# REALIZATION OF TOTAL SPECTRAL RADIANT FLUX SCALE AND CALIBRATION SERVICE AT NIST

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## ABSTRACT

In response to the increasing needs for standards to calibrate sphere-spectroradiometer systems used to measure various types of light sources, we have realized the total spectral radiant flux (TSRF) scale, developed transfer standard lamps, and established a calibration service for incandescent standard lamps in the spectral range of 360 nm to 830 nm with relative expanded uncertainties ($k$=2) between 1 % (at visible and near infrared regions) to 2 % (in ultraviolet (UV) region). The TSRF scale is based on both the NIST spectral irradiance scale and the total luminous flux scale and is realized by using a gonio-spectroradiometer for measuring relative TSRF and a detector-based absolute integrating sphere for measuring total luminous flux.

Keywords: calibration; spectral radiant flux; total flux; integrating sphere; spectroradiometer; measurement; standard lamp; scale

## 1. INTRODUCTION

With recent improvements of the performance of array spectroradiometers and the increasing measurement needs of new types of light sources such as light emitting diodes (LEDs), the conventional sphere-photometer systems are being replaced by sphere-spectroradiometer systems, to measure light sources for total (spatially-integrated) spectral radiant flux (unit: W/nm) and for obtaining photometric, radiometric, and colorimetric quantities of a light source with a single measurement. These sphere-spectroradiometer systems need to be calibrated against total spectral radiant flux standards. In response to this industrial need, NIST has realized the total spectral radiant flux (TSRF) scale, developed transfer standard lamps, and established the calibration service for incandescent type of lamps in the spectral range of 360 nm to 830 nm. This spectral range of 360 nm to 830 nm meets the urgent needs in lighting and LED industries for measurements of total luminous flux, and spatially-integrated color quantities of light sources.

Work on realization of a total spectral radiant flux scale predating this work is reported [1] where the spatial distribution of correlated color temperature (CCT) of a test lamp is measured with a goniophotometer equipped with a colorimeter, and spatially-averaged spectral power distribution (SPD) of the lamp is estimated from the average CCT and a model. We employed a more straightforward method to determine the spatially-averaged SPD by using a spectroradiometer instead of a colorimeter (called gonio-spectroradiometer) for improved uncertainties.

The TSRF scale can be realized using gonio-spectroradiometry to measure absolute spectral radiant intensity or absolute spectral irradiance at many angles and integration of the measured values over $4\pi$ steradian. However, an absolute gonio-spectroradiometer with low measurement uncertainties is not trivial to construct due to many sources of error such as the dead angle, spatial stray light, the sampling error, etc. Such error corrections and uncertainty analyses would not be trivial and would require major efforts. If the scale is realized independently from the luminous flux unit, any discrepancy between the two units would also be a problem for users.

To overcome such difficulties and to provide standards to industry in a timely manner, we employed a method combining two approaches: first to determine the relative total spectral radiant flux scale using the gonio-spectroradiometer, and then to determine the absolute scale from the NIST luminous flux unit [2]. This method is hereinafter called *relative gonio-spectroradiometry method*. We also limit the calibration artifacts to only incandescent lamps. This approach greatly relaxed detailed work for reducing uncertainties and also assured consistency of the scale with the luminous flux unit.

The principle of the relative gonio-spectroradiometry method, the calibration facilities, the transfer standard lamps, and the uncertainty budget are briefly described below.

## 2. PRINCIPLE OF THE RELATIVE GONIO-SPECTRORADIOMETRY METHOD

To determine the TSRF, the test lamp is first measured at many angles using a gonio-spectroradiometer for the relative spectral radiant intensity distribution, $I_{\lambda,\mathrm{rel}}(\lambda,\theta,\varphi)$. The scaling of $I_{\lambda,\mathrm{rel}}(\lambda,\theta,\varphi)$ is set arbitrarily, but is fixed during measurements of each lamp at every angle so that the relative differences of the intensity at different angles of a lamp are accurately measured. After the measurements of $I_{\lambda,\mathrm{rel}}(\lambda,\theta,\varphi)$, the test lamp is then calibrated for total luminous flux, $\Phi_\mathrm{v}$, to determine the scaling factor, $k_\mathrm{scale}$. The TSRF, $\Phi_\lambda(\lambda)$, is obtained by using Equations 1 and 2,

$$\Phi_\lambda(\lambda) = k_\mathrm{scale}\int_{\varphi=0}^{2\pi}\int_{\theta=0}^{\pi} I_{\lambda,\mathrm{rel}}(\lambda,\theta,\varphi)\sin\theta\,\mathrm{d}\theta\,\mathrm{d}\varphi \quad , \tag{1}$$

$$k_\mathrm{scale} = \frac{\Phi_\mathrm{v}}{K_\mathrm{m}\int_{\lambda=0}^{\infty} V(\lambda)\int_{\varphi=0}^{2\pi}\int_{\theta=0}^{\pi} I_{\lambda,\mathrm{rel}}(\lambda,\theta,\varphi)\sin\theta\,\mathrm{d}\theta\,\mathrm{d}\varphi\,\mathrm{d}\lambda} \quad , \tag{2}$$

where $K_\mathrm{m}$ is the maximum spectral luminous efficacy being 683 lm/W, $V(\lambda)$ is the spectral luminous efficiency, and $\theta$ and $\varphi$ are polar coordinates of the goniometer. As indicated in the above two equations, the scaling of $I_{\lambda,\mathrm{rel}}(\lambda,\theta,\varphi)$ is cancelled, and the absolute scale of $\Phi_\lambda(\lambda)$ is determined by total luminous flux, $\Phi_\mathrm{v}$, making $\Phi_\lambda(\lambda)$ consistent with the NIST luminous flux unit. Thus, the TSRF realized at NIST is based on both the NIST spectral irradiance scale [3] and the NIST total luminous flux scale [4].

## 3. CALIBRATION FACILITIES

### 3.1. The Gonio-spectroradiometer for relative TSRF measurements

This gonio-spectroradiometer (Figure 1) is designed to measure incandescent type lamps for relative TSRF. It is composed of a 3-axis scanning mechanism, a fast, cooled (-10° C), charge-coupled device (CCD) array spectroradiometer, and a motion control/data acquisition computer system. The 3-axis scanning mechanism consists of a short arm for the lamp holder (used to set up the orientation of a test lamp), a long arm for the rotation of the irradiance head of the spectroradiometer around the $\theta$ axis, and a lamp holder which rotates for the $\phi$ axis. The dead angle of $\theta$ due to the mechanism of the lamp holder is ± 3 degrees (that is, $\theta$ covers from 0 to 177 degrees). Both scanning motors for $\theta$ and $\phi$ axes stop when a measurement takes place. The total measurement time for a test lamp is approximately one hour with a scanning angle interval of 10 degrees for both $\theta$ and $\phi$.

An irradiance head (a 12.7 mm diameter quartz dome-shaped diffuser) is mounted on one end of the long arm (for $\theta$) with a rotation radius of ≈1.25 m, and a light trap is mounted on the other end of the long arm. A hood is mounted on the irradiance head to minimize the errors arising from scattered ambient stray light. The irradiance head has an approximate cosine response within the field of view limited by the hood.

The CCD array spectroradiometer is placed on the fixed frame of the gonio-spectroradiometer. A 3 mm core diameter, 5 m long quartz fiber bundle is used to couple the rotating irradiance head to the stationary array spectroradiometer. The twisting effect of the fiber bundle on the responsivity of the spectroradiometer was tested to be less than 0.1 %. The spectroradiometer is calibrated against two FEL spectral irradiance standard lamps with the arm for the irradiance head oriented horizontal ( $\theta$ =90°).

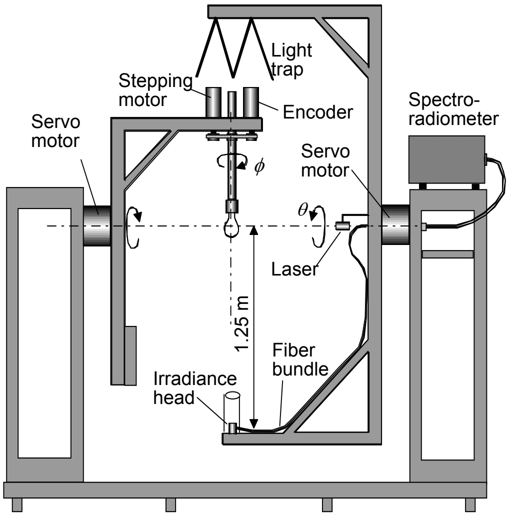

**Figure 1.** The NIST gonio-spectroradiometer

The signal and integration-time nonlinearities of the spectroradiometer were characterized and corrected. In addition, the spectroradiometer was also characterized and corrected for errors from spectral stray light using the stray-light correction matrix method [5]. The stray light corrections are applied for all measurements including the standard FEL lamps measurements (for relative spectral irradiance responsivity calibration) and the test lamp measurements at every rotation angle so that the correction is effective even if the relative SPD varies considerably at different angles. The correction for spectral stray-light errors is critical for reducing the uncertainties in the blue and UV regions if the CCT of a test lamp and that of the standard FEL lamp are considerably different, or if the SPD of a test lamp is very different in the UV region (even though the CCT is similar) compared to that of the standard FEL lamp.

### 3.2. The integrating sphere for total luminous flux measurements

The NIST 2.5 m absolute integrating sphere is used to calibrate the total luminous flux of the test lamp to obtain the absolute TSRF. This integrating sphere facility is used to provide calibration services for total luminous flux [4].

## 4. TRANSFER STANDARDS

An ideal transfer standard for TSRF should have uniform and smooth spectral power distribution with high CCT covering the intended spectral range, low aging rate, uniform spatial intensity distribution, and good reproducibility. Several types of quartz tungsten halogen (QTH) lamps have been tested for use as transfer standards of the TSRF scale. Currently 75 W miniature QTH lamps are used as the transfer standards to be issued by NIST. The miniature lamp itself has a small screw base (E10), thus a special adapter for the common medium screw base socket (E26) was designed and is provided to the customer together with the lamp so that the lamp can be used in normal integrating spheres. A photograph of a 75 W standard lamp and an E26 screw base adapter is shown in Figure 2.

**Figure 2.** Photograph of a 75 W miniature QTH transfer standard lamp and an E26 screw base adapter.

The CCT of the 75 W standard lamp is set to be ≈3100 K that is very close to that of the spectral irradiance standard FEL lamp, thus, measurement errors due to spectral stray light, the wavelength error, and the finite bandpass of the array spectroradiometer are mostly cancelled.

The 75 W standard lamp is operated on DC power at a constant current of ≈2.9 A with ≈32 V. The required stabilization time is only 5 minutes. Figure 3 is the result of an aging test of a 75 W standard lamp at six wavelengths. The increasing radiant intensity with time was the effect of aging, which was a permanent change of the lamp. The aging rate was ≈0.3 % in 24 h of operation, and was very similar at different wavelengths, so the change in CCT was measured to be < 0.5 K in 24 h.

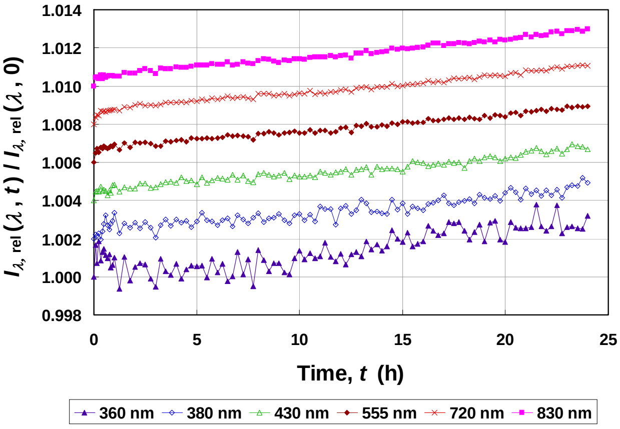

**Figure 3.** Plot of aging curves of relative radiant intensity of a 75 W standard lamp at 3100 K CCT at six wavelengths. The starting points at $t$ = 0 are set to be 1.000 for 360 nm, 1.002 for 380 nm and so on, so that the curves are not overlapped.

## 5. UNCERTAINTY OF CALIBRATION

The uncertainty of the TSRF calibrations is analyzed following the international recommendation [6]. The uncertainty budget of a TSRF calibration of the 75 W, 3100 K miniature QTH transfer standard lamps is shown in Table 1.

**Table 1.** Uncertainty budget for the TSRF calibration of a 75 W, 3100 K miniature QTH lamp

| Uncertainty component | Type | Standard uncertainty contribution (%) | | | | | |
|---|---|---|---|---|---|---|---|
| | | 360 nm | 380 nm | 430 nm | 555 nm | 720 nm | 830 nm |
| 1. Calibration of luminous flux of the test lamp (see Reference 4) | B | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 |
| 2. Standard FEL lamp (see Reference 3) | B | 0.63 | 0.61 | 0.51 | 0.38 | 0.32 | 0.30 |
| 3. Gonio-spectroradiometer | B | 0.41 | 0.29 | 0.19 | 0.19 | 0.19 | 0.19 |
| 4. Calibration of the spectroradiometer | B | 0.34 | 0.25 | 0.21 | 0.18 | 0.18 | 0.18 |
| 5. Measurement of the test lamp | B | 0.15 | 0.11 | 0.11 | 0.11 | 0.11 | 0.15 |
| Relative combined uncertainty of TSRF (%) | | 0.88 | 0.77 | 0.64 | 0.54 | 0.50 | 0.50 |
| **Relative expanded uncertainty (*k*=2) of TSRF (%)** | | **1.8** | **1.5** | **1.3** | **1.1** | **1.0** | **1.0** |

## 6. CONCLUSION

We have realized TSRF scale, developed transfer standard lamps, and established the calibration service for the spectral range of 360 nm to 830 nm. The TSRF is realized by using a relative gonio-spectroradiometry method that is based on both the spectral irradiance scale and the total luminous flux scale. The current transfer standard lamps are 75 W, 3100 K miniature QTH lamps with an aging rate of approximately 0.3 % in 24 h of operation. The relative expanded uncertainties (*k*=2) of TSRF of a transfer standard lamp are less than 2 % in the UV region and approximately 1% in the visible and near infrared regions. The uncertainties in the UV region will be reduced by using an array spectroradiometer with high spectral irradiance responsivity in the UV region.

The TSRF scale can also be realized by applying the Absolute Integrating Sphere method spectrally, using an integrating sphere equipped with a spectroradiometer and an external spectral irradiance standard lamp. This approach is under development and is to be compared to the gonio-spectroradiometry method in the future.

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