lambda^{-5}\left[\exp(c_2/\lambda T) - 1\right]^{-1} \quad (c_2 = 1.4388\times10^{-2}\ \text{m}\cdot\text{K},\ k\text{: normalization constant}) \qquad (3)$$

The calibration factors in Eqs. (1) are initially calculated for T=2856 K (CIE Illuminant A). Then a test lamp is measured with the colorimeter and the color temperature T_1 is obtained. Next, T_1 is replaced in Eqs. (1) and the calibration factors in Eqs. (1) are recalculated, and the color quantities of the test source are recalculated. With this recalculation, the CCT (and thus the spectral distribution) of the reference source is nearly equal to that of the test source, realizing the condition of strict substitution. One time recalculation removes most of the errors for incandescent lamps, but two or three iterations can remove the mismatch error completely. There are only small remaining errors due to the small deviation of the spectral distribution of the test source from the theoretical Planckian curve. The residual errors for a quartz halogen lamp at color temperatures of 2300 K to 3200 K were found to be negligible (< 0.00002 in *x,y*) for our NIST reference colorimeter.

This model works perfectly for Planckian sources, and is also effective to some extent for other general sources, depending on the relative spectral responsivity of the channels.

Another model has been tested for display calibration. The spectral distribution of displays are very similar within each type of display, therefore their spectral distribution can be modeled. A model for a display is prepared as:

$$E(\lambda) = k_B S_B(\lambda) + k_G S_G(\lambda) + k_R S_R(\lambda) \qquad (4)$$

where $S_B(\lambda), S_G(\lambda), S_R(\lambda)$ are the relative spectral distribution of each primary color in a typical LCD or CRT. The mixing factors k_B, k_G, k_R are initially determined so that $E(\lambda)$ gives a white point at 6500 K and a test display is measured with the colorimeter. Based on the first tristimulus values measured, the mixing factors k_B, k_G, k_R are recalculated to give $E(\lambda)$ the same chromaticity coordinates as the measured values of the test source. Based on the new $E(\lambda)$, the color quantities of the test source are recalculated. A single iteration is sufficient. Additional iterations did not converge in our test. Using this process, the spectral distribution of the reference source $E(\lambda)$ is adjusted to be nearly equal to the test source. Although the

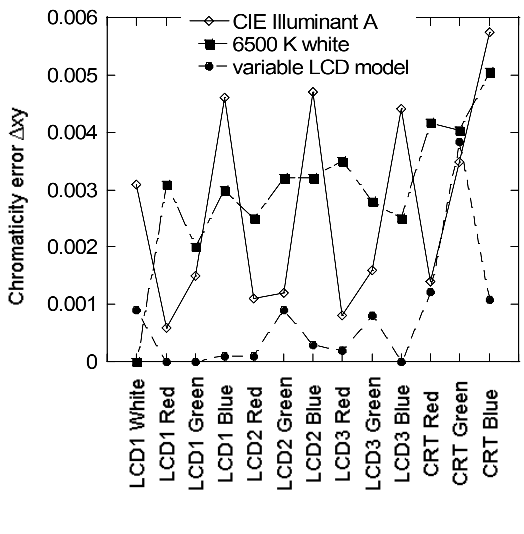

Figure 2: Chromaticity error $\Delta xy = \sqrt{\Delta x^2 + \Delta y^2}$ in the measurement of various display colors due to spectral mismatch of the NIST colorimeter, with various reference sources including the variable LCD model.

spectral distribution of each primary color of the measured display may not be exactly the same, they are very similar within each type of display, and most of the spectral mismatch errors are removed for a given type of display, regardless of the color measured. As a demonstration, Fig. 2. shows a simulation of measurements of three different LCD displays and one CRT, where the reference source model is based on the primary color spectra of LCD1. The results are shown for three cases where displays are measured with colorimeter calibration using Illuminant A, LCD1 white (6500 K), and the variable LCD model. The results for LCD1, shown as zero for all colors, are for verification. The results for LCD2 and LCD3, having slightly different spectra from LCD1, show that errors are reduced by an order of magnitude and kept within 0.001 in Δxy. The results for CRT, having very different spectra, are not improved as much.

4. TRANSFER CALIBRATION

Test colorimeters can be calibrated against the detector-based reference colorimeter under illumination by a reference (transfer) source. For a simple case, a CIE illuminant A source is used, but when the test colorimeter is used to measure other various sources, the spectral mismatch error can be significant. To avoid such errors, the transfer calibration needs to be done with the same type of source that is to be measured by the test colorimeter (strict substitution). If the source is one of the types described in the reference source models above (incandescent lamp, display), then such a real source can be used for calibration transfer. For other source types, the transfer calibration needs to be performed with a known approximate spectral distribution $E_a(\lambda)$ of the source to be measured. The reference colorimeter is calibrated with $E_a(\lambda)$ replaced in Eqs. (1), and determines the tristimuls values X_r, Y_r, Z_r of the source. The test colorimeter is calibrated against the X_r, Y_r, Z_r values. Such transfer calibrations for various sources can be done effectively by using a spectrally tunable source (STS) as reported in Ref. 4. The STS is set to simulate a given test source spectrum $E_m(\lambda)$, and the test colorimeter is calibrated against the reference colorimeter under that illumination. The STS can produce as many spectra as needed, and transfer calibration can be done for each type of source with very small spectral mismatch errors, without knowledge of the relative spectral responsivity of the test colorimeters.

5. CONCLUSIONS

The NIST reference tristimulus colorimeter has been calibrated for absolute spectral irradiance responsivity on our tunable-laser-based spectral calibration facility. The four channels of the colorimeter were calibrated with an uncertainty of 0.15 % (coverage factor k=2), which results in an uncertainty of 0.0004 (k=2) in the x, y chromaticity when measuring a CIE Illuminant A source. The color scale is realized and maintained by the reference colorimeters. For measurement of sources other than Illuminant A, variable reference source models have been developed to avoid or reduce spectral mismatch errors. The model using Planckian radiation at a variable temperature has been introduced and tested. Using this model, the spectral mismatch errors for incandescent lamps are practically eliminated. Another model based on the primary colors of a display has also been tested and shown to be effective. Other models are being explored to measure LEDs and other sources. The transfer calibration to test colorimeters can be performed with real sources used in the variable reference source models or by using a spectrally tunable source to avoid spectral mismatch errors.

References

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