New photometric calibration programmes at the National Institute of Standards and Technology

Y. Ohno and M. Navarro

Abstract. The National Institute of Standards and Technology (NIST) candela is maintained via standard photometers which have shown long-term stability of better than 0.1 % per year. The detector-based method has allowed us to reduce the uncertainties of calibrations and to expand the range of calibration capabilities. There have been several new developments in photometry at the NIST. A high-illuminance calibration facility has been developed. Four temperature-controlled standard photometers, tested for linearity and thermal effects at high illuminances, are used with a high-pressure xenon arc source to provide the illuminance scale at levels up to 100 klx. A flashing-light photometric unit (lx · s) has been realized using four standard photometers equipped with current integrators, and using two independent methods. Calibration services for illuminance meters at high illuminance levels and flashing-light photometers are now available at the NIST. Ongoing new projects include the development of a detector-based luminous-flux calibration facility using a 2.5 m integrating sphere, realization of the total spectral radiant-flux scale, and the development of a reference spectroradiometer for colorimetry of displays. Calibration services are planned in these areas of photometry and colorimetry in the near future.

1. Introduction

Detector-based methods are employed in photometric calibration work as well as in the realization of photometric units at the NIST. The NIST candela has been based on an absolute cryogenic radiometer since 1992 [1, 2]. The unit is maintained via a group of standard photometers (NIST reference photometers), which have shown long-term stability of better than 0.1 % per year. Five of these photometers are used in routine calibrations. The detector-based method has allowed us to reduce the uncertainties of calibrations and to expand the range of calibration services [2, 3]. There have been several new developments in photometry at the NIST.

The range of calibration of illuminance meters and luminance meters has normally been limited to levels up to several klx and several kcd/m^2 using a conventional photometric-bench facility. The calibration of instruments at much higher levels is required in applications such as daylight measurement, evaluation of solar simulators and testing light sources in imaging devices. To meet such measurement needs, a high-illuminance calibration facility has been developed [4]. A solar simulator source utilizing a high-pressure xenon arc lamp is used as a calibration source. The spectral power distribution of the source is modified by filters to match the International Commission on Illumination (CIE) Illuminant A usually used for illuminance meter calibrations [5]. However, for specific sources such as for solar irradiance measurements, an illuminance meter can be calibrated in a similar manner for the xenon lamp spectrum as for CIE Illuminant D_{65}. Four temperature-controlled standard photometers, tested for linearity and thermal effects at high illuminances, are used to provide the illuminance scale at levels up to 100 klx.

There is a need for accurate measurement of the intensity of flashing lights to ensure the proper maintenance of aircraft anticollision lights. A large variation in the measured intensities of anticollision lights has been a problem; thus, the NIST has undertaken the task of establishing flashing-light photometric standards to provide calibration services in this area [6]. Other projects in progress include the development of a detector-based luminous-flux calibration facility using a 2.5 m integrating sphere, realization of the total spectral radiant-flux scale, and the development of a reference spectroradiometer for colorimetry of displays. Details of these new capabilities in photometry and colorimetry programmes at the NIST are described below.

2. Detector-based luminous intensity/illuminance calibrations

At the NIST, eight reference photometers are used to realize the NIST illuminance unit annually, and

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five of these reference photometers are used to maintain the unit and to conduct routine calibrations for luminous intensity and illuminance. Figure 1 shows the calibration history of these reference photometers. Even though these data may be scattered due to the uncertainty of the realization, they imply that these five photometers are stable to better than 0.1 % per year. Note that many other photometer heads can change more significantly over time even without use (often due to contamination or changes in the filters).

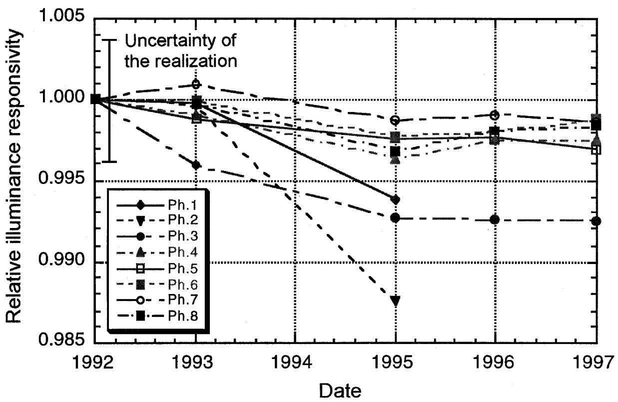

Figure 1. History of the annual calibration of the NIST reference photometers over a five-year period.

By utilizing the detector-based method, transfer standard lamps with a wide range of luminous intensities are calibrated directly using the selected standard photometers with a wide domain of linearity. The photometers do not age with usage time as lamps tend to do; therefore the primary standard photometers can be used in routine calibrations, eliminating the need for creation and maintenance of secondary and tertiary working standards as required for the source-based method, and shortening the calibration chain to reduce uncertainties. Photometers may show short-term reproducibility of the order of 0.01 % if the temperature of the components inside the photometer is kept constant.

The detector-based method has a greater advantage in the calibration of illuminance meters and transfer photometers. At the NIST, illuminance meters and photometers are calibrated directly against the NIST reference photometers by placing their defining apertures in the same illuminated plane. Using such a substitution method, many uncertainty factors are cancelled. There is no need for distance measurements. The lamp alignment and the departure from the inverse square law are no longer critical factors. A working lamp of known distribution temperature (normally 2856 K) is used. The short-term stability of the working lamp is important, but its burning time and ageing characteristics are not critical. The relative expanded uncertainty $(k = 2)$ of luminous intensity and illuminance calibrations at the NIST is now typically 0.5 % [2].

3. High-illuminance calibration

A high-illuminance calibration facility for levels up to 100 klx (the illuminance level of direct sunlight) and luminance up to 30 kcd/m^2 (luminance of a perfect diffuser at that level of illuminance) has recently been developed at the NIST. Figure 2 shows the configuration of this facility. The calibration source was developed utilizing a commercial solar simulator source employing a 1000 W xenon arc lamp with optical feedback control, and is combined with a set of colour glass filters to correct its spectral power distribution to approximate that of the CIE Illuminant A (2856 K Planckian radiation). The illuminance level can be varied without changing the correlated colour temperature significantly and without changing the distance. The new source has a short-term stability of better than 0.2 % for a few hours after a 15 min stabilization period.

Under illumination at a level of 100 klx, the radiation incident on the photometer heats the photometer, resulting in a drift of its responsivity. This introduces additional uncertainties in the measurement, even with

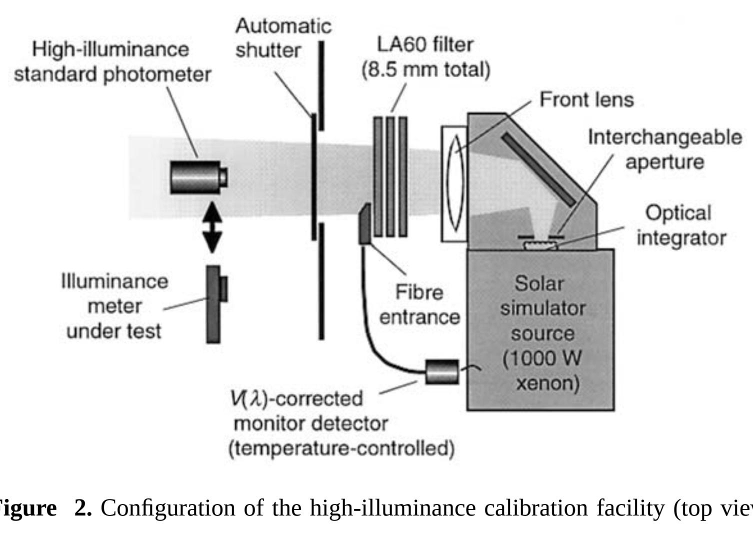

Figure 2. Configuration of the high-illuminance calibration facility (top view).

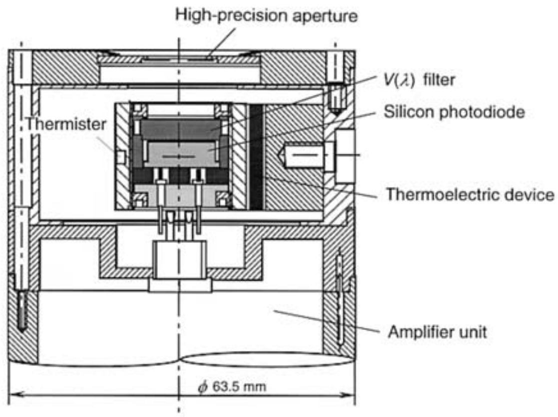

Figure 3. Design of the NIST temperature-controlled photometer used as high-illuminance reference standard.

the temperature-monitored type of photometer. Using the NIST reference photometers, corrections based on the temperature sensor signals were insufficiently accurate because there was a strong temperature gradient within the photometer housing. To solve this problem, a new temperature-controlled type of standard photometer has been developed for this high-illuminance facility. These new photometers employ a new design as shown in Figure 3. The $V(\lambda)$ filter and the photodiode are mounted on a block which is thermally insulated from the housing, and a temperature sensor and a thermoelectric device are directly coupled to the block so that the temperature of the $V(\lambda)$ filter itself is kept constant (at 25 °C), even at such a high level of irradiation. The new photometers have also been verified for linear response to within 0.3 % up to a level of 100 klx. Four photometers of this type are now maintained as reference standards for high illuminance levels.

The effect of heat must be taken into account for the photometers under test. One of the commercial illuminance meters showed a change of 2 % in reading under exposure to 100 klx for 30 min and suffered from permanent damage (contraction of the plastic head) after longer exposure. A procedure has been developed which makes use of a shutter to minimize the exposure time for both standard and test photometers. Calibration services for illuminance meters up to 100 klx are now available at the NIST.

4. Flashing-light photometer calibrations

A flashing-light photometric unit (lx · s) has been realized, based on the NIST illuminance unit, using four flashing-light standard photometers equipped with current integrators. Two independent methods have been employed to calibrate these standard photometers: one based on the electrical calibration of the current integrator, and the other on electronic pulsing of a steady-state photometric standard. With the electrical method, the capacitances for integrating photocurrents are calibrated electrically, and the relationship $Q = CV$ (Q = electric charge, C = capacitance, V = voltage across a capacitor) is used to calculate the responsivity [in V/(lx · s)] of the photometer system. With the pulsed photometry method, under illumination by a known illuminance E (in lx) of steady light, the input gate of the current integrator is opened for a time T. Then the responsivity [in V/(lx · s)] of the photometer system is simply calculated from its output voltage V (in V) and the luminous exposure: $E \cdot T$ (in lx · s).

The photometer consists of a photometer head (consisting of a silicon photodiode, $V(\lambda)$ filter, and an aperture) and a current-integrator unit. The photodiode, Hamamatsu S1226-8BQ, was chosen for its fast rise time (200 ns at 100 Ω load) and other photometric characteristics. The spectral responsivities of the photometer heads are matched to the $V(\lambda)$ function with CIE f_1' values [5] ranging from 1.7 % to 1.9 %. Since anticollision lights have two colours (white and red) with spectral power distributions different from those of the CIE Illuminant A, a spectral mismatch correction factor was evaluated for each colour.

Four current integrator units have been built for use with each photometer head. This integrator operates in two modes: calibration mode (for steady-light measurement with the pulsed-photometry method) and measurement mode (for flashing light). The unit has two current integrator circuits to allow simultaneous measurement of two photometer heads. This feature is useful for correcting for variations in the individual flashes during substitution measurements for photometers.

The electronic components were carefully chosen to assure rapid response and stable operation. The main integrator has three ranges (1000 lx · s, 100 lx · s, and 10 lx · s) and is capable of measuring over two orders of magnitude at each range with sufficient signal-to-noise ratios, thus covering a measurement range over four orders of magnitude.

The instantaneous intensity of a xenon flash source at its peak is very high and can cause saturation of the photodiodes. The flashing-light standard photometers (including the current integrators) were tested for linearity using a relative method, in which a test photometer was compared with a reference photometer of known linearity under illumination by a xenon flash source up to a level of 1000 lx · s.

The units realized using the two independent methods agreed to within 0.2 %, and both methods proved to be appropriate. The relative expanded uncertainty $(k = 2)$ of the NIST flashing-light standard photometers, in the measurement of white xenon flashing light, is estimated to be 0.6 %.

Since xenon flash sources do not reproduce their photometric values accurately, a decision was made to use a transfer method rather than sources to perform the calibration of flashing-light photometers. The arrangement is shown in Figure 4. The measurements

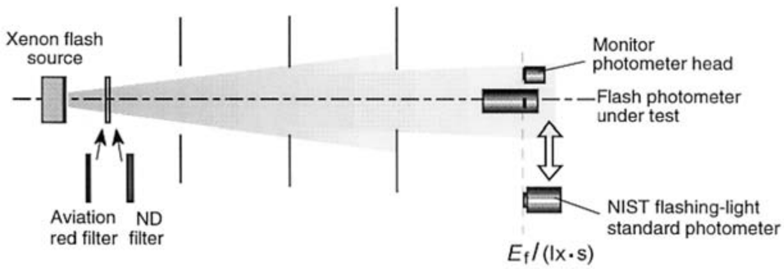

Figure 4. Arrangement for the calibration of flashing-light photometers.

are made by integrating ten flashes and using the NIST photometric bench [2]. A xenon anticollision light system is used as a source to provide illuminance, and photometers are calibrated for integrated illuminance (in lx·s) directly against the NIST flashing-light standard photometers, for both white and red flashing lights. This calibration service is now available.

5. Detector-based luminous-flux calibration

The NIST lumen was realized in 1995 using the Absolute Integrating-Sphere Method [7] developed by the NIST. This method allows realization of the lumen using an integrating sphere rather than a goniophotometer. This method will be applied directly to routine calibration measurements of luminous flux with simpler procedures and with reduced uncertainties. A new luminous-flux calibration facility with a 2.5 m integrating sphere has recently been completed, which allows calibration of test lamps with no need for luminous-flux standard lamps, thus establishing a detector-based procedure for luminous-flux calibrations using an integrating sphere. (Goniophotometer methods are also detector-based methods in this sense.)

The new facility, as shown in Figure 5, is equipped with an aperture/photometer wheel at the sphere opening and will allow automatic measurement of the illuminance from the external source at the aperture plane. Two standard photometers, known to have excellent long-term stability, will be used to measure the illuminance to provide the scale of the luminous flux of the test lamp. The spatial nonuniformity of the sphere response is measured periodically with a scanning beam source in order to maintain the accuracy of the spatial correction factor. To facilitate this measurement, the new 2.5 m integrating sphere is equipped with computer-controlled two-axis rotation stages to scan the internal beam source. Details of this facility and measurement procedures are presented in [8].

The new 2.5 m integrating sphere will also be used to realize the spectral radiant-flux scale in the UV-to-visible region. The sphere has a barium-sulfate-based coating with reflectances of approximately 98 % in the visible region and 92 % to 98 % in the

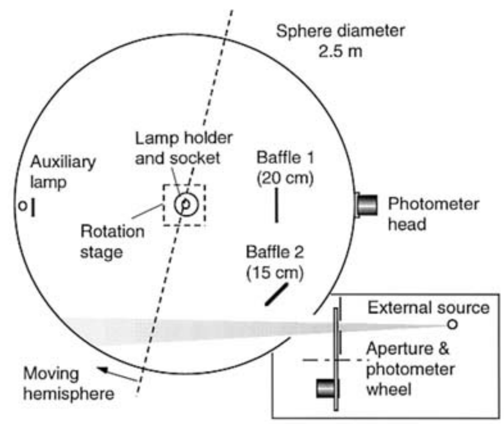

Figure 5. Arrangement of the new NIST 2.5 m integrating sphere (top view).

250 nm to 380 nm region. A double-monochromator-based spectroradiometer connected to the sphere is being developed to allow spectral measurement of lamps and to provide calibration of the chromaticity and colour-rendering indices of fluorescent lamps.

6. Colorimetry of displays

Accurate chromaticity measurements of colour displays, such as cathode ray tubes (CRTs) and flat panel displays, are increasingly important as their qualities improve and customers demand more accurate colour reproduction. There is thus a need for accurate calibration of colour-measuring instruments, including tristimulus colorimeters and spectroradiometers. A new project has just started at the NIST to develop the capability to calibrate such colour-measuring instruments for displays. A reference spectroradiometer designed specially for colorimetry of displays is being built. Test instruments will be calibrated against the reference spectroradiometer for many different colours from a real display (a CRT and a flat panel display).

To allow transfer of the accurate colour-measurement capability, a new calibration method is being developed for tristimulus colorimeters used as transfer standards. Tristimulus colorimeters are commonly used to measure the chromaticity of such displays. However, due to imperfect matching of their spectral responsivities to the colour-matching functions, measurement errors are inevitable when various colours of a display are measured. Matrix techniques, as given by the ASTM [9] are available to improve such errors. However, due to experimental noise and errors, the methods often do not work as expected. To further improve the accuracy of the matrix technique, a new method (Four-Color Method) has been developed [10], and further work is in progress to verify the accuracy of this method for real measurement situations.

7. Conclusion

A detector-based photometric calibration has many advantages over the conventional source-based method, and is now widely employed in photometric measurements at the NIST. A detector-based method provides the benefit of freedom in the selection of light sources to be used in calibrations. To utilize this benefit, a high-illuminance calibration facility has been developed using a xenon arc discharge lamp which extended the illuminance calibration capability up to 100 klx. A flashing-light photometric unit has been realized and calibration services for flash photometers have been established. The detector-based method is the most difficult to apply to the luminous-flux measurement with an integrating sphere, but work is in progress at the NIST to achieve this capability for the first time.

Other ongoing projects include the realization of the total spectral radiant-flux scale and the development of a reference spectroradiometer for colorimetry of displays. Calibration services are planned for these areas of photometry and colorimetry in the near future.

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References

1. Cromer C. L., Eppeldauer G., Hardis J. E., Larason T. C., Parr A. C., *Appl. Opt.*, 1993, **32**, 2936-2948.
2. Ohno Y., NIST Special Publication 250-37, *Photometric Calibrations*, National Institute of Standards and Technology, July 1997.
3. Ohno Y., Navarro M., *Proc. Natl. Council Stds. Labs.*, 1997, 343-353.
4. Ohno Y., *J. Illum. Eng. Soc.*, 1998, **27**(2), 132-140.
5. *CIE Publication No. 69*, International Commission on Illumination, 1987.
6. Ohno Y., Zong Y., *Proc. Soc. Photo-Opt. Instrum. Eng.*, 1997, **3140**, 2-11.
7. Ohno Y., *J. Illum. Eng. Soc.*, 1996, **25**, 13-22.
8. Ohno Y., *Metrologia*, 1998, **35**, 473-478.
9. *ASTM E 1455-96*, American Society for Testing and Materials, 1996.
10. Ohno Y., Hardis J., *Proc. AIC Color'97 Kyoto*, 1997, **2**, 570-573.