Responsivity Calibration Methods for 365-nm Irradiance Meters

Thomas C. Larason, Steven W. Brown, George P. Eppeldauer, and Keith R. Lykke

***Abstract*—Two detector-based responsivity calibration methods have been compared at the National Institute of Standards and Technology for ultraviolet irradiance meters in the 365-nm spectral region. Both methods are based on an electrical substitution high-accuracy cryogenic radiometer, but utilize different facilities and transfer standards. One facility is a monochromator-based spectral-power responsivity measuring system utilizing an aperture-scanning method, while the second is a tunable-laser and integrating-sphere source system using a light-trapping silicon transfer detector with a known aperture area. The first reported comparison of these two fundamentally different methods agreed to 1%–2% near the peak and long wavelength side of the bandpass curves which is comparable to their expanded ($k = 2$) uncertainties.**

***Index Terms*—Calibration, irradiance, photodetectors, radiometry, spectral responsivity, ultraviolet.**

I. Introduction

Ultraviolet (UV) irradiance meters have a broad range of industrial applications, from semiconductor manufacturing (photolithography) to nondestructive testing to curing inks and coatings used in high-volume printing. Increasing industrial application of UV irradiance measurements has led to a steady increase in the number of calibration requests to the National Institute of Standards and Technology (NIST) for UV irradiance meters, particularly those used to measure 365-nm radiation. The measured signal from a given irradiance meter is the integral of the source distribution and the meter spectral-responsivity

$$i = \int_{\lambda} E(\lambda) \cdot S(\lambda) \cdot d\lambda \tag{1}$$

where

i signal;
$E(\lambda)$ spectral irradiance from the source measured;
$S(\lambda)$ spectral irradiance responsivity of the meter.

Knowledge of the spectral irradiance responsivity of a meter is critical for high-accuracy measurements of sources with different spectral power distributions. This is especially critical if more than one model of irradiance meter (i.e., different responsivities) is used in the measurement chain.

NIST currently has two facilities for measuring the spectral responsivity of UV irradiance meters: the UV Spectral Comparator Facility (UV SCF) [1] and the facility for Spectral Irradiance and Radiance Responsivity Calibrations with Uniform Sources (SIRCUS) [2]. Diagrams of these facilities are shown in Figs. 1 and 2, respectively. The irradiance scale of each facility is based on the high-accuracy cryogenic radiometer (HACR), the NIST primary standard cryogenic radiometer. While similar methods have been reported elsewhere [3], [4] this is the first direct comparison of these two fundamentally different techniques.

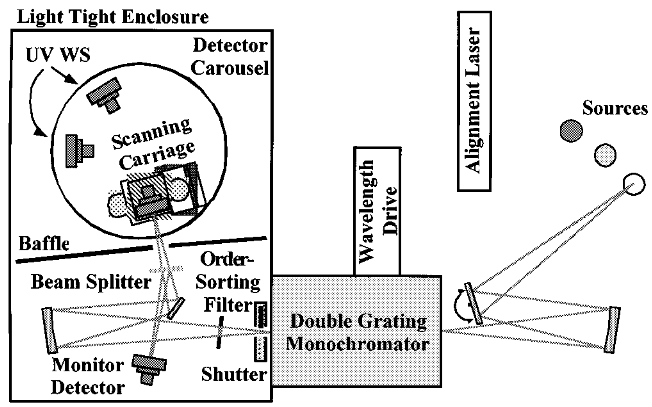

Fig. 1. UV SCF diagram. The irradiance meter-under-test is mounted on the scanning carriage. Spectral-responsivity comparison is accomplished by rotating the detector carousel to place one of the UV working standards (WS) into the beam. The order-sorting filter removes second-order light beyond 400 nm.

A number of 365-nm irradiance meters with different optical diffusers and spectral responsivities were measured in both NIST facilities, and their responsivities compared to verify the irradiance calibration uncertainties of the UV SCF and to refine the SIRCUS irradiance calibration procedures. The results of this intercomparison are shown here for two representative irradiance meters. One irradiance meter, designated IM #1, was a commercial device with an approximately 50-nm bandpass (FWHM). The second, IM #2, was a NIST designed transfer standard with an approximately 25-nm bandpass (FWHM).

II. UV SCF Measurements

The first facility, the UV SCF, is a monochromator-based system developed in the early 1990s to measure the absolute spectral-responsivity and uniformity of photodetectors in the 200–500 nm spectral region. The principal component is a computer-controlled $1/4$-m focal length $f/5$, double-grating monochromator with a 3-nm bandpass. A variety of sources (typically an argon arc) can be selected using a computer-controlled turning mirror to align the source with the spherical mirror that focuses the light onto the monochromator's entrance slit. The argon arc and monochromator operate as a tunable

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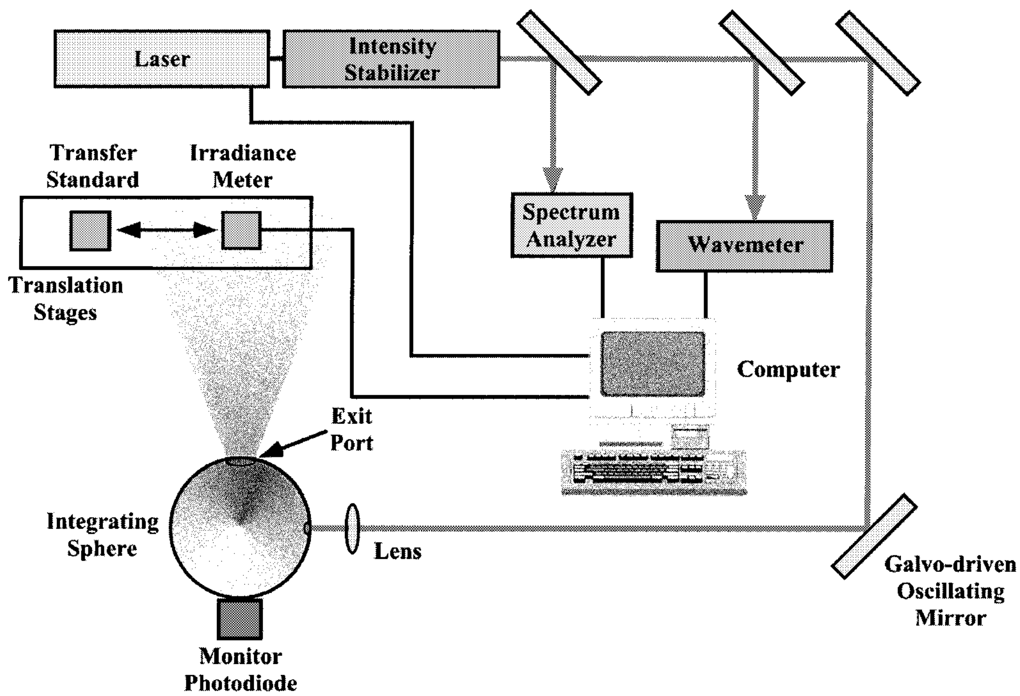

Fig. 2. SIRCUS diagram. The irradiance meter calibration is performed by direct substitution with the irradiance transfer standard.

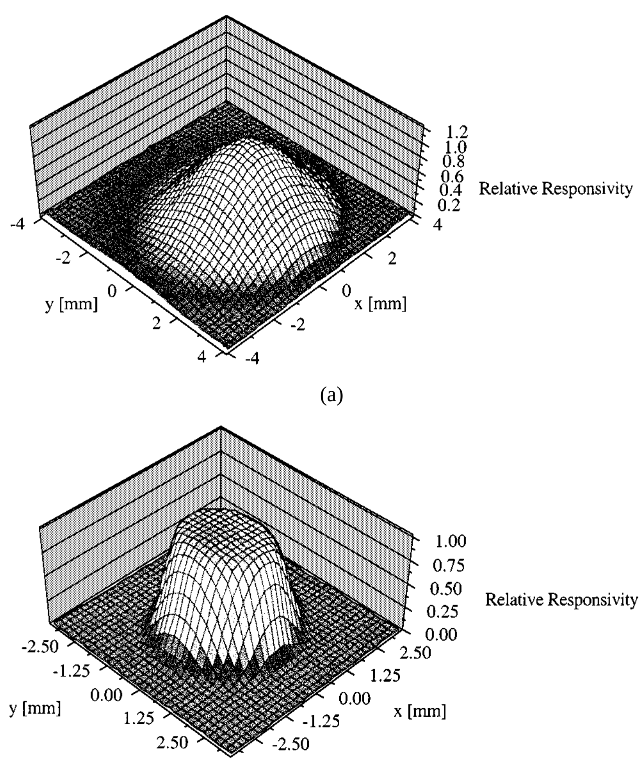

Fig. 3. Surface (3-D) plot of typical 365-nm detectors having different input geometries and diffuser materials. (a) Irradiance Meter #1. (b) Irradiance Meter #2.

monochromatic source. The typical entrance and exit slits are circular 1.5-mm apertures. A shutter is located just after the exit slit. Inside a light-tight box, a rotary stage is used to place an irradiance meter or silicon working standard at the focal plane. The exit aperture is imaged onto the detectors resulting in an oval beam of axis diameters 2.0 and 2.5 mm. The beam was centered on, and underfilled the irradiance meter apertures and working standard detectors. A pair of orthogonal linear-positioning stages translates the irradiance meters for both alignment to the optical axis and scanning for uniformity measurements. The stages' travel range is 50 mm with a manufacturer-specified resolution of 0.1 μm and an accuracy of 0.25 μm per 25 mm. Each detector is mounted to allow its position to be adjusted along the optical axis for focusing. A gimbal mount allows for the rotation and tilt of each detector to be adjusted for perpendicular alignment to the optical axis. The output current of each detector is converted to a voltage by a transimpedance amplifier and measured by a digital voltmeter. A beam splitter directs approximately 10% of the beam to a silicon monitor photodiode. Simultaneously measuring the monitor and detector signals compensates for any source fluctuations.

The absolute spectral power responsivity of the irradiance meters was determined from 300 to 400 nm in 1-nm increments by direct substitution comparisons to the silicon photodiode working standards. The effective aperture area of each irradiance meter was determined by scanning the monochromator output beam over the irradiance meter's entrance aperture in 0.2-mm increments to simulate a uniform irradiance. This method has been used by NIST since 1991 [5]. It has been shown [6] that the effective aperture area is the ratio of the total signal i summed over the scanned area (total irradiance responsivity) to the product of the total beam power Φ $[W]$ and the average spectral power responsivity $s(\lambda)$, within the active area of the aperture

$$A = \frac{\sum i(x,y)\Delta x \Delta y}{\Phi \cdot s(\lambda)} \tag{2}$$

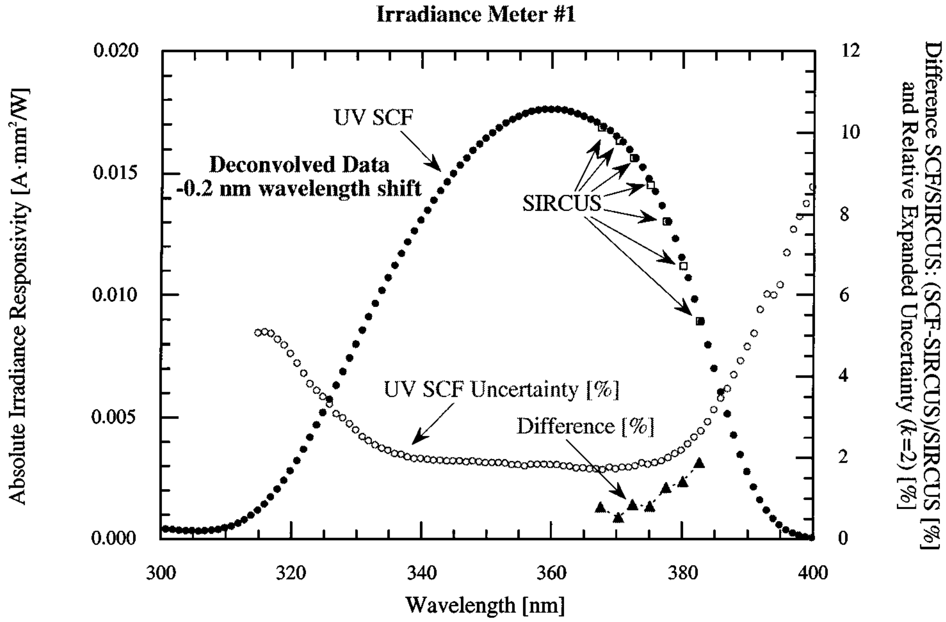

Fig. 4. Plot of irradiance responsivity, UV SCF relative expanded $(k = 2)$ uncertainties, and relative differences for the two methods for irradiance meter #1. Irradiance meter #1 is a typical commercial 365-nm detector with an ≈50-nm bandpass (FWHM).

where Δx and Δy are the small steps taken to completely overscan the aperture. The spectral irradiance responsivity was the product of the effective aperture area and the spectral power responsivity [7].

The aperture-scanning method can be applied to irradiance meters with nonuniform spatial responsivities. Fig. 3 shows the different spatial responsivity uniformities of the two irradiance meters. The large differences are due to different input geometries and diffuser materials. The data are from the UV SCF aperture scans at 0.2-mm steps.

The expanded uncertainty for the UV SCF measurements varies with wavelength, is a minimum at the peak responsivity, and increases at other wavelengths due primarily to wavelength uncertainties and the decreasing signal-to-noise ratio. The expanded uncertainty $(k = 2)$ for both irradiance meters at 365 nm was ≈2%. The uncertainties increased in regions of low responsivity to ≈10%. These higher uncertainties do not contribute significantly to the overall measurement uncertainty of broadband sources.

III. SIRCUS Measurements

Recently, a second facility—the SIRCUS—has been developed. The SIRCUS employs a variety of tunable lasers (Ti:Sapphire and dye lasers) at both fundamental and frequency-doubled wavelengths to cover the spectral range from 275 to 1000 nm. The output of the laser was sent through an intensity stabilizer and a portion into a wavemeter. From the intensity stabilizer, the beam was sent through a lens into a 5-cm diameter integrating sphere. The 8-mm diameter exit port of the sphere approximated a point source, producing a uniform irradiance on the detectors. A beam splitter and monitor silicon photodiode were used to correct for source fluctuations during the measurements. A computer-controlled linear-positioning stage positioned the detectors in front of the integrating sphere exit port at a distance of 25 cm.

The spectral power responsivity of the silicon trap irradiance transfer standard was measured directly against the HACR. The transfer standard was equipped with a known-area aperture. The radiant intensity of the sphere was calculated from the transfer standard power responsivity, aperture area, and sphere to transfer standard distance. The irradiance meters were substituted for the transfer standard in the uniform irradiance of the integrating sphere source. The laser was tuned between 368 and 385 nm, with roughly 2.5-nm steps. The uncertainty for the SIRCUS results was ≈1%, mainly due to the measurement reproducibility.

IV. Results and Discussion

The spectral irradiance responsivity, in A·mm^2/W, of the two irradiance meters is presented in Figs. 4 and 5. The relative expanded uncertainty $(k = 2)$ in the SCF measurements and the relative difference between the SCF and SIRCUS measurements are also shown in Figs. 4 and 5. The two methods using the UV SCF and SIRCUS agreed to the 1% to 2% level in the peak portion of the bandpass curves, as shown in Figs. 4 and 5. This is within the expanded $(k = 2)$ uncertainties for the responsivity measurements. The difference increases at the lower values of the responsivity to just greater than the expanded uncertainties. The UV SCF wavelength uncertainty is larger than that of SIRCUS and may be a factor in the observed differences. Since the UV SCF data were taken in 1-nm intervals and the monochromator bandpass is 3 nm, the data were deconvolved using the monochromator slit-function. A 0.1–0.2 nm wavelength shift in the deconvoluted UV SCF data brings the measurements between these two facilities into agreement on the 1%–2% level over the entire spectral range. The calibration of

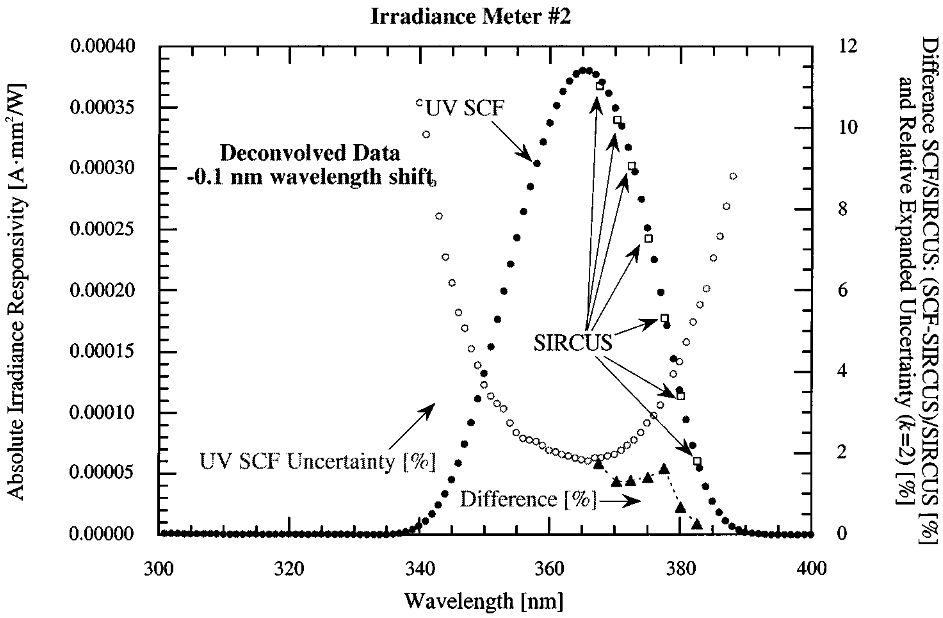

Fig. 5. Plot of irradiance responsivity, UV SCF relative expanded $(k = 2)$ uncertainties, and relative differences for the two methods for irradiance meter #2. Irradiance meter #2 is a NIST designed transfer standard with a ≈25-nm bandpass (FWHM).

the monochromator wavelength scale was checked with spectral line lamps and showed agreement to better than 0.1 nm over this spectral region. The wavelength shift was −0.2 nm for meter #1 and −0.1 nm for meter #2. One would expect the same shift for each irradiance meter if the wavelength scale were indeed the cause of the differences observed. A hypothesized cause is that the effective aperture area changes with wavelength. Thus, it may be necessary to scan the aperture not only at the peak responsivity, but also on either side of the peak. A definitive answer to the observed difference is currently under investigation.

The two independent methods discussed both have advantages and disadvantages. The UV SCF can easily scan spectrally over a wide range, but is limited by low flux levels, the relatively wide spectral bandwidth for filter cutoff regions, and the extremely long time intervals (4–6 h) needed for the spatial scanning of the aperture. The SIRCUS facility has better wavelength accuracy, higher flux, faster measurement comparison (only a few minutes per data point since there is no spatial scanning), and most importantly, lower uncertainty. The lower uncertainty of the SIRCUS facility gives an independent verification of the aperture-scanning method. The major disadvantage of the SIRCUS is the number of measurements needed to trace the responsivity of an irradiance meter. This is especially true over a broad wavelength range where several lasers may be needed.

Because of the labor-intensive nature of the SIRCUS measurements, a third method is proposed, combining the best features of the previous two methods. The UV SCF would measure the relative spectral-responsivity over a wide wavelength range, then the SIRCUS facility would measure a relatively small number of "tie" points at selected wavelengths in the center of the irradiance meter bandpass, in the tails, and in the "cutoff" regions. Measurements using this method would benefit from the lower uncertainties of the SIRCUS facility measurements and the broad spectral coverage of the UV SCF all within a fraction of the time required by the first two methods discussed here.

V. Conclusion

NIST can provide 365-nm irradiance meter spectral-responsivity measurements to support a variety of industrial and laboratory applications using either a monochromator-based facility or tunable-laser and integrating-sphere facility. The agreement between these two fundamentally different methods in this first reported comparison is 1% to 2% in the peak portion of the bandpass curves which is comparable to their expanded $(k = 2)$ uncertainties. The SIRCUS uncertainties are lower than the UV SCF with the potential for 0.1% uncertainties in the future. This will greatly reduce the calibration uncertainties NIST provides for UV irradiance meters in the future.

References

[1] T. C. Larason, S. S. Bruce, and A. C. Parr, *Spectroradiometric Detector Measurements: Part I—Ultraviolet Detectors and Part II—Visible to Near-Infrared Detectors*. Washington, DC: Nat. Inst. Stand. Technol., U.S. Govt. Printing Office, 1998, Spec. Publ. 250-41.

[2] S. W. Brown, G. P. Eppeldauer, and K. R. Lykke, "NIST facility for spectral irradiance and radiance response calibrations with a uniform source," *Metrologia*, vol. 37, pp. 579–582, 2000.

[3] C. A. Schrama and H. Reijn, "Novel calibration method for filter radiometers," *Metrologia*, vol. 36, pp. 179–182, 1999.

[4] T. M. Hunt, N. P. Fox, W. S. Hartree, and N. M. Durant, "Evaluating the performance of filter radiometers as a means of improving the uncertainty of ultraviolet measurements," *Metrologia*, vol. 35, pp. 345–351, 1998.

[5] J. M. Bridges and C. L. Cromer, "Final Report on Calibration and Characterization of I-Line Exposure Meters," SEMATECH, Austin, TX, Rep. 91 090 678A-ENG, Oct. 17, 1991.

[6] C. L. Cromer, G. Eppeldauer, J. E. Hardis, T. C. Larason, Y. Ohno, and A. C. Parr, "The NIST detector-based luminous intensity scale," *J. Res. Nat. Inst. Stand. Technol.*, vol. 101, pp. 109–132, 1996.

[7] G. P. Eppeldauer, M. Racz, and T. C. Larason, "Optical characterization of diffuser-input standard irradiance meters," *Proc. Int. Soc. Opt. Eng.*, vol. 3573, pp. 220–224, 1998.