NIST Facility for Total Spectral Radiant Flux Calibration

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Abstract: Facilities for calibration of total spectral radiant flux of lamps have been developed at NIST. The total spectral radiant flux scale is being realized in the 380 nm to 780 nm region using two independent methods – the spectrogoniophotometric method and the Absolute Integrating Sphere method. A spectrogoniophotometer has been built and is being characterized for the first method. The 2.5 m integrating sphere has been modified for spectral measurements to implement the second method. The principles of the two methods and the details of the NIST facilities for this work are presented.

1. INTRODUCTION

For measurement of total luminous flux of light sources, integrating spheres equipped with a photometer head are commonly used. The luminous flux of a test lamp is calibrated in comparison to the luminous flux from a standard lamp. Recently, however, integrating spheres employing a spectroradiometer are increasingly used in the lighting industry and the light-emitting diode (LED) industry. Such a system performing spectral measurements in an integrating sphere allows for measurement of the color of light sources as well as their total luminous flux at the same time. In addition, spectral mismatch errors, which are inevitable with photometers, can be eliminated, in principle, by spectral measurements. This is beneficial particularly for measurement of single-color LEDs where the correction can be very large but difficult to apply (spectral distribution of the source must be known). There are also increasing need for calibration of total radiant flux of ultra-violet (UV) LEDs, which requires radiant flux standards.

The quantity measured with such integrating sphere systems using a spectroradiometer is total spectral radiant flux (unit: W/nm) – a geometrically total radiant flux for each wavelength. Such an integrating sphere system needs to be calibrated against a total spectral radiant flux standard lamp. The use of a spectral irradiance standard lamp for relative total spectral radiant flux (often done in the industry) would not work accurately because the spectral distributions of the lamps are not perfectly spatially uniform. In addition, it does not provide the absolute scale to total radiant flux. It is reported that total spectral radiant flux standards are in urgent need in the optical radiation measurement community [1].

Total spectral radiant flux standards, however, are currently not commonly available from national laboratories, though one realization in the visible region is reported [2]. Due to the increasing needs for this type of standards in the United States, work is in progress at National Institute of Standards and Technology (NIST) to realize the scale of total spectral radiant flux and to provide lamp standards. The first phase of the project is to make standards available for the visible region (380 – 780 nm). Standards in the UV region will be developed in the second phase.

Two independent methods are employed to realize the scale, allowing for verification of the realized scale by cross check. The first method is using a spectrogoniophotometer, which has been built at NIST and is being characterized. The second method is using the NIST 2.5 m integrating sphere utilizing the Absolute Integrating Sphere method [3-5] modified for the spectral radiant flux measurement. The principles of both methods and the details of the NIST facilities for this work are described.

2. METHODS FOR SCALE REALIZATION

2.1 Spectrogoniophotometric method

The method reported in reference [2] was based on measurement of the correlated color temperature of a test lamp in many directions, and the average spectral distribution of the lamp was derived based on Planck's equation. The method we have employed utilizes a high-speed spectroradiometer now available, and directly measures the spectral power distributions of a test lamp in many directions.

Lower uncertainty of the realized scale is expected. The principles of this method are given below.

The spectral radiant intensity of a light source is measured in many directions (θ, ϕ) over 4π steradian using a goniophotometer equipped with a spectroradiometer – called spectrogoniophotometer. The total spectral radiant flux $\Phi_\lambda(\lambda)$ of the light source is given by

$$\Phi_\lambda(\lambda) = \int_{\phi=0}^{2\pi} \int_{\theta=0}^{\pi} I_\lambda(\lambda,\theta,\phi)\ \sin\theta\, \mathrm{d}\theta \mathrm{d}\phi\,, \qquad (1)$$

where $I_\lambda(\lambda,\theta,\phi)$ is the spectral radiant intensity distribution of the source on spherical coordinates (θ, ϕ). Spectroradiometers are normally calibrated for spectral irradiance. If such a spectroradiometer is used with the goniophotometer, the total spectral radiant flux $\Phi_\lambda(\lambda)$ of the light source is obtained by

$$\Phi_\lambda(\lambda) = r^2 \int_{\phi=0}^{2\pi} \int_{\theta=0}^{\pi} E_\lambda(\lambda,\theta,\phi)\ \sin\theta\, \mathrm{d}\theta \mathrm{d}\phi, \qquad (2)$$

where $E_\lambda(\lambda,\theta,\phi)$ is the spectral irradiance distribution on the spherical surface with radius r around the light source being measured.

The principles given above are straightforward. However, the absolute measurement of total flux with a goniophotometer is not easy due to various imperfections of the instrument, including the dead angle, stray light, the errors associated with sampling intervals, etc. [6]. The realization of the scale can be done more easily if the total luminous flux (lumen) of the lamp is known and the absolute scale is brought from the luminous flux unit. Then the spectral irradiance measurements can be done relatively. In such a method, the total spectral radiant flux of a lamp is given by

$$\Phi_\lambda(\lambda) = k_{\mathrm{scale}} \int_{\phi=0}^{2\pi} \int_{\theta=0}^{\pi} S(\lambda,\theta,\phi)\ \sin\theta\, \mathrm{d}\theta \mathrm{d}\phi, \qquad (3)$$

and

$$k_{\mathrm{scale}} = \frac{\Phi_{\mathrm{v}}}{K_{\mathrm{m}} \int_{\lambda=0}^{\infty} V(\lambda) \int_{\phi=0}^{2\pi} \int_{\theta=0}^{\pi} S(\lambda,\theta,\phi)\ \sin\theta\, \mathrm{d}\theta \mathrm{d}\phi\, \mathrm{d}\lambda} \qquad (4)$$

where $S(\lambda,\theta,\phi)$ is the relative spectral and spatial distribution of the lamp as given by

$$S(\lambda,\theta,\phi) = k \cdot E_\lambda(\lambda,\theta,\phi) \quad (k: \text{an arbitrary constant}), \qquad (5)$$

and Φ_{v} is the total luminous flux (lumen) of the lamp, determined using other methods. With this relative method, errors in the rotation radius r of the goniophotometer, the positioning of lamp and detector, stray light from surrounding walls, and the absolute scale calibration of the spectroradiometer are mostly not relevant.

Further, if the relative spectral distribution $S_{\mathrm{rel}}(\lambda,\theta,\phi)$ (normalized at its peak at each (θ,ϕ)) of the lamp is fairly uniform (as in the case of tungsten halogen lamp), measurement of $S(\lambda,\theta,\phi)$ will not be very critical. In a hypothetical case where the relative spectral distribution is spatially perfectly uniform:

$$S(\lambda,\theta,\phi) = S_{\mathrm{rel}}(\lambda)\, I_{\mathrm{rel}}(\theta,\phi)\,, \qquad (6)$$

where $I_{\mathrm{rel}}(\theta,\phi)$ is the relative intensity distribution, then, Eqs. (3) and (4) would be simplified to

$$\Phi_\lambda(\lambda) = \frac{\Phi_{\mathrm{v}}}{K_{\mathrm{m}} \int_{\lambda=0}^{\infty} V(\lambda) S_{\mathrm{rel}}(\lambda)\, \mathrm{d}\lambda} \cdot S_{\mathrm{rel}}(\lambda)\,. \qquad (7)$$

$I_{\mathrm{rel}}(\theta,\phi)$ is cancelled out in Eq. (7) and is not relevant. In this case, $S_{\mathrm{rel}}(\lambda)$ can be measured in one direction from the lamp, and goniophotometry would not be required. This is a hypothetical case, but this proves that the accuracy of goniophotometry is not critical if the lamp's relative spectral distribution is fairly spatially uniform. The measurement outlined by Eq. (3) to (5) is ascribed to measurement of a spatially averaged relative spectral distribution of the lamp.

2.2 Absolute Integrating Sphere Method

A luminous flux unit was realized at NIST in 1995

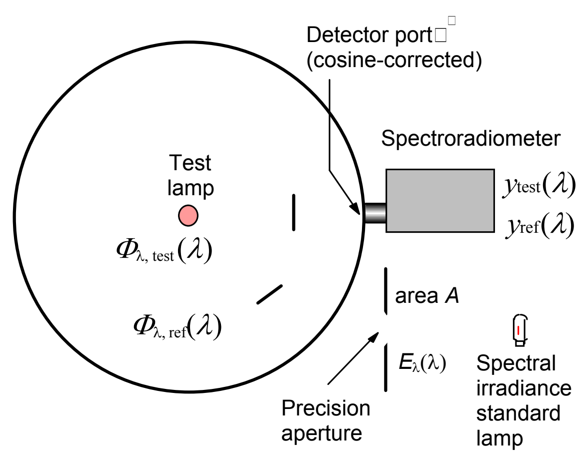

Fig. 1 *Absolute Integrating Sphere Method for total spectral radiant flux measurement.*

using the Absolute Integrating Sphere Method [3-5]. With this method, a known amount of luminous flux is introduced from an external source into an integrating sphere, and the total luminous flux from the lamp in the sphere is measured against the external beam flux. Several corrections are applied to compensate for the imperfections of the integrating sphere. The same principles can be applied to total spectral radiant flux measurement. The benefit of this method is that it does not require a spectrogoniophotometer, which is an expensive instrument to build. An integrating sphere with some modification and additional instrumentation will achieve the purpose.

Figure 1 shows the arrangement of an integrating sphere system for this application. The flux from the spectral irradiance standard lamp is introduced through a calibrated aperture placed in front of the opening. The internal source, a lamp to be calibrated, is mounted in the center of the sphere. The external source and the internal source are operated alternately. The baffles shield the detector port and the opening from direct illumination by the internal source. The flux $\Phi_{\lambda,\mathrm{ref}}(\lambda)$ introduced from the external source is given by,

$$\Phi_{\lambda,\mathrm{ref}}(\lambda) = A \cdot E_{\lambda}(\lambda), \tag{8}$$

where $E_{\lambda}(\lambda)$ is the average spectral irradiance from the external source over the limiting aperture of known area *A.* The total spectral radiant flux $\Phi_{\lambda,\mathrm{test}}(\lambda)$ of the test lamp is obtained by comparison to the external radiant flux:

$$\Phi_{\lambda,\mathrm{test}}(\lambda) = \frac{y_{\mathrm{test}}(\lambda)}{y_{\mathrm{ref}}(\lambda)} \cdot k_{\mathrm{cor}}(\lambda) \cdot \Phi_{\lambda,\mathrm{ref}}(\lambda), \tag{9}$$

where $y_{\mathrm{test}}(\lambda)$ is the detector signal of the spectroradiometer for the test lamp at wavelength λ, and $y_{\mathrm{ref}}(\lambda)$ is that for the introduced flux at wavelength λ. The quantity $k_{\mathrm{cor}}(\lambda)$ is a correction factor for various non-ideal behaviors of the integrating sphere, and given by

$$k_{\mathrm{cor}}(\lambda) = \frac{k_{\mathrm{s,test}}(\lambda)}{k_{\mathrm{s,ref}}(\lambda)} \cdot \frac{\rho_0(\lambda)}{\rho_{45}(\lambda)}, \tag{10}$$

where $k_{\mathrm{s,test}}(\lambda)$ and $k_{\mathrm{s,ref}}(\lambda)$ are the spatial nonuniformity correction factors of the integrating sphere system for the test lamp and for the external reference beam, respectively, against an isotropic point source. To obtain these correction factors, the responsivity of the sphere is mapped by scanning a beam source over the sphere wall [5]. The measurement must be done spectrally. The quantity $\rho_0(\lambda)$ and $\rho_{45}(\lambda)$ are the diffuse reflectances of the sphere coating at 0° and 45° incidence, respectively. This correction is necessary because the light from the test lamp is incident at 0° while the light from the external source is incident at approximately 45°. The ratio $\rho_0(\lambda)/\rho_{45}(\lambda)$ can be measured by moving a beam source inside the sphere [5]. A self-absorption correction, normally necessary for substitution measurements, is not necessary because the test source stays in the sphere when the sphere is calibrated with the external source.

Similar to the case with the spectrogoniophotometric method, the measurement of the Absolute Integrating Sphere Method can be done for relative total spectral radiant flux, with the absolute scale determined by the luminous flux unit. In this case, the correction measurements can be more relaxed focusing on spectral dependence rather than absolute scale difference. The final values can be determined following Eq. (7).

3. INSTRUMENTATION

3.1 Spectrogoniophotometer

A spectrogoniophotometer for this purpose has been developed at NIST. The mechanical design of the instrument is shown in Fig. 2. The rotation radius of the detector is 1.25 m. The detector arm is rotated by a high-power servo motor, in which a rotary

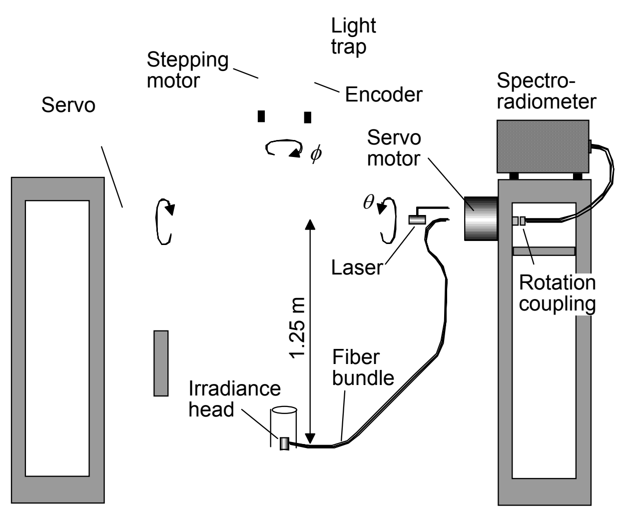

Fig. 2 *Design of the NIST spectrogoniophotometer.*

encoder is incorporated for monitoring the actual angle of the arm. The lamp holder is rotated by a stepping motor and its angle is also measured by a rotary encoder. The rotations of the two axes are controlled by a computer, typically at 5° or 10° intervals, and the motor stops during measurement. The arm holding the lamp holder can also be rotated by another servo motor though this rotation is not frequently needed. This rotation allows changes of the lamp's burning position. Most test lamps for flux measurement are operated in the base-up position, in which case the lamp holder is fixed above the lamp. In some cases, however, lamps must be operated in a base-down position or base-side position. The end of the lamp holder is an interchangeable lamp socket, which can be E26 or E39 screw base or a bi-post socket (for FEL type lamp). The length of the lamp holder can also be adjustable so that the lamp with different sizes can be aligned to the center of rotation.

The spectral irradiance of the test lamp is measured with an array spectroradiometer, employing a fiber optic input. The fiber bundle is connected to the spectroradiometer through a rotation coupler, which allows free rotation of the arm without twisting the fiber. The constancy of the spectral transmittance of the coupler was tested with a white LED mounted on the irradiance head. The variations in measured spectra depending on the arm angle was found to be less than 2 %, and is corrected in actual measurements. From the rotation coupler to the irradiance measuring head, a fiber bundle of 8 mm diameter is used. The fiber bundle on the spectroradiometer side is 5 mm diameter. The irradiance head mounted at the end of the arm has an approximate cosine response within the acceptance angle limited by a hood.

The array spectroradiometer covering the UV and visible region is calibrated by a spectral irradiance standard lamp (1000 W FEL type tungsten halogen lamp) traceable to the NIST spectral irradiance scale [7]. The stray light, linearity, and other characteristics of the spectroradiometer are the components of uncertainty for the realized scale and are being characterized. The stray light error of a single-grating instrument can be serious in general, but in this work, only incandescent lamps (similar to standard lamps) are to be measured with the spectrogoniophotometer so that stray light errors can be mostly avoided.

The mechanism of the spectrogoniophotometer is designed so that the dead angle due to the lamp rotation mechanism is ± 3° (covering 0° to 177° of θ positioning), the angular resolution of both axes to be <0.01°, and uncertainty of the absolute angle to be <0.1°. The rotation radius and its variation have not been calibrated and characterized at the moment because the relative method based on Eqs. (3) and (4) is to be used at the first stage of the project, and this specification will not contribute to uncertainty. These mechanical performances will be characterized in detail when the absolute method based on Eq. (1) or (2) is employed in the future.

3.2 NIST 2.5 m integrating sphere

A 2.5 m integrating sphere is used at NIST for the realization of the lumen and total luminous flux calibration of lamps [5]. This integrating sphere can be equipped with a spectroradiometer, and is to be used for the realization and measurement of total spectral radiant flux. Figure 3 shows the configuration of the NIST 2.5 m sphere employing a spectroradiometer. The external source is a 1000 W FEL type quartz halogen lamp, calibrated for spectral irradiance at 0.5 m. The aperture is 50 mm in diameter. The spectroradiometer is of a double-grating type, using a photomultiplier as the detector. The difficulty is that the flux introduced from the external source is at a low level (≈20 lm), and thus a very low signal from the double-monochromator. We are improving the detector system for high sensitivity, with an option to use a lock-in amplifier [8].

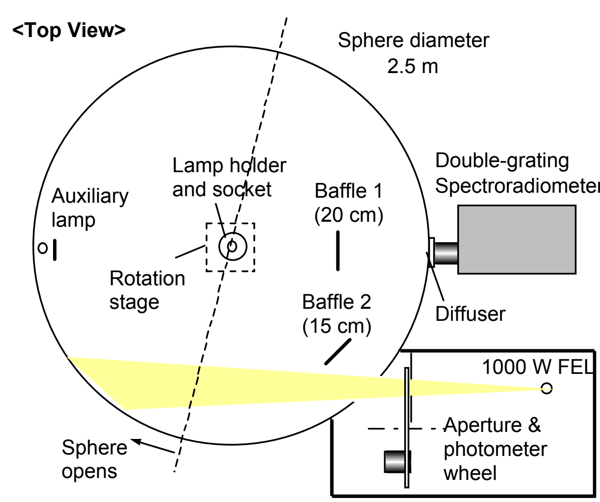

Fig. 3 *NIST 2.5 m integrating sphere configured for the total spectral radiant flux measurement.*

The spatial nonuniformity correction factors $k_{s,test}(\lambda)$ and $k_{s,ref}(\lambda)$ need to be determined by spatially mapping the spectral responsivity of the sphere. The beam source currently used for the luminous flux scale [5] has a very low flux level (≈0.1 lm). For this measurement, an array spectroradiometer with a high sensitivity (employing a back-lit CCD array) is used. The angular correction factor $\rho_0(\lambda)/\rho_{45}(\lambda)$ has been measured with this spectroradiometer. A much brighter beam source using a white LED is being developed to facilitate these measurements.

An experimental realization of total spectral radiant flux scale in the near UV region (360 nm – 450 nm) has been successfully made at NIST using the 2.5 m integrating sphere to calibrate the total radiant flux of deep blue and UV LEDs [9]. A high-sensitivity, array spectroradiometer was used to measure a fairly low-level radiant flux of the UV LEDs in a 2.5 m sphere. The estimated expanded uncertainty (k=2) of this experimental realization was 5.8 %. One of the problems encountered in this work was the fluorescence from the sphere coating with the deep blue and UV irradiation. The error is negligible when measuring white light sources, but can be significant when measuring UV and blue LEDs in an integrating sphere. The fluorescence was evaluated and corrected in this work.

4. TRANSFER STANDARDS

Two types of transfer standard lamps are being developed, 1) 1000 W FEL type quartz halogen lamp with E26 screw base (operated in a base-up position), and 2) 25 W miniature quartz halogen lamp. Both lamps will be operated at ≈3100 K. The FEL type standards will be for integrating spheres more than 1.5 m in diameter – commonly used in lighting industry. The miniature lamp standards are for spheres 0.5 m or less in diameter – commonly used for LED measurements. We plan to supply these types of standard lamp for total spectral radiant flux. Standard lamps of other power levels may be developed in the future depending on the needs.

In addition, we plan to provide calibration services for any other types of lamp for total spectral radiant flux and color, e.g., fluorescent lamps. These light sources can be measured using the 2.5 m integrating sphere with the double-grating spectroradiometer using a substitution method. In other words, the total radiant flux scale is transferred from the standard incandescent lamp to a test lamp in an integrating sphere. This will not require measurement of the external source, so there will be no problem with the spectroradiometer signal level. The self-absorption will be measured spectrally using an auxiliary lamp of a tungsten halogen type. For transfer measurement for LEDs, a 0.5 m integrating sphere system is being developed.

5. UNCERTAINTY CONSIDERATION

5.1 Spectrogoniophotometric method

The uncertainty budget depends largely on whether the absolute method (Eq. (1) or (2)) is used or the relative method (Eqs. (3) and (4)) is used. The uncertainty budget for the absolute method would start from the uncertainty of the spectral irradiance scale and include uncertainty of the spatial integration of radiant intensity or irradiance over 4 π. For spatial integration, the mechanical performance of the goniophotometer, stray light (from the light trap and walls), dead angle correction, linearity of the spectroradiometer, etc. need to be analyzed. The relative method, on the other hand, is hardly affected by these factors and uncertainty budget is much simpler. However, with the relative method, the uncertainty of the scale starts from that of the luminous flux unit, and cannot be lower. The uncertainty components of the spectral irradiance scale are separated between those that are 100 % correlated spectrally (e.g., aperture area, distance, etc.) and all other remaining components. Only the latter are relevant to the relative method. The relative method brings the perfect consistency between the luminous flux unit and the spectral radiant flux scale, which is important for customers.

The use of array spectroradiometer introduces two major sources of uncertainty – stray light and linearity. Linearity can be characterized and corrected. Stray light errors are difficult to correct, so it should be avoided. Stray light errors will be nearly negligible if the relative spectrum of the test source is very close to that of the standard source. We plan to prepare spectral irradiance standards of the same two types of lamps as described in section 4 for calibration of the spectroradiometer. The variation of spectra of incandescent lamps for different directions is small, so the stray light error of the spectroradiometer can be kept nearly negligible. There are other sources of uncertainty related to spectroradiometer, such as wavelength error and bandwidth. The use of the same type of standard lamp as the test lamp will minimize these errors also.

5.2 Absolute Integrating Sphere Method

The detailed uncertainty budget for the photometric application (measurement of luminous flux) is available [5]. For the total spectral radiant flux measurement, the uncertainty budget starts from the spectral irradiance scale on the external source. If the absolute scale is derived based on the spectral irradiance of the external source, the uncertainty of the absolute irradiance of the source at each wavelength will be the main source of uncertainty for the realized total spectral radiant flux scale. The alignment of the lamp and distance setting between the lamp and the aperture are critical. If the absolute scale is brought from the luminous flux unit, the main source of uncertainty will be that of the luminous flux unit, and from the external source, only the uncertainty components of the relative spectral distribution will contribute.

Other sources of uncertainty come from the correction factors and the spectral measurements. Among major components of uncertainty are the sensitivity and linearity of the spectroradiometer due to the low flux level from the external source, and the large difference in flux level between external beam and test lamp. The uncertainty contribution from the spatial nonuniformity correction factors and the angular diffuse reflectance correction factor are relatively small and found not so wavelength dependent [9].

Our plan is to realize the scale using both methods to cross-check the results and verify uncertainty budgets, and adopt the scale that has smaller uncertainty. The goal of our first phase of this project is to develop standards for the visible region with an expanded uncertainty (k=2) of ≈1 %.

6. CONCLUSIONS

Facilities for calibration of total spectral radiant flux of lamps have been developed at NIST and the scale realization work is in progress. Two independent methods are used to realize the scale – the spectrogoniophotometric method and the Absolute Integrating Sphere method. A spectrogoniophotometer has been built and being characterized. The 2.5 m integrating sphere has been modified for spectral measurements. Work is in progress to realize the scale in the 380 nm to 780 nm region and develop two types of lamp standards available with a goal of achieving an expanded uncertainty (k=2) of ≈1 % for total spectral radiant flux in the visible region.

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