

Broadband Outdoor Radiometer Calibration Shortwave

BORCAL-SW 2021-04

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

07/07/2021

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 July 8, 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

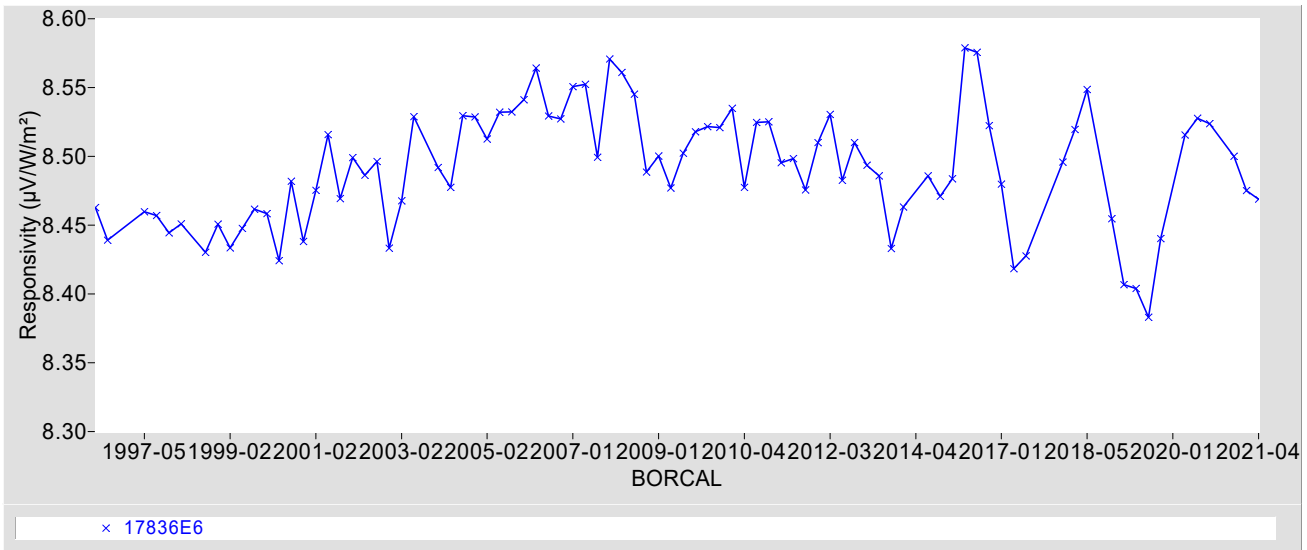


Figure 2. Eppley PSP Control Instrument History

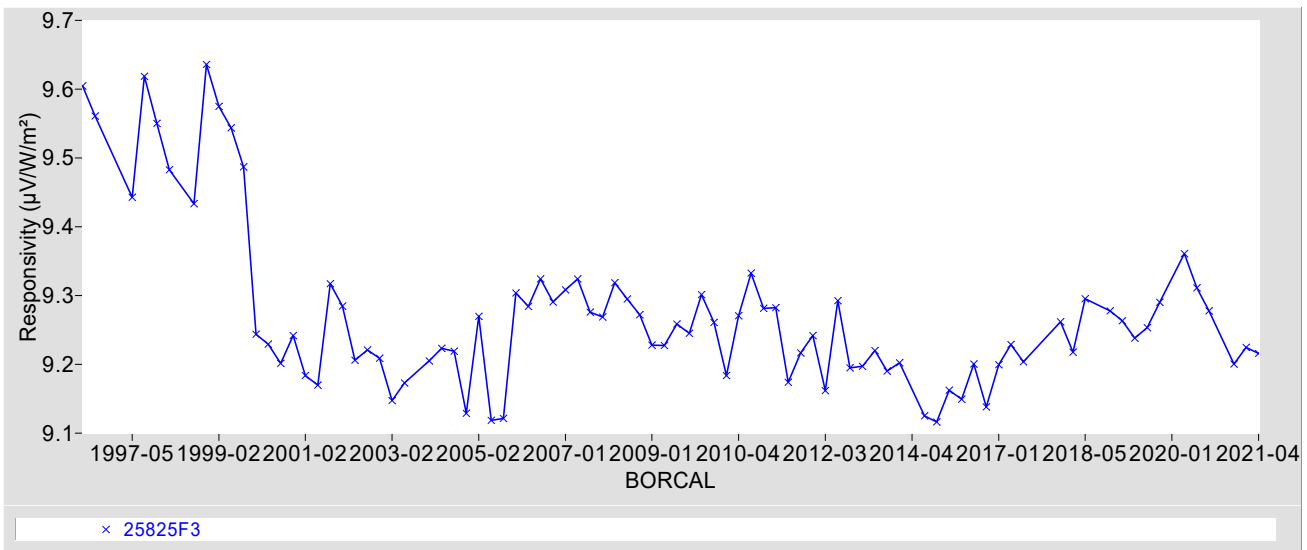
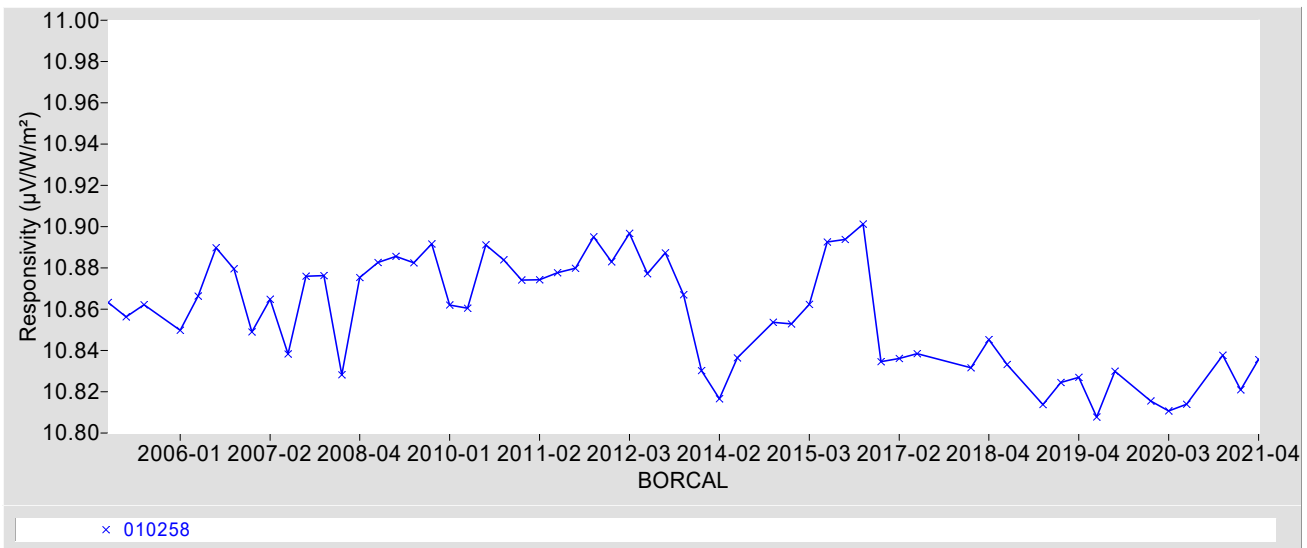


Figure 3. Kipp & Zonen CH1 Control Instrument History



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
125275 Kipp & Zonen SP-LITE2	66.573	15.021	+1.6 / -2.0	0	A1-2
170535 Kipp & Zonen CMP22	9.5799	104.39	+1.7 / -1.6	0.087000	A1-5
970003 Kipp & Zonen SP-LITE	83.052	12.041	+2.0 / -2.4	0	A1-8
PY102023 Licor LI200R	9.7515	102.55	+0.97 / -1.5	0	A1-11

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 A1-14.

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:	Silicon Pyranometer	Manufacturer:	Kipp & Zonen
Model:	SP-LITE2	Serial Number:	125275
Calibration Date:	7/7/2021	Due Date:	7/7/2022
Customer:	NREL-SRRL-BMS	Environmental Conditions:	see page 4
Test Dates:	7/7		

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, Mark Kutchenreiter, and RCC

Ibrahim Reda, Technical Manager

Date

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

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

Calibration Results

125275 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

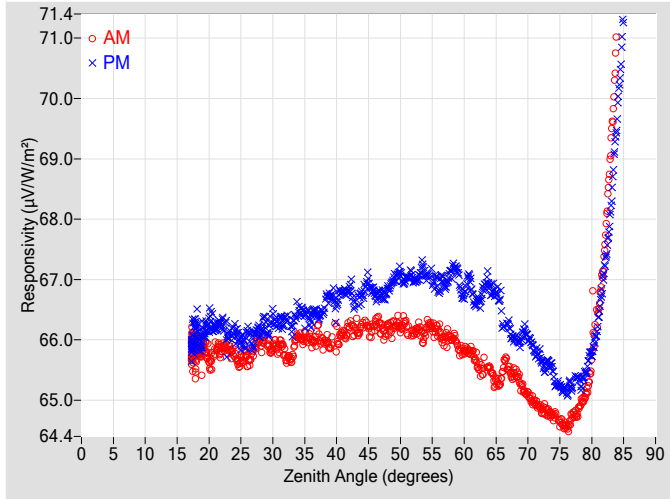


Figure 2. Responsivity vs Local Standard Time

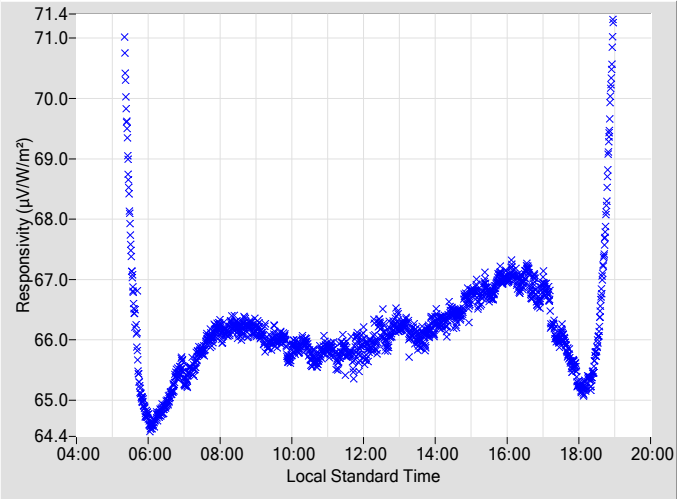


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, $u(B)$

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	66.252	0.33	96.32	66.746	0.33	263.61
2	N/A	N/A	N/A	N/A	N/A	N/A	48	66.198	0.35	94.51	66.822	0.32	265.42
4	N/A	N/A	N/A	N/A	N/A	N/A	50	66.200	0.32	92.72	67.097	0.33	267.21
6	N/A	N/A	N/A	N/A	N/A	N/A	52	66.109	0.35	91.02	67.008	0.34	268.95
8	N/A	N/A	N/A	N/A	N/A	N/A	54	66.169	0.33	89.34	67.071	0.36	270.63
10	N/A	N/A	N/A	N/A	N/A	N/A	56	66.167	0.36	87.70	66.875	0.35	272.24
12	N/A	N/A	N/A	N/A	N/A	N/A	58	66.024	0.39	86.09	67.156	0.38	273.84
14	N/A	N/A	N/A	N/A	N/A	N/A	60	65.818	0.36	84.51	66.764	0.39	275.42
16	N/A	N/A	N/A	N/A	N/A	N/A	62	65.625	0.37	82.99	66.633	0.38	276.94
18	65.729	0.33	162.02	66.199	0.34	197.99	64	65.521	0.38	81.45	66.858	0.39	278.52
20	65.679	0.29	146.03	66.306	0.33	214.16	66	65.479	0.40	79.89	66.365	0.41	280.01
22	65.837	0.31	136.92	66.251	0.34	223.08	68	65.442	0.45	78.37	66.015	0.43	281.57
24	65.782	0.31	130.12	66.119	0.32	229.90	70	65.091	0.45	76.82	66.029	N/A	283.11
26	65.660	0.32	124.69	66.105	0.34	235.29	72	64.862	0.48	75.27	65.697	N/A	284.66
28	65.939	0.34	120.24	66.141	0.30	239.70	74	64.752	N/A	73.72	65.405	N/A	286.21
30	65.876	0.32	116.40	66.346	0.30	243.61	76	64.575	N/A	72.13	65.156	N/A	287.77
32	65.717	0.33	113.09	66.351	0.32	246.90	78	64.851	N/A	70.53	65.345	N/A	289.37
34	66.064	0.31	110.00	66.500	0.35	249.97	80	65.825	N/A	68.91	65.804	N/A	291.06
36	65.997	0.34	107.27	66.316	0.30	252.65	82	67.483	N/A	67.20	67.196	N/A	292.70
38	65.959	0.32	104.81	66.514	0.34	255.15	84	70.886	N/A	65.65	69.724	N/A	294.43
40	66.021	0.32	102.44	66.538	0.33	257.45	86	N/A	N/A	N/A	N/A	N/A	N/A
42	66.240	0.34	100.35	66.861	0.31	259.64	88	N/A	N/A	N/A	N/A	N/A	N/A
44	66.230	0.33	98.36	66.752	0.33	261.68	90	N/A	N/A	N/A	N/A	N/A	N/A

N/A - Not Available

Figure 3. Type-B Standard Uncertainty vs Zenith Angle

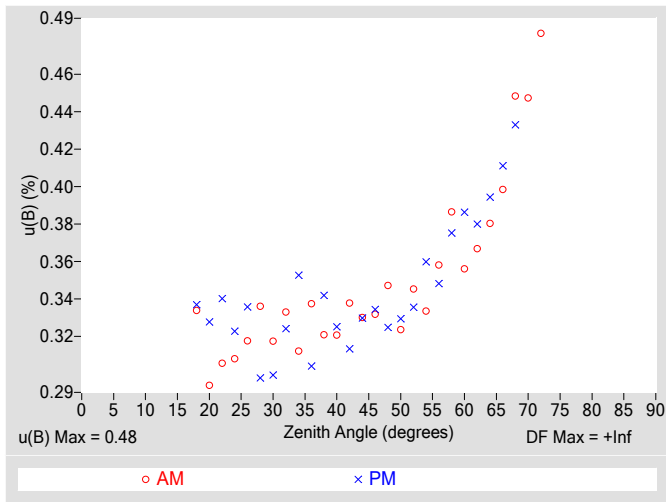


Figure 4. Residuals from Spline Interpolation

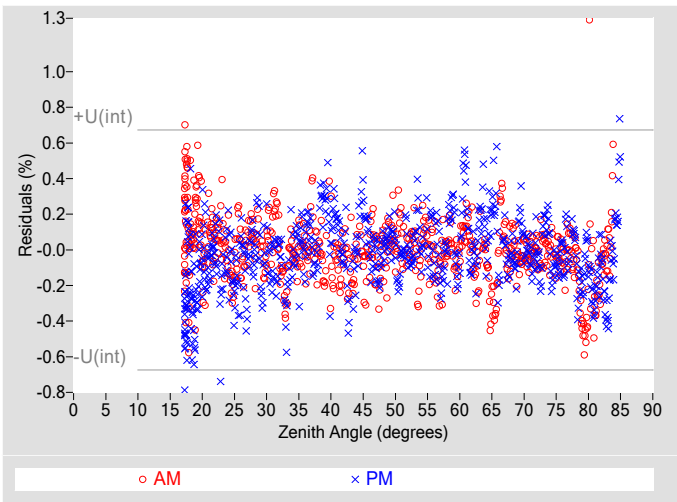


Table 3. Uncertainty using Spline Interpolation ‡

Type-B Standard Uncertainty, $u(B)$ (%)	± 0.48
Type-A Interpolating Function, $u(int)$ (%)	± 0.34
Combined Standard Uncertainty, $u(c)$ (%)	± 0.59
Effective degrees of freedom, $DF(c)$	11073
Coverage factor, k	1.96
Expanded Uncertainty, U_{95} (%)	± 1.2
AM Valid zenith angle range	18° to 72°
PM Valid zenith angle range	18° to 68°

‡ 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

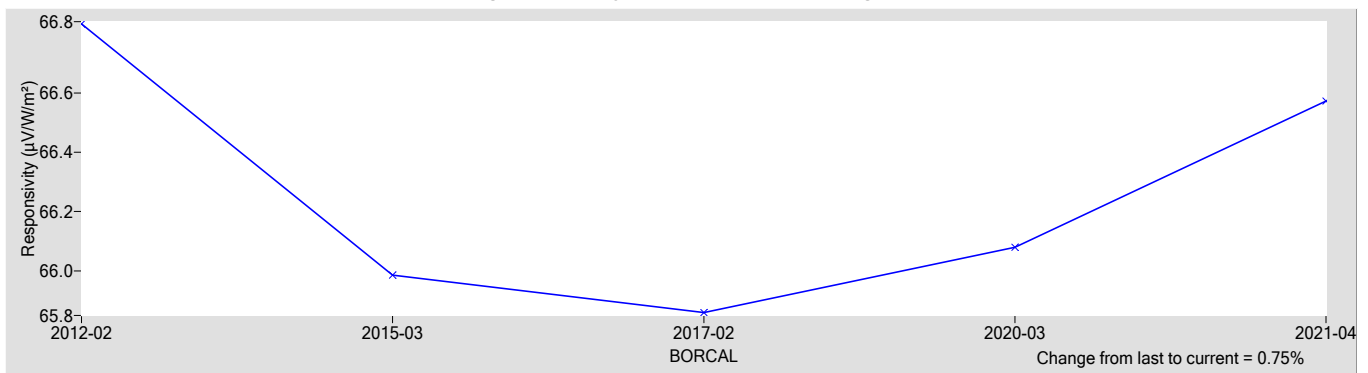
$R @ 45^\circ$ ($\mu V/W/m^2$)	R_{net} ($\mu V/W/m^2$) †
66.573	0

† R_{net} determination date: N/A

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

Type-B Expanded Uncertainty, $U(B)$ (%)	± 0.76
Offset Uncertainty, $U(off)$ (%)	+0.88 / -1.3
Expanded Uncertainty, U (%)	+1.6 / -2.0
Effective degrees of freedom, DF	+Inf
Coverage factor, k	1.96
Valid zenith angle range	30.0° to 60.0°

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



References:

- [1] Reda, I.; Hickey, J.; Long, C.; Myers, D.; Stoffel, T.; Wilcox, S.; Michalsky, J. J.; Dutton, E. G.; Nelson, D. (2005). "Using a Blackbody to Calculate Net Longwave Responsivity of Shortwave Solar Pyranometers to Correct for Their Thermal Offset Error During Outdoor Calibration Using the Component Sum Method." *Journal of Atmospheric and Oceanic Technology*, 2005; pp. 1531-1540; NREL Report No. JA-560-36646. doi:10.1175/JTECH1782.1
- [2] Reda, I.; Myers, D.; Stoffel, T. (2008). "Uncertainty Estimate for the Outdoor Calibration of Solar Pyranometers: A Metrologist Perspective." *Measure*. (NCSLI *Journal of Measurement Science*). Vol. 3(4), December 2008; pp. 58-66; NREL Report No. JA-581-4137
- [3] Reda, I.; Andreas, A. (2004). "Solar Position Algorithm for Solar Radiation Applications." *Solar Energy*. Vol. 76(5), 2004; pp. 577-589; NREL Report No. JA-560-35518. doi:10.1016/j.solener.2003.12.003
- [4] Stoffel, T.; Reda, I. (2009). "NREL Pyrheliometer Comparisons: 22 September - 3 October 2008 (NPC-2008)." 54 pp.; NREL Report No. TP-550-45016.
- [5] Reda, I.; Stoffel, T.; Myers, D. (2003). "Method to Calibrate a Solar Pyranometer for Measuring Reference Diffuse Irradiance." *Solar Energy*. Vol. 74, 2003; pp. 103-112; NREL Report No. JA-560-35025. doi:10.1016/S0038-092X(03)00124-5
- [6] Reda, I. (1996). *Calibration of a Solar Absolute Cavity Radiometer with Traceability to the World Radiometric Reference*. 79 pp.; NREL Report No. TP-463-20619.
- [7] Reda, I.; Gröbner, J.; Stoffel, T.; Myers, D.; Forgan, B. (2008). *Improvements in the Blackbody Calibration of 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:	170535
Calibration Date:	7/7/2021	Due Date:	7/7/2022
Customer:	NREL-SRRL-BMS	Environmental Conditions:	see page 4
Test Dates:	7/7		

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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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, Mark Kutchenreiter, and RCC

Ibrahim Reda, Technical Manager

Date

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

Calibration Results

170535 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

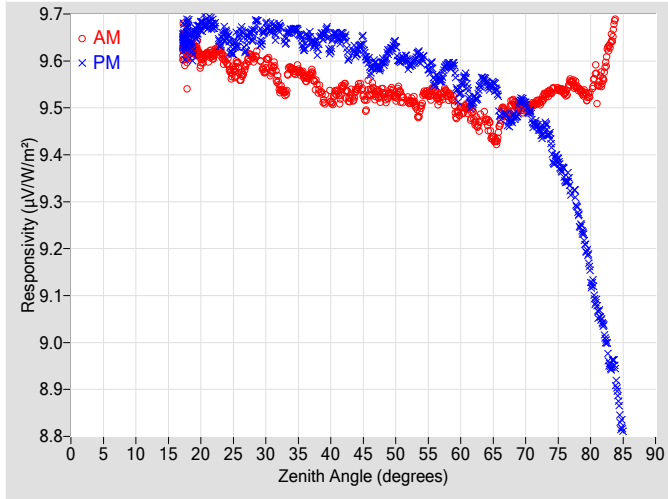


Figure 2. Responsivity vs Local Standard Time

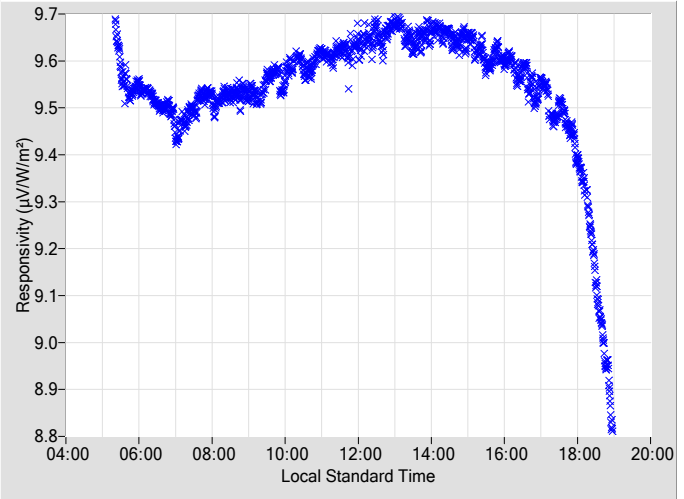


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)

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	9.5367	0.35	96.38	9.5861	0.34	263.61
2	N/A	N/A	N/A	N/A	N/A	N/A	48	9.5325	0.32	94.51	9.5977	0.33	265.47
4	N/A	N/A	N/A	N/A	N/A	N/A	50	9.5227	0.36	92.72	9.6279	0.33	267.22
6	N/A	N/A	N/A	N/A	N/A	N/A	52	9.5138	0.33	90.99	9.5926	0.34	268.95
8	N/A	N/A	N/A	N/A	N/A	N/A	54	9.5097	0.34	89.35	9.6049	0.36	270.59
10	N/A	N/A	N/A	N/A	N/A	N/A	56	9.5344	0.38	87.70	9.5565	0.37	272.24
12	N/A	N/A	N/A	N/A	N/A	N/A	58	9.5284	0.35	86.09	9.5938	0.36	273.85
14	N/A	N/A	N/A	N/A	N/A	N/A	60	9.4952	0.36	84.55	9.5395	0.37	275.43
16	N/A	N/A	N/A	N/A	N/A	N/A	62	9.4811	0.37	82.99	9.5167	0.39	276.98
18	9.6197	0.31	161.33	9.6653	0.33	198.13	64	9.4685	0.39	81.45	9.5526	0.40	278.52
20	9.6057	0.31	146.08	9.6750	0.32	213.78	66	9.4632	0.41	79.89	9.4918	0.42	280.01
22	9.6140	0.32	136.81	9.6775	0.33	222.96	68	9.5109	0.43	78.37	9.4790	0.44	281.57
24	9.6001	0.30	130.16	9.6550	0.34	229.89	70	9.5019	0.46	76.82	9.5053	N/A	283.12
26	9.5730	0.33	124.74	9.6592	0.35	235.25	72	9.5121	0.49	75.27	9.4571	N/A	284.67
28	9.6070	0.33	120.31	9.6567	0.31	239.71	74	9.5356	N/A	73.72	9.4124	N/A	286.21
30	9.5867	0.33	116.45	9.6717	0.31	243.63	76	9.5315	N/A	72.13	9.3524	N/A	287.81
32	9.5482	0.32	113.03	9.6719	0.31	246.98	78	9.5422	N/A	70.53	9.2770	N/A	289.41
34	9.5833	0.33	110.01	9.6659	0.34	249.93	80	9.5296	N/A	68.93	9.1395	N/A	291.03
36	9.5632	0.35	107.28	9.6327	0.31	252.62	82	9.5662	N/A	67.20	9.0254	N/A	292.74
38	9.5458	0.32	104.76	9.6330	0.34	255.14	84	9.6876	N/A	65.70	8.9047	N/A	294.47
40	9.5169	0.33	102.42	9.6285	0.31	257.46	86	N/A	N/A	N/A	N/A	N/A	N/A
42	9.5468	0.37	100.34	9.6527	0.33	259.65	88	N/A	N/A	N/A	N/A	N/A	N/A
44	9.5379	0.36	98.31	9.6170	0.33	261.68	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

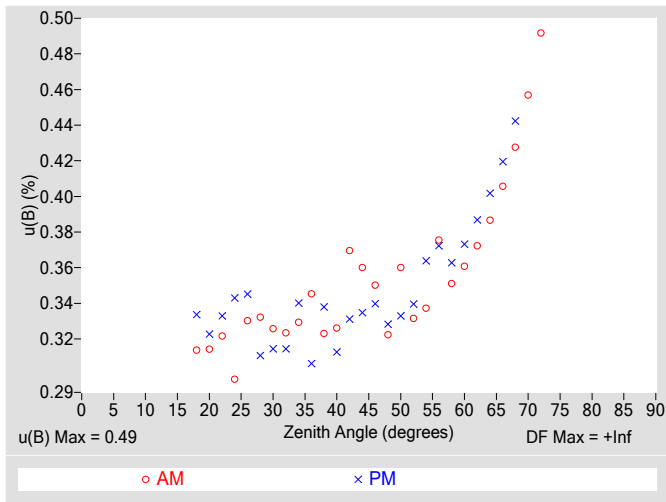


Figure 4. Residuals from Spline Interpolation

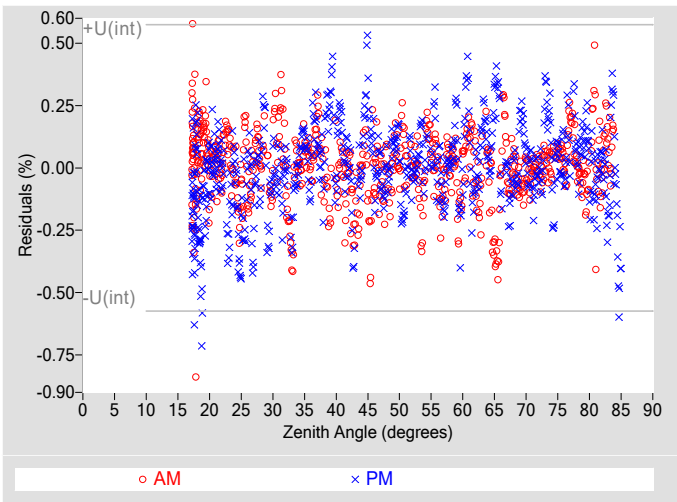


Table 3. Uncertainty using Spline Interpolation ‡

Type-B Standard Uncertainty, $u(B)$ (%)	± 0.49
Type-A Interpolating Function, $u(int)$ (%)	± 0.29
Combined Standard Uncertainty, $u(c)$ (%)	± 0.57
Effective degrees of freedom, $DF(c)$	18417
Coverage factor, k	1.96
Expanded Uncertainty, U_{95} (%)	± 1.1
AM Valid zenith angle range	18° to 72°
PM Valid zenith angle range	18° to 68°

‡ 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

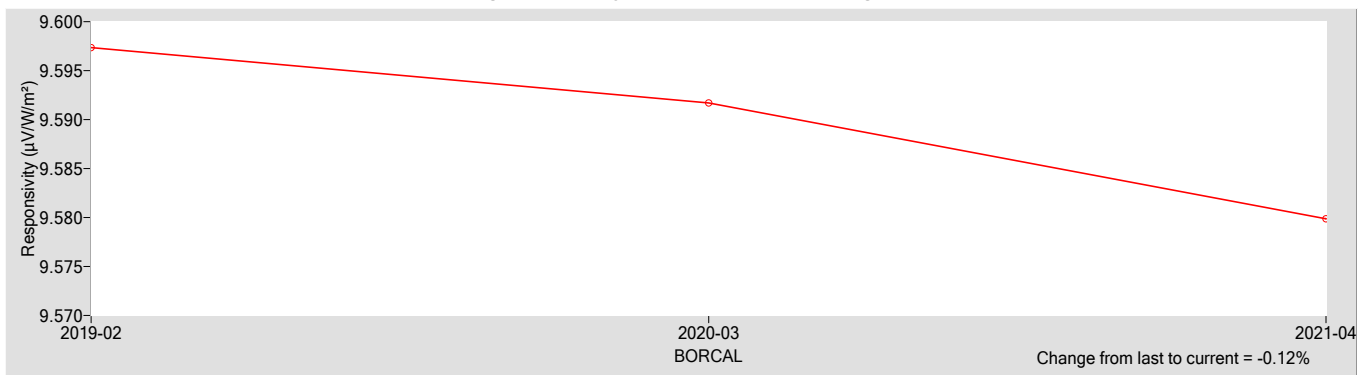
$R @ 45^\circ$ ($\mu V/W/m^2$)	R_{net} ($\mu V/W/m^2$) †
9.5799	0.087000

† R_{net} determination date: Estimated

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

Type-B Expanded Uncertainty, $U(B)$ (%)	± 0.74
Offset Uncertainty, $U(off)$ (%)	+0.96 / -0.88
Expanded Uncertainty, U (%)	+1.7 / -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: Silicon Pyranometer	Manufacturer: Kipp & Zonen
Model: SP-LITE	Serial Number: 970003
Calibration Date: 7/7/2021	Due Date: 7/7/2022
Customer: NREL-SRRL-BMS	Environmental Conditions: see page 4
Test Dates: 7/7	

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, Mark Kutchenreiter, and RCC

Ibrahim Reda, Technical Manager

Date

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

Calibration Results

970003 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

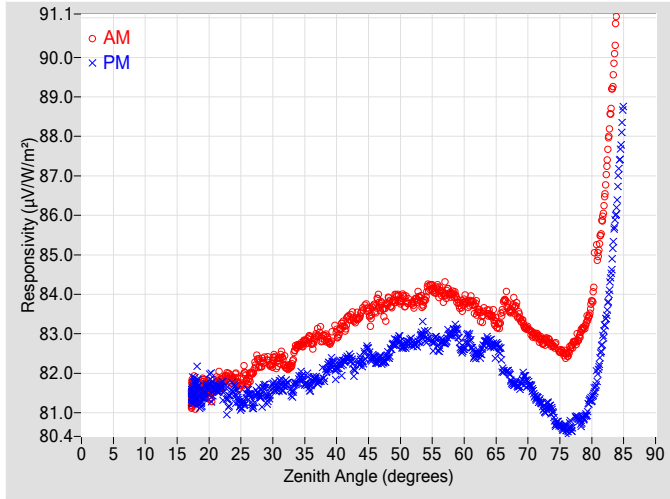


Figure 2. Responsivity vs Local Standard Time

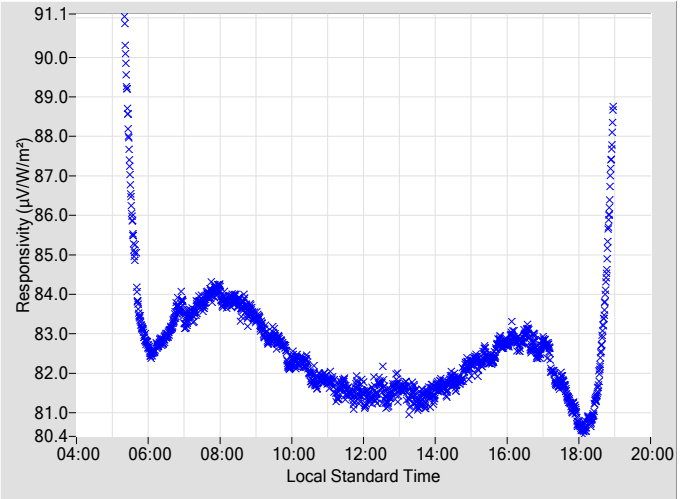


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, $u(B)$

Zenith 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	83.654	0.33	96.32	82.340	0.33	263.61
2	N/A	N/A	N/A	N/A	N/A	N/A	48	83.814	0.34	94.46	82.439	0.32	265.42
4	N/A	N/A	N/A	N/A	N/A	N/A	50	83.843	0.32	92.72	82.810	0.33	267.21
6	N/A	N/A	N/A	N/A	N/A	N/A	52	83.751	0.35	91.02	82.737	0.34	268.95
8	N/A	N/A	N/A	N/A	N/A	N/A	54	83.958	0.33	89.34	82.921	0.36	270.63
10	N/A	N/A	N/A	N/A	N/A	N/A	56	84.114	0.36	87.70	82.697	0.35	272.24
12	N/A	N/A	N/A	N/A	N/A	N/A	58	84.008	0.39	86.09	83.006	0.38	273.84
14	N/A	N/A	N/A	N/A	N/A	N/A	60	83.833	0.36	84.51	82.667	0.39	275.42
16	N/A	N/A	N/A	N/A	N/A	N/A	62	83.643	0.37	82.99	82.484	0.38	276.94
18	81.421	0.33	162.02	81.699	0.34	197.99	64	83.491	0.38	81.45	82.755	0.39	278.52
20	81.508	0.29	146.03	81.733	0.33	214.16	66	83.630	0.40	79.89	82.205	0.41	280.01
22	81.796	0.31	136.92	81.643	0.34	223.08	68	83.716	0.45	78.37	81.731	0.43	281.57
24	81.898	0.31	130.12	81.521	0.32	229.90	70	83.123	0.45	76.82	81.723	N/A	283.11
26	81.815	0.32	124.69	81.498	0.34	235.29	72	82.840	0.48	75.27	81.257	N/A	284.66
28	82.214	0.34	120.24	81.425	0.30	239.70	74	82.689	N/A	73.72	80.910	N/A	286.21
30	82.308	0.32	116.40	81.667	0.30	243.61	76	82.474	N/A	72.13	80.573	N/A	287.77
32	82.207	0.33	113.09	81.727	0.32	246.90	78	82.924	N/A	70.53	80.825	N/A	289.37
34	82.696	0.31	110.00	81.829	0.35	249.97	80	83.775	N/A	68.91	81.381	N/A	291.06
36	82.797	0.34	107.27	81.681	0.30	252.65	82	86.442	N/A	67.20	83.162	N/A	292.70
38	82.899	0.32	104.81	81.957	0.34	255.15	84	90.947	N/A	65.65	86.505	N/A	294.43
40	83.018	0.32	102.44	82.082	0.33	257.45	86	N/A	N/A	N/A	N/A	N/A	N/A
42	83.417	0.34	100.35	82.371	0.31	259.64	88	N/A	N/A	N/A	N/A	N/A	N/A
44	83.557	0.33	98.36	82.309	0.33	261.68	90	N/A	N/A	N/A	N/A	N/A	N/A

N/A - Not Available

Figure 3. Type-B Standard Uncertainty vs Zenith Angle

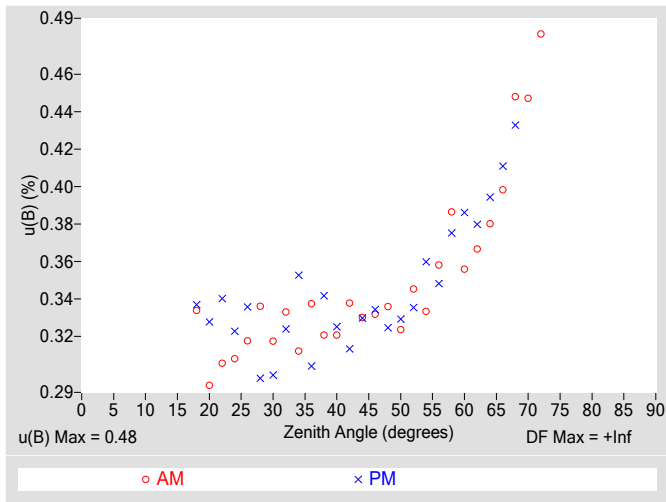


Figure 4. Residuals from Spline Interpolation

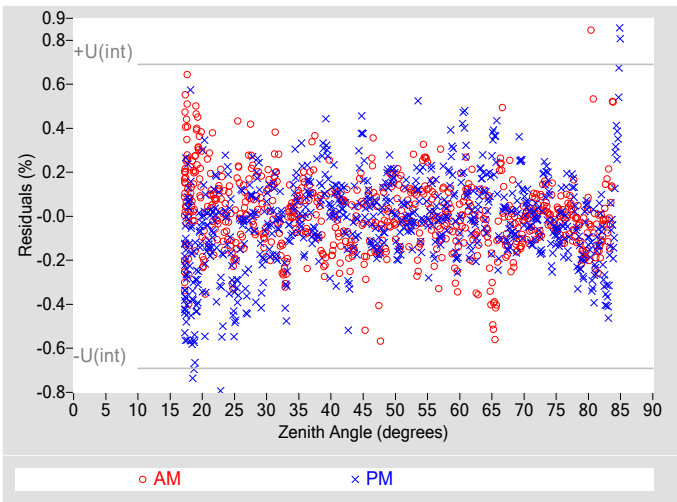


Table 3. Uncertainty using Spline Interpolation ‡

Type-B Standard Uncertainty, $u(B)$ (%)	± 0.48
Type-A Interpolating Function, $u(int)$ (%)	± 0.35
Combined Standard Uncertainty, $u(c)$ (%)	± 0.59
Effective degrees of freedom, $DF(c)$	10336
Coverage factor, k	1.96
Expanded Uncertainty, $U95$ (%)	± 1.2
AM Valid zenith angle range	18° to 72°
PM Valid zenith angle range	18° to 68°

‡ 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

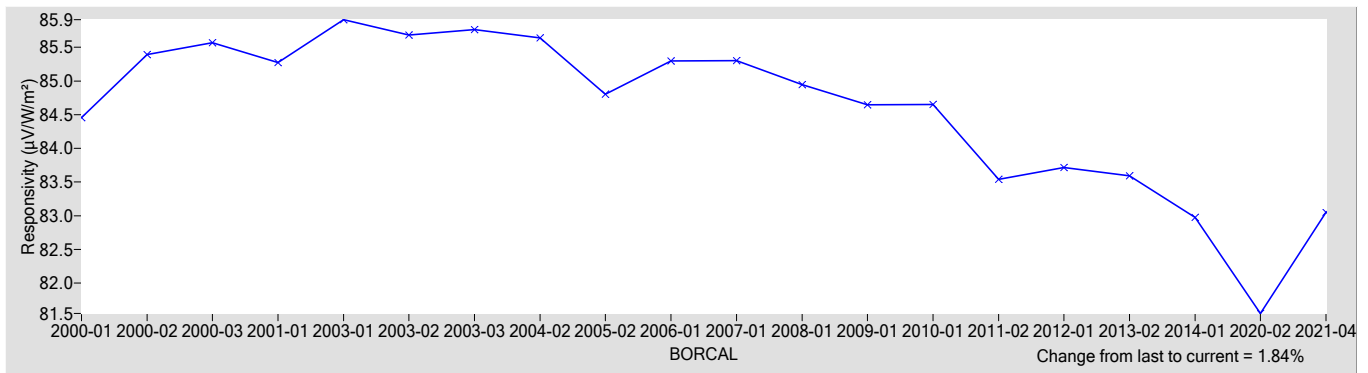
$R @ 45^\circ$ ($\mu V/W/m^2$)	R_{net} ($\mu V/W/m^2$) †
83.052	0

† R_{net} determination date: N/A

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

Type-B Expanded Uncertainty, $U(B)$ (%)	± 0.76
Offset Uncertainty, $U(off)$ (%)	+1.3 / -1.7
Expanded Uncertainty, U (%)	+2.0 / -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

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

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

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

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

[7] Reda, I.; Gröbner, J.; Stoffel, T.; Myers, D.; Forgan, B. (2008). Improvements in the Blackbody Calibration of Pyrgometers. 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:	PY102023
Calibration Date:	7/7/2021	Due Date:	7/7/2022
Customer:	NREL-SRRL-BMS	Environmental Conditions:	see page 4
Test Dates:	7/7		

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, Mark Kutchenreiter, and RCC

Ibrahim Reda, Technical Manager

Date

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

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

Calibration Results

PY102023 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

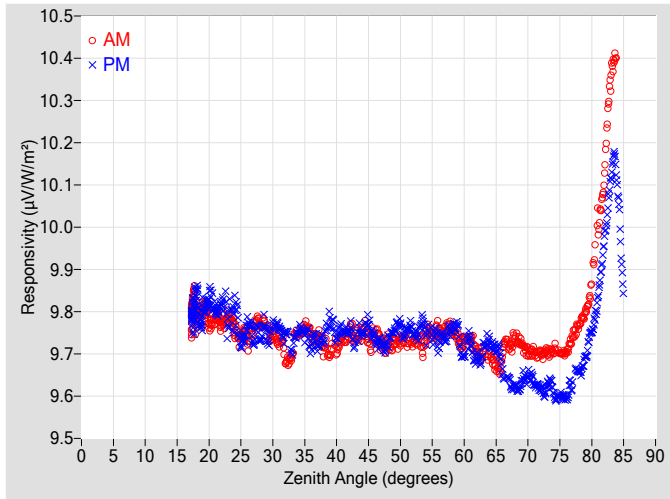


Figure 2. Responsivity vs Local Standard Time

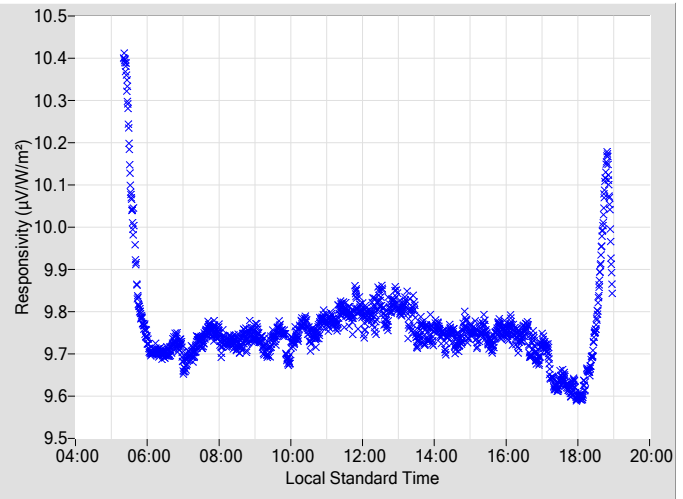


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, $u(B)$

Zenith Angle (deg.)	R ($\mu\text{V}/\text{W}/\text{m}^2$)	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	9.7422	0.32	96.33	9.7363	0.32	263.57
2	N/A	N/A	N/A	N/A	N/A	N/A	48	9.7276	0.35	94.51	9.7277	0.33	265.43
4	N/A	N/A	N/A	N/A	N/A	N/A	50	9.7321	0.33	92.72	9.7651	0.33	267.22
6	N/A	N/A	N/A	N/A	N/A	N/A	52	9.7259	0.33	90.99	9.7505	0.34	268.95
8	N/A	N/A	N/A	N/A	N/A	N/A	54	9.7396	0.34	89.35	9.7462	0.36	270.63
10	N/A	N/A	N/A	N/A	N/A	N/A	56	9.7563	0.40	87.70	9.7266	0.35	272.24
12	N/A	N/A	N/A	N/A	N/A	N/A	58	9.7568	0.35	86.09	9.7568	0.38	273.85
14	N/A	N/A	N/A	N/A	N/A	N/A	60	9.7320	0.36	84.52	9.6952	0.37	275.35
16	N/A	N/A	N/A	N/A	N/A	N/A	62	9.7044	0.37	82.96	9.6909	0.38	276.95
18	9.7913	0.31	161.65	9.8296	0.33	198.13	64	9.7002	0.41	81.42	9.7282	0.40	278.49
20	9.7827	0.34	146.08	9.8314	0.32	213.60	66	9.7007	0.40	79.89	9.6606	0.42	280.01
22	9.7729	0.32	136.81	9.8176	0.32	223.09	68	9.7373	0.43	78.37	9.6220	0.44	281.57
24	9.7619	0.32	130.09	9.7930	0.30	229.83	70	9.7038	0.45	76.82	9.6463	N/A	283.12
26	9.7364	0.31	124.67	9.7677	0.32	235.27	72	9.7026	0.49	75.27	9.6183	N/A	284.67
28	9.7716	0.32	120.31	9.7398	0.30	239.71	74	9.7090	N/A	73.72	9.6075	N/A	286.22
30	9.7442	0.32	116.33	9.7701	0.30	243.73	76	9.7035	N/A	72.13	9.5964	N/A	287.77
32	9.6834	0.32	112.99	9.7466	0.31	246.91	78	9.7677	N/A	70.53	9.6589	N/A	289.38
34	9.7466	0.33	110.03	9.7552	0.35	249.92	80	9.8624	N/A	68.96	9.7563	N/A	291.07
36	9.7448	0.32	107.30	9.7181	0.31	252.66	82	10.131	N/A	67.20	9.9729	N/A	292.70
38	9.7164	0.33	104.81	9.7377	0.35	255.08	84	10.400	N/A	65.66	10.097	N/A	294.43
40	9.7142	0.33	102.48	9.7368	0.36	257.45	86	N/A	N/A	N/A	N/A	N/A	N/A
42	9.7561	0.34	100.31	9.7563	0.33	259.65	88	N/A	N/A	N/A	N/A	N/A	N/A
44	9.7457	0.34	98.26	9.7478	0.32	261.63	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

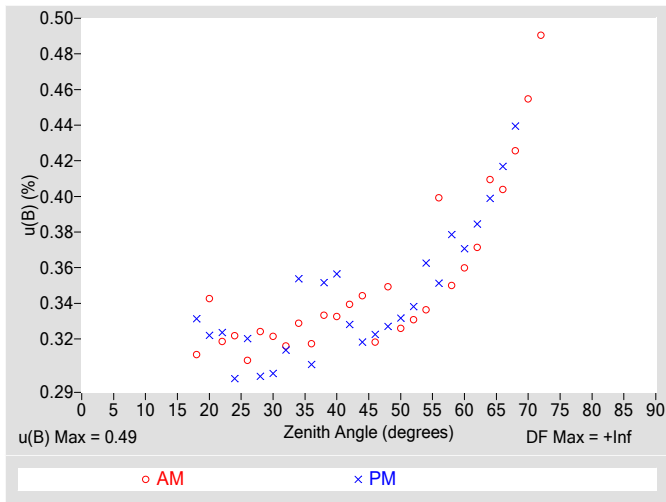


Figure 4. Residuals from Spline Interpolation

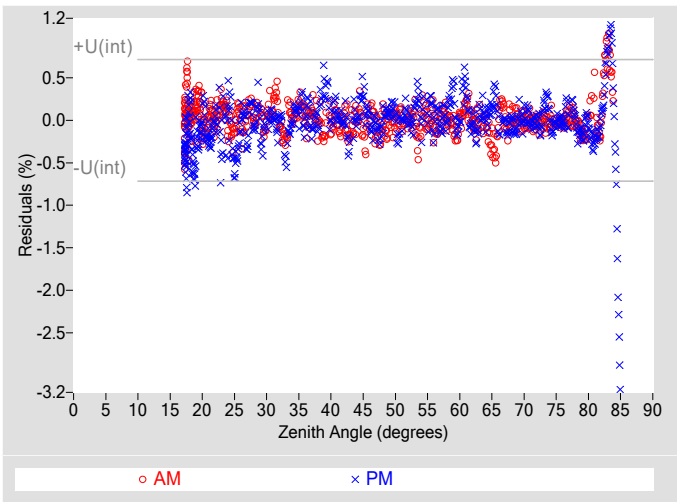


Table 3. Uncertainty using Spline Interpolation ‡

Type-B Standard Uncertainty, $u(B)$ (%)	± 0.49
Type-A Interpolating Function, $u(int)$ (%)	± 0.36
Combined Standard Uncertainty, $u(c)$ (%)	± 0.61
Effective degrees of freedom, $DF(c)$	9996
Coverage factor, k	1.96
Expanded Uncertainty, $U95$ (%)	± 1.2
AM Valid zenith angle range	18° to 72°
PM Valid zenith angle range	18° to 68°

‡ 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

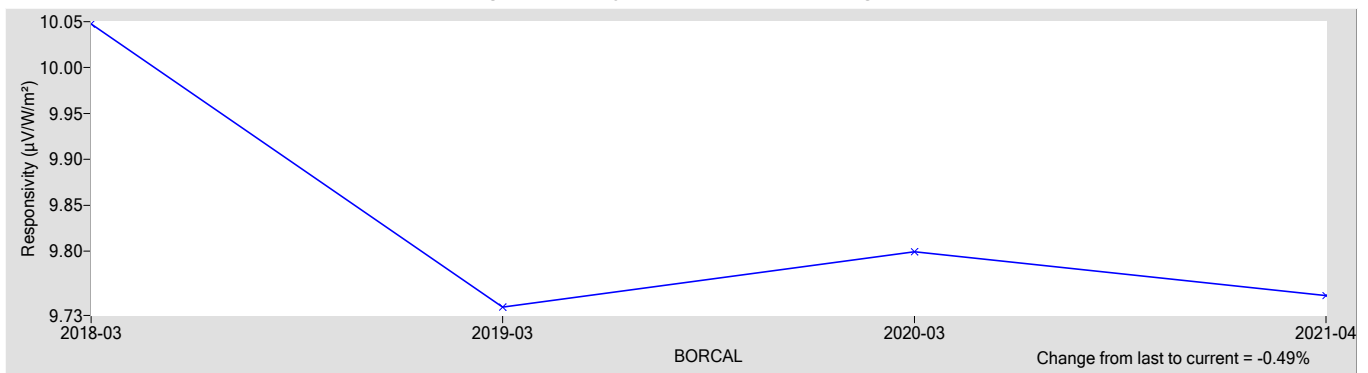
$R @ 45^\circ$ ($\mu V/W/m^2$)	R_{net} ($\mu V/W/m^2$) †
9.7515	0

† R_{net} determination date: N/A

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

Type-B Expanded Uncertainty, $U(B)$ (%)	± 0.78
Offset Uncertainty, $U(off)$ (%)	+0.19 / -0.70
Expanded Uncertainty, U (%)	+0.97 / -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).

Environmental and Sky Conditions for BORCAL-SW 2021-04

Calibration Facility: Solar Radiation Research Laboratory

Latitude: 39.742°N

Longitude: 105.180°W

Elevation: 1828.8 meters AMSL

Time Zone: -7.0

Reference Irradiance:

Figure 6. Reference Irradiance

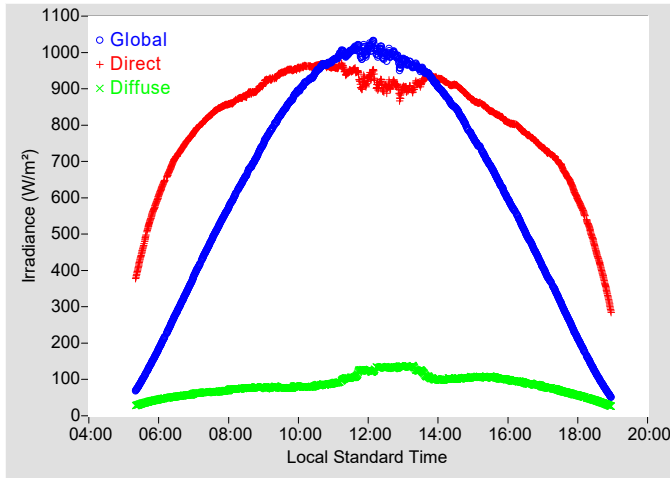
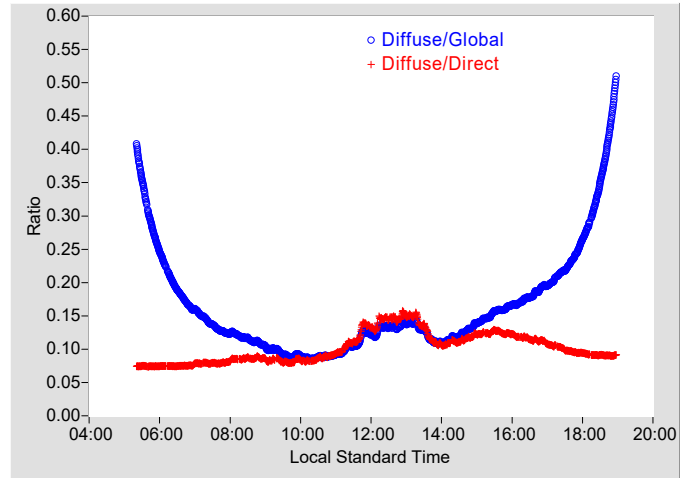


Figure 7. Diffuse Ratios



Meteorological Observations:

Figure 8. Temperature

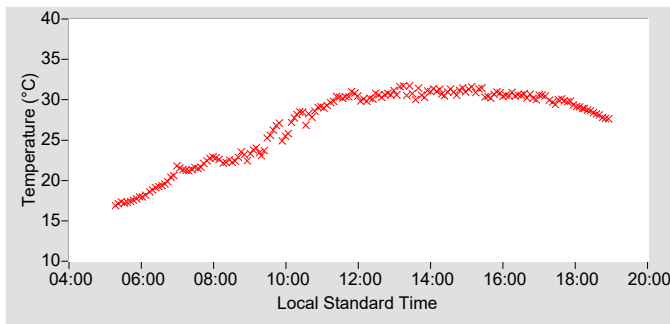


Figure 9. Humidity

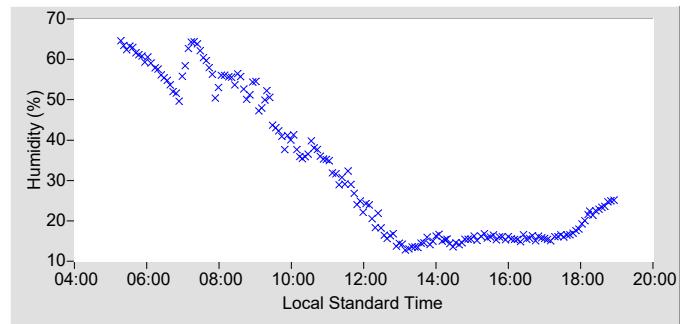


Figure 10. Pressure

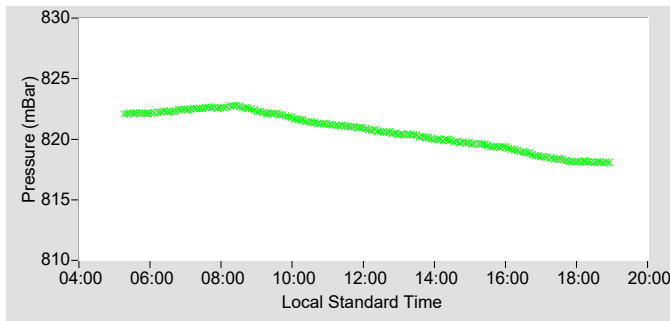


Figure 11. Effective Net Infrared

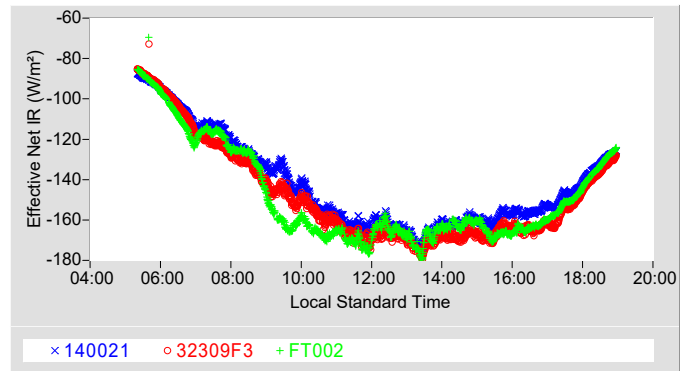


Figure 12. Estimated Broadband Aerosol Optical Depth

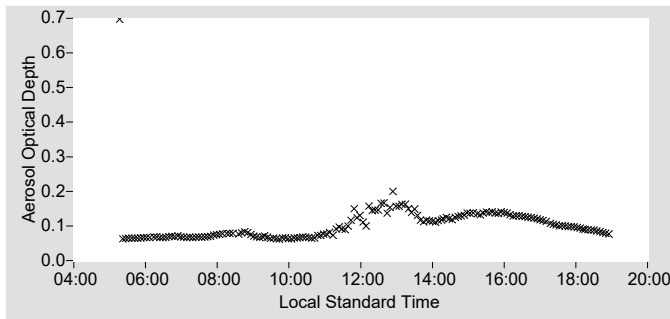


Table 6. Meteorological Observations

Observations	Mean	Min	Max
Temperature (°C)	27.05	16.91	31.73
Humidity (%)	32.45	12.77	64.59
Pressure (mBar)	820.7	818.1	822.8
Est. Aerosol Optical Depth (BB)	0.103	0.062	0.697

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).