Designation: G213 – 17 (Reapproved 2023)

Standard Guide for Evaluating Uncertainty in Calibration and Field Measurements of Broadband Irradiance with Pyranometers and Pyrheliometers[1]

This standard is issued under the fixed designation G213; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This guide provides guidance and recommended practices for evaluating uncertainties when calibrating and performing outdoor measurements with pyranometers and pyrheliometers used to measure total hemispherical- and direct solar irradiance. The approach follows the ISO procedure for evaluating uncertainty, the Guide to the Expression of Uncertainty in Measurement (GUM) JCGM 100:2008 and that of the joint ISO/ASTM standard ISO/ASTM 51707 Standard Guide for Estimating Uncertainties in Dosimetry for Radiation Processing, but provides explicit examples of calculations. It is up to the user to modify the guide described here to their specific application, based on measurement equation and known sources of uncertainties. Further, the commonly used concepts of precision and bias are not used in this document. This guide quantifies the uncertainty in measuring the total (all angles of incidence), broadband (all 52 wavelengths of light) irradiance experienced either indoors or outdoors.

1.2 An interactive Excel spreadsheet is provided as adjunct, ADJG021317. The intent is to provide users real world examples and to illustrate the implementation of the GUM method.

1.3 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

1.4 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.5 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

E772 Terminology of Solar Energy Conversion

G113 Terminology Relating to Natural and Artificial Weathering Tests of Nonmetallic Materials

G167 Test Method for Calibration of a Pyranometer Using a Pyrheliometer

Guide for Estimating Uncertainties in Dosimetry for Radiation Processing

2.2 *ASTM Adjunct:*[2]

ADJG021317 CD Excel spreadsheet- Radiometric Data Uncertainty Estimate Using GUM Method

2.3 *ISO Standards*[3]

ISO 9060 Solar Energy—Specification and Classification of Instruments for Measuring Hemispherical Solar and Direct Solar Radiation

ISO/IEC Guide 98-3 Uncertainty of Measurement—Part 3: Guide to the Expression of Uncertainty in Measurement (GUM:1995)

ISO/IEC JCGM 100:2008 GUM 1995, with Minor Corrections, Evaluation of Measurement Data—Guide to the Expression of Uncertainty in Measurement

3. Terminology

3.1 Standard terminology related to solar radiometry in the fields of solar energy conversion and weather and durability testing are addressed in ASTM Terminologies E772 and G113, respectively. Some of the definitions of terms used in this guide may also be found in ISO/ASTM 51707.

3.2 *Definitions of Terms Specific to This Standard:*

[1] This test method is under the jurisdiction of ASTM Committee G03 on Weathering and Durability and is the direct responsibility of Subcommittee G03.09 on Radiometry.

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[3] Available from International Organization for Standardization (ISO), ISO Central Secretariat, BIBC II, Chemin de Blandonnet 8, CP 401, 1214 Vernier, Geneva, Switzerland, http://www.iso.org.

3.2.1 *aging (non-stability), n*—a percent change of the responsivity per year; it is a measure of long-term non-stability.

3.2.2 *azimuth response error, n*—a measure of deviation due to responsivity change versus solar azimuth angle.

NOTE 1—Often cosine and azimuth response are combined as "Directional response error," which is a percent deviation of the radiometer's responsivity due to both zenith and azimuth responses.

3.2.3 *broadband irradiance, n*—the solar radiation arriving at the surface of the earth from all wavelengths of light (typically wavelength range of radiometers 300 nm to 3000 nm).

3.2.4 *calibration error, n*—the difference between values indicated by the radiometer during calibration and "true value."

3.2.5 *cosine response error, n*—a measure of deviation due to responsivity change versus solar zenith angle. See Note 1.

3.2.6 *coverage factor, n*—numerical factor used as a multiplier of the combined standard uncertainty in order to obtain an expanded uncertainty.

3.2.7 *data logger accuracy error, n*—a deviation of the voltage or current measurement of the data logger due to resolution, precision, and accuracy.

3.2.8 *effective degrees of freedom, n*—v_{eff}, for multiple (N) sources of uncertainty, each with different individual degrees of freedom, v_i that generate a combined uncertainty u_c, the Welch-Satterthwaite formula is used to compute:

$$v_{eff} = \frac{u_c^4}{\sum_{i=1}^{N} \frac{u_4^i}{v_i}} \quad (1)$$

3.2.9 *expanded uncertainty, n*—quantity defining the interval about the result of a measurement that may be expected to encompass a large fraction of the distribution of values that could reasonably be attributed to the measurand.

3.2.9.1 *Discussion*—Expanded uncertainty is also referred to as "overall uncertainty" (BIPM Guide to the Expression of Uncertainty in Measurement).[4] To associate a specific level of confidence with the interval defined by the expanded uncertainty requires explicit or implicit assumptions regarding the probability distribution characterized by the measurement result and its combined standard uncertainty. The level of confidence that may be attributed to this interval can be known only to the extent to which such assumptions may be justified.

3.2.10 *leveling error, n*—a measure of deviation or asymmetry in the radiometer reading due to imprecise leveling from the intended level plane.

3.2.11 *non-linearity, n*—a measure of deviation due to responsivity change versus irradiance level.

3.2.12 *primary standard radiometer, n*—radiometer of the highest metrological quality established and maintained as an irradiance standard by a national (such as National Institute of Standards and Technology (NIST)) or international standards organization (such as the World Radiation Center (WRC) of the World Meteorological Organization (WMO)).

3.2.13 *reference radiometer, n*—radiometer of high metrological quality, used as a standard to provide measurements traceable to measurements made using primary standard radiometer.

3.2.14 *response function, n*—mathematical or tabular representation of the relationship between radiometer response and primary standard reference irradiance for a given radiometer system with respect to some influence quantity. For example, temperature response of a pyrheliometer, or incidence angle response of a pyranometer.

3.2.15 *routine (field) radiometer, n*—instrument calibrated against a primary-, reference-, or transfer-standard radiometer and used for routine solar irradiance measurement.

3.2.16 *sensitivity coefficient (function), n*—describes how sensitive the result is to a particular influence or input quantity.

3.2.16.1 *Discussion*—Mathematically, it is partial derivative of the measurement equation with respect to each of the independent variables in the form:

$$y(x_i) = c_i = \frac{\delta y}{\delta x_i} \quad (2)$$

where $y(x_1, x_2, \ldots x_i)$ is the measurement equation in independent variables, x_i.

3.2.17 *soiling effect, n*—a percent change in measurement due to the amount of soiling on the radiometer's optics.

3.2.18 *spectral mismatch error, radiometer, n*—a deviation introduced by the change in the spectral distribution of the incident solar radiation and the difference between the spectral response of the radiometer to a radiometer with completely homogeneous spectral response in the wavelength range of interest.

3.2.19 *temperature response error, n*—a measure of deviation due to responsivity change versus ambient temperature.

3.2.20 *tilt response error, n*—a measure of deviation due to responsivity change versus instrument tilt angle.

3.2.21 *transfer standard radiometer, n*—radiometer, often a reference standard radiometer, suitable for transport between different locations, used to compare routine (field) solar radiometer measurements with solar radiation measurements by the transfer standard radiometer.

3.2.22 *Type A standard uncertainty, adj*—method of evaluation of a standard uncertainty by the statistical analysis of a series of observations, resulting in statistical results such as sample variance and standard deviation.

3.2.23 *Type B standard uncertainty, adj*—method of evaluation of a standard uncertainty by means other than the statistical analysis of a series of observations, such as published specifications of a radiometer, manufacturers' specifications, calibration, or previous experience, or combinations thereof.

3.2.24 *zero offset A, n*—a deviation in measurement output (W/m^2) due to thermal radiation between the pyranometer and the sky, resulting in a temperature imbalance in the pyranometer.

[4] International Bureau of Weights and Measures (BIPM) Working Group 1 of the Joint Committee for Guides in Metrology (JCGM/WG 1).2008. "Evaluation of Measurement Data—Guide to the Expression of Uncertainty in Measurement (GUM)." JCGM 100:2008 GUM 1995 with minor corrections.

3.2.25 *zero offset B, n*—a deviation in measurement output (W/m^2) due to a change (or ramp) in ambient temperature.

NOTE 2—Both Zero Offset A and Zero Offset B are sometimes combined as "Thermal offset," which are due to energy imbalances not directly caused by the incident short-wave radiation.

4. Summary of Test Method

4.1 The evaluation of the uncertainty of any measurement system is dependent 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 guidance for the basic components of uncertainty in evaluating the uncertainty for both the calibration and measurement uncertainty estimates. The guide is based on the International Bureau of Weights and Measures (acronym from French name: BIPM) Guide to the Uncertainty in Measurements, or GUM.[4]

4.2 The approach explains the following components; defining the measurement equation, determining the sources of uncertainty, calculating standard uncertainty for each source, deriving the sensitivity coefficient using a partial derivative approach from the measurement equation, and combining the standard uncertainty and the sensitivity term using the root sum of the squares, and lastly calculating the expanded uncertainty by multiplying the combined uncertainty by a coverage factor (Fig. 1). Some of the possible sources of uncertainties and associated errors are calibration, non-stability, zenith and azimuth response, spectral mismatch, non-linearity, temperature response, aging per year, datalogger accuracy, soiling, etc. These sources of uncertainties were obtained from manufacturers' specifications, previously published reports on radiometric data uncertainty, or experience, or combinations thereof.

4.2.1 Both calibration and field measurement uncertainty employ the GUM method in estimating the expanded uncertainty (overall uncertainty) and the components mentioned above are applicable to both. The calibration of broadband radiometers involves the direct measurement of a standard source (solar irradiance (outdoor) or artificial light (indoor)). The accuracy of the calibration is dependent on the sky condition or artificial light, specification of the test instrument

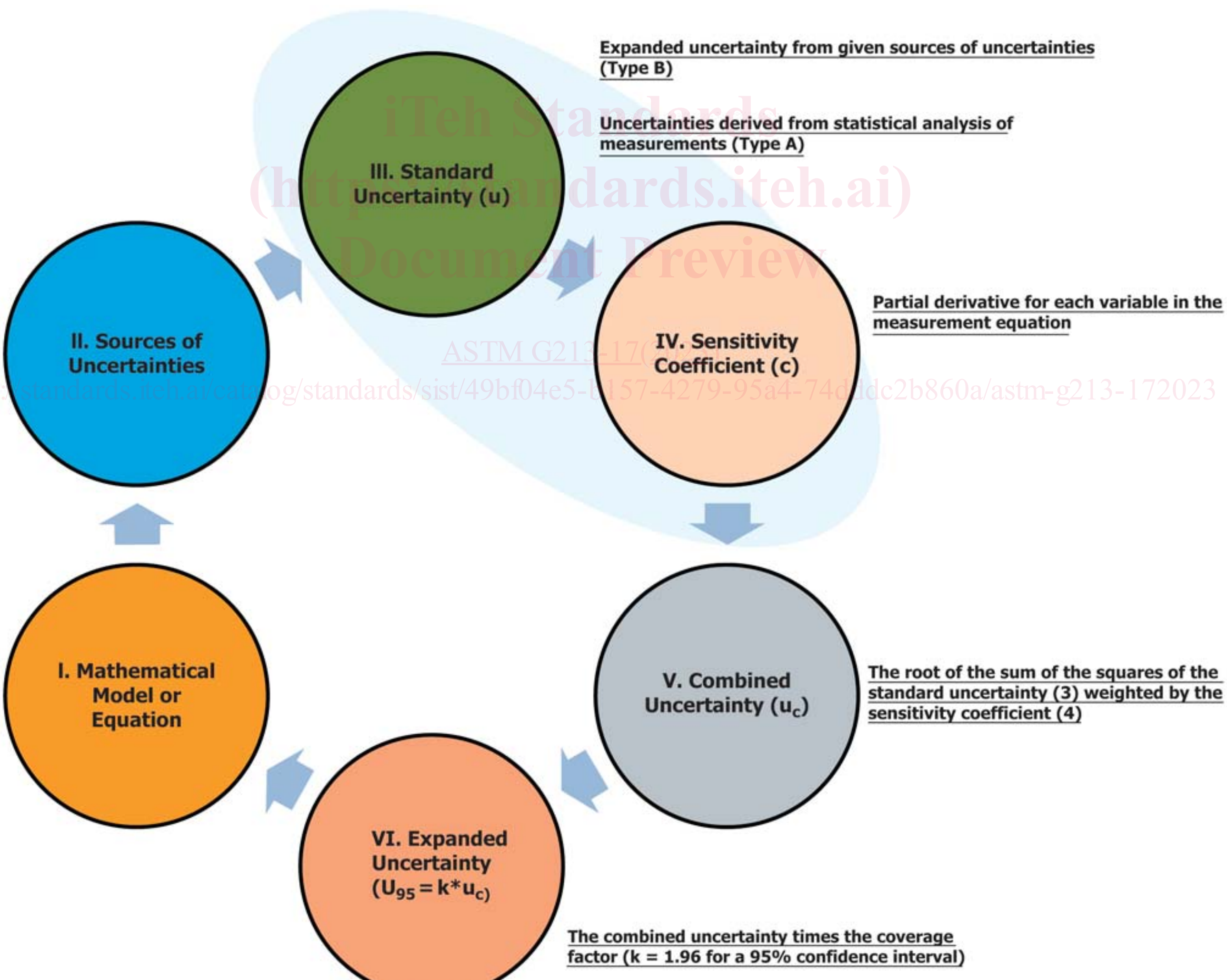

FIG. 1 Calibration and Measurement Uncertainty Estimation Flow Chart

Modified from Habte A., Sengupta M., Andreas A., Reda I., Robinson J. 2016. "The Impact of Indoor and Outdoor Radiometer Calibration on Solar Measurements," NREL/PO-5D00-66668. http://www.nrel.gov/docs/fy17osti/66668.pdf.

(zenith response, spectral response, non-linearity, temperature response, aging per year, tilt response, etc.), and reference instruments. All of these factors are included when estimating calibration uncertainties.

NOTE 3—The calibration method example mentioned in Appendix X1 is based on outdoor calibration using the solar irradiance as the source.

5. Significance and Use

5.1 The uncertainty in outdoor solar irradiance measurement has a significant impact on weathering and durability and the service lifetime of materials systems. Accurate solar irradiance measurement with known uncertainty will assist in determining the performance over time of component materials systems, including polymer encapsulants, mirrors, Photovoltaic modules, coatings, etc. Furthermore, uncertainty estimates in the radiometric data have a significant effect on the uncertainty of the expected electrical output of a solar energy installation.

5.1.1 This influences the economic risk analysis of these systems. Solar irradiance data are widely used, and the economic importance of these data is rapidly growing. For proper risk analysis, a clear indication of measurement uncertainty should therefore be required.

5.2 At present, the tendency is to refer to instrument datasheets only and take the instrument calibration uncertainty as the field measurement uncertainty. This leads to over-optimistic estimates. This guide provides a more realistic approach to this issue and in doing so will also assists users to make a choice as to the instrumentation that should be used and the measurement procedure that should be followed.

5.3 The availability of the adjunct (ADJG021317)[5] uncertainty spreadsheet calculator provides real world example, implementation of the GUM method, and assists to understand the contribution of each source of uncertainty to the overall uncertainty estimate. Thus, the spreadsheet assists users or manufacturers to seek methods to mitigate the uncertainty from the main uncertainty contributors to the overall uncertainty.

6. Basic Uncertainty Components for Evaluating Measurement Uncertainty of Pyranometers and Pyrheliometers

6.1 As described in the BIPM GUM[4] and summarized in Reda et al. 2008,[6] and Reda 2011,[7] the process for both calibration and field measurement uncertainty follows six basic uncertainty components:

6.1.1 *Determine the Measurement Equation for the Calibration Measurement System (or both)*—Mathematical description of the relation between sensor voltage and any other independent variables and the desired output (calibration response, or engineering units for measurements). Eq 3 and Eq 4 are equations used for calculating responsivity or irradiance and they are used here for example purposes.

Calibration Equation: $R = \frac{(V - R_{net} \times W_{net}}{G}$ Field Measurement Equation: $G = \frac{(V - R_{net} \times W_{net})}{R}$ (3)

$$G = N \times Cos(Z) + D$$

where R is the pyranometer's responsivity, in microvolt per watt per square meter μV/(Wm^{-2}),
V is the pyranometer's sensor output voltage, in μV
N is the beam irradiance measured by a primary or standard reference standard pyrheliometer, measuring the beam irradiance directly from the sun's disk in Wm^{-2},
Z is the solar zenith angle, in degrees,
D is the diffuse irradiance, sky irradiance without the beam irradiance from the sun's disk, measured by a shaded pyranometer,
G is the calculated irradiance, in Wm^{-2},
$Rnet$ is the pyranometer's net infrared responsivity, in μV/(Wm^{-2}), and
$Wnet$ is the net infrared irradiance measured by a collocated pyrgeometer, measuring the atmospheric infrared, in Wm^{-2}, if known. If not known, or not applicable, explicit magnitude (even if assumed to be zero, e.g., for a silicon detector radiometer) for the uncertainty associated with these terms must be stated. G is the calculated irradiance. The measurement equation with unknown or not applicable $Wnet$ and $Rnet$ is:

$$G = \frac{V}{R} \quad (4)$$

6.1.2 *Determine Sources of Uncertainties*—Most of the sources of uncertainties (expanded uncertainties, denoted by U) were obtained from manufacturers' specifications, previously published reports on radiometric data uncertainty or professional experience. Some of the common sources of uncertainties are:

Solar Zenith Angle Response: pyranometer specification sheet
Spectral Response: user estimate/pyranometer specification sheet
Non-linearity: pyranometer specification sheet
Temperature response: pyranometer specification sheet
Aging per year: pyranometer specification sheet
Data logger accuracy: data logger specification sheet
Maintenance (for example, soiling): user estimate
Calibration: calibration certificate

6.1.3 *Calculate the Standard Uncertainty, u*—calculate u for each variable in the measurement equation, using either statistical methods (Type A uncertainty component) or other than statistical methods (Type B uncertainty component), such as manufacturer specifications, calibration results, and experimental or engineering experience.

6.1.3.1 *V:* Sensor output voltage: from either the manufacturer's specifications of the data acquisition manual, specification data, or the most recent calibration certificate.

[5] Available from ASTM International Headquarters. Order Adjunct No. ADJG021317. Original adjunct produced in **ADJG021317**. Adjunct last revised in **2017**.

[6] Reda, I.; Myers, D.; Stoffel, T. (2008)." Uncertainty Estimate for the Outdoor Calibration of Solar Pyranometers: A Metrologist Perspective. Measure." *NCSLI Journal of 100 Measurement Science*. Vol. 3(4), December 2008; 58-66.

[7] Reda, I. Technical Report NREL/TP-3B10–52194. *Method to Calculate Uncertainties in Measuring Shortwave Solar Irradiance Using Thermopile and Semiconductor Solar Radiometers*. 2011.

6.1.3.2 *Rnet:* From the manufacturer's specifications, experimental data, or an estimate based on experience.

6.1.3.3 *Wnet:* From an estimate based on historical net infrared at the site using pyrgeometer data and experience.

6.1.3.4 *N:* From the International Pyrheliometer Comparison (IPC) report described in reference or a pyrheliometer comparisons certificate based on annual calibrations or comparisons to primary reference radiometers traceable to the world radiometric reference, or combinations thereof.

6.1.3.5 *Z:* From a solar position algorithm for calculating solar zenith angle and a time resolution of 1 second.

6.1.3.6 *D:* From a diffuse pyranometer calibration described in Test Method G167.

6.1.3.7 *Discussion*—Type A and Type B classification are based on distribution of the measurement, and a requirement of the GUM approach is to associate each source of uncertainty to a specific distribution, either measured or assumed. See Appendix X2 for a summary of typical distribution types (rectangular or uniform, Gaussian or normal, triangular, etc.) and the associated form of standard uncertainty calculation.

In the Type B, when the distribution of the uncertainty is not known, it is common to assume a rectangular distribution. In this case, the expanded uncertainty of a source of uncertainty with unknown distribution is divided by the square root of three.

$$u = \frac{U \times a}{\sqrt{3}} \quad (5)$$

where U is the expanded uncertainty of a variable, and a is the variable in a unit of measurement. For normal distribution, the equation is as follows:

$$u = \frac{U \times a}{k} \quad (6)$$

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

$$SD = \sqrt{\frac{\Sigma_{i=1}^{n}(x_i - \bar{x})^2}{n-1}} \quad (7)$$

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

6.1.4 *Sensitivity Coefficient, c*—The GUM method requires calculating the sensitivity coefficients (c_i) 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 differentiation with respect to each input variable in the measurement equation. The respective sensitivity coefficient equations based on Eq 3 are:

Calibration Sensitivity Equations	Field Measurement Sensitivity Equations
$c_v = \frac{\delta R}{\delta V} = \frac{1}{N \ Cos(Z) + D}$	$c_R = \frac{\delta G}{\delta R} = \frac{-(V - R\text{ net} \quad \times W\text{ net})}{R^2}$
$c_{Rnet} = \frac{\delta R}{\delta Rnet} = \frac{-Wnet}{N \text{ Cos}(Z) + D}$	$c_{Rnet} = \frac{\delta G}{\delta Rnet} = \frac{-Wnet}{R}$
$c_{Wnet} = \frac{\delta R}{\delta Wnet} = \frac{-Rnet}{N\text{Cos}(Z) + D}$	$c_{Wnet} = \frac{\delta G}{\delta Wnet} = \frac{-Rnet}{R}$
$c_N = \frac{\delta R}{\delta N} = \frac{-(V - R\text{ net} \quad W\text{ net}) \ Cos(Z)}{(N \quad \text{Cos}\ (Z) \quad + D)^2}$	$c_v = \frac{\delta G}{\delta V} = \frac{1}{R}$
$c_Z = \frac{\delta R}{\delta Z} = \frac{N \text{ Sin}(Z)\ (V - \quad R\text{ net} \quad W\text{ net})}{(N \quad \text{Cos}\ (Z) \quad + D)^2}$	
$c_D = \frac{\delta R}{\delta D} = \frac{-(V - R\text{ net} \quad W\text{ net})}{(N \quad \text{Cos}\ (Z) \quad + D)^2}$	

6.1.5 *Combined Standard Uncertainty, u_c*—Calculate the combined standard uncertainty using the propagation of errors formula and quadrature (root-sum-of-squares) method.

6.1.5.1 The combined uncertainty is applicable to both Type A and Type B sources of uncertainties. Standard uncertainties (u) multiplied by their sensitivity factors (c) are combined in quadrature to give the combined standard uncertainty, u_c.

$$u_c = \sqrt{\sum_{i=0}^{n-1} (u_i \times c_i)^2} \quad (8)$$

6.1.6 *Calculate the Expanded Uncertainty (U_{95})* by multiplying the combined standard uncertainty by a coverage factor, k, based on the equivalent degrees of freedom (see section 3.2.9).

$$U_{95} = u_c \times k \quad (9)$$

6.1.6.1 Typically, k = 1, 2, or 3 implies that the true value lies within the confidence interval defined by $y \pm U$ with confidence level of either 68.27 %, 95.45 %, or 99.73 % of the time, respectively. These ranges are meant to be analogous to the relation of the coverage of a normally distributed data set by numbers of standard deviations of such a data set. Thus U is often denoted as U_{95} or U_{99}.

7. Keywords

7.1 GUM; irradiance; pyranometers; pyrheliometers

APPENDIXES

(Nonmandatory Information)

X1. EXAMPLE OF CALIBRATION AND MEASUREMENT UNCERTAINTY ESTIMATION

X1.1 Overview

X1.1.1 This section provides examples of a) evaluating the uncertainty in the calibration of pyranometers for measuring total hemispherical solar radiation, and b) evaluating the uncertainty in a routine pyranometer field measurement system for measuring total hemispherical solar radiation. The examples follow the approach described in Reda et al. 2008[6] for calibration, and Reda 2011,[7] for measuring solar irradiance using thermopile or semiconductor radiometers.

X1.1.2 The examples provided here are generally applicable to evaluating the uncertainty in calibration results (instrument response functions, or responsivity) and routine field measurement data. Given the wide variety of instrumentation, radiometric reference (primary, transfer standard) radiometers used, and measurement techniques (indoor or outdoor calibration techniques) the guide cannot address every calibration and measurement system.

X1.1.3 The principles and essential components, including estimation of magnitudes and types of error (A or B), in conjunction with the documentation and reporting of the estimated uncertainties is the responsibility of the user of this guide. The absolutely critical aspect of this approach is to document the measurement equation, identified sources of uncertainty, the type of component (Type A or Type B), the basis for the estimates of magnitude for each variable, of the assumed sample distribution type, effective degrees of freedom, and associated coverage factor, standard uncertainties and sensitivity functions for influencing quantities. Lastly, report the combined standard uncertainties and expanded uncertainty.

X1.2 **Evaluating Field Measurement Uncertainty:** As calibration uncertainty is propagated as an element of field measurement uncertainty; and that to start with a somewhat simpler example, looking at the field measurement uncertainty as an introduction is suggested because the calibration uncertainty is more complicated.

X1.2.1 Determine the measurement equation used to produce the engineering data, Eq 3 and Eq 4.

X1.2.2 Either a single responsivity value (example below is based on single responsivity value) or the responsivity as a function of solar zenith angle can be uniquely determined for an individual pyranometer or pyrheliometer 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.[7]

X1.2.3 List sources of field measurement uncertainty: Table X1.1 shows some of the sources as an example and depending on the type of radiometer, the lists could be different. Further, each source of uncertainty relates to a specific quantity or variable in the measurement equation. For example, calibration source of uncertainty relates to the responsivity quantity or variable in the measurement equation (see Table X1.2).

TABLE X1.1 List of Sources of Uncertainties and Standard Uncertainty Calculation

Source of Uncertainty	Quantity	Statistical Distribution	Uncertainty Type	Standard Uncertainty (u)	Expanded Uncertainty (U)[A]
Calibration	R	Normal	Type B	$\frac{U}{2}=2.81$	5.62 % (calibration done at 45°)
Solar Zenith Angle Response	R	Rectangular	Type B	$\frac{U}{\sqrt{3}}=1.15$	2 % (calibration done at 45°)
Spectral Response	R	Rectangular	Type B	$\frac{U}{\sqrt{3}}=0.58$	1 % (calibration done at 45°)
Non-linearity	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 μ V
Maintenance	R	Rectangular	Type B	$\frac{U}{\sqrt{3}}=0.17$	0.3 %

[A]Expanded uncertainty for each source of uncertainty could be obtained from manufacturer specification, calibration report, historical data, or professional judgment.

TABLE X1.2 Typical Type B Standard Uncertainties (u_B) for Pyranometer Measurement Equation

Variable	Value Units	U%	U	Offset	a=U+ Offset	Distribution	Degrees of Freedom[A]	U_B
V	7930.3 µV	0.001	0.079 µV	1.0 µV	1.079 µV	Rectangular	1000	0.62
R_{net}	0.4 $\mu V/Wm^{-2}$	10	0.04 $\mu V/Wm^{-2}$	...	0.04 $\mu V/Wm^{-2}$	Rectangular	1000	0.02
W_{net}	-150 Wm^{-2}	5	7.5 Wm^{-2}	...	7.5 Wm^{-2}	Rectangular	1000	4.33
N	1000 Wm^{-2}	0.4	4 Wm^{-2}	...	4 Wm^{-2}	Rectangular	1000	2.31
Z	20°	...	2.10^{-5}	...	2.10^{-5}	Rectangular	1000	1.10^{-5}
D	50 Wm^{-2}	3	1.5 Wm^{-2}	...	1.5 Wm^{-2}	Rectangular	1000	1.44
				R=8.0735$\mu V/Wm^{-2}$				

[A] Degrees of freedom assumed large based on the assumption of a typical (mean) values from a large number of samples for each specific variable resulting in the single reported value (as from the datalogger specifications, or zenith angle computations).

X1.2.4 For simplicity, the Wnet and Rnet variables of the measurement equation were not included in the example below for the measurement uncertainty estimation, therefore, Eq 3 is used.

X1.2.5 Compute or estimate the standard uncertainty for each variable in the measurement equation as it is described in Table X1.2. For this example G = 1000 W/m^2 and R = 15 $\mu V/Wm^{-2}$.

$$u^2(V) = \Sigma_{i=1}^{n} u_i^2(V) = \;5.77\mu V^2 = 33.33\mu V \qquad (X1.1)$$

$$u^2(R) = \Sigma_{i=1}^{n} u_i^2(R) \qquad (X1.2)$$

$$= \left(\frac{2.81}{100} \times 15\right)^2 + \left(\frac{1.15}{100} \times 15\right)^2 + \left(\frac{0.58}{100} \times 15\right)^2 + \left(\frac{0.29}{100} \times 15\right)^2 + \left(\frac{0.29}{100} \times 15\right)^2 + \left(\frac{0.58}{100} \times 15\right)^2 + \left(\frac{0.17}{100} \times 15\right)^2 = 0.22\mu V/Wm^{-2} \qquad (X1.3)$$

X1.2.6 Compute the sensitivity coefficients with respect to each variable in the measurement equation, for example:

$$c_V = \frac{\delta G}{\delta V} = \frac{1}{R} = \frac{1}{15} = 0.07Wm^{-2}/uV \qquad (X1.4)$$

$$c_R = \frac{\delta G}{\delta R} = \frac{-V}{R^2} \qquad (X1.5)$$

$$= \frac{abs\left(-\;1000\;W\;m^{-2} \times \frac{15uV}{Wm^{-2}}\right)}{\left(\frac{15uV}{Wm^{-2}}\right)^2} = 66.67uV^{-1}$$

X1.2.7 Using the sensitivity coefficients c_i compute the combined standard uncertainty, $c_i\ u_i$, associated with each variable, and the combined uncertainty is calculated using the root sum of the squares method, standard uncertainty and the respective sensitivity coefficient for individual variable.[4] For this example, only Type B sources of uncertainties are considered.

$$uc = \sqrt{\sum_{j=0}^{n-1} (u \times c)^2} \qquad (X1.6)$$

$$uc = \sqrt{(u\ (V) \times C_V)^2 + (u\ (R) \times C_R)^2} \qquad (X1.7)$$

$$= \sqrt{(33.33 \times 0.07)^2 + (0.22 \times 66.67)^2}$$
$$= 14.85Wm^{-2}$$

Note that the computed irradiance according to the measurement equation would be 1000 Wm^{-2}. The resulting combined standard uncertainty is 14.85 Wm^{-2}. Because the irradiance is computed "instantaneously" at these data points, the total combined uncertainty component u_A is zero (there is no standard deviation to compute) in the equation:

$$u_c = \sqrt{u_A^2 + u_B^2} \qquad (X1.8)$$

Note that the standard uncertainties are calculated at each data point, and R was considered constant. If the responsivity is corrected for zenith angle dependence (i.e. using it as a function of zenith angle) where u_R is usually only about 0.5 %, or 50 % smaller than the constant Rs uncertainty, the combined standard uncertainty will be considerably reduced.

X1.2.8 The expanded uncertainty (U_{95}) 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.

$$U_{95} = ku_c = 1.96 \times 14.85 \;\; Wm^{-2}$$
$$= 29.1 \;\; Wm^{-2} \text{or} \;\; 2.9\% \text{ of the} 1000 \; Wm^{-2} \text{irradiance value} \qquad (X1.9)$$

X1.3 **Outdoor Pyranometer Calibration Uncertainty Evaluation:** The components and principles described for the evaluation of measurement uncertainty are applied to the calibration uncertainty estimation. The example provided here is for a thermopile pyranometer using outdoor calibration methodology.

X1.3.1 Outdoor Thermopile Pyranometer Calibration—Measurement Equation.

X1.3.1.1 *Determine Measurement Equation (Eq 3),* Each measurement data point consists of simultaneously recording the voltage output from the test pyranometer together with the output from a reference standard pyrheliometer, which measures the irradiance from the sun's disk, a pyrgeometer, which is a thermopile instrument that measures the atmospheric infrared irradiance (if known or applicable), and a shaded pyranometer which determines the diffuse irradiance from the sky. The responsivity, R, of the test pyranometer is then calculated using Eq 3 (calibration equation).

NOTE X1.1—W_{net} is very often omitted from the measurement equation, in which case some estimation of the uncertainty contribution due to W_{net} should be made.

X1.3.1.2 All of the variables in the measurement equation are measured independently of each other, and there are no correlations or interdependence between the variables. For