

Broadband Outdoor Radiometer Calibration Shortwave

BORCAL-SW 2021-02

Generated by



Radiometer Calibration and Characterization

Customer

NREL-SRRL-BMS

Organization: NREL

Address: BMS, SRRL, Golden, CO 80401 USA

Phone: 303-384-6326

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

05/06/2021

Report Date

December 9, 2021



NOTICE

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Broadband Outdoor Radiometer Calibration Report

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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.

BORCAL Notes or Comments

This report has been revised to accommodate updated responsivities given by the calibration provider of the BORCAL reference irradiance instruments. This report replaces the report with an issue date of May 7, 2021. This update affects all responsivities for the devices under test issued in this report by approximately -0.675%. There will also be a very slightly change in reported uncertainties due the reference irradiance instruments' uncertainties changing as well.

Control Instrument History

Figure 1. Eppley NIP Control Instrument History

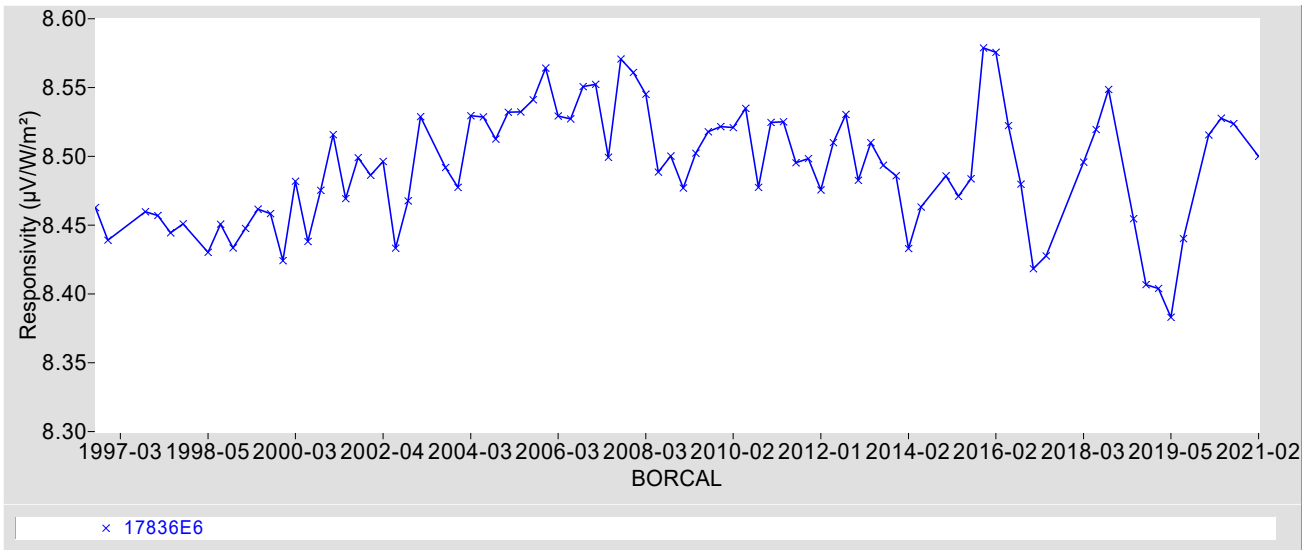


Figure 2. Eppley PSP Control Instrument History

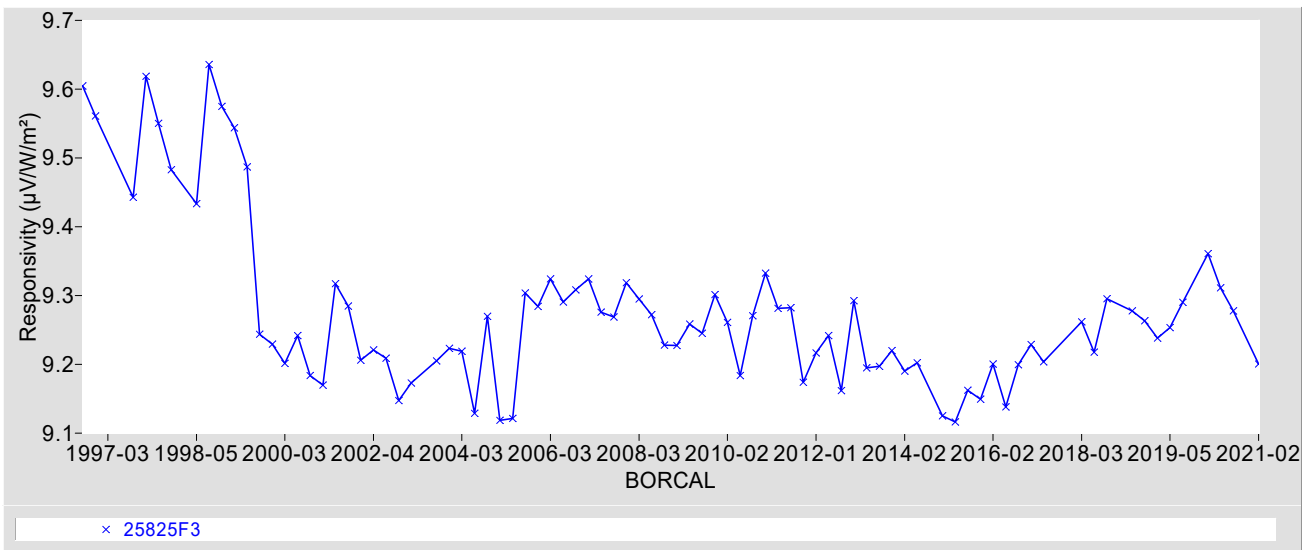
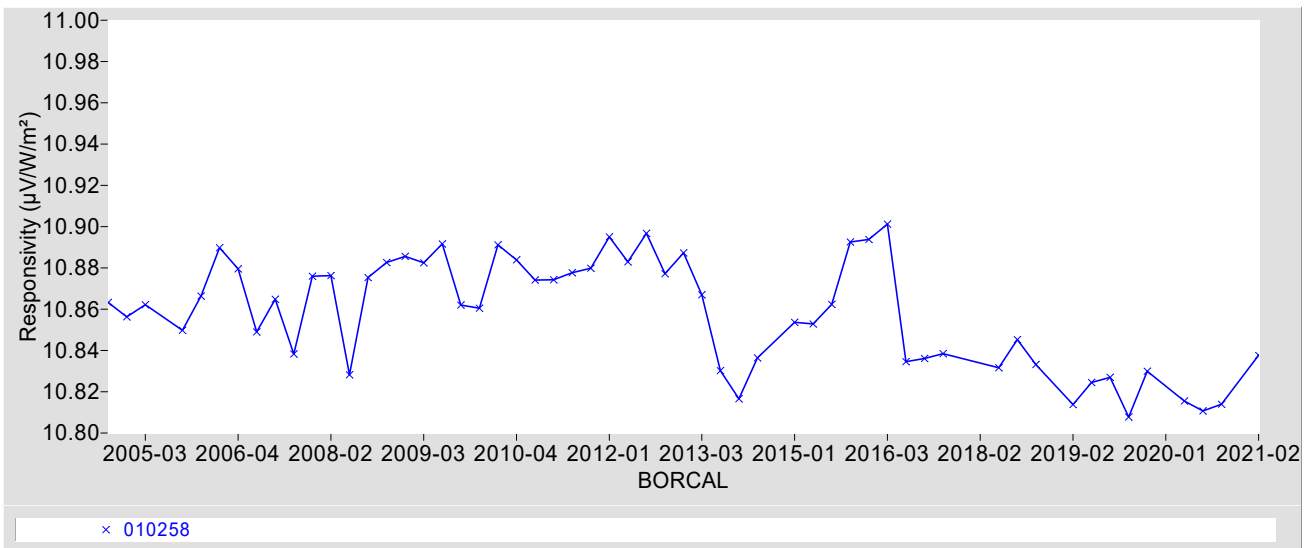


Figure 3. Kipp & Zonen CH1 Control Instrument History



Results Summary

Table 1. Results Summary

Instrument	R@45 ¹ ($\mu\text{V}/\text{W}/\text{m}^2$)	CF@45 ¹ ($\text{W}/\text{m}^2/\text{mV}$)	U ² (%)	Rnet ³ ($\mu\text{V}/\text{W}/\text{m}^2$)	Page
010047 Kipp & Zonen CM22	9.7564	102.50	+1.0 / -0.85	0.087000	A1-2
010995 Kipp & Zonen SP-LITE	75.868	13.181	+2.1 / -1.6	0	A1-5
014261 Kipp & Zonen CM3	21.929	45.602	+2.0 / -1.3	0.40000	A1-8
015189 Kipp & Zonen CM6B	10.906	91.697	+1.6 / -1.3	0.30000	A1-11
0212-2 Yankee TSP-700	2988.1	0.33466	+2.0 / -1.7	0	A1-14
080009 Kipp & Zonen CHP1	7.9411	125.93	+0.90 / -0.79	0	A1-17
080017 Kipp & Zonen CMP22	10.502	95.217	+1.3 / -1.5	0.087000	A1-20
100174 Kipp & Zonen CMP22	9.7980	102.06	+1.2 / -0.99	0.087000	A1-23
1171 Apogee SP-510	52.808	18.937	+3.1 / -5.2	2.5000	A1-26
140043 Kipp & Zonen CMP22	9.0521	110.47	+1.1 / -1.1	0.087000	A1-29
140108 Kipp & Zonen CHP1	8.0952	123.53	+0.94 / -0.87	0	A1-32
140712 Kipp & Zonen CMP11	9.0490	110.51	+1.6 / -1.3	0.20500	A1-35
151027 Kipp & Zonen SP-LITE2	69.425	14.404	+3.3 / -2.4	0	A1-38
151041 Kipp & Zonen SP-LITE2	70.746	14.135	+2.2 / -2.3	0	A1-41
170515 Kipp & Zonen CMP22	9.3252	107.24	+1.2 / -1.2	0.087000	A1-44
2529 Hukseflux SR25	9.3986	106.40	+1.6 / -1.4	0.043000	A1-47
2543 Hukseflux SR25	9.5693	104.50	+1.2 / -1.2	0.043000	A1-50
28402F3 Eppley PSP	6.9859	143.15	+2.3 / -1.9	0.64000	A1-53
31137E6 Eppley NIP	8.4840	117.87	+1.3 / -1.1	0	A1-56
32331 Eppley 8-48	8.9233	112.07	+4.5 / -2.5	0	A1-59
34718 Eppley 8-48	9.3966	106.42	+3.5 / -2.3	0	A1-62
37831F3 Eppley GPP	8.4616	118.18	+1.7 / -2.6	0.15000	A1-65
37839F3 Eppley SPP	8.6760	115.26	+1.7 / -1.7	0.30000	A1-68
37882E6 Eppley sNIP	8.4011	119.03	+0.87 / -0.84	0	A1-71
38860F3 Eppley SPP	7.3114	136.77	+1.8 / -2.2	0.22000	A1-74
40337 Apogee SP-110	183.18	5.4592	+1.8 / -1.6	0	A1-77
9206 Hukseflux DR02	11.028	90.681	+0.91 / -0.84	0	A1-80
A360 Delta-T SPN1	1016.5	0.98377	+7.4 / -4.7	0	A1-83
F14077R EKO MS-802	7.0835	141.17	+1.5 / -2.2	0.18000	A1-86
PY100360 Licor LI200R	10.841	92.242	+1.4 / -1.2	0	A1-89
PY108624 Licor LI200R	10.141	98.611	+1.4 / -1.2	0	A1-92
PY28257 Licor LI200	13.902	71.930	+2.4 / -2.5	0	A1-95
PYHR101 Licor LI201SB	5.6021	178.50	+4.1 / -2.3	0	A1-98
S13071483 EKO MS-602	6.9072	144.78	+2.8 / -2.8	0.30000	A1-101
S13135063 EKO ML-01	41.157	24.297	+1.5 / -1.1	0	A1-104
S13144.085R EKO MS-410	9.2827	107.73	+1.4 / -1.4	0.20000	A1-107
S17096005 EKO MS-80	10.628	94.095	+1.4 / -1.2	0.043000	A1-110
S18015.22 EKO MS-57	6.6900	149.48	+0.73 / -0.89	0	A1-113

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 A1-116.

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



Test Instrument:	Pyranometer (Ventilated)	Manufacturer:	Kipp & Zonen
Model:	CM22	Serial Number:	010047
Calibration Date:	5/6/2021	Due Date:	5/6/2022
Customer:	NREL-SRRL-BMS	Environmental Conditions:	see page 4
Test Dates:	5/6		

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 than 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	09/27/2019	09/27/2021
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/30/2021	04/30/2022
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/30/2021	04/30/2022
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/08/2021	02/08/2023
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/08/2021	02/08/2023
Infrared Irradiance ‡	Kipp & Zonen Pyrgeometer Model CGR4, S/N 140021	04/02/2019	04/02/2023

† 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, Peter Gotseff, 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

010047 Kipp & Zonen CM22

The responsivity (R , $\mu\text{V}/\text{W}/\text{m}^2$) of the test instrument during calibration is calculated using this Measurement Equation:

$$R = (V - R_{net} * W_{net}) / I \tag{1}$$

where,

- V = radiometer output voltage (microvolts),
 - R_{net} = radiometer net infrared responsivity ($\mu\text{V}/\text{W}/\text{m}^2$), see Table 4,
 - W_{net} = effective net infrared measured by pyrgeometer (W/m^2),
 - = $W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
 - where, W_{in} = incoming infrared (W/m^2), $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$,
 - T_c = case temperature of pyrgeometer (K).
- I = reference irradiance (W/m^2), beam (B) or global (G)
 - where, $G = B * \text{COS}(Z) + D$,
 - Z = zenith angle (degrees),
 - D = reference diffuse irradiance (W/m^2).

Figure 1. Responsivity vs Zenith Angle

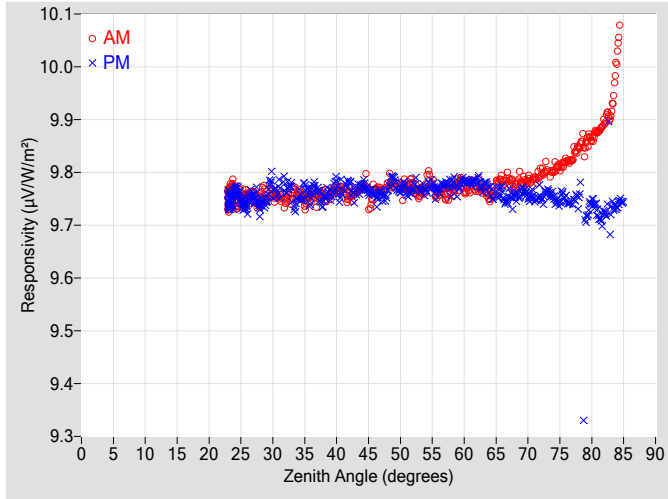


Figure 2. Responsivity vs Local Standard Time

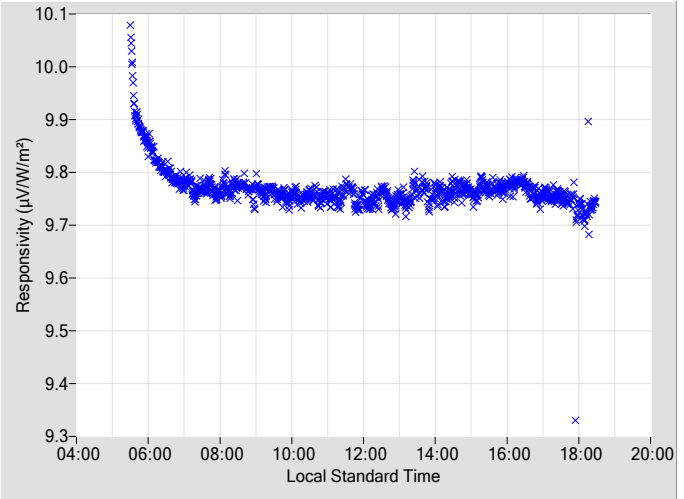


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, $u(B)$

Zenith Angle (deg.)	R ($\mu\text{V}/\text{W}/\text{m}^2$)	AM $u(B)$ \pm (%)	Azimuth Angle	R ($\mu\text{V}/\text{W}/\text{m}^2$)	PM $u(B)$ \pm (%)	Azimuth Angle	Zenith Angle (deg.)	R ($\mu\text{V}/\text{W}/\text{m}^2$)	AM $u(B)$ \pm (%)	Azimuth Angle	R ($\mu\text{V}/\text{W}/\text{m}^2$)	PM $u(B)$ \pm (%)	Azimuth Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	9.7707	0.33	106.44	9.7535	0.35	253.77
2	N/A	N/A	N/A	N/A	N/A	N/A	48	9.7737	0.36	104.35	9.7652	0.32	255.95
4	N/A	N/A	N/A	N/A	N/A	N/A	50	9.7754	0.35	102.04	9.7670	0.37	258.06
6	N/A	N/A	N/A	N/A	N/A	N/A	52	9.7705	0.34	100.03	9.7681	0.33	260.02
8	N/A	N/A	N/A	N/A	N/A	N/A	54	9.7760	0.33	98.15	9.7636	0.34	261.95
10	N/A	N/A	N/A	N/A	N/A	N/A	56	9.7601	0.35	96.32	9.7661	0.34	263.85
12	N/A	N/A	N/A	N/A	N/A	N/A	58	9.7641	0.37	94.52	9.7738	0.37	265.68
14	N/A	N/A	N/A	N/A	N/A	N/A	60	9.7679	0.35	92.72	9.7851	0.36	267.36
16	N/A	N/A	N/A	N/A	N/A	N/A	62	9.7672	0.38	91.09	9.7839	0.37	269.11
18	N/A	N/A	N/A	N/A	N/A	N/A	64	9.7546	0.42	89.39	9.7659	0.39	270.81
20	N/A	N/A	N/A	N/A	N/A	N/A	66	9.7828	0.50	87.71	9.7614	0.41	272.41
22	N/A	N/A	N/A	N/A	N/A	N/A	68	9.7727	0.41	86.16	9.7552	0.43	274.07
24	9.7596	0.34	160.60	9.7586	0.32	199.16	70	9.7860	0.43	84.51	9.7540	0.46	275.62
26	9.7554	0.31	148.28	9.7423	0.32	211.85	72	9.7998	0.47	82.88	9.7566	N/A	277.25
28	9.7468	0.34	140.04	9.7354	0.30	220.16	74	9.8054	0.51	81.32	9.7521	N/A	278.87
30	9.7579	0.30	133.56	9.7744	0.34	226.44	76	9.8220	N/A	79.71	9.7458	N/A	280.49
32	9.7461	0.34	128.55	9.7703	0.34	231.57	78	9.8489	N/A	78.10	9.7560	N/A	282.09
34	9.7608	0.31	124.29	9.7550	0.30	235.82	80	9.8626	N/A	76.49	9.7445	N/A	283.67
36	9.7581	0.33	120.48	9.7531	0.33	239.61	82	9.8936	N/A	74.87	9.7227	N/A	285.35
38	9.7646	0.35	117.06	9.7454	0.32	242.98	84	10.029	N/A	73.15	9.7362	N/A	287.04
40	9.7681	0.32	114.17	9.7796	0.36	246.03	86	N/A	N/A	N/A	N/A	N/A	N/A
42	9.7564	0.34	111.36	9.7777	0.34	248.81	88	N/A	N/A	N/A	N/A	N/A	N/A
44	9.7739	0.36	108.76	9.7755	0.37	251.34	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

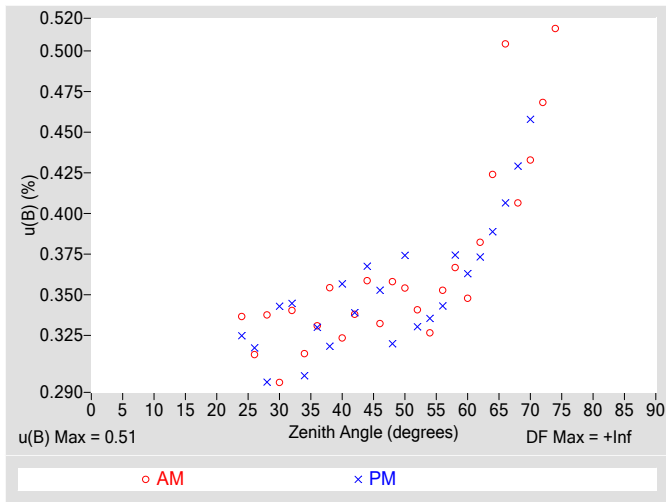


Figure 4. Residuals from Spline Interpolation

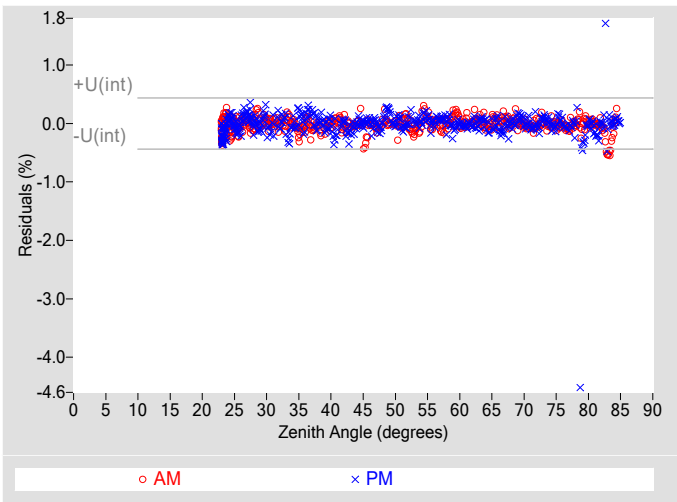


Table 3. Uncertainty using Spline Interpolation ‡

Type-B Standard Uncertainty, u(B) (%)	±0.51
Type-A Interpolating Function, u(int) (%)	±0.22
Combined Standard Uncertainty, u(c) (%)	±0.56
Effective degrees of freedom, DF(c)	38693
Coverage factor, k	1.96
Expanded Uncertainty, U95 (%)	±1.1
AM Valid zenith angle range	24° to 74°
PM Valid zenith angle range	24° 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

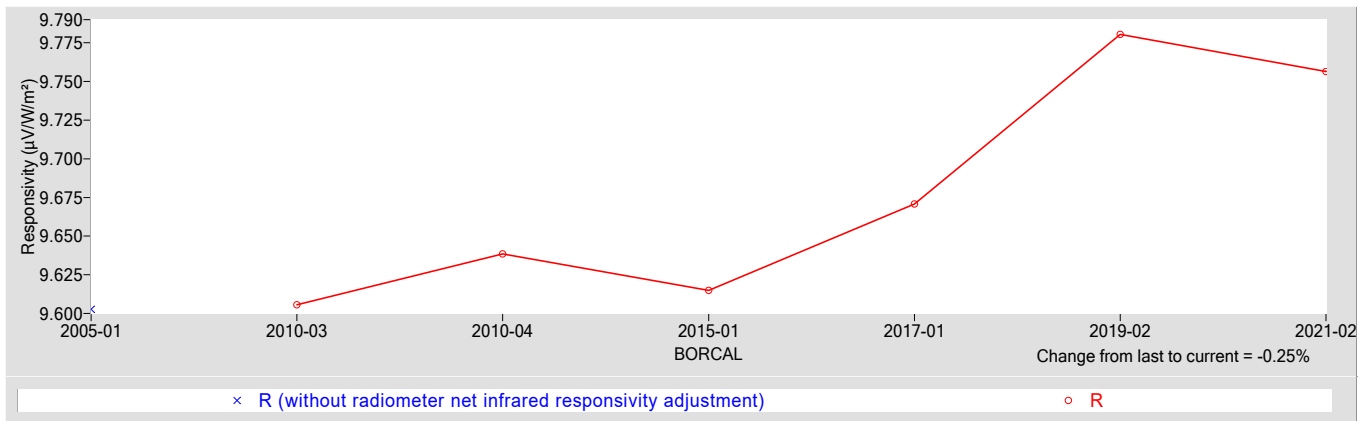
R @ 45° (μV/W/m²)	Rnet (μV/W/m²) †
9.7564	0.087000

† Rnet determination date: Estimated

Table 5. Uncertainty using R @ 45°

Type-B Expanded Uncertainty, U(B) (%)	±0.73
Offset Uncertainty, U(off) (%)	+0.29 / -0.11
Expanded Uncertainty, U (%)	+1.0 / -0.85
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 Pyrgometers. ARM 2008 Science Team Meeting (Poster).

National Renewable Energy Laboratory

Solar Radiation Research Laboratory

Metrology Laboratory

Calibration Certificate



Test Instrument: Silicon Pyranometer
Manufacturer: Kipp & Zonen
Model: SP-LITE
Serial Number: 010995
Calibration Date: 5/6/2021
Due Date: 5/6/2022
Customer: NREL-SRRL-BMS
Environmental Conditions: see page 4
Test Dates: 5/6

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	09/27/2019	09/27/2021
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/30/2021	04/30/2022
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/30/2021	04/30/2022
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/08/2021	02/08/2023
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/08/2021	02/08/2023

† 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, Peter Gotseff, 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

010995 Kipp & Zonen SP-LITE

The responsivity (R , $\mu\text{V}/\text{W}/\text{m}^2$) of the test instrument during calibration is calculated using this Measurement Equation:

$$R = (V - R_{net} * W_{net}) / I \tag{1}$$

where,

- V = radiometer output voltage (microvolts),
 - R_{net} = radiometer net infrared responsivity ($\mu\text{V}/\text{W}/\text{m}^2$), see Table 4,
 - W_{net} = effective net infrared measured by pyrgeometer (W/m^2),
 - = $W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
 - where, W_{in} = incoming infrared (W/m^2), $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$,
 - T_c = case temperature of pyrgeometer (K).
- I = reference irradiance (W/m^2), beam (B) or global (G)
 - where, $G = B * \text{COS}(Z) + D$,
 - Z = zenith angle (degrees),
 - D = reference diffuse irradiance (W/m^2).

Figure 1. Responsivity vs Zenith Angle

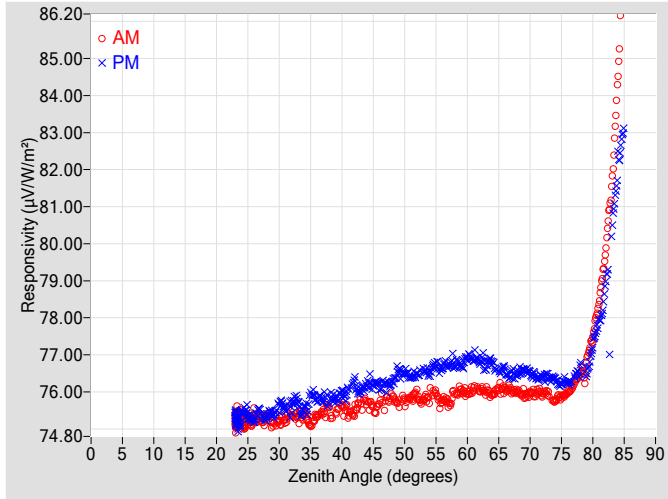


Figure 2. Responsivity vs Local Standard Time

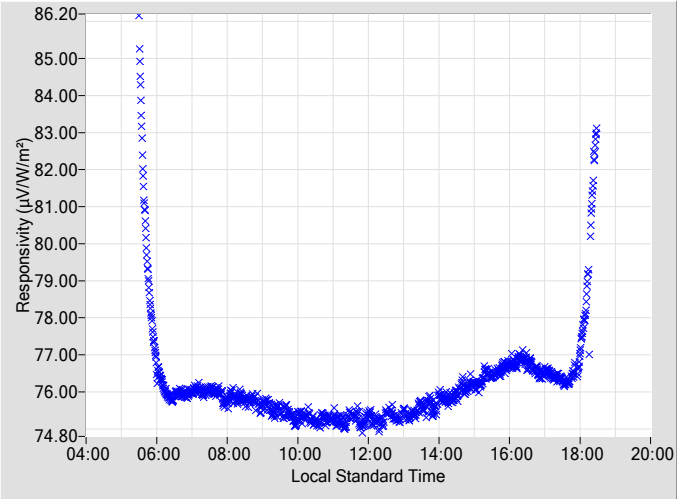


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, $u(B)$

Zenith			AM			PM			Zenith			AM			PM		
Angle	R	u(B)	Azimuth	R	u(B)	Azimuth	Angle	R	u(B)	Azimuth	R	u(B)	Azimuth	R	u(B)	Azimuth	
(deg.)	($\mu\text{V}/\text{W}/\text{m}^2$)	\pm (%)	Angle	($\mu\text{V}/\text{W}/\text{m}^2$)	\pm (%)	Angle	(deg.)	($\mu\text{V}/\text{W}/\text{m}^2$)	\pm (%)	Angle	($\mu\text{V}/\text{W}/\text{m}^2$)	\pm (%)	Angle	($\mu\text{V}/\text{W}/\text{m}^2$)	\pm (%)	Angle	
0	N/A	N/A	N/A	N/A	N/A	N/A	46	75.707	0.34	106.47	76.154	0.33	253.72				
2	N/A	N/A	N/A	N/A	N/A	N/A	48	75.905	0.34	104.13	76.253	0.32	255.94				
4	N/A	N/A	N/A	N/A	N/A	N/A	50	75.752	0.33	102.03	76.522	0.32	258.11				
6	N/A	N/A	N/A	N/A	N/A	N/A	52	75.894	0.36	100.01	76.459	0.36	260.07				
8	N/A	N/A	N/A	N/A	N/A	N/A	54	75.879	0.32	98.24	76.508	0.33	262.00				
10	N/A	N/A	N/A	N/A	N/A	N/A	56	75.767	0.35	96.31	76.650	0.34	263.84				
12	N/A	N/A	N/A	N/A	N/A	N/A	58	75.979	0.37	94.52	76.712	0.35	265.67				
14	N/A	N/A	N/A	N/A	N/A	N/A	60	75.961	0.34	92.70	76.936	0.36	267.35				
16	N/A	N/A	N/A	N/A	N/A	N/A	62	76.041	0.43	91.08	76.810	0.37	269.10				
18	N/A	N/A	N/A	N/A	N/A	N/A	64	75.927	0.37	89.38	76.762	0.38	270.80				
20	N/A	N/A	N/A	N/A	N/A	N/A	66	76.051	0.47	87.70	76.584	0.40	272.40				
22	N/A	N/A	N/A	N/A	N/A	N/A	68	76.011	0.40	86.15	76.503	0.42	274.06				
24	75.294	0.32	161.09	75.319	0.33	198.67	70	75.961	0.42	84.50	76.499	0.45	275.61				
26	75.334	0.31	148.12	75.263	0.33	211.88	72	75.948	0.46	82.92	76.425	N/A	277.24				
28	75.360	0.33	139.87	75.299	0.32	219.92	74	75.758	0.50	81.31	76.342	N/A	278.86				
30	75.178	0.31	133.63	75.654	0.31	226.51	76	76.000	N/A	79.70	76.247	N/A	280.48				
32	75.358	0.31	128.69	75.581	0.32	231.52	78	76.525	N/A	78.09	76.604	N/A	281.98				
34	75.361	0.34	124.22	75.607	0.31	236.00	80	77.505	N/A	76.47	77.250	N/A	283.66				
36	75.358	0.32	120.56	75.772	0.32	239.61	82	79.720	N/A	74.86	78.880	N/A	285.34				
38	75.520	0.34	117.18	75.773	0.34	242.96	84	84.573	N/A	73.14	82.057	N/A	287.03				
40	75.611	0.36	114.03	75.983	0.30	246.02	86	N/A	N/A	N/A	N/A	N/A	N/A				
42	75.481	0.34	111.35	76.243	0.32	248.87	88	N/A	N/A	N/A	N/A	N/A	N/A				
44	75.720	0.33	108.78	76.233	0.31	251.33	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

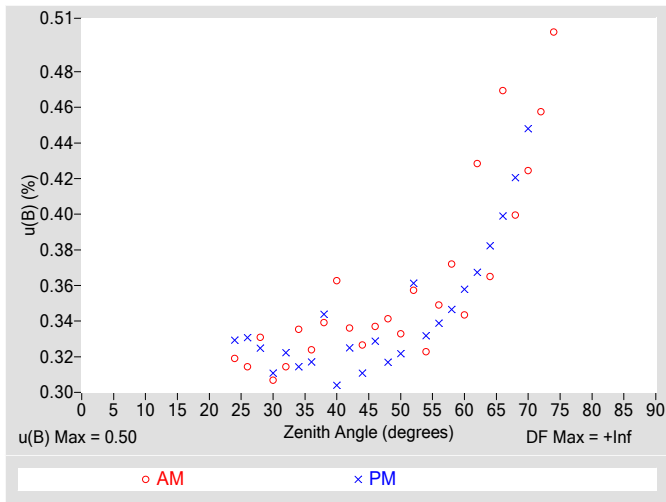


Figure 4. Residuals from Spline Interpolation

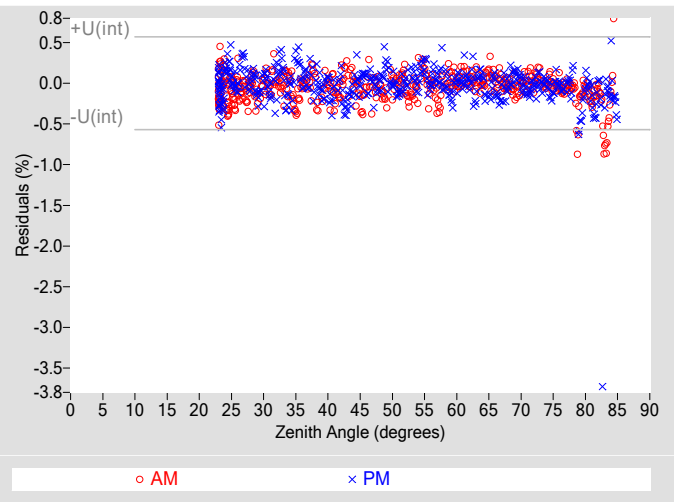


Table 3. Uncertainty using Spline Interpolation ‡

Type-B Standard Uncertainty, $u(B)$ (%)	± 0.50
Type-A Interpolating Function, $u(int)$ (%)	± 0.29
Combined Standard Uncertainty, $u(c)$ (%)	± 0.58
Effective degrees of freedom, $DF(c)$	14985
Coverage factor, k	1.96
Expanded Uncertainty, U_{95} (%)	± 1.1
AM Valid zenith angle range	24° to 74°
PM Valid zenith angle range	24° to 70°

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

Table 4. Calibration Label Values

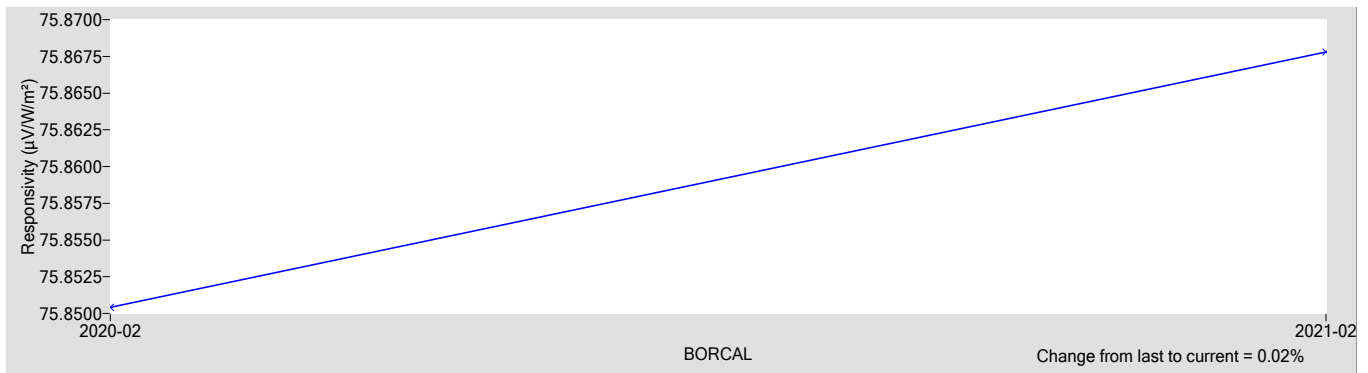
$R @ 45^\circ$ ($\mu V/W/m^2$)	R_{net} ($\mu V/W/m^2$) †
75.868	0

† R_{net} determination date: N/A

Table 5. Uncertainty using $R @ 45^\circ$

Type-B Expanded Uncertainty, $U(B)$ (%)	± 0.73
Offset Uncertainty, $U(off)$ (%)	+1.4 / -0.91
Expanded Uncertainty, U (%)	+2.1 / -1.6
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 Pyrgometers*. ARM 2008 Science Team Meeting (Poster).



National Renewable Energy Laboratory

Solar Radiation Research Laboratory

Metrology Laboratory

Calibration Certificate



Test Instrument:	Pyranometer	Manufacturer:	Kipp & Zonen
Model:	CM3	Serial Number:	014261
Calibration Date:	5/6/2021	Due Date:	5/6/2022
Customer:	NREL-SRRL-BMS	Environmental Conditions:	see page 4
Test Dates:	5/6		

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 than 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	09/27/2019	09/27/2021
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/30/2021	04/30/2022
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/30/2021	04/30/2022
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/08/2021	02/08/2023
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/08/2021	02/08/2023
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, Peter Gotseff, 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

014261 Kipp & Zonen CM3

The responsivity (R , $\mu\text{V}/\text{W}/\text{m}^2$) of the test instrument during calibration is calculated using this Measurement Equation:

$$R = (V - R_{net} * W_{net}) / I \tag{1}$$

where,

- V = radiometer output voltage (microvolts),
 - R_{net} = radiometer net infrared responsivity ($\mu\text{V}/\text{W}/\text{m}^2$), see Table 4,
 - W_{net} = effective net infrared measured by pyrgeometer (W/m^2),
 - = $W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
 - where, W_{in} = incoming infrared (W/m^2), $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$,
 - T_c = case temperature of pyrgeometer (K).
- I = reference irradiance (W/m^2), beam (B) or global (G)
 - where, $G = B * \text{COS}(Z) + D$,
 - Z = zenith angle (degrees),
 - D = reference diffuse irradiance (W/m^2).

Figure 1. Responsivity vs Zenith Angle

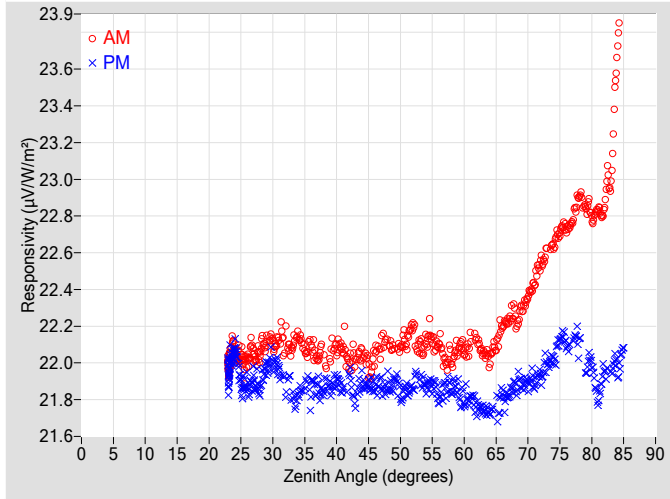


Figure 2. Responsivity vs Local Standard Time

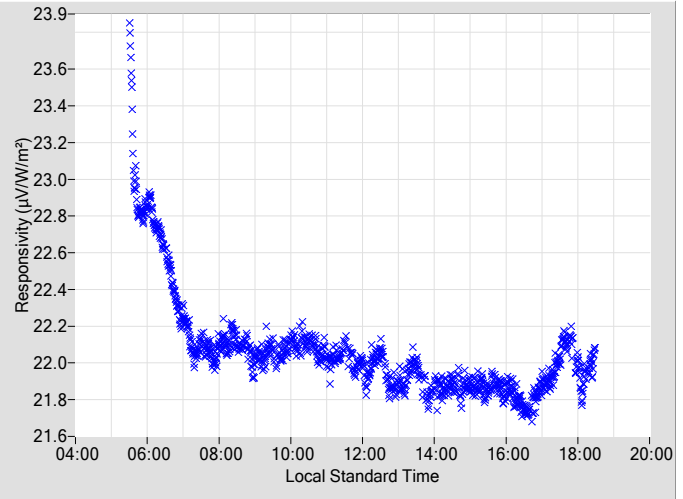


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, $u(B)$

Zenith			AM			PM			Zenith			AM			PM		
Angle	R	u(B)	Azimuth	R	u(B)	Azimuth	Angle	R	u(B)	Azimuth	R	u(B)	Azimuth	R	u(B)	Azimuth	
(deg.)	($\mu\text{V}/\text{W}/\text{m}^2$)	\pm (%)	Angle	($\mu\text{V}/\text{W}/\text{m}^2$)	\pm (%)	Angle	(deg.)	($\mu\text{V}/\text{W}/\text{m}^2$)	\pm (%)	Angle	($\mu\text{V}/\text{W}/\text{m}^2$)	\pm (%)	Angle	($\mu\text{V}/\text{W}/\text{m}^2$)	\pm (%)	Angle	
0	N/A	N/A	N/A	N/A	N/A	N/A	46	22.053	0.36	106.38	21.881	0.33	253.73				
2	N/A	N/A	N/A	N/A	N/A	N/A	48	22.112	0.36	104.10	21.881	0.34	255.96				
4	N/A	N/A	N/A	N/A	N/A	N/A	50	22.087	0.35	102.11	21.829	0.33	258.07				
6	N/A	N/A	N/A	N/A	N/A	N/A	52	22.200	0.34	100.09	21.874	0.35	260.09				
8	N/A	N/A	N/A	N/A	N/A	N/A	54	22.108	0.37	98.15	21.869	0.36	262.01				
10	N/A	N/A	N/A	N/A	N/A	N/A	56	22.109	0.35	96.27	21.805	0.36	263.86				
12	N/A	N/A	N/A	N/A	N/A	N/A	58	22.026	0.38	94.49	21.849	0.35	265.63				
14	N/A	N/A	N/A	N/A	N/A	N/A	60	22.073	0.35	92.77	21.810	0.36	267.42				
16	N/A	N/A	N/A	N/A	N/A	N/A	62	22.122	0.36	91.04	21.753	0.40	269.06				
18	N/A	N/A	N/A	N/A	N/A	N/A	64	22.021	0.37	89.35	21.729	0.42	270.76				
20	N/A	N/A	N/A	N/A	N/A	N/A	66	22.191	0.39	87.77	21.816	0.41	272.41				
22	N/A	N/A	N/A	N/A	N/A	N/A	68	22.252	0.41	86.11	21.872	0.43	274.02				
24	22.064	0.32	160.94	22.049	0.32	198.88	70	22.362	0.46	84.52	21.885	0.46	275.67				
26	22.016	0.32	148.14	21.868	0.31	212.07	72	22.542	0.47	82.93	21.926	N/A	277.21				
28	22.060	0.34	140.05	21.853	0.33	219.95	74	22.643	0.51	81.28	22.016	N/A	278.83				
30	22.109	0.34	133.65	21.982	0.32	226.65	76	22.732	N/A	79.76	22.100	N/A	280.45				
32	22.128	0.33	128.67	21.859	0.32	231.41	78	22.906	N/A	78.15	22.099	N/A	282.04				
34	22.142	0.32	124.25	21.832	0.33	235.93	80	22.791	N/A	76.49	21.989	N/A	283.72				
36	22.092	0.38	120.35	21.855	0.30	239.72	82	22.863	N/A	74.82	21.955	N/A	285.35				
38	22.015	0.38	116.87	21.857	0.31	242.90	84	23.692	N/A	73.15	21.978	N/A	287.04				
40	22.085	0.37	114.06	21.901	0.32	246.04	86	N/A	N/A	N/A	N/A	N/A	N/A				
42	22.010	0.33	111.37	21.938	0.31	248.89	88	N/A	N/A	N/A	N/A	N/A	N/A				
44	22.050	0.33	108.88	21.895	0.33	251.34	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

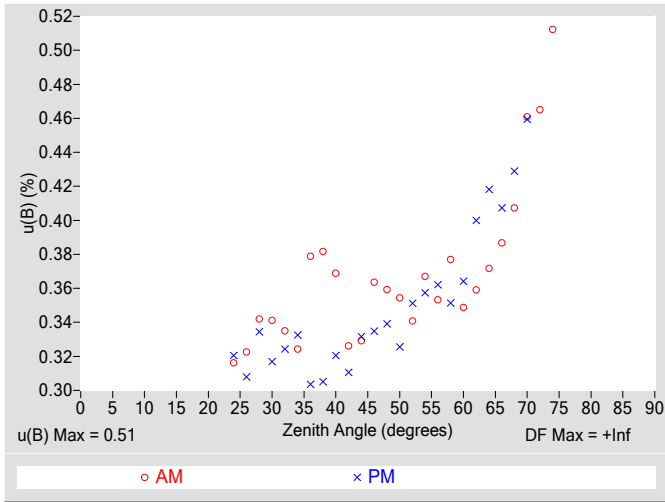


Figure 4. Residuals from Spline Interpolation

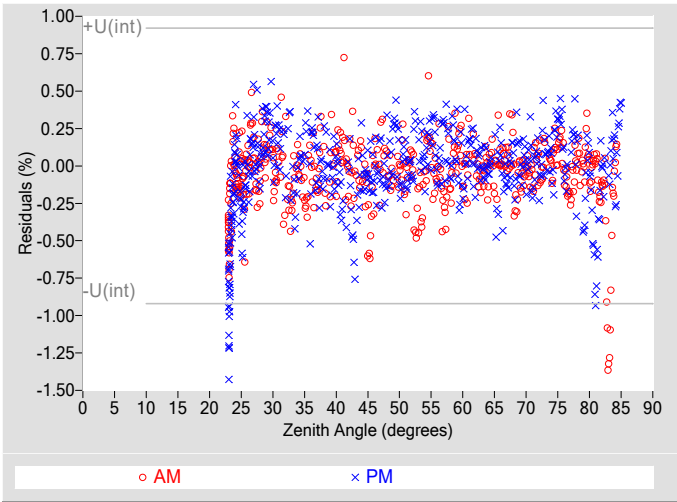


Table 3. Uncertainty using Spline Interpolation ‡

Type-B Standard Uncertainty, $u(B)$ (%)	± 0.51
Type-A Interpolating Function, $u(int)$ (%)	± 0.46
Combined Standard Uncertainty, $u(c)$ (%)	± 0.69
Effective degrees of freedom, $DF(c)$	4458
Coverage factor, k	1.96
Expanded Uncertainty, U_{95} (%)	± 1.4
AM Valid zenith angle range	24° to 74°
PM Valid zenith angle range	24° to 70°

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

Table 4. Calibration Label Values

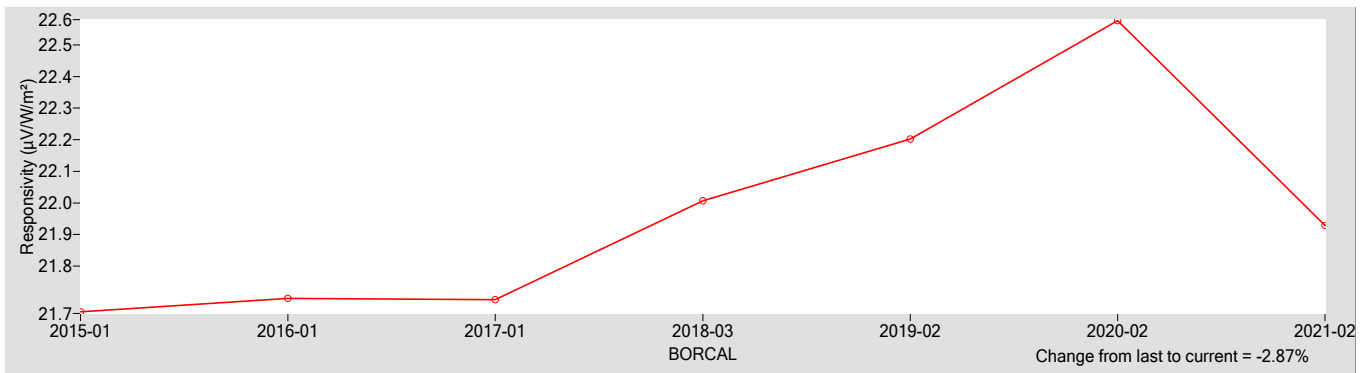
$R @ 45^\circ$ ($\mu V/W/m^2$)	R_{net} ($\mu V/W/m^2$) †
21.929	0.40000

† R_{net} determination date: Estimated

Table 5. Uncertainty using $R @ 45^\circ$

Type-B Expanded Uncertainty, $U(B)$ (%)	± 0.75
Offset Uncertainty, $U(off)$ (%)	+1.2 / -0.56
Expanded Uncertainty, U (%)	+2.0 / -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 Pyrgometers. ARM 2008 Science Team Meeting (Poster).



National Renewable Energy Laboratory

Solar Radiation Research Laboratory

Metrology Laboratory

Calibration Certificate



Test Instrument:	Pyranometer	Manufacturer:	Kipp & Zonen
Model:	CM6B	Serial Number:	015189
Calibration Date:	5/6/2021	Due Date:	5/6/2022
Customer:	NREL-SRRL-BMS	Environmental Conditions:	see page 4
Test Dates:	5/6		

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 than 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	09/27/2019	09/27/2021
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/30/2021	04/30/2022
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/30/2021	04/30/2022
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/08/2021	02/08/2023
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/08/2021	02/08/2023
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, Peter Gotseff, 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

015189 Kipp & Zonen CM6B

The responsivity (R , $\mu\text{V}/\text{W}/\text{m}^2$) of the test instrument during calibration is calculated using this Measurement Equation:

$$R = (V - R_{net} * W_{net}) / I \tag{1}$$

where,

- V = radiometer output voltage (microvolts),
 - R_{net} = radiometer net infrared responsivity ($\mu\text{V}/\text{W}/\text{m}^2$), see Table 4,
 - W_{net} = effective net infrared measured by pyrgeometer (W/m^2),
 - = $W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
 - where, W_{in} = incoming infrared (W/m^2), $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$,
 - T_c = case temperature of pyrgeometer (K).
- I = reference irradiance (W/m^2), beam (B) or global (G)
 - where, $G = B * \text{COS}(Z) + D$,
 - Z = zenith angle (degrees),
 - D = reference diffuse irradiance (W/m^2).

Figure 1. Responsivity vs Zenith Angle

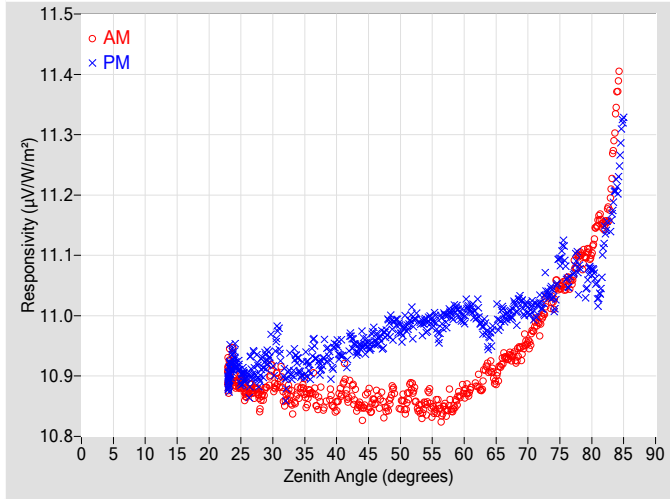


Figure 2. Responsivity vs Local Standard Time

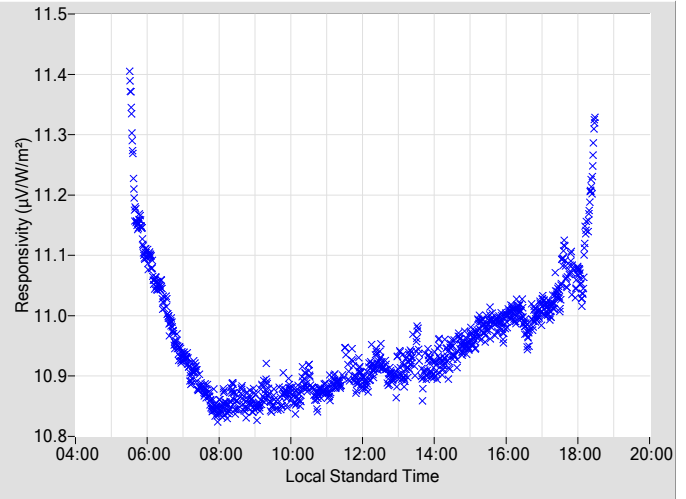


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)

Zenith			AM			PM			Zenith			AM			PM		
Angle	R	u(B)	Azimuth	R	u(B)	Azimuth	Angle	R	u(B)	Azimuth	R	u(B)	Azimuth	R	u(B)	Azimuth	
(deg.)	($\mu\text{V}/\text{W}/\text{m}^2$)	± (%)	Angle	($\mu\text{V}/\text{W}/\text{m}^2$)	± (%)	Angle	(deg.)	($\mu\text{V}/\text{W}/\text{m}^2$)	± (%)	Angle	($\mu\text{V}/\text{W}/\text{m}^2$)	± (%)	Angle	($\mu\text{V}/\text{W}/\text{m}^2$)	± (%)	Angle	
0	N/A	N/A	N/A	N/A	N/A	N/A	46	10.861	0.35	106.38	10.964	0.32	253.74				
2	N/A	N/A	N/A	N/A	N/A	N/A	48	10.848	0.32	104.18	10.984	0.33	255.96				
4	N/A	N/A	N/A	N/A	N/A	N/A	50	10.850	0.32	102.03	10.974	0.35	258.07				
6	N/A	N/A	N/A	N/A	N/A	N/A	52	10.879	0.35	100.09	10.989	0.38	260.09				
8	N/A	N/A	N/A	N/A	N/A	N/A	54	10.851	0.33	98.15	10.985	0.38	262.02				
10	N/A	N/A	N/A	N/A	N/A	N/A	56	10.849	0.36	96.27	10.973	0.35	263.86				
12	N/A	N/A	N/A	N/A	N/A	N/A	58	10.847	0.39	94.45	11.002	0.36	265.63				
14	N/A	N/A	N/A	N/A	N/A	N/A	60	10.875	0.38	92.77	11.001	0.37	267.42				
16	N/A	N/A	N/A	N/A	N/A	N/A	62	10.889	0.37	91.04	11.008	0.41	269.07				
18	N/A	N/A	N/A	N/A	N/A	N/A	64	10.911	0.41	89.33	10.959	0.40	270.77				
20	N/A	N/A	N/A	N/A	N/A	N/A	66	10.924	0.48	87.77	11.005	0.42	272.37				
22	N/A	N/A	N/A	N/A	N/A	N/A	68	10.929	0.42	86.11	11.011	0.44	274.03				
24	10.889	0.33	160.18	10.925	0.33	199.00	70	10.954	0.44	84.52	11.009	0.47	275.67				
26	10.872	0.33	148.31	10.901	0.31	211.76	72	10.987	0.52	82.94	11.020	N/A	277.21				
28	10.861	0.32	140.06	10.901	0.32	220.05	74	11.028	0.53	81.28	11.024	N/A	278.83				
30	10.900	0.33	133.85	10.909	0.30	226.78	76	11.051	N/A	79.77	11.069	N/A	280.45				
32	10.860	0.34	128.51	10.890	0.34	231.46	78	11.100	N/A	78.11	11.067	N/A	282.05				
34	10.872	0.33	124.33	10.917	0.33	235.88	80	11.104	N/A	76.49	11.075	N/A	283.73				
36	10.872	0.35	120.51	10.926	0.36	239.72	82	11.152	N/A	74.82	11.132	N/A	285.36				
38	10.845	0.34	117.13	10.934	0.31	242.91	84	11.369	N/A	73.16	11.216	N/A	287.00				
40	10.851	0.34	114.06	10.949	0.34	246.09	86	N/A	N/A	N/A	N/A	N/A	N/A				
42	10.871	0.31	111.45	10.961	0.34	248.90	88	N/A	N/A	N/A	N/A	N/A	N/A				
44	10.845	0.33	108.78	10.956	0.35	251.35	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

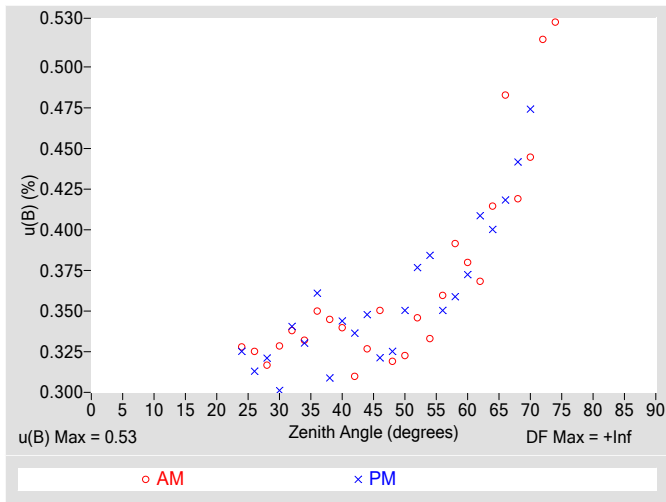


Figure 4. Residuals from Spline Interpolation

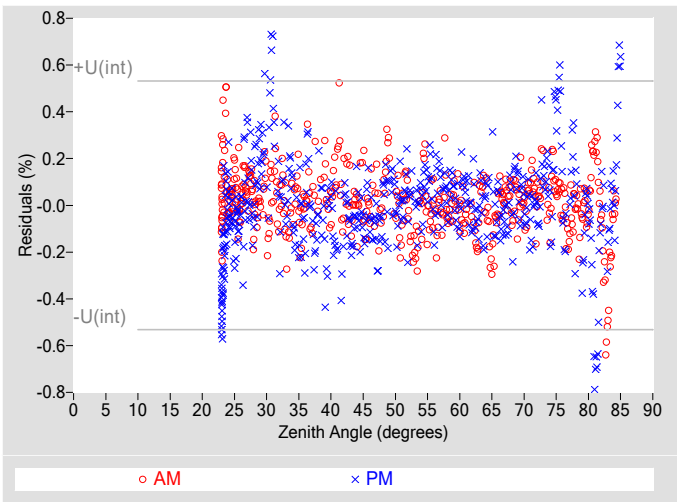


Table 3. Uncertainty using Spline Interpolation ‡

Type-B Standard Uncertainty, $u(B)$ (%)	± 0.53
Type-A Interpolating Function, $u(int)$ (%)	± 0.27
Combined Standard Uncertainty, $u(c)$ (%)	± 0.59
Effective degrees of freedom, $DF(c)$	21637
Coverage factor, k	1.96
Expanded Uncertainty, $U95$ (%)	± 1.2
AM Valid zenith angle range	24° to 74°
PM Valid zenith angle range	24° to 70°

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

Table 4. Calibration Label Values

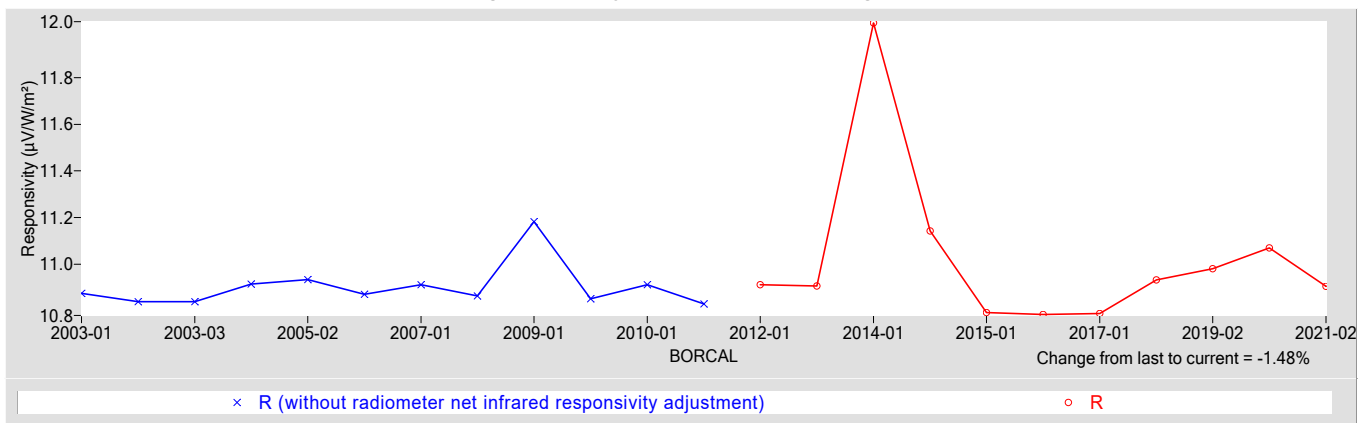
$R @ 45^\circ$ ($\mu V/W/m^2$)	R_{net} ($\mu V/W/m^2$) †
10.906	0.30000

† R_{net} determination date: Estimated

Table 5. Uncertainty using $R @ 45^\circ$

Type-B Expanded Uncertainty, $U(B)$ (%)	± 0.77
Offset Uncertainty, $U(off)$ (%)	+0.88 / -0.55
Expanded Uncertainty, U (%)	+1.6 / -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 Pyrgometers*. ARM 2008 Science Team Meeting (Poster).



National Renewable Energy Laboratory

Solar Radiation Research Laboratory

Metrology Laboratory

Calibration Certificate



Test Instrument:	Pyranometer (Ventilated)	Manufacturer:	Yankee
Model:	TSP-700	Serial Number:	0212-2
Calibration Date:	5/6/2021	Due Date:	5/6/2022
Customer:	NREL-SRRL-BMS	Environmental Conditions:	see page 4
Test Dates:	5/6		

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 than 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	09/27/2019	09/27/2021
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/30/2021	04/30/2022
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/30/2021	04/30/2022
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/08/2021	02/08/2023
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/08/2021	02/08/2023

† 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, Peter Gotseff, 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

0212-2 Yankee TSP-700

The responsivity (R , $\mu\text{V}/\text{W}/\text{m}^2$) of the test instrument during calibration is calculated using this Measurement Equation:

$$R = (V - R_{net} * W_{net}) / I \tag{1}$$

where,

- V = radiometer output voltage (microvolts),
- R_{net} = radiometer net infrared responsivity ($\mu\text{V}/\text{W}/\text{m}^2$), see Table 4,
- W_{net} = effective net infrared measured by pyrgeometer (W/m^2),
- $= W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
- where, W_{in} = incoming infrared (W/m^2), $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$,
- T_c = case temperature of pyrgeometer (K).
- I = reference irradiance (W/m^2), beam (B) or global (G)
- where, $G = B * \text{COS}(Z) + D$,
- Z = zenith angle (degrees),
- D = reference diffuse irradiance (W/m^2).

Figure 1. Responsivity vs Zenith Angle

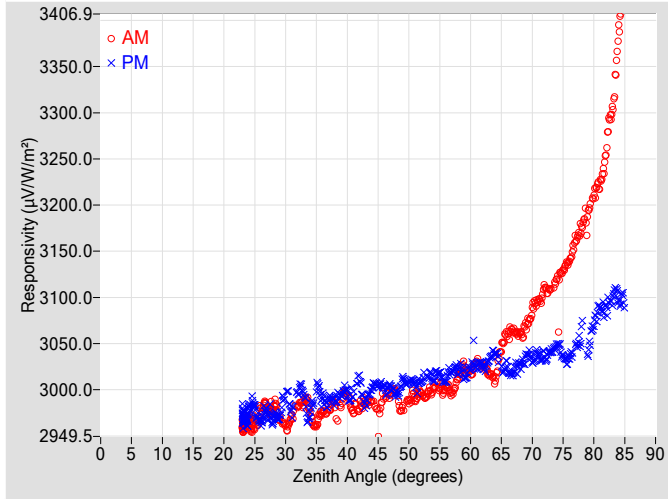


Figure 2. Responsivity vs Local Standard Time

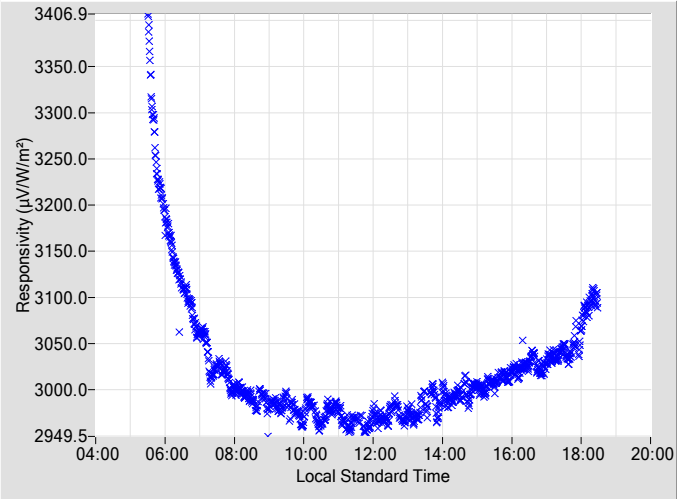


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)

Zenith			AM			PM			Zenith			AM			PM		
Angle	R	u(B)	Azimuth	R	u(B)	Azimuth	Angle	R	u(B)	Azimuth	R	u(B)	Azimuth	R	u(B)	Azimuth	
(deg.)	($\mu\text{V}/\text{W}/\text{m}^2$)	\pm (%)	Angle	($\mu\text{V}/\text{W}/\text{m}^2$)	\pm (%)	Angle	(deg.)	($\mu\text{V}/\text{W}/\text{m}^2$)	\pm (%)	Angle	($\mu\text{V}/\text{W}/\text{m}^2$)	\pm (%)	Angle	($\mu\text{V}/\text{W}/\text{m}^2$)	\pm (%)	Angle	
0	N/A	N/A	N/A	N/A	N/A	N/A	46	2992.3	0.31	106.48	3001.1	0.36	253.73				
2	N/A	N/A	N/A	N/A	N/A	N/A	48	2999.7	0.36	104.35	2995.2	0.32	255.95				
4	N/A	N/A	N/A	N/A	N/A	N/A	50	2988.2	0.33	102.04	3008.5	0.34	258.06				
6	N/A	N/A	N/A	N/A	N/A	N/A	52	2995.7	0.38	100.02	3009.3	0.34	260.08				
8	N/A	N/A	N/A	N/A	N/A	N/A	54	3000.7	0.35	98.14	3010.2	0.35	261.95				
10	N/A	N/A	N/A	N/A	N/A	N/A	56	3001.9	0.33	96.31	3010.3	0.36	263.84				
12	N/A	N/A	N/A	N/A	N/A	N/A	58	3013.9	0.36	94.49	3021.1	0.35	265.68				
14	N/A	N/A	N/A	N/A	N/A	N/A	60	3017.8	0.34	92.71	3024.4	0.36	267.36				
16	N/A	N/A	N/A	N/A	N/A	N/A	62	3026.3	0.38	91.09	3025.4	0.37	269.11				
18	N/A	N/A	N/A	N/A	N/A	N/A	64	3012.5	0.39	89.39	3039.0	0.41	270.80				
20	N/A	N/A	N/A	N/A	N/A	N/A	66	3059.7	0.41	87.71	3024.9	0.40	272.40				
22	N/A	N/A	N/A	N/A	N/A	N/A	68	3061.2	0.40	86.15	3027.2	0.42	274.06				
24	2966.4	0.30	160.41	2974.1	0.32	198.62	70	3085.7	0.42	84.51	3031.9	0.45	275.61				
26	2977.3	0.32	148.32	2966.1	0.32	211.93	72	3110.8	0.46	82.88	3036.6	N/A	277.25				
28	2980.5	0.31	139.89	2966.4	0.32	220.11	74	3119.3	0.50	81.37	3048.3	N/A	278.87				
30	2959.5	0.31	133.55	2995.0	0.32	226.55	76	3139.3	N/A	79.71	3036.8	N/A	280.49				
32	2982.9	0.34	128.32	2997.4	0.37	231.56	78	3176.6	N/A	78.09	3060.1	N/A	281.99				
34	2975.1	0.31	124.25	2976.9	0.32	235.85	80	3210.1	N/A	76.48	3071.8	N/A	283.67				
36	2975.0	0.30	120.47	2989.9	0.33	239.52	82	3259.0	N/A	74.86	3089.4	N/A	285.35				
38	2980.5	0.34	117.15	2987.9	0.32	242.98	84	3386.1	N/A	73.15	3097.0	N/A	287.04				
40	2991.7	0.34	114.12	2996.0	0.35	246.03	86	N/A	N/A	N/A	N/A	N/A	N/A				
42	2980.1	0.32	111.43	3008.3	0.33	248.85	88	N/A	N/A	N/A	N/A	N/A	N/A				
44	2987.5	0.33	108.80	3002.5	0.35	251.34	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

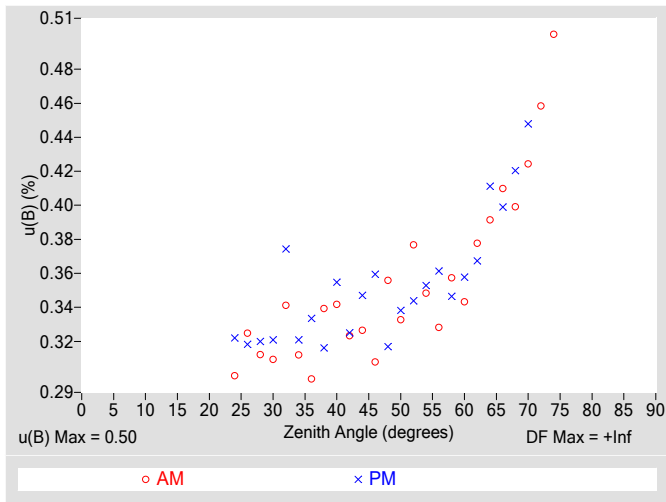


Figure 4. Residuals from Spline Interpolation

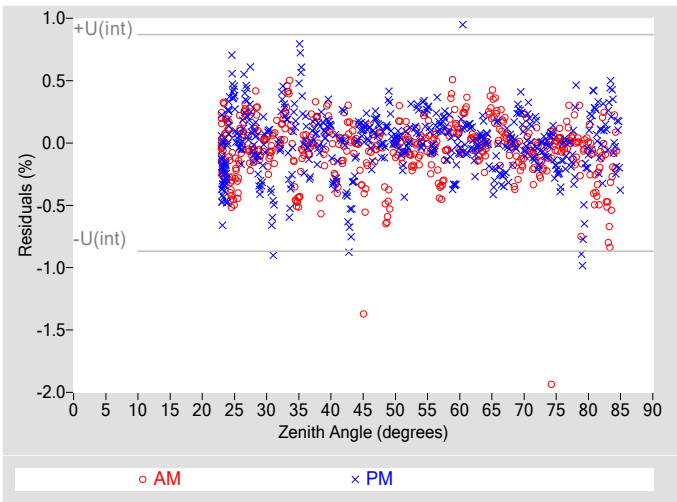


Table 3. Uncertainty using Spline Interpolation ‡

Type-B Standard Uncertainty, u(B) (%)	±0.50
Type-A Interpolating Function, u(int) (%)	±0.43
Combined Standard Uncertainty, u(c) (%)	±0.66
Effective degrees of freedom, DF(c)	4849
Coverage factor, k	1.96
Expanded Uncertainty, U95 (%)	±1.3
AM Valid zenith angle range	24° to 74°
PM Valid zenith angle range	24° 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

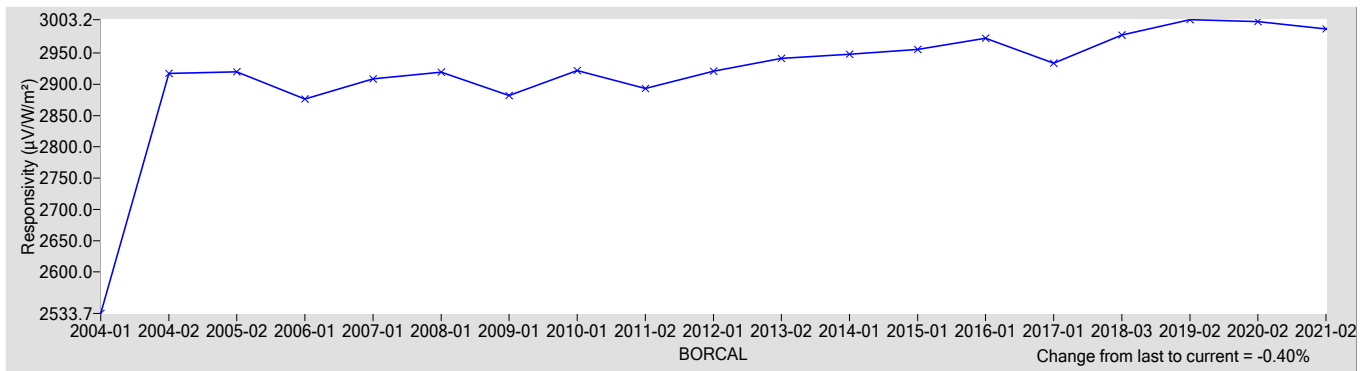
R @ 45° (µV/W/m²)	Rnet (µV/W/m²) †
2988.1	0

† Rnet determination date: N/A

Table 5. Uncertainty using R @ 45°

Type-B Expanded Uncertainty, U(B) (%)	±0.74
Offset Uncertainty, U(off) (%)	+1.2 / -0.96
Expanded Uncertainty, U (%)	+2.0 / -1.7
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 Pyrgometers. ARM 2008 Science Team Meeting (Poster).

National Renewable Energy Laboratory

Solar Radiation Research Laboratory

Metrology Laboratory

Calibration Certificate



Test Instrument: Pyrheliometer
Manufacturer: Kipp & Zonen
Model: CHP1
Serial Number: 080009
Calibration Date: 5/6/2021
Due Date: 5/6/2022
Customer: NREL-SRRL-BMS
Environmental Conditions: see page 4
Test Dates: 5/6

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	09/27/2019	09/27/2021
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/30/2021	04/30/2022
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/30/2021	04/30/2022
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/08/2021	02/08/2023
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/08/2021	02/08/2023

† 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, Peter Gotseff, 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

080009 Kipp & Zonen CHP1

The responsivity (R , $\mu\text{V}/\text{W}/\text{m}^2$) of the test instrument during calibration is calculated using this Measurement Equation:

$$R = (V - R_{net} * W_{net}) / I \tag{1}$$

where,

- V = radiometer output voltage (microvolts),
- R_{net} = radiometer net infrared responsivity ($\mu\text{V}/\text{W}/\text{m}^2$), see Table 4,
- W_{net} = effective net infrared measured by pyrgeometer (W/m^2),
- = $W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
- where, W_{in} = incoming infrared (W/m^2), $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$,
- T_c = case temperature of pyrgeometer (K).
- I = reference irradiance (W/m^2), beam (B) or global (G)
- where, $G = B * \text{COS}(Z) + D$,
- Z = zenith angle (degrees),
- D = reference diffuse irradiance (W/m^2).

Figure 1. Responsivity vs Zenith Angle

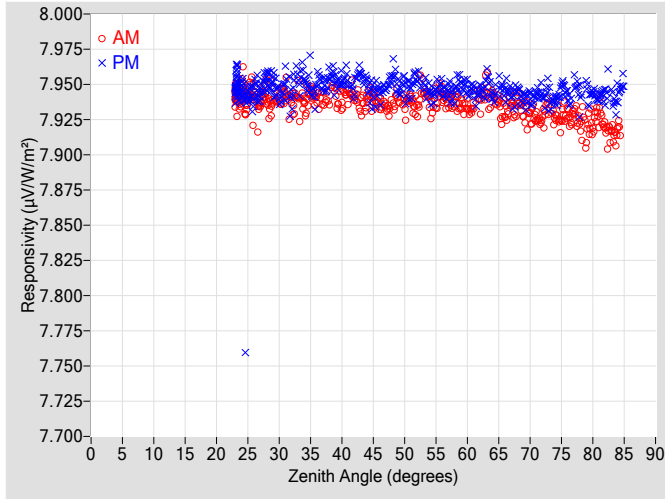


Figure 2. Responsivity vs Local Standard Time

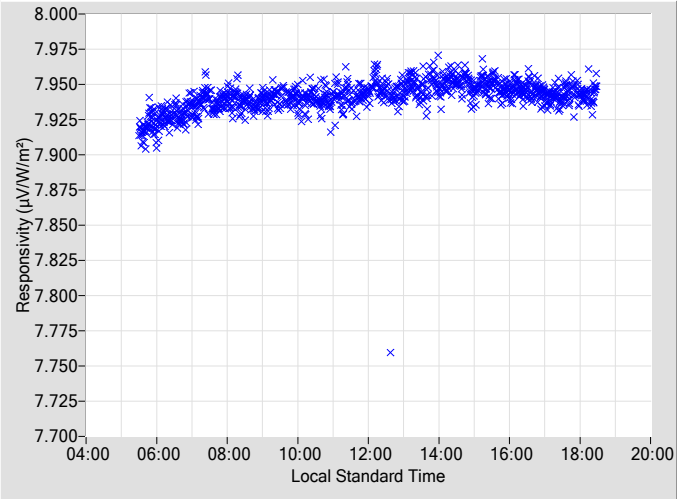


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)

Zenith Angle (deg.)	R ($\mu\text{V}/\text{W}/\text{m}^2$)	AM u(B) \pm (%)	Azimuth Angle	R ($\mu\text{V}/\text{W}/\text{m}^2$)	PM u(B) \pm (%)	Azimuth Angle	Zenith Angle (deg.)	R ($\mu\text{V}/\text{W}/\text{m}^2$)	AM u(B) \pm (%)	Azimuth Angle	R ($\mu\text{V}/\text{W}/\text{m}^2$)	PM u(B) \pm (%)	Azimuth Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	7.9365	0.34	106.42	7.9448	0.31	253.71
2	N/A	N/A	N/A	N/A	N/A	N/A	48	7.9380	0.35	104.14	7.9572	0.30	255.99
4	N/A	N/A	N/A	N/A	N/A	N/A	50	7.9356	0.34	102.02	7.9483	0.30	258.11
6	N/A	N/A	N/A	N/A	N/A	N/A	52	7.9337	0.33	100.07	7.9542	0.33	260.13
8	N/A	N/A	N/A	N/A	N/A	N/A	54	7.9368	0.29	98.18	7.9450	0.33	262.05
10	N/A	N/A	N/A	N/A	N/A	N/A	56	7.9424	0.31	96.30	7.9482	0.30	263.83
12	N/A	N/A	N/A	N/A	N/A	N/A	58	7.9400	0.31	94.48	7.9448	0.30	265.67
14	N/A	N/A	N/A	N/A	N/A	N/A	60	7.9332	0.30	92.70	7.9468	0.32	267.35
16	N/A	N/A	N/A	N/A	N/A	N/A	62	7.9373	0.30	91.08	7.9468	0.31	269.10
18	N/A	N/A	N/A	N/A	N/A	N/A	64	7.9432	0.33	89.38	7.9413	0.31	270.80
20	N/A	N/A	N/A	N/A	N/A	N/A	66	7.9305	0.31	87.70	7.9459	0.31	272.40
22	N/A	N/A	N/A	N/A	N/A	N/A	68	7.9364	0.30	86.14	7.9462	0.31	274.05
24	7.9460	0.31	161.00	7.9463	0.31	198.58	70	7.9265	0.31	84.50	7.9412	0.31	275.60
26	7.9402	0.32	148.36	7.9428	0.33	211.89	72	7.9250	0.31	82.96	7.9433	N/A	277.24
28	7.9409	0.30	139.88	7.9536	0.31	220.26	74	7.9257	0.31	81.31	7.9388	N/A	278.86
30	7.9400	0.33	133.55	7.9421	0.33	226.41	76	7.9275	N/A	79.70	7.9415	N/A	280.48
32	7.9383	0.31	128.52	7.9394	0.29	231.52	78	7.9197	N/A	78.08	7.9404	N/A	282.03
34	7.9336	0.32	124.21	7.9540	0.32	235.99	80	7.9198	N/A	76.47	7.9446	N/A	283.66
36	7.9408	0.31	120.61	7.9479	0.32	239.61	82	7.9194	N/A	74.85	7.9424	N/A	285.39
38	7.9368	0.32	117.26	7.9549	0.32	242.96	84	7.9193	N/A	73.14	7.9430	N/A	287.03
40	7.9384	0.31	114.11	7.9523	0.31	246.01	86	N/A	N/A	N/A	N/A	N/A	N/A
42	7.9400	0.30	111.34	7.9476	0.31	248.75	88	N/A	N/A	N/A	N/A	N/A	N/A
44	7.9395	0.33	108.75	7.9516	0.32	251.33	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

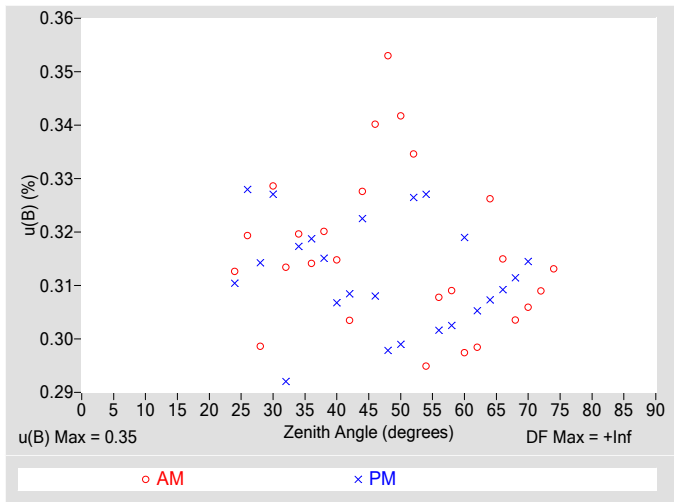


Figure 4. Residuals from Spline Interpolation

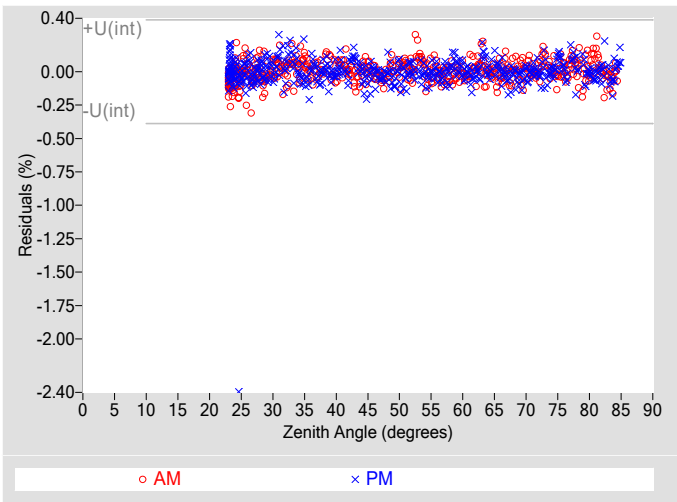


Table 3. Uncertainty using Spline Interpolation ‡

Type-B Standard Uncertainty, $u(B)$ (%)	± 0.35
Type-A Interpolating Function, $u(int)$ (%)	± 0.19
Combined Standard Uncertainty, $u(c)$ (%)	± 0.40
Effective degrees of freedom, $DF(c)$	16889
Coverage factor, k	1.96
Expanded Uncertainty, U_{95} (%)	± 0.79
AM Valid zenith angle range	24° to 74°
PM Valid zenith angle range	24° to 70°

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

Table 4. Calibration Label Values

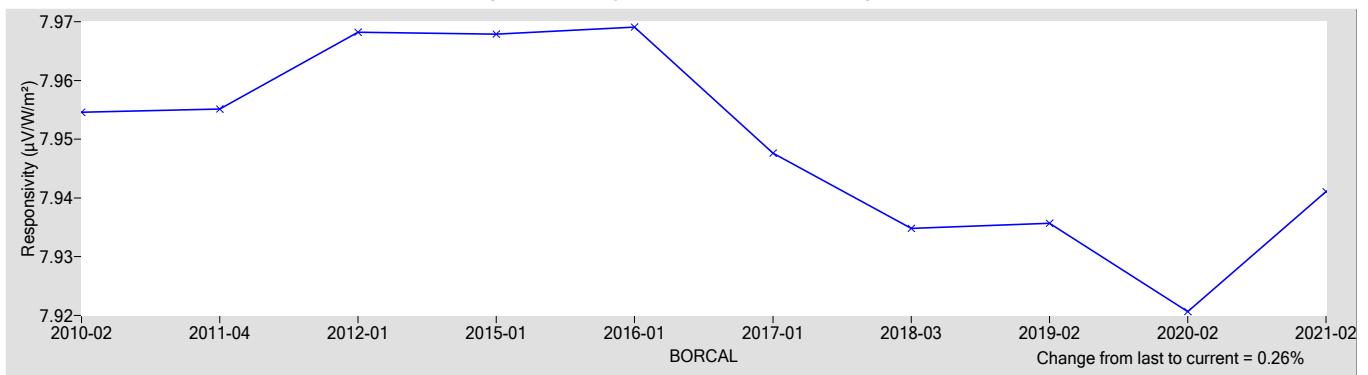
$R @ 45^\circ$ ($\mu V/W/m^2$)	R_{net} ($\mu V/W/m^2$) †
7.9411	0

† R_{net} determination date: N/A

Table 5. Uncertainty using $R @ 45^\circ$

Type-B Expanded Uncertainty, $U(B)$ (%)	± 0.69
Offset Uncertainty, $U(off)$ (%)	+0.20 / -0.098
Expanded Uncertainty, U (%)	+0.90 / -0.79
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 Pyrgometers. ARM 2008 Science Team Meeting (Poster).



National Renewable Energy Laboratory

Solar Radiation Research Laboratory

Metrology Laboratory

Calibration Certificate



Test Instrument:	Pyranometer (Ventilated)	Manufacturer:	Kipp & Zonen
Model:	CMP22	Serial Number:	080017
Calibration Date:	5/6/2021	Due Date:	5/6/2022
Customer:	NREL-SRRL-BMS	Environmental Conditions:	see page 4
Test Dates:	5/6		

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 than 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	09/27/2019	09/27/2021
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/30/2021	04/30/2022
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/30/2021	04/30/2022
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/08/2021	02/08/2023
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/08/2021	02/08/2023
Infrared Irradiance ‡	Kipp & Zonen Pyrgeometer Model CGR4, S/N 140021	04/02/2019	04/02/2023

† 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, Peter Gotseff, 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

080017 Kipp & Zonen CMP22

The responsivity (R , $\mu\text{V}/\text{W}/\text{m}^2$) of the test instrument during calibration is calculated using this Measurement Equation:

$$R = (V - R_{net} * W_{net}) / I \tag{1}$$

where,

- V = radiometer output voltage (microvolts),
 - R_{net} = radiometer net infrared responsivity ($\mu\text{V}/\text{W}/\text{m}^2$), see Table 4,
 - W_{net} = effective net infrared measured by pyrgeometer (W/m^2),
 - = $W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
 - where, W_{in} = incoming infrared (W/m^2), $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$,
 - T_c = case temperature of pyrgeometer (K).
- I = reference irradiance (W/m^2), beam (B) or global (G)
 - where, $G = B * \text{COS}(Z) + D$,
 - Z = zenith angle (degrees),
 - D = reference diffuse irradiance (W/m^2).

Figure 1. Responsivity vs Zenith Angle

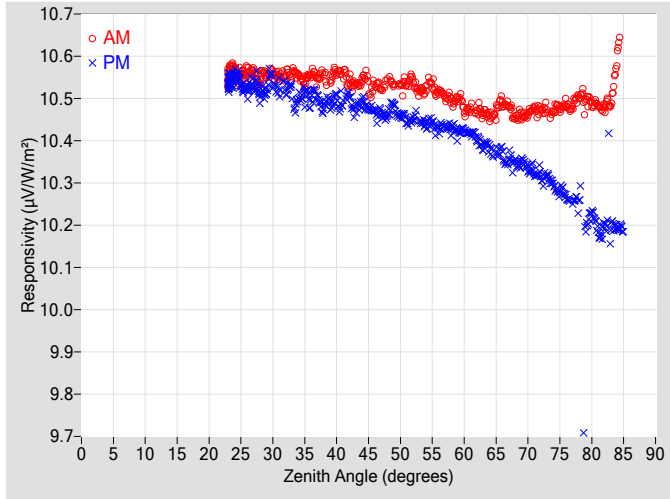


Figure 2. Responsivity vs Local Standard Time

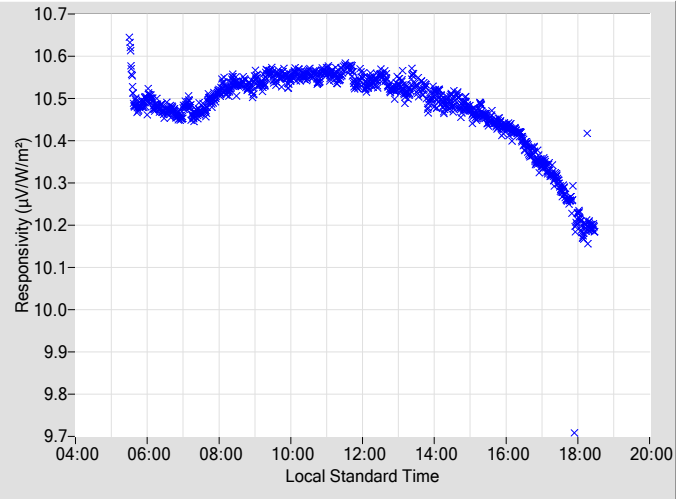


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, $u(B)$

Zenith Angle (deg.)	R ($\mu\text{V}/\text{W}/\text{m}^2$)	AM u(B) \pm (%)	Azimuth Angle	R ($\mu\text{V}/\text{W}/\text{m}^2$)	PM u(B) \pm (%)	Azimuth Angle	Zenith Angle (deg.)	R ($\mu\text{V}/\text{W}/\text{m}^2$)	AM u(B) \pm (%)	Azimuth Angle	R ($\mu\text{V}/\text{W}/\text{m}^2$)	PM u(B) \pm (%)	Azimuth Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	10.533	0.33	106.44	10.463	0.35	253.77
2	N/A	N/A	N/A	N/A	N/A	N/A	48	10.545	0.36	104.35	10.461	0.32	255.95
4	N/A	N/A	N/A	N/A	N/A	N/A	50	10.532	0.35	102.04	10.458	0.37	258.06
6	N/A	N/A	N/A	N/A	N/A	N/A	52	10.537	0.34	100.03	10.449	0.33	260.02
8	N/A	N/A	N/A	N/A	N/A	N/A	54	10.523	0.33	98.15	10.433	0.33	261.95
10	N/A	N/A	N/A	N/A	N/A	N/A	56	10.516	0.35	96.32	10.427	0.34	263.85
12	N/A	N/A	N/A	N/A	N/A	N/A	58	10.494	0.37	94.52	10.428	0.37	265.68
14	N/A	N/A	N/A	N/A	N/A	N/A	60	10.470	0.35	92.72	10.425	0.36	267.36
16	N/A	N/A	N/A	N/A	N/A	N/A	62	10.467	0.38	91.09	10.404	0.37	269.11
18	N/A	N/A	N/A	N/A	N/A	N/A	64	10.459	0.42	89.39	10.379	0.39	270.81
20	N/A	N/A	N/A	N/A	N/A	N/A	66	10.489	0.50	87.71	10.370	0.41	272.41
22	N/A	N/A	N/A	N/A	N/A	N/A	68	10.456	0.41	86.16	10.349	0.43	274.07
24	10.561	0.34	160.60	10.550	0.32	199.16	70	10.464	0.43	84.51	10.331	0.46	275.62
26	10.565	0.31	148.28	10.521	0.32	211.85	72	10.475	0.47	82.88	10.319	N/A	277.25
28	10.545	0.34	140.04	10.510	0.30	220.16	74	10.471	0.51	81.32	10.294	N/A	278.87
30	10.556	0.30	133.56	10.541	0.34	226.44	76	10.486	N/A	79.71	10.263	N/A	280.49
32	10.555	0.34	128.55	10.520	0.34	231.57	78	10.505	N/A	78.10	10.260	N/A	282.09
34	10.554	0.31	124.29	10.503	0.30	235.82	80	10.487	N/A	76.49	10.231	N/A	283.67
36	10.558	0.33	120.48	10.495	0.33	239.61	82	10.477	N/A	74.87	10.198	N/A	285.35
38	10.560	0.35	117.06	10.477	0.32	242.98	84	10.602	N/A	73.15	10.192	N/A	287.04
40	10.562	0.32	114.17	10.501	0.36	246.03	86	N/A	N/A	N/A	N/A	N/A	N/A
42	10.540	0.34	111.36	10.502	0.34	248.81	88	N/A	N/A	N/A	N/A	N/A	N/A
44	10.545	0.36	108.76	10.494	0.37	251.34	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

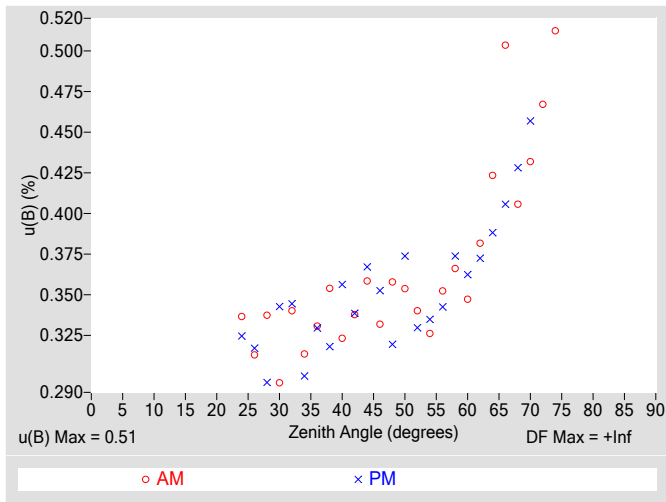


Figure 4. Residuals from Spline Interpolation

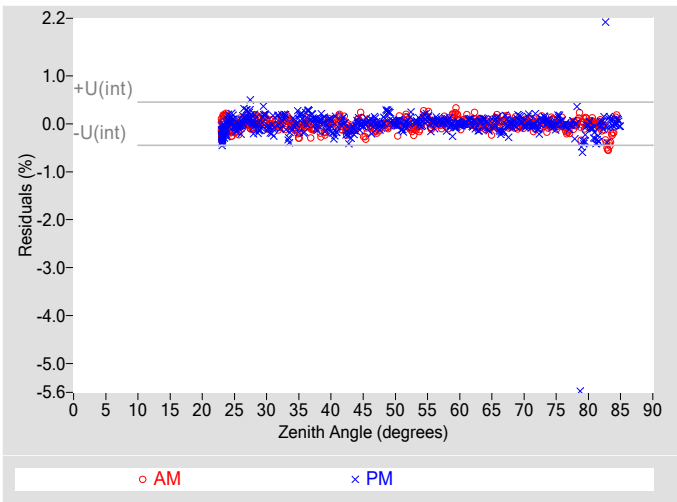


Table 3. Uncertainty using Spline Interpolation ‡

Type-B Standard Uncertainty, $u(B)$ (%)	± 0.51
Type-A Interpolating Function, $u(int)$ (%)	± 0.22
Combined Standard Uncertainty, $u(c)$ (%)	± 0.56
Effective degrees of freedom, $DF(c)$	34741
Coverage factor, k	1.96
Expanded Uncertainty, $U95$ (%)	± 1.1
AM Valid zenith angle range	24° to 74°
PM Valid zenith angle range	24° to 70°

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

Table 4. Calibration Label Values

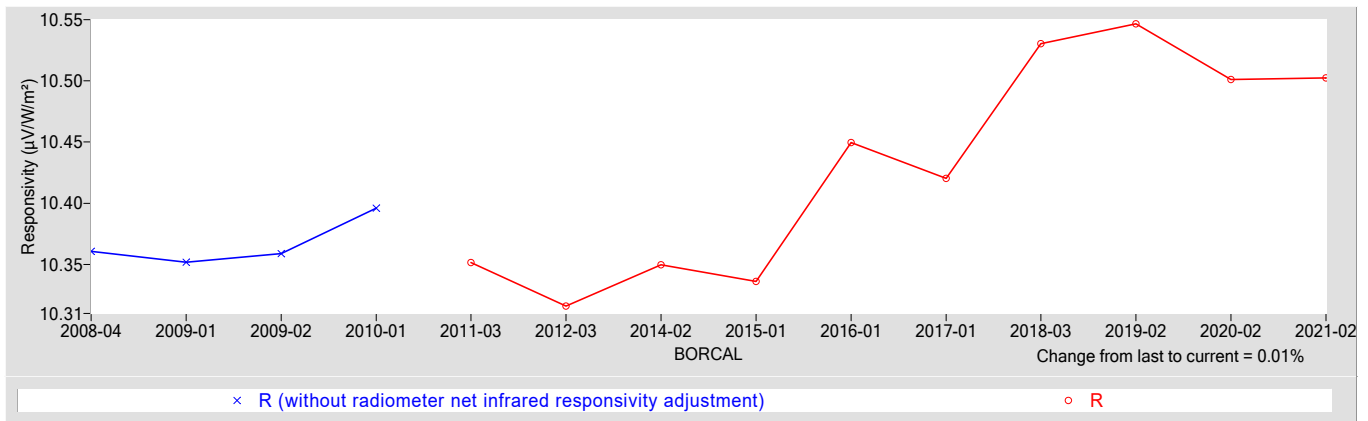
$R @ 45^\circ$ ($\mu V/W/m^2$)	R_{net} ($\mu V/W/m^2$) †
10.502	0.087000

† R_{net} determination date: Estimated

Table 5. Uncertainty using $R @ 45^\circ$

Type-B Expanded Uncertainty, $U(B)$ (%)	± 0.73
Offset Uncertainty, $U(off)$ (%)	+0.56 / -0.73
Expanded Uncertainty, U (%)	+1.3 / -1.5
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 Pyrgometers. ARM 2008 Science Team Meeting (Poster).



National Renewable Energy Laboratory

Solar Radiation Research Laboratory

Metrology Laboratory

Calibration Certificate



Test Instrument:	Pyranometer	Manufacturer:	Kipp & Zonen
Model:	CMP22	Serial Number:	100174
Calibration Date:	5/6/2021	Due Date:	5/6/2022
Customer:	NREL-SRRL-BMS	Environmental Conditions:	see page 4
Test Dates:	5/6		

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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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 than 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	09/27/2019	09/27/2021
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/30/2021	04/30/2022
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/30/2021	04/30/2022
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/08/2021	02/08/2023
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/08/2021	02/08/2023
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, Peter Gotseff, 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

100174 Kipp & Zonen CMP22

The responsivity (R , $\mu\text{V}/\text{W}/\text{m}^2$) of the test instrument during calibration is calculated using this Measurement Equation:

$$R = (V - R_{net} * W_{net}) / I \tag{1}$$

where,

- V = radiometer output voltage (microvolts),
- R_{net} = radiometer net infrared responsivity ($\mu\text{V}/\text{W}/\text{m}^2$), see Table 4,
- W_{net} = effective net infrared measured by pyrgeometer (W/m^2),
- $= W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
- where, W_{in} = incoming infrared (W/m^2), $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$,
- T_c = case temperature of pyrgeometer (K).
- I = reference irradiance (W/m^2), beam (B) or global (G)
- where, $G = B * \text{COS}(Z) + D$,
- Z = zenith angle (degrees),
- D = reference diffuse irradiance (W/m^2).

Figure 1. Responsivity vs Zenith Angle

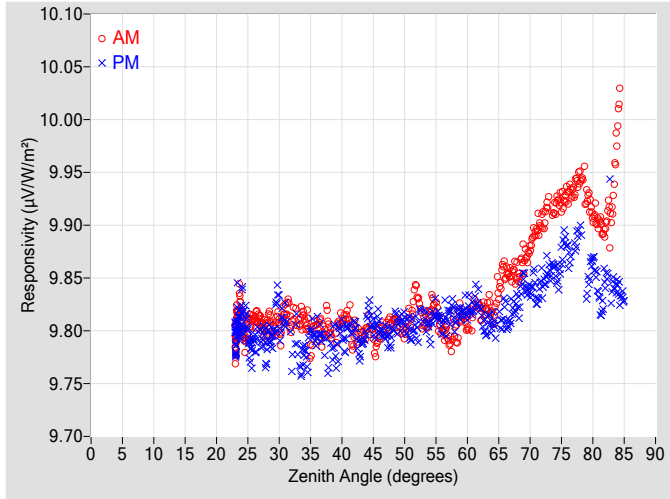


Figure 2. Responsivity vs Local Standard Time

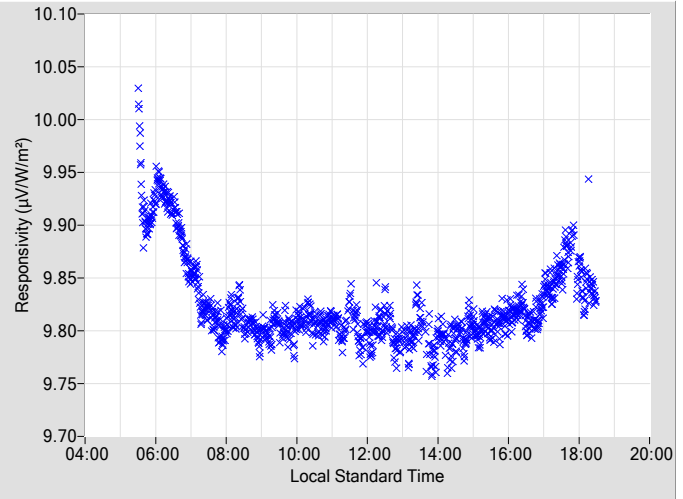


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)

Zenith			AM			PM			Zenith			AM			PM		
Angle	R	u(B)	Azimuth	R	u(B)	Azimuth	Angle	R	u(B)	Azimuth	R	u(B)	Azimuth	R	u(B)	Azimuth	
(deg.)	($\mu\text{V}/\text{W}/\text{m}^2$)	\pm (%)	Angle	($\mu\text{V}/\text{W}/\text{m}^2$)	\pm (%)	Angle	(deg.)	($\mu\text{V}/\text{W}/\text{m}^2$)	\pm (%)	Angle	($\mu\text{V}/\text{W}/\text{m}^2$)	\pm (%)	Angle	($\mu\text{V}/\text{W}/\text{m}^2$)	\pm (%)	Angle	
0	N/A	N/A	N/A	N/A	N/A	N/A	46	9.7974	0.35	106.43	9.8050	0.33	253.72				
2	N/A	N/A	N/A	N/A	N/A	N/A	48	9.8094	0.34	104.12	9.7964	0.34	255.95				
4	N/A	N/A	N/A	N/A	N/A	N/A	50	9.7986	0.34	102.07	9.8080	0.36	258.06				
6	N/A	N/A	N/A	N/A	N/A	N/A	52	9.8359	0.34	100.08	9.8015	0.37	260.08				
8	N/A	N/A	N/A	N/A	N/A	N/A	54	9.8142	0.39	98.14	9.8000	0.34	262.00				
10	N/A	N/A	N/A	N/A	N/A	N/A	56	9.8020	0.33	96.26	9.8037	0.34	263.90				
12	N/A	N/A	N/A	N/A	N/A	N/A	58	9.8039	0.34	94.49	9.8100	0.40	265.62				
14	N/A	N/A	N/A	N/A	N/A	N/A	60	9.8038	0.39	92.76	9.8208	0.36	267.41				
16	N/A	N/A	N/A	N/A	N/A	N/A	62	9.8183	0.36	91.04	9.8257	0.41	269.06				
18	N/A	N/A	N/A	N/A	N/A	N/A	64	9.8130	0.37	89.34	9.8059	0.39	270.76				
20	N/A	N/A	N/A	N/A	N/A	N/A	66	9.8571	0.42	87.76	9.8173	0.41	272.40				
22	N/A	N/A	N/A	N/A	N/A	N/A	68	9.8531	0.41	86.10	9.8254	0.43	274.02				
24	9.8165	0.33	161.44	9.8106	0.33	199.06	70	9.8770	0.43	84.56	9.8377	0.46	275.66				
26	9.8099	0.33	148.08	9.7885	0.33	211.98	72	9.9031	0.47	82.93	9.8454	N/A	277.24				
28	9.8029	0.32	140.17	9.7830	0.32	220.16	74	9.9172	0.51	81.32	9.8562	N/A	278.82				
30	9.8055	0.31	133.78	9.8118	0.33	226.46	76	9.9283	N/A	79.76	9.8750	N/A	280.44				
32	9.8100	0.30	128.61	9.7794	0.32	231.47	78	9.9453	N/A	78.14	9.8953	N/A	282.13				
34	9.8135	0.33	124.39	9.7798	0.30	235.85	80	9.9096	N/A	76.48	9.8648	N/A	283.72				
36	9.8000	0.36	120.48	9.7958	0.34	239.64	82	9.8976	N/A	74.81	9.8500	N/A	285.35				
38	9.8016	0.34	117.11	9.7774	0.33	242.98	84	9.9961	N/A	73.20	9.8389	N/A	287.04				
40	9.8101	0.39	114.11	9.7993	0.37	246.07	86	N/A	N/A	N/A	N/A	N/A	N/A				
42	9.7947	0.32	111.36	9.8056	0.33	248.88	88	N/A	N/A	N/A	N/A	N/A	N/A				
44	9.8027	0.36	108.83	9.8106	0.33	251.34	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

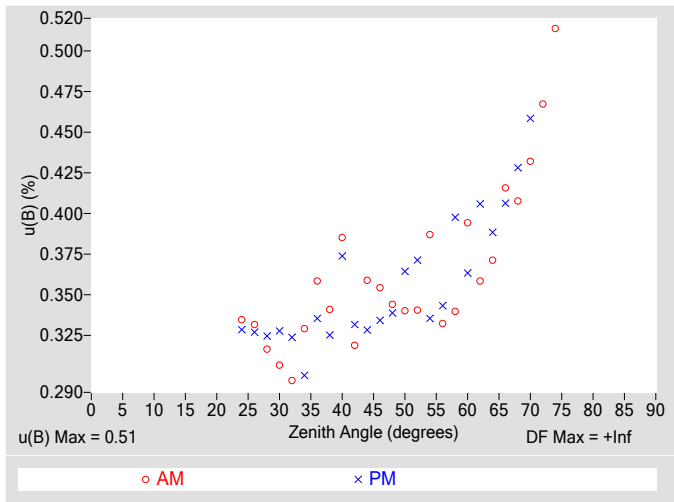


Figure 4. Residuals from Spline Interpolation

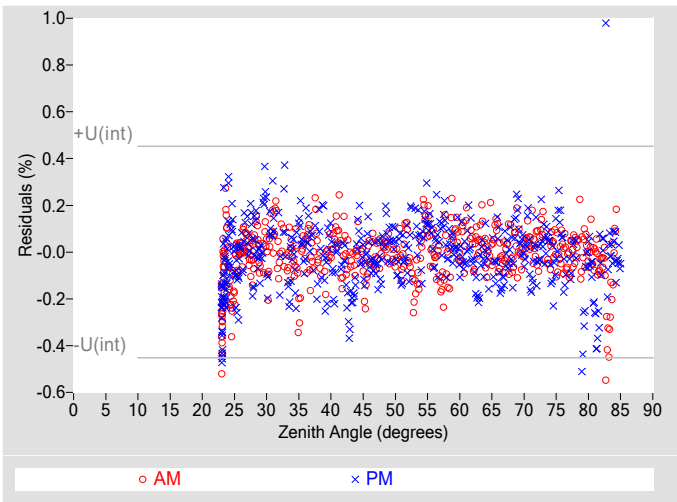


Table 3. Uncertainty using Spline Interpolation ‡

Type-B Standard Uncertainty, $u(B)$ (%)	± 0.51
Type-A Interpolating Function, $u(int)$ (%)	± 0.23
Combined Standard Uncertainty, $u(c)$ (%)	± 0.56
Effective degrees of freedom, $DF(c)$	33848
Coverage factor, k	1.96
Expanded Uncertainty, $U95$ (%)	± 1.1
AM Valid zenith angle range	24° to 74°
PM Valid zenith angle range	24° to 70°

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

Table 4. Calibration Label Values

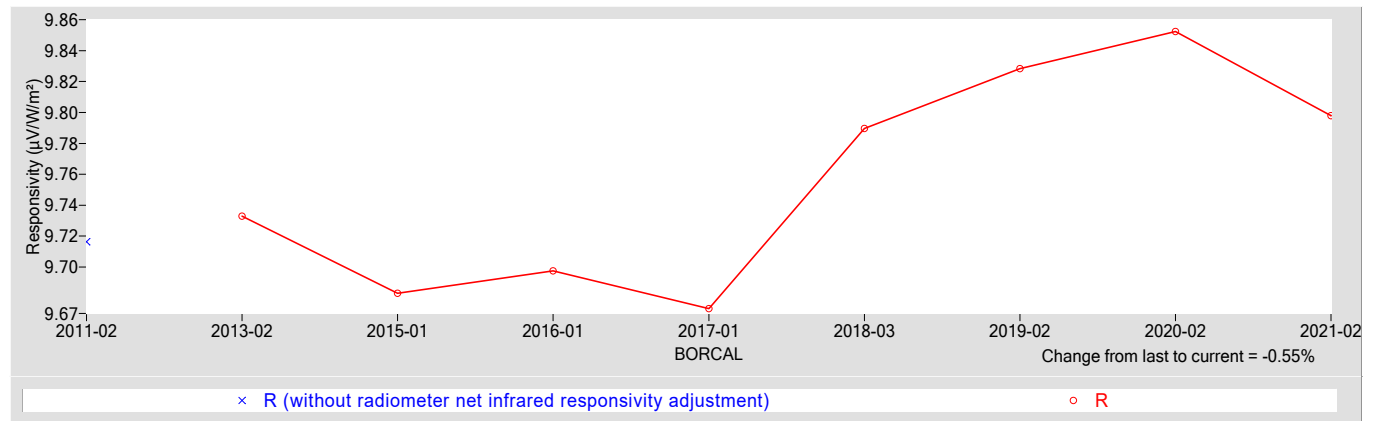
$R @ 45^\circ$ ($\mu V/W/m^2$)	R_{net} ($\mu V/W/m^2$) †
9.7980	0.087000

† R_{net} determination date: Estimated

Table 5. Uncertainty using $R @ 45^\circ$

Type-B Expanded Uncertainty, $U(B)$ (%)	± 0.78
Offset Uncertainty, $U(off)$ (%)	+0.39 / -0.21
Expanded Uncertainty, U (%)	+1.2 / -0.99
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 Pyrgometers. ARM 2008 Science Team Meeting (Poster).



National Renewable Energy Laboratory

Solar Radiation Research Laboratory

Metrology Laboratory

Calibration Certificate



Test Instrument:	Thermopile Pyranometer	Manufacturer:	Apogee
Model:	SP-510	Serial Number:	1171
Calibration Date:	5/6/2021	Due Date:	5/6/2022
Customer:	NREL-SRRL-BMS	Environmental Conditions:	see page 4
Test Dates:	5/6		

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 than 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	09/27/2019	09/27/2021
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/30/2021	04/30/2022
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/30/2021	04/30/2022
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/08/2021	02/08/2023
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/08/2021	02/08/2023
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, Peter Gotseff, 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

1171 Apogee SP-510

The responsivity (R , $\mu\text{V}/\text{W}/\text{m}^2$) of the test instrument during calibration is calculated using this Measurement Equation:

$$R = (V - R_{net} * W_{net}) / I \tag{1}$$

where,

- V = radiometer output voltage (microvolts),
 - R_{net} = radiometer net infrared responsivity ($\mu\text{V}/\text{W}/\text{m}^2$), see Table 4,
 - W_{net} = effective net infrared measured by pyrgeometer (W/m^2),
 - = $W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
 - where, W_{in} = incoming infrared (W/m^2), $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$,
 - T_c = case temperature of radiometer (K).
- I = reference irradiance (W/m^2), beam (B) or global (G)
 - where, $G = B * \text{COS}(Z) + D$,
 - Z = zenith angle (degrees),
 - D = reference diffuse irradiance (W/m^2).

Figure 1. Responsivity vs Zenith Angle

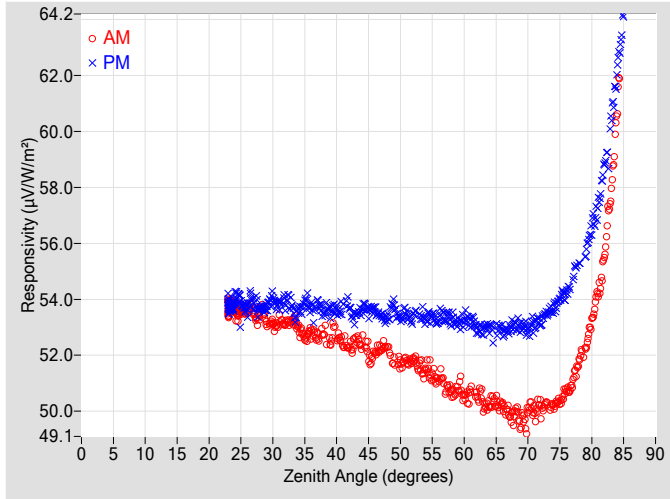


Figure 2. Responsivity vs Local Standard Time

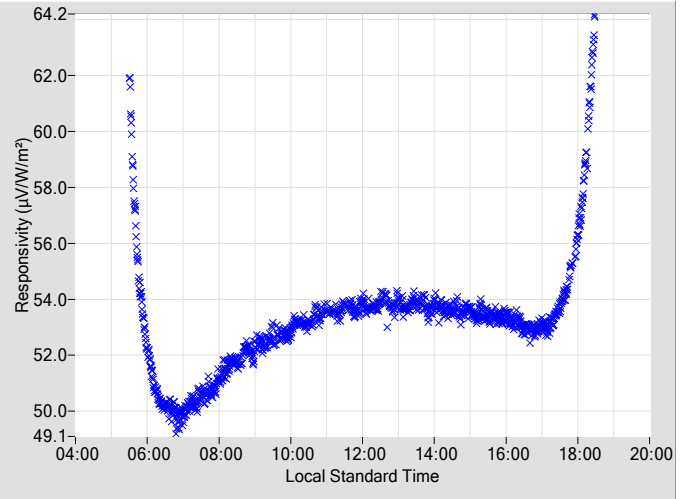


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)

Zenith			AM			PM			Zenith			AM			PM		
Angle	R	u(B)	Azimuth	R	u(B)	Azimuth	Angle	R	u(B)	Azimuth	R	u(B)	Azimuth	R	u(B)	Azimuth	
(deg.)	($\mu\text{V}/\text{W}/\text{m}^2$)	\pm (%)	Angle	($\mu\text{V}/\text{W}/\text{m}^2$)	\pm (%)	Angle	(deg.)	($\mu\text{V}/\text{W}/\text{m}^2$)	\pm (%)	Angle	($\mu\text{V}/\text{W}/\text{m}^2$)	\pm (%)	Angle	($\mu\text{V}/\text{W}/\text{m}^2$)	\pm (%)	Angle	
0	N/A	N/A	N/A	N/A	N/A	N/A	46	52.092	0.37	106.42	53.618	0.33	253.68				
2	N/A	N/A	N/A	N/A	N/A	N/A	48	52.243	0.36	104.14	53.338	0.34	255.96				
4	N/A	N/A	N/A	N/A	N/A	N/A	50	51.707	0.39	102.05	53.349	0.39	258.07				
6	N/A	N/A	N/A	N/A	N/A	N/A	52	51.828	0.38	100.04	53.353	0.35	260.04				
8	N/A	N/A	N/A	N/A	N/A	N/A	54	51.543	0.41	98.10	53.246	0.38	261.97				
10	N/A	N/A	N/A	N/A	N/A	N/A	56	51.143	0.38	96.33	53.325	0.37	263.86				
12	N/A	N/A	N/A	N/A	N/A	N/A	58	50.741	0.39	94.50	53.277	0.38	265.69				
14	N/A	N/A	N/A	N/A	N/A	N/A	60	50.509	0.38	92.73	53.303	0.42	267.37				
16	N/A	N/A	N/A	N/A	N/A	N/A	62	50.555	0.40	91.10	52.908	0.44	269.12				
18	N/A	N/A	N/A	N/A	N/A	N/A	64	50.279	0.43	89.41	53.011	0.46	270.72				
20	N/A	N/A	N/A	N/A	N/A	N/A	66	50.201	0.46	87.72	52.861	0.45	272.42				
22	N/A	N/A	N/A	N/A	N/A	N/A	68	49.880	0.52	86.17	53.028	0.48	274.03				
24	53.664	0.32	160.71	53.902	0.33	198.72	70	49.886	0.52	84.52	52.822	0.52	275.63				
26	53.606	0.32	148.32	53.702	0.32	211.66	72	50.134	0.56	82.89	53.192	N/A	277.26				
28	53.519	0.33	139.93	53.679	0.34	220.00	74	50.195	0.57	81.33	53.683	N/A	278.88				
30	53.126	0.34	133.69	54.031	0.35	226.32	76	50.738	N/A	79.72	54.144	N/A	280.41				
32	53.144	0.34	128.57	53.870	0.31	231.50	78	51.769	N/A	78.11	55.296	N/A	282.10				
34	52.918	0.34	124.26	53.630	0.34	235.88	80	53.189	N/A	76.50	56.642	N/A	283.68				
36	52.798	0.37	120.46	53.702	0.35	239.65	82	55.544	N/A	74.88	58.784	N/A	285.31				
38	52.819	0.34	117.13	53.465	0.32	243.04	84	61.002	N/A	73.16	62.282	N/A	287.05				
40	52.734	0.34	113.99	53.605	0.32	246.05	86	N/A	N/A	N/A	N/A	N/A	N/A				
42	52.345	0.34	111.38	53.787	0.37	248.79	88	N/A	N/A	N/A	N/A	N/A	N/A				
44	52.441	0.35	108.87	53.626	0.33	251.36	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

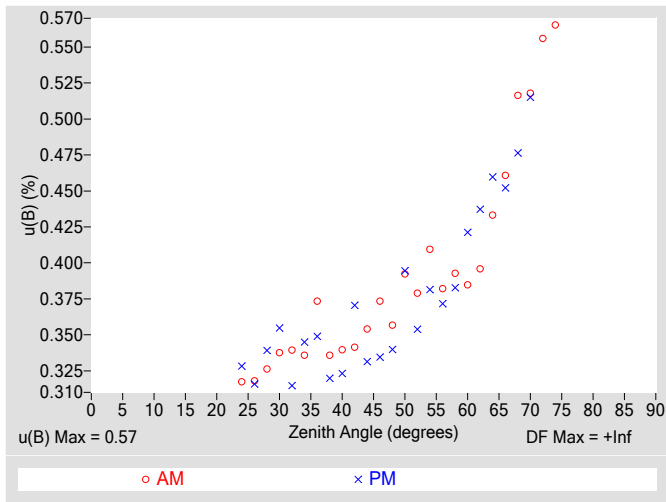


Figure 4. Residuals from Spline Interpolation

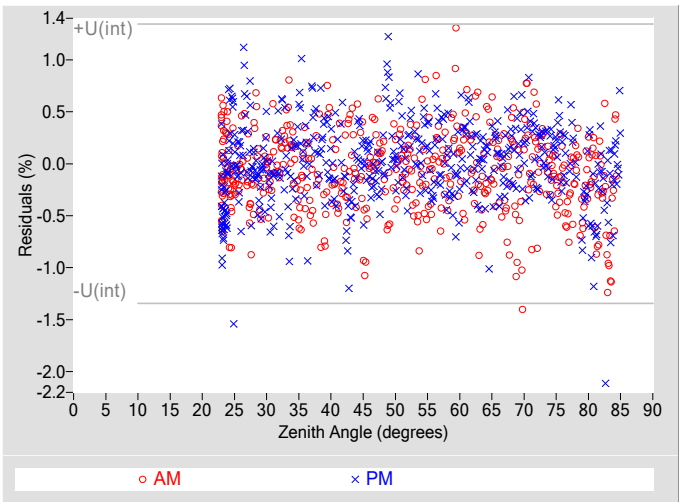


Table 3. Uncertainty using Spline Interpolation ‡

Type-B Standard Uncertainty, $u(B)$ (%)	± 0.57
Type-A Interpolating Function, $u(int)$ (%)	± 0.67
Combined Standard Uncertainty, $u(c)$ (%)	± 0.88
Effective degrees of freedom, $DF(c)$	2574
Coverage factor, k	1.96
Expanded Uncertainty, $U95$ (%)	± 1.7
AM Valid zenith angle range	24° to 74°
PM Valid zenith angle range	24° to 70°

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

Table 4. Calibration Label Values

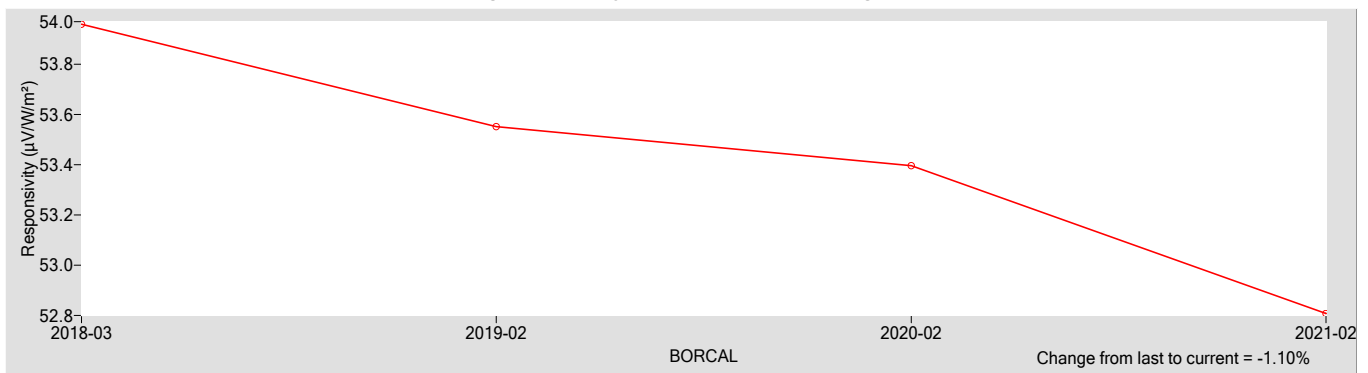
$R @ 45^\circ$ ($\mu V/W/m^2$)	R_{net} ($\mu V/W/m^2$) †
52.808	2.5000

† R_{net} determination date: Estimated

Table 5. Uncertainty using $R @ 45^\circ$

Type-B Expanded Uncertainty, $U(B)$ (%)	± 0.83
Offset Uncertainty, $U(off)$ (%)	+2.3 / -4.4
Expanded Uncertainty, U (%)	+3.1 / -5.2
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



Test Instrument:	Pyranometer	Manufacturer:	Kipp & Zonen
Model:	CMP22	Serial Number:	140043
Calibration Date:	5/6/2021	Due Date:	5/6/2022
Customer:	NREL-SRRL-BMS	Environmental Conditions:	see page 4
Test Dates:	5/6		

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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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	09/27/2019	09/27/2021
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/30/2021	04/30/2022
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/30/2021	04/30/2022
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/08/2021	02/08/2023
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/08/2021	02/08/2023
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, Peter Gotseff, 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

140043 Kipp & Zonen CMP22

The responsivity (R , $\mu\text{V}/\text{W}/\text{m}^2$) of the test instrument during calibration is calculated using this Measurement Equation:

$$R = (V - R_{net} * W_{net}) / I \tag{1}$$

where,

- V = radiometer output voltage (microvolts),
 - R_{net} = radiometer net infrared responsivity ($\mu\text{V}/\text{W}/\text{m}^2$), see Table 4,
 - W_{net} = effective net infrared measured by pyrgeometer (W/m^2),
 - = $W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
 - where, W_{in} = incoming infrared (W/m^2), $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$,
 - T_c = case temperature of pyrgeometer (K).
- I = reference irradiance (W/m^2), beam (B) or global (G)
 - where, $G = B * \text{COS}(Z) + D$,
 - Z = zenith angle (degrees),
 - D = reference diffuse irradiance (W/m^2).

Figure 1. Responsivity vs Zenith Angle

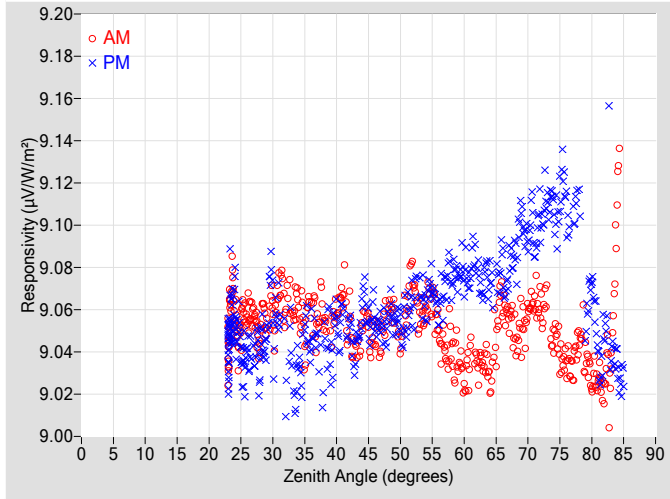


Figure 2. Responsivity vs Local Standard Time

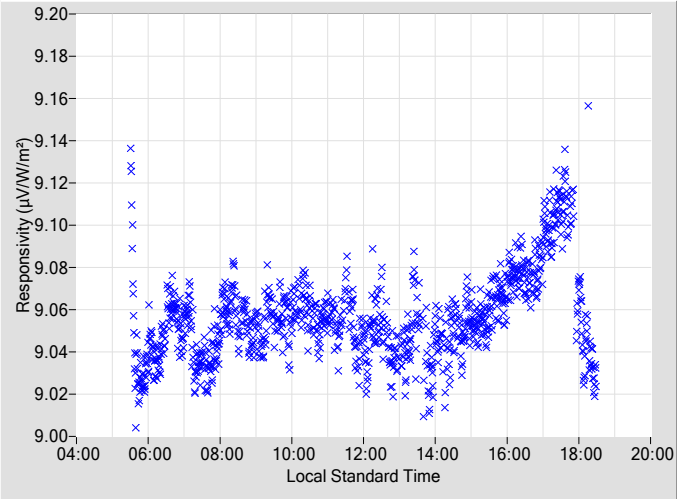


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)

Zenith Angle (deg.)	R ($\mu\text{V}/\text{W}/\text{m}^2$)	AM u(B) \pm (%)	Azimuth Angle	R ($\mu\text{V}/\text{W}/\text{m}^2$)	PM u(B) \pm (%)	Azimuth Angle	Zenith Angle (deg.)	R ($\mu\text{V}/\text{W}/\text{m}^2$)	AM u(B) \pm (%)	Azimuth Angle	R ($\mu\text{V}/\text{W}/\text{m}^2$)	PM u(B) \pm (%)	Azimuth Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	9.0489	0.35	106.43	9.0549	0.33	253.72
2	N/A	N/A	N/A	N/A	N/A	N/A	48	9.0598	0.34	104.12	9.0527	0.34	255.95
4	N/A	N/A	N/A	N/A	N/A	N/A	50	9.0444	0.34	102.07	9.0521	0.36	258.06
6	N/A	N/A	N/A	N/A	N/A	N/A	52	9.0757	0.34	100.08	9.0608	0.37	260.08
8	N/A	N/A	N/A	N/A	N/A	N/A	54	9.0582	0.39	98.14	9.0615	0.34	262.00
10	N/A	N/A	N/A	N/A	N/A	N/A	56	9.0499	0.33	96.26	9.0583	0.34	263.90
12	N/A	N/A	N/A	N/A	N/A	N/A	58	9.0452	0.34	94.49	9.0729	0.40	265.62
14	N/A	N/A	N/A	N/A	N/A	N/A	60	9.0243	0.40	92.76	9.0777	0.36	267.41
16	N/A	N/A	N/A	N/A	N/A	N/A	62	9.0342	0.36	91.04	9.0828	0.41	269.06
18	N/A	N/A	N/A	N/A	N/A	N/A	64	9.0258	0.37	89.34	9.0726	0.39	270.76
20	N/A	N/A	N/A	N/A	N/A	N/A	66	9.0644	0.42	87.76	9.0802	0.41	272.40
22	N/A	N/A	N/A	N/A	N/A	N/A	68	9.0471	0.41	86.10	9.0851	0.43	274.02
24	9.0626	0.33	161.44	9.0550	0.33	199.06	70	9.0584	0.43	84.56	9.0942	0.46	275.66
26	9.0558	0.33	148.08	9.0386	0.33	211.98	72	9.0611	0.47	82.93	9.1031	N/A	277.24
28	9.0459	0.32	140.17	9.0367	0.32	220.16	74	9.0465	0.52	81.32	9.1085	N/A	278.82
30	9.0591	0.31	133.78	9.0550	0.33	226.46	76	9.0344	N/A	79.76	9.1084	N/A	280.44
32	9.0619	0.30	128.61	9.0305	0.32	231.47	78	9.0455	N/A	78.14	9.1106	N/A	282.13
34	9.0639	0.33	124.39	9.0335	0.30	235.85	80	9.0259	N/A	76.48	9.0711	N/A	283.72
36	9.0577	0.36	120.48	9.0446	0.34	239.64	82	9.0247	N/A	74.81	9.0505	N/A	285.35
38	9.0557	0.34	117.11	9.0337	0.33	242.98	84	9.1105	N/A	73.20	9.0326	N/A	287.04
40	9.0591	0.39	114.11	9.0540	0.37	246.07	86	N/A	N/A	N/A	N/A	N/A	N/A
42	9.0529	0.32	111.36	9.0546	0.33	248.88	88	N/A	N/A	N/A	N/A	N/A	N/A
44	9.0511	0.36	108.83	9.0618	0.33	251.34	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

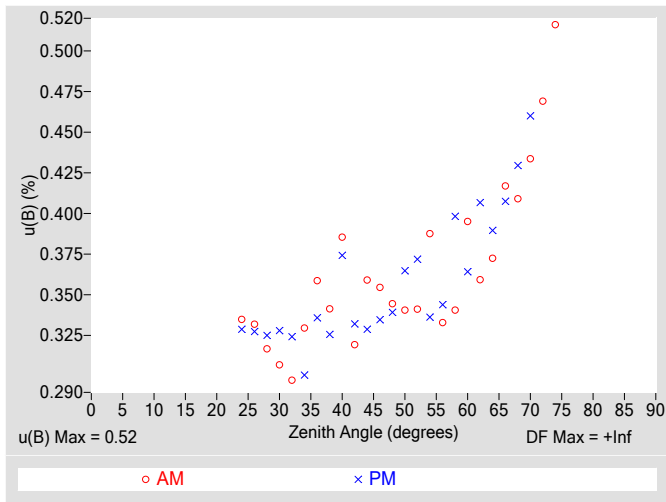


Figure 4. Residuals from Spline Interpolation

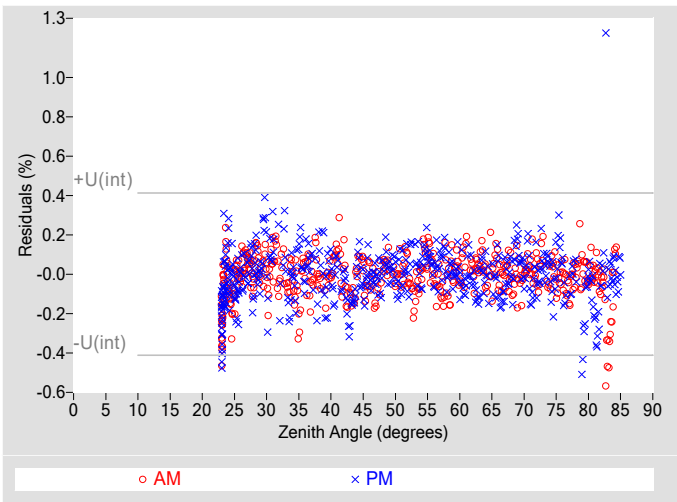


Table 3. Uncertainty using Spline Interpolation ‡

Type-B Standard Uncertainty, $u(B)$ (%)	± 0.52
Type-A Interpolating Function, $u(int)$ (%)	± 0.21
Combined Standard Uncertainty, $u(c)$ (%)	± 0.56
Effective degrees of freedom, $DF(c)$	47167
Coverage factor, k	1.96
Expanded Uncertainty, $U95$ (%)	± 1.1
AM Valid zenith angle range	24° to 74°
PM Valid zenith angle range	24° to 70°

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

Table 4. Calibration Label Values

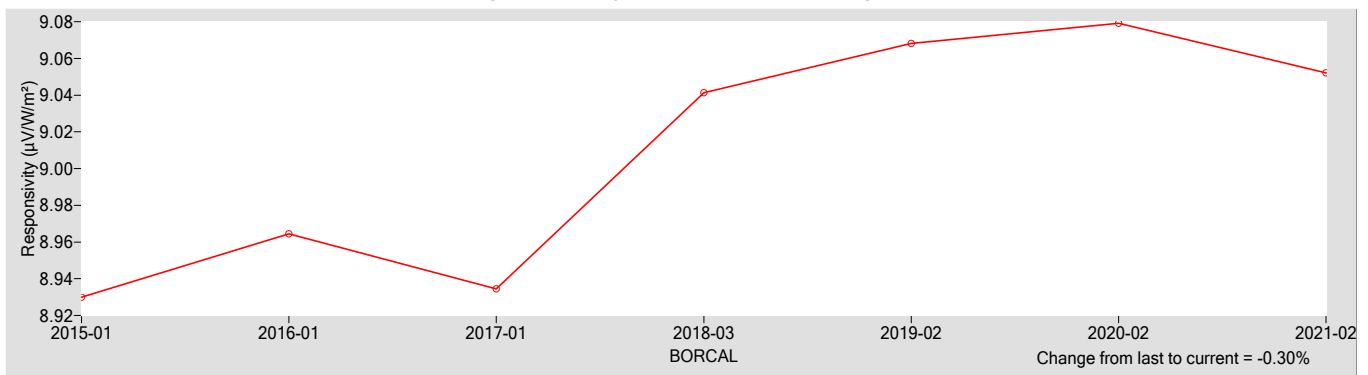
$R @ 45^\circ$ ($\mu V/W/m^2$)	R_{net} ($\mu V/W/m^2$) †
9.0521	0.087000

† R_{net} determination date: Estimated

Table 5. Uncertainty using $R @ 45^\circ$

Type-B Expanded Uncertainty, $U(B)$ (%)	± 0.78
Offset Uncertainty, $U(off)$ (%)	+0.28 / -0.31
Expanded Uncertainty, U (%)	+1.1 / -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 Pyrgometers. ARM 2008 Science Team Meeting (Poster).



National Renewable Energy Laboratory

Solar Radiation Research Laboratory

Metrology Laboratory

Calibration Certificate



Test Instrument:	Pyrheliometer	Manufacturer:	Kipp & Zonen
Model:	CHP1	Serial Number:	140108
Calibration Date:	5/6/2021	Due Date:	5/6/2022
Customer:	NREL-SRRL-BMS	Environmental Conditions:	see page 4
Test Dates:	5/6		

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 than 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	09/27/2019	09/27/2021
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/30/2021	04/30/2022
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/30/2021	04/30/2022
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/08/2021	02/08/2023
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/08/2021	02/08/2023

† 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, Peter Gotseff, 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

140108 Kipp & Zonen CHP1

The responsivity (R , $\mu\text{V}/\text{W}/\text{m}^2$) of the test instrument during calibration is calculated using this Measurement Equation:

$$R = (V - R_{net} * W_{net}) / I \tag{1}$$

where,

- V = radiometer output voltage (microvolts),
 - R_{net} = radiometer net infrared responsivity ($\mu\text{V}/\text{W}/\text{m}^2$), see Table 4,
 - W_{net} = effective net infrared measured by pyrgeometer (W/m^2),
 - = $W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
 - where, W_{in} = incoming infrared (W/m^2), $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$,
 - T_c = case temperature of pyrgeometer (K).
- I = reference irradiance (W/m^2), beam (B) or global (G)
 - where, $G = B * \text{COS}(Z) + D$,
 - Z = zenith angle (degrees),
 - D = reference diffuse irradiance (W/m^2).

Figure 1. Responsivity vs Zenith Angle

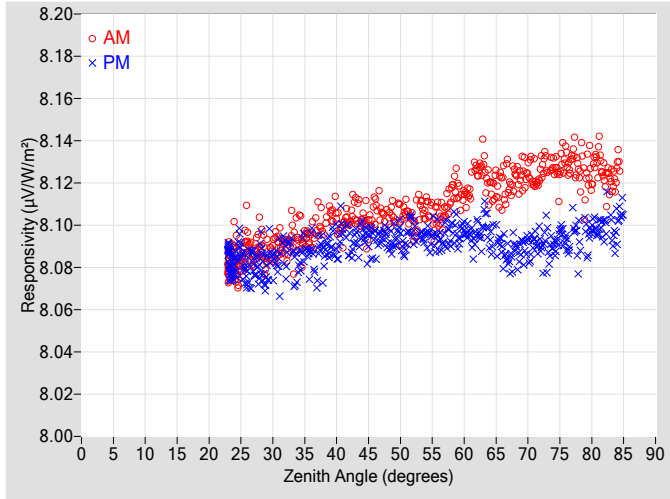


Figure 2. Responsivity vs Local Standard Time

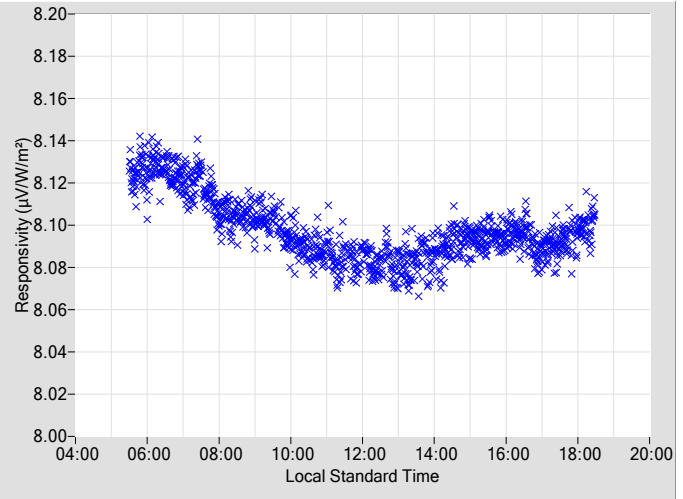


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)

Zenith			AM			PM			Zenith			AM			PM		
Angle	R	u(B)	Azimuth	R	u(B)	Azimuth	Angle	R	u(B)	Azimuth	R	u(B)	Azimuth	R	u(B)	Azimuth	
(deg.)	($\mu\text{V}/\text{W}/\text{m}^2$)	\pm (%)	Angle	($\mu\text{V}/\text{W}/\text{m}^2$)	\pm (%)	Angle	(deg.)	($\mu\text{V}/\text{W}/\text{m}^2$)	\pm (%)	Angle	($\mu\text{V}/\text{W}/\text{m}^2$)	\pm (%)	Angle	($\mu\text{V}/\text{W}/\text{m}^2$)	\pm (%)	Angle	
0	N/A	N/A	N/A	N/A	N/A	N/A	46	8.1089	0.34	106.42	8.0934	0.31	253.71				
2	N/A	N/A	N/A	N/A	N/A	N/A	48	8.1054	0.35	104.14	8.0923	0.30	255.99				
4	N/A	N/A	N/A	N/A	N/A	N/A	50	8.1029	0.34	102.02	8.0952	0.30	258.11				
6	N/A	N/A	N/A	N/A	N/A	N/A	52	8.0989	0.33	100.07	8.0968	0.33	260.13				
8	N/A	N/A	N/A	N/A	N/A	N/A	54	8.1075	0.29	98.18	8.0955	0.33	262.05				
10	N/A	N/A	N/A	N/A	N/A	N/A	56	8.1052	0.31	96.30	8.0948	0.30	263.83				
12	N/A	N/A	N/A	N/A	N/A	N/A	58	8.1154	0.31	94.48	8.0962	0.30	265.67				
14	N/A	N/A	N/A	N/A	N/A	N/A	60	8.1134	0.30	92.70	8.0982	0.32	267.35				
16	N/A	N/A	N/A	N/A	N/A	N/A	62	8.1255	0.30	91.08	8.0982	0.31	269.10				
18	N/A	N/A	N/A	N/A	N/A	N/A	64	8.1182	0.33	89.38	8.0929	0.31	270.80				
20	N/A	N/A	N/A	N/A	N/A	N/A	66	8.1185	0.31	87.70	8.0892	0.31	272.40				
22	N/A	N/A	N/A	N/A	N/A	N/A	68	8.1228	0.30	86.14	8.0898	0.31	274.05				
24	8.0836	0.31	160.94	8.0814	0.31	198.58	70	8.1248	0.31	84.50	8.0899	0.31	275.60				
26	8.0935	0.32	148.36	8.0777	0.33	211.89	72	8.1250	0.31	82.96	8.0922	N/A	277.24				
28	8.0921	0.30	139.88	8.0836	0.31	220.26	74	8.1274	0.31	81.31	8.0895	N/A	278.86				
30	8.0872	0.33	133.55	8.0831	0.33	226.41	76	8.1305	N/A	79.70	8.0914	N/A	280.48				
32	8.0897	0.31	128.52	8.0845	0.29	231.52	78	8.1239	N/A	78.08	8.0890	N/A	282.03				
34	8.0936	0.32	124.21	8.0805	0.32	235.99	80	8.1222	N/A	76.47	8.0991	N/A	283.66				
36	8.0950	0.31	120.61	8.0892	0.32	239.61	82	8.1234	N/A	74.85	8.0988	N/A	285.39				
38	8.0965	0.32	117.26	8.0845	0.32	242.96	84	8.1286	N/A	73.14	8.0999	N/A	287.03				
40	8.1048	0.31	114.11	8.0885	0.31	246.01	86	N/A	N/A	N/A	N/A	N/A	N/A				
42	8.1010	0.30	111.34	8.0910	0.31	248.75	88	N/A	N/A	N/A	N/A	N/A	N/A				
44	8.1025	0.33	108.75	8.0979	0.32	251.33	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

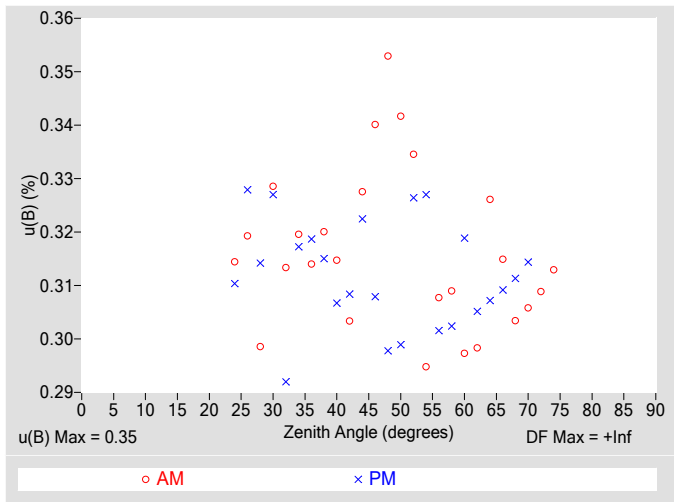


Figure 4. Residuals from Spline Interpolation

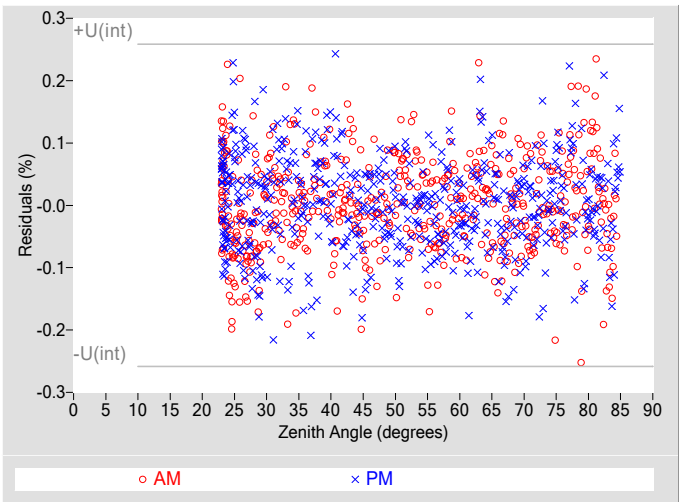


Table 3. Uncertainty using Spline Interpolation ‡

Type-B Standard Uncertainty, $u(B)$ (%)	± 0.35
Type-A Interpolating Function, $u(int)$ (%)	± 0.13
Combined Standard Uncertainty, $u(c)$ (%)	± 0.38
Effective degrees of freedom, $DF(c)$	65186
Coverage factor, k	1.96
Expanded Uncertainty, U_{95} (%)	± 0.74
AM Valid zenith angle range	24° to 74°
PM Valid zenith angle range	24° to 70°

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

Table 4. Calibration Label Values

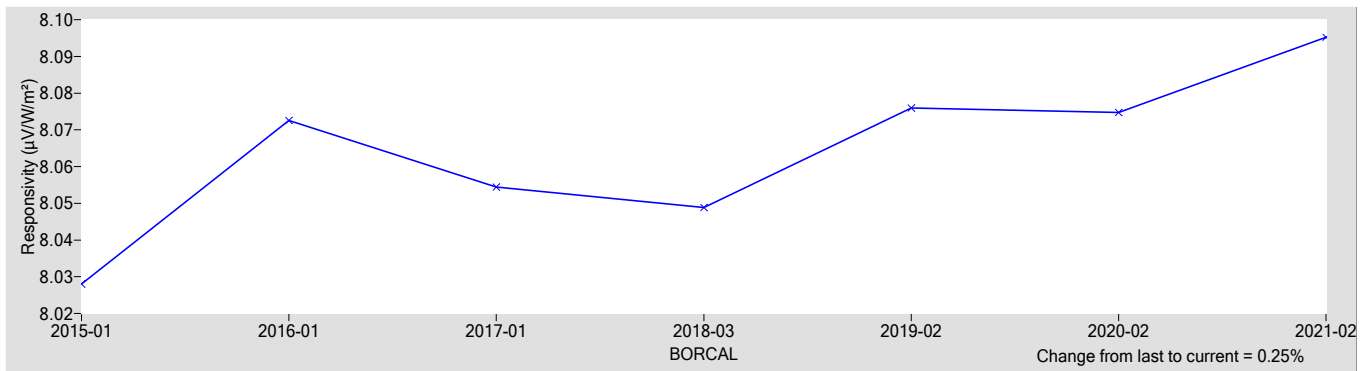
$R @ 45^\circ$ ($\mu V/W/m^2$)	R_{net} ($\mu V/W/m^2$) †
8.0952	0

† R_{net} determination date: N/A

Table 5. Uncertainty using $R @ 45^\circ$

Type-B Expanded Uncertainty, $U(B)$ (%)	± 0.69
Offset Uncertainty, $U(off)$ (%)	+0.25 / -0.18
Expanded Uncertainty, U (%)	+0.94 / -0.87
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 Pyrgometers*. ARM 2008 Science Team Meeting (Poster).



National Renewable Energy Laboratory

Solar Radiation Research Laboratory

Metrology Laboratory

Calibration Certificate



Test Instrument:	Pyranometer	Manufacturer:	Kipp & Zonen
Model:	CMP11	Serial Number:	140712
Calibration Date:	5/6/2021	Due Date:	5/6/2022
Customer:	NREL-SRRL-BMS	Environmental Conditions:	see page 4
Test Dates:	5/6		

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 than 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	09/27/2019	09/27/2021
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/30/2021	04/30/2022
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/30/2021	04/30/2022
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/08/2021	02/08/2023
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/08/2021	02/08/2023
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, Peter Gotseff, 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

140712 Kipp & Zonen CMP11

The responsivity (R , $\mu\text{V}/\text{W}/\text{m}^2$) of the test instrument during calibration is calculated using this Measurement Equation:

$$R = (V - R_{net} * W_{net}) / I \tag{1}$$

where,

- V = radiometer output voltage (microvolts),
- R_{net} = radiometer net infrared responsivity ($\mu\text{V}/\text{W}/\text{m}^2$), see Table 4,
- W_{net} = effective net infrared measured by pyrgeometer (W/m^2),
 $= W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
 where, W_{in} = incoming infrared (W/m^2), $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$,
 T_c = case temperature of pyrgeometer (K).
- I = reference irradiance (W/m^2), beam (B) or global (G)
 where, $G = B * \text{COS}(Z) + D$,
 Z = zenith angle (degrees),
 D = reference diffuse irradiance (W/m^2).

Figure 1. Responsivity vs Zenith Angle

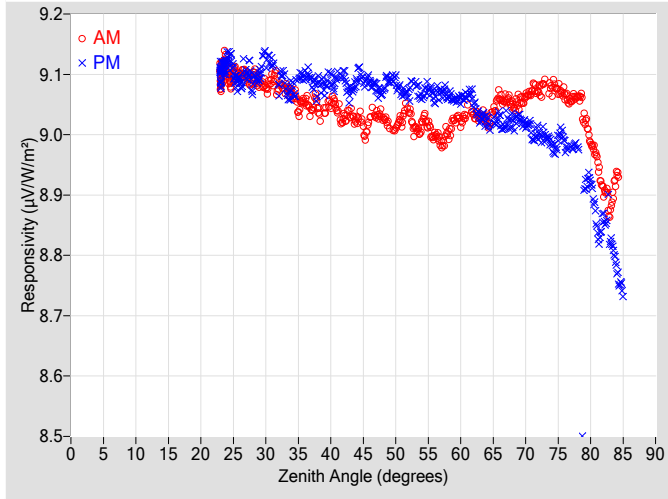


Figure 2. Responsivity vs Local Standard Time

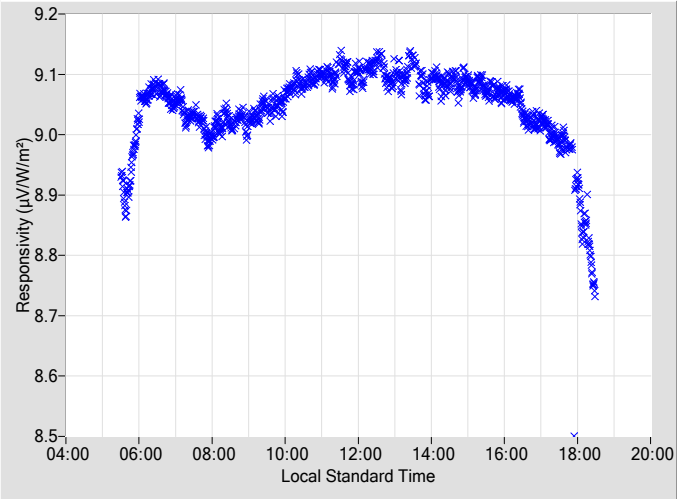


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)

Zenith Angle (deg.)	R ($\mu\text{V}/\text{W}/\text{m}^2$)	u(B) \pm (%)	Azimuth Angle	R ($\mu\text{V}/\text{W}/\text{m}^2$)	u(B) \pm (%)	Azimuth Angle	Zenith Angle (deg.)	R ($\mu\text{V}/\text{W}/\text{m}^2$)	u(B) \pm (%)	Azimuth Angle	R ($\mu\text{V}/\text{W}/\text{m}^2$)	u(B) \pm (%)	Azimuth Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	9.0236	0.34	106.50	9.0880	0.32	253.72
2	N/A	N/A	N/A	N/A	N/A	N/A	48	9.0270	0.39	104.12	9.0704	0.32	255.91
4	N/A	N/A	N/A	N/A	N/A	N/A	50	9.0104	0.34	102.09	9.0870	0.33	258.11
6	N/A	N/A	N/A	N/A	N/A	N/A	52	9.0399	0.33	100.05	9.0684	0.38	260.07
8	N/A	N/A	N/A	N/A	N/A	N/A	54	9.0150	0.37	98.13	9.0618	0.34	261.97
10	N/A	N/A	N/A	N/A	N/A	N/A	56	8.9982	0.36	96.25	9.0602	0.35	263.89
12	N/A	N/A	N/A	N/A	N/A	N/A	58	9.0025	0.39	94.53	9.0630	0.38	265.62
14	N/A	N/A	N/A	N/A	N/A	N/A	60	9.0205	0.36	92.73	9.0609	0.37	267.40
16	N/A	N/A	N/A	N/A	N/A	N/A	62	9.0315	0.39	91.03	9.0574	0.43	269.05
18	N/A	N/A	N/A	N/A	N/A	N/A	64	9.0219	0.40	89.39	9.0219	0.40	270.75
20	N/A	N/A	N/A	N/A	N/A	N/A	66	9.0636	0.40	87.75	9.0254	0.42	272.40
22	N/A	N/A	N/A	N/A	N/A	N/A	68	9.0484	0.42	86.10	9.0207	0.47	274.01
24	9.1098	0.33	160.86	9.1187	0.33	199.00	70	9.0613	0.44	84.55	9.0166	0.47	275.66
26	9.0970	0.33	148.15	9.0880	0.31	211.98	72	9.0722	0.48	82.92	9.0030	N/A	277.24
28	9.0935	0.33	139.88	9.0812	0.31	219.87	74	9.0772	0.52	81.36	8.9827	N/A	278.82
30	9.0793	0.31	133.76	9.1279	0.32	226.38	76	9.0670	N/A	79.75	8.9855	N/A	280.44
32	9.0792	0.34	128.53	9.0841	0.34	231.69	78	9.0632	N/A	78.14	8.9773	N/A	282.13
34	9.0699	0.33	124.42	9.0775	0.32	235.75	80	8.9873	N/A	76.48	8.9197	N/A	283.71
36	9.0545	0.33	120.45	9.0957	0.37	239.79	82	8.9075	N/A	74.81	8.8601	N/A	285.34
38	9.0454	0.34	117.11	9.0777	0.31	242.97	84	8.9296	N/A	73.19	8.7773	N/A	287.03
40	9.0528	0.34	114.10	9.0921	0.33	246.18	86	N/A	N/A	N/A	N/A	N/A	N/A
42	9.0260	0.32	111.35	9.0986	0.31	248.80	88	N/A	N/A	N/A	N/A	N/A	N/A
44	9.0247	0.36	108.82	9.0950	0.32	251.33	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

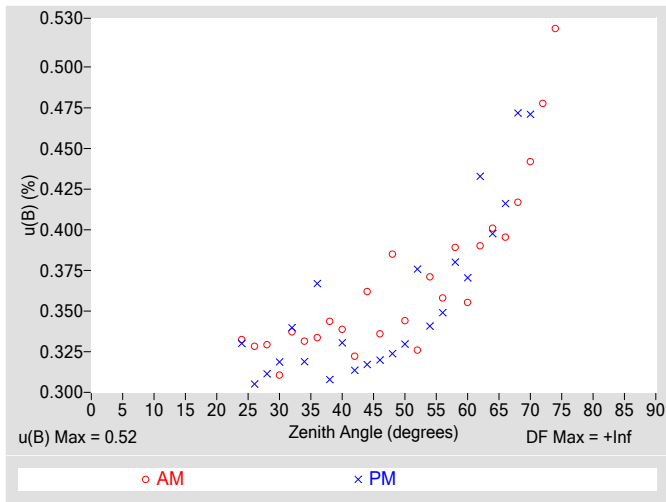


Figure 4. Residuals from Spline Interpolation

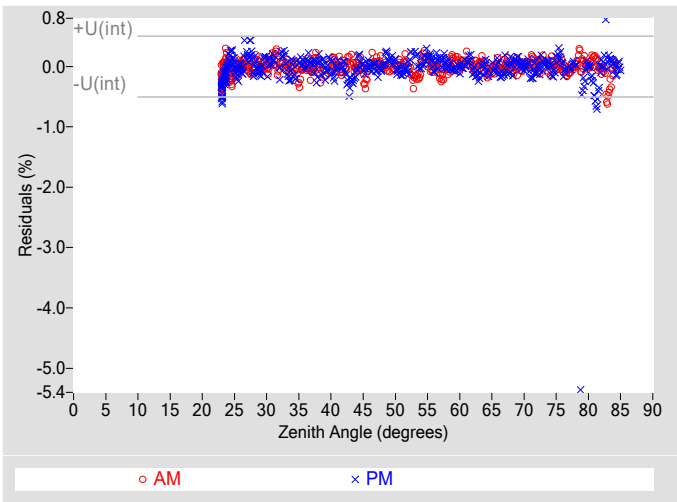


Table 3. Uncertainty using Spline Interpolation ‡

Type-B Standard Uncertainty, $u(B)$ (%)	± 0.52
Type-A Interpolating Function, $u(int)$ (%)	± 0.25
Combined Standard Uncertainty, $u(c)$ (%)	± 0.58
Effective degrees of freedom, $DF(c)$	24839
Coverage factor, k	1.96
Expanded Uncertainty, $U95$ (%)	± 1.1
AM Valid zenith angle range	24° to 74°
PM Valid zenith angle range	24° to 70°

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

Table 4. Calibration Label Values

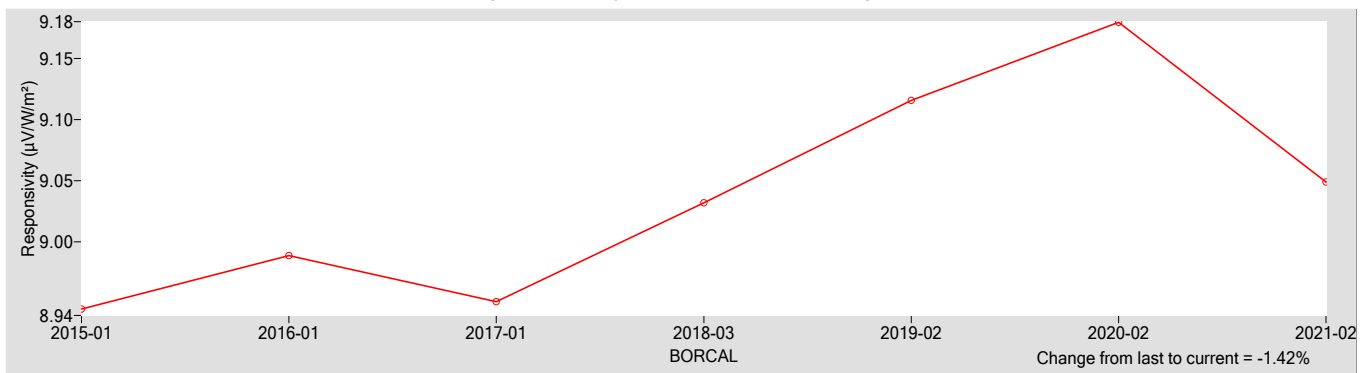
$R @ 45^\circ$ ($\mu V/W/m^2$)	R_{net} ($\mu V/W/m^2$) †
9.0490	0.20500

† R_{net} determination date: Estimated

Table 5. Uncertainty using $R @ 45^\circ$

Type-B Expanded Uncertainty, $U(B)$ (%)	± 0.76
Offset Uncertainty, $U(off)$ (%)	+0.87 / -0.56
Expanded Uncertainty, U (%)	+1.6 / -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 Pyrgometers*. ARM 2008 Science Team Meeting (Poster).



National Renewable Energy Laboratory

Solar Radiation Research Laboratory

Metrology Laboratory

Calibration Certificate



Test Instrument:	Silicon Pyranometer	Manufacturer:	Kipp & Zonen
Model:	SP-LITE2	Serial Number:	151027
Calibration Date:	5/6/2021	Due Date:	5/6/2022
Customer:	NREL-SRRL-BMS	Environmental Conditions:	see page 4
Test Dates:	5/6		

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 than 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	09/27/2019	09/27/2021
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/30/2021	04/30/2022
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/30/2021	04/30/2022
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/08/2021	02/08/2023
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/08/2021	02/08/2023

† 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, Peter Gotseff, 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

151027 Kipp & Zonen SP-LITE2

The responsivity (R , $\mu\text{V}/\text{W}/\text{m}^2$) of the test instrument during calibration is calculated using this Measurement Equation:

$$R = (V - R_{net} * W_{net}) / I \tag{1}$$

where,

- V = radiometer output voltage (microvolts),
 - R_{net} = radiometer net infrared responsivity ($\mu\text{V}/\text{W}/\text{m}^2$), see Table 4,
 - W_{net} = effective net infrared measured by pyrgeometer (W/m^2),
 - = $W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
 - where, W_{in} = incoming infrared (W/m^2), $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$,
 - T_c = case temperature of pyrgeometer (K).
- I = reference irradiance (W/m^2), beam (B) or global (G)
 - where, $G = B * \text{COS}(Z) + D$,
 - Z = zenith angle (degrees),
 - D = reference diffuse irradiance (W/m^2).

Figure 1. Responsivity vs Zenith Angle

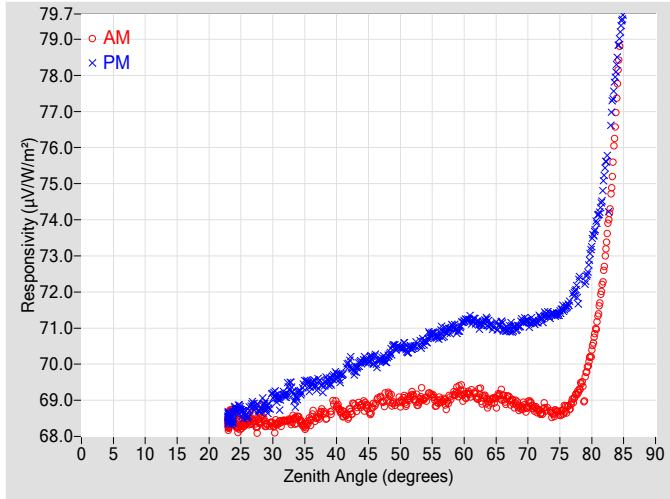


Figure 2. Responsivity vs Local Standard Time

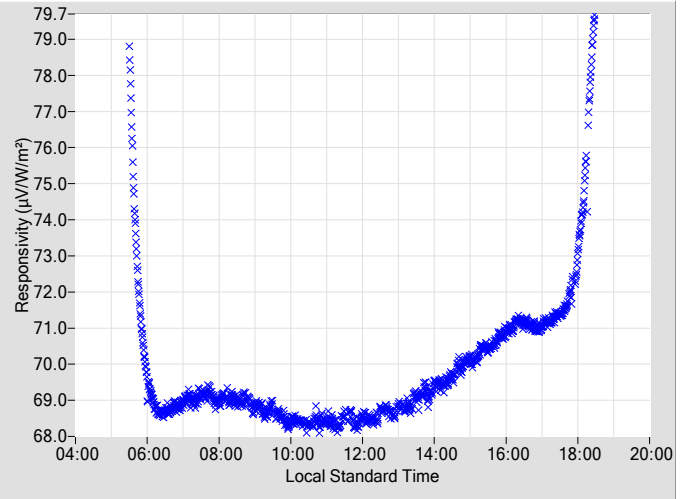


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, $u(B)$

Zenith Angle (deg.)	R ($\mu\text{V}/\text{W}/\text{m}^2$)	$u(B)$ \pm (%)	Azimuth Angle	R ($\mu\text{V}/\text{W}/\text{m}^2$)	$u(B)$ \pm (%)	Azimuth Angle	Zenith Angle (deg.)	R ($\mu\text{V}/\text{W}/\text{m}^2$)	$u(B)$ \pm (%)	Azimuth Angle	R ($\mu\text{V}/\text{W}/\text{m}^2$)	$u(B)$ \pm (%)	Azimuth Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	68.885	0.34	106.47	70.068	0.33	253.72
2	N/A	N/A	N/A	N/A	N/A	N/A	48	69.130	0.34	104.13	70.174	0.32	255.94
4	N/A	N/A	N/A	N/A	N/A	N/A	50	68.964	0.33	102.03	70.449	0.32	258.11
6	N/A	N/A	N/A	N/A	N/A	N/A	52	69.113	0.36	100.01	70.465	0.36	260.07
8	N/A	N/A	N/A	N/A	N/A	N/A	54	69.034	0.32	98.24	70.626	0.33	262.00
10	N/A	N/A	N/A	N/A	N/A	N/A	56	68.979	0.35	96.31	70.775	0.34	263.84
12	N/A	N/A	N/A	N/A	N/A	N/A	58	69.087	0.37	94.52	71.006	0.35	265.67
14	N/A	N/A	N/A	N/A	N/A	N/A	60	69.107	0.34	92.70	71.196	0.36	267.35
16	N/A	N/A	N/A	N/A	N/A	N/A	62	69.101	0.43	91.08	71.142	0.37	269.10
18	N/A	N/A	N/A	N/A	N/A	N/A	64	68.952	0.37	89.38	71.107	0.38	270.80
20	N/A	N/A	N/A	N/A	N/A	N/A	66	69.118	0.47	87.70	71.080	0.40	272.40
22	N/A	N/A	N/A	N/A	N/A	N/A	68	68.899	0.40	86.15	71.008	0.42	274.06
24	68.464	0.32	161.09	68.620	0.33	198.67	70	68.873	0.42	84.50	71.155	0.45	275.61
26	68.445	0.31	148.12	68.622	0.33	211.88	72	68.657	0.46	82.92	71.292	N/A	277.24
28	68.509	0.33	139.87	68.709	0.32	219.92	74	68.609	0.50	81.31	71.391	N/A	278.86
30	68.285	0.31	133.63	69.154	0.31	226.51	76	68.769	N/A	79.70	71.600	N/A	280.48
32	68.437	0.31	128.69	69.144	0.32	231.52	78	69.314	N/A	78.09	72.075	N/A	281.98
34	68.481	0.34	124.22	69.206	0.31	236.00	80	70.383	N/A	76.47	73.319	N/A	283.66
36	68.479	0.32	120.56	69.395	0.32	239.61	82	72.756	N/A	74.86	75.299	N/A	285.34
38	68.679	0.34	117.18	69.381	0.34	242.96	84	77.735	N/A	73.14	78.515	N/A	287.03
40	68.883	0.36	114.03	69.678	0.30	246.02	86	N/A	N/A	N/A	N/A	N/A	N/A
42	68.644	0.34	111.35	70.035	0.32	248.87	88	N/A	N/A	N/A	N/A	N/A	N/A
44	68.890	0.33	108.78	70.075	0.31	251.33	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

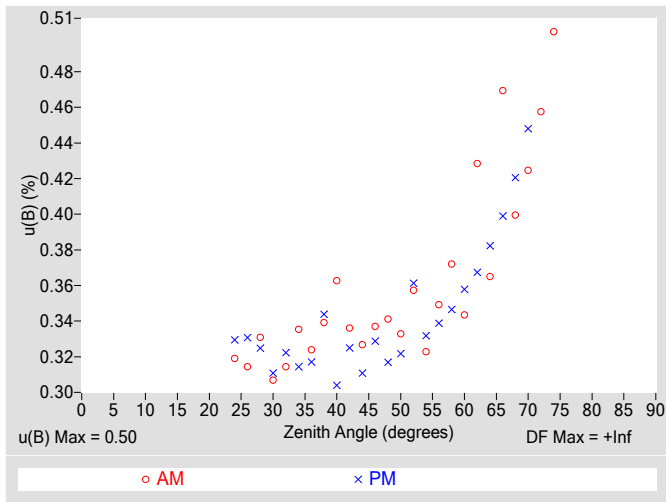


Figure 4. Residuals from Spline Interpolation

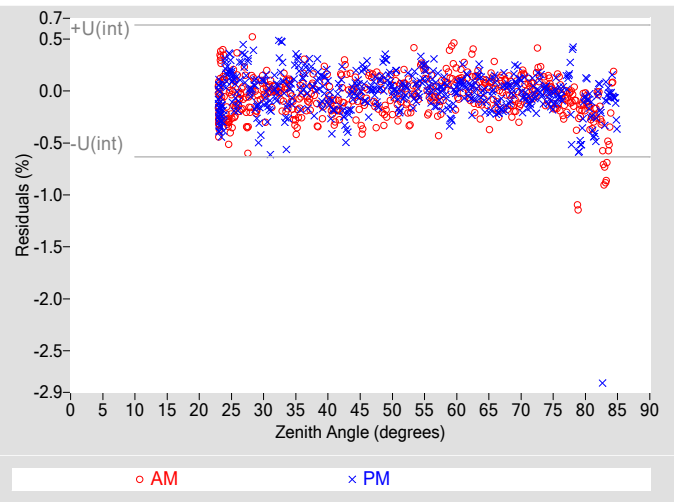


Table 3. Uncertainty using Spline Interpolation ‡

Type-B Standard Uncertainty, u(B) (%)	±0.50
Type-A Interpolating Function, u(int) (%)	±0.32
Combined Standard Uncertainty, u(c) (%)	±0.59
Effective degrees of freedom, DF(c)	10930
Coverage factor, k	1.96
Expanded Uncertainty, U95 (%)	±1.2
AM Valid zenith angle range	24° to 74°
PM Valid zenith angle range	24° 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

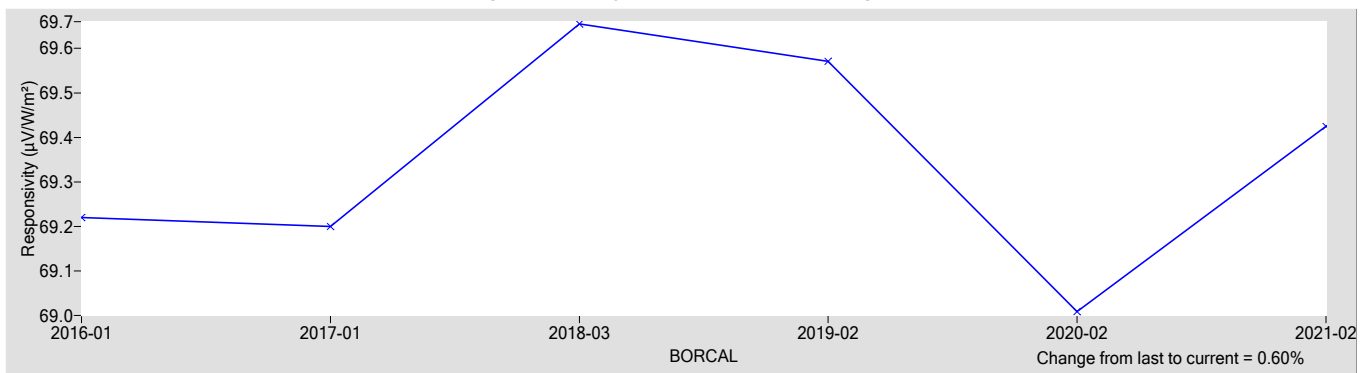
R @ 45° (μV/W/m²)	Rnet (μV/W/m²) †
69.425	0

† Rnet determination date: N/A

Table 5. Uncertainty using R @ 45°

Type-B Expanded Uncertainty, U(B) (%)	±0.73
Offset Uncertainty, U(off) (%)	+2.6 / -1.6
Expanded Uncertainty, U (%)	+3.3 / -2.4
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 Pyrgometers*. ARM 2008 Science Team Meeting (Poster).



National Renewable Energy Laboratory

Solar Radiation Research Laboratory

Metrology Laboratory

Calibration Certificate



Test Instrument:	Silicon Pyranometer	Manufacturer:	Kipp & Zonen
Model:	SP-LITE2	Serial Number:	151041
Calibration Date:	5/6/2021	Due Date:	5/6/2022
Customer:	NREL-SRRL-BMS	Environmental Conditions:	see page 4
Test Dates:	5/6		

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 than 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	09/27/2019	09/27/2021
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/30/2021	04/30/2022
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/30/2021	04/30/2022
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/08/2021	02/08/2023
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/08/2021	02/08/2023

† 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, Peter Gotseff, 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

151041 Kipp & Zonen SP-LITE2

The responsivity (R , $\mu\text{V}/\text{W}/\text{m}^2$) of the test instrument during calibration is calculated using this Measurement Equation:

$$R = (V - R_{net} * W_{net}) / I \tag{1}$$

where,

- V = radiometer output voltage (microvolts),
 - R_{net} = radiometer net infrared responsivity ($\mu\text{V}/\text{W}/\text{m}^2$), see Table 4,
 - W_{net} = effective net infrared measured by pyrgeometer (W/m^2),
 - = $W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
 - where, W_{in} = incoming infrared (W/m^2), $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$,
 - T_c = case temperature of pyrgeometer (K).
- I = reference irradiance (W/m^2), beam (B) or global (G)
 - where, $G = B * \text{COS}(Z) + D$,
 - Z = zenith angle (degrees),
 - D = reference diffuse irradiance (W/m^2).

Figure 1. Responsivity vs Zenith Angle

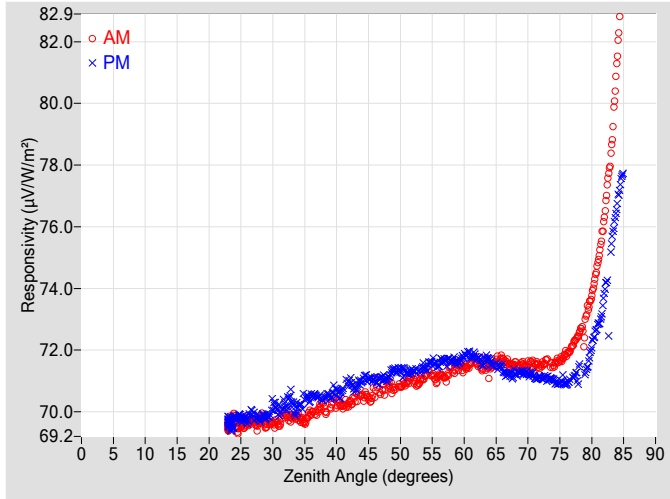


Figure 2. Responsivity vs Local Standard Time

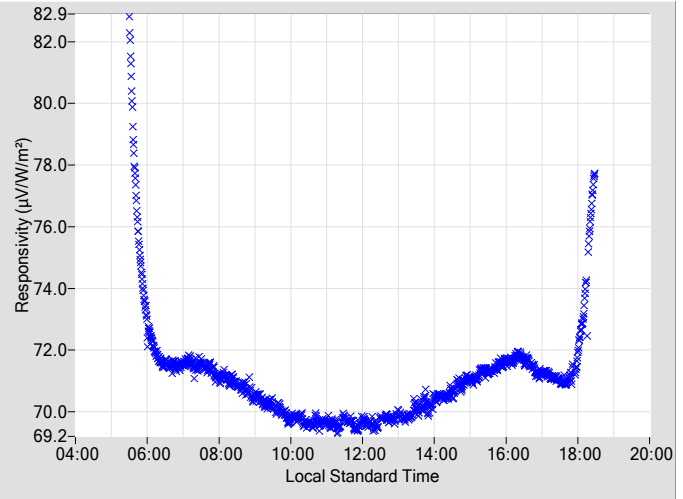


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, $u(B)$

Zenith Angle (deg.)	R ($\mu\text{V}/\text{W}/\text{m}^2$)	AM $u(B)$ \pm (%)	Azimuth Angle	R ($\mu\text{V}/\text{W}/\text{m}^2$)	PM $u(B)$ \pm (%)	Azimuth Angle	Zenith Angle (deg.)	R ($\mu\text{V}/\text{W}/\text{m}^2$)	AM $u(B)$ \pm (%)	Azimuth Angle	R ($\mu\text{V}/\text{W}/\text{m}^2$)	PM $u(B)$ \pm (%)	Azimuth Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	70.644	0.34	106.47	71.008	0.33	253.72
2	N/A	N/A	N/A	N/A	N/A	N/A	48	70.920	0.34	104.13	71.081	0.32	255.94
4	N/A	N/A	N/A	N/A	N/A	N/A	50	70.828	0.33	102.03	71.361	0.32	258.11
6	N/A	N/A	N/A	N/A	N/A	N/A	52	71.075	0.36	100.01	71.318	0.36	260.07
8	N/A	N/A	N/A	N/A	N/A	N/A	54	71.140	0.32	98.24	71.414	0.33	262.00
10	N/A	N/A	N/A	N/A	N/A	N/A	56	71.127	0.35	96.31	71.493	0.34	263.84
12	N/A	N/A	N/A	N/A	N/A	N/A	58	71.399	0.37	94.52	71.650	0.35	265.67
14	N/A	N/A	N/A	N/A	N/A	N/A	60	71.402	0.34	92.70	71.810	0.36	267.35
16	N/A	N/A	N/A	N/A	N/A	N/A	62	71.550	0.43	91.08	71.734	0.37	269.10
18	N/A	N/A	N/A	N/A	N/A	N/A	64	71.372	0.37	89.38	71.652	0.38	270.80
20	N/A	N/A	N/A	N/A	N/A	N/A	66	71.723	0.47	87.70	71.389	0.40	272.40
22	N/A	N/A	N/A	N/A	N/A	N/A	68	71.549	0.40	86.15	71.241	0.42	274.06
24	69.694	0.32	161.09	69.668	0.33	198.67	70	71.485	0.42	84.50	71.221	0.45	275.61
26	69.646	0.31	148.12	69.764	0.33	211.88	72	71.489	0.46	82.92	71.113	N/A	277.24
28	69.730	0.33	139.87	69.761	0.32	219.92	74	71.516	0.50	81.31	71.013	N/A	278.86
30	69.600	0.31	133.63	70.208	0.31	226.51	76	71.883	N/A	79.70	70.918	N/A	280.48
32	69.871	0.31	128.69	70.150	0.32	231.52	78	72.558	N/A	78.09	71.224	N/A	281.98
34	69.832	0.34	124.22	70.149	0.31	236.00	80	73.784	N/A	76.47	72.127	N/A	283.66
36	69.955	0.32	120.56	70.445	0.32	239.61	82	76.339	N/A	74.86	73.887	N/A	285.34
38	70.183	0.34	117.18	70.410	0.34	242.96	84	81.608	N/A	73.14	76.768	N/A	287.03
40	70.270	0.36	114.03	70.665	0.30	246.02	86	N/A	N/A	N/A	N/A	N/A	N/A
42	70.274	0.34	111.35	70.961	0.32	248.87	88	N/A	N/A	N/A	N/A	N/A	N/A
44	70.489	0.33	108.78	71.012	0.31	251.33	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

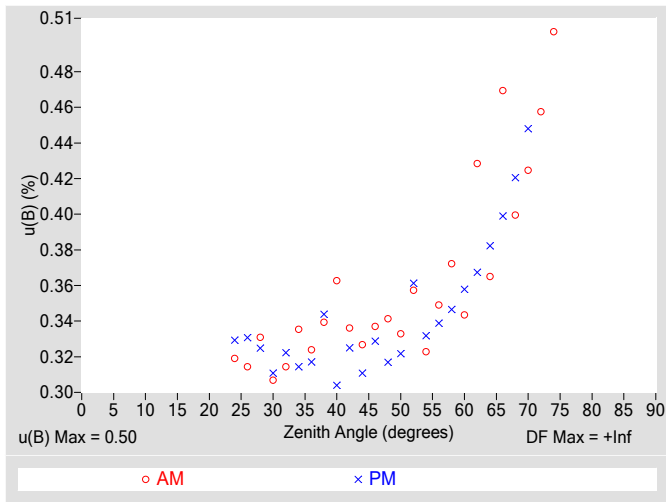


Figure 4. Residuals from Spline Interpolation

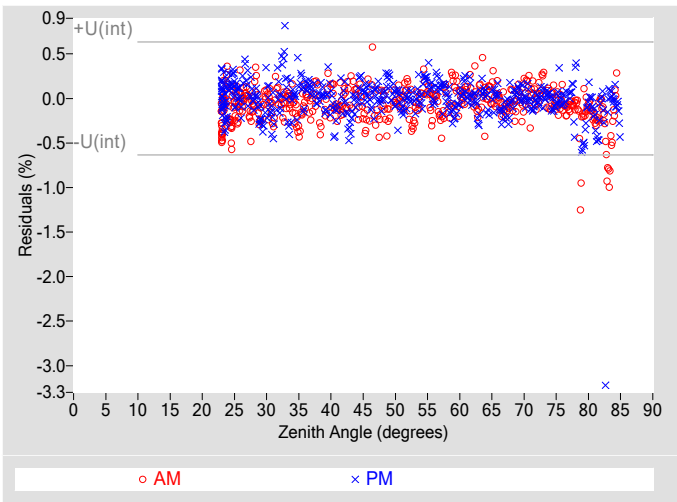


Table 3. Uncertainty using Spline Interpolation ‡

Type-B Standard Uncertainty, $u(B)$ (%)	± 0.50
Type-A Interpolating Function, $u(int)$ (%)	± 0.32
Combined Standard Uncertainty, $u(c)$ (%)	± 0.59
Effective degrees of freedom, $DF(c)$	11003
Coverage factor, k	1.96
Expanded Uncertainty, U_{95} (%)	± 1.2
AM Valid zenith angle range	24° to 74°
PM Valid zenith angle range	24° to 70°

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

Table 4. Calibration Label Values

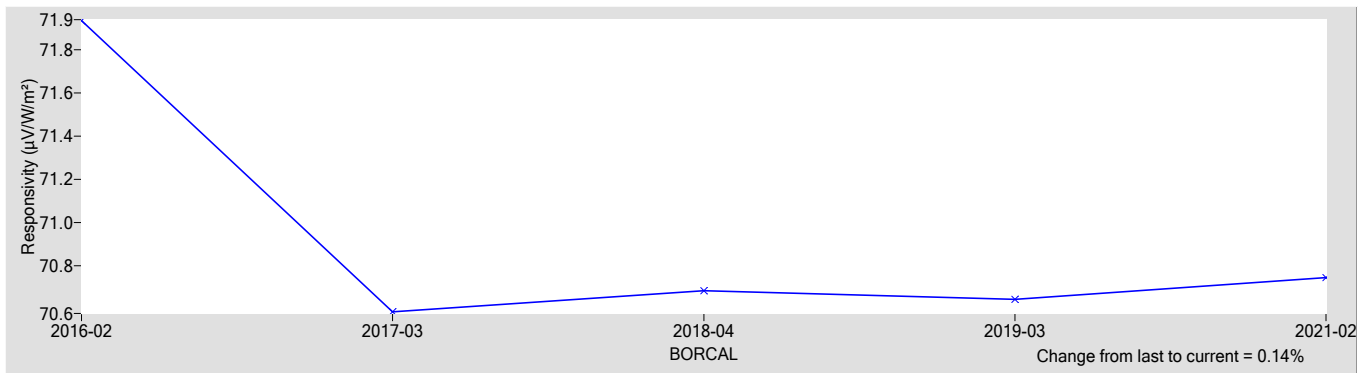
$R @ 45^\circ$ ($\mu V/W/m^2$)	R_{net} ($\mu V/W/m^2$) †
70.746	0

† R_{net} determination date: N/A

Table 5. Uncertainty using $R @ 45^\circ$

Type-B Expanded Uncertainty, $U(B)$ (%)	± 0.73
Offset Uncertainty, $U(off)$ (%)	+1.5 / -1.6
Expanded Uncertainty, U (%)	+2.2 / -2.3
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 Pyrgometers. ARM 2008 Science Team Meeting (Poster).



National Renewable Energy Laboratory

Solar Radiation Research Laboratory

Metrology Laboratory

Calibration Certificate



Test Instrument:	Pyranometer	Manufacturer:	Kipp & Zonen
Model:	CMP22	Serial Number:	170515
Calibration Date:	5/6/2021	Due Date:	5/6/2022
Customer:	NREL-SRRL-BMS	Environmental Conditions:	see page 4
Test Dates:	5/6		

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 than 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	09/27/2019	09/27/2021
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/30/2021	04/30/2022
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/30/2021	04/30/2022
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/08/2021	02/08/2023
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/08/2021	02/08/2023
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, Peter Gotseff, 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

170515 Kipp & Zonen CMP22

The responsivity (R , $\mu\text{V}/\text{W}/\text{m}^2$) of the test instrument during calibration is calculated using this Measurement Equation:

$$R = (V - R_{net} * W_{net}) / I \tag{1}$$

where,

- V = radiometer output voltage (microvolts),
 - R_{net} = radiometer net infrared responsivity ($\mu\text{V}/\text{W}/\text{m}^2$), see Table 4,
 - W_{net} = effective net infrared measured by pyrgeometer (W/m^2),
 - = $W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
 - where, W_{in} = incoming infrared (W/m^2), $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$,
 - T_c = case temperature of pyrgeometer (K).
- I = reference irradiance (W/m^2), beam (B) or global (G)
 - where, $G = B * \text{COS}(Z) + D$,
 - Z = zenith angle (degrees),
 - D = reference diffuse irradiance (W/m^2).

Figure 1. Responsivity vs Zenith Angle

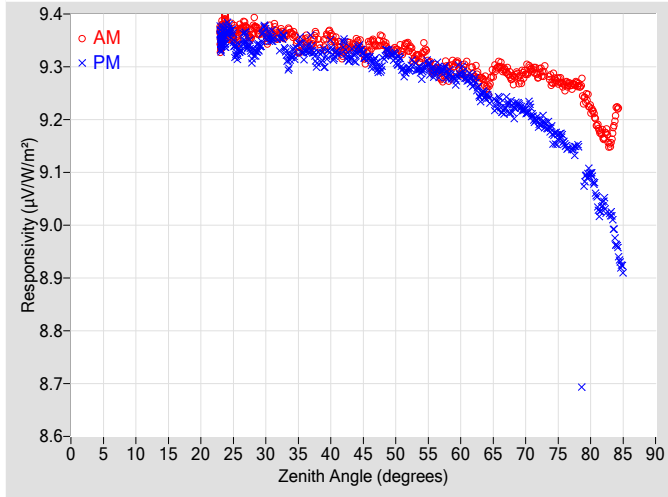


Figure 2. Responsivity vs Local Standard Time

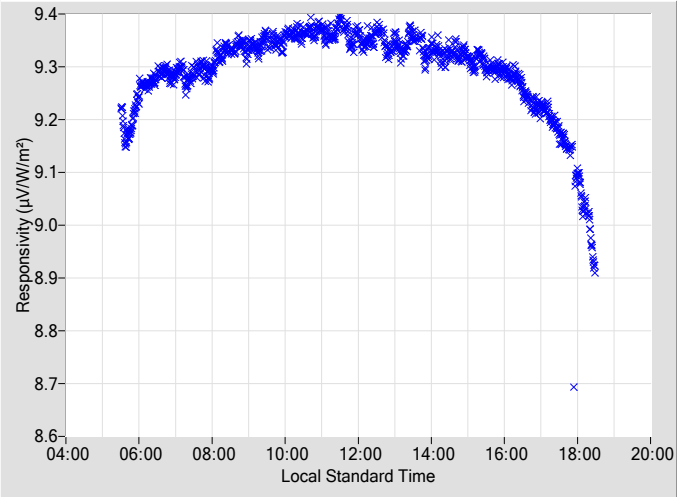


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)

Zenith			AM			PM			Zenith			AM			PM		
Angle	R	u(B)	Azimuth	R	u(B)	Azimuth	Angle	R	u(B)	Azimuth	R	u(B)	Azimuth	R	u(B)	Azimuth	
(deg.)	($\mu\text{V}/\text{W}/\text{m}^2$)	± (%)	Angle	($\mu\text{V}/\text{W}/\text{m}^2$)	± (%)	Angle	(deg.)	($\mu\text{V}/\text{W}/\text{m}^2$)	± (%)	Angle	($\mu\text{V}/\text{W}/\text{m}^2$)	± (%)	Angle	($\mu\text{V}/\text{W}/\text{m}^2$)	± (%)	Angle	
0	N/A	N/A	N/A	N/A	N/A	N/A	46	9.3403	0.35	106.37	9.3131	0.35	253.73				
2	N/A	N/A	N/A	N/A	N/A	N/A	48	9.3471	0.34	104.10	9.3069	0.34	255.92				
4	N/A	N/A	N/A	N/A	N/A	N/A	50	9.3311	0.34	102.16	9.3155	0.33	258.06				
6	N/A	N/A	N/A	N/A	N/A	N/A	52	9.3380	0.36	100.09	9.2960	0.33	260.15				
8	N/A	N/A	N/A	N/A	N/A	N/A	54	9.3192	0.35	98.14	9.2894	0.34	262.01				
10	N/A	N/A	N/A	N/A	N/A	N/A	56	9.2960	0.35	96.26	9.2891	0.38	263.85				
12	N/A	N/A	N/A	N/A	N/A	N/A	58	9.2974	0.36	94.49	9.2836	0.35	265.63				
14	N/A	N/A	N/A	N/A	N/A	N/A	60	9.2895	0.37	92.77	9.2888	0.36	267.42				
16	N/A	N/A	N/A	N/A	N/A	N/A	62	9.2853	0.36	91.04	9.2729	0.37	269.06				
18	N/A	N/A	N/A	N/A	N/A	N/A	64	9.2632	0.40	89.35	9.2436	0.42	270.76				
20	N/A	N/A	N/A	N/A	N/A	N/A	66	9.3037	0.42	87.76	9.2310	0.41	272.41				
22	N/A	N/A	N/A	N/A	N/A	N/A	68	9.2765	0.41	86.11	9.2205	0.43	274.02				
24	9.3776	0.33	161.25	9.3615	0.32	198.93	70	9.2894	0.43	84.56	9.2155	0.46	275.66				
26	9.3678	0.33	148.16	9.3327	0.33	211.45	72	9.2858	0.55	82.93	9.1961	N/A	277.20				
28	9.3707	0.31	139.98	9.3222	0.32	220.16	74	9.2754	0.52	81.33	9.1748	N/A	278.82				
30	9.3612	0.34	133.79	9.3677	0.34	226.27	76	9.2641	N/A	79.76	9.1539	N/A	280.44				
32	9.3591	0.32	128.55	9.3457	0.30	231.55	78	9.2675	N/A	78.15	9.1506	N/A	282.14				
34	9.3622	0.34	124.28	9.3238	0.35	235.86	80	9.2209	N/A	76.49	9.0962	N/A	283.72				
36	9.3517	0.32	120.30	9.3259	0.32	239.69	82	9.1698	N/A	74.82	9.0420	N/A	285.35				
38	9.3525	0.33	117.09	9.3117	0.33	242.87	84	9.2155	N/A	73.15	8.9599	N/A	287.04				
40	9.3596	0.33	114.13	9.3358	0.31	246.20	86	N/A	N/A	N/A	N/A	N/A	N/A				
42	9.3267	0.32	111.36	9.3436	0.36	248.82	88	N/A	N/A	N/A	N/A	N/A	N/A				
44	9.3439	0.31	108.77	9.3277	0.33	251.35	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

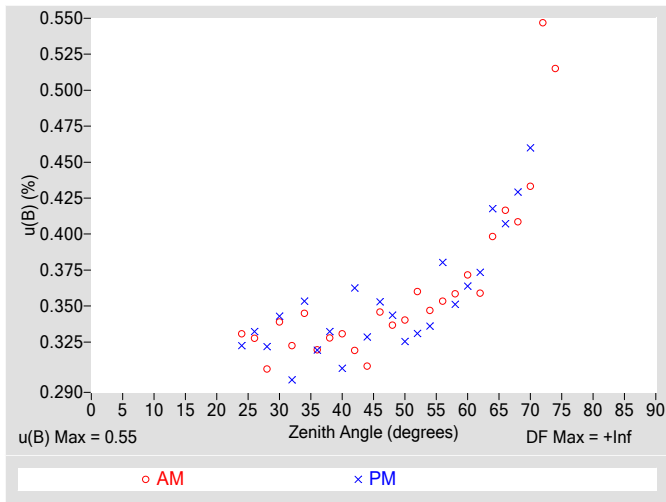


Figure 4. Residuals from Spline Interpolation

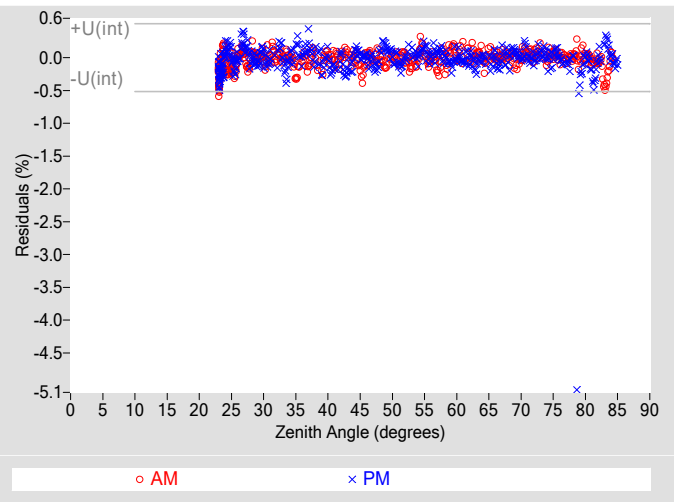


Table 3. Uncertainty using Spline Interpolation ‡

Type-B Standard Uncertainty, $u(B)$ (%)	± 0.55
Type-A Interpolating Function, $u(int)$ (%)	± 0.26
Combined Standard Uncertainty, $u(c)$ (%)	± 0.60
Effective degrees of freedom, $DF(c)$	27614
Coverage factor, k	1.96
Expanded Uncertainty, U_{95} (%)	± 1.2
AM Valid zenith angle range	24° to 74°
PM Valid zenith angle range	24° to 70°

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

Table 4. Calibration Label Values

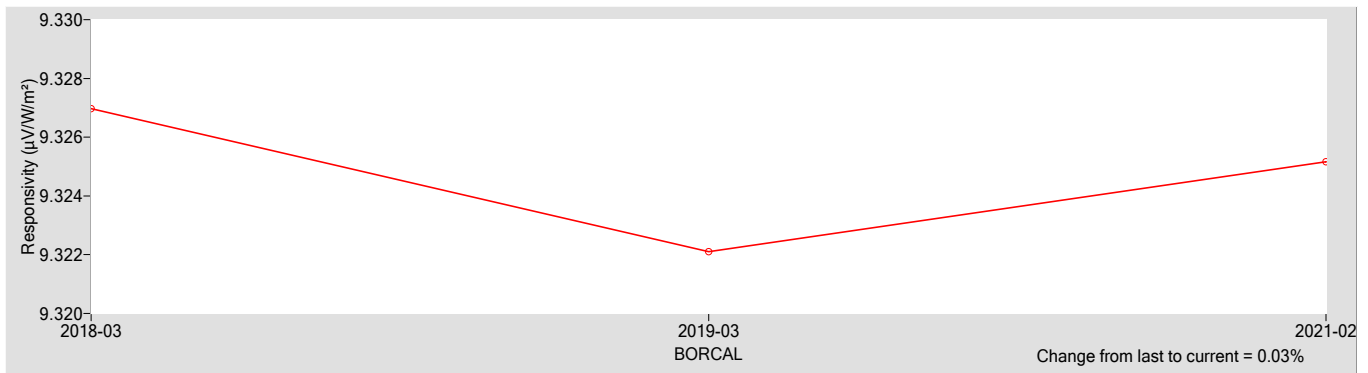
$R @ 45^\circ$ ($\mu V/W/m^2$)	R_{net} ($\mu V/W/m^2$) †
9.3252	0.087000

† R_{net} determination date: Estimated

Table 5. Uncertainty using $R @ 45^\circ$

Type-B Expanded Uncertainty, $U(B)$ (%)	± 0.75
Offset Uncertainty, $U(off)$ (%)	+0.46 / -0.45
Expanded Uncertainty, U (%)	+1.2 / -1.2
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 Pyrgometers. ARM 2008 Science Team Meeting (Poster).



National Renewable Energy Laboratory

Solar Radiation Research Laboratory

Metrology Laboratory

Calibration Certificate



Test Instrument:	Pyranometer	Manufacturer:	Hukseflux
Model:	SR25	Serial Number:	2529
Calibration Date:	5/6/2021	Due Date:	5/6/2022
Customer:	NREL-SRRL-BMS	Environmental Conditions:	see page 4
Test Dates:	5/6		

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	09/27/2019	09/27/2021
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/30/2021	04/30/2022
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/30/2021	04/30/2022
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/08/2021	02/08/2023
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/08/2021	02/08/2023
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, Peter Gotseff, 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

2529 Hukseflux SR25

The responsivity (R , $\mu\text{V}/\text{W}/\text{m}^2$) of the test instrument during calibration is calculated using this Measurement Equation:

$$R = (V - R_{net} * W_{net}) / I \tag{1}$$

where,

- V = radiometer output voltage (microvolts),
 - R_{net} = radiometer net infrared responsivity ($\mu\text{V}/\text{W}/\text{m}^2$), see Table 4,
 - W_{net} = effective net infrared measured by pyrgeometer (W/m^2),
 - = $W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
 - where, W_{in} = incoming infrared (W/m^2), $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$,
 - T_c = case temperature of pyrgeometer (K).
- I = reference irradiance (W/m^2), beam (B) or global (G)
 - where, $G = B * \text{COS}(Z) + D$,
 - Z = zenith angle (degrees),
 - D = reference diffuse irradiance (W/m^2).

Figure 1. Responsivity vs Zenith Angle

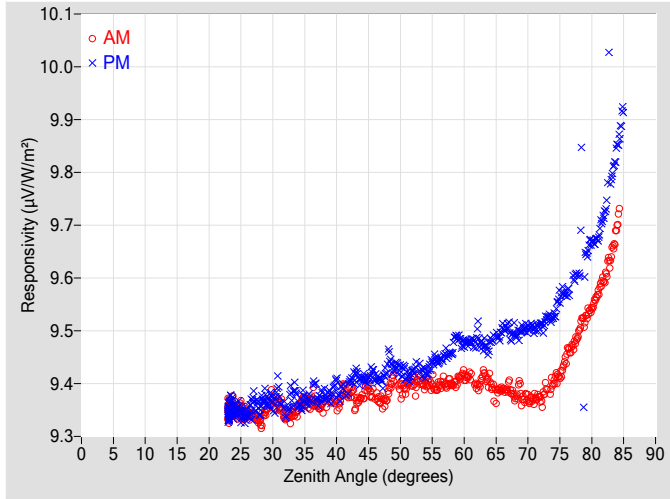


Figure 2. Responsivity vs Local Standard Time

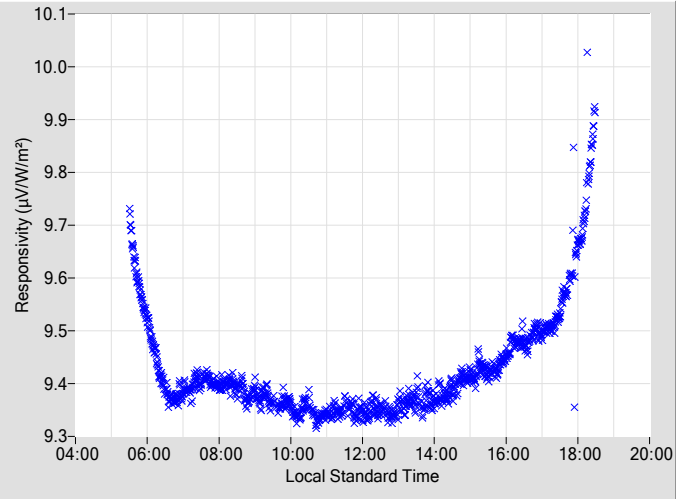


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, $u(B)$

Zenith Angle (deg.)	R ($\mu\text{V}/\text{W}/\text{m}^2$)	AM $u(B)$ \pm (%)	Azimuth Angle	R ($\mu\text{V}/\text{W}/\text{m}^2$)	PM $u(B)$ \pm (%)	Azimuth Angle	Zenith Angle (deg.)	R ($\mu\text{V}/\text{W}/\text{m}^2$)	AM $u(B)$ \pm (%)	Azimuth Angle	R ($\mu\text{V}/\text{W}/\text{m}^2$)	PM $u(B)$ \pm (%)	Azimuth Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	9.3812	0.31	106.39	9.4133	0.33	253.71
2	N/A	N/A	N/A	N/A	N/A	N/A	48	9.3789	0.33	104.14	9.4400	0.32	255.93
4	N/A	N/A	N/A	N/A	N/A	N/A	50	9.3915	0.32	102.08	9.4245	0.32	258.04
6	N/A	N/A	N/A	N/A	N/A	N/A	52	9.4018	0.32	100.07	9.4244	0.33	260.06
8	N/A	N/A	N/A	N/A	N/A	N/A	54	9.3967	0.33	98.12	9.4184	0.36	261.99
10	N/A	N/A	N/A	N/A	N/A	N/A	56	9.3981	0.35	96.24	9.4432	0.36	263.88
12	N/A	N/A	N/A	N/A	N/A	N/A	58	9.4005	0.36	94.52	9.4576	0.35	265.61
14	N/A	N/A	N/A	N/A	N/A	N/A	60	9.4151	0.35	92.75	9.4790	0.36	267.40
16	N/A	N/A	N/A	N/A	N/A	N/A	62	9.3949	0.36	91.02	9.4902	0.37	269.10
18	N/A	N/A	N/A	N/A	N/A	N/A	64	9.4024	0.37	89.38	9.4717	0.39	270.74
20	N/A	N/A	N/A	N/A	N/A	N/A	66	9.3894	0.39	87.75	9.5044	0.41	272.44
22	N/A	N/A	N/A	N/A	N/A	N/A	68	9.3740	0.41	86.09	9.4967	0.43	274.00
24	9.3528	0.31	160.89	9.3491	0.29	198.97	70	9.3711	0.43	84.54	9.5041	0.46	275.65
26	9.3432	0.31	148.22	9.3417	0.31	211.67	72	9.3673	0.47	82.91	9.5127	N/A	277.28
28	9.3265	0.30	140.00	9.3525	0.30	220.12	74	9.4025	0.51	81.35	9.5269	N/A	278.81
30	9.3671	0.30	133.74	9.3623	0.31	226.48	76	9.4505	N/A	79.74	9.5700	N/A	280.43
32	9.3342	0.31	128.75	9.3499	0.34	231.29	78	9.4963	N/A	78.13	9.6343	N/A	282.17
34	9.3483	0.31	124.40	9.3636	0.32	235.88	80	9.5406	N/A	76.52	9.6694	N/A	283.70
36	9.3644	0.35	120.45	9.3740	0.32	239.67	82	9.5995	N/A	74.85	9.7234	N/A	285.33
38	9.3527	0.34	117.43	9.3779	0.33	243.03	84	9.7005	N/A	73.18	9.8492	N/A	287.02
40	9.3619	0.32	114.02	9.4000	0.31	245.95	86	N/A	N/A	N/A	N/A	N/A	N/A
42	9.3805	0.33	111.34	9.3995	0.36	248.79	88	N/A	N/A	N/A	N/A	N/A	N/A
44	9.3740	0.31	108.84	9.4105	0.35	251.33	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

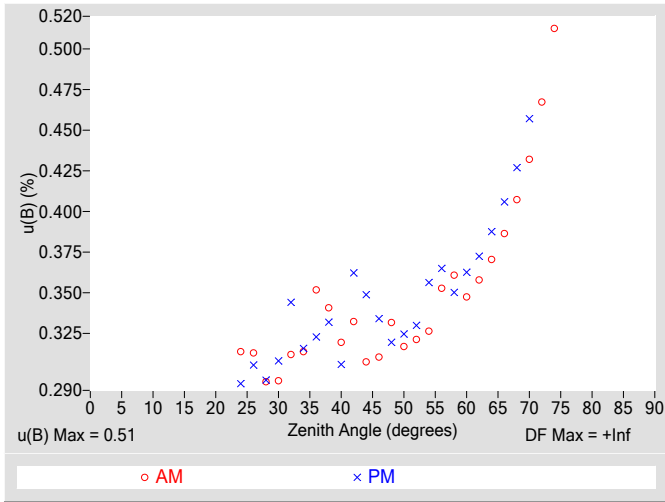


Figure 4. Residuals from Spline Interpolation

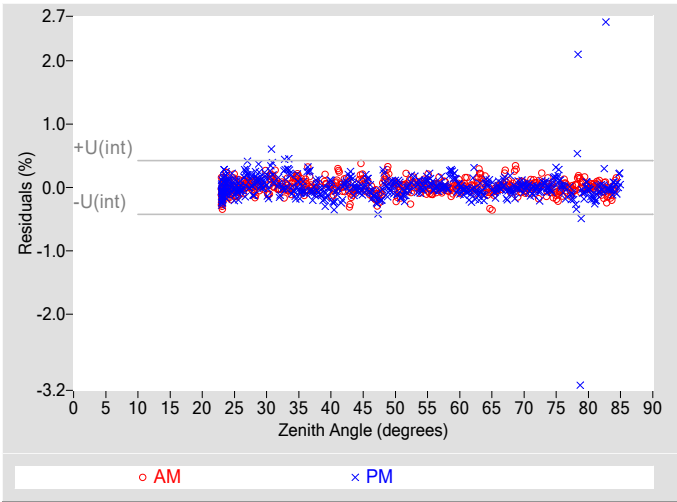


Table 3. Uncertainty using Spline Interpolation ‡

Type-B Standard Uncertainty, u(B) (%)	±0.51
Type-A Interpolating Function, u(int) (%)	±0.21
Combined Standard Uncertainty, u(c) (%)	±0.55
Effective degrees of freedom, DF(c)	43639
Coverage factor, k	1.96
Expanded Uncertainty, U95 (%)	±1.1
AM Valid zenith angle range	24° to 74°
PM Valid zenith angle range	24° 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

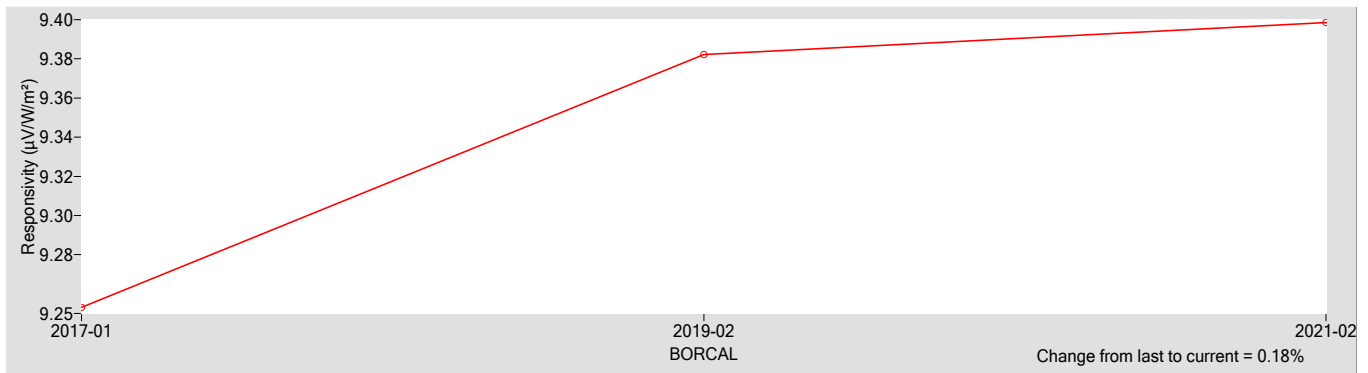
R @ 45° (μV/W/m²)	Rnet (μV/W/m²) †
9.3986	0.043000

† Rnet determination date: Estimated

Table 5. Uncertainty using R @ 45°

Type-B Expanded Uncertainty, U(B) (%)	±0.72
Offset Uncertainty, U(off) (%)	+0.86 / -0.69
Expanded Uncertainty, U (%)	+1.6 / -1.4
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



Test Instrument:	Pyranometer	Manufacturer:	Hukseflux
Model:	SR25	Serial Number:	2543
Calibration Date:	5/6/2021	Due Date:	5/6/2022
Customer:	NREL-SRRL-BMS	Environmental Conditions:	see page 4
Test Dates:	5/6		

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 than 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	09/27/2019	09/27/2021
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/30/2021	04/30/2022
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/30/2021	04/30/2022
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/08/2021	02/08/2023
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/08/2021	02/08/2023
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, Peter Gotseff, 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

2543 Hukseflux SR25

The responsivity (R , $\mu\text{V}/\text{W}/\text{m}^2$) of the test instrument during calibration is calculated using this Measurement Equation:

$$R = (V - R_{net} * W_{net}) / I \quad [1]$$

where,

- V = radiometer output voltage (microvolts),
 - R_{net} = radiometer net infrared responsivity ($\mu\text{V}/\text{W}/\text{m}^2$), see Table 4,
 - W_{net} = effective net infrared measured by pyrgeometer (W/m^2),
 - = $W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
 - where, W_{in} = incoming infrared (W/m^2), $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$,
 - T_c = case temperature of pyrgeometer (K).
- I = reference irradiance (W/m^2), beam (B) or global (G)
 where, $G = B * \text{COS}(Z) + D$,
 Z = zenith angle (degrees),
 D = reference diffuse irradiance (W/m^2).

Figure 1. Responsivity vs Zenith Angle

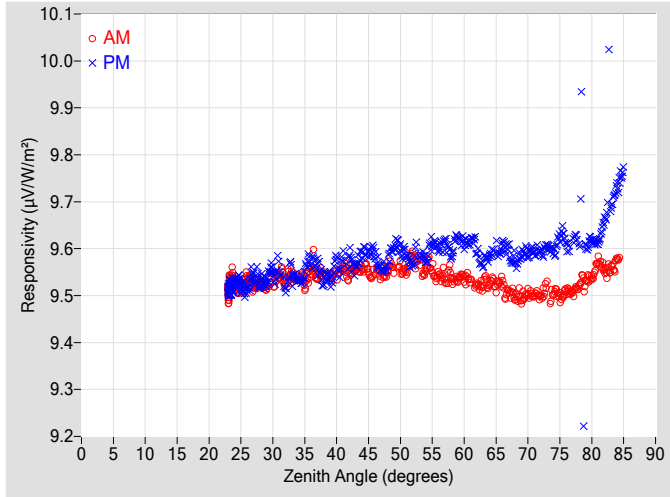


Figure 2. Responsivity vs Local Standard Time

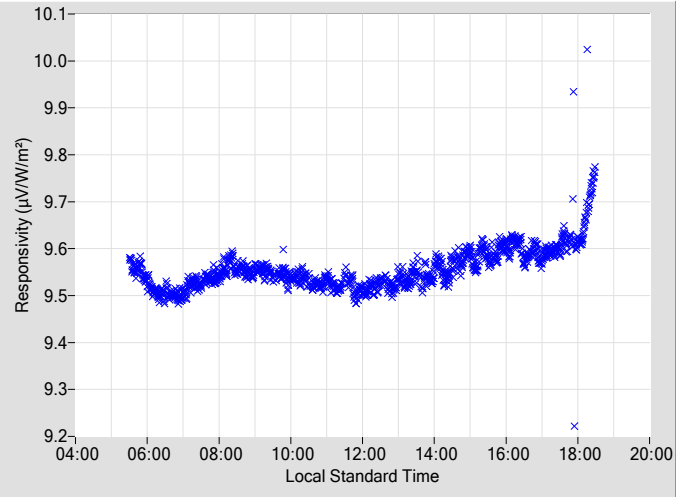


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)

Zenith Angle (deg.)	R ($\mu\text{V}/\text{W}/\text{m}^2$)	AM u(B) \pm (%)	Azimuth Angle	R ($\mu\text{V}/\text{W}/\text{m}^2$)	PM u(B) \pm (%)	Azimuth Angle	Zenith Angle (deg.)	R ($\mu\text{V}/\text{W}/\text{m}^2$)	AM u(B) \pm (%)	Azimuth Angle	R ($\mu\text{V}/\text{W}/\text{m}^2$)	PM u(B) \pm (%)	Azimuth Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	9.5519	0.31	106.39	9.5847	0.33	253.71
2	N/A	N/A	N/A	N/A	N/A	N/A	48	9.5529	0.33	104.14	9.5694	0.32	255.93
4	N/A	N/A	N/A	N/A	N/A	N/A	50	9.5595	0.32	102.08	9.5974	0.32	258.04
6	N/A	N/A	N/A	N/A	N/A	N/A	52	9.5840	0.32	100.07	9.5710	0.33	260.06
8	N/A	N/A	N/A	N/A	N/A	N/A	54	9.5535	0.33	98.12	9.5748	0.36	261.99
10	N/A	N/A	N/A	N/A	N/A	N/A	56	9.5448	0.35	96.24	9.6006	0.36	263.88
12	N/A	N/A	N/A	N/A	N/A	N/A	58	9.5426	0.36	94.52	9.5867	0.35	265.61
14	N/A	N/A	N/A	N/A	N/A	N/A	60	9.5361	0.35	92.75	9.6145	0.36	267.40
16	N/A	N/A	N/A	N/A	N/A	N/A	62	9.5232	0.36	91.02	9.5960	0.37	269.10
18	N/A	N/A	N/A	N/A	N/A	N/A	64	9.5246	0.37	89.38	9.5825	0.39	270.74
20	N/A	N/A	N/A	N/A	N/A	N/A	66	9.5265	0.39	87.75	9.6085	0.41	272.44
22	N/A	N/A	N/A	N/A	N/A	N/A	68	9.4954	0.41	86.09	9.5757	0.43	274.00
24	9.5254	0.31	160.89	9.5258	0.29	198.97	70	9.5030	0.43	84.54	9.5884	0.46	275.65
26	9.5355	0.31	148.22	9.5146	0.31	211.67	72	9.4967	0.47	82.91	9.5941	N/A	277.28
28	9.5259	0.30	140.00	9.5267	0.30	220.12	74	9.5056	0.51	81.35	9.5958	N/A	278.81
30	9.5302	0.30	133.74	9.5466	0.31	226.48	76	9.5105	N/A	79.74	9.6098	N/A	280.43
32	9.5254	0.31	128.75	9.5193	0.34	231.29	78	9.5191	N/A	78.13	9.6404	N/A	282.17
34	9.5357	0.31	124.40	9.5330	0.32	235.88	80	9.5365	N/A	76.52	9.6184	N/A	283.70
36	9.5497	0.35	120.45	9.5699	0.32	239.67	82	9.5557	N/A	74.85	9.6603	N/A	285.33
38	9.5474	0.34	117.43	9.5330	0.33	243.03	84	9.5773	N/A	73.18	9.7320	N/A	287.02
40	9.5459	0.32	114.02	9.5756	0.31	245.95	86	N/A	N/A	N/A	N/A	N/A	N/A
42	9.5453	0.33	111.34	9.5817	0.36	248.79	88	N/A	N/A	N/A	N/A	N/A	N/A
44	9.5552	0.31	108.84	9.5933	0.35	251.33	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

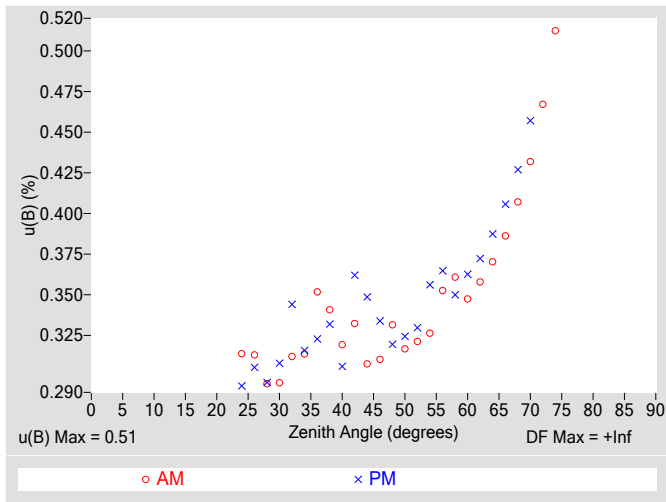


Figure 4. Residuals from Spline Interpolation

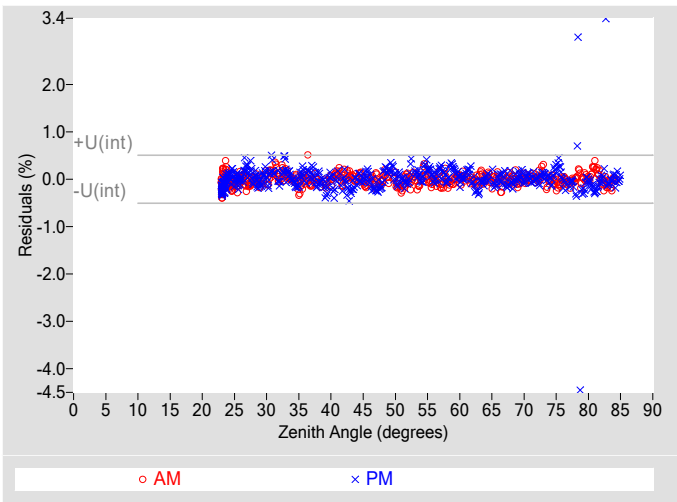


Table 3. Uncertainty using Spline Interpolation ‡

Type-B Standard Uncertainty, u(B) (%)	±0.51
Type-A Interpolating Function, u(int) (%)	±0.25
Combined Standard Uncertainty, u(c) (%)	±0.57
Effective degrees of freedom, DF(c)	24343
Coverage factor, k	1.96
Expanded Uncertainty, U95 (%)	±1.1
AM Valid zenith angle range	24° to 74°
PM Valid zenith angle range	24° 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

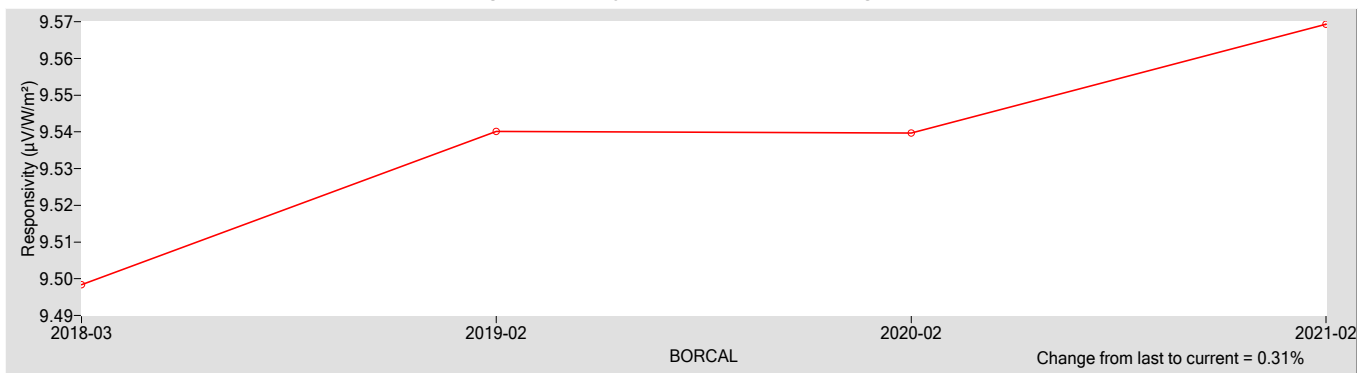
R @ 45° (μV/W/m²)	Rnet (μV/W/m²) †
9.5693	0.043000

† Rnet determination date: Estimated

Table 5. Uncertainty using R @ 45°

Type-B Expanded Uncertainty, U(B) (%)	±0.72
Offset Uncertainty, U(off) (%)	+0.47 / -0.52
Expanded Uncertainty, U (%)	+1.2 / -1.2
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



Test Instrument:	Precision Spectral Pyranometer (Ventilated)	Manufacturer:	Eppley
Model:	PSP	Serial Number:	28402F3
Calibration Date:	5/6/2021	Due Date:	5/6/2022
Customer:	NREL-SRRL-BMS	Environmental Conditions:	see page 4
Test Dates:	5/6		

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 than 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	09/27/2019	09/27/2021
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/30/2021	04/30/2022
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/30/2021	04/30/2022
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/08/2021	02/08/2023
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/08/2021	02/08/2023
Infrared Irradiance ‡	Eppley Downwelling Pyrgeometer (Ventilated) Model PIR-V, S/N 31203F3	04/02/2019	04/02/2023

† 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, Peter Gotseff, 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

28402F3 Eppley PSP

The responsivity (R , $\mu\text{V}/\text{W}/\text{m}^2$) of the test instrument during calibration is calculated using this Measurement Equation:

$$R = (V - R_{net} * W_{net}) / I \tag{1}$$

where,

- V = radiometer output voltage (microvolts),
 - R_{net} = radiometer net infrared responsivity ($\mu\text{V}/\text{W}/\text{m}^2$), see Table 4,
 - W_{net} = effective net infrared measured by pyrgeometer (W/m^2),
 - = $W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
 - where, W_{in} = incoming infrared (W/m^2), $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$,
 - T_c = case temperature of pyrgeometer (K).
- I = reference irradiance (W/m^2), beam (B) or global (G)
 - where, $G = B * \text{COS}(Z) + D$,
 - Z = zenith angle (degrees),
 - D = reference diffuse irradiance (W/m^2).

Figure 1. Responsivity vs Zenith Angle

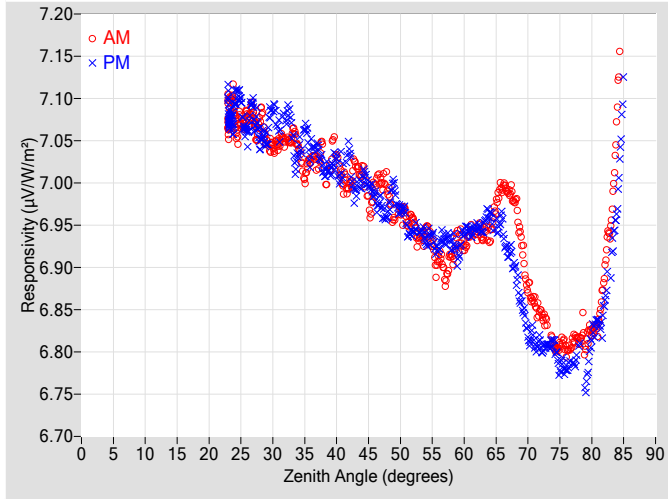


Figure 2. Responsivity vs Local Standard Time

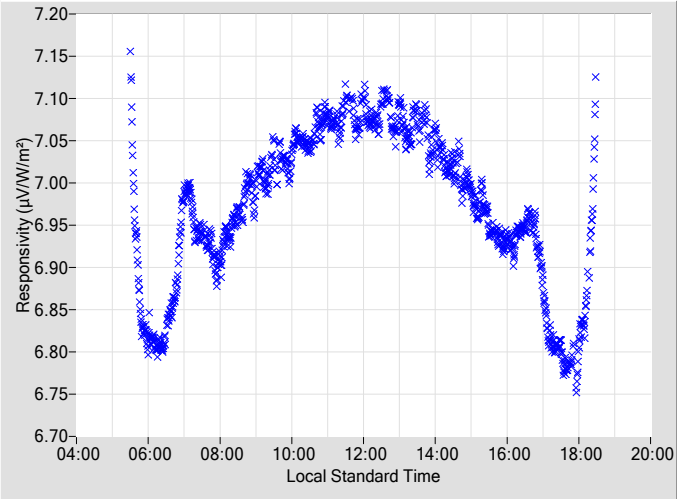


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, $u(B)$

Zenith Angle (deg.)	R ($\mu\text{V}/\text{W}/\text{m}^2$)	AM $u(B)$ \pm (%)	Azimuth Angle	R ($\mu\text{V}/\text{W}/\text{m}^2$)	PM $u(B)$ \pm (%)	Azimuth Angle	Zenith Angle (deg.)	R ($\mu\text{V}/\text{W}/\text{m}^2$)	AM $u(B)$ \pm (%)	Azimuth Angle	R ($\mu\text{V}/\text{W}/\text{m}^2$)	PM $u(B)$ \pm (%)	Azimuth Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	6.9962	0.37	106.47	6.9842	0.33	253.67
2	N/A	N/A	N/A	N/A	N/A	N/A	48	6.9935	0.38	104.10	6.9651	0.35	255.95
4	N/A	N/A	N/A	N/A	N/A	N/A	50	6.9682	0.36	102.05	6.9676	0.38	258.06
6	N/A	N/A	N/A	N/A	N/A	N/A	52	6.9556	0.36	100.03	6.9416	0.41	260.03
8	N/A	N/A	N/A	N/A	N/A	N/A	54	6.9458	0.37	98.09	6.9299	0.38	261.96
10	N/A	N/A	N/A	N/A	N/A	N/A	56	6.9100	0.36	96.32	6.9238	0.39	263.85
12	N/A	N/A	N/A	N/A	N/A	N/A	58	6.9119	0.39	94.49	6.9260	0.38	265.68
14	N/A	N/A	N/A	N/A	N/A	N/A	60	6.9235	0.38	92.72	6.9419	0.40	267.37
16	N/A	N/A	N/A	N/A	N/A	N/A	62	6.9391	0.41	91.10	6.9480	0.41	269.11
18	N/A	N/A	N/A	N/A	N/A	N/A	64	6.9381	0.41	89.37	6.9633	0.43	270.76
20	N/A	N/A	N/A	N/A	N/A	N/A	66	6.9944	0.45	87.72	6.9518	0.45	272.41
22	N/A	N/A	N/A	N/A	N/A	N/A	68	6.9789	0.48	86.16	6.8945	0.51	274.07
24	7.0827	0.33	160.68	7.0850	0.31	198.84	70	6.8774	0.48	84.52	6.8188	0.52	275.62
26	7.0793	0.31	148.37	7.0624	0.33	212.02	72	6.8465	0.56	82.88	6.8076	N/A	277.25
28	7.0779	0.35	139.81	7.0503	0.35	220.18	74	6.8093	0.57	81.33	6.8091	N/A	278.87
30	7.0427	0.32	133.67	7.0890	0.33	226.59	76	6.8016	N/A	79.71	6.7783	N/A	280.45
32	7.0500	0.32	128.68	7.0762	0.31	231.88	78	6.8141	N/A	78.10	6.8085	N/A	282.09
34	7.0432	0.34	124.30	7.0375	0.35	235.77	80	6.8236	N/A	76.49	6.8179	N/A	283.67
36	7.0272	0.39	120.54	7.0345	0.33	239.53	82	6.8907	N/A	74.87	6.8588	N/A	285.35
38	7.0460	0.39	117.46	7.0131	0.32	242.99	84	7.0908	N/A	73.15	6.9775	N/A	287.04
40	7.0323	0.34	114.08	7.0249	0.34	246.04	86	N/A	N/A	N/A	N/A	N/A	N/A
42	6.9983	0.35	111.37	7.0325	0.38	248.89	88	N/A	N/A	N/A	N/A	N/A	N/A
44	7.0139	0.36	108.77	7.0043	0.35	251.42	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

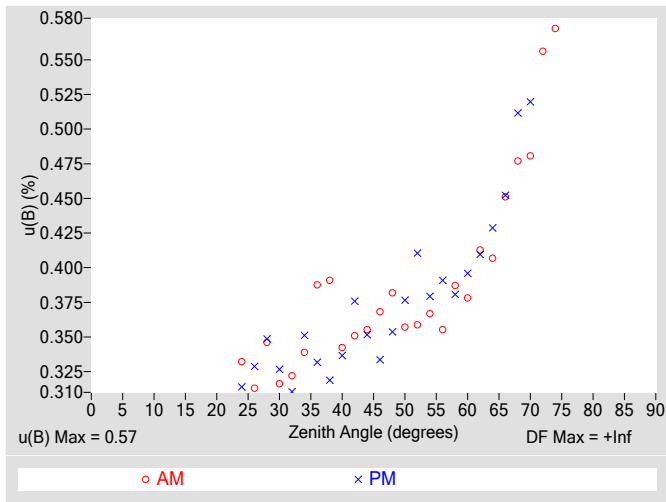


Figure 4. Residuals from Spline Interpolation

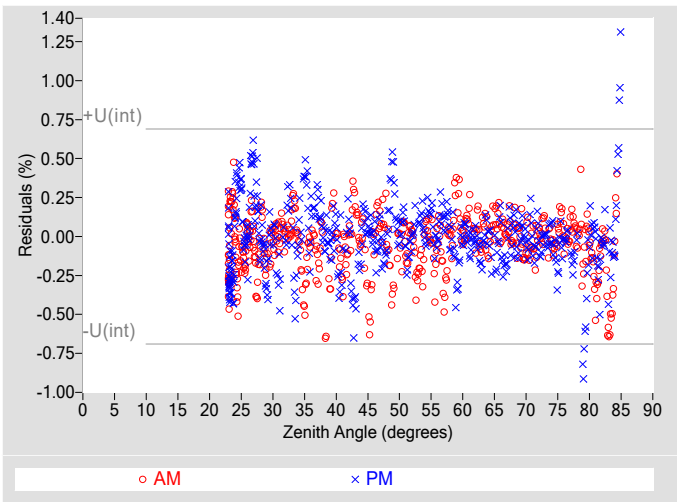


Table 3. Uncertainty using Spline Interpolation ‡

Type-B Standard Uncertainty, $u(B)$ (%)	± 0.57
Type-A Interpolating Function, $u(int)$ (%)	± 0.34
Combined Standard Uncertainty, $u(c)$ (%)	± 0.67
Effective degrees of freedom, $DF(c)$	12927
Coverage factor, k	1.96
Expanded Uncertainty, U_{95} (%)	± 1.3
AM Valid zenith angle range	24° to 74°
PM Valid zenith angle range	24° to 70°

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

Table 4. Calibration Label Values

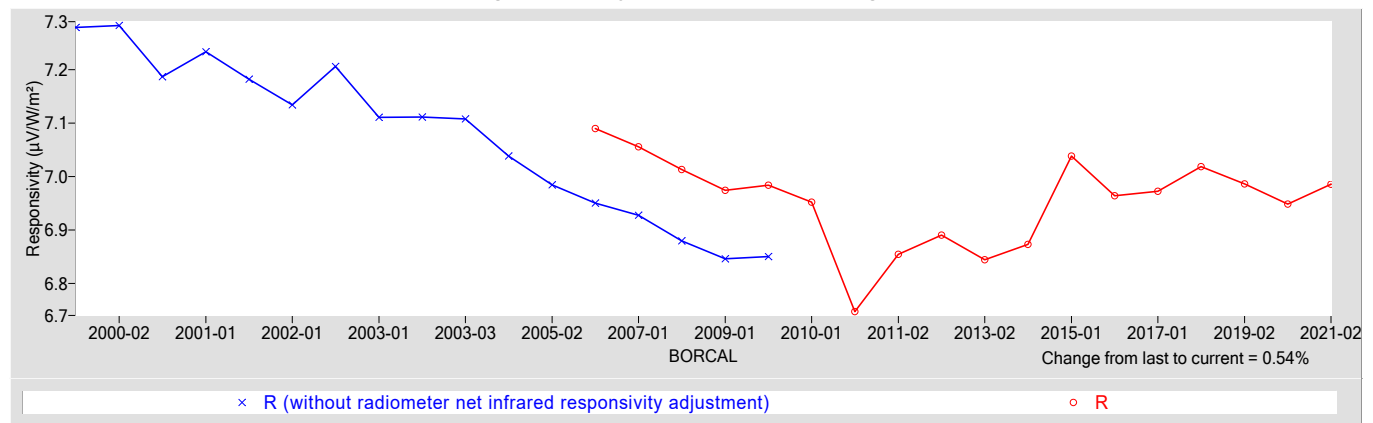
$R @ 45^\circ$ ($\mu V/W/m^2$)	R_{net} ($\mu V/W/m^2$) †
6.9859	0.64000

† R_{net} determination date: 02/28/2006

Table 5. Uncertainty using $R @ 45^\circ$

Type-B Expanded Uncertainty, $U(B)$ (%)	± 0.80
Offset Uncertainty, $U(off)$ (%)	+1.5 / -1.1
Expanded Uncertainty, U (%)	+2.3 / -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



Test Instrument:	Normal Incidence Pyrheliometer	Manufacturer:	Eppley
Model:	NIP	Serial Number:	31137E6
Calibration Date:	5/6/2021	Due Date:	5/6/2022
Customer:	NREL-SRRL-BMS	Environmental Conditions:	see page 4
Test Dates:	5/6		

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 than 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	09/27/2019	09/27/2021
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/30/2021	04/30/2022
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/30/2021	04/30/2022
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/08/2021	02/08/2023
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/08/2021	02/08/2023

† 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, Peter Gotseff, 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

31137E6 Eppley NIP

The responsivity (R , $\mu\text{V}/\text{W}/\text{m}^2$) of the test instrument during calibration is calculated using this Measurement Equation:

$$R = (V - R_{net} * W_{net}) / I \tag{1}$$

where,

- V = radiometer output voltage (microvolts),
 - R_{net} = radiometer net infrared responsivity ($\mu\text{V}/\text{W}/\text{m}^2$), see Table 4,
 - W_{net} = effective net infrared measured by pyrgeometer (W/m^2),
 - $= W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
 - where, W_{in} = incoming infrared (W/m^2), $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$,
 - T_c = case temperature of pyrgeometer (K).
- I = reference irradiance (W/m^2), beam (B) or global (G)
 - where, $G = B * \text{COS}(Z) + D$,
 - Z = zenith angle (degrees),
 - D = reference diffuse irradiance (W/m^2).

Figure 1. Responsivity vs Zenith Angle

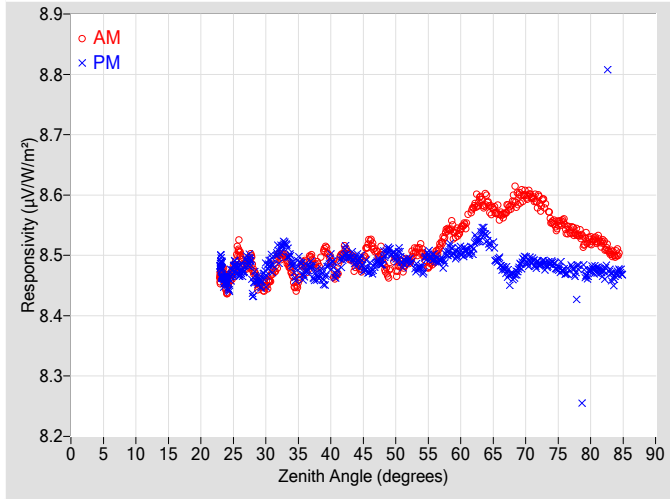


Figure 2. Responsivity vs Local Standard Time

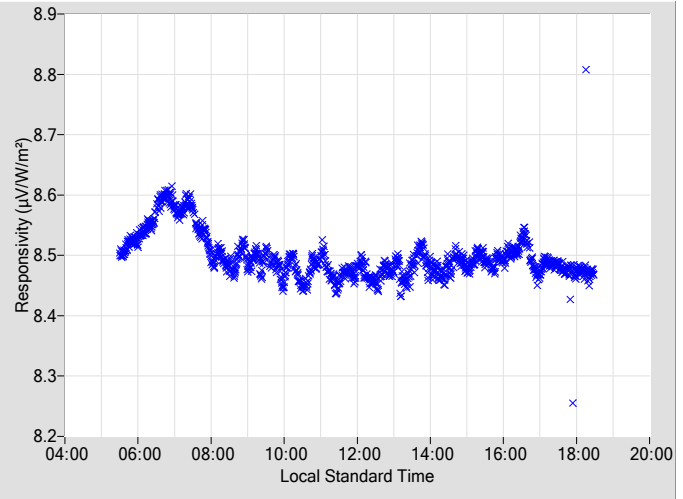


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)

Zenith Angle (deg.)	R ($\mu\text{V}/\text{W}/\text{m}^2$)	u(B) \pm (%)	Azimuth Angle	R ($\mu\text{V}/\text{W}/\text{m}^2$)	u(B) \pm (%)	Azimuth Angle	Zenith Angle (deg.)	R ($\mu\text{V}/\text{W}/\text{m}^2$)	u(B) \pm (%)	Azimuth Angle	R ($\mu\text{V}/\text{W}/\text{m}^2$)	u(B) \pm (%)	Azimuth Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	8.5239	0.31	106.41	8.4757	0.30	253.71
2	N/A	N/A	N/A	N/A	N/A	N/A	48	8.4963	0.32	104.20	8.4931	0.30	255.99
4	N/A	N/A	N/A	N/A	N/A	N/A	50	8.4812	0.33	102.02	8.4974	0.30	258.10
6	N/A	N/A	N/A	N/A	N/A	N/A	52	8.4906	0.29	100.01	8.4911	0.32	260.12
8	N/A	N/A	N/A	N/A	N/A	N/A	54	8.5084	0.31	98.18	8.4766	0.30	262.04
10	N/A	N/A	N/A	N/A	N/A	N/A	56	8.4973	0.31	96.30	8.4952	0.30	263.83
12	N/A	N/A	N/A	N/A	N/A	N/A	58	8.5428	0.30	94.47	8.5059	0.33	265.66
14	N/A	N/A	N/A	N/A	N/A	N/A	60	8.5425	0.30	92.75	8.5067	0.30	267.34
16	N/A	N/A	N/A	N/A	N/A	N/A	62	8.5802	0.30	91.07	8.5162	0.32	269.09
18	N/A	N/A	N/A	N/A	N/A	N/A	64	8.5924	0.30	89.38	8.5268	0.31	270.79
20	N/A	N/A	N/A	N/A	N/A	N/A	66	8.5691	0.31	87.74	8.4904	0.31	272.39
22	N/A	N/A	N/A	N/A	N/A	N/A	68	8.5876	0.30	86.14	8.4658	0.31	274.05
24	8.4506	0.30	161.34	8.4568	0.29	198.75	70	8.5991	0.31	84.49	8.4931	0.31	275.60
26	8.5059	0.30	148.30	8.4726	0.30	211.95	72	8.5903	0.31	82.96	8.4870	N/A	277.23
28	8.4823	0.30	139.99	8.4534	0.29	220.25	74	8.5557	0.31	81.30	8.4871	N/A	278.85
30	8.4484	0.29	133.61	8.4707	0.31	226.35	76	8.5494	N/A	79.69	8.4719	N/A	280.48
32	8.4965	0.29	128.62	8.5046	0.31	231.51	78	8.5353	N/A	78.08	8.4687	N/A	282.02
34	8.4682	0.29	124.20	8.4877	0.29	235.92	80	8.5234	N/A	76.47	8.4765	N/A	283.70
36	8.4862	0.30	120.54	8.4707	0.31	239.58	82	8.5203	N/A	74.85	8.4708	N/A	285.38
38	8.4841	0.31	117.13	8.4650	0.29	242.95	84	8.5023	N/A	73.18	8.4692	N/A	287.02
40	8.4926	0.30	114.10	8.4919	0.29	246.00	86	N/A	N/A	N/A	N/A	N/A	N/A
42	8.5051	0.30	111.34	8.5022	0.31	248.79	88	N/A	N/A	N/A	N/A	N/A	N/A
44	8.4861	0.29	108.85	8.4918	0.30	251.32	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

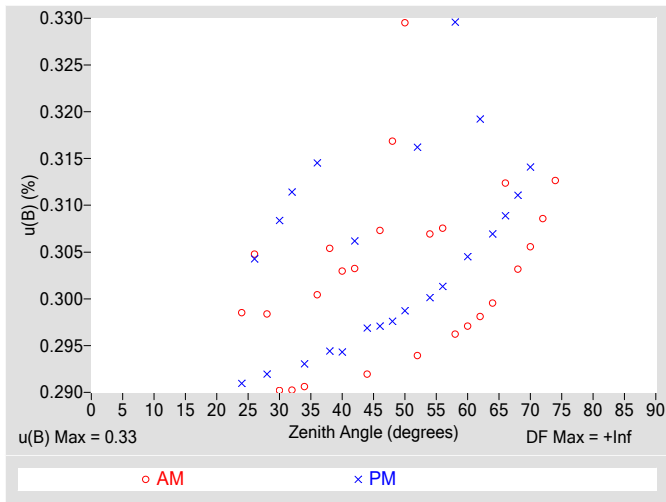


Figure 4. Residuals from Spline Interpolation

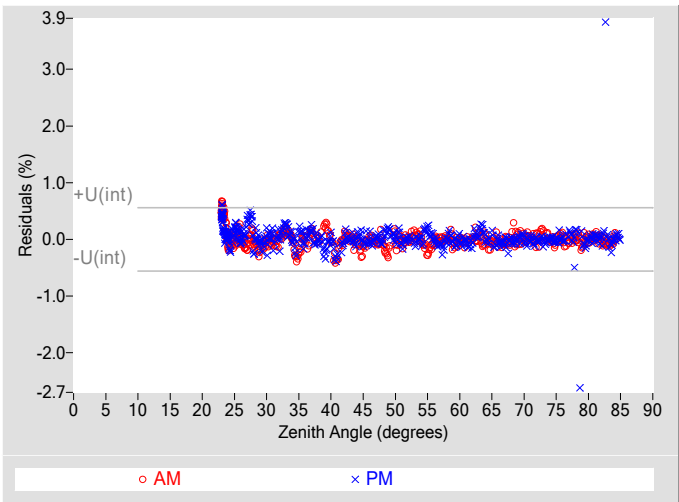


Table 3. Uncertainty using Spline Interpolation ‡

Type-B Standard Uncertainty, $u(B)$ (%)	± 0.33
Type-A Interpolating Function, $u(int)$ (%)	± 0.28
Combined Standard Uncertainty, $u(c)$ (%)	± 0.43
Effective degrees of freedom, $DF(c)$	5465
Coverage factor, k	1.96
Expanded Uncertainty, U_{95} (%)	± 0.85
AM Valid zenith angle range	24° to 74°
PM Valid zenith angle range	24° to 70°

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

Table 4. Calibration Label Values

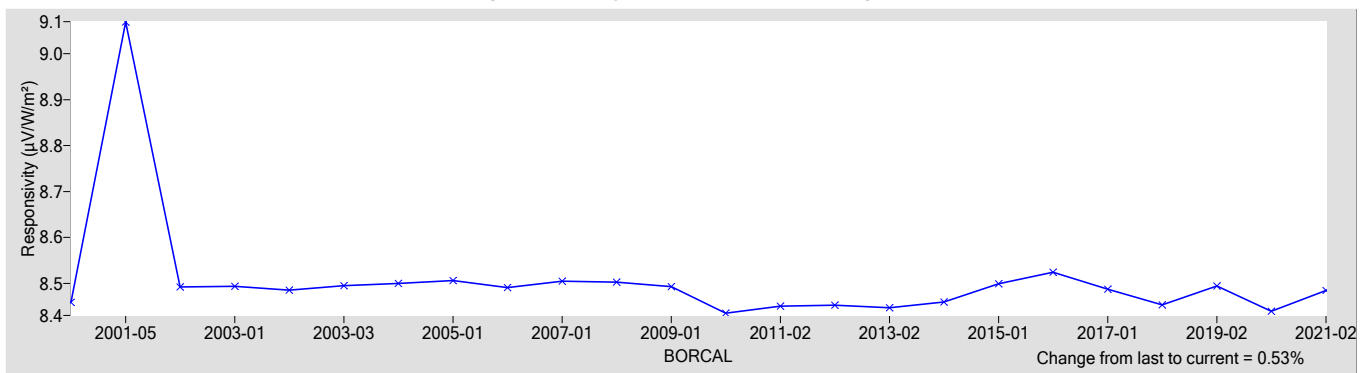
$R @ 45^\circ$ ($\mu V/W/m^2$)	R_{net} ($\mu V/W/m^2$) †
8.4840	0

† R_{net} determination date: N/A

Table 5. Uncertainty using $R @ 45^\circ$

Type-B Expanded Uncertainty, $U(B)$ (%)	± 0.65
Offset Uncertainty, $U(off)$ (%)	+0.69 / -0.42
Expanded Uncertainty, U (%)	+1.3 / -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 Pyrgometers. ARM 2008 Science Team Meeting (Poster).

National Renewable Energy Laboratory

Solar Radiation Research Laboratory

Metrology Laboratory

Calibration Certificate



Test Instrument: Black and White Pyranometer
Manufacturer: Eppley
Model: 8-48
Serial Number: 32331
Calibration Date: 5/6/2021
Due Date: 5/6/2022
Customer: NREL-SRRL-BMS
Environmental Conditions: see page 4
Test Dates: 5/6

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 than 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	09/27/2019	09/27/2021
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/30/2021	04/30/2022
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/30/2021	04/30/2022
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/08/2021	02/08/2023
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/08/2021	02/08/2023

† 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, Peter Gotseff, 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

32331 Eppley 8-48

The responsivity (R , $\mu\text{V}/\text{W}/\text{m}^2$) of the test instrument during calibration is calculated using this Measurement Equation:

$$R = (V - R_{net} * W_{net}) / I \quad [1]$$

where,

- V = radiometer output voltage (microvolts),
 - R_{net} = radiometer net infrared responsivity ($\mu\text{V}/\text{W}/\text{m}^2$), see Table 4,
 - W_{net} = effective net infrared measured by pyrgeometer (W/m^2),
 - = $W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
 - where, W_{in} = incoming infrared (W/m^2), $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$,
 - T_c = case temperature of pyrgeometer (K).
- I = reference irradiance (W/m^2), beam (B) or global (G)
 where, $G = B * \text{COS}(Z) + D$,
 Z = zenith angle (degrees),
 D = reference diffuse irradiance (W/m^2).

Figure 1. Responsivity vs Zenith Angle

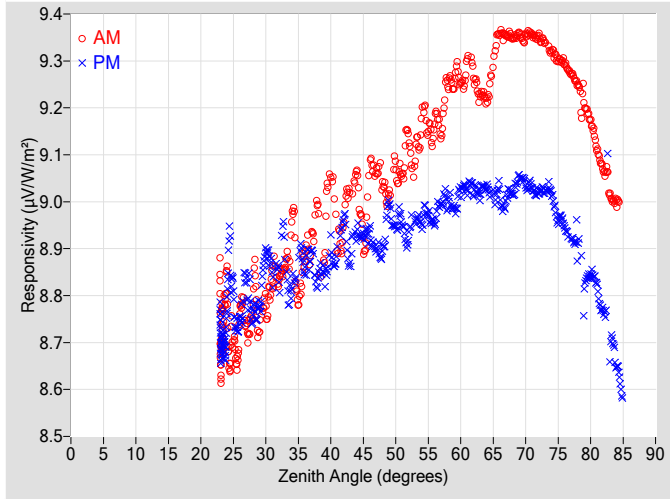


Figure 2. Responsivity vs Local Standard Time

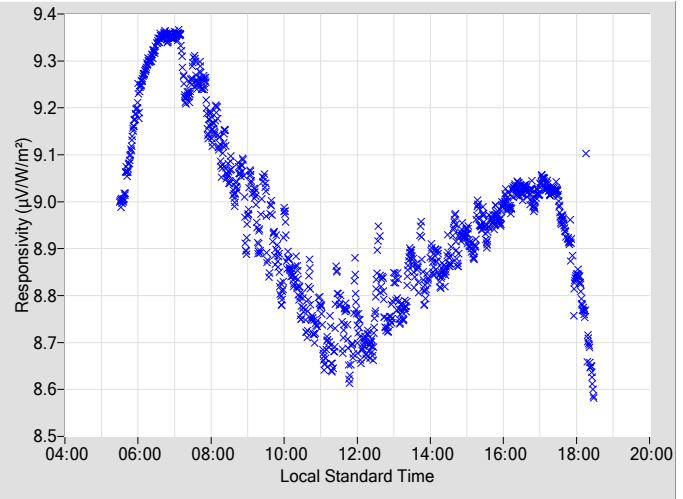


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)

Zenith Angle (deg.)	R ($\mu\text{V}/\text{W}/\text{m}^2$)	u(B) \pm (%)	Azimuth Angle	R ($\mu\text{V}/\text{W}/\text{m}^2$)	u(B) \pm (%)	Azimuth Angle	Zenith Angle (deg.)	R ($\mu\text{V}/\text{W}/\text{m}^2$)	u(B) \pm (%)	Azimuth Angle	R ($\mu\text{V}/\text{W}/\text{m}^2$)	u(B) \pm (%)	Azimuth Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	9.0794	0.37	106.32	8.9296	0.32	253.77
2	N/A	N/A	N/A	N/A	N/A	N/A	48	9.0328	0.38	104.14	8.8978	0.34	255.98
4	N/A	N/A	N/A	N/A	N/A	N/A	50	9.0673	0.36	102.07	8.9448	0.32	258.09
6	N/A	N/A	N/A	N/A	N/A	N/A	52	9.1328	0.39	100.06	8.9307	0.39	260.12
8	N/A	N/A	N/A	N/A	N/A	N/A	54	9.1589	0.35	98.23	8.9542	0.36	262.04
10	N/A	N/A	N/A	N/A	N/A	N/A	56	9.1669	0.33	96.29	8.9567	0.34	263.82
12	N/A	N/A	N/A	N/A	N/A	N/A	58	9.2541	0.36	94.47	8.9962	0.37	265.66
14	N/A	N/A	N/A	N/A	N/A	N/A	60	9.2551	0.39	92.80	9.0246	0.40	267.39
16	N/A	N/A	N/A	N/A	N/A	N/A	62	9.2715	0.43	91.07	9.0255	0.40	269.09
18	N/A	N/A	N/A	N/A	N/A	N/A	64	9.2181	0.37	89.37	9.0285	0.42	270.79
20	N/A	N/A	N/A	N/A	N/A	N/A	66	9.3589	0.39	87.79	9.0184	0.41	272.39
22	N/A	N/A	N/A	N/A	N/A	N/A	68	9.3482	0.41	86.13	9.0174	0.43	274.04
24	8.7757	0.32	161.09	8.7591	0.32	198.73	70	9.3525	0.43	84.49	9.0350	0.46	275.64
26	8.7464	0.34	148.13	8.7498	0.31	212.16	72	9.3522	0.50	82.95	9.0223	N/A	277.23
28	8.7849	0.34	139.89	8.7611	0.34	220.14	74	9.3209	0.51	81.30	9.0153	N/A	278.85
30	8.7721	0.31	133.52	8.8895	0.32	226.38	76	9.2946	N/A	79.69	8.9443	N/A	280.47
32	8.8321	0.36	128.50	8.8425	0.33	231.39	78	9.2506	N/A	78.12	8.9164	N/A	282.02
34	8.9653	0.36	124.09	8.8162	0.30	235.77	80	9.1693	N/A	76.46	8.8449	N/A	283.69
36	8.8846	0.33	120.54	8.8540	0.35	239.52	82	9.0666	N/A	74.85	8.7643	N/A	285.38
38	8.9908	0.34	117.16	8.8328	0.32	243.03	84	9.0003	N/A	73.18	8.6500	N/A	287.02
40	9.0511	0.33	114.09	8.8972	0.31	246.04	86	N/A	N/A	N/A	N/A	N/A	N/A
42	8.9519	0.33	111.37	8.9602	0.32	248.78	88	N/A	N/A	N/A	N/A	N/A	N/A
44	9.0525	0.34	108.80	8.9350	0.31	251.31	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

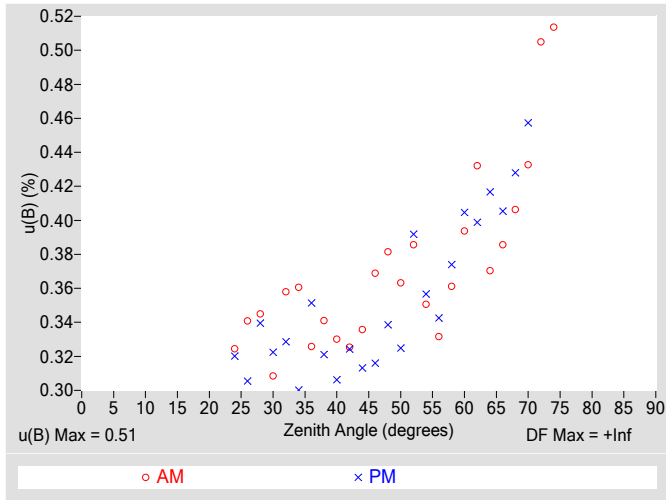


Figure 4. Residuals from Spline Interpolation

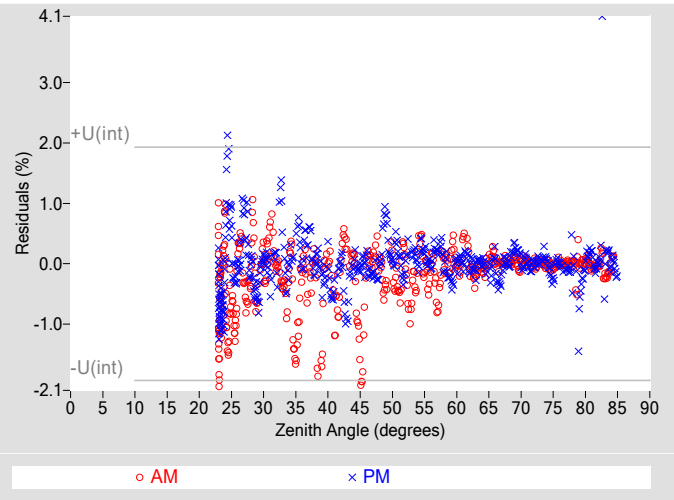


Table 3. Uncertainty using Spline Interpolation ‡

Type-B Standard Uncertainty, $u(B)$ (%)	± 0.51
Type-A Interpolating Function, $u(int)$ (%)	± 0.97
Combined Standard Uncertainty, $u(c)$ (%)	± 1.1
Effective degrees of freedom, $DF(c)$	1485
Coverage factor, k	1.96
Expanded Uncertainty, U_{95} (%)	± 2.1
AM Valid zenith angle range	24° to 74°
PM Valid zenith angle range	24° to 70°

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

Table 4. Calibration Label Values

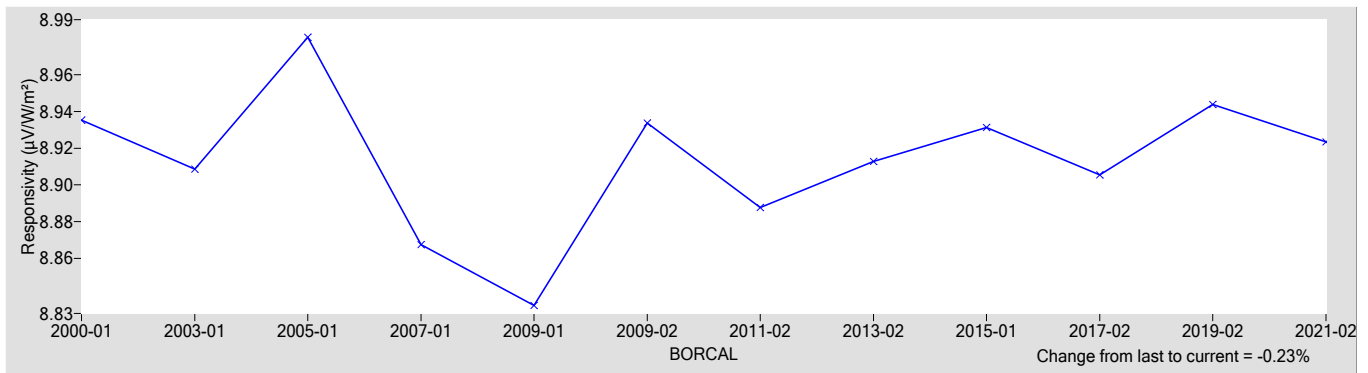
$R @ 45^\circ$ ($\mu V/W/m^2$)	R_{net} ($\mu V/W/m^2$) †
8.9233	0

† R_{net} determination date: N/A

Table 5. Uncertainty using $R @ 45^\circ$

Type-B Expanded Uncertainty, $U(B)$ (%)	± 0.79
Offset Uncertainty, $U(off)$ (%)	+3.7 / -1.7
Expanded Uncertainty, U (%)	+4.5 / -2.5
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 Pyrgometers. ARM 2008 Science Team Meeting (Poster).



National Renewable Energy Laboratory

Solar Radiation Research Laboratory

Metrology Laboratory

Calibration Certificate



Test Instrument:	Black and White Pyranometer	Manufacturer:	Eppley
Model:	8-48	Serial Number:	34718
Calibration Date:	5/6/2021	Due Date:	5/6/2022
Customer:	NREL-SRRL-BMS	Environmental Conditions:	see page 4
Test Dates:	5/6		

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 than 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	09/27/2019	09/27/2021
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/30/2021	04/30/2022
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/30/2021	04/30/2022
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/08/2021	02/08/2023
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/08/2021	02/08/2023

† 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, Peter Gotseff, 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

34718 Eppley 8-48

The responsivity (R , $\mu\text{V}/\text{W}/\text{m}^2$) of the test instrument during calibration is calculated using this Measurement Equation:

$$R = (V - R_{net} * W_{net}) / I \tag{1}$$

where,

- V = radiometer output voltage (microvolts),
- R_{net} = radiometer net infrared responsivity ($\mu\text{V}/\text{W}/\text{m}^2$), see Table 4,
- W_{net} = effective net infrared measured by pyrgeometer (W/m^2),
- = $W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
- where, W_{in} = incoming infrared (W/m^2), $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$,
- T_c = case temperature of pyrgeometer (K).
- I = reference irradiance (W/m^2), beam (B) or global (G)
- where, $G = B * \text{COS}(Z) + D$,
- Z = zenith angle (degrees),
- D = reference diffuse irradiance (W/m^2).

Figure 1. Responsivity vs Zenith Angle

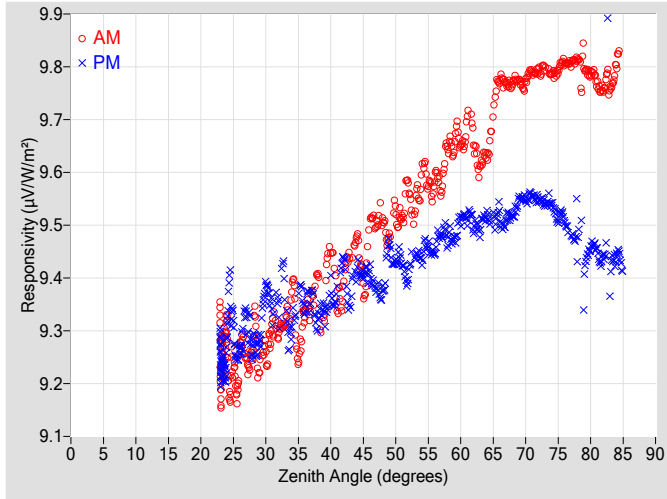


Figure 2. Responsivity vs Local Standard Time

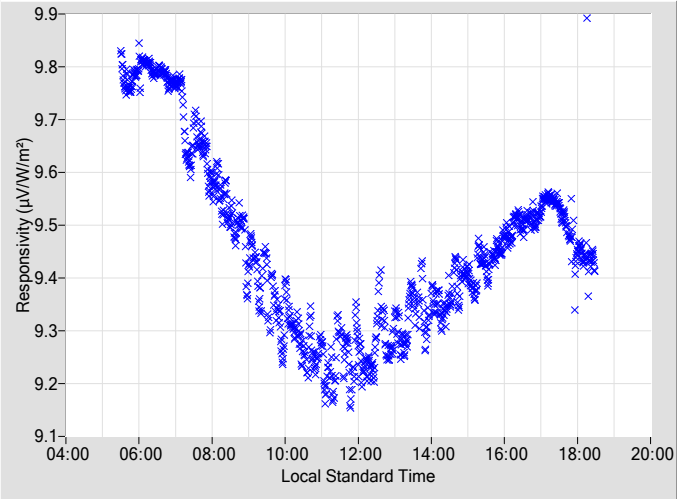


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)

Zenith Angle (deg.)	R ($\mu\text{V}/\text{W}/\text{m}^2$)	u(B) \pm (%)	Azimuth Angle	R ($\mu\text{V}/\text{W}/\text{m}^2$)	u(B) \pm (%)	Azimuth Angle	Zenith Angle (deg.)	R ($\mu\text{V}/\text{W}/\text{m}^2$)	u(B) \pm (%)	Azimuth Angle	R ($\mu\text{V}/\text{W}/\text{m}^2$)	u(B) \pm (%)	Azimuth Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	9.5059	0.37	106.32	9.4071	0.32	253.77
2	N/A	N/A	N/A	N/A	N/A	N/A	48	9.5058	0.38	104.14	9.3746	0.34	255.98
4	N/A	N/A	N/A	N/A	N/A	N/A	50	9.5206	0.36	102.07	9.4298	0.32	258.09
6	N/A	N/A	N/A	N/A	N/A	N/A	52	9.5697	0.39	100.06	9.4110	0.39	260.12
8	N/A	N/A	N/A	N/A	N/A	N/A	54	9.5815	0.35	98.23	9.4368	0.36	262.04
10	N/A	N/A	N/A	N/A	N/A	N/A	56	9.5836	0.33	96.29	9.4496	0.34	263.82
12	N/A	N/A	N/A	N/A	N/A	N/A	58	9.6485	0.36	94.47	9.4728	0.37	265.66
14	N/A	N/A	N/A	N/A	N/A	N/A	60	9.6534	0.39	92.80	9.5111	0.40	267.39
16	N/A	N/A	N/A	N/A	N/A	N/A	62	9.6630	0.43	91.07	9.5004	0.40	269.09
18	N/A	N/A	N/A	N/A	N/A	N/A	64	9.6322	0.37	89.37	9.5159	0.42	270.79
20	N/A	N/A	N/A	N/A	N/A	N/A	66	9.7746	0.39	87.79	9.5199	0.40	272.39
22	N/A	N/A	N/A	N/A	N/A	N/A	68	9.7671	0.41	86.13	9.5180	0.43	274.04
24	9.2766	0.32	161.09	9.2802	0.32	198.73	70	9.7707	0.43	84.49	9.5482	0.46	275.64
26	9.2548	0.34	148.13	9.2682	0.31	212.16	72	9.7936	0.50	82.95	9.5499	N/A	277.23
28	9.2722	0.34	139.89	9.2715	0.34	220.14	74	9.7879	0.51	81.30	9.5387	N/A	278.85
30	9.2529	0.31	133.52	9.3813	0.32	226.38	76	9.8074	N/A	79.69	9.5045	N/A	280.47
32	9.2952	0.36	128.50	9.3404	0.33	231.39	78	9.8136	N/A	78.12	9.4857	N/A	282.02
34	9.3837	0.36	124.09	9.3078	0.30	235.77	80	9.7859	N/A	76.46	9.4578	N/A	283.69
36	9.3338	0.33	120.54	9.3402	0.35	239.52	82	9.7582	N/A	74.85	9.4417	N/A	285.38
38	9.4050	0.34	117.16	9.3164	0.32	243.03	84	9.8059	N/A	73.18	9.4394	N/A	287.02
40	9.4513	0.33	114.09	9.3761	0.31	246.04	86	N/A	N/A	N/A	N/A	N/A	N/A
42	9.3875	0.33	111.37	9.4320	0.32	248.78	88	N/A	N/A	N/A	N/A	N/A	N/A
44	9.4730	0.34	108.80	9.4135	0.31	251.31	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

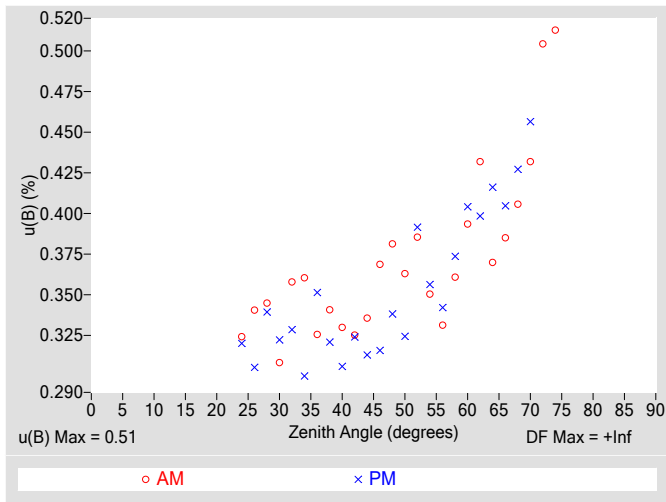


Figure 4. Residuals from Spline Interpolation

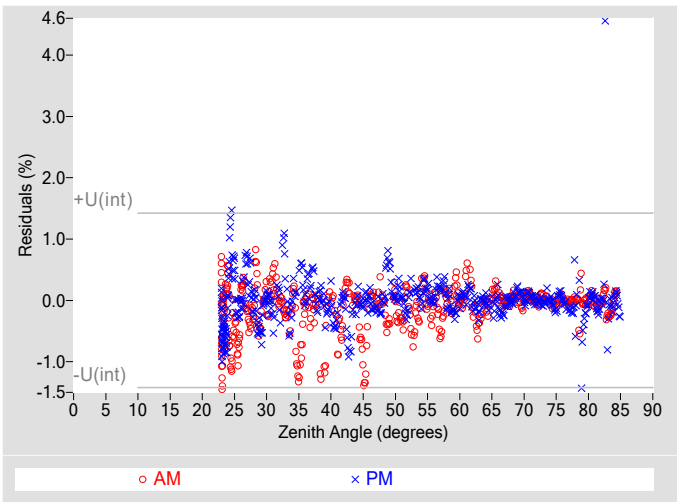


Table 3. Uncertainty using Spline Interpolation ‡

Type-B Standard Uncertainty, u(B) (%)	±0.51
Type-A Interpolating Function, u(int) (%)	±0.71
Combined Standard Uncertainty, u(c) (%)	±0.88
Effective degrees of freedom, DF(c)	2091
Coverage factor, k	1.96
Expanded Uncertainty, U95 (%)	±1.7
AM Valid zenith angle range	24° to 74°
PM Valid zenith angle range	24° 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

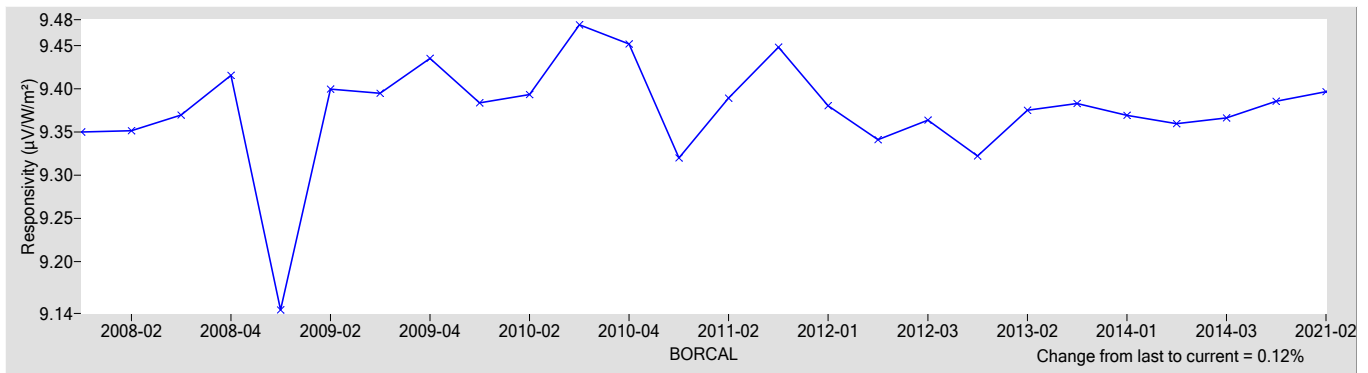
R @ 45° (µV/W/m²)	Rnet (µV/W/m²) †
9.3966	0

† Rnet determination date: N/A

Table 5. Uncertainty using R @ 45°

Type-B Expanded Uncertainty, U(B) (%)	±0.79
Offset Uncertainty, U(off) (%)	+2.7 / -1.5
Expanded Uncertainty, U (%)	+3.5 / -2.3
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 Pyrgometers*. ARM 2008 Science Team Meeting (Poster).



National Renewable Energy Laboratory

Solar Radiation Research Laboratory

Metrology Laboratory

Calibration Certificate



Test Instrument:	GPP Pyranometer	Manufacturer:	Eppley
Model:	GPP	Serial Number:	37831F3
Calibration Date:	5/6/2021	Due Date:	5/6/2022
Customer:	NREL-SRRL-BMS	Environmental Conditions:	see page 4
Test Dates:	5/6		

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 than 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	09/27/2019	09/27/2021
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/30/2021	04/30/2022
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/30/2021	04/30/2022
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/08/2021	02/08/2023
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/08/2021	02/08/2023
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, Peter Gotseff, 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

37831F3 Eppley GPP

The responsivity (R , $\mu\text{V}/\text{W}/\text{m}^2$) of the test instrument during calibration is calculated using this Measurement Equation:

$$R = (V - R_{net} * W_{net}) / I \tag{1}$$

where,

- V = radiometer output voltage (microvolts),
 - R_{net} = radiometer net infrared responsivity ($\mu\text{V}/\text{W}/\text{m}^2$), see Table 4,
 - W_{net} = effective net infrared measured by pyrgeometer (W/m^2),
 - = $W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
 - where, W_{in} = incoming infrared (W/m^2), $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$,
 - T_c = case temperature of pyrgeometer (K).
- I = reference irradiance (W/m^2), beam (B) or global (G)
 - where, $G = B * \text{COS}(Z) + D$,
 - Z = zenith angle (degrees),
 - D = reference diffuse irradiance (W/m^2).

Figure 1. Responsivity vs Zenith Angle

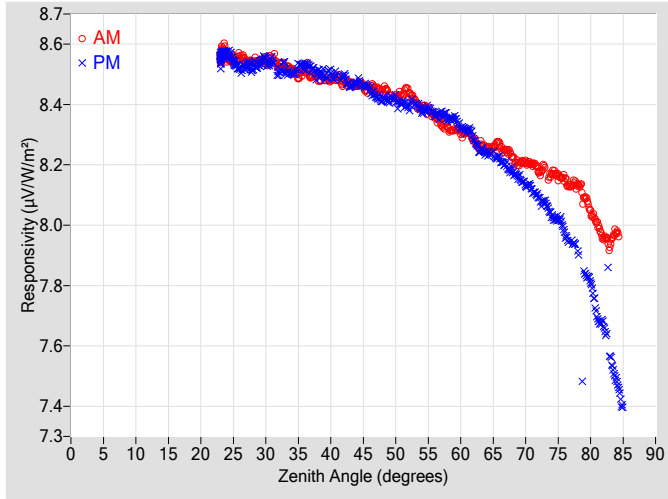


Figure 2. Responsivity vs Local Standard Time

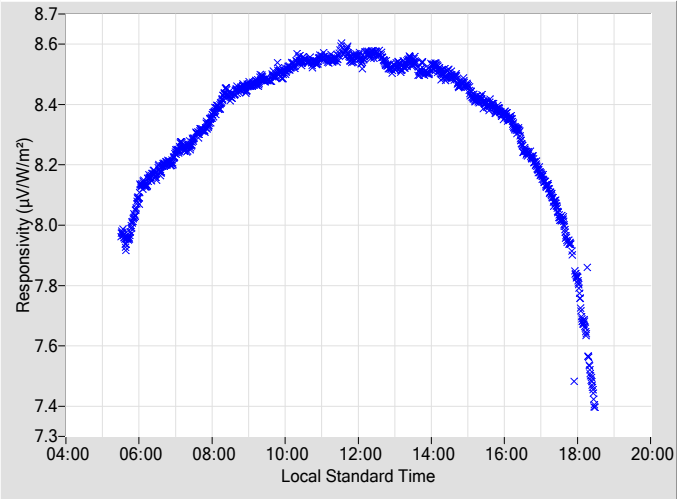


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, $u(B)$

Zenith Angle (deg.)	R ($\mu\text{V}/\text{W}/\text{m}^2$)	AM $u(B)$ \pm (%)	AM Azimuth Angle	R ($\mu\text{V}/\text{W}/\text{m}^2$)	PM $u(B)$ \pm (%)	PM Azimuth Angle	Zenith Angle (deg.)	R ($\mu\text{V}/\text{W}/\text{m}^2$)	AM $u(B)$ \pm (%)	AM Azimuth Angle	R ($\mu\text{V}/\text{W}/\text{m}^2$)	PM $u(B)$ \pm (%)	PM Azimuth Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	8.4563	0.37	106.41	8.4507	0.34	253.73
2	N/A	N/A	N/A	N/A	N/A	N/A	48	8.4492	0.35	104.05	8.4146	0.32	255.92
4	N/A	N/A	N/A	N/A	N/A	N/A	50	8.4267	0.36	102.07	8.4172	0.35	258.03
6	N/A	N/A	N/A	N/A	N/A	N/A	52	8.4415	0.35	100.00	8.3921	0.37	260.06
8	N/A	N/A	N/A	N/A	N/A	N/A	54	8.3906	0.35	98.12	8.3779	0.36	261.98
10	N/A	N/A	N/A	N/A	N/A	N/A	56	8.3600	0.34	96.24	8.3664	0.35	263.88
12	N/A	N/A	N/A	N/A	N/A	N/A	58	8.3279	0.34	94.52	8.3553	0.38	265.60
14	N/A	N/A	N/A	N/A	N/A	N/A	60	8.3064	0.38	92.74	8.3251	0.37	267.39
16	N/A	N/A	N/A	N/A	N/A	N/A	62	8.2827	0.36	91.02	8.2827	0.38	269.14
18	N/A	N/A	N/A	N/A	N/A	N/A	64	8.2529	0.38	89.42	8.2365	0.40	270.74
20	N/A	N/A	N/A	N/A	N/A	N/A	66	8.2684	0.39	87.74	8.2187	0.41	272.44
22	N/A	N/A	N/A	N/A	N/A	N/A	68	8.2205	0.45	86.08	8.1782	0.44	274.00
24	8.5574	0.32	160.83	8.5667	0.30	199.09	70	8.2076	0.44	84.54	8.1333	0.47	275.64
26	8.5578	0.32	148.18	8.5181	0.32	211.94	72	8.1773	0.52	82.91	8.0912	N/A	277.27
28	8.5363	0.32	139.93	8.5190	0.30	220.08	74	8.1707	0.52	81.35	8.0308	N/A	278.85
30	8.5453	0.33	133.73	8.5443	0.34	226.42	76	8.1563	N/A	79.74	7.9757	N/A	280.42
32	8.5274	0.31	128.52	8.5082	0.33	231.43	78	8.1305	N/A	78.12	7.9080	N/A	282.11
34	8.5128	0.33	124.29	8.5046	0.30	235.87	80	8.0440	N/A	76.51	7.8087	N/A	283.70
36	8.5122	0.33	120.44	8.5241	0.33	239.67	82	7.9584	N/A	74.85	7.6676	N/A	285.33
38	8.4887	0.36	117.12	8.5026	0.32	243.02	84	7.9777	N/A	73.18	7.4825	N/A	287.02
40	8.4796	0.34	114.01	8.5032	0.33	246.05	86	N/A	N/A	N/A	N/A	N/A	N/A
42	8.4715	0.33	111.33	8.4954	0.31	248.82	88	N/A	N/A	N/A	N/A	N/A	N/A
44	8.4642	0.36	108.80	8.4736	0.38	251.35	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

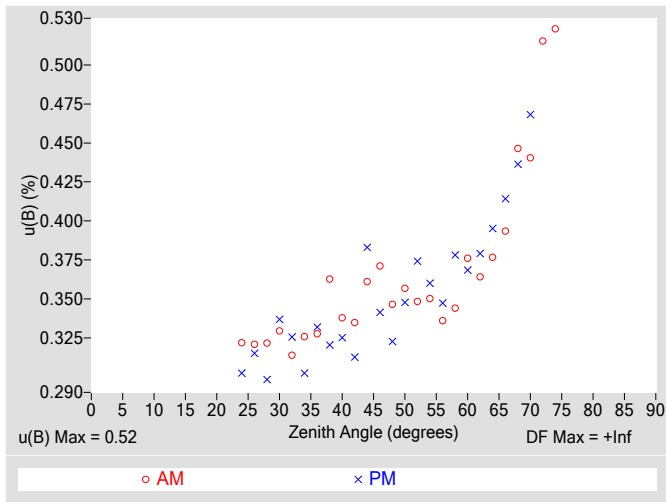


Figure 4. Residuals from Spline Interpolation

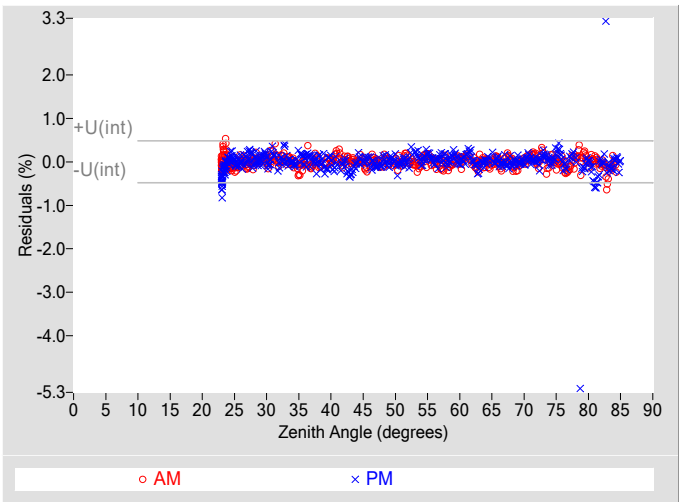


Table 3. Uncertainty using Spline Interpolation ‡

Type-B Standard Uncertainty, u(B) (%)	±0.52
Type-A Interpolating Function, u(int) (%)	±0.24
Combined Standard Uncertainty, u(c) (%)	±0.58
Effective degrees of freedom, DF(c)	29347
Coverage factor, k	1.96
Expanded Uncertainty, U95 (%)	±1.1
AM Valid zenith angle range	24° to 74°
PM Valid zenith angle range	24° 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

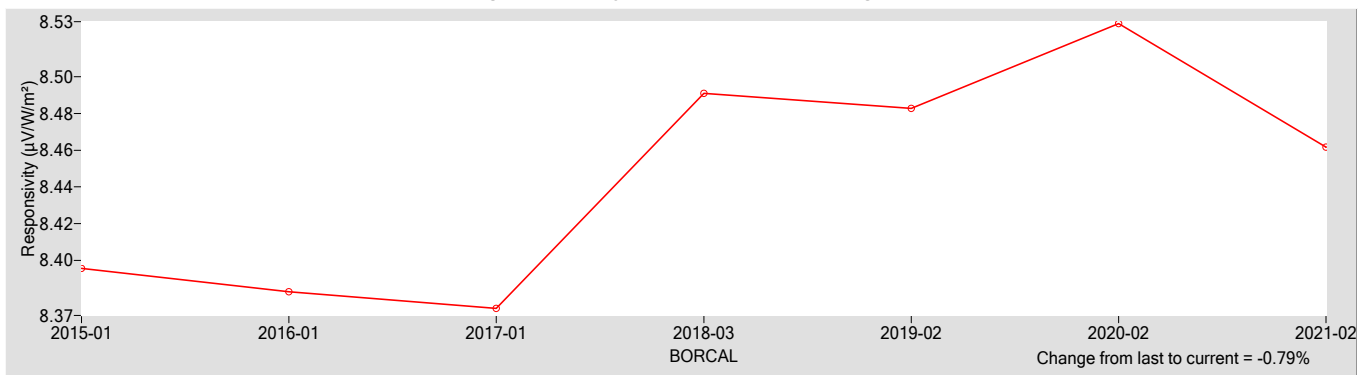
R @ 45° (μV/W/m²)	Rnet (μV/W/m²) †
8.4616	0.15000

† Rnet determination date: Estimated

Table 5. Uncertainty using R @ 45°

Type-B Expanded Uncertainty, U(B) (%)	±0.75
Offset Uncertainty, U(off) (%)	+0.99 / -1.8
Expanded Uncertainty, U (%)	+1.7 / -2.6
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 Pyrgometers. ARM 2008 Science Team Meeting (Poster).



National Renewable Energy Laboratory

Solar Radiation Research Laboratory

Metrology Laboratory

Calibration Certificate



Test Instrument:	Standard Precision Pyranometer (Ventilated)	Manufacturer:	Eppley
Model:	SPP	Serial Number:	37839F3
Calibration Date:	5/6/2021	Due Date:	5/6/2022
Customer:	NREL-SRRL-BMS	Environmental Conditions:	see page 4
Test Dates:	5/6		

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 than 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	09/27/2019	09/27/2021
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/30/2021	04/30/2022
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/30/2021	04/30/2022
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/08/2021	02/08/2023
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/08/2021	02/08/2023
Infrared Irradiance ‡	Eppley Downwelling Pyrgeometer (Ventilated) Model PIR-V, S/N 31203F3	04/02/2019	04/02/2023

† 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, Peter Gotseff, 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

37839F3 Eppley SPP

The responsivity (R , $\mu\text{V}/\text{W}/\text{m}^2$) of the test instrument during calibration is calculated using this Measurement Equation:

$$R = (V - R_{net} * W_{net}) / I \tag{1}$$

where,

- V = radiometer output voltage (microvolts),
 - R_{net} = radiometer net infrared responsivity ($\mu\text{V}/\text{W}/\text{m}^2$), see Table 4,
 - W_{net} = effective net infrared measured by pyrgeometer (W/m^2),
 - $= W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
 - where, W_{in} = incoming infrared (W/m^2), $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$,
 - T_c = case temperature of pyrgeometer (K).
- I = reference irradiance (W/m^2), beam (B) or global (G)
 - where, $G = B * \text{COS}(Z) + D$,
 - Z = zenith angle (degrees),
 - D = reference diffuse irradiance (W/m^2).

Figure 1. Responsivity vs Zenith Angle

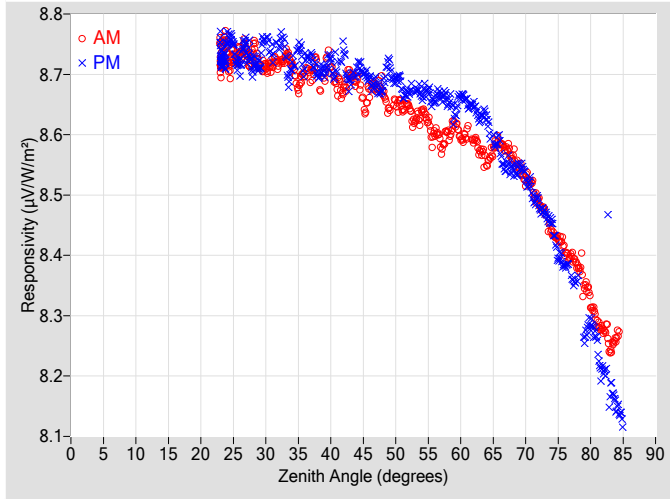


Figure 2. Responsivity vs Local Standard Time

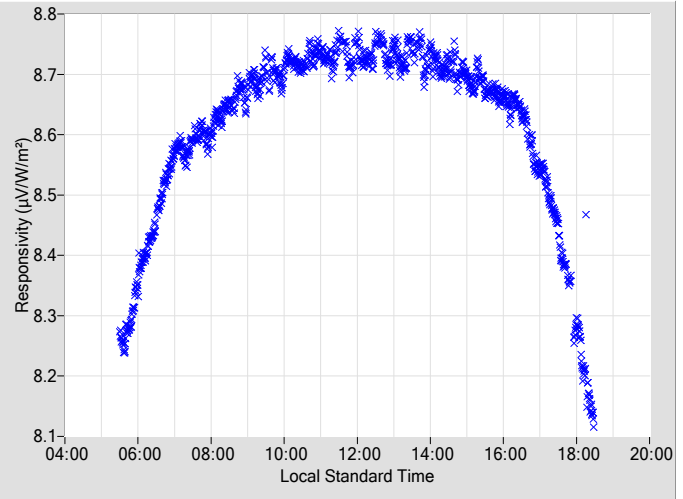


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)

Zenith Angle (deg.)	R ($\mu\text{V}/\text{W}/\text{m}^2$)	u(B) \pm (%)	Azimuth Angle	R ($\mu\text{V}/\text{W}/\text{m}^2$)	u(B) \pm (%)	Azimuth Angle	Zenith Angle (deg.)	R ($\mu\text{V}/\text{W}/\text{m}^2$)	u(B) \pm (%)	Azimuth Angle	R ($\mu\text{V}/\text{W}/\text{m}^2$)	u(B) \pm (%)	Azimuth Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	8.6728	0.36	106.47	8.6910	0.32	253.67
2	N/A	N/A	N/A	N/A	N/A	N/A	48	8.6741	0.38	104.10	8.6793	0.34	255.95
4	N/A	N/A	N/A	N/A	N/A	N/A	50	8.6538	0.35	102.05	8.6908	0.37	258.06
6	N/A	N/A	N/A	N/A	N/A	N/A	52	8.6461	0.35	100.03	8.6692	0.40	260.03
8	N/A	N/A	N/A	N/A	N/A	N/A	54	8.6377	0.36	98.09	8.6638	0.37	261.96
10	N/A	N/A	N/A	N/A	N/A	N/A	56	8.6026	0.34	96.32	8.6566	0.38	263.85
12	N/A	N/A	N/A	N/A	N/A	N/A	58	8.6025	0.37	94.49	8.6536	0.37	265.68
14	N/A	N/A	N/A	N/A	N/A	N/A	60	8.5940	0.36	92.72	8.6634	0.38	267.37
16	N/A	N/A	N/A	N/A	N/A	N/A	62	8.5909	0.40	91.10	8.6484	0.39	269.11
18	N/A	N/A	N/A	N/A	N/A	N/A	64	8.5552	0.39	89.37	8.6258	0.41	270.76
20	N/A	N/A	N/A	N/A	N/A	N/A	66	8.5848	0.43	87.72	8.5841	0.43	272.41
22	N/A	N/A	N/A	N/A	N/A	N/A	68	8.5657	0.46	86.16	8.5429	0.49	274.07
24	8.7375	0.33	160.68	8.7404	0.31	198.84	70	8.5277	0.46	84.52	8.5283	0.49	275.62
26	8.7370	0.31	148.37	8.7190	0.32	212.02	72	8.4893	0.53	82.88	8.4856	N/A	277.25
28	8.7401	0.34	139.81	8.7109	0.34	220.18	74	8.4415	0.54	81.33	8.4521	N/A	278.87
30	8.7113	0.31	133.67	8.7588	0.32	226.59	76	8.4082	N/A	79.71	8.3824	N/A	280.45
32	8.7182	0.32	128.68	8.7488	0.30	231.88	78	8.3817	N/A	78.10	8.3621	N/A	282.09
34	8.7178	0.33	124.30	8.7120	0.35	235.77	80	8.3226	N/A	76.49	8.2875	N/A	283.67
36	8.7014	0.38	120.54	8.7140	0.33	239.53	82	8.2754	N/A	74.87	8.2086	N/A	285.35
38	8.7239	0.39	117.46	8.6982	0.31	242.99	84	8.2650	N/A	73.15	8.1490	N/A	287.04
40	8.7118	0.34	114.08	8.7212	0.33	246.04	86	N/A	N/A	N/A	N/A	N/A	N/A
42	8.6752	0.34	111.37	8.7327	0.37	248.89	88	N/A	N/A	N/A	N/A	N/A	N/A
44	8.6918	0.35	108.77	8.7079	0.34	251.42	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

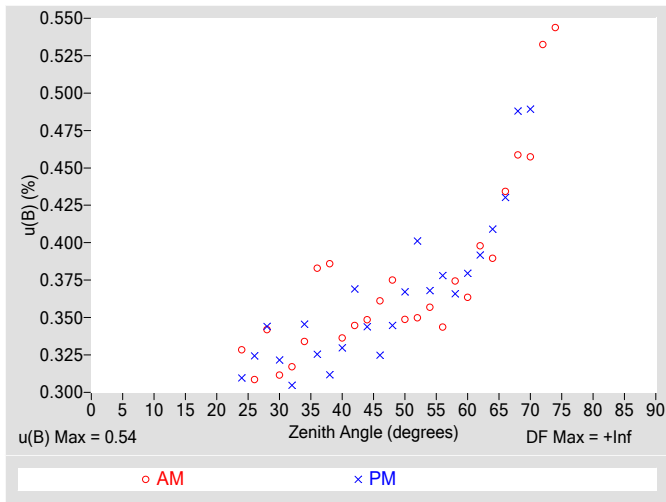


Figure 4. Residuals from Spline Interpolation

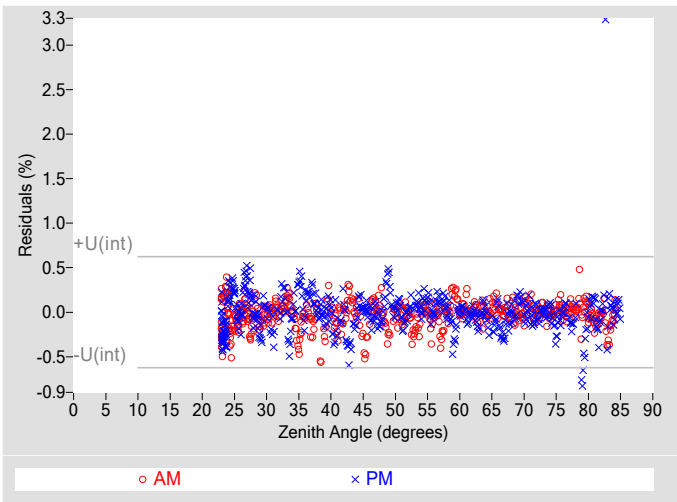


Table 3. Uncertainty using Spline Interpolation ‡

Type-B Standard Uncertainty, $u(B)$ (%)	± 0.54
Type-A Interpolating Function, $u(int)$ (%)	± 0.31
Combined Standard Uncertainty, $u(c)$ (%)	± 0.63
Effective degrees of freedom, $DF(c)$	14958
Coverage factor, k	1.96
Expanded Uncertainty, U_{95} (%)	± 1.2
AM Valid zenith angle range	24° to 74°
PM Valid zenith angle range	24° to 70°

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

Table 4. Calibration Label Values

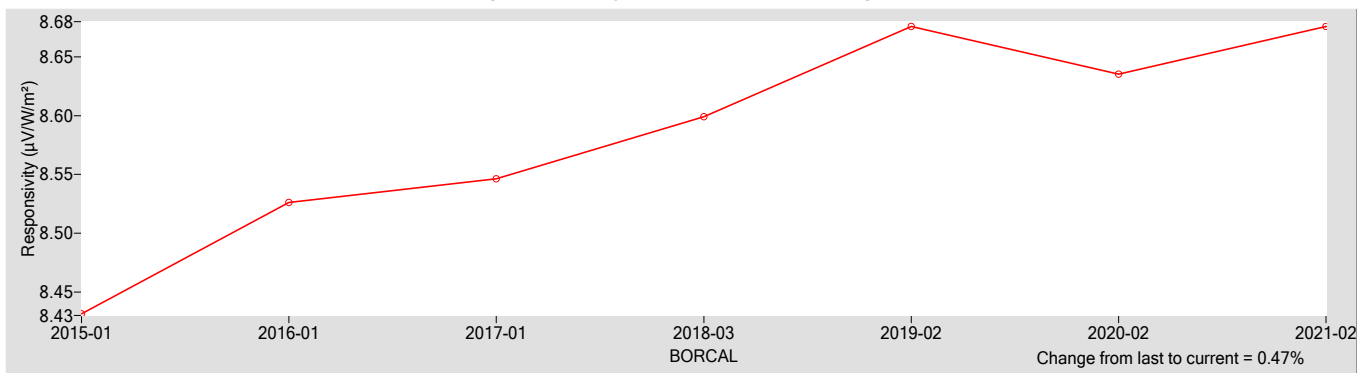
$R @ 45^\circ$ ($\mu V/W/m^2$)	R_{net} ($\mu V/W/m^2$) †
8.6760	0.30000

† R_{net} determination date: Estimated

Table 5. Uncertainty using $R @ 45^\circ$

Type-B Expanded Uncertainty, $U(B)$ (%)	± 0.79
Offset Uncertainty, $U(off)$ (%)	+0.95 / -0.94
Expanded Uncertainty, U (%)	+1.7 / -1.7
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 Pyrgometers. ARM 2008 Science Team Meeting (Poster).

National Renewable Energy Laboratory

Solar Radiation Research Laboratory

Metrology Laboratory

Calibration Certificate



Test Instrument: Short Normal Incidence Pyrheliometer **Manufacturer:** Eppley
Model: sNIP **Serial Number:** 37882E6
Calibration Date: 5/6/2021 **Due Date:** 5/6/2022
Customer: NREL-SRRL-BMS **Environmental Conditions:** see page 4
Test Dates: 5/6

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 than 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	09/27/2019	09/27/2021
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/30/2021	04/30/2022
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/30/2021	04/30/2022
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/08/2021	02/08/2023
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/08/2021	02/08/2023

† 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, Peter Gotseff, 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

37882E6 Eppley sNIP

The responsivity (R , $\mu\text{V}/\text{W}/\text{m}^2$) of the test instrument during calibration is calculated using this Measurement Equation:

$$R = (V - R_{net} * W_{net}) / I \tag{1}$$

where,

- V = radiometer output voltage (microvolts),
 - R_{net} = radiometer net infrared responsivity ($\mu\text{V}/\text{W}/\text{m}^2$), see Table 4,
 - W_{net} = effective net infrared measured by pyrgeometer (W/m^2),
 - = $W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
 - where, W_{in} = incoming infrared (W/m^2), $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$,
 - T_c = case temperature of pyrgeometer (K).
- I = reference irradiance (W/m^2), beam (B) or global (G)
 - where, $G = B * \text{COS}(Z) + D$,
 - Z = zenith angle (degrees),
 - D = reference diffuse irradiance (W/m^2).

Figure 1. Responsivity vs Zenith Angle

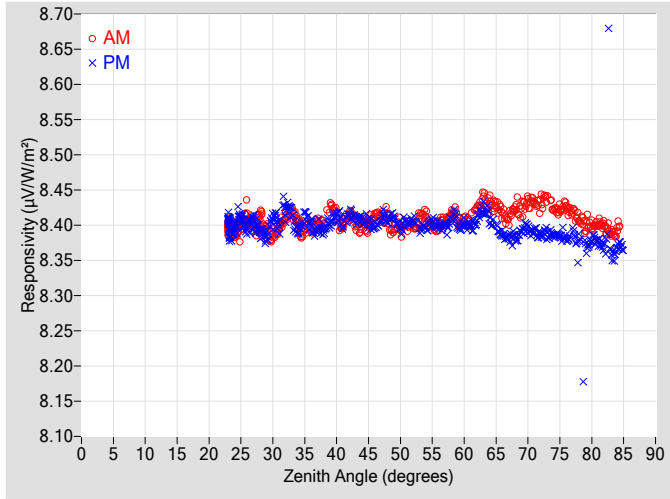


Figure 2. Responsivity vs Local Standard Time

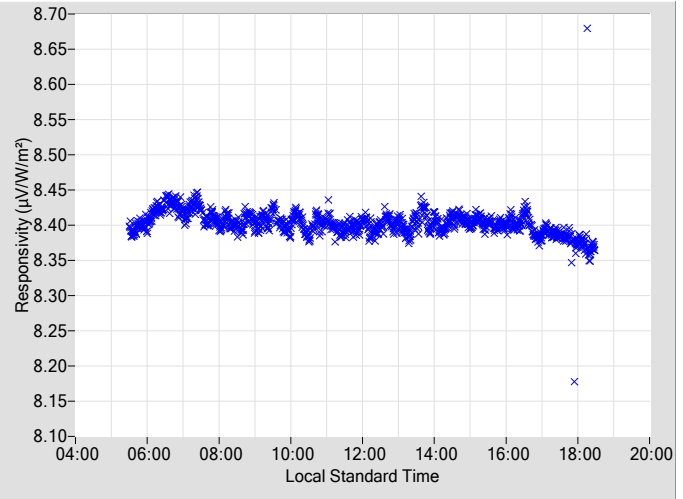


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, $u(B)$

Zenith Angle (deg.)	R ($\mu\text{V}/\text{W}/\text{m}^2$)	$u(B)$ \pm (%)	Azimuth Angle	R ($\mu\text{V}/\text{W}/\text{m}^2$)	$u(B)$ \pm (%)	Azimuth Angle	Zenith Angle (deg.)	R ($\mu\text{V}/\text{W}/\text{m}^2$)	$u(B)$ \pm (%)	Azimuth Angle	R ($\mu\text{V}/\text{W}/\text{m}^2$)	$u(B)$ \pm (%)	Azimuth Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	8.4153	0.31	106.41	8.3986	0.30	253.71
2	N/A	N/A	N/A	N/A	N/A	N/A	48	8.4123	0.32	104.20	8.4074	0.30	255.99
4	N/A	N/A	N/A	N/A	N/A	N/A	50	8.3962	0.33	102.02	8.3959	0.30	258.10
6	N/A	N/A	N/A	N/A	N/A	N/A	52	8.3998	0.29	100.01	8.4071	0.32	260.12
8	N/A	N/A	N/A	N/A	N/A	N/A	54	8.4152	0.31	98.18	8.3950	0.30	262.04
10	N/A	N/A	N/A	N/A	N/A	N/A	56	8.4000	0.31	96.30	8.4002	0.30	263.83
12	N/A	N/A	N/A	N/A	N/A	N/A	58	8.4167	0.30	94.47	8.4099	0.33	265.66
14	N/A	N/A	N/A	N/A	N/A	N/A	60	8.4054	0.30	92.75	8.4027	0.30	267.34
16	N/A	N/A	N/A	N/A	N/A	N/A	62	8.4243	0.30	91.07	8.4074	0.32	269.09
18	N/A	N/A	N/A	N/A	N/A	N/A	64	8.4351	0.30	89.38	8.4068	0.31	270.79
20	N/A	N/A	N/A	N/A	N/A	N/A	66	8.4174	0.31	87.74	8.3872	0.31	272.39
22	N/A	N/A	N/A	N/A	N/A	N/A	68	8.4237	0.30	86.14	8.3822	0.31	274.05
24	8.3926	0.30	161.34	8.3981	0.29	198.75	70	8.4316	0.31	84.49	8.3962	0.31	275.60
26	8.4091	0.31	148.23	8.3977	0.30	211.95	72	8.4324	0.31	82.96	8.3870	N/A	277.23
28	8.4150	0.30	139.99	8.3901	0.29	220.25	74	8.4224	0.31	81.30	8.3850	N/A	278.85
30	8.3847	0.29	133.61	8.4079	0.31	226.35	76	8.4250	N/A	79.69	8.3808	N/A	280.48
32	8.4116	0.29	128.62	8.4199	0.31	231.51	78	8.4074	N/A	78.08	8.3740	N/A	282.02
34	8.4048	0.29	124.20	8.3933	0.29	235.92	80	8.3986	N/A	76.47	8.3802	N/A	283.70
36	8.3967	0.30	120.54	8.4006	0.31	239.58	82	8.3990	N/A	74.85	8.3703	N/A	285.38
38	8.4049	0.31	117.13	8.3926	0.29	242.95	84	8.3931	N/A	73.18	8.3676	N/A	287.02
40	8.4140	0.30	114.10	8.4112	0.29	246.00	86	N/A	N/A	N/A	N/A	N/A	N/A
42	8.4141	0.30	111.34	8.4167	0.31	248.79	88	N/A	N/A	N/A	N/A	N/A	N/A
44	8.4015	0.29	108.85	8.4064	0.30	251.32	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

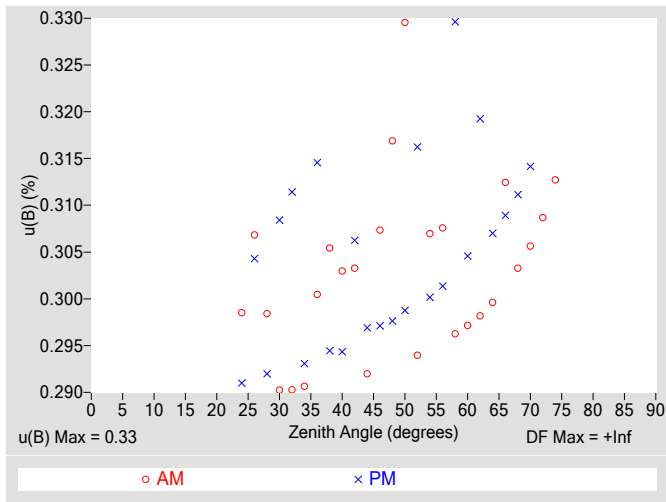


Figure 4. Residuals from Spline Interpolation

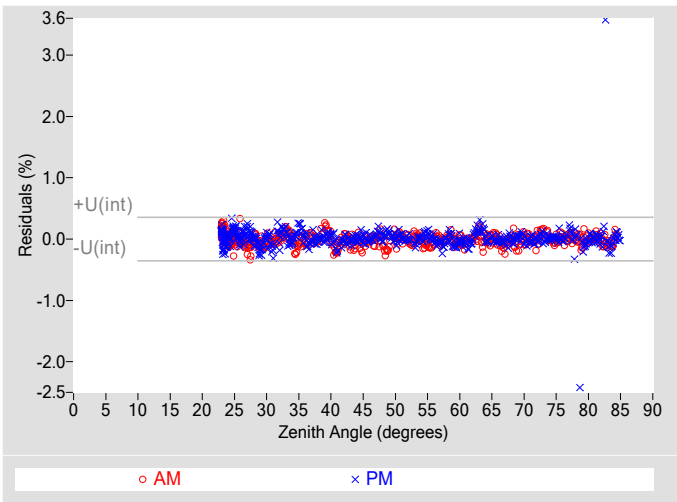


Table 3. Uncertainty using Spline Interpolation ‡

Type-B Standard Uncertainty, $u(B)$ (%)	± 0.33
Type-A Interpolating Function, $u(int)$ (%)	± 0.18
Combined Standard Uncertainty, $u(c)$ (%)	± 0.37
Effective degrees of freedom, $DF(c)$	18908
Coverage factor, k	1.96
Expanded Uncertainty, U_{95} (%)	± 0.73
AM Valid zenith angle range	24° to 74°
PM Valid zenith angle range	24° to 70°

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

Table 4. Calibration Label Values

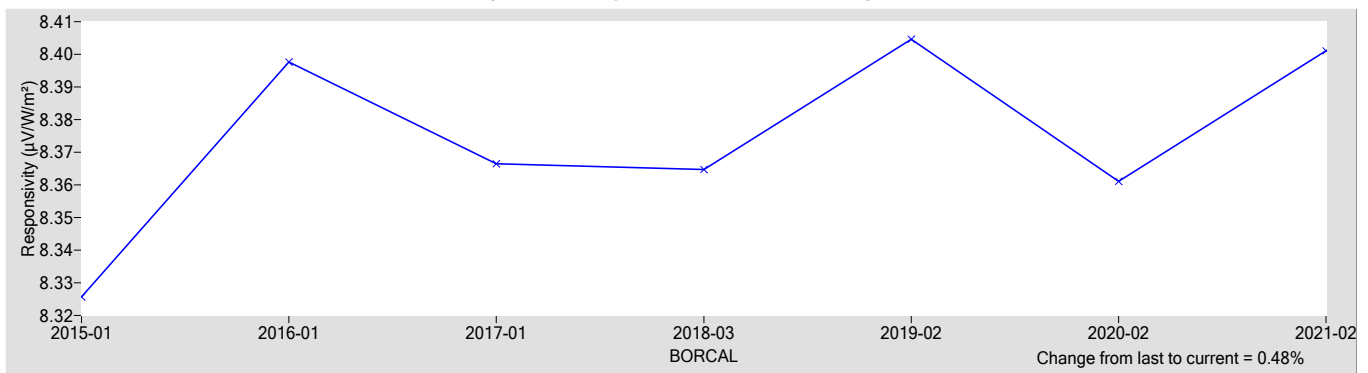
$R @ 45^\circ$ ($\mu V/W/m^2$)	R_{net} ($\mu V/W/m^2$) †
8.4011	0

† R_{net} determination date: N/A

Table 5. Uncertainty using $R @ 45^\circ$

Type-B Expanded Uncertainty, $U(B)$ (%)	± 0.65
Offset Uncertainty, $U(off)$ (%)	+0.22 / -0.20
Expanded Uncertainty, U (%)	+0.87 / -0.84
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 Pyrgometers. ARM 2008 Science Team Meeting (Poster).



National Renewable Energy Laboratory

Solar Radiation Research Laboratory

Metrology Laboratory

Calibration Certificate



Test Instrument:	Standard Precision Pyranometer (Ventilated)	Manufacturer:	Eppley
Model:	SPP	Serial Number:	38860F3
Calibration Date:	5/6/2021	Due Date:	5/6/2022
Customer:	NREL-SRRL-BMS	Environmental Conditions:	see page 4
Test Dates:	5/6		

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 than 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	09/27/2019	09/27/2021
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/30/2021	04/30/2022
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/30/2021	04/30/2022
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/08/2021	02/08/2023
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/08/2021	02/08/2023
Infrared Irradiance ‡	Eppley Downwelling Pyrgeometer (Ventilated) Model PIR-V, S/N 31203F3	04/02/2019	04/02/2023

† 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, Peter Gotseff, 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

38860F3 Eppley SPP

The responsivity (R , $\mu\text{V}/\text{W}/\text{m}^2$) of the test instrument during calibration is calculated using this Measurement Equation:

$$R = (V - R_{net} * W_{net}) / I \tag{1}$$

where,

- V = radiometer output voltage (microvolts),
 - R_{net} = radiometer net infrared responsivity ($\mu\text{V}/\text{W}/\text{m}^2$), see Table 4,
 - W_{net} = effective net infrared measured by pyrgeometer (W/m^2),
 - = $W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
 - where, W_{in} = incoming infrared (W/m^2), $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$,
 - T_c = case temperature of pyrgeometer (K).
- I = reference irradiance (W/m^2), beam (B) or global (G)
 - where, $G = B * \text{COS}(Z) + D$,
 - Z = zenith angle (degrees),
 - D = reference diffuse irradiance (W/m^2).

Figure 1. Responsivity vs Zenith Angle

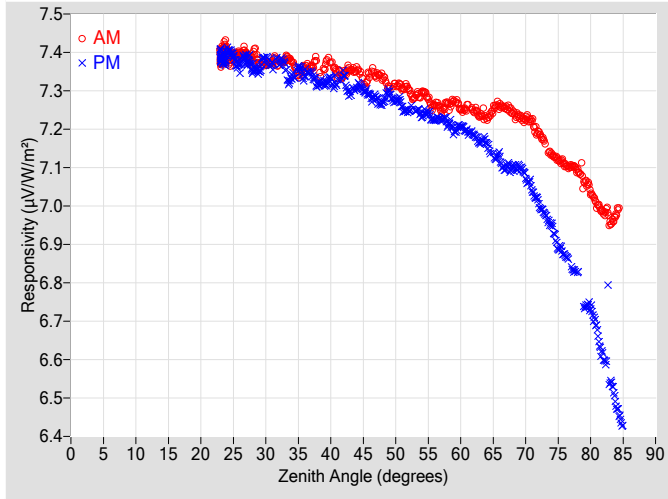


Figure 2. Responsivity vs Local Standard Time

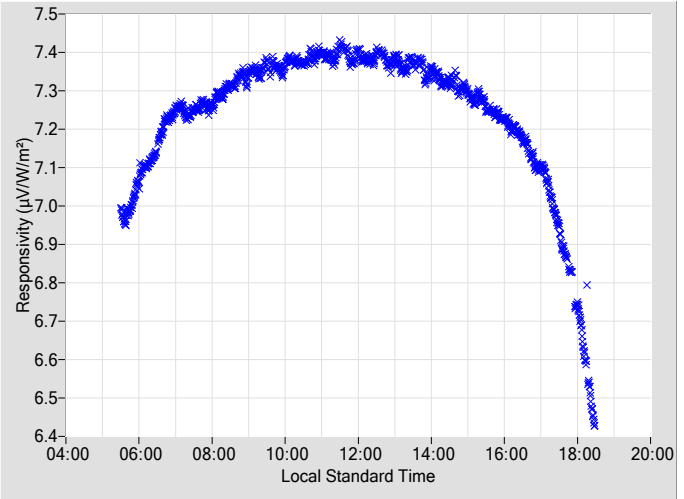


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, $u(B)$

Zenith			AM			PM			Zenith			AM			PM		
Angle	R	u(B)	Azimuth	R	u(B)	Azimuth	Angle	R	u(B)	Azimuth	R	u(B)	Azimuth	R	u(B)	Azimuth	
(deg.)	($\mu\text{V}/\text{W}/\text{m}^2$)	\pm (%)	Angle	($\mu\text{V}/\text{W}/\text{m}^2$)	\pm (%)	Angle	(deg.)	($\mu\text{V}/\text{W}/\text{m}^2$)	\pm (%)	Angle	($\mu\text{V}/\text{W}/\text{m}^2$)	\pm (%)	Angle	($\mu\text{V}/\text{W}/\text{m}^2$)	\pm (%)	Angle	
0	N/A	N/A	N/A	N/A	N/A	N/A	46	7.3422	0.36	106.47	7.2883	0.32	253.67				
2	N/A	N/A	N/A	N/A	N/A	N/A	48	7.3353	0.37	104.10	7.2708	0.34	255.95				
4	N/A	N/A	N/A	N/A	N/A	N/A	50	7.3156	0.35	102.05	7.2743	0.37	258.06				
6	N/A	N/A	N/A	N/A	N/A	N/A	52	7.3024	0.35	100.03	7.2479	0.40	260.03				
8	N/A	N/A	N/A	N/A	N/A	N/A	54	7.2938	0.36	98.09	7.2353	0.37	261.96				
10	N/A	N/A	N/A	N/A	N/A	N/A	56	7.2638	0.34	96.32	7.2240	0.38	263.85				
12	N/A	N/A	N/A	N/A	N/A	N/A	58	7.2642	0.37	94.49	7.2129	0.36	265.68				
14	N/A	N/A	N/A	N/A	N/A	N/A	60	7.2501	0.36	92.72	7.2071	0.38	267.37				
16	N/A	N/A	N/A	N/A	N/A	N/A	62	7.2488	0.40	91.10	7.1840	0.39	269.11				
18	N/A	N/A	N/A	N/A	N/A	N/A	64	7.2292	0.39	89.37	7.1627	0.41	270.76				
20	N/A	N/A	N/A	N/A	N/A	N/A	66	7.2596	0.43	87.72	7.1262	0.43	272.41				
22	N/A	N/A	N/A	N/A	N/A	N/A	68	7.2459	0.46	86.16	7.1011	0.49	274.07				
24	7.3982	0.33	160.68	7.3910	0.31	198.84	70	7.2275	0.45	84.52	7.0740	0.49	275.62				
26	7.3968	0.31	148.37	7.3695	0.32	212.02	72	7.1898	0.53	82.88	7.0063	N/A	277.25				
28	7.3939	0.34	139.81	7.3554	0.34	220.18	74	7.1350	0.54	81.33	6.9471	N/A	278.87				
30	7.3726	0.31	133.67	7.3827	0.32	226.59	76	7.1075	N/A	79.71	6.8712	N/A	280.45				
32	7.3730	0.32	128.68	7.3724	0.30	231.88	78	7.0906	N/A	78.10	6.8281	N/A	282.09				
34	7.3777	0.33	124.30	7.3359	0.34	235.77	80	7.0377	N/A	76.49	6.7350	N/A	283.67				
36	7.3609	0.38	120.54	7.3376	0.32	239.53	82	6.9834	N/A	74.87	6.6032	N/A	285.35				
38	7.3786	0.39	117.46	7.3154	0.31	242.99	84	6.9819	N/A	73.15	6.4768	N/A	287.04				
40	7.3737	0.34	114.08	7.3310	0.33	246.04	86	N/A	N/A	N/A	N/A	N/A	N/A				
42	7.3429	0.34	111.37	7.3370	0.37	248.89	88	N/A	N/A	N/A	N/A	N/A	N/A				
44	7.3541	0.35	108.77	7.3101	0.34	251.42	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

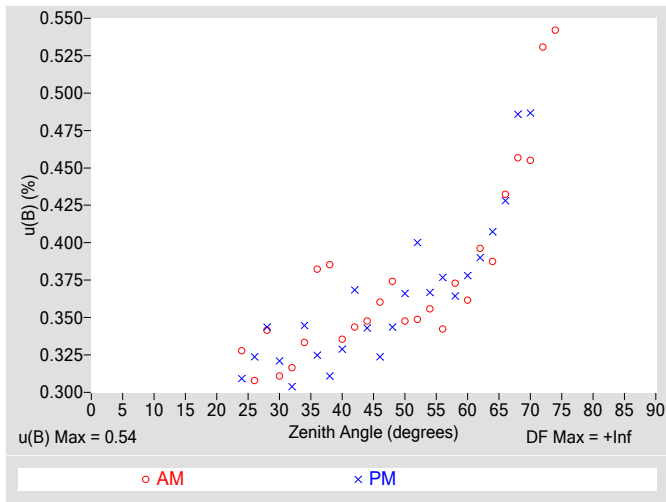


Figure 4. Residuals from Spline Interpolation

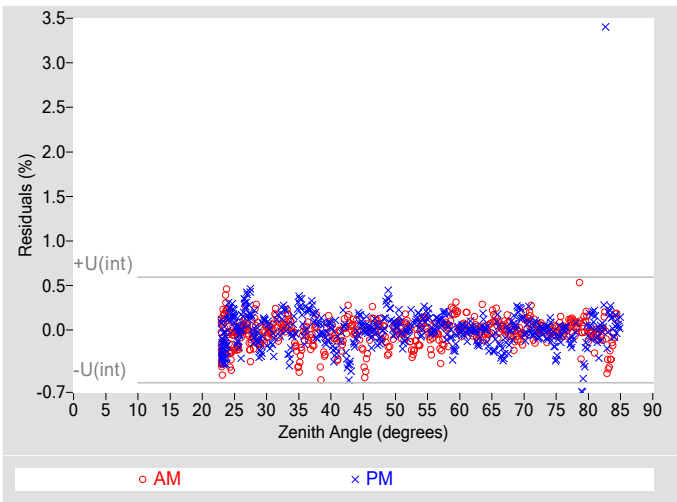


Table 3. Uncertainty using Spline Interpolation ‡

Type-B Standard Uncertainty, $u(B)$ (%)	± 0.54
Type-A Interpolating Function, $u(int)$ (%)	± 0.30
Combined Standard Uncertainty, $u(c)$ (%)	± 0.62
Effective degrees of freedom, $DF(c)$	17229
Coverage factor, k	1.96
Expanded Uncertainty, $U95$ (%)	± 1.2
AM Valid zenith angle range	24° to 74°
PM Valid zenith angle range	24° to 70°

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

Table 4. Calibration Label Values

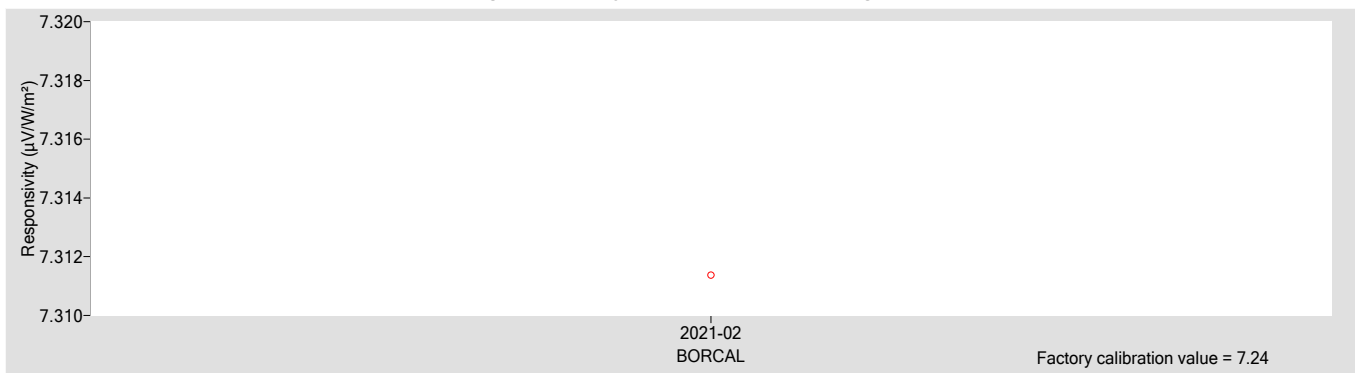
$R @ 45^\circ$ ($\mu V/W/m^2$)	R_{net} ($\mu V/W/m^2$) †
7.3114	0.22000

† R_{net} determination date: Estimated

Table 5. Uncertainty using $R @ 45^\circ$

Type-B Expanded Uncertainty, $U(B)$ (%)	± 0.78
Offset Uncertainty, $U(off)$ (%)	+0.98 / -1.4
Expanded Uncertainty, U (%)	+1.8 / -2.2
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 Pyrgometers. ARM 2008 Science Team Meeting (Poster).

National Renewable Energy Laboratory

Solar Radiation Research Laboratory

Metrology Laboratory

Calibration Certificate



Test Instrument: Si pyranometer
Manufacturer: Apogee
Model: SP-110
Serial Number: 40337
Calibration Date: 5/6/2021
Due Date: 5/6/2022
Customer: NREL-SRRL-BMS
Environmental Conditions: see page 4
Test Dates: 5/6

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	09/27/2019	09/27/2021
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/30/2021	04/30/2022
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/30/2021	04/30/2022
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/08/2021	02/08/2023
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/08/2021	02/08/2023

† 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, Peter Gotseff, 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

40337 Apogee SP-110

The responsivity (R , $\mu\text{V}/\text{W}/\text{m}^2$) of the test instrument during calibration is calculated using this Measurement Equation:

$$R = (V - R_{net} * W_{net}) / I \tag{1}$$

where,

- V = radiometer output voltage (microvolts),
 - R_{net} = radiometer net infrared responsivity ($\mu\text{V}/\text{W}/\text{m}^2$), see Table 4,
 - W_{net} = effective net infrared measured by pyrgeometer (W/m^2),
 - = $W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
 - where, W_{in} = incoming infrared (W/m^2), $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$,
 - T_c = case temperature of pyrgeometer (K).
- I = reference irradiance (W/m^2), beam (B) or global (G)
 - where, $G = B * \text{COS}(Z) + D$,
 - Z = zenith angle (degrees),
 - D = reference diffuse irradiance (W/m^2).

Figure 1. Responsivity vs Zenith Angle

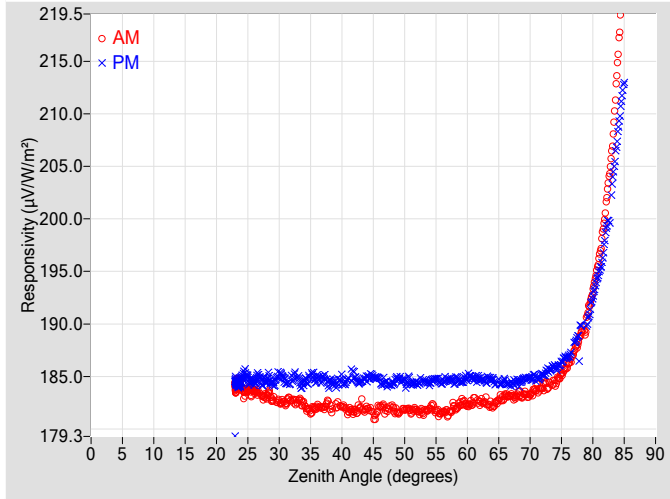


Figure 2. Responsivity vs Local Standard Time

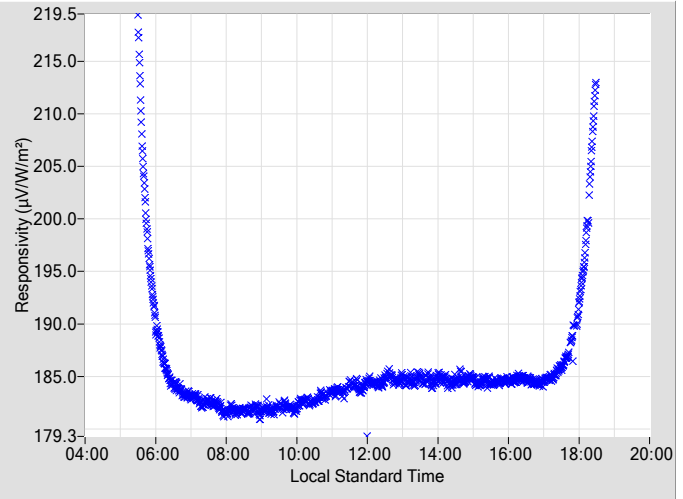


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, $u(B)$

Zenith Angle (deg.)	R ($\mu\text{V}/\text{W}/\text{m}^2$)	$u(B)$ \pm (%)	Azimuth Angle	R ($\mu\text{V}/\text{W}/\text{m}^2$)	$u(B)$ \pm (%)	Azimuth Angle	Zenith Angle (deg.)	R ($\mu\text{V}/\text{W}/\text{m}^2$)	$u(B)$ \pm (%)	Azimuth Angle	R ($\mu\text{V}/\text{W}/\text{m}^2$)	$u(B)$ \pm (%)	Azimuth Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	182.18	0.33	106.39	184.57	0.31	253.79
2	N/A	N/A	N/A	N/A	N/A	N/A	48	182.15	0.37	104.06	184.30	0.32	255.97
4	N/A	N/A	N/A	N/A	N/A	N/A	50	181.87	0.31	102.06	184.47	0.32	258.08
6	N/A	N/A	N/A	N/A	N/A	N/A	52	181.76	0.32	100.10	184.38	0.33	260.11
8	N/A	N/A	N/A	N/A	N/A	N/A	54	181.97	0.32	98.16	184.42	0.35	262.03
10	N/A	N/A	N/A	N/A	N/A	N/A	56	181.59	0.33	96.28	184.37	0.34	263.78
12	N/A	N/A	N/A	N/A	N/A	N/A	58	182.03	0.36	94.45	184.55	0.35	265.64
14	N/A	N/A	N/A	N/A	N/A	N/A	60	182.27	0.34	92.79	184.92	0.36	267.43
16	N/A	N/A	N/A	N/A	N/A	N/A	62	182.58	0.40	91.06	184.83	0.37	269.08
18	N/A	N/A	N/A	N/A	N/A	N/A	64	182.12	0.37	89.34	184.67	0.38	270.78
20	N/A	N/A	N/A	N/A	N/A	N/A	66	183.08	0.44	87.78	184.54	0.40	272.38
22	N/A	N/A	N/A	N/A	N/A	N/A	68	183.25	0.43	86.12	184.49	0.42	274.04
24	184.00	0.32	161.20	184.62	0.31	198.72	70	183.28	0.42	84.48	184.87	0.45	275.68
26	183.64	0.30	148.30	184.53	0.31	211.87	72	183.92	0.46	82.95	185.20	N/A	277.22
28	183.15	0.32	139.73	184.65	0.31	220.21	74	184.39	0.55	81.29	185.87	N/A	278.84
30	182.57	0.32	133.53	185.18	0.34	226.31	76	186.09	N/A	79.73	186.87	N/A	280.46
32	182.74	0.30	128.58	184.70	0.30	231.67	78	188.85	N/A	78.12	188.97	N/A	282.01
34	182.31	0.30	124.19	184.54	0.31	235.89	80	193.26	N/A	76.45	192.60	N/A	283.68
36	182.06	0.30	120.52	184.72	0.32	239.65	82	200.74	N/A	74.84	198.53	N/A	285.37
38	182.38	0.36	117.19	184.38	0.35	243.01	84	215.34	N/A	73.17	208.12	N/A	287.01
40	182.16	0.36	114.04	184.62	0.32	246.11	86	N/A	N/A	N/A	N/A	N/A	N/A
42	181.69	0.32	111.32	185.07	0.32	248.76	88	N/A	N/A	N/A	N/A	N/A	N/A
44	181.93	0.33	108.79	184.90	0.35	251.30	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

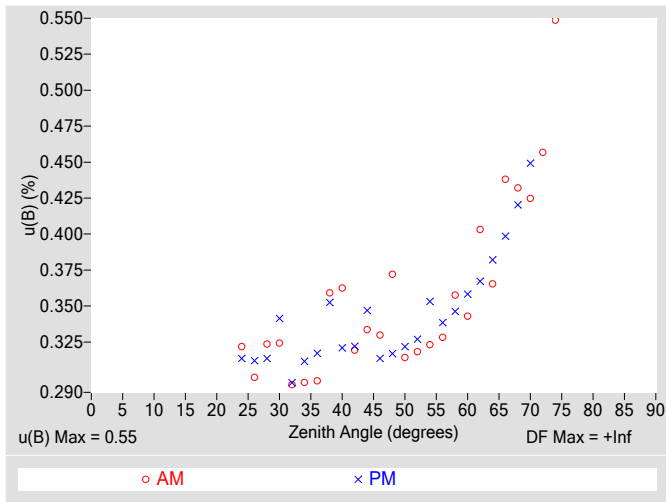


Figure 4. Residuals from Spline Interpolation

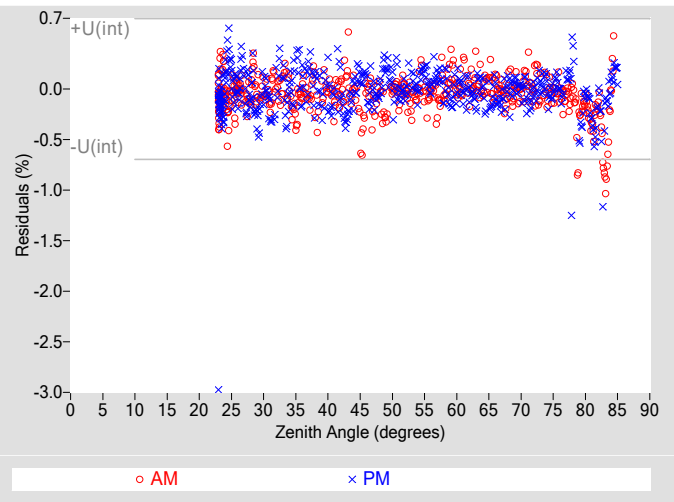


Table 3. Uncertainty using Spline Interpolation ‡

Type-B Standard Uncertainty, $u(B)$ (%)	± 0.55
Type-A Interpolating Function, $u(int)$ (%)	± 0.35
Combined Standard Uncertainty, $u(c)$ (%)	± 0.65
Effective degrees of freedom, $DF(c)$	10942
Coverage factor, k	1.96
Expanded Uncertainty, U_{95} (%)	± 1.3
AM Valid zenith angle range	24° to 74°
PM Valid zenith angle range	24° to 70°

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

Table 4. Calibration Label Values

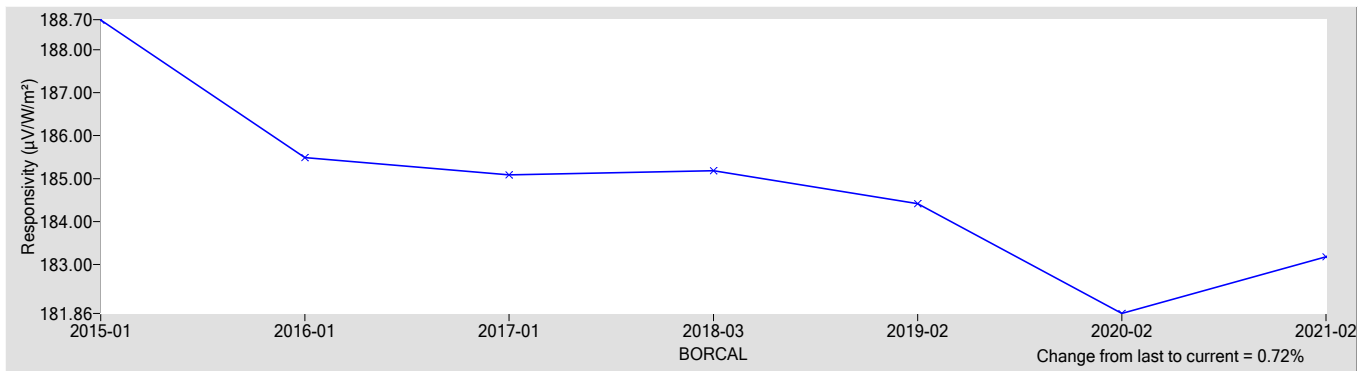
$R @ 45^\circ$ ($\mu V/W/m^2$)	R_{net} ($\mu V/W/m^2$) †
183.18	0

† R_{net} determination date: N/A

Table 5. Uncertainty using $R @ 45^\circ$

Type-B Expanded Uncertainty, $U(B)$ (%)	± 0.73
Offset Uncertainty, $U(off)$ (%)	+1.1 / -0.87
Expanded Uncertainty, U (%)	+1.8 / -1.6
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 Pyrgometers*. ARM 2008 Science Team Meeting (Poster).



National Renewable Energy Laboratory

Solar Radiation Research Laboratory

Metrology Laboratory

Calibration Certificate



Test Instrument: Pyrheliometer **Manufacturer:** Hukseflux
Model: DR02 **Serial Number:** 9206
Calibration Date: 5/6/2021 **Due Date:** 5/6/2022
Customer: NREL-SRRL-BMS **Environmental Conditions:** see page 4
Test Dates: 5/6

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 than 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	09/27/2019	09/27/2021
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/30/2021	04/30/2022
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/30/2021	04/30/2022
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/08/2021	02/08/2023
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/08/2021	02/08/2023

† 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, Peter Gotseff, 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

9206 Hukseflux DR02

The responsivity (R , $\mu\text{V}/\text{W}/\text{m}^2$) of the test instrument during calibration is calculated using this Measurement Equation:

$$R = (V - R_{net} * W_{net}) / I \tag{1}$$

where,

- V = radiometer output voltage (microvolts),
 - R_{net} = radiometer net infrared responsivity ($\mu\text{V}/\text{W}/\text{m}^2$), see Table 4,
 - W_{net} = effective net infrared measured by pyrgeometer (W/m^2),
 - = $W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
 - where, W_{in} = incoming infrared (W/m^2), $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$,
 - T_c = case temperature of pyrgeometer (K).
- I = reference irradiance (W/m^2), beam (B) or global (G)
 - where, $G = B * \text{COS}(Z) + D$,
 - Z = zenith angle (degrees),
 - D = reference diffuse irradiance (W/m^2).

Figure 1. Responsivity vs Zenith Angle

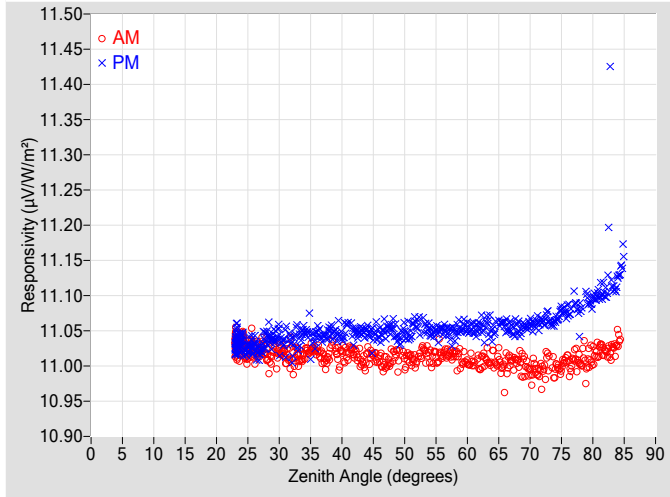


Figure 2. Responsivity vs Local Standard Time

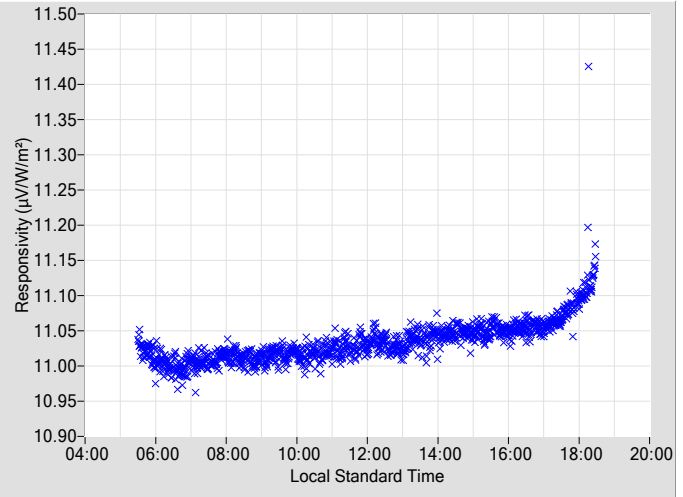


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)

Zenith			AM			PM			Zenith			AM			PM		
Angle	R	u(B)	Azimuth	R	u(B)	Azimuth	Angle	R	u(B)	Azimuth	R	u(B)	Azimuth	R	u(B)	Azimuth	
(deg.)	($\mu\text{V}/\text{W}/\text{m}^2$)	\pm (%)	Angle	($\mu\text{V}/\text{W}/\text{m}^2$)	\pm (%)	Angle	(deg.)	($\mu\text{V}/\text{W}/\text{m}^2$)	\pm (%)	Angle	($\mu\text{V}/\text{W}/\text{m}^2$)	\pm (%)	Angle	($\mu\text{V}/\text{W}/\text{m}^2$)	\pm (%)	Angle	
0	N/A	N/A	N/A	N/A	N/A	N/A	46	11.012	0.29	106.38	11.045	0.31	253.71				
2	N/A	N/A	N/A	N/A	N/A	N/A	48	11.014	0.31	104.20	11.057	0.30	255.99				
4	N/A	N/A	N/A	N/A	N/A	N/A	50	11.009	0.30	102.08	11.048	0.30	258.10				
6	N/A	N/A	N/A	N/A	N/A	N/A	52	11.005	0.31	100.15	11.059	0.30	260.12				
8	N/A	N/A	N/A	N/A	N/A	N/A	54	11.015	0.31	98.24	11.049	0.31	262.04				
10	N/A	N/A	N/A	N/A	N/A	N/A	56	11.016	0.29	96.30	11.052	0.30	263.83				
12	N/A	N/A	N/A	N/A	N/A	N/A	58	11.017	0.30	94.47	11.046	0.30	265.66				
14	N/A	N/A	N/A	N/A	N/A	N/A	60	11.004	0.30	92.69	11.053	0.32	267.34				
16	N/A	N/A	N/A	N/A	N/A	N/A	62	11.003	0.31	91.07	11.061	0.32	269.09				
18	N/A	N/A	N/A	N/A	N/A	N/A	64	11.012	0.30	89.35	11.048	0.31	270.79				
20	N/A	N/A	N/A	N/A	N/A	N/A	66	11.009	0.30	87.73	11.059	0.31	272.39				
22	N/A	N/A	N/A	N/A	N/A	N/A	68	11.006	0.30	86.13	11.056	0.31	274.05				
24	11.031	0.30	161.18	11.037	0.30	198.93	70	10.987	0.30	84.50	11.060	0.31	275.60				
26	11.022	0.30	148.19	11.027	0.30	211.95	72	10.992	0.32	82.96	11.064	N/A	277.23				
28	11.015	0.29	139.90	11.042	0.31	220.25	74	10.994	0.31	81.31	11.064	N/A	278.85				
30	11.021	0.31	133.61	11.049	0.30	226.20	76	11.011	N/A	79.74	11.077	N/A	280.47				
32	11.013	0.31	128.60	11.026	0.30	231.51	78	11.005	N/A	78.13	11.073	N/A	282.02				
34	11.017	0.30	124.20	11.051	0.30	235.90	80	11.010	N/A	76.46	11.094	N/A	283.70				
36	11.023	0.29	120.45	11.045	0.29	239.58	82	11.020	N/A	74.85	11.103	N/A	285.38				
38	11.015	0.30	117.25	11.049	0.30	242.95	84	11.036	N/A	73.18	11.124	N/A	287.02				
40	11.022	0.30	114.10	11.042	0.29	246.00	86	N/A	N/A	N/A	N/A	N/A	N/A				
42	11.018	0.29	111.34	11.047	0.31	248.79	88	N/A	N/A	N/A	N/A	N/A	N/A				
44	11.012	0.29	108.88	11.051	0.30	251.32	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

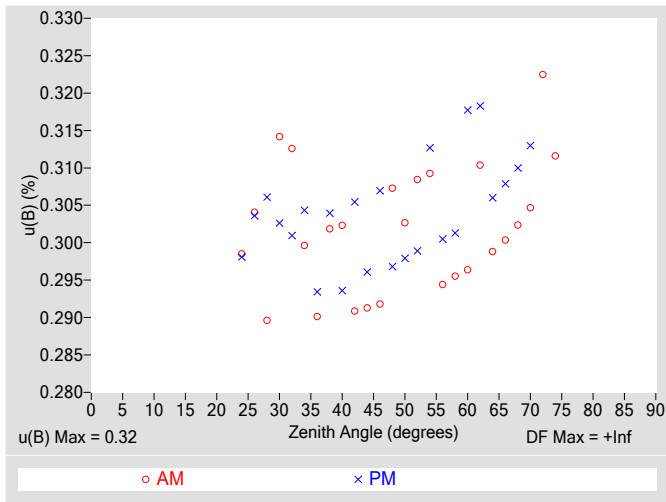


Figure 4. Residuals from Spline Interpolation

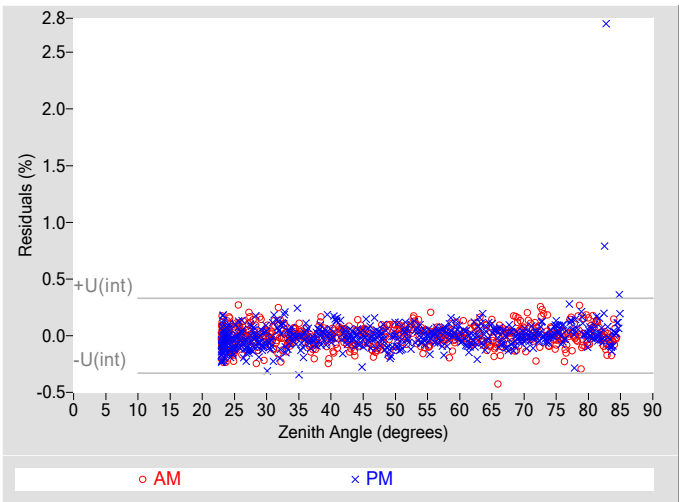


Table 3. Uncertainty using Spline Interpolation ‡

Type-B Standard Uncertainty, $u(B)$ (%)	± 0.32
Type-A Interpolating Function, $u(int)$ (%)	± 0.17
Combined Standard Uncertainty, $u(c)$ (%)	± 0.36
Effective degrees of freedom, $DF(c)$	22295
Coverage factor, k	1.96
Expanded Uncertainty, U_{95} (%)	± 0.71
AM Valid zenith angle range	24° to 74°
PM Valid zenith angle range	24° to 70°

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

Table 4. Calibration Label Values

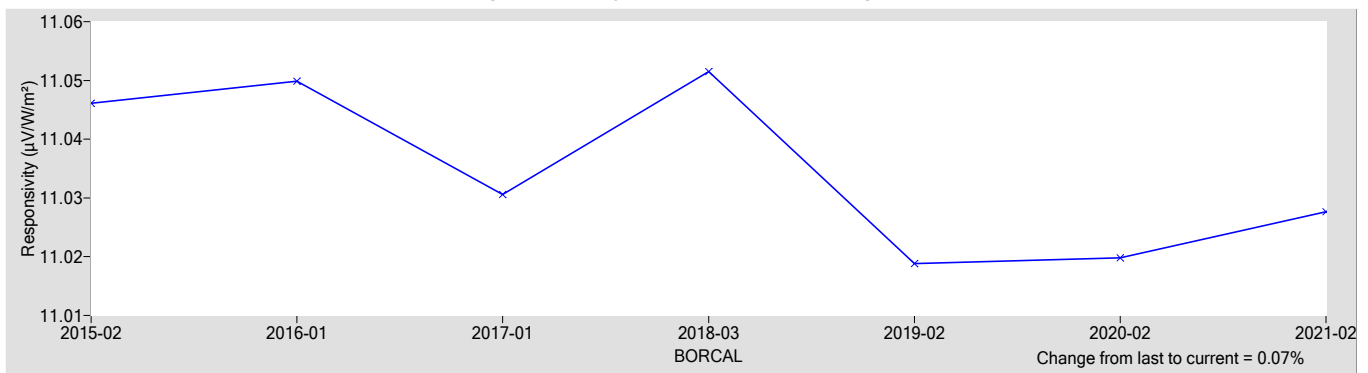
$R @ 45^\circ$ ($\mu V/W/m^2$)	R_{net} ($\mu V/W/m^2$) †
11.028	0

† R_{net} determination date: N/A

Table 5. Uncertainty using $R @ 45^\circ$

Type-B Expanded Uncertainty, $U(B)$ (%)	± 0.62
Offset Uncertainty, $U(off)$ (%)	+0.29 / -0.22
Expanded Uncertainty, U (%)	+0.91 / -0.84
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 Pyrheliometers. ARM 2008 Science Team Meeting (Poster).

National Renewable Energy Laboratory

Solar Radiation Research Laboratory

Metrology Laboratory

Calibration Certificate



Test Instrument: Sunshine Pyranometer - Global Output **Manufacturer:** Delta-T
Model: SPN1 **Serial Number:** A360
Calibration Date: 5/6/2021 **Due Date:** 5/6/2022
Customer: NREL-SRRL-BMS **Environmental Conditions:** see page 4
Test Dates: 5/6

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 than 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	09/27/2019	09/27/2021
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/30/2021	04/30/2022
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/30/2021	04/30/2022
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/08/2021	02/08/2023
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/08/2021	02/08/2023

† 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, Peter Gotseff, 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

A360 Delta-T SPN1

The responsivity (R , $\mu\text{V}/\text{W}/\text{m}^2$) of the test instrument during calibration is calculated using this Measurement Equation:

$$R = (V - R_{net} * W_{net}) / I \quad [1]$$

where,

- V = radiometer output voltage (microvolts),
 - R_{net} = radiometer net infrared responsivity ($\mu\text{V}/\text{W}/\text{m}^2$), see Table 4,
 - W_{net} = effective net infrared measured by pyrgeometer (W/m^2),
 - = $W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
 - where, W_{in} = incoming infrared (W/m^2), $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$,
 - T_c = case temperature of pyrgeometer (K).
- I = reference irradiance (W/m^2), beam (B) or global (G)
 where, $G = B * \text{COS}(Z) + D$,
 Z = zenith angle (degrees),
 D = reference diffuse irradiance (W/m^2).

Figure 1. Responsivity vs Zenith Angle

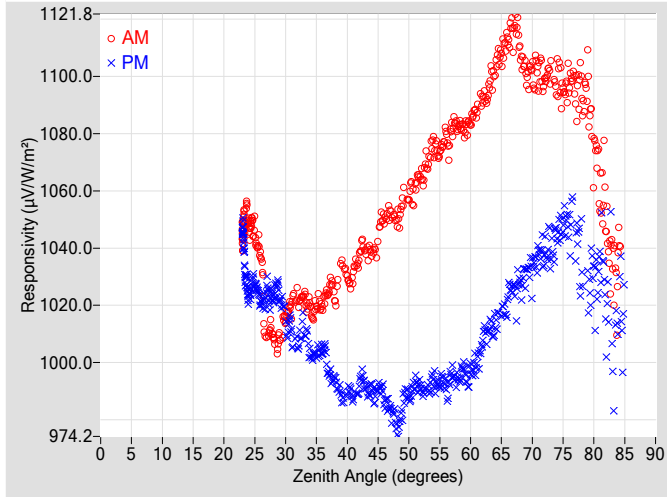


Figure 2. Responsivity vs Local Standard Time

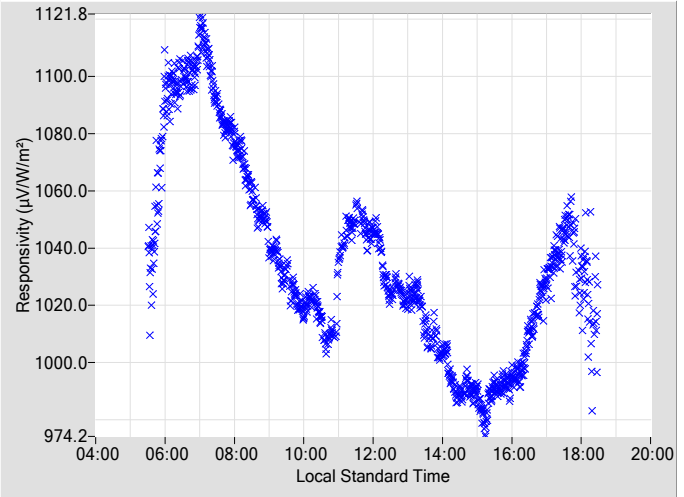


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)

Zenith Angle (deg.)	R ($\mu\text{V}/\text{W}/\text{m}^2$)	u(B) \pm (%)	Azimuth Angle	R ($\mu\text{V}/\text{W}/\text{m}^2$)	u(B) \pm (%)	Azimuth Angle	Zenith Angle (deg.)	R ($\mu\text{V}/\text{W}/\text{m}^2$)	u(B) \pm (%)	Azimuth Angle	R ($\mu\text{V}/\text{W}/\text{m}^2$)	u(B) \pm (%)	Azimuth Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	1050.2	0.37	106.46	987.11	0.33	253.76
2	N/A	N/A	N/A	N/A	N/A	N/A	48	1050.2	0.33	104.16	976.76	0.32	255.97
4	N/A	N/A	N/A	N/A	N/A	N/A	50	1058.4	0.33	102.07	987.96	0.32	258.08
6	N/A	N/A	N/A	N/A	N/A	N/A	52	1064.5	0.36	99.99	990.31	0.33	260.11
8	N/A	N/A	N/A	N/A	N/A	N/A	54	1075.4	0.36	98.16	993.56	0.35	262.03
10	N/A	N/A	N/A	N/A	N/A	N/A	56	1079.3	0.35	96.28	991.04	0.34	263.81
12	N/A	N/A	N/A	N/A	N/A	N/A	58	1082.5	0.34	94.46	994.61	0.37	265.65
14	N/A	N/A	N/A	N/A	N/A	N/A	60	1084.2	0.39	92.79	997.43	0.38	267.44
16	N/A	N/A	N/A	N/A	N/A	N/A	62	1092.3	0.35	91.06	1008.6	0.37	269.08
18	N/A	N/A	N/A	N/A	N/A	N/A	64	1102.3	0.40	89.34	1013.1	0.38	270.78
20	N/A	N/A	N/A	N/A	N/A	N/A	66	1112.3	0.41	87.78	1021.1	0.40	272.38
22	N/A	N/A	N/A	N/A	N/A	N/A	68	1109.6	0.43	86.12	1027.1	0.42	274.04
24	1048.4	0.35	160.85	1023.9	0.32	198.67	70	1100.5	0.42	84.48	1032.3	0.45	275.68
26	1036.6	0.32	148.28	1021.2	0.31	211.74	72	1097.6	0.46	82.95	1037.4	N/A	277.22
28	1008.6	0.33	139.82	1023.2	0.30	220.22	74	1098.3	0.50	81.29	1044.8	N/A	278.84
30	1015.8	0.32	133.59	1015.8	0.37	226.19	76	1097.5	N/A	79.73	1045.7	N/A	280.46
32	1020.8	0.32	128.49	1007.2	0.31	231.63	78	1095.6	N/A	78.12	1031.7	N/A	282.01
34	1019.1	0.33	124.20	1002.5	0.31	235.88	80	1072.7	N/A	76.41	1029.8	N/A	283.69
36	1020.0	0.30	120.58	1004.4	0.32	239.65	82	1049.8	N/A	74.84	1017.9	N/A	285.37
38	1021.9	0.32	117.15	994.51	0.30	243.01	84	1033.9	N/A	73.17	1017.9	N/A	286.98
40	1029.7	0.34	114.04	990.08	0.30	246.30	86	N/A	N/A	N/A	N/A	N/A	N/A
42	1037.0	0.35	111.32	992.25	0.32	248.77	88	N/A	N/A	N/A	N/A	N/A	N/A
44	1038.6	0.34	108.80	990.89	0.31	251.30	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

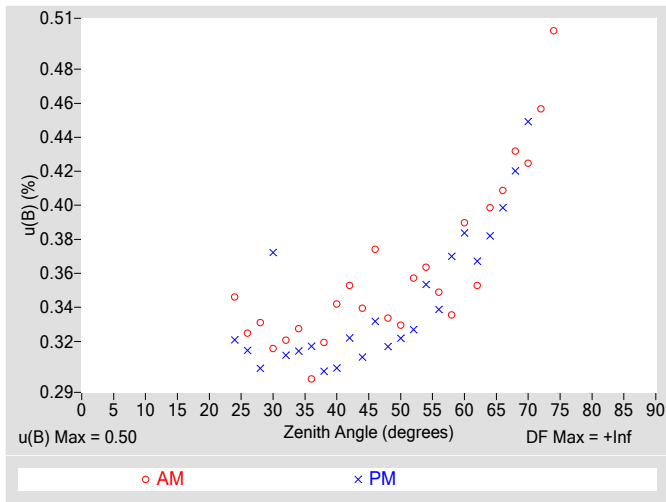


Figure 4. Residuals from Spline Interpolation

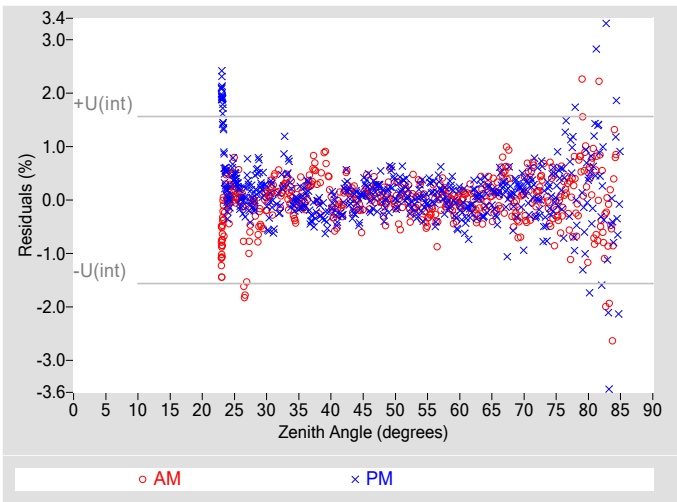


Table 3. Uncertainty using Spline Interpolation ‡

Type-B Standard Uncertainty, $u(B)$ (%)	± 0.50
Type-A Interpolating Function, $u(int)$ (%)	± 0.78
Combined Standard Uncertainty, $u(c)$ (%)	± 0.93
Effective degrees of freedom, $DF(c)$	1782
Coverage factor, k	1.96
Expanded Uncertainty, $U95$ (%)	± 1.8
AM Valid zenith angle range	24° to 74°
PM Valid zenith angle range	24° to 70°

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

Table 4. Calibration Label Values

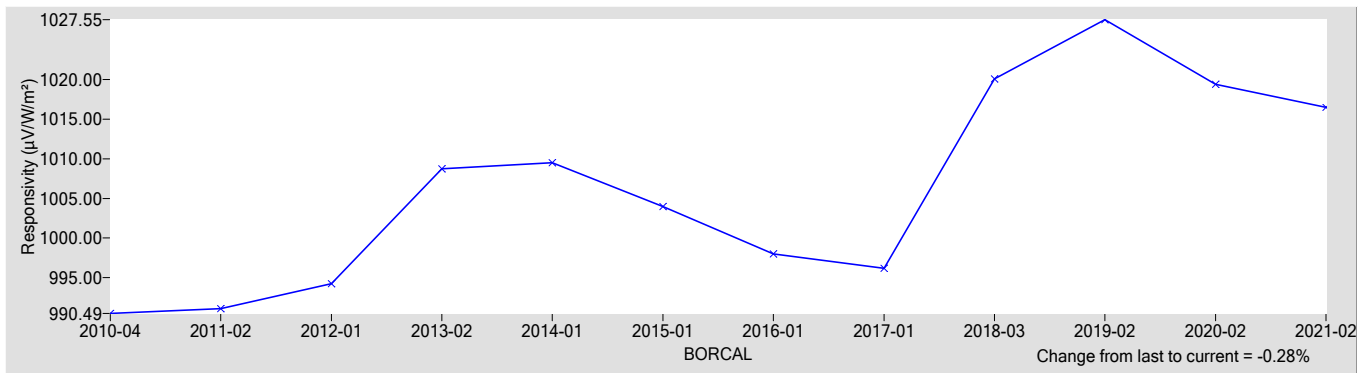
$R @ 45^\circ$ ($\mu V/W/m^2$)	R_{net} ($\mu V/W/m^2$) †
1016.5	0

† R_{net} determination date: N/A

Table 5. Uncertainty using $R @ 45^\circ$

Type-B Expanded Uncertainty, $U(B)$ (%)	± 0.76
Offset Uncertainty, $U(off)$ (%)	+6.7 / -3.9
Expanded Uncertainty, U (%)	+7.4 / -4.7
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 Pyrgometers. ARM 2008 Science Team Meeting (Poster).



National Renewable Energy Laboratory

Solar Radiation Research Laboratory

Metrology Laboratory

Calibration Certificate



Test Instrument:	Pyranometer	Manufacturer:	EKO
Model:	MS-802	Serial Number:	F14077R
Calibration Date:	5/6/2021	Due Date:	5/6/2022
Customer:	NREL-SRRL-BMS	Environmental Conditions:	see page 4
Test Dates:	5/6		

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 than 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	09/27/2019	09/27/2021
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/30/2021	04/30/2022
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/30/2021	04/30/2022
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/08/2021	02/08/2023
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/08/2021	02/08/2023
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, Peter Gotseff, 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

F14077R EKO MS-802

The responsivity (R , $\mu\text{V}/\text{W}/\text{m}^2$) of the test instrument during calibration is calculated using this Measurement Equation:

$$R = (V - R_{net} * W_{net}) / I \tag{1}$$

where,

- V = radiometer output voltage (microvolts),
 - R_{net} = radiometer net infrared responsivity ($\mu\text{V}/\text{W}/\text{m}^2$), see Table 4,
 - W_{net} = effective net infrared measured by pyrgeometer (W/m^2),
 - = $W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
 - where, W_{in} = incoming infrared (W/m^2), $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$,
 - T_c = case temperature of pyrgeometer (K).
- I = reference irradiance (W/m^2), beam (B) or global (G)
 - where, $G = B * \text{COS}(Z) + D$,
 - Z = zenith angle (degrees),
 - D = reference diffuse irradiance (W/m^2).

Figure 1. Responsivity vs Zenith Angle

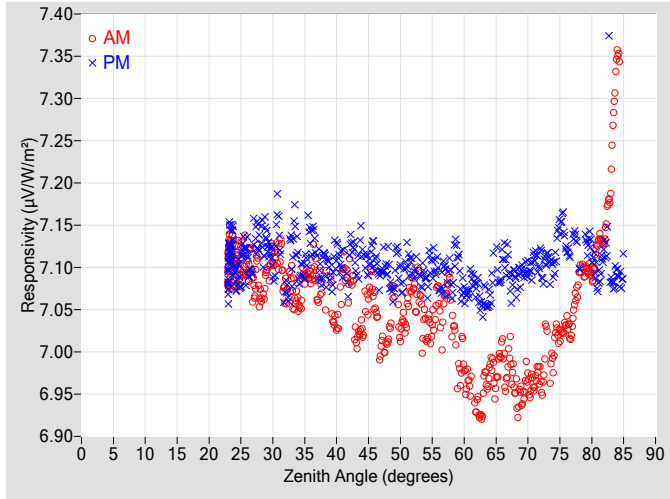


Figure 2. Responsivity vs Local Standard Time

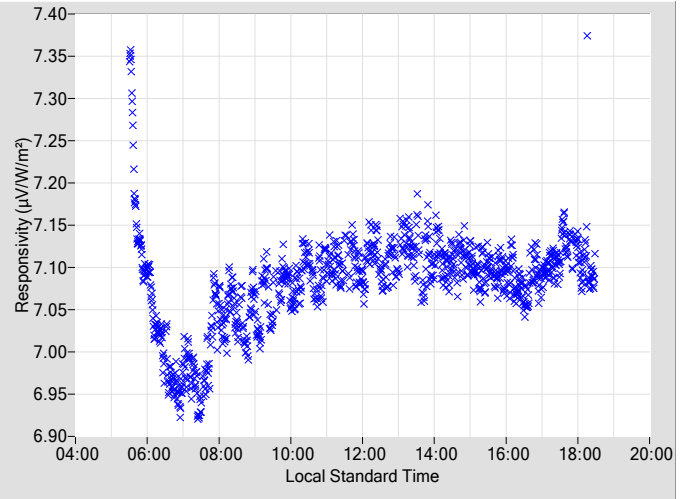


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)

Zenith Angle (deg.)	R ($\mu\text{V}/\text{W}/\text{m}^2$)	u(B) \pm (%)	Azimuth Angle	R ($\mu\text{V}/\text{W}/\text{m}^2$)	u(B) \pm (%)	Azimuth Angle	Zenith Angle (deg.)	R ($\mu\text{V}/\text{W}/\text{m}^2$)	u(B) \pm (%)	Azimuth Angle	R ($\mu\text{V}/\text{W}/\text{m}^2$)	u(B) \pm (%)	Azimuth Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	7.0543	0.35	106.40	7.1104	0.34	253.70
2	N/A	N/A	N/A	N/A	N/A	N/A	48	7.0164	0.36	104.07	7.1032	0.33	255.91
4	N/A	N/A	N/A	N/A	N/A	N/A	50	7.0241	0.34	102.07	7.0883	0.35	258.03
6	N/A	N/A	N/A	N/A	N/A	N/A	52	7.0780	0.35	100.06	7.0964	0.39	260.08
8	N/A	N/A	N/A	N/A	N/A	N/A	54	7.0267	0.35	98.11	7.0837	0.36	261.98
10	N/A	N/A	N/A	N/A	N/A	N/A	56	7.0582	0.36	96.23	7.0867	0.37	263.87
12	N/A	N/A	N/A	N/A	N/A	N/A	58	7.0526	0.35	94.52	7.0843	0.38	265.60
14	N/A	N/A	N/A	N/A	N/A	N/A	60	6.9814	0.38	92.74	7.0731	0.40	267.39
16	N/A	N/A	N/A	N/A	N/A	N/A	62	6.9346	0.37	91.01	7.0735	0.41	269.13
18	N/A	N/A	N/A	N/A	N/A	N/A	64	6.9777	0.38	89.42	7.0612	0.43	270.73
20	N/A	N/A	N/A	N/A	N/A	N/A	66	7.0022	0.43	87.74	7.1111	0.45	272.43
22	N/A	N/A	N/A	N/A	N/A	N/A	68	6.9525	0.45	86.08	7.0870	0.44	273.99
24	7.0981	0.35	160.90	7.0999	0.31	199.05	70	6.9691	0.45	84.54	7.0960	0.48	275.64
26	7.1023	0.32	148.20	7.1044	0.33	211.93	72	6.9620	0.49	82.90	7.1034	N/A	277.27
28	7.0654	0.32	139.92	7.1317	0.32	220.01	74	6.9958	0.53	81.35	7.1024	N/A	278.85
30	7.1145	0.31	133.92	7.1021	0.32	226.26	76	7.0335	N/A	79.73	7.1240	N/A	280.42
32	7.0714	0.31	128.64	7.0727	0.33	231.58	78	7.0871	N/A	78.12	7.0984	N/A	282.11
34	7.0625	0.32	124.29	7.1040	0.34	235.81	80	7.0889	N/A	76.51	7.1161	N/A	283.69
36	7.0914	0.33	120.44	7.1328	0.33	239.66	82	7.1364	N/A	74.84	7.1202	N/A	285.33
38	7.0498	0.38	116.65	7.1062	0.32	243.02	84	7.3478	N/A	73.17	7.0944	N/A	287.01
40	7.0338	0.36	114.04	7.1177	0.35	245.99	86	N/A	N/A	N/A	N/A	N/A	N/A
42	7.0839	0.34	111.40	7.1116	0.32	248.81	88	N/A	N/A	N/A	N/A	N/A	N/A
44	7.0258	0.33	108.80	7.1247	0.39	251.34	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

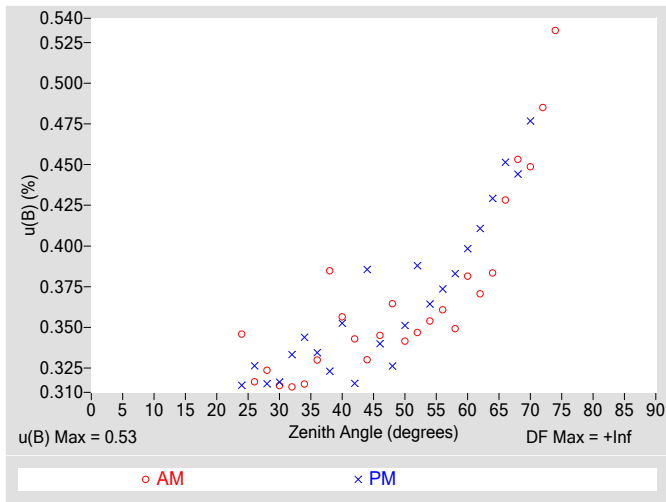


Figure 4. Residuals from Spline Interpolation

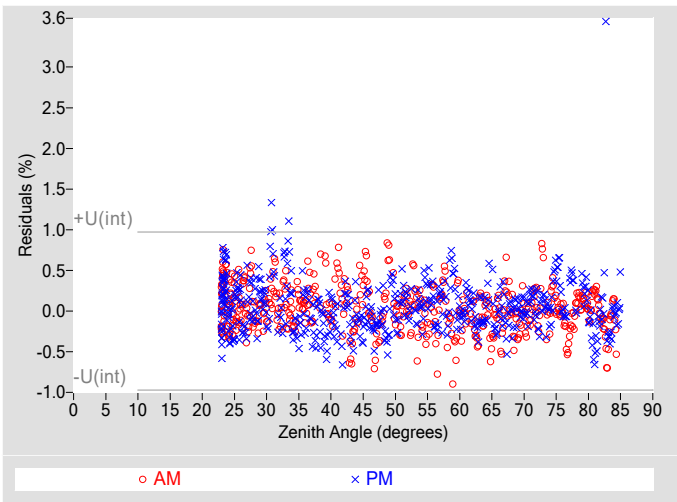


Table 3. Uncertainty using Spline Interpolation ‡

Type-B Standard Uncertainty, $u(B)$ (%)	± 0.53
Type-A Interpolating Function, $u(int)$ (%)	± 0.49
Combined Standard Uncertainty, $u(c)$ (%)	± 0.72
Effective degrees of freedom, $DF(c)$	4325
Coverage factor, k	1.96
Expanded Uncertainty, $U95$ (%)	± 1.4
AM Valid zenith angle range	24° to 74°
PM Valid zenith angle range	24° to 70°

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

Table 4. Calibration Label Values

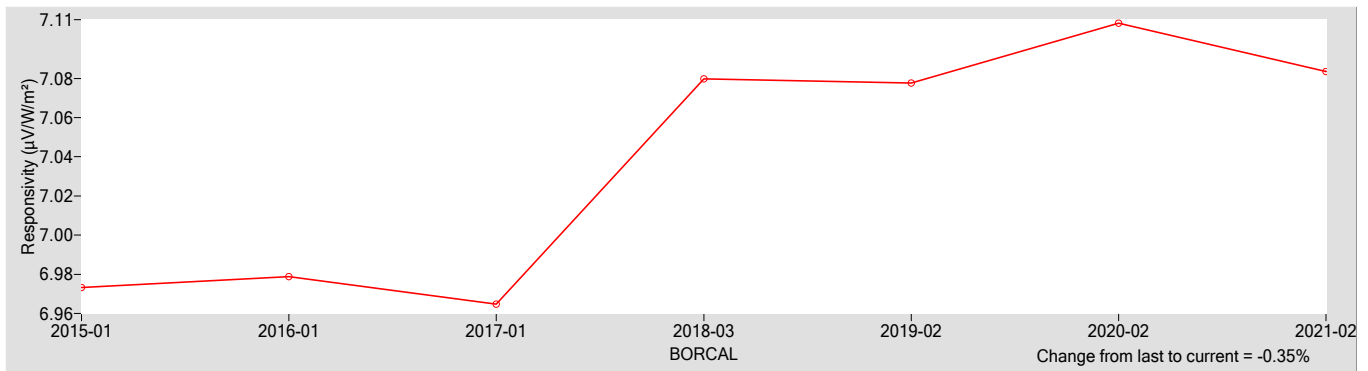
$R @ 45^\circ$ ($\mu V/W/m^2$)	R_{net} ($\mu V/W/m^2$) †
7.0835	0.18000

† R_{net} determination date: Estimated

Table 5. Uncertainty using $R @ 45^\circ$

Type-B Expanded Uncertainty, $U(B)$ (%)	± 0.78
Offset Uncertainty, $U(off)$ (%)	+0.70 / -1.4
Expanded Uncertainty, U (%)	+1.5 / -2.2
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



Test Instrument: Revised Silicon Pyranometer **Manufacturer:** Licor
Model: LI200R **Serial Number:** PY100360
Calibration Date: 5/6/2021 **Due Date:** 5/6/2022
Customer: NREL-SRRL-BMS **Environmental Conditions:** see page 4
Test Dates: 5/6

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 than 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	09/27/2019	09/27/2021
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/30/2021	04/30/2022
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/30/2021	04/30/2022
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/08/2021	02/08/2023
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/08/2021	02/08/2023

† 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, Peter Gotseff, 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

PY100360 Licor LI200R

The responsivity (R , $\mu\text{V}/\text{W}/\text{m}^2$) of the test instrument during calibration is calculated using this Measurement Equation:

$$R = (V - R_{net} * W_{net}) / I \quad [1]$$

where,

- V = radiometer output voltage (microvolts),
 - R_{net} = radiometer net infrared responsivity ($\mu\text{V}/\text{W}/\text{m}^2$), see Table 4,
 - W_{net} = effective net infrared measured by pyrgeometer (W/m^2),
 - = $W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
 - where, W_{in} = incoming infrared (W/m^2), $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$,
 - T_c = case temperature of pyrgeometer (K).
- I = reference irradiance (W/m^2), beam (B) or global (G)
 where, $G = B * \text{COS}(Z) + D$,
 Z = zenith angle (degrees),
 D = reference diffuse irradiance (W/m^2).

Figure 1. Responsivity vs Zenith Angle

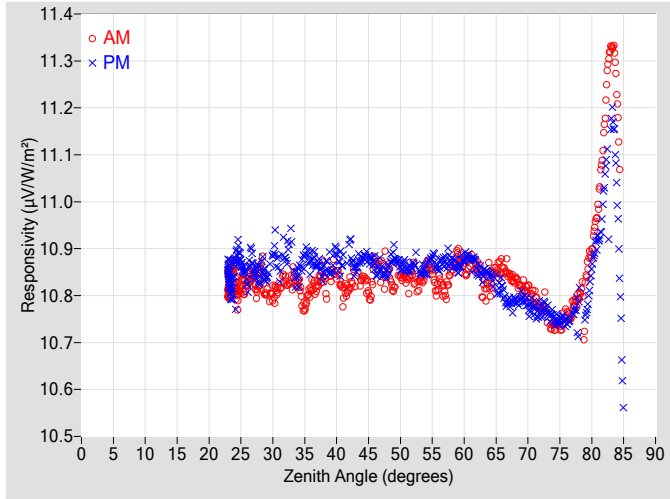


Figure 2. Responsivity vs Local Standard Time

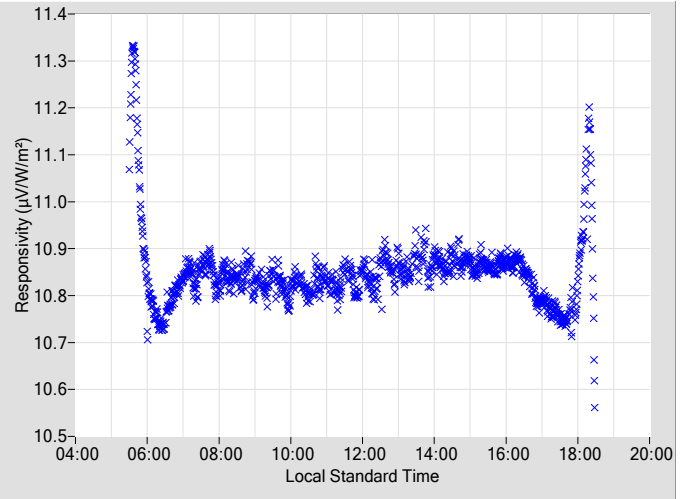


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)

Zenith Angle (deg.)	R ($\mu\text{V}/\text{W}/\text{m}^2$)	u(B) \pm (%)	Azimuth Angle	R ($\mu\text{V}/\text{W}/\text{m}^2$)	u(B) \pm (%)	Azimuth Angle	Zenith Angle (deg.)	R ($\mu\text{V}/\text{W}/\text{m}^2$)	u(B) \pm (%)	Azimuth Angle	R ($\mu\text{V}/\text{W}/\text{m}^2$)	u(B) \pm (%)	Azimuth Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	10.869	0.34	106.43	10.860	0.32	253.72
2	N/A	N/A	N/A	N/A	N/A	N/A	48	10.852	0.31	104.17	10.851	0.32	255.94
4	N/A	N/A	N/A	N/A	N/A	N/A	50	10.845	0.35	102.03	10.860	0.32	258.11
6	N/A	N/A	N/A	N/A	N/A	N/A	52	10.842	0.34	100.02	10.864	0.35	260.08
8	N/A	N/A	N/A	N/A	N/A	N/A	54	10.854	0.33	98.19	10.855	0.37	262.00
10	N/A	N/A	N/A	N/A	N/A	N/A	56	10.826	0.33	96.31	10.863	0.34	263.84
12	N/A	N/A	N/A	N/A	N/A	N/A	58	10.853	0.39	94.51	10.873	0.37	265.67
14	N/A	N/A	N/A	N/A	N/A	N/A	60	10.859	0.35	92.71	10.878	0.36	267.35
16	N/A	N/A	N/A	N/A	N/A	N/A	62	10.861	0.36	91.08	10.857	0.40	269.10
18	N/A	N/A	N/A	N/A	N/A	N/A	64	10.828	0.40	89.39	10.844	0.41	270.80
20	N/A	N/A	N/A	N/A	N/A	N/A	66	10.861	0.44	87.70	10.817	0.40	272.40
22	N/A	N/A	N/A	N/A	N/A	N/A	68	10.834	0.44	86.15	10.790	0.43	274.06
24	10.836	0.34	160.97	10.848	0.32	198.99	70	10.813	0.43	84.51	10.776	0.45	275.61
26	10.827	0.32	148.53	10.835	0.31	211.88	72	10.774	0.46	82.92	10.771	N/A	277.24
28	10.842	0.35	140.02	10.839	0.31	219.98	74	10.733	0.51	81.32	10.752	N/A	278.86
30	10.799	0.31	133.68	10.892	0.33	226.56	76	10.761	N/A	79.70	10.744	N/A	280.49
32	10.830	0.35	128.53	10.876	0.34	231.58	78	10.800	N/A	78.09	10.759	N/A	281.99
34	10.825	0.32	124.22	10.846	0.32	235.94	80	10.899	N/A	76.48	10.855	N/A	283.66
36	10.814	0.32	120.56	10.871	0.33	239.60	82	11.163	N/A	74.86	11.045	N/A	285.34
38	10.845	0.32	117.15	10.847	0.33	242.97	84	11.203	N/A	73.14	10.996	N/A	287.03
40	10.847	0.30	113.95	10.887	0.32	246.02	86	N/A	N/A	N/A	N/A	N/A	N/A
42	10.818	0.32	111.35	10.907	0.37	248.95	88	N/A	N/A	N/A	N/A	N/A	N/A
44	10.836	0.33	108.82	10.879	0.31	251.29	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

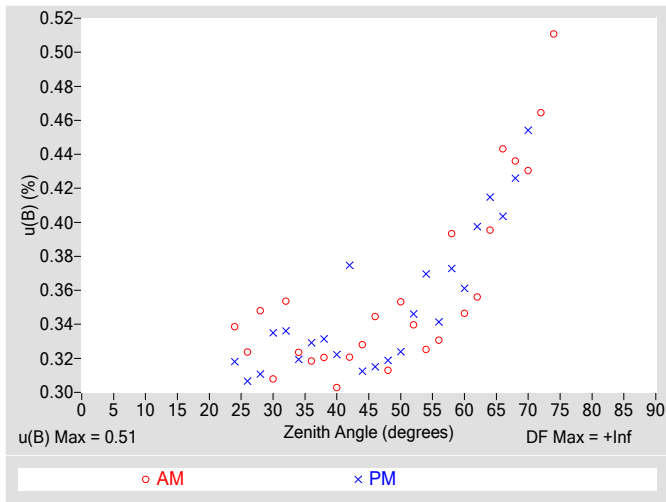


Figure 4. Residuals from Spline Interpolation

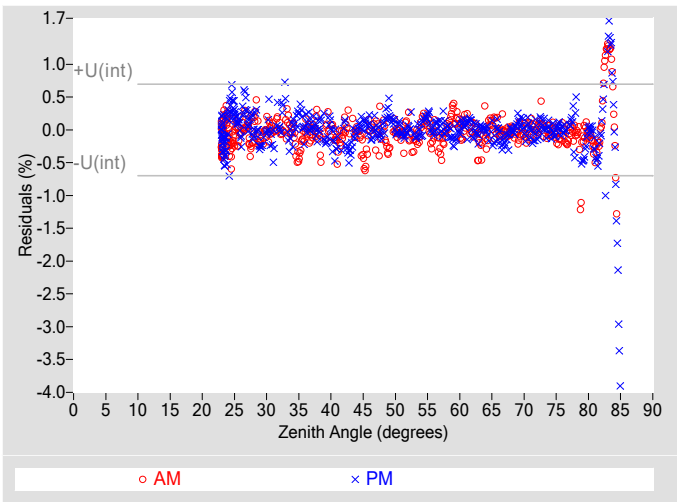


Table 3. Uncertainty using Spline Interpolation ‡

Type-B Standard Uncertainty, $u(B)$ (%)	± 0.51
Type-A Interpolating Function, $u(int)$ (%)	± 0.35
Combined Standard Uncertainty, $u(c)$ (%)	± 0.62
Effective degrees of freedom, $DF(c)$	8808
Coverage factor, k	1.96
Expanded Uncertainty, U_{95} (%)	± 1.2
AM Valid zenith angle range	24° to 74°
PM Valid zenith angle range	24° to 70°

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

Table 4. Calibration Label Values

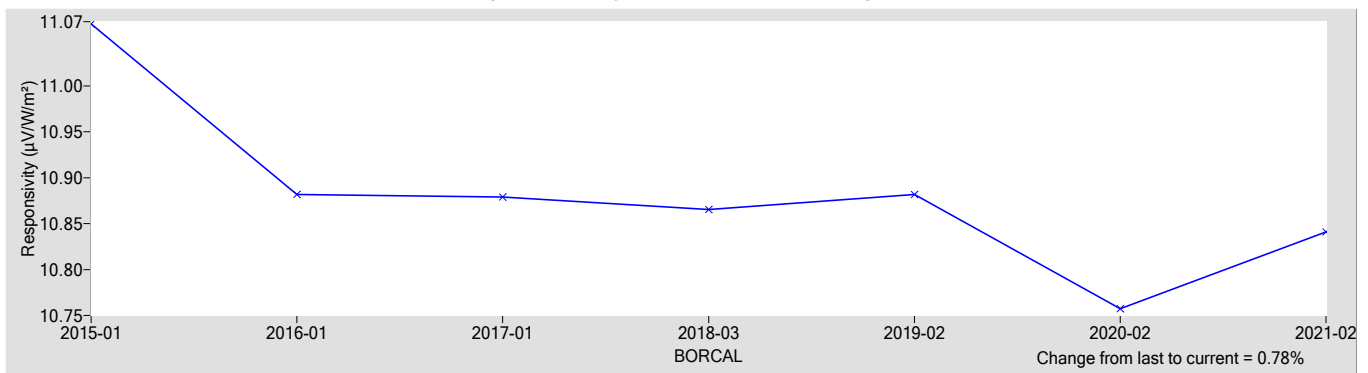
$R @ 45^\circ$ ($\mu V/W/m^2$)	R_{net} ($\mu V/W/m^2$) †
10.841	0

† R_{net} determination date: N/A

Table 5. Uncertainty using $R @ 45^\circ$

Type-B Expanded Uncertainty, $U(B)$ (%)	± 0.77
Offset Uncertainty, $U(off)$ (%)	+0.61 / -0.38
Expanded Uncertainty, U (%)	+1.4 / -1.2
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



Test Instrument:	Revised Silicon Pyranometer	Manufacturer:	Licor
Model:	LI200R	Serial Number:	PY108624
Calibration Date:	5/6/2021	Due Date:	5/6/2022
Customer:	NREL-SRRL-BMS	Environmental Conditions:	see page 4
Test Dates:	5/6		

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 than 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	09/27/2019	09/27/2021
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/30/2021	04/30/2022
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/30/2021	04/30/2022
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/08/2021	02/08/2023
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/08/2021	02/08/2023

† 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, Peter Gotseff, 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

PY108624 Licor LI200R

The responsivity (R , $\mu\text{V}/\text{W}/\text{m}^2$) of the test instrument during calibration is calculated using this Measurement Equation:

$$R = (V - R_{net} * W_{net}) / I \quad [1]$$

where,

- V = radiometer output voltage (microvolts),
 - R_{net} = radiometer net infrared responsivity ($\mu\text{V}/\text{W}/\text{m}^2$), see Table 4,
 - W_{net} = effective net infrared measured by pyrgeometer (W/m^2),
 - = $W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
 - where, W_{in} = incoming infrared (W/m^2), $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$,
 - T_c = case temperature of pyrgeometer (K).
- I = reference irradiance (W/m^2), beam (B) or global (G)
 where, $G = B * \text{COS}(Z) + D$,
 Z = zenith angle (degrees),
 D = reference diffuse irradiance (W/m^2).

Figure 1. Responsivity vs Zenith Angle

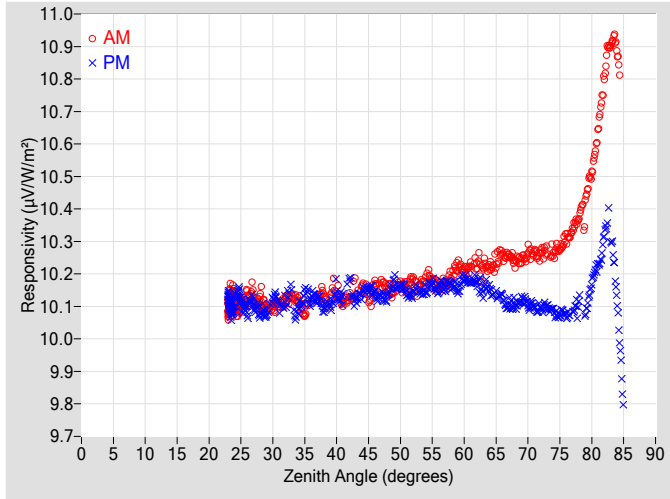


Figure 2. Responsivity vs Local Standard Time

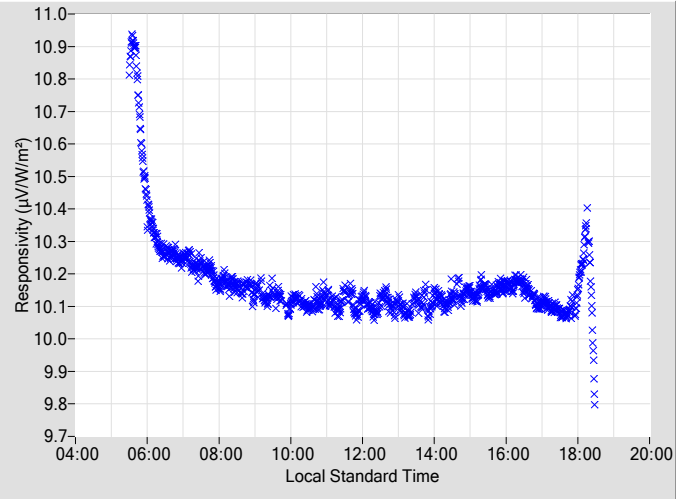


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)

Zenith Angle (deg.)	R ($\mu\text{V}/\text{W}/\text{m}^2$)	u(B) \pm (%)	Azimuth Angle	R ($\mu\text{V}/\text{W}/\text{m}^2$)	u(B) \pm (%)	Azimuth Angle	Zenith Angle (deg.)	R ($\mu\text{V}/\text{W}/\text{m}^2$)	u(B) \pm (%)	Azimuth Angle	R ($\mu\text{V}/\text{W}/\text{m}^2$)	u(B) \pm (%)	Azimuth Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	10.169	0.34	106.43	10.136	0.32	253.72
2	N/A	N/A	N/A	N/A	N/A	N/A	48	10.163	0.31	104.17	10.131	0.32	255.94
4	N/A	N/A	N/A	N/A	N/A	N/A	50	10.161	0.35	102.03	10.162	0.32	258.11
6	N/A	N/A	N/A	N/A	N/A	N/A	52	10.176	0.34	100.02	10.142	0.35	260.08
8	N/A	N/A	N/A	N/A	N/A	N/A	54	10.181	0.33	98.19	10.148	0.37	262.00
10	N/A	N/A	N/A	N/A	N/A	N/A	56	10.163	0.33	96.31	10.153	0.34	263.84
12	N/A	N/A	N/A	N/A	N/A	N/A	58	10.198	0.39	94.51	10.160	0.37	265.67
14	N/A	N/A	N/A	N/A	N/A	N/A	60	10.208	0.35	92.71	10.186	0.36	267.35
16	N/A	N/A	N/A	N/A	N/A	N/A	62	10.231	0.36	91.08	10.174	0.40	269.10
18	N/A	N/A	N/A	N/A	N/A	N/A	64	10.223	0.40	89.39	10.150	0.42	270.80
20	N/A	N/A	N/A	N/A	N/A	N/A	66	10.258	0.44	87.70	10.130	0.40	272.40
22	N/A	N/A	N/A	N/A	N/A	N/A	68	10.234	0.44	86.15	10.107	0.43	274.06
24	10.121	0.34	160.97	10.112	0.32	198.99	70	10.269	0.43	84.51	10.103	0.45	275.61
26	10.134	0.32	148.53	10.092	0.31	211.88	72	10.265	0.47	82.92	10.098	N/A	277.24
28	10.122	0.35	140.02	10.074	0.31	219.98	74	10.266	0.51	81.32	10.085	N/A	278.86
30	10.093	0.31	133.68	10.125	0.34	226.56	76	10.310	N/A	79.70	10.073	N/A	280.49
32	10.120	0.35	128.53	10.113	0.34	231.58	78	10.377	N/A	78.09	10.103	N/A	281.99
34	10.119	0.32	124.22	10.096	0.32	235.94	80	10.513	N/A	76.48	10.171	N/A	283.66
36	N/A	N/A	N/A	10.122	0.33	239.60	82	10.803	N/A	74.86	10.324	N/A	285.34
38	10.136	0.32	117.15	10.094	0.33	242.97	84	10.876	N/A	73.14	10.101	N/A	287.03
40	10.142	0.30	113.95	10.143	0.32	246.02	86	N/A	N/A	N/A	N/A	N/A	N/A
42	10.126	0.32	111.35	10.171	0.37	248.95	88	N/A	N/A	N/A	N/A	N/A	N/A
44	10.161	0.33	108.82	10.140	0.31	251.29	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

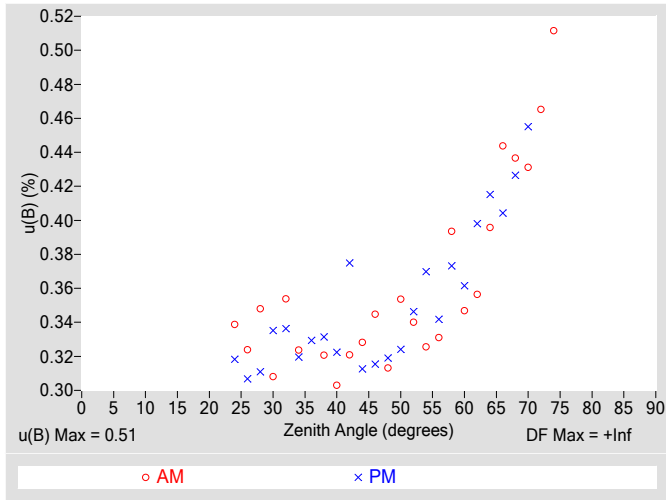


Figure 4. Residuals from Spline Interpolation

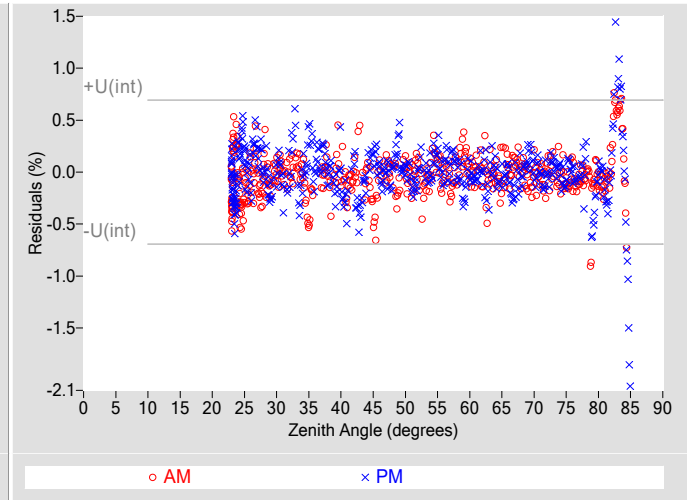


Table 3. Uncertainty using Spline Interpolation ‡

Type-B Standard Uncertainty, $u(B)$ (%)	± 0.51
Type-A Interpolating Function, $u(int)$ (%)	± 0.35
Combined Standard Uncertainty, $u(c)$ (%)	± 0.62
Effective degrees of freedom, $DF(c)$	8847
Coverage factor, k	1.96
Expanded Uncertainty, U_{95} (%)	± 1.2
AM Valid zenith angle range	24° to 74°
PM Valid zenith angle range	24° to 70°

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

Table 4. Calibration Label Values

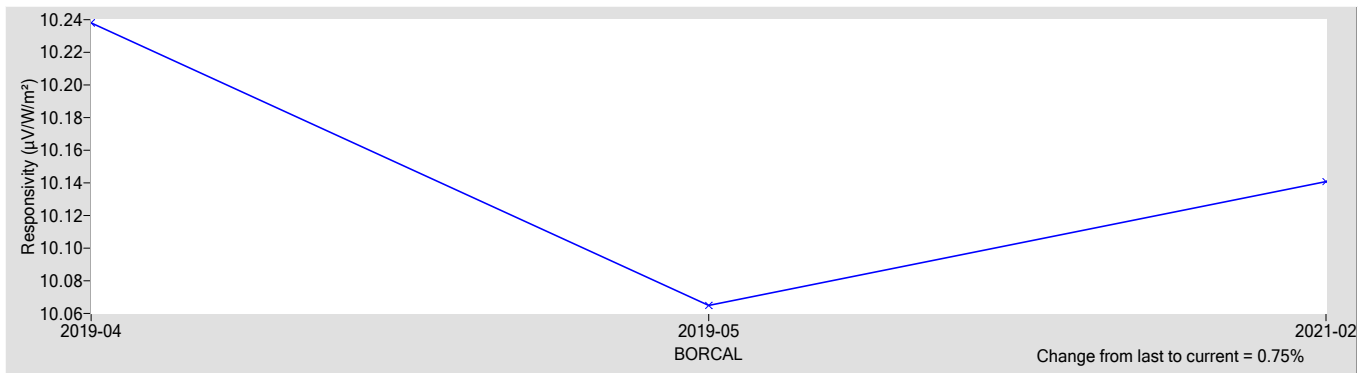
$R @ 45^\circ$ ($\mu V/W/m^2$)	R_{net} ($\mu V/W/m^2$) †
10.141	0

† R_{net} determination date: N/A

Table 5. Uncertainty using $R @ 45^\circ$

Type-B Expanded Uncertainty, $U(B)$ (%)	± 0.77
Offset Uncertainty, $U(off)$ (%)	+0.67 / -0.47
Expanded Uncertainty, U (%)	+1.4 / -1.2
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 Pyrgometers. ARM 2008 Science Team Meeting (Poster).



National Renewable Energy Laboratory

Solar Radiation Research Laboratory

Metrology Laboratory

Calibration Certificate



Test Instrument:	Silicon Pyranometer	Manufacturer:	Licor
Model:	LI200	Serial Number:	PY28257
Calibration Date:	5/6/2021	Due Date:	5/6/2022
Customer:	NREL-SRRL-BMS	Environmental Conditions:	see page 4
Test Dates:	5/6		

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 than 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	09/27/2019	09/27/2021
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/30/2021	04/30/2022
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/30/2021	04/30/2022
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/08/2021	02/08/2023
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/08/2021	02/08/2023

† 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, Peter Gotseff, 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

PY28257 Licor LI200

The responsivity (R , $\mu\text{V}/\text{W}/\text{m}^2$) of the test instrument during calibration is calculated using this Measurement Equation:

$$R = (V - R_{net} * W_{net}) / I \quad [1]$$

where,

- V = radiometer output voltage (microvolts),
 - R_{net} = radiometer net infrared responsivity ($\mu\text{V}/\text{W}/\text{m}^2$), see Table 4,
 - W_{net} = effective net infrared measured by pyrgeometer (W/m^2),
 - = $W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
 - where, W_{in} = incoming infrared (W/m^2), $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$,
 - T_c = case temperature of pyrgeometer (K).
- I = reference irradiance (W/m^2), beam (B) or global (G)
 where, $G = B * \text{COS}(Z) + D$,
 Z = zenith angle (degrees),
 D = reference diffuse irradiance (W/m^2).

Figure 1. Responsivity vs Zenith Angle

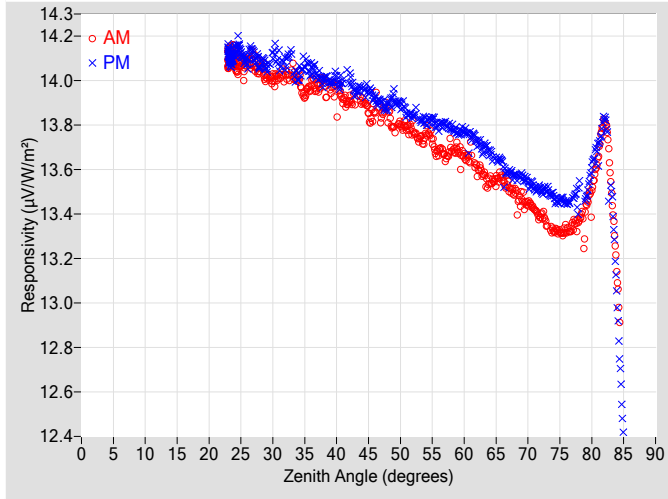


Figure 2. Responsivity vs Local Standard Time

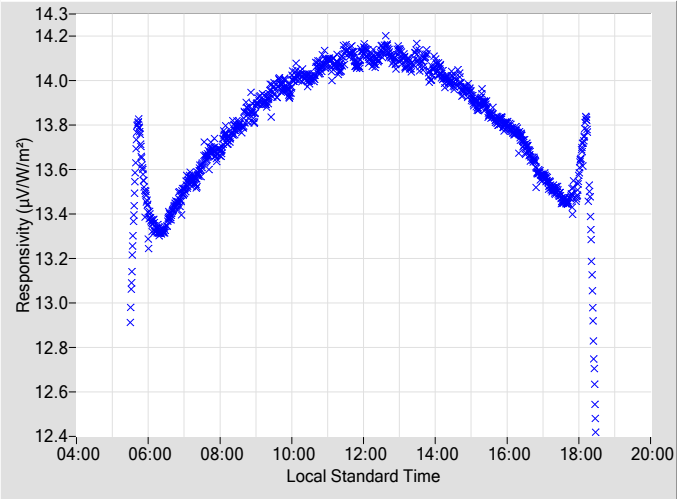


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, $u(B)$

Zenith			AM			PM			Zenith			AM			PM		
Angle	R	u(B)	Azimuth	R	u(B)	Azimuth	Angle	R	u(B)	Azimuth	R	u(B)	Azimuth	R	u(B)	Azimuth	
(deg.)	($\mu\text{V}/\text{W}/\text{m}^2$)	\pm (%)	Angle	($\mu\text{V}/\text{W}/\text{m}^2$)	\pm (%)	Angle	(deg.)	($\mu\text{V}/\text{W}/\text{m}^2$)	\pm (%)	Angle	($\mu\text{V}/\text{W}/\text{m}^2$)	\pm (%)	Angle	($\mu\text{V}/\text{W}/\text{m}^2$)	\pm (%)	Angle	
0	N/A	N/A	N/A	N/A	N/A	N/A	46	13.883	0.34	106.43	13.915	0.31	253.72				
2	N/A	N/A	N/A	N/A	N/A	N/A	48	13.857	0.31	104.17	13.884	0.32	255.94				
4	N/A	N/A	N/A	N/A	N/A	N/A	50	13.802	0.35	102.03	13.890	0.32	258.11				
6	N/A	N/A	N/A	N/A	N/A	N/A	52	13.774	0.34	100.02	13.843	0.35	260.08				
8	N/A	N/A	N/A	N/A	N/A	N/A	54	13.754	0.32	98.19	13.813	0.37	262.00				
10	N/A	N/A	N/A	N/A	N/A	N/A	56	13.684	0.33	96.31	13.794	0.34	263.84				
12	N/A	N/A	N/A	N/A	N/A	N/A	58	13.703	0.39	94.51	13.784	0.37	265.67				
14	N/A	N/A	N/A	N/A	N/A	N/A	60	13.656	0.35	92.71	13.777	0.36	267.35				
16	N/A	N/A	N/A	N/A	N/A	N/A	62	13.605	0.35	91.08	13.723	0.40	269.10				
18	N/A	N/A	N/A	N/A	N/A	N/A	64	13.548	0.39	89.39	13.677	0.41	270.80				
20	N/A	N/A	N/A	N/A	N/A	N/A	66	13.558	0.44	87.70	13.610	0.40	272.40				
22	N/A	N/A	N/A	N/A	N/A	N/A	68	13.498	0.43	86.15	13.572	0.42	274.06				
24	14.103	0.34	160.97	14.122	0.32	198.99	70	13.448	0.43	84.51	13.542	0.45	275.61				
26	14.096	0.32	148.53	14.091	0.31	211.88	72	13.388	0.46	82.92	13.510	N/A	277.24				
28	14.059	0.35	140.02	14.066	0.31	219.98	74	13.323	0.51	81.32	13.478	N/A	278.86				
30	14.000	0.31	133.68	14.123	0.33	226.56	76	13.332	N/A	79.70	13.452	N/A	280.49				
32	14.017	0.35	128.53	14.079	0.34	231.58	78	13.373	N/A	78.09	13.475	N/A	281.99				
34	14.012	0.32	124.22	14.019	0.32	235.94	80	13.491	N/A	76.48	13.610	N/A	283.66				
36	13.972	0.32	120.56	14.044	0.33	239.60	82	13.808	N/A	74.86	13.819	N/A	285.34				
38	13.991	0.32	117.15	13.998	0.33	242.97	84	13.098	N/A	73.14	12.982	N/A	287.03				
40	13.926	0.30	113.95	14.006	0.32	246.02	86	N/A	N/A	N/A	N/A	N/A	N/A				
42	13.910	0.32	111.35	14.006	0.37	248.95	88	N/A	N/A	N/A	N/A	N/A	N/A				
44	13.906	0.33	108.82	13.972	0.31	251.33	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

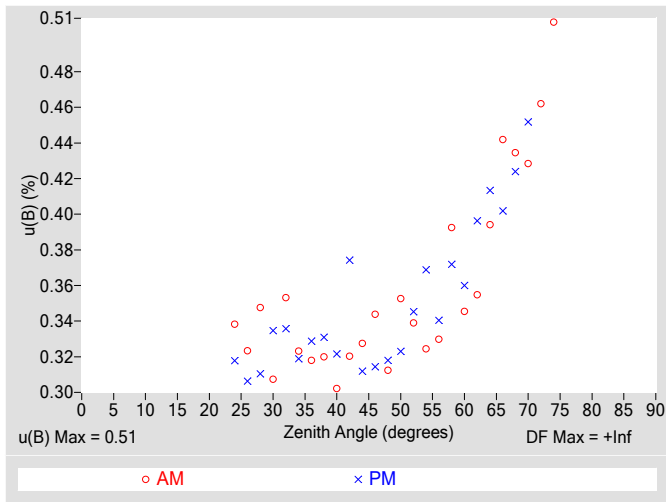


Figure 4. Residuals from Spline Interpolation

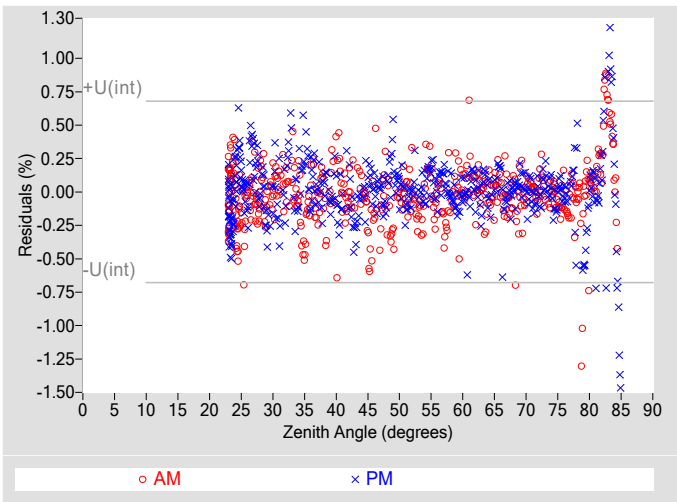


Table 3. Uncertainty using Spline Interpolation ‡

Type-B Standard Uncertainty, $u(B)$ (%)	± 0.51
Type-A Interpolating Function, $u(int)$ (%)	± 0.34
Combined Standard Uncertainty, $u(c)$ (%)	± 0.61
Effective degrees of freedom, $DF(c)$	9299
Coverage factor, k	1.96
Expanded Uncertainty, U_{95} (%)	± 1.2
AM Valid zenith angle range	24° to 74°
PM Valid zenith angle range	24° to 70°

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

Table 4. Calibration Label Values

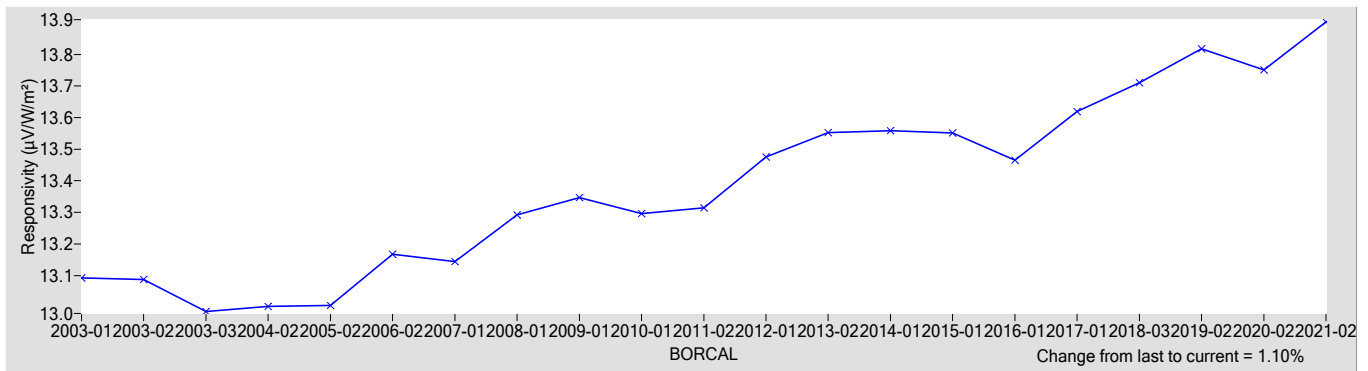
$R @ 45^\circ$ ($\mu V/W/m^2$)	R_{net} ($\mu V/W/m^2$) †
13.902	0

† R_{net} determination date: N/A

Table 5. Uncertainty using $R @ 45^\circ$

Type-B Expanded Uncertainty, $U(B)$ (%)	± 0.77
Offset Uncertainty, $U(off)$ (%)	+1.6 / -1.8
Expanded Uncertainty, U (%)	+2.4 / -2.5
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 Pyrgometers. ARM 2008 Science Team Meeting (Poster).



National Renewable Energy Laboratory

Solar Radiation Research Laboratory

Metrology Laboratory

Calibration Certificate



Test Instrument:	Semiconductor Pyrheliometer	Manufacturer:	Licor
Model:	LI201SB	Serial Number:	PYHR101
Calibration Date:	5/6/2021	Due Date:	5/6/2022
Customer:	NREL-SRRL-BMS	Environmental Conditions:	see page 4
Test Dates:	5/6		

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 than 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	09/27/2019	09/27/2021
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/30/2021	04/30/2022
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/30/2021	04/30/2022
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/08/2021	02/08/2023
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/08/2021	02/08/2023

† 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, Peter Gotseff, 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

PYHR101 Licor LI201SB

The responsivity (R , $\mu\text{V}/\text{W}/\text{m}^2$) of the test instrument during calibration is calculated using this Measurement Equation:

$$R = (V - R_{net} * W_{net}) / I \tag{1}$$

where,

- V = radiometer output voltage (microvolts),
 - R_{net} = radiometer net infrared responsivity ($\mu\text{V}/\text{W}/\text{m}^2$), see Table 4,
 - W_{net} = effective net infrared measured by pyrgeometer (W/m^2),
 - = $W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
 - where, W_{in} = incoming infrared (W/m^2), $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$,
 - T_c = case temperature of pyrgeometer (K).
- I = reference irradiance (W/m^2), beam (B) or global (G)
 - where, $G = B * \text{COS}(Z) + D$,
 - Z = zenith angle (degrees),
 - D = reference diffuse irradiance (W/m^2).

Figure 1. Responsivity vs Zenith Angle

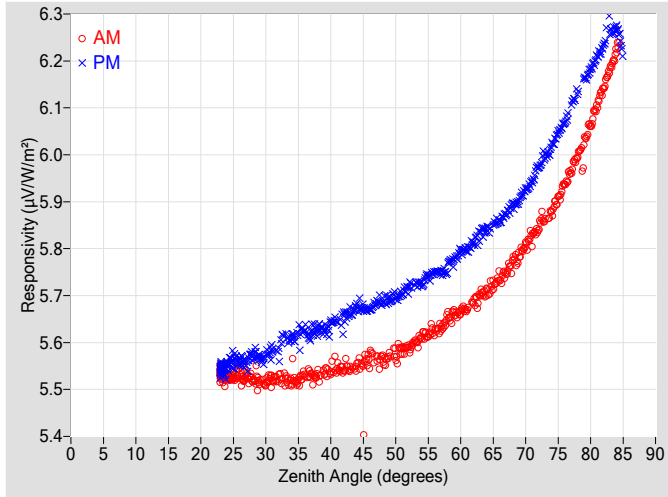


Figure 2. Responsivity vs Local Standard Time

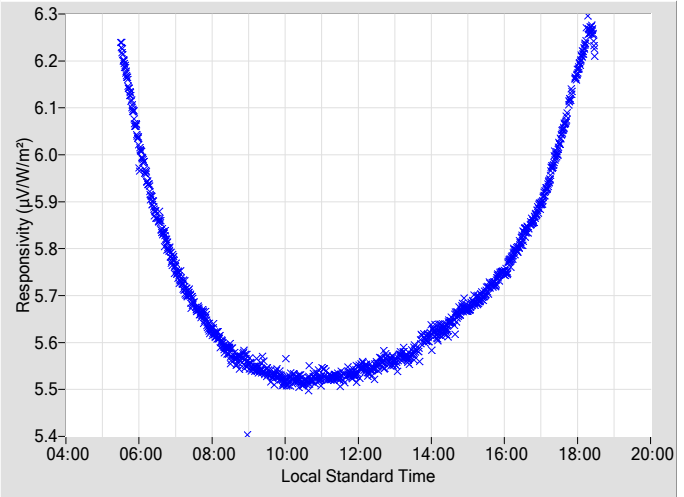


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)

Zenith Angle (deg.)	R ($\mu\text{V}/\text{W}/\text{m}^2$)	u(B) \pm (%)	Azimuth Angle	R ($\mu\text{V}/\text{W}/\text{m}^2$)	u(B) \pm (%)	Azimuth Angle	Zenith Angle (deg.)	R ($\mu\text{V}/\text{W}/\text{m}^2$)	u(B) \pm (%)	Azimuth Angle	R ($\mu\text{V}/\text{W}/\text{m}^2$)	u(B) \pm (%)	Azimuth Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	5.5690	0.33	106.43	5.6713	0.32	253.72
2	N/A	N/A	N/A	N/A	N/A	N/A	48	5.5650	0.30	104.22	5.6872	0.30	255.95
4	N/A	N/A	N/A	N/A	N/A	N/A	50	5.5688	0.32	102.03	5.6974	0.30	258.05
6	N/A	N/A	N/A	N/A	N/A	N/A	52	5.5873	0.31	100.02	5.7191	0.30	260.08
8	N/A	N/A	N/A	N/A	N/A	N/A	54	5.6137	0.31	98.14	5.7247	0.32	261.97
10	N/A	N/A	N/A	N/A	N/A	N/A	56	5.6230	0.30	96.28	5.7496	0.32	263.84
12	N/A	N/A	N/A	N/A	N/A	N/A	58	5.6553	0.30	94.48	5.7617	0.30	265.67
14	N/A	N/A	N/A	N/A	N/A	N/A	60	5.6659	0.31	92.71	5.7942	0.31	267.35
16	N/A	N/A	N/A	N/A	N/A	N/A	62	5.6856	0.31	91.08	5.8130	0.31	269.10
18	N/A	N/A	N/A	N/A	N/A	N/A	64	5.7057	0.30	89.39	5.8438	0.31	270.80
20	N/A	N/A	N/A	N/A	N/A	N/A	66	5.7352	0.30	87.71	5.8577	0.31	272.40
22	N/A	N/A	N/A	N/A	N/A	N/A	68	5.7688	0.32	86.15	5.8936	0.31	274.06
24	5.5271	0.31	161.06	5.5473	0.31	198.69	70	5.8050	0.31	84.51	5.9261	0.32	275.61
26	5.5409	0.33	148.47	5.5613	0.31	212.25	72	5.8458	0.31	82.87	5.9745	N/A	277.24
28	5.5203	0.30	139.93	5.5709	0.31	219.93	74	5.8786	0.32	81.32	6.0202	N/A	278.86
30	5.5137	0.30	133.57	5.5760	0.34	226.50	76	5.9383	N/A	79.71	6.0707	N/A	280.49
32	5.5279	0.33	128.46	5.5760	0.29	231.43	78	5.9987	N/A	78.09	6.1349	N/A	282.03
34	5.5163	0.30	124.28	5.6128	0.34	236.05	80	6.0628	N/A	76.48	6.1822	N/A	283.67
36	5.5325	0.29	120.66	5.6268	0.32	239.51	82	6.1393	N/A	74.86	6.2344	N/A	285.34
38	5.5293	0.34	117.15	5.6271	0.31	242.97	84	6.2248	N/A	73.14	6.2697	N/A	287.03
40	5.5410	0.34	114.03	5.6377	0.31	246.03	86	N/A	N/A	N/A	N/A	N/A	N/A
42	5.5409	0.32	111.35	5.6522	0.35	248.81	88	N/A	N/A	N/A	N/A	N/A	N/A
44	5.5505	0.32	108.79	5.6760	0.33	251.30	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

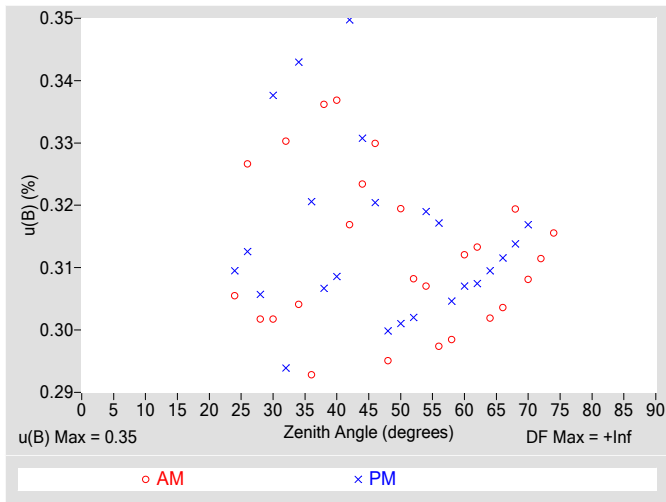


Figure 4. Residuals from Spline Interpolation

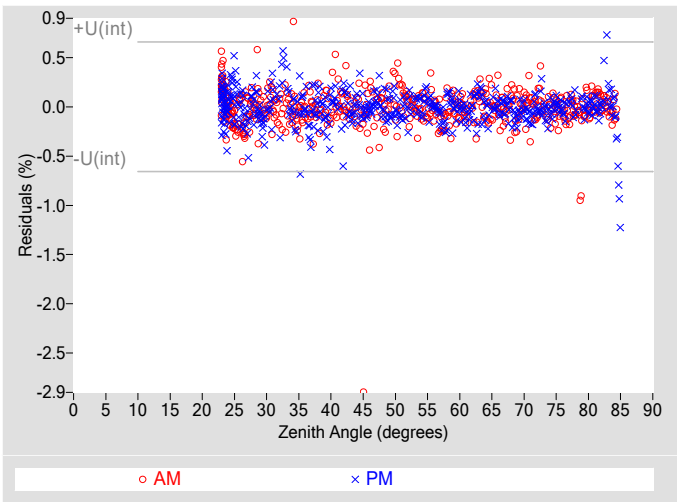


Table 3. Uncertainty using Spline Interpolation ‡

Type-B Standard Uncertainty, $u(B)$ (%)	± 0.35
Type-A Interpolating Function, $u(int)$ (%)	± 0.33
Combined Standard Uncertainty, $u(c)$ (%)	± 0.48
Effective degrees of freedom, $DF(c)$	4090
Coverage factor, k	1.96
Expanded Uncertainty, U_{95} (%)	± 0.94
AM Valid zenith angle range	24° to 74°
PM Valid zenith angle range	24° to 70°

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

Table 4. Calibration Label Values

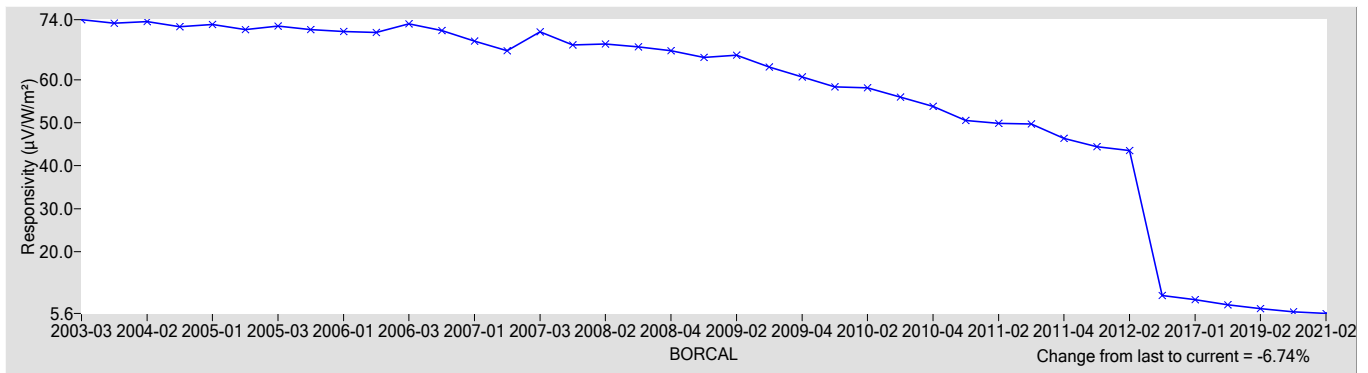
$R @ 45^\circ$ ($\mu V/W/m^2$)	R_{net} ($\mu V/W/m^2$) †
5.6021	0

† R_{net} determination date: N/A

Table 5. Uncertainty using $R @ 45^\circ$

Type-B Expanded Uncertainty, $U(B)$ (%)	± 0.69
Offset Uncertainty, $U(off)$ (%)	+3.4 / -1.6
Expanded Uncertainty, U (%)	+4.1 / -2.3
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 Pyrgometers. ARM 2008 Science Team Meeting (Poster).



National Renewable Energy Laboratory

Solar Radiation Research Laboratory

Metrology Laboratory

Calibration Certificate



Test Instrument:	Pyranometer	Manufacturer:	EKO
Model:	MS-602	Serial Number:	S13071483
Calibration Date:	5/6/2021	Due Date:	5/6/2022
Customer:	NREL-SRRL-BMS	Environmental Conditions:	see page 4
Test Dates:	5/6		

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 than 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	09/27/2019	09/27/2021
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/30/2021	04/30/2022
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/30/2021	04/30/2022
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/08/2021	02/08/2023
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/08/2021	02/08/2023
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, Peter Gotseff, 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

S13071483 EKO MS-602

The responsivity (R , $\mu\text{V}/\text{W}/\text{m}^2$) of the test instrument during calibration is calculated using this Measurement Equation:

$$R = (V - R_{net} * W_{net}) / I \tag{1}$$

where,

- V = radiometer output voltage (microvolts),
- R_{net} = radiometer net infrared responsivity ($\mu\text{V}/\text{W}/\text{m}^2$), see Table 4,
- W_{net} = effective net infrared measured by pyrgeometer (W/m^2),
 $= W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
 where, W_{in} = incoming infrared (W/m^2), $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$,
 T_c = case temperature of pyrgeometer (K).
- I = reference irradiance (W/m^2), beam (B) or global (G)
 where, $G = B * \text{COS}(Z) + D$,
 Z = zenith angle (degrees),
 D = reference diffuse irradiance (W/m^2).

Figure 1. Responsivity vs Zenith Angle

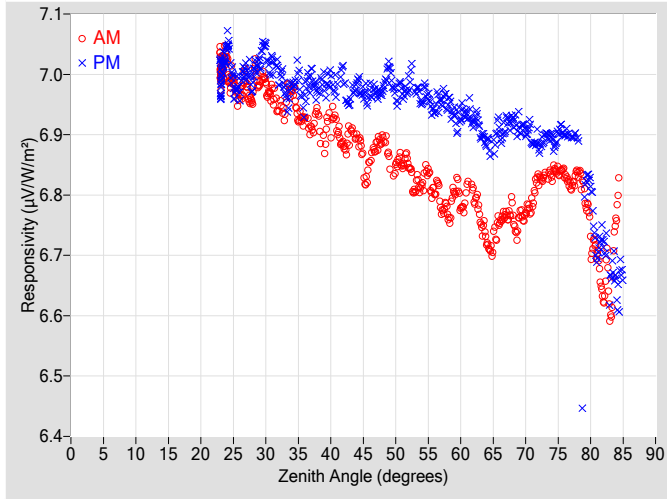


Figure 2. Responsivity vs Local Standard Time

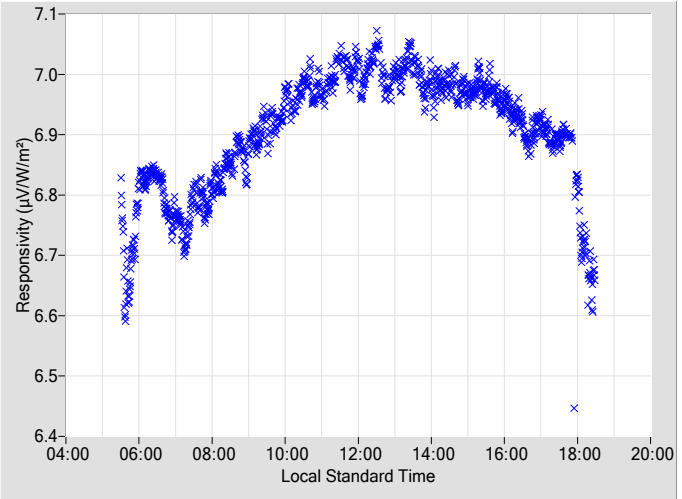


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)

Zenith Angle (deg.)	R ($\mu\text{V}/\text{W}/\text{m}^2$)	u(B) \pm (%)	Azimuth Angle	R ($\mu\text{V}/\text{W}/\text{m}^2$)	u(B) \pm (%)	Azimuth Angle	Zenith Angle (deg.)	R ($\mu\text{V}/\text{W}/\text{m}^2$)	u(B) \pm (%)	Azimuth Angle	R ($\mu\text{V}/\text{W}/\text{m}^2$)	u(B) \pm (%)	Azimuth Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	6.8554	0.39	106.41	6.9713	0.38	253.72
2	N/A	N/A	N/A	N/A	N/A	N/A	48	6.8907	0.38	104.25	6.9731	0.34	255.91
4	N/A	N/A	N/A	N/A	N/A	N/A	50	6.8467	0.36	102.00	6.9654	0.38	258.02
6	N/A	N/A	N/A	N/A	N/A	N/A	52	6.8492	0.36	100.05	6.9795	0.35	260.05
8	N/A	N/A	N/A	N/A	N/A	N/A	54	6.8147	0.39	98.11	6.9531	0.36	261.97
10	N/A	N/A	N/A	N/A	N/A	N/A	56	6.8056	0.37	96.34	6.9408	0.37	263.86
12	N/A	N/A	N/A	N/A	N/A	N/A	58	6.7715	0.41	94.51	6.9512	0.38	265.70
14	N/A	N/A	N/A	N/A	N/A	N/A	60	6.7832	0.38	92.73	6.9338	0.41	267.38
16	N/A	N/A	N/A	N/A	N/A	N/A	62	6.7978	0.44	91.01	6.9213	0.40	269.13
18	N/A	N/A	N/A	N/A	N/A	N/A	64	6.7252	0.40	89.41	6.8876	0.42	270.73
20	N/A	N/A	N/A	N/A	N/A	N/A	66	6.7568	0.42	87.73	6.9048	0.45	272.42
22	N/A	N/A	N/A	N/A	N/A	N/A	68	6.7735	0.44	86.17	6.9236	0.47	274.04
24	7.0154	0.32	160.88	7.0425	0.31	199.05	70	6.7696	0.51	84.53	6.9051	0.51	275.63
26	6.9642	0.35	148.19	6.9784	0.33	211.81	72	6.8280	0.51	82.90	6.8786	N/A	277.31
28	6.9666	0.33	140.13	6.9877	0.33	220.07	74	6.8335	0.56	81.34	6.8923	N/A	278.84
30	6.9824	0.34	133.70	7.0440	0.35	226.19	76	6.8354	N/A	79.73	6.8999	N/A	280.41
32	6.9432	0.34	128.69	7.0000	0.34	231.52	78	6.8372	N/A	78.11	6.8920	N/A	282.10
34	6.9697	0.34	124.33	6.9816	0.34	235.73	80	6.7325	N/A	76.50	6.8155	N/A	283.69
36	6.9246	0.37	120.60	6.9599	0.33	239.65	82	6.6351	N/A	74.84	6.7234	N/A	285.32
38	6.9369	0.33	117.15	6.9696	0.32	242.99	84	6.7702	N/A	73.17	6.6431	N/A	287.06
40	6.9256	0.34	114.00	6.9944	0.32	245.90	86	N/A	N/A	N/A	N/A	N/A	N/A
42	6.8814	0.35	111.31	6.9991	0.35	248.73	88	N/A	N/A	N/A	N/A	N/A	N/A
44	6.8954	0.38	108.83	6.9849	0.36	251.37	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

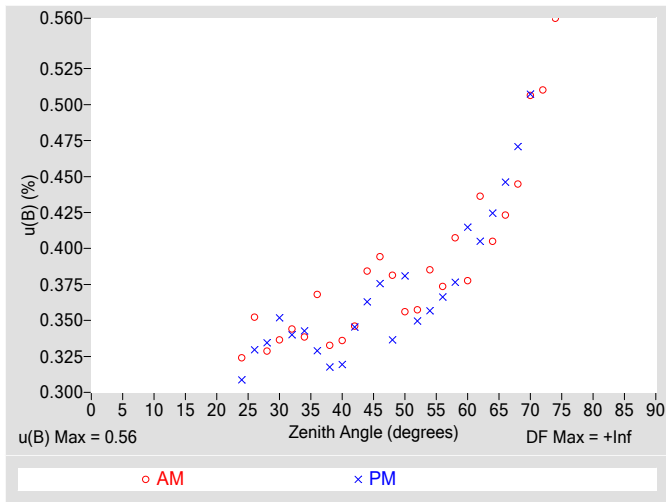


Figure 4. Residuals from Spline Interpolation

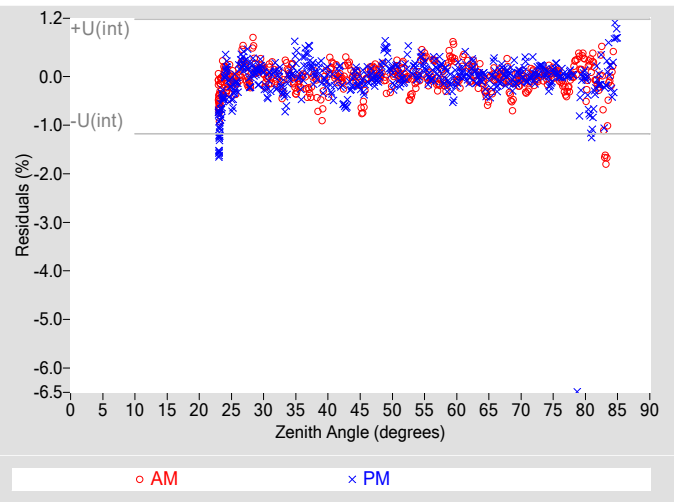


Table 3. Uncertainty using Spline Interpolation ‡

Type-B Standard Uncertainty, $u(B)$ (%)	± 0.56
Type-A Interpolating Function, $u(int)$ (%)	± 0.59
Combined Standard Uncertainty, $u(c)$ (%)	± 0.81
Effective degrees of freedom, $DF(c)$	3208
Coverage factor, k	1.96
Expanded Uncertainty, U_{95} (%)	± 1.6
AM Valid zenith angle range	24° to 74°
PM Valid zenith angle range	24° to 70°

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

Table 4. Calibration Label Values

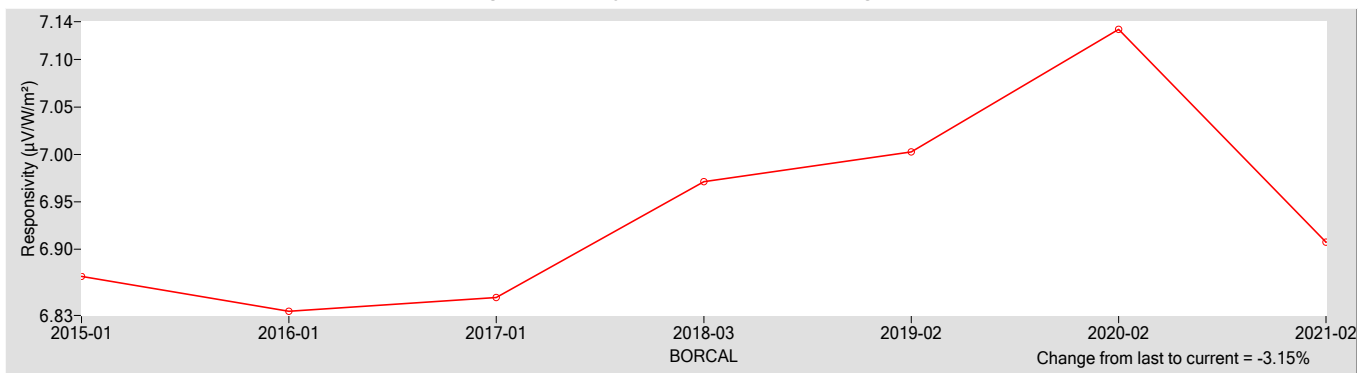
$R @ 45^\circ$ ($\mu V/W/m^2$)	R_{net} ($\mu V/W/m^2$) †
6.9072	0.30000

† R_{net} determination date: Estimated

Table 5. Uncertainty using $R @ 45^\circ$

Type-B Expanded Uncertainty, $U(B)$ (%)	± 0.81
Offset Uncertainty, $U(off)$ (%)	+2.0 / -2.0
Expanded Uncertainty, U (%)	+2.8 / -2.8
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



Test Instrument: Silicon Pyranometer
Manufacturer: EKO
Model: ML-01
Serial Number: S13135063
Calibration Date: 5/6/2021
Due Date: 5/6/2022
Customer: NREL-SRRL-BMS
Environmental Conditions: see page 4
Test Dates: 5/6

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 than 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	09/27/2019	09/27/2021
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/30/2021	04/30/2022
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/30/2021	04/30/2022
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/08/2021	02/08/2023
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/08/2021	02/08/2023

† 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, Peter Gotseff, 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

S13135063 EKO ML-01

The responsivity (R , $\mu\text{V}/\text{W}/\text{m}^2$) of the test instrument during calibration is calculated using this Measurement Equation:

$$R = (V - R_{net} * W_{net}) / I \tag{1}$$

where,

- V = radiometer output voltage (microvolts),
 - R_{net} = radiometer net infrared responsivity ($\mu\text{V}/\text{W}/\text{m}^2$), see Table 4,
 - W_{net} = effective net infrared measured by pyrgeometer (W/m^2),
 - = $W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
 - where, W_{in} = incoming infrared (W/m^2), $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$,
 - T_c = case temperature of pyrgeometer (K).
- I = reference irradiance (W/m^2), beam (B) or global (G)
 - where, $G = B * \text{COS}(Z) + D$,
 - Z = zenith angle (degrees),
 - D = reference diffuse irradiance (W/m^2).

Figure 1. Responsivity vs Zenith Angle

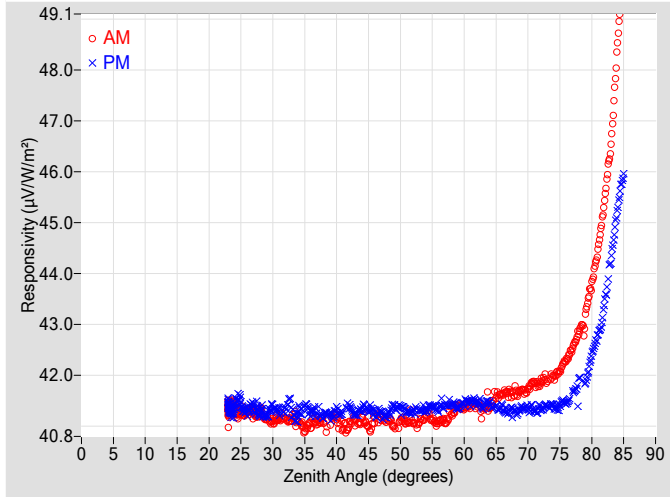


Figure 2. Responsivity vs Local Standard Time

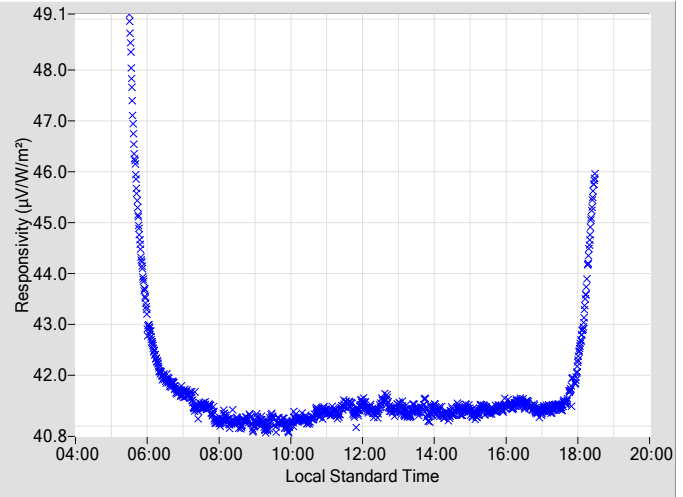


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)

Zenith Angle (deg.)	R ($\mu\text{V}/\text{W}/\text{m}^2$)	u(B) \pm (%)	Azimuth Angle	R ($\mu\text{V}/\text{W}/\text{m}^2$)	u(B) \pm (%)	Azimuth Angle	Zenith Angle (deg.)	R ($\mu\text{V}/\text{W}/\text{m}^2$)	u(B) \pm (%)	Azimuth Angle	R ($\mu\text{V}/\text{W}/\text{m}^2$)	u(B) \pm (%)	Azimuth Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	41.140	0.40	106.53	41.251	0.31	253.80
2	N/A	N/A	N/A	N/A	N/A	N/A	48	41.101	0.31	104.16	41.245	0.32	255.98
4	N/A	N/A	N/A	N/A	N/A	N/A	50	41.089	0.35	102.07	41.389	0.35	258.06
6	N/A	N/A	N/A	N/A	N/A	N/A	52	41.089	0.36	99.99	41.296	0.35	260.11
8	N/A	N/A	N/A	N/A	N/A	N/A	54	41.175	0.32	98.23	41.310	0.35	262.03
10	N/A	N/A	N/A	N/A	N/A	N/A	56	41.084	0.37	96.29	41.342	0.34	263.82
12	N/A	N/A	N/A	N/A	N/A	N/A	58	41.262	0.36	94.46	41.423	0.35	265.65
14	N/A	N/A	N/A	N/A	N/A	N/A	60	41.353	0.37	92.79	41.473	0.39	267.46
16	N/A	N/A	N/A	N/A	N/A	N/A	62	41.411	0.43	91.06	41.460	0.42	269.08
18	N/A	N/A	N/A	N/A	N/A	N/A	64	41.346	0.39	89.37	41.431	0.38	270.78
20	N/A	N/A	N/A	N/A	N/A	N/A	66	41.622	0.38	87.81	41.366	0.40	272.38
22	N/A	N/A	N/A	N/A	N/A	N/A	68	41.660	0.43	86.13	41.285	0.42	274.04
24	41.367	0.32	161.25	41.389	0.30	198.95	70	41.730	0.46	84.49	41.346	0.45	275.69
26	41.283	0.32	148.31	41.301	0.29	212.13	72	41.856	0.50	82.95	41.359	N/A	277.22
28	41.315	0.33	139.96	41.273	0.32	220.21	74	41.965	0.50	81.30	41.394	N/A	278.84
30	41.092	0.29	133.59	41.385	0.33	226.24	76	42.299	N/A	79.73	41.460	N/A	280.47
32	41.150	0.31	128.65	41.319	0.32	231.60	78	42.861	N/A	78.12	41.909	N/A	282.04
34	41.099	0.30	124.33	41.261	0.31	235.91	80	43.805	N/A	76.46	42.402	N/A	283.69
36	41.038	0.35	120.58	41.277	0.33	239.56	82	45.423	N/A	74.84	43.469	N/A	285.37
38	41.112	0.32	117.32	41.211	0.30	243.02	84	48.405	N/A	73.17	45.227	N/A	287.01
40	41.153	0.33	114.09	41.323	0.33	246.03	86	N/A	N/A	N/A	N/A	N/A	N/A
42	41.025	0.32	111.40	41.389	0.33	248.82	88	N/A	N/A	N/A	N/A	N/A	N/A
44	41.130	0.33	108.80	41.354	0.31	251.31	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

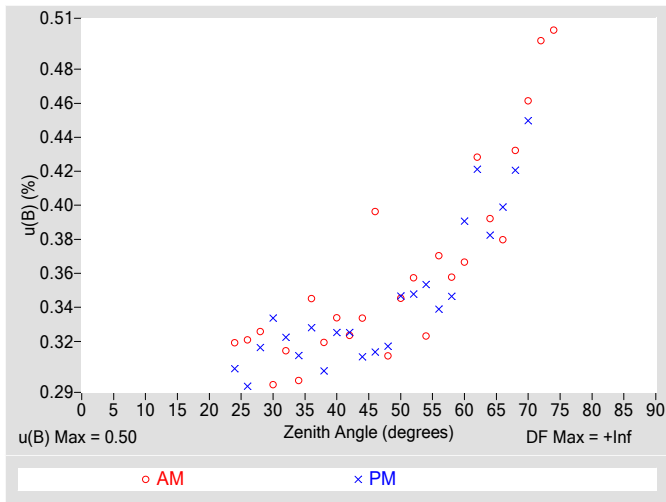


Figure 4. Residuals from Spline Interpolation

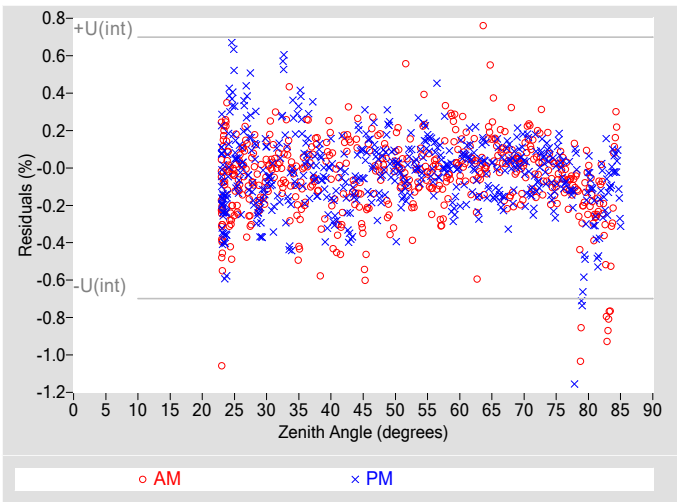


Table 3. Uncertainty using Spline Interpolation ‡

Type-B Standard Uncertainty, $u(B)$ (%)	± 0.50
Type-A Interpolating Function, $u(int)$ (%)	± 0.35
Combined Standard Uncertainty, $u(c)$ (%)	± 0.61
Effective degrees of freedom, $DF(c)$	8535
Coverage factor, k	1.96
Expanded Uncertainty, U_{95} (%)	± 1.2
AM Valid zenith angle range	24° to 74°
PM Valid zenith angle range	24° to 70°

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

Table 4. Calibration Label Values

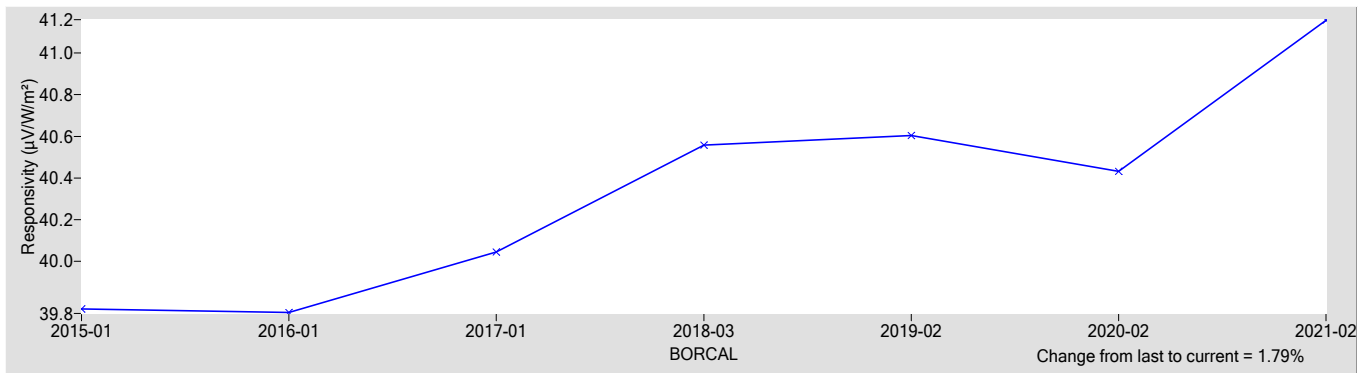
$R @ 45^\circ$ ($\mu V/W/m^2$)	R_{net} ($\mu V/W/m^2$) †
41.157	0

† R_{net} determination date: N/A

Table 5. Uncertainty using $R @ 45^\circ$

Type-B Expanded Uncertainty, $U(B)$ (%)	± 0.78
Offset Uncertainty, $U(off)$ (%)	+0.77 / -0.32
Expanded Uncertainty, U (%)	+1.5 / -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



Test Instrument:	Pyranometer	Manufacturer:	EKO
Model:	MS-410	Serial Number:	S13144.085R
Calibration Date:	5/6/2021	Due Date:	5/6/2022
Customer:	NREL-SRRL-BMS	Environmental Conditions:	see page 4
Test Dates:	5/6		

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 than 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	09/27/2019	09/27/2021
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/30/2021	04/30/2022
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/30/2021	04/30/2022
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/08/2021	02/08/2023
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/08/2021	02/08/2023
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, Peter Gotseff, 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

S13144.085R EKO MS-410

The responsivity (R , $\mu\text{V}/\text{W}/\text{m}^2$) of the test instrument during calibration is calculated using this Measurement Equation:

$$R = (V - R_{net} * W_{net}) / I \tag{1}$$

where,

- V = radiometer output voltage (microvolts),
 - R_{net} = radiometer net infrared responsivity ($\mu\text{V}/\text{W}/\text{m}^2$), see Table 4,
 - W_{net} = effective net infrared measured by pyrgeometer (W/m^2),
 - = $W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
 - where, W_{in} = incoming infrared (W/m^2), $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$,
 - T_c = case temperature of pyrgeometer (K).
- I = reference irradiance (W/m^2), beam (B) or global (G)
 - where, $G = B * \text{COS}(Z) + D$,
 - Z = zenith angle (degrees),
 - D = reference diffuse irradiance (W/m^2).

Figure 1. Responsivity vs Zenith Angle

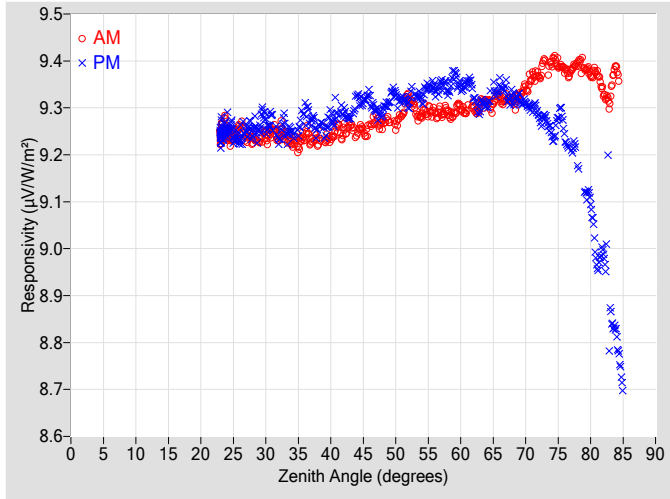


Figure 2. Responsivity vs Local Standard Time

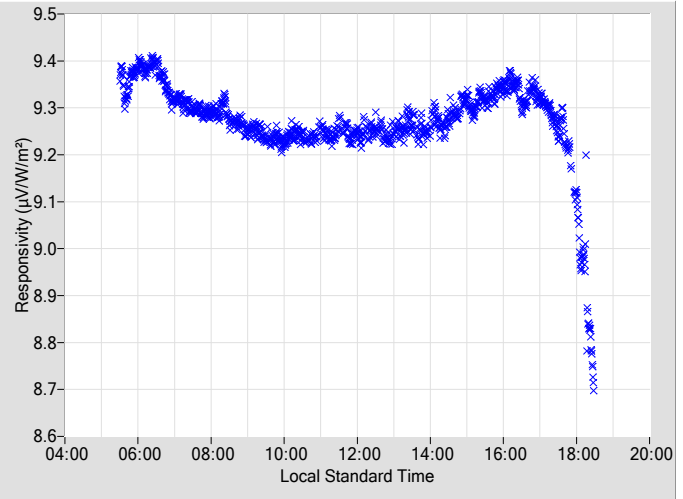


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)

Zenith Angle (deg.)	R ($\mu\text{V}/\text{W}/\text{m}^2$)	u(B) \pm (%)	Azimuth Angle	R ($\mu\text{V}/\text{W}/\text{m}^2$)	u(B) \pm (%)	Azimuth Angle	Zenith Angle (deg.)	R ($\mu\text{V}/\text{W}/\text{m}^2$)	u(B) \pm (%)	Azimuth Angle	R ($\mu\text{V}/\text{W}/\text{m}^2$)	u(B) \pm (%)	Azimuth Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	9.2631	0.34	106.41	9.3239	0.32	253.68
2	N/A	N/A	N/A	N/A	N/A	N/A	48	9.2667	0.33	104.25	9.2931	0.34	255.97
4	N/A	N/A	N/A	N/A	N/A	N/A	50	9.2648	0.36	102.06	9.3283	0.35	258.02
6	N/A	N/A	N/A	N/A	N/A	N/A	52	9.3200	0.36	100.04	9.3085	0.33	260.04
8	N/A	N/A	N/A	N/A	N/A	N/A	54	9.2847	0.35	98.10	9.3160	0.36	261.97
10	N/A	N/A	N/A	N/A	N/A	N/A	56	9.2935	0.34	96.33	9.3379	0.35	263.86
12	N/A	N/A	N/A	N/A	N/A	N/A	58	9.2931	0.39	94.51	9.3334	0.38	265.70
14	N/A	N/A	N/A	N/A	N/A	N/A	60	9.2993	0.35	92.73	9.3463	0.37	267.38
16	N/A	N/A	N/A	N/A	N/A	N/A	62	9.3017	0.39	91.00	9.3235	0.38	269.12
18	N/A	N/A	N/A	N/A	N/A	N/A	64	9.3149	0.38	89.41	9.3044	0.42	270.72
20	N/A	N/A	N/A	N/A	N/A	N/A	66	9.3227	0.48	87.73	9.3477	0.41	272.42
22	N/A	N/A	N/A	N/A	N/A	N/A	68	9.3151	0.41	86.17	9.3228	0.44	274.03
24	9.2514	0.32	160.96	9.2534	0.31	198.74	70	9.3435	0.44	84.53	9.3106	0.47	275.63
26	9.2581	0.32	148.29	9.2360	0.32	211.67	72	9.3677	0.48	82.89	9.2818	N/A	277.26
28	9.2346	0.32	139.66	9.2483	0.33	220.01	74	9.3964	0.52	81.34	9.2447	N/A	278.84
30	9.2396	0.33	133.70	9.2706	0.33	226.43	76	9.3820	N/A	79.72	9.2458	N/A	280.41
32	9.2367	0.34	128.65	9.2318	0.36	231.58	78	9.3944	N/A	78.11	9.1735	N/A	282.10
34	9.2229	0.33	124.37	9.2483	0.31	235.89	80	9.3703	N/A	76.50	9.0942	N/A	283.68
36	9.2381	0.35	120.42	9.2858	0.32	239.65	82	9.3309	N/A	74.83	8.9868	N/A	285.32
38	9.2286	0.32	117.14	9.2536	0.34	242.99	84	9.3822	N/A	73.16	8.8069	N/A	287.05
40	9.2355	0.32	114.06	9.2816	0.36	246.06	86	N/A	N/A	N/A	N/A	N/A	N/A
42	9.2494	0.32	111.31	9.2895	0.33	248.76	88	N/A	N/A	N/A	N/A	N/A	N/A
44	9.2411	0.34	108.83	9.3267	0.32	251.40	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

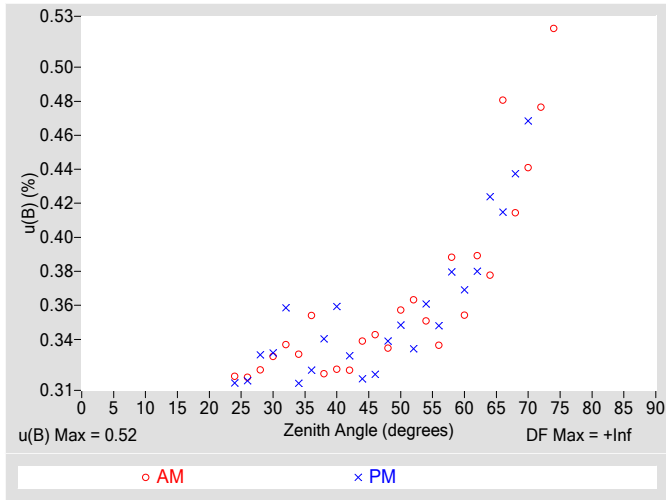


Figure 4. Residuals from Spline Interpolation

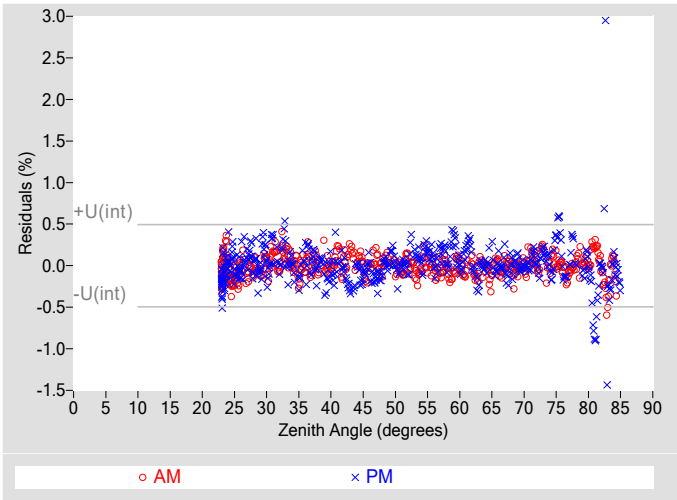


Table 3. Uncertainty using Spline Interpolation ‡

Type-B Standard Uncertainty, $u(B)$ (%)	± 0.52
Type-A Interpolating Function, $u(int)$ (%)	± 0.25
Combined Standard Uncertainty, $u(c)$ (%)	± 0.58
Effective degrees of freedom, $DF(c)$	26650
Coverage factor, k	1.96
Expanded Uncertainty, U_{95} (%)	± 1.1
AM Valid zenith angle range	24° to 74°
PM Valid zenith angle range	24° to 70°

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

Table 4. Calibration Label Values

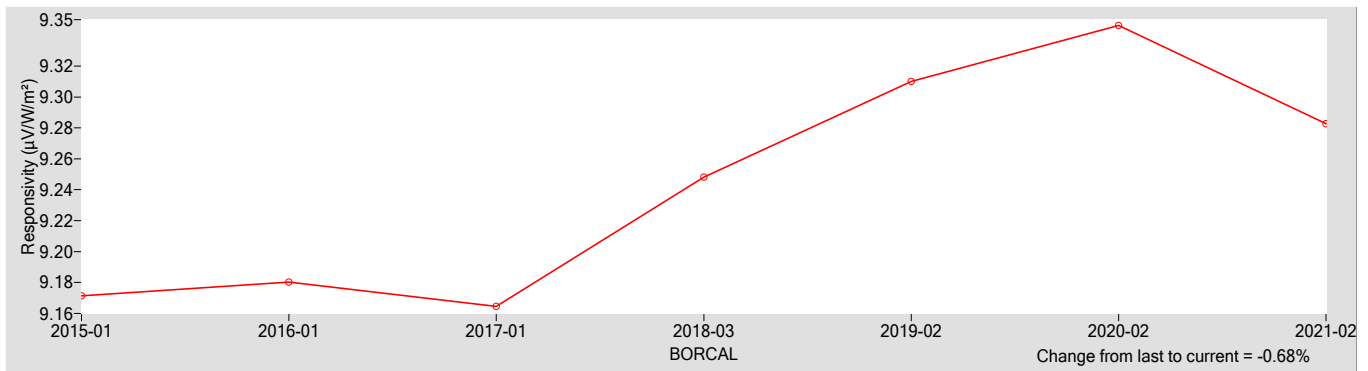
$R @ 45^\circ$ ($\mu V/W/m^2$)	R_{net} ($\mu V/W/m^2$) †
9.2827	0.20000

† R_{net} determination date: Estimated

Table 5. Uncertainty using $R @ 45^\circ$

Type-B Expanded Uncertainty, $U(B)$ (%)	± 0.76
Offset Uncertainty, $U(off)$ (%)	+0.69 / -0.64
Expanded Uncertainty, U (%)	+1.4 / -1.4
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



Test Instrument:	Pyranometer	Manufacturer:	EKO
Model:	MS-80	Serial Number:	S17096005
Calibration Date:	5/6/2021	Due Date:	5/6/2022
Customer:	NREL-SRRL-BMS	Environmental Conditions:	see page 4
Test Dates:	5/6		

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 than 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	09/27/2019	09/27/2021
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/30/2021	04/30/2022
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/30/2021	04/30/2022
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/08/2021	02/08/2023
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/08/2021	02/08/2023
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, Peter Gotseff, 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

S17096005 EKO MS-80

The responsivity (R , $\mu\text{V}/\text{W}/\text{m}^2$) of the test instrument during calibration is calculated using this Measurement Equation:

$$R = (V - R_{net} * W_{net}) / I \tag{1}$$

where,

- V = radiometer output voltage (microvolts),
 - R_{net} = radiometer net infrared responsivity ($\mu\text{V}/\text{W}/\text{m}^2$), see Table 4,
 - W_{net} = effective net infrared measured by pyrgeometer (W/m^2),
 - = $W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
 - where, W_{in} = incoming infrared (W/m^2), $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$,
 - T_c = case temperature of pyrgeometer (K).
- I = reference irradiance (W/m^2), beam (B) or global (G)
 - where, $G = B * \text{COS}(Z) + D$,
 - Z = zenith angle (degrees),
 - D = reference diffuse irradiance (W/m^2).

Figure 1. Responsivity vs Zenith Angle

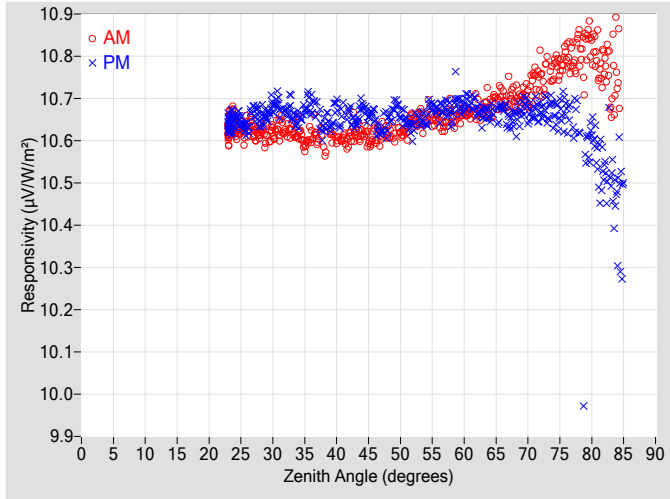


Figure 2. Responsivity vs Local Standard Time

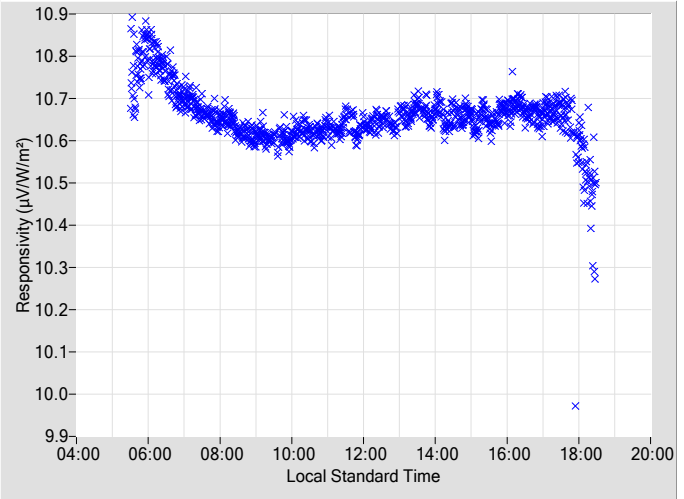


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, $u(B)$

Zenith Angle (deg.)	R ($\mu\text{V}/\text{W}/\text{m}^2$)	AM $u(B)$ \pm (%)	Azimuth Angle	R ($\mu\text{V}/\text{W}/\text{m}^2$)	PM $u(B)$ \pm (%)	Azimuth Angle	Zenith Angle (deg.)	R ($\mu\text{V}/\text{W}/\text{m}^2$)	AM $u(B)$ \pm (%)	Azimuth Angle	R ($\mu\text{V}/\text{W}/\text{m}^2$)	PM $u(B)$ \pm (%)	Azimuth Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	10.614	0.37	106.40	10.651	0.32	253.69
2	N/A	N/A	N/A	N/A	N/A	N/A	48	10.621	0.36	104.13	10.642	0.34	255.91
4	N/A	N/A	N/A	N/A	N/A	N/A	50	10.618	0.33	102.06	10.660	0.36	258.03
6	N/A	N/A	N/A	N/A	N/A	N/A	52	10.656	0.34	100.05	10.629	0.33	260.05
8	N/A	N/A	N/A	N/A	N/A	N/A	54	10.649	0.37	98.11	10.640	0.33	261.97
10	N/A	N/A	N/A	N/A	N/A	N/A	56	10.655	0.37	96.29	10.669	0.36	263.87
12	N/A	N/A	N/A	N/A	N/A	N/A	58	10.667	0.42	94.51	10.662	0.35	265.65
14	N/A	N/A	N/A	N/A	N/A	N/A	60	10.668	0.35	92.74	10.687	0.36	267.38
16	N/A	N/A	N/A	N/A	N/A	N/A	62	10.682	0.41	91.01	10.669	0.37	269.13
18	N/A	N/A	N/A	N/A	N/A	N/A	64	10.675	0.37	89.41	10.657	0.39	270.73
20	N/A	N/A	N/A	N/A	N/A	N/A	66	10.705	0.44	87.73	10.678	0.40	272.43
22	N/A	N/A	N/A	N/A	N/A	N/A	68	10.704	0.41	86.13	10.649	0.43	273.99
24	10.644	0.31	161.30	10.644	0.31	199.00	70	10.700	0.43	84.53	10.667	0.46	275.64
26	10.634	0.33	148.44	10.629	0.29	211.72	72	10.751	0.47	82.90	10.671	N/A	277.27
28	10.624	0.33	139.96	10.647	0.32	219.90	74	10.768	0.51	81.34	10.669	N/A	278.85
30	10.621	0.30	133.71	10.685	0.33	226.32	76	10.806	N/A	79.73	10.669	N/A	280.42
32	10.618	0.33	128.72	10.667	0.34	231.76	78	10.830	N/A	78.12	10.619	N/A	282.10
34	10.621	0.31	124.28	10.652	0.35	235.74	80	10.822	N/A	76.51	10.627	N/A	283.69
36	10.612	0.31	120.48	10.679	0.32	239.56	82	10.783	N/A	74.84	10.530	N/A	285.32
38	10.588	0.36	117.02	10.630	0.33	243.02	84	10.796	N/A	73.17	10.475	N/A	287.06
40	10.604	0.34	114.04	10.681	0.33	245.99	86	N/A	N/A	N/A	N/A	N/A	N/A
42	10.606	0.32	111.32	10.675	0.33	248.74	88	N/A	N/A	N/A	N/A	N/A	N/A
44	10.617	0.33	108.83	10.684	0.31	251.37	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

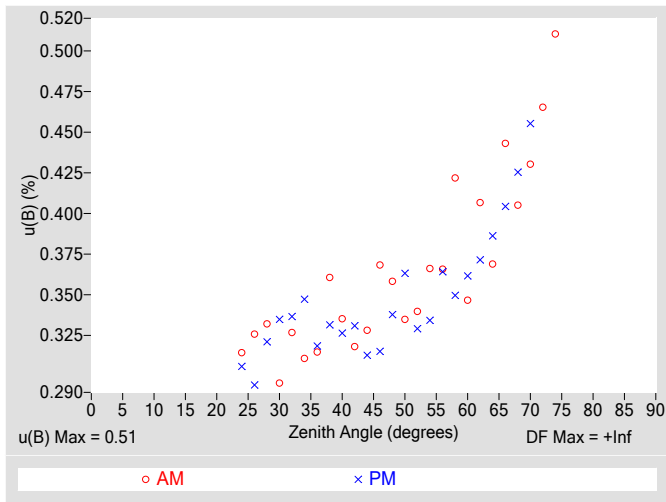


Figure 4. Residuals from Spline Interpolation

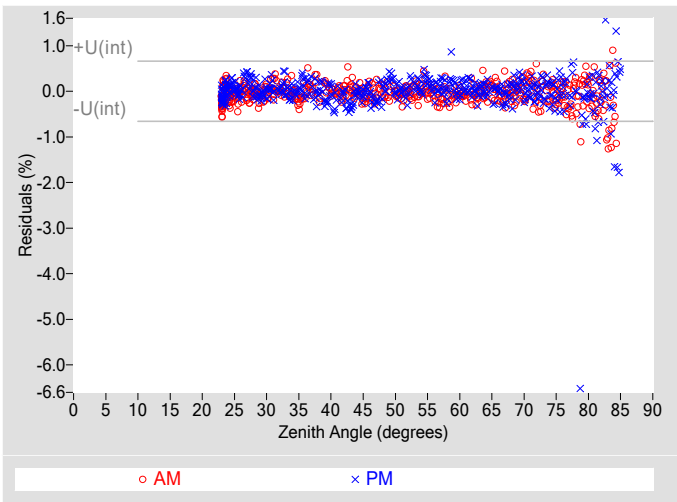


Table 3. Uncertainty using Spline Interpolation ‡

Type-B Standard Uncertainty, $u(B)$ (%)	± 0.51
Type-A Interpolating Function, $u(int)$ (%)	± 0.33
Combined Standard Uncertainty, $u(c)$ (%)	± 0.61
Effective degrees of freedom, $DF(c)$	10101
Coverage factor, k	1.96
Expanded Uncertainty, U_{95} (%)	± 1.2
AM Valid zenith angle range	24° to 74°
PM Valid zenith angle range	24° to 70°

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

Table 4. Calibration Label Values

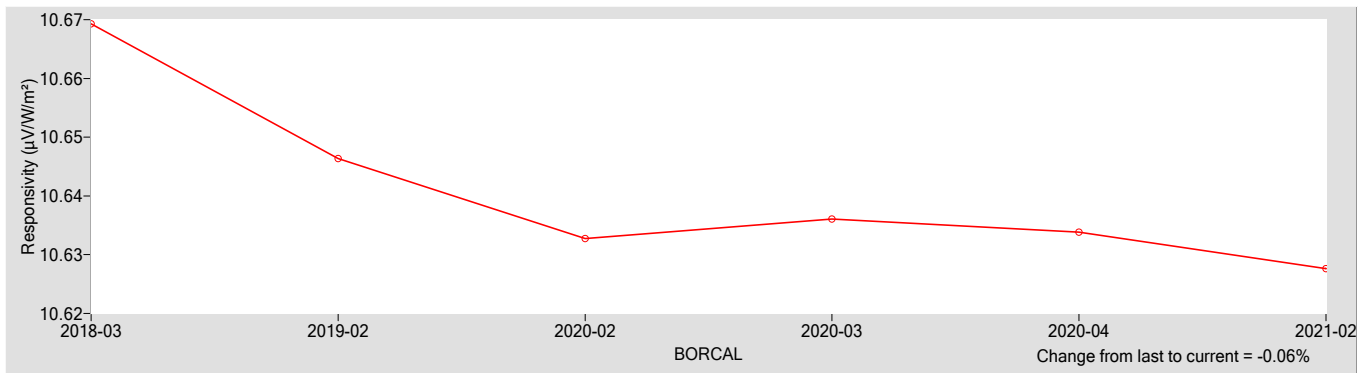
$R @ 45^\circ$ ($\mu V/W/m^2$)	R_{net} ($\mu V/W/m^2$) †
10.628	0.043000

† R_{net} determination date: Estimated

Table 5. Uncertainty using $R @ 45^\circ$

Type-B Expanded Uncertainty, $U(B)$ (%)	± 0.83
Offset Uncertainty, $U(off)$ (%)	+0.56 / -0.38
Expanded Uncertainty, U (%)	+1.4 / -1.2
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 Pyrheliometers*. ARM 2008 Science Team Meeting (Poster).



National Renewable Energy Laboratory

Solar Radiation Research Laboratory

Metrology Laboratory

Calibration Certificate



Test Instrument:	Pyrheliometer	Manufacturer:	EKO
Model:	MS-57	Serial Number:	S18015.22
Calibration Date:	5/6/2021	Due Date:	5/6/2022
Customer:	NREL-SRRL-BMS	Environmental Conditions:	see page 4
Test Dates:	5/6		

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 than 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	09/27/2019	09/27/2021
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/30/2021	04/30/2022
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/30/2021	04/30/2022
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/08/2021	02/08/2023
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/08/2021	02/08/2023

† 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, Peter Gotseff, 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

S18015.22 EKO MS-57

The responsivity (R , $\mu\text{V}/\text{W}/\text{m}^2$) of the test instrument during calibration is calculated using this Measurement Equation:

$$R = (V - R_{net} * W_{net}) / I \tag{1}$$

where,

- V = radiometer output voltage (microvolts),
 - R_{net} = radiometer net infrared responsivity ($\mu\text{V}/\text{W}/\text{m}^2$), see Table 4,
 - W_{net} = effective net infrared measured by pyrgeometer (W/m^2),
 - = $W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
 - where, W_{in} = incoming infrared (W/m^2), $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$,
 - T_c = case temperature of pyrgeometer (K).
- I = reference irradiance (W/m^2), beam (B) or global (G)
 - where, $G = B * \text{COS}(Z) + D$,
 - Z = zenith angle (degrees),
 - D = reference diffuse irradiance (W/m^2).

Figure 1. Responsivity vs Zenith Angle

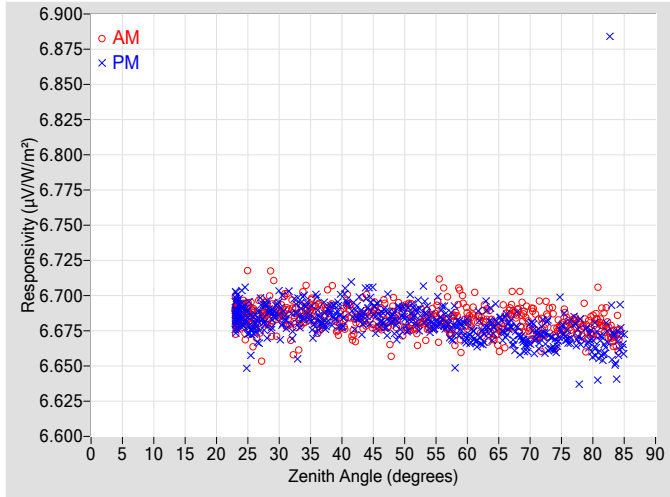


Figure 2. Responsivity vs Local Standard Time

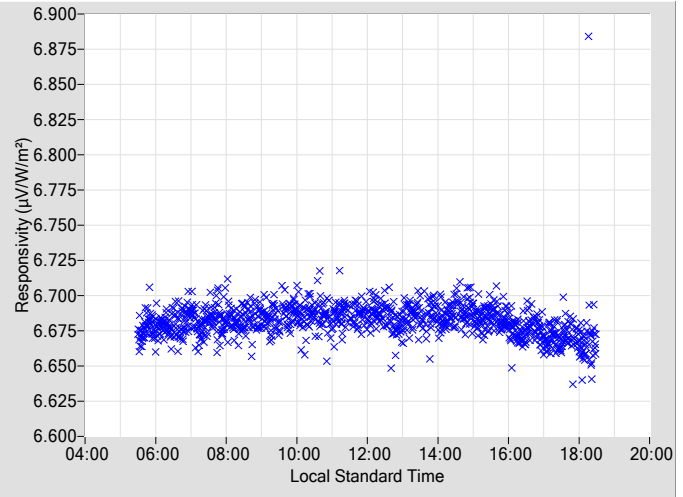


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)

Zenith Angle (deg.)	R ($\mu\text{V}/\text{W}/\text{m}^2$)	AM u(B) \pm (%)	Azimuth Angle	R ($\mu\text{V}/\text{W}/\text{m}^2$)	PM u(B) \pm (%)	Azimuth Angle	Zenith Angle (deg.)	R ($\mu\text{V}/\text{W}/\text{m}^2$)	AM u(B) \pm (%)	Azimuth Angle	R ($\mu\text{V}/\text{W}/\text{m}^2$)	PM u(B) \pm (%)	Azimuth Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	6.6810	0.34	106.43	6.6827	0.31	253.76
2	N/A	N/A	N/A	N/A	N/A	N/A	48	6.6933	0.31	104.07	6.6845	0.30	255.98
4	N/A	N/A	N/A	N/A	N/A	N/A	50	6.6821	0.30	102.07	6.6854	0.31	258.09
6	N/A	N/A	N/A	N/A	N/A	N/A	52	6.6744	0.31	100.00	6.6844	0.31	260.11
8	N/A	N/A	N/A	N/A	N/A	N/A	54	6.6810	0.31	98.17	6.6796	0.30	262.04
10	N/A	N/A	N/A	N/A	N/A	N/A	56	6.6858	0.31	96.29	6.6850	0.30	263.82
12	N/A	N/A	N/A	N/A	N/A	N/A	58	6.6810	0.31	94.46	6.6808	0.32	265.65
14	N/A	N/A	N/A	N/A	N/A	N/A	60	6.6844	0.30	92.79	6.6747	0.33	267.44
16	N/A	N/A	N/A	N/A	N/A	N/A	62	6.6823	0.31	91.07	6.6764	0.32	269.08
18	N/A	N/A	N/A	N/A	N/A	N/A	64	6.6762	0.31	89.37	6.6756	0.32	270.78
20	N/A	N/A	N/A	N/A	N/A	N/A	66	6.6818	0.34	87.81	6.6780	0.31	272.38
22	N/A	N/A	N/A	N/A	N/A	N/A	68	6.6851	0.30	86.13	6.6775	0.31	274.04
24	6.6881	0.31	160.64	6.6883	0.30	198.78	70	6.6759	0.32	84.49	6.6746	0.32	275.69
26	6.6810	0.30	148.30	6.6801	0.30	211.97	72	6.6729	0.32	82.95	6.6753	N/A	277.22
28	6.6863	0.31	139.97	6.6878	0.31	220.10	74	6.6716	0.31	81.30	6.6636	N/A	278.85
30	6.6879	0.30	133.60	6.6941	0.29	226.18	76	6.6782	N/A	79.73	6.6722	N/A	280.47
32	6.6785	0.31	128.44	6.6777	0.29	231.49	78	6.6765	N/A	78.12	6.6652	N/A	282.01
34	6.6911	0.31	124.19	6.6934	0.29	235.89	80	6.6760	N/A	76.46	6.6673	N/A	283.69
36	6.6856	0.30	120.47	6.6864	0.30	239.57	82	6.6815	N/A	74.84	6.6685	N/A	285.37
38	6.6945	0.31	117.24	6.6881	0.31	243.02	84	6.6717	N/A	73.18	6.6604	N/A	287.02
40	6.6857	0.33	114.14	6.6852	0.30	246.03	86	N/A	N/A	N/A	N/A	N/A	N/A
42	6.6758	0.32	111.33	6.6860	0.31	248.79	88	N/A	N/A	N/A	N/A	N/A	N/A
44	6.6893	0.31	108.90	6.6942	0.31	251.31	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

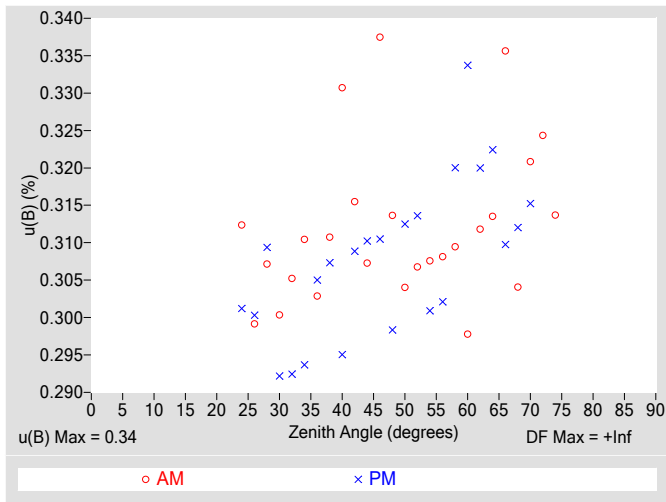


Figure 4. Residuals from Spline Interpolation

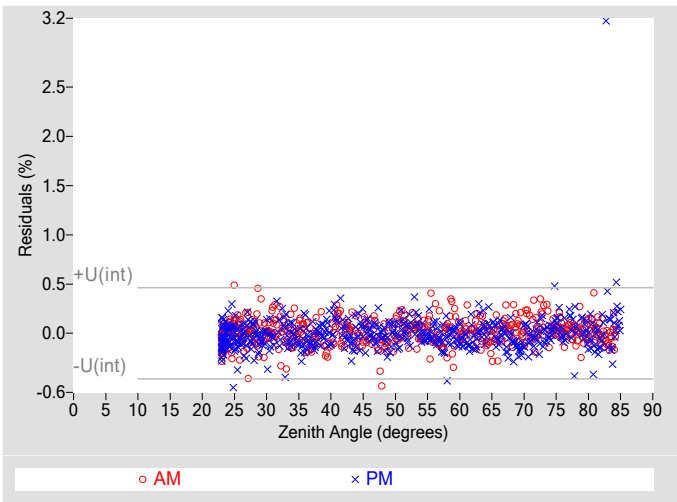


Table 3. Uncertainty using Spline Interpolation ‡

Type-B Standard Uncertainty, $u(B)$ (%)	± 0.34
Type-A Interpolating Function, $u(int)$ (%)	± 0.23
Combined Standard Uncertainty, $u(c)$ (%)	± 0.41
Effective degrees of freedom, $DF(c)$	9006
Coverage factor, k	1.96
Expanded Uncertainty, U_{95} (%)	± 0.80
AM Valid zenith angle range	24° to 74°
PM Valid zenith angle range	24° to 70°

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

Table 4. Calibration Label Values

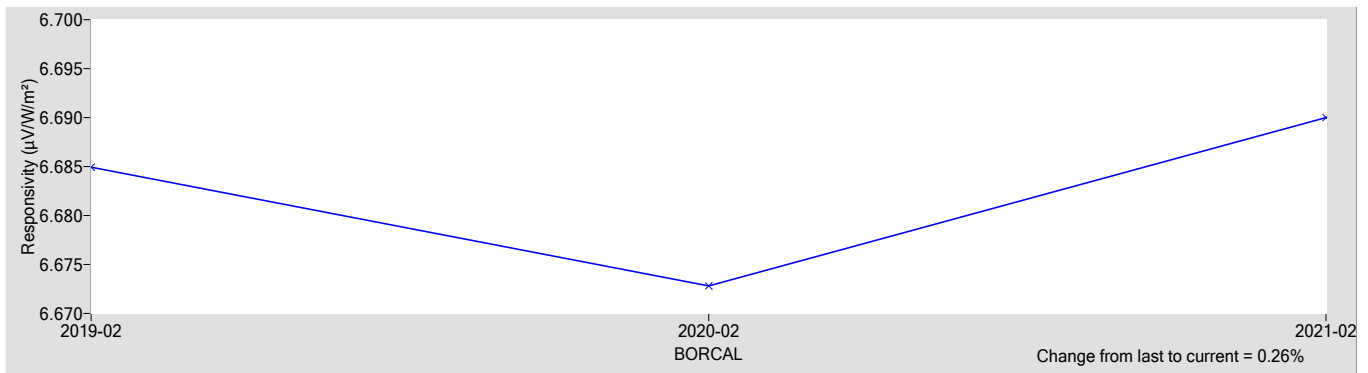
$R @ 45^\circ$ ($\mu V/W/m^2$)	R_{net} ($\mu V/W/m^2$) †
6.6900	0

† R_{net} determination date: N/A

Table 5. Uncertainty using $R @ 45^\circ$

Type-B Expanded Uncertainty, $U(B)$ (%)	± 0.66
Offset Uncertainty, $U(off)$ (%)	+0.068 / -0.23
Expanded Uncertainty, U (%)	+0.73 / -0.89
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 Pyrheliometers*. ARM 2008 Science Team Meeting (Poster).

Environmental and Sky Conditions for BORCAL-SW 2021-02

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

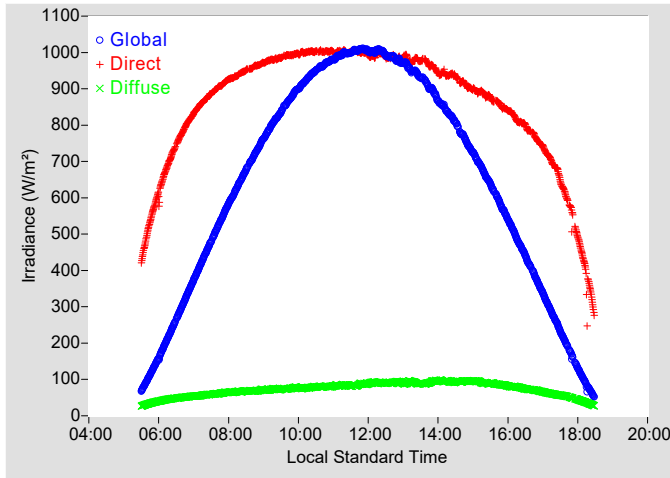
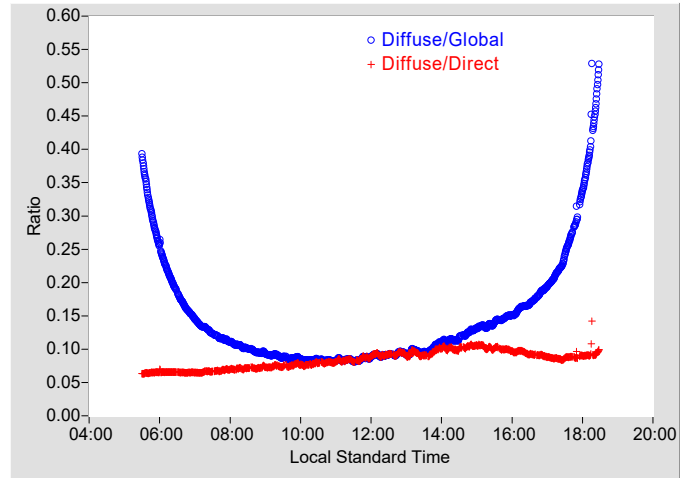


Figure 7. Diffuse Ratios



Meteorological Observations:

Figure 8. Temperature

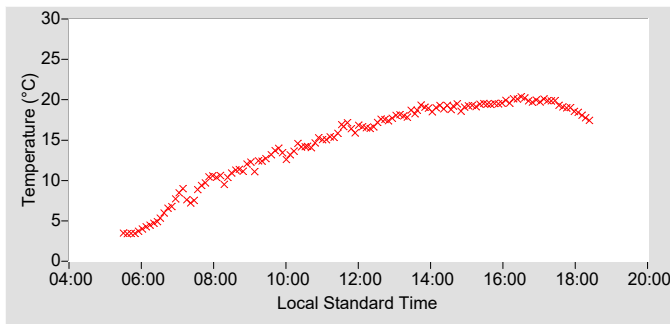


Figure 9. Humidity

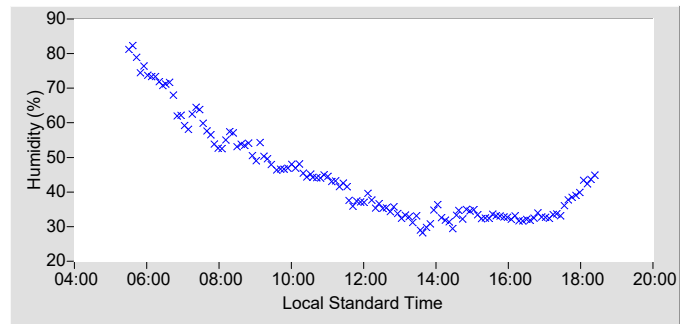


Figure 10. Pressure

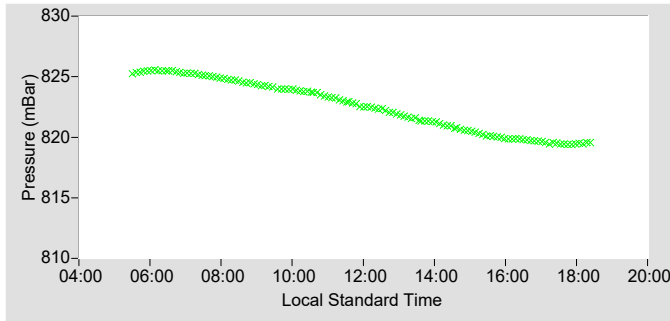


Figure 11. Effective Net Infrared

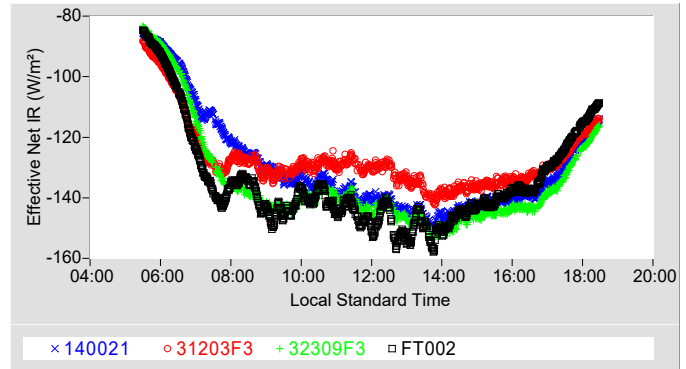


Figure 12. Estimated Broadband Aerosol Optical Depth

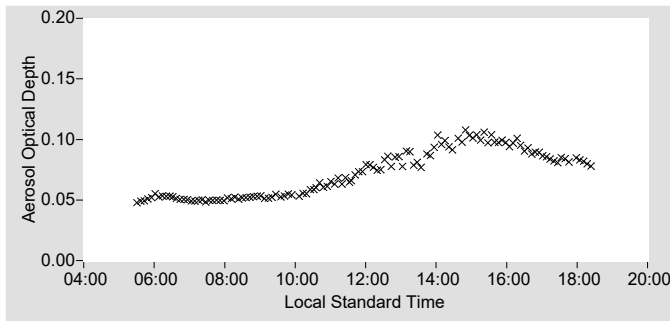


Table 6. Meteorological Observations

Observations	Mean	Min	Max
Temperature (°C)	14.76	3.41	20.37
Humidity (%)	44.65	28.20	82.33
Pressure (mBar)	822.5	819.4	825.6
Est. Aerosol Optical Depth (BB)	0.072	0.048	0.108

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).

Session Config: 1171 Apogee SP-510; Number: 4

Comments:

case temperature measured from case temp of spare apogee pyrgeometer