Uncertainty Analysis of Spectral Irradiance Reference Standards Used for NREL Calibrations

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NREL
NATIONAL RENEWABLE ENERGY LABORATORY

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Executive Summary

Spectral irradiance produced by lamp standards such as the National Institute of Standards and Technology (NIST) FEL-type tungsten halogen lamps are used to calibrate spectroradiometers at the National Renewable Energy Laboratory. Spectroradiometers are often used to characterize spectral irradiance of solar simulators, which in turn are used to characterize photovoltaic device performance, e.g., power output and spectral response. Therefore, quantifying the calibration uncertainty of spectroradiometers is critical to understanding photovoltaic system performance.

In this study, we attempted to reproduce the NIST-reported input variables, including the calibration uncertainty in spectral irradiance for a standard NIST lamp, and quantify uncertainty for measurement setup at the Optical Metrology Laboratory at the National Renewable Energy Laboratory. The NIST primary FEL lamp standard calibration uncertainty is increased by factors such as temporal instability of the lamp current and voltage, stray light, and distance. We described these sources of uncertainty, and we performed an uncertainty analysis of the spectral irradiance following the International Organization for Standardization Guide to the Expression of Uncertainty in Measurement method. The combined expanded uncertainty of the spectral irradiance with a 95% level of confidence ranges from approximately 1% to 2% for the wavelength range from 250 nm to 2400 nm. However, the analysis in this report covers only the uncertainty of spectral irradiances produced from a standard lamp as a result of uncertainties in current, voltage, distance, stray light, and the NIST calibration values. This analysis does not cover the inherent uncertainties in various spectroradiometer systems and/or interpolation of spectral irradiance not included in the reported NIST wavelengths. Users are advised to consider other sources of uncertainty specific to their calibration setup and spectroradiometer.

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1 Introduction

Accurate characterization of photovoltaic (PV) device spectral response is critical to improving photovoltaic (PV) conversion efficiencies and reducing investment risks for PV industries. Spectral irradiance measured by a spectroradiometer is used in international standards for classification of solar simulators and spectral mismatch corrections (Andreas et al. 2008). Thus, measurements of spectral irradiance with quantified uncertainty using well-calibrated spectroradiometers improve the accuracy of PV performance measurements. Before determining the measurement uncertainty of a spectroradiometer used to characterize solar simulators, one should establish the uncertainty of the optical measurement setup using a National Institute of Standards and Technology (NIST) standard lamp. The spectral irradiances of standard lamps obtained from NIST are supplied as measured quantity values (VIM §2.10) with associated measurement uncertainty (VIM §2.26). This report attempted to reproduce these results at the National Renewable Energy Laboratory (NREL) Optical Metrology Laboratory. Based on the measurement setup and equipment used at NREL, a comprehensive uncertainty analysis was performed by developing a measurement model for spectral irradiance (the measurand, VIM §2.3) and determining the sensitivity coefficient for each uncertain input to the model. Further, the measurement model contains the NIST-reported values, and NREL attempted to reproduce these values; however, in the process there was a difference between the NIST-reported spectral irradiance ($W_{\lambda i, NIST}$) and NREL-calculated spectral irradiance ($W_{\lambda i, NREL}$). This difference could have been avoided by using the same laboratory setup as NIST, but it is impractical. Because of this difference in the measurement setup between NIST and NREL, there was a spectral irradiance difference that contributed to the nonequivalence between the NIST-reported and NREL-calculated irradiance. In this report, we included the difference between the two parameters as an additional source of uncertainty when using NIST-calibrated spectral irradiance values.

The uncertainty statement plays an important role in the measurement traceability where the results relate to a reference through unbroken chain of measurement (JCGM/WG 1 2008; Reda 2011). In this report, uncertainty critical for a proper calibration prior to using a spectroradiometer was analyzed using the International Organization for Standardization Guide to the Expression of Uncertainty in Measurement (GUM) method by categorizing the evaluation of uncertainties as Type A or Type B (VIM §2.28 & §2.29). To be clear, this uncertainty analysis covered only the spectral irradiances produced by a standard lamp in a spectroradiometer calibration setup, not the inherent uncertainties in spectroradiometer measurement systems. Users should include additional uncertainty components when calibrating a specific spectroradiometer (for example, wavelength accuracy) and when the spectroradiometer is used for spectral measurements of unknown sources.

2 Method

2.1 Lamp Setup for Spectroradiometer Calibration

NIST provides a tungsten-filament, 1,000 W quartz-halogen FEL standard spectral irradiance lamp that has been calibrated at 31 wavelengths ranging from 250 to 2,400 nm. The calibration distance is 50 cm from the lamp posts to the detector of a reference spectroradiometer with the lamp operated by a constant current supply set at 8 A. NREL reproduced the measurement criteria specified by NIST (Table 1) with minimum uncertainty using a stable computer-controlled power supply, monitoring the power supply voltage setting and lamp current with a precision current shunt in series with the lamp. To ensure a reproducible calibration, laser-aligned geometry and a calibrated distance bar were used to set up the lamp and a spectroradiometer under test on an optical table (Figure 1). Further, NREL performed calibrations under similar meteorological conditions as NIST. There is a difference in relative humidty between the NIST and NREL calibration laboratories; however, the NIST-reported wavelength ranges were not affected by relative humidity changes.

Table 1. Spectral Irradiance and Measurement Setup Input Parameters From NIST and NREL

Input Parameters	Units	NIST-Reported	NREL Calibration Setup
$\mathbf{V_{f,NREL}}$	V	---	111.14
$\mathbf{VR_{,NREL}}$	V	---	0.080025
$\mathbf{R_{,NREL}}$	Ω	---	0.0099986
$\mathbf{D_{,NREL}}$	m	---	0.4998
$\mathbf{V_{f,NIST}}$	V	110.55	---
$\mathbf{I_{f,NIST}}$	A	8.000	---
$\mathbf{D_{,NIST}}$	m	0.5000	---
$\mathbf{W_{\lambda i,\ NIST}}$	$W/m^2/nm$	Reported: Wavelength dependent	Calculated: Wavelength dependent ($\mathbf{W_{\lambda i,\ NREL}}$)

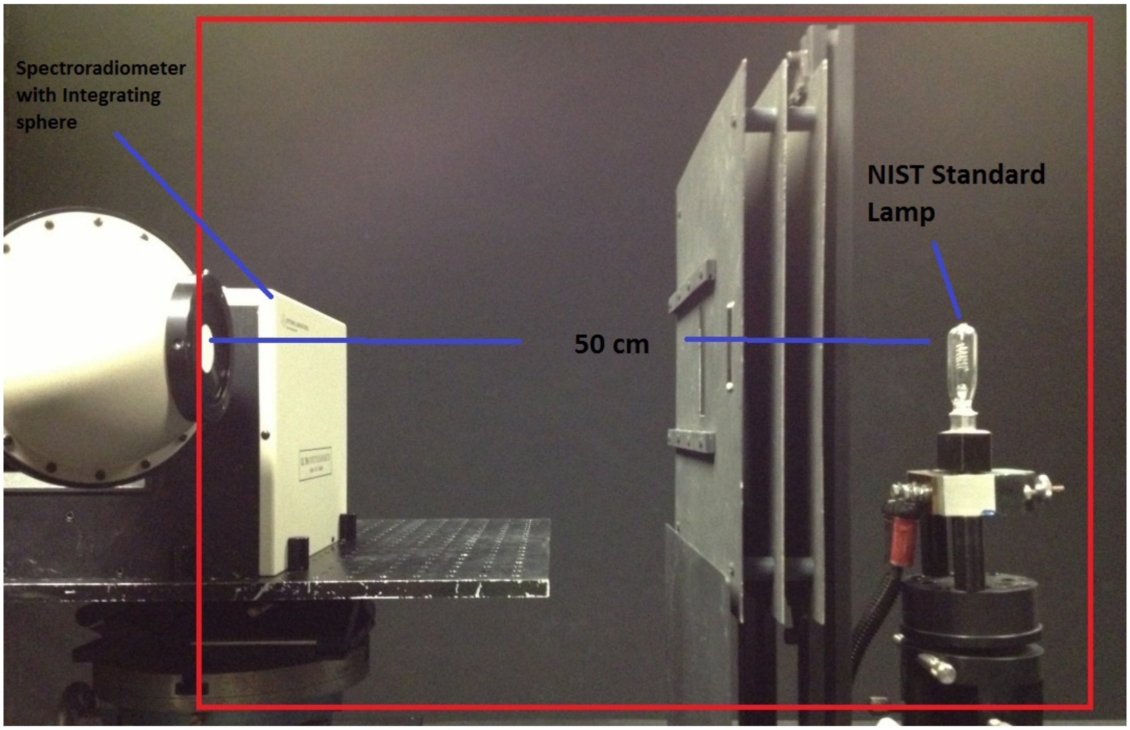

Figure 1. Measurement setup of spectral irradiance using a NIST standard lamp and area of study included in this report (red square).

The NREL measurement setup had some limitation in reproducing the setup provided by the NIST calibration report. For instance, NREL's distance bar was constructed by the NREL machine shop many years ago. Because of limitations of the machine shop at the time, the bar is 0.0002 m short of the desired 0.5 m. Also, we determined a 0.2% expanded uncertainty from our experience and manufacturer specification that is equivalent to 1 mm distance. The manufacturer's specification was also obtained for the voltage at the filament of the NIST lamp, which is 0.0034%, and 0.0087% and 0.01% for measured voltage across the standard resistor and resistance, respectively. Further, many efforts have been made at NREL to minimize stray light. The reflectance of all materials in the lab has been measured from 300 nm to 2,400 nm to understand the reflectance characteristics. Many surfaces that have been black anodized by a machine shop (or other methods) have been found to be highly reflective (up to 80%) above 700 nm. These surfaces, as well as other highly reflective surfaces in the lab, were removed from the field of view of the unit under test. NREL has been using special laser curtains and other surfaces that have been measured to be flat black across the entire wavelength range, with reflectance typically less than approximately 5%. NREL also installed a 12-inch-diameter light tunnel system (not shown in Figure 1) between the baffle system and unit under test to remove reflected stray light in the room from entering the field of view of the unit under test. The only reflected surface that could not be removed from the field of view was stray light that could be generated by light reflecting directly off the unit under test. Many cosine receivers, such as integrating spheres, will also have light exiting in random directions. It is assumed that a minimum of three reflections would be necessary for this stray light to re-enter the unit under test. The first reflection from the unit under test was assumed to be the worst case, at 100% reflectance. The other two reflections were from flat black surfaces at 5% reflectance, which gave a worst-case stray light estimate of 0.25%. Therefore, such differences were accounted for in the measurement model and uncertainty calculation of this report.

The spectral irradiance distribution is affected by the electrical current flowing through the filament of the FEL lamp. Therefore, NREL performed a test by changing the current by 5mA and examined the effect of the change on spectral irradiance. Because of the current control capability at NREL, there could be error in the set current up to +/- 2.5mA. Therefore, a worst-case value of 5mA offset was used for this test. The resulting spectral irradiance change (300 nm to 1,630 nm) for the FEL lamp operating at 5mA delta was about 0.2% to 0.4% in the uncertainty.

2.2 Uncertainty Calculation

2.2.1 Measurement Model

As a first step in the uncertainty analysis, a measurement model was developed that gives the measurand (spectral irradiance) as a function of the input quantities related to the calibration setup (Equation 1) (JCGM/WG 1 2008).

$$W_{\lambda i,\,NREL} = \frac{V_{f,\,NREL} * I_{f,\,NREL} * (1 + f_{s,\,NREL}) * \dfrac{W_{\lambda i,\,NIST}}{V_{f,\,NIST} * I_{f,\,NIST}}}{(D_{NREL} / D_{NIST})^2} \tag{1}$$

where

- $W_{\lambda i,NREL}$ is the calibration spectral irradiance at the i^{th} wavelength at NREL in W m^{-2}/nm (calculated)
- $V_{f,NREL}$ is the measured voltage at the filament of NIST lamp, in V
- $I_{f,NREL}$ is the calculated filament current, in A
- $f_{s,NREL}$ is a fraction of the stray light estimate (0.25%) contribution to the total NREL irradiance, W_{NREL}, in W/m^2

$$W_{NREL} = (V_{f,\,NREL} * I_{f,\,NREL} * (1 + 0.0025)) / D_{NREL}^2 \tag{2}$$

- D_{NREL} is the distance between the lamp and the unit under test at NREL, in m
- $W_{\lambda i,\,NIST}$ is the spectral irradiance at the i^{th} wavelength measured at NIST, in Wm^{-2}/nm
- $V_{f,\,NIST}$ is the reference voltage across the filament measured at NIST, in V
- $I_{f,\,NIST}$ is the reference filament current measured at NIST, in A

$$I_{f,\,NREL} = \frac{V_{R,\,NREL}}{R_{NREL}} \tag{3}$$

where

- $V_{R,NREL}$ is the measured voltage across the standard resistor in volts, and R_{NREL} is the resistance in ohms
- D_{NIST} is the distance between the lamp and NIST reference detector at NIST, in m

In Equation (1), the power and alignment parameters from NIST are constant values (D_{NIST} =0.50 m, $V_{f,NIST}$= 110.55 V, $I_{f,NIST}$= 8 A) and they were obtained from the calibration certificate of the primary NIST FEL lamp. Therefore, the values can be described in the following equation:

$$C_{NIST} = \frac{D_{NIST}^{2}}{V_{f,NIST} * I_{f,NIST}} = Constant \tag{4}$$

where C_{NIST} is constant. However, the irradiance value provided by NIST is wavelength specific for each lamp and was not included in Equation (4).

Then Equation (1) could be rewritten as

$$W_{\lambda i,NREL} = \frac{V_{f,NREL} * I_{f,NREL} * (1 + f_{s,NREL}) * C_{NIST} * W_{\lambda i,NIST}}{(D_{NREL})^{2}} \tag{5}$$

Under ideal conditions using the measurement model, the calculated value irradiance ($W_{\lambda i, NREL}$) and NIST-reported irradiance ($W_{\lambda i, NIST}$) should be equal. This could have been achieved by replicating the same calibration setup as NIST and obtaining the same irradiance output at each reported wavelength; however, because of the slight difference in the measurement setup at NREL as compared to NIST, there was irradiance difference that contributed to the nonequivalence between the NIST-reported and NREL-calculated irradiances. Therefore, in this report, we included the difference between the two parameters as an additional source of uncertainty when using NIST-calibrated spectral irradiance values (Table 2).

According to the GUM method, there are two types of uncertainty evaluations, designated as Type A and Type B (Table 2). The former employs statistical methods; the latter uses any other means such as a manufacture specification or professional judgment. For this study, the input variables were assumed to be uncorrelated. Because all variables were measured or estimated using independent methods, there was no correlation.

Table 2. Contributing Components to the Uncertainty

Source of Uncertainty	Degree of Freedom	Type	Distribution
$V_{f,NREL}$	∞	B	Rectangular
$V_{R,NREL}$	∞	B	Rectangular
R_{NREL}	∞	B	Rectangular
D_{NREL}	∞	B	Rectangular
$W_{\lambda i, NIST}$	∞	B	Normal
$W_{\lambda i, NREL}$ - $W_{\lambda i, NIST}$ (nonequivalence)	∞	B	Rectangular
Estimated stray light (f_s)	∞	B	Rectangular
Randomness (standard deviation) of ($V_{f,NREL}$*$I_{f,NREL}$)	411	A	Normal

Aside from the reported irradiance uncertainty from NIST and the Type A randomness of the $V_{f,\ NREL} * I_{f,\ NREL}$, the remaining sources of uncertainties were considered to have rectangular distribution. Where there was scarce information of the underlying probability distribution, rectangular distribution extended to reasonable bounds beyond which it is improbable that the contribution to the uncertainty lies. This distribution conservatively estimates uncertainty.

2.2.2 Sources of Uncertainties

The following sources were considered in the uncertainty analysis:

1. Stability of the light source
2. Distance from the lamp post to the unit under test
3. Stray light
4. Nonequivalence between the calculated NREL irradiance ($W_{\lambda i,\ NREL}$) and the NIST-reported irradiance ($W_{\lambda i,\ NIST}$).

The voltage from the multimeter and resistance from the shunt resistor measurements at the NREL Optical Metrology Laboratory were related to the stability of the light source. There was also uncertainty in the distance gauge used to establish the distance between the standard lamp and the cosine receiver of the spectroradiometer. Further, there was uncertainty as a result of stray light generated by reflective surfaces in the laboratory that were in the field of view of the spectroradiometer. As mentioned in Section 2.2.1, there was uncertainty as a result of nonequivalence between the NREL-calculated spectral irradiance and NIST-reported value, and this was included as a source of uncertainty. The calibration certificate from NIST provides uncertainty on the spectral irradiance of the standard NIST lamp at several specific wavelengths. A rectangular distribution was associated with the above uncertainty.

2.2.3 Calculating Sensitivity Coefficients

The GUM method includes calculating the sensitivity coefficients (*C*) of the variables in the measurement equation. These coefficients affect the contribution of each input factor to the combined uncertainty of the spectral irradiance at a particular wavelength. Therefore, the sensitivity coefficient for each input was calculated by partially differentiating Equation (5) with respect to each input.

$$\frac{\partial W_{\lambda i,NREL}}{\partial V_{f,NREL}} = CV_{f,NREL} = \frac{V_{R,NREL} * (1 + f_{s,NREL}) * C_{NIST} * W_{\lambda i,NIST}}{R_{NREL} * (D_{NREL})^2} \tag{6}$$

$$\frac{\partial W_{\lambda i,NREL}}{\partial V_{R,NREL}} = CV_{R,NREL} = \frac{V_{f,NREL} * (1 + f_{s,NREL}) * C_{NIST} * W_{\lambda i,NIST}}{R_{NREL} * (D_{NREL})^2} \tag{7}$$

$$\frac{\partial W_{\lambda i,NREL}}{\partial R_{NREL}} = CR_{NREL} = -\frac{V_{f,NREL} * V_{R,NREL} * (1 + f_{s,NREL}) * C_{NIST} * W_{\lambda i,NIST} * D_{NREL}^2}{(R_{NREL} * D_{NREL}^2)^2} \tag{8}$$

$$\frac{\partial W_{\lambda i,NREL}}{\partial D_{NREL}} = CD_{NREL} = -\frac{V_{f,NREL} * V_{R,NREL} * (1 + f_{s,NREL}) * C_{NIST} * W_{\lambda i,NIST} * R * 2 * D_{NREL}}{(R_{NREL} * D_{NREL}^2)^2} \tag{9}$$

$$\frac{\partial W_{\lambda i,NREL}}{\partial f_{s,NREL}} = Cf_{s,NREL} = \frac{V_{f,NREL} * V_{R,NREL} * C_{NIST} * W_{\lambda i,NIST}}{R_{NREL} * (D_{NREL})^2} \tag{10}$$

$$\frac{\partial W_{\lambda i,NREL}}{\partial W_{\lambda i,NIST}} = CW_{\lambda i,NIST} = \frac{V_{f,NREL} * V_{R,NREL} * (1 + f_{s,NREL}) * C_{NIST}}{R_{NREL} * (D_{NREL})^2} \tag{11}$$

where $CV_{f,NREL}$, $CV_{R,NREL,}$ $CR_{,NREL}$,CD_{NREL}, $Cf_{s,NREL,}$ and $CW_{\lambda i,NIST}$ are sensitivity coefficients of $V_{f,NREL}$, $V_{R,NREL,}$ R_{NREL}, D_{NREL}, $f_{s,NREL,}$ and $W_{\lambda i,NIST}$, respectively.

However, for sources of uncertainties that were not associated with the measurement model, the sensitivity coefficient for each parameter had a value of unity and the component uncertainty was equivalent to the standard uncertainty. These sources of uncertainty variables included the nonequivalence between the NREL-calculated spectral irradiance and NIST-reported spectral irradiance, and the randomness or standard deviation of the NREL V_f * I_f parameters.

2.2.4 Standard Uncertainty

Standard uncertainty of the Type B uncertainty (*u*) was calculated for individual inputs using Equation (12). Where information of the expanded uncertainties for such inputs were estimates based on our experience or calibration results, the GUM method assumed a rectangular distribution of the Type B parameters (estimates) (JCGM/WG 1 2008 ; Reda 2011; Taylor and Kuyatt 1994) and divided the expanded uncertainty (*U*) of the individual parameter by square root of three. The calibration results had a normal distribution, and the expanded uncertainty was divided by two.

$$u = \frac{U}{\sqrt{3}} \quad \text{or} \quad u = \frac{U}{2} \tag{12}$$

Type A standard uncertainty was calculated by taking repeated indications (VIM §4.1) of the input quantity value, and the sample mean and sample standard deviation (SD) could be calculated. The standard uncertainty (u) was approximated by

$$u = \frac{SD}{\sqrt{n}} \tag{13}$$

where n equals the number of repeated indications of the quantity value.

2.2.5 Combined Standard Uncertainty

Individual standard uncertainties and their respective sensitivity coefficients can be combined using the root sum of the squares method (JCGM/WG 1 2008 and Kacker, Sommer, and Kessel 2007). The result is called the combined standard uncertainty, as shown in the following equation (u is for all Type B and Type A standard uncertainty values), where C is unity for Type A and, in some cases, for Type B standard uncertainty (e.g., the nonequivalence between NIST irradiance ($W_{\lambda i,NIST}$) and NREL-calculated irradiance ($W_{\lambda i,NREL}$)).

$$u = \sqrt{\sum_{j=0}^{n-1} (u * C)^2} \tag{14}$$

2.2.6 Expanded Uncertainty

The expanded uncertainty (U_{95}) was calculated by multiplying the combined uncertainty (u_j) by a coverage factor (k=1.96, for infinite degrees of freedom), which represents a 95% confidence level.

$$U_{95} = u * k \tag{15}$$

The expanded uncertainty U_{95} as a percentage was then calculated as

$$U_{95\%} = \frac{U_{95}}{W_{\lambda i,\, NIST}} * 100 \tag{16}$$

3 Results

The estimated uncertainty determined from this study followed rigorous measurement protocols to ensure traceability to *Système International d'Unités*. The estimated uncertainty results of 10 wavelengths are summarized in Table 3. NIST reports uncertainty on these 10 wavelengths, and the purpose of this study was to determine how close we could reproduce these uncertainties using our existing spectral irradiance measurement method. The expanded uncertainty was calculated using Equation (16). The 250 nm (approximately 2%) and 2,400 nm (approximately 1.5%) wavelengths had larger expanded uncertainty. Figure 2 shows the nonequivalence between the NREL-calculated spectral irradiance and NIST-reported irradiance. The values are very close to each other; however, the difference between the two was added to the expanded uncertainty. Further, the irradiance of the standard lamp was measured using a spectroradiometer system at a set current with offset of 5mA to evaluate the effect of altering the electrical power of that from NIST (Figure 3). Current was then reset to the original set current to verify no drift in calibration setup or spectroradiometer system. As described in Section 2, the power supply at NREL can be set in 5mA increments; hence, at any time during a calibration there could be a +/- 2.5mA error in the set current. Therefore, a worst-case value of 5mA offset was used for this test. The resulting irradiance difference of this test in the 300 nm to 1,630 nm region was found to be from 0.2% to 0.4% for all the specified wavelengths. Alternatively, the effect of the difference in electrical power on the irradiance was calculated as nonequivalence = $W_{\lambda i,\ NREL} - W_{\lambda i,\ NIST}$; the larger value of 0.4% from the 5mA offset or nonequivalence was then added to the overall uncertainty.

Table 3. Combined Expanded Uncertainty Results for Spectral Irradiance (k=1.96)

Wavelength	NIST-Reported Irradiance ($W/m^2/nm$)	NIST-Reported Uncertainty ($U_{95\%}$)	NREL-Calculated Irradiance ($W_{\lambda,NREL}$) ($W/m^2/nm$)	$W_{\lambda,NREL}-W_{\lambda,NIST}$ (nonequivalence) ($W/m^2/nm$)	$U_{95\%}$
250nm	1.73E-04	1.74	1.74E-04	1.57E-06	**2.06**
350nm	7.86E-03	1.27	7.93E-03	7.16E-05	**1.69**
450nm	4.40E-02	0.91	4.44E-02	4.01E-04	**1.44**
555 nm	1.10E-01	0.77	1.11E-01	9.99E-04	**1.36**
655 nm	1.72E-01	0.69	1.73E-01	1.56E-03	**1.32**
900 nm	2.38E-01	0.57	2.40E-01	2.17E-03	**1.26**
1600 nm	1.23E-01	0.47	1.24E-01	1.12E-03	**1.22**
2000 nm	7.19E-02	0.5	7.26E-02	6.56E-04	**1.23**
2300 nm	4.89E-02	0.49	4.93E-02	4.46E-04	**1.23**
2400 nm	4.31E-02	1.11	4.35E-02	3.93E-04	**1.58**

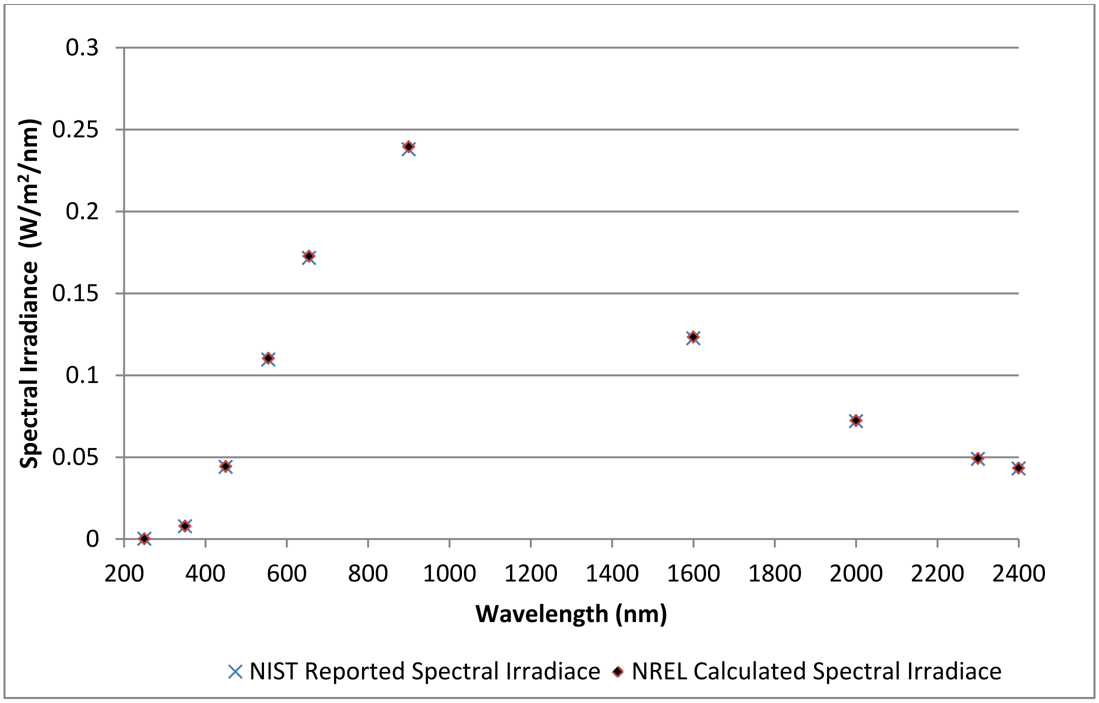

Figure 2. Plot showing nonequivalence comparison between NIST-reported and NREL-calculated spectral irradiance as a function of wavelength.

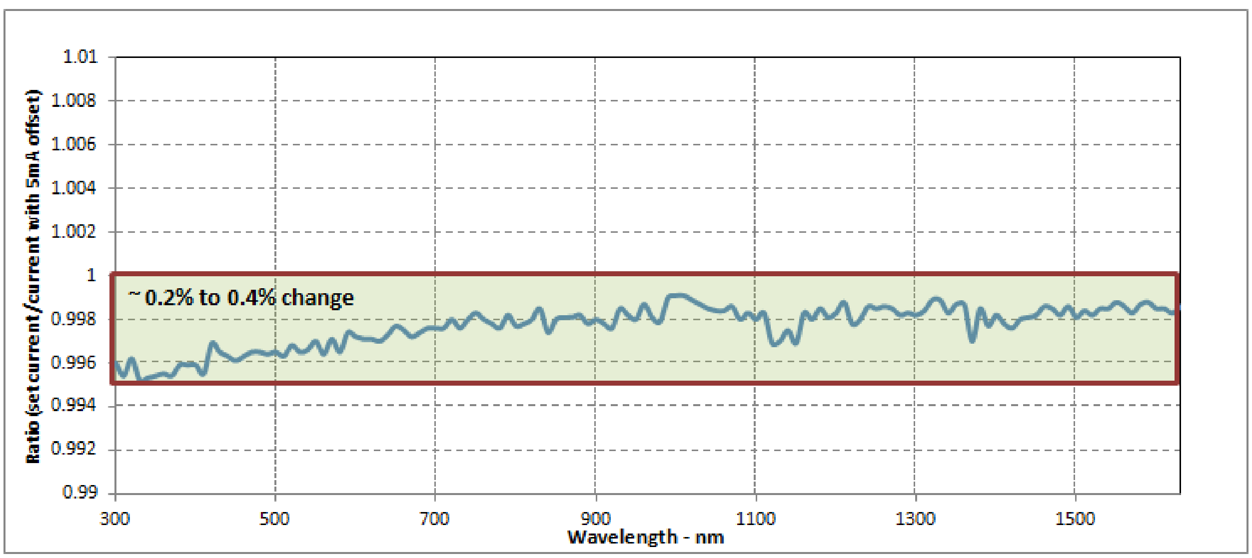

Figure 3. Uncertainty in spectral irradiance as a result of the reduction in the set current.

Among the uncertainty factors, the FEL lamp uncertainty obtained from NIST and the difference between the calculated NREL irradiance using Equation (4) and NIST-reported irradiance were the most dominant part in the contribution list at each wavelength (Figure 2 and Figure 4). For example, Table 4 shows that the NIST-reported calibration uncertainty and the difference between the NIST-reported irradiance and NREL's calculated irradiance were the largest contributors to the expanded uncertainty, 52.3% and 31.3%, respectively.

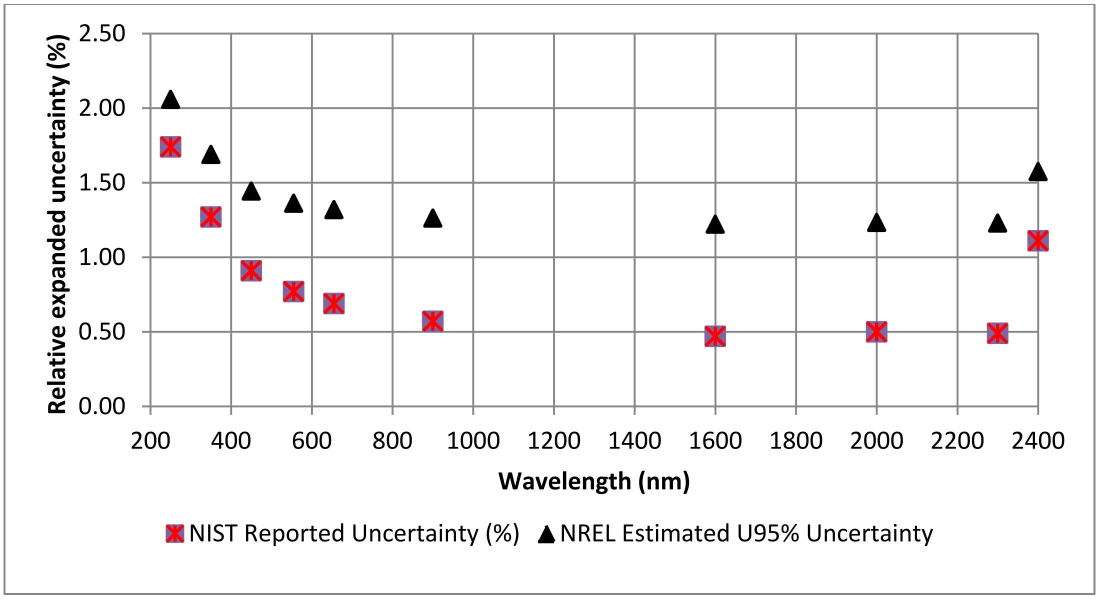

Figure 4. Plot showing the uncertainty values from both the NIST-reported (calibration certificate) and NREL calculated estimates.

Table 4. Each Component Contribution to the Combined Standard Uncertainty for 250 nm Wavelength

Source of Uncertainty	Expanded Uncertainty %	Expanded Uncertainty	Standard Uncertainty	Sensitivity Factor	Absolute Value	Combined Standard Uncertainty	Contribution (%)
$V_{f,NREL}$	0.0034	3.78E-03	2.18E-03	1.57E-06	3.42E-09	1.17E-17	0.1
$V_{R,NREL}$	0.0087	6.96E-06	4.02E-06	2.18E-03	8.75E-09	7.65E-17	0.3
R_{NREL}	0.01	1.00E-06	5.77E-07	-1.74E-02	1.01E-08	1.01E-16	0.4
D_{NREL}	0.2	1.00E-03	5.77E-04	-6.97E-04	4.02E-07	1.62E-13	13.9
$W_{\lambda,NIST}$	1.74	3.00E-06	1.50E-06	1.01E+00	1.52E-06	2.30E-12	52.3
Estimated Stray Light (NREL)	20	5.00E-04	2.89E-04	1.74E-04	5.02E-08	2.52E-15	1.7
Randomness (sdev) of W_{NREL}			3.66E-10	1.00E+00	3.66E-10	1.34E-19	0
$W_{\lambda,NREL}$-$W_{\lambda,NIST}$ (nonequivalence)		1.57E-06	9.08E-07	1.00E+00	9.08E-07	8.25E-13	31.3
Expanded Uncertainty (U95)						**3.55E-06**	
Expanded Uncertainty (U95%)						**2.06**	**100**

4 Validation

Our uncertainty analysis was based upon a linearization of the measurement model (Equation 1). To validate this result, Monte Carlo simulations (JCGM 101 2008) were conducted using the measurement model at two wavelengths: 250 nm and 1600 nm. These were selected for validation because they have higher and lower uncertainty, respectively. The simulation used a measurement function that modeled the NREL spectral irradiance as the NIST spectral irradiance plus an uncertain, zero-mean bias. The bias was modeled by using the nonlinear measurement model (Equation 1) to compute $W_{\lambda i,NREL}$ - $W_{\lambda i,NIST}$, where the sampling distribution for this difference was adjusted to have zero mean. One million samples were drawn from the distributions for the common inputs in the measurement model (Equation1) for the spectral irradiance at 250 nm and at 1600 nm. One million samples each for $W_{\lambda i,NIST}$ at 250 nm and 1,600 nm were drawn for the corresponding normal distributions specified by the NIST calibration. The marginal empirical distributions computed for the spectral irradiance at 250 nm and 1600 nm are shown in Figure 5.

As anticipated by the construction of the measurement function used for the simulations, the estimated spectral irradiance for NREL at 250 nm and at 1,600 nm were numerically identical to the NIST-calibrated values. Monte Carlo standard errors for these sample-based estimates were small, on the order of 10^{-7} to 10^{-9}. The uncertainties in the NREL values were estimated by taking sample standard deviations, which demonstrate lower uncertainties compared to the previous analysis. At 250 nm, the simulation result for the expanded relative uncertainty (k= 1.96) was 1.80%, versus 2.06% for the previous method’s result. At 1,600 nm, the expanded relative uncertainty (k= 1.96) was 0.62%, versus 1.22%. However, for the final stated uncertainties, we chose the more conservative approach instead of the Monte Carlo simulation result.

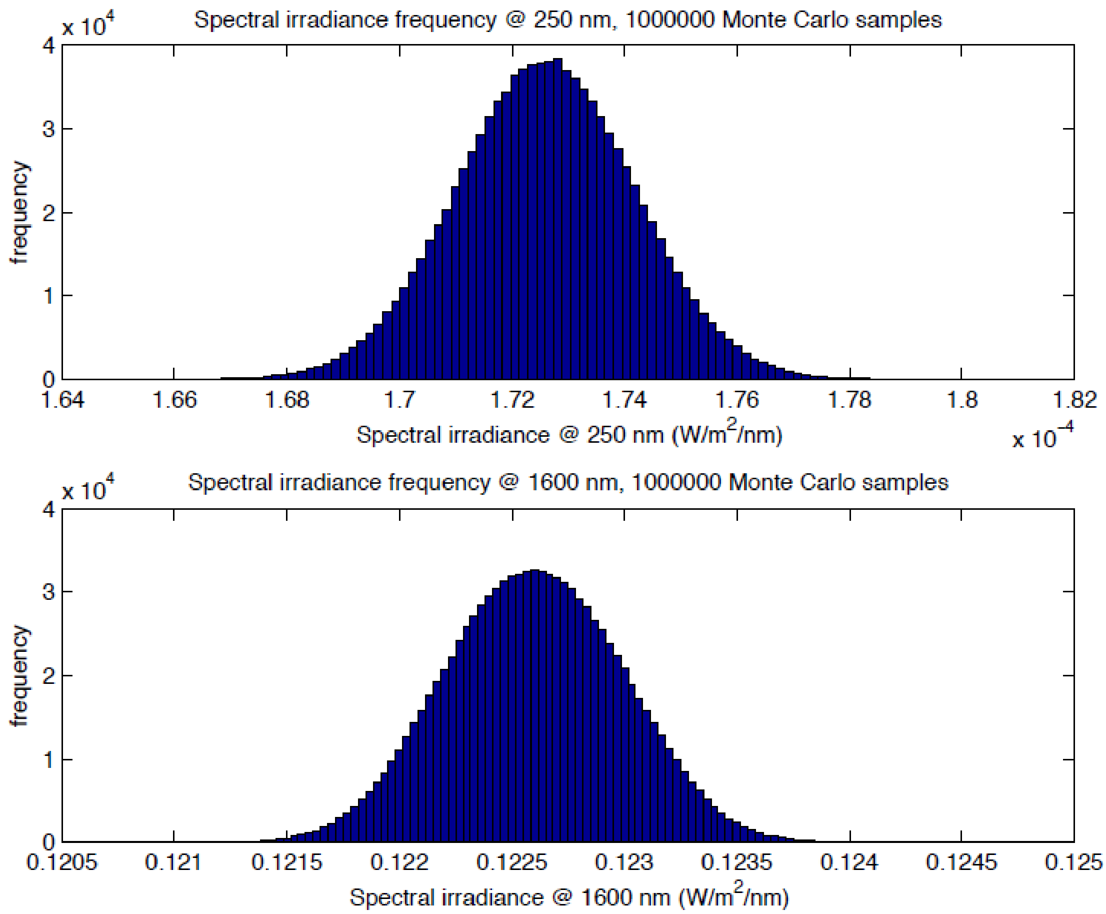

Figure 5. Monte Carlo validation results for (top) 250 nm and (bottom) 1,600 nm

5 Summary

Measurement uncertainty plays a vital role in decision making, managing risk, and attaining laboratory accreditation, and also helps establish standard calibration methods. Thus, quantifying measurement uncertainty of spectral irradiance using NIST FEL lamp and measurement setup during the calibration of spectroradiometers is essential for PV industries and ultimately helps in decision making of such industries. In this study, the measurement uncertainty of the spectral irradiance prior to calibrating the spectroradiometer is discussed using the GUM approach. The expanded uncertainty of the reference irradiance ranged from ±1% to ±2% for specific wavelengths ranging from 250 nm to 2,400 nm. Because of the FEL lamp instability and low signal (Yoon, Proctor, and Gibson 2003), the uncertainty is higher on the two ends of the spectrum. Further, we validated our method using the Monte Carlo simulation, and the results of the uncertainty were lower than the final estimated uncertainty. Overall, this uncertainty was estimated for spectral irradiance using a known source. Users are advised to include additional uncertainty variables based on their measurement setup, environmental conditions, and spectroradiometer used that might vary from the measurement setup and environmental conditions at NREL.

6 References

Andreas, A. M.; Myers, D. R. (2008). "Pulse Analysis Spectroradiometer System for Measuring the Spectral Distribution of Flash Solar Simulators." *Optical Modeling and Measurements for Solar Energy Systems II: Proceedings of SPIE Conference*; August 13–14, 2008, San Diego, California. Paper No. 70460I. Bellingham, WA: SPIE—The International Society for Optical Engineering; 11 pp.

ASTM G 138. (2010). "Calibration of a Spectroradiometer Using a Standard Source of Irradiance." *ASTM Annual Book of Standards, Vol.14.04.* West Conshohocken, PA: ASTM International.

BIPM; IEC; IFCC; ISO; IUPAP; OIML. (1995). *Guide to the Expression of Uncertainty in Measurement*. Geneva: ISO TAG4.

Joint Committee for Guides in Metrology. (2012). *International Vocabulary of Metrology—Basic and General Concepts and Associated Terms*. Accessed March 12, 2013: www.bipm.org/utils/common/documents/jcgm/JCGM_200_2012.pdf.

Joint Committee for Guides in Metrology (BIPM, IEC, IFCC, ILAC, ISO, IUPAC, IUPAP, and OIML). (2008). *Evaluation of Measurement Data: Supplement 1 to the "Guide to the Expression of Uncertainty in Measurement"—Propagation of Distributions Using a Monte Carlo Method.* Paris: International Bureau of Weights and Measures.

Joint Committee for Guides in Metrology Working Group 1 (JCGM/WG 1). (2008). *Guide to the Expression of Uncertainty in Measurement.* Accessed March 12, 2013: www.bipm.org/utils/common/documents/jcgm/JCGM_100_2008_E.pdf

Kacker, R.; Sommer K.-D.; Kessel, R. (2007). "Evolution of Modern Approaches to Express Uncertainty in Measurement." *Metrologia* (44:6); pp. 513–529.

Myers, D.R.; Reda, I.; Wilcox, S.; Andreas, A. (2004). "Optical Radiation Measurements for Photovoltaic Applications: Instrumentation Uncertainty and Performance." Preprint. Prepared for the International Symposium on Optical Science and Technology, SPIE's 49th Annual Meeting, August 2–6, 2004. NREL/CP-560-36321. Golden, CO: National Renewable Energy Laboratory, 14 pp.

Reda, I. (2011). Method to Calculate Uncertainty Estimate of Measuring Shortwave Solar Irradiance Using Thermopile and Semiconductor Solar Radiometers. NREL/TP-3B10-52194. Golden, CO: National Renewable Energy Laboratory.

Taylor, B.N.; Kuyatt; C.K. (1994). *Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results.* NIST Technical Note 1297. Gaithersburg, MD: National Institute of Standards and Technology.

Walker, J.; Saunders, R.D.; Jackson, J.; McSparron, D. (1987). *Spectral Irradiance Calibrations.* NIST SP-250-20. Gaithersburg, MD: National Institute for Standards and Technology.

Yoon, H.W.; Gibson, C.E. (2010). *Spectral Irradiance Calibrations.* NIST SP-250-89. Gaithersburg, MD: National Institute for Standards and Technology.

Yoon, H.W.; Proctor, J.E.; Gibson C.E. (2003). "FASCAL 2: A New NIST Facility for the Calibration of the Spectral Irradiance of Sources." *Metrologia* (40:1); pp. S30–S34.