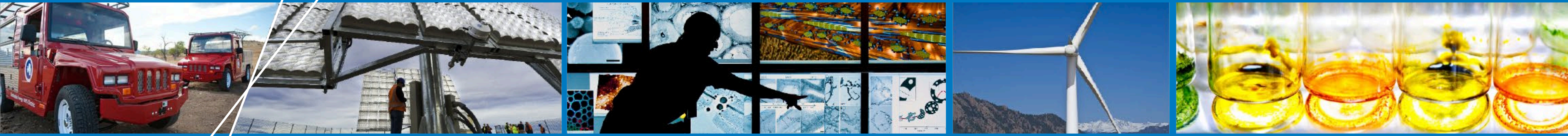
Metrology for Outdoor Radiometry

Broadband Outdoor Radiometer Calibration (BORCAL)



National Center for Atmospheric Research (NCAR)

Atmospheric Radiation Science Workshop

By

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Boulder, Colorado

NREL/PR-3B10-65965
NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Personal Statement

“A measurement will have no significance without an uncertainty statement with respect to the International System of Units (SI) or a consensus reference”

BORCAL Overview

- Has been developed to calibrate NREL radiometers since the late 1970s
- Continuous improvement in reporting the calibration results and reducing the calibration uncertainty
- State of the art automated data acquisition system and software
- Hundreds of radiometers might be calibrated per calibration event
- From ~sunrise to ~sundown calibration for shortwave radiometers. Calibration results are reported versus zenith. Nighttime calibration for longwave radiometers
- Historical calibration results are maintained and reported for trend analysis (exposure, aging, research, etc.)
- Built-in data quality and rejection
- ISO-17025 accredited calibration procedure for shortwave radiometers.

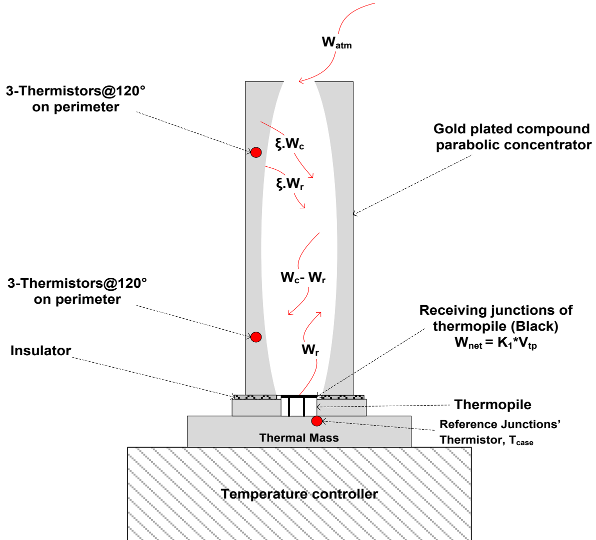
BORCAL-LW: Pyrgeometer Calibration (Longwave)

Traceability: Interim World Infrared Standard Group (WISG) at PMOD in Davos,Switzerland

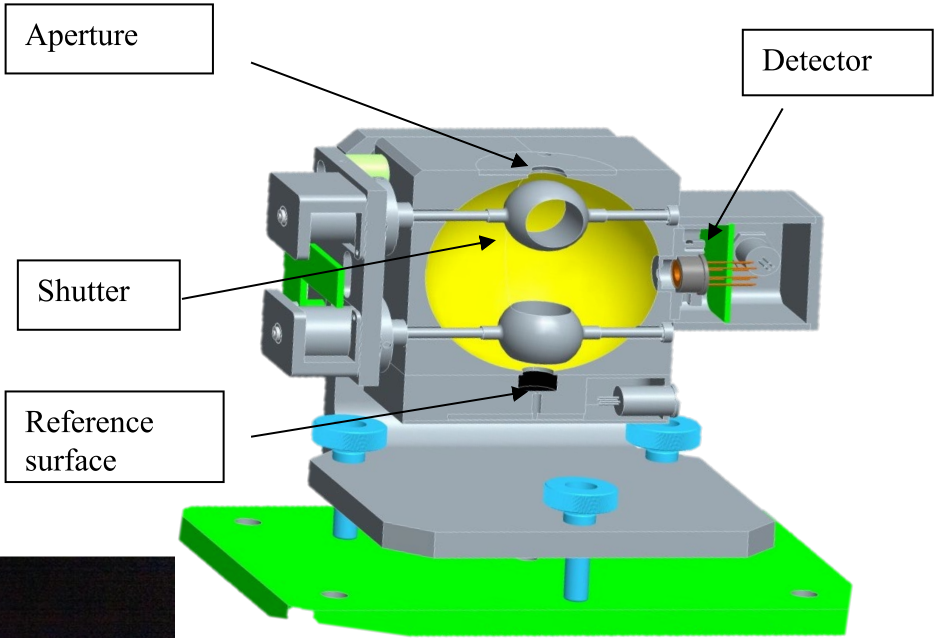
Collaboration between NREL and PMOD to establish a world reference with traceability to SI

BORCAL-LW: Collaboration between NREL & PMOD

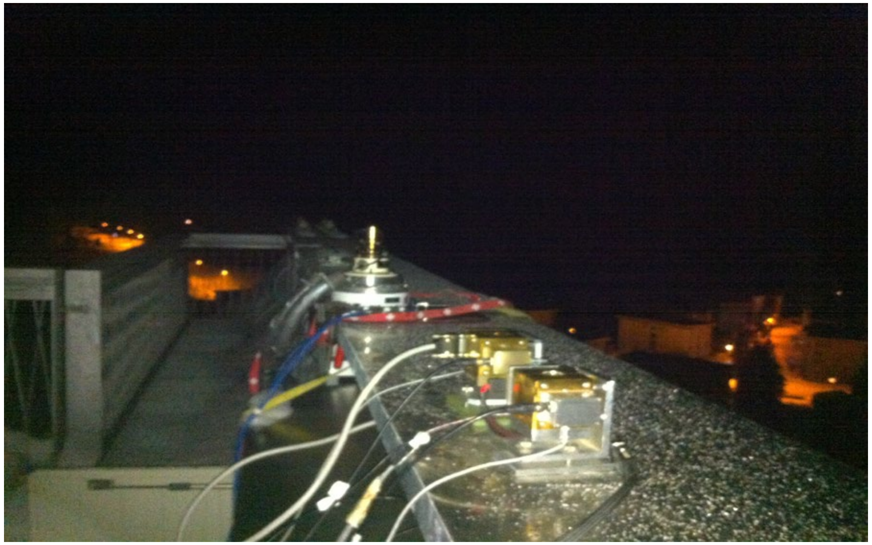
Two absolute radiometers: ACP and IRIS for SI traceability instead of pyrgeometers with domes



NREL's Absolute Cavity Pyrgeometer (ACP)



PMOD's Infra Red Integrating Sphere (IRIS)



ACP & IRIS nighttime comparisons at PMOD; difference is within 2 Wm^{-2} in two comparisons

BORCAL-LW Calibration Procedure

- Calibration is performed outdoors using a group of reference pyrgeometers with traceability to consensus reference, interim-WISG

- Measurement Equation:

$$W_{downwelling} = K_0 + K_1.V_{tp} + K_2.W_r + K_3.(W_{dome} - W_r)$$

Where:

- $W_{downwelling}$ is the incoming irradiance (W/m²).
- K_0, K_1, K_2, and K_3 are the calibration coefficients.
- V_{tp} is the thermopile output voltage (µV).
- W_r is the receiver outgoing irradiance (W/m²),

$= \sigma * T_r{}^4 = \sigma * (T_c + 0.0007044 * V)^4$, where T_r & T_c are the receiver & case temperatures (K).

- W_d is the dome irradiance (W/m²).

$= \sigma * T_d{}^4$, where T_d is the dome temperature (K).

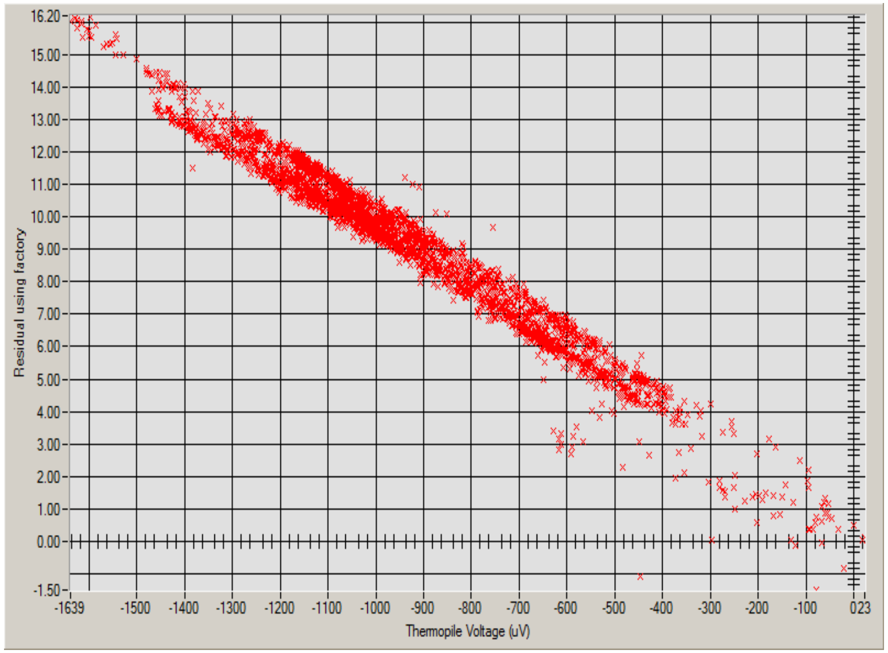
- Linear Regression to calculate the calibration coefficients using outdoor data under all sky conditions, where the reference downwelling irradiance is measured by reference pyrgeometer/s , traceable to WISG.

Reda et al., (2002). *Pyrgeometer Calibration at the National Renewable Energy Laboratory (NREL).* Journal of Atmospheric and Solar-Terrestrial Physics. Vol. 64(15), 2002; pp. 1623-1629.

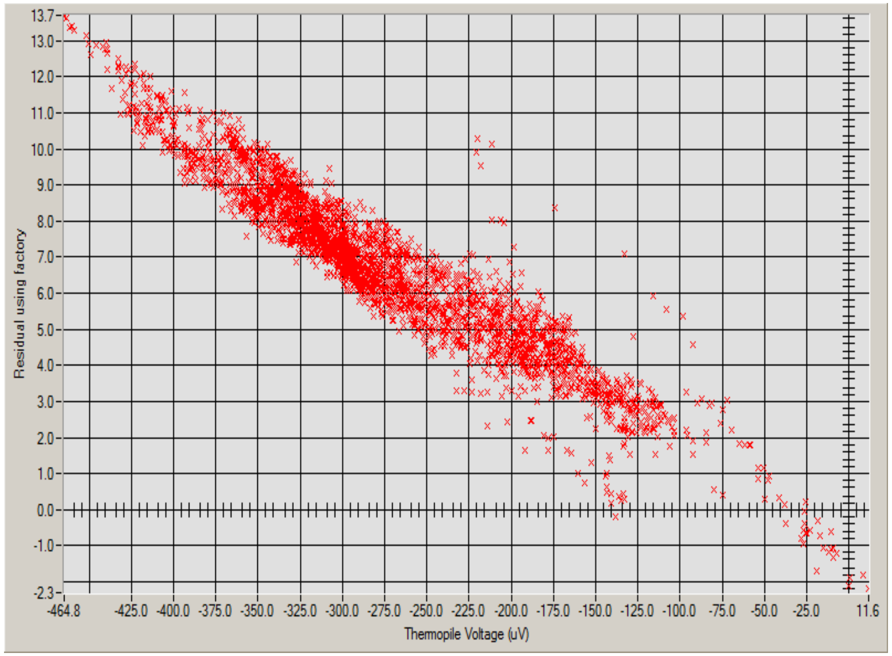
Using Blackbody calibration coefficients

Two graphs to show why blackbody calibrations are not suitable for outdoor measurement

Residuals = difference between the reference irradiance and the irradiance calculated using Albert&Cox equation for a CG4, and a PIR with dome coefficient = 4



CG4



PIR

Results of BORCAL-LW from NREL calibration certificate

$$W_{downwelling} = K_0 + K_1.V_{tp} + K_2.W_r + K_3.(W_{dome} - W_r)$$

CG4

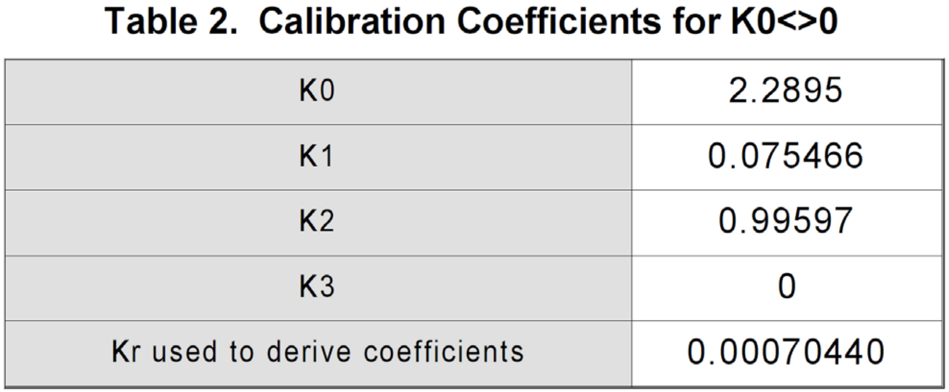


Table 2. Calibration Coefficients for K0<>0

K0	2.2895
K1	0.075466
K2	0.99597
K3	0
Kr used to derive coefficients	0.00070440

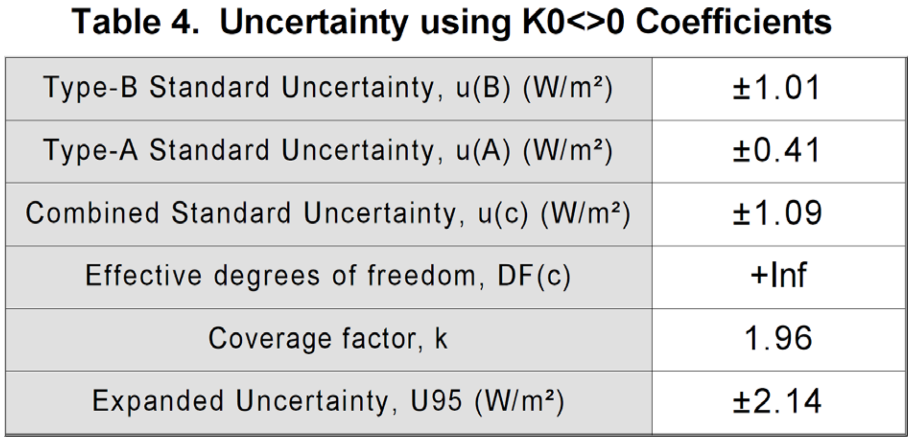


Table 4. Uncertainty using K0<>0 Coefficients

Type-B Standard Uncertainty, u(B) (W/m²)	±1.01
Type-A Standard Uncertainty, u(A) (W/m²)	±0.41
Combined Standard Uncertainty, u(c) (W/m²)	±1.09
Effective degrees of freedom, DF(c)	+Inf
Coverage factor, k	1.96
Expanded Uncertainty, U95 (W/m²)	±2.14

PIR

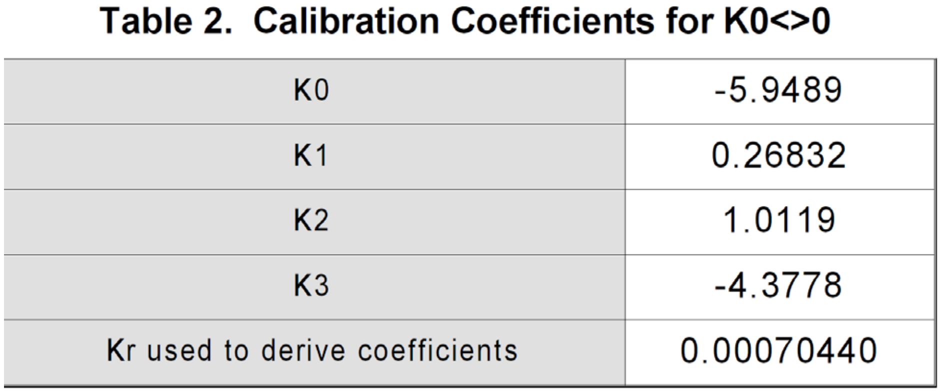


Table 2. Calibration Coefficients for K0<>0

K0	-5.9489
K1	0.26832
K2	1.0119
K3	-4.3778
Kr used to derive coefficients	0.00070440

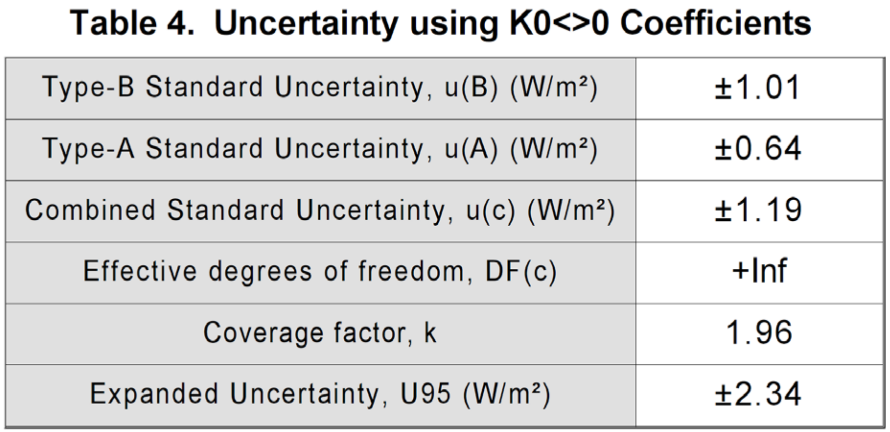


Table 4. Uncertainty using K0<>0 Coefficients

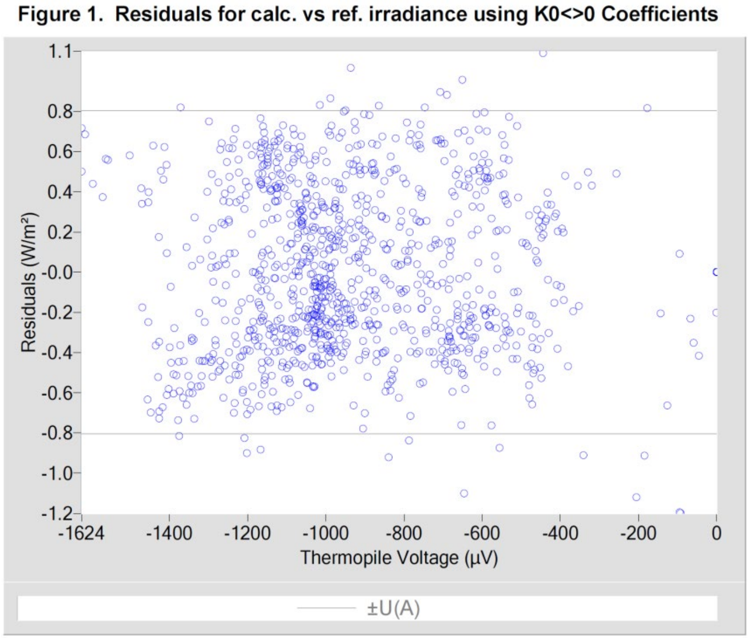
Type-B Standard Uncertainty, u(B) (W/m²)	±1.01
Type-A Standard Uncertainty, u(A) (W/m²)	±0.64
Combined Standard Uncertainty, u(c) (W/m²)	±1.19
Effective degrees of freedom, DF(c)	+Inf
Coverage factor, k	1.96
Expanded Uncertainty, U95 (W/m²)	±2.34

Results of BORCAL-LW- Cont.

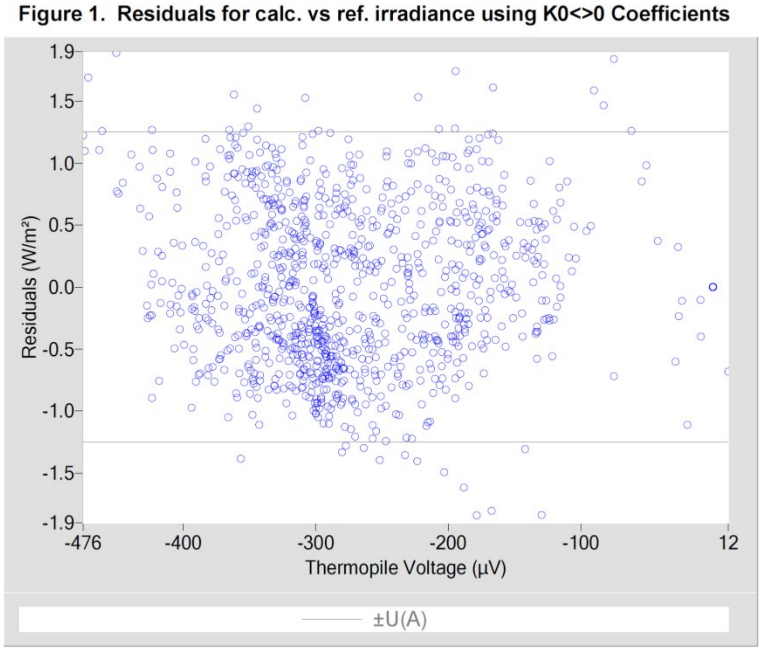
Two graphs to show the residuals after the outdoor calibration

Residuals = difference between the reference irradiance and the irradiance calculated using NREL equation and the outdoor calibration coefficients

CG4



PIR



BORCAL-SW: Pyranometer & Pyrheliometer Calibration (Shortwave)

Traceability: SI through WRR from IPC (quinquennial in Davos, Switzerland) and/or NPC (yearly in NREL)

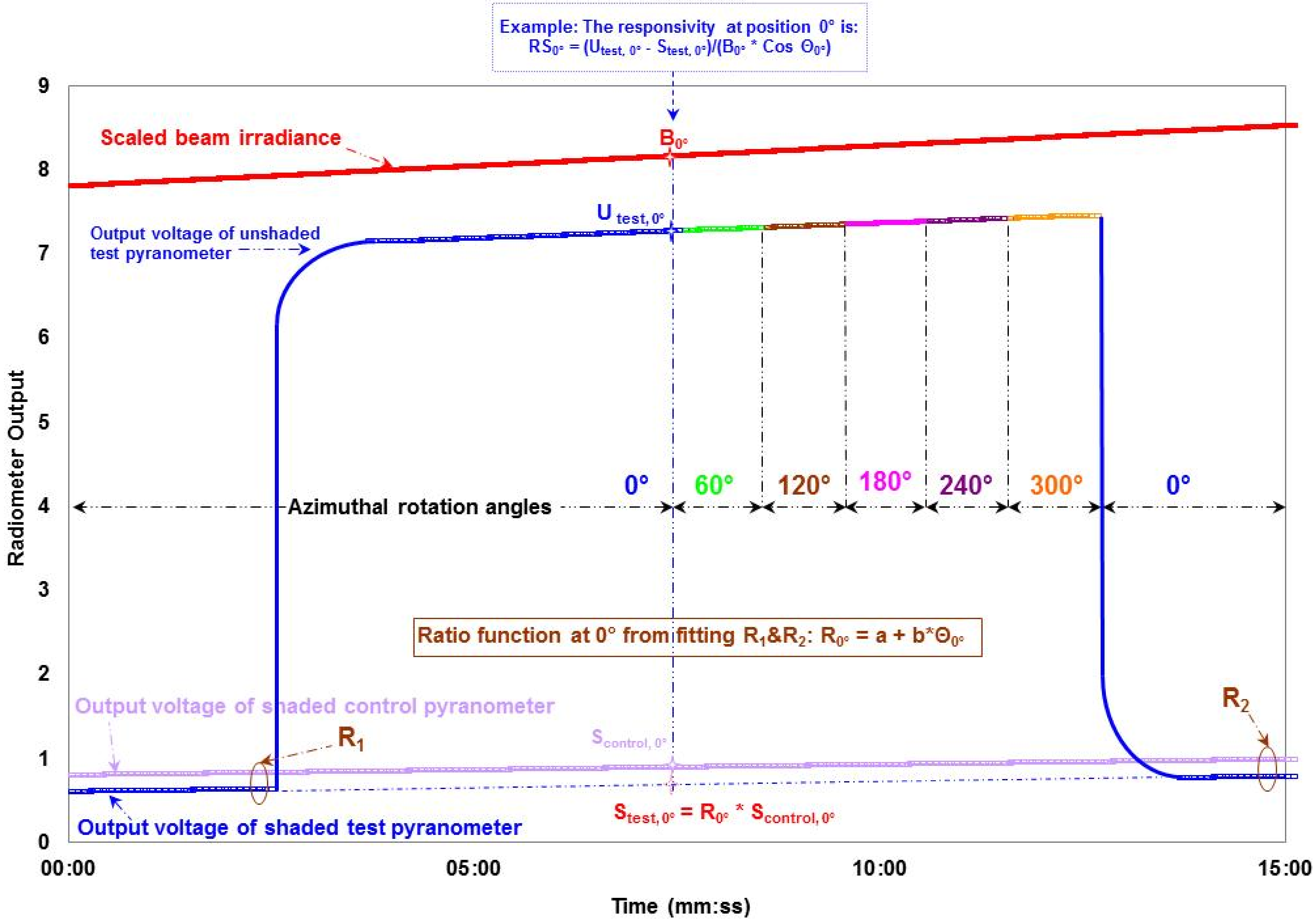
Pyrheliometer
Traceable through
cavity

Reference Diffuse
Traceable through
Cavity using
Shade/Unshade method

Pyranometer
Traceable through
Cavity & Ref. Diffuse
Using component sum method

Establishing diffuse reference: Shade/Unshade

Established yearly before calibration season starts



Example: The responsivity at position 0° is: $RS_{0°} = (U_{test,\,0°} - S_{test,\,0°})/(B_{0°} * \mathrm{Cos}\ \Theta_{0°})$

Ratio function at 0° from fitting R_1&R_2: $R_{0°} = a + b*\Theta_{0°}$

$S_{test,\,0°} = R_{0°} * S_{control,\,0°}$

Reda, I; Myers, D. (1999). Calculating the Diffuse Responsivity of Solar Pyranometers. 15 pp.; NREL Report No. TP-560-26483.

BORCAL-SW calibration procedure

- **Calibration is performed outdoors using an Absolute Cavity Radiometer and diffuse reference pyranometer**
- **Measurement Equation:**

1. Pyrheliometer:

$$RS = \frac{V}{N}$$

where,

- RS = Responsivity [μV/(W/m^2)]
- V = Thermopile output voltage (μV)
- N = Direct normal irradiance measured by the cavity (W/m^2).

2. Pyranometer:

$$RS = \frac{V - RS_{IR,\ NET} * W_{IR,\ NET}}{N * COS\ \Theta + D}$$

where,

- $RS_{IR,\ NET}$ = Infrared Net Responsivity of pyranometer under test [μV/(W/m^2)]
- $W_{IR,\ NET}$ = Infrared net irradiance measured by collocated pyrgeometer (W/m^2)
- Θ = Solar zenith angle (°), calculated using SPA
- D = Diffuse irradiance (W/m^2).

Reda et al., (2005). *Using a Blackbody to Calculate Net Longwave Responsivity of Shortwave Solar Pyranometers to Correct for Their Thermal Offset Error During Outdoor Calibration Using the* Component Sum Method. Journal of Atmospheric and Oceanic Technology 2005 pp. 1531-1540.

Pyranometer responsivity from NREL calibration certificate

Figure 1. Responsivity vs Zenith Angle

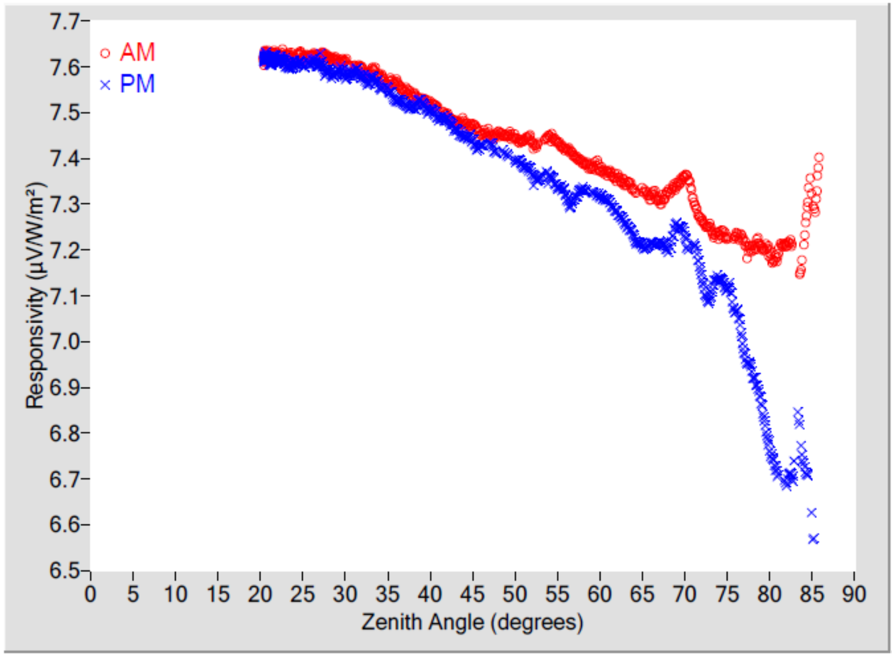
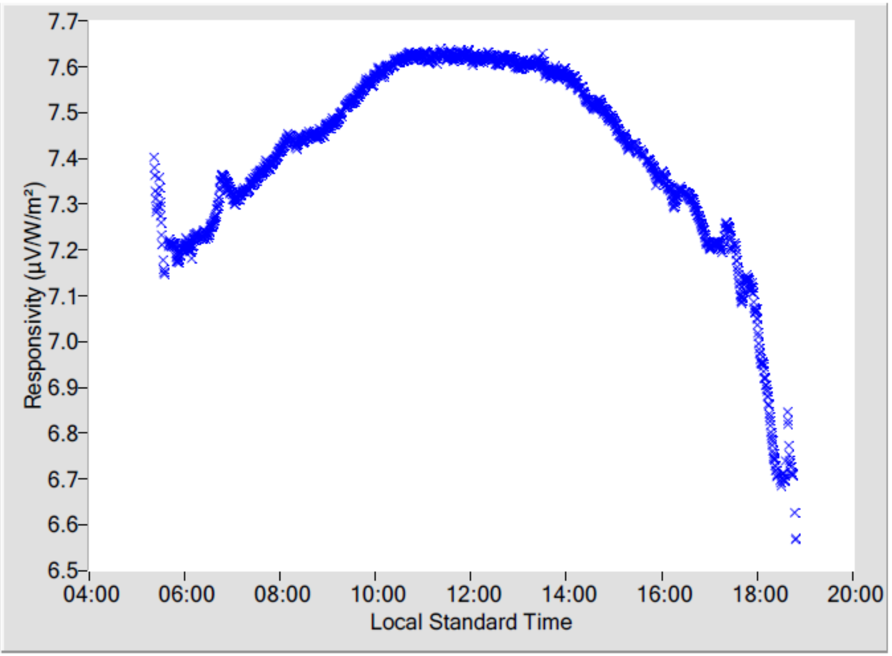
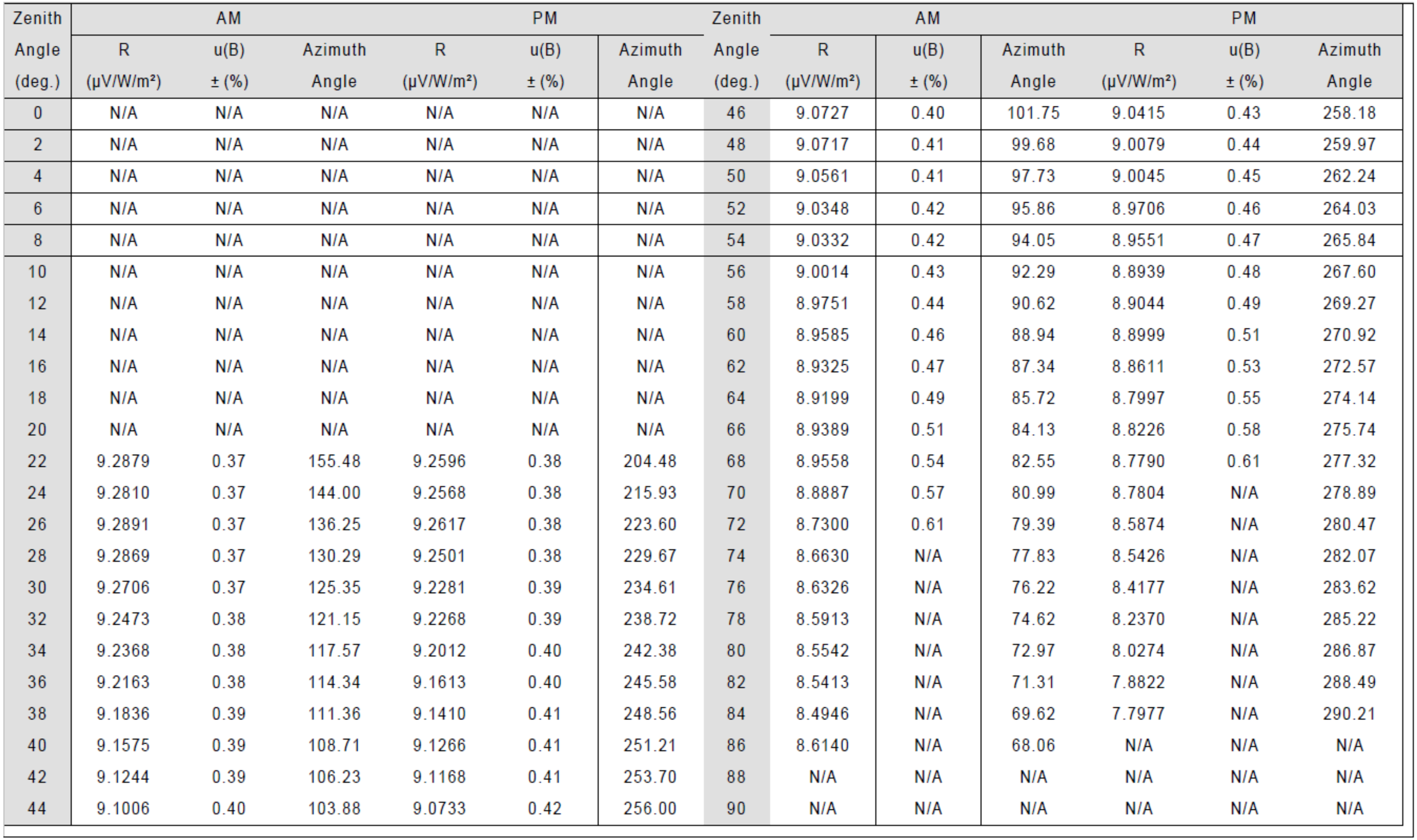


Figure 2. Responsivity vs Local Standard Time



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

Pyranometer responsivity vs even-zenith angle-Table from Certificate



Zenith	AM			PM			Zenith	AM			PM		
Angle (deg.)	R (µV/W/m²)	u(B) ± (%)	Azimuth Angle	R (µV/W/m²)	u(B) ± (%)	Azimuth Angle	Angle (deg.)	R (µV/W/m²)	u(B) ± (%)	Azimuth Angle	R (µV/W/m²)	u(B) ± (%)	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

Results from certificate

Residuals from Piecewise (Spline) Interpolation

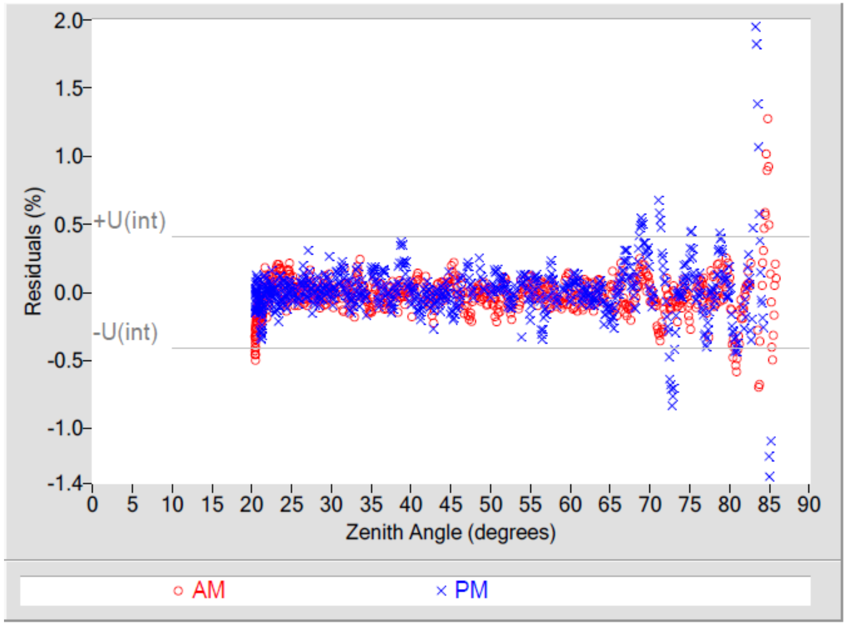
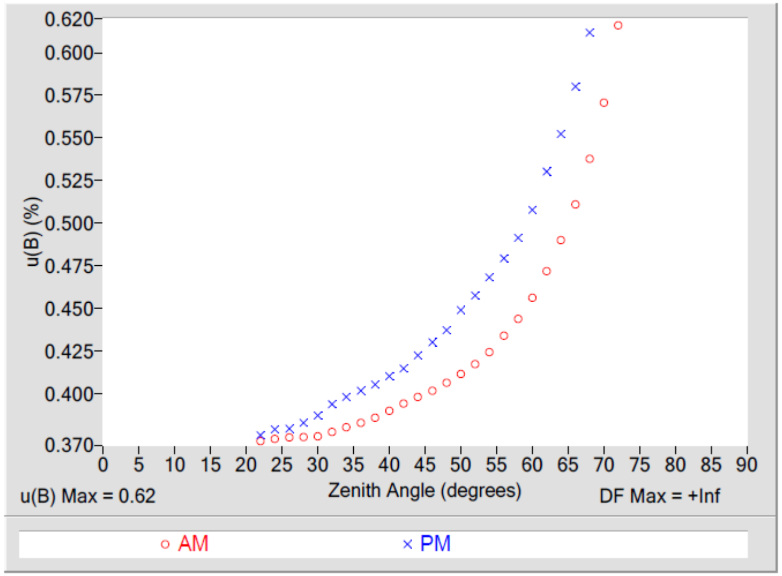
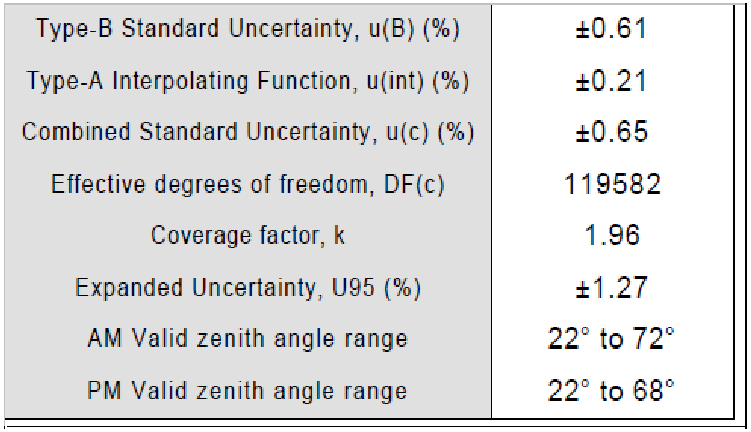


Figure 3. Type-B Standard Uncertainty vs Zenith Angle



Uncertainty Table



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°

Responsivity at zenith angle = 45° (most users !!)

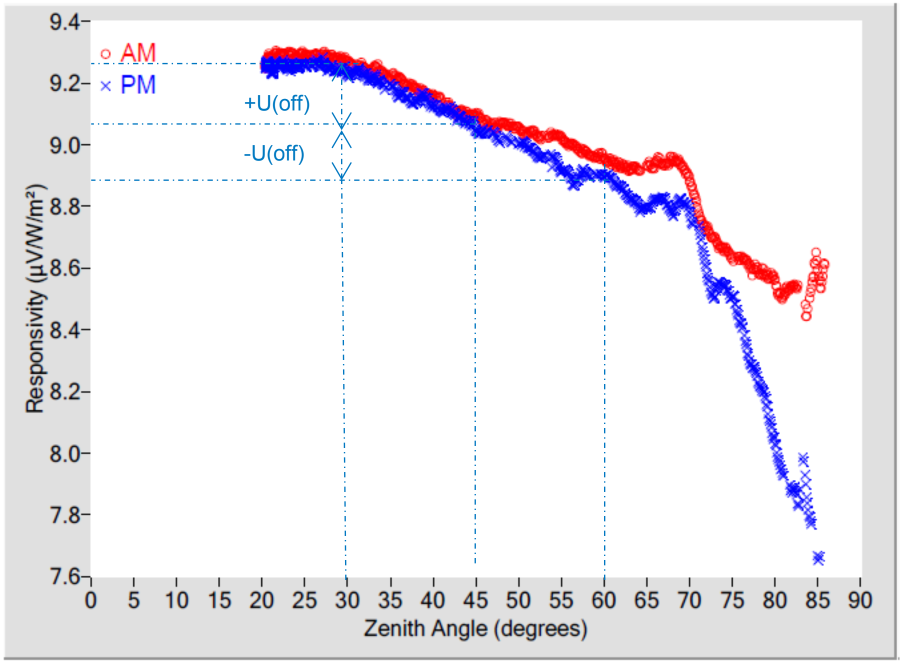
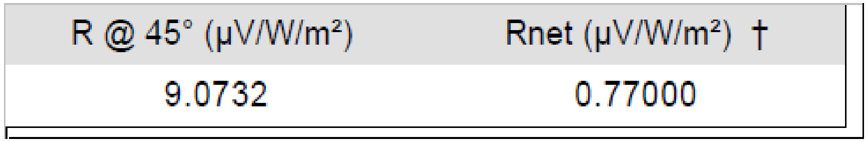


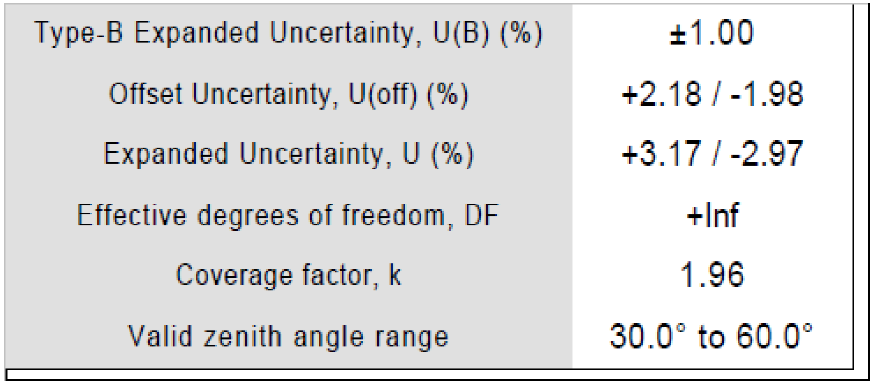
Table 4. Calibration Label Values



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°

Advantage of Being ISO-17025 Accredited

- 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