NIST Special Publication 250-37

NIST MEASUREMENT SERVICES:
PHOTOMETRIC CALIBRATIONS

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PREFACE

The calibration and related measurement services of the National Institute of Standards and Technology are intended to assist the makers and users of precision measuring instruments in achieving the highest possible levels of accuracy, quality, and productivity. NIST offers over 300 different calibrations, special tests, and measurement assurance services. These services allow customers to directly link their measurement systems to measurement systems and standards maintained by NIST. These services are offered to the public and private organizations alike. They are described in NIST Special Publication (SP) 250, NIST Calibration Services Users Guide.

The Users Guide is supplemented by a number of Special Publications (designated as the “SP250 Series”) that provide detailed descriptions of the important features of specific NIST calibration services. These documents provide a description of the: (1) specifications for the services; (2) design philosophy and theory; (3) NIST measurement system; (4) NIST operational procedures; (5) assessment of the measurement uncertainty including random and systematic errors and an error budget; and (6) internal quality control procedures used by NIST. These documents will present more detail than can be given in NIST calibration reports, or than is generally allowed in articles in scientific journals. In the past, NIST has published such information in a variety of ways. This series will make this type of information more readily available to the user.

This document, SP250-37 (1997), NIST Measurement Services: Photometric Calibrations, is a revision of SP250-15 (1987). It covers the calibration of standards of luminous intensity, luminous flux, illuminance, luminance, and color temperature (test numbers 37010C–37100S in SP250, NIST Calibration Services Users Guide). Inquiries concerning the technical content of this document or the specifications for these services should be directed to the author or to one of the technical contacts cited in SP250.

NIST welcomes suggestions on how publications such as this might be made more useful. Suggestions are also welcome concerning the need for new calibrations services, special tests, and measurement assurance programs.

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ABSTRACT

The National Institute of Standards and Technology supplies calibrated standards of luminous intensity, luminance, and color temperature, and provides calibration services for submitted artifacts for luminous intensity, luminance, color temperature, total luminous flux, and luminance. The procedures, equipment, and techniques used to perform these calibrations are described. Detailed estimates and procedures for determining uncertainties of the reported values are also presented.

Key words : Calibration; Candela; Color temperature; Illuminance; Lumen; Luminance; Luminous flux; Luminous intensity; Lux; Photometry; Standards; Total flux; Unit

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1. Introduction

This document supersedes the NBS Special Publication 250-15 (1987). In 1992, a new candela was realized based on an absolute cryogenic radiometer, and the old NIST gold-point blackbody-based unit [1] was replaced by the new detector-based unit [2]. A group of eight standard photometers with calibrations based on the cryogenic radiometer holds the NIST candela, and replaces the lamp scheme formerly used. Further, the photometric calibration procedures have been revised to utilize the detector-based methods [3].

This document describes the new photometric calibration procedures for luminous intensity (candela; cd), illuminance (lux; lx), total luminous flux (lumen; lm), luminance (cd/m^2) and color temperature (kelvin; K). Throughout this document, uncertainty statements follow the NIST policy given by Taylor and Kuyatt [4], which prescribes the use of an expanded uncertainty with a coverage factor $k = 2$ for uncertainties of all NIST calibrations.

Descriptions for the individual standards and calibrations available from NIST, as of April 1996, are listed and explained in Section 2. Updated information about calibration services and prices are published periodically in the NIST Calibration Services Users Guide (SP250) [5] and Fee Schedule (SP250 Appendix).

The material presented in this document describes photometric calibration facilities and procedures as they existed at the time of publication. Further improvement of photometric calibration facilities and procedures are underway. Some of these on-going projects are described in Section 8.

1.1 Photometry, physical photometry, and radiometry

The primary aim of photometry is to measure visible optical radiation, light, in such a way that the results correlate with what the visual sensation is to a normal human observer exposed to that radiation. Until about 1940, visual comparison techniques of measurements were predominant in photometry, whereby an observer was required to match the brightness of two visual fields viewed either simultaneously or sequentially. This method of photometry is so-called visual photometry, and is seldom used today.

In modern photometric practice, measurements are made with photodetectors. This is referred to as physical photometry. In order to achieve the aim of photometry, one must take into account the characteristics of human vision. The relative spectral responsivity of the human eye was first defined by CIE (Commission Internationale de l'Éclairage) in 1924 [6], and redefined as part of colorimetric standard observers in 1931 [7]. It is called *the spectral luminous efficiency function for photopic vision*, or the $V(\lambda)$ function, defined in the domain 360 nm to 830 nm, and is normalized to one at its peak, 555 nm (**Fig. 1**). This model gained wide acceptance, republished by CIE in 1983 [8] and published by CIPM (Comité International des Poids et Mesures) in 1982 [9] to supplement the 1979 definition of candela. The tabulated values of the function at 1 nm increments are available in references [8-10]. In most cases, the region 380 nm to 780 nm is used for calculation with negligible errors because the $V(\lambda)$ function falls below 10^{-4} outside this region. Thus, a photodetector having a spectral responsivity matched to the $V(\lambda)$ function replaced the role of human eyes in photometry.

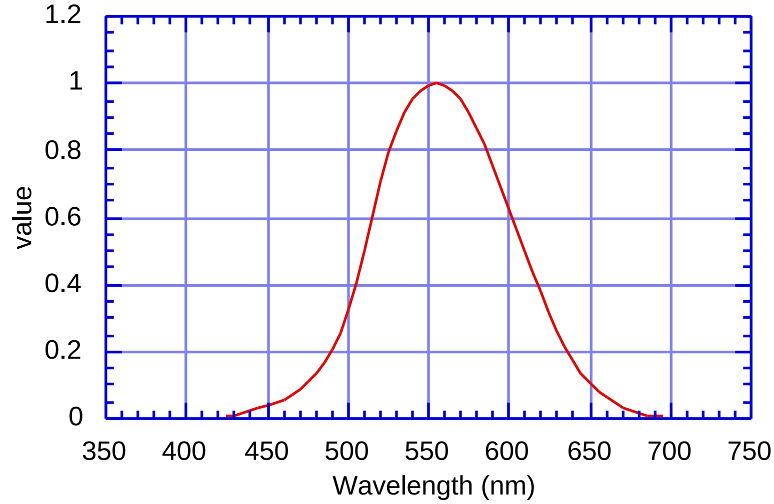


Figure 1 CIE $V(\lambda)$ Function.

Radiometry concerns physical measurement of optical radiation as a function of its wavelength. As specified in the definition of the candela by CGPM (Conférence Générale des Poids et Mesures) in 1979 [11] and CIPM in 1982 [9], a photometric quantity X_v is defined in relation to the corresponding radiometric quantity $X_{e,\lambda}$ by the equation:

$$X_v = K_m \int_{360\,\mathrm{nm}}^{830\,\mathrm{nm}} X_{e,\lambda}\, V(\lambda)\, d\lambda \tag{1}$$

The constant, K_m, relates the photometric quantities and radiometric quantities, and is called the *maximum spectral luminous efficacy (of radiation) for photopic vision*. The value of K_m is given by the 1979 definition of candela which defines the spectral luminous efficacy of light at the frequency 540 x 10^{12} Hz (at the wavelength 555.016 nm in standard air) to be 683 lm/W. The value of K_m is calculated as 683 x V(555.000 nm)/V(555.016 nm) = 683.002 lm/W [8]. K_m is normally rounded to 683 lm/W with negligible errors [9]. Various photometric and radiometric quantities are described in the next section.

It should be noted that the $V(\lambda)$ function is based on the *CIE standard photometric observer for photopic vision*, which assumes additivity of sensation and a 2° field of view at relatively high luminance levels (higher than ~1 cd/m^2). The human vision in this level is called photopic vision. The spectral responsivity of human vision deviates significantly at very low levels of luminance (less than ~10^{-2} cd/m^2). This type of vision is called scotopic vision. Its spectral responsivity, peaking at 507 nm, is designated by the $V'(\lambda)$ function, which was defined by CIE in 1951 [12], recognized by CIPM (Comité International des Poids et Mesures) in 1976 [13], and republished by CIPM in 1982 [9]. The human vision in the region between photopic vision and scotopic vision is called mesopic vision. While active research is being conducted [14], there is no internationally accepted spectral luminous efficiency function for the mesopic region yet. In current practice, almost all photometric quantities are given in terms of photopic vision, even at low light levels, except for special measurements for research purposes. This document, therefore, does not deal with quantities specified in terms of scotopic or mesopic vision. Further details of definitions outlined in this section are given in Reference [8].

To better understand the international metrology system, it is useful to know the relationship between such organizations as CGPM, CIPM, CCPR (Comité Consultatif de Photométrie et Radiométrie), BIPM (Bureau International des Poids et Mesures), and CIE. These are all abbreviations of their French names as appeared before. In English, their names would be: CGPM, General Conference of Weights and Measures; CIPM, International Committee for Weights and Measures; CCPR, Consultative Committee of Photometry and Radiometry; BIPM, International Bureau of Weights and Measures; and CIE, International Commission on Illumination. All the SI units are officially defined by CGPM which is the decision-making body for the Treaty of the Meter (Convention du Mètre), signed in 1875. The decisions of CGPM legally govern the global metrology system among those countries signatory to the Treaty of the Meter or agreeing to its usage. CIPM is a committee under CGPM, charged with the management of the international system of units and related fundamental units, consisting of many subcommittees for each technical field. CCPR is a subcommittee under CIPM, that discusses and recommends the units in photometry and radiometry. It consists of representatives of interested national standardizing laboratories. CCPR also holds international intercomparisons of photometric units and radiometric scales. BIPM is a metrology laboratory under the supervision of CIPM, with staff and facilities in Paris. CIE, on the other hand, is originally an academic society in the field of lighting science and was organized to promote uniformity and quality in optical measurements. Many definitions developed by CIE, such as the $V(\lambda)$ function, the color matching functions, and the standard illuminants, have been adopted by CGPM and by ISO (International Organization for Standardization) as international standards. CIE has recently been recognized officially by ISO as a standards-creating body in the field of optical radiation. NIST staff play active roles in CCPR and CIE activities.

1.2 Photometric quantities and units

1.2.1 Photometric quantities

The base unit of all photometric quantities is the candela. The candela was first defined by CGPM in 1948, based on the radiation from platinum at the temperature of its solidification. It became one of the base SI (Système International) units when SI was established in 1960. Most recently, the candela was redefined by CGPM in 1979 [9] as

> "The candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540 x10^{12} hertz and that has a radiant intensity in that direction of (1/683) watt per steradian."

Table 1 lists photometric quantities and their corresponding radiometric quantities side by side, with units and symbols. The precise definition of each quantity is given by CCPR [10] and CIE [15].

Table 1. Quantities and units used in photometry and radiometry

Photometric quantity	Unit	relationship with lumen	Radiometric Quantity	Unit
Luminous flux	lm (lumen)		Radiant flux	W (watt)
Luminous intensity	cd (candela)	lm sr^{-1}	Radiant intensity	W sr^{-1}
Illuminance	lx (lux)	lm m^{-2}	Irradiance	W m^{-2}
Luminance	cd m^{-2}	lm sr^{-1} m^{-2}	Radiance	W sr^{-1} m^{-2}
Luminous exitance	lm m^{-2}		Radiant exitance	W m^{-2}
Luminous exposure	lx s		Radiant exposure	W m^{-2} s
Luminous energy	lm s		Radiant energy	J (joule)
Color temperature	K (kelvin)		Radiance temperature	K

Although the candela is defined as an SI base unit, luminous flux (lumen) is perhaps the most fundamental photometric quantity, as the four other photometric quantities are defined in terms of lumen with appropriate geometric factors.

Luminous flux (Φ_v) is the time rate of flow of light as weighted by $V(\lambda)$. It is defined as

$$\Phi_v = K_m \int_\lambda \Phi_{e,\lambda} \, V(\lambda) \, d\lambda \quad , \tag{2}$$

where $\Phi_{e,\lambda}$ is the spectral concentration of radiant flux in (W/nm) as a function of wavelength λ in nm.

Luminous intensity (I_v) is the luminous flux (from a point source) emitted per unit solid angle in a given direction. It is defined as

$$I_v = \frac{d\Phi_v}{d\Omega} \quad , \tag{3}$$

where $d\Phi_v$ is the luminous flux leaving the source and propagating in an element of solid angle $d\Omega$ containing the given direction.

Illuminance(E_v) is the density of the luminous flux incident on a given point of a surface or a plane. It is defined as

$$E_v = \frac{d\Phi_v}{dA} \quad , \tag{4}$$

where $d\Phi_v$ is the luminous flux incident on an element dA of the surface containing the point.

Luminance (L_v) is the luminous flux from an element of a surface surrounding a given point, emitted into a small solid angle containing the given direction, per unit area of the element projected on a plane perpendicular to that given direction. It is defined as

$$L_v = \frac{d^2\Phi_v}{d\Omega \; dA \cos\theta} \quad , \tag{5}$$

where $d\Phi_v$ is the luminous flux emitted (reflected or transmitted) by an elementary beam passing through the given point and propagating in the solid angle $d\Omega$ containing the given direction; dA is the area of a section of that beam containing the given point; θ is the angle between the normal to that section and the direction of the beam.

Luminous exitance (M_v) is the density of luminous flux leaving a surface at a point. The equation is the same as equation (4), with $d\Phi_v$ meaning the luminous flux leaving a surface. This quantity is rarely used in the general practice of photometry.

Luminous exposure (H_v) is the time integral of illuminance $E_v(t)$ over a given duration Δt, as defined by

$$H_v = \int_{\Delta t} E_v(t) \, dt \quad . \tag{6}$$

Luminous energy (Q_v) is the time integral of the luminous flux (Φ_v) over a given duration Δt, as defined by

$$Q_v = \int_{\Delta t} \Phi_v(t) \, dt \quad . \tag{7}$$

Color temperature (T_c) is the temperature of a Planckian radiator with radiation of the same chromaticity as that of the light source in question. However, the chromaticity coordinates of most lamps do not fall on the Planckian locus, and in actual lamp calibrations, either distribution temperature or correlated color temperature is used. "Color temperature" is often used informally for the correlated color temperature.

Distribution temperature (T_d) is the temperature of a blackbody with a spectral power distribution closest to that of the light source in question, and it is a useful concept for quasi-Planckian sources.

Correlated color temperature (T_{cp}) is a concept used for sources with a spectral power distribution significantly different from that of Planckian radiation, for example, discharge lamps.

Correlated color temperature is the temperature of the Planckian radiator whose perceived color most closely resembles that of the light source in question. The distribution temperature and correlated color temperature are explained further in Section 7.

General information (definitions, symbols, and expressions) on many other physical quantities and units including photometric and radiometric quantities are given in Reference [16].

1.2.2 Relationship between SI units and English units

Under NIST policy [17], results of all NIST measurements are reported in SI units. However, the English units shown in **Table 2** are still rather widely used. For all the photometric measurements and calculations, use of the SI units shown in **Table 1** is recommended, and use of non-SI units is discouraged [18]. The definitions of the English units are described below for conversion purposes only.

Table 2. English units and definition

Unit	Quantity	Definition
foot-candle (fc)	illuminance	lumen per square foot ($lm\ ft^{-2}$)
foot-Lambert (fL)	luminance	$1/\pi$ candela per square foot ($\pi^{-1}\ cd\ ft^{-2}$)

It should be noted that the definition of foot-Lambert is such that the luminance of a perfect diffuser is 1 fL when illuminated at 1 fc. In SI units, the luminance of a perfect diffuser wouldbe $1/\pi$ (cd/m^2) when illuminated at 1 lx. For convenience of changing from English units to SI units, the conversion factors are listed in **Table 3**. For example, 1000 lx is the same illuminance as 92.9 fc, and 1000 cd/m^2 is the same luminance as 291.9 fL. Conversion factors to and from some other units are given in Reference [19].

Table 3. Conversion between English units and SI units

To obtain the value in	multiply the value in	by
lx from fc	fc	10.764
fc from lx	lx	0.09290
cd/m^2 from fL	fL	3.4263
fL from cd/m^2	cd/m^2	0.29186
m (meter) from feet	feet	0.30480
mm (millimeter) from inch	inch	25.400

1.3 NIST photometric units

1.3.1 NIST Luminous intensity unit

Until 1991, the NIST luminous intensity unit was derived from the NIST spectral irradiance scale [20], which was based on a gold-point blackbody, and therefore, dependent on the temperature scale. In 1990, the international temperature scale was revised [21], and the gold point temperature changed from 1337.58 K to 1337.33 K. Due to this change, the magnitude of NIST luminous intensity unit increased by 0.35 %.

In 1992 at NIST, a new luminous intensity unit (candela) was realized based on the absolute responsivity of detectors (using a 100 % Q.E. silicon detectors [2] and subsequently a cryogenic electrical substitution radiometer [3]). The old luminous intensity unit was replaced with the new unit in 1992.

The new candela is realized and maintained on a group of standard photometers (referred to as the NIST standard photometers) which are calibrated for illuminance responsivity in A/lx. These standard photometers also embody the NIST illuminance unit, and allow luminous intensity to be determined from measured illuminance and distance. The realization and maintenance of the photometric units at NIST are shown in **Figure 2**. The NIST cryogenic

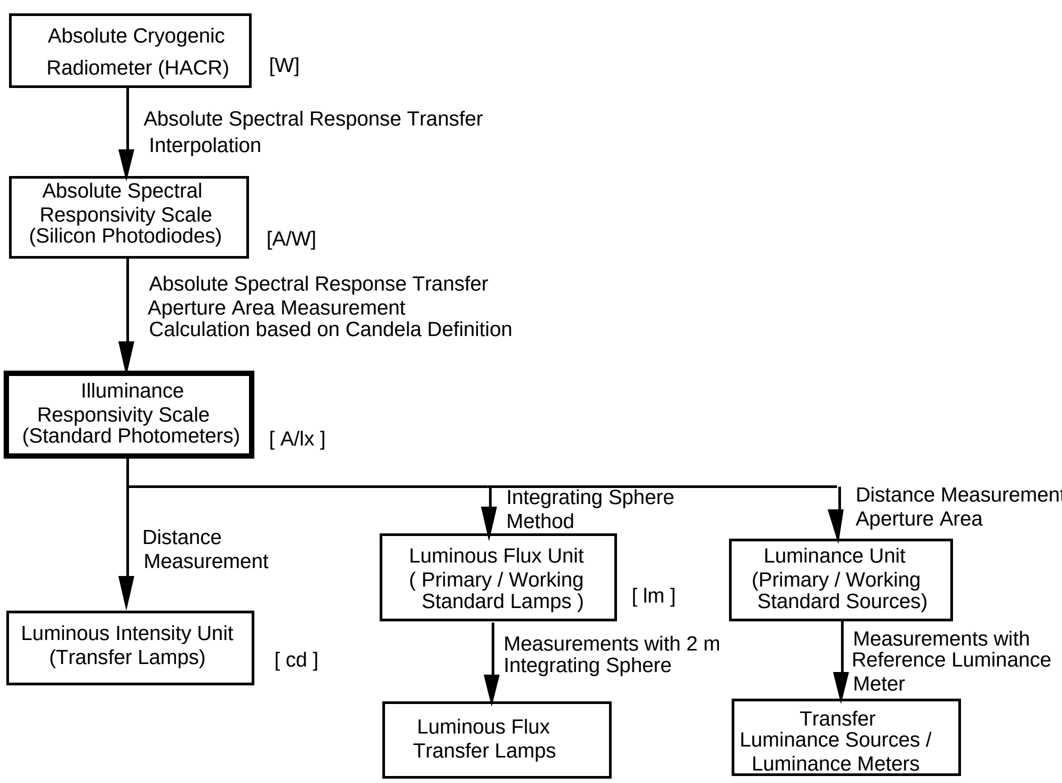


Figure 2 Realization and maintenance of the NIST photometric units.

radiometer [22] acts as the absolute radiometric base at the top of the chain. The radiometer (called HACR; High Accuracy Cryogenic Radiometer) is cooled by liquid helium to 5 K, and works on the principle of electrical substitution. The construction of the HACR is shown in **Figure 3**. Based on laser-beam power measurements with the HACR at several wavelengths, the NIST detector spectral responsivity scale is maintained on silicon photodiode light-trapping detectors [23]. The measurement uncertainty in the calibration of a light-trapping detector against the HACR is 0.06 % (relative expanded uncertainty, k=2[†]) in the visible region [23]. The spectral responsivity scale is transferred to other detectors using the Spectral Comparator Facility (SCF) [25], where the absolute spectral responsivity $s(\lambda)$ (A/W) of each of the NIST standard photometers is determined. The illuminance responsivity [A/lx] of each photometer is

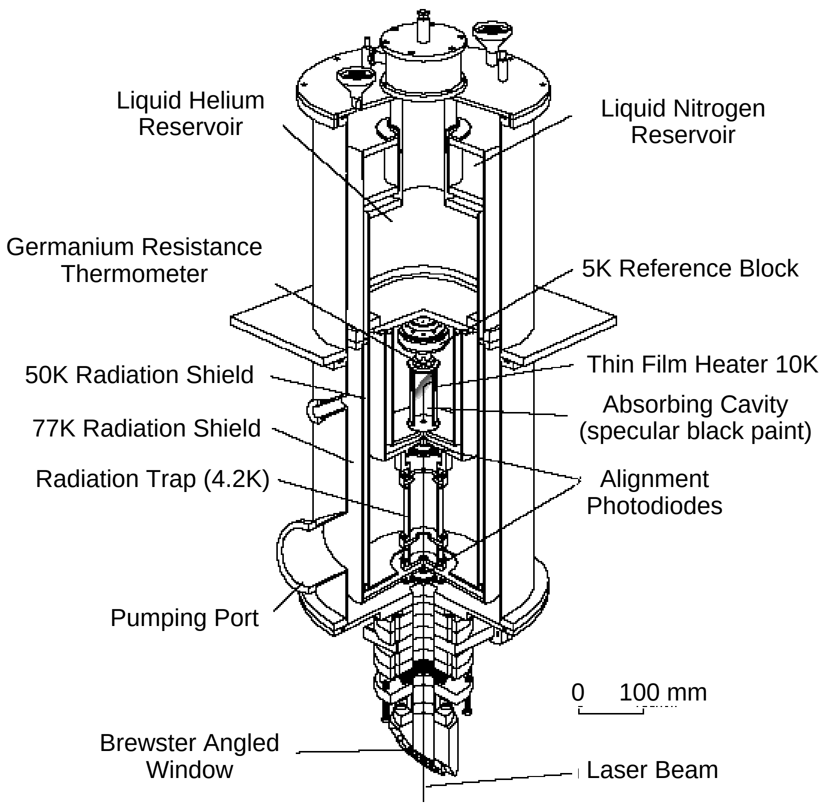


Figure 3 Construction of the NIST High Accuracy Cryogenic Radiometer.

† Throughout this paper, all uncertainty values are given as an expanded uncertainty with coverag factor k=2, thus a two standard deviation estimate. Uncertainties of fundamental units given as a combined standard uncertainty in other documents are restated as an expanded uncertainty (k=2).

then calculated from $s(\lambda)$, the area of the aperture, and other correction factors. The relative expanded uncertainty of the illuminance responsivity determination is 0.39 % [2]. The standard photometers are recalibrated annually utilizing the detector spectral responsivity scale. The details of the candela realization are described in Section 3.1 and in Reference [2].

As the result of the candela realization in 1992, the magnitude of the NIST luminous intensity unit changed (increased) by approximately 0.3 %. With the effect of the change of the international temperature scale in 1990 included, the magnitude of the NIST candela is larger (measured values are smaller) by approximately 0.6 % than that reported before 1990. At the latest CCPR international intercomparison [26] in 1985, the NIST candela was 0.6 % smaller than the world mean. The changes of the NIST candela occurred in the direction to reduce its difference from the world mean. At the time of the 1985 intercomparison, the candela and the lumen standards disseminated in different countries varied by ± 1 %. The most recent status of the differences in the magnitude of photometric units for different countries in the world was last published by BIPM in 1988 [27], the copy of which is attached in the Appendix A. The next international intercomparison of photometric units by CCPR is planned to be completed by 1998. In the mean time, NIST occasionally conducts bilateral intercomparisons of photometric units with other national laboratories [28].

1.3.2 NIST luminous flux unit

Until 1994, the NIST luminous flux unit was derived from the previous luminous intensity unit which was based on blackbody radiation. The previous luminous flux unit was last realized in 1985 by goniophotometric measurements [1], and was maintained on a group of six incandescent standard lamps. The unit was periodically transferred to groups of working standard lamps used for routine calibrations.

In 1995, a new NIST luminous flux unit was derived, based on the detector-based candela introduced in 1992, with a new method using an integrating sphere and an external source. The basic principle of this method (Absolute Integrating Sphere Method) is to measure the total flux of a lamp inside the sphere compared to a known amount of flux introduced into the sphere from a source outside the sphere.

This method was first studied theoretically using a computer simulation technique [29], then experimentally verified [30] using a 0.5 m integrating sphere. Utilizing this method with a 2 m integrating sphere, the new NIST luminous flux unit was established in 1995 [31, 32]. Primary standard lamps and working standard lamps are calibrated periodically against the NIST illuminance unit in order to maintain the luminous flux unit and to provide routine calibrations. The details of the luminous flux unit realization are described in Section 5.1.

The realization of the 1995 luminous flux unit has resulted in a change (increase) of the magnitude of NIST luminous flux unit by approximately 1.1 %. The measured lumen values reported by NIST are smaller by that percentage than those previously reported. At the time of the 1985 CCPR international intercomparison [26], the NIST lumen value was 1.0 % smaller than th world mean. The new luminous flux unit has been disseminated in NIST calibrations since January 1, 1996.

2. Outline of the calibration services

This section provides a list of the photometric calibration services currently available at NIST. The complete description of these services is reported in the NIST Calibration Services Users Guide (SP250) [5]. Chapter 7 (Optical Radiation Measurements) of the SP250 is attached as Appendix B. The details of the artifacts and measurement procedures for calibration are

Table 4. NIST Photometric Calibration Services

Test no.	Item of test	Range	Relative expanded uncertainty (*k*=2)
37010C	Luminous Intensity and Color Temperature Standard Lamps (~1000 cd, 2856 K)		0.5 % 8 K
37020S	Special Tests for Luminous Intensity and Color Temperature of Submitted Lamps	10^{-1} cd – 10^{4} cd 2856 K	0.6 % 8 K
37030C	Color Temperature Standard Lamps	2856 K	8 K
37040C	Each Additional Color Temperature for 37030C	2000 K – 3200 K	4 K – 10 K
37050S	Special Tests for Color Temperature of Submitted Lamps	2000 K – 3200 K	4 K – 10 K
37060S	Special Tests for Total Luminous Flux of Submitted Lamps (Incandescent lamps and fluorescent lamps)	10^{-1} lm – 10^{5} lm	0.8 % – 2.0 %
37070C	Opal Glass Luminance Coefficient Standards	~0.15 sr^{-1}	0.5 %
37080S	Special Tests for Submitted Luminance Sources and Transmitting Diffusers	(1 – 4000) cd/m^2	0.7 %
37090S	Special Tests for Photometer heads, Illuminance meters, and Luminance meters	(0.1 – 3000) lx	0.5 % - 1 %
37100S	Special Photometric Tests		

described in Sections 3 through 7. **Table 4** lists the NIST photometric calibration services with typical measurement ranges and typical uncertainties. All the items listed here, including the Special Tests, are provided routinely. Fixed services (Test Numbers ending in the letter C) are those in which NIST issues calibrated artifacts to customers. Special Tests (Test Number ending with the letter S), on the other hand, are those in which NIST calibrates artifacts submitted by customers.

The fees for the fixed services are listed in the Fee Schedule (SP250 Appendix). The fees for Special Tests depend on the type of artifacts, number of artifacts, measurement range requested, etc. A cost estimate will be given for each request for a Special Test.

Calibrations on special test items or under special conditions, other than listed below, may be available after consultation as Special Photometric Tests 37100S.

3. Luminous intensity (candela) calibrations

3.1 NIST illuminance unit and the NIST candela

3.1.1 Principles of the detector-based candela realization

As stated in Section 1.3, the NIST candela is realized and maintained on a group of eight NIST standard photometers. The illuminance responsivity (A/lx) of these photometers are calibrated annually utilizing the NIST spectral responsivity scale. The principles of the calibration of the photometers are described below.

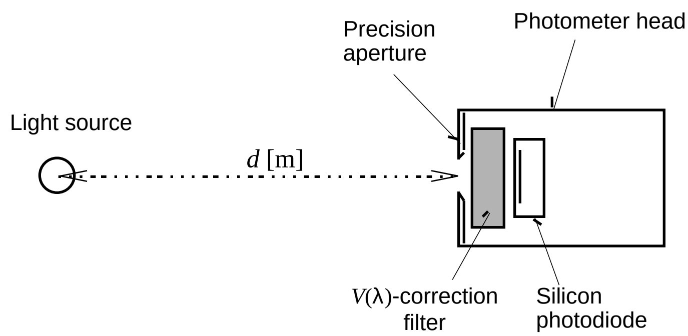


Figure 4 Geometry for the detector-based candela realization.

A standard photometer consists basically of a silicon photodiode, a $V(\lambda)$-correction filter, and a precision aperture, as shown in **Figure 4**. When the absolute spectral responsivity $s(\lambda)$ (A/W) of the photometer is measured, the photometric responsivity $R_{v,f}$ (A/lm) of the photometer within the aperture is given by

$$R_{v,f} = \frac{\int_\lambda P(\lambda)\, s(\lambda) d\lambda}{K_m \int_\lambda P(\lambda)\, V(\lambda)\, d\lambda} \tag{8}$$

where $P(\lambda)$ is the spectral power distribution of light to be measured, $V(\lambda)$ is the spectral luminous efficiency function, and K_m is the maximum spectral efficacy (683 lm/W). Usually a Planckian radiator at 2856 K (CIE Illuminant A) is used to provide the light flux $P(\lambda)$. If the area A (m^2) of the aperture is known and the responsivity $R_{v,f}$ is uniform over the aperture, the illuminance responsivity $R_{v,i}$ (A/lx) of the photometer is given by

$$R_{v,i} = A \cdot R_{v,f} \tag{9}$$

When a photometer calibrated for $R_{v,i}$ is used to measure the illuminance from a point source, the luminous intensity I_v (cd) of the source is given by

$$I_v = d^2 \cdot y \; / R_{v,i} \; , \tag{10}$$

where d is the distance (m) from the light source to the aperture surface of the photometer and y is the output current (A) of the photometer. In practice, d must be larger than the minimum distance where the deviation from the inverse square law of the light source is negligibly small.

3.1.2 Design of the NIST standard photometers

Figure 5 shows the design of the NIST standard photometers. A silicon photodiode, a $V(\lambda)$-correction filter, and a precision aperture are mounted in a cylindrical housing. The photodiode is plugged into a socket with a teflon base of low electrical conductivity. The $V(\lambda)$–correction filter is made of several layers of glass filters, and affixed to the photodiode. On the front side of the filter, the precision aperture is glued to a holder which is carefully machined so that its front surface (the reference surface of the photometer) is 3.0 mm from the plane of the aperture knife edge.

An electronic assembly containing a current-to-voltage converter circuit having a high sensitivity and a wide dynamic range [33] is mounted directly behind the photodiode to minimize noise. The circuit has a switchable gain setting from 10^4 V/A to 10^{10} V/A (10^{11} V/A for two of the photometers). 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 bandwidth of 0.3 Hz. This high sensitivity feature allows precise measurement of $s(\lambda)$ even in the wings of the $V(\lambda)$ curve.

Since the characteristics of the filter and photodiode can change with temperature, a temperature sensor is installed in the front piece of the housing to monitor the photometer temperature [34].

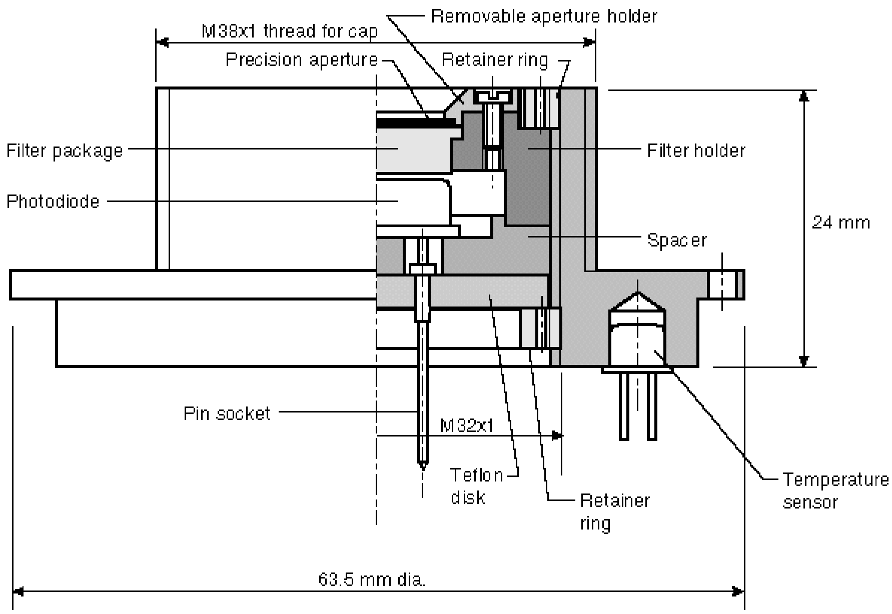


Figure 5 Design of the NIST standard photometer.

3.1.3 Calibration of the NIST standard photometers

The spectral responsivity $s(\lambda)$ of the photometers is measured with the NIST Spectral Comparator Facility (SCF) [25]. The photometer aperture is underfilled with a beam of 1 mm diameter from the monochromator, and the responsivity of the photometer is mapped over the entire area of the precision aperture at several wavelengths. From the mapping data, the ratio of the average responsivity over the aperture to the responsivity at the center of the aperture is calculated and applied in the responsivity calculation. The f_1' values of the eight photometers range from 1.4 % to 6 %. The f_1' is a term recommended by CIE [35] to indicate the degree of spectral mismatch of a photometer to the $V(\lambda)$ function. The illuminance responsivity of NIST photometers, $R_{v,i}$ [A/lx], are calculated for Planckian radiation at 2856 K (CIE Illuminant A) according to eqs (8) and (9).

3.1.4 Spectral mismatch correction

When the photometers measure light sources whose spectral distribution is different from the 2856 K Planckian source, an error occurs due to the spectral mismatch of the photometers. This error is corrected by a spectral mismatch correction factor, ccf^*, as given by

$$ccf^*(S_t(\lambda)) = \frac{\int_\lambda S_A(\lambda)\, s_{rel}(\lambda)\, d\lambda \int_\lambda S_t(\lambda)\, V(\lambda)\, d\lambda}{\int_\lambda S_A(\lambda)\, V(\lambda)\, d\lambda \int_\lambda S_t(\lambda)\, s_{rel}(\lambda)\, d\lambda}, \qquad (11)$$

where $S_t(\lambda)$ is the spectral power distribution of the test lamp, $S_A(\lambda)$ is the spectral data of the CIE Illuminant A, and $s_{rel}(\lambda)$ is the relative spectral responsivity of the photometer. Using this equation, the correction factor can be obtained for any light source with known spectral power distribution.

For convenience in measuring incandescent lamps, ccf^* is expressed as a function of the distribution temperature T_d of the lamp to be measured. The $ccf^*(S_t(\lambda))$ is calculated for Planckian radiation of four temperatures, and then the correction factors are fitted into a polynomial function. The $ccf^*(T_d)$ is then given by,

$$ccf^*(T_d) = \sum_{j=0}^{3} a_j \, T_d^{\,j} \quad . \tag{12}$$

The polynomial constants are obtained for each of the NIST standard photometers. An example is shown in **Figure 6**. The spectral mismatch correction factors for incandescent lamps of known distribution temperature are automatically calculated using this polynomial. The output signal of the photometer is multiplied by this correction factor.

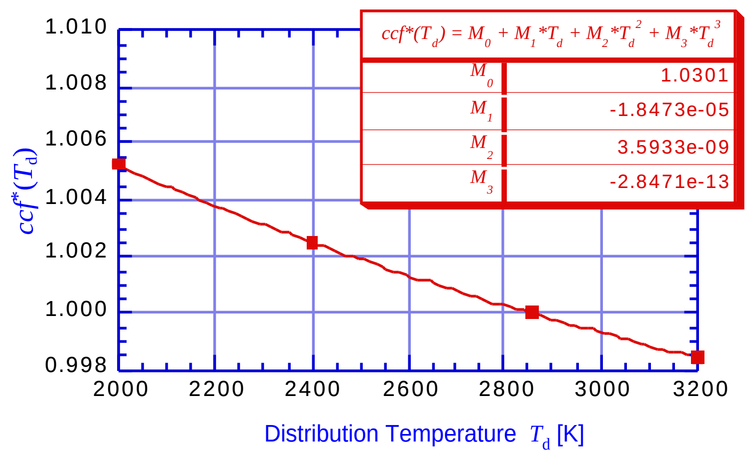


Figure 6 Polynomial fit for the spectral mismatch correction factors.

3.1.5 Correction for the photometer temperature

The temperature coefficients of the illuminance responsivity of the photometers, measured in a temperature-controlled chamber, are shown in **Figure 7**. The figure shows the data for three different photometers in the group. The temperature coefficients, c_p, for the eight photometers range from -0.049 %/°C to -0.088 %/°C. Whenever the photometers are used, the temperature correction factor, $k(T_p)$, as given below, is calculated, and the output signal is multiplied by this correction factor.

$$k(T_p) = 1 - (T_p - T_0)\, c_p \tag{13}$$

where T_0 is the temperature at which each photometer was calibrated.

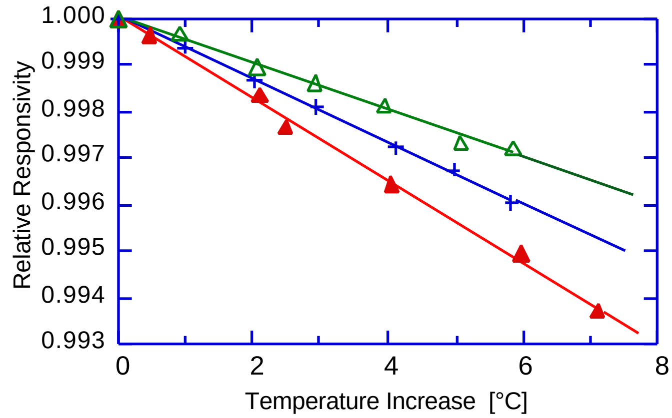
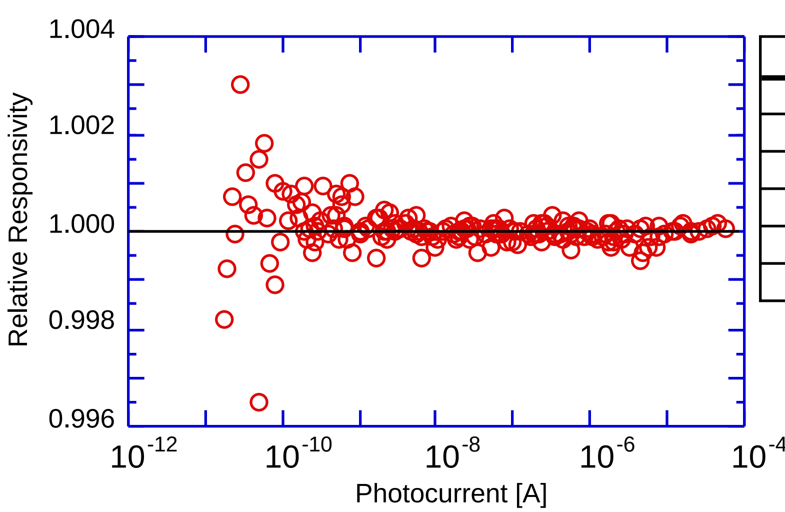


Figure 7 The temperature dependence of the photometers' illuminance responsivity.

3.1.6 Linearity of the NIST standard photometers

The linearity of the photometers was measured using a beam conjoiner instrument [36], which is a ratio-and-additive beam device designed to test the linearity of photodetectors. **Figure 8** shows the result from one of the NIST standard photometers for a 2856 K source. These data indicate that the photometer is linear over an output current range of 10^{-10} A to 10^{-4} A. This corresponds to an illuminance range of 10^{-2} lx to 10^{4} lx, and means the photometers can be used to measure a luminous intensity as low as 10 mcd at 1 m, and as high as 10^{5} cd at 3 m, without significantly increasing the uncertainty. If the integration time for the signal is longer, the photometer can be used for even lower levels [33]. The linearity data also assures negligible non-linearity error in the spectral responsivity measurements.



Decade	Average
-10 – -9	1.00016
-9 – -8	1.00001
-8 – -7	0.99999
-7 – -6	1.00001
-6 – -5	0.99993
-5 – -4	1.00003

Figure 8 Linearity of one of the NIST standard photometers.

3.1.7 Uncertainty of the NIST illuminance unit and the candela realization

The uncertainty budgets for the NIST illuminance unit realization and the NIST candela realization are shown in **Table 5** and **Table 6**, respectively. Long-term drift of the standard photometers are not included in these tables, but are taken into account in the uncertainty budgets for the calibrations. Type A evaluation of uncertainty is made by statistical analysis, and type B evaluation of uncertainty is made by means other than the statistical analysis [4]. The overall uncertainty is calculated as the quadrature sum of all factors. Further details of the characterization, calibration, and uncertainty analysis for the NIST standard photometers are described in Reference [2].

Table 5. Uncertainty budget for the NIST illuminance unit realization

Uncertainty factor	Relative expanded uncertainty (*k*=2) [%] Type A	Type B
NIST absolute responsivity scale (visible region)		0.22
Comparison of photometer to the scale	0.08	
Wavelength calibration of monochromator		0.08
Numerical aperture of SCF output beam		0.10
Area of the photometer aperture		0.10
Temperature variation	0.06	
Other factors	0.24	
Overall uncertainty of the NIST illuminance unit realization	**0.39**	

Table 6. Uncertainty budget for the NIST candela realization

Uncertainty factor	Relative expanded uncertainty (*k*=2) [%] Type A	Type B
The NIST illuminance unit (Table 5)		0.39
Distance measurement (uncertainty of the linear encoder at 3 m)		0.02
Alignment of the lamp distance (0.5 mm in 3 m)	0.03	
Determination of *ccf**		0.04
Photometer temperature variation	0.03	
Lamp current regulation	0.02	
Stray light		0.05
Random noise	0.10	
Overall uncertainty of the NIST candela realization	**0.41**	

3.1.8 Long-term stability of the NIST standard photometers

The NIST standard photometers are usually calibrated on annual basis at the NIST Spectral Comparator Facility [25] utilizing the spectral responsivity scale. The drift of the illuminance responsivity of the NIST standard photometers over a 5 year period is shown in **Figure 9**. Note that these results include the uncertainty of the illuminance unit realization (0.39 %) shown in **Table 5**. The filter surface of the photometers were not cleaned during this time period. Photometers 1, 2, and 3, which showed larger drift than the rest, employ $V(\lambda)$-correction filters from different manufacturers than the rest. On the filter surface of Photometers 1 and 2, which have a larger aperture (0.5 cm^2) than the rest, a cloudy deposit of unknown composition and origin was observed. After cleaning the filter surface of these photometers, the responsivity increased to slightly higher than the 1991 values. In contrast to this, photometers 4 through 8 have been quite stable, with an average drift of 0.05 % per year. The illuminance unit is now maintained on these five photometers. Photometers 1, 2, and 3 are used only for the annual realization of the unit.

The data shown in **Table 5** are not yet sufficient to evaluate the long-term stability of the photometers due to the much larger uncertainty of the calibration of the photometers. However, in order to assign the uncertainty of the calibration, the maximum drift per year (0.15 %) of Photometers 4 through 8 is tentatively used as the uncertainty value for the long-term drift of the five photometers. This value may be reduced in the future as more data are accumulated for precise analysis.

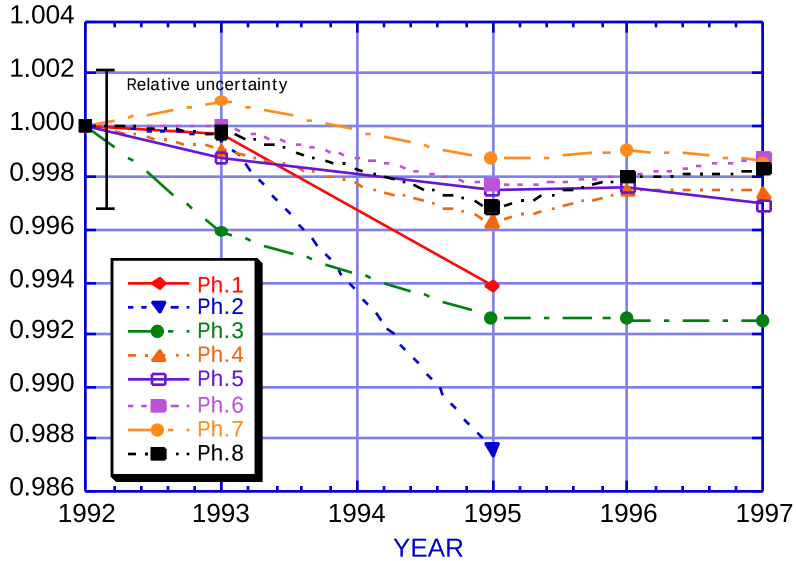


Figure 9 Drift of the illuminance responsivity of the NIST standard photometers over a 5 year period.

3.2 Artifacts for calibration

3.2.1 Type of test lamps and their characteristics

For many years, NIST issued gas-filled, inside-frosted, GE† Airway Beacon type lamps (100 W, 500 W and 1000 W) as luminous intensity transfer standards of approximately 150 cd, 700 cd, and 1400 cd, respectively. These lamps are still accepted for recalibration by NIST. The 100 W and 500 W lamps have T-20 bulbs, and the 1000 W lamps have T-24 bulbs. They all have medium bi-post bases and C-13B filaments. The lamp designation number is etched on the bulb. **Figure 10** (left) shows the appearance of this type of lamp and the electrical polarity applied during calibration by NIST. The designation number on the bulb always faces opposite to the direction of calibration.

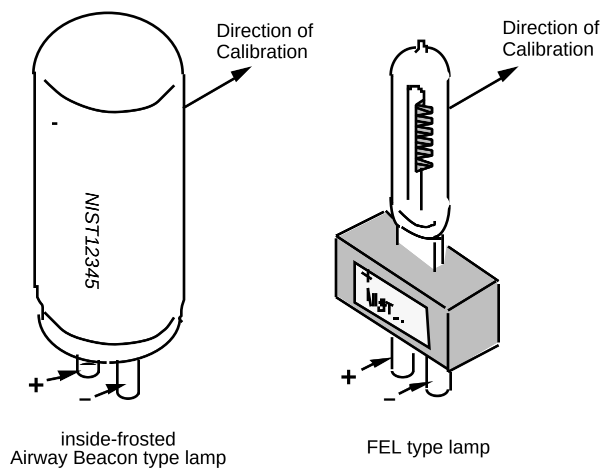


Figure 10 Appearance of the luminous intensity standard lamps and their electrical polarity.

Figure 11 shows the aging characteristics (drift as a function of operating time) of a typical Airway Beacon type lamp at 2856 K**.** The lamp needs to be recalibrated after a certain operation time depending on the user's uncertainty requirements, and the aging characteristics of the individual lamp should be taken into account in the uncertainty budget. It is generally recommended that this type of lamp be recalibrated after 25 h of operating time.

NIST now issues standard lamps calibrated for luminous intensity and color temperature. The type of lamp issued by NIST is a 1000 W, FEL type, quartz halogen lamp with a coiled-coil tungsten filament, as shown in **Figure 10** (right). The lamps, manufactured by Osram-Sylvania

† 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.

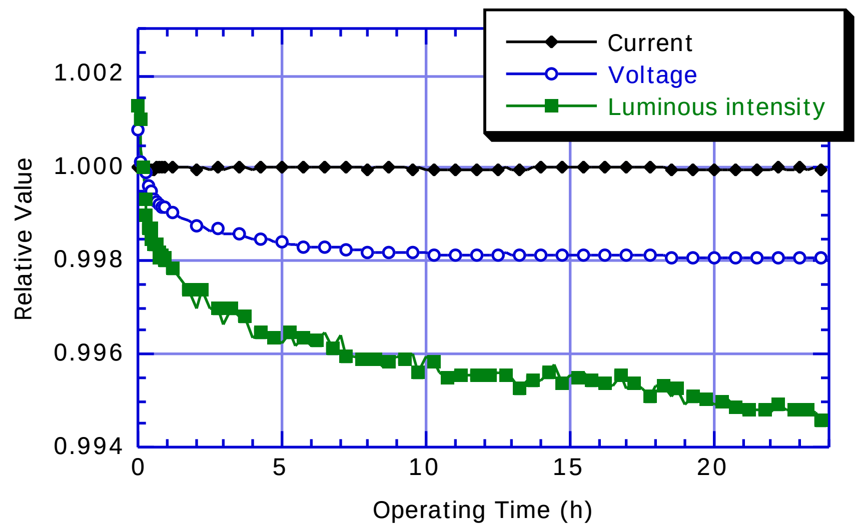


Figure 11 Aging characteristics of a typical Airway Beacon type lamp at 2856 K.

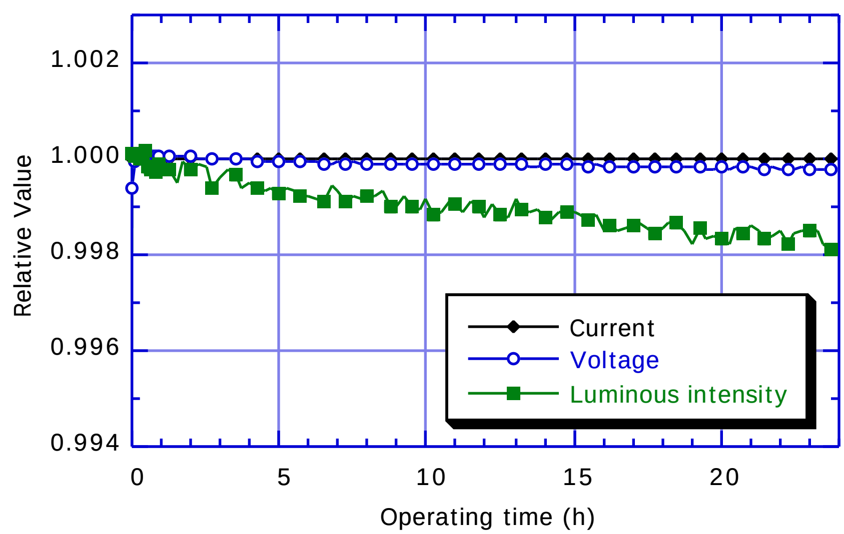


Figure 12 Aging characteristics of a selected FEL type lamp at 2856 K.

Inc., are potted on a medium bi-post base, and seasoned with DC power for 48 h at 8.5 A and then for 72 h at 7.2 A. Lamps are operated and calibrated at a color temperature of 2856 K with an operating current of ~7.2 A and voltage of ~85 V. The lamp designation numbers and the electrical polarity are engraved on an identification plate affixed to the lamp base (See **Fig. 10**).

Figure 12 shows the aging characteristics of a typical selected FEL type lamp at 2856 K. The luminous intensity lamps issued by NIST are screened to obtain a luminous intensity drift of smaller than 0.3 % during a continuous 24 h period of operation. It can be assumed that the lamp changes at a similar rate in ensuing hours of operation. It is generally recommended that this type of lamp be recalibrated after no longer than 50 h of operating time. Further details of the characteristics of these FEL type lamps are described in Reference [37].

The FEL type lamps issued by NIST are also screened for angular uniformity of luminous intensity. **Figure 13** shows the data of a typical selected FEL type lamp. If the filament is tilted from the perpendicular of the optical axis, the angular uniformity is degraded. The lamps are selected for the variation of luminous intensity not to exceed ± 0.5 % in a ±1° rectangular region around the optical axis. It should be noted that, even though the lamps are selected as mentioned above, the angular alignment of the FEL type lamps with a clear bulb is more critical than with the frosted lamps previously issued by NIST. NIST plans to issue FEL type lamps with frosted bulbs when they become available.

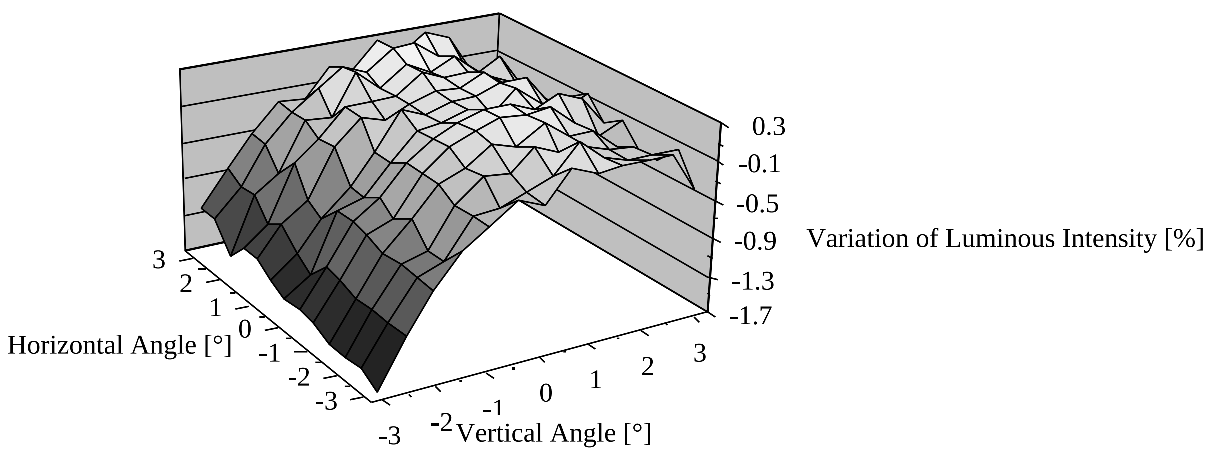


Figure 13 Spatial nonuniformity of a typical FEL type lamp.

3.2.2 Alignment of test lamps

Each test lamp is mounted on a photometry bench in the base-down position, and with the identifying number facing the direction opposite to the photometer. Lamp orientation is accomplished, as shown in **Figure 14**, by aligning the lamp socket so the lamp posts are held vertically and the plane formed by the axes of the posts is perpendicular to the optical axis of the photometer. An alignment jig (a mirror mounted on a bi-post base to be parallel to the plane formed by the axes of the posts) is used in combination with a laser. The laser is placed in the photometer's position and the beam is autocollimated.

The alignment of the distance origin and the height of the lamps are performed using a side viewing telescope as shown in **Figure 15**. For an FEL lamp with a clear bulb, the center of the lamp filament is adjusted to the distance origin of the photometric bench. For inside-frosted Airway Beacon type lamps, the center of the posts of the jig is adjusted to the distance origin, and the height of the lamp, *h*, is aligned so that the optical axis is 12.7 cm (5 in) for 100 W and

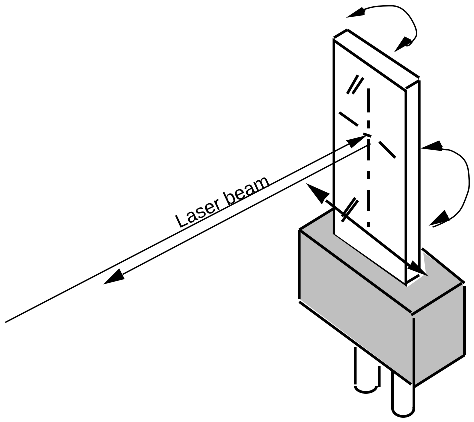


Figure 14 Alignment of the bi-post base socket using a jig and a laser beam.

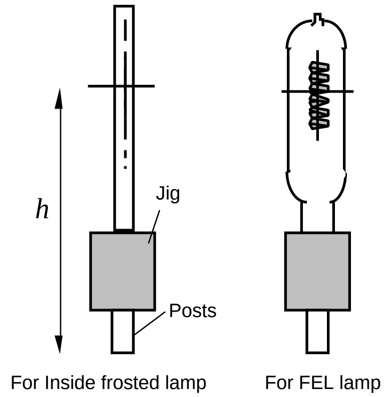


Figure 15 Alignment of the distance origin and height of the lamp.

500 W lamps and 11.4 cm (4.5 in) for 1000 W lamps, from the bottom of the posts. It should be noted that, although the FEL type lamp is the same type as used for spectral irradiance calibrations [20], the distance origin of the lamp for luminous intensity is different from that for the spectral irradiance calibration. For spectral irradiance calibrations, the front surface of the jig plate is used, which is 3 mm off from the center of posts.

For lamps with a screw-base (E27 and E40) and with a clear bulb, alignment is performed by viewing the filament with the telescope. The distance origin of lamps with a screw base is aligned to the center of the lamp filament, and the height of the lamp is aligned so that the filament center is on the optical axis.

3.2.3 Operation and handling of test lamps

The lamps should be carefully aligned in accordance with the procedures described above. The lamps should be operated on DC power with the polarity described above, and only at the current specified in the calibration report. The lamp current should be ramped up and down slowly (approximately 30 s). Photometric measurements should be made after the lamp has stabilized (~10 min after turning on).

The lamps should be handled very carefully to avoid mechanical shocks to the filament. The bulb of any lamp should not be touched with bare hands. Before operation, the bulb of the lamp should be cleaned with a soft, lint-free cloth to remove any dust accumulation from the packing material. Lamps are best kept in a container when not used.

Special attention should be paid to quartz halogen lamps (FEL lamps) to avoid moisture on the envelop. Water droplets on the bulb can cause a white spot on the quartz envelope after burning the lamp, and can result in a permanent damage to the lamp. If a quartz halogen lamp is accidentally touched with a bare hand, the bulb should be cleaned using ethyl alcohol.

3.3 Equipment for calibration

3.3.1 Photometry bench

The photometry bench shown in **Figure 16** is used for luminous intensity and illuminance calibrations. 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 photometers are aligned against the front surface of the mounts fixed on the carousel. The position of the carriage on the rails is monitored by a computer-readable, linear encoder that provides an absolute position with a resolution of 0.01 mm. The encoder reading was verified by comparison with a 2.75 m NIST calibrated vernier caliper, and the uncertainty† of distance was determined to be 0.36 mm. 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 %, most of this is reflection from the edges of variable aperture diaphragms between the compartments of the photometric bench. Besides the shutter, a $V(\lambda)$-

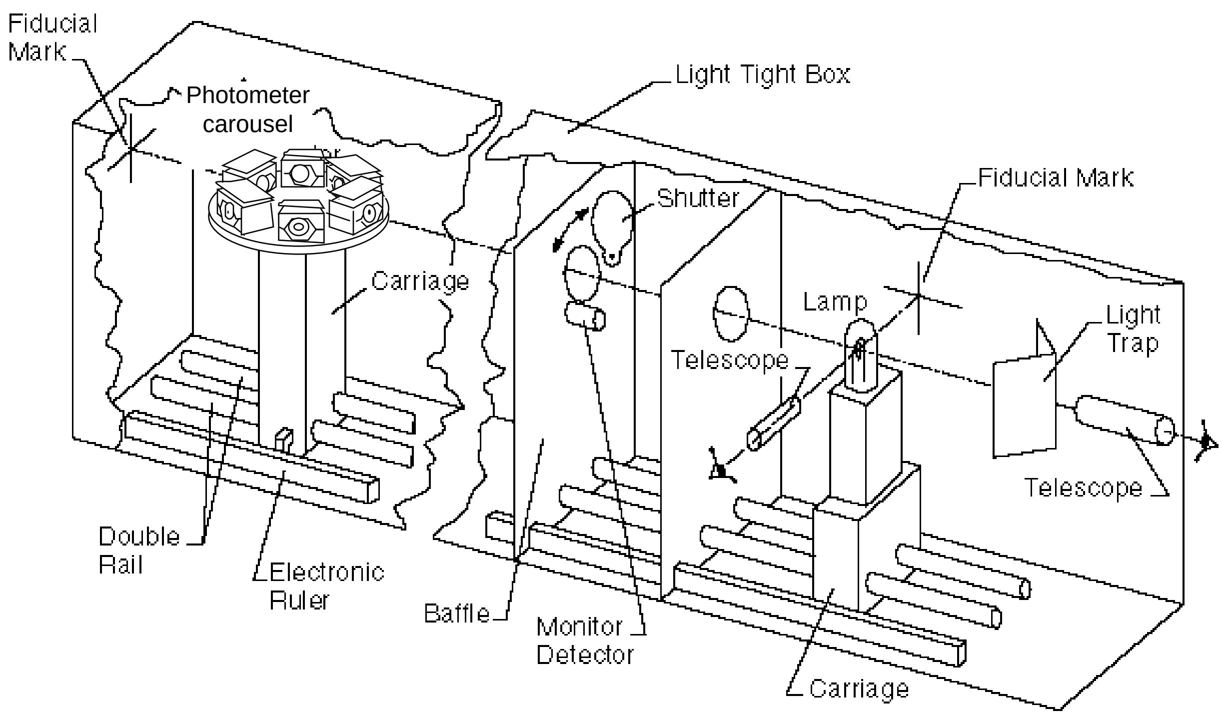


Figure 16 NIST Photometry Bench.

† Throughout this paper, all uncertainty values are given as an expanded uncertainty with coverage factor k=2, thus a two standard deviation estimate.

corrected monitor detector is mounted to monitor the stability of the lamp during calibration of photometers. This monitor detector gives a consistent signal regardless of the shutter position and the photometer mounted or not on the carriage.

3.3.2 Electrical power supply

All the standard lamps and test lamps are operated at a specified current rather than a specified voltage because lamp voltage, in general, does not reproduce well due to the variation of sockets used among customers. However, if the socket is designed well, the lamp voltage reproduces fairly well on the same socket, and the lamp voltage is useful to monitor for changes in the lamp.

The NIST photometric 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. For luminous intensity calibrations, the lamp voltage is reported, only for reference, without an uncertainty value. The bench is also equipped with a medium screw-base socket (E27) which has four contacts. Screw-based lamps submitted by a customer can be calibrated.

A DC constant-current power supply 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 DVM, with an uncertainty better 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 %. The power supply is operated in an external control mode, in which the output current is regulated by an external reference voltage. The external voltage is supplied by an 18 bit D-to-A converter controlled by the computer.

3.4 Calibration procedures

When a new lamp is calibrated for luminous intensity, the operating current of the lamp is first determined for a color temperature of 2856 K. When a submitted lamp is calibrated with the lamp current specified by the customer, the color temperature of the lamp is measured and reported. The procedures for color temperature measurements are described in Section 7.

After the operating current of the lamp is assigned, the luminous intensity of the lamp is calibrated using the following procedures. The test lamp is mounted on the photometry bench, and its orientation and position are aligned precisely according to the procedures described in Section 3.2.2. The lamp is operated on DC power with the electrical polarity as shown in **Figure 10**. The lamp current is ramped up slowly (~30 s) to the specified value, and allowed to stabilize (typically for 10 min). Then the illuminance from the test lamp at a distance of approximately 3.5 m is measured using three of the NIST standard photometers. The average illuminance measured by the three photometers and the lamp-to-photometer distance are used to determine the luminous intensity of the test lamp.

The measured illuminance is usually the average of five readings taken between 10 minto 15 min after turning on the lamp. Each reading consists of twenty DVM samples with the shutter open, and ten DVM samples with the shutter closed. This process takes approximately 0.5 min. The dark signal is subtracted from each reading. As soon as the measurement is finished, the lamp current is ramped down and turned off. The operating time of the test lamp is usually less than 15 min. The test lamp is operated and measured three times, and the average value is reported.

When a luminous intensity measurement is made, the color temperature of the test lamp is also measured if it is not known, and the spectral mismatch correction factor, as described in Section 3.1.4, is calculated and applied to the results. The temperature of the photometer during calibration is monitored and the correction factor, as described in Section 3.1.5, is applied to the results. This correction is made automatically by the measurement program.

3.5 Uncertainty of calibration

Table 7 shows the uncertainty budget for luminous intensity calibrations for a typical luminous intensity standard lamp. The details of the uncertainty of the NIST illuminance unit are given in 3.1.7. Lamp stability and reproducibility depend upon the individual lamps to be calibrated. If the test lamp is unstable, the overall uncertainty of the calibration will increase.

Table 7. Uncertainty budget for the luminous intensity calibrations (typical)

Uncertainty factor	Relative expanded uncertainty (k=2) [%] Type A	Type B
The NIST illuminance unit realization		0.39
Long-term drift of the NIST standard photometers		0.15
Photometer temperature variation	0.03	
Distance measurement (uncertainty of the linear encoder at 3 m)		0.02
Alignment of the lamp distance (1 mm in 3 m)	0.07	
Deviation from inverse square law (3 mm in 2 m – 10 m)**		0.30
Determination of *ccf*[*]		0.04
Lamp current regulation and measurement uncertainty	0.02	
Stray light		0.05
Random noise (scatter by dust, lamp drift, etc.)	0.10	
Lamp reproducibility in 3 lightings (typical) **	0.20	
Overall uncertainty of test lamp calibration	**0.57**	

** Uncertainty value depends on the test item.

4. Illuminance calibrations

Significant improvement in the quality of commercial photometers and illuminance meters has been made due to availability of high quality silicon photodiodes. As a result, many types of commercially available photometers can be used as photometric standards instead of traditional luminous intensity standard lamps. Standard lamps are sensitive to mechanical shocks, change with burning time, and drift during the stabilization period. Experience shows that well maintained photometers are less subject to such problems, and provide a dynamic range of several orders of magnitude. NIST experience indicates that the short-term stability of photometers is superior to lamps, and although the long-term stability has not been tested for many types of photometers, a few particular types tested have shown satisfactory stability (~0.1 % per year). It should be noted that some photometers have shown changes greater than 1 % in a year, making their use as standards difficult. In general, for luminous intensity and illuminance measurements, the use of standard photometers is recommended, but the photometers should be calibrated frequently (at least once a year) until the long-term stability data are accumulated for the particular photometers a user laboratory may employ.

4.1 Equipment for calibration

The equipment used for the calibration of photometers and illuminance meters is the same equipment used in the luminous intensity calibrations described in 3.3.

4.2 Artifacts for calibration

Photometer heads or photometers (photometer heads with a display unit) and illuminance meters are accepted for calibration by NIST. The requirements and recommendations for photometers used as transfer standards and reference standards are described below.

4.2.1 Types of photometers and illuminance meters

A standard photometer head should have either a limiting aperture (whose area is much smaller than the photodiode area) or a flat diffuser such as an opal glass in front of the $V(\lambda)$-correction filter so that the reference plane of the photometer is accurately and clearly defined. Some commercial photometer heads only have a $V(\lambda)$-correction filter attached in front of the silicon photodiode. If a photometer head does not have an aperture or a diffuser, the photodiode surface might be used as the reference plane of the photometer head. In this case, due to the refraction index of the $V(\lambda)$-correction filter which is usually several mm in thickness, the effective reference plane can be several mm from the photodiode surface. Sometimes, the front surface of the filter is simply defined as the reference plane of such photometer heads, in which case the true reference plane can be more than 1 cm from the filter surface. When the reference plane is not correctly defined, the departure from the inverse square law causes the responsivity of the photometer to vary depending on the distance to the source, and serious errors may occur when the photometer is used at close distances to the source. This is the same problem with a large-size lamp, for which the inverse square law does not hold well at close distances. To avoid these difficulties, standard photometers having a limiting aperture or a flat diffuser on the front are recommended.

Some illuminance meter heads employ a dome-shaped or mesa-shaped diffuser in the front. In this case, it is usually difficult to define the correct reference plane. Such illuminance meters are not recommended to be used as standard photometers unless the meters are always used at the same distance from the source. Also, illuminance meters with poor spectral match and (or) with only a 3 digit display are not adequate for use as standard photometers.

Illuminance meters may have various structure of the light-receiving surface for cosine correction. The reference plane of the illuminance meter heads should be provided by the customer. Upon request, the reference plane of photometer heads (without an aperture or a diffuser) and illuminance meter heads can be experimentally determined.

4.2.2 Operation and handling of photometer heads and illuminance meters

Illuminance meters are generally not designed to measure illuminance at very close distances to a source. It should be noted that the measurement error may increase greatly if an illuminance meter whose reference plane is not correctly defined is placed very close to a light source (e.g., less than 0.5 m).

As described in 3.1.5, the responsivity of a photometer can be a function of temperature. If the photometer is neither a temperature-controlled type nor a temperature-monitored type, the photometer must be used close to the calibration temperature to avoid errors. If not, the temperature coefficient of the photometer should be measured, and correction factors should be applied as appropriate. The photometer should be placed in the laboratory several hours in advance of use so that the photometer's temperature equilibrates to the ambient temperature.

At NIST, photometers and illuminance meters are calibrated using incandescent lamps operated at 2856 K unless otherwise requested by the customer. In this case, when the photometers are used to measure light sources other than incandescent lamps of that color temperature, spectral mismatch errors occur, and in order to quantify or correct for this error, the relative spectral responsivity of the photometers or illuminance meters must be measured. The details of this calibration are described in 4.3.2.

4.3 Calibration procedures

4.3.1 Illuminance responsivity of photometers

Photometers and photometer heads are calibrated for illuminance responsivity in A/lx, V/lx or readings/lx. Calibration is performed on the NIST photometry bench using a 1000 W FEL type lamp operated at 2856 K (CIE Illuminant A). The calibration is performed by direct comparison with three of the NIST standard photometers. The responsivity is usually measured at two distances, 2.5 m and 3.5 m from the lamp, at illuminance levels of 85 lx and 150 lx. Calibrations can also be made at other illuminance levels from 0.1 lx to 3000 lx for a linearity check, if requested by customers, using procedures described in 4.3.2. The procedure for regular calibration is described below.

After the lamp has been stabilized, the illuminance on a reference point ~3 m from the lamp is first determined by three NIST standard photometers. This measurement is performed in the same manner as described in 3.4. Then the third NIST standard photometer is replaced by the photometer under test, and the readings are recorded. If the reference plane of the photometer head is located different from that of the NIST standard photometers, the distance offset is measured and recorded. The illuminance on the reference plane of the test illuminance meter is calculated from the corrected distance to the lamp and the luminous intensity of the lamp. Data are usually taken within 5 min at each illuminance level. During the comparison, the luminous intensity stability of the lamp is monitored by the monitor detector installed in the photometry bench (See 3.3.1). The ambient temperature during the calibration (usually ~25 °C) is measured and reported.

4.3.2 Illuminance meter calibration

Calibrations for illuminance meters are performed basically the same way as described in 4.3.1, using an FEL type lamp at 2856 K, with various illuminance levels from 100 lx to 3000 lx at distances from 0.6 m to 3 m. Since the distance from the lamp to the photometer is small at higher illuminance levels, the definition of the reference plane of the illuminance meter head is important as discussed previously. For lower illuminance levels, a variable slit is used in front of the FEL lamp so that the illuminance levels can be lowered with negligible change of color temperature, and without changing the lamp.

At each illuminance level, the NIST standard photometer is replaced by the illuminance meter head under test with their reference planes positioned at the same location. During the comparison, the luminous intensity stability of the lamp is monitored by the monitor detector installed in the photometry bench. The ambient temperature of the photometer under test during the calibration (usually ~25 °C) is measured and reported.

When an illuminance meter is calibrated, the errors of the reading at each illuminance level are reported. The meter reading is usually not adjusted. However, if the illuminance meter is so manufactured that the user can adjust the readings easily, the meter can be adjusted by NIST upon request by customers. In this case the instructions for the reading adjustment should be provided by the customer.

Illuminance meters can be calibrated for specific sources other than 2856 K source upon request by customers. In this case, the calibration is first performed using the 2856 K source as described in 4.3.1. Then, the spectral mismatch correction factors for the specific sources are obtained by the following procedure.

The relative spectral responsivity of the illuminance meter head is measured by the Spectral Comparator Facility [25] in the 350 nm to 1100 nm region at 5 nm increments. The monochromator output of the SCF is defocused on the photometer head to irradiate an area of several mm in diameter. The illuminance meter head is underfilled in this case. Measurements are made with the beam incident on several different spots of the receiving surface of the illuminance meter head, and the average is taken. This method can only be applied for illuminance meters whose relative spectral responsivity is fairly uniform over the receiving surface. From the relative spectral responsivity data and the spectral power distribution data (supplied by customer) of any particular light sources to be measured by the illuminance meter, the spectral mismatch correction factors for the particular sources are calculated using equation (11) as described in 3.1.4. The relative spectral responsivity data and the correction factors are reported to the customer.

4.4 Uncertainty of calibration

Table 8 shows the uncertainty budget for the calibration of illuminance responsivity of a typical photometer head in the illuminance range 50 lx to 200 lx. The details of the uncertainty of the NIST illuminance unit are given in 3.1 and reference [2]. For much lower illuminance levels, the uncertainty of calibration will increase depending on the random noise of the photometers under test.

Table 8. Uncertainty budget for the illuminance responsivity calibrations (typical)

Uncertainty factor	Relative expanded uncertainty (k=2) [%] Type A	Relative expanded uncertainty (k=2) [%] Type B
The NIST illuminance unit realization		0.39
Long-term drift of the NIST standard photometers		0.15
Photometer temperature variation	0.03	
Determination of *ccf*[*] of NIST standard photometers		0.04
Photometer head alignment (0.5 mm in 2.5 m - for 150 lx)	0.04	
Illuminance nonuniformity		0.05
Lamp current regulation	0.02	
Stray light in the photometry bench		0.05
Random noise (scatter by dust, lamp drift, etc.)	0.10	
Transimpedance gain of the amplifier		0.02
Inconsistency at two illuminance levels (typical)**		0.12
Overall uncertainty of calibration	**0.46**	

** Uncertainty value depends on the test item.

Table 9. Uncertainty budget for the calibration of an illuminance meter (an example)

Uncertainty factor	Relative expanded uncertainty (k=2) [%] Type A	Type B
The NIST illuminance unit realization (See 3.1.7)		0.39
Long-term drift of the NIST standard photometers (See 3.1.8)		0.15
Photometer temperature variation	0.03	
Determination of *ccf** of NIST standard photometers		0.04
Random noise in the photometer measurements	0.10	
Illuminance nonuniformity		0.05
Lamp current regulation	0.02	
Stray light in the bench		0.05
Illuminance meter head alignment (distance and angle)**	0.08	
Display resolution of the illuminance meter (1 in 199)**	0.50	
Inconsistency of the calibration factors at different levels**		0.30
Overall uncertainty of calibration	**0.73**	

** Uncertainty value depends on the test item.

Table 9 shows an example of the uncertainty budget for the calibration of a typical illuminance meter in the illuminance range 300 lx to 3000 lx. The overall uncertainty value depends on each individual illuminance meter and the illuminance levels. "Inconsistency of the calibration factors" is the range of the calibration factors obtained at the illuminance levels tested. For example, if the calibration factor is 0.999 at 300 lx and 1.005 at 3000 lx, the inconsistency (± 0.3 %) will be added. This inconsistency is most often caused by the incorrect definition of the reference plane of the illuminance meter head since the calibration is conducted at different distances.

5. Total luminous flux calibrations

5.1 NIST luminous flux unit

Traditionally, the luminous flux unit is realized using goniophotometers [38]. It is often difficult, however, to build and maintain high accuracy goniophotometers which require a large dark room and costly high precision positioning mechanisms. The measurements are also time consuming, resulting in longer burning times for the lamps.

To alleviate these difficulties, an alternative method (the Absolute Integrating Sphere Method) has been developed at NIST using an integrating sphere with an external source. The total flux of a lamp inside the sphere is calibrated against the known amount of flux coming into the sphere from the external source through an aperture. This method has the advantage that a conventional integrating sphere can be used with minor modifications, and the sphere can still be used for ordinary substitution measurements. Measurements are accomplished faster, resulting in shorter burning times for the lamps. Corrections are needed for the spatial nonuniformity and the incident angle dependence of the sphere response and the spectral mismatch of the integrating sphere system. The NIST luminous flux unit has been maintained using the integrating sphere method since 1995, and is directly tied to the NIST detector-based candela established in 1992.

5.1.1 Principles of the Absolute Integrating Sphere Method [30-32]

Figure 17 shows the geometry of an integrating sphere designed originally for this method. An opening is placed at an angle of 135° away from the detector, and the flux from the external source is introduced through a calibrated aperture placed in front of the opening. Two baffles are used to shield the detector and the opening from direct illumination by the internal source. The detector is exposed to the first reflection of the introduced flux from the external source in order to equalize the sphere responsivity for the internal source and that for the external source.

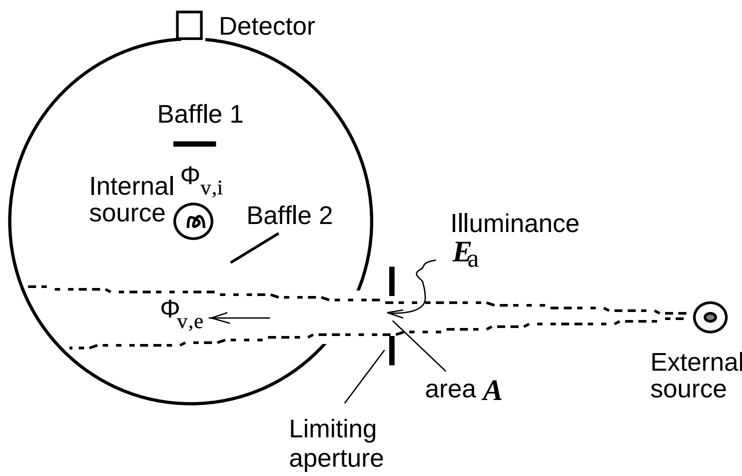


Figure 17 Basic geometry of the Absolute Integrating Sphere Method

The luminous flux $\Phi_{v,e}$ (lm) from the external source introduced into the sphere is given by

$$\Phi_{v,e} = E_a \, A \, , \tag{14}$$

where E_a is the average illuminance (lx) over the limiting aperture of known area A. The internal source or the external source is turned on alternately. The introduced flux $\Phi_{v,e}$ is used as a reference, and the luminous flux of the internal source $\Phi_{v,i}$ is measured in comparison with the flux $\Phi_{v,e}$ as given by

$$\Phi_{v,i} = c\, \Phi_{v,e}\; y_i \;/\; y_e\,, \tag{15}$$

where y_i is the detector current for the internal source, y_e is that for the external source, and c is a correction factor.

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 wall. The light from the external source is incident at 45° while the light from the internal source located at the sphere center is incident at the normal. When the incident angle is different, the diffuse reflectance of the sphere coating changes [39], which affects the sphere response. When the spectral power distribution of the internal source is different from that of the external source, a spectral mismatch error occurs. All these corrections are made to determine the correction factor c, as described in 5.1.3 through 5.1.5 in detail.

5.1.2 Design of the NIST integrating sphere for the lumen realization

Figure 18 shows the geometry of the modified NIST 2 m integrating sphere used in the realization work. The sphere is coated with barium sulfate paint with a reflectance of 96 % to 97 % in the visible region. An opening of 10 cm in diameter was cut at a position 45° away from the detector. The geometry was modified from the original design (**Fig. 17**) for the convenience of installing the external source. The portion illuminated by the external source is located in the same geometry (135° from the detector). Baffle 1 (20 cm in diameter) is located at 50 cm from the sphere center. Baffle 2 (15 cm in diameter) is located at 60 cm from the sphere center.

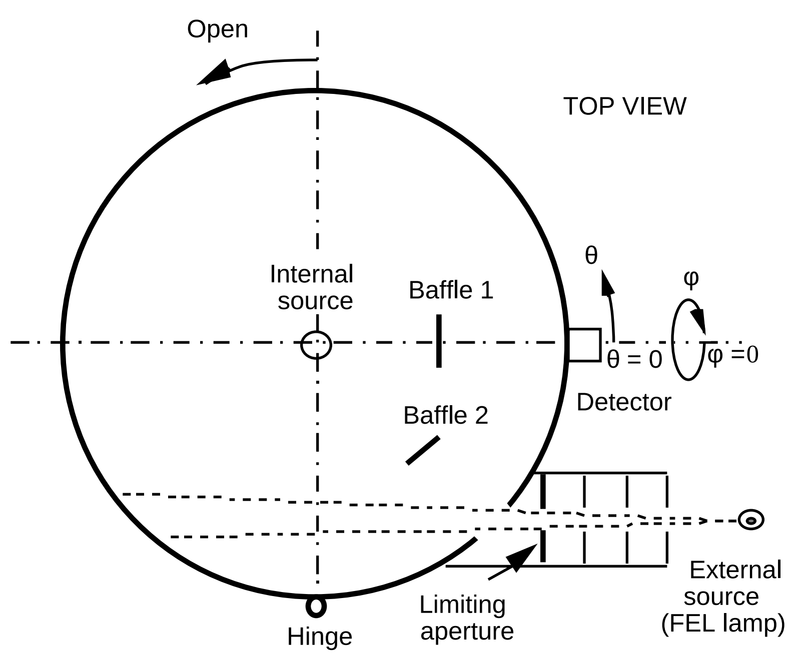


Figure 18 Geometry of the integrating sphere for the luminous flux unit realization.

The detector is a $V(\lambda)$-corrected and cosine-corrected photometer with an opal diffuser (20 mm diameter) attached in front. It has a built-in transimpedance amplifier with gain settings from 10^4 V/A to 10^{10} V/A calibrated at each range (except 10^{10} range) with an uncertainty of 0.02 %. A built-in temperature sensor allows for corrections of the photometer temperature drift. The linearity of the photometer was measured, using a beam conjoiner instrument [36], to be constant over a luminous flux range of 10^{-1} lm to 10^5 lm to within 0.05 %.

A 1000 W frosted FEL type quartz halogen lamp operated at 2856 K is used as the external source. The lamp is placed 70 cm from the limiting aperture, introducing a flux of ~2.7 lm through the 40 mm aperture. Two stainless steel limiting apertures of 40 mm and 50 mm diameter and 3 mm thick, having sharp edges, are used. The area of the apertures was determined by the NIST Fabrication Technology Division with an uncertainty of 0.03 %. The apertures are placed as close to the opening as possible to minimize diffraction losses [40]. This facility is being reconstructed employing a new 2.5 m integrating sphere.

5.1.3 Correction for the spatial nonuniformity of the sphere responsivity

The responsivity of the integrating sphere is not uniform over the sphere wall. The spatial response distribution function (SRDF), $K(\theta, \varphi)$, of the sphere is defined as the sphere response at a point (θ, φ) of the sphere wall (or on a baffle surface) divided by the sphere response at (0, 0). $K(\theta, \varphi)$ can be obtained by measuring the detector signal while rotating a narrow beam inside the sphere. $K(\theta, \varphi)$ is then normalized for the sphere response to an isotropic point source. The normalized SRDF, $K^*(\theta, \varphi)$, is defined as

$$K^*(\theta,\varphi) = 4\pi\, K(\theta,\varphi) \Big/ \int_{\varphi=0}^{2\pi} \int_{\theta=0}^{\pi} K(\theta,\varphi) \sin\theta \, d\theta \, d\varphi \, . \tag{16}$$

Using $K^*(\theta,\varphi)$, the spatial correction factor scf_e for the external source with respect to an isotropic point source is given by

$$scf_e = 1 \,/\, K^*(\theta_e,\varphi_e)\,, \tag{17}$$

where (θ_e,φ_e) is the point on which the center of the illuminated area by the external source is located. It is assumed that the area illuminated by the external source is small enough so that $K^*(\theta_e,\varphi_e)$ represents the average SRDF over the area. The spatial correction factor, scf_i, for the internal source with respect to an isotropic point source is given by

$$scf_i = 1 \Big/ \int_{\varphi=0}^{2\pi} \int_{\theta=0}^{\pi} I^*(\theta,\varphi)\, K^*(\theta,\varphi) \sin\theta \, d\theta \, d\varphi \, , \tag{18}$$

where $I^*(\theta,\varphi)$ is the normalized luminous intensity distribution of the internal source given by

$$I^*(\theta,\varphi) = I_{rel}(\theta,\varphi) \Big/ \int_{\varphi=0}^{2\pi} \int_{\theta=0}^{\pi} I_{rel}(\theta,\varphi) \sin\theta \, d\theta \, d\varphi, \qquad (19)$$

where $I_{rel}(\theta,\varphi)$ is the relative luminous intensity distribution of the internal source. $I^*(\theta,\varphi)$ is normalized so that its total luminous flux becomes 1 lm. Goniophotometry is necessary to obtain $I_{rel}(\theta,\varphi)$, but corrections for scf_i (using goniophotometry data) may not be necessary if the internal sources have uniform spatial distribution [41].

The SRDF, $K(\theta,\varphi)$, is measured by rotating a beam source which is burning position insensitive. A 6 V (1.2 W) vacuum incandescent lamp equipped with a reflector (40 mm diameter) and a cylindrical hood (100 mm long) is used. The inside of the hood is painted black, and the outside is painted white. The beam angle is ~10°. The SRDF measurements are made at 5° intervals for θ and 15° intervals for φ.

Figure 19 shows an example of the SRDF, $K^*(\theta,\varphi)$, of the NIST integrating sphere. The polar coordinate (θ,φ) in the graph is originated in the position of the detector as illustrated in **Figure 18**. φ = 0 is the plane passing through the bottom of the sphere. The scf_i for the group of 40 W opal lamps was calculated using equation (18) and determined to be 1.0003, which turned out to be almost negligible. The scf_e for the external source was calculated using eq (17) and determined to be 0.9870.

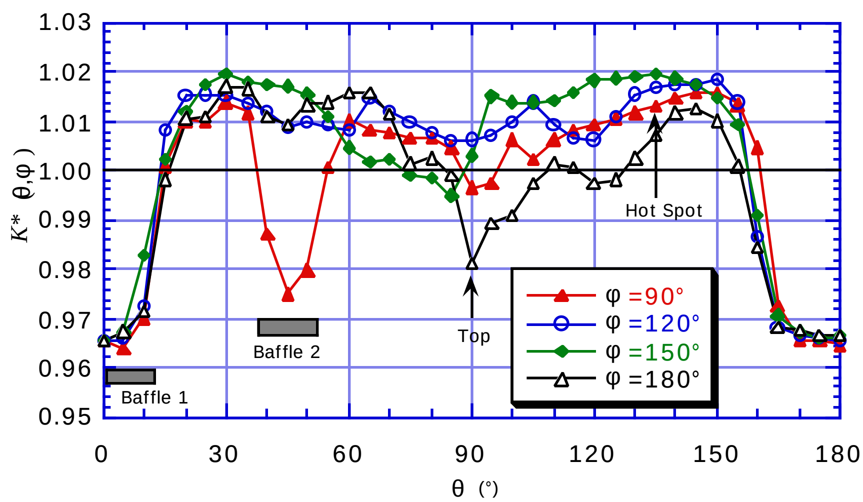


Figure 19 SRDF of the NIST 2 m integrating sphere. (θ = 0 is at the detector. φ = 0 is the plane passing through the sphere bottom.)

5.1.4 Incident angle dependence correction

The SRDF is defined for normal incidence to the sphere wall. The light from the external source is incident at 45°. When the incident angle is different, the diffuse reflectance of the sphere coating changes, which affects the sphere response. The incident angle dependence correction factor β is obtained by

$$\beta = y_0 \,/\, y_{45} \,, \tag{20}$$

where y_0 is the detector signal when a stable beam source is placed in the center of the sphere irradiating the sphere wall at (θ_e, φ_e) at 0° incidence, and y_{45} is the detector signal when the source is placed on the optical axis of the external source irradiating nearly the same part of the sphere wall at 45° incidence.

The correction factor β was measured using the same beam source (used for the SRDF measurement). The correction factor *b* was determined to be 0.9966.

5.1.5 Spectral mismatch correction

The spectral power distribution of the internal source may be different from that of the external source, and a spectral mismatch correction is needed. The spectral mismatch correction factor, ccf_i^*, of the internal source against the Illuminant A (2856 K Planckian source) is given by

$$ccf_i^* = \frac{\int_\lambda S_A(\lambda)\, R_s(\lambda)\, d\lambda \int_\lambda S_i(\lambda)\, V(\lambda)\, d\lambda}{\int_\lambda S_A(\lambda)\, V(\lambda)\, d\lambda \int_\lambda S_i(\lambda)\, R_s(\lambda)\, d\lambda} \,, \tag{21}$$

where $S_i(\lambda)$ is the relative spectral power distribution of the internal source, $S_A(\lambda)$ is that of the Illuminant A, $V(\lambda)$ is the spectral luminous efficiency function, and $R_s(\lambda)$ is the relative spectral responsivity of the sphere system. $R_s(\lambda)$ can be obtained by measuring the relative spectral responsivity of the detector $R_d(\lambda)$, and the relative spectral throughput of the integrating sphere $T_s(\lambda)$ as

$$R_s(\lambda) = R_d(\lambda)\, T_s(\lambda) \,. \tag{22}$$

The spectral mismatch correction factor, ccf_e^*, of the external source against the Illuminant A is given by equation (21) with $S_i(\lambda)$ replaced by the relative spectral power distribution $S_e(\lambda)$ of the external source.

Spectral mismatch correction factors were obtained for the external source (2856 K) and the internal sources (2730 K). The relative spectral throughput $T_s(\lambda)$ of the sphere was obtained using a spectroradiometer by taking the ratios of the spectral irradiance on the detector port of the sphere (in which a 500 W clear-bulb flux standard lamp was operated) and the spectral irradiance of the same lamp measured on the photometry bench. The relative spectral responsivity $R_s(\lambda)$ of the total integrating sphere system was then obtained using eq (22). Using eq (21), the spectral mismatch correction factors ccf_i^* and ccf_e^* were calculated to be 0.9982 and 1.0000, respectively.

5.1.6 Calibration of the primary standard lamps

The illuminance from the external source at the aperture plane was measured using a transfer photometer which was calibrated against the NIST standard photometers under illumination by the same frosted FEL lamp (used as the external source, operated at 2856 K), at a distance of ~3.5 m. The transfer photometer, with an opal diffuser (10 mm in diameter) in front, is equipped with a built-in temperature sensor which allow for compensation of the photometer temperature drift.

The illuminance distribution over the aperture area was measured by spatially scanning the transfer photometer to determine the average illuminance factor, k_a, which is a ratio of the average illuminance E_a to the illuminance on the aperture center, E_c. Once k_a is determined, only E_c needs to be measured to obtain E_a.

The transfer photometer is attached to a holding plate which can be mounted interchangeably with the aperture. The position of the photometer on the holding plate is aligned, using an alignment telescope, so that the reference plane of the photometer and that of the limiting aperture coincide when they are mounted. After measuring the illuminance E_c, the aperture is mounted, and the signal of the integrating sphere photometer, y_e, is taken. The integrating sphere responsivity, R_s', is then determined by

$$R_s' = y_e \, ccf_e^* \, scf_e \, \beta \, / \, (E_c \, k_a \, S \,) \, . \qquad (23)$$

R_s' is determined with a particular internal source (a representative lamp) inside the sphere. If a different test lamp is measured, a self-absorption correction must be applied. The self-absorption correction factor α is obtained by

$$\alpha = y_{r,e} \, / \, y_{t,e} \, , \qquad (24)$$

where $y_{r,e}$ is the detector signal with the representative lamp inside the sphere, and $y_{t,e}$ is the detector signal with the test lamp inside the sphere, when only the external source is operated. Then the total luminous flux Φ_i (lm) of an internal source (test lamp) is obtained by

$$\Phi_i = y_i \; ccf_i^* \, scf_i \, \alpha \, / \, R_s' \, . \qquad (25)$$

According to this procedure, a group of twelve 40 W opal-bulb incandescent lamps are calibrated to serve as the total luminous flux primary standards. At the same time, eight 60 W inside frosted incandescent lamps are also calibrated to serve as working standards. Routine calibrations for luminous flux are performed using these working standard lamps. The working standard lamps are recalibrated at every 10 h of total operating time. The uncertainty budget for the luminous flux realization is shown in **Table 10**.

Table 10. Uncertainty budget for the NIST 1995 luminous flux unit

Uncertainty factor	Relative expanded uncertainty (k=2) [%] Type A	Type B
Uncertainty of the determination of Φ_e composed of:		
The NIST Illuminance unit realization		0.39
Ave. long-term drift of the standard photometers (2 months)		0.03
Transfer to the transfer photometer	0.07	
Transfer photometer position alignment (±0.2 mm)	0.06	
Aperture alignment (difference of the two apertures)		0.05
Aperture area		0.03
Average illuminance factor k_a		0.03
Stray light		0.05
Drift of the external source during calibration	0.02	
Uncertainty of the lamp luminous flux with respect to Φ_e composed of:		
Spatial nonuniformity correction factor scf_i / scf_e		0.30
Incident angle dependence correction factor β	0.06	
Spectral mismatch correction factor ccf_i^* / ccf_e^*		0.03
Self-absorption correction factor α	0.03	
Random variation in the R_s determination	0.04	
Detector linearity		0.05
Reproducibility of the standard lamps	0.06	
Overall uncertainty of the NIST 1995 luminous flux unit	**0.53**	

5.2 Artifacts for calibration

5.2.1 Types of test lamps

For many years NIST has issued gas-filled, incandescent lamps (100 W, 200 W, 500 W, and 1000 W) with medium screw base or mogul screw base and miniature lamps ranging from 1.2 W to 30 W as luminous flux transfer standards. These lamps and other standard quality incandescent lamps, including miniature lamps, ranging from 0.1 lm to 10^5 lm are accepted for calibration at NIST.

Four foot linear fluorescent lamps of any color submitted by customers are also accepted for calibration at NIST, and while other types of fluorescent lamps are currently not accepted, there are plans to expand the types of fluorescent lamps approved for calibration.

At the moment, NIST does not provide luminous flux standard lamps due to unavailability of standard quality lamps, although a search for commercially available lamps for this purpose is underway.

When lamps are submitted to NIST for calibration, the lamps must be seasoned and tested for stability by the customer. In case of new lamps, the lamps usually have to be seasoned for 5 % of the rated life time, at the current to be used for calibration. The operating current, or operating color temperature, and burning position must be specified by the customer.

For miniature lamps, the size of the sockets tend to be much larger relative to the size of the lamps. When a miniature lamps is mounted in a socket, the total flux may decrease significantly due to the absorption by the socket surfaces. Sometimes miniature lamps are calibrated in combination with a particular socket, and in such cases, a combination of lamp and socket is required as a calibration artifact.

5.2.2 Operation and handling of test lamps

As with other standard lamps, care must be shown in the handling of luminous flux lamps. Lamps should be handled very carefully to avoid mechanical shocks to the filament, and the bulb of the lamps should not be touched with bare hands. Before calibration, the bulb of the lamps should be cleaned with a soft, lint-free cloth to remove any dust from the packing material. Lamps should be kept in a container when not used.

Incandescent standard lamps should be operated on DC power with the specified polarity, and only at the current specified in the calibration report. The lamp current should be ramped up and down slowly (approximately 30 s). Photometric measurements should be made after the lamp has stabilized (approximately 10 min after turning on).

Most of the lamps, including gas-filled tungsten lamps, are sensitive to burning position. The calibrated lamps must be operated in the same burning position as described in the calibration report. Linear fluorescent lamps are always operated in the horizontal position. Linear fluorescent lamps should be operated on AC power at a specified current, using a reference ballast as described in the calibration report. Calibration can be performed with the cathode power either on or off by request from the customer. The luminous flux of fluorescent lamps changes significantly with ambient temperature. The ambient temperature (usually measured at the back side of the baffle) must be controlled within 25 °C ± 1 °C. Before starting the measurements, the lamps should be stabilized for 15 min with the integrating sphere open. When the measurement starts, the sphere should be closed very slowly to avoid drafts.

5.3 Equipment for calibration

5.3.1 2 m integrating sphere

Figure 20 shows the geometry of the NIST 2 m integrating sphere in the routine calibration setting. The integrating sphere is equipped with a $V(\lambda)$-corrected, cosine-corrected detector, a baffle screen, an auxiliary lamp, a temperature sensor, and a spectroradiometer.

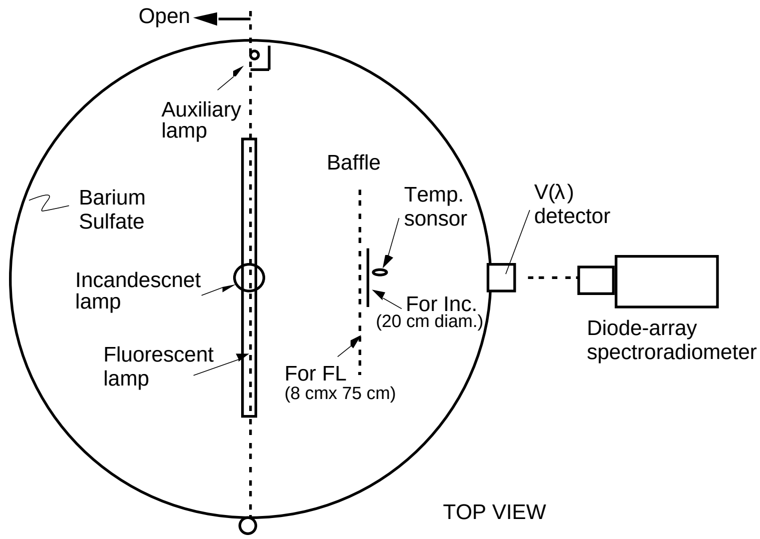


Figure 20 NIST 2 m integrating sphere set up for routine calibrations.

A baffle of 20 cm or 30 cm diameter is used for incandescent lamps. A rectangular baffle (8.5 cm x 75 cm) is used for fluorescent lamps. The rectangular baffle has a circular part of 15 cm in diameter in the center so that either standard lamps or fluorescent lamps can be baffled. The baffles are placed at 1/2 the sphere radius from the lamp.

The $V(\lambda)$-corrected detector is of the same design as the NIST standard photometers for the illuminance unit, but equipped with an opal glass diffuser. The detector has a linearity response in the range 10^{-10} A to 10^{-4} A. Based on these characteristics, total luminous flux from 10^{-1} lm to 10^{5} lm can be measured in direct substitution with total luminous flux standard lamps of any wattage.

The sphere wall is coated with barium sulfate paint with diffuse reflectance approximately 0.97 in the visible region. However, the reflectance of the coating drops slightly in the shorter wavelength region, resulting in a significant drop of sphere throughput in that region, which affects the total spectral response of the sphere system. The spectral throughput of the sphere is obtained by measuring the relative spectral irradiance of a tungsten lamp operated inside and outside the sphere with a spectroradiometer. The distribution temperature of this lamp, as a function of emitting angle, is fairly uniform (within ±10 K) over the entire solid angle. The measured spectral throughput of the sphere is shown in **Figure 21** (solid line).

The spectral throughput data are multiplied by the spectral responsivity of the detector (broken line) to obtain the spectral responsivity of the total system as shown in the dotted line. This data is used to obtain the spectral mismatch correction factors for the test lamps as given by eq (21). For incandescent lamps, the spectral mismatch correction factors, $ccf^*(T_d)$, are fitted to a polynomial function of the distribution temperature T_d as

$$ccf^*(T_d) = \sum_{j=0}^{2} M_j \, T_d^{\,j} \quad . \tag{26}$$

This function obtained for the NIST 2 m integrating sphere is shown in **Figure 22**. The integrating sphere is also equipped with an auxiliary lamp (30 W tungsten) on the sphere wall. The auxiliary lamp is used to measure the self-absorption effects of a lamp in the sphere.

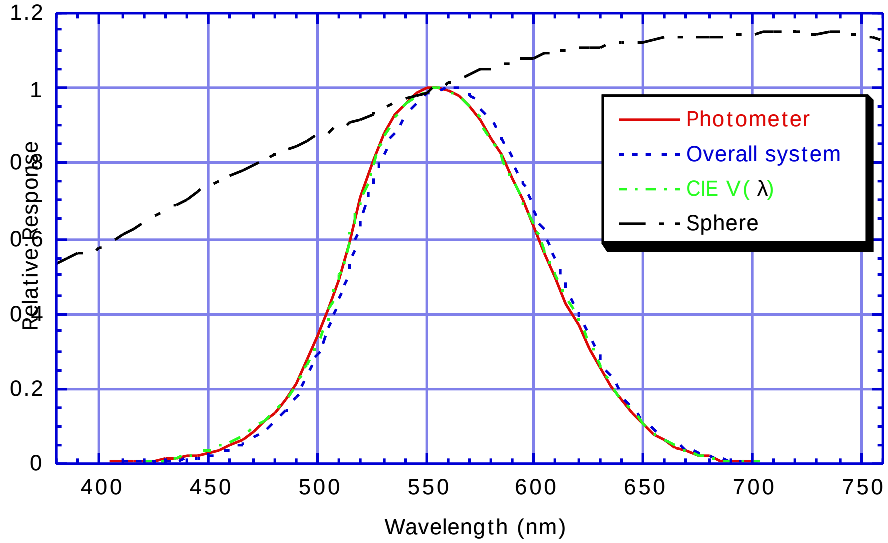


Figure 21 Spectral characteristics of the NIST integrating sphere.

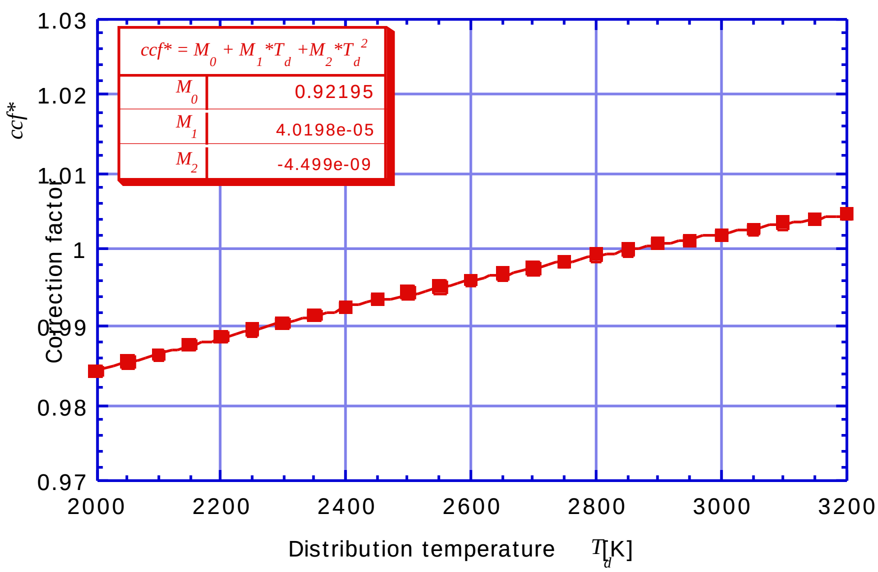


Figure 22 Spectral mismatch correction factor of the NIST 2 m integrating sphere as a function of the distribution temperature of a Planckian source.

The room temperature of the Photometry Laboratory at NIST is controlled to be approximately 24 °C. A temperature sensor is mounted at the back side of the baffle, and the air temperature inside the sphere during measurement is monitored. The temperature inside the sphere tends to increase when a lamp is operated in the sphere. This provides for an ambient temperature in the sphere of approximately 25 °C.

5.3.2 Electrical facility for incandescent lamps

All the standard lamps and test lamps are operated at a specified current rather than a specified voltage because the lamp voltage, in general, does not reproduce well due to the construction of the sockets used among customers. However, lamp voltages reproduce fairly well on the same socket, and the lamp voltage is a useful indicator of changes in the lamps.

The NIST 2 m integrating sphere can be equipped with a medium screw base socket, mogul screw base socket, medium bi-post base socket, or a special small socket (top surface is 3 mm in diameter) for miniature lamps with leads. These are two-contact sockets, but four separate wires, two for the current supply and the other two for voltage measurements, are soldered to separate parts of the socket. For luminous flux calibration, the lamp voltage is reported, only for reference purposes, without an uncertainty value.

A DC constant-current power supply 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 DVM with a stated uncertainty better than 0.01 %. The DVM is calibrated every 12 months. The current shunt is periodically calibrated 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 %. The power supply is operated in an external control mode, in which the output current is regulated by an external reference voltage. The external voltage is supplied by an 18 bit D-to-A converter which is controlled by the computer.

5.3.3 Electrical facility for fluorescent lamp

The electrical circuits for fluorescent lamp measurements are constructed according to the IES Guide LM-9-1988 [42] and ANSI standards [43, 44]. A regulated AC power supply (1 kVA, 60 Hz) is used as the main power supply. The output voltage is transformed into higher voltage (400 V maximum) by using a variac and a step-up transformer. The high voltage is fed to a measurement circuit with a reference ballast. **Figure 23** shows the measurement circuit for rapid start type linear fluorescent lamps.

Prior to photometric measurements, the electrical parameters of the measurement circuit are set up according to the specification of the lamp to be tested. The cathode transformer is calibrated, in advance, in terms of the primary voltage needed to provide the desired secondary voltage under normal load conditions, and the power loss in the transformer under this normal load condition. The input voltage on V_3 is adjusted to the calibrated value. Input power for the cathode transformer is read on W_2. The impedance (reactance and resistance) of the reference

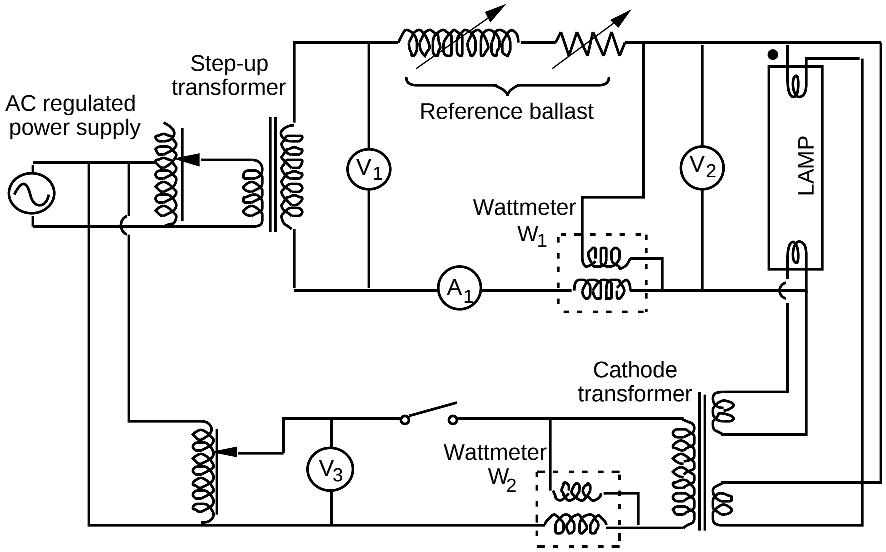


Figure 23 Measurement circuit for a rapid start fluorescent lamp.

ballast is set in accordance with the specification of the lamp. The lamp is mounted on the socket, and turned on, and the supply voltage V_1 is adjusted so that the lamp current A_1 equals the specified value. When the lamp current is adjusted, the cathode power is usually kept on. Measurements can be made with the cathode power off if requested by customer. During photometric measurements, the supply voltage, V_1, the lamp current, A_1, the lamp voltage, V_2, and the lamp power, W_1, and the cathode power, W_2 are measured and recorded. If the cathode power is kept on during the measurements, the sum of W_1 and W_2 (corrected by the power loss of the cathode transformer) is reported as the total lamp power.

5.4 Calibration procedures

5.4.1 Correction for the sphere detector temperature

When a lamp is turned on in the integrating sphere, the sphere detector is heated due to heat from the lamp. For a 1000 W incandescent lamp that is turned on for 10 min in the NIST 2 m integrating sphere, the detector temperature increases by ~3 °C. The responsivity of the sphere detector slightly changes with its temperature and is monitored with a temperature sensor installed in the detector package. The temperature coefficient c_p, of the photometric responsivity of the detector was measured in a temperature chamber, and found to be - 0.088 %/°C, and the detector signal is corrected (multiplied) by the temperature correction factor, $k(T_p)$, as given by

$$k(T_p) = 1 - (T_p - T_r)\, c_p \,, \qquad (27)$$

where T_p is the detector temperature at the measurement, T_r is a reference temperature that can be chosen arbitrary. At NIST, T_r = 298 K is used. In other words, the detector signal is always corrected to the value at 298 K.

5.4.2 Self-absorption correction

As the first step of the luminous flux calibration, the self-absorption of the lamps is measured. The auxiliary lamp (30 W miniature lamp) in the 2 m integrating sphere is turned on and allowed to stabilize for 15 min. The detector signal y_{01} is first taken with the test lamps and lamp holders removed from the sphere (null condition). Then the detector signal, y_i, is taken with each standard lamp and test lamp (1,...,*i*,..,*n*) plus appropriate holders installed in the sphere. These lamps are not turned on during self-absorption measurements. Then the detector signal, y_{02}, is taken for the null condition again, and the self-absorption factor, α_i, of lamp *i* is obtained by,

$$\alpha_i = y_i \; / \; \{(y_{01} + y_{02}) / \; 2\}. \qquad (28)$$

The measured detector signal for lamp *i* is divided by α_i for the self-absorption correction.

5.4.3 Spectral mismatch correction

The spectral power distributions of all the standard lamps and test lamps are measured using the spectroradiometer described in Section 7.4. The spectroradiometer is first calibrated by measuring a relative spectral radiant flux standard lamp operated in the sphere, and subsequently the test lamps are measured. For incandescent lamps, only the color temperature of the lamp is recorded.

The spectral mismatch correction factor $ccf(S_t, S_s)$ of the integrating sphere system, for a test lamp with spectral distribution $S_t(\lambda)$ against a standard lamp with spectral distribution $S_s(\lambda)$ is given by

$$ccf(S_t, S_s) = \frac{\int_\lambda S_s(\lambda)\, R_s(\lambda)\, d\lambda \int_\lambda S_t(\lambda)\, V(\lambda)\, d\lambda}{\int_\lambda S_s(\lambda)\, V(\lambda)\, d\lambda \int_\lambda S_t(\lambda)\, R_s(\lambda)\, d\lambda}\,, \qquad (29)$$

where $R_s(\lambda)$ is the relative spectral responsivity of the sphere system, and $V(\lambda)$ is the spectral luminous efficiency function.

However, luminous flux working standard lamps often have different color temperatures, depending on wattage, and these standard lamps are often used in combination. Calculation by eq (29) will be confusing when more than two different types of standard lamps are used. Therefore, at NIST, a normalized spectral mismatch correction factor, ccf^*, is introduced. The theory is given below.

The relationship between *ccf* 's for three arbitrary sources with spectral distributions $S_1(\lambda)$, $S_2(\lambda)$, and $S_3(\lambda)$ is given by

$$ccf\,(S_3,S_1) = \frac{ccf\,(S_3,S_2)}{ccf\,(S_1,S_2)}. \qquad (30)$$

The total flux of test lamp Φ_t is given by

$$\Phi_t = \Phi_s \quad y_t \,/\, y_s, \qquad (31)$$

where Φ_s is the total flux of the standard lamp, y_t is the signal for the test lamp, y_s is the signal for the standard lamp. The correction factor, $ccf\,(S_t, S_s)$, can be applied as

$$\begin{aligned} \Phi_t &= \Phi_s \quad \frac{y_t}{y_s}\, ccf\,(S_t, S_s) \\ &= \Phi_s \quad \frac{y_t \quad ccf\,(S_t,S_A)}{y_s \quad ccf\,(S_s,S_A)} \end{aligned}, \qquad (32)$$

where $S_A(\lambda)$ is the spectral distribution of CIE Illuminant A (2856 K blackbody). With $ccf(S_t,S_A)$ defined as $ccf^*(S_t)$, eq (32) is expressed as

$$\Phi_t = \Phi_s \quad \frac{y_t \quad ccf^*(S_t)}{y_s \quad ccf^*(S_s)}. \qquad (33)$$

This means that the spectral mismatch correction factors for all the standard lamps and test lamps can be calculated against CIE Illuminant A as given by $ccf^*(S_t)$. All the detector readings are simply multiplied by this factor.

5.4.4 Correction for the spatial nonuniformity of the sphere response

The response of the sphere is not spatially uniform because of various objects in the sphere, contamination of the sphere wall, gaps between the hemispheres, etc. Therefore, when measuring a test lamp whose luminous intensity distribution is different from the standard lamp, an error can occur and can be corrected using the following theory.

Total luminous flux, Φ_V, of a lamp is obtained from the luminous intensity distribution of the lamp, $I\,(\theta,\varphi)$, by the following equation:

$$\Phi_V = \int_A E\,\mathrm{d}A = \int_{\varphi=0}^{2\pi} \int_{\theta=0}^{\pi} I\,(\theta,\varphi)\,\sin\theta\,\mathrm{d}\theta\,\mathrm{d}\varphi. \qquad (34)$$

A normalized luminous intensity distribution, $I^*(\theta,\varphi)$, is defined as

$$I^*(\theta,\varphi) = (4\,\pi/\Phi_v) \quad I\,(\theta,\varphi)\;. \qquad (35)$$

Then, the spatial nonuniformity correction factor, scf^*, of the lamp against an isotropic point source is calculated by

$$scf^* = \frac{\int_{\varphi=0}^{2\pi} \int_{\theta=0}^{\pi} K(\theta,\varphi) \sin\theta \; d\theta \; d\varphi}{\int_{\varphi=0}^{2\pi} \int_{\theta=0}^{\pi} I^*(\theta,\varphi) \, K(\theta,\varphi) \sin\theta \; d\theta \; d\varphi}, \tag{36}$$

where $K(\theta,\varphi)$ is the spatial response distribution function. $K(\theta,\varphi)$ can be measured by rotating a beam lamp (which is burning-position insensitive) at the center of the sphere. $I^*(\theta,\varphi)$ does not need to be highly accurate. Manufacturer's typical data is usually sufficient to calculate scf^* accurately enough for this correction.

5.4.5 Determination of luminous flux

Incandescent lamps are operated in the sphere center with the base up position unless otherwise stated. The lamps are operated at the lamp current or at the color temperature specified by the customer. When the color temperature is specified, the lamp current is first determined by color temperature measurements as described in Section 7.5. When the lamp current is specified, the color temperature of the lamp is measured and reported together with the luminous flux value. The lamps are allowed to stabilize, usually for 10 min. The color temperature values are used for the spectral mismatch corrections.

Linear fluorescent lamps are operated horizontally in the center of the integrating sphere. The lamp is operated at a specified current using the electric circuit described in 5.3.3. The lamp is stabilized for at least 15 min with the sphere open, and the sphere is closed very slowly immediately before the measurements. The ambient temperature inside the sphere is kept at 25 ° C ± 1 °C.

The photometer output voltage is measured with a DVM. The average of 20 DVM readings is recorded. The measurement program records the electrical parameters and the burning time of the lamp, the signal and temperature of the detector, the ambient temperature of the lamp inside the sphere, and the correction factors**.** After the data are taken, the lamp is turned off (ramped down slowly for incandescent lamps), and the dark readings are taken. Finally, the detector signal, *y*, for a standard lamp or a test lamp is corrected by

$$y' = y \cdot k\,(T_p) \cdot ccf^* \cdot scf^* \,/\, \alpha_i \,, \tag{37}$$

where $k\,(T_p)$ is the temperature correction factor, ccf^* is the spectral mismatch correction factor, scf^* is the spatial nonuniformity correction factor, and α_i is the self-absorption factor. The spatial nonuniformity correction factor, scf^*, is usually not applied in the routine calibrations for regular incandescent lamps. The scf^* is applied for special types of lamps such as reflector type lamps.

The luminous flux of test lamps is determined by substitution with the standard lamps. First, two standard lamps are measured, then the test lamps are measured three times (remounted and relighted), and at the end, the same two standard lamps are measured. Let the corrected signals of the standard lamp 1 be $y_{1,1}'$ and $y_{1,2}'$ and the corrected signals of standard lamp 2 be $y_{2,1}'$ and $y_{2,2}'$, the total luminous flux of the standard lamps 1 and 2 be Φ_1 and Φ_2, respectively, and the corrected signals for test lamp *i* be $y_{i,1}'$, $y_{i,2}'$, and $y_{i,3}'$. The total luminous flux Φ_i of test lamp *i* is obtained by,

$$\Phi_i = \frac{1}{3}\sum_{j=1}^{3} y_{i,j}' \Big/ \frac{1}{4}\sum_{j=1}^{2}\sum_{k=1}^{2}\frac{y_{j,k}'}{\Phi_j}. \tag{38}$$

A two standard deviation of the luminous flux values of each test lamp in the three lightings is calculated and included in the uncertainty for the calibration. The voltage across the lamp socket is reported only for reference information because the measured voltage usually does not reproduce well on other sockets used by customers.

5.5 Uncertainty of calibration

The uncertainty budgets for the luminous flux calibration of incandescent lamps and of 4 ft linear fluorescent lamps are shown in **Table 11** and **Table 12**, respectively.

Table 11. Uncertainty budget for total luminous flux calibrations of standard incandescent lamps (typical)

Uncertainty factor	Relative expanded uncertainty (*k*=2) [%] Type A	Type B
NIST luminous flux unit (primary/working standard lamps)		0.53
Aging of the working standard lamps between calibrations		0.30
Transfer from working standards to test lamps:		
Geometric differences		0.30
Self-absorption correction	0.10	
Spectral mismatch correction		0.20
Reproducibility of test lamps (typical)**	0.20	
Overall uncertainty of test lamp calibration	**0.74**	

** Uncertainty value depends on test item

Table 12. Uncertainty budget for total luminous flux calibrations of 4 ft linear fluorescent lamps (typical)

Uncertainty factor	Relative expanded uncertainty (k=2) [%] Type A	Type B
NIST luminous flux unit (primary/working standard lamps)		0.53
Aging of the working standard lamps between calibrations		0.30
Transfer from working standards to test lamps consists of:		
Geometric differences		0.30
Self-absorption correction	0.10	
Spectral mismatch correction		0.20
Current variation (±0.2 %)	0.20	
Temperature variation (± 1 °C)	0.50	
Reproducibility of test lamps (typical)**	1.80	
Overall uncertainty of test lamp calibration	**2.0**	

** Uncertainty value depends on test item.

6. Luminance calibrations

6.1 NIST luminance unit

Luminance units are commonly established using a white reflectance standard or a transmitting diffuser illuminated by a luminous intensity standard lamp [35]. 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, and which makes precise calibration difficult. The uncertainty is also limited by that of the standard lamp used.

Using the NIST standard photometers, a detector-based luminance unit is realized on a reference integrating-sphere source operated at 2856 K. **Figure 24** shows the arrangement. The sphere source is 15 cm in diameter and has a $V(\lambda)$-corrected monitor detector on the sphere wall. The source has a double sphere structure, the large sphere being irradiated by an intermediate 5 cm sphere which is irradiated by a quartz halogen lamp. The sphere source is operated by a constant-current power supply. Precision apertures of 6 mm and 21 mm diameter were attached, alternately, to the exit port (50 mm diameter) of the sphere source. The sphere source and the photometers are placed on the photometry bench (see 3.3.1) in a light tight box to reduce stray light. The illuminances at 2 m from the sphere source are measured by the eight NIST standard photometers that hold the illuminance unit. The distance is measured from the front surface of the aperture by using a length gage. The sphere source is allowed to stabilize for

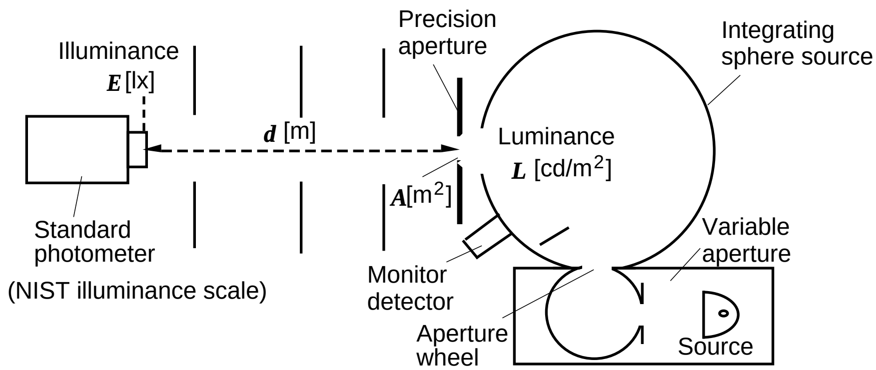


Figure 24 Arrangement for NIST luminance unit realization.

60 min before calibration since the responsivity of the monitor detector drifts as the sphere warms up. The average luminance L (cd/m^2) over the aperture plane is determined from the illuminance E (lx), the distance, d (m), and the aperture area, A (m^2), as given by

$$L = k\ E\ d^2/A\ , \tag{39}$$

where k is a geometrical correction factor determined by the radius, r_a, of the aperture, the radius, r_d, of the detector sensitive area, and the distance, d, as given by

$$k \approx 1 + \left(\frac{r_a}{d}\right)^2 + \left(\frac{r_d}{d}\right)^2 \qquad ; r_a, r_d < \frac{d}{10} \tag{40}$$

The error, 1- k, is negligible with distance d = 2 m. The data with the 21 mm aperture are corrected for the interreflections (between the sphere and the aperture) and the spatial nonuniformity of the luminance, and converted into values equivalent to the 6 mm aperture condition. Therefore, the luminance is determined for a circular area of 6 mm diameter on the center of the exit port. The diffraction loss with the aperture [40] is calculated to be negligible (< 0.01 %) in the geometry used in this measurement. When the luminance, L, is determined, the monitor detector signal, y, is recorded, and the monitor detector responsivity, R_{LUM} A/(cd/m^2), is determined.

For routine calibrations of luminance when a luminance surface with larger area is needed, the precision aperture is removed from the sphere source, and the sphere port can be full open (50 mm diameter) or equipped with another aperture (25 mm diameter). In these cases, the luminance changes due to the interreflections between the aperture surface, and the sphere wall. This change of luminance is determined by the signal from the monitor detector installed on the sphere wall. The correction factors are obtained for each condition. The average luminance over the exit port or 25 mm aperture is calculated from the spatial distributions of the luminance. The ratio of the center luminance versus the average luminance is obtained and used as a correction factor.

The luminance unit is realized annually using the same procedures, and maintained by the responsivity, R_{LUM}, of the monitor detector. The color temperature of the sphere source is also calibrated annually. The unit is transferred to a reference luminance meter used as a working standard for routine calibrations. The uncertainty budget for the NIST luminance unit realization is shown in **Table 13.**

Table 13. Uncertainty budget for the NIST luminance unit realization

Uncertainty factor	Relative expanded uncertainty (k=2) [%] Type A	Type B
NIST illuminance unit realization		0.39
Long-term drift of the average of 5 standard photometers		0.10
Determination of the spectral mismatch correction factor		0.04
Distance measurement (0.5 mm in 2 m)	0.05	
Aperture area		0.20
Stray light in luminous intensity measurement		0.10
Drift of the sphere source during calibration	0.10	
Reproducibility of the sphere source	0.16	
Total uncertainty of the luminance unit realization	**0.50**	

6.2 Artifacts for calibration

Commercially available luminance sources and luminance meters of various types, submitted by the customers, are accepted for calibration at NIST. For sphere sources, operating current or voltage, or a set point for the monitor detector, and the stabilization time must be specified by customer. The customers are responsible for ensuring stability of the sources. For luminance meters, luminance levels and measurement angles must be specified for calibration. The luminance range for calibration is 1 cd/m^2 to 4000 cd/m^2.

NIST issues opal glasses calibrated for luminance coefficient (ratio of luminance to illuminance), and recalibrates submitted opal glasses. The opal glass issued by NIST is 50 mm x 50 mm in size and 3 mm in thickness. It has a diaphragm of 25 mm diameter attached on the flashed side of the opal glass.

In general, use of opal glass requires a luminous intensity standard lamp and a photometric bench (distance measurement capability) in a dark room. Sphere sources usually do not need such facilities (of course, ambient light must be reduced) and are more convenient in terms of instrumentation. Use of sphere sources with a monitor detector is highly recommended because the monitor detector can maintain the scale more stably than the lamp of the source (almost regardless of the operating time of the source). If there is no monitor detector, it is recommended that the source be recalibrated after every 50 h of use. The luminance of typical commercial sphere sources can change (decrease) by 1 % to 2 % and color temperature by 10 K to 20 K per 100 h of operation at 2856 K. It should be noted, however, that a sphere monitor detector, without temperature control, can drift by ~0.5 % during the first hour while the sphere warms up. It should also be noted that the sphere coating or the monitor detector will be contaminated or degraded after use or storage of a long period of time. Even when the scale is maintained on the monitor detector or when the source is not used, it is recommended that the sphere source be calibrated yearly. The exit port of the sphere source should always be capped when not used, and care exercised to monitor dust-free optical surfaces.

6.3 Equipment for calibration

The integrating sphere source shown in **Figure 24** and a reference luminance meter are used in the luminance calibration. The integrating sphere source is described in 6.1. The reference luminance meter has measurement angles of 6', 20', 1°, and 3°. The luminance meter is equipped with a 3 $^1/_2$ digit display and an analog output, the voltage of which is measured with a 6 $^1/_2$ digit DVM. The stray light error (due to the surrounding field outside the measured area) of this luminance meter was checked according to the CIE Pub. 69 [35] and found to be less than 0.1 %. **Figure 25** shows the relative spectral responsivity of the luminance meter measured at the Spectral Comparator Facility [25]. The f_1' value [35]derived from the data is 2.1 %.

A spectroradiometer described in 7.4 is used to measure the color temperature of the sphere sources or spectral distribution of sources with phosphor simulation filters.

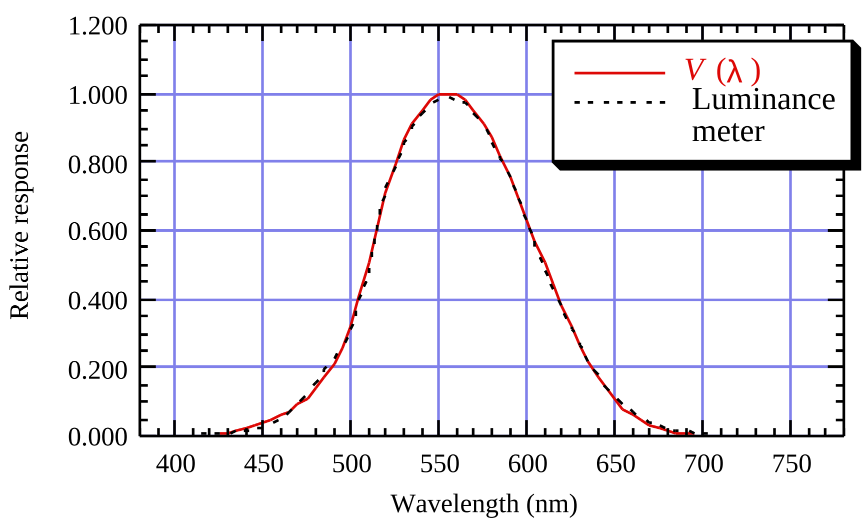


Figure 25 Relative spectral responsivity of the reference luminance meter.

6.4 Calibration of luminance sources

Luminance sources under test are calibrated against the reference sphere source described in 6.1 using the following procedures. Prior to calibration, the reference sphere source is turned on and stabilized for 1 h, and the reference luminance meter described in 6.3 is calibrated against the luminance value indicated by the monitor detector signal of the sphere source. At this time, the value from the monitor detector is cross-checked by the value of the reference luminance meter.

The sphere source under test is aligned so that the center of the exit port of the source is on the optical axis and so that the front surface around the exit port is normal to the optical axis. The reference luminance meter is normally placed on the optical axis at approximately 1.5 m from the source for a measurement area of 9 mm in diameter, with the measurement angle of the reference luminance meter to be 0.33 °. The luminance meter is focused on the plane of the exit port.

The test source is turned on and allowed to stabilize for the time period specified by the customer. The room temperature during the calibration is usually ~24 °C. The mean value of several readings is reported. The color temperature of the source is also measured using the facilities and procedures described in Section 7 to obtain a spectral mismatch correction factor (See 3.1.4). Equation (12) is used for ordinary sphere sources, and eq (11) is used for sphere sources with phosphor simulation filters. The relative expanded uncertainty (k = 2) of the luminance source calibration is typically 0.7 %, and depends on the test item and measurement conditions. The uncertainty budget is shown in **Table 14**.

Table 14. Uncertainty budget for luminance source calibrations (typical)

Uncertainty factor	Relative expanded uncertainty (k=2) [%] Type A	Type B
The NIST luminance unit realization		0.49
Long-term drift of the reference luminance source		0.30
Uncertainty in transfer to the test instrument composed of:		
Range calibration of the reference luminance meter		0.15
Out-of-field sensitivity of the reference luminance meter	0.10	
Spatial nonuniformity of the reference sphere source		0.15
Alignment of the measured spot (1 mm) to the center	0.10	
Spectral mismatch correction for the test source		0.10
Stability of the test source during calibration (typical)	0.20	
Overall uncertainty of the calibration with respect to SI	**0.67**	

6.5 Calibration of luminance meters

A luminance meter under test is calibrated against the reference luminance source (described in 6.3) operated at 2856 K using the following procedures. Prior to calibration, the reference sphere source is turned on and allowed to stabilize for 1 h, and the luminance value determined from the monitor detector signal is cross-checked by the value of the reference luminance meter.

The reference sphere source is aligned so that the center of the exit port of the source is on the optical axis, and that the front surface around the exit port is normal to the optical axis. The luminance meter under test is placed and aligned on the optical axis, using a laser beam, at 1 m to 3 m from the source depending on the measurement angle of the luminance meter. If the measurement area is more than 10 mm in diameter on the exit port of the reference sphere source, the luminance value is corrected for the spatial nonuniformity. The luminance meter is focused on the plane of the exit port, aiming at the center of the exit port of the reference sphere source.

The luminance values indicated by the luminance meter under test are compared with the luminance values determined from the monitor detector signal of the reference sphere source. The room temperature at calibration is usually ~24 °C.

Luminance meters used for particular sources other than incandescent sources can be calibrated for those specific sources (e.g., color displays) upon request by customers. In this case, the calibration is first performed using the 2856 K source as described above. Then, the spectral mismatch correction factors for the sources are obtained using the following procedures.

The relative spectral responsivity of the NIST luminance meter is measured by the Spectral Comparator Facility [25] in the 350 nm to 1100 nm region. The monochromator output of the SCF is defocused on an PTFE (polytetrafluoroethylene) plaque to irradiate an area of several mm in diameter. The luminance meter under test is placed so that it will measure the luminance of the spot on the PTFE plaque at 0/45 geometry, and that the irradiated spot underfills the measurement area of the luminance meter. This method can only be applied for luminance meters whose relative spectral responsivity is fairly spatially uniform within the measurement angle. From the relative spectral responsivity data and the spectral power distribution data (supplied by customer) of the light sources to be measured by the luminance meter, the spectral mismatch correction factors are calculated using equation (11) as described in 3.1.4. The relative spectral responsivity data and the correction factors are reported to the customer.

The uncertainty budget for the calibration of a typical luminance meter is shown in **Table 15**. This budget does not include the uncertainty factor for the out-of-field sensitivity of the test instrument. If the luminance meter's out-of-field blocking is poor, the responsivity of the instrument is affected by the illuminance of the area outside the measurement angle. Therefore, the calibration value is reported with the measurement geometry used at the calibration, and may not be valid with other geometry.

Table 15. Uncertainty budget for luminance meter calibrations (typical)

Uncertainty factor	Relative expanded uncertainty (k=2) [%] Type A	Type B
The NIST luminance unit realization		0.49
Long-term drift of the reference luminance source		0.30
Transfer to the luminance meter under test:		
Spatial nonuniformity of the reference luminance source*1		0.10
Alignment of the measured spot (1 mm) to the center	0.10	
Inconsistency of the calibration factors at different levels*2		0.20
Display resolution of the test luminance meter*2	0.20	
Overall uncertainty of the calibration*3	**0.66**	

*1 Depends on the measurement angle of the test instrument.
*2 Depends on the test instrument.
*3 Out-of-field responsivity of the test instrument is not included in this budget.

6.6 Calibration of opal glass luminance coefficient

6.6.1 Calibration procedures

An opal glass under test is calibrated for luminance coefficient (ratio of luminance to illuminance, unit [sr^{-1}]) of diffuse transmission, by comparison with three reference opal glass standards. The reference opal glasses are calibrated by directly measuring the incident illuminance by using the NIST standard photometers (See 3.1), and the transmitted luminance on the opal glass surface by using a reference luminance meter which is calibrated against the NIST luminance unit. When the illuminance, E [lx], and the luminance, L [cd/m2], are measured, the luminance coefficient, q [sr^{-1}], of the opal glass is given by,

$$q = L / E \qquad (41)$$

Figure 26 shows the arrangement for opal glass calibration. All the instruments are placed on the photometry bench (See 3.3.1) in a light tight box. The reference opal glasses and the opal glass under test are placed alternately and irradiated by a 1000 W frosted quartz halogen lamp operated at a color temperature of 2856 K (unless otherwise stated in the report) at a distance of approximately 2 m from the opal glass. A reference luminance meter is placed at ~1.5 m from the opal glass. The centers of the lamp filament, the opal glass, and the luminance meter lens are aligned on the optical axis. The opal glasses are placed with the aperture side facing the luminance meter. The glass surface is aligned to be perpendicular to the optical axis.

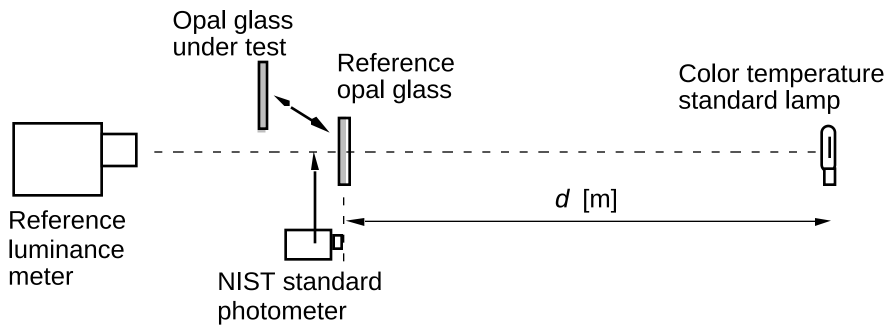


Figure 26 Configuration for opal glass calibration.

The luminance meter is aimed at the center of the circular apertured area and set to a measurement angle of 20'(1/3)°. With these dimensions, the luminance of the center area of 9 mm in diameter is measured. The luminance coefficient of the opal glass under test is calculated by comparison to the reference opal glasses.

It should be noted that the color temperature of the transmitted light is shifted due to the spectral transmittance of the opal glass and decreases typically by 100 K to 200 K. As an option, if a set of a luminous intensity standard lamp and an opal glass are submitted for calibration, the operating current of the lamp can be set so that the transmitted light from the opal glass produces color temperature of 2856 K (See Section 7 for color temperature calibration), and the luminance coefficient of the opal glass can be calibrated under that condition.

6.6.2 Use of opal glass standards for luminance coefficient

NIST issues opal glasses of 50 mm square, 3 mm thick, having an aperture of 25 mm in diameter, as calibrated standards for luminance coefficient. A luminance standard can be obtained by combining these standards and an incandescent lamp operated at approximately 2856 K. The opal glass should be placed so that the transparent glass side (with no aperture) faces the lamp. The luminance standard will be on the opal side with the aperture. The luminance, L [cd/m^2], of the illuminated opal glass is obtained by

$$L = q \cdot E, \tag{42}$$

where q is the luminance coefficient [sr^{-1}] and E is the illuminance [lx] on the reference plane of the opal glass. The reference plane is 2 mm inside from the surface of the transparent glass side. Illuminance E can be measured by placing a standard photometer on the reference plane of the opal glass. Illuminance E can also be determined by using a luminous intensity standard lamp applying the inverse square law. In this case the distance should be measured from the reference plane of the opal glass.

It is recommended that distance, *d*, be greater than 1 m because a small distance error creates a large luminance error at shorter distances. It should be noted that the luminance coefficient, *q*, is calibrated for the central 9 mm diameter area of the opal glass (unless otherwise stated in the calibration report) and in the direction normal to the opal surface. Luminance may vary up to ± 1 % typically, outside that central area. Luminance may also vary if viewed at different angles.

An opal glass is sensitive to stray light on both sides of the glass. Extreme care should be taken to minimize ambient reflection from both the front side and the back side. It is important that an opal glass is illuminated uniformly over its entire surface area, since light incident on one part of the glass affects to luminance on other parts by volume diffusion. For example, a holder for the glass should not block the light falling on the edges of the glass. No labels should be affixed on the glass surface after calibration. The calibration will not be valid if the aperture is removed from the opal glass or if the black coating around the edges of the glass is removed.

6.6.3 Uncertainty of calibration

The uncertainty budget for calibration of NIST-issued opal glasses is shown in **Table 16.** For calibration of customer-submitted opal glasses of sizes different from the reference opal glasses, additional uncertainty factors such as (1) difference in stray light around the opal glass, (2) Calibration to different angle (3° or 0.1°) of the reference luminance meter, (3) nonuniformity of illuminance field, are taken into account.

Table 16. Uncertainty budget for opal glass calibrations

Uncertainty factor	Relative expanded uncertainty (k=2) [%] Type A	Relative expanded uncertainty (k=2) [%] Type B
Uncertainty of the reference opal glass standards composed of:		
Luminance unit with respect to NIST illuminance unit (See 6.1)		0.30
Luminance measurement with respect to NIST luminance unit		0.20
Illuminance measurement with respect to NIST illuminance unit		0.13
Opal glass position relative to the reference plane	0.04	
Stray light around the opal glass		0.10
Uncertainty in transfer to test opal glass composed of:		
Drift of the standard lamp during calibration	0.10	
Orientation alignment of the opal glass	0.20	
Position alignment of the opal glass (0.5 mm in 2 m)	0.05	
Overall uncertainty of the luminance coefficient calibration	**0.46**	

7. Color temperature calibrations

7.1 General descriptions

Color temperature is a concept used to express the color of a light source in a simple manner using just one number. According to CIE [15], color temperature is defined as “the temperature of a Planckian radiator whose radiation has the same chromaticity as that of a given stimulus.” The spectral power distribution of the test source is not necessarily identical or even similar to that of a blackbody. Strictly speaking, however, the chromaticity coordinate of most of the light sources including incandescent lamps do not fall on the Planckian locus. The CIE definition does not say how close the chromaticity should be to be considered as “the same.” Therefore, the definition of color temperature is somewhat vague, and this term is considered to be a general term to introduce the concept.

For practical calibration of sources used in photometry, either “distribution temperature” or “correlated color temperature” is used. Another similar concept is a radiance temperature, which is defined as “Temperature of the Planckian radiator for which the radiance at the specified wavelength has the same spectral concentration as for the thermal radiator considered” [15]. Radiance temperature is used only for blackbodies and transfer lamps to blackbodies.

Distribution temperature is defined as “Temperature of the Planckian radiator whose relative spectral distribution $S_t(\lambda)$ is the same or nearly the same as that of the radiation considered in the spectral range of interest” by CIE [15]. Practically speaking, distribution temperature is a concept to represent the relative spectral power distribution of a near Planckian source, such as an incandescent lamp, by one number. CIE [45] gives more precise definition of distribution temperature (T_d) given by the equation;

$$\begin{aligned} &\text{minimum} \int_{\lambda_1}^{\lambda_2} \left[1 - S_t(\lambda) \;/\; a\, S_b(\lambda, T_d)\right]^2 d\lambda \\ &\text{where } S_b(\lambda, T_d) = \lambda^{-5}\left[\exp\left(c_2 / \lambda T_d\right) - 1\right]^{-1} \end{aligned} \qquad (43)$$

The distribution temperature of the source $S_t(\lambda)$ is the temperature T of the Planckian radiation $S_b(\lambda, T)$ when the value of equation (43) is minimized by varying T and a (a normalization factor). CIE also specifies that the wavelength region shall be 380 nm to 780 nm, and the wavelength interval for calculation shall be less than 10 nm. It is also specified that the difference of the relative spectral power distribution of the radiation considered and that of a Planckian radiation should be less than 10 % in order to use distribution temperature.

Correlated color temperature (T_{cp}) is used for sources whose spectral power distribution is significantly different from that of Planckian radiation; such as discharge lamps. Correlated color temperature is defined as “Temperature of the Planckian radiator whose perceived color most closely resembles that of a given stimulus at the same brightness and under specified viewing conditions" [15]. Practically, correlated color temperature is obtained from the chromaticity coordinate (on the CIE 1960 u,v diagram) of the point on the Planckian locus which is at the closest distance from that of the light source in question [46].

If the relative spectral power distribution of the given radiation is identical to that of the Planckian radiator, the values of color temperature, distribution temperature, and correlated color temperature will be all the same. The differences between distribution temperature and correlated color temperature for typical incandescent lamps are only 2 K or 3 K, but can be much larger depending on lamp type.

7.2 NIST color temperature scale

NIST has traditionally used the term "color temperature" for incandescent lamps even though their chromaticity coordinates are not exactly the same as the Planckian radiator. The NIST color temperature scale is based on the computation of correlated color temperature from the relative spectral power distributions of sources.

The NIST color temperature scale is derived from the NIST spectral irradiance scale [20] which is based on the International Temperature Scale of 1990 [21]. The scale realization chain for the spectral irradiance scale and the color temperature scale is shown in **Figure 27**.

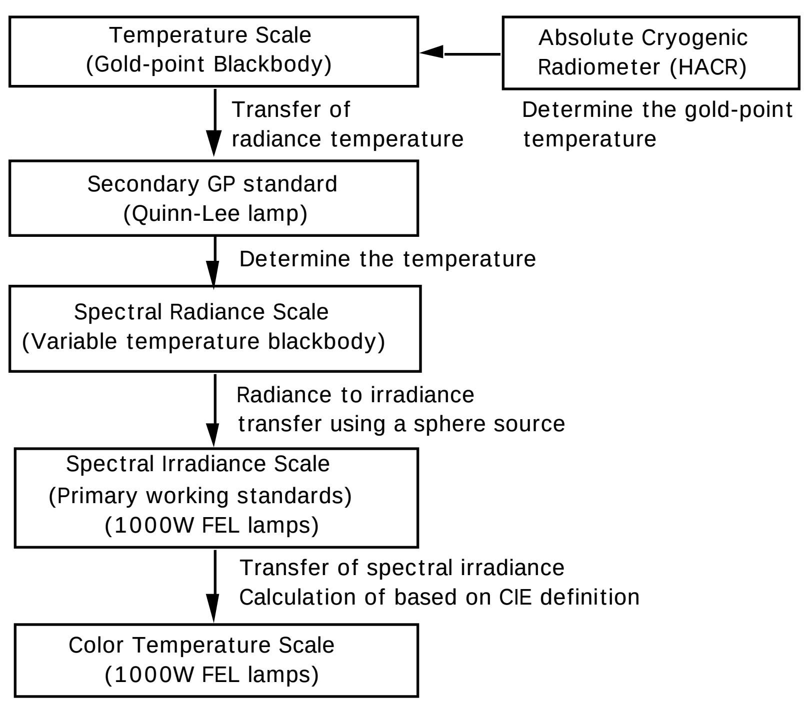


Figure 27 Realization of the NIST spectral irradiance scale and the color temperature scale.

Three 1000 W FEL type quartz halogen lamps are maintained as the NIST color temperature primary standard lamps in the range of 2000 K to 3200 K. These lamps have demonstrated stability of operation in this color temperature range [37]. The spectral irradiance of these lamps is calibrated periodically against the NIST spectral irradiance scale [20] at 2000 K, 2300 K, 2600 K, 2856 K, and 3200 K. The correlated color temperatures of these lamps are computed from the spectral irradiance values according to the procedures recommended by reference [46]. The color temperature scale on these lamps are transferred to several other FEL type lamps and 200 W quartz halogen lamps for routine calibration work. A spectroradiometer described in Section 7.4 is used for the transfer measurements.

7.3 Artifacts for calibration

For many years in the past, NIST issued 500 W Airway Beacon lamps as color temperature standards. These lamps are still accepted for recalibration at NIST. These lamps have medium bi-post bases, clear bulbs, and C-13B filaments. The lamp designation number is etched on the bulb. The appearance and the electrical polarity of this type of lamp is shown in **Figure 10**.

NIST now issues FEL type 1000 W quartz halogen lamps calibrated for color temperature. This is the same type of lamp used for luminous intensity standards as described in 3.2. The lamps are manufactured by Osram-Sylvania Inc., and potted on a medium bi-post base, and seasoned on DC power for at least 72 h at 7.2 A. Lamps are usually calibrated at a color temperature of 2856 K, but can be used for color temperature standards in the range of 2000 K to 3200 K. The operating current and voltage of the lamp are approximately 7.2 A and 85 V at 2856 K. The lamp designation numbers and the electrical polarity are engraved on an identification plate affixed on the lamp base as shown in **Figure 10**.

7.4 Equipment for calibration

Figure 28 shows the arrangement used for color temperature calibration. A PTFE plaque is placed in the photometry bench (described in 3.3.1). The plaque is placed approximately 1 m from the lamp, and irradiated at normal incidence. The diffuse reflection at 45° is directed to a spectroradiometer. The plaque is mounted on a kinematic base, and can be removed when the luminous intensity is measured.

The spectroradiometer is a diode-array system, consisting of imaging optics in front, a single diffraction grating, and a cooled 256 element photodiode array, and is calibrated against the NIST spectral irradiance standards. This spectroradiometer has measurement angles of 0.125° circular and 0.5° x 1.5° rectangular. The rectangular aperture is 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

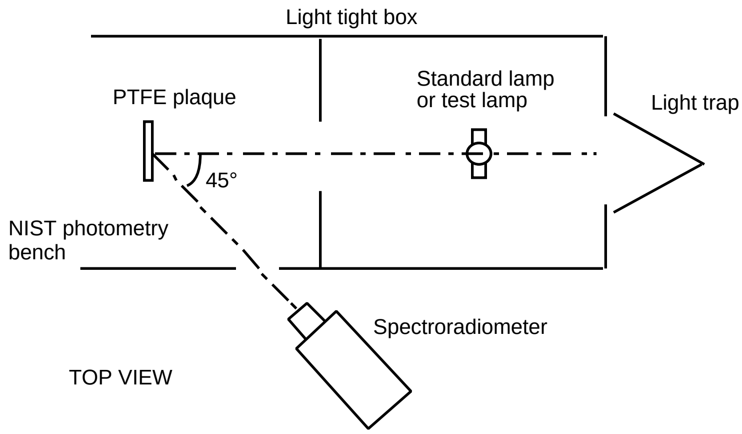


Figure 28 Configuration for color temperature calibration.

precisely within a few min, minimizing the labor time and the lamp burning time. The spectroradiometer is connected to a computer which calculates chromaticity coordinates and the correlated color temperature of the source almost instantly.

The red-blue ratio substitution method is commonly used for color temperature transfer measurements, but is not used at NIST. This method is liable to errors caused by even a slight difference in spectral emissivity of the test lamp and the standard lamp; for example when a gas-filled incandescent lamp is measured against a quartz-halogen standard lamp. A diode-array type spectroradiometer gives better results in this respect.

This type of spectroradiometer, however, is subject to fairly large stray light errors due to a single diffraction grating installed in a compact unit. When the radiometer is calibrated using a 2856 K Planckian source, there will be errors when sources of different color temperatures are measured. For calibrations at NIST, therefore, this spectroradiometer is used basically to transfer the same color temperature from the standard lamp to the test lamp. For this reason, the color temperature standards for several different color temperatures are maintained.

Since the procedures for the spectral calibration of the instrument are not simple, and since the responsivity of the spectroradiometer is fairly stable over a long period of time, its internal calibration factors are calibrated only every 6 months. Instead, prior to each calibration of test lamps, the spectroradiometer’s color temperature reading is calibrated by measuring two color temperature working standard lamps, and correction values as shown in **Figure 29** is determined and applied to the measured values. If the measurement point lies between the calibration points of the standard lamps, the correction value is determined by interpolation based on the second order polynomial function.

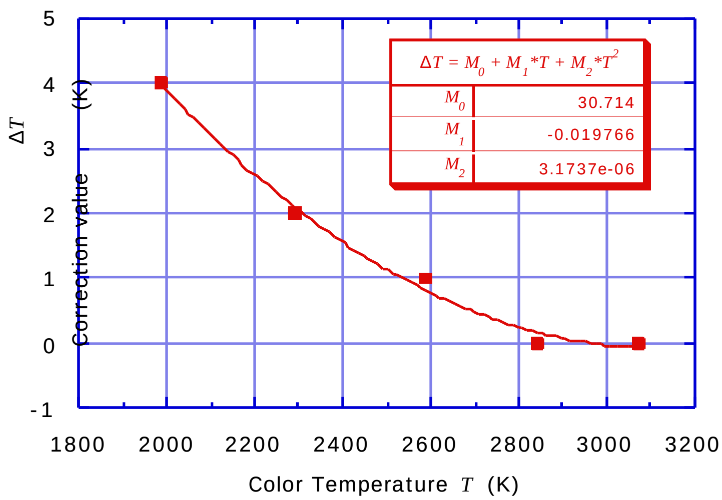


Figure 29 Color temperature correction values for the NIST diode-array spectroradiometer.

7.5 Calibration procedures

Prior to the measurement of test lamps, the spectroradiometer's color temperature reading is calibrated against two color temperature working standard lamps at the color temperature points required for the calibration. The test lamp is mounted on the photometry bench and aligned with the same procedure as the luminous intensity measurements. The lamp is operated in the base-down position, with the identifying number on the opposite side from the spectroradiometer. Lamp orientation is accomplished by aligning the lamp socket so that the lamp posts are held vertically, and the plane formed by the axes of the posts is perpendicular to the optical axis of the spectroradiometer. An alignment jig (a mirror mounted on a bi-post base to be parallel to the plane formed by the axes of the posts) is used in combination with a laser and an end-viewing telescope. The distance from the lamp to the input optics (a PTFE plaque) of the spectroradiometer is approximately 1 m.

The lamp is operated on DC power. The electrical polarity is marked on the identification plate of the lamp. The test lamp is slowly (~30 s) ramped up to the specified current, and allowed to stabilize for at least ten minutes before calibration. When a lamp current is to be determined for a specified color temperature, the lamp current is adjusted repeatedly until the spectroradiometer indicates the specified color temperature. The lamp current and voltage are recorded when the lamp reaches that color temperature. When the same lamp is calibrated for different color temperatures, at least 3 min are allowed before any measurements after the lamp current is changed from one color temperature to another.

Color temperature calibrations at NIST are most often done at 2856 K. Requests for calibration at any other color temperatures between 2000 K to 3200 K are accepted.

7.6 Uncertainty of calibration

The NIST color temperature scale is derived from the NIST spectral irradiance scale [20]. The uncertainty of the color temperature scale, however, depends on the uncertainty of the relative spectral irradiance. According to Reference [20], the uncertainty of the spectral irradiance calibration on 1000 W FEL lamps with respect to the NIST spectral radiance scale is analyzed in **Table 17**. The values shown in the table are regarded as the uncertainty of the relative spectral irradiance calibrations less the uncertainty of the spectral radiance scale on the variable temperature blackbody. The time drift model uncertainty included in Table V of Reference [20] is not included because this factor contributes mostly to the absolute irradiance and not to the relative spectral irradiance. To convert these uncertainty values of irradiance into

Table 17. The uncertainty of the spectral irradiance calibration with respect to the NIST spectral radiance scale

Uncertainty factor	Relative expanded uncertainty (k = 2) [%] 350 nm	655 nm	900 nm
Spectral radiance on the integrating sphere source	0.28	0.17	0.23
Radiance to irradiance transfer to FEL lamp*	0.22	0.19	0.59
Test lamp irradiance transfer	0.15	0.11	0.28
Overall uncertainty of the spectral irradiance calibration with respect to the NIST spectral radiance scale	0.39	0.28	0.69

* The time drift model uncertainty [20] is not included.

Table 18. The uncertainty budget for the NIST color temperature calibration

Factor	Expanded uncertainty (k=2) [K]				
	2000 K	2300 K	2600 K	2856 K	3200 K
NIST radiance temperature scale	0.8	1.0	1.3	1.5	1.9
Relative spectral irradiance calibration	3.0	4.1	5.3	6.4	7.9
Transfer to working standard lamps	1.0	1.0	1.0	1.0	1.0
Aging of the working standard lamps	1.4	1.9	2.5	3.0	3.6
Reproducibility of working standards	1.0	1.0	1.0	1.0	1.0
Transfer to the test lamp	1.0	1.0	1.0	1.0	1.0
Reproducibility of test lamp	1.0	1.0	1.0	1.0	1.0
Overall uncertainty of calibration	3.9	5.0	6.3	7.5	9.1

an uncertainty value of color temperature, a worst case is assumed where the errors are at the high (low) end of the uncertainty at wavelengths shorter than 555 nm and at the low (high) end of the uncertainty at wavelengths longer than 555 nm. This computation has the nature of a limit-of-error calculation and thus is approximately an estimate in an expanded uncertainty with coverage factor $k = 3$. Therefore, the results are restated in an expanded uncertainty with coverage factor $k = 2$, and are shown in **Table 18**. The overall uncertainty of the color temperature calibration is calculated as the quadrature sum of the uncertainty factors listed in this table. The NIST radiance temperature scale (on the variable temperature blackbody) is given in Reference [47].

8. Future work

8.1 Total spectral radiant flux scale realization

Total spectral radiant flux is the geometrically total radiant flux of a given bandwidth at a given wavelength. The unit is W/nm. This quantity is often used to evaluate the total power of light sources at given wavelengths, especially in UV and IR, or to determine the color of light sources. Total spectral radiant flux standards are most often used in an integrating sphere to calibrate a spectroradiometer which is connected to the integrating sphere. For color measurement, only the relative values of total spectral radiant flux are required.

At NIST, work is underway to establish a total spectral radiant flux scale based on the integrating sphere method described in Section 5.1. A double monochromator is installed at the NIST 2 m integrating sphere. A 1000 W FEL type lamp calibrated for spectral irradiance against the NIST spectral irradiance scale [20] is used as an external source. The distance from the lamp to the aperture is set to be exactly the same as that at the spectral irradiance calibration. The total spectral radiant flux $\Phi_i(\lambda)$ of the internal source is then obtained by

$$\Phi_i(\lambda) = c(\lambda)\ S\ E(\lambda)\, y_i(\lambda) / y_e(\lambda)\ , \tag{44}$$

where $E(\lambda)$ is the average spectral irradiance ($W\,m^{-2}\,nm^{-1}$) over the limiting aperture of known area S(m^2), $y_e(\lambda)$ is the detector current for the external source, and $y_i(\lambda)$ is the detector current for the internal source. $c(\lambda)$ is a correction factor which consists of the spatial nonuniformity correction and the incident angle dependence correction factor which are determined spectrally using the method described in subsections 5.1.3 and 5.1.4.

When the total spectral radiant flux is established in the near future, NIST plans to start providing calibration services for this quantity from the near UV to near the IR region.

8.2 Total luminous flux calibration of other discharge lamps

At the time of publication, for total luminous flux, NIST routinely provides calibration services only for incandescent lamps and 4 ft linear fluorescent lamps. Basically, NIST entrusts industrial laboratories to transfer the luminous flux unit of incandescent lamps (provided by NIST) to other discharge lamps by themselves. NIST develops calibration procedures for industrial laboratories to do such transfer measurement as accurately as possible by applying correction techniques. However, luminous flux standards of various types of discharge lamps are still needed in order to allow direct substitution measurements. Even though most of the discharge lamps are not satisfactory in terms of reproducibility of light output, NIST plans to expand the calibration services for several more types of discharge lamps, such as linear fluorescent lamps of other sizes, compact fluorescent lamps, and limited types of HID (High Intensity Discharge) lamps if they have acceptable reproducibility.

8.3 Issuing calibrated standard lamps

As of September 1995, standard quality incandescent lamps for total luminous flux are not commercially available with reasonable cost. The luminous intensity standards issued by NIST are limited to 1000 W FEL type lamps. The unavailability of standard lamps is a world-wide concern. However, there is some hope that a few lamp companies are preparing to produce standard quality lamps again. When high quality lamps are available, NIST will investigate the stability and reproducibility of these newly available lamps, and if satisfactory, will plan to issue luminous flux standard lamps and more types of luminous intensity standard lamps.

8.4 Flashing light photometric standards

All the photometric standards now available at NIST are in the form of steady light. NIST has entrusted flashing light industries to transfer from steady light standards (such as candela) to flashing light standards (such as candela·second). However, there are rather large uncertainties in the transfer measurements in industrial laboratories. Needs for much higher accuracies are addressed as the flashing light sources are used for safety purposes such as the anti-collision lights of aircraft. Driven by such circumstances, work on developing flashing light standards has started at NIST. A group of standard photometers to measure flashing light (in lux·second) will be developed, and NIST plans to start providing calibration services for submitted flashing light meters in the near future.

8.5 High Illuminance Calibration

The range of calibration of illuminance meters and luminance meters has been normally limited to levels up to several thousand lx and several thousand cd/m^2 using a high-power luminous intensity standard lamp. The calibration of instruments at much higher levels is required in applications such as daylight measurement, evaluation of solar simulators, and testing of lighting optics in imaging devices. A calibration facility and procedures are being developed at NIST to provide calibration services at illuminance levels up to 100 klx.

Acknowledgments

There have been tremendous efforts by many staff members of Optical Technology Division in establishing the new photometric units and reconstructing the NIST photometry laboratory. Albert Parr and Chris Cromer developed the concept of the NIST detector-based candela, and established the project. George Eppeldauer played a key role in designing and constructing the NIST standard photometers and characterizing them. Jonathan Hardis contributed with theoretical studies and detailed analyses on the candela realization. Tom Larason contributed with the absolute spectral responsivity measurements, computer automation, and other calibration work. Sally Bruce now provides the annual calibration of the spectral responsivities of the NIST standard photometers. Magdalena Navarro is now engaged in photometric calibration work and keeps improving the facilities. The author is grateful to these and other staff members in the Division who have contributed and is contributing to the photometry work at NIST. Thanks are also due to Tom Larason, Jack Hsia, Bob Saunders, Albert Parr, Chris Kuyatt, and Georg Sauter, who kindly reviewed this document and gave precious comments and discussions.

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Appendix A - Relationship between national photometric units in 1988.

Attached below is a reprint published by BIPM in 1988. Note that NIST (NBS then) and some other national laboratories revised their photometric units after this publication.

Appendix B - SP250, Optical Radiation Measurements, Chapter 7

A. Photometric Measurements

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Test No.	Items
37010C	Luminous Intensity and Color Temperature Standard Lamps
37020S	Special Tests for Luminous Intensity and Color Temperature of Submitted Lamps
37030C	Color Temperature Standard Lamps
37040C	Each Additional Color Temperature for 37030C
37050S	Special Tests for Color Temperature of Submitted Lamps
37060S	Special Tests for Total Luminous Flux of Submitted Incandescent Lamps and Fluorescent Lamps
37070C	Opal Glass Luminance Coefficient Standards
37080S	Special Tests for Submitted Luminance Sources and Transmitting Diffusers
37090S	Special Tests for Submitted Photometers, Illuminance meters, and Luminance meters
37100S	Special Photometric Tests

General Information

Calibration services in this area provide access to the photometric units realized and maintained at NIST. Lamp standards of luminous intensity, luminous flux, and color temperature as well as reference photometers and materials as described below are issued or calibrated on a routine basis.

Luminous Intensity and Color Temperature Standard Lamps (37010C)

NIST will issue to the customer 1000 W modified FEL quartz halogen lamps calibrated for luminous intensity (candela) and color temperature (kelvin). The lamps have a double coil filament with a clear bulb, and are potted on a medium bi-post base. The lamps are usually operated at approximately 7A (85V) DC, at a color temperature of 2856 K. The relative expanded uncertainty (k = 2) of the luminous intensity of these lamps is 0.6 %, and the expanded uncertainty (k = 2) of the color temperature is 8 K at 2856 K with respect to the SI units.

Special Tests for Luminous Intensity and Color Temperature of Submitted Lamps (37020S)

NIST will calibrate the luminous intensity and color temperature of incandescent lamps with a medium bi-post base submitted by customers. The inside frosted lamps, the airway beacon lamps, and the 1000 W FEL lamps previously issued from NIST can be submitted for recalibration. Customers can either specify the lamp current or the color temperature of the lamp (normally 2856 K) for calibration. The uncertainty of calibration is described above.

Color Temperature Standard Lamps (37030C)

NIST will issue to the customer 1000 W modified FEL quartz halogen lamps as described in 37010C calibrated for color temperature. The lamps are usually calibrated for a color temperature of 2856 K. The expanded uncertainty (k = 2) of the color temperature of these lamps is 8 K at 2856 K with respect to the SI units.

Each Additional Color Temperature for 37040C

The color temperature standard lamps requested for 37030C can be calibrated for additional color temperature points in a range from 2000 K to 3200 K. The expanded uncertainty (k = 2) of this calibration is 4 K to 11 K in the range from 2000 K to 3200 K.

Special Tests for Color Temperature of Submitted Lamps (37050S)

NIST will calibrate the color temperature of incandescent lamps with a medium bi-post base submitted by customers. The inside frosted lamps, the airway beacon lamps, and the 1000 W FEL lamps previously issued from NIST can be submitted for recalibration. The expanded uncertainty (k = 2) of this calibration is 4 K to 11 K in the range from 2000 K to 3200 K.

Special Tests for Total Luminous Flux of Submitted Incandescent lamps and Fluorescent Lamps (37060S)

NIST will calibrate the total luminous flux (lumen) of incandescent lamps and fluorescent lamps submitted by customers. The standard lamps previously issued from NIST can be submitted for recalibration. Miniature lamps may also be accepted. Customers should contact NIST before submitting lamps. The relative expanded uncertainty (k = 2) of this calibration, which depends on the reproducibility of test lamps, is typically 0.8 % for incandescent lamps and 1.8 % for fluorescent lamps, with respect to the SI units.

Opal Glass Luminance Coefficient Standards (37070C)

NIST will issue flashed opal glasses, 51 mm x 51 mm, calibrated for luminance coefficient (ratio of luminance / illuminance, unit: sr^{-1}) for CIE Illuminant A (2856 K source). The glasses, masked with a circular aperture of 25 mm in diameter, are calibrated for the luminance within a circular area of 1 cm in diameter in the center of the aperture. The relative expanded uncertainty (k = 2) of this calibration is 0.5 %.

Special Tests for Submitted Luminance Sources and Transmitting Diffusers (37080S)

NIST will calibrate the luminance (cd/m^2) of submitted sources and luminance coefficient (sr^{-1}) of submitted transmitting diffusers including opal glasses previously issued from NIST. Customers should contact NIST before sending sources or diffusers. The relative expanded uncertainty (k = 2) of the luminance calibration is 0.7 % with respect to the SI units.

Special Tests for Submitted Photometers, Illuminance meters, and Luminance meters (37090S)

NIST will calibrate photometers, illuminance meters, and luminance meters submitted by customers. Calibration is usually made with the CIE illuminance A (2856 K incandescent source) in a range from 0.001 lx to 3000 lx for illuminance and 0.1 cd/m^2 to 4000 cd/m^2 for luminance. The relative expanded uncertainty (k = 2) of calibration is 0.5 % for illuminance and 0.7 % for luminance at normal levels, which will increase at low levels. As an option, NIST can measure the relative spectral responsivity of submitted instruments and calculate spectral mismatch correction factors for a source of known spectral power distribution.

Special Photometric Tests (37100S)

NIST can provide special tests for sources, detectors, and photometric instruments other than those stated above under limited conditions with special arrangements of the NIST facility. Customers should contact NIST for consultation.

REPORT OF CALIBRATION

Luminous Intensity and Color Temperature of Standard Lamps 37010C

for

One 1000 watt type T6 FEL lamp # NIST0000

Supplied to:

ABC Company
123 Calibration Ct.
Measurement City, MD 00000-0000

(See your Purchase Order No. ABC000 dated January 1, 1996)

1. Calibration Item

One 1000 watt type T6 FEL lamp was calibrated for 2856 K color temperature and luminous intensity. The lamp has a tungsten coiled-coil filament in a clear quartz bulb and a medium bi-post base. The lamp designation (NIST0000 as well as its polarity are indicated on the lamp base plate.

2. Description of the Calibration

The luminous intensity measurement is based on the NIST detector-based candela [1] realized in 1994 and therefore on the international definition of candela in effect since 1979. The color temperature measurement is based on the international temperature scale of 1990 (ITS-90).

The test lamp was placed on a photometry bench in the base-down position with the lamp designation number facing away from the photometer. The lamp orientation was accomplished by aligning the lamp socket so that the lamp posts were held vertical and so that the plane formed by the center lines of the posts was perpendicular to the optical axis of the photometer. A lamp alignment jig (a mirror set parallel to the plane formed by the center lines of an identical bi-post base) was used in combination with a laser (positioned to duplicate the optical axis of the photometer) to facilitate this alignment. The lamp was aligned horizontally so that the center line between the center lines of the posts intersects the optical axis. The height of the lamp was aligned so that the optical axis was 9.5 cm (3.75 inches) above the bottom of the posts. The distance origin of the lamp was the center of the lamp posts.
The operating current of the test lamp was first determined so that the lamp produced a color

temperature of 2856 K. The color temperature of the lamp was measured, using a spectroradiometer, by comparison with two 2856 K color temperature working standard lamps (NBS10000 and NBS10005) which were calibrated in the NIST Facility for Automated Spectroradiometric Calibrations (FASCAL) described in reference [2].

After determining the lamp current, the luminous intensity of the lamp was measured with three of the NIST standard photometers which embody the NIST illuminance unit [3]. The lamp was operated on DC power with the electrical polarity as marked on the lamp bulb near the positive post. The lamp current was slowly (30 seconds) ramped up to the prescribed current and allowed to stabilize for at least ten minutes before luminous intensity measurements were made.

The standard photometers measured the illuminance of the test lamp at a distance of approximately 3.5 m. The luminous intensity was determined from the measured illuminance and the exact distance between the lamp and the photometer. Measurements were made for three lightings of the test lamp to check its reproducibility, and the average values were reported. The details of the calibration procedures are described in reference [2]. The total operating time of each lamp was approximately 40 minutes. The room temperature was 23 °C and relative humidity was 18 % at the time of calibration.

3. Results of the Calibration

The results of the calibration are shown in Table 1. The relative expanded uncertainty (with coverage factor k=2 and thus a two standard deviation estimate) of the luminous intensity value is 0.52 %. The expanded uncertainty (k=2) of the color temperature value is 8 K. The uncertainty budget is shown in Table 2. The NIST policy on uncertainty statements is described in reference [3].

Table 1. Results of Calibration

Lamp No.	Current DC [A]	Voltage* DC [V]	Color Temperature [K]	Luminous Intensity [cd]
NIST10000	7.201	85.09	2856	964.5
NIST10001	7.203	8554	2856	989.9

*Voltage is for reference only.

4. General Information

The lamp should be carefully aligned in accordance with the procedures described above. The lamp should be operated on DC power at the reported current and at the prescribed polarity. Photometric measurements should be made after the lamp has stabilized (approximately 10 minutes after turn on).

Further details of the NIST photometric units, calibration procedures, and uncertainty analysis are described in reference [3].

The Calibration Report shall not be reproduced except in full, without the written approval of NIST.

Prepared by :

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References:

[1] C. L. Cromer, G. Eppeldauer, J. E. Hardis, T. C. Larason, and A. C. Parr, “National Institute of Standards and Technology detector-based photometric scale,” Applied Optics, 32-16, 2936-2948 (1993)

[2] NBS Special Publication 250-20 (1987), Spectral Irradiance Calibrations

[3] NIST Special Publication 250-15 (1995), Photometric Calibrations

[4] B. N. Taylor and C. E. Kuyatt, "Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results," NIST Technical Note 1297 (1993).

Table 2. Uncertainty budget for this luminous intensity calibration

Uncertainty factor	Relative expanded uncertainty (*k*=2) [%] Type A	Type B
The NIST illuminance unit realization		0.38
Long-term drift of the NIST standard photometers		0.26
Photometer temperature variation	0.03	
Distance measurement (uncertainty of the linear encoder at 3 m)		0.02
Alignment of the lamp distance (0.5 mm in 3 m)	0.03	
Determination of *ccf**		0.04
Lamp current regulation	0.02	
Stray light		0.05
Random noise (scatter by dust, lamp drift, etc.)	0.10	
Test lamp reproducibility in 3 lightings	0.20	
Overall uncertainty of test lamp calibration with respect to SI	**0.52**	

REPORT OF CALIBRATION

Special Test for Luminous Flux of Submitted Lamps 37060S

for

Three Incandescent Lamps with s/n: 000-001, 000-001, 000-003

Submitted by:

ABC Company
123 Calibration Ct.
Measurement City, MD 00000-0000

(See your Purchase Order No. ABC123 dated January 1, 1996)

1. Description of Calibration Item

Three 1000 W gas-filled, frosted-bulb incandescent lamps with designation numbers; 000-001, 000-002, and 000-003 were calibrated for total luminous flux.

2. Description of Calibration

This total luminous flux measurement is based on the NIST luminous flux unit [1] realized in 1995 which has been derived from the NIST detector-based candela [2] realized in 1994 and therefore based on the international definition of candela in effect since 1979.

The test lamps were calibrated in a 2 m integrating sphere by comparison with the 60 W total luminous flux working standard lamps (TF6-1, TF6-2, and TF6-3). The working standard lamps are calibrated periodically using the integrating sphere against the NIST primary total luminous flux standard lamps (40 W, TF4 Group). The primary standard lamps are calibrated using the procedures described in reference [1]. The details of the 2 m integrating sphere system are described in reference [3].

The lamps were operated in the base up position. The operating current for each lamp was first determined for a color temperature of approximately 2856 K by measuring the relative spectral irradiance in one direction using a spectroradiometer. The total luminous flux measurements were made in three runs. Each run consisted of measurements of standard lamps and the test lamps. The current of the lamp was ramped up slowly to the prescribed value, and stabilized for 10 minutes. The lamp current, the lamp voltage, and the photometer output signal were recorded together with the data on the environmental conditions. Corrections were made for the dark readings, the self-absorption effects, and the spectral mismatch correction factors to calculate the total luminous flux of the test lamps. The mean values of each test lamp in the three runs are reported. The variations of luminous flux values in the three runs (in a two standard deviation estimate) are included in the uncertainty of this calibration. The room temperature was 23 °C and relative humidity was 28 % at the time of calibration.

3. Results of Calibration

The results of the calibration are shown in Table 1. The relative expanded uncertainty (coverage factor k=2 and thus a two standard deviation estimate) of the reported luminous flux values is 1.0 %. The uncertainty budget is shown in Table 2. The relative expanded uncertainty (k=2) of the current values is 0.01%. The NIST policy on uncertainty statements is described in reference [4].

Table 1. Results of Calibration

Lamp Designation	Lamp Current [A]	Lamp Voltage* [V]	Color Temperature* [K]	Total Luminous Flux [lm]
000-001	7.570	104.8	2856	13350
000-002	7.590	105.0	2856	13420
000-003	7.590	104.1	2856	13980

* Lamp voltage and color temperature are for reference only.

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Calibration Date: January 1, 1995
NIST Test No. : 844 / 00000-95

References:

[1] Ohno, Y., "Realization of NIST 1995 Luminous Flux Scale using Integrating Sphere Method", (to be published in J.IES, Winter 1996 Issue)
[2] C. L. Cromer, G. Eppeldauer, J. E. Hardis, T. C. Larason, and A. C. Parr, National Institute of Standards and Technology detector-based photometric scale, Applied Optics, 32-16, 2936-2948 (1993)
[3] NBS Special Publication 250-15, Photometric Calibrations (1995)
[4] B. N. Taylor and C. E. Kuyatt, Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results, NIST Technical Note 1297. (1993)

Table 2. Uncertainty budget for this total luminous flux calibration

Uncertainty factor	Relative expanded uncertainty (*k*=2) [%] Type A	Type B
NIST luminous flux scale (primary/working standard lamps)		0.53
Aging of the working standard lamps between calibrations		0.30
Transfer from working standards to test lamps:		
Geometric differences		0.50
Self-absorption correction	0.10	
Spectral mismatch correction		0.10
Reproducibility of test lamps (typical)	0.20	
Overall uncertainty of test lamp calibration with respect to SI	**0.83**	