Uncertainty in Pyranometer and Pyrheliometer Calibrations Using GUM for NREL's ISO-17025 Accreditation Effort

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Preview

- Motivation (Why is this important?)
- GUM?
- GUM guidelines
- NREL’s scope of accreditation
- Uncertainty analysis and reporting.

Motivation

NREL is expected to maintain high quality results

- Use peer reviewed quality/calibration procedure
- Provide Nationally/Internationally accepted calibration
- Use controlled process for continuous improvement and early detection of problems/solutions
- Provide consistent reporting of calibration results and associated uncertainties

Broadband Outdoor Radiometer Calibrations

Reference Absolute Cavity
Radiometer traceable to WRR

- Pyrheliometers
- Pyranometers

www.nrel.gov/solar_radiation

GUM

"Guide to the expression of uncertainty in measurement," BIPM, IEC, IFCC, ISO, IUPAC, IUPAP and OIML, ISO TAG 4, Geneva, 1995.

Uncertainty components:

-Type-A from statistical methods (~~random~~)

-Type-B from non statistical methods, such as manufacturer specifications, calibration results, and experimental or judgment information (~~bias~~).

Available on line at

http://www.bipm.org/utils/common/documents/jcgm/JCGM_100_2008_E.pdf

GUM Guidelines

1. Determine the measurement equation
2. List or estimate the standard uncertainty, for each variable in the measurement equation and for each component (e.g. curve fitting uncertainty, environmental conditions uncertainty, etc.) that might introduce uncertainty to the calibration process
3. Calculate the combined standard uncertainty using the root-sum-of-squares method of all standard uncertainties in step 2
4. Calculate the expanded uncertainty by multiplying the combined standard uncertainty by the coverage factor, typically Student's "t".

Note: Report calibration data only, no extrapolation

Reference: Reda, I.; Myers, D.; Stoffel, T. (2008). Uncertainty Estimate for the Outdoor Calibration of Solar Pyranometers: A Metrologist Perspective. Measure. (NCSLI Journal of Measurement Science). Vol. 3(4), December 2008; pp. 58-66; NREL Report No. JA-581-41370

Scope of Accreditation-I

- **Calibration Conditions:**

Outdoors under natural sunlight

Pyranometers on horizontal plane

Pyrheliometers on sun trackers

-Traceability:

An unbroken chain of comparisons relating an instrument's measurements to a consensus reference

Here: *International System* of units (SI), through World Radiometric Reference (WRR) maintained by using a set of World Standard Group of absolute cavity radiometers.

-Reference irradiance level:

Direct beam ≥ 700 W/m2 0.35% (restricted by WRR)

Diffuse: **10 W/m2 to 150 W/m2** (2.6%+1 W/m2) [clear sky conditions]

Scope of Accreditation-II

- Zenith angle range of calibration:

Minimum zenith angle range: 30° to 60° [to include 45°]

Maximum zenith angle range: 16.5° to 80° (varies)

- Uncertainty of nominal values:

reported with 95% confidence level, and coverage factor k = 1.96

-**The Best Expanded Uncertainty, U_{95} , of Unit Under Test (UUT):**

Pyranometers: < **1.5%,** depending on the valid z-range

Pyrheliometers: < **1%,** depending on the valid z-range.

Guideline 1: Measurement equation

$$R_i = \frac{V_i - R_{net} * W_{i,net}}{N_i * COS(Z_i) + D_i}$$

where:

I	= i^{th} data point during calibration
R_i	= responsivity [uV/(Wm^{-2})]
V_i	= thermopile output voltage (uV)
R_{net}	= longwave net responsivity of the pyranometer [uV/(Wm^{-2})]
$W_{i, net}$	= infrared net irradiance measured by collocated pyrgeometer (Wm^{-2})
N_i	= beam irradiance measured by a reference pyrheliometer (Wm^{-2})
Z_i	= solar zenith angle ( )
D_i	= diffuse irradiance (Wm^{-2}).

Guideline 2: List/Estimate standard uncertainty

Standard uncertainty for common distributions

Type of Distribution or Data Source	Parameters	Standard Uncertainty, u
Experimental Data (Assumed Normal)	**Standard deviation = s Number of readings = n**	$u = \frac{s}{\sqrt{n-1}}$
Rectangular	**Uncertainty Bounds: $-a$ to $+a$**	$u = \frac{a}{\sqrt{3}}$
Triangular	**Uncertainty Bounds: $-a$ to $+a$**	$u = \frac{a}{\sqrt{6}}$
Calibration Certificate (Expanded Uncertainty and Coverage Factor Stated)	**Expanded Unc., U_{cert} Coverage Factor, $k = 2$**	$u = \frac{U_{cert}}{2}$

Use Rectangular distribution if:

1. If reported uncertainty from calibration provider is not reported with coverage factor

2. If the uncertainty is estimated based on experimental data/knowledge

The estimated standard uncertainties from a typical NREL calibration

$$R_i = \frac{V_i - R_{net} * W_{i,net}}{N_i * COS(Z_i) + D_i}$$

Example

Variable	Value	*U* %	*U*	*Offset*	*a=U+Offset*	Distribution	DF	*u*
V	7930.3 µV	0.001	0.079 µV	1 µV	1.079 µV	Rectangular	1000	0.62
R_{net}	0.4 µV/Wm^{-2}	10	0.04 µV/Wm^{-2}	--	0.04 µV/(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°	--	0.00002	--	0.00002	Rectangular	1000	0.00001
D	50 Wm^{-2}	3	1.5 Wm^{-2}	1 Wm^{-2}	2.5 Wm^{-2}	Rectangular	1000	1.44
***R* = 8.0735 µV/Wm^{-2}**								

* The uncertainty of *Z* is ±0.003°, therefore the uncertainty is calculated as *U*=COS(*Z*+0.003)-COS(*Z*).

- u = a/√3 for rectangular distribution
- This table is calculated at each data point

Sensitivity coefficients

$$R_i = \frac{V_i - R_{net} * W_{i,net}}{N_i * COS(Z_i) + D_i}$$

$$c_{i,v} = \frac{\partial R_i}{\partial V_i} = \frac{1}{N_i * COS(Z_i) + D_i}$$

..Thermopile voltage

$$c_{i,R_{net}} = \frac{\partial R_i}{\partial R_{net}} = \frac{-W_{i,net}}{N_i * COS(Z_i) + D_i}$$

..IR responsivity

$$c_{i,W_{net}} = \frac{\partial R_i}{\partial W_{i,net}} = \frac{-R_{net}}{N_i * COS(Z_i) + D_i}$$

..Net IR irradiance

$$c_{i,N} = \frac{\partial R_i}{\partial N_i} = \frac{-(V_i - R_{net} * W_{i,net}) * COS(Z_i)}{[N_i * COS(Z_i) + D_i]^2}$$

..Direct beam

$$c_{i,Z} = \frac{\partial R_i}{\partial Z_i} = \frac{N_i * SIN(Z_i) * (V_i - R_{net} * W_{i,net})}{[N_i * COS(Z_i) + D_i]^2}$$

..Zenith angle

$$c_{i,D} = \frac{\partial R_i}{\partial D_i} = \frac{-(V_i - R_{net} * W_{i,net})}{[N_i * COS(Z_i) + D\ ]^2}$$

..Diffuse irradiance

Guideline 3:Calculate combined standard uncertainty

$$u_B = \sqrt{\sum_{j=1}^{\ell} (c_j . u_j)^2}$$

- Then calculate the combined degrees of freedom

$$DF_B = \frac{[u_B]^4}{\sum_{j=1}^{\ell} \frac{(c_j . u_j)^4}{df_j}}$$

where df_j is the degrees of freedom of the j^{th} variable (e.g. df=nu. of readings – 1)

The Type-B standard uncertainty contribution to the responsivity for each variable at Z = 20

Example

Variable	c_j	$c_j . u_j$ (μV/(Wm^{-2}))	% of Sum
V	0.0010 $(Wm^{-2})^{-1}$	0.00063	2 %
R_{net}	0.1516	0.0035	9 %
W_{net}	0.0004 μV/$(Wm^{-2})^2$	0.00175	5 %
N	0.0077 μV/$(Wm^{-2})^2$	0.0177	50 %
Z	2.7901 μV/(Wm^{-2})	0.00003	0.1 %
D	0.0082 μV/$(Wm^{-2})^2$	0.0118	33 %
u_B		0.022 (μV/(Wm^{-2}))	
DF_B		1860	

DF is calculated using 1000 to check on calculation, should be infinity

Pyranometer responsivity from NREL calibration certificate

Calibration is performed outdoor from sunrise to sunset under clear sky conditions

Example

Figure 1. Responsivity vs Zenith Angle

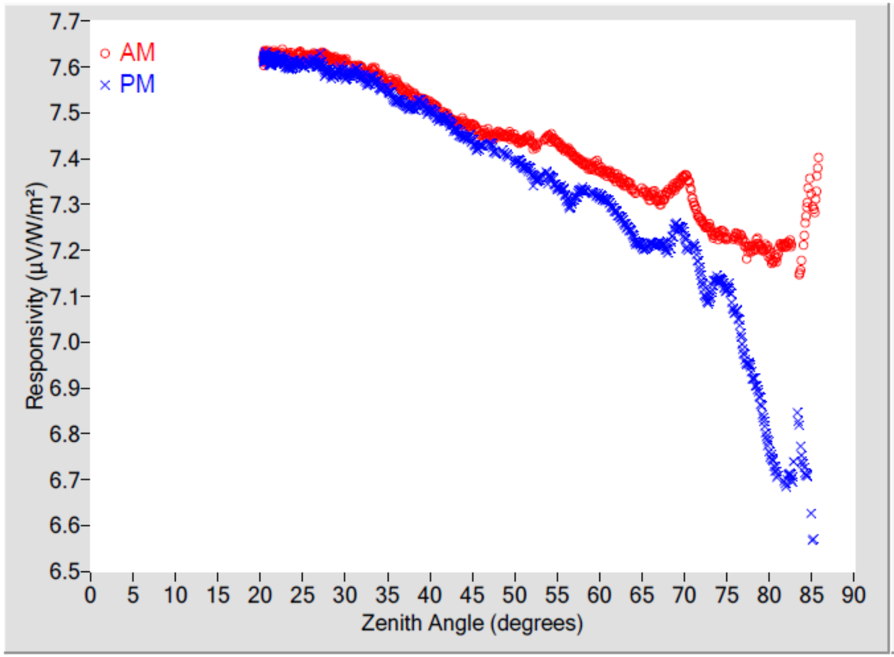
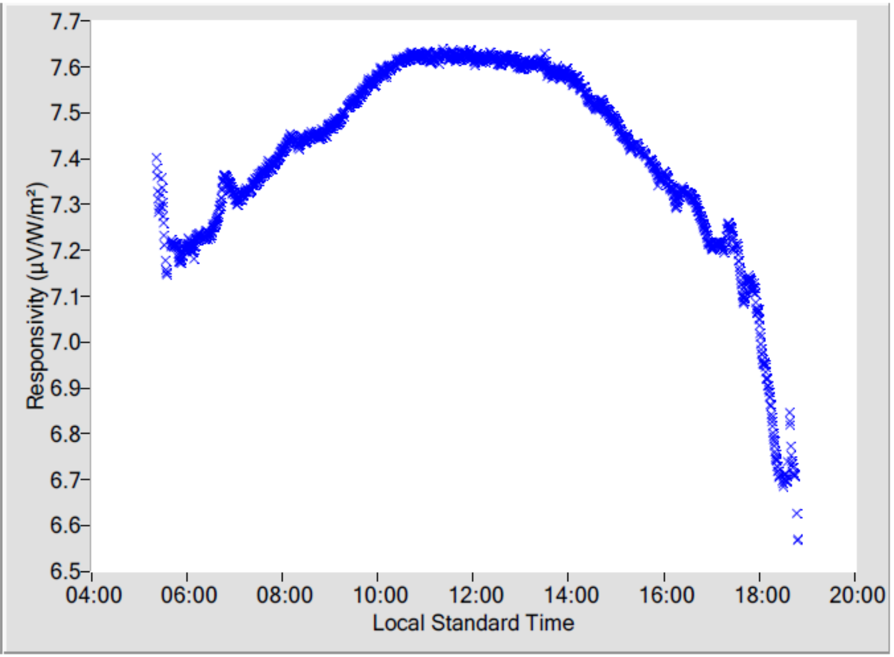


Figure 2. Responsivity vs Local Standard Time



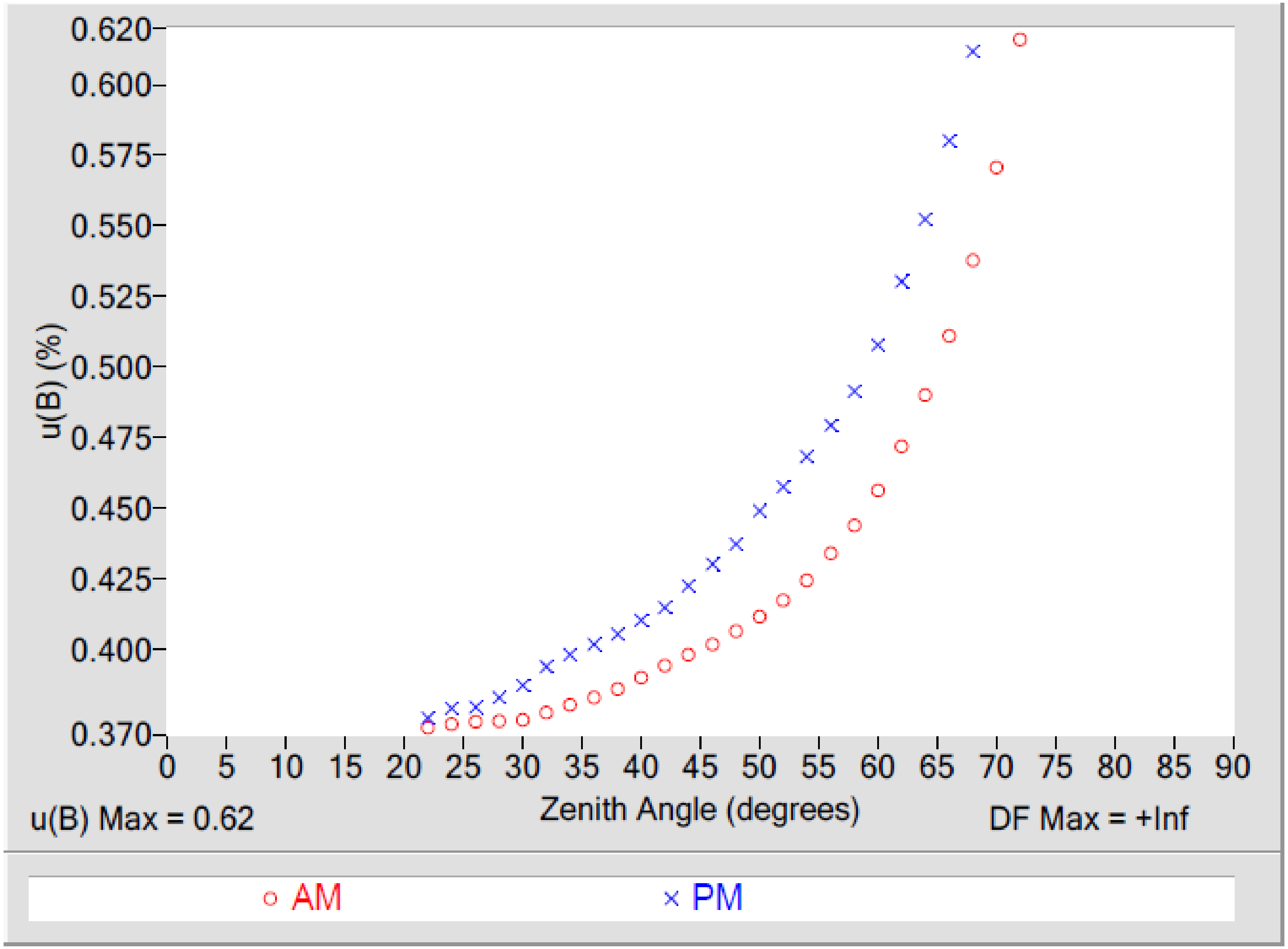
An example of pyranometer responsivity versus even zenith angle during NREL calibration

Example

Zenith Angle (deg.)	AM R (µV/W/m²)	AM u(B) ± (%)	AM Azimuth Angle	PM R (µV/W/m²)	PM u(B) ± (%)	PM Azimuth Angle	Zenith Angle (deg.)	AM R (µV/W/m²)	AM u(B) ± (%)	AM Azimuth Angle	PM R (µV/W/m²)	PM u(B) ± (%)	PM Azimuth Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	9.0727	0.40	101.75	9.0415	0.43	258.18
2	N/A	N/A	N/A	N/A	N/A	N/A	48	9.0717	0.41	99.68	9.0079	0.44	259.97
4	N/A	N/A	N/A	N/A	N/A	N/A	50	9.0561	0.41	97.73	9.0045	0.45	262.24
6	N/A	N/A	N/A	N/A	N/A	N/A	52	9.0348	0.42	95.86	8.9706	0.46	264.03
8	N/A	N/A	N/A	N/A	N/A	N/A	54	9.0332	0.42	94.05	8.9551	0.47	265.84
10	N/A	N/A	N/A	N/A	N/A	N/A	56	9.0014	0.43	92.29	8.8939	0.48	267.60
12	N/A	N/A	N/A	N/A	N/A	N/A	58	8.9751	0.44	90.62	8.9044	0.49	269.27
14	N/A	N/A	N/A	N/A	N/A	N/A	60	8.9585	0.46	88.94	8.8999	0.51	270.92
16	N/A	N/A	N/A	N/A	N/A	N/A	62	8.9325	0.47	87.34	8.8611	0.53	272.57
18	N/A	N/A	N/A	N/A	N/A	N/A	64	8.9199	0.49	85.72	8.7997	0.55	274.14
20	N/A	N/A	N/A	N/A	N/A	N/A	66	8.9389	0.51	84.13	8.8226	0.58	275.74
22	9.2879	0.37	155.48	9.2596	0.38	204.48	68	8.9558	0.54	82.55	8.7790	0.61	277.32
24	9.2810	0.37	144.00	9.2568	0.38	215.93	70	8.8887	0.57	80.99	8.7804	N/A	278.89
26	9.2891	0.37	136.25	9.2617	0.38	223.60	72	8.7300	0.61	79.39	8.5874	N/A	280.47
28	9.2869	0.37	130.29	9.2501	0.38	229.67	74	8.6630	N/A	77.83	8.5426	N/A	282.07
30	9.2706	0.37	125.35	9.2281	0.39	234.61	76	8.6326	N/A	76.22	8.4177	N/A	283.62
32	9.2473	0.38	121.15	9.2268	0.39	238.72	78	8.5913	N/A	74.62	8.2370	N/A	285.22
34	9.2368	0.38	117.57	9.2012	0.40	242.38	80	8.5542	N/A	72.97	8.0274	N/A	286.87
36	9.2163	0.38	114.34	9.1613	0.40	245.58	82	8.5413	N/A	71.31	7.8822	N/A	288.49
38	9.1836	0.39	111.36	9.1410	0.41	248.56	84	8.4946	N/A	69.62	7.7977	N/A	290.21
40	9.1575	0.39	108.71	9.1266	0.41	251.21	86	8.6140	N/A	68.06	N/A	N/A	N/A
42	9.1244	0.39	106.23	9.1168	0.41	253.70	88	N/A	N/A	N/A	N/A	N/A	N/A
44	9.1006	0.40	103.88	9.0733	0.42	256.00	90	N/A	N/A	N/A	N/A	N/A	N/A

Example

Figure 3. Type-B Standard Uncertainty vs Zenith Angle



Maximum u_B = 0.62% and *DF* = Infinity for all zenith angles

Type-A standard uncertainty and effective degrees of freedom

- AM and PM piecewise interpolating polynomials

$$R_{i,\,AM}(Z) = \sum_{j=0}^{3} a_j (Z - Z_i)^j$$

$$R_{i,\,PM}(Z) = \sum_{j=0}^{3} b_j (Z - Z_i)^j$$

- AM and PM residuals

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

- Standard Deviation

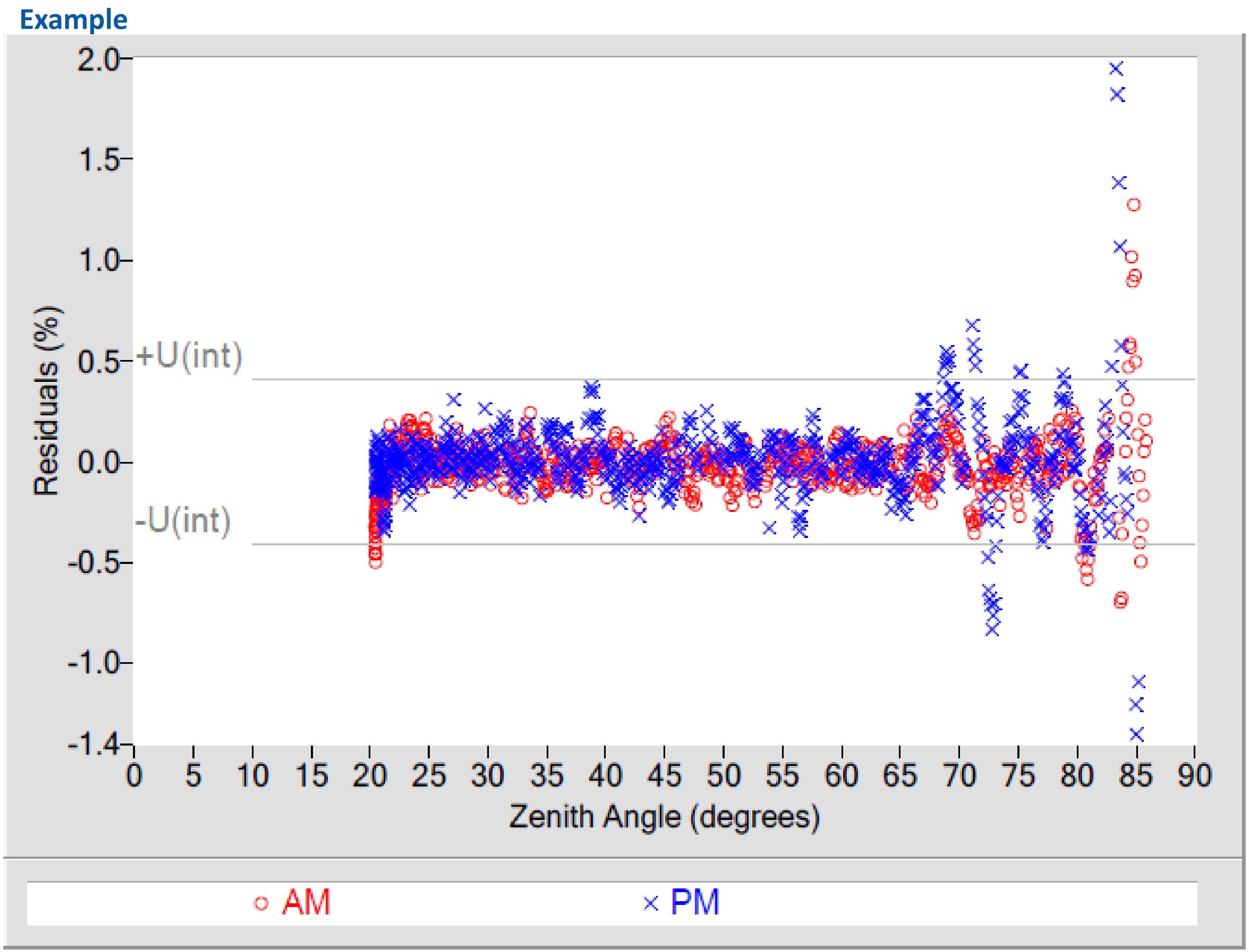
$$\sigma = \sqrt{\frac{\sum_{i=0}^{j+k} (r - r_i)^2}{j + k - 2}}$$

- Standard Uncertainty

$$u_{\text{int}} = \sqrt{r^2 + \sigma^2}$$

- DF = m+n-2

Residuals from Spline Interpolation



The standard uncertainty contribution using the AM and PM interpolating functions

Example

Standard Uncertainty Source	Standard uncertainty	DF	% of Sum
Type-B: u_B	0.57 %	$DF_B = 1860$	80
Type-A: Interpolating Functions, u_{int}	0.14 %	$DF_f = 1419$	20

Guideline 4:Expanded Uncertainty and Reporting

-Calculate combined standard uncertainty

$$u_c = \sqrt{(u_B^2 + u_{int}^2)}$$

-Calculate Student's "t" from the effective degrees of freedom = k

-Calculate the Expanded Uncertainty U_{95}

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

Example

Type-B Standard Uncertainty, u(B) (%)	±0.61
Type-A Interpolating Function, u(int) (%)	±0.21
Combined Standard Uncertainty, u(c) (%)	±0.65
Effective degrees of freedom, DF(c)	119582
Coverage factor, k	1.96
Expanded Uncertainty, U95 (%)	±1.27
AM Valid zenith angle range	22° to 72°
PM Valid zenith angle range	22° to 68°

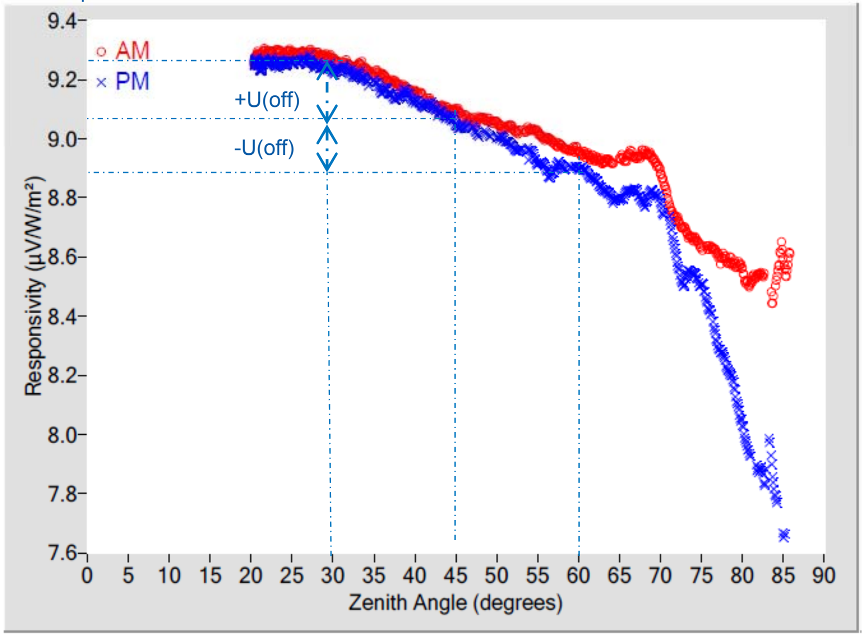
Another method of reporting

-Calculate Type-B Expanded Uncertainty at z = 45°, U(B)

-Calculate Maximum and minimum responsivity in the z-range 30° to 60°, R_{max} & R_{min} , then calculate $U(off)_{\pm} = (R_{max/min} - R_{45})_{\pm}$

-Calculate the Expanded Uncertainty, $U_{\pm} = U(B)_{\pm} + U(off)_{\pm}$

Example



Example

Table 4. Calibration Label Values

R @ 45° (µV/W/m²)	Rnet (µV/W/m²) †
9.0732	0.77000

† Rnet determination date: 02/28/2006

Table 5. Uncertainty using R @ 45°

Type-B Expanded Uncertainty, U(B) (%)	±1.00
Offset Uncertainty, U(off) (%)	+2.18 / -1.98
Expanded Uncertainty, U (%)	+3.17 / -2.97
Effective degrees of freedom, DF	+Inf
Coverage factor, k	1.96
Valid zenith angle range	30.0° to 60.0°

Closing Remarks

- NREL is ISO-17025 accredited for outdoor pyranometer and pyrheliometer calibrations

- Reported uncertainty is the calibration process uncertainty only

- Users must add uncertainties associated with field set-up and environmental conditions different from that of the calibration conditions

- Interpolating the responsivity versus zenith angle for field measurement improves the field measurement uncertainty with respect to using a SINGLE responsivity (>2 times??)

NREL Metrology Laboratory: http://www.nrel.gov/solar_radiation/metrology_lab.html