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LED-based spectrally tunable source for radiometric, photometric, and colorimetric applications

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Abstract. A spectrally tunable light source using a large number of LEDs and an integrating sphere has been designed and is being constructed at the National Institute of Standards and Technology. The source is designed to have a capability of producing any spectral distribution, mimicking various light sources in the visible region by feedback control of individual LEDs. The output spectral irradiance or radiance of the source will be calibrated by a reference instrument, and the source will be used as a spectroradiometric as well as a photometric and colorimetric standard. A series of simulations have been conducted to predict the performance of the designed tunable source when used for calibration of display colorimeters. The results indicate that the errors can be reduced by an order of magnitude when the tunable source is used to calibrate the colorimeters, compared with measurement errors when the colorimeters are calibrated against Illuminant A. The source can also approximate various CIE daylight illuminants and common lamp spectral distributions for other photometric and colorimetric applications. [DOI: 10.1117/1.2127952]

Subject terms: calibration; color; colorimeter; display; light-emitting diode; light source; photometer; spectral power distribution; spectroradiometer.

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1 Introduction

The radiometric, photometric, and colorimetric properties of light sources play a vital role in a wide variety of human activities. Consequently, measurement of the relevant properties of the optical radiation, such as the spectral power distribution, illuminance, luminance, or color, is important. Photometric and colorimetric quantities of a light source can be measured with a spectroradiometer (calculated from its spectral power distribution) or with a photometer or a colorimeter that has a relative spectral responsivity approximated to the spectral luminous efficiency function $V(\lambda)$ or to the color-matching functions defined by the International Committee on Illumination (CIE).[1,2] The spectral correction filter is an essential component of a photometer or colorimeter. Colorimeters typically use three or four channels of detectors with filters to mimic the CIE color-matching functions as shown in Fig. 1. No photometer or colorimeter exactly matches its spectral responsivities to $V(\lambda)$ or the color-matching functions. For this reason, measurement errors are inevitable. These measurement errors can increase dramatically when the relative spectral power distribution (SPD) of a test source is dissimilar from that of the calibration source.

Consider color measurements of displays. Some measurement protocols for such measurements are available.[3,4] Colorimeters are normally calibrated against an incandescent standard lamp operated at ≈2856 K, approximating the CIE Standard Illuminant A. When the instruments subsequently measure different colors of a display, measurement errors can be significant. For example, interinstrument variations for chromaticity measurements of various colors

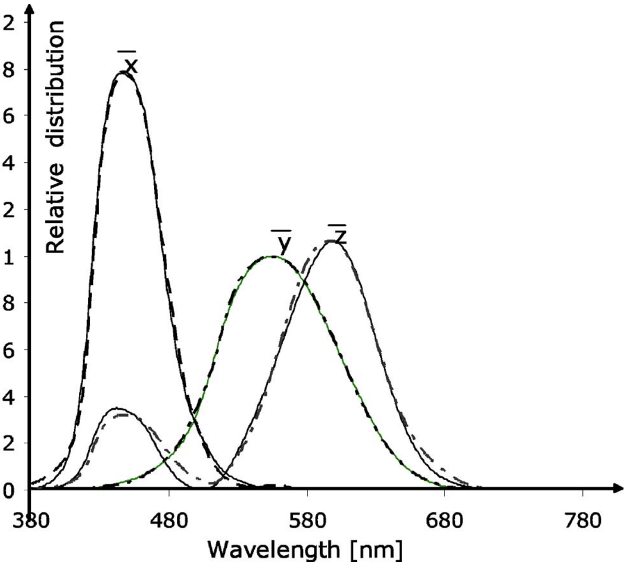

Fig. 1 CIE 1931 color-matching functions $\bar{x}$, $\bar{y}$, $\bar{z}$ (solid lines) and an example of a real colorimeter (dashed lines).

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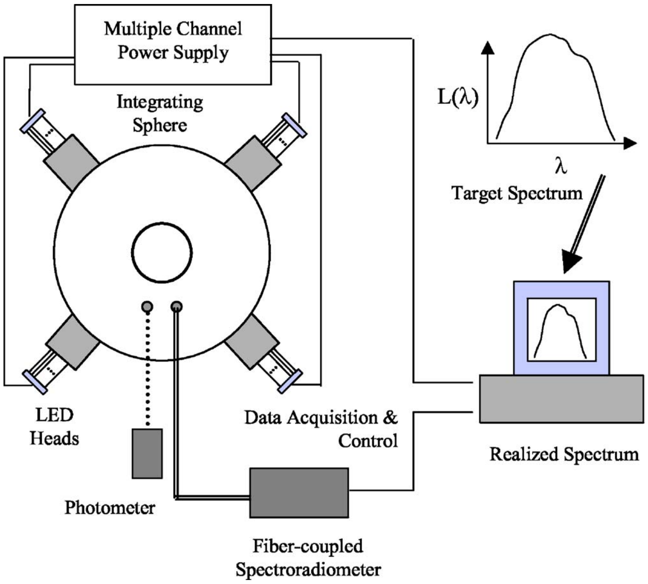

Fig. 2 Configuration of the STS designed and being developed at NIST.

of a display are often found as large as 0.01 in chromaticity (x,y) and 10% in luminance (Y) (corresponding to $\approx 10\Delta E^*_{\mathrm{ab}}$), while the manufacturers' specifications (specified for Illuminant A) are 0.002 in (x,y) and 2% in Y. Higher accuracies are needed in many applications. International standards,[5,6] for example, require measurement uncertainty of 0.005 or less in x, y and 4% or less for Y when measuring red, green, blue, and white colors of CRT or LCD displays.

Spectroradiometers theoretically do not have a spectral mismatch problem, but they are susceptible to measurement errors due to wavelength error, stray light, and bandwidth-related discrepancies. These radiometric measurement errors introduce errors in calculated photometric and colorimetric quantities similar to spectral mismatch errors in photometers and colorimeters.

A spectrally tunable source, capable of matching its SPD to a variety of light sources, including displays, would enable accurate and rapid calibration of a colorimeter or photometer used to measure various types of displays and other sources. Such a spectrally tunable source using multiple LEDs has been designed and is being constructed at the National Institute of Standards and Technology (NIST). A series of simulations have been conducted to predict the performance of the designed tunable source. The simulations indicate that the measurement uncertainties of colorimeters or photometers used to measure displays can be reduced by an order of magnitude compared with those achievable when the instruments are calibrated against Illuminant A. Similar reductions in the uncertainty in colorimetric and photometric measurements of other types of sources can be expected. Results of the simulations and the predicted performance of the spectrally tunable source are discussed.

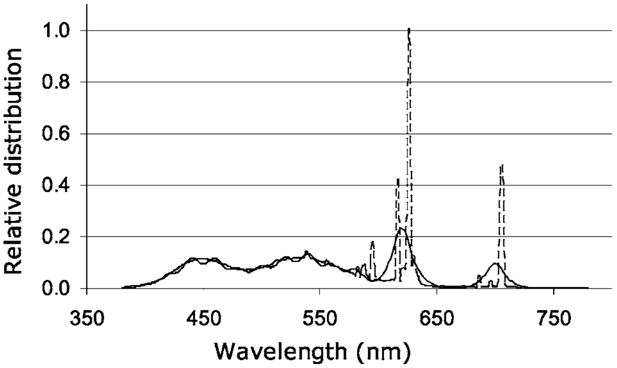

Fig. 4 SPD of a (white) CRT (dashed line) and the STS model with 20-nm LED intervals.

2 Applications of the Spectrally Tunable Source

Many photometry calibration facilities are equipped with large number of different standard sources of optical radiation, e.g., different types of lamps. Control and maintenance of these sources is very inconvenient and expensive. A spectrally tunable light source (STS) that can mimic different source spectral distributions would eliminate the need for maintaining a wide variety of different standard sources. Most instruments are calibrated against incandescent standard lamps that approximate a CIE Standard Illuminant A. The SPD of this source peaks in the infrared (IR), around 950 nm and is having relatively low power in the blue and ultraviolet region. This is not an ideal calibra-

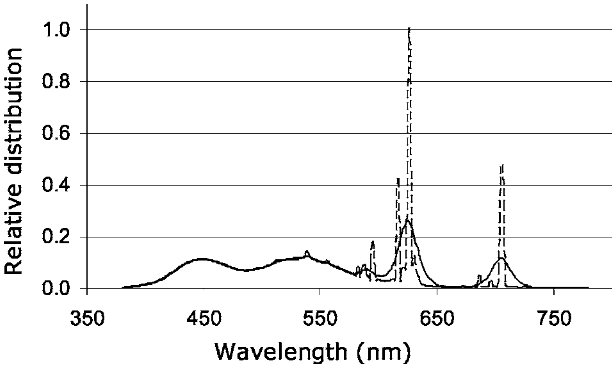

Fig. 3 SPD of a (white) CRT (dashed line) and the STS model with 5-nm LED intervals.

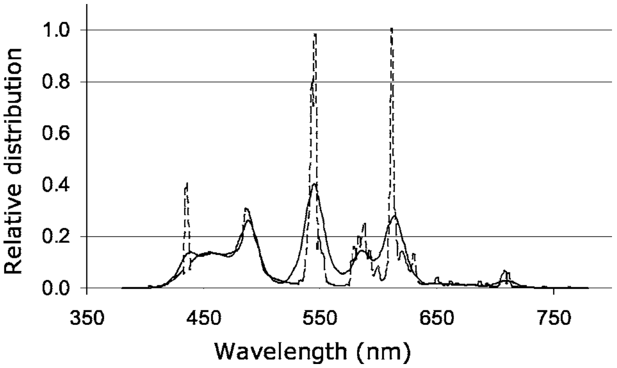

Fig. 5 SPD of a white LCD (dashed line) and the STS model at 5-nm LED intervals (solid line).

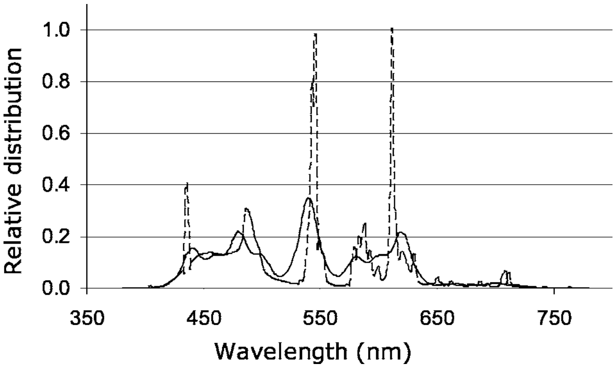

Fig. 6 SPD of a white LCD (dashed line) and the STS model with 20-nm LED intervals (solid line).

tion source for photometers and colorimeters, which have maximum responsivities in the visible region. This also means that calibration errors using these types of sources can arise from small leakage in colorimeter or photometer filter channels or stray light in spectroradiometers. When the STS is calibrated for absolute spectral irradiance or radiance, it can be used as a standard source for spectroradiometers as well as for colorimeters, and for photometers. It is not limited to one particular spectral distribution. For example, instead of approximating CIE Standard Illuminant A, an equienergy distribution or other CIE Standard Illuminants (e.g., D65), may be approximated by the calibration source. In addition to conventional standard source distributions, a STS could create source distributions that are close to the SPD of special sources such as display red, green, blue, and white; traffic signals; and discharge lamps. Also, a tunable source could approximate novel and unique spectral distributions that cannot be realized using conventional sources. Even object colors (such as color checker charts) under different illuminants can be approximated and used for colorimetric experiments. Since, in principle, the calibration setup would remain the same for different source SPDs, calibrations of photometers and colorimeters for different SPDs would be greatly simplified.

The STS has a special role in detector-based tristimulus colorimeter calibrations. The SPD of the test source is always included in the broadband calibration factors of the colorimeter channels.[7] Usually, a rough knowledge (or low-accuracy measurement) of the test source SPD is enough to obtain low color measurement uncertainty. The uncertainty of this detector-based color measurement will be dominated by the uncertainty of the spectral responsivity measurements of the channels.[7,8] The STS can be used to determine the required quality (the allowable spectral mismatch) for the test-source SPD used to obtain the broadband calibration factors of the tristimulus colorimeters.[7] The STS also can be used to propagate the reference color scale to field-level colorimeters with a minimum increase in the color measurement uncertainty. An advantage of this detector-based color calibration method is that only short-term stability is needed for the STS. Also, the STS can be relatively simple and inexpensive when it realizes the target source distribution with the allowable spectral mismatch. Using the STS, field-level tristimulus meters can be calibrated against the reference colorimeter with low color measurement uncertainty even if their relative spectral responsivities are not known.[8]

The STS will be useful for a number of radiometric applications as well. For example, a source that can mimic the solar spectral distribution will be useful in the calibration of sun photometers; one that can mimic the ocean blue color spectrum will be useful in the calibration of remote sensing instruments.[9] Generation of high-temperature blackbody radiators with different temperatures (up to 10,000 K) will be useful in reducing errors in stellar photometry.

3 Development of a Spectrally Tunable LED Source

A spectrally tunable source using a conventional lamp and monochromator with a multielement liquid-crystal filter has been reported.[10] This source suffers from low flux, especially in the UV, due to the SPD of the lamp. This means that, using a tunable source based on conventional lamps, it is difficult to get a good spectral match for the UV and blue region. A more efficient and more flexible option is to mix the luminous flux of several different LEDs. A source able to mimic a given color (or chromaticity), but not a given spectral distribution, has been reported as well.[11,12] A spectrally tunable source (STS) using a number of LEDs having different peak wavelengths has been designed at NIST to mimic the spectral distributions of a wide variety of light sources over the spectral range from 380 to 780 nm.

3.1 *Construction of the STS*

The STS is an integrating sphere source illuminated by a large number of LEDs having different spectral peaks and

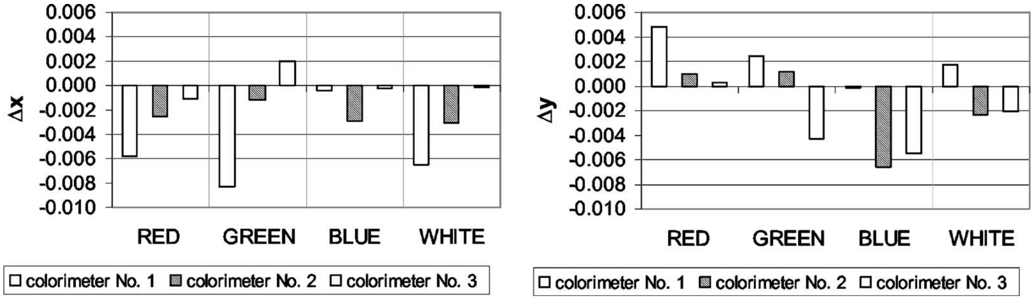

Fig. 7 Errors in chromaticity *x*, *y* when the three colorimeters measure LCD colors after calibration with Illuminant A.

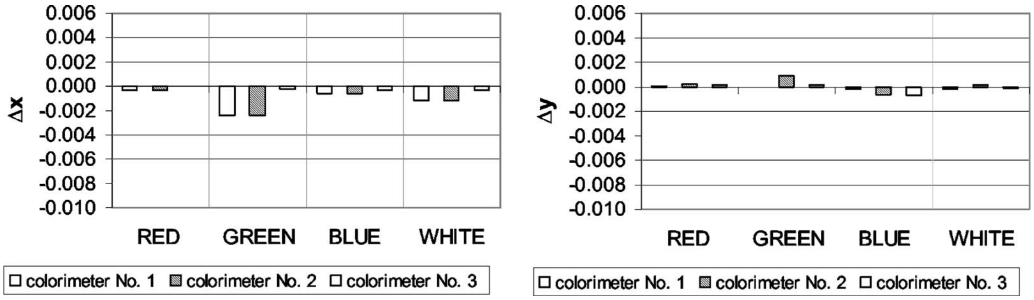

Fig. 8 Errors in chromaticity *x*, *y* when the three colorimeters measure LCD colors after calibration with the STS model using 5-nm LED intervals.

distributions, as shown in Fig. 2. 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 matching of fine structure in target source SPDs. A diode-array spectroradiometer and a photometer are used as monitoring devices to determine the real-time radiometric and 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 will be mounted in eight to ten heads (Fig. 2 shows only four heads) equipped with a temperature-controlled mounting plate to stabilize the LED temperature.

3.2 *Matching Algorithm*

Spectral radiance (irradiance) distributions of the LED-based source are realized using an optimization algorithm that calculates the difference between the spectral distribution of the STS and the target SPD for each wavelength. Different target SPDs for special sources, such as discharge lamps and displays, can be realized using an optimization algorithm based on the gradient method.[13] Extending this algorithm, the values of the power coefficients k_i, $i = 1, \ldots, n$, for the n different LEDs are determined. Note that the variable k is strongly related to the radiant flux from (or the current applied to) the LED belonging to that variable:

1. Select the initial values of power coefficients $k_i^{(0)}$, $i = 1, \ldots, n$, of the i'th LED. They can be any positive numbers.

In step 2 a recursion relation is described where the values of the variables k_i are determined in an iterative way:

2. Calculation of the j'th value of k_i from the $j-1$'th value is based on the partial derivative with respect to k_i of the square of the difference between the target spectrum and the STS spectrum built up from the LED spectra weighted by the variables k:

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

Iterations continue until the solution converges.

Step 3 sets the equality limits that determine the final values of the k_i:

3. If

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

then stop the iteration. This can be interpreted as saying that the algorithm stops when the values of k reach a steady-state solution. The equality in Eq. (2)

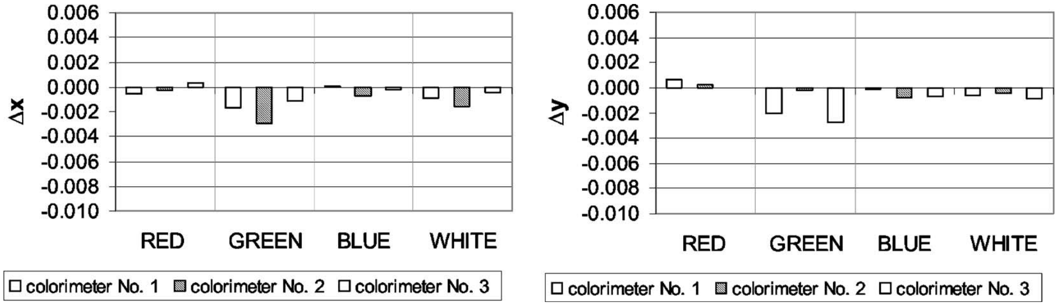

Fig. 9 Errors in chromaticity *x*, *y* when the three colorimeters measure LCD colors after calibration with the STS model using 20-nm LED intervals.

is obtained from a large number of iterations [Eq. (1)]

where the individual LED currents (power coeffi-

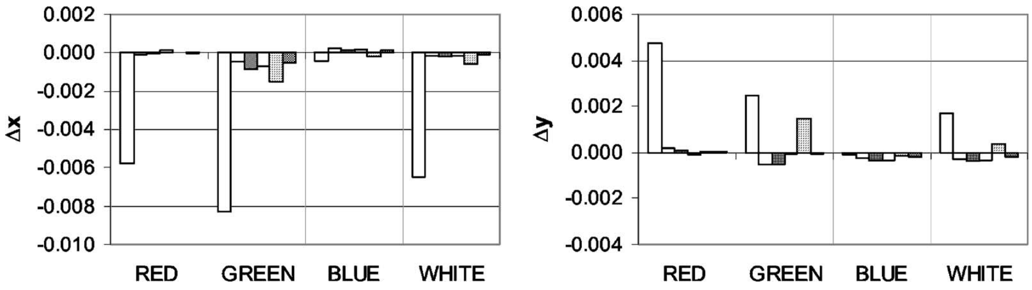

Fig. 10 Errors in chromaticity *x*, *y* when a colorimeter measures LCD colors after calibration with Illuminant A (the leftmost bar for each display color) and with the STS model using 5-nm LED intervals with random spectral deviations within ±5 nm (four sets of randomizations and no shift; next five bars with different shades).

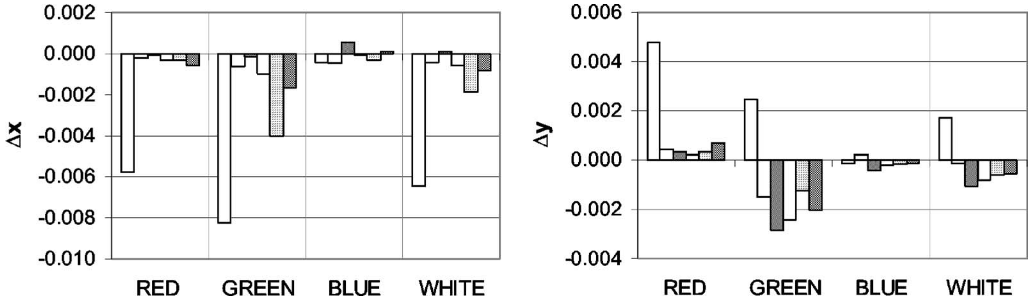

Fig. 11 Errors in chromaticity *x*, *y* when a colorimeter measures LCD colors after calibration with Illuminant A (the leftmost bar at each color) and with the STS model using 20-nm LED intervals with random deviations within ±5 nm (four sets of randomizations and no shift; next five bars with different shades).

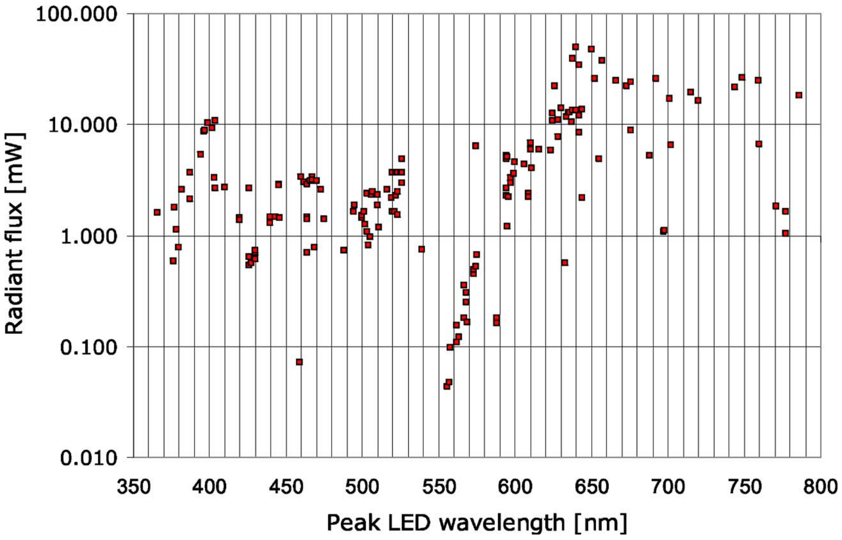

Fig. 12 Total radiant flux of the LED samples to be used for the STS, plotted as a function of their peak wavelengths.

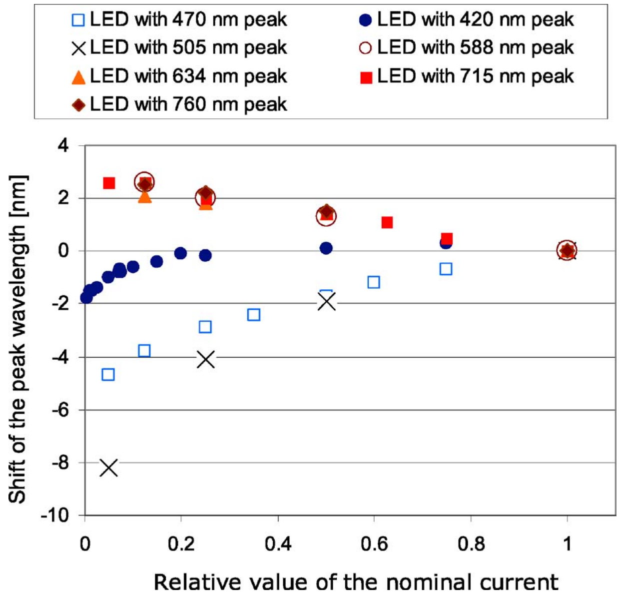

Fig. 13 Shift of the peak wavelength versus relative value of the LED's nominal current.

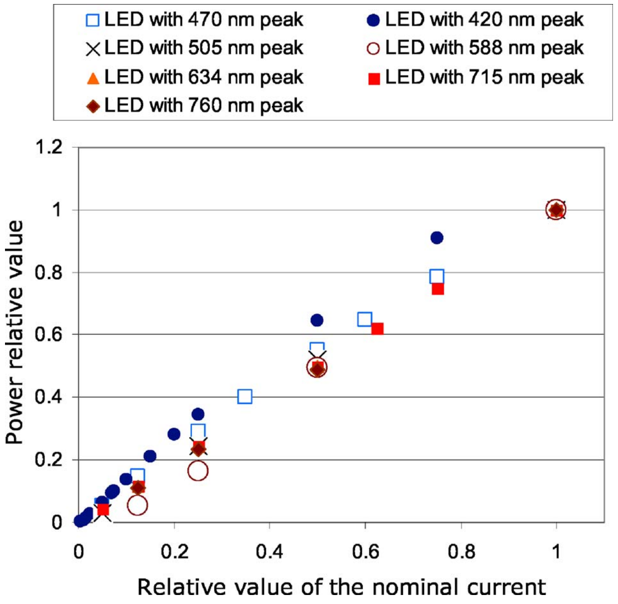

Fig. 14 Relative radiant power versus relative value of the current of the LEDs.

cients *k*) are increased or decreased in small increments (step 2). The coefficient for the step size (0.001) was determined empirically. The individual LED currents are obtained from that optimization. The sum of the differences at each wavelength [Eq. (2)] shows the quality of the realized spectral match.

3.3 *Simulation of the STS*

A series of simulations have been conducted to clarify design requirements, in particular to establish the number of LEDs necessary to match a source SPD for calibration purposes, and to predict the performance of the designed tunable source. The simulations evaluated the accuracies of calibrating colorimeters for various light sources (CRT and LCD) using LED models[14] based on a Gaussian function with spectral width (FWHM) of 20 nm. Simulations were run with 5-, 10-, and 20-nm intervals of LED peak wavelengths in the 380- to 780-nm region. Thus, a total of 80, 40, or 20 LEDs were used for the intervals of 5, 10, or 20 nm, respectively. The resulting spectrum, the sum of all model LEDs weighted according to the optimization given in Sec. 3.2, is referred to as an *STS model*. Figures 3 and 4 show the SPD of the STS model matched to a CRT display producing white color using model LEDs at 5-nm intervals (Fig. 3) and 20-nm intervals (Fig. 4). The figures depict the SPD of the original white display as well as that of the STS model. Figures 5 and 6 present the results for an LCD display presented in the same way.

In the next investigation, three different tristimulus colorimeters were analyzed for their measurement accuracy when using the STS model. All three colorimeters were first calibrated with CIE Illuminant A, then with the STS model (5- and 20-nm LED intervals). The errors in chromaticity x, y of display colors (red, green, blue, and white) measured by the colorimeters (calibrated by Illuminant A or the STS) were calculated. Figures 7–9 show the results, where the errors in x and y are presented in two separate graphs, comparing the results when the colorimeter is calibrated against Illuminant A (Fig. 7), the STS model at 5-nm LED intervals (Fig. 8), and the STS model at 20-nm LED intervals (Fig. 9).

As compared in Figs. 7 and 8, errors are generally reduced an order of magnitude when the colorimeters are calibrated with the STS (5-nm interval) than when calibrated with Illuminant A. Figure 9 shows that even 20-nm intervals for the STS model still work very effectively. In the case when the STS using LEDs with 20-nm FWHM has to match a spectrum having narrow peaks, it sometimes happens that the spectral responsivity of the given colorimeter and the spectral distribution of the STS optical signal can create a slightly larger measurement error (Fig. 8) than when Illuminant A was used as calibration source (LCD green color with colorimeter 2). Still, the measurement error is less than 0.005 in x and y.

While more and more LED types are becoming available, LEDs are not readily available in exact peak wavelengths at a given interval. To analyze the consequences of nonideal LED distributions, to be encountered when a real STS is developed, the reported simulation analysis was repeated with the peak wavelengths of the model LEDs shifted randomly within ±5 nm, centered around the wavelengths at given equal intervals.

Figures 10 and 11 show the results of this simulation for one of the colorimeters previously analyzed, plotting the errors in measured chromaticity coordinates of each color when the colorimeter is calibrated against Illuminant A and against the four STS models with different random deviations in LED peak wavelengths. The results show that the deviations in LED peak wavelength do not significantly compromise the effectiveness of reducing errors using the STS model (though errors increase slightly in some cases).

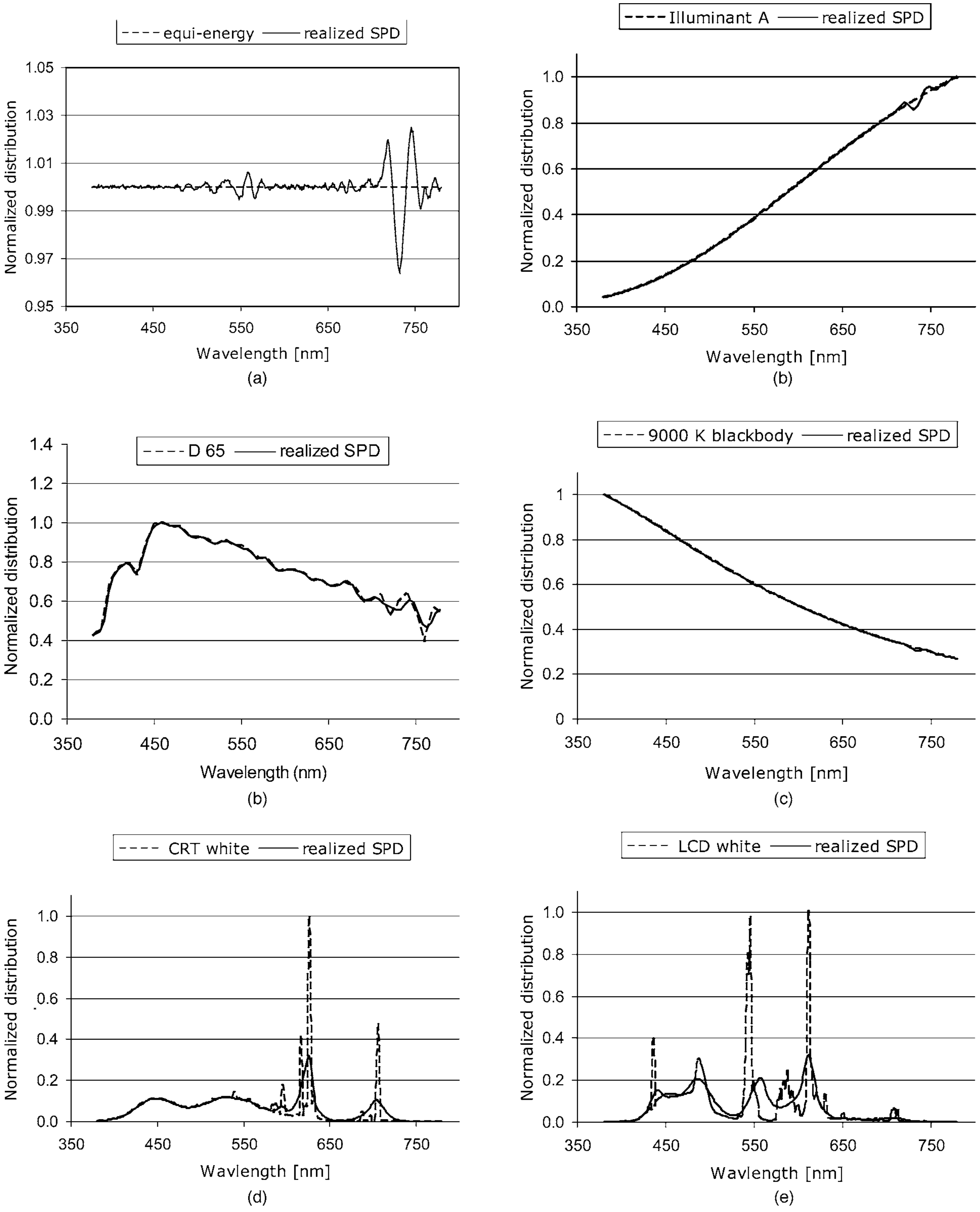

Fig. 15 Expected realizations of some specific SPDs—(a) equienergy, (b) Illuminant A, (c) Illuminant D 65, (d) 9000-K blackbody, (e) CRT display, (f) LCD display—created by the STS.

From studying the diagrams, it is obvious that much higher accuracy may be achieved when applying the STS, even with nonideal LED spectral distributions.

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 their characterization and incorporation into the source to improve their radiometric stability. Spectral measurements were made with a spectroradiometer between 190 and 800 nm as a function of drive current. LED characteristics vary significantly, depending on material composition and manufacturer. The following results show both the variability with LED color and the individual variations from the same batch. Figure 12 shows the values of radiant flux for these LEDs versus their peak wavelength. The measurements were made using a 0.5-m integrating sphere with calibrated standard LEDs with relative expanded uncertainty ($k=2$) of $\approx 5\%$. As shown in the figure, 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, LEDs between 525 and 555 nm (the so-called "green hole") are hard to procure (one LED at about 540 nm uses a phosphor). LEDs with output centered between 720 and 760 nm are also lacking. The shift in the peak wavelengths of representative LEDs as a function of drive current is shown in Fig. 13. Figure 14 shows the relationship between the relative radiant power of the LED and the relative current supplied to the LEDs.

4 SPD Realizations by the STS

The STS is designed to match any spectral distribution over the range from 380 to 780 nm. The matching of the SPDs is realized using the optimization algorithm described in Sec. 3.2, based on measurements by a reference spectroradiometer. The optimization takes a long time due to the large number of iterations of measurements and calculations involved. 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), and 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 depends on the specific spectral distribution, and is between one hundred and several hundred candelas per square meter.

Figure 15(a)–15(f) show the expected realizations of some specific SPDs (equienergy, Illuminant A, Illuminant D 65, 9000-K blackbody, and CRT and LCD displays) by the STS using the LEDs procured so far. Due to gaps in the availability of LEDs, some parts of the spectra cannot be well matched. But with the exception of the lack of LEDs near 550 nm, these imperfections are not considered serious for photometric and colorimetric calibration purposes. Also, due to the spectral width of LEDs, narrow peaks of spectra cannot be realized well. This shortcoming, also, is not so much of a problem for calibration purposes, as demonstrated in Sec. 3.3.

5 Conclusions

A spectrally tunable LED source has been designed and is being constructed at NIST. A series of simulations have been conducted to clarify design requirements and predict the performance of the designed tunable source. Results of the simulations for the calibration of colorimeters indicate that the errors in color measurements of displays can be reduced an order of magnitude compared with those when the colorimeters are calibrated against Illuminant A. The source can be used to transfer the photometric and colorimetric scales from reference instruments to test artifacts with minimal increase in uncertainty, not requiring various different types of real light sources. The source can also approximate various CIE daylight illuminants (D 65, etc.) and common lamp spectral distributions for other photometric and colorimetric applications, and may be useful for visual experiments on colorimetry.

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