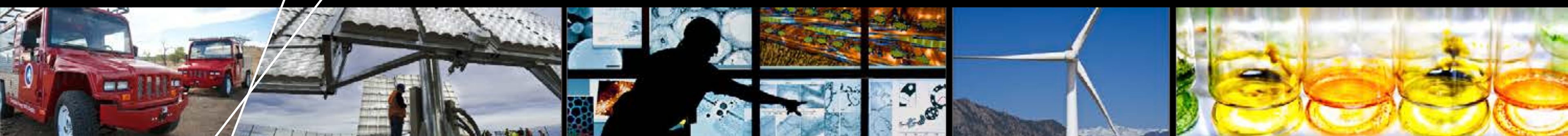
Quantifying Measurement Uncertainty in Thermopile Instrument



2015 PV Solar Resource Workshop, Golden, Colorado

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Motivation:

- To develop a consensus standard to estimate radiometric measurement uncertainty.
  - At present the tendency is to look at instrument datasheets and take the instrument calibration uncertainty as the measurement uncertainty.

Outline:

- Quantifying measurement uncertainty using the GUM method
- Inter-comparison of radiometric measurements from various instruments
- Developing consensus standards through American Society for Testing Materials (ASTM) International

Measuring Solar Radiation with Thermopiles

Direct Normal

Measured by a *Pyrheliometer* on a sun-following tracker

Global Horizontal

Measured by a *Pyranometer* with a horizontal sensor

Diffuse

Measured by a shaded *Pyranometer* under a tracking ball

Traceability of Radiometric Measurements

Uncertainty Increases

World Radiation Reference (WRR) ~±0.3%

International Pyrheliometer Comparison (IPC) ~±0.36%

NREL Pyrheliometer Comparison (NPC) ~±0.4%

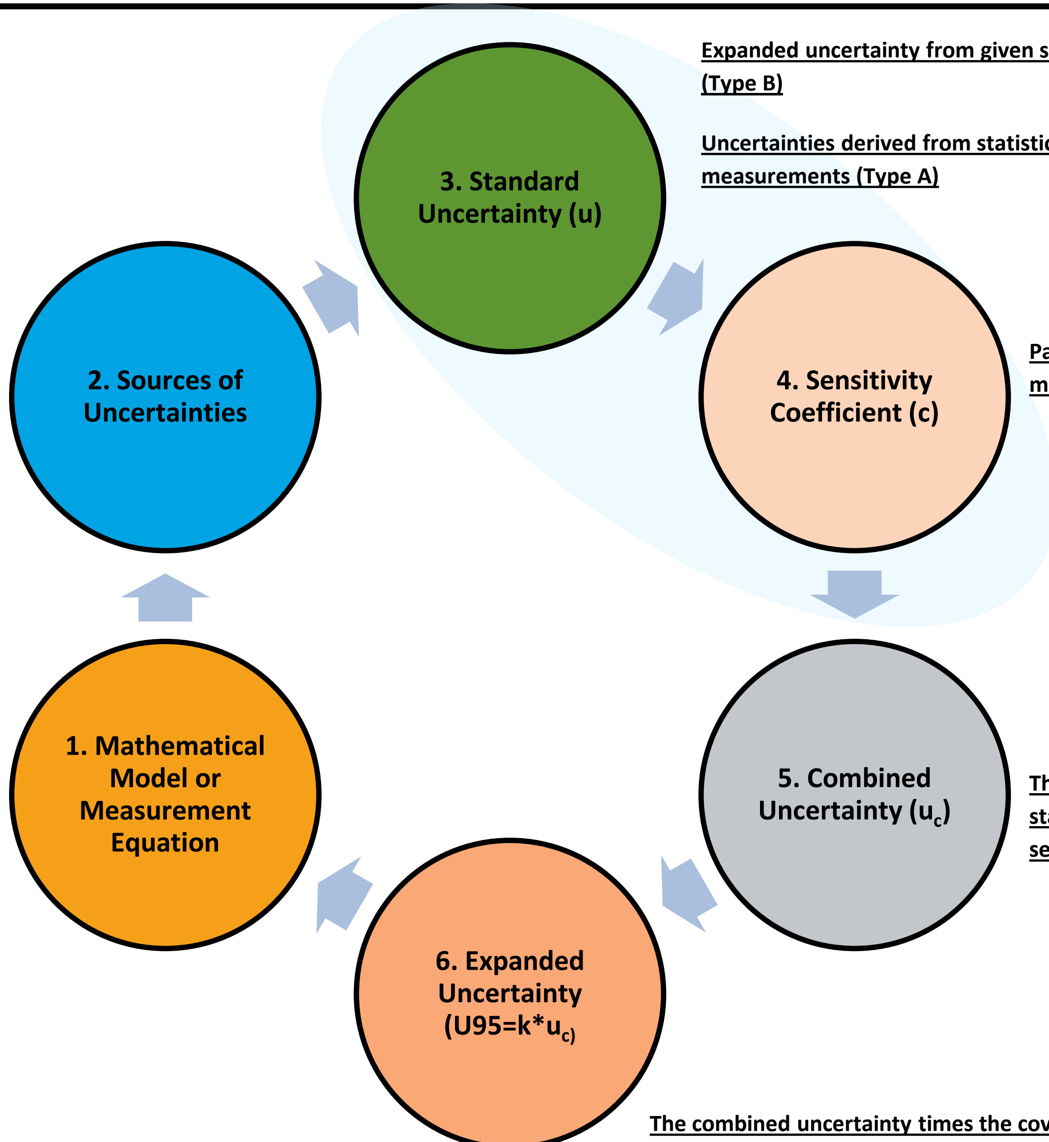
Calibrate Pyrheliometer (~±1%-2%)
Standards: BORCAL, ASTM E816, ISO 9059

Diffuse Reference (Shade/Unshade) (~±3%+1W/m^2)
Standards: BORCAL, ASTM G167

Calibrate Pyranometer (~±2%-3%)
Standards: BORCAL, ASTM G167, ISO 9846

Field deployment (~±3%-5%)

Steps for Measurement Uncertainty Estimation



Expanded uncertainty from given sources of uncertainties (Type B)

Uncertainties derived from statistical analysis of measurements (Type A)

Partial derivative for each variable in the measurement equation

The root of the sum of the squares of the standard uncertainty (3) weighted by the sensitivity coefficient (4)

The combined uncertainty times the coverage factor (k =1.96 for a 95% confidence interval)

Reda et al., 2011:http://www.nrel.gov/docs/fy11osti/52194.pdf; JCGM/WG 1. (2008). www.bipm.org/utils/common/documents/jcgm/JCGM_100_2008_E.pdf

Measurement Equation – Step 1

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

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_{net} is the pyranometer's net longwave responsivity estimated or determined by blackbody characterization in µV/(Wm^{-2})

W_{net} 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 µV/(Wm^{-2}).

Sources of Measurement Uncertainties – Step 2

- **In field deployments, add uncertainties in Measurement Equation Variables *(V, R_{net}, W_{net} and R)* due to**
  - Calibration (R)
    - NREL radiometer calibrations are done outdoors.
    - Calibration certificate reports the calibration results under specific environmental conditions that are different from conditions in the field.
  - Spectral Response (R)
  - Zenith Angle (R)
  - Maintenance----Soiling (dust, rain, bird droppings, etc.) (R)
  - Data logger uncertainty (V)
  - Temperature dependence (R)
  - Non-linearity (R)
  - Aging (R)

Quantifying Standard Uncertainty – Step 3

- **Type B uncertainties** - Method of evaluation of a standard uncertainty by means other than the statistical analysis of a series of observations such as, **manufacturers' specifications, calibration, and/or previous experience/literature estimates**
  - Example, **rectangular distribution** for a source of uncertainty with unknown distribution

where *U* is the expanded uncertainty of a variable.

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

  - For **normal distribution**: $u = \frac{U}{2}$

- **Type A uncertainties** – A standard uncertainty is **derived from Measurements** using the statistical analysis of a series of observations.

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

Sensitivity Coefficient Calculations – Step 4

Measurement Equation

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

Sensitivity Coefficient Calculations: e.g. (sensitivity coefficient of R)

$$C_R = \frac{\partial G}{\partial R} = \frac{-(V - R_{net} * W_{net})}{R^2}$$

Combined Uncertainty – Step 5

- The standard uncertainty (*u*) and sensitivity coefficients (*c*) are combined using the root sum of the squares method to calculate the **combined uncertainty**

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

Note: The combined uncertainty is applicable to both Type A and Type B sources of uncertainties.

Expanded Uncertainty (U_{95}) – Step 6

- 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, in W/m^2.

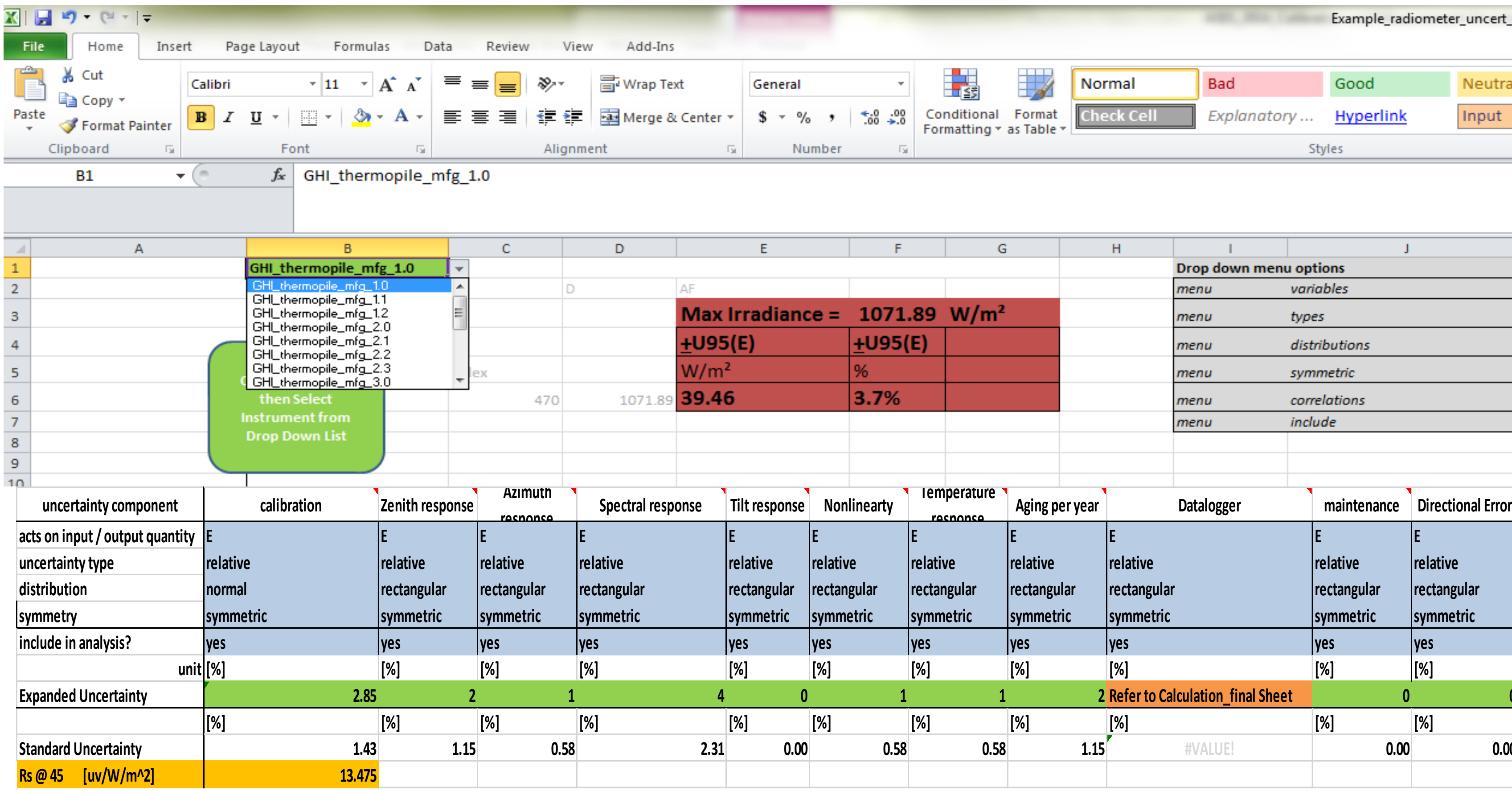
$$U_{95} = u_c * k$$

- The **expanded uncertainty U_{95}** as a percentage is then calculated as

$$U_{95} = \frac{U_{95}}{\text{Measured Irradiance}} * 100$$

Excel® spreadsheet- Radiometric Data Uncertainty Estimate Using GUM method

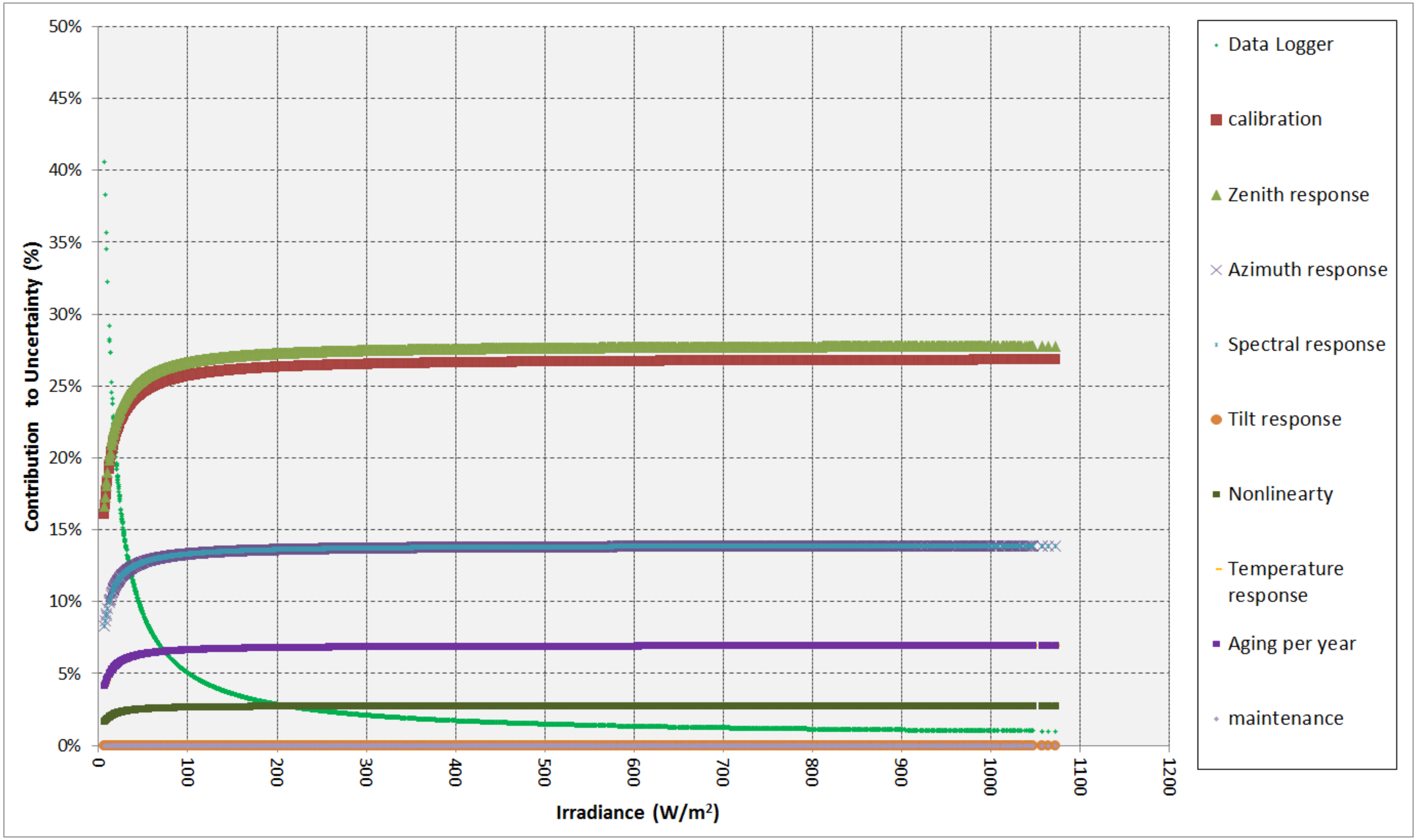
- **The spreadsheet provides a comprehensive estimation of measurement uncertainty associated with measurands using GUM method.**



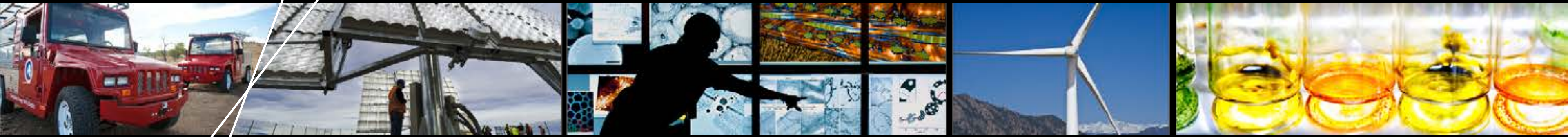
uncertainty component	calibration	Zenith response	Azimuth response	Spectral response	Tilt response	Nonlinearity	Temperature response	Aging per year	Datalogger	maintenance	Directional Error
acts on input / output quantity	E	E	E	E	E	E	E	E	E	E	E
uncertainty type	relative	relative	relative	relative	relative	relative	relative	relative	relative	relative	relative
distribution	normal	rectangular	rectangular	rectangular	rectangular	rectangular	rectangular	rectangular	rectangular	rectangular	rectangular
symmetry	symmetric	symmetric	symmetric	symmetric	symmetric	symmetric	symmetric	symmetric	symmetric	symmetric	symmetric
include in analysis?	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
unit	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]
Expanded Uncertainty	2.85	2	1	4	0	1	1	2	Refer to Calculation_final Sheet	0	0
	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]
Standard Uncertainty	1.43	1.15	0.58	2.31	0.00	0.58	0.58	1.15	#VALUE!	0.00	0.00
Rs @ 45 [uv/W/m^2]	13.475										

Link: http://www.nrel.gov/midc/srrl_bms/ and look for Excel® uncertainty spreadsheet at the bottom of the page.

Contribution of various sources of uncertainty to expanded uncertainty



Evaluation of Radiometers Deployed at the National Renewable Energy Laboratory's Solar Radiation Research Laboratory



Purpose:

- **Comparing various radiometers to the best instrument**
  - Provides relative performance of instruments under test
  - Offers information in quantifying/understanding sources of uncertainties of a measurement
  - Assists in justifying measurement uncertainties

Available: http://www.nrel.gov/docs/fy14osti/60896.pdf

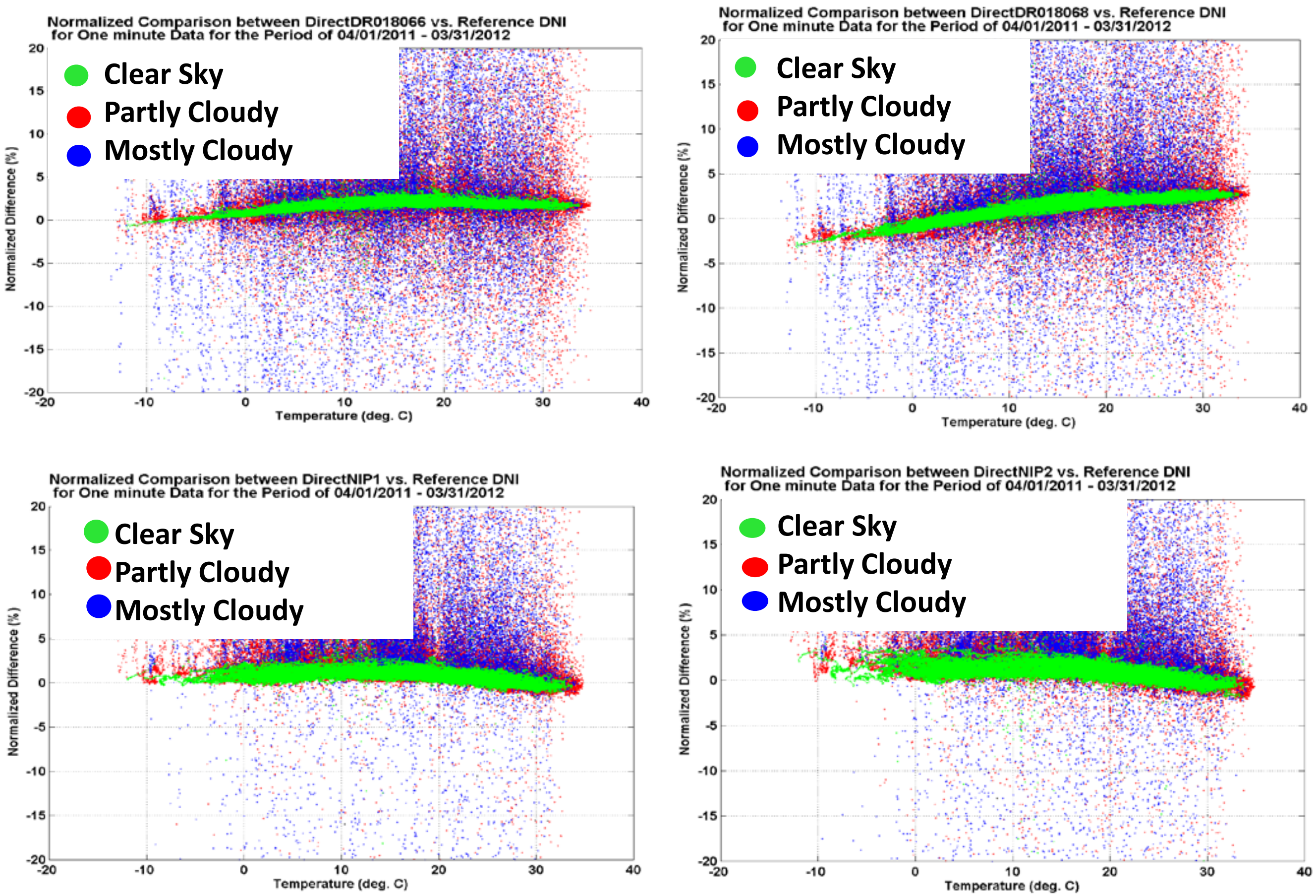
Method and Experimental Design:

- Test Instruments: 32 Global Horizontal and 19 Direct Normal irradiance measuring radiometers
- Data was quality assessed
- Best practices for Operation and Maintenance of the instruments was followed.

Reference Instrument Used for comparison

- **Reference Data**
  - **A Kipp and Zonen CH1 (DNI)** instrument and **an Eppley Laboratory, Inc., black-and-white model 8-48** (diffuse horizontal irradiance, or DHI) instrument
    - Traceable to SI through the World Radiometric Reference (WRR)
    - Lowest calibration and measurement uncertainties

Temperature dependence of DNI Instruments



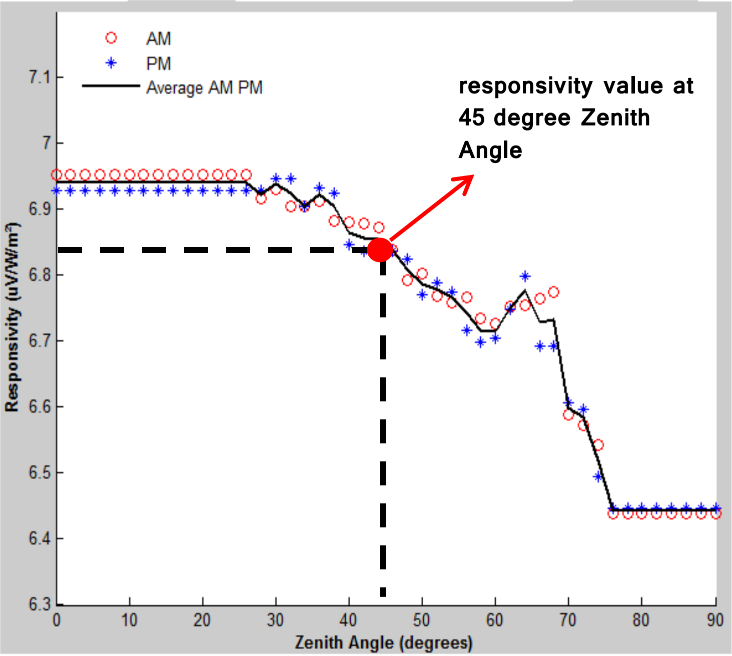
Effect of temperature on DNI measurement, (Top) Hukseflux radiometer and (bottom) Eppley NIP model

- The Hukseflux radiometer model number DR108068 had relatively more evident temperature dependence than model number DR108066.
- The two Eppley NIP radiometers tend to have less temperature dependence.

Evaluating Radiometric Measurements Using a Fixed 45° Responsivity and Zenith Angle Dependent Responsivities

MBE for the NREL EPPLEY PSP (28402F3)

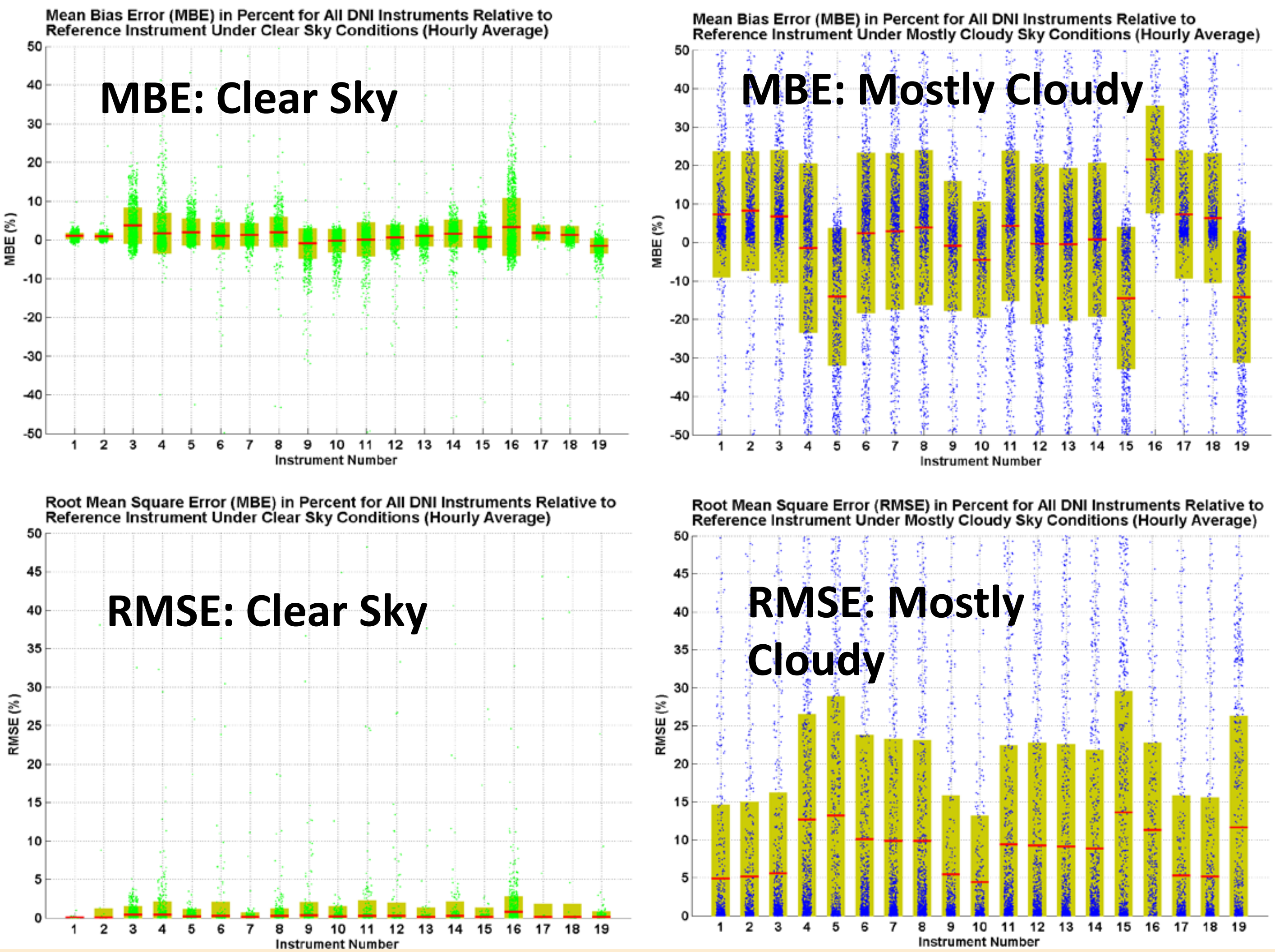
Solar Zenith Angle Bins	Responsivity using Zenith Function		Responsivity at 45 degree Zenith	
	MBE%	MBE in W/m²	MBE%	MBE in W/m²
10-20	-0.36	-2.77	3.01	22.12
20-30	-1.55	-4.62	1.77	19.61
30-40	-1.40	-5.04	1.93	17.47
40-50	-1.10	-4.15	2.25	16.04
50-60	-0.77	-2.74	2.58	13.13
60-70	-0.83	-2.99	2.52	8.60
70-80	3.03	3.68	6.48	9.97



Solid line– shows the average and interpolated responsivity values for all zenith angles

- As stated in the above table using the responsivity function, the irradiance MBE decreased by more than 50%. This reduction is mostly attributed to the uncertainty reduction of the instrument's responsivity.

Result: DNI Dataset



Clear- and mostly cloudy sky condition: (top) MBE and (bottom) RMSE in percent for the hourly average for all DNI data under study.

- Relative differences are higher under cloudy sky conditions, some factors, such as temporal responsivity, field of view of the radiometers, and spectral response become an influence for these higher differences.
- The clear-sky conditions demonstrated tighter differences among the instruments.

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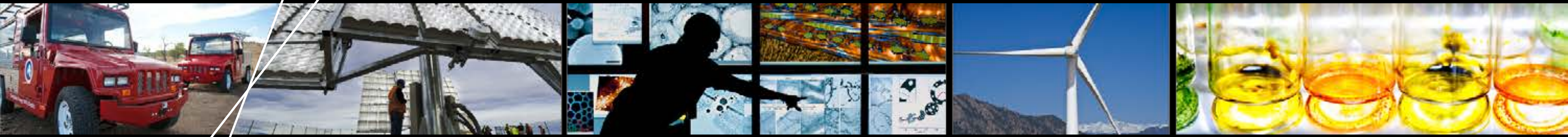


Overview of ASTM International Activities through Radiometry Subcommittee

Current ASTM Radiometry Standard Development Activities

Two of the Proposed New Standards under Radiometry Subcommittee

- **WK36479 New Practice for uncertainty evaluation of calibration and measurements with pyranometers and pyrheliometers**
  - Standardized procedure according to GUM (Guideline to evaluation of Uncertainty in Measurement)
  - Standard is currently in balloting cycle
- **WK38983 New Guide for Performance Classification of Solar Radiometers**
  - Classification of radiometers serves as a reference for use in other standards to define what instruments are recommended for use, such as in solar energy system performance monitoring, material testing etc.,
  - A division in classes allows users with different target measurement uncertainties to easily make a choice between instruments at different cost price levels.

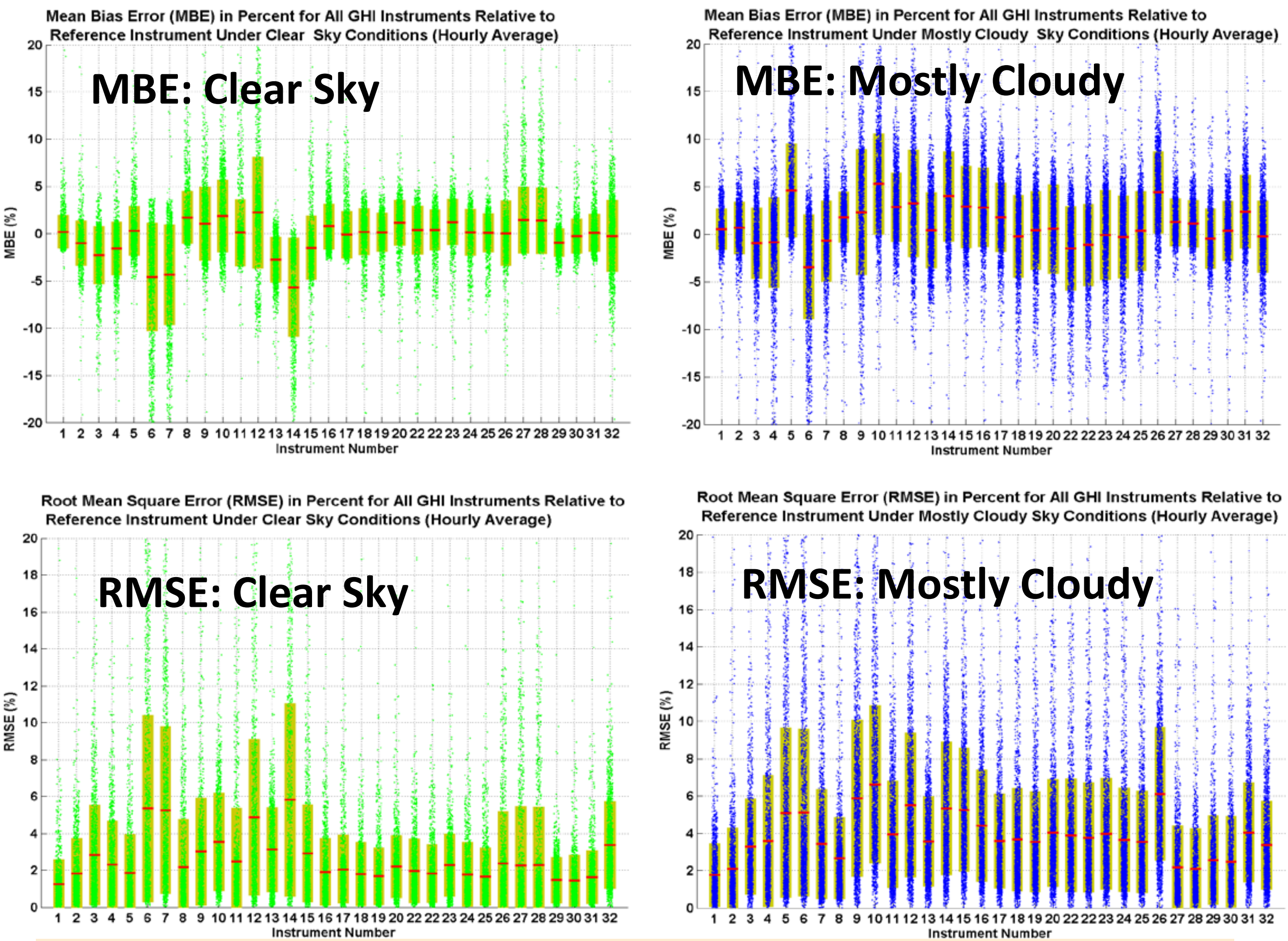
Summary

- 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.
- **Comparison of the radiometric data** provides valuable information- differences due to the various instrument design characteristics for time response, spectral response, angular (cosine) response, field of view and temperature response, etc.
- Adopting such **standardized method** will ensure that the uncertainty quoted for data collected by radiometers can be compared based on documented methods of derivation and provides global uniformity and acceptance.

Thank You!

Questions?

Result: GHI Dataset



Clear and mostly cloudy sky condition: (top) MBE and (bottom) RMSE in percent for the hourly average for all GHI data under study. The red line signifies the mean value of the differences for the 95% confidence level.

Instrument List:

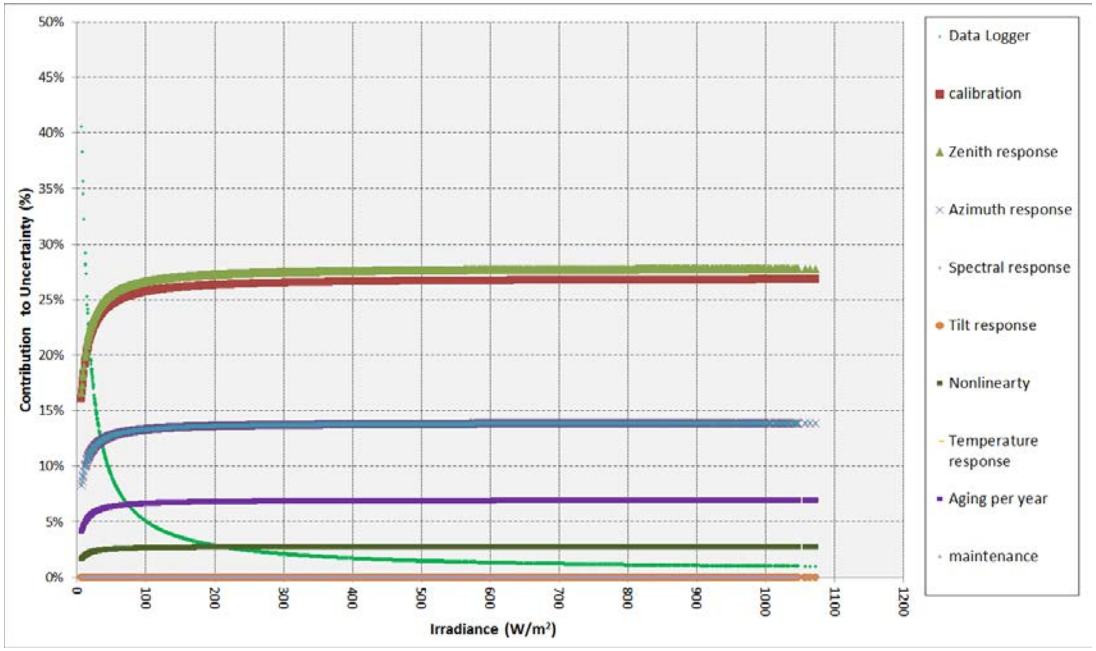
GHI Instrument List:

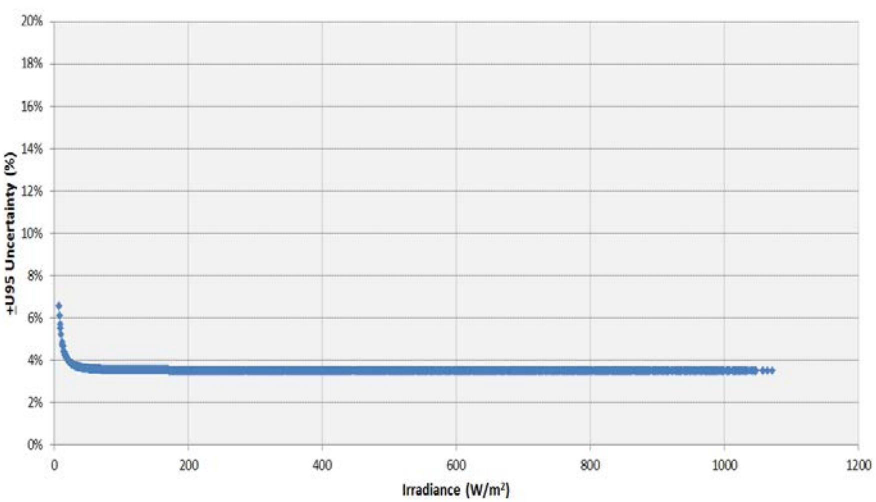
Instrument Number	Instrument Type	Model	Manufacturer	Instrument Number	Instrument Type	Model	Manufacturer
1	Thermopile	CM22	Kipp & Zonen	17	Semiconductor	RSP (secondary)	LI-COR
2	Thermopile	CM6b	Kipp & Zonen	18	Thermopile	TSR-590	YES, Inc.
3	Thermopile	CM3-CNR1	Kipp & Zonen	19	Thermopile	TSR-591	YES, Inc.
4	Thermopile	PSP	Eppley Laboratory, Inc.	20	Thermopile	TSR-592	YES, Inc.
5	Thermopile	PSP	Eppley Laboratory, Inc.	21	Thermopile	TSR-590-LH[a]	YES, Inc.
6	Thermopile	PSP	Eppley Laboratory, Inc.	22	Thermopile	TSR-591-LH	YES, Inc.
7	Thermopile	PSP	Eppley Laboratory, Inc.	23	Thermopile	TSR-592-LH	YES, Inc.
8	Thermopile	TSP-700	YES, Inc.	24	Thermopile	TSR-590-JM[b]	YES, Inc.
9	Thermopile	TSP-1	YES, Inc.	25	Thermopile	TSR-591-JM	YES, Inc.
10	Thermopile	SPN1	Delta-T	26	Thermopile	TSR-592-JM	YES, Inc.
11	Semiconductor	SPLite	Kipp & Zonen	27	Thermopile	SR11-7196	Hukseflux
12	Semiconductor	SP-110	Apogee	28	Thermopile	SR11-7242	Hukseflux
13	Semiconductor	LI-200	LI-COR	29	Thermopile	LP02-41120	Hukseflux
14	Semiconductor	P007	David Brooks	30	Thermopile	LP02-41272	Hukseflux
15	Semiconductor	ATI	Ascension Technology, Inc. RSR/LI-COR	31	Semiconductor	NREL-CRADA-RSR2	Irradiance Inc./LI-COR
16	Semiconductor	RSP	LI-Cor	32	Semiconductor	Solar-Mil.-CRADA-RSR	Solar Millennium AG./LI-Cor

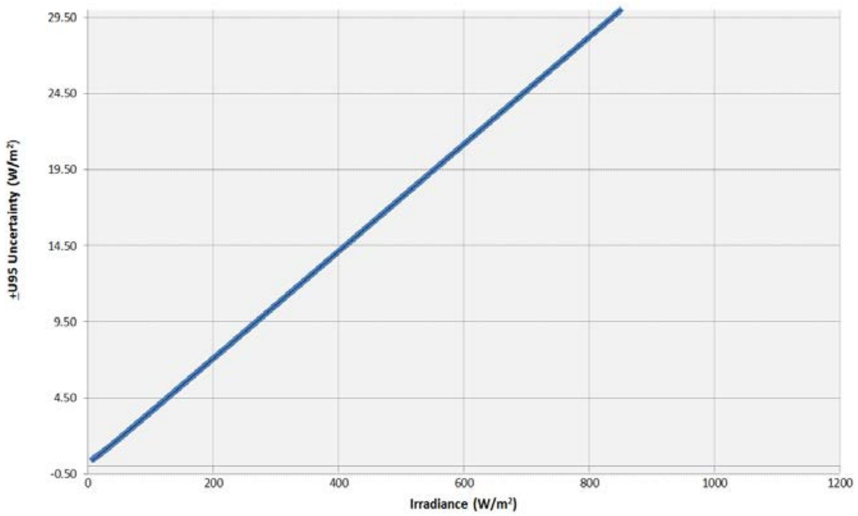
GHI Instrument List:

Instrument Number	Instrument Type	Model	Manufacturer
1	Thermopile	NIP2	Eppley Laboratory, Inc.
2	Thermopile	NIP1	Eppley Laboratory, Inc.
3	Semiconductor	LI-201	LI-COR
4	Semiconductor	ATI/LI-COR	Ascension Technology Inc./LI-COR
5	Semiconductor	RSP/LI-COR	Irradiance Inc./LI-Cor
6	Thermopile	TSR-590	YES, Inc.
7	Thermopile	TSR-591	YES, Inc.
8	Thermopile	TSR-592	YES, Inc.
9	Thermopile	TSR-590LH	YES, Inc.
10	Thermopile	TSR-591LH	YES, Inc.
11	Thermopile	TSR-592LH	YES, Inc.
12	Thermopile	TSR-590JM	YES, Inc.
13	Thermopile	TSR-591JM	YES, Inc.
14	Thermopile	TSR-592JM	YES, Inc.
15	Semiconductor	NREL-CRADA-RSR2/LI-Cor	Irradiance Inc./LI-COR
16	Thermopile	SPN1	Delta-T
17	Thermopile	DR018066	Hukseflux
18	Thermopile	DR018068	Hukseflux
19	Semiconductor	Solar-Mil.-CRADA-RSR/LI-COR	Solar Millennium AG./LI-COR

Example Output Plots:







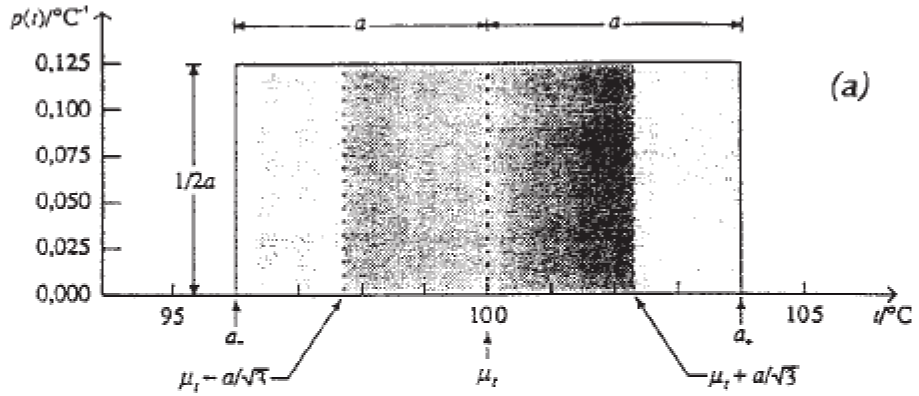
Example of Calibration and Field Measurement Uncertainty Sources:

Example Of Typical Calibration Type B Standard Uncertainties (U) For A Pyranometers								
Sources of Uncertainties	Expanded Uncertainties of the Sources					Distribution	Degrees of Freedom	Standard Uncertainty (u)
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
R_{net}	0.4 uV/Wm^{-2}	10	0.04 uV/Wm^{-2}	--	0.04 uV/Wm^{-2}	Rectangular	∞	0.02 uV/ Wm^{-2}
W_{net}	-150 Wm^{-2}	5	7.5 Wm^{-2}	--	7.5 Wm^{-2}	Rectangular	∞	4.33 Wm^{-2}
N	1,000 Wm^{-2}	0.4	4 Wm^{-2}	--	4 Wm^{-2}	Normal	∞	2 Wm^{-2}
Z	20°	--	2. 10^{-5}	--	2. 10^{-5}	Rectangular	∞	1. 10^{-5}
D	50 Wm^{-2}	3	1.5 Wm^{-2}	1 Wm^{-2}	2.5 Wm^{-2}	Normal	∞	1.25 Wm^{-2}

Example Of Measurement Sources of Uncertainty for A Pyranometers					
Uncertainty component	Quantity	Statistical Distribution	Uncertainty Type	Standard Uncertainty (u)	Expanded Uncertainty (U)*
Calibration	R	Normal	Type B	$\frac{U}{2} = 2.81\%$	5.62% (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	$\frac{U}{\sqrt{3}} = 5.77uv$	10 µV
Maintenance	R	Rectangular	Type B	$\frac{U}{\sqrt{3}} = 0.17\%$	0.3%

Measurement Equation and Sensitivity Coefficient Calculations :

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



p(t)/°C⁻¹
0,125
0,100
0,075
0,050
0,025
0,000
a
a
1/2a
(a)
95
100
105
t/°C
a₋
a₊
μₜ − a/√3
μₜ
μₜ + a/√3

31