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ABSTRACT

Evaluating the performance of photovoltaic cells, modules, and arrays that form large solar deployments relies on accurate measurements of the available solar resource. Therefore, determining the accuracy of these solar radiation measurements provides a better understanding of investment risks. This becomes especially important as deployment size and investment costs grow to hundreds of millions of dollars. The accuracy of measurements is also important for acceptance testing and operations.

Radiometers such as pyranometers are used to measure global horizontal irradiance or plane of array irradiance, whereas pyrheliometers are used to measure direct normal irradiance. Currently, most radiometric data users rely on manufacturers' specifications of calibration uncertainty to quantify the uncertainty of measurements. However, the accuracy of solar radiation measured by radiometers depends not only on the specifications of the instrument but also on the (a) calibration procedure, (b) measurement conditions and maintenance, and (c) environmental conditions. Therefore, statements about the overall measurement uncertainty can be made only on an individual basis, taking all relevant factors into account. This paper provides guidelines and recommended procedures for estimating the uncertainty in calibrations and measurements by radiometers using methods that follow the Guide to the Expression of Uncertainty (GUM). Standardized analysis based on these procedures ensures that the uncertainty quoted is well documented.

Keywords: Global Horizontal Irradiance; Direct Normal Irradiance; Type A; Type B; Uncertainty

1. INTRODUCTION

Accuracy of radiometric data is essential for understanding and assessing investment risks of the system performance of renewable energy. Most applications of uncertainty calculations use factory radiometric specifications as final uncertainty values for calibration and field measurements or other methods of calculating uncertainties. Accuracy and uncertainty specifications for radiometers are based on a wide range of approaches and data analysis techniques. This paper addresses a detailed application to calculate calibration and field measurement uncertainties. This method provides guidelines and recommended procedures for estimating uncertainties in the calibrations and measurements by solar pyranometers and pyrheliometers using a Guide to the Expression of Uncertainty (GUM) method. Standardized analysis based on these procedures will ensure that the uncertainty quoted for data collected by these radiometers can be compared based on documented methods of derivation. One important note: the calibration uncertainty example provided here is based on the Broadband Outdoor Radiometer CALibration method, which is employed at the National Renewable Energy Laboratory. However, the methodology described below is applicable to all radiometer calibration systems. The principles and essential steps, including the estimation of magnitudes and types of uncertainties (Type A and/or Type B), are similar.

2. METHOD AND RESULT

The purpose of estimating uncertainties is to maintain measurement traceability by establishing an unbroken chain of comparisons that a measurement is in agreement within acceptable limits of uncertainty with respect to the International System of Units. Meanwhile, the uncertainty estimates in the radiometric data have a significant effect on the uncertainty of the expected electrical output of solar energy systems. The uncertainty estimate of broadband radiometric data is performed on two specific components: (a) the uncertainty in the calibration of the measurement system and (b) the uncertainty in the routine or field measurement system. This guide provides steps for evaluating the uncertainty in each of the calibration and measurement stages. The guide is based on the International Bureau of Weights and Measures (BIPM, from the French name) Guide to the Uncertainty in Measurements, or GUM.

The calibration of broadband radiometers involves the direct measurement of a standard source (solar irradiance or artificial light). However, in this paper the calibration method is based on outdoor calibration using the solar irradiance as the source. The accuracy of the calibration is dependent on the sky condition, maintenance of the test, and reference instruments, including the leveling of the instruments. All of these factors are included when estimating calibration uncertainties. Five steps are carried out in the estimation of calibration uncertainty (Fig. 1). These steps are adopted from (1), which includes a summarized version of the BIPM GUM. The GUM method employs two types of uncertainty estimates: Type A and Type B. Type A uncertainty uses a statistical method of valuation, such as standard deviation. Type B is based on any non-statistical evaluation, such as manufacturers' specifications, literature, or professional judgment. One assumption considered in this paper is that the sources of uncertainty variables are uncorrelated because each of them are measured or estimated using independent methods.

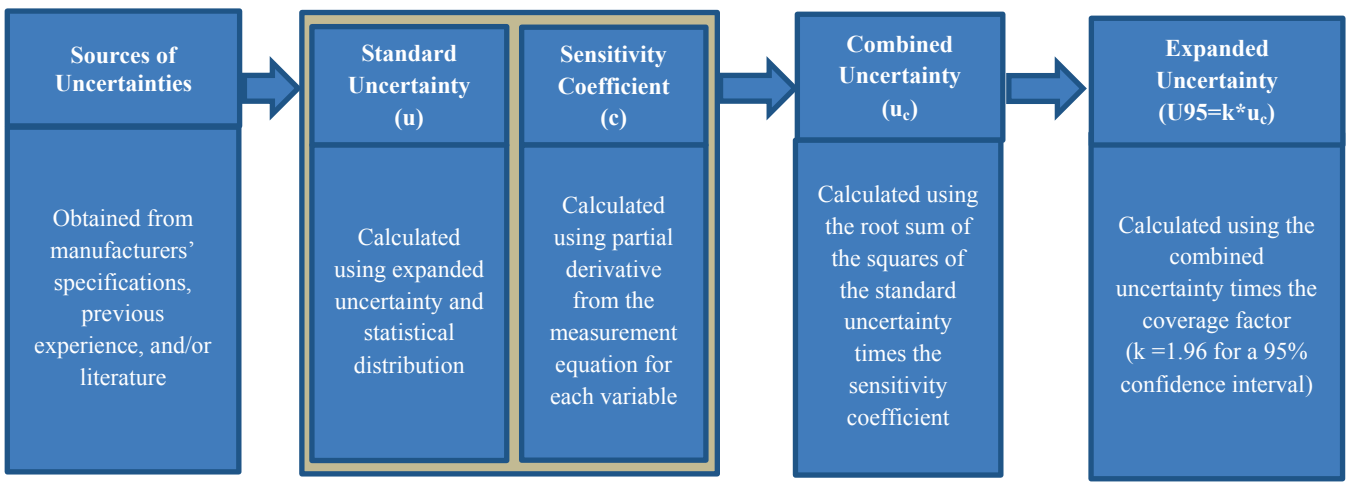

Fig.1 Calibration and measurement uncertainty estimation flow chart

2.1 Measurand and Measurement Equation

The first step in the uncertainty calculation is to determine the measurement equation. This is a mathematical description of the relation of the measurand (solar irradiance) as a function of the input variables (such as instrument voltage and responsivities). In this case, the equation

$$G = \frac{(V - R_{net} * W_{net})}{R}$$

where V is the radiometer output voltage, in μV; R is responsivity, in μV/(Wm^{-2}); and $Rnet$, in μV/(Wm^{-2}), and Wnet, in Wm^{-2}, are the net infrared responsivity and net infrared irradiance, respectively, if known. If not known, or not applicable, an explicit magnitude (even if assumed to be zero—for example, for a silicon detector radiometer) of the estimated uncertainty associated with these terms must be stated. G is the calculated irradiance.

$$G = N * Cos(Z) + D$$

where N is the beam irradiance, in Wm^{-2}; Z is the solar zenith angle, in degrees; and D is the diffuse irradiance, in Wm^{-2}.

After the measurement equation is stated, the steps shown in Fig.1 follow.

2.2 Determine Sources of Uncertainties

Most of the sources of uncertainties (expanded uncertainties, denoted by U) shown in Table 1 were obtained from manufacturers' specifications or previously published reports on radiometric data uncertainty.

2.3 Standard Uncertainty

Calculate the standard uncertainty (u) for variables in the measurement equation. The uncertainty for each variable is obtained as follows:

- V, sensor output voltage: from either the manufacturer's specifications of the data acquisition manual, specification data, or the most recent calibration certificate
- Rnet: from the manufacturer's specifications, experimental data, or an estimate based on experience
- Wnet: from an estimate based on historical net IR at the site using pyrgeometer data and experience
- N: from the International Pyrheliometer Comparison (IPC)-XI report described in reference (2) and/or a pyrheliometer comparisons certificate based on annual calibrations or comparisons to primary reference radiometers traceable to the world radiometric reference.
- Z: from a solar position algorithm for calculating zenith angle and a time resolution of 1 second
- D: from a diffuse pyranometer calibration described in references (2), (4)

In the GUM method, when the distribution of the uncertainty is not known, it is common to assume a rectangular distribution (1), (5). In this case, the expanded uncertainty of a source of uncertainty with unknown distribution is divided by the square root of three.

$$u = \frac{U * a}{\sqrt{3}}$$

where U is the expanded uncertainty of a variable, and a_i is the variable in a unit of measurement.

For normal distribution, the equation is as follows:

$$u = \frac{U * a}{2}$$

Type A standard uncertainty is calculated by taking repeated indications (6) of the input quantity value, from which the sample mean and sample standard deviation can be calculated. The Type A standard uncertainty (u) is estimated by

$$SD = \sqrt{\frac{\sum_{i=1}^{n}(X_i - \overline{X})^2}{n-1}}$$

where X represents individual input quantity, $\overline{X}$ is the mean of the input quantity, and n equals the number of repeated indications of the quantity value.

2.4 Sensitivity Coefficient

The GUM method requires calculating the sensitivity coefficients (c) of the variables in a measurement equation. These coefficients affect the contribution of each input factor to the combined uncertainty of the irradiance value. Therefore, the sensitivity coefficient for each input is calculated by partial differentiating with respect to each input variable.

TABLE 1: MEASUREMENT EQUATION AND SENSITIVITY COEFFICIENT CALCULATIONS

Calibration Sensitivity Equations	**Field Measurement Sensitivity Equations**
Equation: $\boldsymbol{R = \frac{(V - R_{net} * W_{net})}{N * Cos(Z) + D}}$	Equation: $\boldsymbol{G = \frac{(V - R_{net} * W_{net})}{R}}$
$c_V = \frac{\partial R}{\partial V} = \frac{1}{N\,Cos(Z) + D}$	$c_R = \frac{\partial G}{\partial R} = \frac{-(V - R_{net} * W_{net})}{R^2}$
$c_{Rnet} = \frac{\partial R}{\partial Rnet} = \frac{-Wnet}{N\,Cos(Z) + D}$	$c_{R_{net}} = \frac{\partial G}{\partial R_{net}} = \frac{-W_{net}}{R}$
$c_{Wnet} = \frac{\partial R}{\partial Wnet} = \frac{-Rnet}{N\,Cos(Z) + D}$	$c_{W_{net}} = \frac{\partial G}{\partial W_{net}} = \frac{-R_{net}}{R}$
$c_N = \frac{\partial R}{\partial N} = \frac{-(V - Rnet\,Wnet)Cos(Z)}{(N\,Cos(Z) + D)^2}$	$c_V = \frac{\partial G}{\partial V} = \frac{1}{R}$
$c_Z = \frac{\partial R}{\partial Z} = \frac{N\,Sin(Z)\,(V - Rnet\,Wnet)}{(N\,Cos(Z) + D)^2}$	
$c_D = \frac{\partial R}{\partial D} = \frac{-(V - Rnet\,Wnet)}{(N\,Cos(Z) + D)^2}$	

2.5 Combined Standard Uncertainty

The standard uncertainty (u) and sensitivity coefficients (c) are calculated using the above equations for each variable in the measurement equation, then they are combined using the root sum of the squares method (7), (8). The combined uncertainty is applicable to both Type A and Type B sources of uncertainties.

$$u_c = \sqrt{\sum_{j=0}^{n-1}(u * c)^2}$$

2.6 Expanded Uncertainty

The expanded uncertainty ($U95$) was calculated by multiplying the combined uncertainty (u_c) by a coverage factor (k = 1.96 for infinite degrees of freedom), which represents a 95% confidence level.

$$U_{95} = u_c * k$$

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

$$U95\% = \frac{U95}{Variable} * 100$$

In calibration uncertainty estimation, the variable is the responsivity of the radiometer under calibration. In measurement uncertainty, it is the solar irradiance measured by the radiometer.

2.7 Examples

The above-mentioned steps are applicable to both calibration and measurement uncertainty estimations using the equations described in Table 1. Some of the sources of uncertainties are common to both, but the measurement uncertainty estimation has additional sources (Table 3).

2.7.1 Calibration Uncertainty

This subsection covers the evaluation of uncertainty in the calibration of broadband radiometers. The variable needed in the calibration step is the responsivity of the radiometer. The example below follows previous approach described by (9) for calibration and (1) for measuring solar irradiance using thermopile or semiconductor radiometers. Table 2 demonstrates the Type B sources of uncertainties, corresponding standard uncertainties, and sensitivity coefficients. The values described in Table 2 were obtained using the above equations corresponding to each step. Note that the values are hypothetical and are used only for illustration purposes. During the calibrations, both Type A and Type B sources of uncertainties were considered.

A standard deviation calculation of the measured irradiance was applied to estimate the Type A standard uncertainty (*u*). In the case of most pyranometers, the lack of uniform Lambertian (cosine) response results in a strong response function with respect to the solar zenith angle for a horizontal surface. In this example, there was only one source of Type A uncertainty: *u*. This is the variation (variance) of the specific responsivity chosen by the user. Two choices available to the user: (a) a single responsivity at a 45-degree solar zenith angle or (b) a response function based on a 2-degree bin (look-up table). The former is typical and used for simplicity; one responsivity value at 45 degrees represents all solar zenith angles. The later provides responsivities at all solar zenith angles and has lower overall uncertainty, provided that the range of complex example of the responsivities observed during calibration exceeds the mean, or a representative single responsivity at 45 degrees, by more than approximately 1.0% (10), (11). In the responsivity function, the Type A uncertainty estimates use the residuals of an interpolating function used to fit the response function, which is often different for the morning (AM) and afternoon (PM) outdoor calibration data (Fig. 2).

TABLE 2. EXAMPLE OF TYPICAL CALIBRATION TYPE B STANDARD UNCERTAINTIES (*U*) FOR A PYRANOMETERS (MODIFIED FROM (9)).

Sources of Uncertainties	**Expanded Uncertainties of the Sources**					**Distribution**	**Degrees of Freedom**	**Standard Uncertainty (u)**	**Sensitivity Coefficient (c)**	**Combined Uncertainty (Type B) (u*c) µV/ Wm^{-2}**
Input Variable	**Value and Units**	**U%**	**U**	**Offset**	**a=U+ Offset**					
V	7930.3 uV	0.001	0.079 uV	1.0 uV	1.079 uV	Rectangular	∞	0.62 uV	0.001 (1/Wm^{-2})	0.00062
R_{net}	0.4 uV/Wm^{-2}	10	0.04 uV/Wm^{-2}	--	0.04 uV/Wm^{-2}	Rectangular	∞	0.02 uV/ Wm^{-2}	0.1516	0.003032
W_{net}	-150 Wm^{-2}	5	7.5 Wm^{-2}	--	7.5 Wm^{-2}	Rectangular	∞	4.33 Wm^{-2}	0.0004 uV/(Wm^{-2})^2	0.001732
N	1,000 Wm^{-2}	0.4	4 Wm^{-2}	--	4 Wm^{-2}	Normal	∞	2 Wm^{-2}	0.0077 uV/(Wm^{-2})^2	0.0154
Z	20°	--	2. 10^{-5}	--	2. 10^{-5}	Rectangular	∞	1. 10^{-5}	2.7901 uV/ Wm^{-2}	2.79E-05
D	50 Wm^{-2}	3	1.5 Wm^{-2}	1 Wm^{-2}	2.5 Wm^{-2}	Normal	∞	1.25 Wm^{-2}	0.0082 uV/(Wm^{-2})^2	0.01025
Example: R = 8.0735 µV/Wm^{-2}				**Type B: u_c = 0.02 uV/Wm^{-2}**						

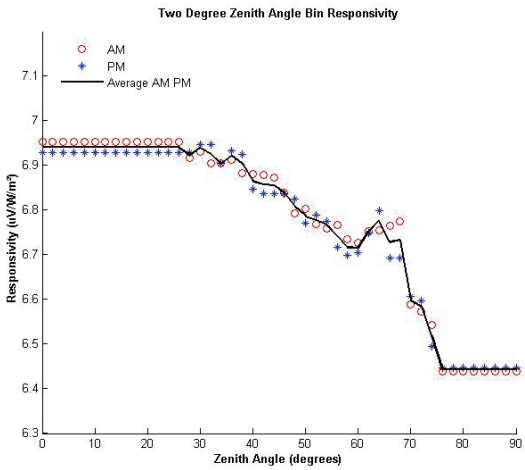

Fig. 2. Example of morning and afternoon responsivity functions and interpolated values (dark line)

The residual estimation from the interpolation method (Fig 3.) shows only the bias of the morning and afternoon.

$$r_{res}{}^2 = \frac{\sum_{i=1}^{m}(R_{i,m} - R_{i,AM})^2 + \sum_{i=1}^{k}(R_{i,m} - R_{i,PM})^2}{m + k}$$

where $R_{i,m}$ is the ith average measured AM or PM responsivity, and $R_{i,AM}$ and $R_{i,\ PM}$ are the interpolated or calculated AM and PM responsivity from the fitted response function. The degrees of freedom for the average $r_{res}{}^2$ are DF = m + k -2.

Therefore, to quantify the systematic deviation, the standard deviation of the residuals should also be calculated using the following equation.

$$\sigma_{res} = \sqrt{\frac{\sum_{j=1}^{j=m+k}(r_j - \bar{r})^2}{j + k - 2}}$$

where $\bar{r}$ is the mean residual, and r_j is the individual residuals from the fitted response function.

Therefore, the overall Type A standard uncertainty is calculated using

$$u_A = \sqrt{r_{res}{}^2 + \sigma_{res}{}^2}$$

where r_{res} is the residuals from the interpolation method.

Typical example values of r_{res} and σ_{res} are 0.05 and 0.1, respectively. Then

$$u_A = \sqrt{0.05^2 + 0.1^2} = 0.11 \text{ uV/Wm}^{-2}$$

Therefore, the Type A and Type B uncertainties are calculated using

$$u_c = \sqrt[2]{u_A^2 + u_B^2} = \sqrt{0.11^2 + 0.02^2} = 0.114 \text{ uV/Wm}^{-2}$$

$$U95 = 1.96 * 0.114 = 0.223 \text{ uV/Wm}^{-2}$$

$$U95\% = \frac{0.223}{8.0735} * 100 = 2.76\%$$

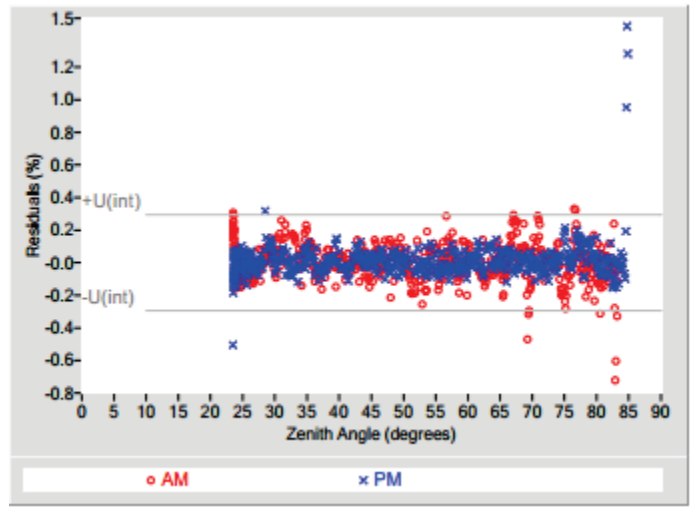

Fig 3. Example of residuals from the spline interpolation method (modified from (10)

2.7.2 Measurement Uncertainty

The same steps and principles of uncertainty estimation used for calibration apply to measurement. The only difference is that the calibration uncertainty becomes one of the sources of uncertainties. Further, the uncertainty estimation is based on solar irradiance (*G*), whereas in calibration the uncertainty estimation is in regards to the responsivity of the radiometer.

The measurement equation applies here as described in Table 1, and either a single responsivity value (the example below is based on a single responsivity value) or the responsivity as a function of solar zenith angle can be uniquely determined for an individual pyranometer or pyrheliometer from the calibration and used to compute the global or direct irradiance data, respectively. 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 (9). Table 3 shows examples of sources of uncertainties. Depending of the type of the radiometer, the lists could be different. The examples also provide relevant information on how different sources can act upon an input quantity.

Most of the sources of uncertainties are obtained from manufacturers' specifications, professional judgements, or previously published reports on radiometric data uncertainty.

TABLE 3. EXAMPLE OF SOURCES OF UNCERTAINTIES THAT CONTRIBUTE TO THE RADIOMETRIC MEASUREMENT UNCERTAINTY

Uncertainty component	Quantity	Statistical Distribution	Uncertainty Type	Standard Uncertainty (*u*)	Expanded Uncertainty (U)*
Calibration	R	Normal	Type B	$\frac{U}{2} = 1.38$	2.76 % (calibration done at 45 degrees)
Zenith Response	R	Rectangular	Type B	$\frac{U}{\sqrt{3}} = 1.15$	2% (calibration done at 45 degrees)
Spectral Response	R	Rectangular	Type B	$\frac{U}{\sqrt{3}} = 0.58$	1% (calibration done at 45 degrees)
Nonlinearty	R	Rectangular	Type B	$\frac{U}{\sqrt{3}} = 0.29$	0.5%
Temperature Response	R	Rectangular	Type B	$\frac{U}{\sqrt{3}} = 0.29$	1%
Aging per Year	R	Rectangular	Type B	$\frac{U}{\sqrt{3}} = 0.58$	1%
Datalogger Accuracy	V	Rectangular	Type B	$\frac{U}{\sqrt{3}} = 5.77$	10 µV
Maintenance	R	Rectangular	Type B	$\frac{U}{\sqrt{3}} = 0.17$	0.3%

For simplicity, the W_{net} and R_{net} variables of the measurement equation were not included in the example below for the measurement uncertainty estimation. The measurement equation will be reduced to;

$$G = \frac{V}{R}$$

Using the values from Table 3, the standard uncertainties for each variable in the measurement equation were calculated and are shown in Table 3.

For this example, G = 1,000 Wm^{-2} and R = 8.0735 uV/Wm^{-2}

$$u^2(V) = \sum_{i=1}^{n} u^2{}_i\,(V) = (5.77\ \mu\text{V})^2 \ = 33.33\ (\mu\text{V})^2$$

$$u(V) = \sqrt{33.33(\mu V)^2} \ = 5.77\ \mu\text{V}$$

$$u^2(R) = \sum_{i=1}^{n} u^2{}_i\,(R)$$

$$= (\frac{1.38}{100} * 8.0735)^2 + (\frac{1.15}{100} * 8.0735)^2 + (\frac{0.58}{100} * 8.0735)^2 + (\frac{0.29}{100} * 8.0735)^2 + (\frac{0.29}{100} * 8.0735)^2 + (\frac{0.58}{100} * 8.0735)^2 + (\frac{0.17}{100} * 8.0735)^2$$

$$u(R) = \sqrt{0.027(\text{uV/Wm} - 2)^2} = 0.163\ \text{uV/Wm}^{-2}$$

Then the sensitivity coefficients were computed with respect to each variable as described in the previous section.

$$c_V = \frac{\partial G}{\partial V} = \frac{1}{R}$$

$$= \frac{1}{8.0735} = 0.12\text{Wm}^{-2}/\text{uV}$$

$$c_R = \frac{\partial G}{\partial R} = \frac{-V}{R^2}$$

$$= \frac{abs(-1000Wm^{-2} * 8.0735\text{uV/Wm}^{-2}}{(\frac{8.0735uV}{Wm^{-2}})^2} = 123.86(\text{Wm}^{-2})^2 uV^{-1}$$

Next, the combined standard uncertainty, u_c, was calculated. For this example, only Type B sources of uncertainties were considered.

$$u_c = \sqrt{\sum_{j=0}^{n-1} (u * c)^2}$$

$$u_c = \sqrt{(u(V) * c_V)^2 + (u(R) * c_R)^2}$$

$$= \sqrt{(5.77 * 0.12)^2 + (0.163 * 123.86)^2}$$

$$= 20.20\text{Wm}^{-2}$$

The 20.20Wm^{-2} combined uncertainty value is based on the 1,000 Wm^{-2} reading. Because the irradiance is computed "instantaneously" at these data points, the total combined uncertainty component u_A is zero (i.e., there is no "standard deviation" to compute).

The expanded uncertainty (*U95*) is calculated by multiplying the combined uncertainty (u_c) by a coverage factor (k = 1.96, for infinite degrees of freedom), which represents a 95% confidence level.

U95 = k u_c = 1.96 * 20.20 Wm^{-2} = 39.59 Wm^{-2} or 4 % of the 1,000 Wm^{-2} irradiance value.

3. SUMMARY

Solar resource data with known and traceable uncertainty estimates are essential for the site selection of renewable energy technology deployment, system design, system performance, and system operations. Estimating calibration and measurement uncertainties of radiometric data using the GUM method would assist financiers and developers in the decision-making process for deploying renewable energy projects. Further, adopting such standardized methods will ensure that the uncertainty quoted for data collected by radiometers can be compared based on documented methods of derivation.

4. ACKNOWLEDGMENT

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