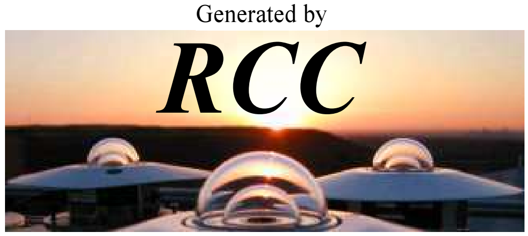
Broadband Outdoor Radiometer Calibration Shortwave

BORCAL-SW 2018-04

Generated by



Radiometer Calibration and Characterization

Customer

Mike Dooraghi

Organization: NREL

Phone: 303.384.6329

Calibration Facility

Solar Radiation Research Laboratory

Latitude: 39.742°N

Longitude: 105.180°W

Elevation: 1828.8 meters AMSL

Time Zone: -7.0

Calibration date

05/25/2018 to 05/26/2018

Report Date

May 30, 2018

NREL

NOTICE

Broadband Outdoor Radiometer Calibration Report

Table of contents

Introduction

This report compiles the calibration results from a Broadband Outdoor Radiometer Calibration (BORCAL). The work was accomplished at the Radiometer Calibration Facility shown on the front of this report. The calibration results reported here are traceable to the International System (SI) Units of Measurement.

This report includes these sections:

- Control Instruments - a group of instruments included in each BORCAL event that provides a measure of process consistency.
- Results Summary - a table of all instruments included in this report summarizing their calibration results and uncertainty.
- Instrument Details - the calibration certificates for each instrument.
- Environmental and Sky Conditions - meteorological conditions and reference irradiance during the calibration event.

Control Instrument History

Figure 1. Eppley NIP Control Instrument History

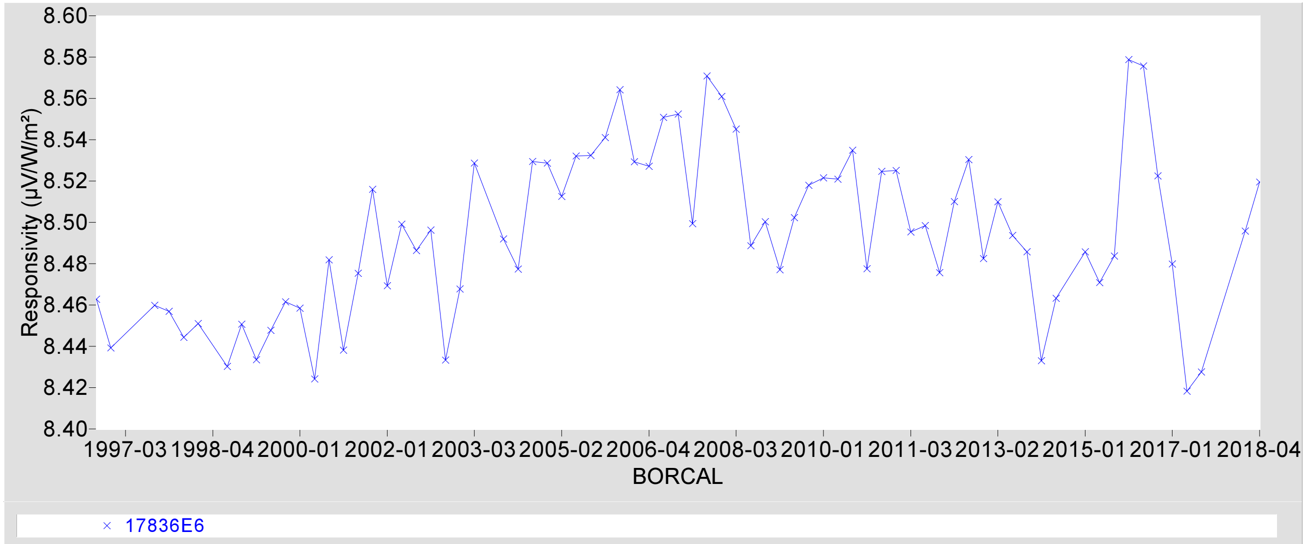
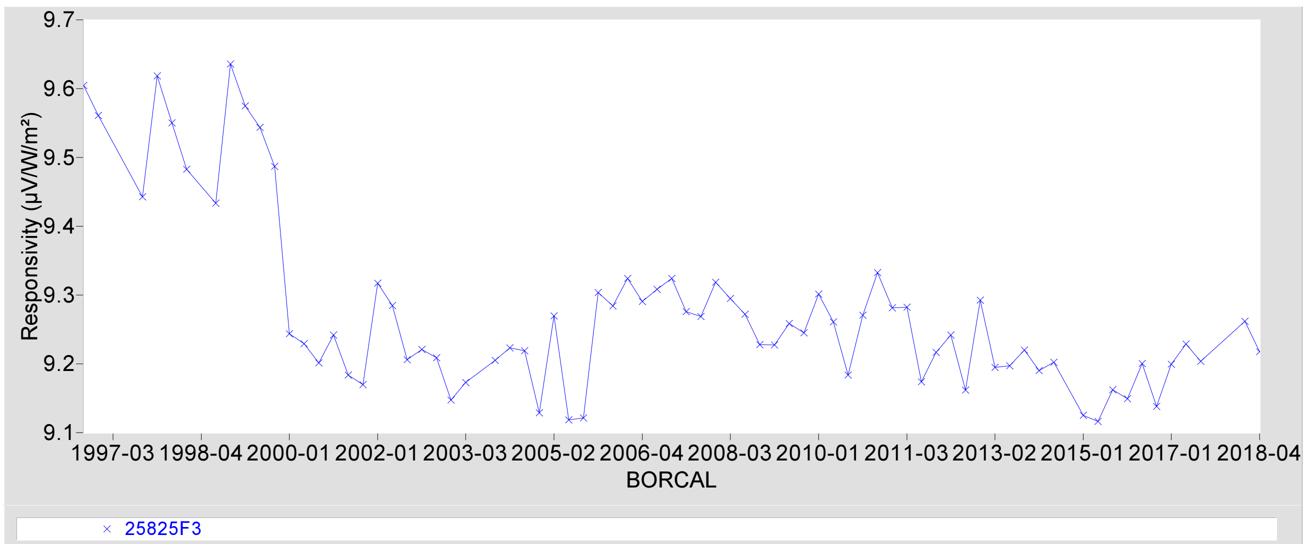


Figure 2. Eppley PSP Control Instrument History



Results Summary

Table 1. Results Summary

Instrument	R@45 ¹ (µV/W/m²)	CF@45 ¹ (W/m²/mV)	U ² (%)	Rnet ³ (µV/W/m²)	Page
080016 Kipp & Zonen CMP22	9.5493	104.72	+1.1 / -1.3	0.087000	A1-2
151041 Kipp & Zonen SP-LITE2	70.685	14.147	+2.5 / -1.9	0	A1-5
151729 Kipp & Zonen SP-LITE2	63.588	15.726	+4.7 / -3.1	0	A1-8
160430 Kipp & Zonen CMP22	9.7109	102.98	+1.2 / -1.0	0.087000	A1-11
40338 Apogee SP-110	190.51	5.2490	+1.7 / -2.0	0	A1-14
920058 Kipp & Zonen CM21	13.373	74.776	+1.4 / -1.1	0.57000	A1-17
PY89785 Licor LI200X	4.7469	210.66	+1.4 / -1.1	0	A1-20
PY89872 Licor LI200X	4.8273	207.16	+1.5 / -1.3	0	A1-23
S13135061 EKO ML-01	37.603	26.594	+2.4 / -1.1	0	A1-26
S17096007 EKO MS-80	10.113	98.887	+2.0 / -0.66	0.043000	A1-29

¹ CF = 1000 / R ² See certificate for valid zenith angle range ³ Instrument's Effective Net IR Response

Note: Environmental Conditions for BORCAL starts on page A1-32.

Appendix 1
Instrument Details

Calibration Certificates: 3 pages for each radiometer (4 including Environmental Conditions)
Environmental Conditions for BORCAL: Last Page of a Calibration Certificate. Note: This appears only once, at the end of Appendix 1.

National Renewable Energy Laboratory

Solar Radiation Research Laboratory

Metrology Laboratory

Calibration Certificate

Calibration CERT #1239.02

Test Instrument:	Pyranometer	**Manufacturer:**	Kipp & Zonen
Model:	CMP22	**Serial Number:**	080016
Calibration Date:	5/26/2018	**Due Date:**	5/26/2019
Customer:	Mike Dooraghi	**Environmental Conditions:**	see page 4
Test Dates:	5/25-26		

This certifies that the above product was calibrated in compliance with ISO/IEC 17025:2005. Measurement uncertainties at the time of calibration are consistent with the Guide to the Expression of Uncertainty in Measurement (GUM) using Reda et al., 2008. All nominal values are traceable to the International System (SI) Units of Measurement.

No statement of compliance with specifications is made or implied on this certificate. However, the estimated uncertainties are the uncertainties of the calibration process; users must add other uncertainties that are relevant to their measuring system, environmental and sky conditions, outdoor set-up, and site location.

The Type-B Standard Uncertainty of using the responsivity at each even zenith angle is reported, and the Expanded Uncertainty of the calibration is reported using two methods:

1. The Expanded Uncertainty of using the responsivity at zenith angle = 45°, within the zenith angle range from 30.0° to 60.0°
2. The Expanded Uncertainty of using Spline Interpolating Functions for the responsivity versus zenith angle.

This certificate applies only to the item identified above and shall not be reproduced other that in full, without specific written approval from the calibration facility. Certificate without signature is not valid.

Table 1. Traceability

Measurement Type	Instrument	Calibration Date	Calibration Due Date
Beam Irradiance †	Eppley Absolute Cavity Radiometer Model HF, S/N 29219	09/25/2017	09/25/2018
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/11/2018	04/11/2019
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/18/2018	04/18/2019
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	04/12/2017	04/12/2019
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	04/12/2017	04/12/2019
Infrared Irradiance ‡	Kipp & Zonen Pyrgeometer Model CG4, S/N FT002	04/16/2018	04/16/2022

† Through the World Radiometric Reference (WRR)   ‡ Through the World Infrared Standard Group (WISG)

Number of pages of certificate: 4

Calibration Procedure: BORCAL-P00-Calibration and QA Procedure; available upon request.

Setup: Radiometers are calibrated outdoors, using the sun as the source. Pyranometers and pyrgeometers are installed for horizontal measurements, with their signal connectors oriented north, if their design permits.
The shading disk for the reference diffuse subtends a solid angle of 5°. Pyrheliometers are installed on solar trackers.

Calibrated by: Afshin Andreas, Mark Kutchenreiter, and RCC

_______________________________ _______________

Ibrahim Reda, Technical Manager   Date

For questions or comments, please contact the technical manager at:
ibrahim.reda@nrel.gov; 303-384-6385; 15013 Denver West Parkway, Golden, CO 80401, USA

Calibration Results

080016 Kipp & Zonen CMP22

The responsivity (R, μV/W/m²) of the test instrument during calibration is calculated using this Measurement Equation:

$$R = (V - Rnet * Wnet) / I \quad [1]$$

where,

- V = radiometer output voltage (microvolts),
- $Rnet$ = radiometer net infrared responsivity (μV/W/m²), see Table 4,
- $Wnet$ = effective net infrared measured by pyrgeometer (W/m²),
  = $Win - Wout$ = $Win - \sigma * Tc^4$
  where, Win = incoming infrared (W/m²), σ = 5.6704e-8 W·m-2·K-4,
  Tc = case temperature of pyrgeometer (K).
- I = reference irradiance (W/m²), beam (B) or global (G)
  where, $G = B * COS(Z) + D$,
  Z = zenith angle (degrees),
  D = reference diffuse irradiance (W/m²).

Figure 1. Responsivity vs Zenith Angle

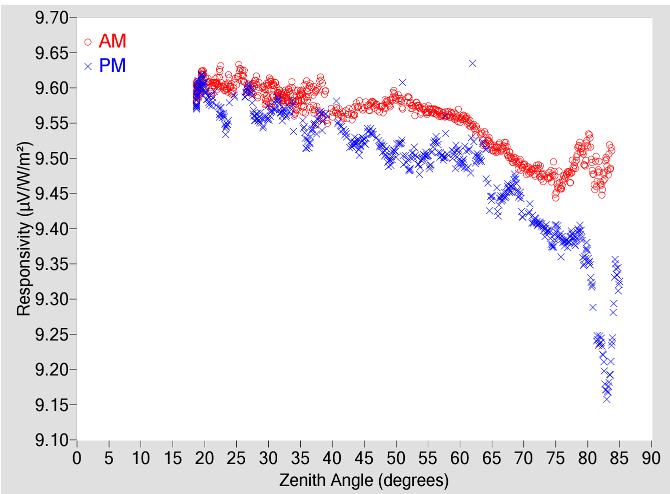


Figure 2. Responsivity vs Local Standard Time

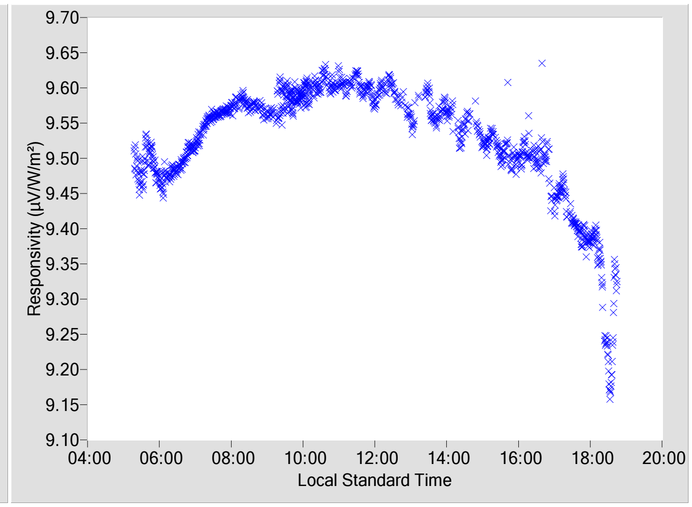


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)

Zenith	AM			PM			Zenith	AM			PM		
Angle	R	u(B)	Azimuth	R	u(B)	Azimuth	Angle	R	u(B)	Azimuth	R	u(B)	Azimuth
(deg.)	(μV/W/m²)	± (%)	Angle	(μV/W/m²)	± (%)	Angle	(deg.)	(μV/W/m²)	± (%)	Angle	(μV/W/m²)	± (%)	Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	9.5749	0.29	98.59	9.5372	0.29	261.23
2	N/A	N/A	N/A	N/A	N/A	N/A	48	9.5734	0.29	96.67	9.5116	0.30	263.16
4	N/A	N/A	N/A	N/A	N/A	N/A	50	9.5866	0.29	94.91	9.5105	0.30	264.90
6	N/A	N/A	N/A	N/A	N/A	N/A	52	9.5829	0.30	93.05	9.4866	0.30	266.82
8	N/A	N/A	N/A	N/A	N/A	N/A	54	9.5675	0.30	91.39	9.4977	0.30	268.53
10	N/A	N/A	N/A	N/A	N/A	N/A	56	9.5676	0.30	89.64	9.5234	0.31	270.20
12	N/A	N/A	N/A	N/A	N/A	N/A	58	9.5634	0.30	88.00	9.5143	0.32	271.72
14	N/A	N/A	N/A	N/A	N/A	N/A	60	9.5553	0.31	86.33	9.4994	0.32	273.45
16	N/A	N/A	N/A	N/A	N/A	N/A	62	9.5462	0.31	84.79	9.5625	0.35	275.00
18	N/A	N/A	N/A	N/A	N/A	N/A	64	9.5265	0.32	83.23	9.4989	0.35	276.65
20	9.6140	0.28	157.49	9.5984	0.28	203.14	66	9.5163	0.33	81.68	9.4369	0.35	278.18
22	9.6064	0.28	144.27	9.5688	0.28	216.19	68	9.5024	0.34	80.15	9.4559	0.36	279.72
24	9.6054	0.28	136.14	9.5793	0.28	223.37	70	9.4894	0.35	78.65	9.4166	0.37	281.11
26	9.6163	0.28	129.84	9.5875	0.28	231.03	72	9.4847	0.37	77.02	9.4095	0.39	282.81
28	9.6051	0.28	124.67	9.5585	0.29	235.29	74	9.4752	0.39	75.47	9.3916	N/A	284.41
30	9.5962	0.28	120.34	9.5601	0.29	239.61	76	9.4631	0.43	73.90	9.3798	N/A	286.01
32	9.5869	0.28	116.49	9.5633	0.29	243.33	78	9.4917	N/A	72.29	9.3834	N/A	287.59
34	9.5783	0.29	113.21	9.5654	0.29	246.31	80	9.5208	N/A	70.67	9.3651	N/A	289.22
36	9.5908	0.29	110.26	9.5207	0.29	249.54	82	9.4691	N/A	68.99	9.2396	N/A	290.91
38	9.5896	0.29	107.66	9.5626	0.29	252.31	84	9.5127	N/A	67.49	9.2829	N/A	292.61
40	9.5648	0.29	105.01	N/A	N/A	N/A	86	N/A	N/A	N/A	N/A	N/A	N/A
42	9.5599	0.29	102.78	9.5352	0.29	257.01	88	N/A	N/A	N/A	N/A	N/A	N/A
44	9.5764	0.29	100.59	9.5174	0.29	259.20	90	N/A	N/A	N/A	N/A	N/A	N/A

N/A - Not Available

Figure 3. Type-B Standard Uncertainty vs Zenith Angle

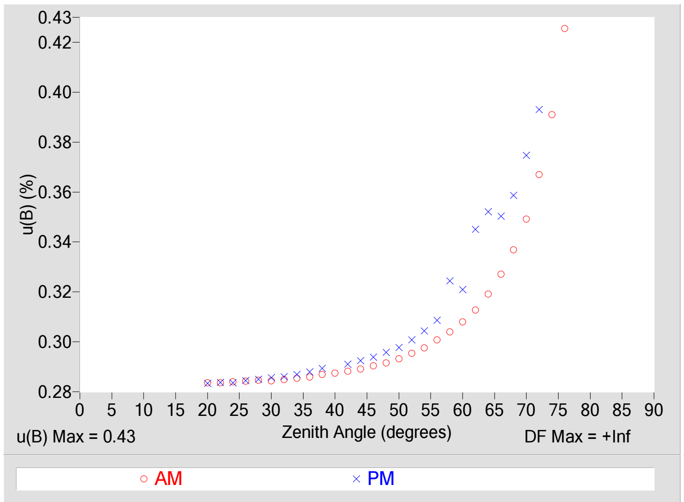


Figure 4. Residuals from Spline Interpolation

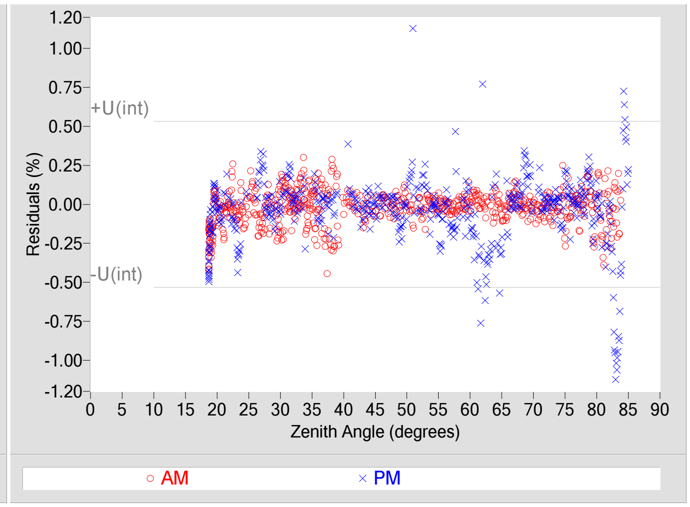


Table 3. Uncertainty using Spline Interpolation

Type-B Standard Uncertainty, u(B) (%)	±0.43
Type-A Interpolating Function, u(int) (%)	±0.27
Combined Standard Uncertainty, u(c) (%)	±0.50
Effective degrees of freedom, DF(c)	12964
Coverage factor, k	1.96
Expanded Uncertainty, U95 (%)	±0.98
AM Valid zenith angle range	20° to 76°
PM Valid zenith angle range	20° to 72°

Table 4. Calibration Label Values

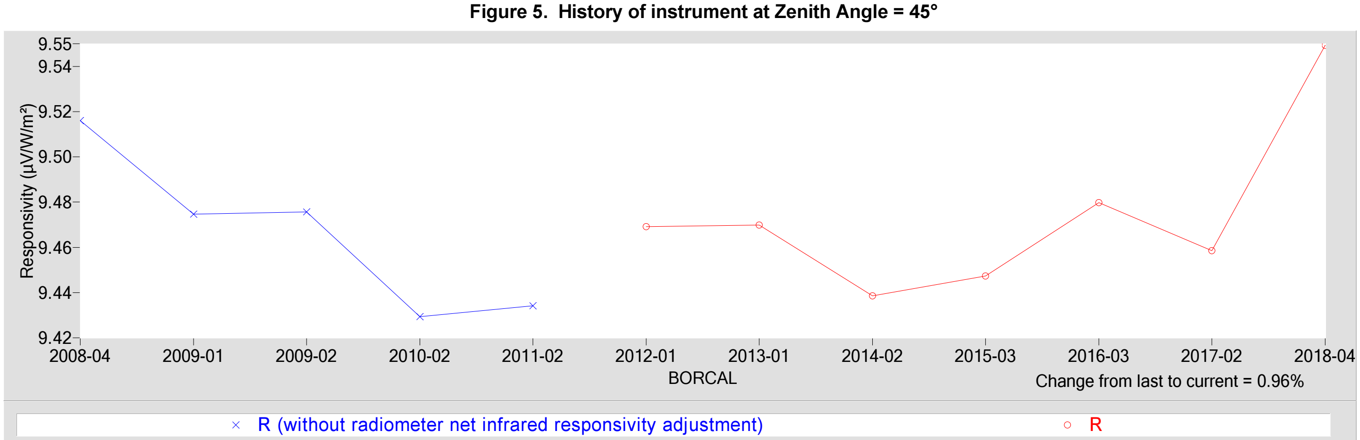
R @ 45° (µV/W/m²)	Rnet (µV/W/m²) †
9.5493	0.087000

† Rnet determination date: Estimated

Table 5. Uncertainty using R @ 45°

Type-B Expanded Uncertainty, U(B) (%)	±0.64
Offset Uncertainty, U(off) (%)	+0.49 / -0.66
Expanded Uncertainty, U (%)	+1.1 / -1.3
Effective degrees of freedom, DF	+Inf
Coverage factor, k	1.96
Valid zenith angle range	30.0° to 60.0°

Figure 5. History of instrument at Zenith Angle = 45°



References:

[1] Reda, I.; Hickey, J.; Long, C.; Myers, D.; Stoffel, T.; Wilcox, S.; Michalsky, J. J.; Dutton, E. G.; Nelson, D. (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; NREL Report No. JA-560-36646. doi:10.1175/JTECH1782.1

[2] 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-581-4137

[3] Reda, I.; Andreas, A. (2004). "Solar Position Algorithm for Solar Radiation Applications." Solar Energy. Vol. 76(5), 2004; pp. 577-589; NREL Report No. JA-560-35518. doi:10.1016/j.solener.2003.12.003

[4] Stoffel, T.; Reda, I. (2009). "NREL Pyrheliometer Comparisons: 22 September - 3 October 2008 (NPC-2008)." 54 pp.; NREL Report No. TP-550-45016.

[5] Reda, I.; Stoffel, T.; Myers, D. (2003). "Method to Calibrate a Solar Pyranometer for Measuring Reference Diffuse Irradiance." Solar Energy. Vol. 74, 2003; pp. 103-112; NREL Report No. JA-560-35025. doi:10.1016/S0038-092X(03)00124-5

[6] Reda, I. (1996). Calibration of a Solar Absolute Cavity Radiometer with Traceability to the World Radiometric Reference. 79 pp.; NREL Report No. TP-463-20619.

[7] Reda, I.; Gröbner, J.; Stoffel, T.; Myers, D.; Forgan, B. (2008). Improvements in the Blackbody Calibration of Pyrgeometers. ARM 2008 Science Team Meeting (Poster).

National Renewable Energy Laboratory

Solar Radiation Research Laboratory

Metrology Laboratory

Calibration Certificate

Calibration CERT #1239.02

Test Instrument:	Silicon Pyranometer	**Manufacturer:**	Kipp & Zonen
Model:	SP-LITE2	**Serial Number:**	151041
Calibration Date:	5/26/2018	**Due Date:**	5/26/2019
Customer:	Mike Dooraghi	**Environmental Conditions:**	see page 4
Test Dates:	5/25-26		

This certifies that the above product was calibrated in compliance with ISO/IEC 17025:2005. Measurement uncertainties at the time of calibration are consistent with the Guide to the Expression of Uncertainty in Measurement (GUM) using Reda et al., 2008. All nominal values are traceable to the International System (SI) Units of Measurement.

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1. The Expanded Uncertainty of using the responsivity at zenith angle = 45°, within the zenith angle range from 30.0° to 60.0°
2. The Expanded Uncertainty of using Spline Interpolating Functions for the responsivity versus zenith angle.

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Table 1. Traceability

Measurement Type	Instrument	Calibration Date	Calibration Due Date
Beam Irradiance †	Eppley Absolute Cavity Radiometer Model HF, S/N 29219	09/25/2017	09/25/2018
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/11/2018	04/11/2019
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/18/2018	04/18/2019
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	04/12/2017	04/12/2019
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	04/12/2017	04/12/2019

† Through the World Radiometric Reference (WRR)

Number of pages of certificate: 4

Calibration Procedure: BORCAL-P00-Calibration and QA Procedure; available upon request.

Setup: Radiometers are calibrated outdoors, using the sun as the source. Pyranometers and pyrgeometers are installed for horizontal measurements, with their signal connectors oriented north, if their design permits.
The shading disk for the reference diffuse subtends a solid angle of 5°. Pyrheliometers are installed on solar trackers.

Calibrated by: Afshin Andreas, Mark Kutchenreiter, and RCC

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Ibrahim Reda, Technical Manager Date

For questions or comments, please contact the technical manager at:
ibrahim.reda@nrel.gov; 303-384-6385; 15013 Denver West Parkway, Golden, CO 80401, USA

Calibration Results

151041 Kipp & Zonen SP-LITE2

The responsivity (R, µV/W/m²) of the test instrument during calibration is calculated using this Measurement Equation:

*R = (V - Rnet * Wnet) / I* [1]

where,

V = radiometer output voltage (microvolts),
Rnet = radiometer net infrared responsivity (µV/W/m²), see Table 4,
Wnet = effective net infrared measured by pyrgeometer (W/m²),
= *Win - Wout* = *Win - σ * Tc^4*
where, *Win* = incoming infrared (W/m²), *σ* = 5.6704e-8 W·m-2·K-4,
Tc = case temperature of pyrgeometer (K).

I = reference irradiance (W/m²), beam (B) or global (G)
where, *G = B * COS(Z) + D,*
Z = zenith angle (degrees),
D = reference diffuse irradiance (W/m²).

Figure 1. Responsivity vs Zenith Angle

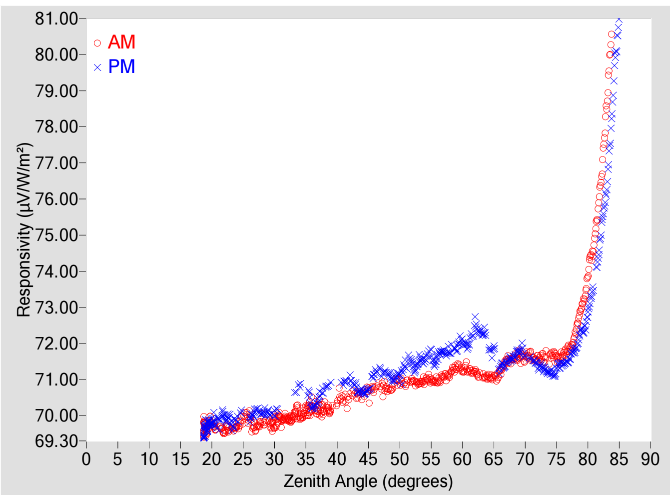


Figure 2. Responsivity vs Local Standard Time

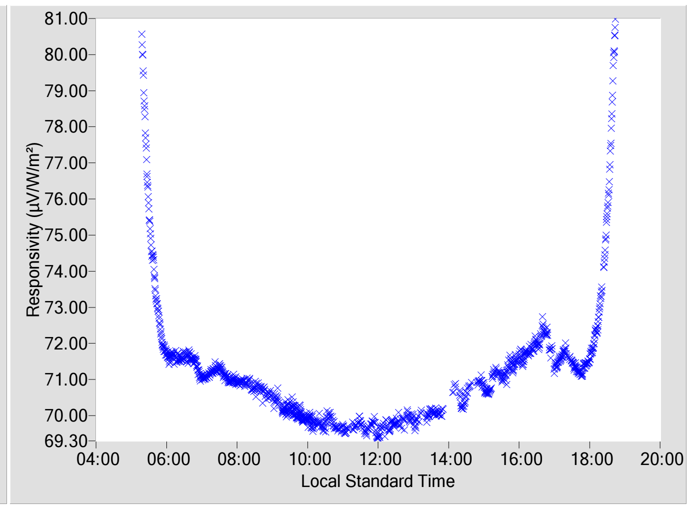


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)

Zenith	AM			PM			Zenith	AM			PM		
Angle	R	u(B)	Azimuth	R	u(B)	Azimuth	Angle	R	u(B)	Azimuth	R	u(B)	Azimuth
(deg.)	(µV/W/m²)	± (%)	Angle	(µV/W/m²)	± (%)	Angle	(deg.)	(µV/W/m²)	± (%)	Angle	(µV/W/m²)	± (%)	Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	70.732	0.29	98.72	71.192	0.29	261.25
2	N/A	N/A	N/A	N/A	N/A	N/A	48	70.740	0.29	96.70	71.172	0.29	263.14
4	N/A	N/A	N/A	N/A	N/A	N/A	50	70.942	0.29	94.76	71.085	0.30	265.04
6	N/A	N/A	N/A	N/A	N/A	N/A	52	70.970	0.29	93.00	71.379	0.30	266.81
8	N/A	N/A	N/A	N/A	N/A	N/A	54	70.985	0.30	91.31	71.546	0.30	268.50
10	N/A	N/A	N/A	N/A	N/A	N/A	56	70.978	0.30	89.68	71.644	0.31	270.23
12	N/A	N/A	N/A	N/A	N/A	N/A	58	71.148	0.30	88.03	71.780	0.32	271.83
14	N/A	N/A	N/A	N/A	N/A	N/A	60	71.243	0.30	86.39	72.031	0.32	273.45
16	N/A	N/A	N/A	N/A	N/A	N/A	62	71.215	0.31	84.84	72.526	0.34	275.12
18	N/A	N/A	N/A	N/A	N/A	N/A	64	71.071	0.31	83.26	71.853	0.34	276.79
20	69.813	0.28	157.21	69.816	0.28	202.92	66	71.197	0.32	81.71	71.333	0.34	278.14
22	69.562	0.28	144.21	69.980	0.28	215.73	68	71.552	0.33	80.14	71.598	0.35	279.76
24	69.695	0.28	136.14	69.897	0.28	223.78	70	71.598	0.34	78.56	71.630	0.37	281.14
26	69.917	0.28	129.66	69.943	0.28	230.69	72	71.585	0.36	77.05	71.380	0.38	282.85
28	69.848	0.28	124.75	70.061	0.28	235.36	74	71.639	0.38	75.43	71.202	N/A	284.41
30	69.812	0.28	120.27	70.077	0.28	239.78	76	71.683	0.41	73.90	71.427	N/A	285.97
32	69.924	0.28	116.52	N/A	N/A	N/A	78	72.297	N/A	72.28	71.820	N/A	287.58
34	69.960	0.28	113.28	70.844	0.29	246.56	80	73.895	N/A	70.66	72.856	N/A	289.25
36	70.260	0.28	110.39	70.240	0.29	249.58	82	76.347	N/A	68.98	74.941	N/A	290.90
38	70.193	0.29	107.78	70.747	0.29	252.30	84	80.568	N/A	67.49	79.024	N/A	292.65
40	70.449	0.29	104.94	N/A	N/A	N/A	86	N/A	N/A	N/A	N/A	N/A	N/A
42	70.521	0.29	102.79	71.020	0.29	257.19	88	N/A	N/A	N/A	N/A	N/A	N/A
44	70.525	0.29	100.63	70.670	0.29	259.13	90	N/A	N/A	N/A	N/A	N/A	N/A

N/A - Not Available

Figure 3. Type-B Standard Uncertainty vs Zenith Angle

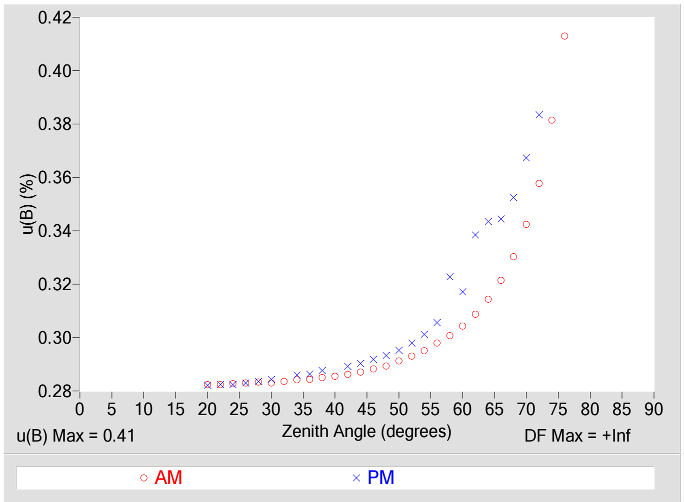


Figure 4. Residuals from Spline Interpolation

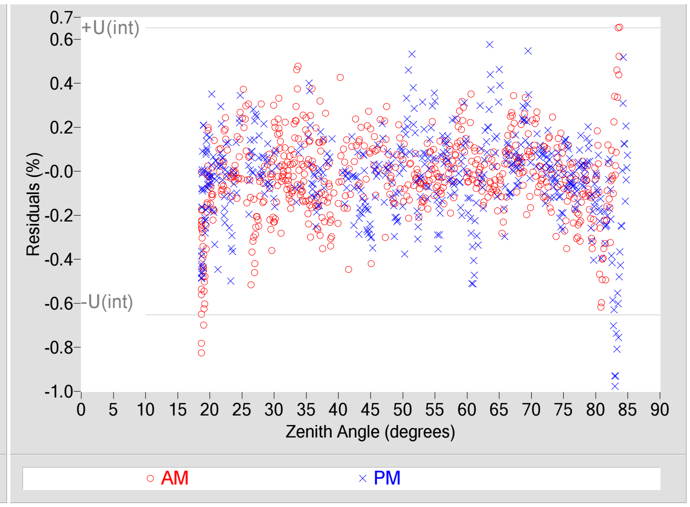


Table 3. Uncertainty using Spline Interpolation

Type-B Standard Uncertainty, u(B) (%)	±0.41
Type-A Interpolating Function, u(int) (%)	±0.33
Combined Standard Uncertainty, u(c) (%)	±0.53
Effective degrees of freedom, DF(c)	6731
Coverage factor, k	1.96
Expanded Uncertainty, U95 (%)	±1.0
AM Valid zenith angle range	20° to 76°
PM Valid zenith angle range	20° to 72°

Table 4. Calibration Label Values

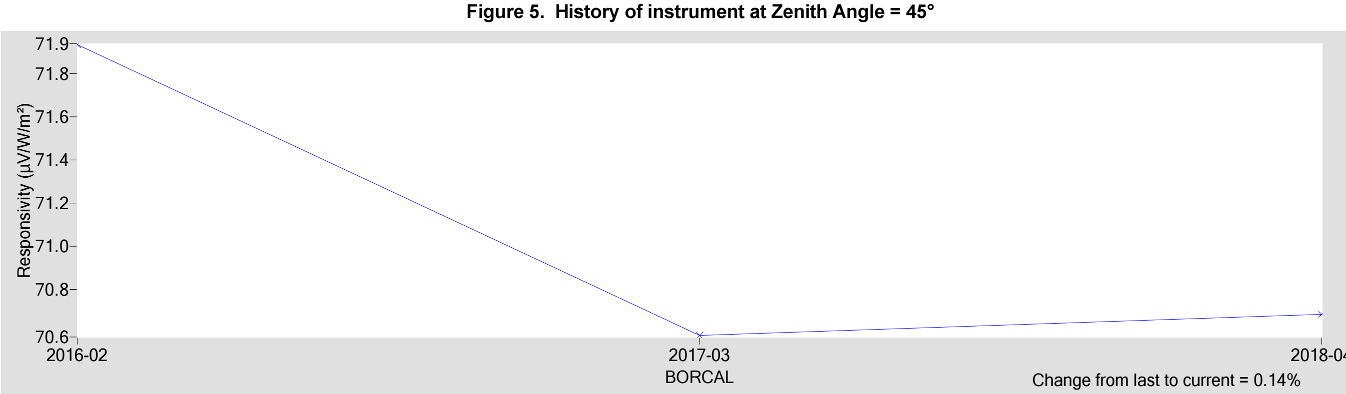
R @ 45° (μV/W/m²)	Rnet (μV/W/m²) †
70.685	0

† Rnet determination date: N/A

Table 5. Uncertainty using R @ 45°

Type-B Expanded Uncertainty, U(B) (%)	±0.63
Offset Uncertainty, U(off) (%)	+1.9 / -1.2
Expanded Uncertainty, U (%)	+2.5 / -1.9
Effective degrees of freedom, DF	+Inf
Coverage factor, k	1.96
Valid zenith angle range	30.0° to 60.0°

Figure 5. History of instrument at Zenith Angle = 45°



References:

[1] Reda, I.; Hickey, J.; Long, C.; Myers, D.; Stoffel, T.; Wilcox, S.; Michalsky, J. J.; Dutton, E. G.; Nelson, D. (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; NREL Report No. JA-560-36646. doi:10.1175/JTECH1782.1

[2] 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-581-4137

[3] Reda, I.; Andreas, A. (2004). "Solar Position Algorithm for Solar Radiation Applications." Solar Energy. Vol. 76(5), 2004; pp. 577-589; NREL Report No. JA-560-35518. doi:10.1016/j.solener.2003.12.003

[4] Stoffel, T.; Reda, I. (2009). "NREL Pyrheliometer Comparisons: 22 September - 3 October 2008 (NPC-2008)." 54 pp.; NREL Report No. TP-550-45016.

[5] Reda, I.; Stoffel, T.; Myers, D. (2003). "Method to Calibrate a Solar Pyranometer for Measuring Reference Diffuse Irradiance." Solar Energy. Vol. 74, 2003; pp. 103-112; NREL Report No. JA-560-35025. doi:10.1016/S0038-092X(03)00124-5

[6] Reda, I. (1996). Calibration of a Solar Absolute Cavity Radiometer with Traceability to the World Radiometric Reference. 79 pp.; NREL Report No. TP-463-20619.

[7] Reda, I.; Gröbner, J.; Stoffel, T.; Myers, D.; Forgan, B. (2008). Improvements in the Blackbody Calibration of Pyrgeometers. ARM 2008 Science Team Meeting (Poster).

National Renewable Energy Laboratory

Solar Radiation Research Laboratory

Metrology Laboratory

Calibration Certificate

Calibration CERT #1239.02

Test Instrument:	Silicon Pyranometer	**Manufacturer:**	Kipp & Zonen
Model:	SP-LITE2	**Serial Number:**	151729
Calibration Date:	5/26/2018	**Due Date:**	5/26/2019
Customer:	Mike Dooraghi	**Environmental Conditions:**	see page 4
Test Dates:	5/25-26		

This certifies that the above product was calibrated in compliance with ISO/IEC 17025:2005. Measurement uncertainties at the time of calibration are consistent with the Guide to the Expression of Uncertainty in Measurement (GUM) using Reda et al., 2008. All nominal values are traceable to the International System (SI) Units of Measurement.

No statement of compliance with specifications is made or implied on this certificate. However, the estimated uncertainties are the uncertainties of the calibration process; users must add other uncertainties that are relevant to their measuring system, environmental and sky conditions, outdoor set-up, and site location.

The Type-B Standard Uncertainty of using the responsivity at each even zenith angle is reported, and the Expanded Uncertainty of the calibration is reported using two methods:

1. The Expanded Uncertainty of using the responsivity at zenith angle = 45°, within the zenith angle range from 30.0° to 60.0°
2. The Expanded Uncertainty of using Spline Interpolating Functions for the responsivity versus zenith angle.

This certificate applies only to the item identified above and shall not be reproduced other that in full, without specific written approval from the calibration facility. Certificate without signature is not valid.

Table 1. Traceability

Measurement Type	Instrument	Calibration Date	Calibration Due Date
Beam Irradiance †	Eppley Absolute Cavity Radiometer Model HF, S/N 29219	09/25/2017	09/25/2018
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/11/2018	04/11/2019
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/18/2018	04/18/2019
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	04/12/2017	04/12/2019
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	04/12/2017	04/12/2019

† Through the World Radiometric Reference (WRR)

Number of pages of certificate: 4

Calibration Procedure: BORCAL-P00-Calibration and QA Procedure; available upon request.

Setup: Radiometers are calibrated outdoors, using the sun as the source. Pyranometers and pyrgeometers are installed for horizontal measurements, with their signal connectors oriented north, if their design permits.
The shading disk for the reference diffuse subtends a solid angle of 5°. Pyrheliometers are installed on solar trackers.

Calibrated by: Afshin Andreas, Mark Kutchenreiter, and RCC

______________________________ ____________

Ibrahim Reda, Technical Manager Date

For questions or comments, please contact the technical manager at:
ibrahim.reda@nrel.gov; 303-384-6385; 15013 Denver West Parkway, Golden, CO 80401, USA

Calibration Results

151729 Kipp & Zonen SP-LITE2

The responsivity (R, µV/W/m²) of the test instrument during calibration is calculated using this Measurement Equation:

$$R = (V - Rnet * Wnet) / I \qquad [1]$$

where,

- V = radiometer output voltage (microvolts),
- $Rnet$ = radiometer net infrared responsivity (µV/W/m²), see Table 4,
- $Wnet$ = effective net infrared measured by pyrgeometer (W/m²),
  - = $Win - Wout$ = $Win - \sigma * Tc^4$
  - where, Win = incoming infrared (W/m²), σ = 5.6704e-8 W·m-2·K-4,
  - Tc = case temperature of pyrgeometer (K).
- I = reference irradiance (W/m²), beam (B) or global (G)
  - where, $G = B * COS(Z) + D$,
  - Z = zenith angle (degrees),
  - D = reference diffuse irradiance (W/m²).

Figure 1. Responsivity vs Zenith Angle

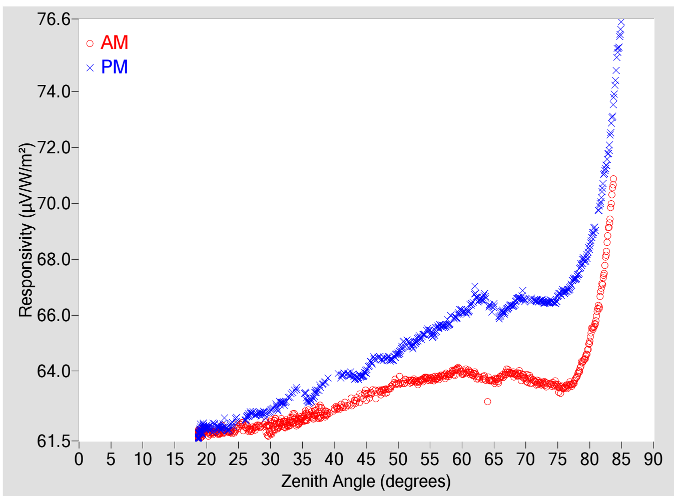


Figure 2. Responsivity vs Local Standard Time

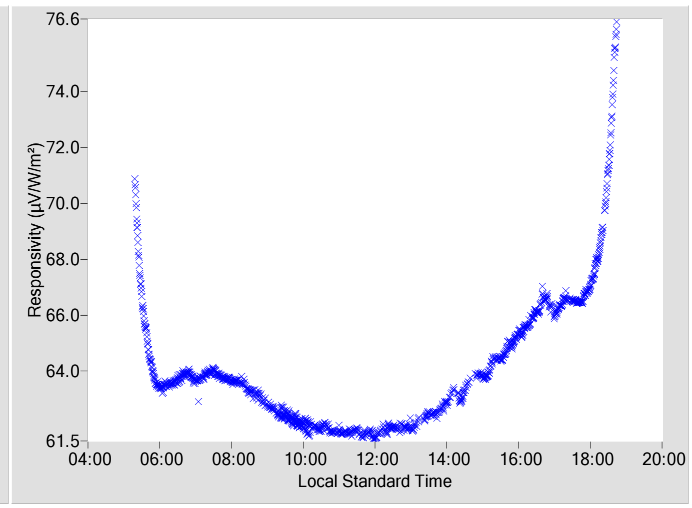


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)

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	63.243	0.29	98.72	64.394	0.29	261.25
2	N/A	N/A	N/A	N/A	N/A	N/A	48	63.292	0.29	96.70	64.476	0.29	263.14
4	N/A	N/A	N/A	N/A	N/A	N/A	50	63.604	0.29	94.76	64.630	0.30	265.04
6	N/A	N/A	N/A	N/A	N/A	N/A	52	63.631	0.29	93.00	64.925	0.30	266.81
8	N/A	N/A	N/A	N/A	N/A	N/A	54	63.715	0.30	91.31	65.299	0.30	268.50
10	N/A	N/A	N/A	N/A	N/A	N/A	56	63.745	0.30	89.68	65.519	0.31	270.23
12	N/A	N/A	N/A	N/A	N/A	N/A	58	63.873	0.30	88.03	65.735	0.32	271.83
14	N/A	N/A	N/A	N/A	N/A	N/A	60	63.929	0.30	86.39	66.143	0.32	273.45
16	N/A	N/A	N/A	N/A	N/A	N/A	62	63.904	0.31	84.84	66.772	0.34	275.12
18	N/A	N/A	N/A	N/A	N/A	N/A	64	63.707	0.31	83.22	66.334	0.34	276.79
20	61.855	0.28	157.21	61.981	0.28	202.92	66	63.751	0.32	81.71	65.994	0.34	278.14
22	61.787	0.28	144.21	61.976	0.28	215.73	68	63.896	0.33	80.14	66.350	0.35	279.76
24	61.839	0.28	136.14	62.097	0.28	223.78	70	63.721	0.34	78.56	66.514	0.37	281.14
26	62.014	0.28	129.66	62.294	0.28	230.69	72	63.591	0.36	77.05	66.516	0.38	282.85
28	62.042	0.28	124.75	62.462	0.28	235.36	74	63.527	0.38	75.43	66.491	N/A	284.41
30	61.996	0.28	120.27	62.607	0.28	239.78	76	63.400	0.41	73.90	66.845	N/A	285.97
32	62.124	0.28	116.52	62.867	0.28	243.34	78	63.825	N/A	72.28	67.372	N/A	287.58
34	62.196	0.28	113.28	63.354	0.29	246.56	80	65.066	N/A	70.66	68.507	N/A	289.25
36	62.416	0.28	110.39	62.928	0.29	249.58	82	67.183	N/A	68.98	70.579	N/A	290.90
38	62.525	0.29	107.78	63.502	0.29	252.30	84	70.881	N/A	67.49	74.555	N/A	292.65
40	62.652	0.29	104.94	N/A	N/A	N/A	86	N/A	N/A	N/A	N/A	N/A	N/A
42	62.738	0.29	102.79	63.882	0.29	257.19	88	N/A	N/A	N/A	N/A	N/A	N/A
44	63.023	0.29	100.63	63.801	0.29	259.13	90	N/A	N/A	N/A	N/A	N/A	N/A

N/A - Not Available

Figure 3. Type-B Standard Uncertainty vs Zenith Angle

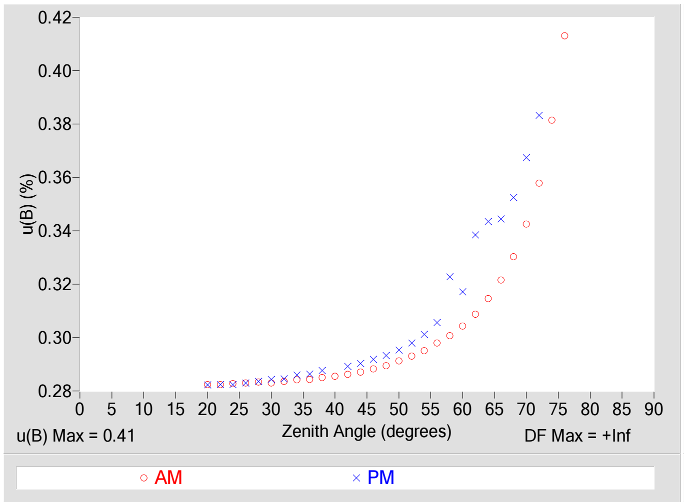


Figure 4. Residuals from Spline Interpolation

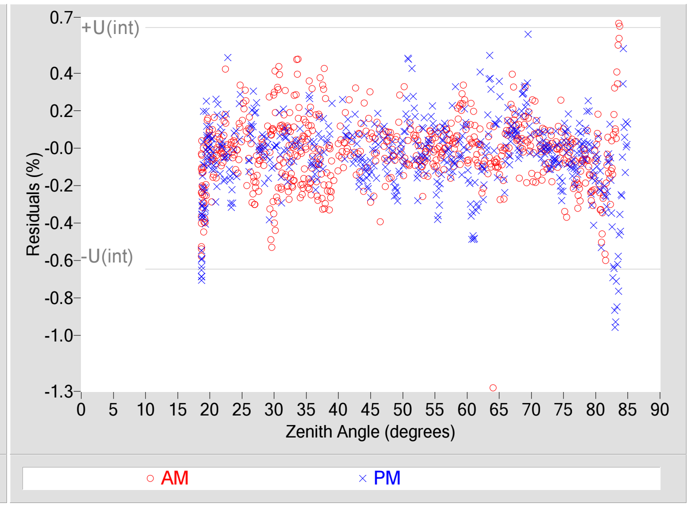


Table 3. Uncertainty using Spline Interpolation

Type-B Standard Uncertainty, u(B) (%)	±0.41
Type-A Interpolating Function, u(int) (%)	±0.32
Combined Standard Uncertainty, u(c) (%)	±0.52
Effective degrees of freedom, DF(c)	7069
Coverage factor, k	1.96
Expanded Uncertainty, U95 (%)	±1.0
AM Valid zenith angle range	20° to 76°
PM Valid zenith angle range	20° to 72°

Table 4. Calibration Label Values

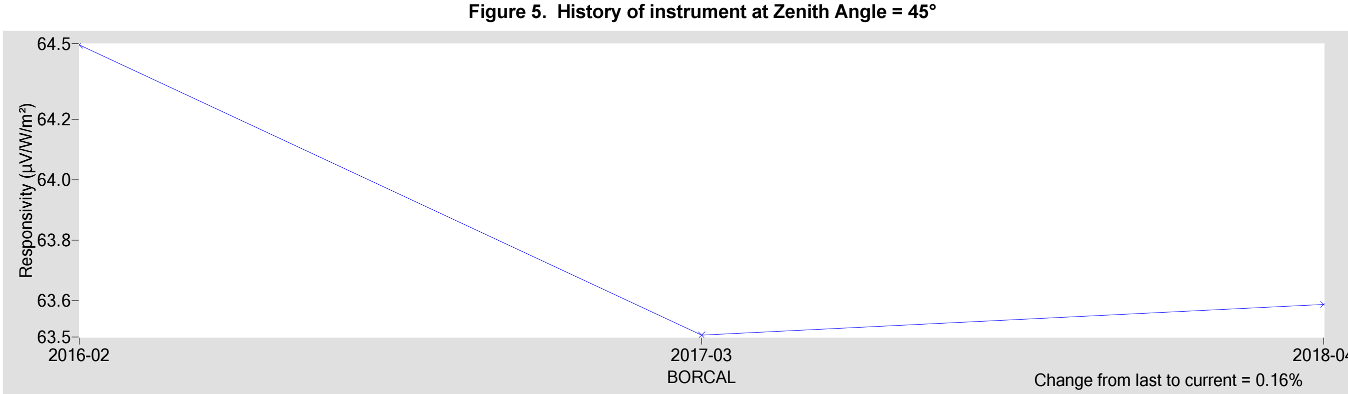
R @ 45° (µV/W/m²)	Rnet (µV/W/m²) †
63.588	0

† Rnet determination date: N/A

Table 5. Uncertainty using R @ 45°

Type-B Expanded Uncertainty, U(B) (%)	±0.63
Offset Uncertainty, U(off) (%)	+4.0 / -2.5
Expanded Uncertainty, U (%)	+4.7 / -3.1
Effective degrees of freedom, DF	+Inf
Coverage factor, k	1.96
Valid zenith angle range	30.0° to 60.0°

Figure 5. History of instrument at Zenith Angle = 45°



References:

[1] Reda, I.; Hickey, J.; Long, C.; Myers, D.; Stoffel, T.; Wilcox, S.; Michalsky, J. J.; Dutton, E. G.; Nelson, D. (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; NREL Report No. JA-560-36646. doi:10.1175/JTECH1782.1

[2] 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-581-4137

[3] Reda, I.; Andreas, A. (2004). "Solar Position Algorithm for Solar Radiation Applications." Solar Energy. Vol. 76(5), 2004; pp. 577-589; NREL Report No. JA-560-35518. doi:10.1016/j.solener.2003.12.003

[4] Stoffel, T.; Reda, I. (2009). "NREL Pyrheliometer Comparisons: 22 September - 3 October 2008 (NPC-2008)." 54 pp.; NREL Report No. TP-550-45016.

[5] Reda, I.; Stoffel, T.; Myers, D. (2003). "Method to Calibrate a Solar Pyranometer for Measuring Reference Diffuse Irradiance." Solar Energy. Vol. 74, 2003; pp. 103-112; NREL Report No. JA-560-35025. doi:10.1016/S0038-092X(03)00124-5

[6] Reda, I. (1996). Calibration of a Solar Absolute Cavity Radiometer with Traceability to the World Radiometric Reference. 79 pp.; NREL Report No. TP-463-20619.

[7] Reda, I.; Gröbner, J.; Stoffel, T.; Myers, D.; Forgan, B. (2008). Improvements in the Blackbody Calibration of Pyrgeometers. ARM 2008 Science Team Meeting (Poster).

National Renewable Energy Laboratory

Solar Radiation Research Laboratory

Metrology Laboratory

Calibration Certificate

Calibration CERT #1239.02

Test Instrument:	Pyranometer	**Manufacturer:**	Kipp & Zonen
Model:	CMP22	**Serial Number:**	160430
Calibration Date:	5/26/2018	**Due Date:**	5/26/2019
Customer:	Mike Dooraghi	**Environmental Conditions:**	see page 4
Test Dates:	5/25-26		

This certifies that the above product was calibrated in compliance with ISO/IEC 17025:2005. Measurement uncertainties at the time of calibration are consistent with the Guide to the Expression of Uncertainty in Measurement (GUM) using Reda et al., 2008. All nominal values are traceable to the International System (SI) Units of Measurement.

No statement of compliance with specifications is made or implied on this certificate. However, the estimated uncertainties are the uncertainties of the calibration process; users must add other uncertainties that are relevant to their measuring system, environmental and sky conditions, outdoor set-up, and site location.

The Type-B Standard Uncertainty of using the responsivity at each even zenith angle is reported, and the Expanded Uncertainty of the calibration is reported using two methods:

1. The Expanded Uncertainty of using the responsivity at zenith angle = 45°, within the zenith angle range from 30.0° to 60.0°
2. The Expanded Uncertainty of using Spline Interpolating Functions for the responsivity versus zenith angle.

This certificate applies only to the item identified above and shall not be reproduced other that in full, without specific written approval from the calibration facility. Certificate without signature is not valid.

Table 1. Traceability

Measurement Type	Instrument	Calibration Date	Calibration Due Date
Beam Irradiance †	Eppley Absolute Cavity Radiometer Model HF, S/N 29219	09/25/2017	09/25/2018
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/11/2018	04/11/2019
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/18/2018	04/18/2019
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	04/12/2017	04/12/2019
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	04/12/2017	04/12/2019
Infrared Irradiance ‡	Kipp & Zonen Pyrgeometer Model CG4, S/N FT002	04/16/2018	04/16/2022

† Through the World Radiometric Reference (WRR) ‡ Through the World Infrared Standard Group (WISG)

Number of pages of certificate: 4

Calibration Procedure: BORCAL-P00-Calibration and QA Procedure; available upon request.

Setup: Radiometers are calibrated outdoors, using the sun as the source. Pyranometers and pyrgeometers are installed for horizontal measurements, with their signal connectors oriented north, if their design permits.
The shading disk for the reference diffuse subtends a solid angle of 5°. Pyrheliometers are installed on solar trackers.

Calibrated by: Afshin Andreas, Mark Kutchenreiter, and RCC

______________________________ ____________

Ibrahim Reda, Technical Manager Date

For questions or comments, please contact the technical manager at:
ibrahim.reda@nrel.gov; 303-384-6385; 15013 Denver West Parkway, Golden, CO 80401, USA

Calibration Results

160430 Kipp & Zonen CMP22

The responsivity (R, μV/W/m²) of the test instrument during calibration is calculated using this Measurement Equation:

$$R = (V - Rnet * Wnet) / I \quad [1]$$

where,

- *V* = radiometer output voltage (microvolts),
- *Rnet* = radiometer net infrared responsivity (μV/W/m²), see Table 4,
- *Wnet* = effective net infrared measured by pyrgeometer (W/m²),
  = *Win - Wout* = *Win - σ * Tc^4*
  where, *Win* = incoming infrared (W/m²), *σ* = 5.6704e-8 W·m-2·K-4,
  Tc = case temperature of pyrgeometer (K).
- *I* = reference irradiance (W/m²), beam (B) or global (G)
  where, *G = B * COS(Z) + D,*
  Z = zenith angle (degrees),
  D = reference diffuse irradiance (W/m²).

Figure 1. Responsivity vs Zenith Angle

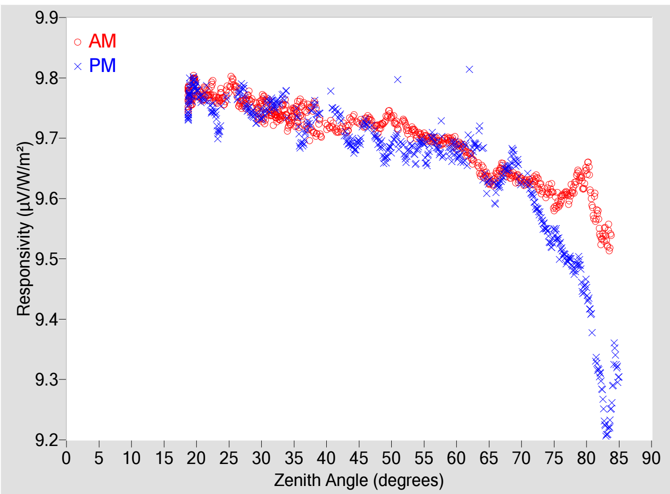


Figure 2. Responsivity vs Local Standard Time

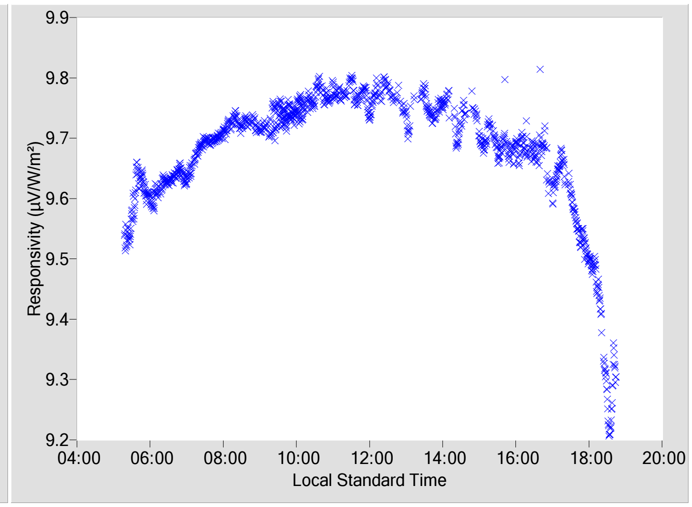


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)

Zenith	AM			PM			Zenith	AM			PM		
Angle	R	u(B)	Azimuth	R	u(B)	Azimuth	Angle	R	u(B)	Azimuth	R	u(B)	Azimuth
(deg.)	(μV/W/m²)	± (%)	Angle	(μV/W/m²)	± (%)	Angle	(deg.)	(μV/W/m²)	± (%)	Angle	(μV/W/m²)	± (%)	Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	9.7264	0.29	98.59	9.7254	0.29	261.23
2	N/A	N/A	N/A	N/A	N/A	N/A	48	9.7176	0.29	96.67	9.6927	0.30	263.16
4	N/A	N/A	N/A	N/A	N/A	N/A	50	9.7361	0.29	94.91	9.6847	0.30	264.90
6	N/A	N/A	N/A	N/A	N/A	N/A	52	9.7268	0.30	93.05	9.6715	0.30	266.82
8	N/A	N/A	N/A	N/A	N/A	N/A	54	9.7046	0.30	91.39	9.6803	0.30	268.53
10	N/A	N/A	N/A	N/A	N/A	N/A	56	9.6991	0.30	89.64	9.6954	0.31	270.20
12	N/A	N/A	N/A	N/A	N/A	N/A	58	9.6963	0.30	88.00	9.6805	0.32	271.72
14	N/A	N/A	N/A	N/A	N/A	N/A	60	9.6900	0.31	86.38	9.6792	0.32	273.45
16	N/A	N/A	N/A	N/A	N/A	N/A	62	9.6736	0.31	84.79	9.7400	0.34	275.00
18	N/A	N/A	N/A	N/A	N/A	N/A	64	9.6444	0.32	83.23	9.6660	0.35	276.65
20	9.7862	0.28	157.49	9.7819	0.28	203.14	66	9.6368	0.33	81.68	9.6108	0.35	278.18
22	9.7720	0.28	144.27	9.7524	0.28	216.19	68	9.6431	0.34	80.15	9.6504	0.36	279.72
24	9.7689	0.28	136.14	9.7533	0.28	223.37	70	9.6324	0.35	78.65	9.6246	0.37	281.11
26	9.7819	0.28	129.84	9.7638	0.28	231.03	72	9.6313	0.37	77.02	9.5939	0.39	282.81
28	9.7647	0.28	124.67	9.7479	0.28	235.29	74	9.6117	0.39	75.47	9.5428	N/A	284.41
30	9.7513	0.28	120.34	9.7359	0.29	239.61	76	9.5952	0.43	73.90	9.5163	N/A	286.01
32	9.7387	0.28	116.49	9.7535	0.29	243.33	78	9.6160	N/A	72.29	9.4823	N/A	287.59
34	9.7308	0.29	113.21	9.7635	0.29	246.31	80	9.6471	N/A	70.67	9.4476	N/A	289.22
36	9.7447	0.29	110.26	9.6916	0.29	249.54	82	9.5496	N/A	68.99	9.3097	N/A	290.91
38	9.7360	0.29	107.66	9.7546	0.29	252.31	84	9.5403	N/A	67.49	9.2901	N/A	292.61
40	9.7199	0.29	105.01	N/A	N/A	N/A	86	N/A	N/A	N/A	N/A	N/A	N/A
42	9.7116	0.29	102.78	9.7367	0.29	257.01	88	N/A	N/A	N/A	N/A	N/A	N/A
44	9.7332	0.29	100.59	9.6868	0.29	259.20	90	N/A	N/A	N/A	N/A	N/A	N/A

N/A - Not Available

Figure 3. Type-B Standard Uncertainty vs Zenith Angle

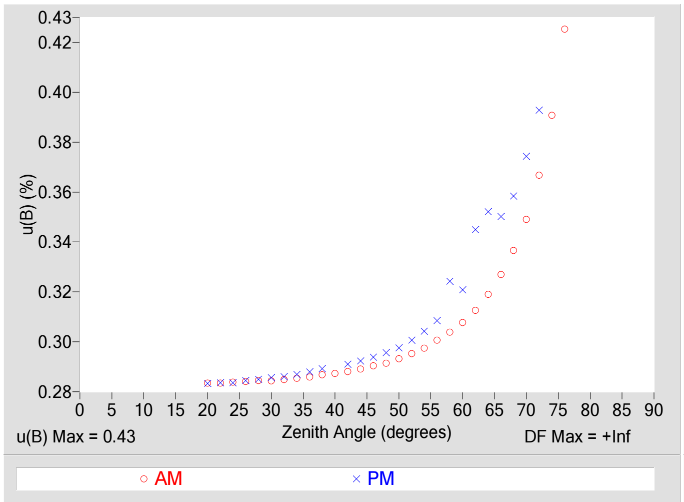


Figure 4. Residuals from Spline Interpolation

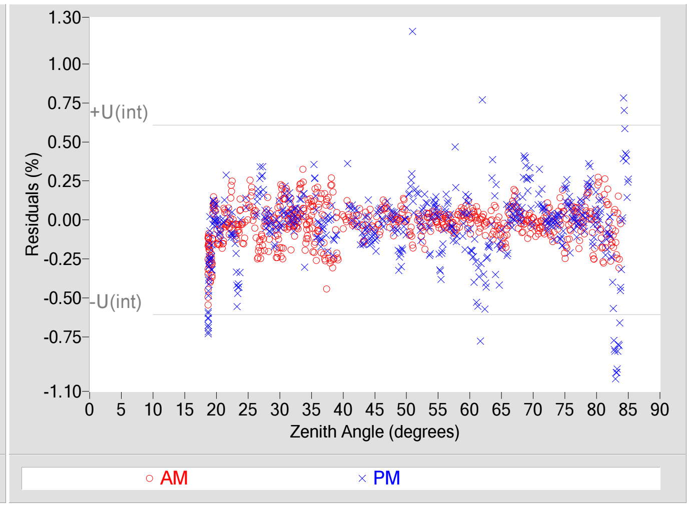


Table 3. Uncertainty using Spline Interpolation

Type-B Standard Uncertainty, u(B) (%)	±0.43
Type-A Interpolating Function, u(int) (%)	±0.30
Combined Standard Uncertainty, u(c) (%)	±0.52
Effective degrees of freedom, DF(c)	8947
Coverage factor, k	1.96
Expanded Uncertainty, U95 (%)	±1.0
AM Valid zenith angle range	20° to 76°
PM Valid zenith angle range	20° to 72°

Table 4. Calibration Label Values

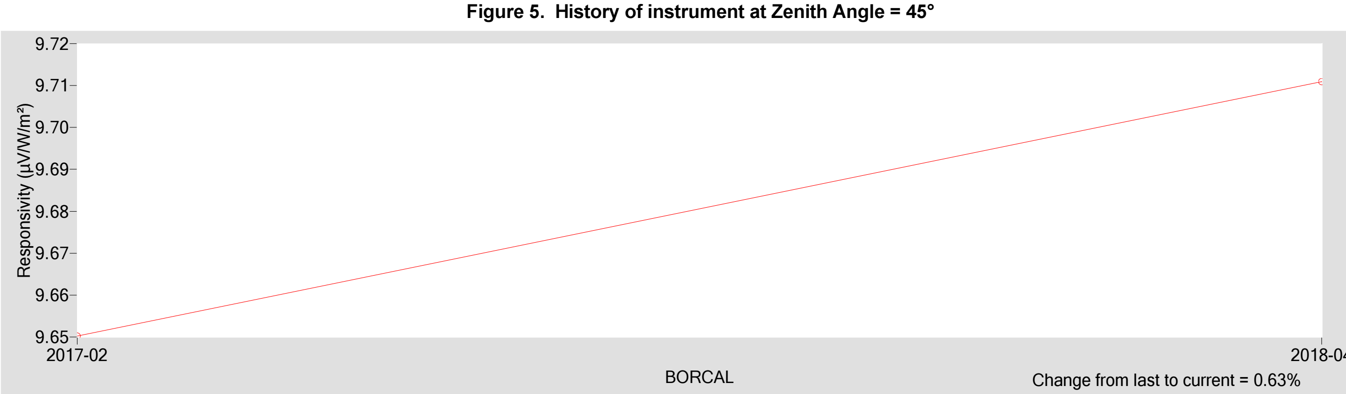
R @ 45° (µV/W/m²)	Rnet (µV/W/m²) †
9.7109	0.087000

† Rnet determination date: Estimated

Table 5. Uncertainty using R @ 45°

Type-B Expanded Uncertainty, U(B) (%)	±0.64
Offset Uncertainty, U(off) (%)	+0.54 / -0.41
Expanded Uncertainty, U (%)	+1.2 / -1.0
Effective degrees of freedom, DF	+Inf
Coverage factor, k	1.96
Valid zenith angle range	30.0° to 60.0°

Figure 5. History of instrument at Zenith Angle = 45°



References:

[1] Reda, I.; Hickey, J.; Long, C.; Myers, D.; Stoffel, T.; Wilcox, S.; Michalsky, J. J.; Dutton, E. G.; Nelson, D. (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; NREL Report No. JA-560-36646. doi:10.1175/JTECH1782.1

[2] 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-581-4137

[3] Reda, I.; Andreas, A. (2004). "Solar Position Algorithm for Solar Radiation Applications." Solar Energy. Vol. 76(5), 2004; pp. 577-589; NREL Report No. JA-560-35518. doi:10.1016/j.solener.2003.12.003

[4] Stoffel, T.; Reda, I. (2009). "NREL Pyrheliometer Comparisons: 22 September - 3 October 2008 (NPC-2008)." 54 pp.; NREL Report No. TP-550-45016.

[5] Reda, I.; Stoffel, T.; Myers, D. (2003). "Method to Calibrate a Solar Pyranometer for Measuring Reference Diffuse Irradiance." Solar Energy. Vol. 74, 2003; pp. 103-112; NREL Report No. JA-560-35025. doi:10.1016/S0038-092X(03)00124-5

[6] Reda, I. (1996). Calibration of a Solar Absolute Cavity Radiometer with Traceability to the World Radiometric Reference. 79 pp.; NREL Report No. TP-463-20619.

[7] Reda, I.; Gröbner, J.; Stoffel, T.; Myers, D.; Forgan, B. (2008). Improvements in the Blackbody Calibration of Pyrgeometers. ARM 2008 Science Team Meeting (Poster).

National Renewable Energy Laboratory

Solar Radiation Research Laboratory

Metrology Laboratory

Calibration Certificate

Calibration CERT #1239.02

Test Instrument:	Si pyranometer	**Manufacturer:**	Apogee
Model:	SP-110	**Serial Number:**	40338
Calibration Date:	5/26/2018	**Due Date:**	5/26/2019
Customer:	Mike Dooraghi	**Environmental Conditions:**	see page 4
Test Dates:	5/25-26		

This certifies that the above product was calibrated in compliance with ISO/IEC 17025:2005. Measurement uncertainties at the time of calibration are consistent with the Guide to the Expression of Uncertainty in Measurement (GUM) using Reda et al., 2008. All nominal values are traceable to the International System (SI) Units of Measurement.

No statement of compliance with specifications is made or implied on this certificate. However, the estimated uncertainties are the uncertainties of the calibration process; users must add other uncertainties that are relevant to their measuring system, environmental and sky conditions, outdoor set-up, and site location.

The Type-B Standard Uncertainty of using the responsivity at each even zenith angle is reported, and the Expanded Uncertainty of the calibration is reported using two methods:

1. The Expanded Uncertainty of using the responsivity at zenith angle = 45°, within the zenith angle range from 30.0° to 60.0°
2. The Expanded Uncertainty of using Spline Interpolating Functions for the responsivity versus zenith angle.

This certificate applies only to the item identified above and shall not be reproduced other that in full, without specific written approval from the calibration facility. Certificate without signature is not valid.

Table 1. Traceability

Measurement Type	Instrument	Calibration Date	Calibration Due Date
Beam Irradiance †	Eppley Absolute Cavity Radiometer Model HF, S/N 29219	09/25/2017	09/25/2018
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/11/2018	04/11/2019
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/18/2018	04/18/2019
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	04/12/2017	04/12/2019
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	04/12/2017	04/12/2019

† Through the World Radiometric Reference (WRR)

Number of pages of certificate: 4

Calibration Procedure: BORCAL-P00-Calibration and QA Procedure; available upon request.

Setup: Radiometers are calibrated outdoors, using the sun as the source. Pyranometers and pyrgeometers are installed for horizontal measurements, with their signal connectors oriented north, if their design permits.
The shading disk for the reference diffuse subtends a solid angle of 5°. Pyrheliometers are installed on solar trackers.

Calibrated by: Afshin Andreas, Mark Kutchenreiter, and RCC

______________________________ ______________

Ibrahim Reda, Technical Manager   Date

For questions or comments, please contact the technical manager at:
ibrahim.reda@nrel.gov; 303-384-6385; 15013 Denver West Parkway, Golden, CO 80401, USA

Calibration Results

40338 Apogee SP-110

The responsivity (R, µV/W/m²) of the test instrument during calibration is calculated using this Measurement Equation:

$$R = (V - Rnet * Wnet) / I \qquad [1]$$

where,

- V = radiometer output voltage (microvolts),
- $Rnet$ = radiometer net infrared responsivity (µV/W/m²), see Table 4,
- $Wnet$ = effective net infrared measured by pyrgeometer (W/m²),
  = $Win - Wout$ = $Win - \sigma * Tc^4$
  where, Win = incoming infrared (W/m²), σ = 5.6704e-8 W·m-2·K-4,
  Tc = case temperature of pyrgeometer (K).
- I = reference irradiance (W/m²), beam (B) or global (G)
  where, $G = B * COS(Z) + D$,
  Z = zenith angle (degrees),
  D = reference diffuse irradiance (W/m²).

Figure 1. Responsivity vs Zenith Angle

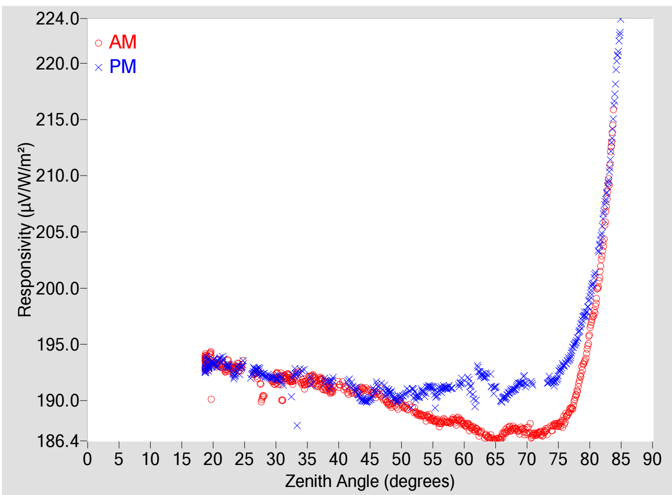


Figure 2. Responsivity vs Local Standard Time

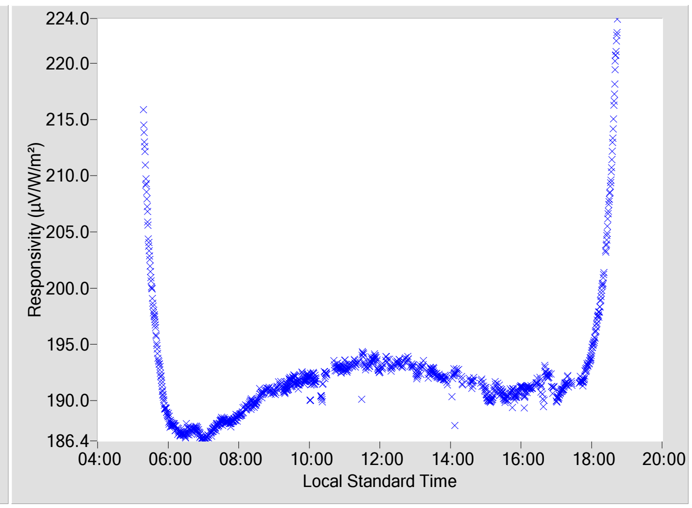


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)

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	190.56	0.29	98.58	191.22	0.29	261.25
2	N/A	N/A	N/A	N/A	N/A	N/A	48	189.69	0.29	96.68	190.79	0.29	263.17
4	N/A	N/A	N/A	N/A	N/A	N/A	50	189.75	0.29	94.82	190.25	0.30	265.01
6	N/A	N/A	N/A	N/A	N/A	N/A	52	189.17	0.29	93.03	190.57	0.30	266.80
8	N/A	N/A	N/A	N/A	N/A	N/A	54	188.52	0.30	91.35	191.09	0.30	268.57
10	N/A	N/A	N/A	N/A	N/A	N/A	56	188.02	0.30	89.66	191.01	0.31	270.24
12	N/A	N/A	N/A	N/A	N/A	N/A	58	188.16	0.30	88.02	191.09	0.32	271.82
14	N/A	N/A	N/A	N/A	N/A	N/A	60	187.86	0.30	86.41	N/A	N/A	N/A
16	N/A	N/A	N/A	N/A	N/A	N/A	62	187.38	0.31	84.82	192.16	0.34	275.12
18	N/A	N/A	N/A	N/A	N/A	N/A	64	186.71	0.31	83.25	191.80	0.34	276.78
20	193.39	0.28	155.81	193.39	0.28	203.16	66	186.77	0.32	81.70	190.09	0.34	278.20
22	192.80	0.28	144.22	193.08	0.28	216.44	68	187.52	0.33	80.16	191.01	0.35	279.74
24	193.02	0.28	135.96	192.84	0.28	223.98	70	187.32	0.34	78.57	191.38	0.37	281.12
26	N/A	N/A	N/A	192.27	0.28	230.71	72	187.12	0.36	77.04	N/A	N/A	N/A
28	190.31	0.28	124.90	192.26	0.28	235.36	74	187.57	0.38	75.45	191.70	N/A	284.43
30	191.99	0.28	120.23	191.91	0.28	239.70	76	188.35	0.41	73.89	193.22	N/A	286.00
32	192.05	0.28	116.58	N/A	N/A	N/A	78	190.91	N/A	72.27	195.61	N/A	287.61
34	191.59	0.28	113.28	192.62	0.29	246.54	80	196.13	N/A	70.64	199.28	N/A	289.24
36	192.00	0.28	110.39	N/A	N/A	N/A	82	203.26	N/A	68.97	205.79	N/A	290.93
38	191.23	0.29	107.58	191.74	0.29	252.03	84	215.88	N/A	67.47	217.58	N/A	292.63
40	191.41	0.29	104.94	N/A	N/A	N/A	86	N/A	N/A	N/A	N/A	N/A	N/A
42	190.81	0.29	102.67	191.38	0.29	257.02	88	N/A	N/A	N/A	N/A	N/A	N/A
44	191.03	0.29	100.67	190.02	0.29	259.17	90	N/A	N/A	N/A	N/A	N/A	N/A

N/A - Not Available

Figure 3. Type-B Standard Uncertainty vs Zenith Angle

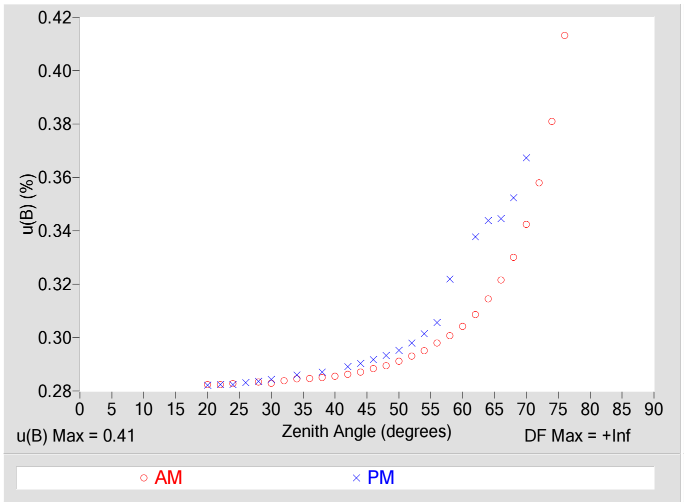


Figure 4. Residuals from Spline Interpolation

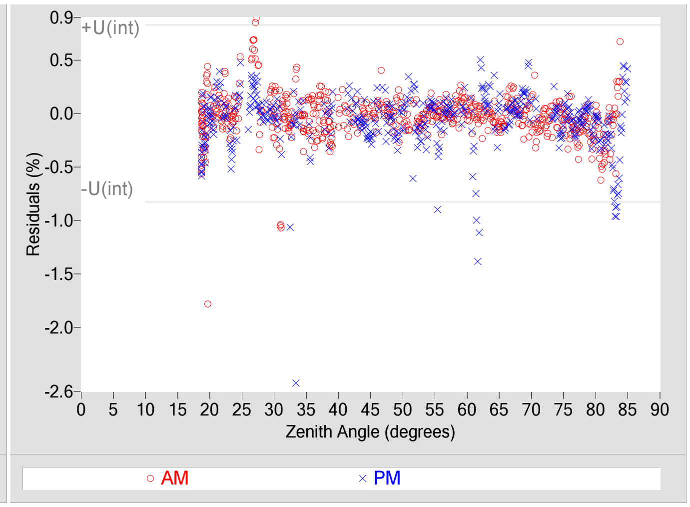


Table 3. Uncertainty using Spline Interpolation

Type-B Standard Uncertainty, u(B) (%)	±0.41
Type-A Interpolating Function, u(int) (%)	±0.41
Combined Standard Uncertainty, u(c) (%)	±0.58
Effective degrees of freedom, DF(c)	3685
Coverage factor, k	1.96
Expanded Uncertainty, U95 (%)	±1.1
AM Valid zenith angle range	20° to 76°
PM Valid zenith angle range	20° to 70°

Table 4. Calibration Label Values

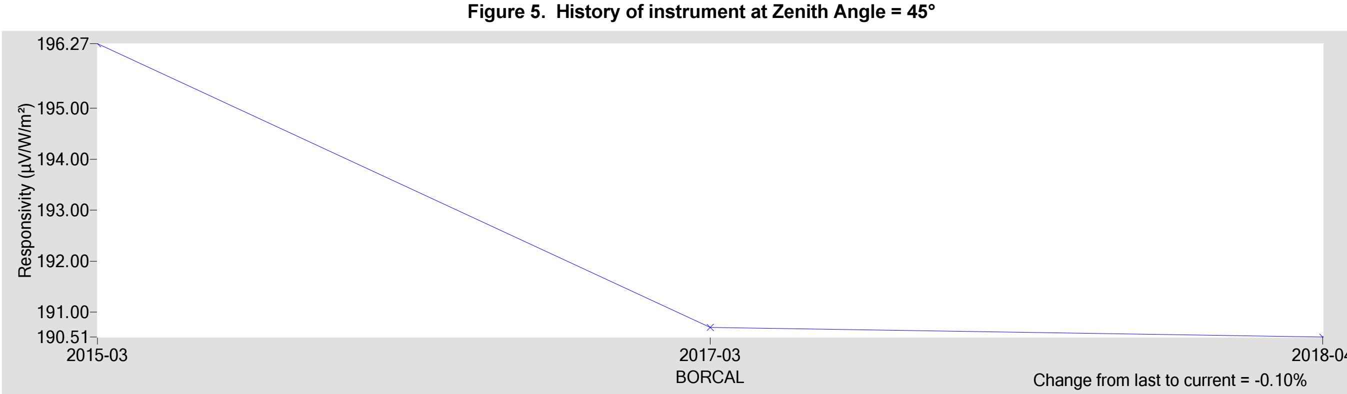
R @ 45° (µV/W/m²)	Rnet (µV/W/m²) †
190.51	0

† Rnet determination date: N/A

Table 5. Uncertainty using R @ 45°

Type-B Expanded Uncertainty, U(B) (%)	±0.63
Offset Uncertainty, U(off) (%)	+1.1 / -1.4
Expanded Uncertainty, U (%)	+1.7 / -2.0
Effective degrees of freedom, DF	+Inf
Coverage factor, k	1.96
Valid zenith angle range	30.0° to 60.0°

Figure 5. History of instrument at Zenith Angle = 45°



References:

[1] Reda, I.; Hickey, J.; Long, C.; Myers, D.; Stoffel, T.; Wilcox, S.; Michalsky, J. J.; Dutton, E. G.; Nelson, D. (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; NREL Report No. JA-560-36646. doi:10.1175/JTECH1782.1

[2] 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-581-4137

[3] Reda, I.; Andreas, A. (2004). "Solar Position Algorithm for Solar Radiation Applications." Solar Energy. Vol. 76(5), 2004; pp. 577-589; NREL Report No. JA-560-35518. doi:10.1016/j.solener.2003.12.003

[4] Stoffel, T.; Reda, I. (2009). "NREL Pyrheliometer Comparisons: 22 September - 3 October 2008 (NPC-2008)." 54 pp.; NREL Report No. TP-550-45016.

[5] Reda, I.; Stoffel, T.; Myers, D. (2003). "Method to Calibrate a Solar Pyranometer for Measuring Reference Diffuse Irradiance." Solar Energy. Vol. 74, 2003; pp. 103-112; NREL Report No. JA-560-35025. doi:10.1016/S0038-092X(03)00124-5

[6] Reda, I. (1996). Calibration of a Solar Absolute Cavity Radiometer with Traceability to the World Radiometric Reference. 79 pp.; NREL Report No. TP-463-20619.

[7] Reda, I.; Gröbner, J.; Stoffel, T.; Myers, D.; Forgan, B. (2008). Improvements in the Blackbody Calibration of Pyrgeometers. ARM 2008 Science Team Meeting (Poster).

National Renewable Energy Laboratory

Solar Radiation Research Laboratory

Metrology Laboratory

Calibration Certificate

Calibration CERT #1239.02

Test Instrument:	Pyranometer	**Manufacturer:**	Kipp & Zonen
Model:	CM21	**Serial Number:**	920058
Calibration Date:	5/26/2018	**Due Date:**	5/26/2019
Customer:	Mike Dooraghi	**Environmental Conditions:**	see page 4
Test Dates:	5/25-26		

This certifies that the above product was calibrated in compliance with ISO/IEC 17025:2005. Measurement uncertainties at the time of calibration are consistent with the Guide to the Expression of Uncertainty in Measurement (GUM) using Reda et al., 2008. All nominal values are traceable to the International System (SI) Units of Measurement.

No statement of compliance with specifications is made or implied on this certificate. However, the estimated uncertainties are the uncertainties of the calibration process; users must add other uncertainties that are relevant to their measuring system, environmental and sky conditions, outdoor set-up, and site location.

The Type-B Standard Uncertainty of using the responsivity at each even zenith angle is reported, and the Expanded Uncertainty of the calibration is reported using two methods:

1. The Expanded Uncertainty of using the responsivity at zenith angle = 45°, within the zenith angle range from 30.0° to 60.0°
2. The Expanded Uncertainty of using Spline Interpolating Functions for the responsivity versus zenith angle.

This certificate applies only to the item identified above and shall not be reproduced other that in full, without specific written approval from the calibration facility. Certificate without signature is not valid.

Table 1. Traceability

Measurement Type	Instrument	Calibration Date	Calibration Due Date
Beam Irradiance †	Eppley Absolute Cavity Radiometer Model HF, S/N 29219	09/25/2017	09/25/2018
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/11/2018	04/11/2019
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/18/2018	04/18/2019
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	04/12/2017	04/12/2019
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	04/12/2017	04/12/2019
Infrared Irradiance ‡	Kipp & Zonen Pyrgeometer Model CG4, S/N FT002	04/16/2018	04/16/2022

† Through the World Radiometric Reference (WRR)   ‡ Through the World Infrared Standard Group (WISG)

Number of pages of certificate: 4

Calibration Procedure: BORCAL-P00-Calibration and QA Procedure; available upon request.

Setup: Radiometers are calibrated outdoors, using the sun as the source. Pyranometers and pyrgeometers are installed for horizontal measurements, with their signal connectors oriented north, if their design permits.
The shading disk for the reference diffuse subtends a solid angle of 5°. Pyrheliometers are installed on solar trackers.

Calibrated by: Afshin Andreas, Mark Kutchenreiter, and RCC

______________________________ ______________

Ibrahim Reda, Technical Manager   Date

For questions or comments, please contact the technical manager at:
ibrahim.reda@nrel.gov; 303-384-6385; 15013 Denver West Parkway, Golden, CO 80401, USA

Calibration Results

920058 Kipp & Zonen CM21

The responsivity (R, μV/W/m²) of the test instrument during calibration is calculated using this Measurement Equation:

$$R = (V - Rnet * Wnet) / I \quad [1]$$

where,

- V = radiometer output voltage (microvolts),
- $Rnet$ = radiometer net infrared responsivity (μV/W/m²), see Table 4,
- $Wnet$ = effective net infrared measured by pyrgeometer (W/m²),
  - = $Win - Wout$ = $Win - \sigma * Tc^4$
  - where, Win = incoming infrared (W/m²), σ = 5.6704e-8 W·m-2·K-4,
  - Tc = case temperature of pyrgeometer (K).
- I = reference irradiance (W/m²), beam (B) or global (G)
  - where, $G = B * COS(Z) + D$,
  - Z = zenith angle (degrees),
  - D = reference diffuse irradiance (W/m²).

Figure 1. Responsivity vs Zenith Angle

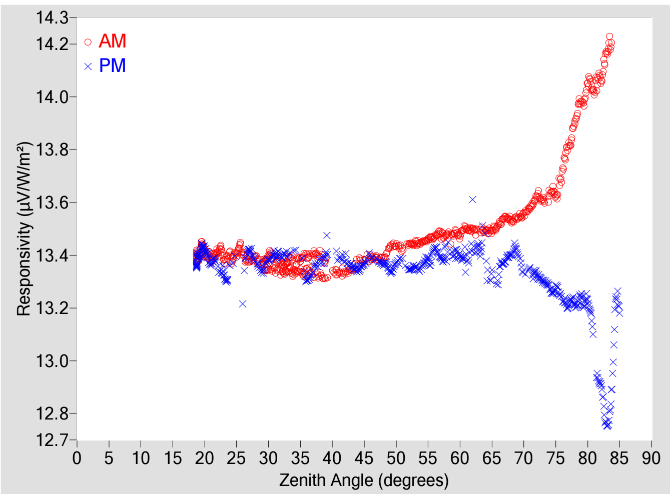


Figure 2. Responsivity vs Local Standard Time

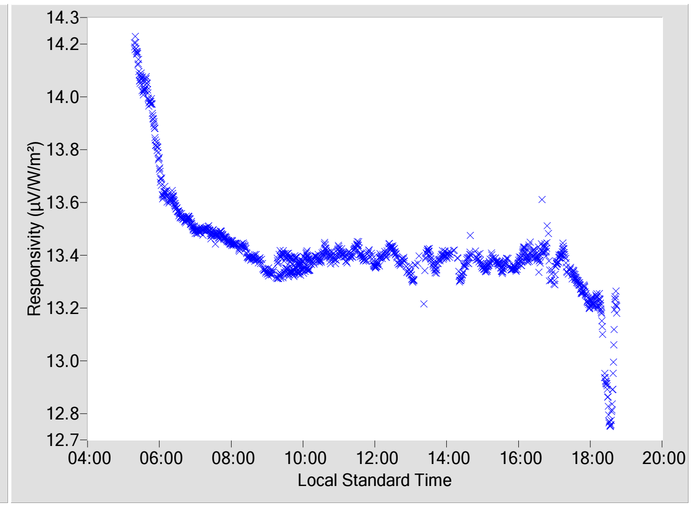


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)

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	13.390	0.29	98.60	13.397	0.30	261.19
2	N/A	N/A	N/A	N/A	N/A	N/A	48	13.391	0.30	96.68	13.367	0.30	263.14
4	N/A	N/A	N/A	N/A	N/A	N/A	50	13.435	0.30	94.90	13.370	0.30	264.98
6	N/A	N/A	N/A	N/A	N/A	N/A	52	13.442	0.30	93.01	13.346	0.31	266.81
8	N/A	N/A	N/A	N/A	N/A	N/A	54	13.448	0.30	91.31	13.359	0.31	268.58
10	N/A	N/A	N/A	N/A	N/A	N/A	56	13.468	0.31	89.63	13.425	0.31	270.16
12	N/A	N/A	N/A	N/A	N/A	N/A	58	13.479	0.31	87.99	13.414	0.33	271.79
14	N/A	N/A	N/A	N/A	N/A	N/A	60	13.477	0.31	86.38	13.395	0.33	273.46
16	N/A	N/A	N/A	N/A	N/A	N/A	62	13.498	0.32	84.80	13.425	0.35	275.03
18	N/A	N/A	N/A	N/A	N/A	N/A	64	13.493	0.33	83.22	13.388	0.36	276.69
20	13.416	0.29	157.32	13.420	0.29	203.32	66	13.515	0.34	81.67	13.327	0.36	278.21
22	13.409	0.29	144.21	13.345	0.29	216.44	68	13.532	0.35	80.14	13.401	0.37	279.71
24	13.397	0.29	135.90	13.362	0.29	223.58	70	13.555	0.36	78.61	13.333	0.39	281.21
26	13.406	0.29	129.92	13.278	0.29	230.47	72	13.623	0.38	77.05	13.327	0.41	282.84
28	13.391	0.29	124.84	13.367	0.29	235.53	74	13.628	0.41	75.46	13.277	N/A	284.40
30	13.382	0.29	120.38	13.382	0.29	239.52	76	13.713	0.44	73.89	13.230	N/A	286.06
32	13.349	0.29	116.41	13.395	0.29	243.40	78	13.904	N/A	72.28	13.210	N/A	287.62
34	13.343	0.29	113.23	13.418	0.29	246.79	80	14.046	N/A	70.66	13.223	N/A	289.25
36	13.376	0.29	110.30	13.307	0.29	249.57	82	14.069	N/A	68.98	12.909	N/A	290.90
38	13.353	0.29	107.62	13.378	0.29	252.26	84	14.204	N/A	67.52	13.014	N/A	292.60
40	13.338	0.29	104.85	N/A	N/A	N/A	86	N/A	N/A	N/A	N/A	N/A	N/A
42	13.333	0.29	102.85	13.382	0.30	257.12	88	N/A	N/A	N/A	N/A	N/A	N/A
44	13.380	0.29	100.56	13.343	0.30	259.18	90	N/A	N/A	N/A	N/A	N/A	N/A

N/A - Not Available

Figure 3. Type-B Standard Uncertainty vs Zenith Angle

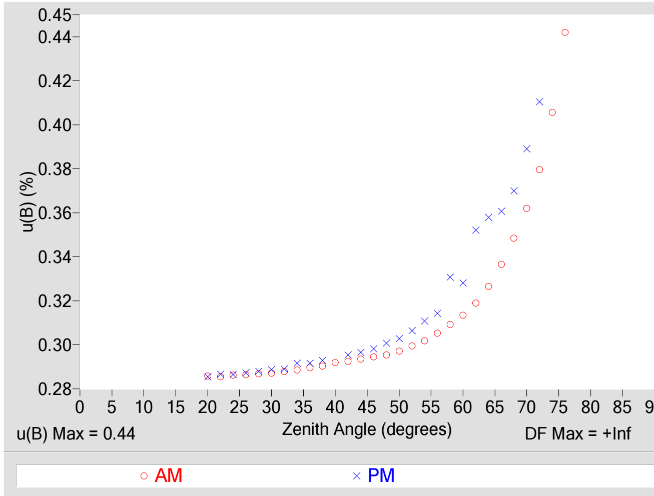


Figure 4. Residuals from Spline Interpolation

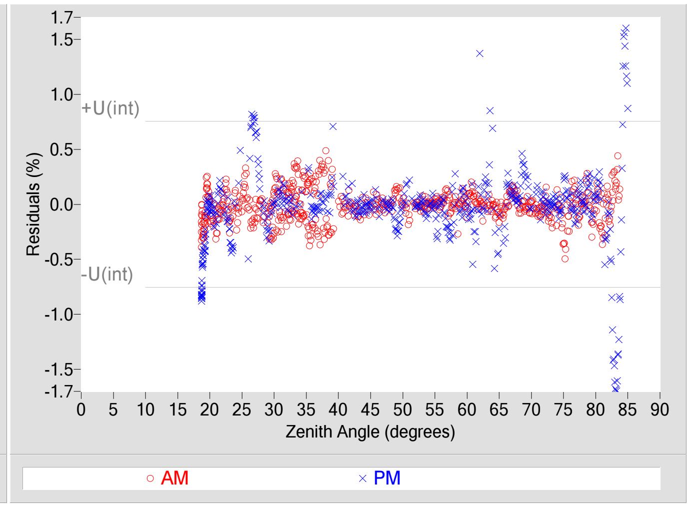


Table 3. Uncertainty using Spline Interpolation

Type-B Standard Uncertainty, u(B) (%)	±0.44
Type-A Interpolating Function, u(int) (%)	±0.38
Combined Standard Uncertainty, u(c) (%)	±0.58
Effective degrees of freedom, DF(c)	5840
Coverage factor, k	1.96
Expanded Uncertainty, U95 (%)	±1.1
AM Valid zenith angle range	20° to 76°
PM Valid zenith angle range	20° to 72°

Table 4. Calibration Label Values

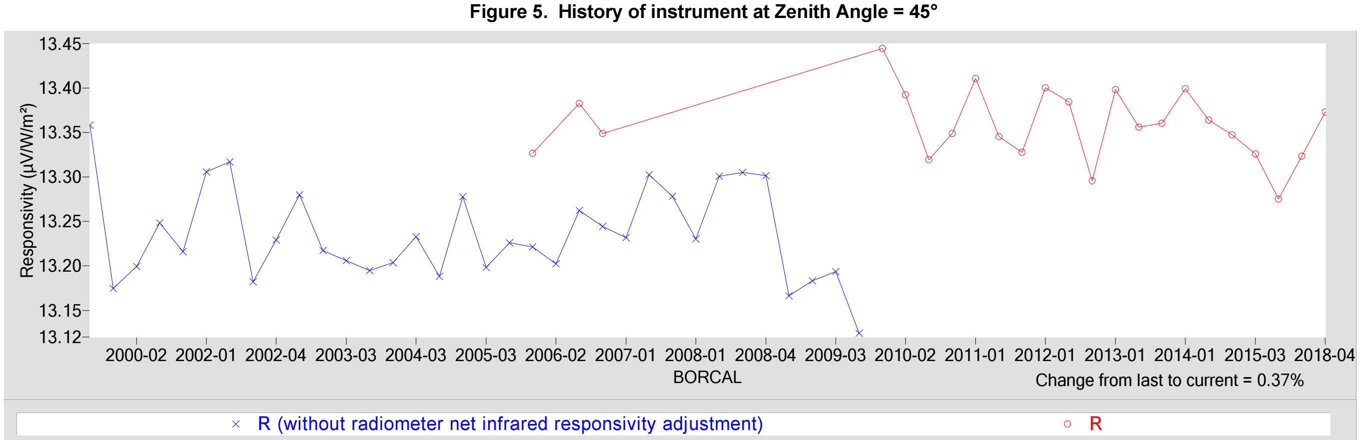
R @ 45° (μV/W/m²)	Rnet (μV/W/m²) †
13.373	0.57000

† Rnet determination date: 03/03/2006

Table 5. Uncertainty using R @ 45°

Type-B Expanded Uncertainty, U(B) (%)	±0.65
Offset Uncertainty, U(off) (%)	+0.79 / -0.50
Expanded Uncertainty, U (%)	+1.4 / -1.1
Effective degrees of freedom, DF	+Inf
Coverage factor, k	1.96
Valid zenith angle range	30.0° to 60.0°

Figure 5. History of instrument at Zenith Angle = 45°



References:

[1] Reda, I.; Hickey, J.; Long, C.; Myers, D.; Stoffel, T.; Wilcox, S.; Michalsky, J. J.; Dutton, E. G.; Nelson, D. (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; NREL Report No. JA-560-36646. doi:10.1175/JTECH1782.1

[2] 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-581-4137

[3] Reda, I.; Andreas, A. (2004). "Solar Position Algorithm for Solar Radiation Applications." Solar Energy. Vol. 76(5), 2004; pp. 577-589; NREL Report No. JA-560-35518. doi:10.1016/j.solener.2003.12.003

[4] Stoffel, T.; Reda, I. (2009). "NREL Pyrheliometer Comparisons: 22 September - 3 October 2008 (NPC-2008)." 54 pp.; NREL Report No. TP-550-45016.

[5] Reda, I.; Stoffel, T.; Myers, D. (2003). "Method to Calibrate a Solar Pyranometer for Measuring Reference Diffuse Irradiance." Solar Energy. Vol. 74, 2003; pp. 103-112; NREL Report No. JA-560-35025. doi:10.1016/S0038-092X(03)00124-5

[6] Reda, I. (1996). Calibration of a Solar Absolute Cavity Radiometer with Traceability to the World Radiometric Reference. 79 pp.; NREL Report No. TP-463-20619.

[7] Reda, I.; Gröbner, J.; Stoffel, T.; Myers, D.; Forgan, B. (2008). Improvements in the Blackbody Calibration of Pyrgeometers. ARM 2008 Science Team Meeting (Poster).

National Renewable Energy Laboratory

Solar Radiation Research Laboratory

Metrology Laboratory

Calibration Certificate

Calibration CERT #1239.02

Test Instrument:	Campbell Scientific's Licor LI200	**Manufacturer:**	Licor
Model:	LI200X	**Serial Number:**	PY89785
Calibration Date:	5/26/2018	**Due Date:**	5/26/2019
Customer:	Mike Dooraghi	**Environmental Conditions:**	see page 4
Test Dates:	5/25-26		

This certifies that the above product was calibrated in compliance with ISO/IEC 17025:2005. Measurement uncertainties at the time of calibration are consistent with the Guide to the Expression of Uncertainty in Measurement (GUM) using Reda et al., 2008. All nominal values are traceable to the International System (SI) Units of Measurement.

No statement of compliance with specifications is made or implied on this certificate. However, the estimated uncertainties are the uncertainties of the calibration process; users must add other uncertainties that are relevant to their measuring system, environmental and sky conditions, outdoor set-up, and site location.

The Type-B Standard Uncertainty of using the responsivity at each even zenith angle is reported, and the Expanded Uncertainty of the calibration is reported using two methods:

1. The Expanded Uncertainty of using the responsivity at zenith angle = 45°, within the zenith angle range from 30.0° to 60.0°
2. The Expanded Uncertainty of using Spline Interpolating Functions for the responsivity versus zenith angle.

This certificate applies only to the item identified above and shall not be reproduced other that in full, without specific written approval from the calibration facility. Certificate without signature is not valid.

Table 1. Traceability

Measurement Type	Instrument	Calibration Date	Calibration Due Date
Beam Irradiance †	Eppley Absolute Cavity Radiometer Model HF, S/N 29219	09/25/2017	09/25/2018
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/11/2018	04/11/2019
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/18/2018	04/18/2019
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	04/12/2017	04/12/2019
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	04/12/2017	04/12/2019

† Through the World Radiometric Reference (WRR)

Number of pages of certificate: 4

Calibration Procedure: BORCAL-P00-Calibration and QA Procedure; available upon request.

Setup: Radiometers are calibrated outdoors, using the sun as the source. Pyranometers and pyrgeometers are installed for horizontal measurements, with their signal connectors oriented north, if their design permits.
The shading disk for the reference diffuse subtends a solid angle of 5°. Pyrheliometers are installed on solar trackers.

Calibrated by: Afshin Andreas, Mark Kutchenreiter, and RCC

______________________________ ________________

Ibrahim Reda, Technical Manager Date

For questions or comments, please contact the technical manager at:
ibrahim.reda@nrel.gov; 303-384-6385; 15013 Denver West Parkway, Golden, CO 80401, USA

Calibration Results

PY89785 Licor LI200X

The responsivity (R, µV/W/m²) of the test instrument during calibration is calculated using this Measurement Equation:

$R = (V - Rnet * Wnet) / I$ [1]

where,

- V = radiometer output voltage (microvolts),
- $Rnet$ = radiometer net infrared responsivity (µV/W/m²), see Table 4,
- $Wnet$ = effective net infrared measured by pyrgeometer (W/m²),
  - = $Win - Wout$ = $Win - \sigma * Tc^4$
  - where, Win = incoming infrared (W/m²), σ = 5.6704e-8 W·m-2·K-4,
  - Tc = case temperature of pyrgeometer (K).
- I = reference irradiance (W/m²), beam (B) or global (G)
  - where, $G = B * COS(Z) + D$,
  - Z = zenith angle (degrees),
  - D = reference diffuse irradiance (W/m²).

Figure 1. Responsivity vs Zenith Angle

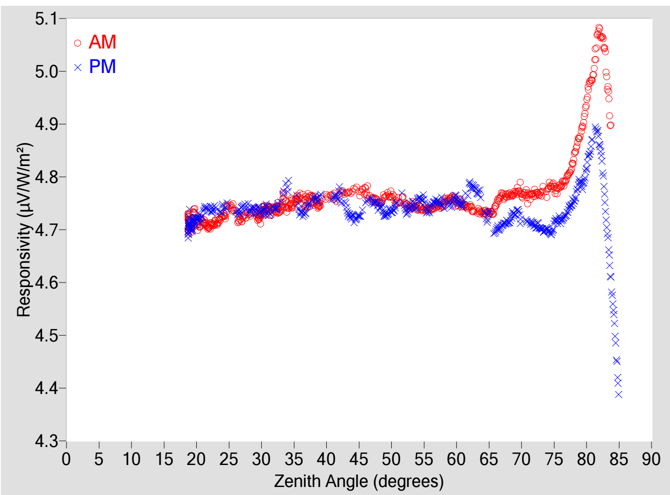


Figure 2. Responsivity vs Local Standard Time

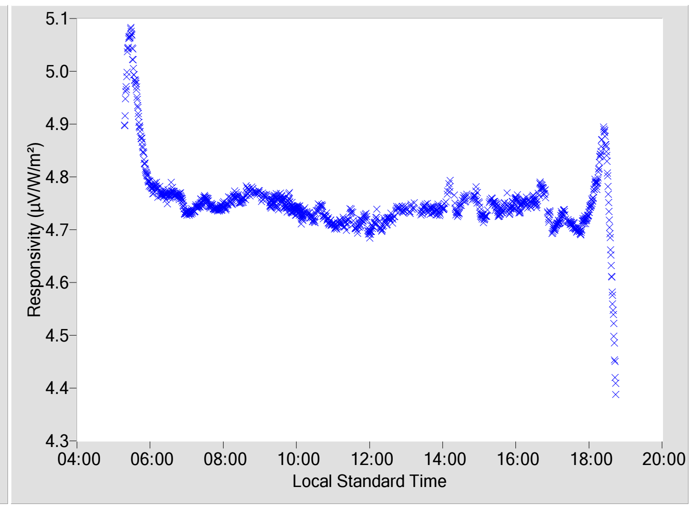


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)

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	4.7742	0.29	98.53	4.7541	0.30	261.36
2	N/A	N/A	N/A	N/A	N/A	N/A	48	4.7527	0.29	96.64	4.7459	0.30	263.10
4	N/A	N/A	N/A	N/A	N/A	N/A	50	4.7651	0.30	94.82	4.7358	0.30	264.99
6	N/A	N/A	N/A	N/A	N/A	N/A	52	4.7515	0.30	92.98	4.7405	0.30	266.87
8	N/A	N/A	N/A	N/A	N/A	N/A	54	4.7423	0.30	91.28	4.7548	0.31	268.59
10	N/A	N/A	N/A	N/A	N/A	N/A	56	4.7392	0.30	89.64	4.7425	0.31	270.18
12	N/A	N/A	N/A	N/A	N/A	N/A	58	4.7487	0.31	88.04	4.7503	0.33	271.79
14	N/A	N/A	N/A	N/A	N/A	N/A	60	4.7519	0.31	86.43	4.7570	0.32	273.45
16	N/A	N/A	N/A	N/A	N/A	N/A	62	4.7442	0.32	84.84	4.7810	0.35	275.07
18	N/A	N/A	N/A	N/A	N/A	N/A	64	4.7326	0.32	83.27	4.7341	0.35	276.84
20	4.7169	0.28	156.68	4.7207	0.28	203.25	66	4.7425	0.33	81.72	4.6977	0.36	278.17
22	4.7063	0.28	144.15	4.7381	0.28	216.04	68	4.7651	0.34	80.14	4.7150	0.37	279.72
24	4.7260	0.29	135.98	4.7395	0.28	223.73	70	4.7649	0.36	78.54	4.7156	0.38	281.14
26	4.7344	0.29	129.69	4.7334	0.29	230.49	72	4.7677	0.38	77.06	4.7076	0.40	282.85
28	4.7312	0.29	124.77	4.7384	0.29	235.57	74	4.7759	0.41	75.43	4.6996	N/A	284.41
30	4.7293	0.29	120.22	4.7335	0.29	239.74	76	4.7827	0.44	73.90	4.7194	N/A	285.98
32	4.7387	0.29	116.58	4.7404	0.29	243.38	78	4.8333	N/A	72.29	4.7538	N/A	287.59
34	4.7428	0.29	113.27	4.7833	0.29	246.56	80	4.9422	N/A	70.67	4.8176	N/A	289.22
36	4.7619	0.29	110.41	4.7332	0.29	249.58	82	5.0719	N/A	68.99	4.8618	N/A	290.91
38	4.7569	0.29	107.66	4.7606	0.29	252.27	84	4.8984	N/A	67.49	4.5624	N/A	292.65
40	4.7622	0.29	104.97	N/A	N/A	N/A	86	N/A	N/A	N/A	N/A	N/A	N/A
42	4.7700	0.29	102.64	4.7649	0.29	257.00	88	N/A	N/A	N/A	N/A	N/A	N/A
44	4.7728	0.29	100.62	4.7234	0.29	259.14	90	N/A	N/A	N/A	N/A	N/A	N/A

N/A - Not Available

Figure 3. Type-B Standard Uncertainty vs Zenith Angle

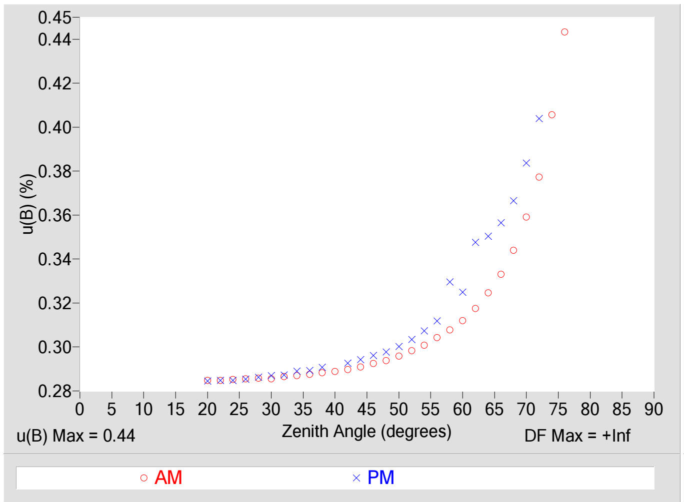


Figure 4. Residuals from Spline Interpolation

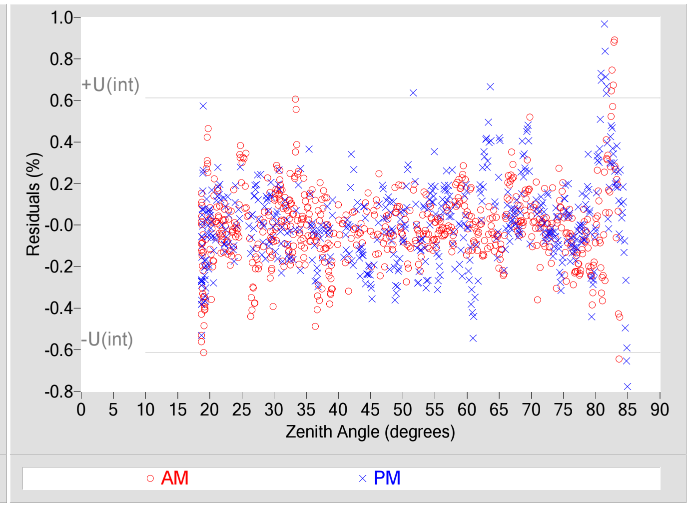


Table 3. Uncertainty using Spline Interpolation

Type-B Standard Uncertainty, u(B) (%)	±0.44
Type-A Interpolating Function, u(int) (%)	±0.31
Combined Standard Uncertainty, u(c) (%)	±0.54
Effective degrees of freedom, DF(c)	9787
Coverage factor, k	1.96
Expanded Uncertainty, U95 (%)	±1.1
AM Valid zenith angle range	20° to 76°
PM Valid zenith angle range	20° to 72°

Table 4. Calibration Label Values

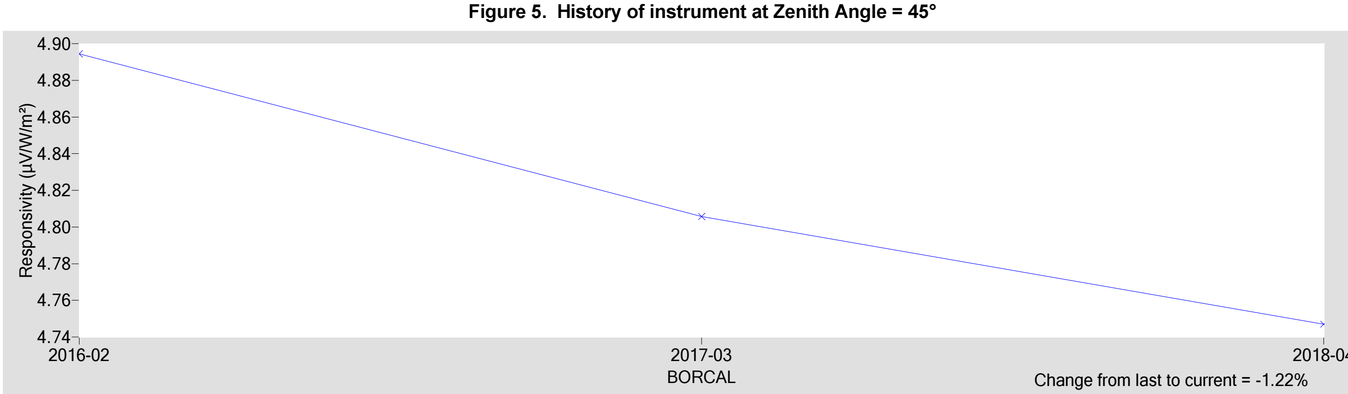
R @ 45° (μV/W/m²)	Rnet (μV/W/m²) †
4.7469	0

† Rnet determination date: N/A

Table 5. Uncertainty using R @ 45°

Type-B Expanded Uncertainty, U(B) (%)	±0.65
Offset Uncertainty, U(off) (%)	+0.77 / -0.49
Expanded Uncertainty, U (%)	+1.4 / -1.1
Effective degrees of freedom, DF	+Inf
Coverage factor, k	1.96
Valid zenith angle range	30.0° to 60.0°

Figure 5. History of instrument at Zenith Angle = 45°



References:

[1] Reda, I.; Hickey, J.; Long, C.; Myers, D.; Stoffel, T.; Wilcox, S.; Michalsky, J. J.; Dutton, E. G.; Nelson, D. (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; NREL Report No. JA-560-36646. doi:10.1175/JTECH1782.1

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[3] Reda, I.; Andreas, A. (2004). "Solar Position Algorithm for Solar Radiation Applications." Solar Energy. Vol. 76(5), 2004; pp. 577-589; NREL Report No. JA-560-35518. doi:10.1016/j.solener.2003.12.003

[4] Stoffel, T.; Reda, I. (2009). "NREL Pyrheliometer Comparisons: 22 September - 3 October 2008 (NPC-2008)." 54 pp.; NREL Report No. TP-550-45016.

[5] Reda, I.; Stoffel, T.; Myers, D. (2003). "Method to Calibrate a Solar Pyranometer for Measuring Reference Diffuse Irradiance." Solar Energy. Vol. 74, 2003; pp. 103-112; NREL Report No. JA-560-35025. doi:10.1016/S0038-092X(03)00124-5

[6] Reda, I. (1996). Calibration of a Solar Absolute Cavity Radiometer with Traceability to the World Radiometric Reference. 79 pp.; NREL Report No. TP-463-20619.

[7] Reda, I.; Gröbner, J.; Stoffel, T.; Myers, D.; Forgan, B. (2008). Improvements in the Blackbody Calibration of Pyrgeometers. ARM 2008 Science Team Meeting (Poster).

National Renewable Energy Laboratory

Solar Radiation Research Laboratory

Metrology Laboratory

Calibration Certificate

Calibration CERT #1239.02

Test Instrument:	Campbell Scientific's Licor LI200	**Manufacturer:**	Licor
Model:	LI200X	**Serial Number:**	PY89872
Calibration Date:	5/26/2018	**Due Date:**	5/26/2019
Customer:	Mike Dooraghi	**Environmental Conditions:**	see page 4
Test Dates:	5/25-26		

This certifies that the above product was calibrated in compliance with ISO/IEC 17025:2005. Measurement uncertainties at the time of calibration are consistent with the Guide to the Expression of Uncertainty in Measurement (GUM) using Reda et al., 2008. All nominal values are traceable to the International System (SI) Units of Measurement.

No statement of compliance with specifications is made or implied on this certificate. However, the estimated uncertainties are the uncertainties of the calibration process; users must add other uncertainties that are relevant to their measuring system, environmental and sky conditions, outdoor set-up, and site location.

The Type-B Standard Uncertainty of using the responsivity at each even zenith angle is reported, and the Expanded Uncertainty of the calibration is reported using two methods:

1. The Expanded Uncertainty of using the responsivity at zenith angle = 45°, within the zenith angle range from 30.0° to 60.0°
2. The Expanded Uncertainty of using Spline Interpolating Functions for the responsivity versus zenith angle.

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Table 1. Traceability

Measurement Type	Instrument	Calibration Date	Calibration Due Date
Beam Irradiance †	Eppley Absolute Cavity Radiometer Model HF, S/N 29219	09/25/2017	09/25/2018
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/11/2018	04/11/2019
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/18/2018	04/18/2019
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	04/12/2017	04/12/2019
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	04/12/2017	04/12/2019

† Through the World Radiometric Reference (WRR)

Number of pages of certificate: 4

Calibration Procedure: BORCAL-P00-Calibration and QA Procedure; available upon request.

Setup: Radiometers are calibrated outdoors, using the sun as the source. Pyranometers and pyrgeometers are installed for horizontal measurements, with their signal connectors oriented north, if their design permits.
The shading disk for the reference diffuse subtends a solid angle of 5°. Pyrheliometers are installed on solar trackers.

Calibrated by: Afshin Andreas, Mark Kutchenreiter, and RCC

______________________________ ____________

Ibrahim Reda, Technical Manager Date

For questions or comments, please contact the technical manager at:

ibrahim.reda@nrel.gov; 303-384-6385; 15013 Denver West Parkway, Golden, CO 80401, USA

Calibration Results

PY89872 Licor LI200X

The responsivity (R, μV/W/m²) of the test instrument during calibration is calculated using this Measurement Equation:

$$R = (V - Rnet * Wnet) / I \quad [1]$$

where,

- V = radiometer output voltage (microvolts),
- $Rnet$ = radiometer net infrared responsivity (μV/W/m²), see Table 4,
- $Wnet$ = effective net infrared measured by pyrgeometer (W/m²),
  = $Win - Wout$ = $Win - \sigma * Tc^4$
  - where, Win = incoming infrared (W/m²), σ = 5.6704e-8 W·m-2·K-4,
  - Tc = case temperature of pyrgeometer (K).
- I = reference irradiance (W/m²), beam (B) or global (G)
  - where, $G = B * COS(Z) + D$,
  - Z = zenith angle (degrees),
  - D = reference diffuse irradiance (W/m²).

Figure 1. Responsivity vs Zenith Angle

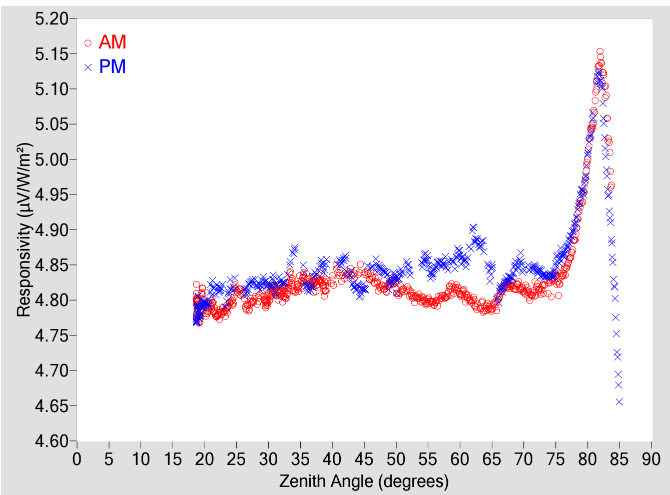


Figure 2. Responsivity vs Local Standard Time

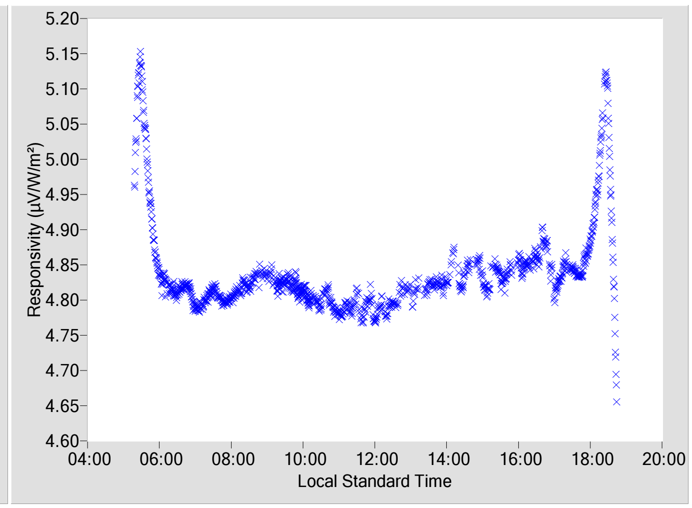


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)

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	4.8322	0.29	98.53	4.8472	0.30	261.36
2	N/A	N/A	N/A	N/A	N/A	N/A	48	4.8183	0.29	96.64	4.8415	0.30	263.10
4	N/A	N/A	N/A	N/A	N/A	N/A	50	4.8185	0.30	94.82	4.8281	0.30	264.99
6	N/A	N/A	N/A	N/A	N/A	N/A	52	4.8124	0.30	92.98	4.8441	0.30	266.78
8	N/A	N/A	N/A	N/A	N/A	N/A	54	4.8012	0.30	91.28	4.8520	0.31	268.64
10	N/A	N/A	N/A	N/A	N/A	N/A	56	4.7961	0.30	89.64	4.8421	0.31	270.18
12	N/A	N/A	N/A	N/A	N/A	N/A	58	4.8062	0.31	88.04	4.8512	0.33	271.79
14	N/A	N/A	N/A	N/A	N/A	N/A	60	4.8100	0.31	86.43	4.8627	0.32	273.45
16	N/A	N/A	N/A	N/A	N/A	N/A	62	4.8002	0.32	84.84	4.8908	0.35	275.07
18	N/A	N/A	N/A	N/A	N/A	N/A	64	4.7877	0.32	83.27	4.8516	0.35	276.84
20	4.7907	0.28	156.68	4.7947	0.28	203.25	66	4.7996	0.33	81.72	4.8063	0.36	278.17
22	4.7783	0.28	144.15	4.8148	0.28	216.04	68	4.8209	0.34	80.14	4.8326	0.37	279.72
24	4.7965	0.29	135.98	4.8162	0.28	223.73	70	4.8140	0.36	78.58	4.8415	0.38	281.14
26	4.8072	0.29	129.69	4.8064	0.29	230.49	72	4.8177	0.38	77.06	4.8415	0.40	282.85
28	4.8004	0.29	124.77	4.8229	0.29	235.57	74	4.8197	0.41	75.43	4.8352	N/A	284.41
30	4.8012	0.29	120.22	4.8213	0.29	239.74	76	4.8354	0.44	73.90	4.8642	N/A	285.98
32	4.8098	0.29	116.58	4.8249	0.29	243.38	78	4.8894	N/A	72.29	4.9079	N/A	287.59
34	4.8161	0.29	113.47	4.8700	0.29	246.56	80	5.0026	N/A	70.67	5.0030	N/A	289.22
36	4.8338	0.29	110.51	4.8195	0.29	249.58	82	5.1352	N/A	68.99	5.1116	N/A	290.91
38	4.8283	0.29	107.66	4.8491	0.29	252.27	84	4.9632	N/A	67.49	4.8379	N/A	292.65
40	4.8270	0.29	104.97	N/A	N/A	N/A	86	N/A	N/A	N/A	N/A	N/A	N/A
42	4.8333	0.29	102.64	4.8515	0.29	257.00	88	N/A	N/A	N/A	N/A	N/A	N/A
44	4.8390	0.29	100.62	4.8168	0.29	259.14	90	N/A	N/A	N/A	N/A	N/A	N/A

N/A - Not Available

Figure 3. Type-B Standard Uncertainty vs Zenith Angle

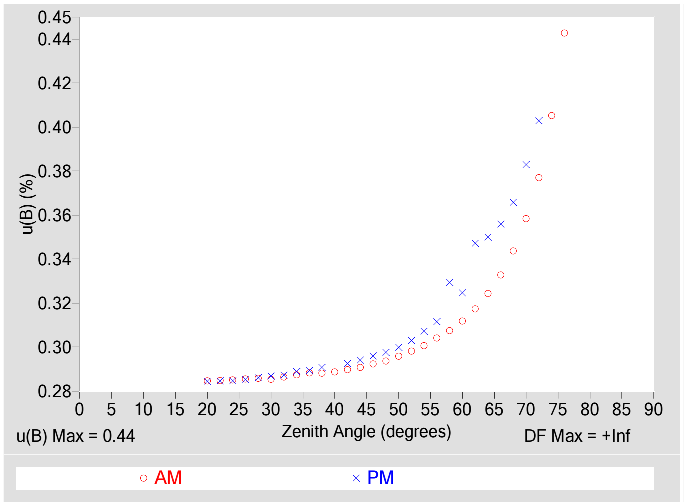


Figure 4. Residuals from Spline Interpolation

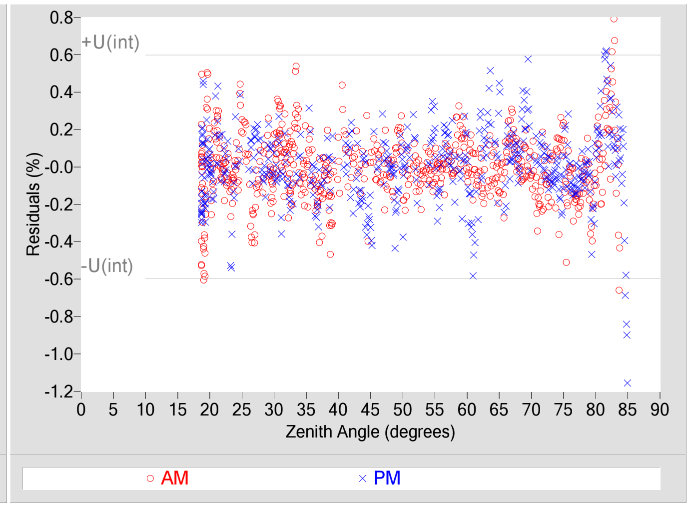


Table 3. Uncertainty using Spline Interpolation

Type-B Standard Uncertainty, u(B) (%)	±0.44
Type-A Interpolating Function, u(int) (%)	±0.30
Combined Standard Uncertainty, u(c) (%)	±0.53
Effective degrees of freedom, DF(c)	10182
Coverage factor, k	1.96
Expanded Uncertainty, U95 (%)	±1.0
AM Valid zenith angle range	20° to 76°
PM Valid zenith angle range	20° to 72°

Table 4. Calibration Label Values

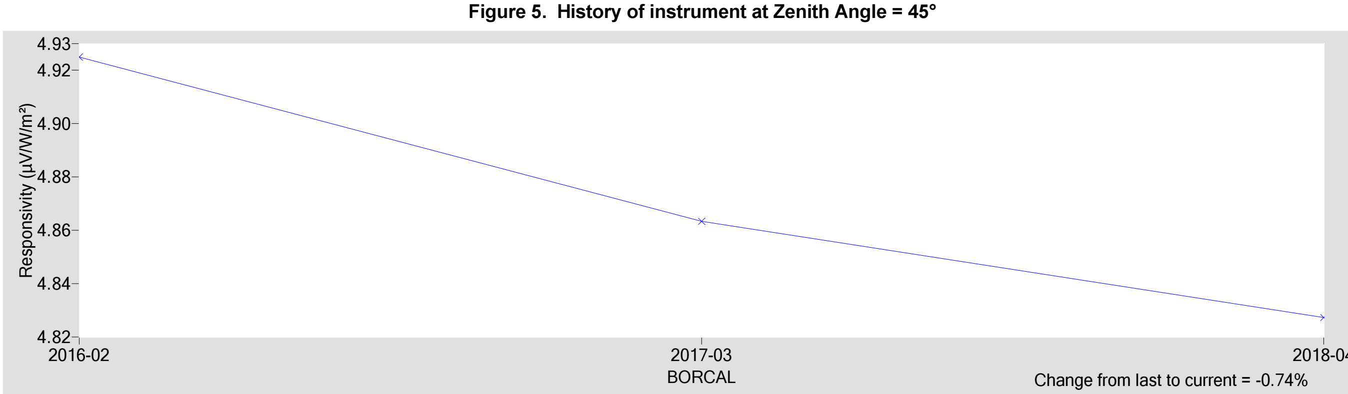
R @ 45° (µV/W/m²)	Rnet (µV/W/m²) †
4.8273	0

† Rnet determination date: N/A

Table 5. Uncertainty using R @ 45°

Type-B Expanded Uncertainty, U(B) (%)	±0.65
Offset Uncertainty, U(off) (%)	+0.89 / -0.65
Expanded Uncertainty, U (%)	+1.5 / -1.3
Effective degrees of freedom, DF	+Inf
Coverage factor, k	1.96
Valid zenith angle range	30.0° to 60.0°

Figure 5. History of instrument at Zenith Angle = 45°



References:

[1] Reda, I.; Hickey, J.; Long, C.; Myers, D.; Stoffel, T.; Wilcox, S.; Michalsky, J. J.; Dutton, E. G.; Nelson, D. (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; NREL Report No. JA-560-36646. doi:10.1175/JTECH1782.1

[2] 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-581-4137

[3] Reda, I.; Andreas, A. (2004). "Solar Position Algorithm for Solar Radiation Applications." Solar Energy. Vol. 76(5), 2004; pp. 577-589; NREL Report No. JA-560-35518. doi:10.1016/j.solener.2003.12.003

[4] Stoffel, T.; Reda, I. (2009). "NREL Pyrheliometer Comparisons: 22 September - 3 October 2008 (NPC-2008)." 54 pp.; NREL Report No. TP-550-45016.

[5] Reda, I.; Stoffel, T.; Myers, D. (2003). "Method to Calibrate a Solar Pyranometer for Measuring Reference Diffuse Irradiance." Solar Energy. Vol. 74, 2003; pp. 103-112; NREL Report No. JA-560-35025. doi:10.1016/S0038-092X(03)00124-5

[6] Reda, I. (1996). Calibration of a Solar Absolute Cavity Radiometer with Traceability to the World Radiometric Reference. 79 pp.; NREL Report No. TP-463-20619.

[7] Reda, I.; Gröbner, J.; Stoffel, T.; Myers, D.; Forgan, B. (2008). Improvements in the Blackbody Calibration of Pyrgeometers. ARM 2008 Science Team Meeting (Poster).

National Renewable Energy Laboratory

Solar Radiation Research Laboratory

Metrology Laboratory

Calibration Certificate

Calibration CERT #1239.02

Test Instrument:	Silicon Pyranometer	**Manufacturer:**	EKO
Model:	ML-01	**Serial Number:**	S13135061
Calibration Date:	5/26/2018	**Due Date:**	5/26/2019
Customer:	Mike Dooraghi	**Environmental Conditions:**	see page 4
Test Dates:	5/25-26		

This certifies that the above product was calibrated in compliance with ISO/IEC 17025:2005. Measurement uncertainties at the time of calibration are consistent with the Guide to the Expression of Uncertainty in Measurement (GUM) using Reda et al., 2008. All nominal values are traceable to the International System (SI) Units of Measurement.

No statement of compliance with specifications is made or implied on this certificate. However, the estimated uncertainties are the uncertainties of the calibration process; users must add other uncertainties that are relevant to their measuring system, environmental and sky conditions, outdoor set-up, and site location.

The Type-B Standard Uncertainty of using the responsivity at each even zenith angle is reported, and the Expanded Uncertainty of the calibration is reported using two methods:

1. The Expanded Uncertainty of using the responsivity at zenith angle = 45°, within the zenith angle range from 30.0° to 60.0°
2. The Expanded Uncertainty of using Spline Interpolating Functions for the responsivity versus zenith angle.

This certificate applies only to the item identified above and shall not be reproduced other that in full, without specific written approval from the calibration facility. Certificate without signature is not valid.

Table 1. Traceability

Measurement Type	Instrument	Calibration Date	Calibration Due Date
Beam Irradiance †	Eppley Absolute Cavity Radiometer Model HF, S/N 29219	09/25/2017	09/25/2018
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/11/2018	04/11/2019
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/18/2018	04/18/2019
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	04/12/2017	04/12/2019
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	04/12/2017	04/12/2019

† Through the World Radiometric Reference (WRR)

Number of pages of certificate: 4

Calibration Procedure: BORCAL-P00-Calibration and QA Procedure; available upon request.

Setup: Radiometers are calibrated outdoors, using the sun as the source. Pyranometers and pyrgeometers are installed for horizontal measurements, with their signal connectors oriented north, if their design permits.
The shading disk for the reference diffuse subtends a solid angle of 5°. Pyrheliometers are installed on solar trackers.

Calibrated by: Afshin Andreas, Mark Kutchenreiter, and RCC

____ ________________

Ibrahim Reda, Technical Manager Date

For questions or comments, please contact the technical manager at:
ibrahim.reda@nrel.gov; 303-384-6385; 15013 Denver West Parkway, Golden, CO 80401, USA

Calibration Results

S13135061 EKO ML-01

The responsivity (R, µV/W/m²) of the test instrument during calibration is calculated using this Measurement Equation:

$R = (V - Rnet * Wnet) / I$ [1]

where,

- V = radiometer output voltage (microvolts),
- $Rnet$ = radiometer net infrared responsivity (µV/W/m²), see Table 4,
- $Wnet$ = effective net infrared measured by pyrgeometer (W/m²),
  - = $Win - Wout$ = $Win - \sigma * Tc^4$
  - where, Win = incoming infrared (W/m²), σ = 5.6704e-8 W·m-2·K-4,
  - Tc = case temperature of pyrgeometer (K).
- I = reference irradiance (W/m²), beam (B) or global (G)
  - where, $G = B * COS(Z) + D$,
  - Z = zenith angle (degrees),
  - D = reference diffuse irradiance (W/m²).

Figure 1. Responsivity vs Zenith Angle

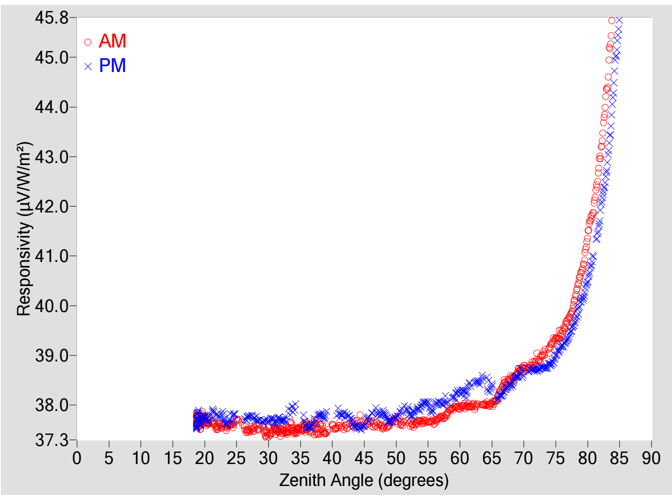


Figure 2. Responsivity vs Local Standard Time

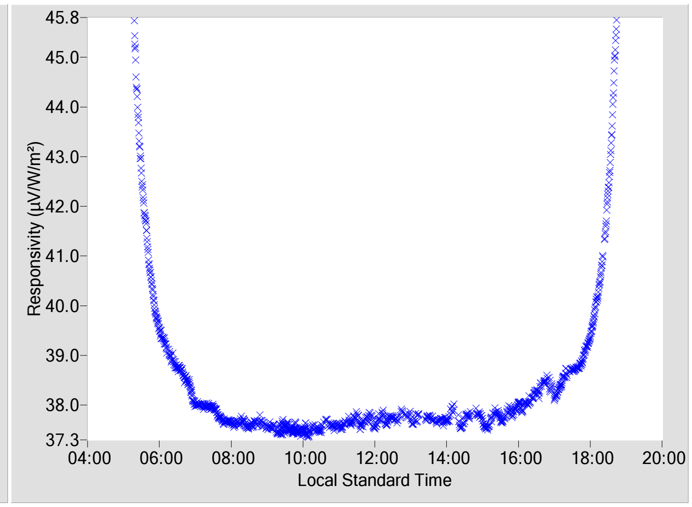


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)

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	37.649	0.29	98.51	37.814	0.29	261.28
2	N/A	N/A	N/A	N/A	N/A	N/A	48	37.555	0.29	96.69	37.828	0.29	263.18
4	N/A	N/A	N/A	N/A	N/A	N/A	50	37.701	0.29	94.80	37.763	0.30	265.01
6	N/A	N/A	N/A	N/A	N/A	N/A	52	37.644	0.29	92.99	37.853	0.30	266.80
8	N/A	N/A	N/A	N/A	N/A	N/A	54	37.667	0.30	91.35	38.007	0.30	268.53
10	N/A	N/A	N/A	N/A	N/A	N/A	56	37.672	0.30	89.67	37.989	0.31	270.26
12	N/A	N/A	N/A	N/A	N/A	N/A	58	37.836	0.30	88.02	38.054	0.32	271.82
14	N/A	N/A	N/A	N/A	N/A	N/A	60	37.952	0.30	86.41	38.263	0.32	273.55
16	N/A	N/A	N/A	N/A	N/A	N/A	62	37.992	0.31	84.83	38.448	0.33	275.26
18	N/A	N/A	N/A	N/A	N/A	N/A	64	38.017	0.31	83.25	38.440	0.34	276.79
20	37.708	0.28	156.57	37.737	0.28	202.80	66	38.190	0.32	81.70	38.155	0.34	278.20
22	37.555	0.28	144.42	37.792	0.28	215.91	68	38.534	0.33	80.17	38.406	0.35	279.74
24	37.602	0.28	136.14	37.727	0.28	224.26	70	38.753	0.34	78.60	38.578	0.37	281.12
26	37.612	0.28	129.79	37.725	0.28	231.08	72	38.905	0.36	77.06	38.715	0.38	282.83
28	37.553	0.28	124.82	37.716	0.28	235.45	74	39.141	0.38	75.45	38.827	N/A	284.43
30	37.432	0.28	120.24	37.684	0.28	239.69	76	39.474	0.41	73.89	39.194	N/A	286.00
32	37.471	0.28	116.53	37.682	0.28	243.37	78	40.158	N/A	72.27	39.692	N/A	287.61
34	37.476	0.28	113.29	37.939	0.29	246.56	80	41.417	N/A	70.65	40.528	N/A	289.24
36	37.552	0.28	110.28	37.557	0.29	249.57	82	43.059	N/A	68.97	41.884	N/A	290.89
38	37.502	0.29	107.62	37.803	0.29	252.22	84	45.737	N/A	67.48	44.360	N/A	292.63
40	37.582	0.29	104.95	N/A	N/A	N/A	86	N/A	N/A	N/A	N/A	N/A	N/A
42	37.564	0.29	102.72	37.814	0.29	256.95	88	N/A	N/A	N/A	N/A	N/A	N/A
44	37.627	0.29	100.82	37.558	0.29	259.17	90	N/A	N/A	N/A	N/A	N/A	N/A

N/A - Not Available

Figure 3. Type-B Standard Uncertainty vs Zenith Angle

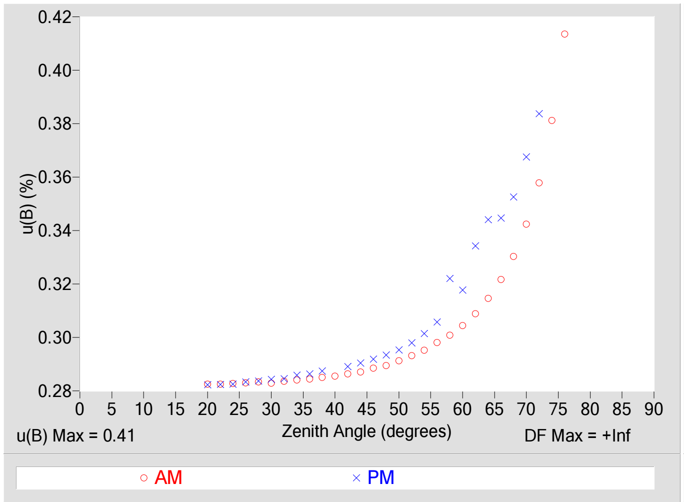


Figure 4. Residuals from Spline Interpolation

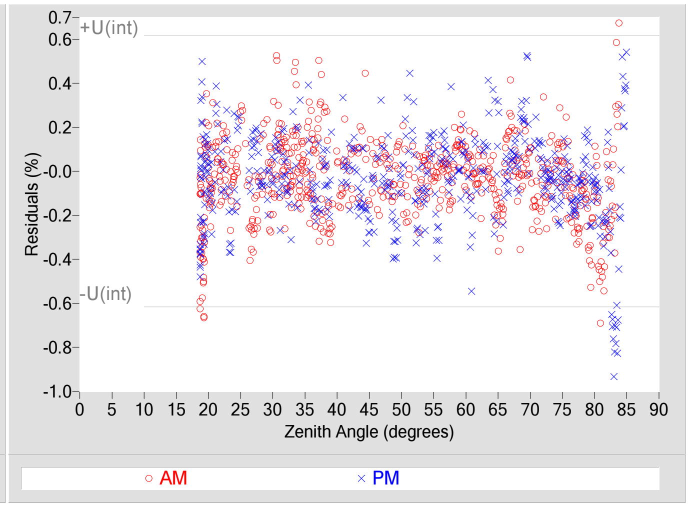


Table 3. Uncertainty using Spline Interpolation

Type-B Standard Uncertainty, u(B) (%)	±0.41
Type-A Interpolating Function, u(int) (%)	±0.31
Combined Standard Uncertainty, u(c) (%)	±0.52
Effective degrees of freedom, DF(c)	7877
Coverage factor, k	1.96
Expanded Uncertainty, U95 (%)	±1.0
AM Valid zenith angle range	20° to 76°
PM Valid zenith angle range	20° to 72°

Table 4. Calibration Label Values

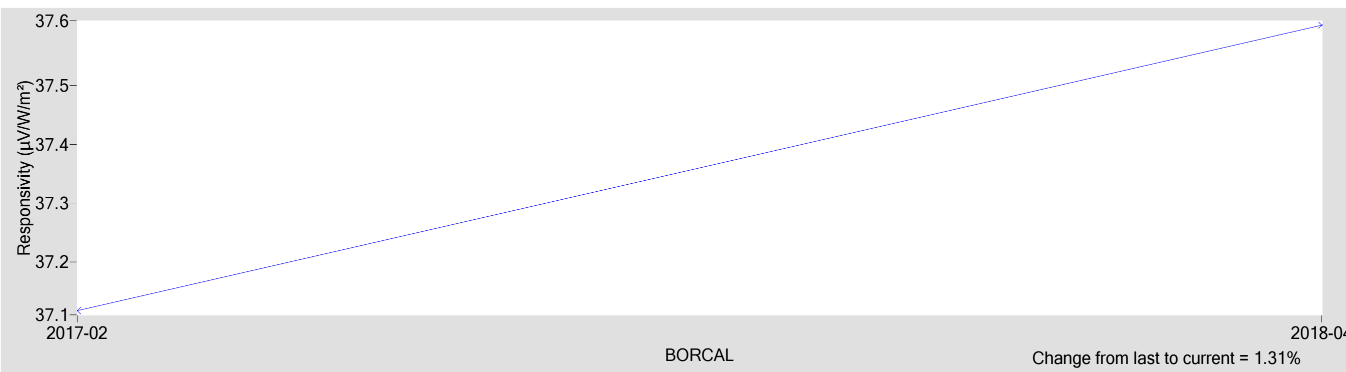
R @ 45° (µV/W/m²)	Rnet (µV/W/m²) †
37.603	0

† Rnet determination date: N/A

Table 5. Uncertainty using R @ 45°

Type-B Expanded Uncertainty, U(B) (%)	±0.63
Offset Uncertainty, U(off) (%)	+1.8 / -0.45
Expanded Uncertainty, U (%)	+2.4 / -1.1
Effective degrees of freedom, DF	+Inf
Coverage factor, k	1.96
Valid zenith angle range	30.0° to 60.0°

Figure 5. History of instrument at Zenith Angle = 45°



References:

[1] Reda, I.; Hickey, J.; Long, C.; Myers, D.; Stoffel, T.; Wilcox, S.; Michalsky, J. J.; Dutton, E. G.; Nelson, D. (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; NREL Report No. JA-560-36646. doi:10.1175/JTECH1782.1

[2] 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-581-4137

[3] Reda, I.; Andreas, A. (2004). "Solar Position Algorithm for Solar Radiation Applications." Solar Energy. Vol. 76(5), 2004; pp. 577-589; NREL Report No. JA-560-35518. doi:10.1016/j.solener.2003.12.003

[4] Stoffel, T.; Reda, I. (2009). "NREL Pyrheliometer Comparisons: 22 September - 3 October 2008 (NPC-2008)." 54 pp.; NREL Report No. TP-550-45016.

[5] Reda, I.; Stoffel, T.; Myers, D. (2003). "Method to Calibrate a Solar Pyranometer for Measuring Reference Diffuse Irradiance." Solar Energy. Vol. 74, 2003; pp. 103-112; NREL Report No. JA-560-35025. doi:10.1016/S0038-092X(03)00124-5

[6] Reda, I. (1996). Calibration of a Solar Absolute Cavity Radiometer with Traceability to the World Radiometric Reference. 79 pp.; NREL Report No. TP-463-20619.

[7] Reda, I.; Gröbner, J.; Stoffel, T.; Myers, D.; Forgan, B. (2008). Improvements in the Blackbody Calibration of Pyrgeometers. ARM 2008 Science Team Meeting (Poster).

National Renewable Energy Laboratory

Solar Radiation Research Laboratory

Metrology Laboratory

Calibration Certificate

Calibration CERT #1239.02

Test Instrument:	Pyranometer	**Manufacturer:**	EKO
Model:	MS-80	**Serial Number:**	S17096007
Calibration Date:	5/26/2018	**Due Date:**	5/26/2019
Customer:	Mike Dooraghi	**Environmental Conditions:**	see page 4
Test Dates:	5/25-26		

This certifies that the above product was calibrated in compliance with ISO/IEC 17025:2005. Measurement uncertainties at the time of calibration are consistent with the Guide to the Expression of Uncertainty in Measurement (GUM) using Reda et al., 2008. All nominal values are traceable to the International System (SI) Units of Measurement.

No statement of compliance with specifications is made or implied on this certificate. However, the estimated uncertainties are the uncertainties of the calibration process; users must add other uncertainties that are relevant to their measuring system, environmental and sky conditions, outdoor set-up, and site location.

The Type-B Standard Uncertainty of using the responsivity at each even zenith angle is reported, and the Expanded Uncertainty of the calibration is reported using two methods:

1. The Expanded Uncertainty of using the responsivity at zenith angle = 45°, within the zenith angle range from 30.0° to 60.0°
2. The Expanded Uncertainty of using Spline Interpolating Functions for the responsivity versus zenith angle.

This certificate applies only to the item identified above and shall not be reproduced other that in full, without specific written approval from the calibration facility. Certificate without signature is not valid.

Table 1. Traceability

Measurement Type	Instrument	Calibration Date	Calibration Due Date
Beam Irradiance †	Eppley Absolute Cavity Radiometer Model HF, S/N 29219	09/25/2017	09/25/2018
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/11/2018	04/11/2019
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/18/2018	04/18/2019
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	04/12/2017	04/12/2019
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	04/12/2017	04/12/2019
Infrared Irradiance ‡	Kipp & Zonen Pyrgeometer Model CG4, S/N FT002	04/16/2018	04/16/2022

† Through the World Radiometric Reference (WRR)   ‡ Through the World Infrared Standard Group (WISG)

Number of pages of certificate: 4

Calibration Procedure: BORCAL-P00-Calibration and QA Procedure; available upon request.

Setup: Radiometers are calibrated outdoors, using the sun as the source. Pyranometers and pyrgeometers are installed for horizontal measurements, with their signal connectors oriented north, if their design permits.
The shading disk for the reference diffuse subtends a solid angle of 5°. Pyrheliometers are installed on solar trackers.

Calibrated by: Afshin Andreas, Mark Kutchenreiter, and RCC

______________________________ ____________

Ibrahim Reda, Technical Manager   Date

For questions or comments, please contact the technical manager at:
ibrahim.reda@nrel.gov; 303-384-6385; 15013 Denver West Parkway, Golden, CO 80401, USA

Calibration Results

S17096007 EKO MS-80

The responsivity (R, μV/W/m²) of the test instrument during calibration is calculated using this Measurement Equation:

$$R = (V - Rnet * Wnet) / I \quad [1]$$

where,

- V = radiometer output voltage (microvolts),
- $Rnet$ = radiometer net infrared responsivity (μV/W/m²), see Table 4,
- $Wnet$ = effective net infrared measured by pyrgeometer (W/m²),
  = $Win - Wout$ = $Win - \sigma * Tc^4$
  - where, Win = incoming infrared (W/m²), σ = 5.6704e-8 W·m-2·K-4,
  - Tc = case temperature of pyrgeometer (K).
- I = reference irradiance (W/m²), beam (B) or global (G)
  - where, $G = B * COS(Z) + D$,
  - Z = zenith angle (degrees),
  - D = reference diffuse irradiance (W/m²).

Figure 1. Responsivity vs Zenith Angle

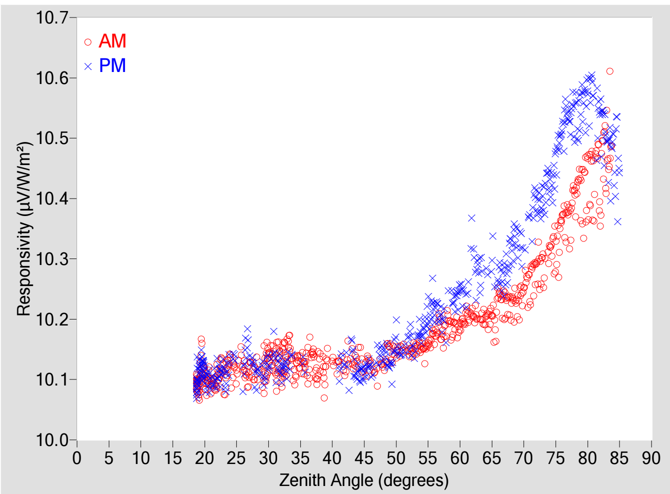


Figure 2. Responsivity vs Local Standard Time

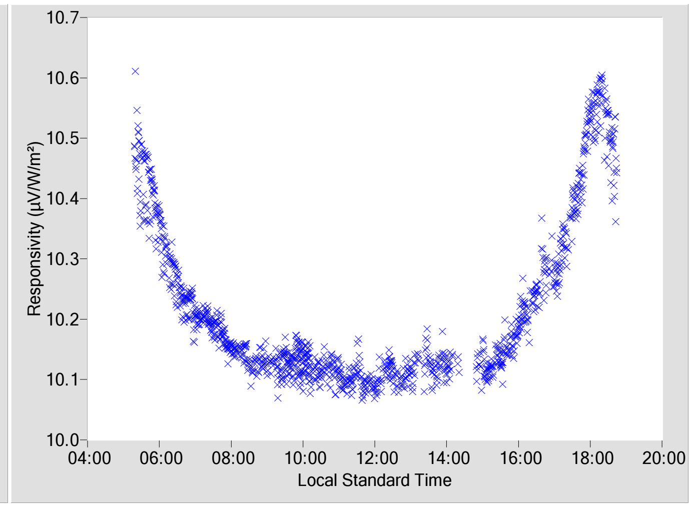


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)

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	10.125	0.29	98.70	10.121	0.29	261.16
2	N/A	N/A	N/A	N/A	N/A	N/A	48	10.122	0.29	96.68	10.143	0.29	263.09
4	N/A	N/A	N/A	N/A	N/A	N/A	50	10.146	0.29	94.76	10.163	0.30	264.96
6	N/A	N/A	N/A	N/A	N/A	N/A	52	10.147	0.29	92.99	10.172	0.30	266.79
8	N/A	N/A	N/A	N/A	N/A	N/A	54	10.152	0.30	91.29	10.174	0.30	268.48
10	N/A	N/A	N/A	N/A	N/A	N/A	56	10.174	0.30	89.61	10.222	0.31	270.17
12	N/A	N/A	N/A	N/A	N/A	N/A	58	10.196	0.30	87.95	10.204	0.32	271.81
14	N/A	N/A	N/A	N/A	N/A	N/A	60	10.188	0.31	86.36	10.247	0.32	273.43
16	N/A	N/A	N/A	N/A	N/A	N/A	62	10.205	0.31	84.78	10.326	0.34	275.01
18	N/A	N/A	N/A	N/A	N/A	N/A	64	10.203	0.32	83.28	10.284	0.35	276.70
20	10.098	0.28	156.81	10.114	0.28	202.58	66	10.237	0.32	81.69	10.272	0.35	278.19
22	10.102	0.28	144.19	10.109	0.28	215.98	68	10.223	0.33	80.12	10.320	0.36	279.70
24	10.126	0.28	136.22	10.125	0.28	223.28	70	10.251	0.35	78.61	10.317	0.37	281.27
26	10.124	0.28	129.76	10.110	0.28	230.64	72	10.288	0.36	77.03	10.391	0.39	282.86
28	10.116	0.28	124.80	10.102	0.28	235.47	74	10.314	0.39	75.44	10.426	N/A	284.38
30	10.137	0.28	120.24	10.125	0.29	239.51	76	10.368	0.42	73.92	10.509	N/A	285.99
32	10.125	0.28	116.50	10.119	0.29	243.28	78	10.407	N/A	72.30	10.540	N/A	287.61
34	10.115	0.28	113.11	N/A	N/A	N/A	80	10.415	N/A	70.64	10.570	N/A	289.23
36	10.125	0.29	110.36	10.112	0.29	249.14	82	10.423	N/A	69.00	10.537	N/A	290.92
38	10.129	0.29	107.79	N/A	N/A	N/A	84	10.488	N/A	67.51	10.476	N/A	292.62
40	10.130	0.29	104.94	N/A	N/A	N/A	86	N/A	N/A	N/A	N/A	N/A	N/A
42	10.115	0.29	102.85	10.129	0.29	257.08	88	N/A	N/A	N/A	N/A	N/A	N/A
44	10.135	0.29	100.74	10.110	0.29	259.16	90	N/A	N/A	N/A	N/A	N/A	N/A

N/A - Not Available

Figure 3. Type-B Standard Uncertainty vs Zenith Angle

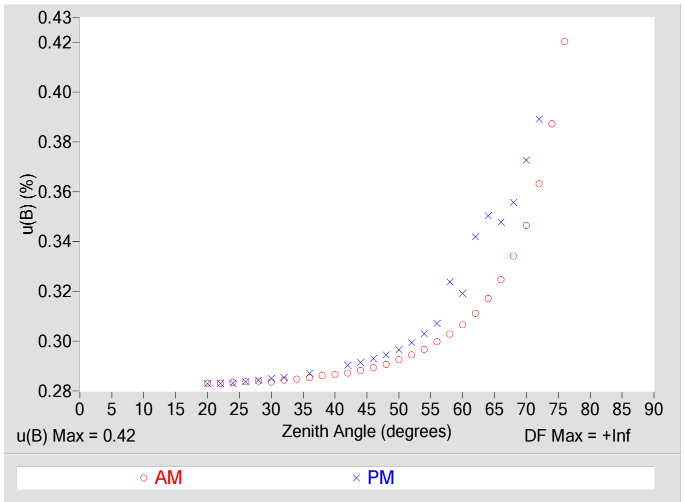


Figure 4. Residuals from Spline Interpolation

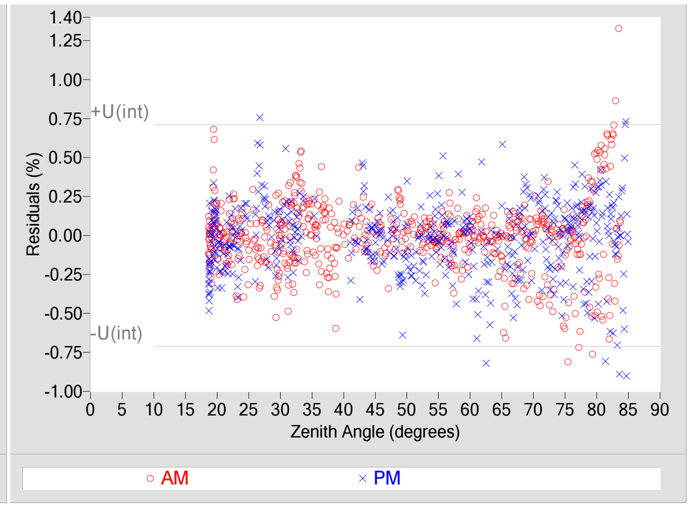


Table 3. Uncertainty using Spline Interpolation

Type-B Standard Uncertainty, u(B) (%)	±0.42
Type-A Interpolating Function, u(int) (%)	±0.36
Combined Standard Uncertainty, u(c) (%)	±0.55
Effective degrees of freedom, DF(c)	5575
Coverage factor, k	1.96
Expanded Uncertainty, U95 (%)	±1.1
AM Valid zenith angle range	20° to 76°
PM Valid zenith angle range	20° to 72°

Table 4. Calibration Label Values

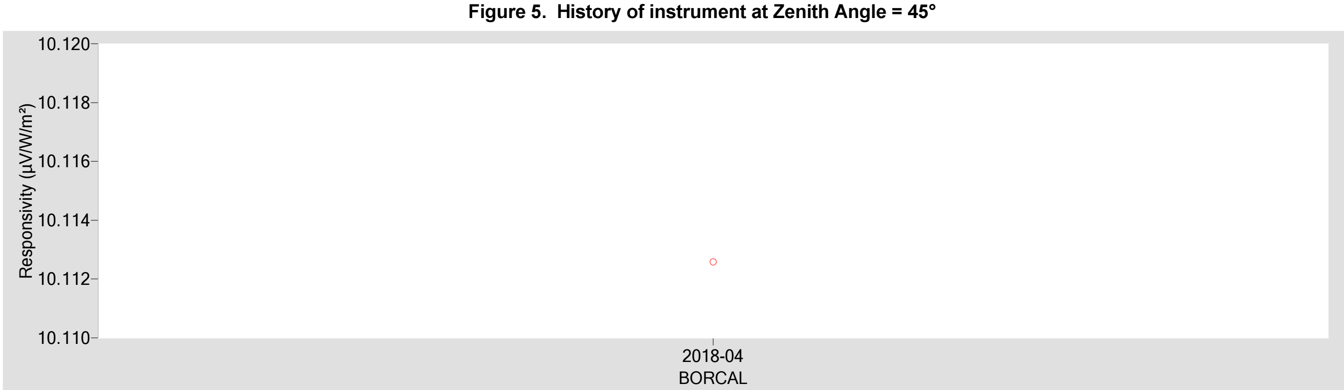
R @ 45° (µV/W/m²)	Rnet (µV/W/m²) †
10.113	0.043000

† Rnet determination date: Estimated

Table 5. Uncertainty using R @ 45°

Type-B Expanded Uncertainty, U(B) (%)	±0.63
Offset Uncertainty, U(off) (%)	+1.3 / -0.025
Expanded Uncertainty, U (%)	+2.0 / -0.66
Effective degrees of freedom, DF	+Inf
Coverage factor, k	1.96
Valid zenith angle range	30.0° to 60.0°

Figure 5. History of instrument at Zenith Angle = 45°



References:

[1] Reda, I.; Hickey, J.; Long, C.; Myers, D.; Stoffel, T.; Wilcox, S.; Michalsky, J. J.; Dutton, E. G.; Nelson, D. (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; NREL Report No. JA-560-36646. doi:10.1175/JTECH1782.1

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Environmental and Sky Conditions for BORCAL-SW 2018-04

Calibration Facility: Solar Radiation Research Laboratory

Latitude: 39.742°N Longitude: 105.180°W Elevation: 1828.8 meters AMSL Time Zone: -7.0

Reference Irradiance:

Figure 6. Reference Irradiance

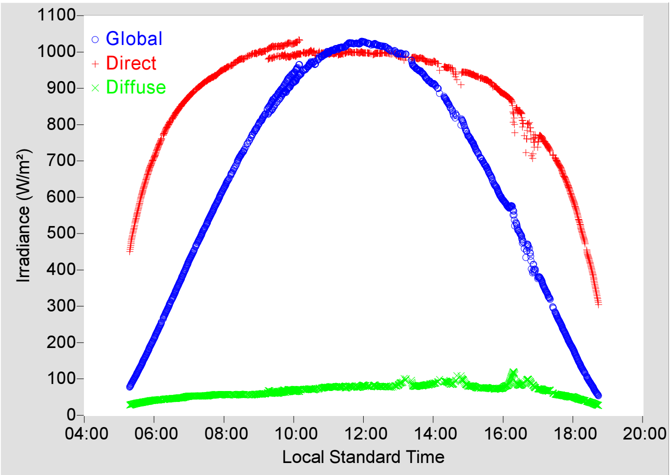
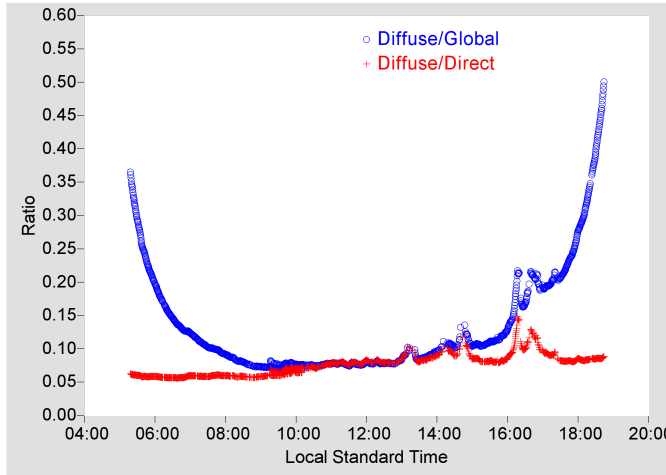


Figure 7. Diffuse Ratios



Meteorological Observations:

Figure 8. Temperature

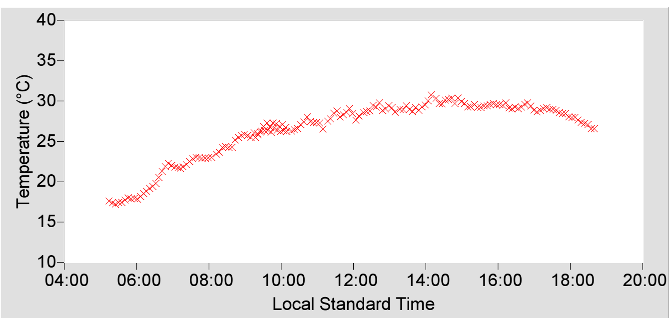


Figure 9. Humidity

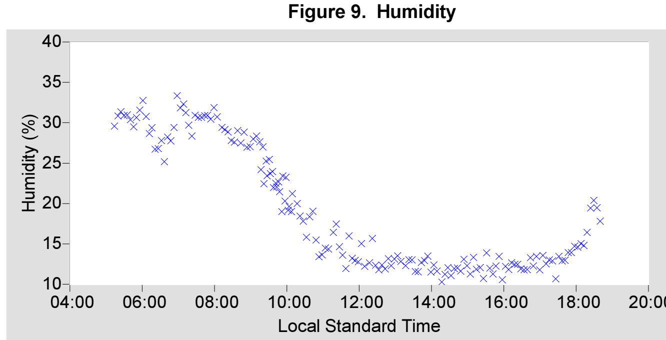


Figure 10. Pressure

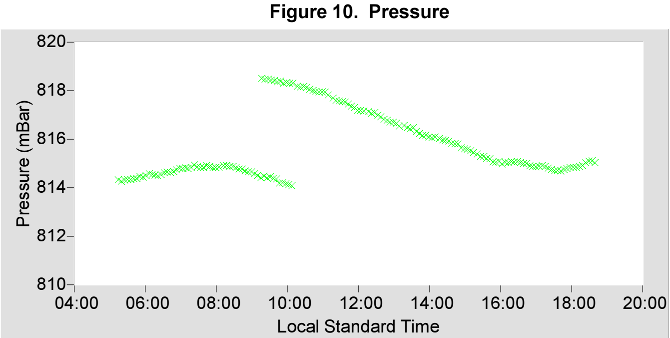


Figure 11. Effective Net Infrared

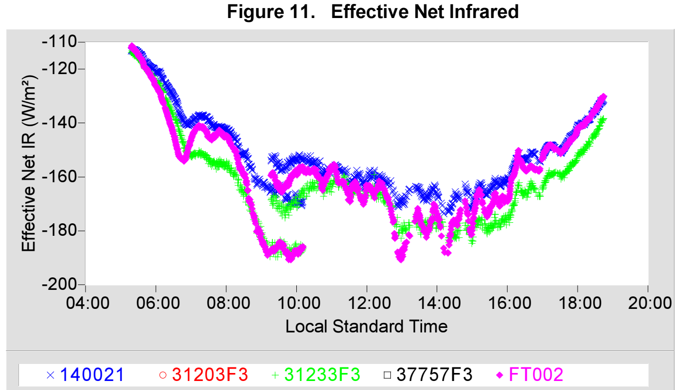


Figure 12. Estimated Broadband Aerosol Optical Depth

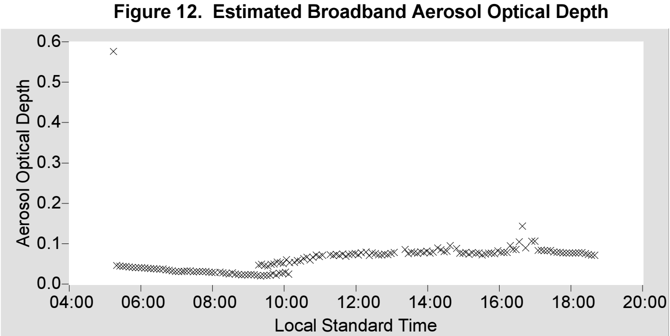


Table 6. Meteorological Observations

Observations	Mean	Min	Max
Temperature (°C)	26.40	17.22	30.75
Humidity (%)	19.29	10.28	33.34
Pressure (mBar)	815.7	814.1	818.5
Est. Aerosol Optical Depth (BB)	0.063	0.020	0.576

For other information about the calibration facility visit: http://www.nrel.gov/esif/solar-radiation-research-laboratory.html

Appendix 2
BORCAL Notes

Instrument, Configuration, and Session Notes for the BORCAL

BORCAL Notes

Facility: Solar Radiation Research Laboratory
Comments:
Avg. Station Pressure & Temperature is for Denver, CO, which is used for the Solar Position Algorithm (SPA).