Method to Calculate Uncertainties in Measuring Shortwave Solar Irradiance Using Thermopile and Semiconductor Solar Radiometers

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Abstract

The uncertainty of measuring solar irradiance is fundamentally important for solar energy and atmospheric science applications. Without an uncertainty statement, the quality of a result, model, or testing method cannot be quantified, the chain of traceability is broken, and confidence cannot be maintained in the measurement. Measurement results are incomplete and meaningless without a statement of the estimated uncertainty with traceability to the International System of Units (SI) or to another internationally recognized standard.

This report explains how to use International Guidelines of Uncertainty in Measurement (GUM) to calculate such uncertainty. The report also shows that without appropriate corrections to solar measuring instruments (solar radiometers), the uncertainty of measuring shortwave solar irradiance can exceed 4% using present state-of-the-art pyranometers and 2.7% using present state-of-the-art pyrheliometers. Finally, the report demonstrates that by applying the appropriate corrections, uncertainties may be reduced by at least 50%. The uncertainties, with or without the appropriate corrections might not be compatible with the needs of solar energy and atmospheric science applications; yet, this report may shed some light on the sources of uncertainties and the means to reduce overall uncertainty in measuring solar irradiance.

1 Introduction

The uncertainty of measuring solar irradiance is fundamentally important for solar energy and atmospheric science applications. Without an uncertainty statement, the quality of a result, model, or testing method cannot be quantified, the chain of traceability is broken, and confidence cannot be maintained in the measurement. Measurement results are incomplete and meaningless without a statement of the estimated uncertainty with traceability to the International System of Units (SI) or to another internationally recognized standard.

The International Guidelines of Uncertainty in Measurement GUM (JCGM/WG, 2008) are used for calibrating solar radiometers at the National Renewable Energy Laboratory (NREL) (Reda et. al 2008). This report describes a method for calculating estimated measurement uncertainties of solar irradiance data obtained with properly calibrated pyranometers and pyrheliometers. It also outlines GUM guidelines used to calculate the estimated uncertainty for field measurement. Uncertainty in field measurement is a result of radiometer calibration, equipment installation, data acquisition, system maintenance methods, and the environmental conditions at the site where the radiometer is deployed.

2 GUM Guidelines

The GUM process can be summarized in four steps:

1.1 Determine the measurement equation.

1.2 List or estimate the standard uncertainty analogous to a standard deviation associated with each variable in the measurement equation (e.g. voltage, irradiance) and for each component that might introduce uncertainty to the calibration process (e.g. interpolation, environmental conditions).

1.3 Calculate the combined standard uncertainty using the root-sum-of-squares method for all standard uncertainties in step 1.2.

1.4 Calculate the expanded uncertainty by multiplying the combined standard uncertainty by the coverage factor, k (typically known as Student's "t"), or prescribed coverage factors for known distributions of measurements representing the single value of the quantity to be measured (e.g. Gaussian, triangular, rectangular).

3 Measurement Equation

The following equation is used to calculate global solar irradiance using a thermopile pyranometer at each data point:

$$G = \frac{V - R_{nt} * W_{nt}}{R} \qquad (1)$$

where:

G is the calculated global solar irradiance in watts per square meter (Wm^{-2})

V is the pyranometer's thermopile output voltage in microvolts (μV)

R_{nt} is the pyranometer's net longwave responsivity estimated or determined by Blackbody characterization in $\mu V/(Wm^{-2})$

W_{nt} is the net longwave irradiance measured by a collocated pyrgeometer in W/m^{-2} (Pyrgeometers are radiometers that measure atmospheric longwave irradiance)

R is the pyranometer's responsivity determined by calibration in $\mu V/(Wm^{-2})$.

Either a single responsivity value or the responsivity as a function of solar zenith angle can be uniquely determined for an individual pyranometer from calibration and used to compute global irradiance data. The uncertainty in the responsivity value can be reduced by as much as 50% if the responsivity as a function of solar zenith angle is used (Reda, 1998 and Reda et al., 2008).

For other types of solar radiometers, the same equation is used by removing or adding variables relevant to the type of radiometer. For example, in the case of pyrheliometers and semiconductor pyranometers with no thermal offset response, R_{nt} equals zero; therefore, G equals V divided by R.

Note that all the variables in Equation 1 are measured or calculated using independent methods; therefore, they are assumed to be independent with no correlation.

4 Standard Uncertainties

A standard uncertainty (u) can be estimated using statistical methods (Type A), non-statistical methods (Type B), or both. For example, a standard deviation of a number of data points is a Type A uncertainty. A manufacturer's specification of radiometer performance characteristics or an uncertainty reported by a calibration vendor is a Type B uncertainty (Taylor and Kuyatt 1994). A Type B uncertainty that changes as a function of one or more variables may be a combination of Type A and Type B.

Standard uncertainty calculations depend on the distribution of sources of uncertainty. A requirement of the GUM approach is to state the type of statistical distribution, either measured or assumed, for uncertainty calculations. Table 1 shows how to estimate the standard uncertainty for some common distributions using the expanded uncertainty. Throughout this report, *standard* uncertainties are denoted by "u" and *expanded* uncertainties by "U".

Table 1. Standard uncertainty estimation for common distributions

Distribution	Source	Standard uncertainty
Normal: **Standard deviation = σ** **Number of readings = n** **or** **Expanded uncertainty = U** **and coverage factor = k**	Statistical (Type A)	$u = \frac{\sigma}{\sqrt{n}}$ OR $u = \frac{U}{k}$
Rectangular	Non-statistical (Type B)	$u = \frac{U}{\sqrt{3}}$
Triangular	Non-statistical (Type B)	$u = \frac{U}{\sqrt{6}}$
Normal **k = 2 (or t)**	Non-statistical (Type B)	$u = \frac{U}{2}$ OR $u = \frac{U}{t}$

The following steps explain how to calculate the combined standard uncertainty and its effective degrees of freedom for Type B uncertainties first, then for Type A uncertainties.

To calculate the combined standard uncertainty and its effective degrees of freedom for Type B uncertainties:

4.1 List the estimated expanded uncertainty (U_{95}) for each variable in Equation 1. The expanded uncertainty is obtained as follows:

A. The uncertainty of measuring the radiometer's output voltage (V) is calculated with a calibrated data acquisition system. This uncertainty is typically listed in the manufacturer specifications in the user's manual. Table 2 displays the expanded uncertainty calculated using a Campbell Scientific, Inc. Model CR3000 data logger[1].

[1] NREL makes no product endorsement, this product was chosen as an example.

Table 2. Expanded uncertainty listed in manufacturer specifications

Model	Range	Resolution (Differential)	Temperature Range	Offset	U_{95} (%)
Campbell CR3000	20 millivolts (mV)	0.67 uV	-25 C to 50 C	3*resolution+2 uV	0.07% reading + offset

B. The uncertainty of the net responsivity (R_{nt}) is listed in a solar radiometer's calibration certificate or manufacturer specifications. From experience, an estimated uncertainty of 20% is used in this report.

C. The uncertainty of the net longwave irradiance (W_{nt}) is listed in a pyrgeometer's calibration certificate. It may also be estimated by users based on experience.

D. The uncertainty of the solar radiometer Responsivity (R) is listed in the radiometer's calibration certificate. Other sources of uncertainties must be included in the uncertainty of the responsivity. Such sources are a result of responses to change in solar zenith angle, solar azimuth angle, spectral irradiance distribution, ambient temperature, etc. These uncertainties are listed in the manufacturer specifications or may be estimated based on prior experience.

Table 3 is an example of uncertainty estimates for four types of solar radiometers: a thermopile pyranometer, a semiconductor pyranometer, a thermopile pyrheliometer, and a semiconductor pyrheliometer (Semiconductor pyrheliometers are not frequently available to solar data users, but are used here to illustrate the effects of spectral irradiance distributions on measurements). These estimates are for current state-of- the-art radiometers and have been determined via calibrations such as NREL's (NREL-Annual), data collection and experience with hundreds of radiometers over many years. Actual values may be listed on manufacturers' web sites or in radiometers specifications. Additional uncertainties may be added depending on the instrument type and instrument set-up onsite.

Table 3. Example of uncertainty estimates for solar radiometer responsivity (R)

Uncertainty Source	Thermopile pyranometer	Semiconductor pyranometer	Thermopile pyrheliometer	Semiconductor pyrheliometer
Calibration[a]	3%	5%	2%	3%
Zenith response[b]	2%	2%	0.5%	1%
Azimuth response	1%	1%	0%	0%
Spectral response	1%	5%	1.5%	8%
Tilt[c]	0.2%	0.2%	0%	0%
Nonlinearity	0.5%	1%	0.5%	1%
Temperature response	1%	1%	1%	1%
Aging per year	0.2%	0.5%	0.1%	0.5%
Total U = Sum	8.9%	15.7%	5.6%	14.5%
Total U = RSS	4.1%	8.0%	2.7%	8.9%

[a] Includes zenith angle response from 30° to 60°
[b] Includes zenith angle response from 0° to 30° and 60° to 90°
[c] This uncertainty is set to zero for untilted radiometers

The percentage contribution of each uncertainty source listed in Table 3 is calculated to show which source contributes the most to the total uncertainty. This contribution is calculated by dividing the value of each source listed in the table by the sum of all uncertainties for each radiometer type. For example, for the calibration value for thermopile pyranometers, 3% divided by 8.9% multiplied by 100 = 33.7%. Table 4 is a list of the percentage contributions for the values in Table 3.

In Table 4, the greatest contributors to the uncertainty of the responsivity are the uncertainties resulting from calibration. For pyranometers, most of the calibration uncertainty is from the radiometers zenith angle response; see Figure 1 for an example of zenith angle response during pyranometer calibration. Therefore, reducing the overall uncertainty can be accomplished by reducing the uncertainty resulting from the calibration process. One method, used at NREL, is to report the uncertainty of the responsivity after being corrected for the zenith angle response. NREL's Broadband Outdoor Radiometer Calibration (BORCAL) reports (NREL-Annual) show that this is accomplished by fitting the responsivity to an AM and PM spline interpolation functions. Under clear-sky conditions, this may reduce the overall uncertainty by at least 30%. Other fitting methods may be used to fit the responsivity versus zenith angle, yet users must calculate the Type A standard uncertainty resulting from the fitting (u_A), where u_A equals the standard deviation of the calculated residuals resulting from the fitting.

Table 4. Uncertainty sources contributing to the total uncertainty of the responsivity, R

Uncertainty Source	Thermopile pyranometer	Semiconductor pyranometer	Thermopile pyrheliometer	Semiconductor pyrheliometer
Calibration	33.7%	31.9%	35.7%	20.7%
Zenith response	22.5%	12.7%	8.9%	6.9%
Azimuth response	11.2%	6.4%	0%	0%
Spectral response	11.2%	31.9%	26.8%	55.2%
Tilt	2.3%	1.3%	0%	0%
Nonlinearity	5.6%	6.4%	8.9%	6.9%
Temperature response	11.2%	6.4%	17.9%	6.9%
Aging per year	2.3%	3.2%	1.8%	3.5%
Total U = Sum	100%	100%	100%	100%

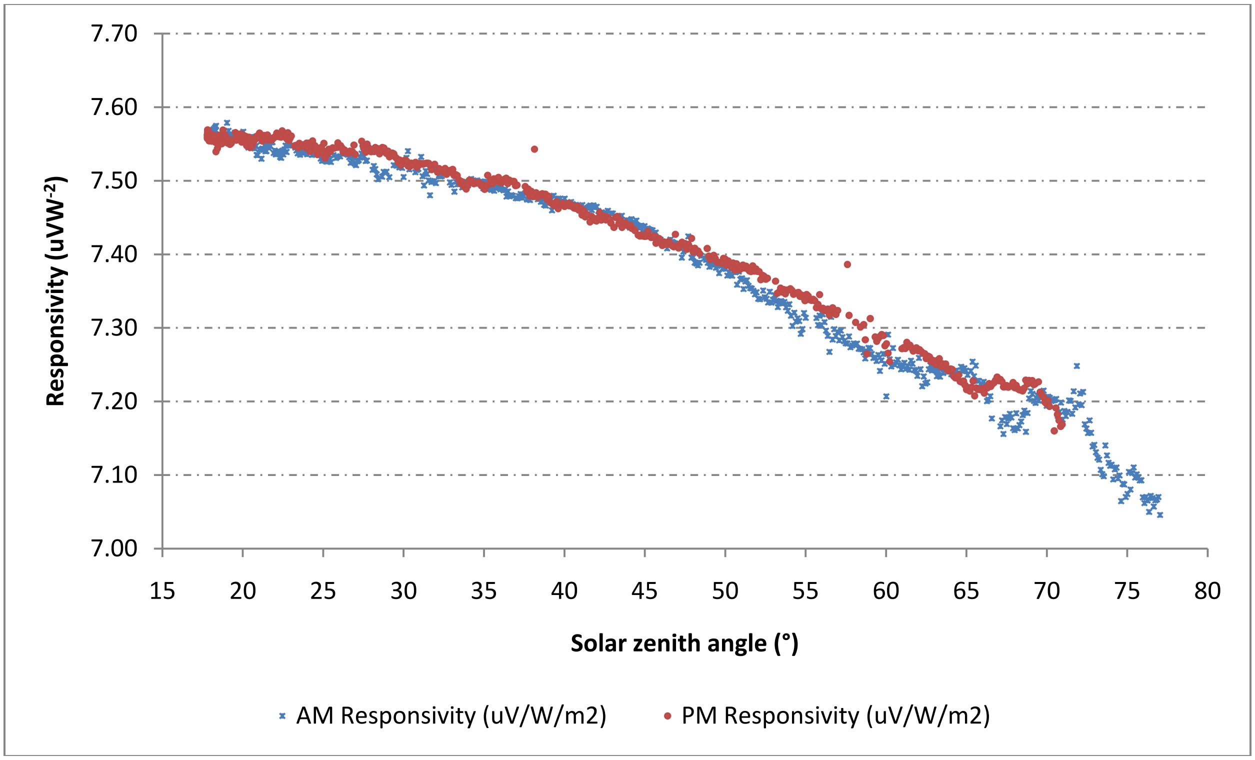

Figure 1. Responsivity versus zenith angle for PSP-33852F3 from outdoor calibration

Models can also be used to correct for other sources of uncertainty (e.g. spectral irradiance distribution, ambient temperature, etc.). The uncertainties due to using such models must be added as Type A and/or Type B standard uncertainties when computing expanded uncertainty.

4.2 Using Table 1 for the most common distribution, list the distribution, degrees of freedom, and coverage factor for each variable in Equation 1. When the distribution of the expanded uncertainty is not known, it is common to assume a rectangular distribution with infinite (∞) degrees of freedom (Taylor and Kuyatt 1994). Table 5 lists the distribution, degrees of freedom, and coverage factor for each variable.

Table 5. Distribution, degrees of freedom, and coverage factor for the variables in the measurement equation

Variable	Distribution	Degrees of freedom	Coverage Factor
V	Rectangular (from manufacturer)	∞	$\sqrt{3}$
R_{nt}	Rectangular (from estimate)	∞	$\sqrt{3}$
W_{nt}	Normal (from calibration)	n>500 data points	1.96
R	Normal (from calibration)	n>500 data points	1.96

4.3 Calculate the estimated standard uncertainty (u) for each variable in Equation 1. For example, a calibrated voltmeter is used to measure the output voltage of a solar radiometer. Using the manufacturer specifications for the voltmeter, the expanded uncertainty of the voltage variable (V) in Equation 1 equals $U_{V,\,95}$ with 95 % confidence level, and the distribution is assumed to be rectangular. Therefore, the standard uncertainty for the voltage measurement is u_V, and equals $U_{V,\,95}$ divided by the coverage factor listed in Table 5:

$$u_V = \frac{U_{V,95}}{\sqrt{3}} \qquad (2)$$

Table 6 is a list of standard uncertainties for the variable in the measurement equation. The standard uncertainties listed in the table are based on the listed values in the "Value" column. The coverage factors are obtained from Table 5. Note that the standard uncertainties are calculated at each data point, except for R_{nt}, which is constant. Also, R can be considered constant, unless it is corrected for zenith angle dependence (i.e. using it as a function of zenith angle as mentioned in 4.1.1 above).

Table 6. Standard uncertainty for each variable in the measurement equation

Variable	Value	%U_{95}	U_{95} (Absolute Value)	u (Absolute Value)
V (uV)	5083.5	N/A	7.57	4.37
R_{nt} [uV/(Wm^{-2})]	0.61	20%	0.122	0.07
W_{nt} (Wm^{-2})	-174.2	5%	8.711	4.44
R [uV/(Wm^{-2})]	7.4	4%	0.296	0.15

4.4 Calculate the sensitivity factor (c_j) for the jth variable in the measurement equation (Equation 1) by using the partial derivative of the global solar irradiance (G) with respect to each variable as follows (Taylor and Kuyatt 1994):

$$c_V = \frac{\partial G}{\partial V} = \frac{1}{R} \quad (3)$$

$$c_{R_{nt}} = \frac{\partial G}{\partial R_{nt}} = \frac{-W_{nt}}{R} \quad (4)$$

$$c_{W_{nt}} = \frac{\partial G}{\partial W_{nt}} = \frac{-R_{nt}}{R} \quad (5)$$

$$c_R = \frac{\partial G}{\partial R} = \frac{-(V - R_{nt} * W_{nt})}{R^2} \quad (6)$$

Table 7 lists the calculated value of c_j at a specific data point using the values listed in Table 6.

Table 7. Sensitivity factors for variables in the measurement equation at a specific data point

	c_V	c_{Rnt}	c_{Wnt}	c_R
Sensitivity Factor	0.135 (Wm^{-2}/uV)	23.557 [(Wm^{-2})^2/uV)	-0.0825 (Unity)	-94.88 [(Wm^{-2})^2/uV]

4.5 Calculate the combined standard uncertainty for Type B, u_B (Taylor and Kuyatt 1994):

$$u_B = \sqrt{\sum_{j=0}^{\ell-1} (c_j * u_j)^2} \quad (7)$$

where j is the jth variable and ℓ is the number of variables. As an example, Table 8 is a list of c_j * u_j and the calculated u_B for the above data point.

Table 8. Combined standard uncertainty for Type B uncertainties

$c_V * u_V$ (Wm^2)	$c_{Rnt} * u_{Rnt}$ (Wm^2)	$c_{Wnt} * u_{Wnt}$ (Wm^2)	$c_R * u_R$ (Wm^2)	Combined Standard Uncertainty, u_B (Wm^2)
0.591	1.659	0.367	-14.321	14.433

The standard uncertainty u_B is calculated, and the contribution of each variable in the measurement equation to the total Type B uncertainty of measuring the solar irradiance is also calculated. The contribution is used to decide which variable contributes the most to the total standard uncertainty, and consequently to the expanded uncertainty. This contribution is calculated at each data point by dividing each $c_j * u_j$ by the sum of all $c_j * u_j$. Figure 2 shows the percentage contribution for each variable versus zenith angle. In the figure, the uncertainty in the responsivity value is the greatest contributor to the overall uncertainty. Therefore, improving the uncertainty in the responsivity would have the greatest effect on the overall uncertainty in measuring solar irradiance.

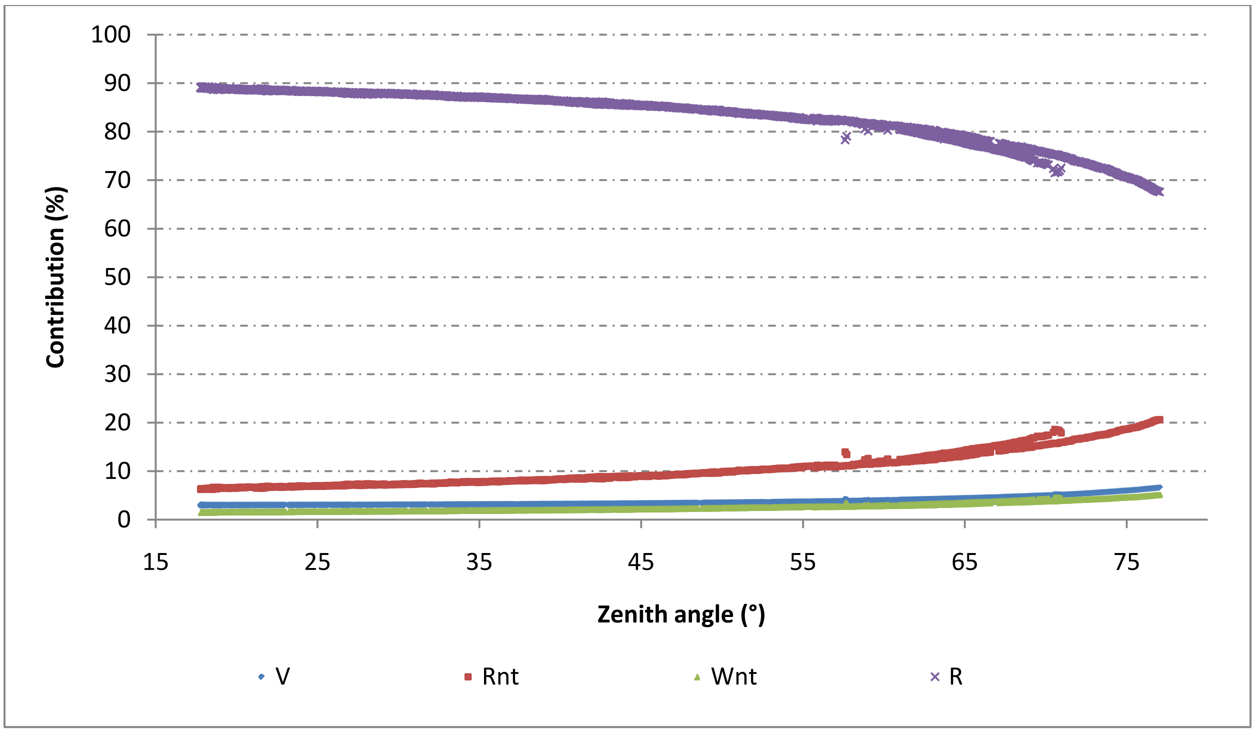

Figure 2. Contribution of each variable in the measurement equation to the total uncertainty versus zenith angle

4.6 Calculate the effective degrees of freedom for Type B $DF_{B\text{-}eff}$ where df_j is the degrees of freedom of the j^{th} variable in Equation 1 (Taylor and Kuyatt 1994):

$$DF_{B,eff} = \frac{(u_B)^4}{\sum_{j=0}^{\ell-1} \frac{(c_j * u_j)^4}{df_j}} \quad (8)$$

Note that the value of df_j equals ∞ for most variables; therefore $DF_{B,\,eff}$ equals ∞.

4.7 Calculate Type A standard uncertainty (u_A). This uncertainty is calculated as the standard deviation of a data set or of a set of measured irradiance.

4.8 Calculate the combined standard uncertainty (u_c):

$$u_c = \sqrt{u_A^2 + u_B^2} \quad (9)$$

Then calculate the effective degrees of freedom (DF_{eff}) using Equation 8 by replacing u_B with u_c and $c_j * u_j$ with u_A and u_B . As stated in 4.1.6, DF_{eff} equals infinity because all other values are infinity. Note that in this report, the measured irradiance is calculated instantaneously; therefore, u_A equals zero.

Since u_c will change at each data point, it is plotted against the zenith angle. Therefore, a conservative value for the standard uncertainty equals the maximum value of $u_c = u_{c,\,max}$. Figure 3 shows the u_c for PSP 33852F3, where $u_{c,\,max}$ = 2.1 %

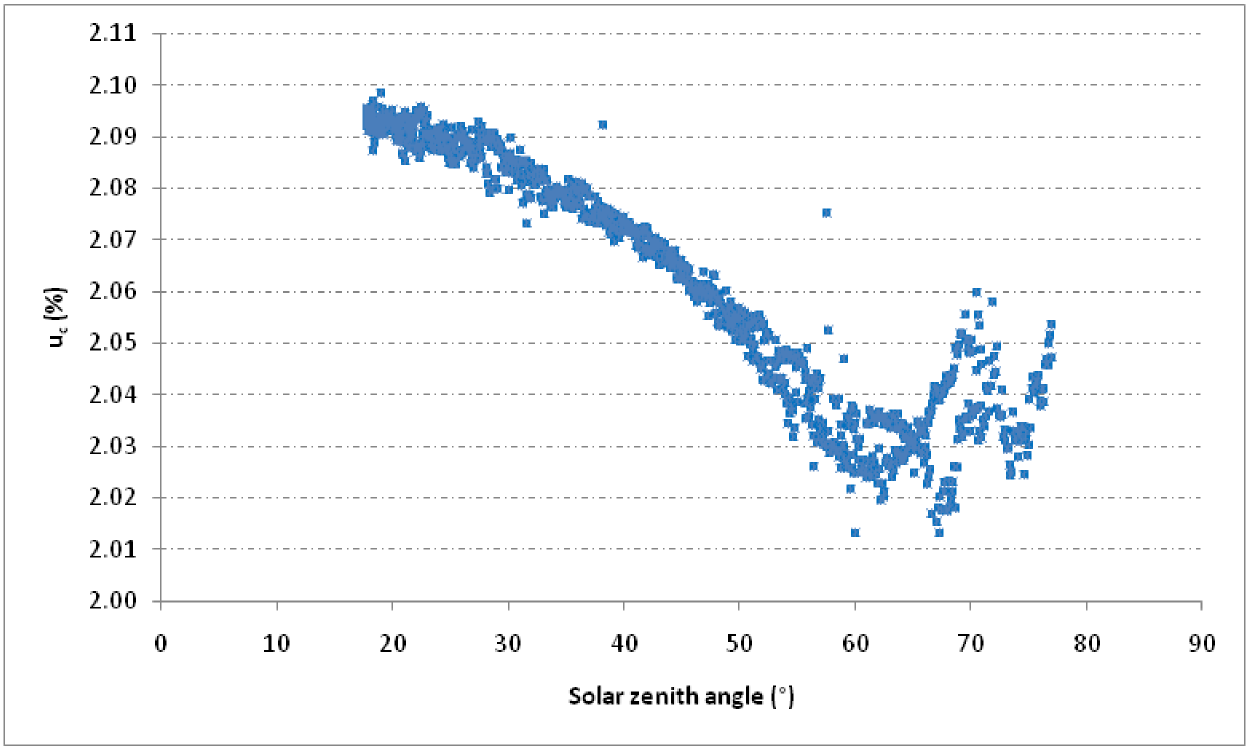

Figure 3. Standard Uncertainty versus zenith angle for PSP-33852F3

5 The Expanded Uncertainty and Reporting

The expanded uncertainty with 95% confidence level (U_{95}) is calculated as follows:

$$U_{95} = k * u_c \tag{10}$$

where k is the coverage factor, calculated using student "t" tables. For DF_{eff} equals infinity, k equals 1.96.

The reporting of uncertainty must include Type A and Type B standard uncertainties, coverage factors, and expanded uncertainties with 95% confidence level. Table 9 is a list of the reported results for PSP-33852F3. In the table, there are two lists, one using one value for the responsivity (R) and the other using R as a function of zenith [F(z)].

Table 9. The reported uncertainty for PSP-33852F3

	Responsivity = constant	Responsivity = F(z)
Type A standard uncertainty (u_A)	0%	0.3 % = standard deviation of fitting residuals
Type B standard uncertainty (u_B)	2.1%	1.34%
Combined standard uncertainty (u_c)	2.1%	1.37%
Coverage factor (k)	1.96	1.96
Expanded uncertainty (U_{95})	4.1%	2.69%

Table 10 is a list of expanded uncertainties for current state-of-the-art solar radiometers. Using the radiometers without any corrections and using responsivity as a constant will yield estimated expanded uncertainties of 4.4% and 2.7% for thermopile pyranometers and pyrheliometers, and 8% and 8.9% for semiconductor pyranometers and pyrheliometers. These uncertainties are consistent those previously reported (Myers et al. 2004) (King 1997). For each radiometer, the expanded uncertainty is calculated by using the responsivity as a constant value and as a function of zenith angle. In the list, note that improvement in the expanded uncertainty exceeds 29%. Correcting for other uncertainty contributors might result in reduction in the uncertainty that is at least 20% greater. Therefore, when correcting for other sources, the zenith angle correction may result in a reduction of at least 50% for clear-sky conditions similar to those during the pyranometer calibration.

Table 10. Expanded uncertainties for solar radiometers

	Thermopile pyranometer	Semiconductor pyranometer	Thermopile pyrheliometer	Semiconductor pyrheliometer
U_{95} Using R = Constant	4.1%	8.0%	2.7%	8.9%
U_{95} using R = F(z)	2.6%	4.0%	1.9%	4.7%
U_{95} Improvement due to F(z)	38%	50%	29%	47%

6 Conclusion

Measurement uncertainties must be reported with any solar irradiance data. The described procedure in this report is consistent with GUM guidelines and may be used for calculating uncertainty estimates for field measurements of solar irradiance. It is evident from the results shown in this report that the uncertainty in measuring solar irradiance using current state-of-the-art radiometers is greater than 4% for pyranometers and greater than 2.7% for pyrheliometers under clear-sky conditions similar to those during the radiometer calibration.

Since the radiometer's inception in the late 1800s, there have been major improvements in the manufacturing process, but very little improvement in measurement accuracy. Many methods and models have been implemented to improve the uncertainty of solar irradiance data (Reda et al. 2008) (King and Myers 1997) (King et al. 1997). Implementing such methods and models can reduce the uncertainty of measuring solar irradiance by at least 50% (as discussed in Section 5); therefore, the best achievable uncertainty is 2% for pyranometers and 1.35% for pyrheliometers under clear-sky conditions.

The goal of this report is to raise user awareness of the measurement uncertainties associated with solar radiometer data and inform users that these uncertainties might not meet the requirements for solar energy and atmospheric science applications. This report may also encourage manufacturers and interested researchers to improve the manufacturing process and develop improved methods for characterizing radiometers so that better corrections can be developed for the sources of uncertainty. Increased demand for accurate solar irradiance measurement may result in an Expanded Uncertainty (U_{95}) of less than ±1% in the near future.

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