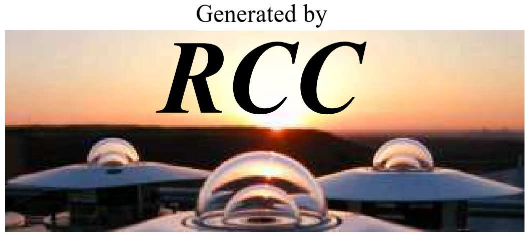
Broadband Outdoor Radiometer Calibration
Shortwave

BORCAL-SW
2024-04

Generated by



Radiometer Calibration and Characterization

<u>Customer</u>

Afshin Andreas

Organization: NREL
Address: Metrology Lab, 2054 Quaker St, Golden, CO 80401 USA
Phone: 303-384-6383

<u>Calibration Facility</u>

Solar Radiation Research Laboratory

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

Calibration date
07/08/2024

Report Date
July 9, 2024

NREL

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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

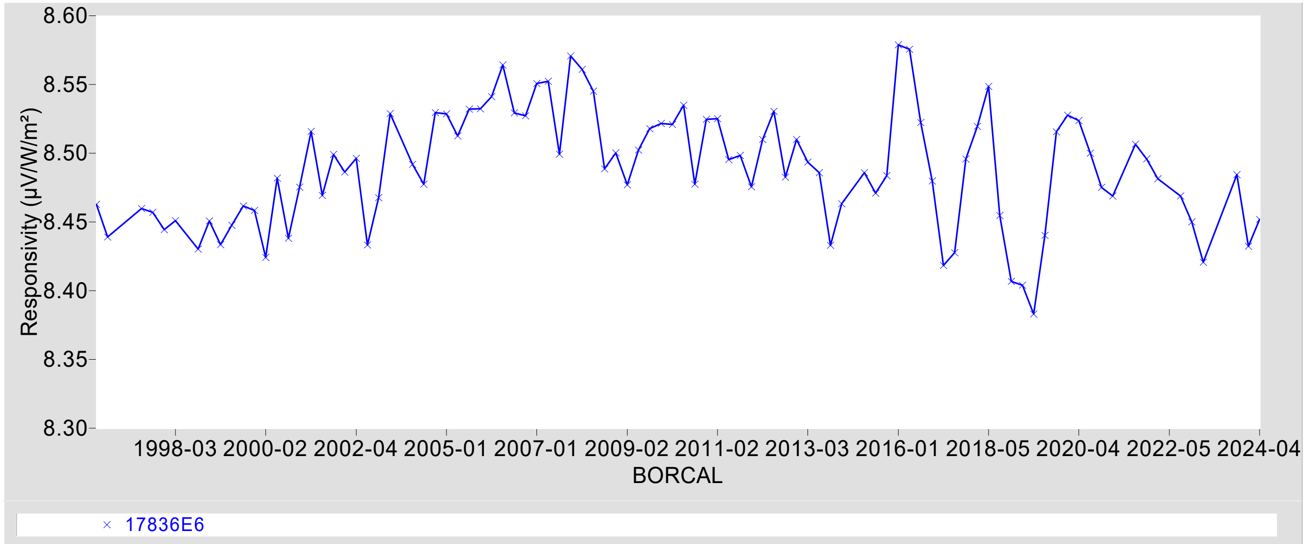


Figure 2. Eppley PSP Control Instrument History

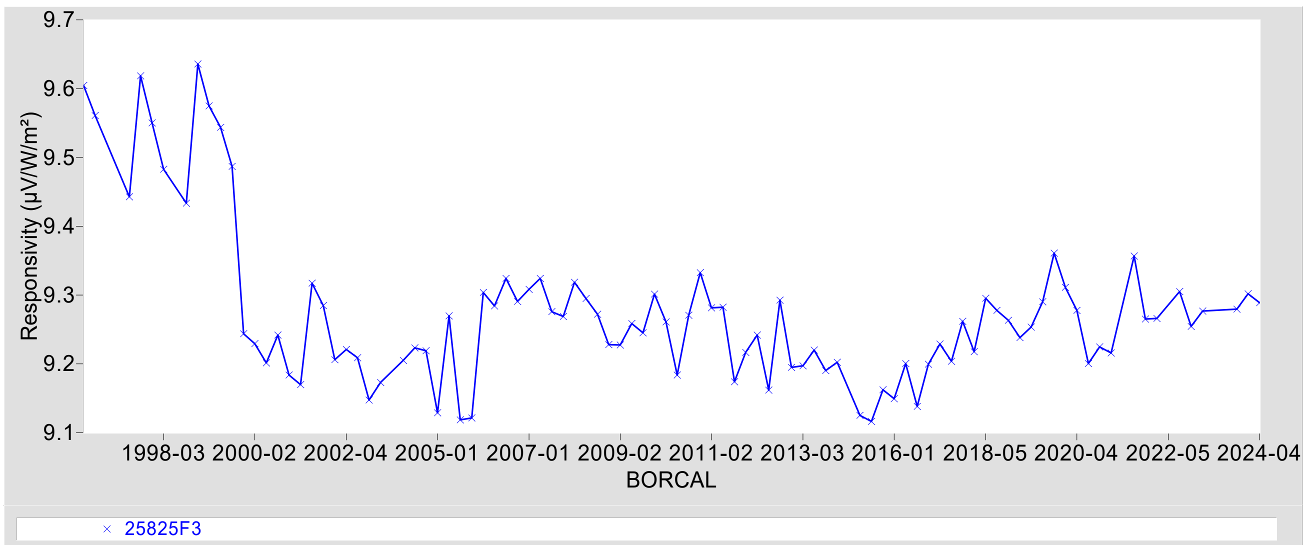
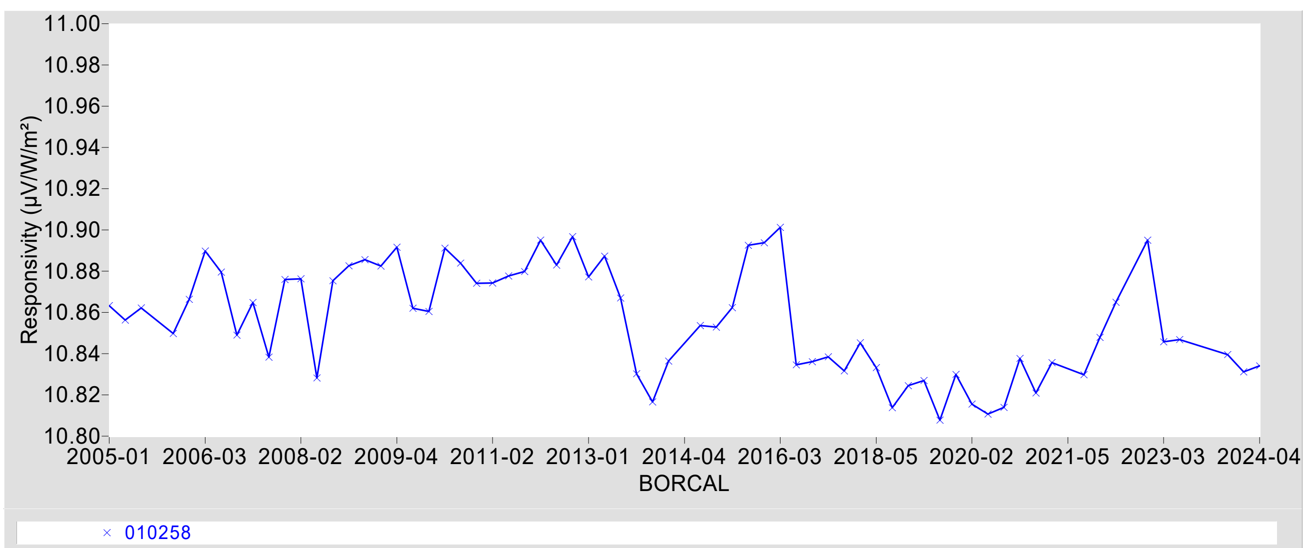


Figure 3. Kipp & Zonen CH1 Control Instrument History



Control Instrument History

Figure 4. Kipp & Zonen CHP1 Control Instrument History

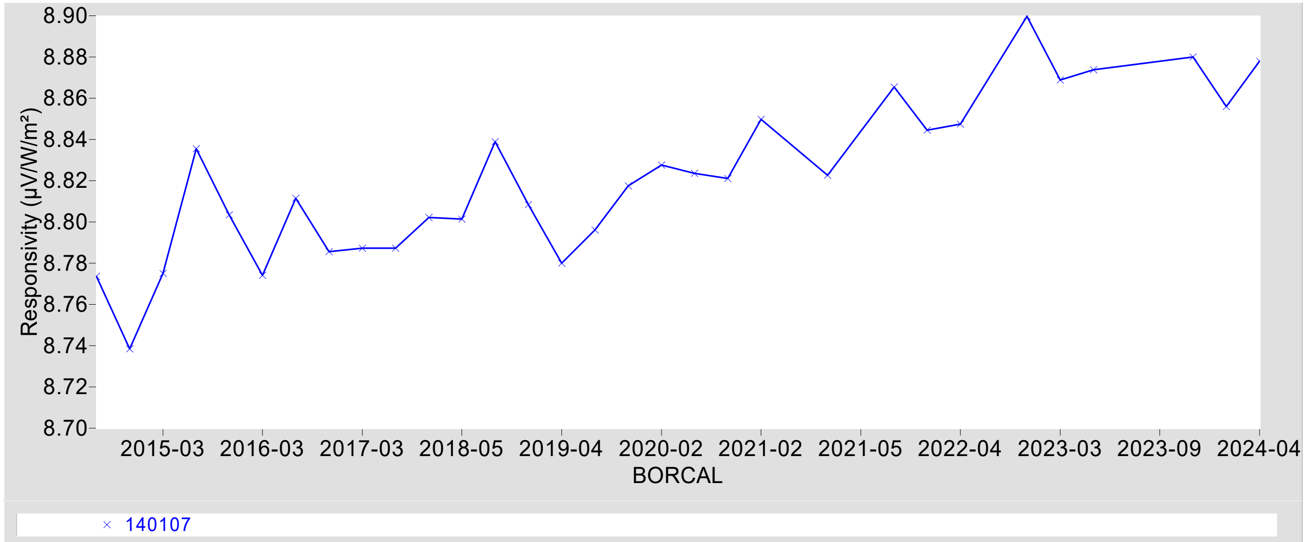


Figure 5. Kipp & Zonen CM22 Control Instrument History

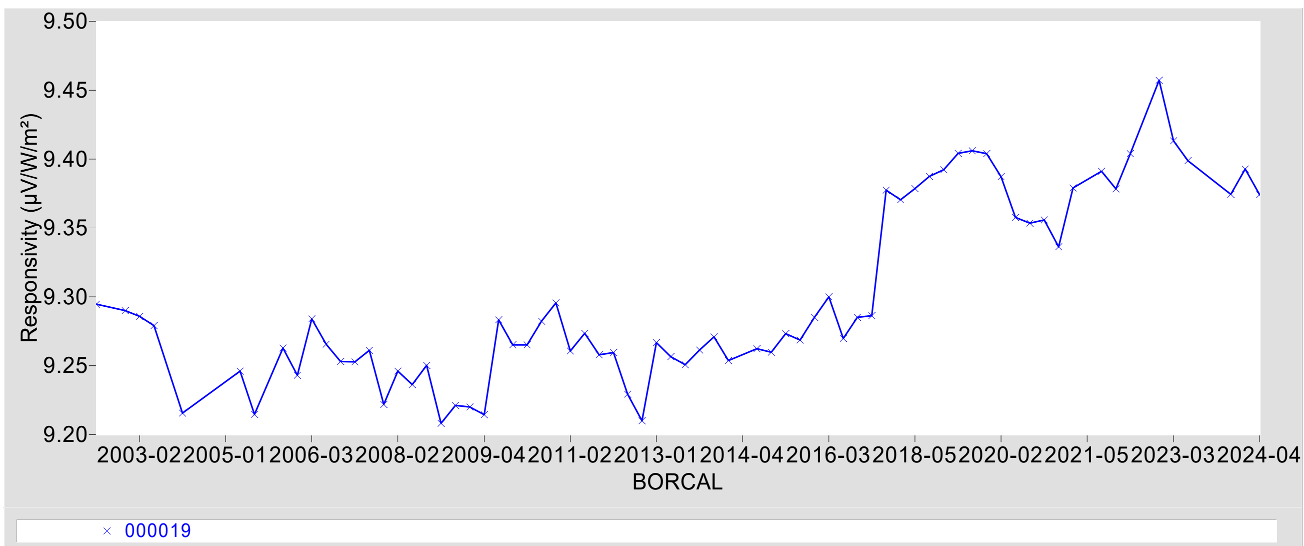
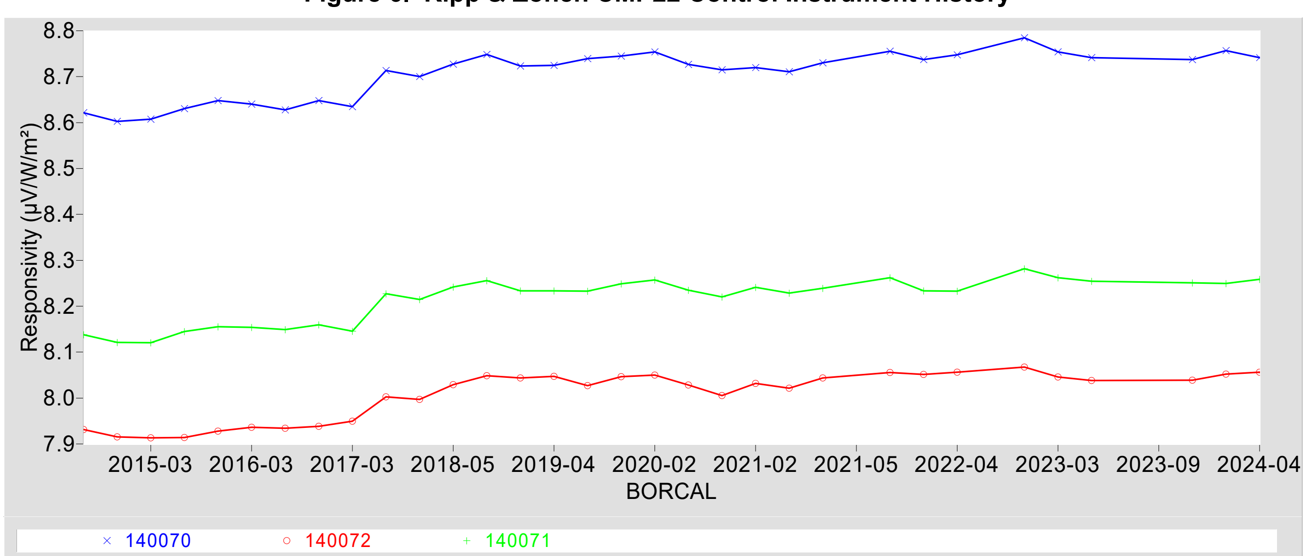


Figure 6. Kipp & Zonen CMP22 Control Instrument History



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
120076 Kipp & Zonen SMP11	10.156	98.461	+1.4 / -1.9	0.20500	A1-2
220057 Kipp & Zonen SMP12	7.0450	141.95	+1.7 / -1.3	0	A1-5
27806 Hukseflux SR30	9.3610	106.83	+1.1 / -1.2	0	A1-8
28571 Hukseflux SR30	10.733	93.173	+1.4 / -1.5	0	A1-11
4246 Hukseflux SR30	10.359	96.535	+1.1 / -1.0	0	A1-14
S20066320 EKO MS-80S	10.817	92.443	+1.8 / -1.9	0	A1-17

[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 A1-20.

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:	Digital Pyranometer	**Manufacturer:**	Kipp & Zonen
Model:	SMP11	**Serial Number:**	120076
Calibration Date:	7/8/2024	**Due Date:**	7/8/2025
Customer:	Afshin Andreas	**Environmental Conditions:**	see page 4
Test Dates:	7/8		

This certifies that the above product was calibrated in compliance with ISO/IEC 17025:2017. 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	09/28/2023	09/28/2024
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/14/2024	04/14/2025
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/14/2024	04/14/2025
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/03/2023	02/03/2025
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/03/2023	02/03/2025
Infrared Irradiance ‡	Kipp & Zonen Pyrgeometer Model CG4, S/N FT002	03/31/2022	03/31/2027

† 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, Aron Habte, RCC, and Shawn L. Jaker

Ibrahim Reda, Technical Manager   07/09/2024
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

120076 Kipp & Zonen SMP11

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 radiometer (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

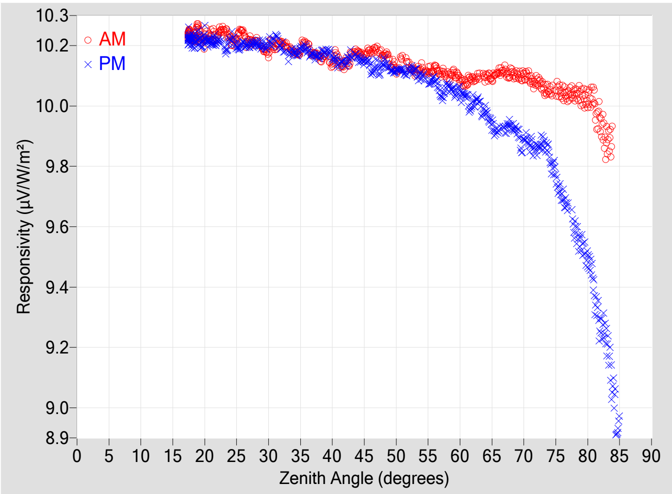


Figure 2. Responsivity vs Local Standard Time

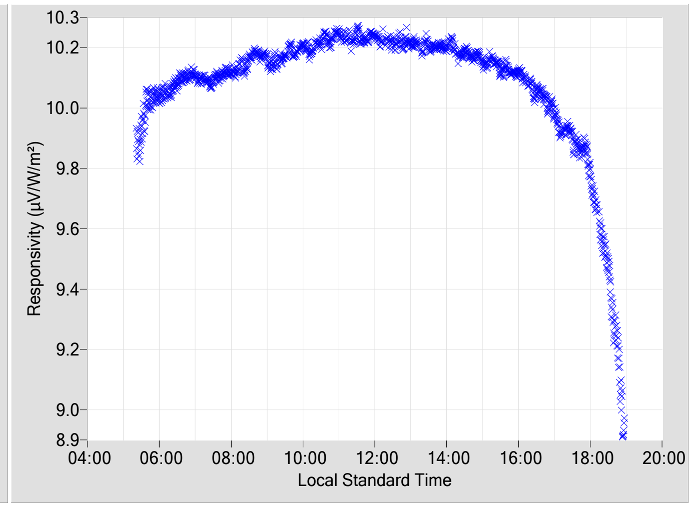


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)

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	10.181	0.34	96.58	10.125	0.33	263.32
2	N/A	N/A	N/A	N/A	N/A	N/A	48	10.165	0.35	94.78	10.144	0.37	265.21
4	N/A	N/A	N/A	N/A	N/A	N/A	50	10.123	0.37	92.96	10.119	0.33	267.02
6	N/A	N/A	N/A	N/A	N/A	N/A	52	10.133	0.35	91.20	10.122	0.33	268.74
8	N/A	N/A	N/A	N/A	N/A	N/A	54	10.125	0.41	89.60	10.101	0.34	270.42
10	N/A	N/A	N/A	N/A	N/A	N/A	56	10.127	0.34	87.93	10.089	0.38	271.99
12	N/A	N/A	N/A	N/A	N/A	N/A	58	10.101	0.37	86.28	10.069	0.36	273.62
14	N/A	N/A	N/A	N/A	N/A	N/A	60	10.089	0.38	84.70	10.041	0.41	275.23
16	N/A	N/A	N/A	N/A	N/A	N/A	62	10.089	0.39	83.19	10.009	0.40	276.73
18	10.227	0.32	164.01	10.222	0.32	195.84	64	10.096	0.43	81.66	9.9846	0.40	278.30
20	10.228	0.32	146.73	10.222	0.32	212.81	66	10.112	0.40	80.11	9.9193	0.41	279.81
22	10.234	0.33	137.37	10.214	0.32	222.18	68	10.111	0.42	78.57	9.9324	0.44	281.36
24	10.222	0.34	130.56	10.221	0.34	229.20	70	10.098	0.45	77.03	9.8818	0.47	282.90
26	10.246	0.33	125.30	10.208	0.34	234.87	72	10.079	0.48	75.49	9.8606	N/A	284.43
28	10.216	0.33	120.57	10.207	0.31	239.31	74	10.049	N/A	73.88	9.8241	N/A	286.05
30	10.185	0.32	116.80	10.212	0.33	243.16	76	10.038	N/A	72.31	9.7001	N/A	287.59
32	10.211	0.34	113.42	10.195	0.31	246.59	78	10.037	N/A	70.72	9.5849	N/A	289.19
34	10.176	0.35	110.33	10.180	0.31	249.57	80	10.025	N/A	69.08	9.4878	N/A	290.83
36	10.203	0.30	107.58	10.187	0.36	252.30	82	9.9527	N/A	67.41	9.2617	N/A	292.50
38	10.160	0.30	105.09	10.167	0.32	254.88	84	9.8989	N/A	65.86	9.0506	N/A	294.27
40	10.138	0.32	102.73	10.158	0.33	257.25	86	N/A	N/A	N/A	N/A	N/A	N/A
42	10.143	0.32	100.61	10.142	0.35	259.41	88	N/A	N/A	N/A	N/A	N/A	N/A
44	10.178	0.37	98.55	10.160	0.37	261.40	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

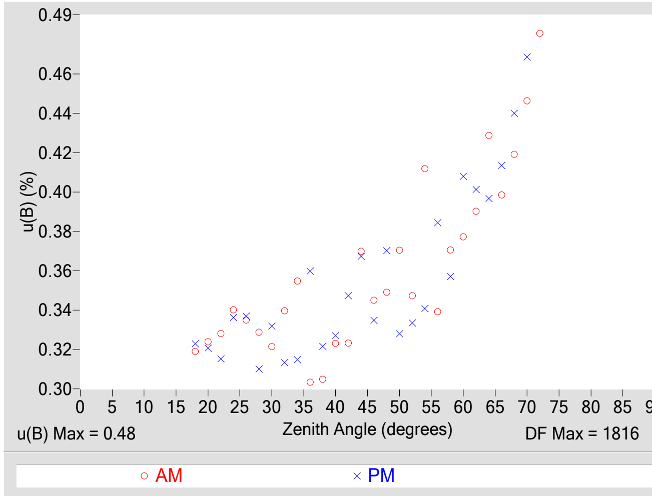


Figure 4. Residuals from Spline Interpolation

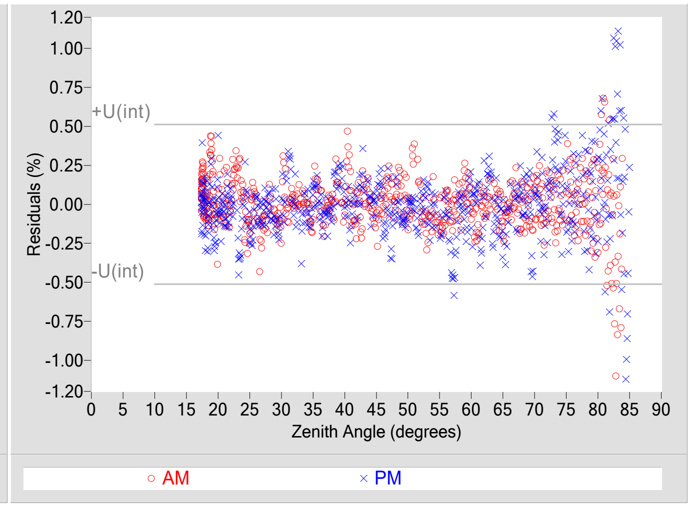


Table 3. Uncertainty using Spline Interpolation ‡

Type-B Standard Uncertainty, u(B) (%)	±0.48
Type-A Interpolating Function, u(int) (%)	±0.26
Combined Standard Uncertainty, u(c) (%)	±0.54
Effective degrees of freedom, DF(c)	2644
Coverage factor, k	1.96
Expanded Uncertainty, U95 (%)	±1.1
AM Valid zenith angle range	18° to 72°
PM Valid zenith angle range	18° to 70°

‡ An illustration for how to reduce the uncertainty in calculating the irradiance using a function rather than R@45°. Not accredited.

Table 4. Calibration Label Values

R @ 45° (µV/W/m²)	Rnet (µV/W/m²) †
10.156	0.20500

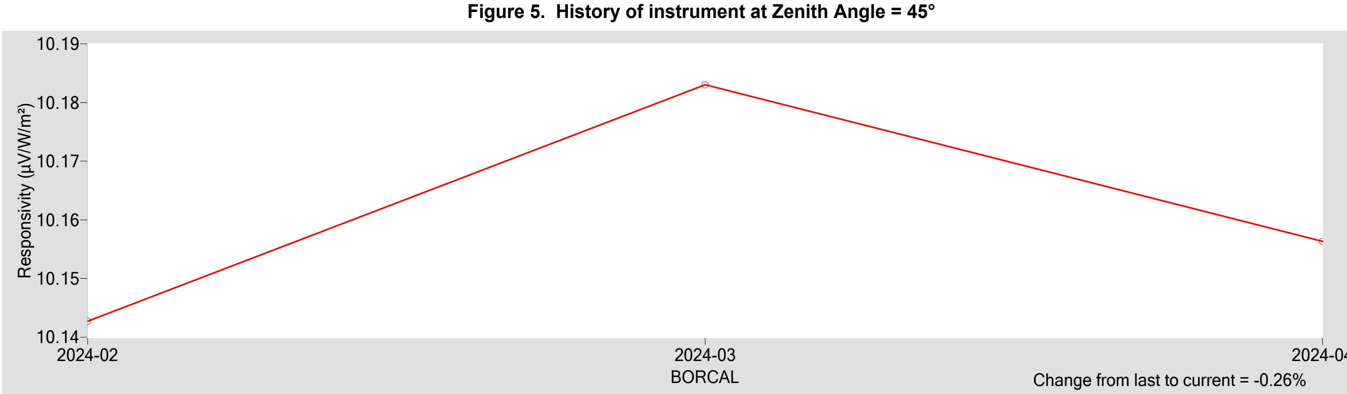
† Rnet determination date: Estimated

Table 5. Uncertainty using R @ 45°

Type-B Expanded Uncertainty, U(B) (%)	±0.81
Offset Uncertainty, U(off) (%)	+0.55 / -1.1
Expanded Uncertainty, U (%)	+1.4 / -1.9
Effective degrees of freedom, DF *	1970
Coverage factor, k	1.96
Valid zenith angle range	30.0° to 60.0°

* The DF of each variable in Eq 1 is commonly assumed to be infinite per the GUM for rectangular distribution, but for simplicity 1000 is used for each.

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

ACCREDITED
Calibration CERT #1239.02

Test Instrument:	Digital Pyranometer	**Manufacturer:**	Kipp & Zonen
Model:	SMP12	**Serial Number:**	220057
Calibration Date:	7/8/2024	**Due Date:**	7/8/2025
Customer:	Afshin Andreas	**Environmental Conditions:**	see page 4
Test Dates:	7/8		

This certifies that the above product was calibrated in compliance with ISO/IEC 17025:2017. 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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Table 1. Traceability

Measurement Type	Instrument	Calibration Date	Calibration Due Date
Beam Irradiance †	Eppley Absolute Cavity Radiometer Model HF, S/N 29219	09/28/2023	09/28/2024
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/14/2024	04/14/2025
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/14/2024	04/14/2025
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/03/2023	02/03/2025
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/03/2023	02/03/2025

† 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, Aron Habte, RCC, and Shawn L. Jaker

Ibrahim Reda, Technical Manager — Date: 07/09/2024

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

220057 Kipp & Zonen SMP12

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

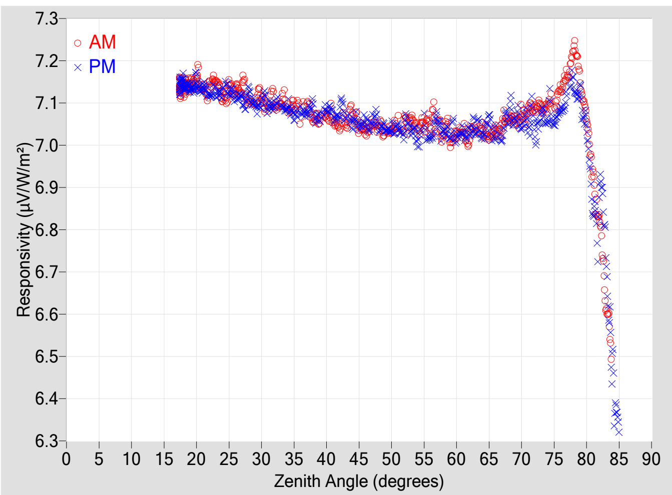


Figure 2. Responsivity vs Local Standard Time

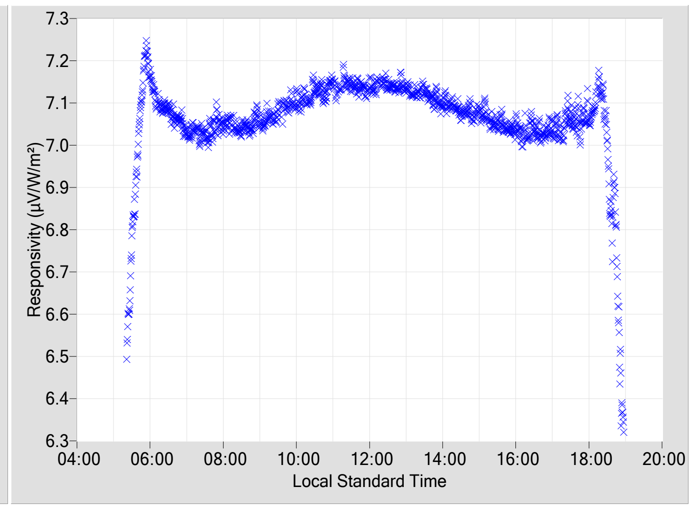


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)

Zenith	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	7.0347	0.34	96.61	7.0571	0.35	263.35
2	N/A	N/A	N/A	N/A	N/A	N/A	48	7.0426	0.33	94.71	7.0406	0.34	265.25
4	N/A	N/A	N/A	N/A	N/A	N/A	50	7.0359	0.32	92.98	7.0403	0.37	266.96
6	N/A	N/A	N/A	N/A	N/A	N/A	52	7.0553	0.34	91.26	7.0452	0.35	268.73
8	N/A	N/A	N/A	N/A	N/A	N/A	54	7.0435	0.35	89.55	7.0079	0.37	270.35
10	N/A	N/A	N/A	N/A	N/A	N/A	56	7.0520	0.35	87.88	7.0187	0.36	272.02
12	N/A	N/A	N/A	N/A	N/A	N/A	58	7.0245	0.36	86.33	7.0313	0.37	273.65
14	N/A	N/A	N/A	N/A	N/A	N/A	60	7.0256	0.37	84.72	7.0150	0.38	275.17
16	N/A	N/A	N/A	N/A	N/A	N/A	62	7.0214	0.39	83.14	7.0339	0.37	276.76
18	7.1399	0.30	163.79	7.1452	0.30	196.00	64	7.0368	0.42	81.61	7.0218	0.41	278.32
20	7.1585	0.32	146.94	7.1526	0.30	213.13	66	7.0341	0.39	80.09	7.0242	0.43	279.80
22	7.1369	0.32	137.42	7.1188	0.33	222.51	68	7.0601	0.41	78.59	7.0709	0.43	281.39
24	7.1145	0.33	130.72	7.1244	0.33	229.24	70	7.0700	0.44	77.05	7.0473	0.45	282.93
26	7.1334	0.33	125.22	7.1104	0.32	234.57	72	7.0830	0.47	75.44	7.0316	N/A	284.46
28	7.1037	0.33	120.67	7.1246	0.34	239.37	74	7.0944	N/A	73.90	7.0634	N/A	285.99
30	7.1109	0.30	116.77	7.1044	0.31	243.21	76	7.1312	N/A	72.34	7.0832	N/A	287.61
32	7.1053	0.31	113.36	7.0920	0.32	246.52	78	7.2262	N/A	70.71	7.1449	N/A	289.21
34	7.0869	0.32	110.27	7.0899	0.31	249.55	80	7.0629	N/A	69.06	7.0420	N/A	290.82
36	7.0746	0.32	107.72	7.0803	0.36	252.45	82	6.8214	N/A	67.40	6.8938	N/A	292.56
38	7.0591	0.32	105.08	7.0886	0.32	254.76	84	6.5127	N/A	65.88	6.4548	N/A	294.25
40	7.0687	0.34	102.77	7.0826	0.32	257.17	86	N/A	N/A	N/A	N/A	N/A	N/A
42	7.0422	0.31	100.58	7.0840	0.32	259.40	88	N/A	N/A	N/A	N/A	N/A	N/A
44	7.0784	0.35	98.58	7.0523	0.36	261.38	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

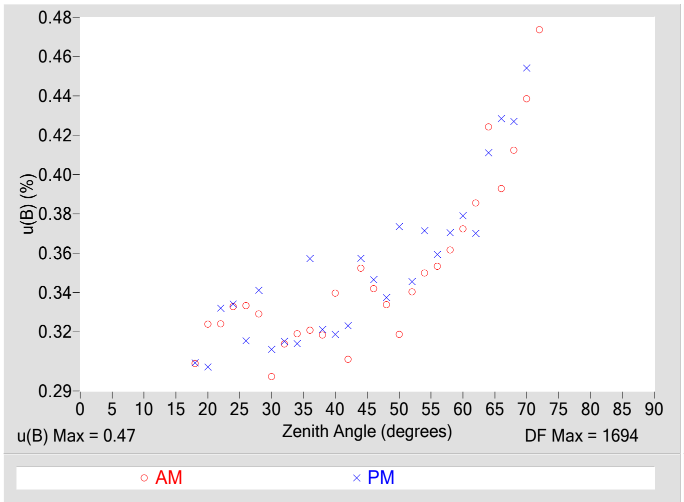


Figure 4. Residuals from Spline Interpolation

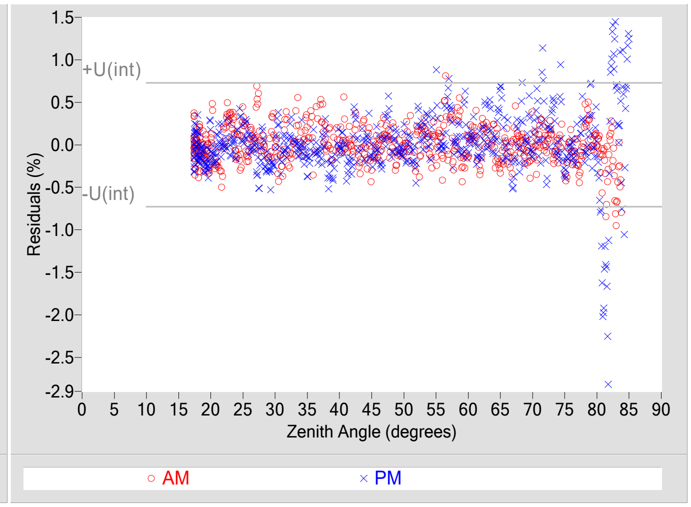


Table 3. Uncertainty using Spline Interpolation ‡

Type-B Standard Uncertainty, u(B) (%)	±0.47
Type-A Interpolating Function, u(int) (%)	±0.36
Combined Standard Uncertainty, u(c) (%)	±0.60
Effective degrees of freedom, DF(c)	2807
Coverage factor, k	1.96
Expanded Uncertainty, U95 (%)	±1.2
AM Valid zenith angle range	18° to 72°
PM Valid zenith angle range	18° to 70°

‡ An illustration for how to reduce the uncertainty in calculating the irradiance using a function rather than R@45°. Not accredited.

Table 4. Calibration Label Values

R @ 45° (µV/W/m²)	Rnet (µV/W/m²) †
7.0450	0

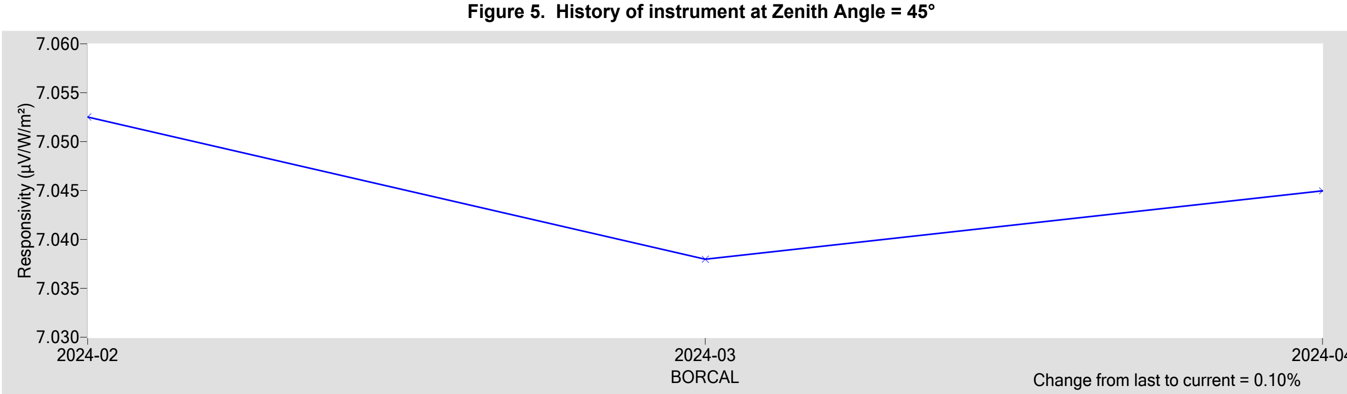
† Rnet determination date: N/A

Table 5. Uncertainty using R @ 45°

Type-B Expanded Uncertainty, U(B) (%)	±0.74
Offset Uncertainty, U(off) (%)	+0.94 / -0.53
Expanded Uncertainty, U (%)	+1.7 / -1.3
Effective degrees of freedom, DF *	2000
Coverage factor, k	1.96
Valid zenith angle range	30.0° to 60.0°

* The DF of each variable in Eq 1 is commonly assumed to be infinite per the GUM for rectangular distribution, but for simplicity 1000 is used for each.

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: Digital Pyranometer

Manufacturer: Hukseflux

Model: SR30

Serial Number: 27806

Calibration Date: 7/8/2024

Due Date: 7/8/2025

Customer: Afshin Andreas

Environmental Conditions: see page 4

Test Dates: 7/8

This certifies that the above product was calibrated in compliance with ISO/IEC 17025:2017. 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	09/28/2023	09/28/2024
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/14/2024	04/14/2025
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/14/2024	04/14/2025
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/03/2023	02/03/2025
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/03/2023	02/03/2025

† 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, Aron Habte, RCC, and Shawn L. Jaker

Ibrahim Reda, Technical Manager — Date: 07/09/2024

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

27806 Hukseflux SR30

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

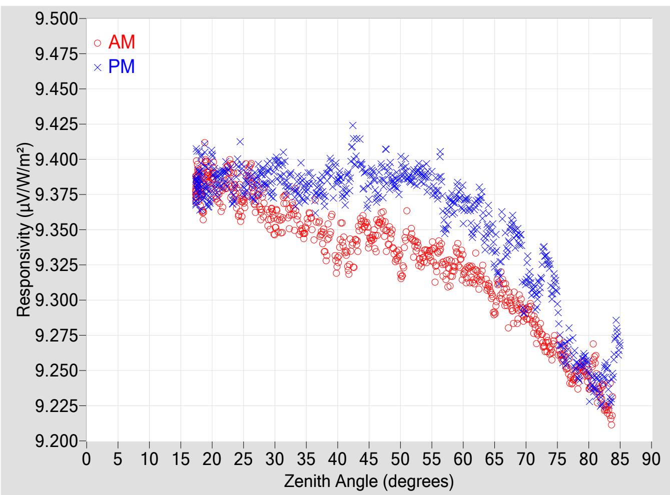


Figure 2. Responsivity vs Local Standard Time

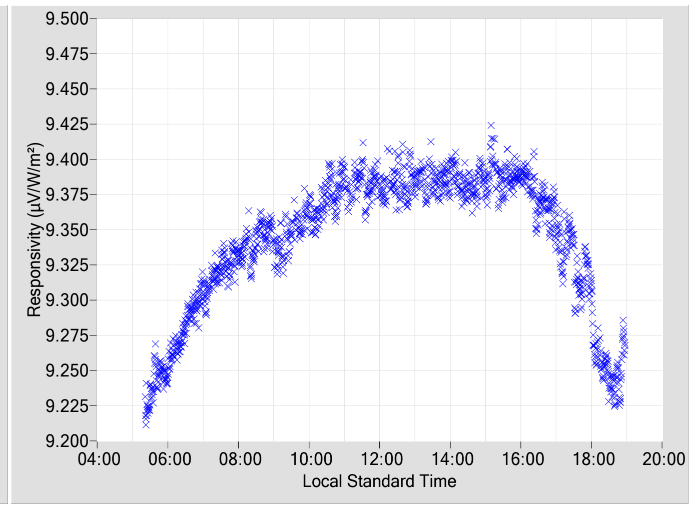


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)

Zenith	AM			PM			Zenith	AM			PM		
Angle (deg.)	R (μV/W/m²)	u(B) ± (%)	Azimuth Angle	R (μV/W/m²)	u(B) ± (%)	Azimuth Angle	Angle (deg.)	R (μV/W/m²)	u(B) ± (%)	Azimuth Angle	R (μV/W/m²)	u(B) ± (%)	Azimuth Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	9.3445	0.34	96.61	9.3771	0.35	263.35
2	N/A	N/A	N/A	N/A	N/A	N/A	48	9.3430	0.33	94.71	9.3871	0.34	265.25
4	N/A	N/A	N/A	N/A	N/A	N/A	50	9.3250	0.32	92.98	9.3892	0.37	266.96
6	N/A	N/A	N/A	N/A	N/A	N/A	52	9.3426	0.34	91.26	9.3878	0.35	268.73
8	N/A	N/A	N/A	N/A	N/A	N/A	54	9.3321	0.35	89.55	9.3868	0.37	270.35
10	N/A	N/A	N/A	N/A	N/A	N/A	56	9.3339	0.35	87.88	9.3818	0.36	272.02
12	N/A	N/A	N/A	N/A	N/A	N/A	58	9.3204	0.36	86.33	9.3687	0.37	273.65
14	N/A	N/A	N/A	N/A	N/A	N/A	60	9.3233	0.37	84.72	9.3668	0.38	275.17
16	N/A	N/A	N/A	N/A	N/A	N/A	62	9.3206	0.39	83.14	9.3621	0.37	276.76
18	9.3806	0.30	163.79	9.3866	0.30	196.00	64	9.3090	0.42	81.61	9.3555	0.41	278.32
20	9.3861	0.32	146.94	9.3936	0.30	213.13	66	9.3081	0.39	80.09	9.3339	0.43	279.80
22	9.3838	0.32	137.42	9.3887	0.33	222.51	68	9.2947	0.41	78.59	9.3499	0.43	281.39
24	9.3719	0.33	130.72	9.3947	0.33	229.24	70	9.2896	0.44	77.05	9.3150	0.45	282.93
26	9.3902	0.33	125.22	9.3874	0.32	234.57	72	9.2785	0.47	75.44	9.3060	N/A	284.46
28	9.3662	0.33	120.67	9.3866	0.34	239.37	74	9.2626	N/A	73.90	9.3113	N/A	285.99
30	9.3531	0.30	116.77	9.3929	0.31	243.21	76	9.2620	N/A	72.34	9.2608	N/A	287.61
32	9.3635	0.31	113.36	9.3795	0.32	246.52	78	9.2460	N/A	70.71	9.2524	N/A	289.21
34	9.3499	0.32	110.27	9.3814	0.31	249.55	80	9.2418	N/A	69.06	9.2456	N/A	290.82
36	9.3524	0.32	107.72	9.3814	0.36	252.45	82	9.2353	N/A	67.40	9.2327	N/A	292.53
38	9.3358	0.32	105.08	9.3750	0.32	254.76	84	9.2246	N/A	65.88	9.2597	N/A	294.25
40	9.3281	0.34	102.77	9.3880	0.32	257.17	86	N/A	N/A	N/A	N/A	N/A	N/A
42	9.3322	0.31	100.58	9.3942	0.32	259.40	88	N/A	N/A	N/A	N/A	N/A	N/A
44	9.3547	0.35	98.58	9.3892	0.36	261.38	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

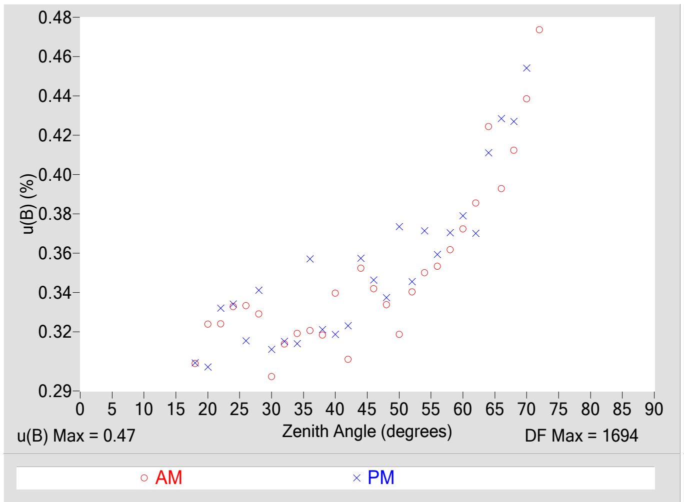


Figure 4. Residuals from Spline Interpolation

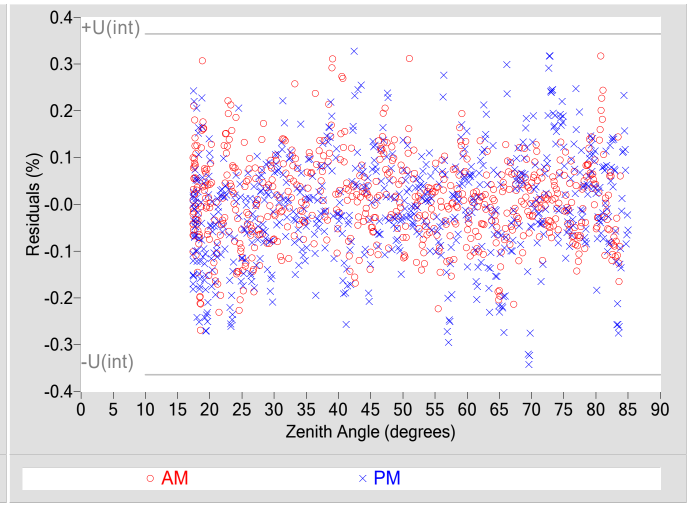


Table 3. Uncertainty using Spline Interpolation ‡

Type-B Standard Uncertainty, u(B) (%)	±0.47
Type-A Interpolating Function, u(int) (%)	±0.18
Combined Standard Uncertainty, u(c) (%)	±0.51
Effective degrees of freedom, DF(c)	2161
Coverage factor, k	1.96
Expanded Uncertainty, U95 (%)	±1.00
AM Valid zenith angle range	18° to 72°
PM Valid zenith angle range	18° to 70°

‡ An illustration for how to reduce the uncertainty in calculating the irradiance using a function rather than R@45°. Not accredited.

Table 4. Calibration Label Values

R @ 45° (µV/W/m²)	Rnet (µV/W/m²) †
9.3610	0

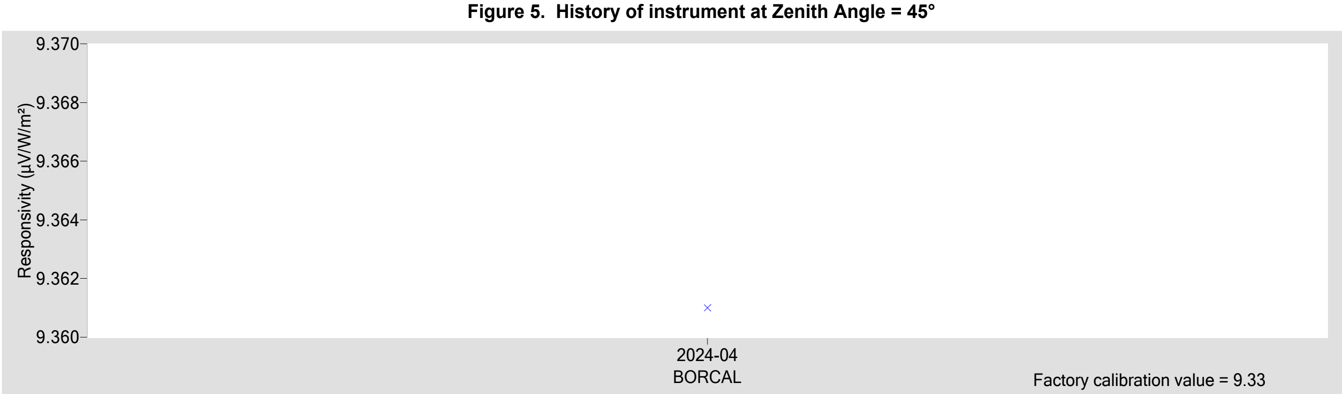
† Rnet determination date: N/A

Table 5. Uncertainty using R @ 45°

Type-B Expanded Uncertainty, U(B) (%)	±0.74
Offset Uncertainty, U(off) (%)	+0.35 / -0.43
Expanded Uncertainty, U (%)	+1.1 / -1.2
Effective degrees of freedom, DF *	2000
Coverage factor, k	1.96
Valid zenith angle range	30.0° to 60.0°

* The DF of each variable in Eq 1 is commonly assumed to be infinite per the GUM for rectangular distribution, but for simplicity 1000 is used for each.

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: Digital Pyranometer
Manufacturer: Hukseflux
Model: SR30
Serial Number: 28571
Calibration Date: 7/8/2024
Due Date: 7/8/2025
Customer: Afshin Andreas
Environmental Conditions: see page 4
Test Dates: 7/8

This certifies that the above product was calibrated in compliance with ISO/IEC 17025:2017. 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	09/28/2023	09/28/2024
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/14/2024	04/14/2025
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/14/2024	04/14/2025
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/03/2023	02/03/2025
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/03/2023	02/03/2025

† 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, Aron Habte, RCC, and Shawn L. Jaker

______________________________ 07/09/2024
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

28571 Hukseflux SR30

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

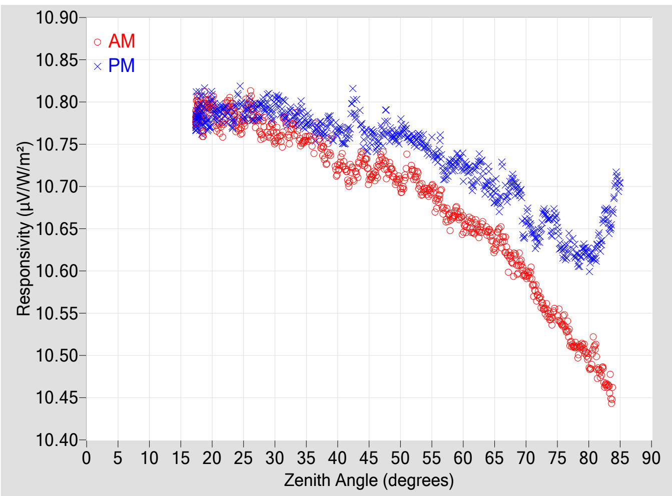


Figure 2. Responsivity vs Local Standard Time

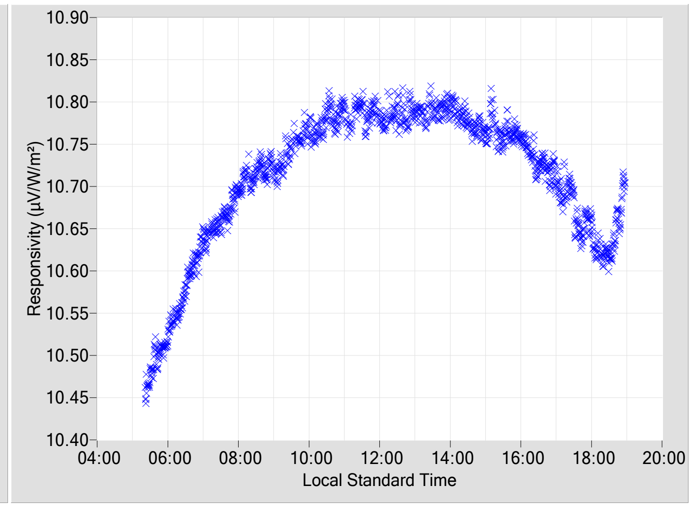


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)

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	10.716	0.34	96.61	10.751	0.35	263.35
2	N/A	N/A	N/A	N/A	N/A	N/A	48	10.718	0.33	94.71	10.764	0.34	265.25
4	N/A	N/A	N/A	N/A	N/A	N/A	50	10.702	0.32	92.98	10.766	0.37	266.96
6	N/A	N/A	N/A	N/A	N/A	N/A	52	10.718	0.34	91.26	10.756	0.35	268.73
8	N/A	N/A	N/A	N/A	N/A	N/A	54	10.695	0.35	89.55	10.746	0.37	270.35
10	N/A	N/A	N/A	N/A	N/A	N/A	56	10.684	0.35	87.88	10.739	0.36	272.02
12	N/A	N/A	N/A	N/A	N/A	N/A	58	10.662	0.36	86.33	10.726	0.37	273.65
14	N/A	N/A	N/A	N/A	N/A	N/A	60	10.654	0.37	84.72	10.721	0.38	275.17
16	N/A	N/A	N/A	N/A	N/A	N/A	62	10.653	0.39	83.14	10.717	0.37	276.76
18	10.787	0.30	163.79	10.790	0.30	196.00	64	10.646	0.42	81.61	10.710	0.41	278.32
20	10.794	0.32	146.94	10.797	0.30	213.13	66	10.639	0.39	80.09	10.696	0.43	279.80
22	10.784	0.32	137.42	10.788	0.33	222.51	68	10.610	0.41	78.59	10.704	0.43	281.39
24	10.776	0.33	130.72	10.803	0.33	229.24	70	10.595	0.44	77.05	10.661	0.45	282.93
26	10.801	0.33	125.22	10.797	0.32	234.57	72	10.571	0.47	75.44	10.639	N/A	284.46
28	10.766	0.33	120.67	10.795	0.34	239.37	74	10.543	N/A	73.90	10.650	N/A	285.99
30	10.756	0.30	116.77	10.799	0.31	243.21	76	10.540	N/A	72.34	10.621	N/A	287.61
32	10.764	0.31	113.36	10.779	0.32	246.52	78	10.511	N/A	70.74	10.617	N/A	289.21
34	10.752	0.32	110.27	10.785	0.31	249.55	80	10.491	N/A	69.06	10.616	N/A	290.82
36	10.749	0.32	107.72	10.771	0.36	252.45	82	10.481	N/A	67.40	10.639	N/A	292.53
38	10.733	0.32	105.08	10.763	0.32	254.76	84	10.455	N/A	65.88	10.686	N/A	294.25
40	10.719	0.34	102.77	10.767	0.32	257.17	86	N/A	N/A	N/A	N/A	N/A	N/A
42	10.714	0.31	100.58	10.778	0.32	259.40	88	N/A	N/A	N/A	N/A	N/A	N/A
44	10.733	0.35	98.58	10.764	0.36	261.38	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

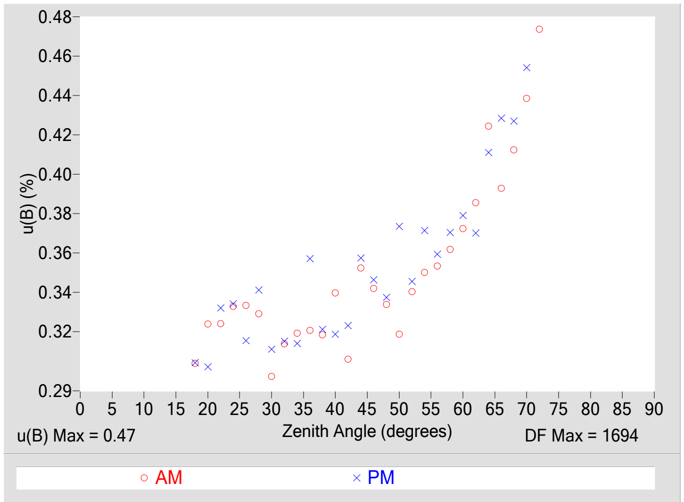


Figure 4. Residuals from Spline Interpolation

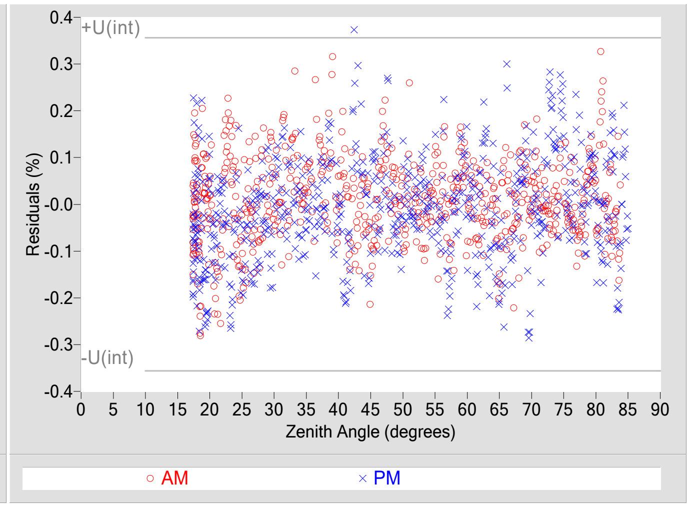


Table 3. Uncertainty using Spline Interpolation ‡

Type-B Standard Uncertainty, u(B) (%)	±0.47
Type-A Interpolating Function, u(int) (%)	±0.18
Combined Standard Uncertainty, u(c) (%)	±0.51
Effective degrees of freedom, DF(c)	2142
Coverage factor, k	1.96
Expanded Uncertainty, U95 (%)	±0.99
AM Valid zenith angle range	18° to 72°
PM Valid zenith angle range	18° to 70°

‡ An illustration for how to reduce the uncertainty in calculating the irradiance using a function rather than R@45°. Not accredited.

Table 4. Calibration Label Values

R @ 45° (µV/W/m²)	Rnet (µV/W/m²) †
10.733	0

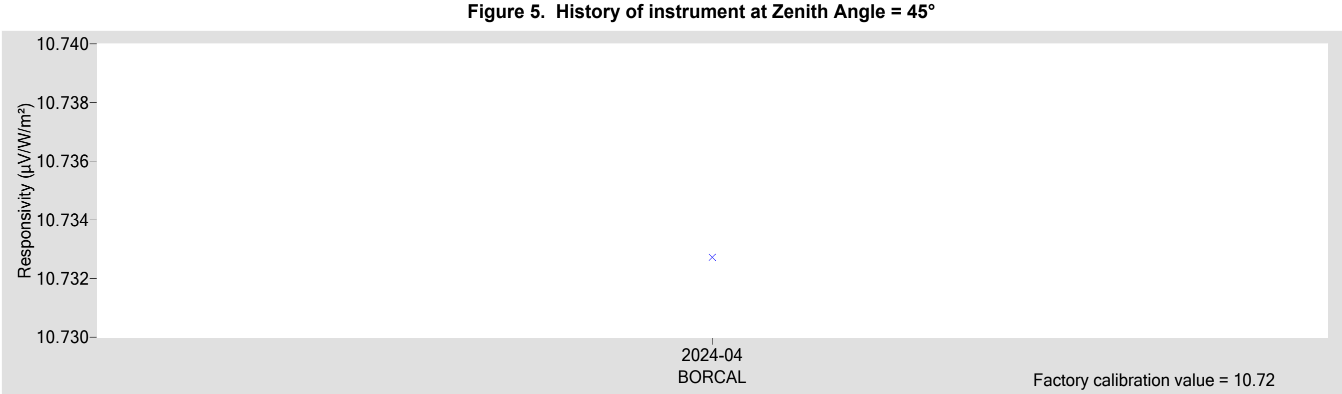
† Rnet determination date: N/A

Table 5. Uncertainty using R @ 45°

Type-B Expanded Uncertainty, U(B) (%)	±0.74
Offset Uncertainty, U(off) (%)	+0.62 / -0.73
Expanded Uncertainty, U (%)	+1.4 / -1.5
Effective degrees of freedom, DF *	2000
Coverage factor, k	1.96
Valid zenith angle range	30.0° to 60.0°

* The DF of each variable in Eq 1 is commonly assumed to be infinite per the GUM for rectangular distribution, but for simplicity 1000 is used for each.

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:	Digital Pyranometer	**Manufacturer:**	Hukseflux
Model:	SR30	**Serial Number:**	4246
Calibration Date:	7/8/2024	**Due Date:**	7/8/2025
Customer:	Afshin Andreas	**Environmental Conditions:**	see page 4
Test Dates:	7/8		

This certifies that the above product was calibrated in compliance with ISO/IEC 17025:2017. 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	09/28/2023	09/28/2024
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/14/2024	04/14/2025
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/14/2024	04/14/2025
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/03/2023	02/03/2025
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/03/2023	02/03/2025

† 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, Aron Habte, RCC, and Shawn L. Jaker

______________________________ 07/09/2024

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

4246 Hukseflux SR30

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

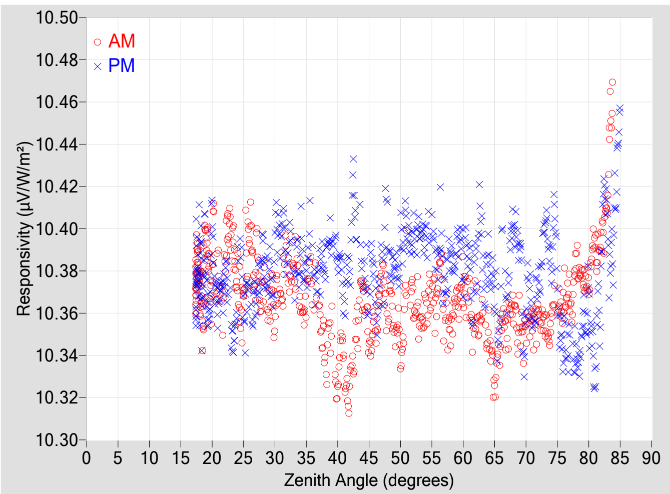


Figure 2. Responsivity vs Local Standard Time

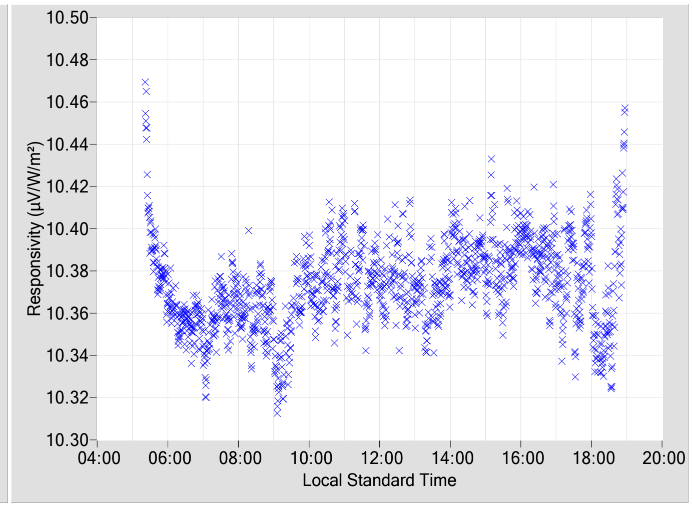


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)

Zenith	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	10.355	0.34	96.61	10.367	0.35	263.35
2	N/A	N/A	N/A	N/A	N/A	N/A	48	10.359	0.33	94.71	10.392	0.34	265.25
4	N/A	N/A	N/A	N/A	N/A	N/A	50	10.345	0.32	92.98	10.390	0.37	266.96
6	N/A	N/A	N/A	N/A	N/A	N/A	52	10.369	0.34	91.26	10.397	0.35	268.73
8	N/A	N/A	N/A	N/A	N/A	N/A	54	10.362	0.35	89.55	10.394	0.37	270.35
10	N/A	N/A	N/A	N/A	N/A	N/A	56	10.374	0.35	87.88	10.386	0.36	272.02
12	N/A	N/A	N/A	N/A	N/A	N/A	58	10.354	0.36	86.33	10.386	0.37	273.65
14	N/A	N/A	N/A	N/A	N/A	N/A	60	10.372	0.37	84.72	10.381	0.38	275.17
16	N/A	N/A	N/A	N/A	N/A	N/A	62	10.361	0.39	83.14	10.383	0.37	276.76
18	10.375	0.30	163.79	10.382	0.30	196.00	64	10.349	0.42	81.61	10.384	0.41	278.32
20	10.383	0.32	146.94	10.394	0.30	213.13	66	10.351	0.39	80.09	10.372	0.43	279.80
22	10.385	0.32	137.42	10.376	0.33	222.51	68	10.362	0.41	78.59	10.400	0.43	281.39
24	10.372	0.33	130.72	10.374	0.33	229.24	70	10.353	0.44	77.05	10.363	0.45	282.93
26	10.399	0.33	125.22	10.368	0.32	234.57	72	10.360	0.47	75.44	10.372	N/A	284.46
28	10.371	0.33	120.67	10.387	0.34	239.37	74	10.355	N/A	73.90	10.384	N/A	285.99
30	10.361	0.30	116.77	10.395	0.31	243.21	76	10.365	N/A	72.34	10.344	N/A	287.61
32	10.384	0.31	113.36	10.386	0.32	246.52	78	10.384	N/A	70.71	10.340	N/A	289.21
34	10.364	0.32	110.27	10.387	0.31	249.55	80	10.376	N/A	69.06	10.363	N/A	290.82
36	10.372	0.32	107.72	10.384	0.36	252.45	82	10.396	N/A	67.40	10.384	N/A	292.53
38	10.337	0.32	105.08	10.382	0.32	254.76	84	10.462	N/A	65.88	10.400	N/A	294.25
40	10.327	0.34	102.77	10.387	0.32	257.17	86	N/A	N/A	N/A	N/A	N/A	N/A
42	10.328	0.31	100.58	10.392	0.32	259.40	88	N/A	N/A	N/A	N/A	N/A	N/A
44	10.369	0.35	98.58	10.378	0.36	261.38	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

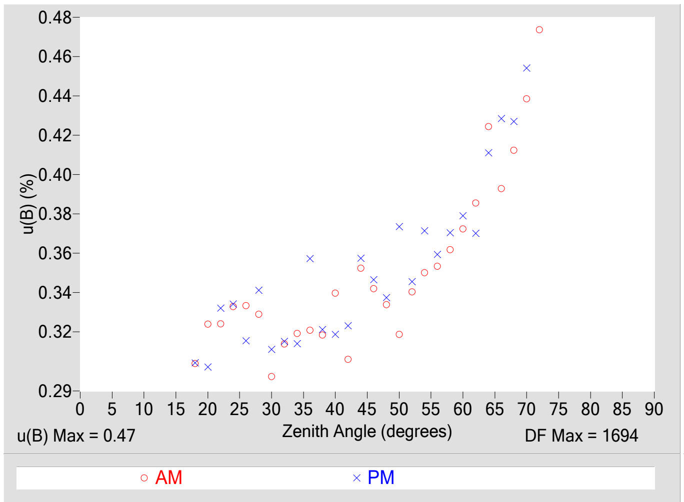


Figure 4. Residuals from Spline Interpolation

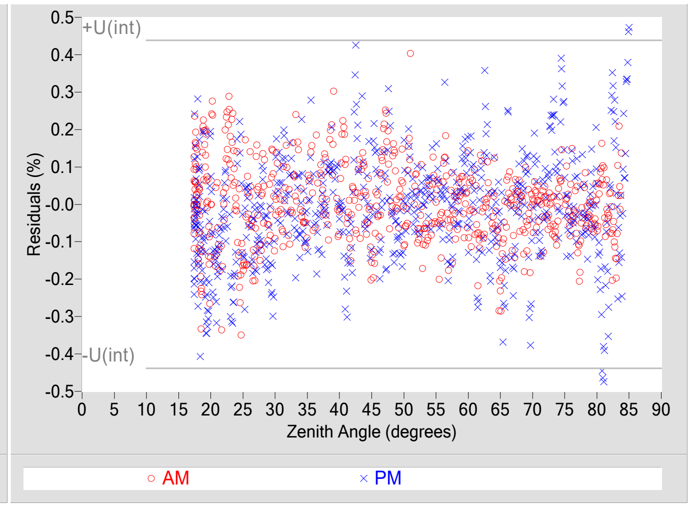


Table 3. Uncertainty using Spline Interpolation ‡

Type-B Standard Uncertainty, u(B) (%)	±0.47
Type-A Interpolating Function, u(int) (%)	±0.22
Combined Standard Uncertainty, u(c) (%)	±0.52
Effective degrees of freedom, DF(c)	2335
Coverage factor, k	1.96
Expanded Uncertainty, U95 (%)	±1.0
AM Valid zenith angle range	18° to 72°
PM Valid zenith angle range	18° to 70°

‡ An illustration for how to reduce the uncertainty in calculating the irradiance using a function rather than R@45°. Not accredited.

Table 4. Calibration Label Values

R @ 45° (µV/W/m²)	Rnet (µV/W/m²) †
10.359	0

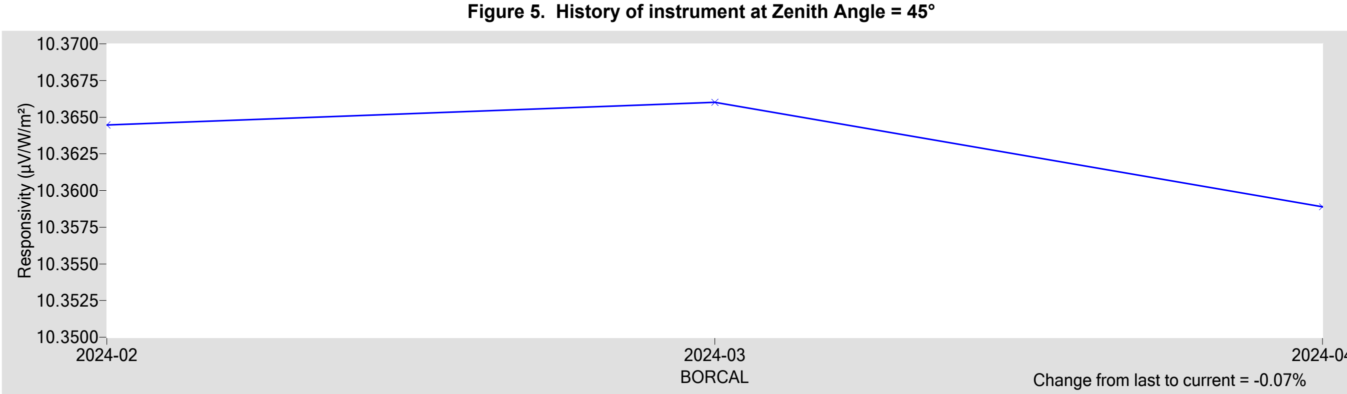
† Rnet determination date: N/A

Table 5. Uncertainty using R @ 45°

Type-B Expanded Uncertainty, U(B) (%)	±0.74
Offset Uncertainty, U(off) (%)	+0.37 / -0.30
Expanded Uncertainty, U (%)	+1.1 / -1.0
Effective degrees of freedom, DF *	2000
Coverage factor, k	1.96
Valid zenith angle range	30.0° to 60.0°

* The DF of each variable in Eq 1 is commonly assumed to be infinite per the GUM for rectangular distribution, but for simplicity 1000 is used for each.

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

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[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

ACCREDITED
Calibration CERT #1239.02

Test Instrument:	Digital Pyranometer	**Manufacturer:**	EKO
Model:	MS-80S	**Serial Number:**	S20066320
Calibration Date:	7/8/2024	**Due Date:**	7/8/2025
Customer:	Afshin Andreas	**Environmental Conditions:**	see page 4
Test Dates:	7/8		

This certifies that the above product was calibrated in compliance with ISO/IEC 17025:2017. 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	09/28/2023	09/28/2024
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/14/2024	04/14/2025
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/14/2024	04/14/2025
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/03/2023	02/03/2025
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/03/2023	02/03/2025

† 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, Aron Habte, RCC, and Shawn L. Jaker

______________________________ 07/09/2024

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

S20066320 EKO MS-80S

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

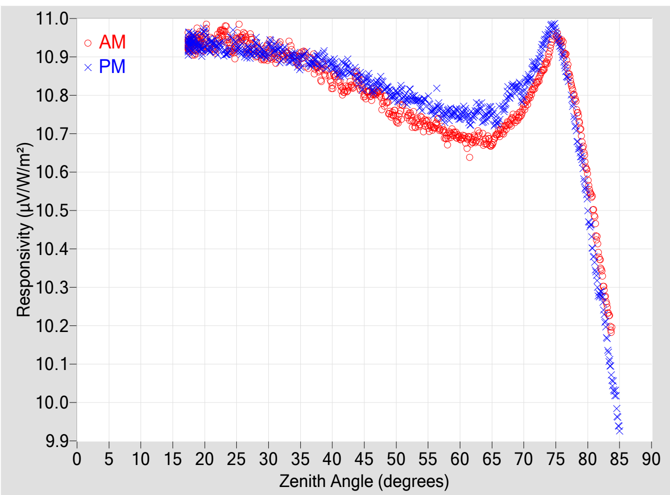


Figure 2. Responsivity vs Local Standard Time

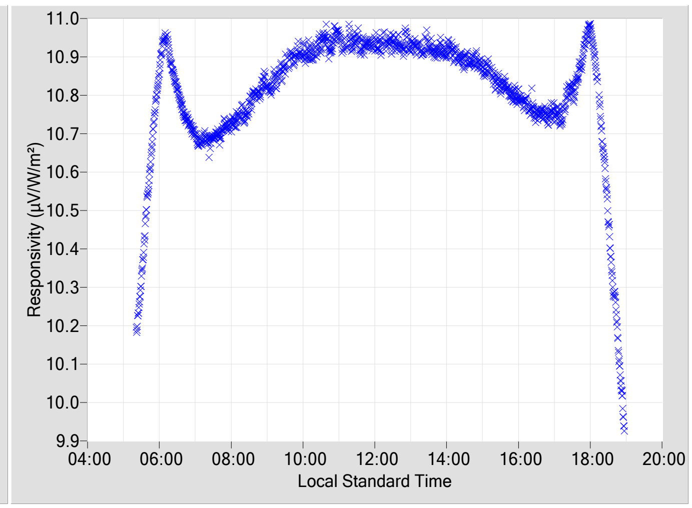


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)

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	10.802	0.34	96.61	10.825	0.35	263.35
2	N/A	N/A	N/A	N/A	N/A	N/A	48	10.779	0.33	94.71	10.823	0.34	265.25
4	N/A	N/A	N/A	N/A	N/A	N/A	50	10.744	0.32	92.98	10.800	0.37	266.96
6	N/A	N/A	N/A	N/A	N/A	N/A	52	10.746	0.34	91.26	10.799	0.35	268.73
8	N/A	N/A	N/A	N/A	N/A	N/A	54	10.730	0.35	89.55	10.775	0.37	270.35
10	N/A	N/A	N/A	N/A	N/A	N/A	56	10.720	0.35	87.88	10.759	0.36	272.02
12	N/A	N/A	N/A	N/A	N/A	N/A	58	10.687	0.36	86.33	10.754	0.37	273.65
14	N/A	N/A	N/A	N/A	N/A	N/A	60	10.689	0.37	84.72	10.745	0.38	275.17
16	N/A	N/A	N/A	N/A	N/A	N/A	62	10.685	0.39	83.14	10.747	0.37	276.76
18	10.931	0.30	163.79	10.940	0.30	196.00	64	10.679	0.42	81.61	10.749	0.41	278.32
20	10.946	0.32	146.94	10.956	0.30	213.13	66	10.700	0.39	80.09	10.740	0.43	279.80
22	10.946	0.32	137.42	10.923	0.33	222.51	68	10.731	0.41	78.59	10.813	0.43	281.39
24	10.925	0.33	130.72	10.936	0.33	229.24	70	10.768	0.44	77.05	10.815	0.45	282.93
26	10.952	0.33	125.22	10.913	0.32	234.57	72	10.834	0.47	75.44	10.874	N/A	284.46
28	10.916	0.33	120.67	10.928	0.34	239.37	74	10.911	N/A	73.90	10.967	N/A	285.99
30	10.915	0.30	116.77	10.927	0.31	243.21	76	10.933	N/A	72.34	10.905	N/A	287.61
32	10.917	0.31	113.36	10.901	0.32	246.52	78	10.788	N/A	70.71	10.727	N/A	289.21
34	10.903	0.32	110.27	10.900	0.31	249.55	80	10.585	N/A	69.06	10.511	N/A	290.82
36	10.890	0.32	107.72	10.893	0.36	252.45	82	10.360	N/A	67.40	10.281	N/A	292.53
38	10.855	0.32	105.08	10.889	0.32	254.76	84	10.189	N/A	65.88	10.039	N/A	294.25
40	10.835	0.34	102.77	10.881	0.32	257.17	86	N/A	N/A	N/A	N/A	N/A	N/A
42	10.812	0.31	100.58	10.868	0.32	259.40	88	N/A	N/A	N/A	N/A	N/A	N/A
44	10.844	0.35	98.58	10.845	0.36	261.38	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

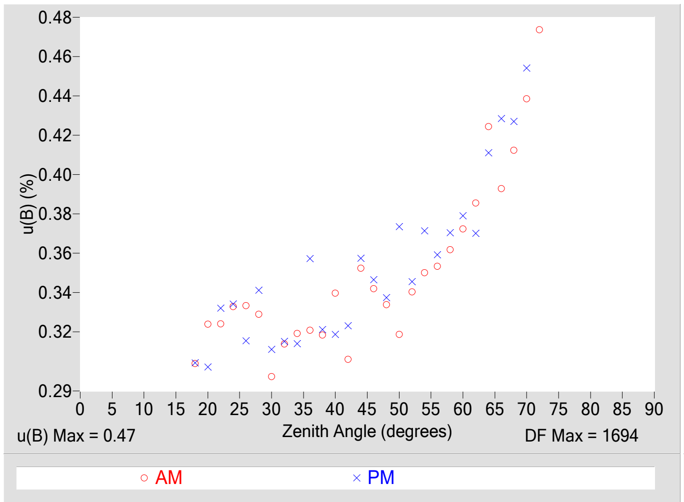


Figure 4. Residuals from Spline Interpolation

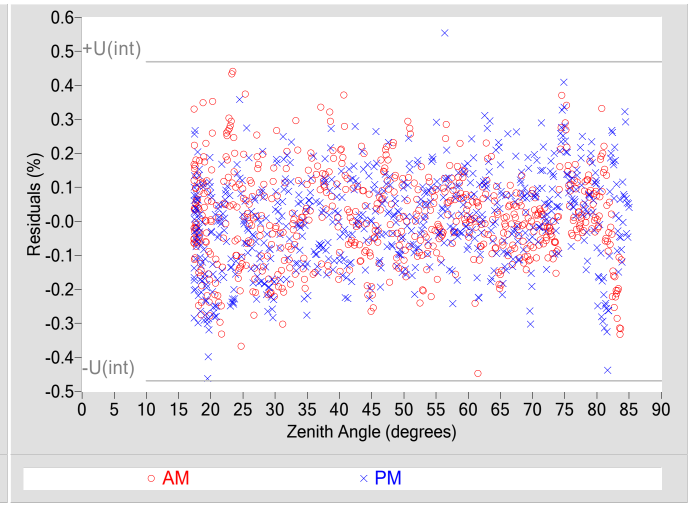


Table 3. Uncertainty using Spline Interpolation ‡

Type-B Standard Uncertainty, u(B) (%)	±0.47
Type-A Interpolating Function, u(int) (%)	±0.23
Combined Standard Uncertainty, u(c) (%)	±0.53
Effective degrees of freedom, DF(c)	2407
Coverage factor, k	1.96
Expanded Uncertainty, U95 (%)	±1.0
AM Valid zenith angle range	18° to 72°
PM Valid zenith angle range	18° to 70°

‡ An illustration for how to reduce the uncertainty in calculating the irradiance using a function rather than R@45°. Not accredited.

Table 4. Calibration Label Values

R @ 45° (µV/W/m²)	Rnet (µV/W/m²) †
10.817	0

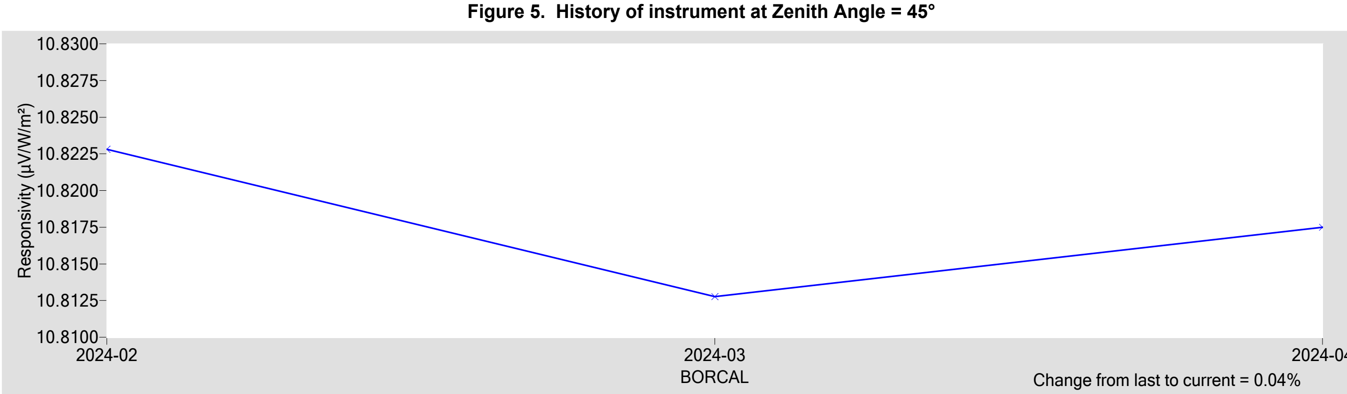
† Rnet determination date: N/A

Table 5. Uncertainty using R @ 45°

Type-B Expanded Uncertainty, U(B) (%)	±0.74
Offset Uncertainty, U(off) (%)	+1.0 / -1.2
Expanded Uncertainty, U (%)	+1.8 / -1.9
Effective degrees of freedom, DF *	2000
Coverage factor, k	1.96
Valid zenith angle range	30.0° to 60.0°

* The DF of each variable in Eq 1 is commonly assumed to be infinite per the GUM for rectangular distribution, but for simplicity 1000 is used for each.

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 2024-04

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

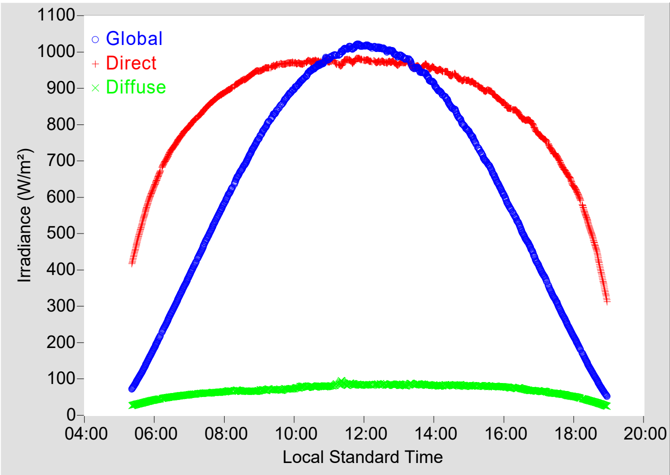
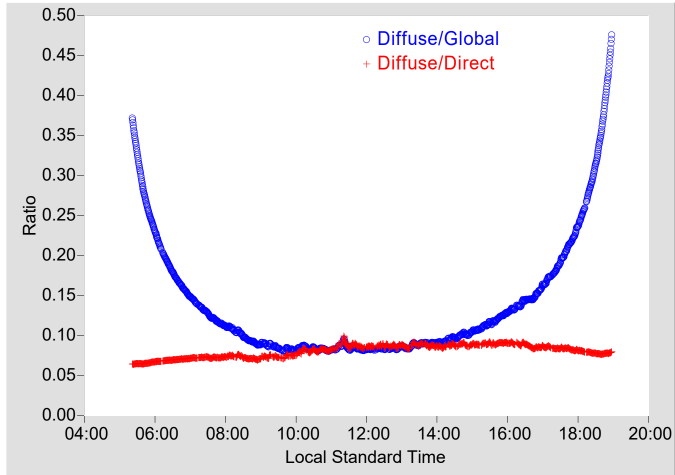


Figure 7. Diffuse Ratios



Meteorological Observations:

Figure 8. Temperature

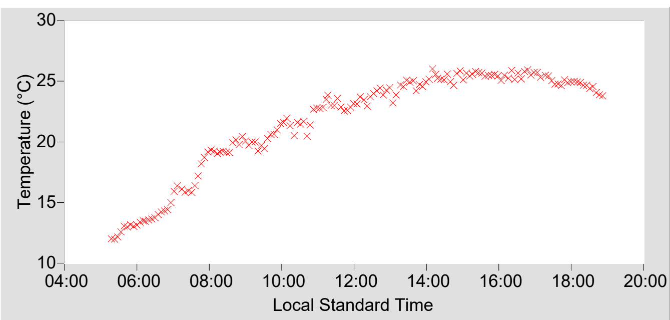


Figure 9. Humidity

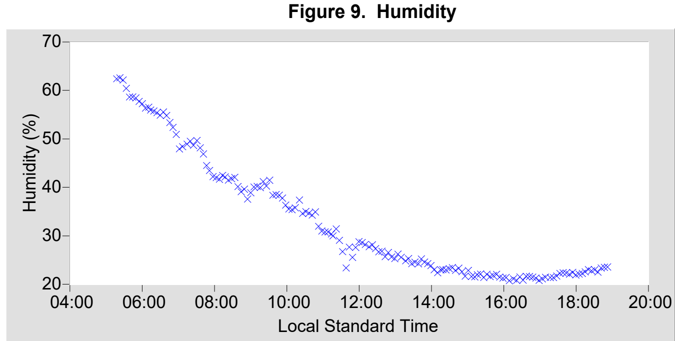


Figure 10. Pressure

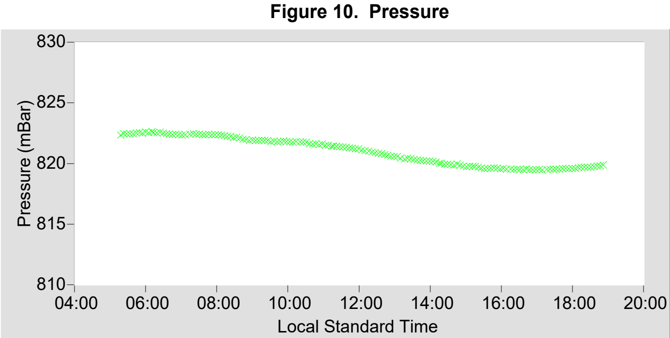


Figure 11. Effective Net Infrared

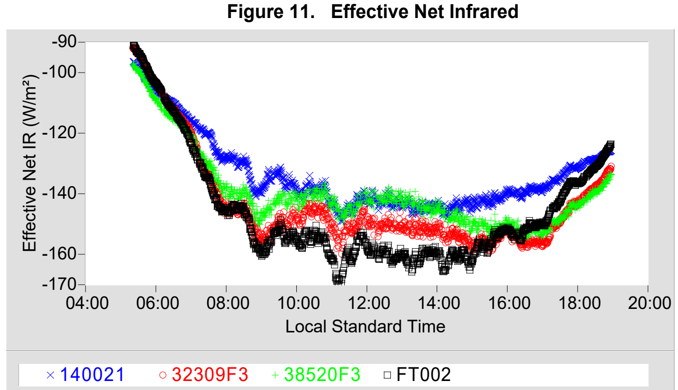


Figure 12. Estimated Broadband Aerosol Optical Depth

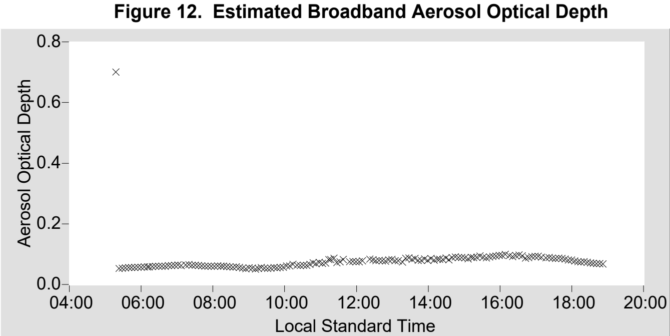


Table 6. Meteorological Observations

Observations	Mean	Min	Max
Temperature (°C)	21.70	11.98	26.01
Humidity (%)	33.03	20.73	62.62
Pressure (mBar)	821.0	819.5	822.6
Est. Aerosol Optical Depth (BB)	0.077	0.051	0.701

For other information about the calibration facility visit: https://www.nrel.gov/grid/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).