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Improved Photometric and Colorimetric Calibrations at NIST

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Abstract

Detector-based methods are applied to the photometric calibration work as well as the realization of the photometric units at NIST, significantly reducing the uncertainties of the calibrations. A high-illuminance calibration facility has been developed utilizing the detector-based method. The NIST luminous flux unit is now realized using the Absolute Integrating Sphere Method, and this method will be applied to the calibration of test lamps using a new 2.5 m integrating sphere, thereby bringing the luminous flux calibration into a detector-based procedure, shortening the calibration chain, and further reducing the measurement uncertainty. The color temperature scale is derived from the NIST spectral irradiance scale and maintained via a group of quartz-halogen standard lamps. A measurement facility for spectral radiant flux is being built using the 2.5 m integrating sphere, and calibrations will be provided for spectral radiant flux and chromaticity of light sources. A new project on colorimetry of displays has started at NIST, and a capability for calibration of color measuring instruments is being developed.

Key words: calibration, candela, colorimetry, color temperature, display, illuminance, lumen, luminous flux, luminous intensity, lux.

1. Introduction

A detector-based luminous intensity unit (candela) was realized at the National Institute of Standards and Technology (NIST) in 1992, based on an absolute cryogenic radiometer [1,2]. The NIST candela is maintained via a group of standard photometers (NIST reference photometers) which are calibrated for illuminance responsivity (A/lx) and embody the NIST illuminance unit. Photometers (consisting of a silicon photodiode, a $V(\lambda)$ filter, and an aperture) are preferred to standard lamps as transfer standards for the luminous intensity/illuminance scale. Photometers are robust and shock resistant, making them more suitable as transfer standards, which must be shipped between laboratories. In addition, selected high-quality photometers are stable over many years. As the scale is provided by the photometers, light sources other than incandescent lamps can be used as calibration sources as long as the source is stable during each calibration. The detector-based method is utilized in various photometric calibrations at NIST, exhibiting a shorter calibration chain and reduced uncertainties than the source-based method. As an extension of these capabilities, a high illuminance calibration facility using a Xenon discharge lamp has been developed at NIST [3]. This facility allows illuminance meter calibrations at levels up to 100 klx.

The luminous flux unit (lumen) is derived from the NIST illuminance unit by using the Absolute Integrating Sphere Method developed in 1995 [4]. This method has made possible the realization of the lumen, for the first time, using an integrating sphere rather than a goniophotometer. This new method will be utilized in the routine calibration of total luminous flux, eliminating the need for total luminous flux standard lamps. The integrating sphere errors caused by the spatial nonuniformity of the sphere response have been investigated theoretically and experimentally; and, subsequently, a correction technique was developed [5].

The NIST color temperature scale is realized with a gold-point blackbody, the temperature of which is determined radiometrically [6]. The color temperature standards are maintained on a group of FEL-type quartz halogen lamps. Color temperature calibrations are provided via incandescent standard lamps and colorimeters. A reference spectroradiometer is being developed to realize the spectral radiant flux scale and to provide calibration services for chromaticity and the color rendering index of fluorescent lamps. A new project has also started to address the colorimetry of displays and to provide calibration services in this area. A new matrix method is being developed to improve the accuracy of tristimulus colorimeters used for displays.

The details of these new improved calibration capabilities and procedures for photometry and colorimetry at NIST are described below.

2. Luminous Intensity/Illuminance Calibrations

2.1 Photometric bench facility

The photometry bench shown in Fig. 1 is used for luminous intensity and illuminance calibrations at NIST. The base of the bench consists of three 1.8 m long steel optical tables. A 5 m long rail system with movable carriages is mounted on the table. Two telescopes are rigidly mounted to the table for alignment of the lamps. Six photometers can be mounted on the carousel, and measurements with standard photometers and test photometers are made automatically. The position of the reference plane of the photometers is measured by a computer-readable linear encoder. The optical bench is covered by a light-tight box, the inside of which is covered with black velvet. The stray light, checked with various arrangements, is consistently less than 0.05 %. A $V(\lambda)$-corrected monitor detector is mounted beside the shutter to monitor the stability of the lamp during calibration of photometers. This monitor detector gives a continuous signal independent of the shutter position and the photometer positions on the carousel.

Most of the calibrations conducted at NIST are for lamps with bipost bases. The bench is equipped with a medium bipost-base socket which has four separate contacts, two for the current supply and the other two for voltage measurements. The bench is also equipped with a medium screw-base socket (E26) to provide calibrations for screw-base lamps.

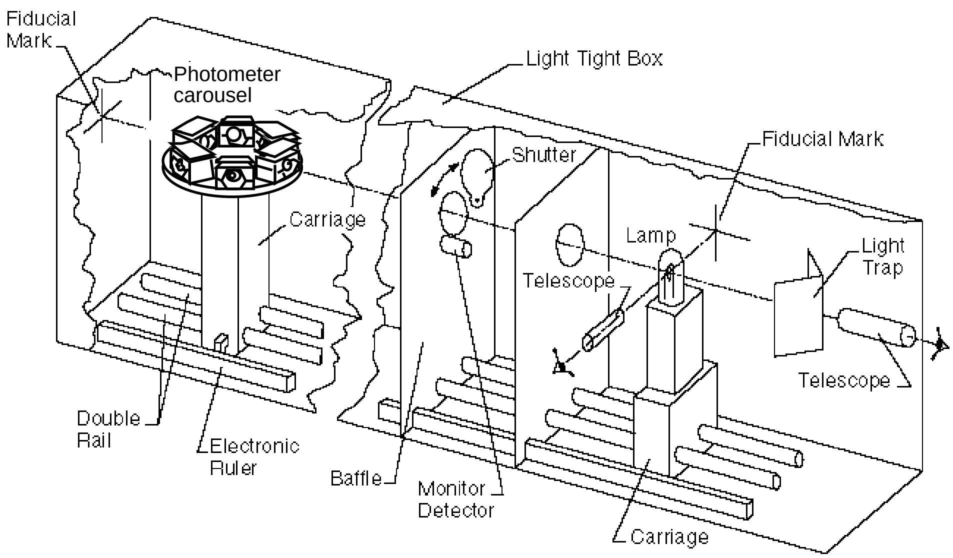

Figure 1. NIST Photometry Bench.

A DC constant-current power supply with a maximum current of 30 A is used to operate standard lamps and test lamps. The lamp current is measured as the voltage across a reference current shunt (0.1 Ω), using a 6 $^1/_2$ digit voltmeter (DVM), with an uncertainty[†1] less than 0.01 %. The DVM is on a one year calibration cycle. The current shunt is periodically calibrated at three different current levels with an uncertainty of 0.005 %.

The lamp current is automatically controlled by a computer feedback system to keep the current drift within ± 0.002 %. A high level of stability is needed for the operating current because the change in current causes ~7 times the change in photometric output of incandescent lamps.

2.2 Detector-based luminous intensity calibration

At NIST, the luminous intensities of test lamps were previously calibrated against luminous intensity standard lamps. Working standard lamps, operating at several different power levels, were compared to test lamps operating at similar power levels to avoid linearity errors in the detector system. The standard lamps used at NIST in the past [7] exhibit a typical aging rate of 2 %/100 h. The burning time of the lamps was strictly limited in order to minimize the aging of the lamps. The lamps also exhibit luminous intensity drifts of a few tenths of a percent in the first hour after stabilization. These characteristics of the primary and working standard lamps yielded additional sources of uncertainty in calibrating test lamps.

By utilizing the detector-based method, lamps with a wide range of luminous intensities are directly calibrated using standard photometers with a wide domain of linearity. Photometers do not age with use as lamps tend to do; therefore, primary standard photometers can be used in

[†1] Throughout this paper, uncertainty is given in relative expanded uncertainty with coverage factor k=2, thus a two standard deviation estimate.

routine calibrations, eliminating the need for creating and maintaining secondary and tertiary working standards as needed with the source-based method and keeping the calibration chain shorter to reduce uncertainties. Photometers have short-term reproducibility at a level of 0.01 % if the temperature of the components inside the photometer is kept constant.

A photometric bench with an accurate length scale remains essential for luminous intensity calibrations. The need for luminous intensity standard lamps, however, can be eliminated in most cases by replacing standard lamps with standard photometers. The color temperature of the test lamps (normally operated at ~2856 K) must be known to correct for the spectral mismatch errors if necessary. The additional signal introduced by the stray light is not canceled when replacing standard lamps with standard photometers as it tends to be in the lamp-to-lamp substitution measurements, therefore, greater care has been taken to minimize stray light. It should also be noted that the responsivities of some photometers are subject to drift over time. While some types of photometers show excellent long-term stability (within 0.1 %/year), other types of photometers exhibit significant changes (over 1 %/year). Photometers to be used as reference standards must be selected for their long-term stability.

At NIST, eight reference photometers are used to realize the NIST illuminance unit annually, and five of these reference photometers are used to maintain the unit and for routine calibrations for luminous intensity and illuminance. Figure 2 shows the updated calibration history of these reference photometers. Even though these data include uncertainty of the scale realization, the data imply a stability of these five photometers to be better than 0.2 % over a five year period. In the luminous intensity calibrations at NIST, corrections are applied for the dark readings, the spectral mismatch errors, and the temperature variations of the photometers; details are given in references [1,8]. The relative expanded uncertainty (k=2) of luminous intensity calibrations at NIST is now typically 0.52 %, which includes the uncertainty of the illuminance unit (0.38 %), the long-term drift of the standard photometers (0.26 %), and the reproducibility of test lamps (typically 0.2 %) [9].

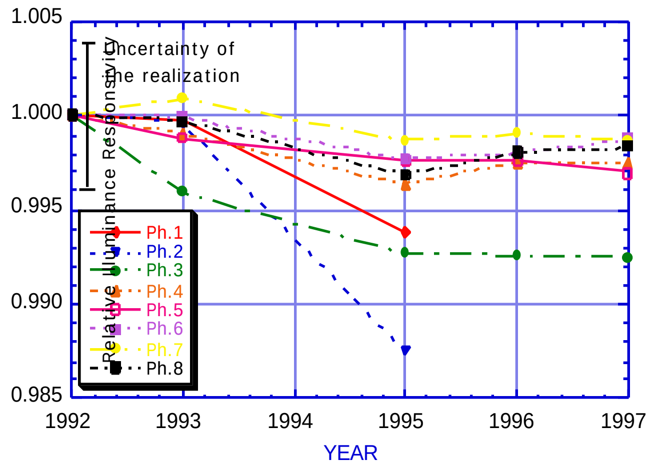

Figure 2. History of the annual calibration of the NIST reference photometers over a five year period.

2.3 Detector-based illuminance meter calibration

With the conventional source-based method, illuminance calibrations rely on the luminous intensity of a standard lamp, the inverse square law, and accurate measurements of distance between the test lamp and standard lamp. Alignment of the standard lamp is critical. The reproducibility of the lamp itself and the departure from the inverse-square law at short distances are the major uncertainty components.

The detector-based method has a greater advantage in the calibration of illuminance meters and transfer photometers. At NIST, illuminance meters and photometers are calibrated by direct substitution with the NIST reference photometers by placing them on the same illuminated plane. In such substitution methods, many uncertainty factors are canceled. 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 color temperature (normally 2856 K) is used. The short-term stability of the working lamp is important, but its burning time and aging characteristics are not critical.

The relative expanded uncertainty (k=2) of the illuminance meter calibrations at NIST is typically 0.5 %, which includes the uncertainty of the illuminance unit (0.38 %), long-term drift of the standard photometers (0.26 %), random variations in transfer measurement (0.1 %), and other factors. This value does not include uncertainty factors inherent to the illuminance meter under test [9].

2.4 High Illuminance Calibration

In another application of the detector-based method, an illuminance calibration facility and procedures have been recently developed at NIST for levels up to 100 klx (the illuminance level of direct sun light) and luminance up to 30 kcd/m^2 (luminance of a perfect diffuser at that level of illuminance). Figure 3 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 color glass filters that corrects its spectral power distribution to approximate the CIE[†2] Illuminant A (2856 K Planckian radiation). The illuminance level can be varied without changing the color temperature significantly and without changing the distance. The developed source has a short-term stability of better than 0.2 % for several hours after a 15 minutes stabilization period.

Under illumination at a level of 100 klx, the radiation incident on the photometer heats the photometer. This introduced additional uncertainties in the measurement using temperature-monitored type standard photometers [1], even with corrections using the temperature sensor signals, due to a strong temperature gradient in the photometer housing. To solve this problem, new temperature-controlled type standard photometers have been developed. With a new design as shown in Fig. 4, 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 is directly coupled to the block so that the temperature of the $V(\lambda)$ filter is maintained constant (at 25 °C) even when the photometer housing is heated by radiation. These new

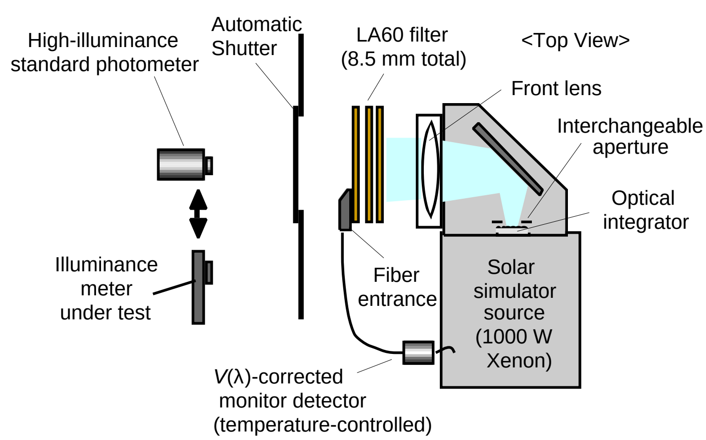

Figure 3. Configuration of the high illuminance calibration facility.

[†2] Commission Internationale de l'Eclairage (International Commission on Illumination)

photometers employ a silicon photodiode (Hamamatsu[†3] S1226-8BQ) with a 0.3 cm^2 sensitive area, a precision aperture of 3 mm diameter, and a built-in current-to-voltage converter amplifier. While the previous type of the NIST standard photometers exhibited 3 % drift of its responsivity under exposure to 100 klx for 30 min, the new temperature-controlled type photometers showed a drift of less than 0.2 % under the same exposure. The new photometers also demonstrated a linear response within 0.3 % to luminous flux up to a level of 100 klx. Four photometers of this type are now maintained as the reference standards for high illuminance levels.

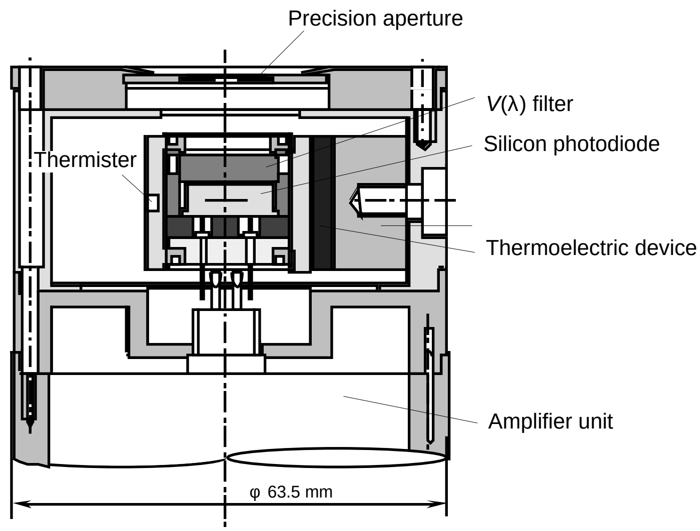

Figure 4. Design of the NIST temperature-controlled photometer used as high illuminance reference standards.

3. Luminous Flux Calibrations

3.1 Absolute Integrating Sphere Method

Luminous flux units are commonly realized using goniophotometers, which require a large dark room and costly high precision positioning equipment. It takes about one hour for a typical goniophotometer to take data for one lamp every 5° over the 4 π angle, and yet the photometer sensitive area covers less than 1 % of the total solid angle, which necessitates rigorous uncertainty analysis. A new method for realizing a luminous flux unit (Absolute Integrating Sphere Method) was developed at NIST using a special integrating sphere instead of a goniophotometer [4]. As the sphere is a spatially continuous integrator, it has an inherent potential for higher accuracy with short measurement time.

The basic principle of this method is to calibrate the total flux of a lamp inside the sphere against the known amount of flux introduced from a source outside the sphere through an opening. Figure 5 shows the arrangement for this method. The flux from the external source (Φ_{in}) is introduced through a calibrated aperture placed in front of the opening. Φ_{in} is given by,

$$\Phi_{in} = E \cdot A, \qquad (1)$$

where E is the average illuminance from the external source over the limiting aperture of known area A. The internal source, a lamp to be calibrated, is mounted in the center of the sphere. The external source and the internal source are operated alternately and the total luminous flux Φ of the internal source is obtained by comparison to the luminous flux introduced from the external source as given by,

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†3 Specific firms and trade names are identified in this paper to specify the experimental procedure adequately. 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.

$$\Phi_{test} = c_f \Phi_{in}\, y_{test}\ / y_{in}\ , \qquad (2)$$

where y_{test} is the detector signal for the internal source, and y_{in} is the detector signal for the introduced flux. The quantity c_f is an important correction factor for various non-ideal properties of the integrating sphere. The response of the integrating sphere is not uniform over the sphere wall due to baffles and other structures inside the sphere, and also due to nonuniform reflectance of the sphere surface due to contamination. When the incident angle is different, the diffuse reflectance of the sphere coating changes, which affects the sphere responsivity. These corrections are made to determine the correction factor c_f. The details of these corrections are described in references [2,4]. Using this method, a group of primary luminous flux standard lamps and working standard lamps were calibrated in 1995, and the new NIST lumen was established.

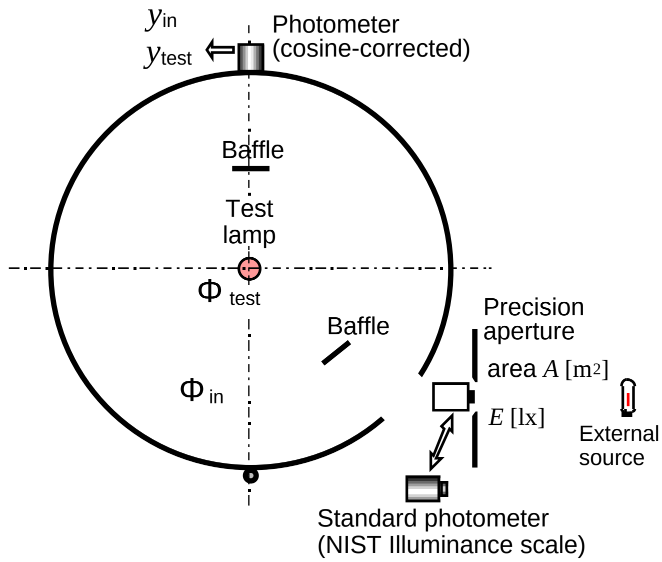

Figure 5. Concept of the Absolute Integrating Sphere Method.

3.2 Procedures for the luminous flux calibration

In the past, a strict substitution method was employed at NIST. Secondary working-standard lamps of 500 W, 200 W, 100 W, and 6 types of miniature lamps ranging from 400 lm to 6 lm were maintained for luminous flux calibration [7]. Additional uncertainty components were added when transferring the scale from the primary to secondary working standard lamps, starting from the 300 W primary standard lamps. The relative expanded uncertainties (k=2) of working standard lamps ranged from 1.0 % to 1.9 %.

With the Absolute Integrating Sphere Method described above, the luminous flux unit is realized on a periodic basis. The primary standard lamps are maintained only to cross-check the consistency of the unit, and working standard lamps are used for routine calibrations. Based on the wide range of linearity of the photometer used with the sphere and a high-accuracy self-absorption correction, test lamps with outputs ranging from 10^{-1} lm to 10^{5} lm can be measured in the 2 m sphere against one type of working standard lamp (40 W/24 V opal-bulb lamps). This keeps the calibration chain shorter and reduces the uncertainty of calibration. Although this is still a substitution method, working standard lamps of many different power levels are no longer needed.

In normal calibrations at NIST, corrections are made for lamp self-absorption, spectral mismatch errors, and photometer temperature variations. For the spectral mismatch correction, the spectral power distributions or the color temperatures of test lamps are measured. A spatial nonuniformity correction is made only when special types of lamps having directional intensity distributions are calibrated [8].

The relative expanded uncertainty (k=2) of the luminous flux calibration of incandescent lamps is now typically 0.8 %, which includes the uncertainty of the NIST luminous flux unit (0.53 %), aging of the working standard lamps between calibrations (0.30 %), transfer from working standards to test lamps (0.5 %), and reproducibility of test lamps (typically 0.2 %) [9].

3.3 Plan for the detector-based luminous flux calibration

A new calibration facility with a 2.5 m integrating sphere is being built at NIST to establish a capability for the detector-based luminous flux calibrations. The Absolute Integrating Sphere Method, described above, will be used to calibrate test lamps directly, eliminating the need for the working standard lamps and thus reducing the calibration uncertainty further. The new facility, shown in Fig. 6, 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 should be measured periodically 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 rotation stages to turn the internal beam source.

The new 2.5 m integrating sphere will also be used to realize the spectral radiant flux scale in the UV-visible region. The sphere has a barium-sulfate-based coating with reflectances higher than 98 % in the visible and 92 % to 98 % in the 250 nm to 380 nm region. A double- monochromator-based detection system will be connected to the sphere to allow spectral measurement of lamps and to provide calibration of the chromaticity and color rendering indices of fluorescent lamps.

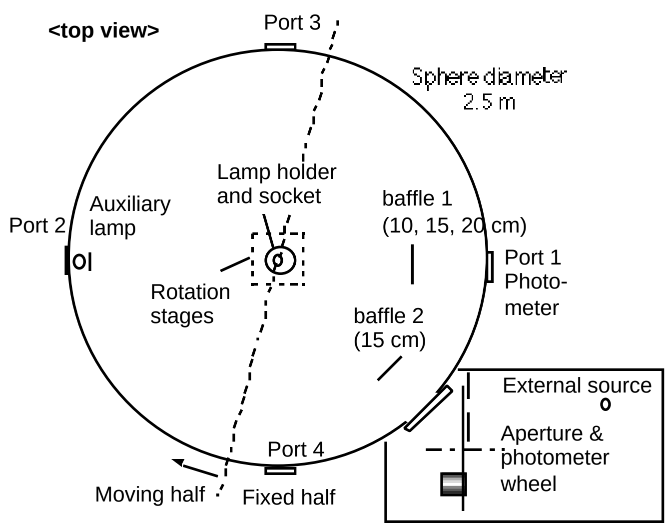

Figure 6. Arrangement of the new NIST 2.5 m integrating sphere.

4. Color Temperature Measurement

4.1 NIST color temperature scale

The NIST color temperature scale is derived from the NIST spectral irradiance scale [10] which is based on the International Temperature Scale of 1990. The scale realization chain for the spectral irradiance scale and the color temperature scale is shown in Fig. 7.

Three 1000 W FEL-type quartz halogen lamps are used as the NIST color temperature primary standard lamps in the range from 2000 K to 3200 K. These lamps have demonstrated stable operation in this color temperature range [11]. The spectral irradiance of these lamps is calibrated periodically against the NIST spectral irradiance scale at 2000 K, 2300 K, 2600 K, 2856 K, and 3200 K. The correlated color temperatures of these lamps are computed from the relative spectral irradiance values. The color temperature scale of these lamps is transferred to several other FEL-type lamps for routine calibration work.

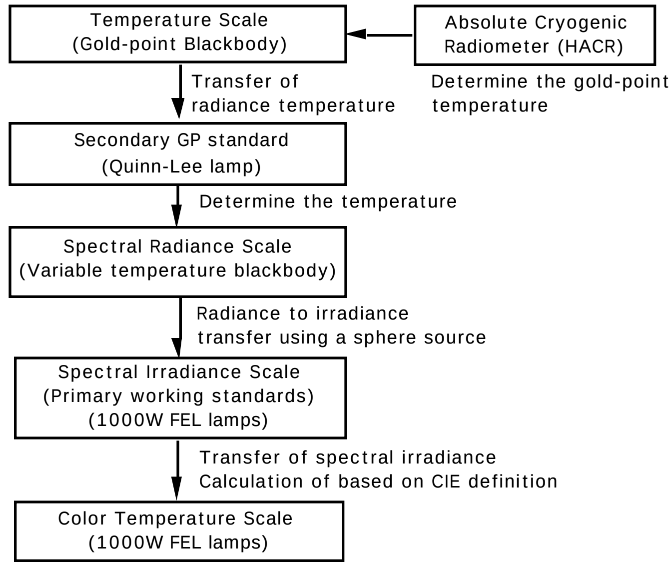

Figure 7. Realization of the NIST spectral irradiance scale and the color temperature scale.

NIST now issues FEL-type 1000 W quartz halogen lamps calibrated for color temperature as well as for luminous intensity. The lamps are manufactured by Osram-Sylvania Inc., and potted on a medium bipost base, and seasoned on DC power with an appropriate procedure. The lamps are usually calibrated at a color temperature of 2856 K, but can be calibrated at any temperatures in the range from 2000 K to 3200 K. The operating current and voltage of the lamps are approximately 7.2 A and 85 V for 2856 K operation.

4.2 Equipment for color temperature calibration

Figure 8 shows the arrangement used for color temperature calibration. A polytetrafluoro-ethylene (PTFE) plaque is placed on the photometry bench approximately 1 m from the lamp and irradiated at normal incidence. The diffuse reflection from the plaque at 45° is measured by a spectroradiometer. The plaque is mounted on a kinematic base, and can be removed when the luminous intensity is measured. The spectroradiometer is calibrated, together with the plaque, against the color temperature standard lamps, so the spectral reflectance of the plaque does not need to be known.

The spectroradiometer is a diode-array system consisting of imaging optics in front, a single diffraction grating, and a cooled 256 element photodiode array. This spectroradiometer has measurement angles of 0.125° circular and 0.5° x 1.5° rectangular. The rectangular aperture is normally used for color temperature calibrations. The short measurement time (normally less than 10 s) of the spectroradiometer allows for the determination of the operating current of a lamp for a specified color temperature within a few min. The spectroradiometer

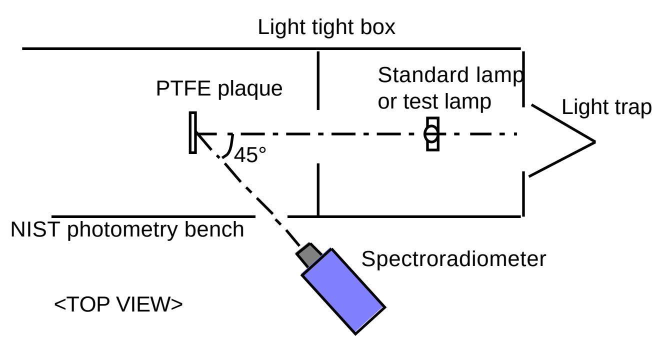

Figure 8. Arrangement for the color temperature calibration.

is connected to a computer which calculates chromaticity coordinates and the correlated color temperature of the source.

Diode-array type spectroradiometers equipped with a single diffraction grating are in general subject to considerable stray light errors. When the radiometer is calibrated using a 2856 K Planckian source, it may not give accurate results at other color temperatures. Therefore, the spectroradiometer at NIST is used to transfer the same color temperature from the standard lamp to the test lamp, and that is why the color temperature standard lamps are calibrated for several different color temperatures.

The red-blue ratio substitution method is commonly used for color temperature transfer measurements, but is not used at NIST to avoid the following problem. When using this method, one must be careful about errors caused by the difference in the spectral power distributions of the standard lamp and the test lamp. Figure 9 shows an example of the difference in spectral power distributions between normal gas-filled lamps and quartz halogen lamps which have the same color temperature. The curves in the figure show that the blue-to-red ratio will not be constant and may cause significant errors if the wavelengths for the blue and the red detectors are not chosen appropriately. For best results, peak wavelengths of 460 nm and 680 nm are recommended for the blue and the red detectors, respectively.

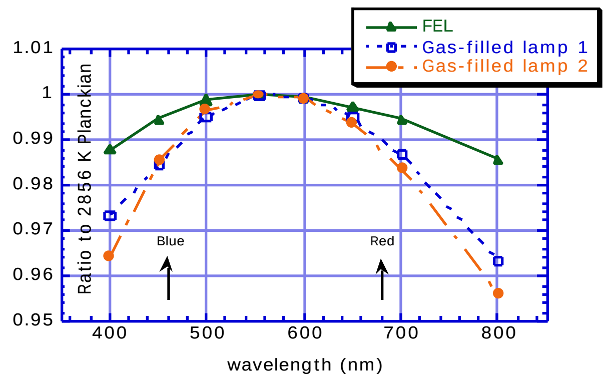

Figure 9. Ratio of the relative spectral power distributions of incandescent lamps to that of a Planckian source at the same color temperature (normalized to unity at the peak wavelength).

4.3 Colorimetry of displays

Accurate chromaticity measurements of color displays such as cathode ray tubes (CRTs) and flat panel displays are increasingly important as their qualities improve and customers demand more accurate color reproduction. NIST is addressing the need of developing methods to evaluate the accuracy of color measuring instruments, including tristimulus colorimeters and spectroradiometers. A new project has just started to develop a capability to calibrate such color measuring instruments for displays. A reference spectroradiometer, with optimized design for colorimetry, is being built and will be used to measure colors of displays. Test instruments will be calibrated against the NIST reference spectroradiometer for several different colors of a real display.

As a means to transfer the accurate color measurement capability, a new calibration method is being developed for tristimulus colorimeters used as transfer standards. Tristimulus colorimeters are commonly used to measure chromaticity of such displays. However, due to imperfect matching of their spectral responsivities to the color matching functions, measurement errors are inevitable when the spectral power distribution of a test source is dissimilar to that of the calibration source. Tristimulus colorimeters and luminance meters are normally calibrated with CIE Illuminant A. Matrix techniques, such as the one recommended by ASTM E1455, are known to improve the accuracy of tristimulus colorimeters for color display measurements. These matrix methods, however, often do not work as expected due to experimental noise and errors. To further improve the accuracy of the matrix technique, a new method (Four-Color Method) has been developed [12], which uses 4 colors (red, green, blue, and white) to calibrate a tristimulus colorimeter for all other colors. A detailed analysis of the accuracy of this method for real measurements is being studied. Official calibration services will be available in the near future.

5. Conclusion

The detector-based method has several advantages over the conventional source-based method for calibration of illuminance meters and transfer photometers. Uncertainty has been reduced considerably due to a shorter calibration chain and to the excellent stability of the reference photometers. The detector-based method is utilized in the luminous intensity and illuminance calibrations at NIST. A high illuminance calibration facility and procedures have been recently developed at NIST for levels up to 100 klx (the level of direct sun light) and luminance up to 30 kcd/m^2 (the luminance of a perfect diffuser at that level of illuminance).

The Absolute Integrating Sphere Method is used at NIST for the realization of the luminous flux unit. This method will be applied to calibration of test lamps, thereby eliminating the need for luminous flux working standard lamps and shortening the calibration chain for further reduction of measurement uncertainty. NIST is building a new calibration facility with a 2.5 m integrating sphere for detector-based luminous flux calibrations. This facility will also be used to realize the spectral radiant flux scale in the UV-visible region.

The color temperature scale is maintained on quartz halogen standard lamps. NIST now issues FEL-type 1000 W quartz halogen lamps calibrated for color temperature as well as for luminous intensity. A spectroradiometer is now used in the transfer measurement for better accuracy than the blue-red ratio method. In response to increasing demand for accurate color reproduction, NIST has started a new project on colorimetry of displays to evaluate the accuracy of color measuring instruments, including tristimulus colorimeters and spectroradiometers. Calibration services for color measuring instruments for displays will be available in the near future.

Acknowledgement

We thank George Eppeldauer who developed the new temperature-controlled standard photometers, Sally Bruce who provides the annual calibration of the standard photometers, and other staff members at Optical Technology Division who established the base of the detector-based photometric units [1].

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