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Measurement of Light: Errors in Broad Band Photometry

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ABSTRACT

Broad band photometry is the most widely practiced method of measuring illumination in buildings. Errors in such measurements could occur if the photometer relative spectral responsivity does not exactly match the spectral luminous efficiency of the human eye. This note reports the variation in photometric errors observed when measuring different fluorescent and incandescent sources of illumination. Procedures for quantifying and minimizing such errors are discussed.

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INTRODUCTION

To evaluate the effectiveness of a lighting retrofit in a building, one typically uses a "pocket" illuminance meter to measure illuminance values both before and after the change of lighting equipment. To evaluate the effectiveness of different window designs, one might use the same type of meter to compare the magnitudes of natural and artificial lighting at different locations in a building or mock-up. To verify that a newly designed office space meets the requirements of the Illuminating Engineering Society's RP-24 Recommended Practice for Video Display Terminals, one might use a luminance photometer to ensure that luminance ratios between luminaires and their surroundings are within tolerance. To determine if a colored exit sign meets the requirements of the U.S. National Fire Protection Association, a technician in a testing laboratory might use a luminance photometer to ensure that the sign's luminance meets the minimal acceptable value of 14 cd/m^2. To convince a judge that the poor visibility of a farm tractor's faded safety triangle was indeed the direct cause of a disputed traffic accident, an expert witness might present calculations of visibility based upon measurements of the luminance and contrast of the old sign in comparison with a new one. To compare the effects of different types of lamps on visual performance, productivity, pupil size, fatigue, health, mood, or state of mind, a researcher might use an illuminance meter and/or luminance meter to ensure that illumination levels remain constant under all test conditions so as not to confound experimental results. In all cases, broad band photometry is practiced.

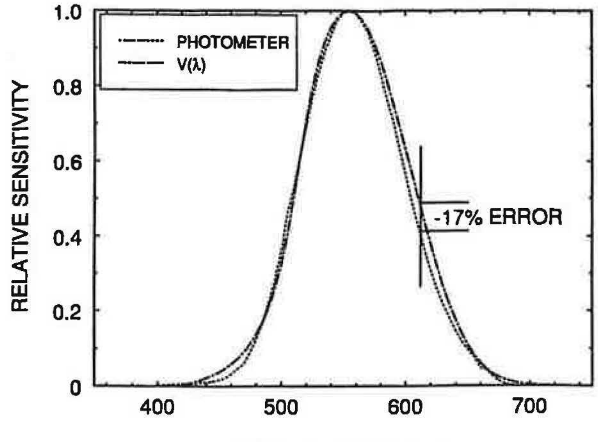

Figure 1. Spectral match of the four photometers tested. Manufacturer's data.

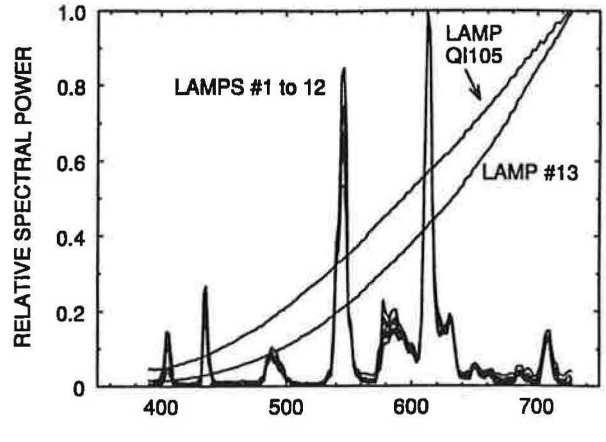

Figure 2. Relative spectral power distributions of compact fluorescent (nos. 1 to 12) and incandescent lamps (nos. 13 & QI105).

Broad band photometry is indeed the most widely used method of photopic light measurement (Wyszecki and Stiles 1982). Central to the method is a luminance or illuminance photometer consisting mainly of a photodetector with relative spectral responsivity modified or corrected to approximate that of the CIE Standard Photometric Observer (CIE 1983). This spectral modification is typically achieved by colored glass placed anterior to the detector surface (Wyszecki and Stiles 1982 and Wright et al. 1969). The spectral response of the CIE Standard Photometric Observer is represented by the V(λ) function, also called the relative photopic luminosity function.

The V(λ) function is shown in **Figure 1** together with the spectral responsivity of a typical moderately priced illuminance photometer as provided by its manufacturer. For accurate measurements, the two curves should match (Nielsen 1987). With colored glass correction, they rarely do. This introduces the potential for systematic errors which vary with the spectral composition of the light source being measured. The poorer the match, the greater the probability of the photometer responding differently to different light sources of equal luminosity.

The type of photometer characterized in **Figure 1** shows, for example, a 17 percent error at 612nm, the primary wavelength of many compact fluorescent and other triphosphor lamps (**Figure 2**). The overall photometric error would not necessarily be as large, however, due to the tendency of overestimates at some wavelengths to cancel underestimates elsewhere in the spectrum.

The CIE proposes two methods of error designation for photometers (CIE 1982 and CIE 1987). The first, $f_1(Z)$, is a direct measure of the error that would occur if a lamp Z of relative spectral distribution $S(\lambda)_z$ were measured. It can serve as a correction factor for subsequent measurements of distributions $S(\lambda)_z$.

$$f_1(Z) = 100\ [\ (\ s(Z)\ /\ s(A)\ ) - 1\ ] \qquad (1)$$

where

$s(Z)$ = sensitivity (responsivity) of photometer when illuminated with lamp Z; and

$s(A)$ = sensitivity (responsivity) of photometer when illuminated with lamp type A used in calibration.

The second error designation, f'_1, is independent of target illuminant and does not allow positive departures from V(λ) to cancel negative ones. It cannot be used as a correction factor.

$$f'_1(Z) = \frac{\int \left| s*(\lambda)_{rel} - V(\lambda) \right| d\lambda}{\int V(\lambda)\, d\lambda} \times 100\ \% \qquad (2)$$

$$s*(\lambda)_{rel} = \frac{\int S(\lambda)_A\, V(\lambda)\; d\lambda}{\int S(\lambda)_A\, s(\lambda)_{rel}\, d\lambda} \times s(\lambda)_{rel} \qquad (3)$$

where

λ = wavelength of incident radiation, from 0 to ∞;

$V(\lambda)$ = relative photopic luminosity function;

$S(\lambda)_A$ = relative spectral distribution of the illuminant used in calibration of the photometer; and

$s(\lambda)_{rel}$ = relative spectral responsivity of the photometer.

Unfortunately, these agreed error designations are not commonly used. More common is a statement like that given by the manufacturer of the photometer characterized in **Figure 1**: "spectral response falls within ± 2 percent of the CIE photopic luminosity curve." This describes only the accuracy of response to the source used in calibration, typically CIE Illuminant A (Wyszecki and Stiles 1982 and CIE 1986). It says nothing of the instrument's spectral responsivity and accuracy to other illuminants (Nielsen 1987). Consequently, additional calibration would be required before the photometer could be used to measure light from any source other than the one used for calibration (Ouellette et al. 1991).

This technical note describes the calibration procedures developed for this purpose and reports relative photometric errors observed for four different units of the same model illuminance photometer while measuring different light sources. The general conclusions drawn from the results are applicable to the photometric measurement of any light source that differs spectrally from the source used for calibration.

MATERIALS AND PROCEDURES

A wide range of compact fluorescent sources were used (Ouellette et al. 1991 and Ouellette and Arseneau 1992). Their rated color temperatures ranged from 2700K to 2800K. Three of the illuminants were enclosed within frosted glass or plastic diffusers which modified lamp spectral power distribution to some degree. These illuminants, except lamp 12, were powered at 120 Volts AC. Lamp 12, with DC ballast, was powered at 12 Volts DC. The 13th illuminant was a tube-shaped incandescent lamp introduced for comparison. The lamps were aged, base up, for at least 100 hours and were stabilized for at least 45 minutes at room temperature before being measured. **Figure 2** shows the spectral power distributions of the 13 illuminants.

A 14th illuminant, Lamp QI105, was a 200 watt incandescent luminous intensity standard obtained directly from the Institute for National Measurement Standards, National Research Council, Canada. It approximated a CIE Illuminant A.

All measurements were taken in a black windowless room to remove the effects of stray light. Ambient temperature was constant to within ± 1°C. Air flow in the room was negligible. Lamps were mounted base-up at all times.

The calibration procedure began with a portable spectroradiometer, a device capable of measuring absolute spectral distributions of sources. From these distributions, the instrument calculates the appropriate photometric quantity (i.e., luminance). Since the calculation procedure (Wyszecki and Stiles 1982) involves the $V(\lambda)$ function, the instrument's response need not be physically matched to $V(\lambda)$. Spectroradiometers used in this manner are therefore not subject to errors caused by changes in lamp spectral power distribution.

The spectroradiometer was modified by replacing its objective lens with a cosine diffuser.[1] The instrument was mounted on a photometric bench and calibrated against Lamp QI105 using conventional calibration procedures (i.e., Hewitt and Vause 1966) for illuminance meters. The standard lamp QI105 was then replaced by one of the 13 lamps, Z, in ques-

[1] This situation is fundamentally no different than using an unmodified, calibrated spectroradiometer to measure lamps enclosed within a luminaire equipped with a diffuser of the same material. In both cases, the spectral bias imposed by the diffuser is applied equally to each lamp. Neither situation limits the present study which is concerned with characterizing changes in responsivity rather than in characterizing the spectral power distributions of the lamps themselves. Where absolute measurements are necessary, the modified instrument would require a wavelength-by-wavelength calibration.

tion. Illuminance E(Z,R) reported by the spectroradiometer was noted. The spectroradiometer was replaced by one of the four illuminance photometers, P_i (**Figure 1**). Illuminance, $E(Z,P_i)$ was noted. Relative error, $f(Z,P_i)$, for the measurement of lamp Z by photometer P_i was determined in a manner analogous to (1):

$$f(Z,P_i) = 100[(E(Z,P_i)/E(Z,R)) - 1] \quad (4)$$

This procedure was carried out at least once for each combination of 13 lamps × 4 illuminance photometers. Variability was assessed by repeating the procedure on the following day with four of the lamps.

RESULTS

Table 1 reports relative percent errors across the different combinations of lamps and photometers. Ideal photometers would give constant values for all lamps. Instead, the values ranged from approximately 1 percent to 11 percent.

The results were reproducible to within approximately 1 or 2 percentage points as given by the consistency in repeated measurements for Lamps 5, 6, 8, and 13. Therefore, differences of less than 2 percentage points between any two entries in **Table 1** cannot be considered significant.

Most notably, there was considerable variation across the 12 different compact fluorescent sources. Although these lamps radiated at approximately the same wavelengths (**Figure 2**), the proportion of energy in each of the wavelengths differed slightly. The differences were sufficient to produce relative errors varying by up to 9 percentage points across the different lamps for any of the given photometers.

Errors across the 4 photometers for any given lamp varied by approximately 3 percentage points. Greater variability could be expected across different model units from different manufacturers.

Interestingly, errors for the two incandescent sources (Lamps 13 and QI105) varied by 3 or 4 percentage points from each other. Lamp 13 was a 130 watt long-life source operating at a much lower color temperature than Lamp QI105 (**Figure 2**). As with the compact fluorescent lamps, the incandescent lamps differed sufficiently in their spectral power distributions to cause small but noticeable differences in relative photometric error.

Table I. Relative percent error $f(Z,P_i)$ of photometers P_i in measuring different compact fluorescent and incandescent sources.

LampZ	P_1	P_2	P_3	P_4
1	-2.2	-3.4	-4.5	-6.2
2	-5.9	-6.5	-8.8	-8.2
3	-7.8	9.5	-7.8	-6.2
4	-1.8	-0.7	-3.3	-2.7
5	-6.9	-7.8	-10.2	-7.0
5*	-7.7	-8.6	-9.4	-9.8
6	-5.2	-6.1	-8.2	-8.6
6*	-5.0	-6.8	-7.7	-8.1
7	-7.9	-8.3	-10.0	-9.7
8	-8.4	-8.8	-10.6	-10.6
8*	-8.0	-8.7	-9.3	-9.7
9	-7.7	-8.0	-10.3	-10.0
10	-8.4	-7.7	-10.7	-7.7
11	-6.1	-7.5	-7.5	-6.8
12	-7.7	-8.6	-9.6	-9.1
13	-8.0	-8.9	-10.3	-9.7
13*	-8.8	-9.5	-11.0	-10.2
QI105	-5.3	-5.6	-8.0	-6.7

**Repeated measure*

Finally, it might be noticed that the relative errors for the CIE Illuminant A, lamp QI105, ranged from 5.3 percent to 8.0 percent. This implies a 5 to 8 percent disagreement with the manufacturer's expired calibrations against a presumed CIE Illuminant A. Explanations for disagreement include:

- Inevitable changes in detector responsivity due to aging; and
- The constant bias imposed by the diffuser attached to the spectroradiometer.

For reasons discussed in the Materials and Procedures section of this paper, such constant biases are of no significance to this study which is concerned with relative rather than absolute values.

CONCLUSIONS

Relative photometric errors of 1 to 11 percent were observed in the measurement of different triphosphor fluorescent sources using mid-priced broad band photometers. Variation in the errors was most likely due to inexact matches in spectral responsivity of the photometers to the V(λ) function (Figure 1), especially at 612 nm where the compact fluorescent lamps were most dominant (Figure 2). In some cases, the variation in errors greatly exceeded that which one might infer from manufacturer specifications (i.e., "within 2 percent of the CIE photopic luminosity curve"). Photometer manufacturers should adopt the CIE designations to more completely represent the errors applicable to their instruments.

The extent of such reported errors might not be significant in many routine illuminating engineering practices involving the estimation of average illuminance. Indeed, variations in illuminance throughout a sampled space might exceed all sources of photometric uncertainty. In such cases, measurements of the highest accuracy and precision are not necessary. Nevertheless, there remain cases in lighting practice when routine indifference to accuracy in measurement is not entirely justified.

For example, field practices often involve comparing relative illuminance or luminance at a specific location under one condition against values under another condition. From such measurements, conclusions are drawn about the relative merits of one lighting condition versus the other. Practices of this kind require accurate measurement to ensure that uncertainties in photometry do not exceed the possible small differences between the conditions under test.

In general, the importance of photometric error increases whenever one is concerned not with average illuminance in a space, but rather illuminance or luminance as a function of different lighting conditions involving different spectral distributions. Practical examples might include measuring the reflectances of colored room surfaces for use as input parameters to zonal cavity calculations for lighting design. Large errors in estimating surface reflectances cause large errors in lighting design calculations. Another example involves comparing illuminance at a given location as a function of lamp type, perhaps to compare the cost effectiveness of two alternative lighting situations. Here, too, an 11 percent photometric error could prove costly.

It should be noted that 11 percent is not an upper limit to spectral mismatch errors. For the instruments represented by Figure 1, errors in the violet region (400 to 460 nm) generally exceeded 50 percent. They reached as high as 500 percent at 405 nm. Measurements of compact fluorescent lamps were not affected to this extent because these sources produced relatively little violet energy (Figure 2). The errors would be more prevalent in the measurement of samples which are rich in short-wavelength energy. These might include daylight, discharge lamps with a strong component of the mercury peaks of 405 nm and 436 nm, and any room surface finished in cool colors.

Where accurate photometric measurements are required, a number of procedures are proposed:

- Calibrate each photometer separately, as described above, for each illuminant to be measured;
- Use spectroradiometric photometry instead of broad band photometry; or
- Use a broad band photometer having superior spectral responsivity correction.

The latter might be achieved through the integration of such technologies as diffraction gratings, photodiode arrays and microprocessors (Roberston 1987). Alternatively, the error can be eliminated by a calculation procedure (CIE 1987) involving the relative spectral responsivity of the photometer, the spectral power distribution of the illuminant to be measured, and the spectral power distribution of the source used to calibrate the photometer.

Such higher accuracy procedures are undoubtedly practiced in well-equipped laboratories. The procedures are not always feasible, however, to practitioners contending with more economical photometers and a diversity of changing sources. Under such conditions, a conventional photometer of the type studied here cannot necessarily be used to accurately compare the luminous output of different lamp types nor sometimes even different models of the same lamp type. Where such measurements are attempted, the implicit inaccuracies in the methodology should be reported.

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