The Detector-Based Candela Scale and Related Photometric Calibration Procedures at NIST

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Introduction

Since the redefinition of the candela in 1979, national standards laboratories have been free to realize the candela by use of whatever radiometric means they found most suitable. Different national laboratories[1-8] and other research facilities[9,10] have employed various techniques to realize their luminous intensity scales.

Until recently, the luminous intensity scale at the National Institute of Standards Technology was based on a gold-point blackbody.[1] The blackbody radiation at the gold point (1337.33 K; determined at NIST from absolute radiometric detectors[12]) was used to calibrate a variable temperature blackbody, which provided the spectral radiance scale.[13] From this, the spectral-irradiance scale was derived.[14] The luminous-intensity scale was realized through spectral irradiance measurements of a primary reference group of candela lamps using the spectral irradiance working standards. A secondary reference group, calibrated against the primary group, was used for routine calibrations. The final uncertainty of 0.8 percent (2σ)[15] contained a relatively large component due to the uncertainty in the gold-point temperature at the top of the chain, and additional uncertainty accumulated in the long calibration chain using sources.

Recently at the Radiometric Physics Division of NIST, the candela scale has been realized using a group of absolutely calibrated photometers. Other national laboratories have employed absolutely calibrated radiometers or photometers using either thermal detectors or self-calibrated silicon photodiodes. NIST chose calibrated silicon photodiodes with filters to make photometers on account of their wide dynamic range and simplicity of operation. The photometers had their relative spectral responsivity matched to the spectral luminous efficiency function V(λ), and were calibrated against the NIST absolute spectral responsivity scale, which is currently based on a cryogenic radiometer.[16] The design, characterization, and calibration of the photometers are described in this paper.

The procedures of various photometric calibrations, such as those for luminous intensity, illuminance, luminance, and total luminous flux, have also been drastically revised, and the absolute accuracy of calibrations have been significantly improved. The new calibration procedures developed and being developed are described here. Uncertainty statements in this paper follow Taylor,[15] which recommends the use of 2σ values for calibrations and 1σ values for most other results including the uncertainty of scales.

The detector-based candela scale

Principles

Let us assume a photometer as shown in **Figure 1** is constructed, using a silicon photodiode, a V(λ) filter, and a precision aperture. When the absolute spectral responsivity s(λ) (in amps/watt) of the photometer is measured, the responsivity R_{vf} (in amps/lumen) of the photometer for luminous flux (lm) is given by

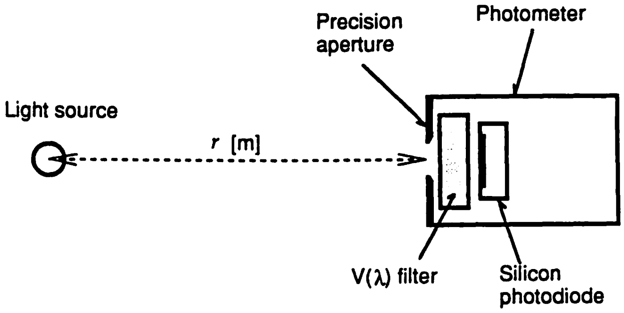

Figure 1—Geometry for the detector-based candela scale realization

$$R_{vf} = \frac{\int_\lambda P(\lambda)\, s(\lambda)\, d\lambda}{K_m \int_\lambda P(\lambda)\, V(\lambda)\, d\lambda} \quad \text{(A/lm)} \qquad (1)$$

where P(λ) is the spectral power distribution of light to be measured, V(λ) is the spectral luminous efficiency function, and K_m is the maximum spectral efficacy (683 lm/W). If the area S(m^2) of the aperture is known and the responsivity R_{vf} is uniform within the aperture opening, the responsivity R_{vi} of the photometer for illuminance (lx) is given by

$$R_{vi} = S \cdot R_{vf} \text{ (A/lx)} \qquad (2)$$

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When a photometer calibrated for R_{vi} is used to measure the illuminance from a point source, the luminous intensity I_v (in candelas) of the source is given by

$$I_v = r^2 \cdot (I/R_{vi}) \text{ (cd)} \qquad (3)$$

where r is the distance (in meters) from the light source to the aperture surface of the photometer and I is the output current (amps) of the photometer.

To realize the candela scale, although the principles are simple, uncertainties in measuring each of the quantities and uncertainties associated with the assumptions must be evaluated. **Figure 2** shows the calibration chain for the candela scale as revised by this work. A cryogenic radiometer which has recently been installed at NIST acts as the absolute radiometric base at the top of the chain. The radiometer, (called HACR; High Accuracy Cryogenic Radiometer), cooled by liquid helium to 5 K, works on the principles of electrical substitution. The HACR's measurement uncertainty in the calibration of a light-trapping detector is 0.026 percent (2σ) at 633 nm.[16] The absolute responsivities at several laser wavelengths are transferred to the Spectral Comparator Facility (SCF), where the spectral responsivity scale is realized with a light-trapping detector. It is described below. The absolute spectral responsivity s(λ) of each photometer in the group is determined using this spectral response scale. The photometric responsivities R_{vi} of the photometers are obtained by **Equations 1** and **2** for given P(λ), thus providing the illuminance scale. Using the photometers, the luminous intensity of a candela lamp is determined from the illuminance measurement and the given distance r in **Equation 3**. This procedure for a candela scale realization is simpler than the conventional source-based method. The details of each calibration step are discussed below.

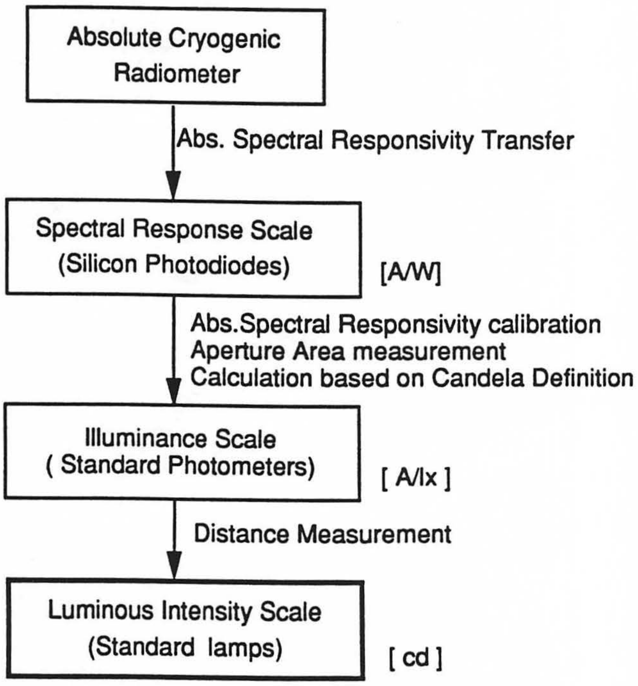


Figure 2—Calibration chain for the detector-based candela scale as revised by the present work

Construction of standard photometers

A group of eight photometers has been developed. **Figure 3** depicts the photometer design. A silicon photodiode, a V(λ) filter, and a precision aperture are mounted in the front piece of a cylindrical housing. The photodiode is plugged into a socket with a teflon base of low electrical conductivity. On the front side of the filter, the precision aperture is glued to a holder carefully machined so that its front surface (the reference surface of the photometer) is 3.00 mm from the plane of the aperture knife edge.

Under this front piece, an electronic assembly containing a current-to-voltage converter circuit with a high sensitivity and a wide dynamic range[17] is built-in to minimize noise. The circuit has a switchable gain setting from 10^4 to 10^{10} or 10^{11} V/A. An input equivalent noise of ~1 fA is achieved at the gain setting of 10^{11} V/A with an integration time of 1.67 s and a measurement bandwidth of 0.3 Hz. This high sensitivity feature allows precise measurement of s(λ) even in the wings of the V(λ) curve.

Because characteristics of the filter and photodiode change with temperature, a temperature sensor is installed in the front piece of the housing to monitor the photometer temperature.[18]

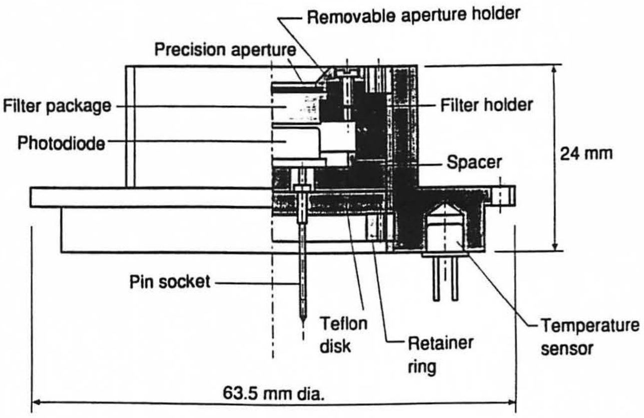


Figure 3—Photometer design

** Specific firms and trade names are identified in this paper in order to adequately specify the experimental procedure. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.*

Characterization of components

Hamamatsu* S1226 and S1227 series silicon photodiodes were used for the photometers. They were selected for the largest shunt resistance that the manufacturer could provide, 2.5–7.0 GΩ, in order to minimize noise and drift in the amplifier circuit.[17] The reduced infrared sensitivity of these photodiodes compared to others is advantageous for application in photometry. S1227-1010BQ photodiodes with 1-cm^2 areas were used for photometers 1 and 2, which possess larger-area V(λ) filters. S1226-8BQ photodiodes with 0.3-cm^2 areas were used for the other six photometers. The photodiodes were screened for their uniformity of response over their active areas. The uniformities of the photodiodes were measured at several wavelengths using the SCF (described in the next section), and the maximum deviation from the mean value was less than 0.2 percent. The temperature dependence of the photodiode responsivity was also measured in a temperature-controlled housing. It was less than 0.03 percent/°C in the 400–700-nm region.

For V(λ) filters, colored glass filters from different sources were used. Filters 1 and 2 were provided by the National Research Council (NRC) of Canada, filter 3 by the National Physical Laboratory (NPL) of the UK, and filters 4–8 were manufactured by PRC Krochmann. They were all made of several layers of different glasses. Filters 4–8 were selected from among 24 total candidates by visual inspection and by a uniformity test: scanning a ~2-mm white light spot over the surface. The spectral transmittances of the selected filters were then measured using the SCF at 530, 555, and 580 nm on 37 spots for the larger filters and seven spots for the smaller filters. The nonuniformities were found to be typically ~0.1 percent or less.

The temperature dependence of the filter transmittance was also measured using a commercial spectrophotometer equipped with a sample heater. The temperature dependence of the filters was found to be typically −0.3 to −0.2 percent/°C for the 450−500-nm region, and −0.1−0.0 percent/°C for 550 to 650-nm region. These data indicate a significant temperature dependence of the overall photometer, which is analyzed in the next section.

Precision apertures with areas nominally 0.5 cm^2 were used for photometers 1 and 2, while 0.1-cm^2 areas were used for photometers 3 through 8. The apertures were electroformed using nickel-clad copper and given a black, nickel finish. The areas of the apertures were measured by Precision Engineering Division at NIST using a vision-based measuring machine. After making a pass to find the approximate center of the aperture, 720 radii were measured from the center to the lip at 0.5 degree intervals. From these radii, the area was calculated by a polygonal approximation. The uncertainty of this area measurement was given as 0.04 percent for the larger apertures and 0.1 percent (both 2σ) for the smaller.

The transfer gains of the current-to-voltage converters in the photometers were calibrated electrically by replacing the photodiode with a computer-controlled voltage source and calibrated resistors in series. The amplifier gains were determined by a linear fitting of data for many combinations of input current and measured output voltage. The gains so determined have an uncertainty of less than 0.01 percent (2σ).

Characterization and calibration of photometers

After characterizing the components, the photometers were assembled as shown in **Figure 3**. The photometers were characterized for overall performance and calibrated for photometric responsivity as follows.

An essential part of the calibration is to determine the absolute spectral responsivity s(λ) using the spectral comparator facility (SCF) (**Figure 4**). A detector under test is held in a carriage, which can be translated under computer control. Any point on the active area of the detector can be positioned at the focus of a 1.1-mm, nearly circular spot from the monochromator. The carriage also holds reference detectors, which serve as secondary standards and which are measured alternately with the device under test. Compensation for changes in the light source during the course of the measurements is made using the signal from a monitor detector. The computer controls the monochromator, which has a bandpass of 4 nm for this spot size and a wavelength setting uncertainty of ~0.2 nm (2σ).[19] The system typically delivers a few microwatts of optical power to the detector.

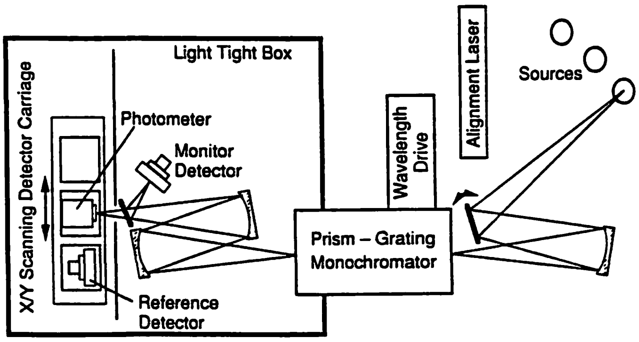
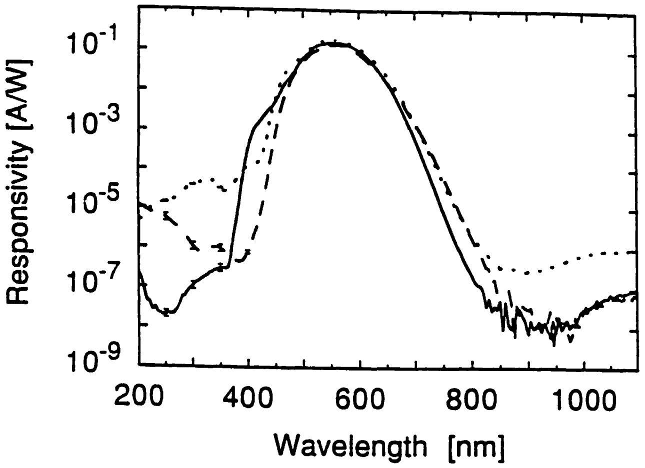
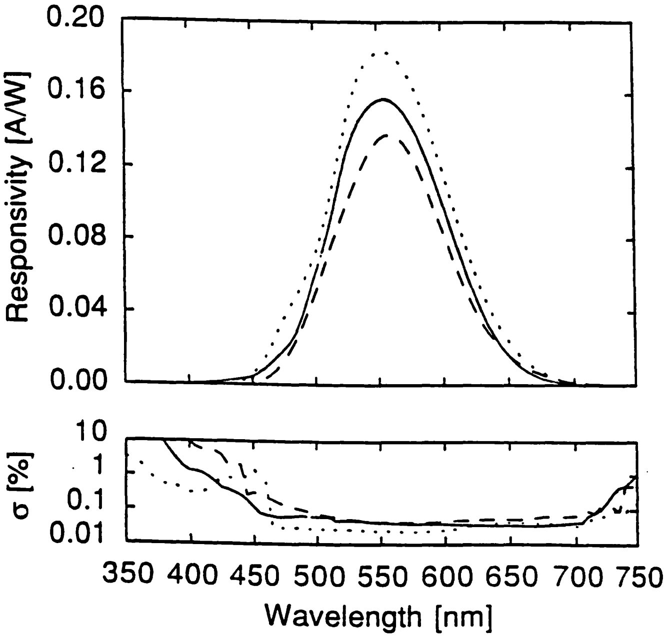


Figure 4—Spectral comparator facility

The absolute spectral responsivity s(λ) was obtained as an average of measurements on a fine, rectangular mesh of points over the aperture area at ~0.25-mm intervals. To perform this measurement efficiently, s(λ) was measured at 5-nm intervals only at the center of the aperture, and at 50-nm intervals at all the other spots in the aperture. The average responsivities were obtained at 5-nm intervals by multiplying the center-point measurement by a correction function, a polynomial fit to the 50-nm ratios. These correction factors typically range from 0.998–1.002 throughout the visible region, but some photometers showed ~0.99 in the blue region. The data from representative photometers (at the center spot) are shown in **Figure 5 (a)**. Of particular importance in these data is the degree of IR and UV suppression, the latter including both transmission and fluorescence signal. The final spectral responsivities of representative photometers are shown in **Figure 5 (b)**. The curves given in the lower part of the figure are the standard deviations in three measurements of the center spot.



(a) At the center of the aperture



(b) Corrected for the entire aperture area

Figure 5—Absolute spectral responsivity of photometers (a) at the center of the aperture and (b) corrected for the entire aperture area. Solid curve: PRC, dashed curve: NRC, dotted curve: NPL

The temperature dependence of the overall photometer responsivity for a 2856 K incandescent lamp was measured in a temperature-controlled housing. The photometer being tested was placed in the housing and allowed to reach thermal equilibrium overnight. The temperature during the measurement was monitored using the temperature sensor inside the photometer. **Figure 6** shows the results. The data about photometers employing filters from the same source are considered together and fit to a common line. The temperature correction factors were determined to be 0.063 percent/°C for photometers 1 and 2, 0.049 percent/°C for photometer 3, and 0.088 percent/°C for photometers 4 through 8.

The linearities of the photometers were measured using a beam conjoiner device.[20] **Figure 7** shows the results for a typical photometer. These data indicate that the photometer is linear over an output current range of 10^{-11}–10^{-4} A. This corresponds to an illuminance of 10^{-3}–10^{4} lx for those photometers. This means that the photometers can be used to measure a luminous intensity as low as 1 mcd at ~1 m, and as high as 10^{5} cd at ~3 m. These linearity data also assure negligible nonlinearity error in the spectral responsivity and other measurements described in this paper.

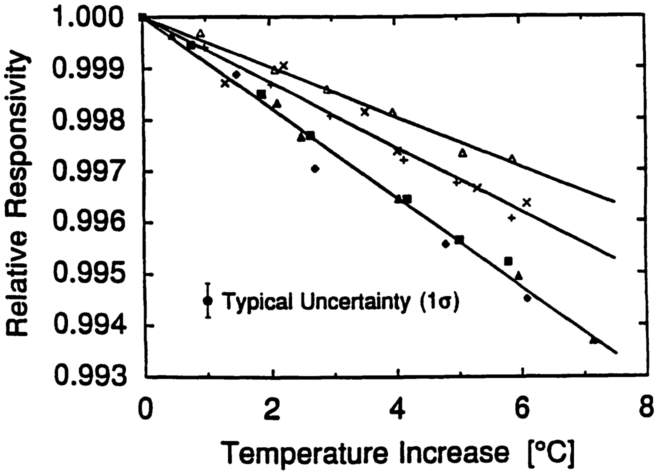


Figure 6—Temperature dependence of photometer responsivity for 2856 K source. Δ: 3(NPL), ×: 1(NRC), +: 2(NRC), ■ :5(PRC), ♦ :6(PRC), ▲ :8(PRC)

After all the necessary data were obtained as described above, the photometric responsivity of each photometer was calculated using **Equations 1 and 2.** The spectral power distribution P(λ) in **Equation 1** was

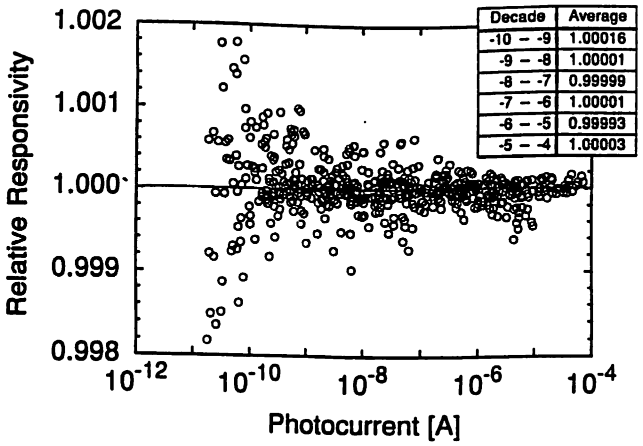


Figure 7—Linearity of a typical photometer measured with the beam conjoiner

that of a 2856 K blackbody. Tests showed that spectral distributions of actual lamps, of the type used for luminous intensity calibrations at NIST, operated at a color temperature of 2856 K have a sufficiently approximate Planckian distribution so that differences are negligible. The responsivities were calculated to be $\sim 1 \times 10^{-8}$ A/lx for photometers 1 and 2, and $\sim 3 \times 10^{-9}$ A/lx for photometers 3 through 8. After a responsivity was found for each photometer, the self-consistency within the eight-photometer group was checked by measuring five inside-frosted lamps using each photometer. Illuminance values measured by eight photometers varied by 0.13 percent (1σ). This fluctuation is considered to be due to random errors in the calibration. The variation was reduced (self-consistency improved) by applying correction factors to the original calibrations, which maintained the group average. To show the degree of $V(\lambda)$ matching, the CIE f_1' values[11] of the photometers range from 1.4 – 7.2 percent.

By the procedures described so far, the illuminance scale was realized on the group of photometers with detailed characterizations and corrections. The uncertainty analysis of the scale is reported in detail elsewhere.[21] The major factors of the uncertainty are in the absolute spectral responsivity scale (0.11 percent), the wavelength calibration (0.04 percent), the effect of the numeric aperture of SCF (0.05 percent), the aperture area (0.05 percent), and other factors (0.12 percent), resulting in an overall uncertainty (combined standard uncertainty[15]) of 0.19 percent (1σ) for the illuminance scale. This is an improvement by almost a factor of two over the old photometric scale at NIST.

Realization of the candela scale

Once an illuminance scale is established, the luminous intensity of a source can be determined by measuring the illuminance at a known distance from the source as calculated by **Equation 3**.

The optical bench shown in **Figure 8** was used for this purpose. The base comprised three 1.8-m-long steel optical tables. A 5-m-long rail system with movable carriages was mounted on the table. Two telescopes were rigidly mounted to the table for alignment of the lamps. The photometers were aligned against the front surface of a mount, which was fixed on a carriage. The position of the carriage on the rails was monitored by a computer-readable, linear encoder that provided an absolute position with a resolution of 0.01 mm. The encoder reading was verified by comparison with a 2.75-m vernier caliper, and the distance uncertainty was determined to be 0.18 mm (1σ). The optical bench was covered by a light-tight box, the inside of which was covered with black velvet. The stray light, checked with various arrangements, was consistently less than 0.03 percent.

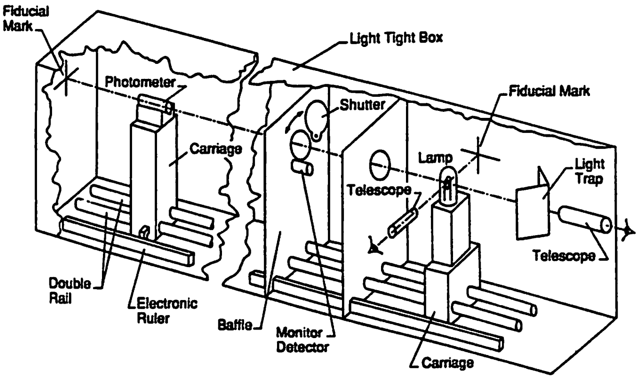


Figure 8—NIST photometry bench

By using the calibrated photometers and the optical bench, the luminous intensity of lamps could be measured with almost the same uncertainty as the illuminance scale. Luminous intensity standard lamps are not maintained any more. Instead, the group of eight photometers are maintained at NIST for the candela scale.

Application of the new scale

Luminous intensity calibration

In the past, luminous intensity calibrations have been performed by comparing test lamps to a standard lamp with a monitor photometer. Working standard lamps were needed to limit the burning time on reference standard lamps. Working standard lamps of several different wattages were used to calibrate lamps of similar wattage, to avoid linearity errors in the detector system. By using the detector-based method described in this paper, there is no need for maintaining standard lamps. The different wattages of test lamps can be directly calibrated by the standard photometers because of their wide domain of linearity. The standard photometers do not degrade with use as do some lamps.

Lamps, however, are still needed as transfer standards in many cases. At NIST, inside-frosted incandescent lamps[1] are normally used. The filaments of this type of lamp are not visible from outside, so the lamp socket instead of the lamp filament is aligned by using a fixture. This method of alignment may ignore a discrepancy between the socket position and the effective optical center of the lamp. With this factor taken into consideration, the overall uncertainty of a luminous intensity calibration for that type of lamp is estimated to be 0.46 percent (2σ).[21] When using the photometers, their temperature sensors allow their readings to be adjusted for the prevailing conditions.

An optical bench with an accurate-length scale remains essential for luminous-intensity calibrations. The necessity of luminous intensity standard lamps, however, can be eliminated in most cases by replacing standard lamps with standard photometers. A method of determining the spectral distribution of the lamps, such as the color temperature of an incandescent lamp, is required for the highest accuracy measurements. Lamp standards are needed still for spectroradiometric, colorimetric, and color temperature calibrations.

Illuminance meter calibration

Illuminance meter calibrations are often performed using standard lamps of different wattages, the meter head being placed at different distances from a lamp. The calibration is subject to errors caused by misalignment of the lamp and by departure from the inverse-square law near the lamp. Thus, a long optical bench with an accurate length scale is used.

Illuminance meters can be calibrated by direct substitution against the standard photometers, by placing them on the same illuminated plane. Since the actual illuminance is measured by the standard photometers, distance readings on the bench are not necessary, and calibration of the lamp is not an essential factor. The lamp alignment and the inverse square law departures are no longer an issue for accurate measurement. The short-term stability and color temperature of the lamp are important for accurate measurement.

At NIST, color-temperature standard lamps[1] operating at 2856 K are normally used for the purpose. A monitor detector is used to correct for the drift of the lamp during substitution. In this manner, the uncertainty of the transfer measurement is kept below 0.05 percent (1σ). With the illuminance scale uncertainty being 0.19 percent (1σ), the uncertainty of calibration for illuminance meters and photometers is estimated to be ~0.4 percent (2σ). This value does not include uncertainty factors inherent to the illuminance meter or photometer under test. Illuminance meters can be calibrated for different sources of known spectral power distribution by computing R_{vf} for the source distribution.

For calibration over a wide range of illuminance, there is still a need for a long optical bench and different wattages of lamps. We plan at NIST to develop a variable-illuminance source with a constant spectral power distribution to eliminate the necessity for multiple standard lamps.

Detector-based luminance scale

Luminance scales are commonly realized using a white reflectance standard or a transmitting diffuser illuminated by a luminous intensity standard lamp.[11] The determination of the luminance factor of the material includes comparison of the incident and outgoing illuminances, which differ by three to four orders of magnitude, making precise calibration difficult. The uncertainty is also limited by that of the standard lamp used.

With the use of the standard photometers, a detector-based luminance scale has been realized at NIST on a reference integrating-sphere source operated at 2856 K. **Figure** 9 shows the set-up. The sphere source was 15 cm in diameter and had a V(λ)-corrected monitor detector on the sphere wall. The source had a double-sphere structure, the large sphere being irradiated by an intermediate 5-cm sphere, which was irradiated by a quartz halogen lamp. The sphere source was operated by a constant-current power supply. Precision apertures of 6 and 21-mm in diameter were attached, alternately, to the exit port (25-mm diameter) of the sphere source. The sphere source and the photometers were used on the optical bench mentioned above. The illuminances at 50 cm and at 90 cm from the sphere source aperture edge were measured by the standard photometers. The distances were set using a length gauge. The luminance L (in candelas/square meter) was determined

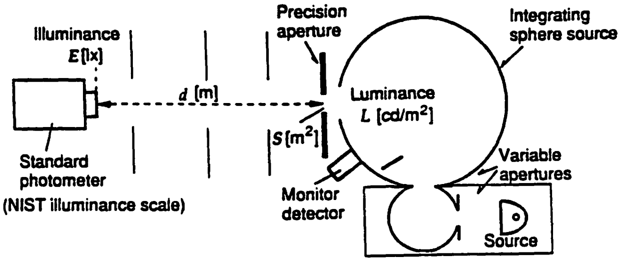


Figure 9—Set up for the luminance scale realization

from the illuminance E (lx), the distance d (m), and the aperture area S (m²):

$$L = k\,E\,d^2/S \text{ (cd/m}^2\text{)} \qquad (4)$$

where k is a geometrical correction factor determined by the size of the aperture and the distance d. The factor k was 1.0004 and 1.00004 for 21-mm and 6-mm apertures respectively, at 50 cm. In the comparison of the data obtained using apertures of different sizes, corrections were made for the spatial non-uniformity of luminance over the exit port. The internal reflections from the aperture differed depending on the aperture size, which was compensated using the monitor detector signal of the sphere source. The diffraction loss with the aperture[23] was calculated to be negligible ($<$ 0.01 percent) in this geometry. The entire measurement was performed twice, including realignment of the setup. The luminance values obtained under several different conditions agreed within 0.2 percent.

The uncertainty factors include the illuminance scale (0.19 percent), distance measurement (0.06 percent), aperture area (0.05 percent), stray light (0.1 percent), and random variations (0.08 percent), all 1σ, resulting in the overall uncertainty (combined standard uncertainty) of $\sim$0.25 percent for the luminance scale. The scale has been transferred to a reference luminance meter, and the long-term stability of the sphere source and the reference luminance meter are being studied.

Total luminous flux calibration

Working standard lamps of 500, 200, and 100 W and six types of miniature lamps ranging from 400–lm have been maintained at NIST for luminous flux calibration. Because of the number of transfer measurements involved, from 300-W primary standard lamps, the uncertainty of working standard lamps ranged from 0.9 to 1.9 percent (2σ).[1]

By employing a photometer of the design described in this paper with the 2-m integrating sphere at NIST, the need for many of these working standard lamps has been eliminated. The operating range of the photometer corresponds to 10^{-2} to 10^{5} lm in the 2-m sphere. Only one type of working-standard lamp (100 W) is now used with the 2-m sphere for routine calibrations of incandescent lamps of various wattages, including miniature lamps. Correction is made for the self-absorption of the lamps, being measured by using an auxiliary lamp, and for the change of photometer temperature during measurement.

Corrections for the spectral power distributions of lamps are also applied. The spectral throughput of the integrating sphere was measured using a spectroradiometer and a tungsten lamp whose relative spectral radiant intensity was sufficiently constant over all angles. The result is shown in **Figure 10** (solid curve). These data were multiplied by the relative spectral responsivity of the photometer, giving the spectral responsivity of the overall system (shown in the dash-dot curve, CIE f_1' being 5.2 percent). The correction factor k_c is given by the CIE.[22]

$$k_c = \frac{\int_\lambda P_s(\lambda)S_r(\lambda)d\lambda \int_\lambda P_t(\lambda)V(\lambda)d\lambda}{\int_\lambda P_s(\lambda)V(\lambda)d\lambda \int_\lambda P_t(\lambda)S_r(\lambda)d\lambda} \qquad (5)$$

where $P_s(\lambda)$ is the spectral power distribution of the standard lamp, $P_t(\lambda)$ is the spectral power distribution of the test lamp, $s_r(\lambda)$ is the relative spectral responsivity of the overall system, and $V(\lambda)$ is the spectral luminous efficiency. k_c is applied to get the measured total luminous flux values.

The largest contributions to the measurement uncertainty are from the primary standards (0.27 percent), in the transfer to working standards (0.2 percent), in the luminous intensity distribution of test lamps (estimated to be 0.15 to 0.3 percent depending on the lamp, including socket loss), and random variations (0.1 to 0.25 percent), all 1σ. The expanded uncertainty of calibration is 0.8 to 1.1 percent (2σ).

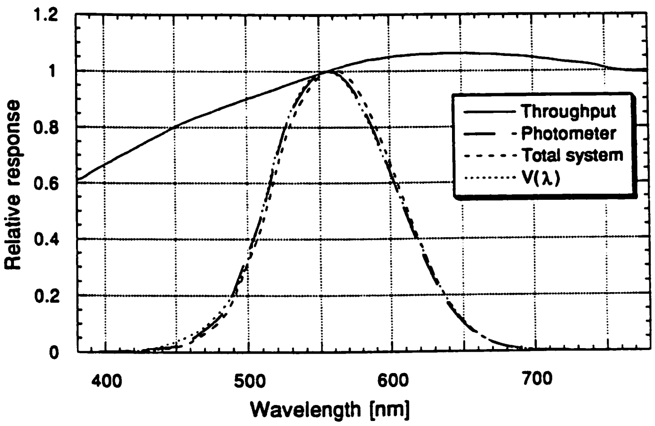


Figure 10—Spectral characteristics of the NIST integrating sphere

Conclusion

A luminous intensity scale has been realized with the detector-based method in a simpler and more direct manner than before. In the process, the uncertainty of luminous intensity calibrations has been reduced by almost a factor of two.

It is expected that the principal uncertainties in the illuminance scale, those of the spectral-response scale and the aperture area, will be reduced significantly by ongoing research and development in our division.

The long-term stability of the photometers will also be studied further. The establishment of the detector-based illuminance scale has given a great benefit to other photometric calibrations. Traditional photometry has always relied on lamp standards, which in many cases have limited the improvement of accuracy. At NIST, the procedures for calibrating luminous intensity, illuminance, luminance, and total luminous flux have been revised by taking advantage of detector-based methods. The calibration procedures have been simplified, and the uncertainties have been reduced significantly. With standard-quality lamps becoming more and more difficult to procure, detector-based methods merit particular attention.

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Discussion

Dr. Ohno presents an interesting and comprehensive description of a new photometric calibration scheme developed at NIST. I would agree from a purely technical standpoint that the detector-based methodology based on cryogenic radiometry is superior to past realizations and that the improvement in uncertainty in the candela base unit is noteworthy. However, as a member of the commercial lighting industry who relies on photometric calibration traceability to NIST, I am not convinced that we will derive any practical benefit from the new capability.

In my view, the implementation of a detector-based method for maintaining the candela underscores the importance of luminous flux calibrations. For general lighting sources the consumer or end user is almost exclusively interested in the total light output that the source supplies. Even directional sources (e.g., reflector lamps), which have historically been characterized in terms of luminous intensity distribution or intensity in a specified direction, are now being evaluated for total lumen output and rated in terms of efficacy (lumens per watt). In your paper you give a lengthy description of the luminous intensity and illuminance calibrations, but only three short paragraphs near the end of the paper were devoted to the luminous flux calibrations. Here you describe color corrections, but there is no mention of how the geometric transfer from illuminance to luminous flux was made. I assume that you deployed one of the eight detectors previously discussed; this is also not clear.

Some other specific questions follow. Were the new 100-W working standards for flux characterized goniometrically or by some other method? What 2-m sphere are you referring to here—the one used in NBS Publication 250-15? On the absolute spectral responsivity calibration using the spectral comparator facility, it is not clear from **Figure 4** how the calibration scale from the cryogenic radiometer itself was obtained; only sources are depicted in the figure. Could you clarify this process? If luminous flux calibrations of lamps are provided to laboratories requesting them, how do these calibrations take advantage of the reduced uncertainties in the candela? Finally, you state that photometric calibrations performed at NIST are now more versatile and flexible. Consequently, can we expect the response time of photometric calibration services from NIST to improve?

In summary, I think that flux calibrations are treated as an afterthought in your paper. My impression is that if lighting companies want to get the most viable calibration from NIST they need to purchase or rent one of the characterized detectors rather than submit sources. Lumen levels must then be derived from the candela calibration. In most commercial laboratories this is not a trivial exercise that can be accomplished with any degree of confidence. I still feel that as an industry we have been cast adrift when it comes to maintaining our own flux calibration levels. Also I believe the problem of limitations in filament lamp stability being a barrier to obtaining accurate calibrations has been historically overstated by NIST. The superiority of silicon detectors in this respect is well known; however, quality lamps are still commercially available and when used in groups where measurement data are given the appropriate statistical treatment, the reproducibility of lumen output is as good as the stated uncertainty in your new candela scale. This should be quite acceptable except perhaps for the rarest of applications.

R. Collins
Philips Lighting

Author's response

To R. Collins

We agree that the total luminous flux standards are probably the most important in lighting industry. However, the candela is the SI unit for photometry and serves as the base of all other photometric units, including the lumen. As the title of the paper indicates, the main purpose of this paper is to announce the new realization of the candela at NIST and to report its technical details. The description regarding the photometric calibration procedures in the later part of the paper is limited to those directly related to the detector-based method. The methodology to derive a total luminous flux scale from the luminous intensity scale is another substantial issue, and therefore, is not covered in the limited scope of this paper.

The total luminous flux scale at NIST, at the moment, is still source-based, realized back in 1985. Efforts are now being made to improve this situation by placing the total luminous flux scale on our new candela scale. A new method of total flux scale realization is also being developed at NIST, which will be published elsewhere. This new technique will, of course, provide accurate calibration of appropriate lamp standards.

The uncertainty of the total luminous flux calibration has been improved as described in the paper by utilizing a detector for the integrating sphere with a large linearity range and a high sensitivity. When the new total luminous flux scale based on the new candela scale is realized, the uncertainty will be further reduced—a substantial benefit for the luminous flux scale.

This paper does not imply or state that detectors can replace total luminous flux standard lamps. We do not intend to stop the calibration services for total luminous flux; on the contrary, efforts are being made to expand the total flux calibration services to include more lamp types.

It should also be noted that illuminance and luminance standards also are very important for photometer manufacturers—as well as the photography, display, and aircraft industry, us among others—who have direct benefits from the new candela scale.

Answering other specific questions, the 100-W working-standard lamps mentioned in the paper are calibrated by comparison with the 300-W primary standard lamps using the 2-m integrating sphere. The 2-m sphere mentioned in the paper is the same one as described in SP250-15. **Figure 4** is revised slightly to make it clearer: It shows that the responsivity of a photometer is calibrated against a reference detector which has been calibrated against services at the cryogenic radiometer. The response time of radiometric calibration services at NIST is usually not a technical problem, but we would like to improve it.