To be published in Proc., CIE Symposium'99 -75 Years of CIE Photometry, Budapest 1999

Recent Developments in Detector-Based Photometry and Future Needs in Photometry

Yoshi Ohno

1. Introduction

In the early history of photometry, sources such as candles, lamps, or blackbodies were always used as standards to realize, maintain and transfer the photometric base unit. Even after the advent of photodetectors in the early twentieth century, lamps have been traditionally used to maintain and transfer the units of luminous intensity and luminous flux. In this case, a group of primary standard lamps is maintained as reference standards, which is transferred to secondary standard lamps, and then further transferred to working standard lamps for routine calibration work. Uncertainties are added at each transfer step in this calibration chain.

In 1979, the candela was redefined based on the relationship with radiant power, and since then the photometric base unit is commonly realized based on absolute detectors. As a consequence, a photometric unit (lux) is now derived first on photometers ($V(\lambda)$-corrected detectors) rather than lamps. However, lamps are still dominantly used to maintain the candela because the realization of the unit has not been performed frequently due to the difficulties in the use of absolute radiometers and because photometers have not been believed to be sufficiently stable to maintain the unit.

In the 1980s, silicon photodiode self-calibration technique [1] (or 100 % quantum efficient silicon radiometers) became common, and more recently in the 1990s, absolute cryogenic radiometers [2] have become common among many national laboratories. These new technologies have allowed easy access to a spectral responsivity scale with much lower uncertainties, and the realization of a photometric unit can be performed more frequently. With a shorter calibration cycle, standard photometers can be used to maintain and transfer the photometric unit. As the photometers do not age by use, there is no need to use secondary and working standards, allowing for a shorter calibration chain with reduced uncertainties.

A group of standard photometers are now used to realize, maintain, and transfer the photometric units at the National Institute of Standards and Technology (NIST) [3]. The calibration procedures based on standard photometers (detector-based method) have been implemented in various photometric calibrations including those for luminous intensity, illuminance, luminance, and flashing-light [4]. A detector-based calibration facility for total luminous flux has also been developed recently at NIST [5]. This paper describes these new capabilities that utilize the detector-based method, and discusses future needs for standards in photometry.

2. Characteristics of Standard Photometers

Standard photometers are generally constructed with a silicon photodiode, a $V(\lambda)$ filter, and an aperture (and a diffuser, optionally). The high quality of recent silicon photodiodes provides many advantages of such photometers over lamps. The photometers do not age by use, they are robust against mechanical shocks – thus easy to transport, and they have excellent short-term stability (0.01 %) and a large linearity range (over 8 orders of magnitude). The long-term stability of photometers varies depending on the $V(\lambda)$ filter. Selected photometers exhibit a stability of better than 0.1 % / year, while poor ones show changes over 1 % / year. The long-term stability of photometers must be evaluated before they can be used as standards. Lamps are generally more stable than photometers for long-term storage over many years, but lamps age by use and are generally not as reproducible as photometers due to difficulty in alignment and other characteristics. Selected photometers can be used as low-uncertainty photometric standards with periodic calibrations.

Work is in progress at the CIE technical committee TC2-37 (Photometry Using Detectors as Transfer Standards) to publish a technical report on the properties and use of $V(\lambda)$-corrected detectors for disseminating and maintaining photometric units. The report is close to completion.

3. Detector-Based Method for Photometric Calibrations

In the traditional method for luminous intensity calibrations, test lamps are calibrated against a group of standard lamps (source-based method). In this case, the scale comes from the lamp, and the photometer is used only as a monitor device. The calibration is a substitution measurement, and thus, various errors including stray light tend to be cancelled out. This procedure is safer to avoid errors, but the calibration chain is long, involving maintenance of many standard lamps.

With the detector-based method, the test lamps are calibrated by using the standard photometers that maintain the illuminance scale. The photometers measure the illuminance, and then the luminous intensity is determined from the illuminance and the distance. In this case, the calibration is more susceptible to errors such as stray light, but has an advantage of a shorter calibration chain.

The situation reverses in the case of calibration of illuminance meters. With the source-based method, the test illuminance meter is calibrated against the illuminance determined from the luminous intensity of the standard lamp and the distance, and thus not in the form of a substitution measurement. Therefore, the calibration is susceptible to errors due to stray light, departure from the inverse square-law, etc. On the other hand, with the detector-based method, the illuminance meter under test is calibrated against the standard photometers, thus in the form of a substitution measurement. The scale comes from the standard photometer, and thus, with no need to know the luminous intensity of the lamp nor precise alignment of the lamp. The results are free from the inverse-square law errors of the lamp. A working lamp of a known color temperature (normally 2856 K) is used as a calibration source. The short-term stability of the working lamp is important, but its reproducibility, burning time, and aging characteristics are not critical.

4. Realization and Maintenance of the Candela at NIST, and Transfer to Industry

The candela is annually realized at NIST based on an absolute cryogenic radiometer and through the spectral responsivity scale, as shown in Fig. 1. The candela is realized and maintained via a group of standard photometers (NIST reference photometers). The stability of these photometers for the past seven years is shown in Fig. 2. Five of the photometers have shown long-term stability within 0.4 % over a seven year period and better than 0.1 % per year.

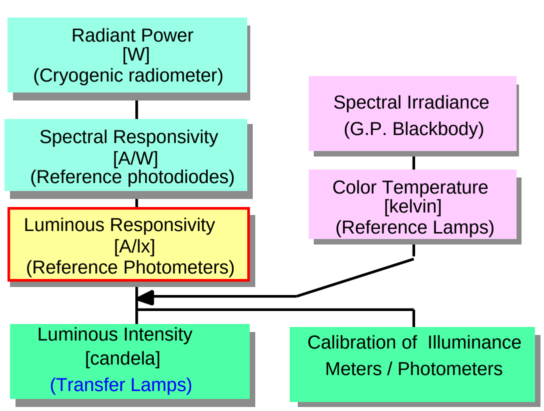

Figure 1. Realization and maintenance of the photometric units at NIST.

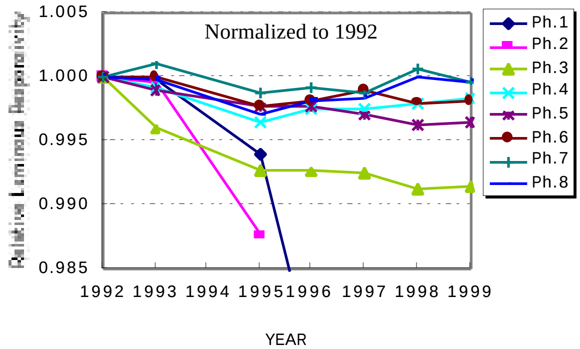

Figure 2. Stability of the NIST reference photometers (Data normalized to 1992.)

These five photometers are also used in the routine calibrations of luminous intensity and illuminance.

The detector-based method is introduced in the industry level also. Several companies in the United States use standard photometers as their corporate reference standards for photometry. These photometers are annually calibrated by NIST. As an example, Fig. 3 shows the calibration history of eight standard photometers from a customer. Since 1996, the photometers were divided into two groups, and each group of four photometers is calibrated in a two-year cycle, overlapping one year with each other. These data show the stability of the

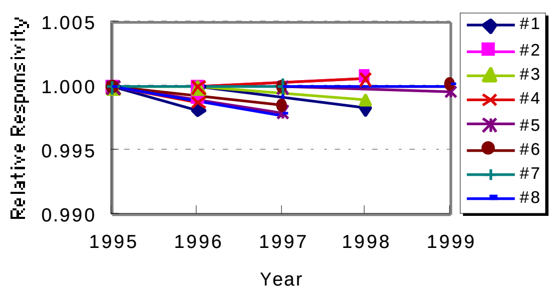

Figure 3. Calibration history of eight standard photometers from a customer. (Data points normalized to previous calibrations.)

photometers (against NIST scale) to be within 0.2 % over each two year period and that the average scale of each group maintains the traceability to the NIST scale within 0.1 %. Some other photometers are not performing as well as this case.

5. Applications of the Detector-Based Method at NIST

5.1 High Illuminance Calibration Facility

With traditional luminous intensity lamp standards, the illuminance scale is available up to a level of ~5000 lx. A much higher illuminance level is often required for calibration of illuminance meters. To meet such needs, a high illuminance calibration facility was developed at NIST [6]. The facility utilizes a commercial solar simulator source employing a 1000 W xenon arc lamp with an optical feedback control and originally provides ~300 klx of illumination of xenon spectra (6500 K). The source is combined with a set of color glass filters that modify its spectral power distribution to approximate CIE Illuminant A (2856 K Planckian radiation) at an illuminance level of ~75 klx. The illuminance level can be varied without changing the color temperature significantly and without changing the distance.

The illuminance scale is provided by a set of high-illuminance standard photometers that are calibrated against the NIST reference photometers (used to maintain the candela) and have been verified for linear response up to 100 klx. This is an example utilizing the large linearity range of detector standards.

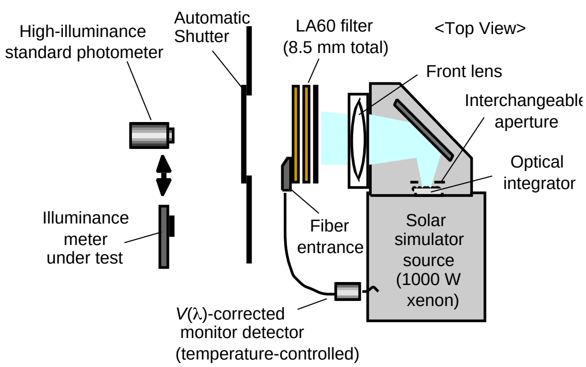

Figure 4. Configuration of the high illuminance calibration facility.

5.2 Measurement of Flashing Light

A photometric unit for flashing light, lux·second (lx·s), is realized at NIST using flashing-light standard photometers [4]. As one of the derivation methods employed in this scheme, a flashing-light standard photometer is calibrated for illuminance responsivity [A/ lx] with steady light against NIST reference photometers, and then, the same value holds for the responsivity in coulomb / (lux·second), [C / (lx·s)]. Combined with a current integrator using a calibrated capacitor, the photometer is calibrated for [V/ (lx·s)] to be used for measurement of luminous exposure [lx·s] of flashing light (see Fig. 5). The unit is derived annually since 1997 and maintained on the four flashing-light standard photometers with an expanded uncertainty (k=2) of less than 1 %. The standard photometers have shown a stability within 0.2 % over a two year period. The unit is transferred to industry via commercial flashing-light photometers rather than flashing-light sources.

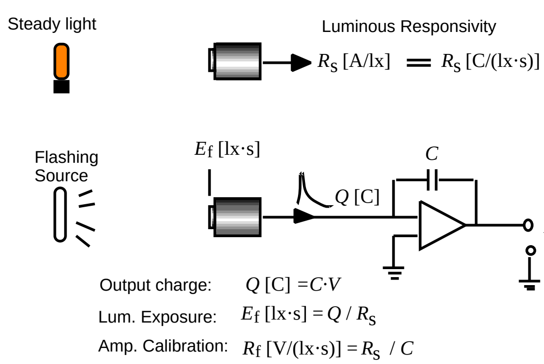

Figure 5. Derivation of a photometric unit for flashing light.

5.3 Measurement of Luminous Flux

The measurement of total luminous flux of lamps using integrating spheres has historically been source-based. Test lamps must be calibrated in comparison with standard lamps, resulting in a long calibration chain with additional transfer uncertainties. The Absolute Integrating-Sphere Method, developed for realization of the lumen in 1995 at NIST, is now applied to the routine calibration measurements of total luminous flux [5]. Figure 6 shows the NIST integrating sphere facility for this method. The test lamp is calibrated against the flux introduced from the external source through a calibrated aperture, with a correction for spatial nonuniformity of the sphere responsivity. The measurement of the external source is automated so that the sphere is calibrated every time a test lamp is measured. This new method is based on the illuminance measurement of the external source using standard photometers and allows for calibration of test lamps with no need for luminous flux standard lamps. This brings the luminous flux calibration into a detector-based measurement procedure, thereby eliminating the uncertainties associated with the use of working standard lamps.

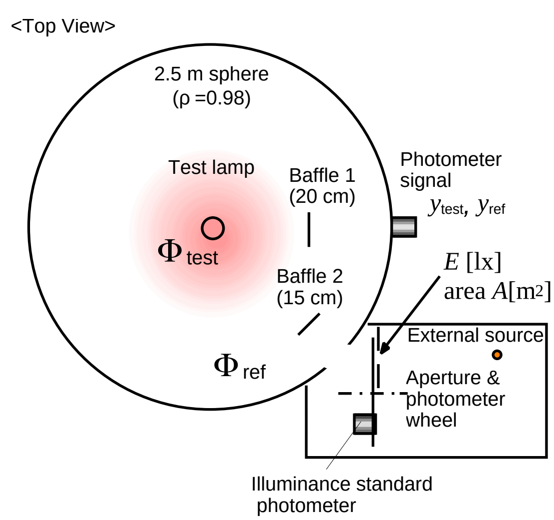

Figure 6. Arrangement of the NIST 2.5 m integrating sphere for the detector-based total luminous flux calibration.

Lower uncertainties are achieved by shortening the calibration chain. In addition, the measurement is simplified with the self-absorption of test lamps and other errors automatically corrected.

5.4 Measurement of LEDs

For measurement of Light Emitting Diodes (LEDs), CIE recommends that test LEDs be calibrated against standard LEDs having spectral power distributions and geometrical characteristics as close to the test LEDs as possible [7], whereby no corrections are needed with such substitution measurements (source-based method). While this method would assure simple and accurate measurements in industry, many standard LEDs of different colors and types would be needed. For example, Fig. 7 shows the relative spectral responsivity of a medium-class commercial photometer head, and Fig. 8 shows the spectral mismatch error of this photometer for an LED (Gaussian model with spectral width=20 nm) as a function of its peak wavelength. It is shown that, if the spectral mismatch error is to be kept within 5 % for the 450 nm to 650 nm region, 15 standard LEDs would be required for direct substitution. It would not be practical to maintain so many standard LEDs. As an alternative, assuming that the approximate peak wavelengths of LEDs under test are usually known, a detector-based method can be employed where the photometer is simply calibrated against Illuminant A and always used with a spectral mismatch correction function as shown in Fig. 8.

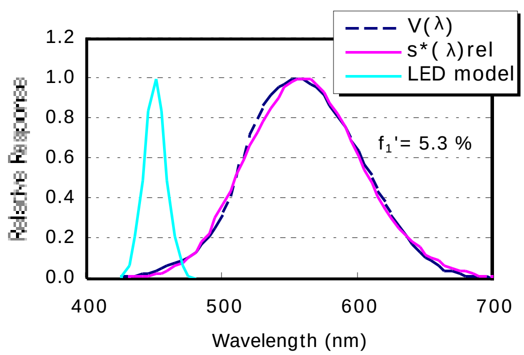

Figure 7. Relative spectral responsivity of a commercial photometer.

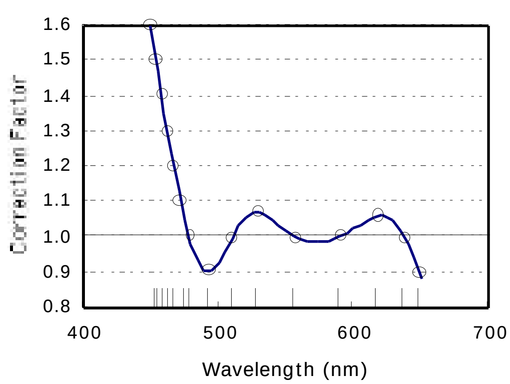

Figure 8. Spectral mismatch correction factor F^* for an LED Gaussian model.

6. Conclusion – Future Needs in Photometry

The substitution method based on lamp standards has been preferred in industry, with the least need for corrections. However, much better agreement in measurement results among different companies, and thus, much lower uncertainties of photometric measurements are desired in industry. With the increasing number of the types of light sources produced, it would be impossible for national and commercial calibration laboratories to produce all types of lamp (or source) standards. While the substitution method is always the safest and easiest way for less-equipped laboratories in industry, one direction to improve the situation might be to utilize the detector-based method with correction capabilities. The detector-based standards can transfer the national photometric units with the lowest uncertainty available, while some source standards can be used to verify the uncertainties of applied measurements. To utilize the new scheme, however, higher capabilities will be needed at commercial laboratories, possibly with the help of more intelligent photometric instruments. Education and further standardization in industrial practice will play key roles in future improvements in photometry.

References

[1] E. F. Zalewski and J. Geist, “Silicon photodiode absolute spectral response self-calibration,” *Appl. Opt.* **19**-8, 1214 (1980).
[2] J. E. Martin, N. P. Fox, and P. J. Key, “A cryogenic radiometer for absolute radiometric measurements,” *Metrologia* **21**, 147-155 (1985).
[3] Y. Ohno, *Photometric Calibrations,* NIST Special Publication 250-37 (1997).
[4] Y. Ohno and Y. Zong, “Establishment of the NIST Flashing-Light Photometric Unit,” *Proc., SPIE* **3140**, 2-11 (1997).
[5] Y. Ohno and Y. Zong, “Detector-Based Integrating Sphere Photometry”, *Proc., 24th Session of the CIE*, **1**-1, 155-160 (1999).
[6] Y. Ohno, “High Illuminance Calibration Facility and Procedures,” *J. IES*, **27**-2, 132-140 (1998).
[7] CIE Pub. 127, Measurement of LEDs (1997).

Yoshi Ohno
National Institute of Standards and Technology
100 Bureau Drive, Mailstop 8442
Gaithersburg, MD 20899-8442 USA
Email: ohno@nist.gov