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Assessment of Colour Measurement Systems Using Interference Filters

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ABSTRACT

Spectroradiometers and tristimulus colorimeters are used in display measurements to measure color in one of several color space coordinate systems. How well these instruments can measure the color coordinates can be simply checked by using interference filters. If a narrow-band interference filter is measured, the chromaticity coordinates obtained from the instrument should fall very near the spectrum locus of a standard color space. Assuming the instrument is linear and the white point calibrated accurately, if the colors on the spectrum locus are measured correctly, then all other colors within the color gamut should be measured accurately. The filter bandwidth and background noise in the instrumentation are modeled and shown to contribute to the distance of the color coordinates from the spectrum locus. Error sources within the measuring system are identified which could explain these observed anomalies. This method serves as a diagnostic tool, not a calibration.

1. INTRODUCTION

Spectroradiometers and tristimulus filter colorimeters are often used to measure chromaticity coordinates of electronic displays in a standard color space. However, these instruments can introduce errors caused by such sources as a spectral mismatch of the filters from the theoretical Commission Internationale de L'Eclairage (CIE) color matching function, or background subtraction errors [1].

This paper describes a simple and relatively inexpensive diagnostic test which can be performed to provide some assurance of proper colorimetric performance of the instrument. If the instrument has been calibrated at known white point (such as from a calibrated source), and the instrument can accurately measure several points along the spectrum locus and if one can demonstrate that the instrument is linear, then the operator should feel comfortable with the ability of the instrument to measure not only highly saturated colors, but any color point within the spectrum locus.

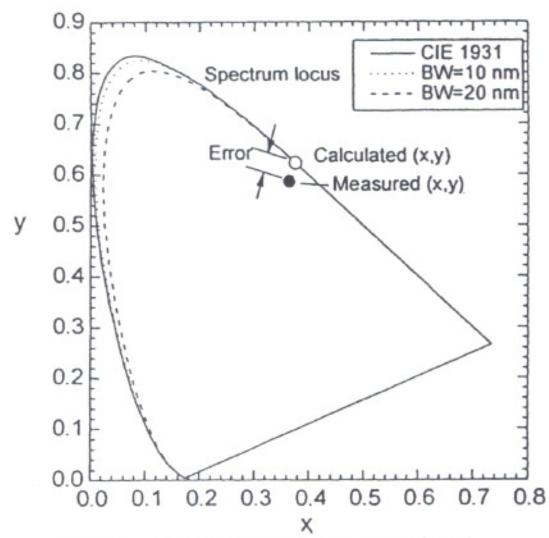

Figure 1. Comparison of measured and calculated chromaticity coordinates for interference filters

Narrow-band interference filters can be used to determine the ability of the instrument to measure highly saturated colors. The distance from the measured chromaticity coordinates to the spectrum locus depends upon the bandwidth of the illumination and the errors of the measuring instrument (see Fig. 1). If the measurements do not fall on the locus, this can point to limitations of the instrument. The results obtained from these interference-filter measurements can reveal instrumentation limitations.

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2. APPARATUS

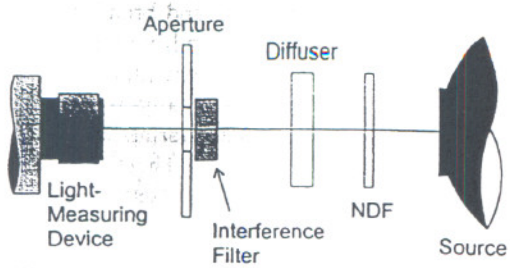

Figure 2. Apparatus (distances not to scale)

Figure 2 shows the arrangement of the apparatus used. A spectroradiometer or colorimeter with imaging optics views the central part of the interference filter. An aperture is provided to ensure that the edge of the filter is not used in the measurement (the filter can be non-uniform in the outer diameter region). A light-transmitting diffuser made of opal glass is used to provide uniform illumination. An optional neutral density filter (NDF) can be used to attenuate the light if it is too bright or to test the uniformity of the results with a change in light intensity. The light source can range from a simple incandescent lamp to an integrating sphere source.

At least three sources of error need to be considered with the measurement configuration: the characteristics of the interference filter, the dispersion introduced by light which is not parallel to the normal of the interference filter, and an overall error in establishing the normal direction of the interference filter. These errors would cause the data to shift from the calculated values. Additionally, the bandwidth of the spectroradiometer may limit the ability to approach the calculated values, and background light or scattering within the instrument could be a factor. For now, we will assume such a background is controllable and negligible.

2.1 FILTER CHARACTERISTICS

The most important filter parameters of concern are wavelength, bandwidth, and out-of-band leakage. Filters with a bandwidth of b = 10 nm or less with center wavelength tolerances of ± 2.0 nm are inexpensive and readily available for various wavelengths. Filters with narrower bandwidth are available, but at higher cost. Larger bandwidths move the measured point inward away from the spectrum locus, effectively reducing the color gamut (see dashed lines in Fig. 1).

The most rigorous way to evaluate the measured results would be to have the interference filters calibrated for spectral transmittance immediately before measurements are made, and compared with the calculated chromaticity coordinates. When this method is not available, data provided by the filter manufacturer can be used. When the manufacturer's data are used, one should consider that the filter characteristics are subject to long-term drift and temperature dependency.

The central wavelength changes linearly with variations in ambient temperature, usually between 0.015 nm/°C to 0.03 nm/°C [2]. Since most laboratory environments are temperature- controlled around 21.0 °C to 23.0 °C, this effect can be ignored. To avoid heating of the filter due to the radiant heat of the source, it is best to place the mirrored side of the filter (an absorptive blocking layer) facing the source. Most of the radiant heat will be reflected away from the rest of the filter layers.

Wavelength drift may occur over time due to the external environment (such as prolonged exposure to high temperature or humidity) or an inherent instability in the filter itself [3]. Special processes are used by manufacturers to improve the stability, including baking and sealing the filter. Filters typically drift on the order of 0.05 nm/year, keeping well within the resolution of most spectroradiometers for display measurement use.

2.2 DIVERGENT ILLUMINATION

Using the simple lens configuration of Fig. 3, the detector object is related to the image of the detector in the region of the interference filter or beyond – the point of focus of the instrument.

Often the measuring instrument has a viewing area that has a hole or disk corresponding to the measured region. The instrument should

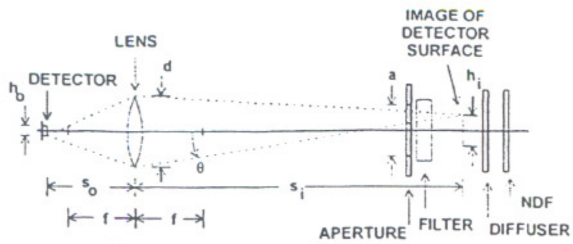

Figure 3. Lens configuration

be focused on or near the diffusion screen or light source, at infinity, or even on the surface of the interference filter itself. The dashed lines represent the cone of light rays that combine to illuminate one point on the detector. In this case, the extreme edge point is shown. The maximum angular deviation from the normal of a light ray entering the detection region is given by θ. Assuming a perfect alignment of the instrument optical axis with the normal of the interference filter, the simple lens equation

$$\frac{1}{f}=\frac{1}{s_o}+\frac{1}{s_i} \tag{1}$$

and the geometry of the apparatus provides an expression for the maximum angular deviation owing to the finite aperture of the detector (recall, $h_i/h_o = s_i/s_o$):

$$\theta = \arctan\left[\frac{1}{s_i}\left(\frac{h_i}{2}+\frac{d}{2}\right)\right] \tag{2}$$

This reduces to θ_∞ = arctan $(h_o/2s_o)$ when the instrument is focused at infinity. θ_∞ is simply the instrument aperture viewing angle for the detector, typically 1° or smaller. The central wavelength is given by

$$\lambda_\theta = \lambda_0\left[1-\left(\frac{n_0}{n}\right)^2 \sin^2\theta\right]^{\frac{1}{2}} \tag{3}$$

where n_0 is the refractive index of the medium surrounding the filter (in this case, air), n is the effective refractive index of the filter, and λ_0 is the central wavelength at normal incidence. (For a further discussion of optical thin-film theory and calculations, see [4].)

As the instrument is brought closer to the filter, the maximum angle of incidence increases, shifting the central wavelength and broadening the bandwidth. This shift and broadening are usually smaller than the full-width at half-maximum (FWHM) bandwidth of the interference filters used, typically b = 10 nm. If we move the instrument farther back from the filter, the shift is less. Therefore, if we exercise reasonable care in setting up the experiment, the shift and broadening introduced by the divergent illumination are entirely negligible

2.3 OPTICAL ALIGNMENT

Another error can result from the misalignment of the instrument optical axis with the normal of the filter. As the axis tilts, the effective optical path through the interference filter increases, broadening the bandwidth and decreasing the central wavelength. The broadening is a result of the divergent light passing through the filter from all angles. The bandwidth does not increase perceptibly until at least θ = 25°. Thus the bandwidth is essentially determined by the intrinsic bandwidth of the filters employed, b = 10 nm. The central wavelength changes according to equation 3, with θ being the off-axis angle. If we use the retro-reflective technique (see section 4), it is unlikely that an error greater than 1° will result; and any wavelength shift error is negligible. If the filter is not aligned with this technique, the off-axis angle can be much longer, producing a shift that may be significant.

3. LINEARITY TEST PROCEDURES

To verify the linearity of the spectroradiometer or colorimeter for color measurements, two integrating spheres with a two-aperture system between the source sphere and the measurement sphere were used (see Fig. 4). A different wide-band filter was placed over each aperture, and the chromaticity coordinates with both shutters open (position "C") and with one shutter open at a time (positions "A" and "B") were measured. If the device is linear, the resulting coordinates should fall in a straight line when plotted (see Fig. 6), and the luminance at each position should be additive ($L_C = L_A + L_B$). Alternatively, additive tristimulus values would indicate linearity (i.e., $X_C = X_A + X_B$).

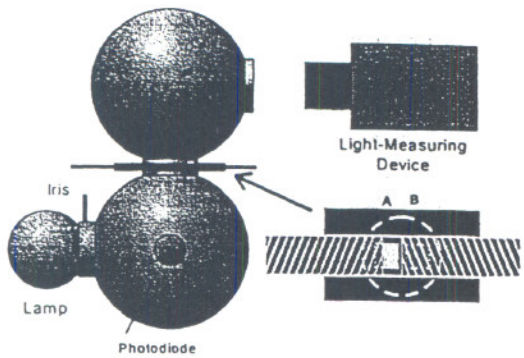

Figure 4. Color linearity apparatus

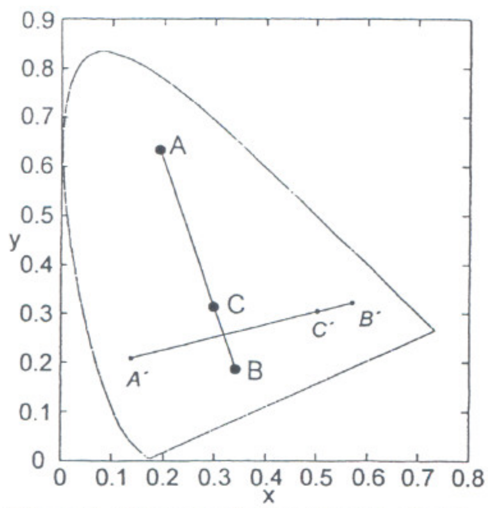

Figure 5. Chromaticity coordinates of wide-band filters using an A+B shutter.

Keep in mind that each shutter configuration could cause slight changes in the integrating sphere response. A photodiode was used to monitor luminance changes in the source sphere (see Fig. 5). To determine the worst case error, we measured the luminance at each position with a glossy white shutter. We found the errors to be approximately 2% using 150 mm diameter spheres.

One method for indicating colinearity of the chromaticity coordinates is to show that they are linearly related:

$$x'_C = x_A + k(x_B - x_A) \tag{5}$$

and

$$y'_C = y_A + k(y_B - y_A), \tag{6}$$

where x and y are the chromaticity coordinates of the measured colors in CIE 1931 color space, x'_C and y'_C are the calculated chromaticity coordinates for the combined color, and

$$k = (1 + y_B L_A / y_A L_B)^{-1} \tag{7}$$

How far the measured values x_C and y_C deviate from x'_C and y'_C give an indication to how non-linear the light-measuring device (LMD) may be. If the luminances are additive, $x'_C \neq x_C$ and $y'_C \neq y_C$, this would point to an error in color measurement. For a set of quasi-orthogonal color measurements (as in Fig. 5), if the above equations are verified by measurements, the linearity of the device for color measurements is suggested. In the case for the instruments used in these measurements, two sets of data (green-magenta and blue-orange) were measured, and indicated a color space linearity of 1% or less.

4. INTERFERNECE FILTER MEASUREMENT PROCEDURES

For our measurements, we set up the configuration shown in Figs. 2 and 3. We set s_i to be from 50 cm to 1 m, depending upon the instrument. Initially, we placed an aperture in front of the interference filter to be sure the edges of the filter are not contributing to the light output. Light from that region can bounce off the lens, off the filter, and back into the lens to contribute to the measurement. We found that this effect was negligible.

A filter holder was chosen which would ensure that each filter used would be placed in the same position. We used the reflection of the lens of the spectroradiometer in the interference filter to align the optics. Once this alignment was made, the holder was not repositioned. Room lights and monitor illumination were shown to contribute, so light reflecting off walls and other objects in the room can be a factor. We eliminated all background illumination as much as possible and shrouded the apparatus with black felt to avoid any stray light. When shrouding the apparatus, we found it necessary to be careful not to heat up the filter and thus cause a wavelength shift.

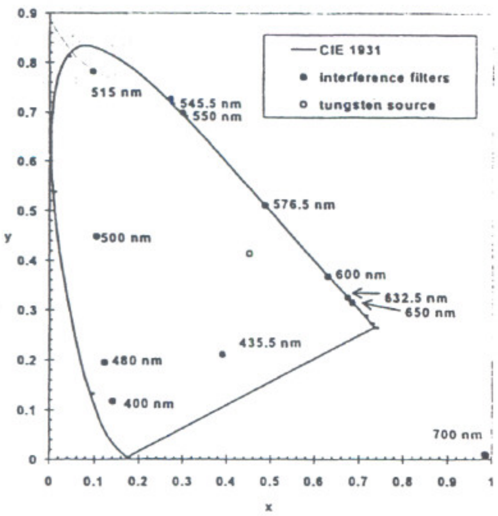

Figure 6. Chromaticity Measurements with colorimeter A.

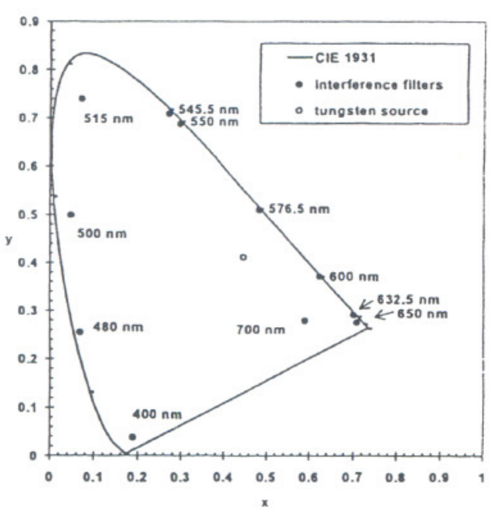

Figure 7. Chromaticity Measurements with spectroradiometer B.

Using a commercial diode-array type spectroradiometer and a tristimulus colorimeter, the luminance and chromaticity coordinates were recorded for a selection of interference filters and plotted on the CIE 1931 chromaticity diagram to see how close they come to the spectrum locus. In the case of the two spectroradiometers, the dominant wavelength, spectral purity, radiometric transmittance, and spectral response were also recorded. Enough readings were taken for each filter to obtain some understanding of the repeatability of the measurement.

5. RESULTS

Typical data are plotted in Figs. 6 and 7. The instruments had not been calibrated for color measurements for several years. All instruments measured a tungsten source with a (Δx, Δy) variation of (±0.003, ±0.001), but we observed an apparent shift away from the locus, when compared to the calculated values based on the measured filters. However, the spectroradiometer exhibited a different behavior from the colorimeter.

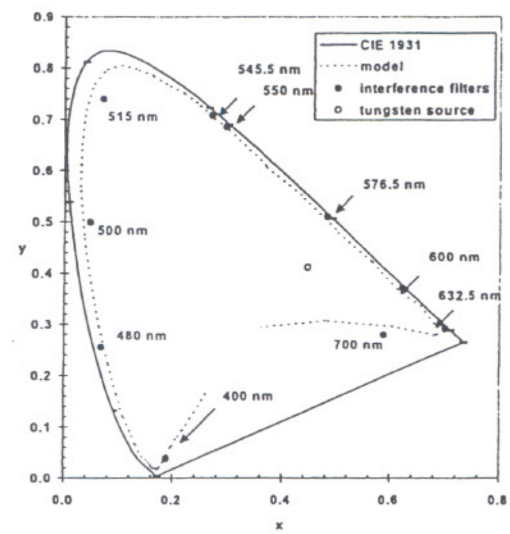

Figure 8. Model data versus measured data for spectroradiometer B.

6. EXAMPLE OF DIAGNOSTICS

For the wavelengths between 480 nm to 500 nm and 540 nm to 650 nm, the spectroradiometer data fall fairly close to the spectrum locus. The data in other regions are further away from the locus. These results suggest effects caused by the bandwidth of the filters, stray light and background noise. In many instruments a background noise is subtracted from the measured data, giving rise to negative data. Some instrument algorithms truncate the negative values to zero to avoid the confusion of having negative spectral data or the possibility of a data point appearing outside of the color space. This is indeed the case for several of the spectroradiometers we observed. Thus the background contribution to the measured data is not completely eliminated, and causes the measured point to move away from the locus toward the center.

A simple model illustrates the shift caused by the negative value elimination. The dashed line in Fig. 8 shows the locus of a Gaussian-shaped spectral distribution with a full-width half-maximum equal to the bandwidths of the interference filters. Noise clamped to eliminate negative values was added to the distribution that was characteristic of the noise measured by the spectroradiometers. Figure 8 also illustrates how well the model compares to the measured data.

The inward curving at the ends of the visible spectrum are most sensitive to these sources of error due to the relative contributions of the tristimulus values. It should be noted that in this case, the noise contribution overshadowed any bandwidth effect. The signal-to-noise ratio of the spectroradiometer is greater in the middle of the visible region and is thus less effected by noise-induced errors. Figure 9 illustrates how other errors can contribute to the measured value deviation from the calculated value.

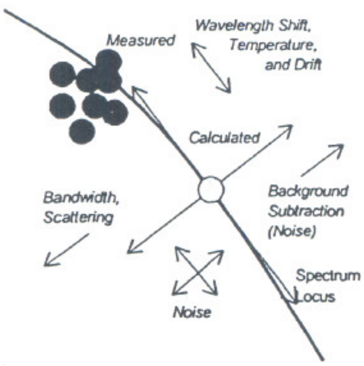

Fig. 9. Model for Analysis of Error

7. CONCLUSIONS

Having a spectroradiometer or colorimeter calibrated at a white point doesn't guarantee that the instrument will measure all colors equally within the gamut. If the instrument has a calibrated white point, the linearity and interference filter diagnostics suggested here will provide some confidence of the instrument's performance.

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