15.3: Interference-Filter Characterizaton of Spectraradiometers and Colorimeters

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Abstract

Spectroradiometers and colorimeters are used in display measurements to measure color in one of several color space coordinate systems. How accurately these instruments can measure the color coordinates can be simply tested by using interference filters. Error sources within the measuring system are identified which could explain several observed anomalies.

Introduction

Photodiode-array type spectroradiometers and tristimulus colorimeters are often used in display measurements to measure chromaticity coordinates on a standard color space such as the Commission Internationale de L'Eclairage (CIE) 1931 color space. Some aspects of the accuracy of such color measuring instruments can be simply checked by using interference filters. If pure monochromatic light, such as from a laser, is measured, the (x,y) coordinates obtained from the instrument should fall very near or on the spectrum locus. Similarly, if a narrowband interference filter is measured, then the measured chromaticity coordinate should also be close to the spectrum locus. The idea is that, assuming the instrument is linear, if the colors on the spectrum locus are measured correctly, then all other colors within the color gamut should be measured accurately.

The distance from the measured chromaticity coordinates to the spectrum locus depends upon the bandwidth of the illumination, and the errors of the measuring instruments (see Fig. 1). Based on the results obtained from the interference filter measurements, we intend to determine an upper bound of possible errors of the measuring instruments within the entire color gamut.

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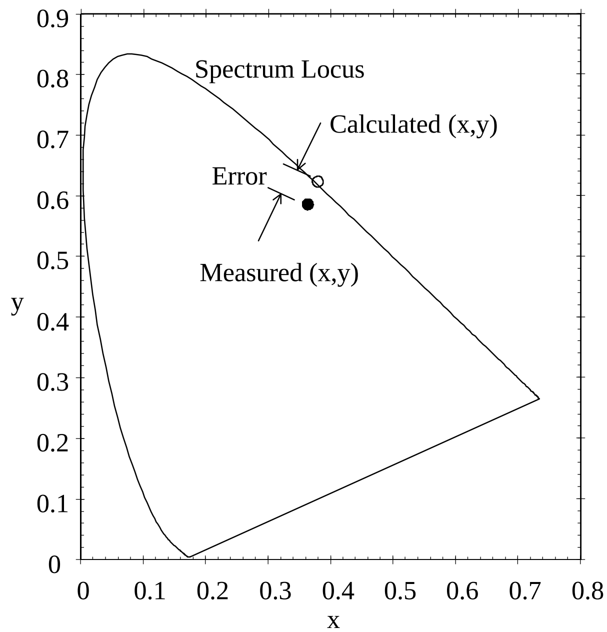

Fig. 1. Comparison of measured and calculated chromaticity coordinates for interference filters.

Apparatus

Figure 2 shows the arrangement of the apparatus used in the interference filter measurements. A spectroradiometer or colorimeter with imaging optics views the

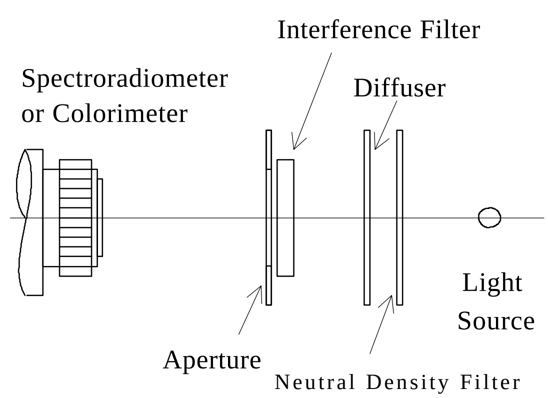

Fig. 2. Apparatus configuration.

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central part of the interference filter. An aperture is provided to ensure that the edge of the filter is not used in the measurement (this outer diameter region is where the filter can be nonuniform). A light-transmitting diffuser made of opal glass is used to provide uniform illumination. An optional neutral density filter 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 be an incandescent lamp or an integrating sphere source.

A simplified geometry of the apparatus is shown in Fig. 3. There are at least three sources of errors associated 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. Any background light or scattering within the instrument could be an additional factor. For now, we will assume such a background is controllable and negligible.

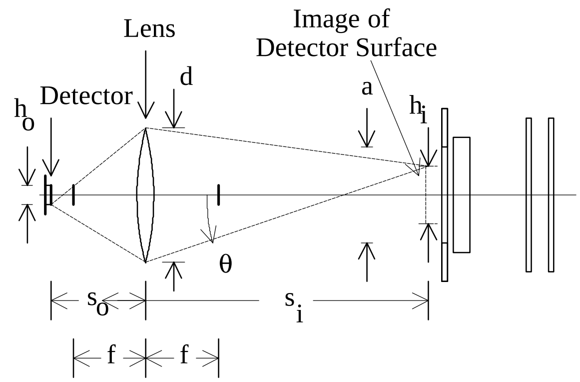

Fig. 3. Simplified geometry of apparatus.

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. Narrower-band filters are available at higher cost.

The central wavelength changes linearly with variations in ambient temperature, usually between 0.015 nm/°C to 0.03 nm/°C [1]. 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.

The most rigorous way to evaluate the measured results would be to have the interference filters calibrated for spectrum 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 data are used, one should consider that the filter characteristics are subject to long-term drift and temperature dependency.

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 – the focus point of the instrument. Often the measuring instrument has a viewing area that has a hole or disk corresponding to the measured region. The instrument is focused on the interference filter itself. The dashed lines represent the cones of light rays that combine to illuminate one point on the detector. In Fig. 3, 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. The central wavelength, λ_θ, at angle of incidence θ is given by

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

where n_0 is the refractive index of the medium surrounding the filter, n is the effective refractive index for the filter, λ_0 is the central wavelength at normal incidence. (For a further discussion of optical thin-film theory and calculations, see [2].) For a worst case we can observe a shift of 3 nm for a 700 nm filter. Thus, an upper limit on the shift and bandwidth broadening of the interference filter is approximately $\delta\lambda = -3$ nm or less. 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 is entirely negligible.

Optical Misalignment

A second 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 Eq. 1, with θ being the off-axis angle. Again, unless we are deliberately careless, it is unlikely that an error greater than 1° will result; so, again, any wavelength shift error is negligible.

Procedures

To verify the linearity of the spectroradiometer, an integrating sphere with a two-aperture system between the source and the sphere is used. A different wideband filter is placed over each aperture, and the chromaticity coordinates with both shutters open and with one shutter open at a time are measured. The resulting calculated tristimulus values are found to be additive. 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.

For our measurements, we arranged the elements as shown in Figs. 2 and 3. We set s_i to be from 50 cm to 1 m, depending upon the instrument. 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. We eliminated all background illumination as much as possible and shrouded the apparatus with black felt to avoid any stray light.

Using two commercial diode-array type spectroradiometers and a tristimulus colorimeter, the luminance and chromaticity coordinates were recorded for a selection of interference filters (with bandwidth less than 10 nm) and plotted the data on the CIE 1931 chromaticity diagram to see how close they come to the spectrum locus. In the case of the spectroradiometers,

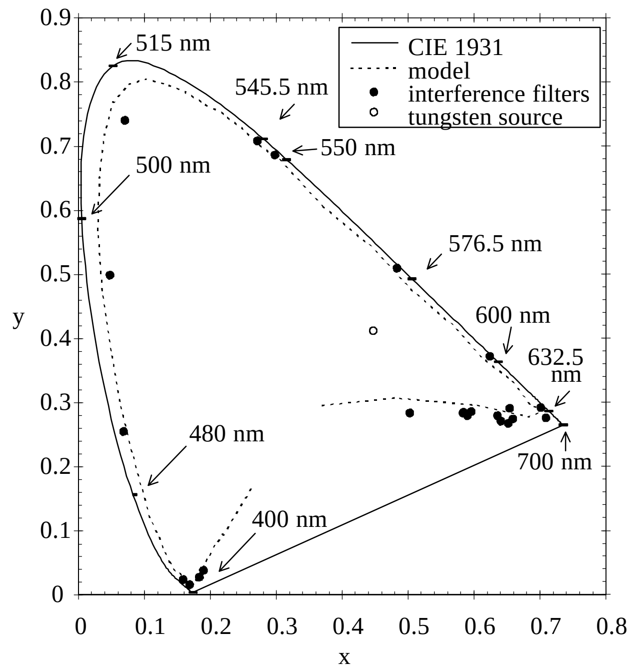

Fig. 4 Measurement of chromaticity coordinates of various interference filters using a spectroradiometer.

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 stability of the measurement.

Results

Typical data are plotted in Fig. 4. All instruments measured a tungsten source with a (Δx, Δy) variation of (±0.003, ±0.001), but we observed an apparent shift of the data away from the locus and along the locus, when compared to the calculated values based on the filter values. However, the spectroradiometers exhibited a different behavior from the colorimeter. It is on this former data that we focus our attention.

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.

Figure 5 shows the breakdown of some typical raw data taken during the light measurement and dark cycles of the spectroradiometer, respectively, and the difference. The dark cycle noise consists mostly of dark current noise. The difference between light and dark can reveal

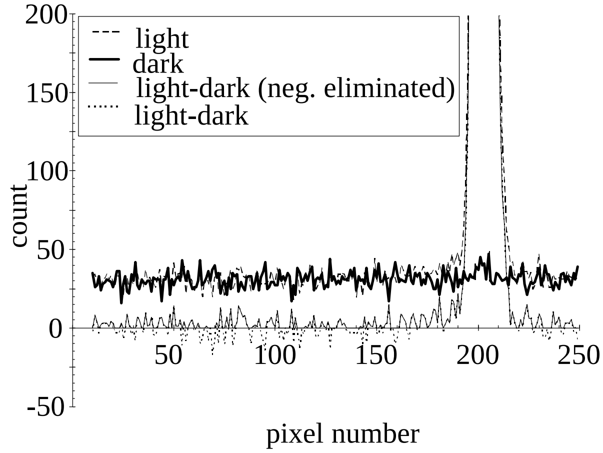

Fig. 5. Spectroradiometer raw data of a 700 nm interference filter. In this scale the peak is at a level of 3700 counts.

possible stray light from internal reflections within the instrument when using a narrowband source. Some data have indicated that either stray light or inter-pixel diffusion can result in broadening of the bandwidth. The use of infrared blocking filters can reduce this effect to some extent.

Any background noise is subtracted from the measured data, giving rise to negative data (see Fig. 5). Some instrument algorithms eliminate this 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 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. To illustrate the shift caused by the negative value elimination, a model was made of this effect. The model uses a Gaussian-shaped transmittance curve with a FWHM similar to the interference filters used. Noise clamped to eliminate negative values was added that was characteristic of the noise measured by the spectroradiometers. The dashed line in Fig. 4 shows how well this idea models 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.

Conclusions

The performance of laboratory measurement equipment is often taken for granted. The operator must not only understand the quantity being measured, but also how well the results reflect the "true" quantity. With careful consideration, interference filters can provide an inexpensive and straightforward method to confirm the performance of spectroradiometers and colorimeters in measuring the chromaticity coordinates of highly saturated colors. If the instrument can accurately measure several points along the spectrum locus, and a white point, and if the instrument is linear, then the operator should feel comfortable with the ability of the instrument to measure any point within the locus. That is, not just for light sources whose chromaticity coordinates fall on the spectrum locus (such as a red phosphor), but for all devices that emit light within the color space. Additionally, for the manufacturer this method serves as a diagnostic tool to improve system performance.

References

[1] J. M. Cotton, and W. Casey, "Narrowband Optical Interference Filters," Proceedings of the SPIE, vol. 1417, 1991, pp. 525-536.

[2] P. H. Berning, "Theory and Calculations of Optical Thin Films," Physics of Thin Films, vol. 1, 1963, pp. 69-121.