f_1' EVALUATION AND MEASUREMENT COMPARISON

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ABSTRACT

The mismatch of spectral responsivity to the CIE $V(\lambda)$ function, *i.e.,* the f_1' index, is the most critical characteristic of photometers and tristimulus colorimeters. The f_1' value varies with measurement conditions, which is often omitted in the f_1' evaluation. We investigated the variations of the f_1' value with different measurement conditions such as angle of incidence, spatial uniformity, and ambient temperature, by measuring eight high-grade commercial photometer heads from four manufacturers. The f_1' values measured by three different facilities as well as manufacturers' data were compared. The results indicate that f_1' value can change considerably under different measurement conditions depending on the design of photometer.

Keywords: Photometer heads, spectral responsivity, f_1' index, measurement condition, photometry.

1. INTRODUCTION

High-accuracy photometers are increasingly important in many applications, e.g. for measurement of LED lighting products. In the International Commission on Ilumination (CIE) Technical Committee TC 2-40 draft[1] under discussion, it is proposed that the photometers be classified as Class L (1.5%), Class A (3%), Class B (6%), or Class C (9%) by the f_1' number. In such classification, especially for Class L, measurement uncertainty and variation of results for the f_1' are in question. The f_1' index is calculated from the spectral responsivity of the photometer head according to publication of CIE 69-1987; thus the uncertainty or variation in the measurement of spectral responsivity is the key factor for the f_1' evaluation.

Simulation analyses were first conducted to estimate measurement errors due to difference in monochromator bandpass and other conditions. Then, eight high-grade commercial photometer heads were measured to evaluate the effects of different measurement conditions - The photometers were measured at NIST and Everfine using a laser-based facility and monochromator based facilities for the comparison of measured f_1'. The results were also compared with the data provided by the manufacturers.

2. MEASUREMENT GEOMETRY AND SETUP

Monochromators are normally used for the measurement of spectral responsivity detectors, but facilities using interference filters or tunable lasers are also used. An example of the laser-based system, the Spectral Irradiance and Radiance Responsivity Calibrations using Uniform Sources (SIRCUS) developed at NIST, is shown in Figure 1.

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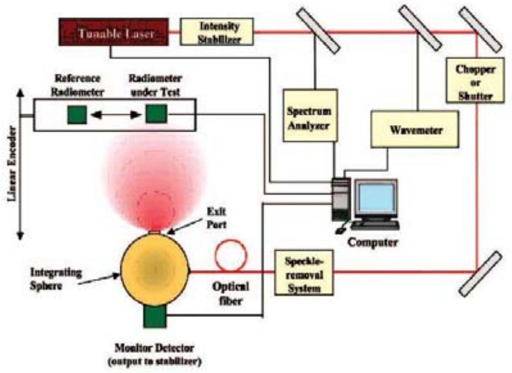
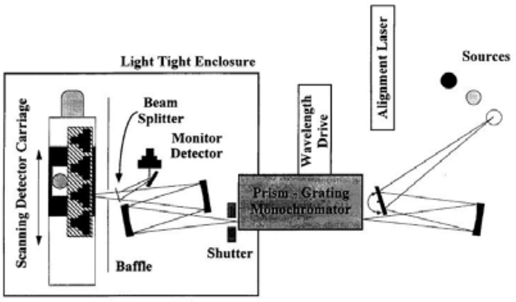
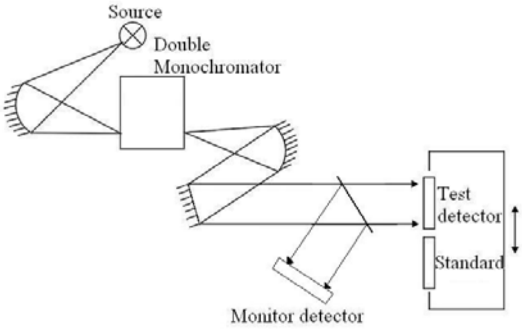


Figure 1. Schematic diagram of the SIRCUS facility[2] at NIST.

The most commonly type of spectral responsivity measurement facility is monochromator based. Fig. 2 shows the NIST Spectral Comparator Facility (SCF)[3] and a similar facility used at Everfine[4].



(a) NIST SCF



(b) Everfine SCF

Figure 2. Schematic diagram of monochromator-based spectral responsivity measurement facilities.

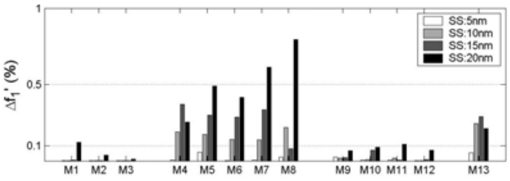
In Figure 2(a), the monochromator output is focused on the detector surface, and the detector is underfilled. In Figure 2(b) overfilling geometry is applied. An integrating sphere can be also used in the output optics for better irradiance uniformity[5] with sacrifice of detector signal.

3. MEASUREMENT ERROR ANALYSIS BY SIMULATION

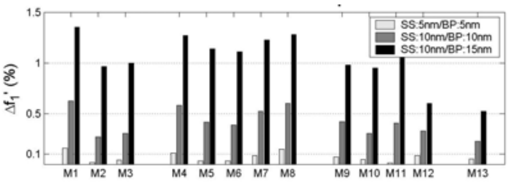
Measurement errors were analysed by simulation for a monochromator-based system. According to our previous research[6], measurement error $\Delta f_1' \leq 0.1\%$ was taken as the tolerance for an accurate assessment of f_1' value of high grade photometers with $f_1' \leq 3\%$,

3.1 Sampling step size and bandpass

Figure 3 shows the measurement errors in f_1' due to wavelength sampling step size and bandpass (FWHM) of the monochromator. M1 trough M13 represents photometer models having different spectral distributions. M1 is ideal V(λ). M2 and M3 have the same shape as V(λ) but with 0.2 nm wavelength shift. M4–M8 are of narrow region mismatch. M9–M12 are of low frequency modulation. M13 is of the combination of narrow region mismatch and low frequency modulation. $\Delta f_1'$ (%) is the absolute error. The results indicate that a 5 nm step size and 5 nm bandpass (FWHM) or less are required for accurate assessment of f_1' value of high grade photometer heads, unless bandpass correction is applied. Note that the effect of bandpass is more significant than step size.



(a) Errors due to sampling size with zero badpass



(b) Errors due to bandpass

Figure 3. Measurement errors of f_1’ due to wavelength sampling step size (SS) and bandpass (BP) of the monochromator.

3.2 Other sources of error

Due to steep slope of the V(*λ*) curve, the wavelength error of the monochromator is also critical. A 0.1 nm shift of V(λ) in the whole region would yield f_1’ of ~0,2%, while errors will be less for uncorrelated wavelength uncertainty. A wavelength uncertainty of 0.1 nm (*k*=2) or larger is desirable for high accuracy f_1’ measurement.

According to CIE 69-1987, the f_1’ is to be calculated for the whole wavelength range where the photometer under test has sensitivity. However, spectral responsivity of photometers is often measured only for the visible region or at smaller region, e.g., 380 nm to 780 nm. The calculated f_1’ value can vary significantly if the photometer has siginificant responsivity at the wings of V(λ). The variation depends on the actual spectral responsivity of the photometer, and it is difficult to generalize.

4. EXPERIMENTAL EVALUATION OF PHOTOMETER f_1’ VARIATIONS

The spectral responsivity and the f_1’ of photometer heads vary with different application conditions or measurement conditions. To investigate the influence of these conditions, several different commercial photometer heads were measured under the different conditions, and the changes in f_1’ were evaluated.

4.1. Non-uniformity

The relative spectral responsivity over the sensing area of a photometer head is more or less non-uniform, thus, f_1’ should be measured under an overfilled geometry with an uniform beam. However, f_1’ is often measured under an underfilled geometry or under an overfilled geometry but with an non-uniform beam which results in measurement errors. To evaluate such errors, spatial nonuniformity of f_1’ of a few photometer heads were measured with Everfine SCF. The results, summarized in Table 1, show that the full filter photometers with diffusers have the best f_1’ value uniformity, that the clear full filter photometer heads also have very good f_1’ value uniformity and that the partial filter photometers have the poorest f_1’ value uniformity. It is important that partial filter photometers be measured with uniform, overfilled radiation.

Table 1. Deviations from the center f_1’ value at different measurement positions (D: with diffuser, C: clear window, FF: full filter type, PF: partial filter type).

	Position1	**Position2**	**Position3**	**Position4**
D/FF	0.03%	-0.01%	-0.04%	0.01%
D/FF	-0.03%	0.05%	0.03%	-0.02%
D/FF	-0.03%	-0.04%	0.02%	0.05%
C/FF	-0.02%	0.11%	0.03%	-0.13%
C/FF	0.04%	-0.13%	0.06%	-0.07%
D/PF	13.38%	-1.27%	7.02%	5.01%
D/PF	0.23%	-0.22%	0.78%	-0.80%

4.2. Temperature dependence

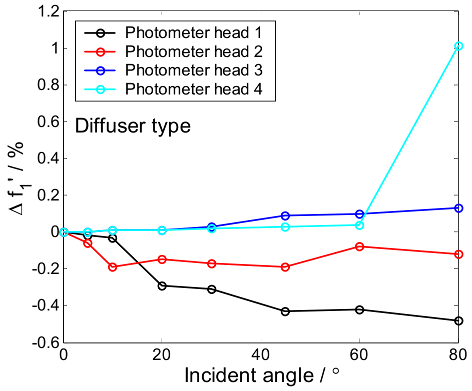
Temperature dependence of $V(\lambda)$ filters has been reported in many publications. But in the f_1' evaluation, only 25°C laboratory condition is considered, while temperature may vary in a wide range in practical situations. Table 2 shows the ambient temperature dependence of f_1' of five photometers measured at Everfine SCF. Such changes can be an issue for Class L photometers. These results suggest that f_1' value should be specified for applicable temperature range (the largest value in the range), or reported at different temperatures.

Table 2. Deviations of f_1' value for different ambient temperature difference from 25°C.

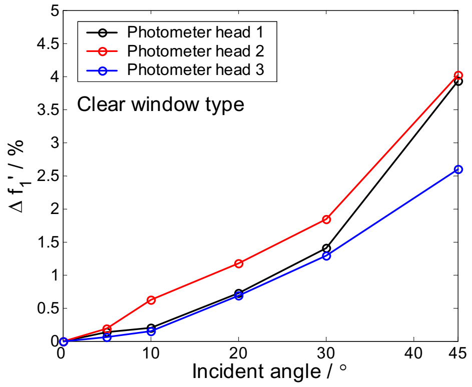
Photometer	15°C	20°C	30°C	35°C
1	0.36%	0.12%	0.18%	0.24%
2	-0.13%	-0.08%	0.14%	0.25%
3	-0.18%	-0.11%	0.17%	0.40%
4	-0.13%	-0.07%	0.08%	0.17%
5	0.21%	0.09%	-0.10%	-0.19%

4.3. Incident angle dependence

The spectral responsivities of the seven photometer heads (four diffuser type and three clear window type) for different angle of incidence were also measured at Everfine SCF. The results are shown in Fig. 4. Some of the photometers show notable differences. Spectral responsivity of photometers is normally measured at one angle of incidence, while illuminance meters are designed to measure light from wide angle range. There can be a large difference in f_1' value between different angular conditions.



(a) Diffuser type photometer heads



(b) Clear window photometer heads

Figure 4. f_1' values measured under different incident angles.

4.4. Polarization dependence

The spectral responsivities of photometer heads can also be polarization dependent. This effect is insignificant for common photometer heads, but the effect can be serious (e.g., for colorimeter heads using splitters). Use of such instruments should be limited to measurement of non-polarized light and spectral responsivity should also be measured with non-polarized monochromatic radiation.

5. MEASUREMENT COMPARISON OF f_1'

Eight commercial photometer heads from four manufacturers were measured at NIST and Everfine. Six are diffuser type with five cosine corrected,and two clear window ones. The relative spectral responsivities of these photometers were first measured at Everfine SCF, and then at the NIST SIRCUS and finally two of them at NIST SCF. The results are listed in Table 3, where the manufacturer's f_1' value, typically measured at ambient temperature of 25°C, is also listed. Note that some of the photometers are manufactured by Everfine.

Table 3. Measurement results from different laboratories.

Photometer heads	NIST SIRCUS % 23°C	NIST SCF % 25°C	Everfine SCF % 25°C	Manufacturer Certificate % 25°C
1. Clear/FF	1.40		1.33	1.50
2. Diffuser/FF	2.34		2.51	1.70
3. Clear/FF	1.40	1.37	1.17	1.19
4. Diffuser/FF	1.24		1.52	1.33
5. Diffuser/FF	2.86		3.26	3.23
6. Diffuser/FF	2.13		2.46	2.45
7. Diffuser/FF	2.42	2.23	2.40	2.38
8. Diffuser/PF	1.15		1.23	0.50

The measurement conditions at different facilities are described as the following:

NIST SIRCUS

All the eight photometer heads were measured at 23°C ambient temperature and with 5 nm wavelength interval covering from 380 nm to 780 nm. The photometers are overfilled with a Lambertian beam from a 3.8 cm integrating sphere at 0.5 m distance at the normal incident angle.

NIST SCF

The No.3 and No.7 photometer heads were mounted on the stage with two compare working standard detectors (silicon photodiode) at the same time under the ambient temperature of 25°C.The measurement wavelength is from 380 nm to 780 nm, and both with 5 nm step size and 4 nm bandpass.

EVERFINE SCF

All the eight photometer heads were measured on the EVERFINE SCF, after the facility was calibrated by the NIST traceable silicon photodiode. The No.8 photometer head (partial filter type) was measured with integrating sphere output. The ambient temperature was 25 C. The measurement wavelength is from 380 nm to 780 nm with both the step size and bandpass 5 nm.

6. DISCUSSIONS

The maximum deviation is 0.19% between NIST SIRCUS and NIST SCF and 0.40% between NIST SIRCUS and EVERFINE SCF. The standard deviation between NIST SIRCUS and EVERFINE SCF is 0.14%.The maximum deviation of all the data (including manufacturers data) is 0.73%, which occurred in the partial filter photometer head, and the standard deviation of all the data is 0.25%. The detailed measurement conditions of the manufacturers' data are not available.

The variations may arise from the different in instrument condictions such as bandwith and scanning interval, spatial non-uniformity of the monochromator output, wavelength uncertainty, etc. Deviations can also arise from differences in the process of calculation, including wavelength range, interpolation and rounding of results.

7. CONCLUSIONS

The variation of f_1' with temperature and incident angle can be significant for high-grade photometer, and it may not be sufficient to evaluate them at one condition.

In spectral responsitivity measurement, uniform illumination overfilling the sensitive area is desirable. For the partial filter type photometers, the output from the monochromatic device must be very uniform and the sensitive area must be fully overfilled.

The bandwith and scanning interval of 5 nm or less is recommended for high accuracy f_1’ measurement, unless some correction methods are applied.

Wavelength uncertainty is a significant uncertainty contribution for f_1’ measurement. An uncertainty of ≈0.1 nm (k=2) is desirable for high accuracy measurement.

It is not discussed in this paper, but some guidance may be needed for f_1’ evaluation of luminance meters. Future activity might focus on this area.

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