

# Broadband Outdoor Radiometer Calibration Shortwave

## BORCAL-SW 2025-02

Generated by



*Radiometer Calibration and Characterization*

### Customer

**NREL-SRRL-BMS**

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### 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

05/02/2025

Report Date

May 5, 2025



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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.

# Control Instrument History

Figure 1. Eppley NIP Control Instrument History

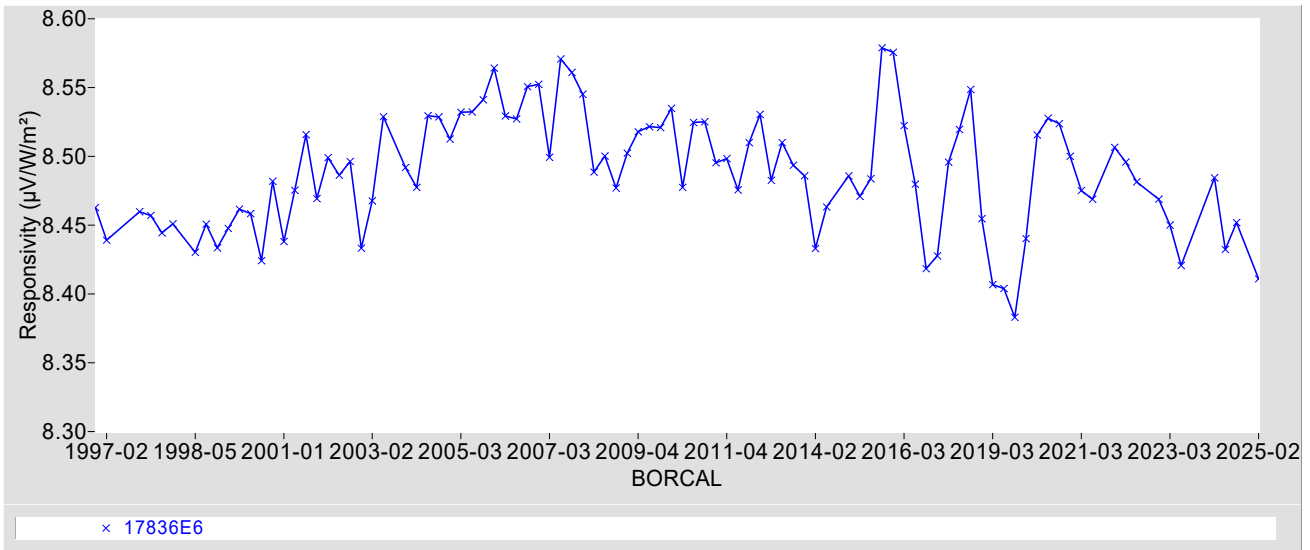


Figure 2. Eppley PSP Control Instrument History

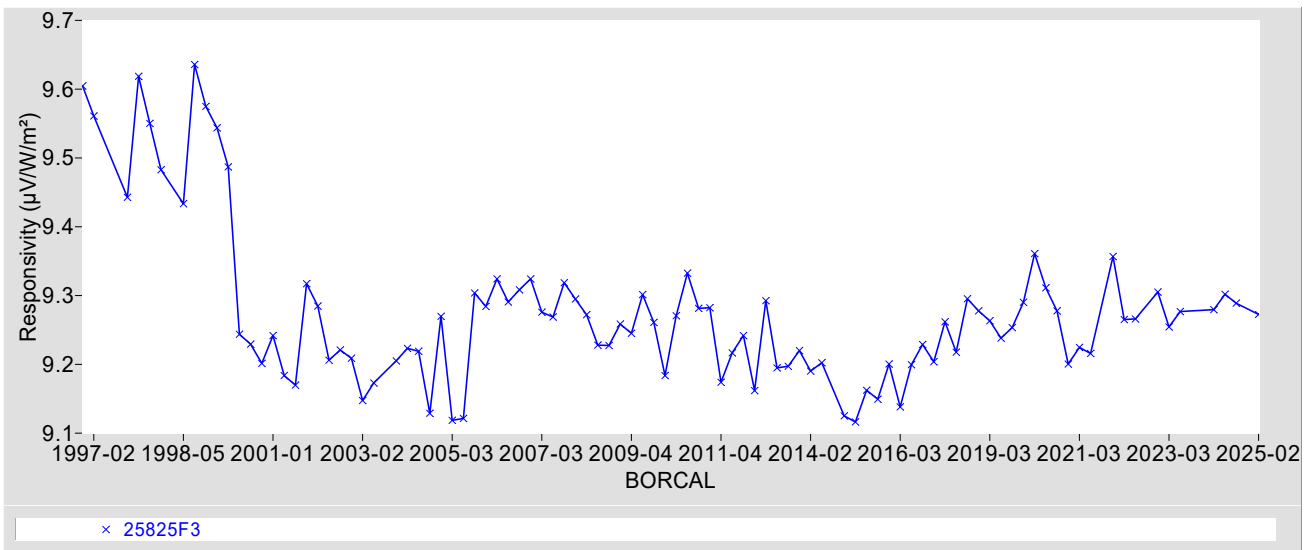
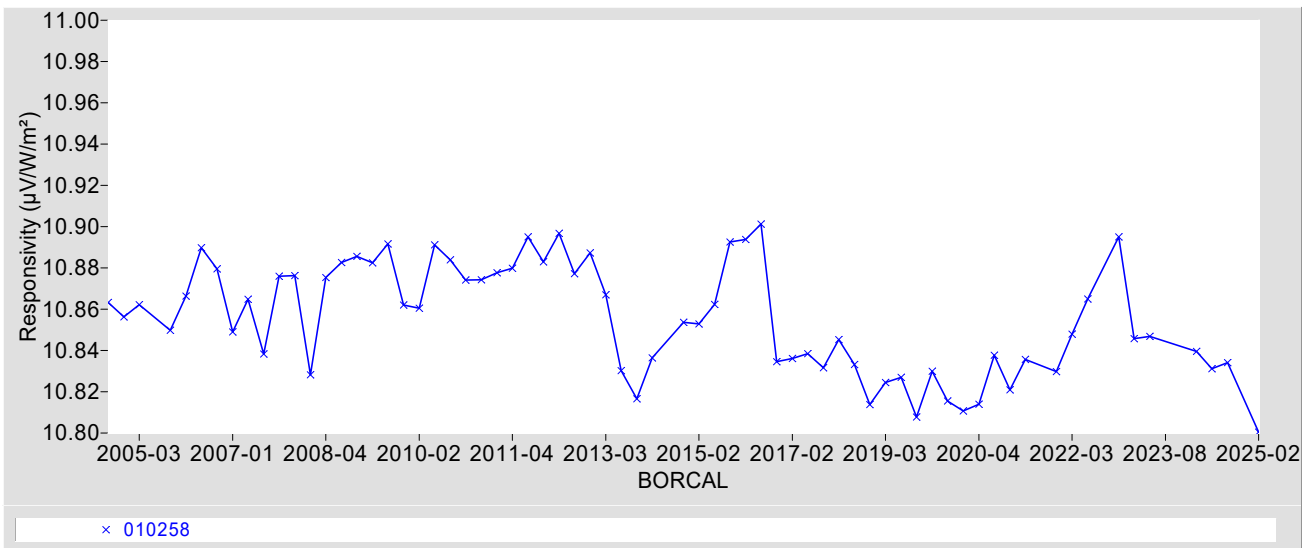


Figure 3. Kipp & Zonen CH1 Control Instrument History



# Control Instrument History

Figure 4. Kipp & Zonen CHP1 Control Instrument History

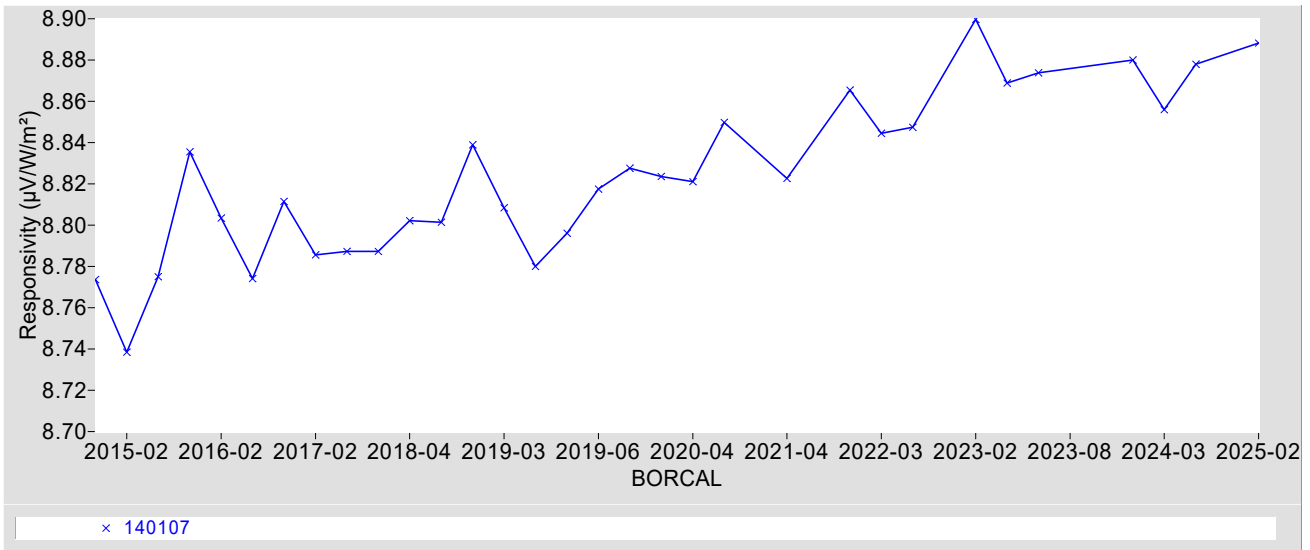


Figure 5. Kipp & Zonen CM22 Control Instrument History

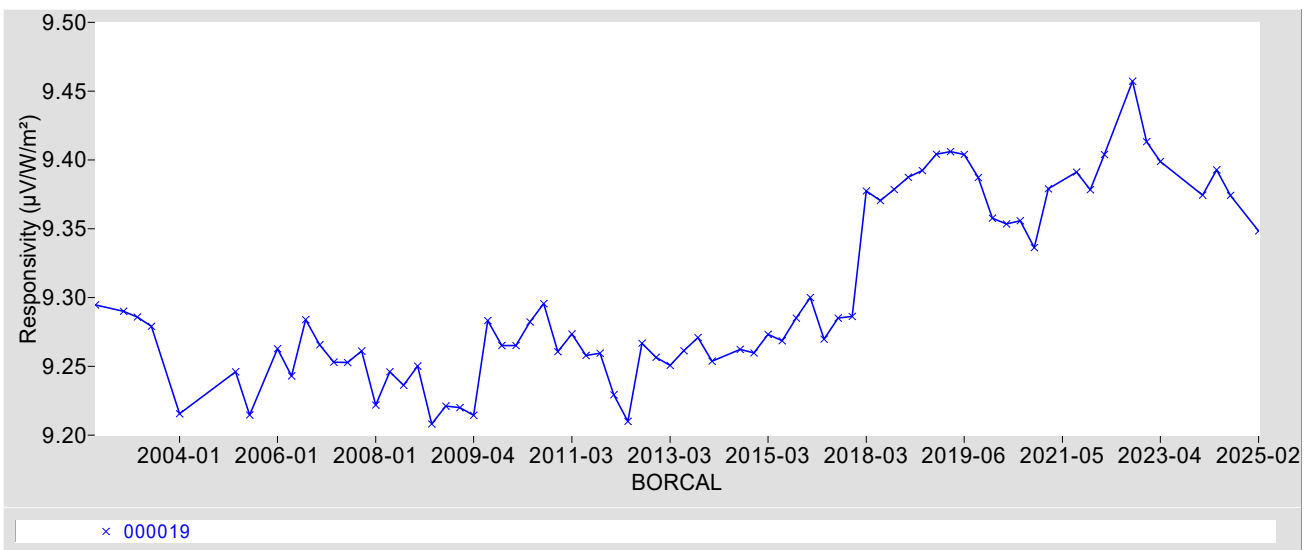
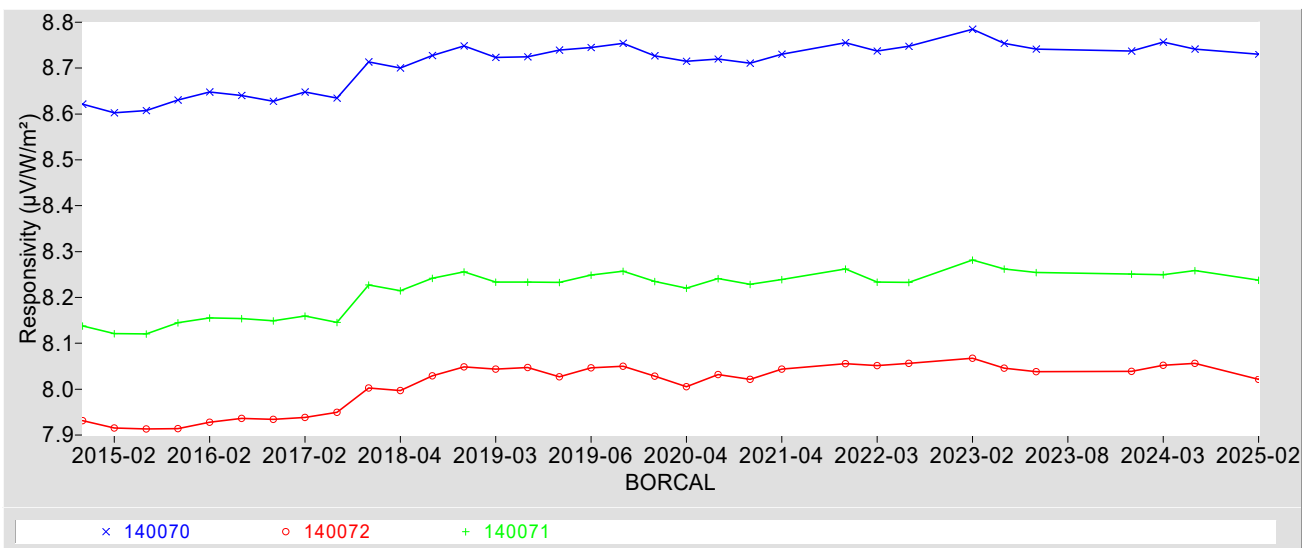


Figure 6. Kipp & Zonen CMP22 Control Instrument History



# Results Summary

**Table 1. Results Summary**

Instrument	R@45 <sup>1</sup> ( $\mu\text{V}/\text{W}/\text{m}^2$ )	CF@45 <sup>1</sup> ( $\text{W}/\text{m}^2/\text{mV}$ )	U <sup>2</sup> (%)	Rnet <sup>3</sup> ( $\mu\text{V}/\text{W}/\text{m}^2$ )	Page
010034 Kipp & Zonen CM22	10.817	92.449	+1.8 / -1.6	0.087000	A1-2
010047 Kipp & Zonen CM22	9.7217	102.86	+1.0 / -1.1	0.087000	A1-5
010284-UW-CM3 Kipp & Zonen CM3	18.188	54.980	+1.9 / -3.0	0.40000	A1-8
010995 Kipp & Zonen SP-LITE	75.778	13.196	+1.8 / -1.5	0	A1-11
014261 Kipp & Zonen CM3	22.058	45.335	+1.6 / -2.5	0.40000	A1-14
015189 Kipp & Zonen CM6B	10.903	91.714	+1.2 / -1.4	0.30000	A1-17
0212-2 Yankee TSP-700	2945.1	0.33955	+2.5 / -1.9	0	A1-20
080009 Kipp & Zonen CHP1	7.9200	126.26	+0.80 / -0.79	0	A1-23
100174 Kipp & Zonen CMP22	9.8110	101.93	+1.3 / -0.99	0.087000	A1-26
1171 Apogee SP-510	51.510	19.414	+2.8 / -5.7	2.5000	A1-29
120076 Kipp & Zonen SMP11	10.149	98.527	+1.3 / -2.0	0.20500	A1-32
125275 Kipp & Zonen SP-LITE2	65.928	15.168	+1.8 / -1.7	0	A1-35
140043 Kipp & Zonen CMP22	9.0961	109.94	+1.2 / -1.1	0.087000	A1-38
140108 Kipp & Zonen CHP1	8.1250	123.08	+0.91 / -0.80	0	A1-41
140712 Kipp & Zonen CMP11	9.0664	110.30	+1.6 / -1.7	0.20500	A1-44
140910 Kipp & Zonen CMP11	9.2422	108.20	+1.3 / -1.9	0.20500	A1-47
151027 Kipp & Zonen SP-LITE2	68.851	14.524	+3.1 / -2.2	0	A1-50
15357 Hukseflux SR20-T2	16.973	58.917	+1.3 / -1.3	0.18000	A1-53
15360 Hukseflux SR20-T2	16.493	60.630	+1.2 / -1.6	0.18000	A1-56
15366 Hukseflux SR20-T2	16.767	59.640	+1.4 / -1.4	0.18000	A1-59
170535 Kipp & Zonen CMP22	9.6564	103.56	+1.4 / -1.7	0.087000	A1-62
210757 Kipp & Zonen CMP22	9.0905	110.01	+1.2 / -1.3	0.087000	A1-65
220057 Kipp & Zonen SMP12	7.0270	142.31	+1.6 / -1.3	0	A1-68
2529 Hukseflux SR25	9.3938	106.45	+1.6 / -1.5	0.043000	A1-71
2543 Hukseflux SR25	9.5986	104.18	+1.3 / -1.3	0.043000	A1-74
28402F3 Eppley PSP	6.8387	146.23	+2.4 / -2.5	0.64000	A1-77
31137E6 Eppley NIP	8.4522	118.31	+2.1 / -1.0	0	A1-80
32331 Eppley 8-48	8.9255	112.04	+4.1 / -2.6	0	A1-83
34718 Eppley 8-48	9.4242	106.11	+3.5 / -2.4	0	A1-86
37831F3 Eppley GPP	8.4785	117.94	+1.8 / -2.8	0.15000	A1-89
37839F3 Eppley SPP	8.6569	115.52	+1.9 / -2.3	0.30000	A1-92
37882E6 Eppley sNIP	8.4075	118.94	+1.2 / -0.91	0	A1-95
40337 Apogee SP-110	180.63	5.5362	+1.5 / -1.4	0	A1-98
4246 Hukseflux SR30	10.333	96.779	+1.1 / -1.1	0	A1-101
65089 Hukseflux DR20-A1-T2	18.599	53.767	+0.74 / -0.99	0	A1-104
70006 Hukseflux DR20-A1-T2	18.796	53.203	+0.75 / -0.92	0	A1-107
9206 Hukseflux DR02	10.999	90.915	+0.85 / -0.93	0	A1-110
A360 Delta-T SPN1	1022.2	0.97833	+9.7 / -5.0	0	A1-113
F14077R EKO MS-802	7.0858	141.13	+1.8 / -2.3	0.18000	A1-116
PY100360 Licor LI200R	10.659	93.819	+2.0 / -1.2	0	A1-119
PY102023 Licor LI200R	10.183	98.205	+1.6 / -1.4	0	A1-122
PY28257 Licor LI200	13.819	72.363	+2.2 / -2.8	0	A1-125
PY66482 Licor LI200	7.3814	135.48	+2.1 / -2.7	0	A1-128
PYHR101 Licor LI201SB	4.3024	232.43	+3.3 / -2.0	0	A1-131
S13071483 EKO MS-602	6.9633	143.61	+1.9 / -2.2	0.30000	A1-134
S13135063 EKO ML-01	40.573	24.647	+2.2 / -1.2	0	A1-137
S13144.085R EKO MS-410	9.2822	107.73	+1.6 / -1.4	0.20000	A1-140
S17096005 EKO MS-80	10.630	94.078	+1.4 / -1.1	0.043000	A1-143
S18015.22 EKO MS-57	6.6903	149.47	+0.76 / -0.90	0	A1-146

<sup>1</sup> CF = 1000 / R

<sup>2</sup> See certificate for valid zenith angle range

<sup>3</sup> Instrument's Effective Net IR Response

# Results Summary

**Table 1. Results Summary**

Instrument	R@45 <sup>1</sup> ( $\mu\text{V}/\text{W}/\text{m}^2$ )	CF@45 <sup>1</sup> ( $\text{W}/\text{m}^2/\text{mV}$ )	U <sup>2</sup> (%)	Rnet <sup>3</sup> ( $\mu\text{V}/\text{W}/\text{m}^2$ )	Page
S20066320 EKO MS-80S	10.799	92.601	+1.7 / -1.8	0	A1-149

<sup>1</sup> CF = 1000 / R

<sup>2</sup> See certificate for valid zenith angle range

<sup>3</sup> Instrument's Effective Net IR Response

Note: Environmental Conditions for BORCAL starts on page A1-152.

# 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



<b>Test Instrument:</b>	Pyranometer	<b>Manufacturer:</b>	Kipp & Zonen
<b>Model:</b>	CM22	<b>Serial Number:</b>	010034
<b>Calibration Date:</b>	5/2/2025	<b>Due Date:</b>	5/2/2026
<b>Customer:</b>	NREL-SRRL-BMS	<b>Environmental Conditions:</b>	see page 4
<b>Test Dates:</b>	5/2		

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	09/27/2024	09/27/2025
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/21/2025	04/21/2026
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/21/2025	04/21/2026
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/07/2025	02/07/2027
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/07/2025	02/07/2027
Infrared Irradiance ‡	Kipp & Zonen Pyrgeometer Model CG4, S/N FT002	03/31/2022	03/31/2027

† Through the World Radiometric Reference (WRR)

‡ Through the World Infrared Standard Group (WISG)

**Number of pages of certificate:** 4

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

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

**Calibrated by:** Afshin Andreas, RCC, and Shawn L. Jaker

-----  
Ibrahim Reda, Technical Manager

05/05/2025

-----  
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

## 010034 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:

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

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 ( $\text{W}/\text{m}^2$ ),
- =  $W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
- where,  $W_{in}$  = incoming infrared ( $\text{W}/\text{m}^2$ ),  $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$ ,
- $T_c$  = case temperature of pyrgeometer (K).
- $I$  = reference irradiance ( $\text{W}/\text{m}^2$ ), beam (B) or global (G)
- where,  $G = B * \text{COS}(Z) + D$ ,
- $Z$  = zenith angle (degrees),
- $D$  = reference diffuse irradiance ( $\text{W}/\text{m}^2$ ).

Figure 1. Responsivity vs Zenith Angle

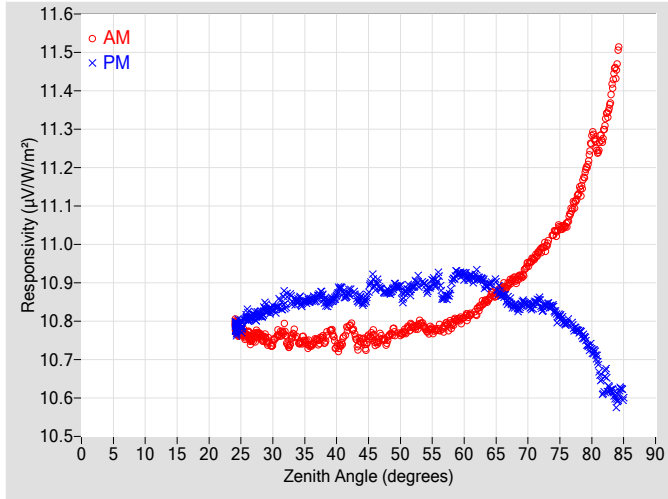


Figure 2. Responsivity vs Local Standard Time

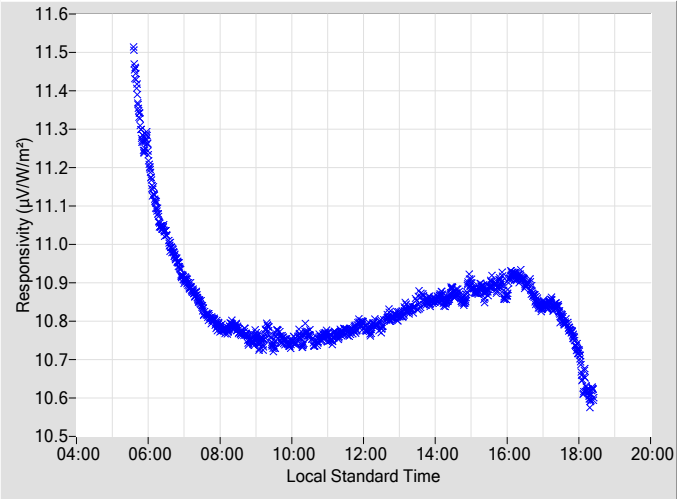
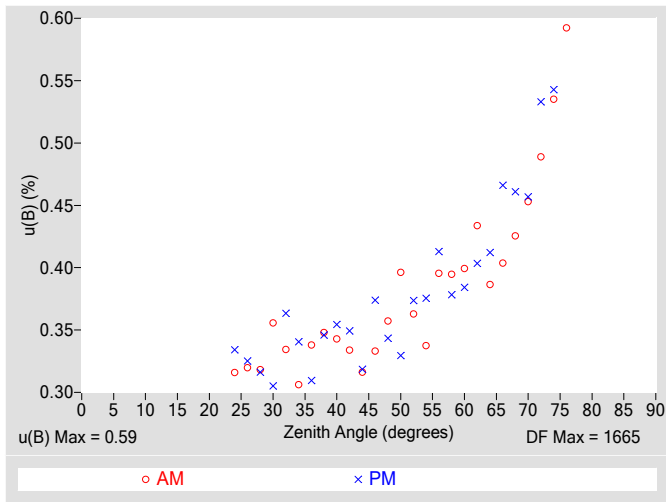


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty,  $u(B)$

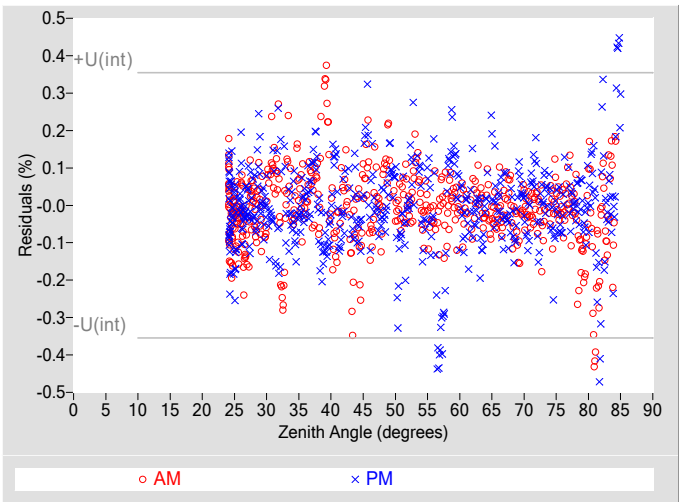
Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	AM $u(B)$ $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	PM $u(B)$ $\pm$ (%)	Azimuth Angle	Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	AM $u(B)$ $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	PM $u(B)$ $\pm$ (%)	Azimuth Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	10.753	0.33	108.45	10.894	0.37	251.63
2	N/A	N/A	N/A	N/A	N/A	N/A	48	10.751	0.36	106.17	10.877	0.34	253.98
4	N/A	N/A	N/A	N/A	N/A	N/A	50	10.767	0.40	103.94	10.883	0.33	256.17
6	N/A	N/A	N/A	N/A	N/A	N/A	52	10.786	0.36	101.89	10.890	0.37	258.26
8	N/A	N/A	N/A	N/A	N/A	N/A	54	10.779	0.34	99.93	10.887	0.38	260.25
10	N/A	N/A	N/A	N/A	N/A	N/A	56	10.781	0.40	97.94	10.909	0.41	262.10
12	N/A	N/A	N/A	N/A	N/A	N/A	58	10.793	0.39	96.16	10.895	0.38	263.98
14	N/A	N/A	N/A	N/A	N/A	N/A	60	10.811	0.40	94.39	10.920	0.38	265.75
16	N/A	N/A	N/A	N/A	N/A	N/A	62	10.825	0.43	92.65	10.917	0.40	267.52
18	N/A	N/A	N/A	N/A	N/A	N/A	64	10.863	0.39	90.95	10.898	0.41	269.19
20	N/A	N/A	N/A	N/A	N/A	N/A	66	10.887	0.40	89.32	10.866	0.47	270.85
22	N/A	N/A	N/A	N/A	N/A	N/A	68	10.907	0.43	87.67	10.841	0.46	272.50
24	10.788	0.32	175.98	10.783	0.33	184.41	70	10.948	0.45	86.04	10.843	0.46	274.13
26	10.766	0.32	155.03	10.811	0.33	205.18	72	10.985	0.49	84.43	10.843	0.53	275.75
28	10.763	0.32	144.95	10.817	0.32	215.21	74	11.028	0.54	82.80	10.833	0.54	277.35
30	10.742	0.36	137.85	10.833	0.31	222.20	76	11.050	0.59	81.21	10.795	N/A	278.99
32	10.767	0.33	132.09	10.853	0.36	227.98	78	11.135	N/A	79.57	10.774	N/A	280.59
34	10.747	0.31	127.28	10.855	0.34	232.77	80	11.272	N/A	77.98	10.726	N/A	282.23
36	10.737	0.34	123.36	10.854	0.31	236.74	82	11.302	N/A	76.34	10.647	N/A	283.88
38	10.752	0.35	119.70	10.856	0.35	240.39	84	11.475	N/A	74.65	10.595	N/A	285.53
40	10.731	0.34	116.46	10.871	0.35	243.62	86	N/A	N/A	N/A	N/A	N/A	N/A
42	10.785	0.33	113.75	10.876	0.35	246.48	88	N/A	N/A	N/A	N/A	N/A	N/A
44	10.751	0.32	110.91	10.851	0.32	249.22	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, $u(B)$ (%)	$\pm 0.59$
Type-A Interpolating Function, $u(int)$ (%)	$\pm 0.18$
Combined Standard Uncertainty, $u(c)$ (%)	$\pm 0.62$
Effective degrees of freedom, $DF(c)$	1951
Coverage factor, $k$	1.96
Expanded Uncertainty, $U_{95}$ (%)	$\pm 1.2$
AM Valid zenith angle range	24° to 76°
PM Valid zenith angle range	24° to 74°

‡ 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**

$R @ 45^\circ$ ( $\mu V/W/m^2$ )	$R_{net}$ ( $\mu V/W/m^2$ ) †
10.817	0.087000

†  $R_{net}$  determination date: Estimated

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

Type-B Expanded Uncertainty, $U(B)$ (%)	$\pm 0.81$
Offset Uncertainty, $U(off)$ (%)	+0.96 / -0.79
Expanded Uncertainty, $U$ (%)	+1.8 / -1.6
Effective degrees of freedom, $DF^*$	2081
Coverage factor, $k$	1.96
Valid zenith angle range	30.0° to 60.0°

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

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



**References:**

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



# National Renewable Energy Laboratory

## Solar Radiation Research Laboratory

### Metrology Laboratory

### Calibration Certificate



<b>Test Instrument:</b>	Pyranometer	<b>Manufacturer:</b>	Kipp & Zonen
<b>Model:</b>	CM22	<b>Serial Number:</b>	010047
<b>Calibration Date:</b>	5/2/2025	<b>Due Date:</b>	5/2/2026
<b>Customer:</b>	NREL-SRRL-BMS	<b>Environmental Conditions:</b>	see page 4
<b>Test Dates:</b>	5/2		

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.

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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.

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	09/27/2024	09/27/2025
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/21/2025	04/21/2026
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/21/2025	04/21/2026
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/07/2025	02/07/2027
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/07/2025	02/07/2027
Infrared Irradiance ‡	Kipp & Zonen Pyrgeometer Model CG4, S/N FT002	03/31/2022	03/31/2027

† Through the World Radiometric Reference (WRR)

‡ Through the World Infrared Standard Group (WISG)

**Number of pages of certificate:** 4

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

**Setup:** Radiometers are calibrated outdoors, using the sun as the source. Pyranometers and pyrgeometers are installed for horizontal measurements, with their signal connectors oriented north, if their design permits.

The shading disk for the reference diffuse subtends a solid angle of 5°. Pyrheliometers are installed on solar trackers.

**Calibrated by:** Afshin Andreas, RCC, and Shawn L. Jaker

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Ibrahim Reda, Technical Manager

05/05/2025

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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 ( $\text{W}/\text{m}^2$ ),
  - =  $W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
  - where,  $W_{in}$  = incoming infrared ( $\text{W}/\text{m}^2$ ),  $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$ ,
  - $T_c$  = case temperature of pyrgeometer (K).
- $I$  = reference irradiance ( $\text{W}/\text{m}^2$ ), beam (B) or global (G)
  - where,  $G = B * \text{COS}(Z) + D$ ,
  - $Z$  = zenith angle (degrees),
  - $D$  = reference diffuse irradiance ( $\text{W}/\text{m}^2$ ).

Figure 1. Responsivity vs Zenith Angle

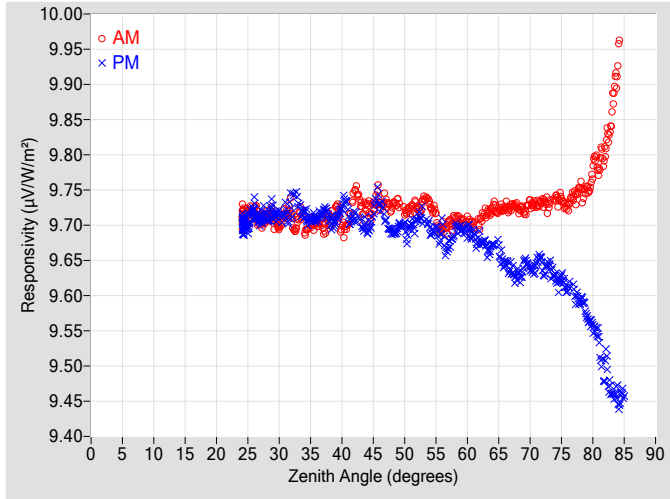


Figure 2. Responsivity vs Local Standard Time

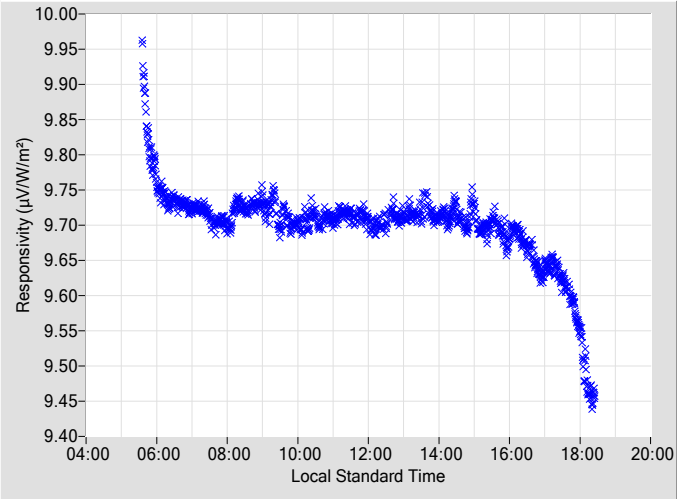
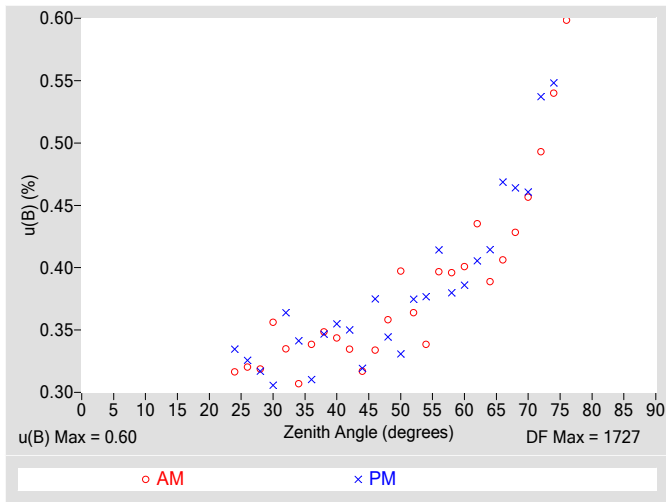


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)

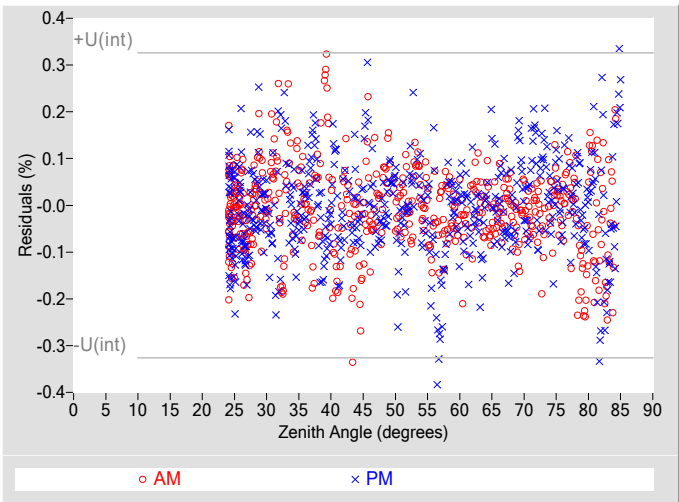
Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	AM u(B) $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	PM u(B) $\pm$ (%)	Azimuth Angle	Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	AM u(B) $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	PM u(B) $\pm$ (%)	Azimuth Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	9.7354	0.33	108.45	9.7303	0.37	251.63
2	N/A	N/A	N/A	N/A	N/A	N/A	48	9.7255	0.36	106.17	9.6904	0.34	253.98
4	N/A	N/A	N/A	N/A	N/A	N/A	50	9.7199	0.40	103.94	9.6965	0.33	256.17
6	N/A	N/A	N/A	N/A	N/A	N/A	52	9.7259	0.36	101.89	9.7089	0.37	258.26
8	N/A	N/A	N/A	N/A	N/A	N/A	54	9.7302	0.34	99.93	9.6942	0.38	260.25
10	N/A	N/A	N/A	N/A	N/A	N/A	56	9.6976	0.40	97.94	9.6941	0.41	262.10
12	N/A	N/A	N/A	N/A	N/A	N/A	58	9.7079	0.40	96.16	9.6939	0.38	263.98
14	N/A	N/A	N/A	N/A	N/A	N/A	60	9.7075	0.40	94.39	9.6941	0.39	265.75
16	N/A	N/A	N/A	N/A	N/A	N/A	62	9.7047	0.44	92.65	9.6793	0.41	267.52
18	N/A	N/A	N/A	N/A	N/A	N/A	64	9.7245	0.39	90.95	9.6720	0.41	269.19
20	N/A	N/A	N/A	N/A	N/A	N/A	66	9.7256	0.41	89.32	9.6437	0.47	270.85
22	N/A	N/A	N/A	N/A	N/A	N/A	68	9.7247	0.43	87.67	9.6310	0.46	272.50
24	9.7130	0.32	175.98	9.7000	0.33	184.41	70	9.7307	0.46	86.04	9.6388	0.46	274.13
26	9.7192	0.32	155.03	9.7199	0.33	205.18	72	9.7329	0.49	84.43	9.6384	0.54	275.75
28	9.7127	0.32	144.95	9.7102	0.32	215.21	74	9.7386	0.54	82.80	9.6247	0.55	277.35
30	9.6979	0.36	137.85	9.7163	0.31	222.20	76	9.7264	0.60	81.21	9.6101	N/A	278.99
32	9.7146	0.33	132.09	9.7276	0.36	227.98	78	9.7505	N/A	79.57	9.5921	N/A	280.59
34	9.6950	0.31	127.28	9.7168	0.34	232.77	80	9.7792	N/A	77.98	9.5572	N/A	282.23
36	9.7017	0.34	123.36	9.7083	0.31	236.74	82	9.8059	N/A	76.34	9.5005	N/A	283.88
38	9.7064	0.35	119.70	9.7062	0.35	240.39	84	9.9305	N/A	74.65	9.4543	N/A	285.53
40	9.6940	0.34	116.46	9.7274	0.35	243.62	86	N/A	N/A	N/A	N/A	N/A	N/A
42	9.7443	0.33	113.75	9.7125	0.35	246.48	88	N/A	N/A	N/A	N/A	N/A	N/A
44	9.7290	0.32	110.91	9.6940	0.32	249.22	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, $u(B)$ (%)	$\pm 0.60$
Type-A Interpolating Function, $u(int)$ (%)	$\pm 0.16$
Combined Standard Uncertainty, $u(c)$ (%)	$\pm 0.62$
Effective degrees of freedom, $DF(c)$	1974
Coverage factor, $k$	1.96
Expanded Uncertainty, $U_{95}$ (%)	$\pm 1.2$
AM Valid zenith angle range	24° to 76°
PM Valid zenith angle range	24° to 74°

‡ 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**

$R @ 45^\circ$ ( $\mu V/W/m^2$ )	$R_{net}$ ( $\mu V/W/m^2$ ) †
9.7217	0.087000

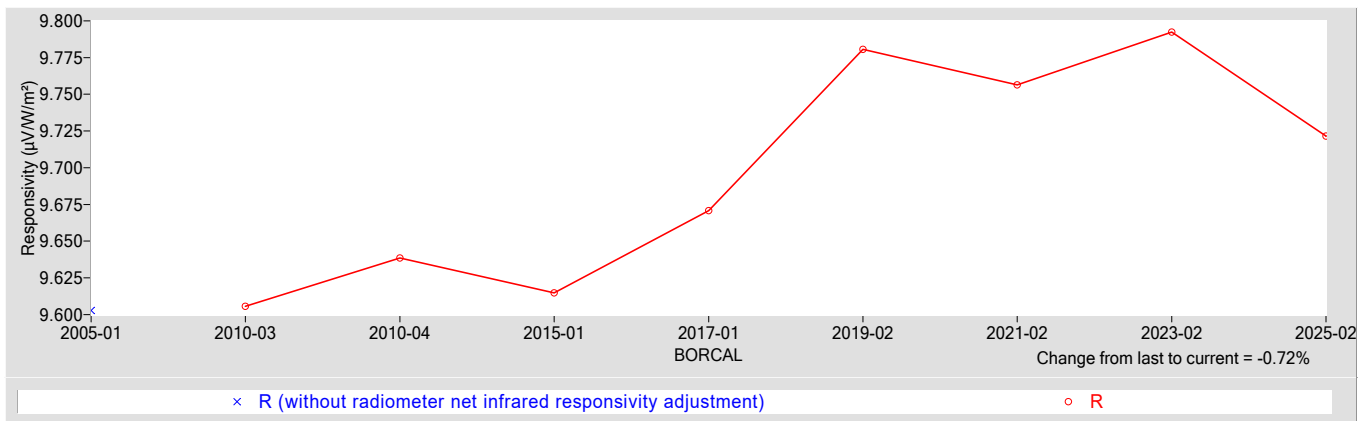
†  $R_{net}$  determination date: Estimated

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

Type-B Expanded Uncertainty, $U(B)$ (%)	$\pm 0.81$
Offset Uncertainty, $U(off)$ (%)	+0.23 / -0.32
Expanded Uncertainty, $U$ (%)	+1.0 / -1.1
Effective degrees of freedom, $DF^*$	2104
Coverage factor, $k$	1.96
Valid zenith angle range	30.0° to 60.0°

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

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



**References:**

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



# National Renewable Energy Laboratory

## Solar Radiation Research Laboratory

### Metrology Laboratory

### Calibration Certificate



<b>Test Instrument:</b>	Pyranometer	<b>Manufacturer:</b>	Kipp & Zonen
<b>Model:</b>	CM3	<b>Serial Number:</b>	010284-UW-CM3
<b>Calibration Date:</b>	5/2/2025	<b>Due Date:</b>	5/2/2026
<b>Customer:</b>	NREL-SRRL-BMS	<b>Environmental Conditions:</b>	see page 4
<b>Test Dates:</b>	5/2		

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	09/27/2024	09/27/2025
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/21/2025	04/21/2026
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/21/2025	04/21/2026
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/07/2025	02/07/2027
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/07/2025	02/07/2027
Infrared Irradiance ‡	Kipp & Zonen Pyrgeometer Model CG4, S/N FT002	03/31/2022	03/31/2027

† Through the World Radiometric Reference (WRR)

‡ Through the World Infrared Standard Group (WISG)

**Number of pages of certificate:** 4

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

**Setup:** Radiometers are calibrated outdoors, using the sun as the source. Pyranometers and pyrgeometers are installed for horizontal measurements, with their signal connectors oriented north, if their design permits.

The shading disk for the reference diffuse subtends a solid angle of 5°. Pyrheliometers are installed on solar trackers.

**Calibrated by:** Afshin Andreas, RCC, and Shawn L. Jaker

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Ibrahim Reda, Technical Manager

05/05/2025

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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

## 010284-UW-CM3 Kipp & Zonen CM3

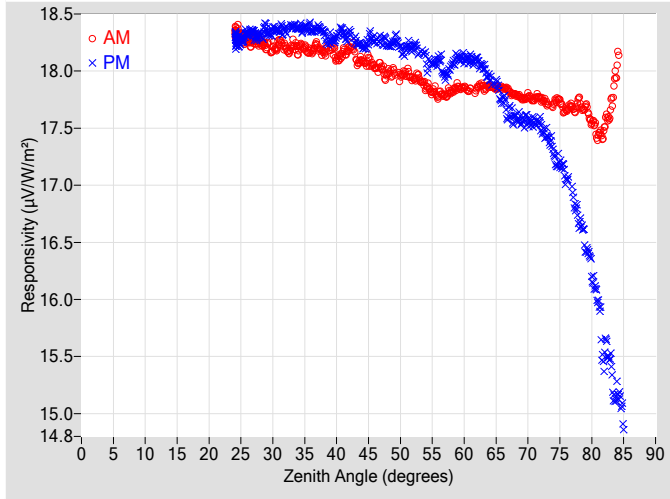
The responsivity ( $R$ ,  $\mu\text{V}/\text{W}/\text{m}^2$ ) of the test instrument during calibration is calculated using this Measurement Equation:

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

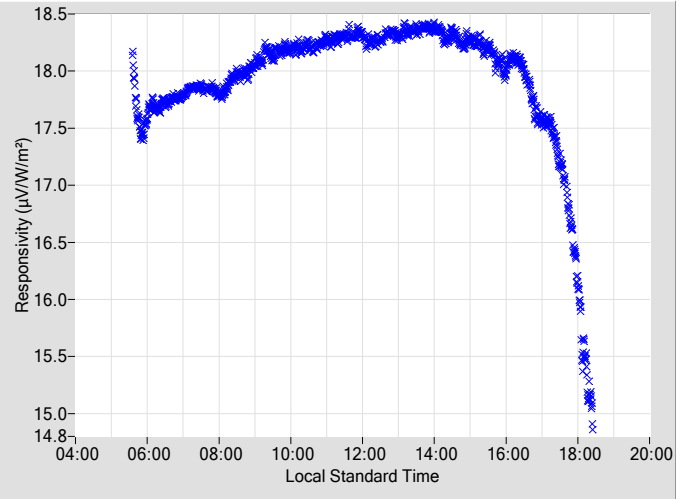
where,

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

**Figure 1. Responsivity vs Zenith Angle**



**Figure 2. Responsivity vs Local Standard Time**

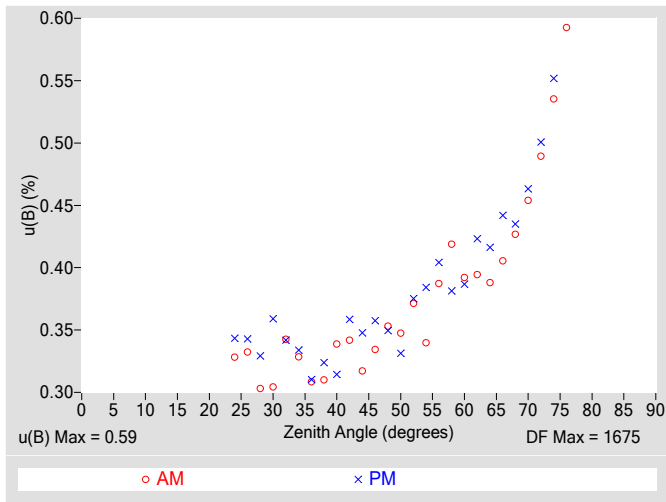


**Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)**

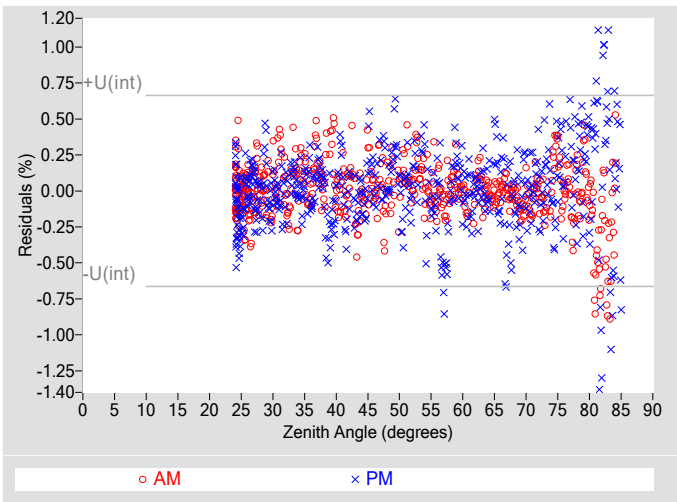
Zenith			AM			PM			Zenith			AM			PM		
Angle	R	u(B)	Azimuth	R	u(B)	Azimuth	Angle	R	u(B)	Azimuth	R	u(B)	Azimuth	R	u(B)	Azimuth	
(deg.)	( $\mu\text{V}/\text{W}/\text{m}^2$ )	$\pm$ (%)	Angle	( $\mu\text{V}/\text{W}/\text{m}^2$ )	$\pm$ (%)	Angle	(deg.)	( $\mu\text{V}/\text{W}/\text{m}^2$ )	$\pm$ (%)	Angle	( $\mu\text{V}/\text{W}/\text{m}^2$ )	$\pm$ (%)	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	18.036	0.33	108.46	18.266	0.36	251.69				
2	N/A	N/A	N/A	N/A	N/A	N/A	48	17.985	0.35	106.12	18.221	0.35	253.99				
4	N/A	N/A	N/A	N/A	N/A	N/A	50	17.958	0.35	103.98	18.198	0.33	256.21				
6	N/A	N/A	N/A	N/A	N/A	N/A	52	17.931	0.37	101.84	18.209	0.38	258.26				
8	N/A	N/A	N/A	N/A	N/A	N/A	54	17.861	0.34	99.89	18.074	0.38	260.31				
10	N/A	N/A	N/A	N/A	N/A	N/A	56	17.788	0.39	98.00	18.093	0.40	262.14				
12	N/A	N/A	N/A	N/A	N/A	N/A	58	17.821	0.42	96.17	18.055	0.38	263.99				
14	N/A	N/A	N/A	N/A	N/A	N/A	60	17.859	0.39	94.37	18.109	0.39	265.76				
16	N/A	N/A	N/A	N/A	N/A	N/A	62	17.844	0.39	92.66	18.105	0.42	267.49				
18	N/A	N/A	N/A	N/A	N/A	N/A	64	17.868	0.39	90.95	17.931	0.42	269.20				
20	N/A	N/A	N/A	N/A	N/A	N/A	66	17.854	0.41	89.28	17.744	0.44	270.86				
22	N/A	N/A	N/A	N/A	N/A	N/A	68	17.794	0.43	87.68	17.602	0.44	272.51				
24	18.328	0.33	176.25	18.283	0.34	183.68	70	17.782	0.45	86.05	17.565	0.46	274.14				
26	18.292	0.33	155.10	18.326	0.34	205.14	72	17.760	0.49	84.44	17.524	0.50	275.75				
28	18.247	0.30	144.96	18.319	0.33	215.10	74	17.712	0.54	82.80	17.287	0.55	277.36				
30	18.193	0.30	137.93	18.362	0.36	222.41	76	17.655	0.59	81.21	17.047	N/A	278.96				
32	18.203	0.34	132.14	18.365	0.34	228.00	78	17.734	N/A	79.58	16.683	N/A	280.59				
34	18.192	0.33	127.44	18.378	0.33	232.68	80	17.559	N/A	77.99	16.238	N/A	282.23				
36	18.172	0.31	123.20	18.368	0.31	236.84	82	17.520	N/A	76.30	15.534	N/A	283.88				
38	18.161	0.31	119.71	18.331	0.32	240.41	84	18.049	N/A	74.65	15.164	N/A	285.54				
40	18.107	0.34	116.48	18.302	0.31	243.58	86	N/A	N/A	N/A	N/A	N/A	N/A				
42	18.196	0.34	113.68	18.339	0.36	246.56	88	N/A	N/A	N/A	N/A	N/A	N/A				
44	18.093	0.32	110.93	18.221	0.35	249.22	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, $u(B)$ (%)	$\pm 0.59$
Type-A Interpolating Function, $u(int)$ (%)	$\pm 0.33$
Combined Standard Uncertainty, $u(c)$ (%)	$\pm 0.68$
Effective degrees of freedom, $DF(c)$	2488
Coverage factor, $k$	1.96
Expanded Uncertainty, $U95$ (%)	$\pm 1.3$
AM Valid zenith angle range	24° to 76°
PM Valid zenith angle range	24° to 74°

‡ 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**

$R @ 45^\circ$ ( $\mu V/W/m^2$ )	$R_{net}$ ( $\mu V/W/m^2$ ) †
18.188	0.40000

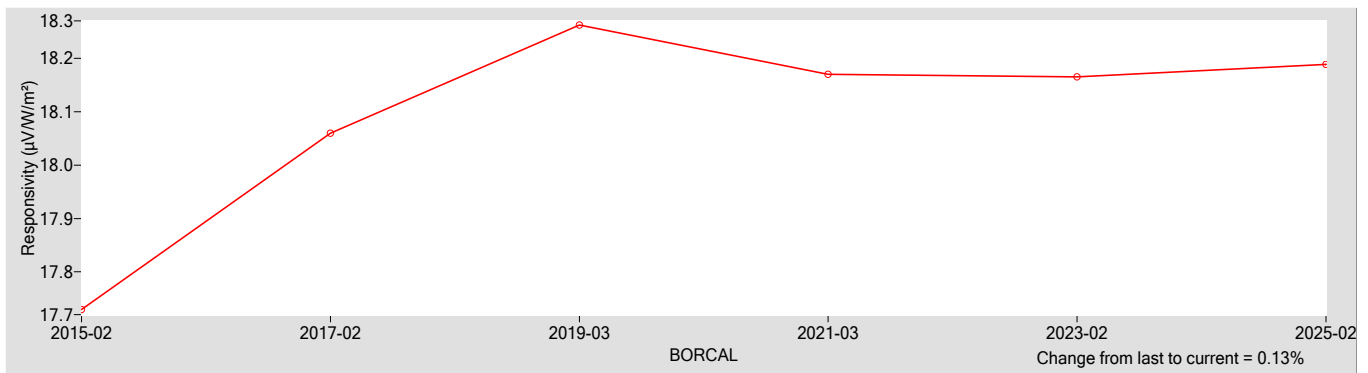
†  $R_{net}$  determination date: Estimated

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

Type-B Expanded Uncertainty, $U(B)$ (%)	$\pm 0.82$
Offset Uncertainty, $U(off)$ (%)	+1.0 / -2.2
Expanded Uncertainty, $U$ (%)	+1.9 / -3.0
Effective degrees of freedom, $DF^*$	2036
Coverage factor, $k$	1.96
Valid zenith angle range	30.0° to 60.0°

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

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



**References:**

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



# National Renewable Energy Laboratory

## Solar Radiation Research Laboratory

### Metrology Laboratory

### Calibration Certificate



<b>Test Instrument:</b>	Silicon Pyranometer	<b>Manufacturer:</b>	Kipp & Zonen
<b>Model:</b>	SP-LITE	<b>Serial Number:</b>	010995
<b>Calibration Date:</b>	5/2/2025	<b>Due Date:</b>	5/2/2026
<b>Customer:</b>	NREL-SRRL-BMS	<b>Environmental Conditions:</b>	see page 4
<b>Test Dates:</b>	5/2		

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	09/27/2024	09/27/2025
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/21/2025	04/21/2026
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/21/2025	04/21/2026
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/07/2025	02/07/2027
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/07/2025	02/07/2027

† 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, RCC, and Shawn L. Jaker

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Ibrahim Reda, Technical Manager

05/05/2025

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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 ( $\text{W}/\text{m}^2$ ),
  - =  $W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
  - where,  $W_{in}$  = incoming infrared ( $\text{W}/\text{m}^2$ ),  $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$ ,
  - $T_c$  = case temperature of pyrgeometer (K).
- $I$  = reference irradiance ( $\text{W}/\text{m}^2$ ), beam (B) or global (G)
  - where,  $G = B * \text{COS}(Z) + D$ ,
  - $Z$  = zenith angle (degrees),
  - $D$  = reference diffuse irradiance ( $\text{W}/\text{m}^2$ ).

Figure 1. Responsivity vs Zenith Angle

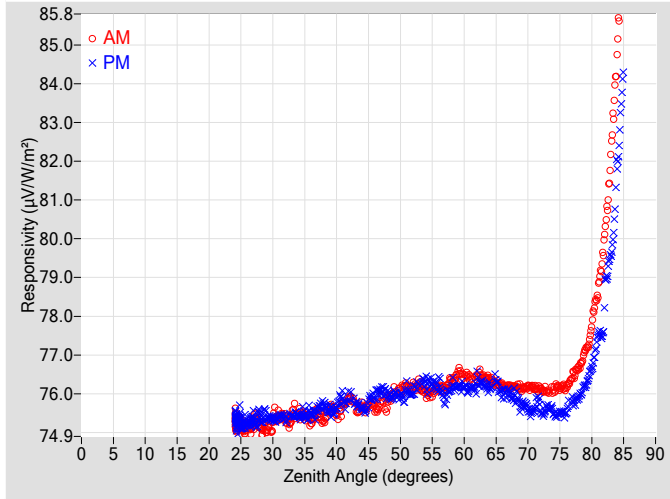


Figure 2. Responsivity vs Local Standard Time

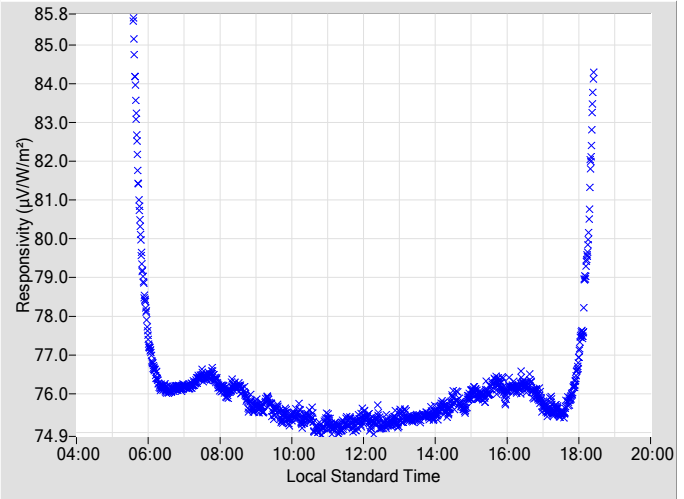
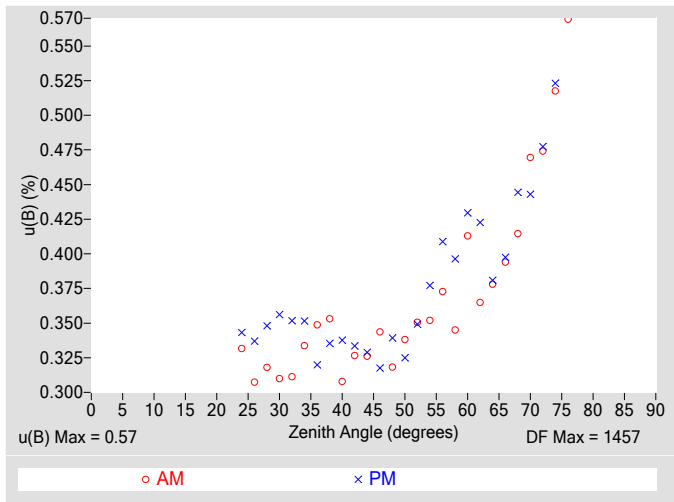


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty,  $u(B)$

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	75.671	0.34	108.51	75.993	0.32	251.64				
2	N/A	N/A	N/A	N/A	N/A	N/A	48	75.736	0.32	106.11	75.956	0.34	253.99				
4	N/A	N/A	N/A	N/A	N/A	N/A	50	76.103	0.34	103.96	75.947	0.32	256.17				
6	N/A	N/A	N/A	N/A	N/A	N/A	52	76.205	0.35	101.83	76.032	0.35	258.20				
8	N/A	N/A	N/A	N/A	N/A	N/A	54	76.042	0.35	99.93	76.207	0.38	260.24				
10	N/A	N/A	N/A	N/A	N/A	N/A	56	76.164	0.37	97.99	76.270	0.41	262.13				
12	N/A	N/A	N/A	N/A	N/A	N/A	58	76.367	0.35	96.16	76.186	0.40	263.97				
14	N/A	N/A	N/A	N/A	N/A	N/A	60	76.468	0.41	94.38	76.182	0.43	265.75				
16	N/A	N/A	N/A	N/A	N/A	N/A	62	76.407	0.36	92.65	76.296	0.42	267.49				
18	N/A	N/A	N/A	N/A	N/A	N/A	64	76.365	0.38	90.94	76.152	0.38	269.19				
20	N/A	N/A	N/A	N/A	N/A	N/A	66	76.215	0.39	89.32	76.024	0.40	270.85				
22	N/A	N/A	N/A	N/A	N/A	N/A	68	76.188	0.41	87.67	75.926	0.44	272.50				
24	75.266	0.33	176.04	75.352	0.34	184.33	70	76.170	0.47	86.05	75.613	0.44	274.13				
26	75.200	0.31	155.28	75.246	0.34	204.85	72	76.140	0.47	84.43	75.601	0.48	275.74				
28	75.119	0.32	144.84	75.423	0.35	215.29	74	76.097	0.52	82.80	75.526	0.52	277.35				
30	75.266	0.31	137.68	75.352	0.36	222.34	76	76.170	0.57	81.21	75.526	N/A	278.95				
32	75.358	0.31	132.09	75.356	0.35	227.91	78	76.678	N/A	79.61	75.935	N/A	280.58				
34	75.462	0.33	127.21	75.435	0.35	232.85	80	77.782	N/A	77.98	76.674	N/A	282.23				
36	75.292	0.35	123.27	75.486	0.32	236.83	82	80.016	N/A	76.34	78.389	N/A	283.88				
38	75.289	0.35	119.76	75.721	0.34	240.39	84	84.934	N/A	74.64	81.947	N/A	285.57				
40	75.474	0.31	116.59	75.664	0.34	243.54	86	N/A	N/A	N/A	N/A	N/A	N/A				
42	75.899	0.33	113.67	75.940	0.33	246.48	88	N/A	N/A	N/A	N/A	N/A	N/A				
44	75.688	0.33	110.98	75.619	0.33	249.15	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, $u(B)$ (%)	$\pm 0.57$
Type-A Interpolating Function, $u(int)$ (%)	$\pm 0.26$
Combined Standard Uncertainty, $u(c)$ (%)	$\pm 0.63$
Effective degrees of freedom, $DF(c)$	2015
Coverage factor, $k$	1.96
Expanded Uncertainty, $U95$ (%)	$\pm 1.2$
AM Valid zenith angle range	24° to 76°
PM Valid zenith angle range	24° to 74°

‡ 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**

$R @ 45^\circ$ ( $\mu V/W/m^2$ )	$R_{net}$ ( $\mu V/W/m^2$ ) †
75.778	0

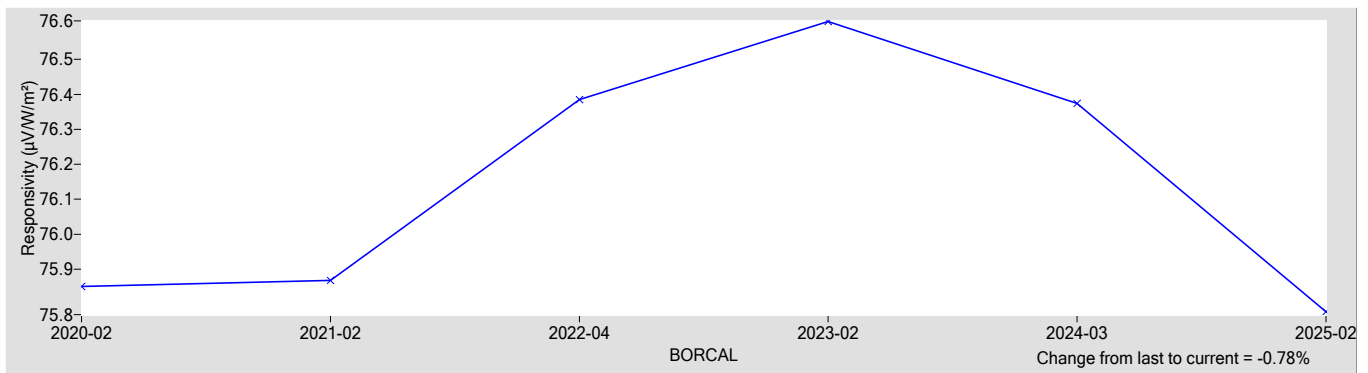
†  $R_{net}$  determination date: N/A

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

Type-B Expanded Uncertainty, $U(B)$ (%)	$\pm 0.84$
Offset Uncertainty, $U(off)$ (%)	+0.91 / -0.68
Expanded Uncertainty, $U$ (%)	+1.8 / -1.5
Effective degrees of freedom, $DF^*$	2002
Coverage factor, $k$	1.96
Valid zenith angle range	30.0° to 60.0°

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

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



**References:**

[1] Reda, I.; Hickey, J.; Long, C.; Myers, D.; Stoffel, T.; Wilcox, S.; Michalsky, J. J.; Dutton, E. G.; Nelson, D. (2005). "Using a Blackbody to Calculate Net Longwave Responsivity of Shortwave Solar Pyranometers to Correct for Their Thermal Offset Error During Outdoor Calibration Using the Component Sum Method." *Journal of Atmospheric and Oceanic Technology*, 2005; pp. 1531-1540; NREL Report No. JA-560-36646. doi:10.1175/JTECH1782.1

[2] Reda, I.; Myers, D.; Stoffel, T. (2008). "Uncertainty Estimate for the Outdoor Calibration of Solar Pyranometers: A Metrologist Perspective." *Measure*. (NCSLI *Journal of Measurement Science*). Vol. 3(4), December 2008; pp. 58-66; NREL Report No. JA-581-4137

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

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

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

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

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



# National Renewable Energy Laboratory

## Solar Radiation Research Laboratory

### Metrology Laboratory

### Calibration Certificate



<b>Test Instrument:</b>	Pyranometer	<b>Manufacturer:</b>	Kipp & Zonen
<b>Model:</b>	CM3	<b>Serial Number:</b>	014261
<b>Calibration Date:</b>	5/2/2025	<b>Due Date:</b>	5/2/2026
<b>Customer:</b>	NREL-SRRL-BMS	<b>Environmental Conditions:</b>	see page 4
<b>Test Dates:</b>	5/2		

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	09/27/2024	09/27/2025
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/21/2025	04/21/2026
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/21/2025	04/21/2026
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/07/2025	02/07/2027
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/07/2025	02/07/2027
Infrared Irradiance ‡	Kipp & Zonen Pyrgeometer Model CG4, S/N FT002	03/31/2022	03/31/2027

† Through the World Radiometric Reference (WRR)

‡ Through the World Infrared Standard Group (WISG)

**Number of pages of certificate:** 4

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

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

**Calibrated by:** Afshin Andreas, RCC, and Shawn L. Jaker

-----  
Ibrahim Reda, Technical Manager

05/05/2025

-----  
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 ( $\text{W}/\text{m}^2$ ),
  - =  $W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
  - where,  $W_{in}$  = incoming infrared ( $\text{W}/\text{m}^2$ ),  $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$ ,
  - $T_c$  = case temperature of pyrgeometer (K).
- $I$  = reference irradiance ( $\text{W}/\text{m}^2$ ), beam (B) or global (G)
  - where,  $G = B * \text{COS}(Z) + D$ ,
  - $Z$  = zenith angle (degrees),
  - $D$  = reference diffuse irradiance ( $\text{W}/\text{m}^2$ ).

Figure 1. Responsivity vs Zenith Angle

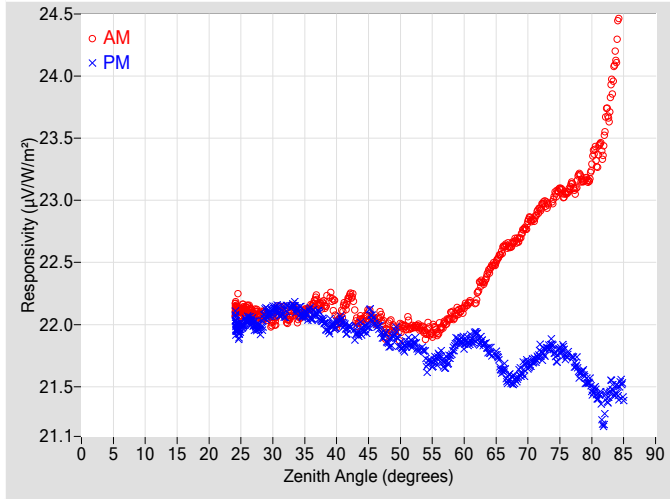


Figure 2. Responsivity vs Local Standard Time

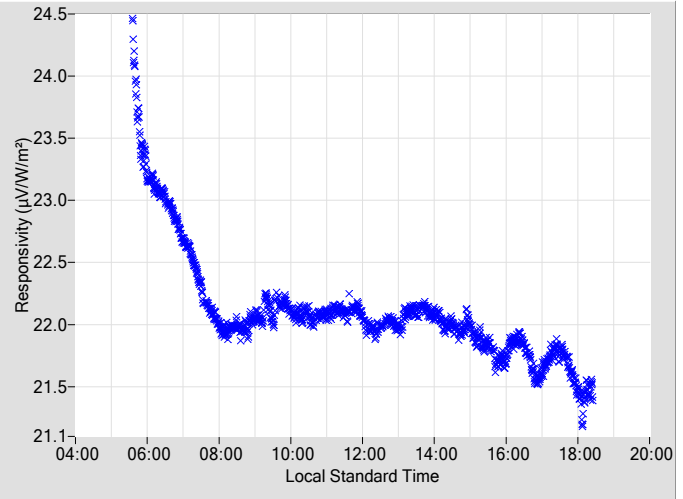
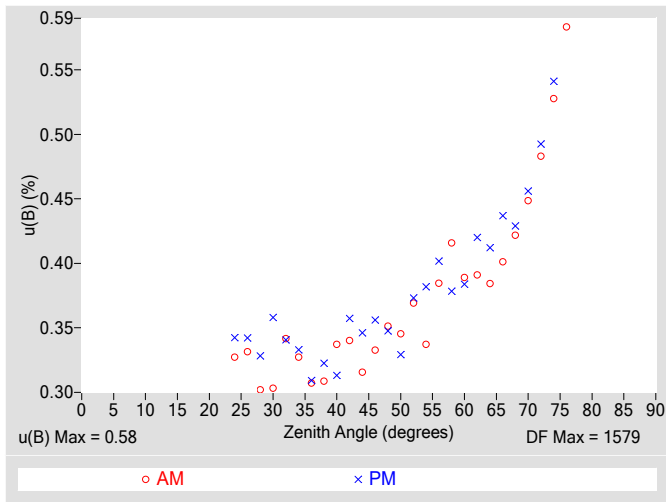


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty,  $u(B)$

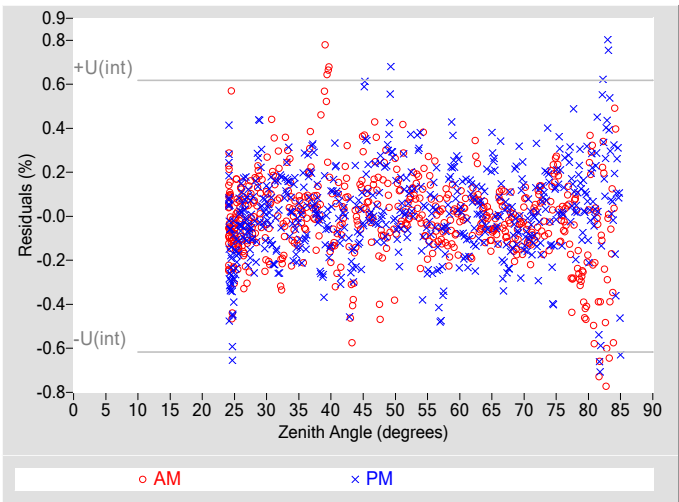
Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	AM $u(B)$ $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	PM $u(B)$ $\pm$ (%)	Azimuth Angle	Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	AM $u(B)$ $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	PM $u(B)$ $\pm$ (%)	Azimuth Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	22.031	0.33	108.46	22.009	0.36	251.69
2	N/A	N/A	N/A	N/A	N/A	N/A	48	21.976	0.35	106.12	21.846	0.35	253.99
4	N/A	N/A	N/A	N/A	N/A	N/A	50	21.952	0.35	103.98	21.826	0.33	256.21
6	N/A	N/A	N/A	N/A	N/A	N/A	52	21.983	0.37	101.84	21.839	0.37	258.26
8	N/A	N/A	N/A	N/A	N/A	N/A	54	21.929	0.34	99.89	21.695	0.38	260.31
10	N/A	N/A	N/A	N/A	N/A	N/A	56	21.952	0.38	98.00	21.736	0.40	262.14
12	N/A	N/A	N/A	N/A	N/A	N/A	58	22.080	0.42	96.17	21.770	0.38	263.99
14	N/A	N/A	N/A	N/A	N/A	N/A	60	22.137	0.39	94.37	21.857	0.38	265.76
16	N/A	N/A	N/A	N/A	N/A	N/A	62	22.222	0.39	92.66	21.916	0.42	267.49
18	N/A	N/A	N/A	N/A	N/A	N/A	64	22.444	0.38	90.95	21.781	0.41	269.20
20	N/A	N/A	N/A	N/A	N/A	N/A	66	22.601	0.40	89.28	21.625	0.44	270.86
22	N/A	N/A	N/A	N/A	N/A	N/A	68	22.671	0.42	87.68	21.559	0.43	272.51
24	22.120	0.33	176.25	22.016	0.34	183.68	70	22.824	0.45	86.05	21.676	0.46	274.14
26	22.128	0.33	155.10	22.036	0.34	205.14	72	22.939	0.48	84.44	21.774	0.49	275.75
28	22.072	0.30	144.96	21.975	0.33	215.10	74	23.013	0.53	82.80	21.802	0.54	277.36
30	22.031	0.30	137.93	22.122	0.36	222.41	76	23.059	0.58	81.21	21.744	N/A	278.96
32	22.088	0.34	132.14	22.115	0.34	228.00	78	23.189	N/A	79.58	21.612	N/A	280.59
34	22.063	0.33	127.44	22.116	0.33	232.68	80	23.281	N/A	77.99	21.482	N/A	282.23
36	22.144	0.31	123.20	22.070	0.31	236.84	82	23.547	N/A	76.30	21.311	N/A	283.88
38	22.163	0.31	119.71	22.014	0.32	240.41	84	24.288	N/A	74.65	21.453	N/A	285.54
40	22.022	0.34	116.48	21.999	0.31	243.58	86	N/A	N/A	N/A	N/A	N/A	N/A
42	22.223	0.34	113.68	21.984	0.36	246.56	88	N/A	N/A	N/A	N/A	N/A	N/A
44	22.044	0.32	110.93	21.965	0.35	249.22	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, $u(B)$ (%)	$\pm 0.58$
Type-A Interpolating Function, $u(int)$ (%)	$\pm 0.31$
Combined Standard Uncertainty, $u(c)$ (%)	$\pm 0.66$
Effective degrees of freedom, $DF(c)$	2307
Coverage factor, $k$	1.96
Expanded Uncertainty, $U95$ (%)	$\pm 1.3$
AM Valid zenith angle range	24° to 76°
PM Valid zenith angle range	24° to 74°

‡ 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**

$R @ 45^\circ$ ( $\mu V/W/m^2$ )	$R_{net}$ ( $\mu V/W/m^2$ ) †
22.058	0.40000

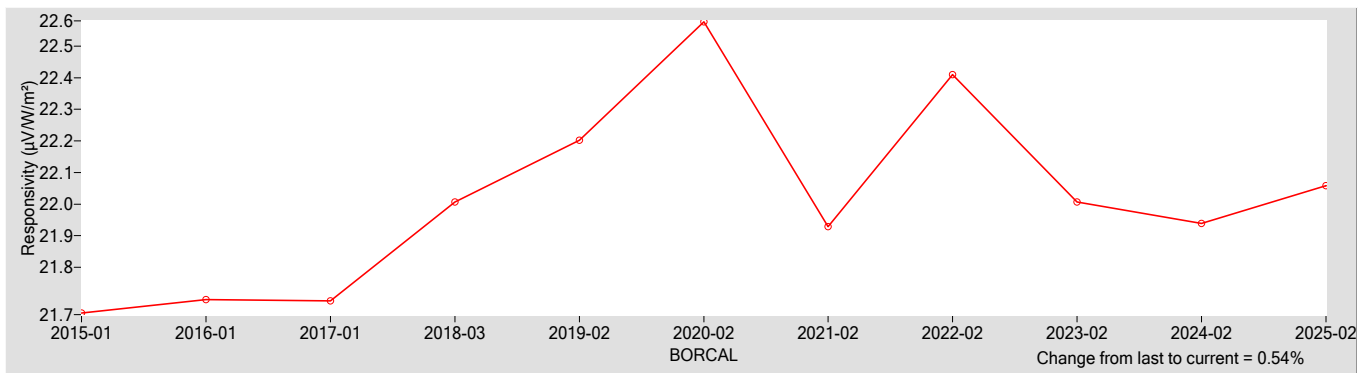
†  $R_{net}$  determination date: Estimated

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

Type-B Expanded Uncertainty, $U(B)$ (%)	$\pm 0.82$
Offset Uncertainty, $U(off)$ (%)	+0.75 / -1.6
Expanded Uncertainty, $U$ (%)	+1.6 / -2.5
Effective degrees of freedom, $DF^*$	2023
Coverage factor, $k$	1.96
Valid zenith angle range	30.0° to 60.0°

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

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



**References:**

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



# National Renewable Energy Laboratory

## Solar Radiation Research Laboratory

### Metrology Laboratory

### Calibration Certificate



<b>Test Instrument:</b>	Pyranometer	<b>Manufacturer:</b>	Kipp & Zonen
<b>Model:</b>	CM6B	<b>Serial Number:</b>	015189
<b>Calibration Date:</b>	5/2/2025	<b>Due Date:</b>	5/2/2026
<b>Customer:</b>	NREL-SRRL-BMS	<b>Environmental Conditions:</b>	see page 4
<b>Test Dates:</b>	5/2		

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	09/27/2024	09/27/2025
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/21/2025	04/21/2026
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/21/2025	04/21/2026
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/07/2025	02/07/2027
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/07/2025	02/07/2027
Infrared Irradiance ‡	Kipp & Zonen Pyrgeometer Model CG4, S/N FT002	03/31/2022	03/31/2027

† Through the World Radiometric Reference (WRR)

‡ Through the World Infrared Standard Group (WISG)

**Number of pages of certificate:** 4

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

**Setup:** Radiometers are calibrated outdoors, using the sun as the source. Pyranometers and pyrgeometers are installed for horizontal measurements, with their signal connectors oriented north, if their design permits.

The shading disk for the reference diffuse subtends a solid angle of 5°. Pyrheliometers are installed on solar trackers.

**Calibrated by:** Afshin Andreas, RCC, and Shawn L. Jaker

-----  
Ibrahim Reda, Technical Manager

05/05/2025

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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 ( $\text{W}/\text{m}^2$ ),
  - =  $W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
  - where,  $W_{in}$  = incoming infrared ( $\text{W}/\text{m}^2$ ),  $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$ ,
  - $T_c$  = case temperature of pyrgeometer (K).
- $I$  = reference irradiance ( $\text{W}/\text{m}^2$ ), beam (B) or global (G)
  - where,  $G = B * \text{COS}(Z) + D$ ,
  - $Z$  = zenith angle (degrees),
  - $D$  = reference diffuse irradiance ( $\text{W}/\text{m}^2$ ).

Figure 1. Responsivity vs Zenith Angle

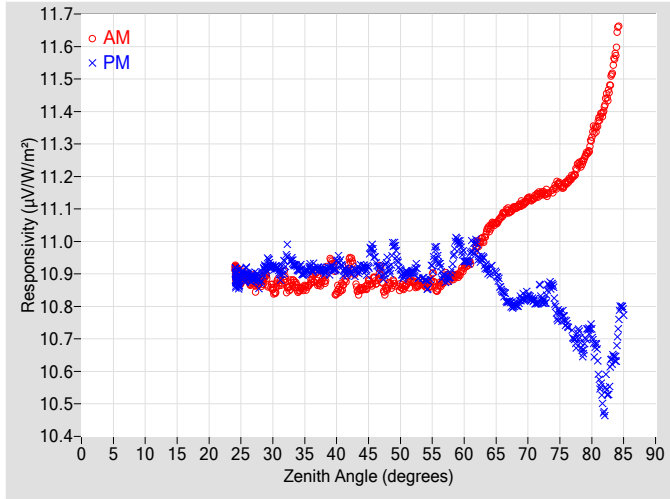


Figure 2. Responsivity vs Local Standard Time

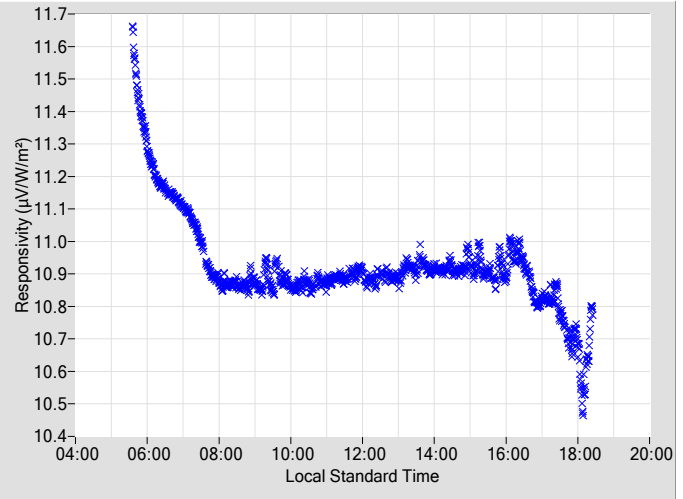
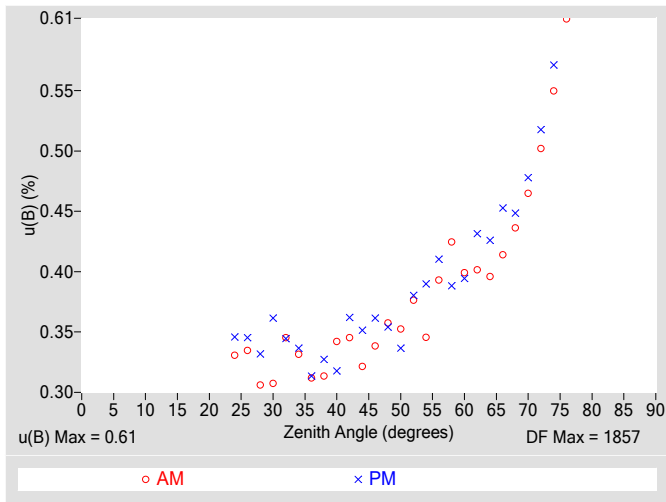


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty,  $u(B)$

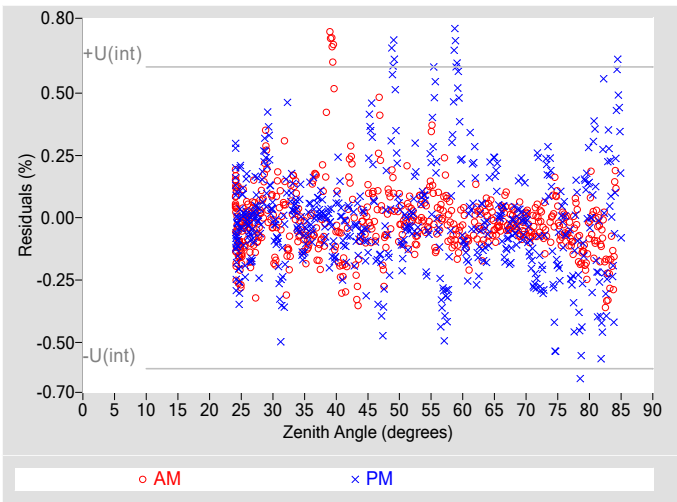
Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	AM $u(B)$ $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	PM $u(B)$ $\pm$ (%)	Azimuth Angle	Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	AM $u(B)$ $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	PM $u(B)$ $\pm$ (%)	Azimuth Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	10.881	0.34	108.46	10.946	0.36	251.69
2	N/A	N/A	N/A	N/A	N/A	N/A	48	10.861	0.36	106.12	10.930	0.35	253.99
4	N/A	N/A	N/A	N/A	N/A	N/A	50	10.859	0.35	103.98	10.908	0.34	256.21
6	N/A	N/A	N/A	N/A	N/A	N/A	52	10.876	0.38	101.84	10.908	0.38	258.26
8	N/A	N/A	N/A	N/A	N/A	N/A	54	10.865	0.35	99.89	10.870	0.39	260.31
10	N/A	N/A	N/A	N/A	N/A	N/A	56	10.861	0.39	98.00	10.937	0.41	262.14
12	N/A	N/A	N/A	N/A	N/A	N/A	58	10.891	0.42	96.17	10.918	0.39	263.99
14	N/A	N/A	N/A	N/A	N/A	N/A	60	10.920	0.40	94.37	10.947	0.39	265.76
16	N/A	N/A	N/A	N/A	N/A	N/A	62	10.986	0.40	92.66	10.978	0.43	267.49
18	N/A	N/A	N/A	N/A	N/A	N/A	64	11.043	0.40	90.95	10.911	0.43	269.20
20	N/A	N/A	N/A	N/A	N/A	N/A	66	11.082	0.41	89.28	10.844	0.45	270.86
22	N/A	N/A	N/A	N/A	N/A	N/A	68	11.104	0.44	87.68	10.806	0.45	272.51
24	10.907	0.33	176.25	10.887	0.35	183.68	70	11.132	0.47	86.05	10.834	0.48	274.14
26	10.890	0.33	155.10	10.902	0.35	205.14	72	11.148	0.50	84.44	10.840	0.52	275.75
28	10.873	0.31	144.96	10.878	0.33	215.10	74	11.161	0.55	82.80	10.846	0.57	277.36
30	10.856	0.31	137.93	10.921	0.36	222.41	76	11.181	0.61	81.21	10.748	N/A	278.96
32	10.878	0.35	132.14	10.944	0.34	228.00	78	11.237	N/A	79.58	10.713	N/A	280.59
34	10.853	0.33	127.44	10.914	0.34	232.68	80	11.321	N/A	77.99	10.716	N/A	282.23
36	10.881	0.31	123.20	10.917	0.31	236.84	82	11.421	N/A	76.30	10.511	N/A	283.88
38	10.886	0.31	119.71	10.907	0.33	240.41	84	11.627	N/A	74.65	10.693	N/A	285.54
40	10.846	0.34	116.48	10.933	0.32	243.58	86	N/A	N/A	N/A	N/A	N/A	N/A
42	10.929	0.35	113.68	10.909	0.36	246.56	88	N/A	N/A	N/A	N/A	N/A	N/A
44	10.853	0.32	110.93	10.920	0.35	249.22	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, $u(B)$ (%)	$\pm 0.61$
Type-A Interpolating Function, $u(int)$ (%)	$\pm 0.30$
Combined Standard Uncertainty, $u(c)$ (%)	$\pm 0.68$
Effective degrees of freedom, $DF(c)$	2597
Coverage factor, $k$	1.96
Expanded Uncertainty, $U_{95}$ (%)	$\pm 1.3$
AM Valid zenith angle range	24° to 76°
PM Valid zenith angle range	24° to 74°

‡ 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**

$R @ 45^\circ$ ( $\mu V/W/m^2$ )	$R_{net}$ ( $\mu V/W/m^2$ ) †
10.903	0.30000

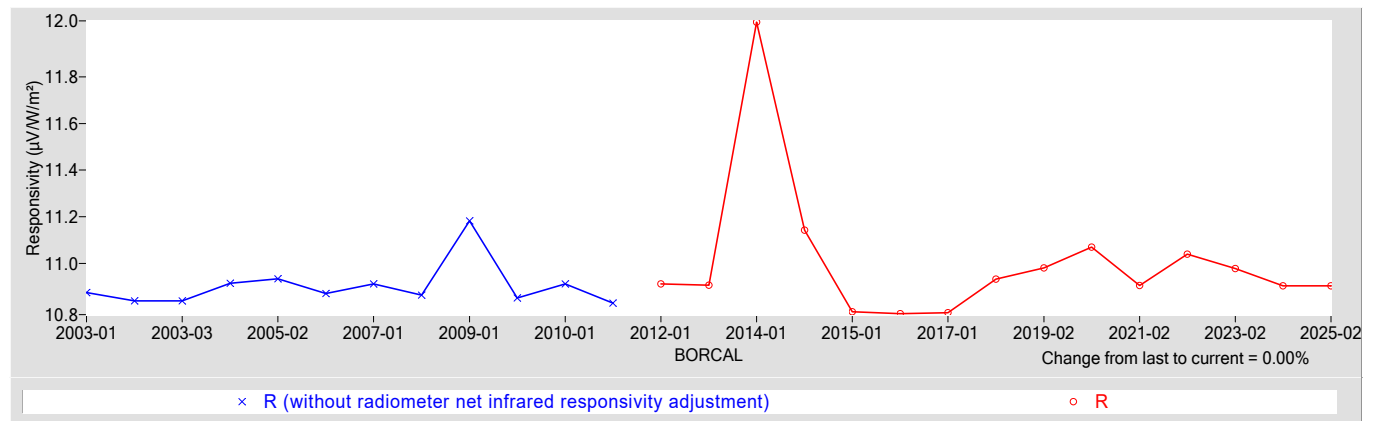
†  $R_{net}$  determination date: Estimated

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

Type-B Expanded Uncertainty, $U(B)$ (%)	$\pm 0.83$
Offset Uncertainty, $U(off)$ (%)	+0.40 / -0.53
Expanded Uncertainty, $U$ (%)	+1.2 / -1.4
Effective degrees of freedom, $DF^*$	2093
Coverage factor, $k$	1.96
Valid zenith angle range	30.0° to 60.0°

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

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



**References:**

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



# National Renewable Energy Laboratory

## Solar Radiation Research Laboratory

### Metrology Laboratory

### Calibration Certificate



<b>Test Instrument:</b>	Pyranometer (Ventilated)	<b>Manufacturer:</b>	Yankee
<b>Model:</b>	TSP-700	<b>Serial Number:</b>	0212-2
<b>Calibration Date:</b>	5/2/2025	<b>Due Date:</b>	5/2/2026
<b>Customer:</b>	NREL-SRRL-BMS	<b>Environmental Conditions:</b>	see page 4
<b>Test Dates:</b>	5/2		

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	09/27/2024	09/27/2025
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/21/2025	04/21/2026
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/21/2025	04/21/2026
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/07/2025	02/07/2027
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/07/2025	02/07/2027

† 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, RCC, and Shawn L. Jaker

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Ibrahim Reda, Technical Manager

05/05/2025

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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 ( $\text{W}/\text{m}^2$ ),
  - =  $W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
  - where,  $W_{in}$  = incoming infrared ( $\text{W}/\text{m}^2$ ),  $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$ ,
  - $T_c$  = case temperature of pyrgeometer (K).
- $I$  = reference irradiance ( $\text{W}/\text{m}^2$ ), beam (B) or global (G)  
 where,  $G = B * \text{COS}(Z) + D$ ,  
 $Z$  = zenith angle (degrees),  
 $D$  = reference diffuse irradiance ( $\text{W}/\text{m}^2$ ).

Figure 1. Responsivity vs Zenith Angle

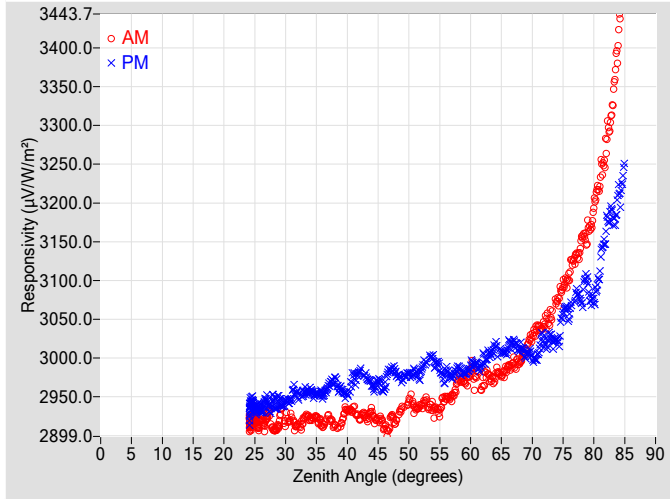


Figure 2. Responsivity vs Local Standard Time

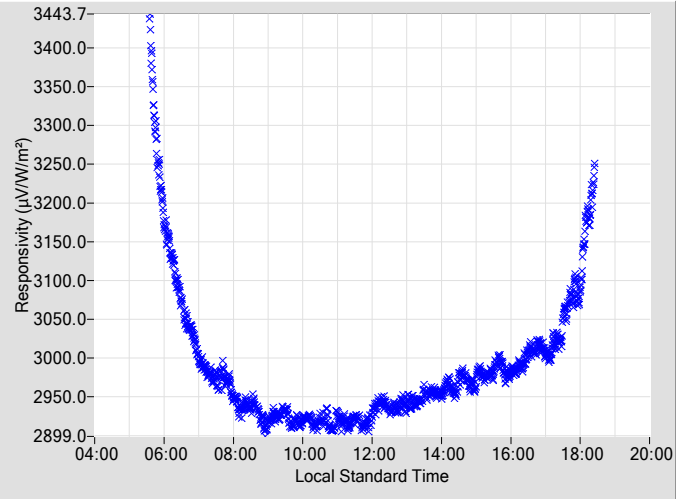
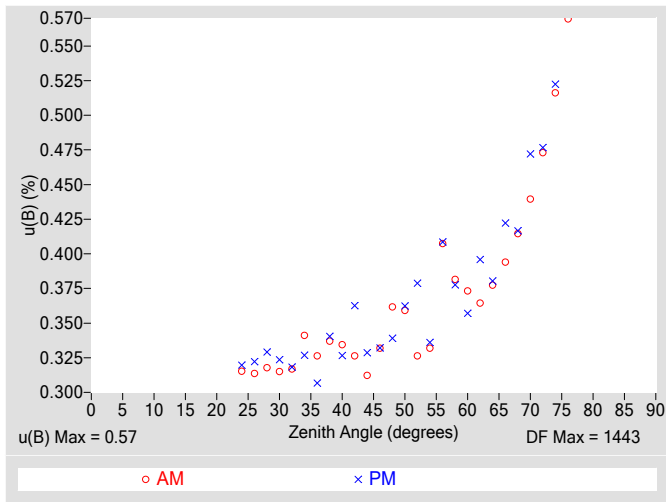


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty,  $u(B)$

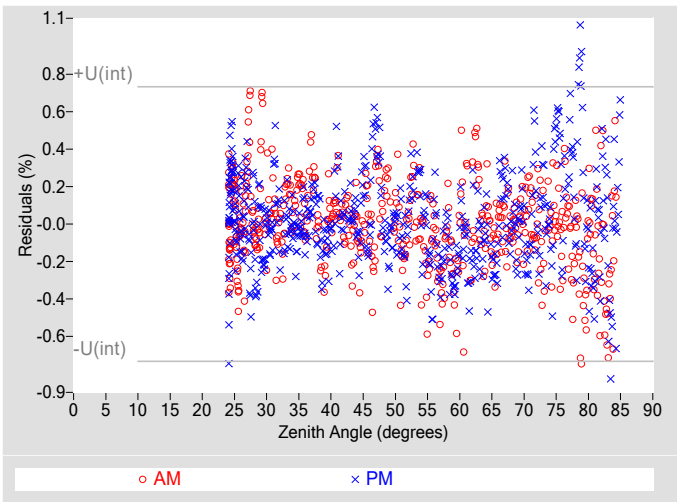
Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	$u(B)$ $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	$u(B)$ $\pm$ (%)	Azimuth Angle	Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	$u(B)$ $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	$u(B)$ $\pm$ (%)	Azimuth Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	2911.5	0.33	108.46	2961.1	0.33	251.64
2	N/A	N/A	N/A	N/A	N/A	N/A	48	2917.4	0.36	106.30	2978.3	0.34	253.95
4	N/A	N/A	N/A	N/A	N/A	N/A	50	2943.2	0.36	104.04	2979.4	0.36	256.18
6	N/A	N/A	N/A	N/A	N/A	N/A	52	2938.5	0.33	101.87	2983.7	0.38	258.26
8	N/A	N/A	N/A	N/A	N/A	N/A	54	2934.6	0.33	99.89	2996.1	0.34	260.20
10	N/A	N/A	N/A	N/A	N/A	N/A	56	2948.4	0.41	98.00	2980.4	0.41	262.14
12	N/A	N/A	N/A	N/A	N/A	N/A	58	2972.1	0.38	96.17	2988.3	0.38	263.98
14	N/A	N/A	N/A	N/A	N/A	N/A	60	2984.5	0.37	94.39	2991.4	0.36	265.76
16	N/A	N/A	N/A	N/A	N/A	N/A	62	2965.1	0.36	92.66	2997.9	0.40	267.50
18	N/A	N/A	N/A	N/A	N/A	N/A	64	2977.3	0.38	90.95	3016.4	0.38	269.20
20	N/A	N/A	N/A	N/A	N/A	N/A	66	2987.5	0.39	89.28	3013.5	0.42	270.86
22	N/A	N/A	N/A	N/A	N/A	N/A	68	2994.7	0.41	87.64	3012.7	0.42	272.51
24	2915.5	0.32	175.53	2935.1	0.32	184.08	70	3028.9	0.44	86.05	3001.4	0.47	274.14
26	2920.8	0.31	155.22	2933.7	0.32	204.91	72	3043.5	0.47	84.44	3018.7	0.48	275.75
28	2908.1	0.32	144.87	2945.8	0.33	215.32	74	3073.0	0.52	82.81	3023.0	0.52	277.36
30	2919.1	0.32	138.01	2944.1	0.32	222.23	76	3108.0	0.57	81.22	3059.3	N/A	278.96
32	2913.7	0.32	132.39	2953.2	0.32	227.91	78	3152.5	N/A	79.58	3074.3	N/A	280.60
34	2921.2	0.34	127.41	2957.8	0.33	232.68	80	3193.2	N/A	77.99	3078.0	N/A	282.23
36	2913.3	0.33	123.29	2952.1	0.31	236.85	82	3272.6	N/A	76.35	3166.6	N/A	283.88
38	2912.8	0.34	119.88	2971.2	0.34	240.36	84	3414.0	N/A	74.66	3209.4	N/A	285.58
40	2932.8	0.33	116.56	2953.7	0.33	243.48	86	N/A	N/A	N/A	N/A	N/A	N/A
42	2923.1	0.33	113.58	2982.9	0.36	246.42	88	N/A	N/A	N/A	N/A	N/A	N/A
44	2930.1	0.31	111.00	2965.3	0.33	249.16	90	N/A	N/A	N/A	N/A	N/A	N/A

N/A - Not Available

**Figure 3. Type-B Standard Uncertainty vs Zenith Angle**



**Figure 4. Residuals from Spline Interpolation**



**Table 3. Uncertainty using Spline Interpolation ‡**

Type-B Standard Uncertainty, $u(B)$ (%)	$\pm 0.57$
Type-A Interpolating Function, $u(int)$ (%)	$\pm 0.37$
Combined Standard Uncertainty, $u(c)$ (%)	$\pm 0.68$
Effective degrees of freedom, $DF(c)$	2325
Coverage factor, $k$	1.96
Expanded Uncertainty, $U95$ (%)	$\pm 1.3$
AM Valid zenith angle range	24° to 76°
PM Valid zenith angle range	24° to 74°

‡ 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**

$R @ 45^\circ$ ( $\mu V/W/m^2$ )	$R_{net}$ ( $\mu V/W/m^2$ ) †
2945.1	0

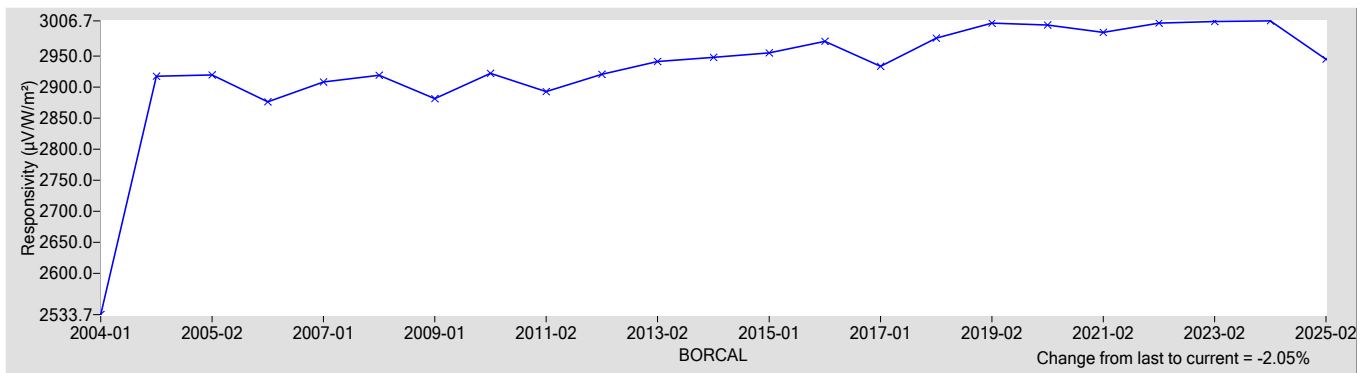
†  $R_{net}$  determination date: N/A

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

Type-B Expanded Uncertainty, $U(B)$ (%)	$\pm 0.80$
Offset Uncertainty, $U(off)$ (%)	+1.7 / -1.1
Expanded Uncertainty, $U$ (%)	+2.5 / -1.9
Effective degrees of freedom, $DF^*$	1994
Coverage factor, $k$	1.96
Valid zenith angle range	30.0° to 60.0°

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

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



**References:**

[1] Reda, I.; Hickey, J.; Long, C.; Myers, D.; Stoffel, T.; Wilcox, S.; Michalsky, J. J.; Dutton, E. G.; Nelson, D. (2005). "Using a Blackbody to Calculate Net Longwave Responsivity of Shortwave Solar Pyranometers to Correct for Their Thermal Offset Error During Outdoor Calibration Using the Component Sum Method." Journal of Atmospheric and Oceanic Technology. , 2005; pp. 1531-1540; NREL Report No. JA-560-36646. doi:10.1175/JTECH1782.1

[2] Reda, I.; Myers, D.; Stoffel, T. (2008). "Uncertainty Estimate for the Outdoor Calibration of Solar Pyranometers: A Metrologist Perspective." Measure. (NCSLI Journal of Measurement Science). Vol. 3(4), December 2008; pp. 58-66; NREL Report No. JA-581-4137

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

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

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

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

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



# National Renewable Energy Laboratory

## Solar Radiation Research Laboratory

### Metrology Laboratory

### Calibration Certificate



<b>Test Instrument:</b>	Pyrheliometer	<b>Manufacturer:</b>	Kipp & Zonen
<b>Model:</b>	CHP1	<b>Serial Number:</b>	080009
<b>Calibration Date:</b>	5/2/2025	<b>Due Date:</b>	5/2/2026
<b>Customer:</b>	NREL-SRRL-BMS	<b>Environmental Conditions:</b>	see page 4
<b>Test Dates:</b>	5/2		

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	09/27/2024	09/27/2025
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/21/2025	04/21/2026
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/21/2025	04/21/2026
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/07/2025	02/07/2027
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/07/2025	02/07/2027

† 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, RCC, and Shawn L. Jaker

-----  
Ibrahim Reda, Technical Manager

05/05/2025

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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

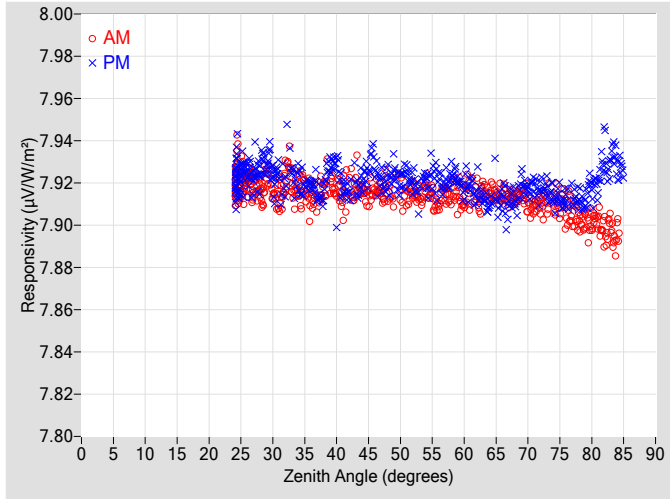
The responsivity ( $R$ ,  $\mu\text{V}/\text{W}/\text{m}^2$ ) of the test instrument during calibration is calculated using this Measurement Equation:

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

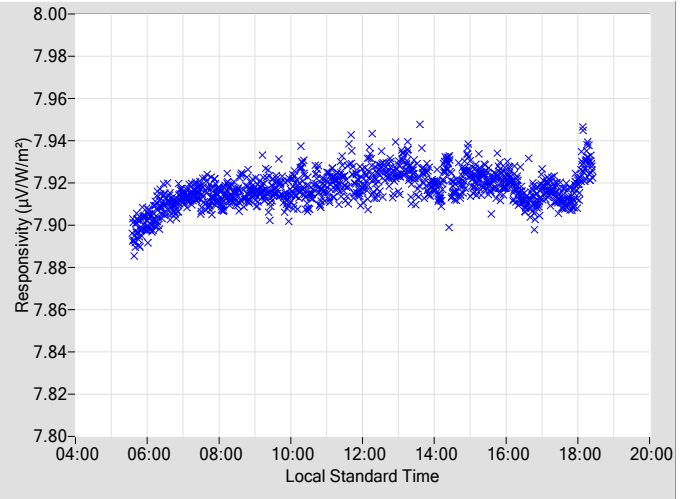
where,

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

**Figure 1. Responsivity vs Zenith Angle**



**Figure 2. Responsivity vs Local Standard Time**

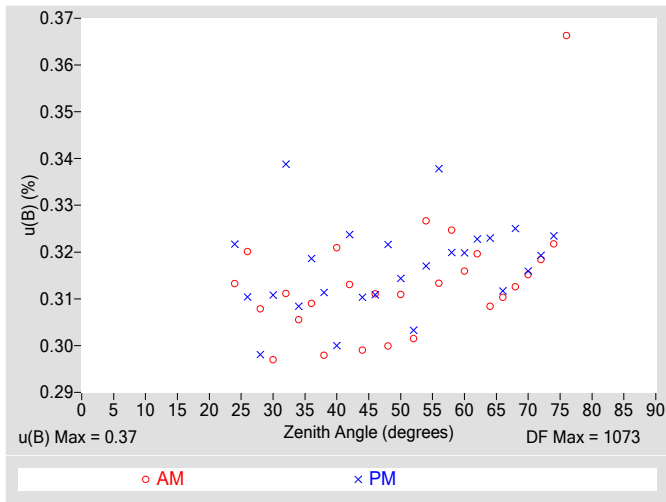


**Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)**

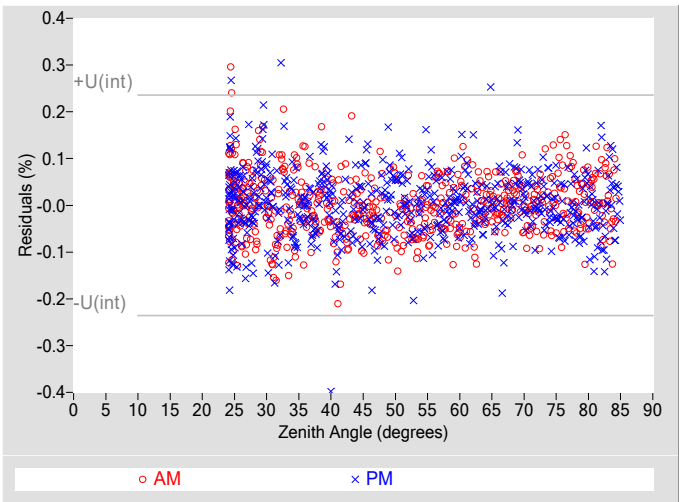
Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	AM u(B) $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	PM u(B) $\pm$ (%)	Azimuth Angle	Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	AM u(B) $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	PM u(B) $\pm$ (%)	Azimuth Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	7.9172	0.31	108.47	7.9294	0.31	251.62
2	N/A	N/A	N/A	N/A	N/A	N/A	48	7.9173	0.30	106.20	7.9211	0.32	253.97
4	N/A	N/A	N/A	N/A	N/A	N/A	50	7.9184	0.31	103.96	7.9198	0.31	256.16
6	N/A	N/A	N/A	N/A	N/A	N/A	52	7.9155	0.30	101.91	7.9209	0.30	258.25
8	N/A	N/A	N/A	N/A	N/A	N/A	54	7.9200	0.33	99.92	7.9222	0.32	260.24
10	N/A	N/A	N/A	N/A	N/A	N/A	56	7.9098	0.31	97.98	7.9197	0.34	262.08
12	N/A	N/A	N/A	N/A	N/A	N/A	58	7.9164	0.32	96.16	7.9245	0.32	263.96
14	N/A	N/A	N/A	N/A	N/A	N/A	60	7.9136	0.32	94.38	7.9160	0.32	265.74
16	N/A	N/A	N/A	N/A	N/A	N/A	62	7.9154	0.32	92.64	7.9159	0.32	267.48
18	N/A	N/A	N/A	N/A	N/A	N/A	64	7.9148	0.31	90.98	7.9102	0.32	269.18
20	N/A	N/A	N/A	N/A	N/A	N/A	66	7.9140	0.31	89.31	7.9135	0.31	270.85
22	N/A	N/A	N/A	N/A	N/A	N/A	68	7.9120	0.31	87.67	7.9108	0.33	272.49
24	7.9189	0.31	175.93	7.9214	0.32	184.30	70	7.9109	0.32	86.03	7.9166	0.32	274.12
26	7.9205	0.32	154.90	7.9249	0.31	205.00	72	7.9097	0.32	84.42	7.9170	0.32	275.74
28	7.9162	0.31	144.92	7.9261	0.30	215.23	74	7.9109	0.32	82.84	7.9133	0.32	277.34
30	7.9145	0.30	137.54	7.9213	0.31	222.39	76	7.9048	0.37	81.20	7.9138	N/A	278.99
32	7.9224	0.31	132.07	7.9237	0.34	227.91	78	7.9016	N/A	79.61	7.9129	N/A	280.58
34	7.9182	0.31	127.31	7.9218	0.31	232.74	80	7.9016	N/A	77.97	7.9152	N/A	282.22
36	7.9109	0.31	123.36	7.9193	0.32	236.82	82	7.8964	N/A	76.33	7.9334	N/A	283.87
38	7.9183	0.30	119.68	7.9158	0.31	240.46	84	7.8953	N/A	74.64	7.9276	N/A	285.57
40	7.9173	0.32	116.55	7.9303	0.30	243.51	86	N/A	N/A	N/A	N/A	N/A	N/A
42	7.9203	0.31	113.56	7.9169	0.32	246.45	88	N/A	N/A	N/A	N/A	N/A	N/A
44	7.9166	0.30	110.97	7.9206	0.31	249.14	90	N/A	N/A	N/A	N/A	N/A	N/A

N/A - Not Available

**Figure 3. Type-B Standard Uncertainty vs Zenith Angle**



**Figure 4. Residuals from Spline Interpolation**



**Table 3. Uncertainty using Spline Interpolation ‡**

Type-B Standard Uncertainty, $u(B)$ (%)	$\pm 0.37$
Type-A Interpolating Function, $u(int)$ (%)	$\pm 0.12$
Combined Standard Uncertainty, $u(c)$ (%)	$\pm 0.38$
Effective degrees of freedom, $DF(c)$	1292
Coverage factor, $k$	1.96
Expanded Uncertainty, $U95$ (%)	$\pm 0.75$
AM Valid zenith angle range	24° to 76°
PM Valid zenith angle range	24° to 74°

‡ 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**

$R @ 45^\circ$ ( $\mu V/W/m^2$ )	$R_{net}$ ( $\mu V/W/m^2$ ) †
7.9200	0

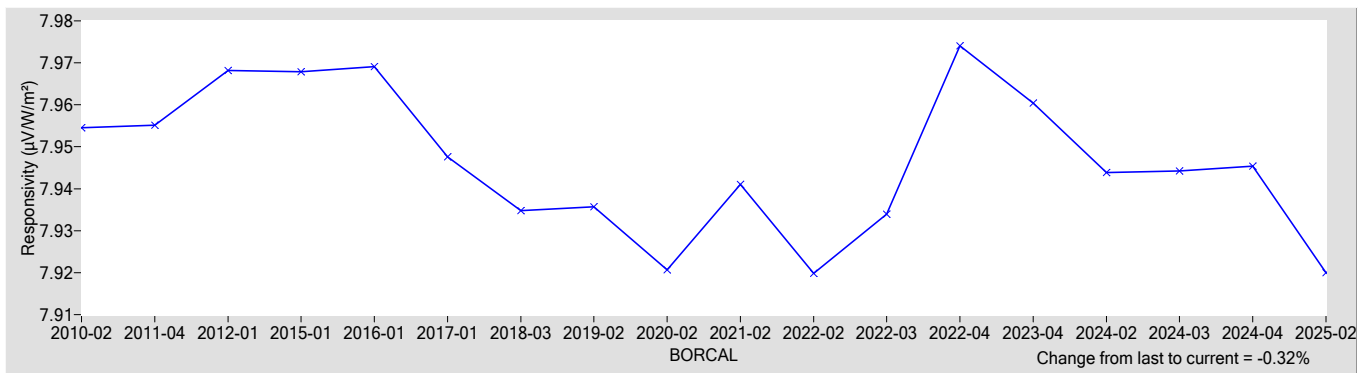
†  $R_{net}$  determination date: N/A

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

Type-B Expanded Uncertainty, $U(B)$ (%)	$\pm 0.66$
Offset Uncertainty, $U(off)$ (%)	+0.13 / -0.13
Expanded Uncertainty, $U$ (%)	+0.80 / -0.79
Effective degrees of freedom, $DF^*$	1044
Coverage factor, $k$	1.96
Valid zenith angle range	30.0° to 60.0°

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

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



**References:**

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



# National Renewable Energy Laboratory

## Solar Radiation Research Laboratory

### Metrology Laboratory

### Calibration Certificate



<b>Test Instrument:</b>	Pyranometer	<b>Manufacturer:</b>	Kipp & Zonen
<b>Model:</b>	CMP22	<b>Serial Number:</b>	100174
<b>Calibration Date:</b>	5/2/2025	<b>Due Date:</b>	5/2/2026
<b>Customer:</b>	NREL-SRRL-BMS	<b>Environmental Conditions:</b>	see page 4
<b>Test Dates:</b>	5/2		

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	09/27/2024	09/27/2025
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/21/2025	04/21/2026
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/21/2025	04/21/2026
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/07/2025	02/07/2027
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/07/2025	02/07/2027
Infrared Irradiance ‡	Kipp & Zonen Pyrgeometer Model CG4, S/N FT002	03/31/2022	03/31/2027

† Through the World Radiometric Reference (WRR)

‡ Through the World Infrared Standard Group (WISG)

**Number of pages of certificate:** 4

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

**Setup:** Radiometers are calibrated outdoors, using the sun as the source. Pyranometers and pyrgeometers are installed for horizontal measurements, with their signal connectors oriented north, if their design permits.

The shading disk for the reference diffuse subtends a solid angle of 5°. Pyrheliometers are installed on solar trackers.

**Calibrated by:** Afshin Andreas, RCC, and Shawn L. Jaker

-----  
Ibrahim Reda, Technical Manager

05/05/2025

-----  
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 ( $\text{W}/\text{m}^2$ ),
  - =  $W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
  - where,  $W_{in}$  = incoming infrared ( $\text{W}/\text{m}^2$ ),  $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$ ,
  - $T_c$  = case temperature of pyrgeometer (K).
- $I$  = reference irradiance ( $\text{W}/\text{m}^2$ ), beam (B) or global (G)
  - where,  $G = B * \text{COS}(Z) + D$ ,
  - $Z$  = zenith angle (degrees),
  - $D$  = reference diffuse irradiance ( $\text{W}/\text{m}^2$ ).

Figure 1. Responsivity vs Zenith Angle

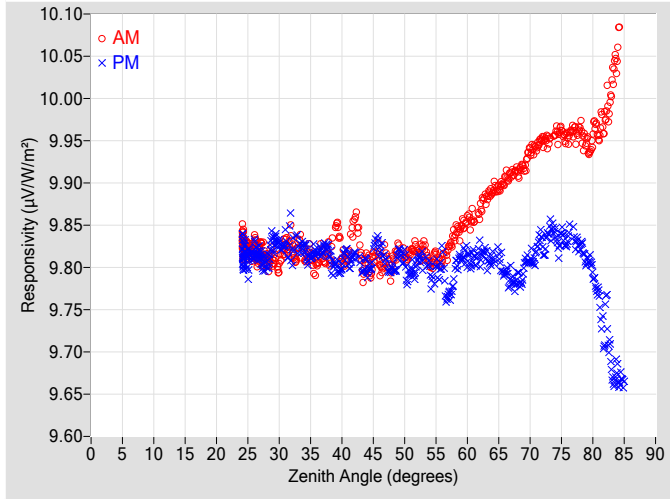


Figure 2. Responsivity vs Local Standard Time

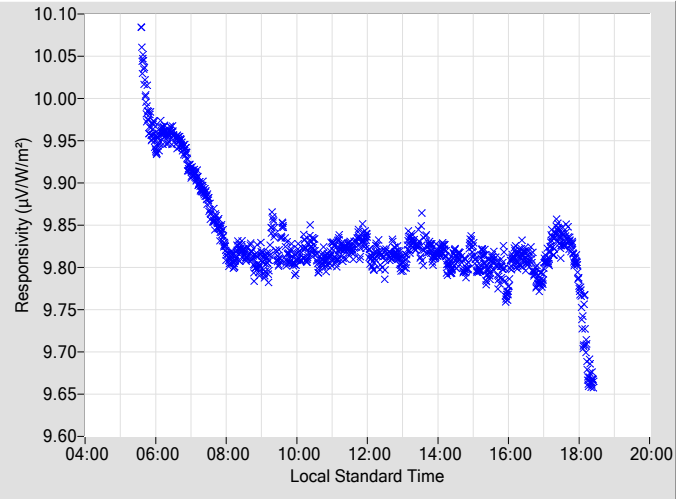
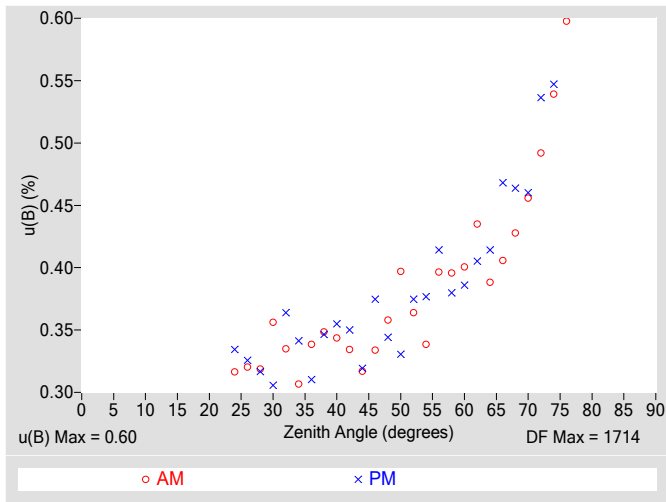


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty,  $u(B)$

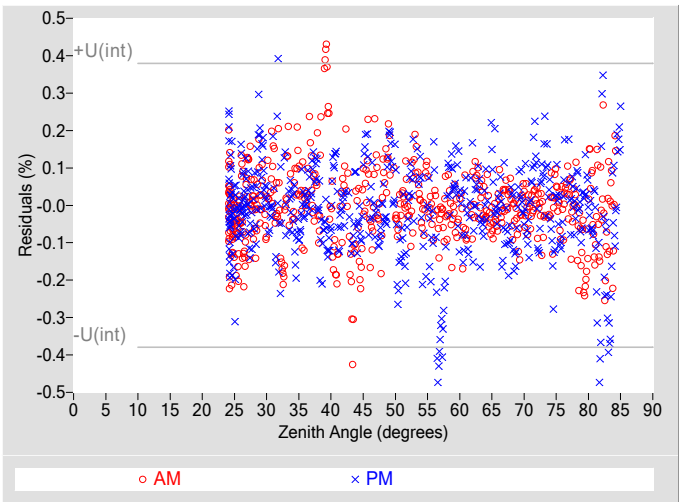
Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	AM $u(B)$ $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	PM $u(B)$ $\pm$ (%)	Azimuth Angle	Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	AM $u(B)$ $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	PM $u(B)$ $\pm$ (%)	Azimuth Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	9.8066	0.33	108.45	9.8226	0.37	251.63
2	N/A	N/A	N/A	N/A	N/A	N/A	48	9.8010	0.36	106.17	9.7988	0.34	253.98
4	N/A	N/A	N/A	N/A	N/A	N/A	50	9.8147	0.40	103.94	9.8054	0.33	256.17
6	N/A	N/A	N/A	N/A	N/A	N/A	52	9.8210	0.36	101.89	9.8065	0.37	258.26
8	N/A	N/A	N/A	N/A	N/A	N/A	54	9.8054	0.34	99.93	9.7937	0.38	260.25
10	N/A	N/A	N/A	N/A	N/A	N/A	56	9.8105	0.40	97.94	9.8094	0.41	262.10
12	N/A	N/A	N/A	N/A	N/A	N/A	58	9.8402	0.40	96.16	9.7960	0.38	263.98
14	N/A	N/A	N/A	N/A	N/A	N/A	60	9.8594	0.40	94.39	9.8128	0.39	265.75
16	N/A	N/A	N/A	N/A	N/A	N/A	62	9.8657	0.44	92.65	9.8156	0.41	267.52
18	N/A	N/A	N/A	N/A	N/A	N/A	64	9.8915	0.39	90.95	9.8100	0.41	269.19
20	N/A	N/A	N/A	N/A	N/A	N/A	66	9.9049	0.41	89.32	9.7928	0.47	270.85
22	N/A	N/A	N/A	N/A	N/A	N/A	68	9.9122	0.43	87.67	9.7893	0.46	272.50
24	9.8322	0.32	175.98	9.8151	0.33	184.41	70	9.9376	0.46	86.04	9.8103	0.46	274.13
26	9.8258	0.32	155.03	9.8175	0.33	205.18	72	9.9504	0.49	84.43	9.8250	0.54	275.75
28	9.8100	0.32	144.95	9.8055	0.32	215.21	74	9.9595	0.54	82.80	9.8393	0.55	277.35
30	9.8020	0.36	137.85	9.8281	0.31	222.20	76	9.9547	0.60	81.21	9.8355	N/A	278.99
32	9.8328	0.33	132.09	9.8253	0.36	227.98	78	9.9628	N/A	79.57	9.8251	N/A	280.59
34	9.8117	0.31	127.28	9.8237	0.34	232.77	80	9.9558	N/A	77.98	9.7940	N/A	282.23
36	9.8014	0.34	123.36	9.8162	0.31	236.74	82	9.9756	N/A	76.34	9.7411	N/A	283.88
38	9.8118	0.35	119.70	9.8144	0.35	240.39	84	10.061	N/A	74.65	9.6730	N/A	285.53
40	9.8105	0.34	116.46	9.8037	0.35	243.62	86	N/A	N/A	N/A	N/A	N/A	N/A
42	9.8519	0.33	113.75	9.8154	0.35	246.48	88	N/A	N/A	N/A	N/A	N/A	N/A
44	9.8104	0.32	110.91	9.7996	0.32	249.22	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) (%)	±0.60
Type-A Interpolating Function, u(int) (%)	±0.19
Combined Standard Uncertainty, u(c) (%)	±0.63
Effective degrees of freedom, DF(c)	2042
Coverage factor, k	1.96
Expanded Uncertainty, U95 (%)	±1.2
AM Valid zenith angle range	24° to 76°
PM Valid zenith angle range	24° to 74°

‡ 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) †
9.8110	0.087000

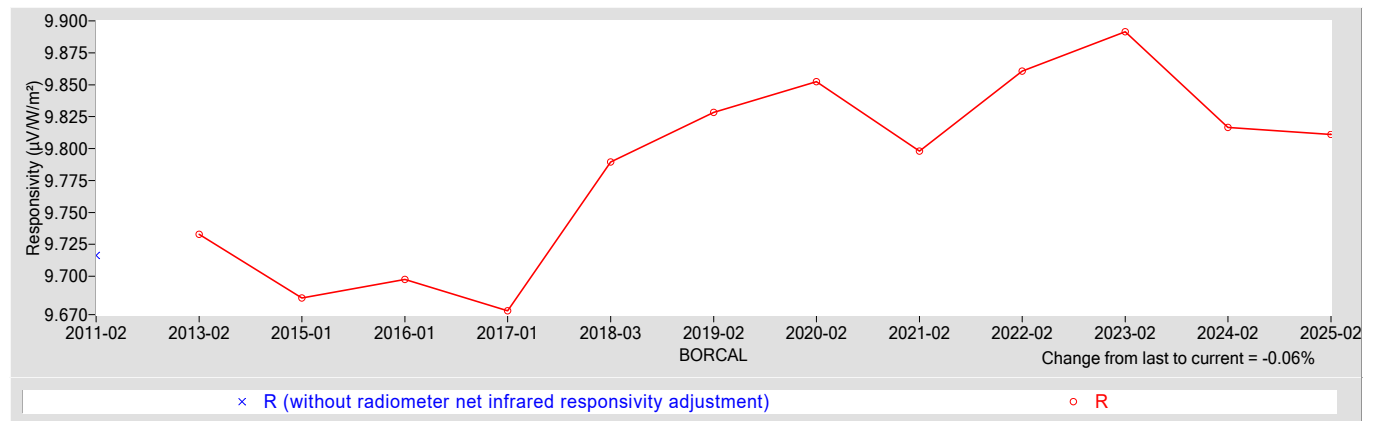
† Rnet determination date: Estimated

**Table 5. Uncertainty using R @ 45°**

Type-B Expanded Uncertainty, U(B) (%)	±0.81
Offset Uncertainty, U(off) (%)	+0.49 / -0.18
Expanded Uncertainty, U (%)	+1.3 / -0.99
Effective degrees of freedom, DF *	2101
Coverage factor, k	1.96
Valid zenith angle range	30.0° to 60.0°

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

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



**References:**

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



# National Renewable Energy Laboratory

## Solar Radiation Research Laboratory

### Metrology Laboratory

### Calibration Certificate



<b>Test Instrument:</b>	Thermopile Pyranometer	<b>Manufacturer:</b>	Apogee
<b>Model:</b>	SP-510	<b>Serial Number:</b>	1171
<b>Calibration Date:</b>	5/2/2025	<b>Due Date:</b>	5/2/2026
<b>Customer:</b>	NREL-SRRL-BMS	<b>Environmental Conditions:</b>	see page 4
<b>Test Dates:</b>	5/2		

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	09/27/2024	09/27/2025
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/21/2025	04/21/2026
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/21/2025	04/21/2026
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/07/2025	02/07/2027
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/07/2025	02/07/2027
Infrared Irradiance ‡	Kipp & Zonen Pyrgeometer Model CG4, S/N FT002	03/31/2022	03/31/2027

† Through the World Radiometric Reference (WRR)

‡ Through the World Infrared Standard Group (WISG)

**Number of pages of certificate:** 4

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

**Setup:** Radiometers are calibrated outdoors, using the sun as the source. Pyranometers and pyrgeometers are installed for horizontal measurements, with their signal connectors oriented north, if their design permits.

The shading disk for the reference diffuse subtends a solid angle of 5°. Pyrheliometers are installed on solar trackers.

**Calibrated by:** Afshin Andreas, RCC, and Shawn L. Jaker

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Ibrahim Reda, Technical Manager

05/05/2025

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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 ( $\text{W}/\text{m}^2$ ),
  - =  $W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
  - where,  $W_{in}$  = incoming infrared ( $\text{W}/\text{m}^2$ ),  $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$ ,
  - $T_c$  = case temperature of pyrgeometer (K).
- $I$  = reference irradiance ( $\text{W}/\text{m}^2$ ), beam (B) or global (G)
  - where,  $G = B * \text{COS}(Z) + D$ ,
  - $Z$  = zenith angle (degrees),
  - $D$  = reference diffuse irradiance ( $\text{W}/\text{m}^2$ ).

Figure 1. Responsivity vs Zenith Angle

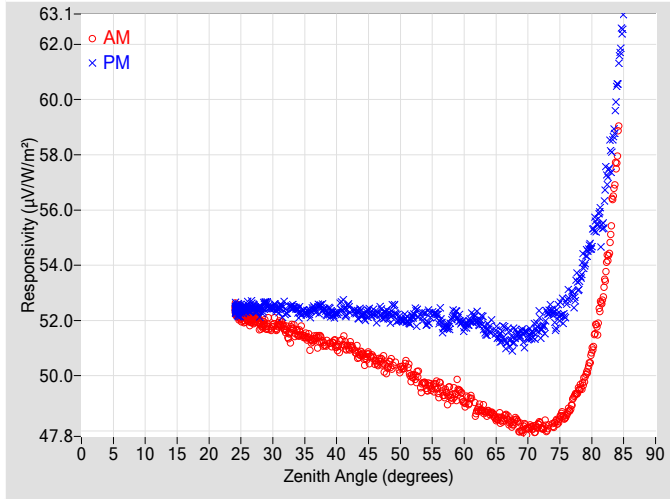


Figure 2. Responsivity vs Local Standard Time

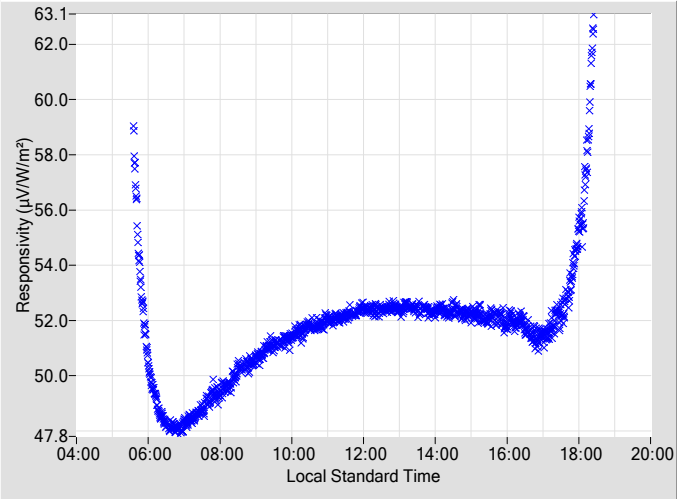
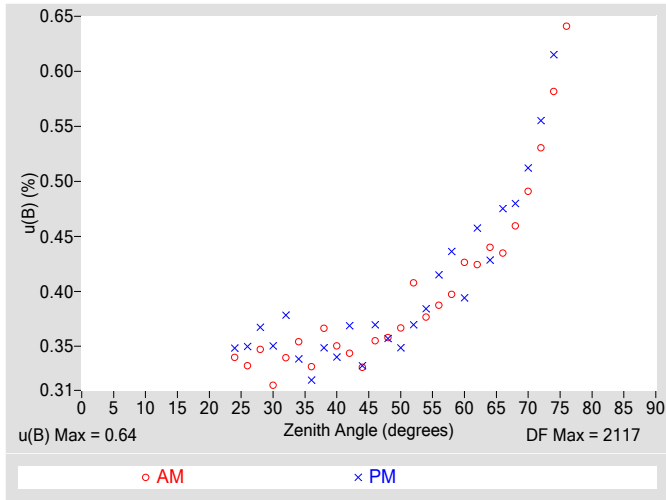


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty,  $u(B)$

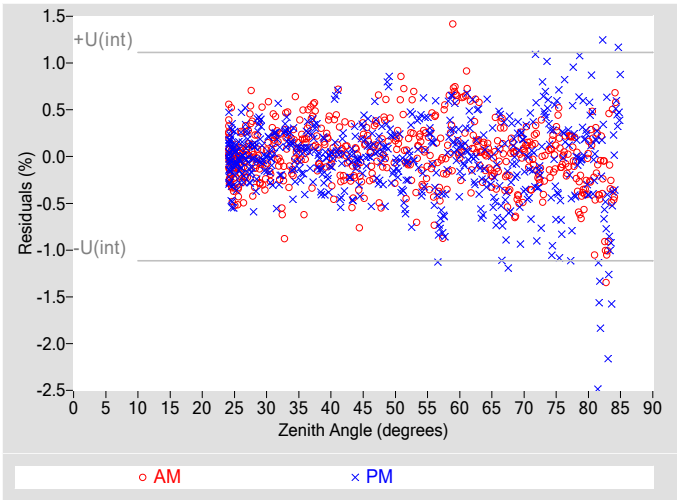
Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	AM $u(B)$ $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	PM $u(B)$ $\pm$ (%)	Azimuth Angle	Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	AM $u(B)$ $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	PM $u(B)$ $\pm$ (%)	Azimuth Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	50.534	0.35	108.45	52.191	0.37	251.67
2	N/A	N/A	N/A	N/A	N/A	N/A	48	50.326	0.36	106.14	52.216	0.36	254.01
4	N/A	N/A	N/A	N/A	N/A	N/A	50	50.242	0.37	103.94	52.041	0.35	256.17
6	N/A	N/A	N/A	N/A	N/A	N/A	52	49.960	0.41	101.90	52.223	0.37	258.29
8	N/A	N/A	N/A	N/A	N/A	N/A	54	49.607	0.38	99.91	52.033	0.38	260.25
10	N/A	N/A	N/A	N/A	N/A	N/A	56	49.565	0.39	98.02	52.150	0.42	262.16
12	N/A	N/A	N/A	N/A	N/A	N/A	58	49.281	0.40	96.19	52.102	0.44	264.02
14	N/A	N/A	N/A	N/A	N/A	N/A	60	49.015	0.43	94.41	51.811	0.39	265.78
16	N/A	N/A	N/A	N/A	N/A	N/A	62	48.672	0.42	92.67	52.012	0.46	267.51
18	N/A	N/A	N/A	N/A	N/A	N/A	64	48.659	0.44	90.97	51.719	0.43	269.22
20	N/A	N/A	N/A	N/A	N/A	N/A	66	48.402	0.43	89.30	51.557	0.48	270.88
22	N/A	N/A	N/A	N/A	N/A	N/A	68	48.389	0.46	87.65	51.486	0.48	272.52
24	52.348	0.34	176.11	52.410	0.35	184.14	70	48.045	0.49	86.02	51.487	0.51	274.15
26	52.119	0.33	155.03	52.448	0.35	205.10	72	48.182	0.53	84.41	51.823	0.56	275.77
28	51.857	0.35	144.92	52.429	0.37	215.10	74	48.230	0.58	82.78	52.117	0.62	277.37
30	51.814	0.31	137.76	52.496	0.35	222.52	76	48.532	0.64	81.23	52.569	N/A	278.97
32	51.685	0.34	132.14	52.373	0.38	228.05	78	49.513	N/A	79.59	53.355	N/A	280.61
34	51.544	0.35	127.28	52.333	0.34	232.71	80	50.837	N/A	77.96	54.879	N/A	282.20
36	51.197	0.33	123.23	52.309	0.32	236.76	82	53.345	N/A	76.32	56.462	N/A	283.89
38	51.143	0.37	119.74	52.423	0.35	240.44	84	58.129	N/A	74.67	60.570	N/A	285.55
40	51.067	0.35	116.58	52.254	0.34	243.50	86	N/A	N/A	N/A	N/A	N/A	N/A
42	51.064	0.34	113.60	52.484	0.37	246.37	88	N/A	N/A	N/A	N/A	N/A	N/A
44	50.813	0.33	110.95	52.223	0.33	249.18	90	N/A	N/A	N/A	N/A	N/A	N/A

N/A - Not Available

**Figure 3. Type-B Standard Uncertainty vs Zenith Angle**



**Figure 4. Residuals from Spline Interpolation**



**Table 3. Uncertainty using Spline Interpolation ‡**

Type-B Standard Uncertainty, $u(B)$ (%)	$\pm 0.64$
Type-A Interpolating Function, $u(int)$ (%)	$\pm 0.56$
Combined Standard Uncertainty, $u(c)$ (%)	$\pm 0.85$
Effective degrees of freedom, $DF(c)$	2983
Coverage factor, $k$	1.96
Expanded Uncertainty, $U95$ (%)	$\pm 1.7$
AM Valid zenith angle range	24° to 76°
PM Valid zenith angle range	24° to 74°

‡ 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**

$R @ 45^\circ$ ( $\mu V/W/m^2$ )	$R_{net}$ ( $\mu V/W/m^2$ ) †
51.510	2.5000

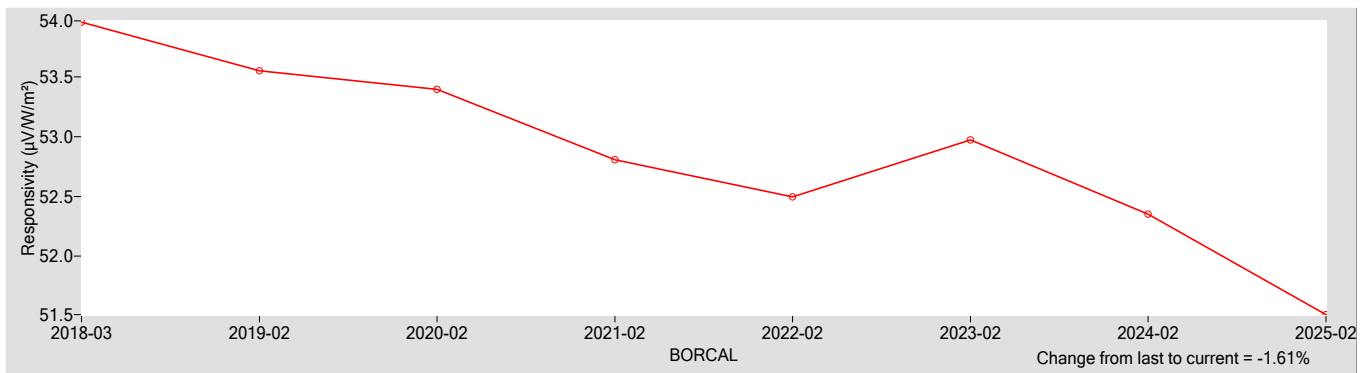
†  $R_{net}$  determination date: Estimated

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

Type-B Expanded Uncertainty, $U(B)$ (%)	$\pm 0.86$
Offset Uncertainty, $U(off)$ (%)	+1.9 / -4.8
Expanded Uncertainty, $U$ (%)	+2.8 / -5.7
Effective degrees of freedom, $DF^*$	2005
Coverage factor, $k$	1.96
Valid zenith angle range	30.0° to 60.0°

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

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



**References:**

[1] Reda, I.; Hickey, J.; Long, C.; Myers, D.; Stoffel, T.; Wilcox, S.; Michalsky, J. J.; Dutton, E. G.; Nelson, D. (2005). "Using a Blackbody to Calculate Net Longwave Responsivity of Shortwave Solar Pyranometers to Correct for Their Thermal Offset Error During Outdoor Calibration Using the Component Sum Method." *Journal of Atmospheric and Oceanic Technology*, 2005; pp. 1531-1540; NREL Report No. JA-560-36646. doi:10.1175/JTECH1782.1

[2] Reda, I.; Myers, D.; Stoffel, T. (2008). "Uncertainty Estimate for the Outdoor Calibration of Solar Pyranometers: A Metrologist Perspective." *Measure*. (NCSLI *Journal of Measurement Science*). Vol. 3(4), December 2008; pp. 58-66; NREL Report No. JA-581-4137

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

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

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

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

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# National Renewable Energy Laboratory

## Solar Radiation Research Laboratory

### Metrology Laboratory

### Calibration Certificate



<b>Test Instrument:</b>	Digital Pyranometer	<b>Manufacturer:</b>	Kipp & Zonen
<b>Model:</b>	SMP11	<b>Serial Number:</b>	120076
<b>Calibration Date:</b>	5/2/2025	<b>Due Date:</b>	5/2/2026
<b>Customer:</b>	NREL-SRRL-BMS	<b>Environmental Conditions:</b>	see page 4
<b>Test Dates:</b>	5/2		

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	09/27/2024	09/27/2025
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/21/2025	04/21/2026
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/21/2025	04/21/2026
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/07/2025	02/07/2027
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/07/2025	02/07/2027
Infrared Irradiance ‡	Kipp & Zonen Pyrgeometer Model CG4, S/N FT002	03/31/2022	03/31/2027

† Through the World Radiometric Reference (WRR)

‡ Through the World Infrared Standard Group (WISG)

**Number of pages of certificate:** 4

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

**Setup:** Radiometers are calibrated outdoors, using the sun as the source. Pyranometers and pyrgeometers are installed for horizontal measurements, with their signal connectors oriented north, if their design permits.

The shading disk for the reference diffuse subtends a solid angle of 5°. Pyrheliometers are installed on solar trackers.

**Calibrated by:** Afshin Andreas, RCC, and Shawn L. Jaker

-----  
Ibrahim Reda, Technical Manager

05/05/2025

-----  
Date

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

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

# Calibration Results

## 120076 Kipp & Zonen SMP11

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

Figure 1. Responsivity vs Zenith Angle

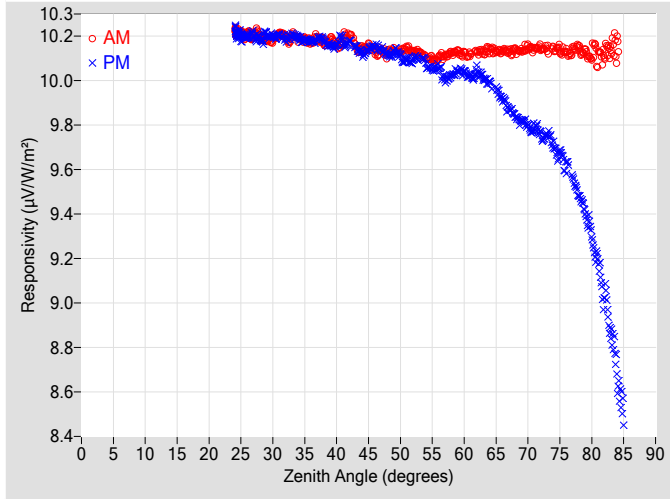


Figure 2. Responsivity vs Local Standard Time

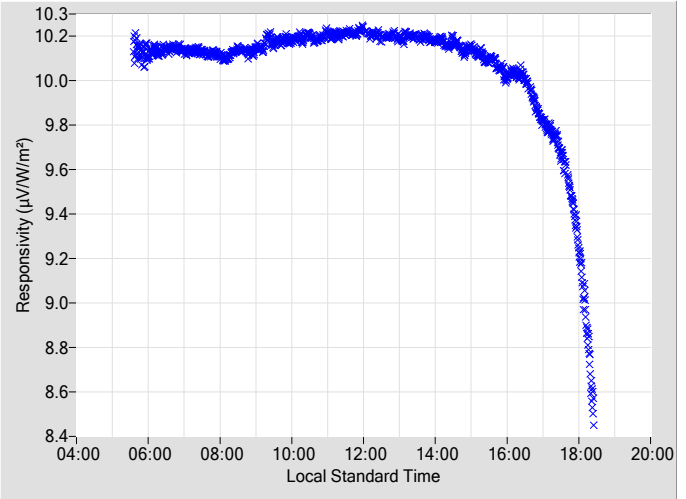
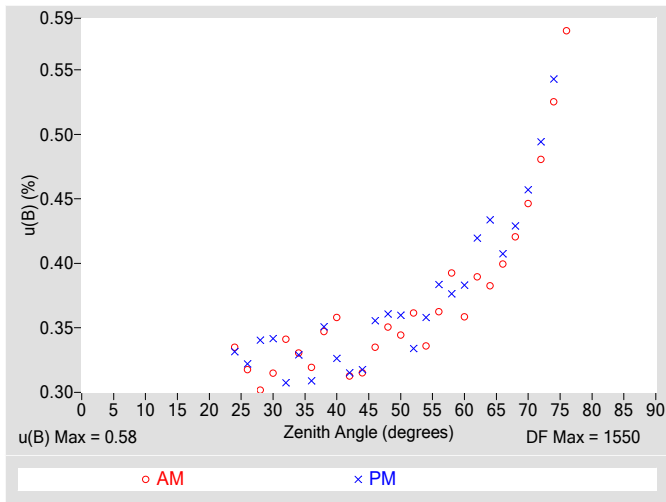


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty,  $u(B)$

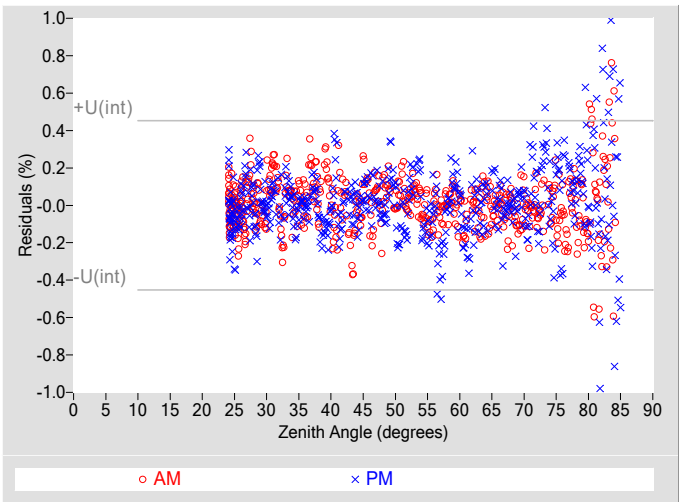
Zenith			AM			PM			Zenith			AM			PM		
Angle	R	u(B)	Azimuth	R	u(B)	Azimuth	Angle	R	u(B)	Azimuth	R	u(B)	Azimuth	R	u(B)	Azimuth	
(deg.)	( $\mu\text{V}/\text{W}/\text{m}^2$ )	$\pm$ (%)	Angle	( $\mu\text{V}/\text{W}/\text{m}^2$ )	$\pm$ (%)	Angle	(deg.)	( $\mu\text{V}/\text{W}/\text{m}^2$ )	$\pm$ (%)	Angle	( $\mu\text{V}/\text{W}/\text{m}^2$ )	$\pm$ (%)	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	10.134	0.33	108.43	10.150	0.36	251.69				
2	N/A	N/A	N/A	N/A	N/A	N/A	48	10.124	0.35	106.12	10.120	0.36	253.99				
4	N/A	N/A	N/A	N/A	N/A	N/A	50	10.133	0.34	103.98	10.107	0.36	256.18				
6	N/A	N/A	N/A	N/A	N/A	N/A	52	10.132	0.36	101.90	10.095	0.33	258.27				
8	N/A	N/A	N/A	N/A	N/A	N/A	54	10.105	0.34	99.89	10.074	0.36	260.26				
10	N/A	N/A	N/A	N/A	N/A	N/A	56	10.105	0.36	98.00	10.059	0.38	262.14				
12	N/A	N/A	N/A	N/A	N/A	N/A	58	10.125	0.39	96.17	10.025	0.38	263.98				
14	N/A	N/A	N/A	N/A	N/A	N/A	60	10.125	0.36	94.40	10.037	0.38	265.76				
16	N/A	N/A	N/A	N/A	N/A	N/A	62	10.128	0.39	92.66	10.041	0.42	267.50				
18	N/A	N/A	N/A	N/A	N/A	N/A	64	10.139	0.38	90.95	9.9875	0.43	269.20				
20	N/A	N/A	N/A	N/A	N/A	N/A	66	10.133	0.40	89.28	9.9176	0.41	270.86				
22	N/A	N/A	N/A	N/A	N/A	N/A	68	10.139	0.42	87.64	9.8395	0.43	272.51				
24	10.219	0.34	175.54	10.221	0.33	184.26	70	10.150	0.45	86.05	9.7967	0.46	274.14				
26	10.210	0.32	155.14	10.201	0.32	205.16	72	10.148	0.48	84.44	9.7531	0.49	275.75				
28	10.197	0.30	144.84	10.191	0.34	215.26	74	10.143	0.53	82.81	9.7047	0.54	277.36				
30	10.181	0.31	138.05	10.202	0.34	222.43	76	10.133	0.58	81.22	9.6165	N/A	278.96				
32	10.198	0.34	132.15	10.191	0.31	228.13	78	10.145	N/A	79.58	9.4794	N/A	280.60				
34	10.190	0.33	127.42	10.194	0.33	232.78	80	10.112	N/A	77.99	9.2935	N/A	282.23				
36	10.176	0.32	123.29	10.177	0.31	236.85	82	10.130	N/A	76.31	9.0323	N/A	283.88				
38	10.170	0.35	119.72	10.183	0.35	240.33	84	10.139	N/A	74.66	8.6735	N/A	285.54				
40	10.162	0.36	116.47	10.162	0.33	243.64	86	N/A	N/A	N/A	N/A	N/A	N/A				
42	10.204	0.31	113.69	10.177	0.32	246.49	88	N/A	N/A	N/A	N/A	N/A	N/A				
44	10.150	0.32	110.93	10.122	0.32	249.23	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, $u(B)$ (%)	$\pm 0.58$
Type-A Interpolating Function, $u(int)$ (%)	$\pm 0.23$
Combined Standard Uncertainty, $u(c)$ (%)	$\pm 0.62$
Effective degrees of freedom, $DF(c)$	1986
Coverage factor, $k$	1.96
Expanded Uncertainty, $U95$ (%)	$\pm 1.2$
AM Valid zenith angle range	24° to 76°
PM Valid zenith angle range	24° to 74°

‡ 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**

$R @ 45^\circ$ ( $\mu V/W/m^2$ )	$R_{net}$ ( $\mu V/W/m^2$ ) †
10.149	0.20500

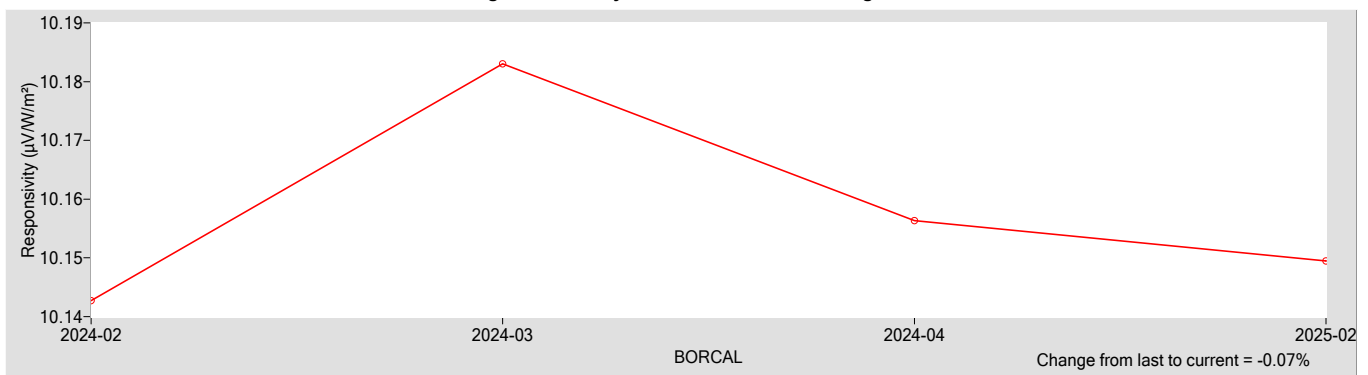
†  $R_{net}$  determination date: Estimated

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

Type-B Expanded Uncertainty, $U(B)$ (%)	$\pm 0.77$
Offset Uncertainty, $U(off)$ (%)	+0.54 / -1.2
Expanded Uncertainty, $U$ (%)	+1.3 / -2.0
Effective degrees of freedom, $DF^*$	1991
Coverage factor, $k$	1.96
Valid zenith angle range	30.0° to 60.0°

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

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



**References:**

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



# National Renewable Energy Laboratory

## Solar Radiation Research Laboratory

### Metrology Laboratory

### Calibration Certificate



<b>Test Instrument:</b>	Silicon Pyranometer	<b>Manufacturer:</b>	Kipp & Zonen
<b>Model:</b>	SP-LITE2	<b>Serial Number:</b>	125275
<b>Calibration Date:</b>	5/2/2025	<b>Due Date:</b>	5/2/2026
<b>Customer:</b>	NREL-SRRL-BMS	<b>Environmental Conditions:</b>	see page 4
<b>Test Dates:</b>	5/2		

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	09/27/2024	09/27/2025
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/21/2025	04/21/2026
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/21/2025	04/21/2026
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/07/2025	02/07/2027
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/07/2025	02/07/2027

† 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, RCC, and Shawn L. Jaker

\_\_\_\_\_  
Ibrahim Reda, Technical Manager

05/05/2025

\_\_\_\_\_  
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 ( $\text{W}/\text{m}^2$ ),
  - =  $W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
  - where,  $W_{in}$  = incoming infrared ( $\text{W}/\text{m}^2$ ),  $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$ ,
  - $T_c$  = case temperature of pyrgeometer (K).
- $I$  = reference irradiance ( $\text{W}/\text{m}^2$ ), beam (B) or global (G)
  - where,  $G = B * \text{COS}(Z) + D$ ,
  - $Z$  = zenith angle (degrees),
  - $D$  = reference diffuse irradiance ( $\text{W}/\text{m}^2$ ).

Figure 1. Responsivity vs Zenith Angle

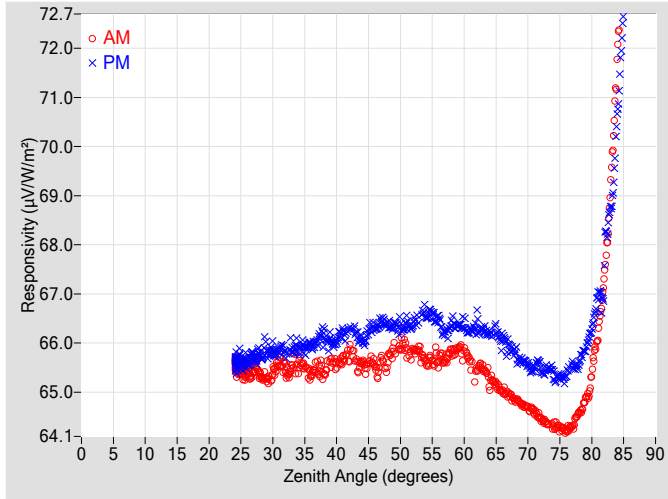


Figure 2. Responsivity vs Local Standard Time

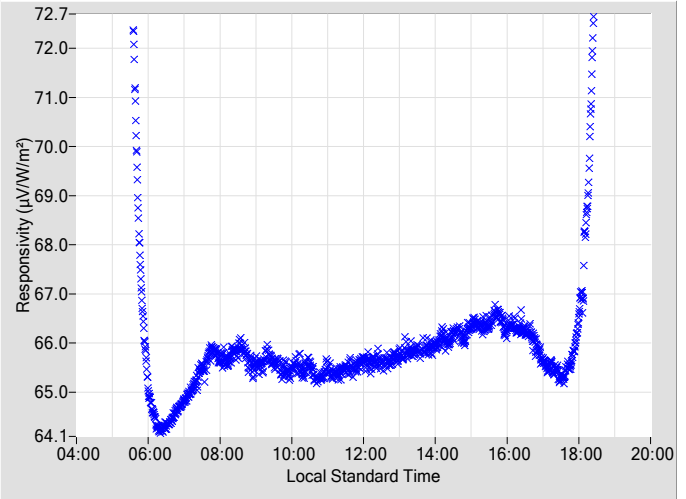
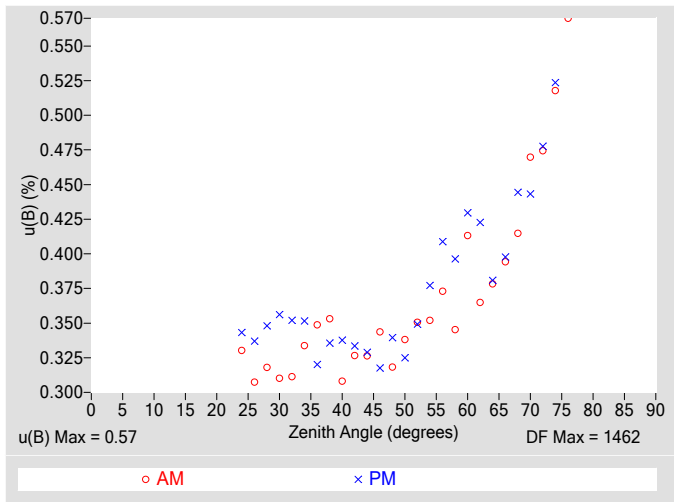


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty,  $u(B)$

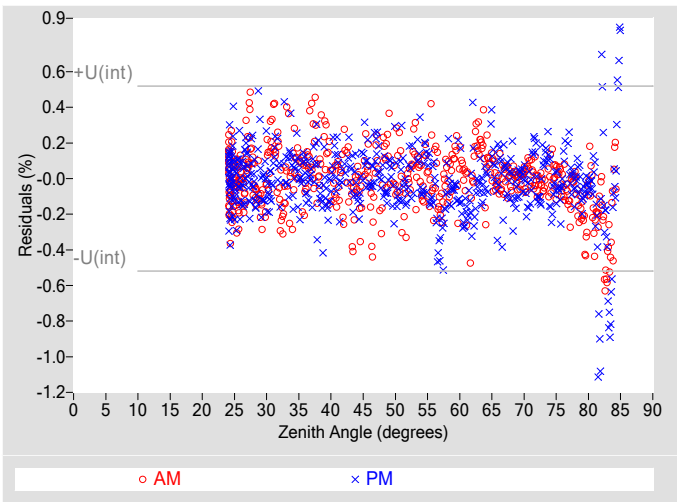
Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	$u(B)$ $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	$u(B)$ $\pm$ (%)	Azimuth Angle	Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	$u(B)$ $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	$u(B)$ $\pm$ (%)	Azimuth Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	65.550	0.34	108.51	66.310	0.32	251.64
2	N/A	N/A	N/A	N/A	N/A	N/A	48	65.613	0.32	106.11	66.381	0.34	253.99
4	N/A	N/A	N/A	N/A	N/A	N/A	50	65.922	0.34	103.96	66.336	0.33	256.17
6	N/A	N/A	N/A	N/A	N/A	N/A	52	65.867	0.35	101.83	66.391	0.35	258.20
8	N/A	N/A	N/A	N/A	N/A	N/A	54	65.612	0.35	99.93	66.572	0.38	260.24
10	N/A	N/A	N/A	N/A	N/A	N/A	56	65.648	0.37	97.99	66.502	0.41	262.13
12	N/A	N/A	N/A	N/A	N/A	N/A	58	65.825	0.35	96.16	66.404	0.40	263.97
14	N/A	N/A	N/A	N/A	N/A	N/A	60	65.801	0.41	94.38	66.391	0.43	265.75
16	N/A	N/A	N/A	N/A	N/A	N/A	62	65.464	0.36	92.65	66.386	0.42	267.49
18	N/A	N/A	N/A	N/A	N/A	N/A	64	65.209	0.38	90.94	66.203	0.38	269.19
20	N/A	N/A	N/A	N/A	N/A	N/A	66	65.034	0.39	89.32	66.062	0.40	270.85
22	N/A	N/A	N/A	N/A	N/A	N/A	68	64.845	0.41	87.67	65.797	0.44	272.50
24	65.569	0.33	176.23	65.622	0.34	184.33	70	64.677	0.47	86.05	65.546	0.44	274.13
26	65.401	0.31	155.28	65.632	0.34	204.85	72	64.473	0.47	84.43	65.486	0.48	275.74
28	65.338	0.32	144.84	65.758	0.35	215.29	74	64.305	0.52	82.80	65.355	0.52	277.35
30	65.375	0.31	137.68	65.869	0.36	222.34	76	64.224	0.57	81.21	65.338	N/A	278.95
32	65.473	0.31	132.09	65.790	0.35	227.91	78	64.572	N/A	79.61	65.596	N/A	280.58
34	65.563	0.33	127.21	65.871	0.35	232.85	80	65.374	N/A	77.98	66.299	N/A	282.23
36	65.366	0.35	123.27	65.938	0.32	236.83	82	67.391	N/A	76.34	67.692	N/A	283.88
38	65.347	0.35	119.76	66.152	0.34	240.39	84	71.822	N/A	74.64	70.674	N/A	285.57
40	65.573	0.31	116.59	66.046	0.34	243.54	86	N/A	N/A	N/A	N/A	N/A	N/A
42	65.791	0.33	113.67	66.285	0.33	246.48	88	N/A	N/A	N/A	N/A	N/A	N/A
44	65.612	0.33	110.98	66.060	0.33	249.15	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, $u(B)$ (%)	$\pm 0.57$
Type-A Interpolating Function, $u(int)$ (%)	$\pm 0.26$
Combined Standard Uncertainty, $u(c)$ (%)	$\pm 0.63$
Effective degrees of freedom, $DF(c)$	2006
Coverage factor, $k$	1.96
Expanded Uncertainty, $U_{95}$ (%)	$\pm 1.2$
AM Valid zenith angle range	24° to 76°
PM Valid zenith angle range	24° to 74°

‡ 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**

$R @ 45^\circ$ ( $\mu V/W/m^2$ )	$R_{net}$ ( $\mu V/W/m^2$ ) †
65.928	0

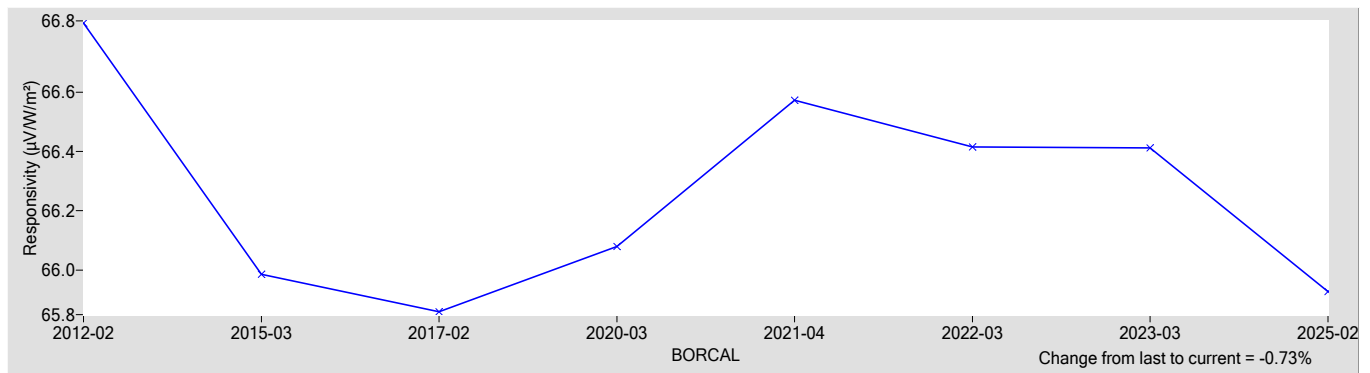
†  $R_{net}$  determination date: N/A

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

Type-B Expanded Uncertainty, $U(B)$ (%)	$\pm 0.84$
Offset Uncertainty, $U(off)$ (%)	+0.98 / -0.88
Expanded Uncertainty, $U$ (%)	+1.8 / -1.7
Effective degrees of freedom, $DF^*$	2004
Coverage factor, $k$	1.96
Valid zenith angle range	30.0° to 60.0°

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

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



**References:**

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



# National Renewable Energy Laboratory

## Solar Radiation Research Laboratory

### Metrology Laboratory

### Calibration Certificate



<b>Test Instrument:</b>	Pyranometer (Ventilated)	<b>Manufacturer:</b>	Kipp & Zonen
<b>Model:</b>	CMP22	<b>Serial Number:</b>	140043
<b>Calibration Date:</b>	5/2/2025	<b>Due Date:</b>	5/2/2026
<b>Customer:</b>	NREL-SRRL-BMS	<b>Environmental Conditions:</b>	see page 4
<b>Test Dates:</b>	5/2		

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	09/27/2024	09/27/2025
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/21/2025	04/21/2026
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/21/2025	04/21/2026
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/07/2025	02/07/2027
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/07/2025	02/07/2027
Infrared Irradiance ‡	Kipp & Zonen Pyrgeometer Model CGR4, S/N 140021	07/18/2023	07/18/2028

† 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, RCC, and Shawn L. Jaker

-----  
Ibrahim Reda, Technical Manager

05/05/2025

-----  
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 ( $\text{W}/\text{m}^2$ ),
- $= W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
- where,  $W_{in}$  = incoming infrared ( $\text{W}/\text{m}^2$ ),  $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$ ,
- $T_c$  = case temperature of pyrgeometer (K).
- $I$  = reference irradiance ( $\text{W}/\text{m}^2$ ), beam (B) or global (G)
- where,  $G = B * \text{COS}(Z) + D$ ,
- $Z$  = zenith angle (degrees),
- $D$  = reference diffuse irradiance ( $\text{W}/\text{m}^2$ ).

Figure 1. Responsivity vs Zenith Angle

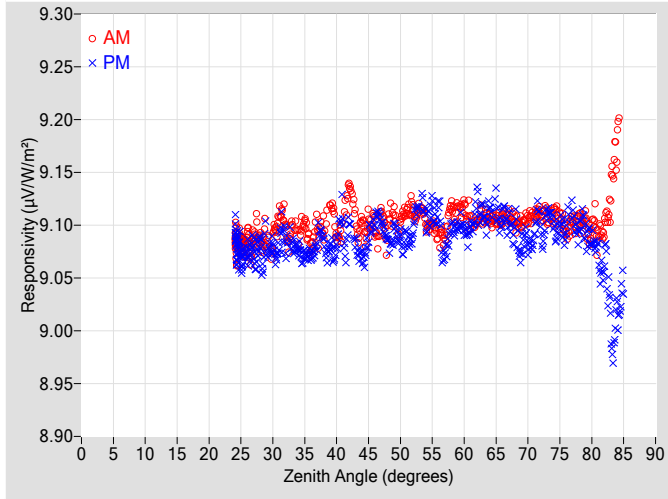


Figure 2. Responsivity vs Local Standard Time

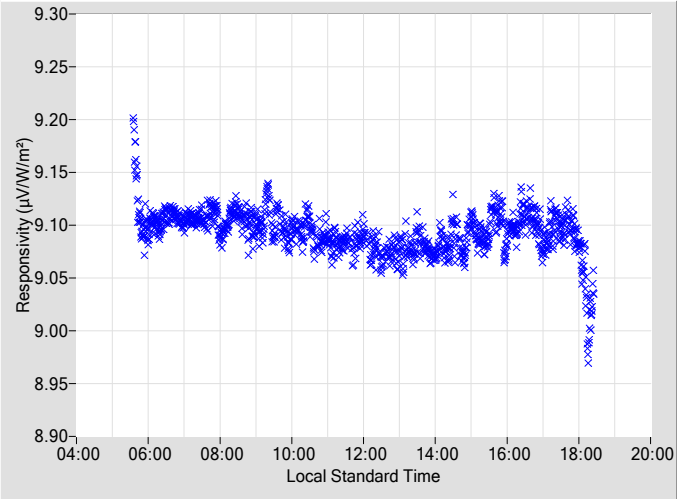
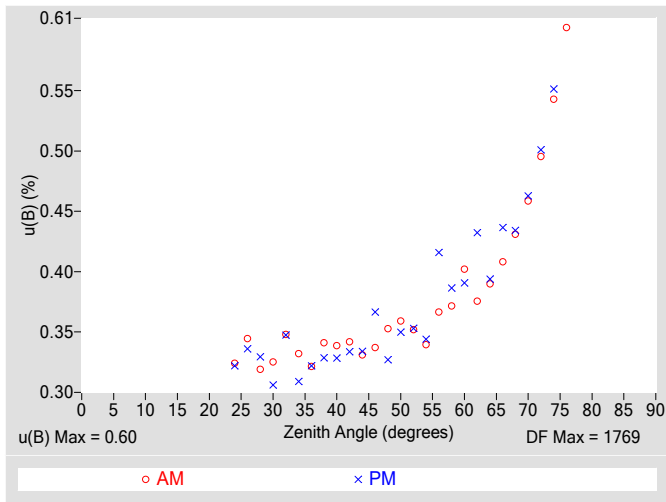


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty,  $u(B)$

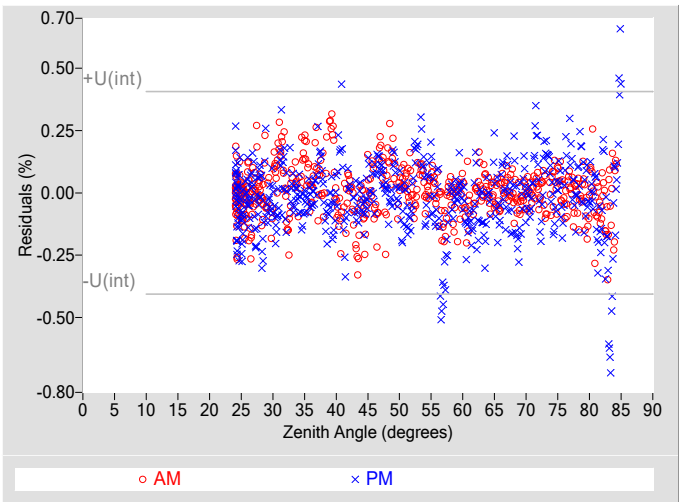
Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	AM $u(B)$ $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	PM $u(B)$ $\pm$ (%)	Azimuth Angle	Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	AM $u(B)$ $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	PM $u(B)$ $\pm$ (%)	Azimuth Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	9.0982	0.34	108.47	9.1036	0.37	251.64
2	N/A	N/A	N/A	N/A	N/A	N/A	48	9.0934	0.35	106.18	9.0847	0.33	253.96
4	N/A	N/A	N/A	N/A	N/A	N/A	50	9.1019	0.36	103.98	9.0882	0.35	256.18
6	N/A	N/A	N/A	N/A	N/A	N/A	52	9.1155	0.35	101.90	9.0974	0.35	258.26
8	N/A	N/A	N/A	N/A	N/A	N/A	54	9.1018	0.34	99.89	9.1047	0.34	260.21
10	N/A	N/A	N/A	N/A	N/A	N/A	56	9.0883	0.37	98.00	9.1146	0.42	262.15
12	N/A	N/A	N/A	N/A	N/A	N/A	58	9.1171	0.37	96.18	9.1001	0.39	263.98
14	N/A	N/A	N/A	N/A	N/A	N/A	60	9.1169	0.40	94.40	9.0966	0.39	265.76
16	N/A	N/A	N/A	N/A	N/A	N/A	62	9.1036	0.38	92.66	9.1211	0.43	267.50
18	N/A	N/A	N/A	N/A	N/A	N/A	64	9.1051	0.39	90.96	9.1170	0.39	269.20
20	N/A	N/A	N/A	N/A	N/A	N/A	66	9.1071	0.41	89.29	9.1088	0.44	270.86
22	N/A	N/A	N/A	N/A	N/A	N/A	68	9.1036	0.43	87.64	9.0949	0.43	272.51
24	9.0857	0.32	175.77	9.0864	0.32	183.99	70	9.1074	0.46	86.06	9.0822	0.46	274.14
26	9.0864	0.34	154.97	9.0737	0.34	205.17	72	9.1103	0.50	84.44	9.0940	0.50	275.76
28	9.0863	0.32	144.85	9.0799	0.33	215.20	74	9.1100	0.54	82.81	9.0997	0.55	277.36
30	9.0842	0.33	137.73	9.0808	0.31	222.49	76	9.0953	0.60	81.22	9.0969	N/A	278.96
32	9.0896	0.35	132.07	9.0830	0.35	228.14	78	9.1078	N/A	79.58	9.0958	N/A	280.60
34	9.0909	0.33	127.42	9.0787	0.31	232.69	80	9.0964	N/A	77.94	9.0851	N/A	282.24
36	9.0798	0.32	123.21	9.0721	0.32	236.77	82	9.0982	N/A	76.35	9.0673	N/A	283.88
38	9.0950	0.34	119.88	9.0834	0.33	240.37	84	9.1801	N/A	74.66	9.0181	N/A	285.58
40	9.0905	0.34	116.57	9.0816	0.33	243.56	86	N/A	N/A	N/A	N/A	N/A	N/A
42	9.1345	0.34	113.62	9.1002	0.33	246.43	88	N/A	N/A	N/A	N/A	N/A	N/A
44	9.1041	0.33	111.00	9.0693	0.33	249.17	90	N/A	N/A	N/A	N/A	N/A	N/A

N/A - Not Available

**Figure 3. Type-B Standard Uncertainty vs Zenith Angle**



**Figure 4. Residuals from Spline Interpolation**



**Table 3. Uncertainty using Spline Interpolation ‡**

Type-B Standard Uncertainty, $u(B)$ (%)	$\pm 0.60$
Type-A Interpolating Function, $u(int)$ (%)	$\pm 0.20$
Combined Standard Uncertainty, $u(c)$ (%)	$\pm 0.64$
Effective degrees of freedom, $DF(c)$	2145
Coverage factor, $k$	1.96
Expanded Uncertainty, $U95$ (%)	$\pm 1.2$
AM Valid zenith angle range	24° to 76°
PM Valid zenith angle range	24° to 74°

‡ 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**

$R @ 45^\circ$ ( $\mu V/W/m^2$ )	$R_{net}$ ( $\mu V/W/m^2$ ) †
9.0961	0.087000

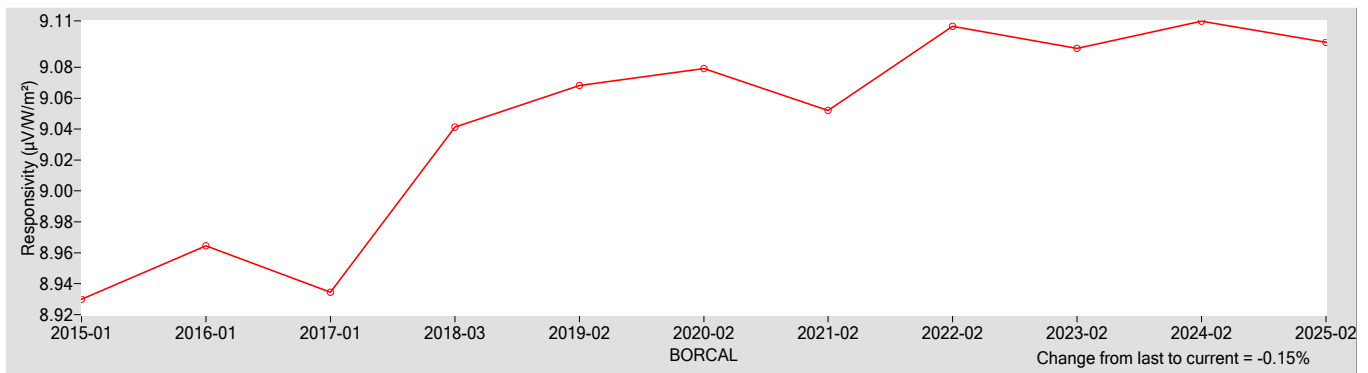
†  $R_{net}$  determination date: Estimated

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

Type-B Expanded Uncertainty, $U(B)$ (%)	$\pm 0.82$
Offset Uncertainty, $U(off)$ (%)	+0.42 / -0.29
Expanded Uncertainty, $U$ (%)	+1.2 / -1.1
Effective degrees of freedom, $DF^*$	2119
Coverage factor, $k$	1.96
Valid zenith angle range	30.0° to 60.0°

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

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



**References:**

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



# National Renewable Energy Laboratory

## Solar Radiation Research Laboratory

### Metrology Laboratory

### Calibration Certificate



<b>Test Instrument:</b>	Pyrheliometer	<b>Manufacturer:</b>	Kipp & Zonen
<b>Model:</b>	CHP1	<b>Serial Number:</b>	140108
<b>Calibration Date:</b>	5/2/2025	<b>Due Date:</b>	5/2/2026
<b>Customer:</b>	NREL-SRRL-BMS	<b>Environmental Conditions:</b>	see page 4
<b>Test Dates:</b>	5/2		

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	09/27/2024	09/27/2025
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/21/2025	04/21/2026
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/21/2025	04/21/2026
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/07/2025	02/07/2027
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/07/2025	02/07/2027

† 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, RCC, and Shawn L. Jaker

-----  
Ibrahim Reda, Technical Manager

05/05/2025

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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

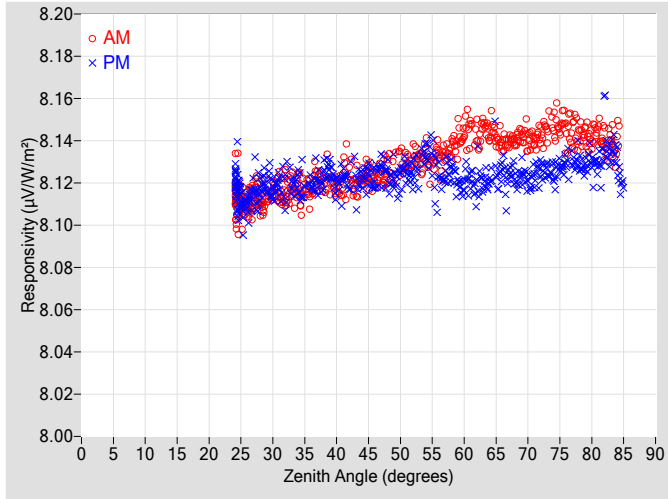
The responsivity ( $R$ ,  $\mu\text{V}/\text{W}/\text{m}^2$ ) of the test instrument during calibration is calculated using this Measurement Equation:

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

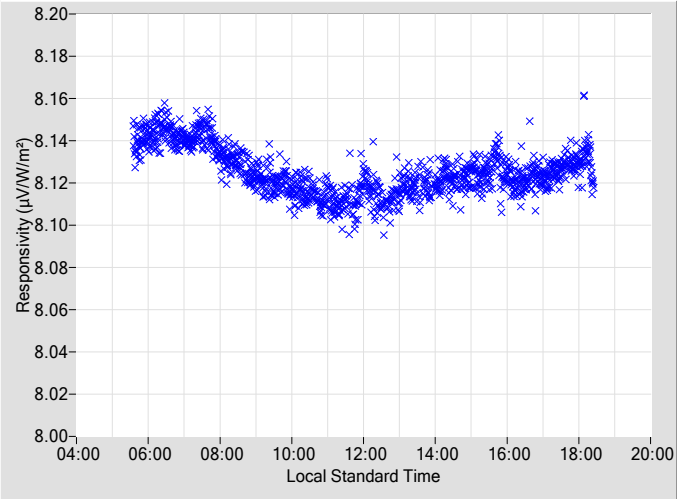
where,

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

**Figure 1. Responsivity vs Zenith Angle**



**Figure 2. Responsivity vs Local Standard Time**

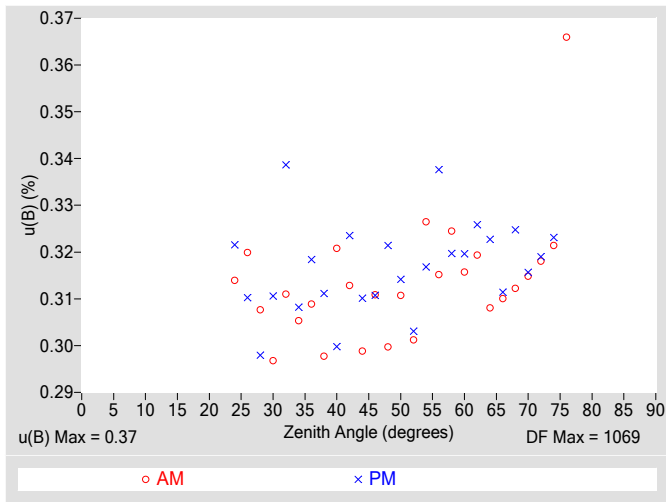


**Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)**

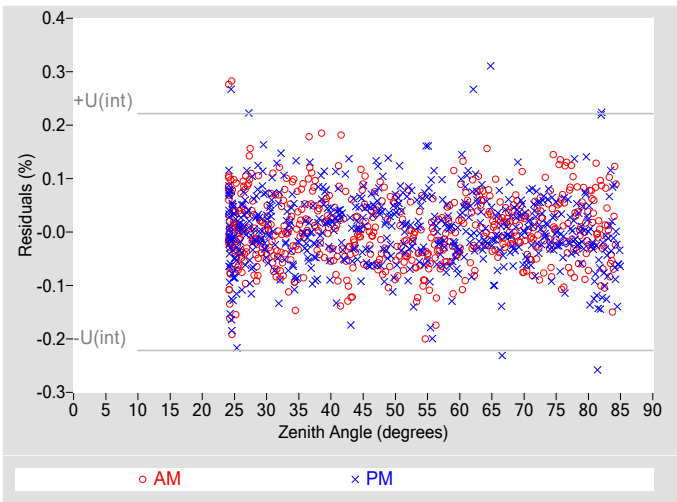
Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	AM u(B) $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	PM u(B) $\pm$ (%)	Azimuth Angle	Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	AM u(B) $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	PM u(B) $\pm$ (%)	Azimuth Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	8.1210	0.31	108.47	8.1229	0.31	251.62
2	N/A	N/A	N/A	N/A	N/A	N/A	48	8.1265	0.30	106.20	8.1226	0.32	253.97
4	N/A	N/A	N/A	N/A	N/A	N/A	50	8.1309	0.31	103.96	8.1217	0.31	256.16
6	N/A	N/A	N/A	N/A	N/A	N/A	52	8.1320	0.30	101.91	8.1242	0.30	258.25
8	N/A	N/A	N/A	N/A	N/A	N/A	54	8.1358	0.33	99.92	8.1352	0.32	260.24
10	N/A	N/A	N/A	N/A	N/A	N/A	56	8.1353	0.32	98.04	8.1205	0.34	262.08
12	N/A	N/A	N/A	N/A	N/A	N/A	58	8.1368	0.32	96.16	8.1271	0.32	263.96
14	N/A	N/A	N/A	N/A	N/A	N/A	60	8.1447	0.32	94.38	8.1190	0.32	265.74
16	N/A	N/A	N/A	N/A	N/A	N/A	62	8.1423	0.32	92.64	8.1153	0.33	267.46
18	N/A	N/A	N/A	N/A	N/A	N/A	64	8.1420	0.31	91.03	8.1220	0.32	269.18
20	N/A	N/A	N/A	N/A	N/A	N/A	66	8.1384	0.31	89.31	8.1270	0.31	270.85
22	N/A	N/A	N/A	N/A	N/A	N/A	68	8.1395	0.31	87.67	8.1222	0.32	272.49
24	8.1116	0.31	175.78	8.1203	0.32	184.30	70	8.1413	0.31	86.03	8.1208	0.32	274.12
26	8.1100	0.32	154.90	8.1092	0.31	205.00	72	8.1428	0.32	84.42	8.1249	0.32	275.74
28	8.1109	0.31	144.92	8.1175	0.30	215.23	74	8.1475	0.32	82.84	8.1233	0.32	277.34
30	8.1165	0.30	137.54	8.1158	0.31	222.39	76	8.1424	0.37	81.20	8.1314	N/A	278.99
32	8.1165	0.31	132.07	8.1179	0.34	227.91	78	8.1422	N/A	79.61	8.1288	N/A	280.61
34	8.1173	0.31	127.31	8.1205	0.31	232.74	80	8.1418	N/A	77.97	8.1273	N/A	282.22
36	8.1141	0.31	123.36	8.1195	0.32	236.82	82	8.1389	N/A	76.33	8.1436	N/A	283.87
38	8.1191	0.30	119.68	8.1242	0.31	240.46	84	8.1395	N/A	74.64	8.1294	N/A	285.57
40	8.1175	0.32	116.55	8.1189	0.30	243.53	86	N/A	N/A	N/A	N/A	N/A	N/A
42	8.1255	0.31	113.56	8.1212	0.32	246.45	88	N/A	N/A	N/A	N/A	N/A	N/A
44	8.1220	0.30	110.97	8.1216	0.31	249.14	90	N/A	N/A	N/A	N/A	N/A	N/A

N/A - Not Available

**Figure 3. Type-B Standard Uncertainty vs Zenith Angle**



**Figure 4. Residuals from Spline Interpolation**



**Table 3. Uncertainty using Spline Interpolation ‡**

Type-B Standard Uncertainty, u(B) (%)	±0.37
Type-A Interpolating Function, u(int) (%)	±0.11
Combined Standard Uncertainty, u(c) (%)	±0.38
Effective degrees of freedom, DF(c)	1262
Coverage factor, k	1.96
Expanded Uncertainty, U95 (%)	±0.75
AM Valid zenith angle range	24° to 76°
PM Valid zenith angle range	24° to 74°

‡ 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) †
8.1250	0

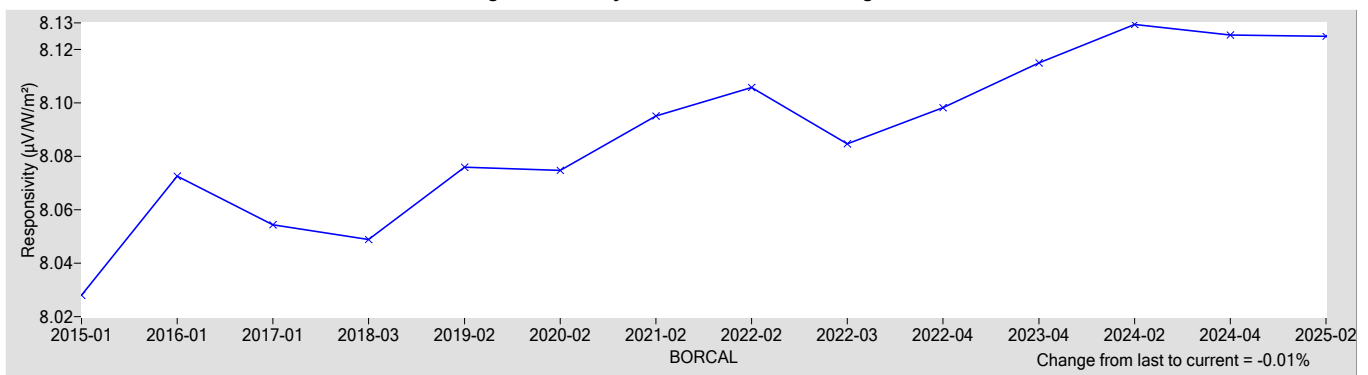
† Rnet determination date: N/A

**Table 5. Uncertainty using R @ 45°**

Type-B Expanded Uncertainty, U(B) (%)	±0.66
Offset Uncertainty, U(off) (%)	+0.24 / -0.13
Expanded Uncertainty, U (%)	+0.91 / -0.80
Effective degrees of freedom, DF *	1042
Coverage factor, k	1.96
Valid zenith angle range	30.0° to 60.0°

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

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



**References:**

[1] Reda, I.; Hickey, J.; Long, C.; Myers, D.; Stoffel, T.; Wilcox, S.; Michalsky, J. J.; Dutton, E. G.; Nelson, D. (2005). "Using a Blackbody to Calculate Net Longwave Responsivity of Shortwave Solar Pyranometers to Correct for Their Thermal Offset Error During Outdoor Calibration Using the Component Sum Method." Journal of Atmospheric and Oceanic Technology. , 2005; pp. 1531-1540; NREL Report No. JA-560-36646. doi:10.1175/JTECH1782.1

[2] Reda, I.; Myers, D.; Stoffel, T. (2008). "Uncertainty Estimate for the Outdoor Calibration of Solar Pyranometers: A Metrologist Perspective." Measure. (NCSLI Journal of Measurement Science). Vol. 3(4), December 2008; pp. 58-66; NREL Report No. JA-581-4137

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

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

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

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

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



# National Renewable Energy Laboratory

## Solar Radiation Research Laboratory

### Metrology Laboratory

### Calibration Certificate



<b>Test Instrument:</b>	Pyranometer	<b>Manufacturer:</b>	Kipp & Zonen
<b>Model:</b>	CMP11	<b>Serial Number:</b>	140712
<b>Calibration Date:</b>	5/2/2025	<b>Due Date:</b>	5/2/2026
<b>Customer:</b>	NREL-SRRL-BMS	<b>Environmental Conditions:</b>	see page 4
<b>Test Dates:</b>	5/2		

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	09/27/2024	09/27/2025
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/21/2025	04/21/2026
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/21/2025	04/21/2026
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/07/2025	02/07/2027
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/07/2025	02/07/2027
Infrared Irradiance ‡	Kipp & Zonen Pyrgeometer Model CG4, S/N FT002	03/31/2022	03/31/2027

† Through the World Radiometric Reference (WRR)

‡ Through the World Infrared Standard Group (WISG)

**Number of pages of certificate:** 4

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

**Setup:** Radiometers are calibrated outdoors, using the sun as the source. Pyranometers and pyrgeometers are installed for horizontal measurements, with their signal connectors oriented north, if their design permits.

The shading disk for the reference diffuse subtends a solid angle of 5°. Pyrheliometers are installed on solar trackers.

**Calibrated by:** Afshin Andreas, RCC, and Shawn L. Jaker

-----  
Ibrahim Reda, Technical Manager

05/05/2025

-----  
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 ( $\text{W}/\text{m}^2$ ),
  - =  $W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
  - where,  $W_{in}$  = incoming infrared ( $\text{W}/\text{m}^2$ ),  $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$ ,
  - $T_c$  = case temperature of pyrgeometer (K).
- $I$  = reference irradiance ( $\text{W}/\text{m}^2$ ), beam (B) or global (G)
  - where,  $G = B * \text{COS}(Z) + D$ ,
  - $Z$  = zenith angle (degrees),
  - $D$  = reference diffuse irradiance ( $\text{W}/\text{m}^2$ ).

Figure 1. Responsivity vs Zenith Angle

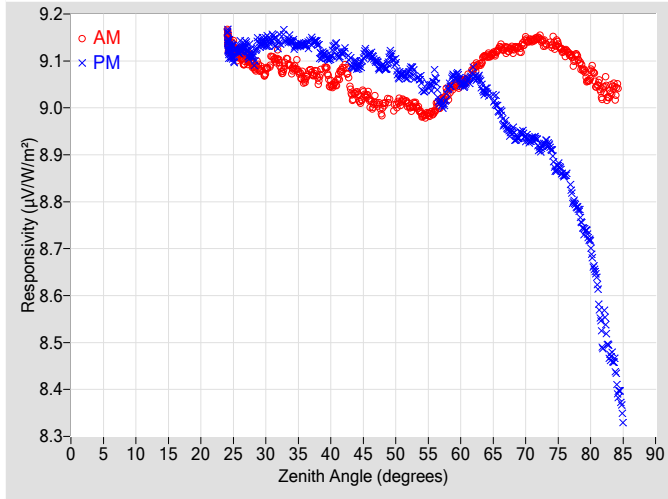


Figure 2. Responsivity vs Local Standard Time

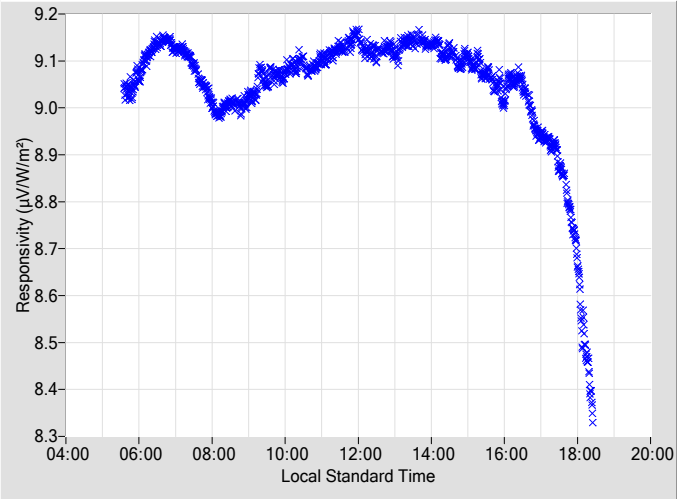
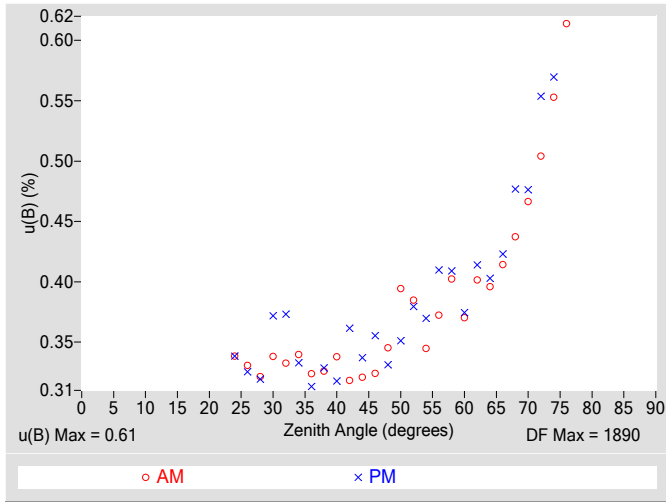


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)

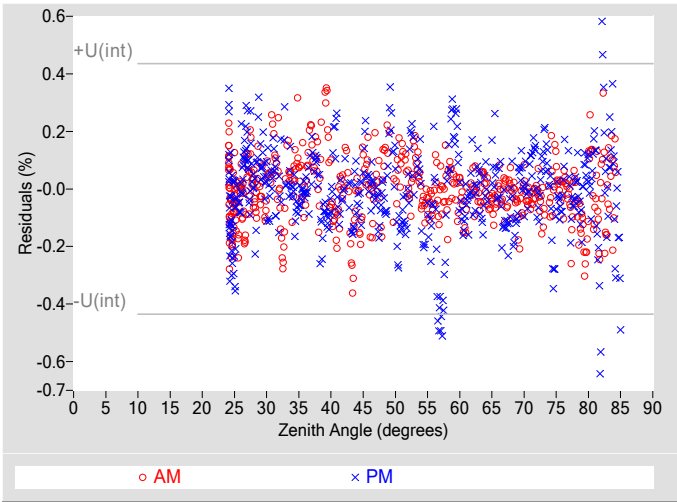
Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) $\pm$ (%)	Azimuth Angle	Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) $\pm$ (%)	Azimuth Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	9.0168	0.32	108.45	9.1126	0.36	251.68
2	N/A	N/A	N/A	N/A	N/A	N/A	48	8.9968	0.35	106.16	9.0899	0.33	253.97
4	N/A	N/A	N/A	N/A	N/A	N/A	50	9.0048	0.39	103.92	9.0906	0.35	256.16
6	N/A	N/A	N/A	N/A	N/A	N/A	52	9.0045	0.38	101.89	9.0724	0.38	258.25
8	N/A	N/A	N/A	N/A	N/A	N/A	54	8.9866	0.34	99.93	9.0509	0.37	260.21
10	N/A	N/A	N/A	N/A	N/A	N/A	56	8.9950	0.37	97.99	9.0623	0.41	262.13
12	N/A	N/A	N/A	N/A	N/A	N/A	58	9.0318	0.40	96.16	9.0361	0.41	263.97
14	N/A	N/A	N/A	N/A	N/A	N/A	60	9.0559	0.37	94.38	9.0545	0.37	265.74
16	N/A	N/A	N/A	N/A	N/A	N/A	62	9.0826	0.40	92.64	9.0720	0.41	267.51
18	N/A	N/A	N/A	N/A	N/A	N/A	64	9.1101	0.40	90.99	9.0347	0.40	269.19
20	N/A	N/A	N/A	N/A	N/A	N/A	66	9.1287	0.41	89.32	8.9907	0.42	270.85
22	N/A	N/A	N/A	N/A	N/A	N/A	68	9.1244	0.44	87.67	8.9508	0.48	272.50
24	9.1479	0.34	175.88	9.1363	0.34	184.12	70	9.1438	0.47	86.04	8.9364	0.48	274.13
26	9.1164	0.33	155.12	9.1228	0.33	205.25	72	9.1501	0.50	84.43	8.9176	0.55	275.74
28	9.0910	0.32	144.93	9.1074	0.32	215.15	74	9.1377	0.55	82.79	8.9089	0.57	277.35
30	9.0762	0.34	137.81	9.1415	0.37	222.35	76	9.1197	0.61	81.20	8.8561	N/A	278.99
32	9.1032	0.33	132.18	9.1402	0.37	228.18	78	9.1086	N/A	79.61	8.7856	N/A	280.58
34	9.0829	0.34	127.30	9.1415	0.33	232.75	80	9.0716	N/A	77.97	8.7039	N/A	282.22
36	9.0589	0.32	123.27	9.1348	0.31	236.82	82	9.0363	N/A	76.34	8.5248	N/A	283.87
38	9.0643	0.33	119.69	9.1322	0.33	240.36	84	9.0358	N/A	74.64	8.4204	N/A	285.52
40	9.0500	0.34	116.54	9.1101	0.32	243.61	86	N/A	N/A	N/A	N/A	N/A	N/A
42	9.0852	0.32	113.71	9.1210	0.36	246.47	88	N/A	N/A	N/A	N/A	N/A	N/A
44	9.0312	0.32	110.90	9.0893	0.34	249.21	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, $u(B)$ (%)	$\pm 0.61$
Type-A Interpolating Function, $u(int)$ (%)	$\pm 0.22$
Combined Standard Uncertainty, $u(c)$ (%)	$\pm 0.65$
Effective degrees of freedom, $DF(c)$	2325
Coverage factor, $k$	1.96
Expanded Uncertainty, $U95$ (%)	$\pm 1.3$
AM Valid zenith angle range	24° to 76°
PM Valid zenith angle range	24° to 74°

‡ 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**

$R @ 45^\circ$ ( $\mu V/W/m^2$ )	$R_{net}$ ( $\mu V/W/m^2$ ) †
9.0664	0.20500

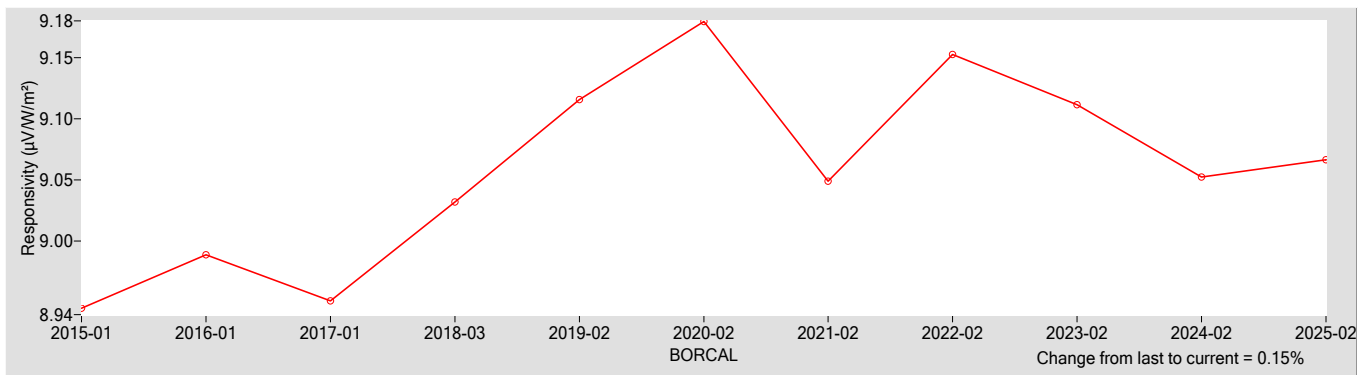
†  $R_{net}$  determination date: Estimated

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

Type-B Expanded Uncertainty, $U(B)$ (%)	$\pm 0.80$
Offset Uncertainty, $U(off)$ (%)	+0.83 / -0.88
Expanded Uncertainty, $U$ (%)	+1.6 / -1.7
Effective degrees of freedom, $DF^*$	2122
Coverage factor, $k$	1.96
Valid zenith angle range	30.0° to 60.0°

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

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



**References:**

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



# National Renewable Energy Laboratory

## Solar Radiation Research Laboratory

### Metrology Laboratory

### Calibration Certificate



<b>Test Instrument:</b>	Pyranometer	<b>Manufacturer:</b>	Kipp & Zonen
<b>Model:</b>	CMP11	<b>Serial Number:</b>	140910
<b>Calibration Date:</b>	5/2/2025	<b>Due Date:</b>	5/2/2026
<b>Customer:</b>	NREL-SRRL-BMS	<b>Environmental Conditions:</b>	see page 4
<b>Test Dates:</b>	5/2		

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	09/27/2024	09/27/2025
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/21/2025	04/21/2026
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/21/2025	04/21/2026
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/07/2025	02/07/2027
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/07/2025	02/07/2027
Infrared Irradiance ‡	Kipp & Zonen Pyrgeometer Model CG4, S/N FT002	03/31/2022	03/31/2027

† Through the World Radiometric Reference (WRR)

‡ Through the World Infrared Standard Group (WISG)

**Number of pages of certificate:** 4

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

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

**Calibrated by:** Afshin Andreas, RCC, and Shawn L. Jaker

-----  
Ibrahim Reda, Technical Manager

05/05/2025

-----  
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

## 140910 Kipp & Zonen CMP11

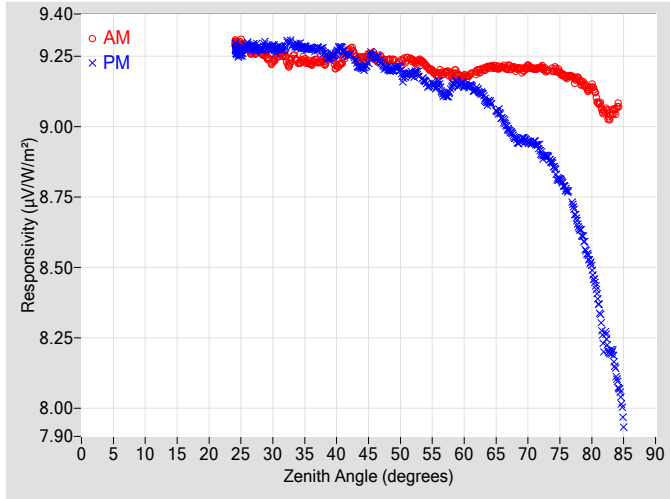
The responsivity ( $R$ ,  $\mu\text{V}/\text{W}/\text{m}^2$ ) of the test instrument during calibration is calculated using this Measurement Equation:

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

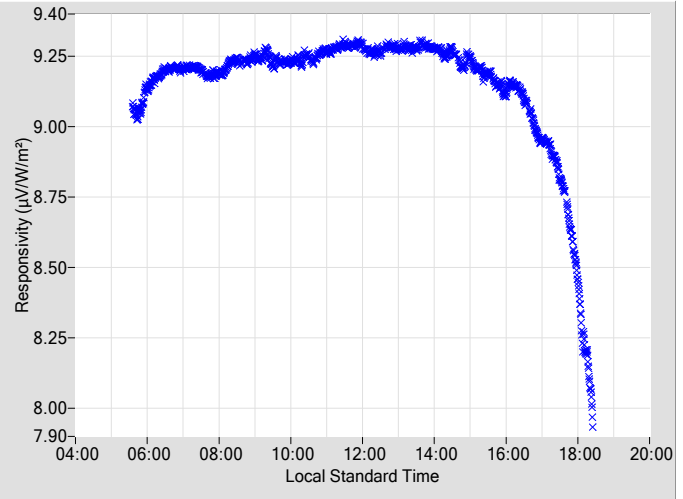
where,

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

**Figure 1. Responsivity vs Zenith Angle**



**Figure 2. Responsivity vs Local Standard Time**

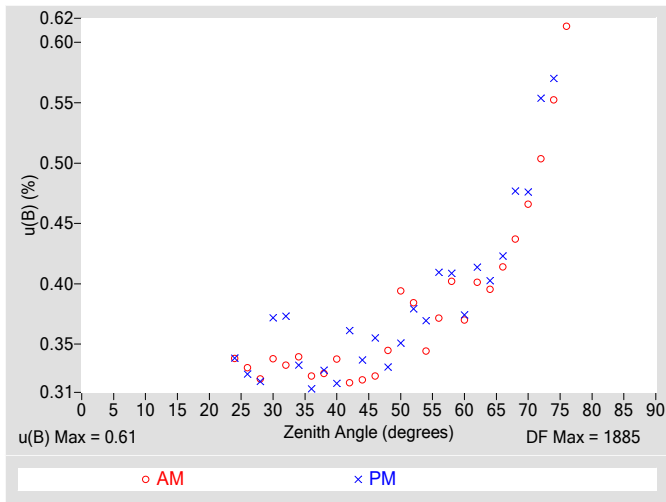


**Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)**

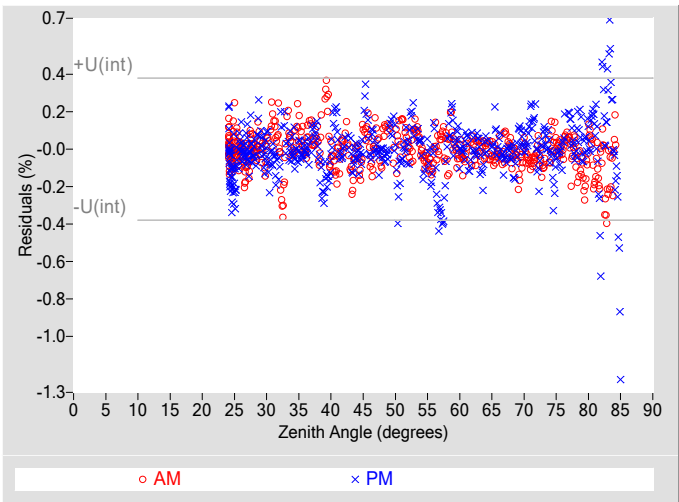
Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) $\pm$ (%)	Azimuth Angle	Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) $\pm$ (%)	Azimuth Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	9.2469	0.32	108.45	9.2469	0.35	251.68
2	N/A	N/A	N/A	N/A	N/A	N/A	48	9.2282	0.34	106.16	9.2049	0.33	253.97
4	N/A	N/A	N/A	N/A	N/A	N/A	50	9.2274	0.39	103.92	9.1983	0.35	256.16
6	N/A	N/A	N/A	N/A	N/A	N/A	52	9.2340	0.38	101.89	9.1838	0.38	258.25
8	N/A	N/A	N/A	N/A	N/A	N/A	54	9.2173	0.34	99.93	9.1558	0.37	260.21
10	N/A	N/A	N/A	N/A	N/A	N/A	56	9.1894	0.37	97.99	9.1507	0.41	262.13
12	N/A	N/A	N/A	N/A	N/A	N/A	58	9.1851	0.40	96.16	9.1395	0.41	263.97
14	N/A	N/A	N/A	N/A	N/A	N/A	60	9.1795	0.37	94.38	9.1492	0.37	265.74
16	N/A	N/A	N/A	N/A	N/A	N/A	62	9.1946	0.40	92.64	9.1313	0.41	267.51
18	N/A	N/A	N/A	N/A	N/A	N/A	64	9.2125	0.40	90.99	9.0861	0.40	269.19
20	N/A	N/A	N/A	N/A	N/A	N/A	66	9.2128	0.41	89.32	9.0252	0.42	270.85
22	N/A	N/A	N/A	N/A	N/A	N/A	68	9.2061	0.44	87.67	8.9586	0.48	272.50
24	9.2939	0.34	175.88	9.2744	0.34	184.12	70	9.2142	0.47	86.04	8.9446	0.48	274.13
26	9.2799	0.33	155.12	9.2863	0.33	205.25	72	9.2116	0.50	84.43	8.9123	0.55	275.74
28	9.2668	0.32	144.93	9.2765	0.32	215.15	74	9.2025	0.55	82.79	8.8629	0.57	277.35
30	9.2300	0.34	137.81	9.2813	0.37	222.35	76	9.1759	0.61	81.20	8.7748	N/A	278.99
32	9.2502	0.33	132.18	9.2889	0.37	228.18	78	9.1687	N/A	79.61	8.6402	N/A	280.58
34	9.2284	0.34	127.30	9.2864	0.33	232.75	80	9.1409	N/A	77.97	8.4931	N/A	282.22
36	9.2228	0.32	123.27	9.2773	0.31	236.82	82	9.0552	N/A	76.34	8.2414	N/A	283.87
38	9.2274	0.33	119.69	9.2647	0.33	240.36	84	9.0668	N/A	74.64	8.0992	N/A	285.52
40	9.2125	0.34	116.54	9.2679	0.32	243.61	86	N/A	N/A	N/A	N/A	N/A	N/A
42	9.2746	0.32	113.71	9.2550	0.36	246.47	88	N/A	N/A	N/A	N/A	N/A	N/A
44	9.2454	0.32	110.90	9.2070	0.34	249.21	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, $u(B)$ (%)	$\pm 0.61$
Type-A Interpolating Function, $u(int)$ (%)	$\pm 0.19$
Combined Standard Uncertainty, $u(c)$ (%)	$\pm 0.64$
Effective degrees of freedom, $DF(c)$	2225
Coverage factor, $k$	1.96
Expanded Uncertainty, $U95$ (%)	$\pm 1.3$
AM Valid zenith angle range	24° to 76°
PM Valid zenith angle range	24° to 74°

‡ 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**

$R @ 45^\circ$ ( $\mu V/W/m^2$ )	$R_{net}$ ( $\mu V/W/m^2$ ) †
9.2422	0.20500

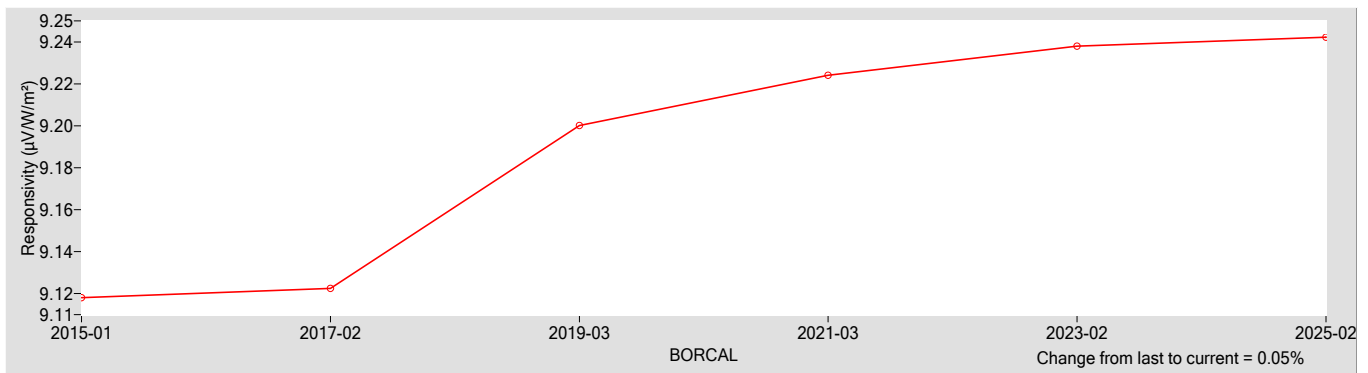
†  $R_{net}$  determination date: Estimated

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

Type-B Expanded Uncertainty, $U(B)$ (%)	$\pm 0.80$
Offset Uncertainty, $U(off)$ (%)	+0.50 / -1.1
Expanded Uncertainty, $U$ (%)	+1.3 / -1.9
Effective degrees of freedom, $DF^*$	2119
Coverage factor, $k$	1.96
Valid zenith angle range	30.0° to 60.0°

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

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



**References:**

[1] Reda, I.; Hickey, J.; Long, C.; Myers, D.; Stoffel, T.; Wilcox, S.; Michalsky, J. J.; Dutton, E. G.; Nelson, D. (2005). "Using a Blackbody to Calculate Net Longwave Responsivity of Shortwave Solar Pyranometers to Correct for Their Thermal Offset Error During Outdoor Calibration Using the Component Sum Method." Journal of Atmospheric and Oceanic Technology. , 2005; pp. 1531-1540; NREL Report No. JA-560-36646. doi:10.1175/JTECH1782.1

[2] Reda, I.; Myers, D.; Stoffel, T. (2008). "Uncertainty Estimate for the Outdoor Calibration of Solar Pyranometers: A Metrologist Perspective." Measure. (NCSLI Journal of Measurement Science). Vol. 3(4), December 2008; pp. 58-66; NREL Report No. JA-581-4137

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

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

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

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

[7] Reda, I.; Gröbner, J.; Stoffel, T.; Myers, D.; Forgan, B. (2008). Improvements in the Blackbody Calibration of 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:** 5/2/2025 **Due Date:** 5/2/2026  
**Customer:** NREL-SRRL-BMS **Environmental Conditions:** see page 4  
**Test Dates:** 5/2

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	09/27/2024	09/27/2025
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/21/2025	04/21/2026
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/21/2025	04/21/2026
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/07/2025	02/07/2027
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/07/2025	02/07/2027

† 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, RCC, and Shawn L. Jaker

Ibrahim Reda, Technical Manager

05/05/2025

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 ( $\text{W}/\text{m}^2$ ),
  - =  $W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
  - where,  $W_{in}$  = incoming infrared ( $\text{W}/\text{m}^2$ ),  $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$ ,
  - $T_c$  = case temperature of pyrgeometer (K).
- $I$  = reference irradiance ( $\text{W}/\text{m}^2$ ), beam (B) or global (G)
  - where,  $G = B * \text{COS}(Z) + D$ ,
  - $Z$  = zenith angle (degrees),
  - $D$  = reference diffuse irradiance ( $\text{W}/\text{m}^2$ ).

Figure 1. Responsivity vs Zenith Angle

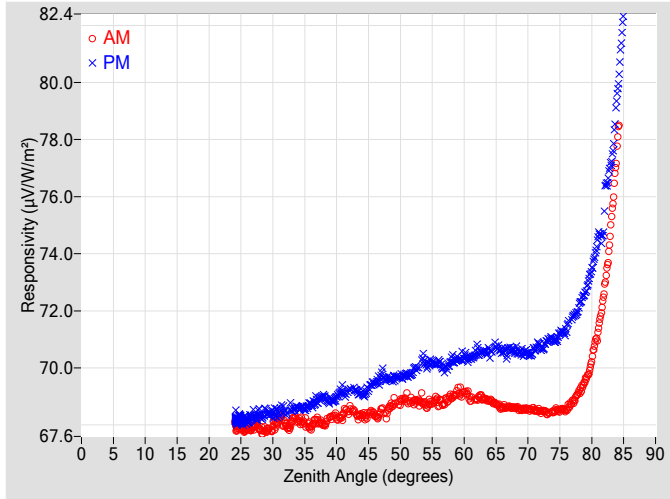


Figure 2. Responsivity vs Local Standard Time

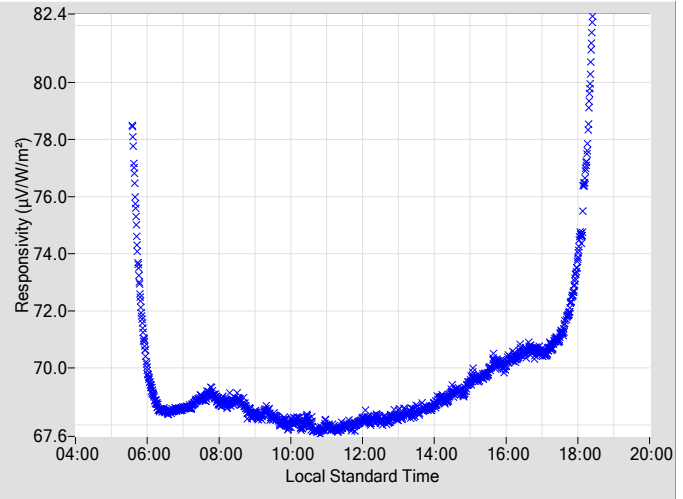
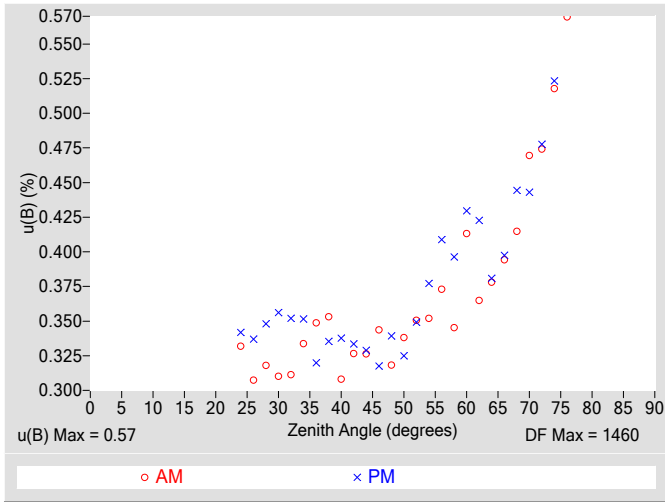


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)

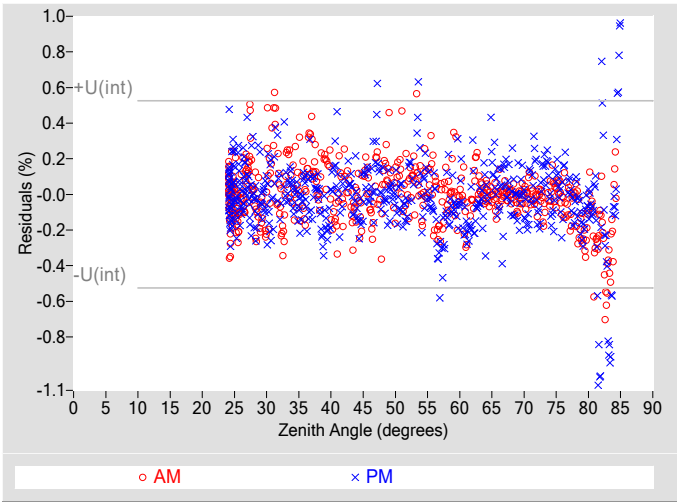
Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) $\pm$ (%)	Azimuth Angle	Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) $\pm$ (%)	Azimuth Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	68.363	0.34	108.51	69.475	0.32	251.64
2	N/A	N/A	N/A	N/A	N/A	N/A	48	68.475	0.32	106.11	69.606	0.34	253.99
4	N/A	N/A	N/A	N/A	N/A	N/A	50	68.808	0.34	103.96	69.696	0.32	256.17
6	N/A	N/A	N/A	N/A	N/A	N/A	52	68.805	0.35	101.83	69.876	0.35	258.20
8	N/A	N/A	N/A	N/A	N/A	N/A	54	68.693	0.35	99.93	70.111	0.38	260.24
10	N/A	N/A	N/A	N/A	N/A	N/A	56	68.799	0.37	97.99	70.190	0.41	262.13
12	N/A	N/A	N/A	N/A	N/A	N/A	58	68.991	0.35	96.16	70.292	0.40	263.97
14	N/A	N/A	N/A	N/A	N/A	N/A	60	69.155	0.41	94.38	70.378	0.43	265.75
16	N/A	N/A	N/A	N/A	N/A	N/A	62	68.921	0.36	92.65	70.609	0.42	267.49
18	N/A	N/A	N/A	N/A	N/A	N/A	64	68.861	0.38	90.94	70.585	0.38	269.19
20	N/A	N/A	N/A	N/A	N/A	N/A	66	68.617	0.39	89.32	70.590	0.40	270.85
22	N/A	N/A	N/A	N/A	N/A	N/A	68	68.608	0.41	87.67	70.587	0.44	272.50
24	68.056	0.33	176.35	68.196	0.34	184.35	70	68.550	0.47	86.05	70.514	0.44	274.13
26	67.890	0.31	155.28	68.136	0.34	204.85	72	68.495	0.47	84.43	70.731	0.48	275.74
28	67.834	0.32	144.84	68.367	0.35	215.29	74	68.469	0.52	82.80	70.967	0.52	277.35
30	67.944	0.31	137.68	68.437	0.36	222.34	76	68.548	0.57	81.21	71.340	N/A	278.95
32	68.013	0.31	132.09	68.442	0.35	227.91	78	69.153	N/A	79.61	72.157	N/A	280.58
34	68.142	0.33	127.21	68.583	0.35	232.85	80	70.281	N/A	77.98	73.484	N/A	282.23
36	67.938	0.35	123.27	68.715	0.32	236.83	82	72.767	N/A	76.34	75.689	N/A	283.88
38	68.001	0.35	119.76	68.996	0.34	240.39	84	77.830	N/A	74.64	79.688	N/A	285.57
40	68.272	0.31	116.59	68.969	0.34	243.54	86	N/A	N/A	N/A	N/A	N/A	N/A
42	68.511	0.33	113.67	69.228	0.33	246.48	88	N/A	N/A	N/A	N/A	N/A	N/A
44	68.352	0.33	110.98	69.104	0.33	249.15	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, $u(B)$ (%)	$\pm 0.57$
Type-A Interpolating Function, $u(int)$ (%)	$\pm 0.26$
Combined Standard Uncertainty, $u(c)$ (%)	$\pm 0.63$
Effective degrees of freedom, $DF(c)$	2015
Coverage factor, $k$	1.96
Expanded Uncertainty, $U95$ (%)	$\pm 1.2$
AM Valid zenith angle range	24° to 76°
PM Valid zenith angle range	24° to 74°

‡ 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**

$R @ 45^\circ$ ( $\mu V/W/m^2$ )	$R_{net}$ ( $\mu V/W/m^2$ ) †
68.851	0

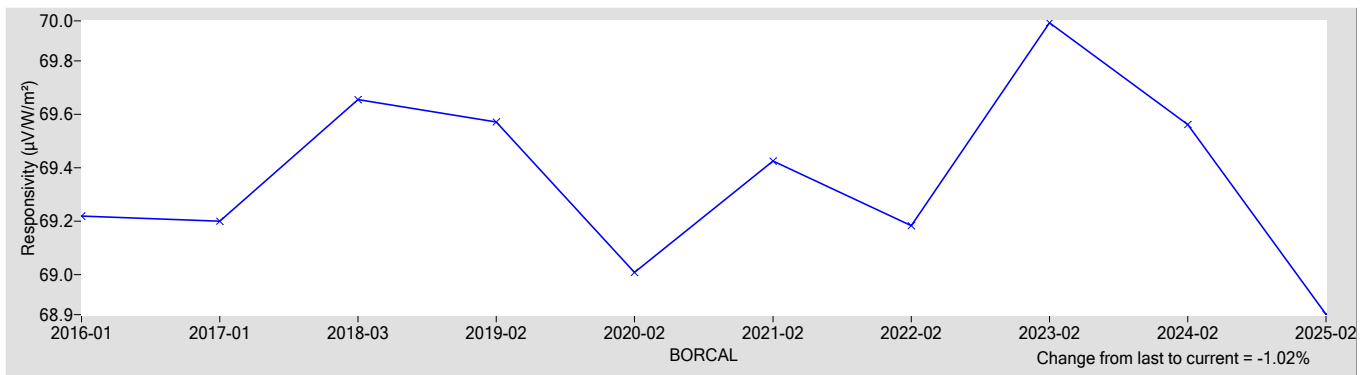
†  $R_{net}$  determination date: N/A

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

Type-B Expanded Uncertainty, $U(B)$ (%)	$\pm 0.84$
Offset Uncertainty, $U(off)$ (%)	+2.2 / -1.3
Expanded Uncertainty, $U$ (%)	+3.1 / -2.2
Effective degrees of freedom, $DF^*$	2003
Coverage factor, $k$	1.96
Valid zenith angle range	30.0° to 60.0°

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

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



**References:**

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



# National Renewable Energy Laboratory

## Solar Radiation Research Laboratory

### Metrology Laboratory

### Calibration Certificate



<b>Test Instrument:</b>	Pyranometer (Ventilated)	<b>Manufacturer:</b>	Hukseflux
<b>Model:</b>	SR20-T2	<b>Serial Number:</b>	15357
<b>Calibration Date:</b>	5/2/2025	<b>Due Date:</b>	5/2/2026
<b>Customer:</b>	NREL-SRRL-BMS	<b>Environmental Conditions:</b>	see page 4
<b>Test Dates:</b>	5/2		

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	09/27/2024	09/27/2025
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/21/2025	04/21/2026
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/21/2025	04/21/2026
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/07/2025	02/07/2027
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/07/2025	02/07/2027
Infrared Irradiance ‡	Eppley Downwelling Pyrgeometer Model PIR, S/N 38520F3	03/31/2022	03/31/2027

† Through the World Radiometric Reference (WRR)

‡ Through the World Infrared Standard Group (WISG)

**Number of pages of certificate:** 4

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

**Setup:** Radiometers are calibrated outdoors, using the sun as the source. Pyranometers and pyrgeometers are installed for horizontal measurements, with their signal connectors oriented north, if their design permits.

The shading disk for the reference diffuse subtends a solid angle of 5°. Pyrheliometers are installed on solar trackers.

**Calibrated by:** Afshin Andreas, RCC, and Shawn L. Jaker

-----  
Ibrahim Reda, Technical Manager

05/05/2025

-----  
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

## 15357 Hukseflux SR20-T2

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 ( $\text{W}/\text{m}^2$ ),
  - =  $W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
  - where,  $W_{in}$  = incoming infrared ( $\text{W}/\text{m}^2$ ),  $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$ ,
  - $T_c$  = case temperature of pyrgeometer (K).
- $I$  = reference irradiance ( $\text{W}/\text{m}^2$ ), beam (B) or global (G)
  - where,  $G = B * \text{COS}(Z) + D$ ,
  - $Z$  = zenith angle (degrees),
  - $D$  = reference diffuse irradiance ( $\text{W}/\text{m}^2$ ).

Figure 1. Responsivity vs Zenith Angle

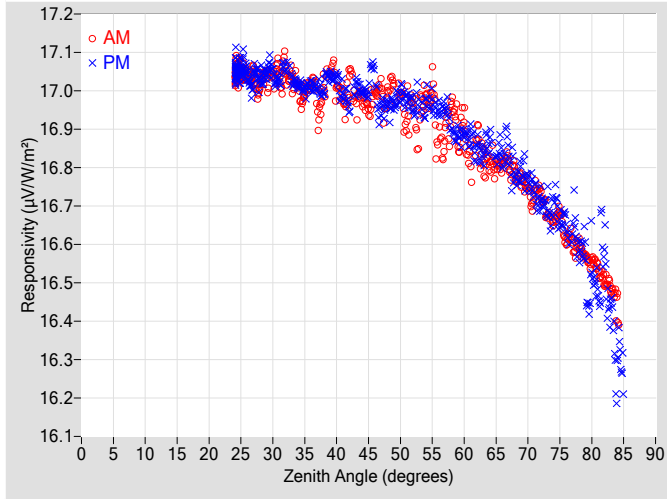


Figure 2. Responsivity vs Local Standard Time

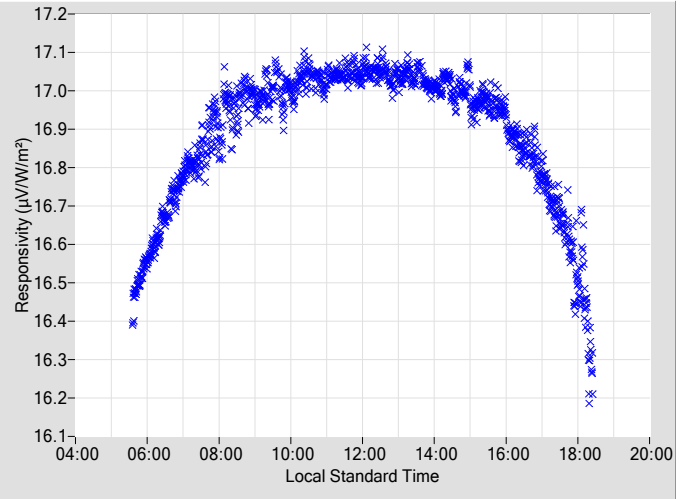
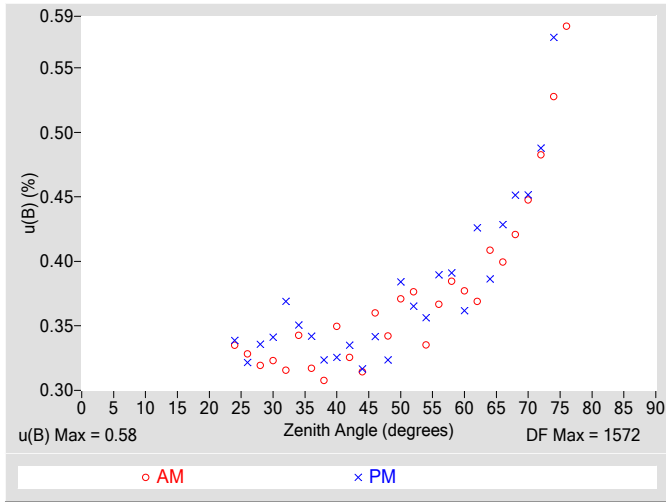


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)

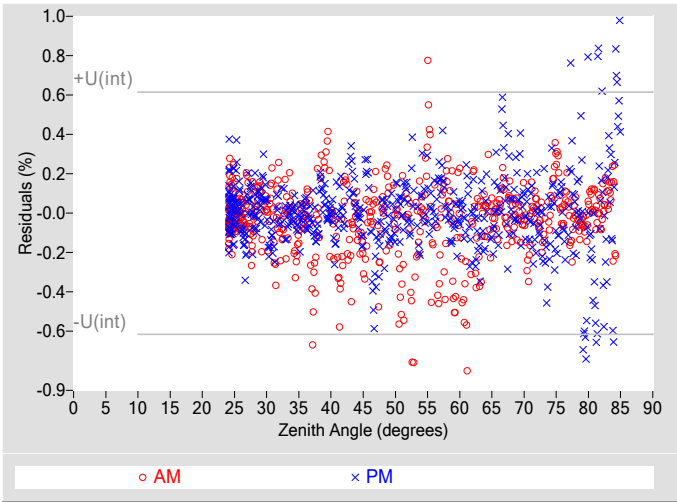
Zenith			AM			PM			Zenith			AM			PM		
Angle	R	u(B)	Azimuth	R	u(B)	Azimuth	Angle	R	u(B)	Azimuth	R	u(B)	Azimuth	R	u(B)	Azimuth	
(deg.)	( $\mu\text{V}/\text{W}/\text{m}^2$ )	$\pm$ (%)	Angle	( $\mu\text{V}/\text{W}/\text{m}^2$ )	$\pm$ (%)	Angle	(deg.)	( $\mu\text{V}/\text{W}/\text{m}^2$ )	$\pm$ (%)	Angle	( $\mu\text{V}/\text{W}/\text{m}^2$ )	$\pm$ (%)	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	16.996	0.36	108.42	17.036	0.34	251.65				
2	N/A	N/A	N/A	N/A	N/A	N/A	48	16.996	0.34	106.19	16.960	0.32	254.01				
4	N/A	N/A	N/A	N/A	N/A	N/A	50	16.995	0.37	103.99	16.995	0.38	256.19				
6	N/A	N/A	N/A	N/A	N/A	N/A	52	16.967	0.38	101.97	16.952	0.37	258.27				
8	N/A	N/A	N/A	N/A	N/A	N/A	54	16.989	0.34	99.90	16.966	0.36	260.22				
10	N/A	N/A	N/A	N/A	N/A	N/A	56	16.877	0.37	98.01	16.947	0.39	262.16				
12	N/A	N/A	N/A	N/A	N/A	N/A	58	16.938	0.38	96.19	16.896	0.39	264.02				
14	N/A	N/A	N/A	N/A	N/A	N/A	60	16.918	0.38	94.41	16.888	0.36	265.77				
16	N/A	N/A	N/A	N/A	N/A	N/A	62	16.880	0.37	92.67	16.856	0.43	267.51				
18	N/A	N/A	N/A	N/A	N/A	N/A	64	16.809	0.41	90.96	16.869	0.39	269.21				
20	N/A	N/A	N/A	N/A	N/A	N/A	66	16.808	0.40	89.29	16.825	0.43	270.87				
22	N/A	N/A	N/A	N/A	N/A	N/A	68	16.789	0.42	87.65	16.772	0.45	272.52				
24	17.044	0.33	175.86	17.050	0.34	183.98	70	16.751	0.45	86.02	16.765	0.45	274.15				
26	17.042	0.33	155.02	17.043	0.32	204.98	72	16.732	0.48	84.41	16.716	0.49	275.76				
28	17.019	0.32	144.90	17.030	0.34	215.22	74	16.660	0.53	82.77	16.710	0.57	277.37				
30	17.035	0.32	137.85	17.046	0.34	222.26	76	16.609	0.58	81.22	16.649	N/A	278.97				
32	17.061	0.32	132.14	17.060	0.37	228.09	78	16.603	N/A	79.59	16.591	N/A	280.60				
34	17.005	0.34	127.31	17.012	0.35	232.71	80	16.554	N/A	77.96	16.527	N/A	282.20				
36	17.016	0.32	123.31	17.013	0.34	236.78	82	16.505	N/A	76.31	16.559	N/A	283.89				
38	17.004	0.31	119.82	17.009	0.32	240.43	84	16.434	N/A	74.67	16.276	N/A	285.55				
40	17.011	0.35	116.58	17.040	0.33	243.57	86	N/A	N/A	N/A	N/A	N/A	N/A				
42	17.029	0.33	113.63	16.955	0.34	246.37	88	N/A	N/A	N/A	N/A	N/A	N/A				
44	16.981	0.31	110.92	16.994	0.32	249.18	90	N/A	N/A	N/A	N/A	N/A	N/A				

N/A - Not Available

**Figure 3. Type-B Standard Uncertainty vs Zenith Angle**



**Figure 4. Residuals from Spline Interpolation**



**Table 3. Uncertainty using Spline Interpolation ‡**

Type-B Standard Uncertainty, u(B) (%)	±0.58
Type-A Interpolating Function, u(int) (%)	±0.31
Combined Standard Uncertainty, u(c) (%)	±0.66
Effective degrees of freedom, DF(c)	2296
Coverage factor, k	1.96
Expanded Uncertainty, U95 (%)	±1.3
AM Valid zenith angle range	24° to 76°
PM Valid zenith angle range	24° to 74°

‡ 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) †
16.973	0.18000

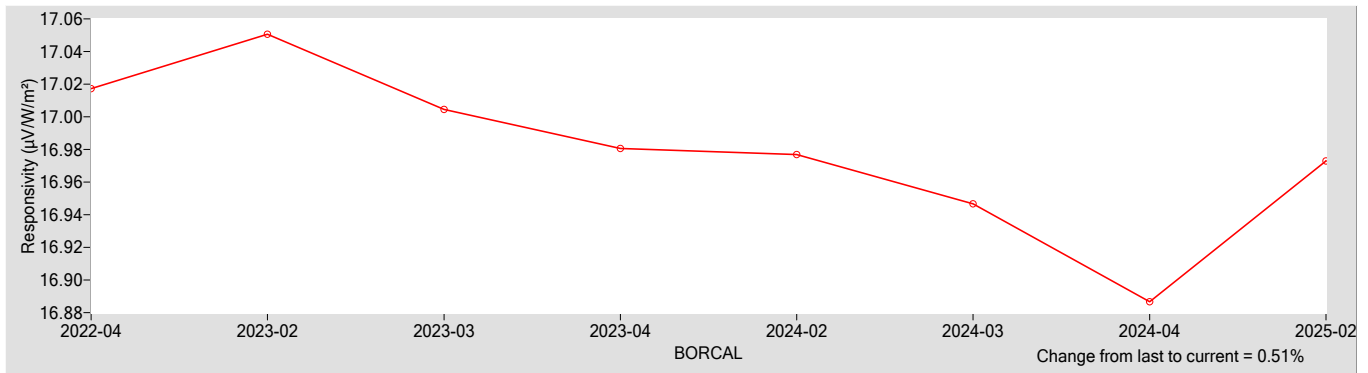
† Rnet determination date: Estimated

**Table 5. Uncertainty using R @ 45°**

Type-B Expanded Uncertainty, U(B) (%)	±0.77
Offset Uncertainty, U(off) (%)	+0.52 / -0.57
Expanded Uncertainty, U (%)	+1.3 / -1.3
Effective degrees of freedom, DF *	2043
Coverage factor, k	1.96
Valid zenith angle range	30.0° to 60.0°

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

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



**References:**

[1] Reda, I.; Hickey, J.; Long, C.; Myers, D.; Stoffel, T.; Wilcox, S.; Michalsky, J. J.; Dutton, E. G.; Nelson, D. (2005). "Using a Blackbody to Calculate Net Longwave Responsivity of Shortwave Solar Pyranometers to Correct for Their Thermal Offset Error During Outdoor Calibration Using the Component Sum Method." *Journal of Atmospheric and Oceanic Technology*, 2005; pp. 1531-1540; NREL Report No. JA-560-36646. doi:10.1175/JTECH1782.1

[2] Reda, I.; Myers, D.; Stoffel, T. (2008). "Uncertainty Estimate for the Outdoor Calibration of Solar Pyranometers: A Metrologist Perspective." *Measure*. (NCSLI Journal of Measurement Science). Vol. 3(4), December 2008; pp. 58-66; NREL Report No. JA-581-4137

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

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

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

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

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



# National Renewable Energy Laboratory

## Solar Radiation Research Laboratory

### Metrology Laboratory

### Calibration Certificate



<b>Test Instrument:</b>	Pyranometer (Ventilated)	<b>Manufacturer:</b>	Hukseflux
<b>Model:</b>	SR20-T2	<b>Serial Number:</b>	15360
<b>Calibration Date:</b>	5/2/2025	<b>Due Date:</b>	5/2/2026
<b>Customer:</b>	NREL-SRRL-BMS	<b>Environmental Conditions:</b>	see page 4
<b>Test Dates:</b>	5/2		

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	09/27/2024	09/27/2025
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/21/2025	04/21/2026
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/21/2025	04/21/2026
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/07/2025	02/07/2027
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/07/2025	02/07/2027
Infrared Irradiance ‡	Eppley Downwelling Pyrgeometer Model PIR, S/N 38520F3	03/31/2022	03/31/2027

† Through the World Radiometric Reference (WRR)

‡ Through the World Infrared Standard Group (WISG)

**Number of pages of certificate:** 4

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

**Setup:** Radiometers are calibrated outdoors, using the sun as the source. Pyranometers and pyrgeometers are installed for horizontal measurements, with their signal connectors oriented north, if their design permits.

The shading disk for the reference diffuse subtends a solid angle of 5°. Pyrheliometers are installed on solar trackers.

**Calibrated by:** Afshin Andreas, RCC, and Shawn L. Jaker

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Ibrahim Reda, Technical Manager

05/05/2025

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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

## 15360 Hukseflux SR20-T2

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 ( $\text{W}/\text{m}^2$ ),
  - =  $W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
  - where,  $W_{in}$  = incoming infrared ( $\text{W}/\text{m}^2$ ),  $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$ ,
  - $T_c$  = case temperature of pyrgeometer (K).
- $I$  = reference irradiance ( $\text{W}/\text{m}^2$ ), beam (B) or global (G)
  - where,  $G = B * \text{COS}(Z) + D$ ,
  - $Z$  = zenith angle (degrees),
  - $D$  = reference diffuse irradiance ( $\text{W}/\text{m}^2$ ).

Figure 1. Responsivity vs Zenith Angle

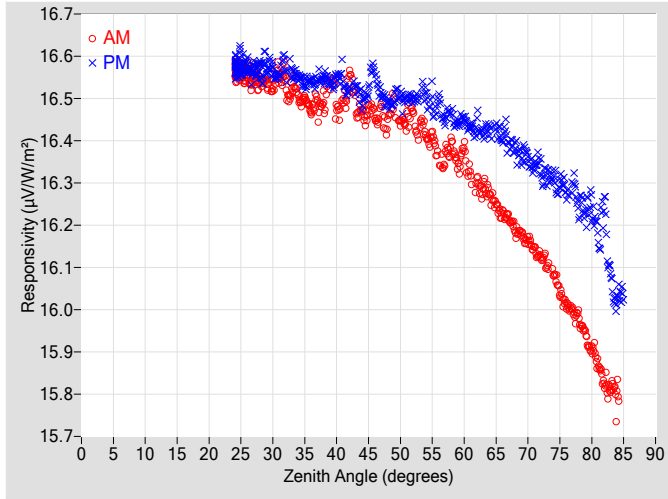


Figure 2. Responsivity vs Local Standard Time

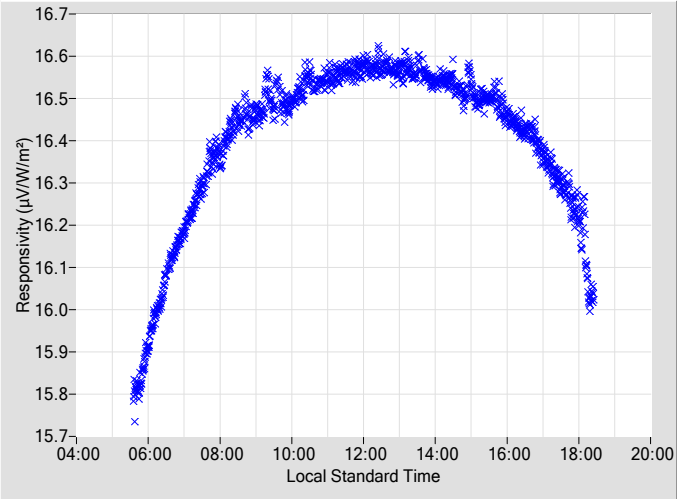
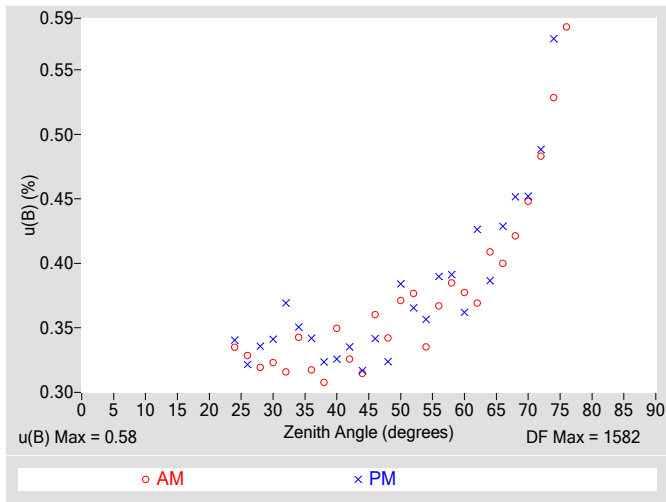


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)

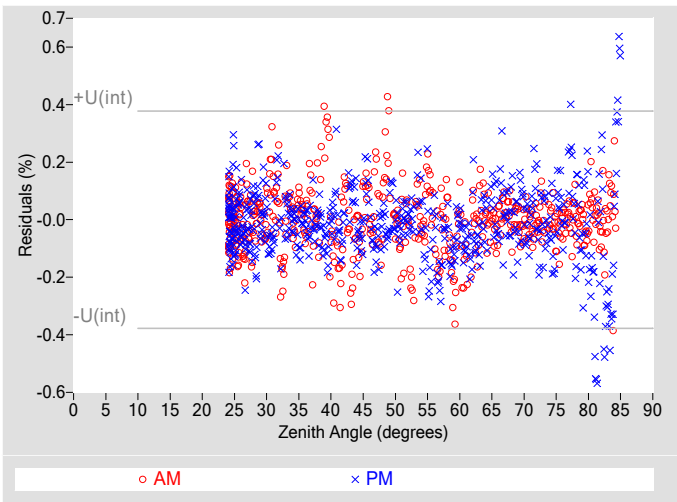
Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	AM u(B) $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	PM u(B) $\pm$ (%)	Azimuth Angle	Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	AM u(B) $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	PM u(B) $\pm$ (%)	Azimuth Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	16.456	0.36	108.42	16.560	0.34	251.65
2	N/A	N/A	N/A	N/A	N/A	N/A	48	16.438	0.34	106.19	16.488	0.32	254.01
4	N/A	N/A	N/A	N/A	N/A	N/A	50	16.445	0.37	103.99	16.506	0.38	256.19
6	N/A	N/A	N/A	N/A	N/A	N/A	52	16.471	0.38	101.97	16.498	0.37	258.27
8	N/A	N/A	N/A	N/A	N/A	N/A	54	16.416	0.34	99.90	16.503	0.36	260.22
10	N/A	N/A	N/A	N/A	N/A	N/A	56	16.356	0.37	98.01	16.497	0.39	262.16
12	N/A	N/A	N/A	N/A	N/A	N/A	58	16.386	0.38	96.19	16.468	0.39	264.02
14	N/A	N/A	N/A	N/A	N/A	N/A	60	16.377	0.38	94.41	16.452	0.36	265.77
16	N/A	N/A	N/A	N/A	N/A	N/A	62	16.300	0.37	92.67	16.439	0.43	267.51
18	N/A	N/A	N/A	N/A	N/A	N/A	64	16.271	0.41	90.96	16.424	0.39	269.21
20	N/A	N/A	N/A	N/A	N/A	N/A	66	16.229	0.40	89.29	16.408	0.43	270.87
22	N/A	N/A	N/A	N/A	N/A	N/A	68	16.189	0.42	87.65	16.377	0.45	272.52
24	16.569	0.33	175.86	16.576	0.34	184.03	70	16.166	0.45	86.02	16.355	0.45	274.15
26	16.560	0.33	155.02	16.575	0.32	204.98	72	16.126	0.48	84.41	16.325	0.49	275.76
28	16.542	0.32	144.90	16.569	0.34	215.22	74	16.085	0.53	82.77	16.315	0.57	277.37
30	16.526	0.32	137.85	16.566	0.34	222.26	76	16.013	0.58	81.22	16.278	N/A	278.97
32	16.544	0.32	132.14	16.567	0.37	228.09	78	15.978	N/A	79.59	16.245	N/A	280.60
34	16.502	0.34	127.31	16.550	0.35	232.71	80	15.905	N/A	77.96	16.244	N/A	282.20
36	16.475	0.32	123.31	16.541	0.34	236.78	82	15.829	N/A	76.31	16.227	N/A	283.89
38	16.486	0.31	119.82	16.550	0.32	240.43	84	15.792	N/A	74.67	16.026	N/A	285.55
40	16.484	0.35	116.58	16.552	0.33	243.57	86	N/A	N/A	N/A	N/A	N/A	N/A
42	16.544	0.33	113.63	16.523	0.34	246.37	88	N/A	N/A	N/A	N/A	N/A	N/A
44	16.472	0.31	110.92	16.497	0.32	249.18	90	N/A	N/A	N/A	N/A	N/A	N/A

N/A - Not Available

**Figure 3. Type-B Standard Uncertainty vs Zenith Angle**



**Figure 4. Residuals from Spline Interpolation**



**Table 3. Uncertainty using Spline Interpolation ‡**

Type-B Standard Uncertainty, $u(B)$ (%)	$\pm 0.58$
Type-A Interpolating Function, $u(int)$ (%)	$\pm 0.19$
Combined Standard Uncertainty, $u(c)$ (%)	$\pm 0.61$
Effective degrees of freedom, $DF(c)$	1899
Coverage factor, $k$	1.96
Expanded Uncertainty, $U95$ (%)	$\pm 1.2$
AM Valid zenith angle range	24° to 76°
PM Valid zenith angle range	24° to 74°

‡ 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**

$R @ 45^\circ$ ( $\mu V/W/m^2$ )	$R_{net}$ ( $\mu V/W/m^2$ ) †
16.493	0.18000

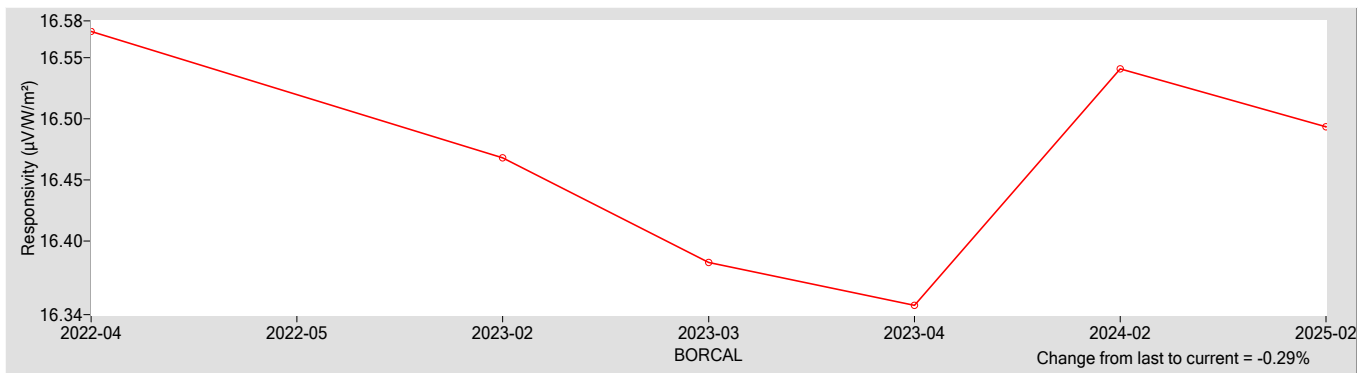
† Rnet determination date: Estimated

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

Type-B Expanded Uncertainty, $U(B)$ (%)	$\pm 0.77$
Offset Uncertainty, $U(off)$ (%)	+0.45 / -0.84
Expanded Uncertainty, $U$ (%)	+1.2 / -1.6
Effective degrees of freedom, $DF^*$	2046
Coverage factor, $k$	1.96
Valid zenith angle range	30.0° to 60.0°

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

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



**References:**

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



# National Renewable Energy Laboratory

## Solar Radiation Research Laboratory

### Metrology Laboratory

### Calibration Certificate



<b>Test Instrument:</b>	Pyranometer (Ventilated)	<b>Manufacturer:</b>	Hukseflux
<b>Model:</b>	SR20-T2	<b>Serial Number:</b>	15366
<b>Calibration Date:</b>	5/2/2025	<b>Due Date:</b>	5/2/2026
<b>Customer:</b>	NREL-SRRL-BMS	<b>Environmental Conditions:</b>	see page 4
<b>Test Dates:</b>	5/2		

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	09/27/2024	09/27/2025
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/21/2025	04/21/2026
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/21/2025	04/21/2026
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/07/2025	02/07/2027
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/07/2025	02/07/2027
Infrared Irradiance ‡	Eppley Downwelling Pyrgeometer Model PIR, S/N 38520F3	03/31/2022	03/31/2027

† Through the World Radiometric Reference (WRR)

‡ Through the World Infrared Standard Group (WISG)

**Number of pages of certificate:** 4

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

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

**Calibrated by:** Afshin Andreas, RCC, and Shawn L. Jaker

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Ibrahim Reda, Technical Manager

05/05/2025

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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

## 15366 Hukseflux SR20-T2

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 ( $\text{W}/\text{m}^2$ ),
  - =  $W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
  - where,  $W_{in}$  = incoming infrared ( $\text{W}/\text{m}^2$ ),  $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$ ,
  - $T_c$  = case temperature of pyrgeometer (K).
- $I$  = reference irradiance ( $\text{W}/\text{m}^2$ ), beam (B) or global (G)  
 where,  $G = B * \text{COS}(Z) + D$ ,  
 $Z$  = zenith angle (degrees),  
 $D$  = reference diffuse irradiance ( $\text{W}/\text{m}^2$ ).

Figure 1. Responsivity vs Zenith Angle

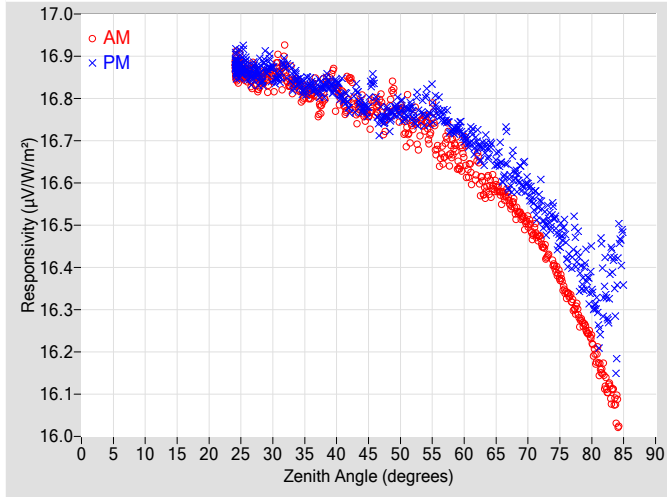


Figure 2. Responsivity vs Local Standard Time

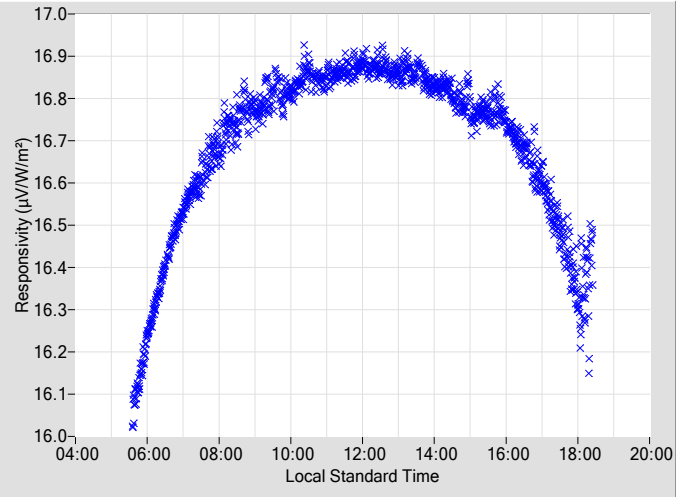
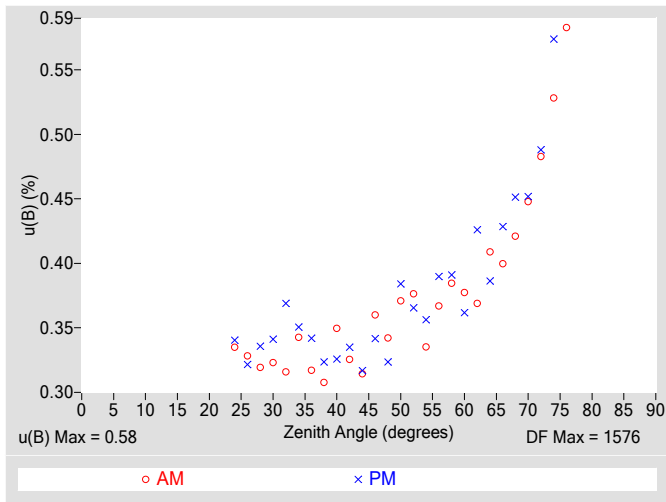


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)

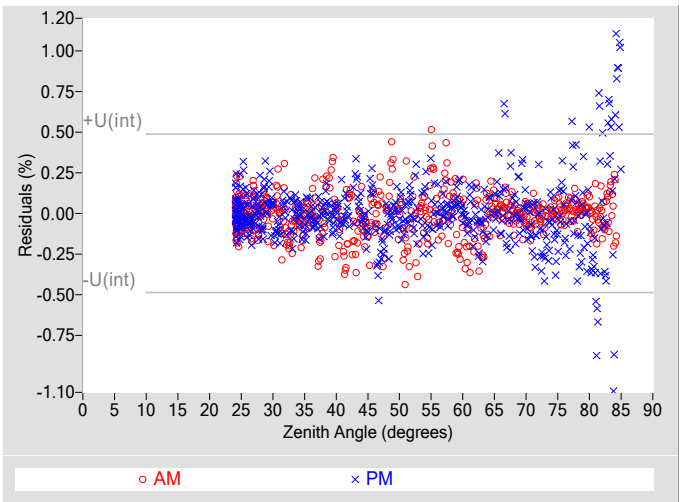
Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) $\pm$ (%)	Azimuth Angle	Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) $\pm$ (%)	Azimuth Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	16.781	0.36	108.42	16.819	0.34	251.65
2	N/A	N/A	N/A	N/A	N/A	N/A	48	16.764	0.34	106.19	16.767	0.32	253.94
4	N/A	N/A	N/A	N/A	N/A	N/A	50	16.771	0.37	103.99	16.777	0.38	256.19
6	N/A	N/A	N/A	N/A	N/A	N/A	52	16.742	0.38	101.97	16.757	0.37	258.27
8	N/A	N/A	N/A	N/A	N/A	N/A	54	16.743	0.34	99.90	16.781	0.36	260.22
10	N/A	N/A	N/A	N/A	N/A	N/A	56	16.667	0.37	98.01	16.773	0.39	262.16
12	N/A	N/A	N/A	N/A	N/A	N/A	58	16.671	0.38	96.19	16.723	0.39	264.02
14	N/A	N/A	N/A	N/A	N/A	N/A	60	16.676	0.38	94.41	16.707	0.36	265.77
16	N/A	N/A	N/A	N/A	N/A	N/A	62	16.642	0.37	92.67	16.699	0.43	267.51
18	N/A	N/A	N/A	N/A	N/A	N/A	64	16.591	0.41	90.96	16.684	0.39	269.21
20	N/A	N/A	N/A	N/A	N/A	N/A	66	16.570	0.40	89.29	16.623	0.43	270.87
22	N/A	N/A	N/A	N/A	N/A	N/A	68	16.538	0.42	87.65	16.613	0.45	272.52
24	16.875	0.33	175.86	16.878	0.34	184.03	70	16.509	0.45	86.02	16.588	0.45	274.15
26	16.860	0.33	155.02	16.869	0.32	204.98	72	16.464	0.48	84.41	16.558	0.49	275.76
28	16.840	0.32	144.90	16.855	0.34	215.22	74	16.406	0.53	82.77	16.529	0.57	277.37
30	16.846	0.32	137.85	16.863	0.34	222.26	76	16.339	0.58	81.22	16.449	N/A	278.97
32	16.877	0.32	132.14	16.874	0.37	228.09	78	16.281	N/A	79.59	16.413	N/A	280.60
34	16.831	0.34	127.31	16.838	0.35	232.71	80	16.222	N/A	77.96	16.361	N/A	282.20
36	16.812	0.32	123.31	16.833	0.34	236.78	82	16.138	N/A	76.31	16.343	N/A	283.89
38	16.811	0.31	119.82	16.826	0.32	240.43	84	16.056	N/A	74.67	16.323	N/A	285.55
40	16.814	0.35	116.58	16.836	0.33	243.57	86	N/A	N/A	N/A	N/A	N/A	N/A
42	16.830	0.33	113.63	16.779	0.34	246.37	88	N/A	N/A	N/A	N/A	N/A	N/A
44	16.780	0.31	110.92	16.778	0.32	249.18	90	N/A	N/A	N/A	N/A	N/A	N/A

N/A - Not Available

**Figure 3. Type-B Standard Uncertainty vs Zenith Angle**



**Figure 4. Residuals from Spline Interpolation**



**Table 3. Uncertainty using Spline Interpolation ‡**

Type-B Standard Uncertainty, u(B) (%)	±0.58
Type-A Interpolating Function, u(int) (%)	±0.24
Combined Standard Uncertainty, u(c) (%)	±0.63
Effective degrees of freedom, DF(c)	2077
Coverage factor, k	1.96
Expanded Uncertainty, U95 (%)	±1.2
AM Valid zenith angle range	24° to 76°
PM Valid zenith angle range	24° to 74°

‡ 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) †
16.767	0.18000

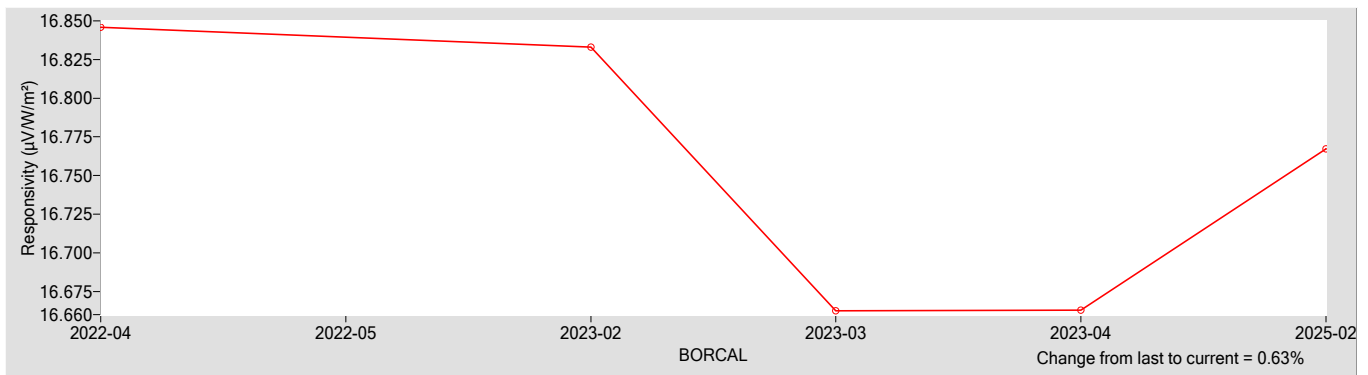
† Rnet determination date: Estimated

**Table 5. Uncertainty using R @ 45°**

Type-B Expanded Uncertainty, U(B) (%)	±0.77
Offset Uncertainty, U(off) (%)	+0.65 / -0.60
Expanded Uncertainty, U (%)	+1.4 / -1.4
Effective degrees of freedom, DF *	2044
Coverage factor, k	1.96
Valid zenith angle range	30.0° to 60.0°

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

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



**References:**

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



# National Renewable Energy Laboratory

## Solar Radiation Research Laboratory

### Metrology Laboratory

### Calibration Certificate



<b>Test Instrument:</b>	Pyranometer	<b>Manufacturer:</b>	Kipp & Zonen
<b>Model:</b>	CMP22	<b>Serial Number:</b>	170535
<b>Calibration Date:</b>	5/2/2025	<b>Due Date:</b>	5/2/2026
<b>Customer:</b>	NREL-SRRL-BMS	<b>Environmental Conditions:</b>	see page 4
<b>Test Dates:</b>	5/2		

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	09/27/2024	09/27/2025
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/21/2025	04/21/2026
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/21/2025	04/21/2026
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/07/2025	02/07/2027
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/07/2025	02/07/2027
Infrared Irradiance ‡	Kipp & Zonen Pyrgeometer Model CG4, S/N FT002	03/31/2022	03/31/2027

† Through the World Radiometric Reference (WRR)

‡ Through the World Infrared Standard Group (WISG)

**Number of pages of certificate:** 4

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

**Setup:** Radiometers are calibrated outdoors, using the sun as the source. Pyranometers and pyrgeometers are installed for horizontal measurements, with their signal connectors oriented north, if their design permits.

The shading disk for the reference diffuse subtends a solid angle of 5°. Pyrheliometers are installed on solar trackers.

**Calibrated by:** Afshin Andreas, RCC, and Shawn L. Jaker

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Ibrahim Reda, Technical Manager

05/05/2025

-----  
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 ( $\text{W}/\text{m}^2$ ),
  - =  $W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
  - where,  $W_{in}$  = incoming infrared ( $\text{W}/\text{m}^2$ ),  $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$ ,
  - $T_c$  = case temperature of pyrgeometer (K).
- $I$  = reference irradiance ( $\text{W}/\text{m}^2$ ), beam (B) or global (G)
  - where,  $G = B * \text{COS}(Z) + D$ ,
  - $Z$  = zenith angle (degrees),
  - $D$  = reference diffuse irradiance ( $\text{W}/\text{m}^2$ ).

Figure 1. Responsivity vs Zenith Angle

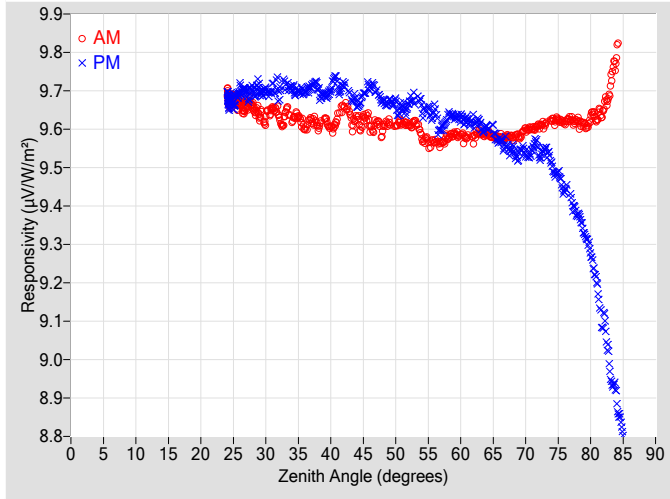


Figure 2. Responsivity vs Local Standard Time

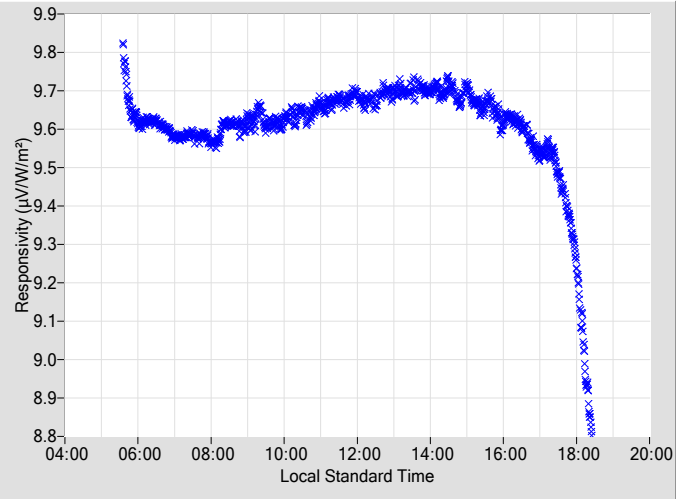
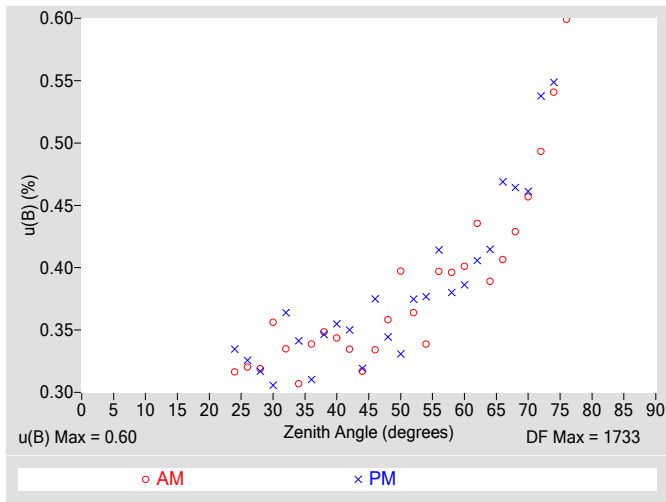


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty,  $u(B)$

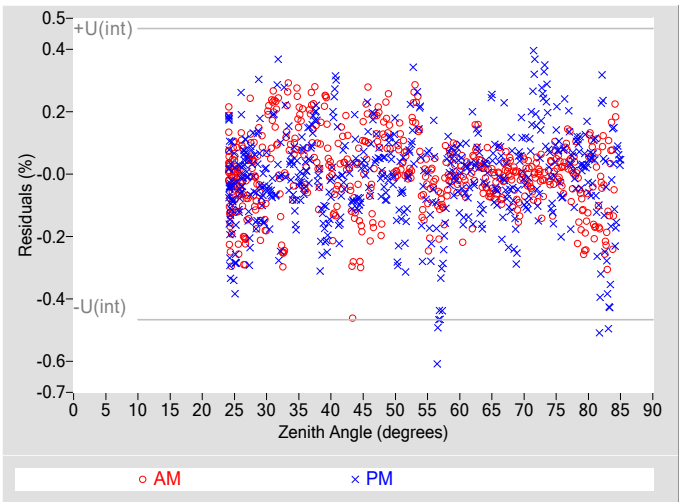
Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	AM $u(B)$ $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	PM $u(B)$ $\pm$ (%)	Azimuth Angle	Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	AM $u(B)$ $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	PM $u(B)$ $\pm$ (%)	Azimuth Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	9.6139	0.33	108.45	9.7085	0.37	251.63
2	N/A	N/A	N/A	N/A	N/A	N/A	48	9.5947	0.36	106.17	9.6715	0.34	253.98
4	N/A	N/A	N/A	N/A	N/A	N/A	50	9.6089	0.40	103.94	9.6629	0.33	256.17
6	N/A	N/A	N/A	N/A	N/A	N/A	52	9.6111	0.36	101.89	9.6666	0.37	258.26
8	N/A	N/A	N/A	N/A	N/A	N/A	54	9.5808	0.34	99.93	9.6570	0.38	260.25
10	N/A	N/A	N/A	N/A	N/A	N/A	56	9.5678	0.40	97.94	9.6479	0.41	262.10
12	N/A	N/A	N/A	N/A	N/A	N/A	58	9.5799	0.40	96.16	9.6339	0.38	263.98
14	N/A	N/A	N/A	N/A	N/A	N/A	60	9.5854	0.40	94.39	9.6297	0.39	265.75
16	N/A	N/A	N/A	N/A	N/A	N/A	62	9.5782	0.44	92.65	9.6183	0.41	267.52
18	N/A	N/A	N/A	N/A	N/A	N/A	64	9.5889	0.39	90.95	9.6044	0.41	269.19
20	N/A	N/A	N/A	N/A	N/A	N/A	66	9.5799	0.41	89.32	9.5686	0.47	270.85
22	N/A	N/A	N/A	N/A	N/A	N/A	68	9.5787	0.43	87.67	9.5486	0.46	272.50
24	9.6880	0.32	175.98	9.6790	0.33	184.41	70	9.5985	0.46	86.04	9.5367	0.46	274.13
26	9.6713	0.32	155.03	9.6958	0.33	205.18	72	9.6083	0.49	84.43	9.5369	0.54	275.75
28	9.6598	0.32	144.95	9.7012	0.32	215.21	74	9.6245	0.54	82.80	9.5077	0.55	277.35
30	9.6269	0.36	137.85	9.7023	0.31	222.20	76	9.6176	0.60	81.21	9.4416	N/A	278.99
32	9.6376	0.33	132.09	9.6999	0.36	227.98	78	9.6201	N/A	79.57	9.3768	N/A	280.59
34	9.6266	0.31	127.28	9.7080	0.34	232.77	80	9.6299	N/A	77.98	9.2774	N/A	282.23
36	9.6034	0.34	123.36	9.6947	0.31	236.74	82	9.6502	N/A	76.34	9.1017	N/A	283.88
38	9.6070	0.35	119.70	9.7054	0.35	240.39	84	9.7906	N/A	74.65	8.8981	N/A	285.53
40	9.6029	0.34	116.46	9.7047	0.36	243.62	86	N/A	N/A	N/A	N/A	N/A	N/A
42	9.6554	0.33	113.75	9.7162	0.35	246.48	88	N/A	N/A	N/A	N/A	N/A	N/A
44	9.6294	0.32	110.91	9.6653	0.32	249.22	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, $u(B)$ (%)	$\pm 0.60$
Type-A Interpolating Function, $u(int)$ (%)	$\pm 0.23$
Combined Standard Uncertainty, $u(c)$ (%)	$\pm 0.64$
Effective degrees of freedom, $DF(c)$	2211
Coverage factor, $k$	1.96
Expanded Uncertainty, $U_{95}$ (%)	$\pm 1.3$
AM Valid zenith angle range	24° to 76°
PM Valid zenith angle range	24° to 74°

‡ 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**

$R @ 45^\circ$ ( $\mu V/W/m^2$ )	$R_{net}$ ( $\mu V/W/m^2$ ) †
9.6564	0.087000

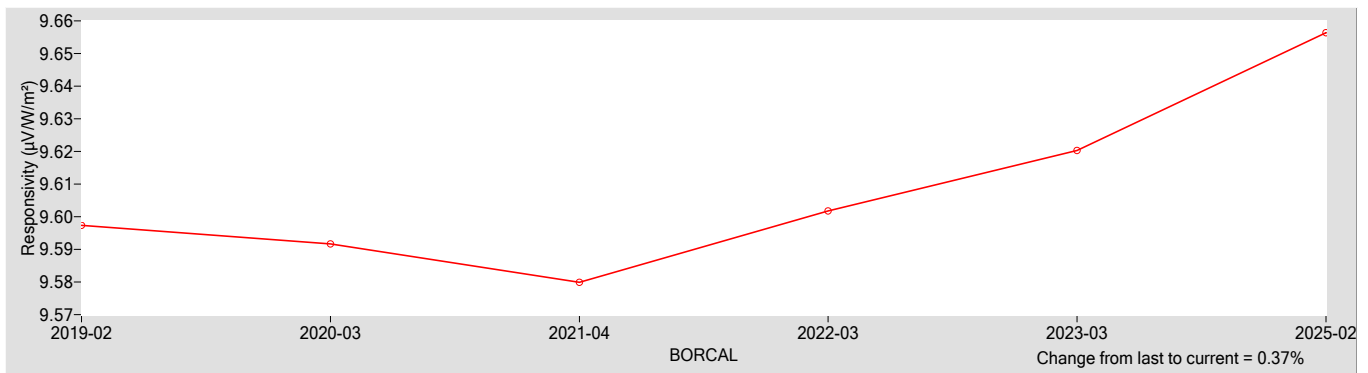
†  $R_{net}$  determination date: Estimated

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

Type-B Expanded Uncertainty, $U(B)$ (%)	$\pm 0.81$
Offset Uncertainty, $U(off)$ (%)	+0.62 / -0.92
Expanded Uncertainty, $U$ (%)	+1.4 / -1.7
Effective degrees of freedom, $DF^*$	2105
Coverage factor, $k$	1.96
Valid zenith angle range	30.0° to 60.0°

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

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



**References:**

- [1] Reda, I.; Hickey, J.; Long, C.; Myers, D.; Stoffel, T.; Wilcox, S.; Michalsky, J. J.; Dutton, E. G.; Nelson, D. (2005). "Using a Blackbody to Calculate Net Longwave Responsivity of Shortwave Solar Pyranometers to Correct for Their Thermal Offset Error During Outdoor Calibration Using the Component Sum Method." *Journal of Atmospheric and Oceanic Technology*, 2005; pp. 1531-1540; NREL Report No. JA-560-36646. doi:10.1175/JTECH1782.1
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- [5] Reda, I.; Stoffel, T.; Myers, D. (2003). "Method to Calibrate a Solar Pyranometer for Measuring Reference Diffuse Irradiance." *Solar Energy*. Vol. 74, 2003; pp. 103-112; NREL Report No. JA-560-35025. doi:10.1016/S0038-092X(03)00124-5
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# National Renewable Energy Laboratory

## Solar Radiation Research Laboratory

### Metrology Laboratory

### Calibration Certificate



<b>Test Instrument:</b>	Pyranometer	<b>Manufacturer:</b>	Kipp & Zonen
<b>Model:</b>	CMP22	<b>Serial Number:</b>	210757
<b>Calibration Date:</b>	5/2/2025	<b>Due Date:</b>	5/2/2026
<b>Customer:</b>	NREL-SRRL-BMS	<b>Environmental Conditions:</b>	see page 4
<b>Test Dates:</b>	5/2		

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	09/27/2024	09/27/2025
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/21/2025	04/21/2026
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/21/2025	04/21/2026
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/07/2025	02/07/2027
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/07/2025	02/07/2027
Infrared Irradiance ‡	Kipp & Zonen Pyrgeometer Model CG4, S/N FT002	03/31/2022	03/31/2027

† Through the World Radiometric Reference (WRR)

‡ Through the World Infrared Standard Group (WISG)

**Number of pages of certificate:** 4

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

**Setup:** Radiometers are calibrated outdoors, using the sun as the source. Pyranometers and pyrgeometers are installed for horizontal measurements, with their signal connectors oriented north, if their design permits.

The shading disk for the reference diffuse subtends a solid angle of 5°. Pyrheliometers are installed on solar trackers.

**Calibrated by:** Afshin Andreas, RCC, and Shawn L. Jaker

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Ibrahim Reda, Technical Manager

05/05/2025

-----  
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

## 210757 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 ( $\text{W}/\text{m}^2$ ),
  - =  $W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
  - where,  $W_{in}$  = incoming infrared ( $\text{W}/\text{m}^2$ ),  $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$ ,
  - $T_c$  = case temperature of pyrgeometer (K).
- $I$  = reference irradiance ( $\text{W}/\text{m}^2$ ), beam (B) or global (G)
  - where,  $G = B * \text{COS}(Z) + D$ ,
  - $Z$  = zenith angle (degrees),
  - $D$  = reference diffuse irradiance ( $\text{W}/\text{m}^2$ ).

Figure 1. Responsivity vs Zenith Angle

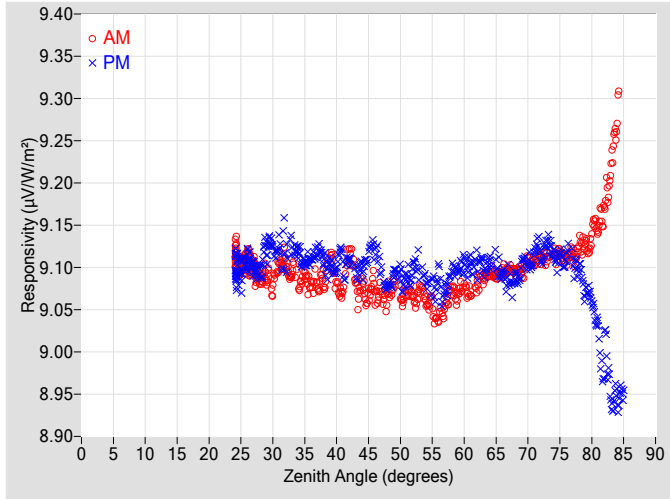


Figure 2. Responsivity vs Local Standard Time

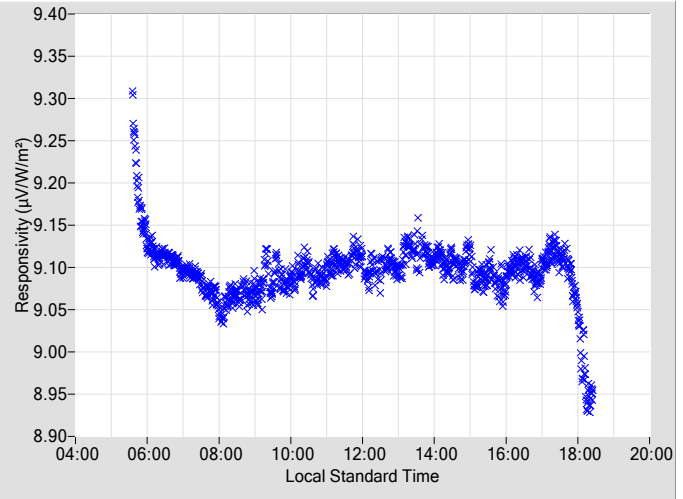
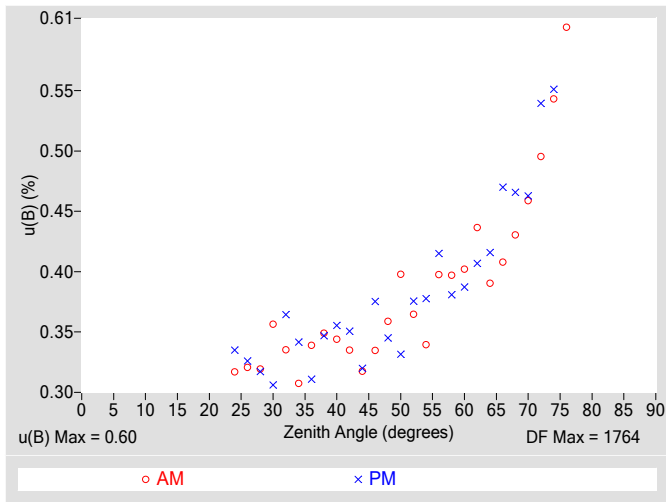


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty,  $u(B)$

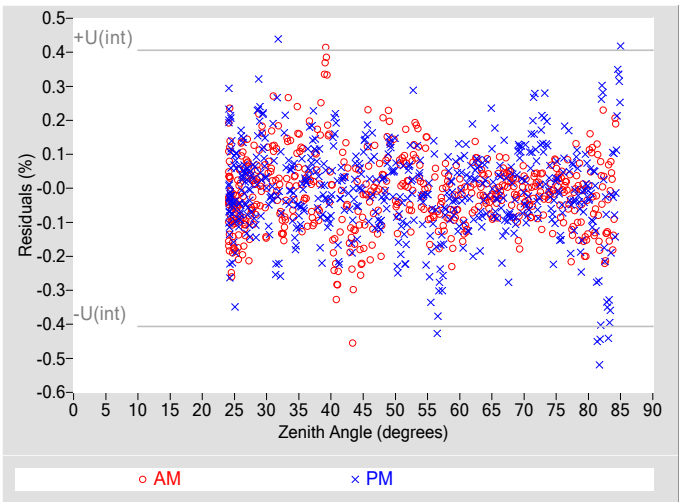
Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	AM $u(B)$ $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	PM $u(B)$ $\pm$ (%)	Azimuth Angle	Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	AM $u(B)$ $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	PM $u(B)$ $\pm$ (%)	Azimuth Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	9.0747	0.33	108.45	9.1193	0.38	251.63
2	N/A	N/A	N/A	N/A	N/A	N/A	48	9.0646	0.36	106.17	9.0779	0.35	253.98
4	N/A	N/A	N/A	N/A	N/A	N/A	50	9.0662	0.40	103.94	9.0909	0.33	256.17
6	N/A	N/A	N/A	N/A	N/A	N/A	52	9.0645	0.36	101.89	9.1015	0.38	258.26
8	N/A	N/A	N/A	N/A	N/A	N/A	54	9.0592	0.34	99.93	9.0836	0.38	260.25
10	N/A	N/A	N/A	N/A	N/A	N/A	56	9.0429	0.40	97.94	9.0918	0.42	262.10
12	N/A	N/A	N/A	N/A	N/A	N/A	58	9.0745	0.40	96.16	9.0960	0.38	263.98
14	N/A	N/A	N/A	N/A	N/A	N/A	60	9.0784	0.40	94.39	9.1038	0.39	265.75
16	N/A	N/A	N/A	N/A	N/A	N/A	62	9.0764	0.44	92.65	9.1031	0.41	267.52
18	N/A	N/A	N/A	N/A	N/A	N/A	64	9.0931	0.39	90.95	9.1058	0.42	269.19
20	N/A	N/A	N/A	N/A	N/A	N/A	66	9.0958	0.41	89.32	9.0920	0.47	270.85
22	N/A	N/A	N/A	N/A	N/A	N/A	68	9.0939	0.43	87.67	9.0887	0.47	272.50
24	9.1161	0.32	175.98	9.0947	0.33	184.41	70	9.1084	0.46	86.04	9.1058	0.46	274.13
26	9.1108	0.32	155.03	9.1074	0.33	205.18	72	9.1112	0.50	84.43	9.1116	0.54	275.75
28	9.0889	0.32	144.95	9.0951	0.32	215.21	74	9.1170	0.54	82.80	9.1146	0.55	277.35
30	9.0788	0.36	137.85	9.1247	0.31	222.20	76	9.1111	0.60	81.21	9.1139	N/A	278.99
32	9.1097	0.34	132.09	9.1175	0.36	227.98	78	9.1252	N/A	79.57	9.0981	N/A	280.59
34	9.0805	0.31	127.28	9.1196	0.34	232.77	80	9.1384	N/A	77.98	9.0601	N/A	282.23
36	9.0789	0.34	123.36	9.1074	0.31	236.74	82	9.1682	N/A	76.34	9.0019	N/A	283.88
38	9.0827	0.35	119.70	9.1072	0.35	240.39	84	9.2790	N/A	74.65	8.9449	N/A	285.53
40	9.0784	0.34	116.46	9.1015	0.36	243.62	86	N/A	N/A	N/A	N/A	N/A	N/A
42	9.1155	0.34	113.75	9.1081	0.35	246.48	88	N/A	N/A	N/A	N/A	N/A	N/A
44	9.0796	0.32	110.91	9.0982	0.32	249.22	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, $u(B)$ (%)	$\pm 0.60$
Type-A Interpolating Function, $u(int)$ (%)	$\pm 0.20$
Combined Standard Uncertainty, $u(c)$ (%)	$\pm 0.64$
Effective degrees of freedom, $DF(c)$	2138
Coverage factor, $k$	1.96
Expanded Uncertainty, $U_{95}$ (%)	$\pm 1.2$
AM Valid zenith angle range	24° to 76°
PM Valid zenith angle range	24° to 74°

‡ 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**

$R @ 45^\circ$ ( $\mu V/W/m^2$ )	$R_{net}$ ( $\mu V/W/m^2$ ) †
9.0905	0.087000

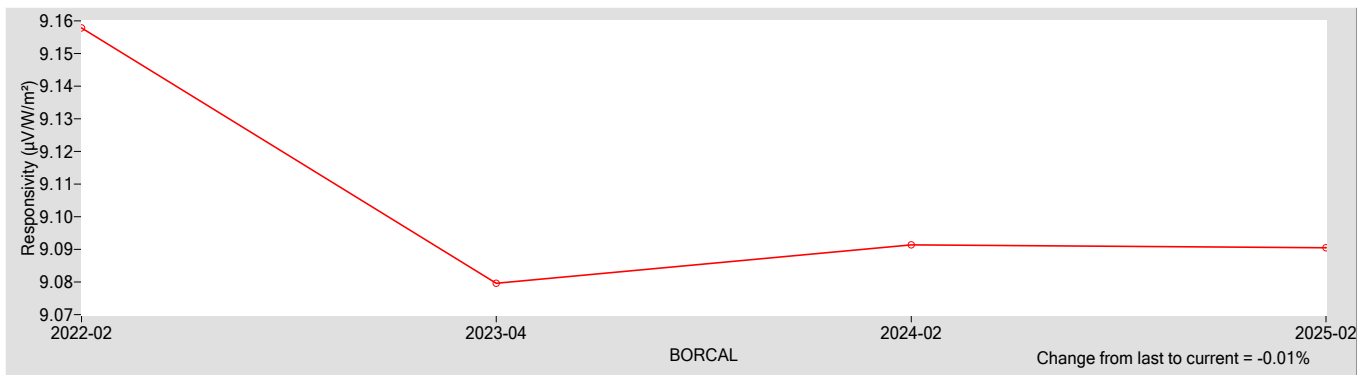
†  $R_{net}$  determination date: Estimated

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

Type-B Expanded Uncertainty, $U(B)$ (%)	$\pm 0.81$
Offset Uncertainty, $U(off)$ (%)	+0.38 / -0.52
Expanded Uncertainty, $U$ (%)	+1.2 / -1.3
Effective degrees of freedom, $DF^*$	2118
Coverage factor, $k$	1.96
Valid zenith angle range	30.0° to 60.0°

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

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



**References:**

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



# National Renewable Energy Laboratory

## Solar Radiation Research Laboratory

### Metrology Laboratory

### Calibration Certificate



<b>Test Instrument:</b>	Digital Pyranometer	<b>Manufacturer:</b>	Kipp & Zonen
<b>Model:</b>	SMP12	<b>Serial Number:</b>	220057
<b>Calibration Date:</b>	5/2/2025	<b>Due Date:</b>	5/2/2026
<b>Customer:</b>	NREL-SRRL-BMS	<b>Environmental Conditions:</b>	see page 4
<b>Test Dates:</b>	5/2		

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	09/27/2024	09/27/2025
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/21/2025	04/21/2026
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/21/2025	04/21/2026
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/07/2025	02/07/2027
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/07/2025	02/07/2027

† 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, RCC, and Shawn L. Jaker

-----  
Ibrahim Reda, Technical Manager

05/05/2025

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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

## 220057 Kipp & Zonen SMP12

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 ( $\text{W}/\text{m}^2$ ),
  - =  $W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
  - where,  $W_{in}$  = incoming infrared ( $\text{W}/\text{m}^2$ ),  $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$ ,
  - $T_c$  = case temperature of pyrgeometer (K).
- $I$  = reference irradiance ( $\text{W}/\text{m}^2$ ), beam (B) or global (G)
  - where,  $G = B * \text{COS}(Z) + D$ ,
  - $Z$  = zenith angle (degrees),
  - $D$  = reference diffuse irradiance ( $\text{W}/\text{m}^2$ ).

Figure 1. Responsivity vs Zenith Angle

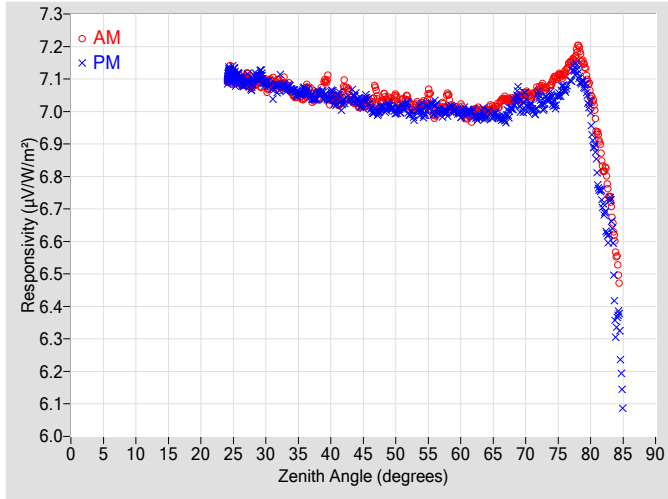


Figure 2. Responsivity vs Local Standard Time

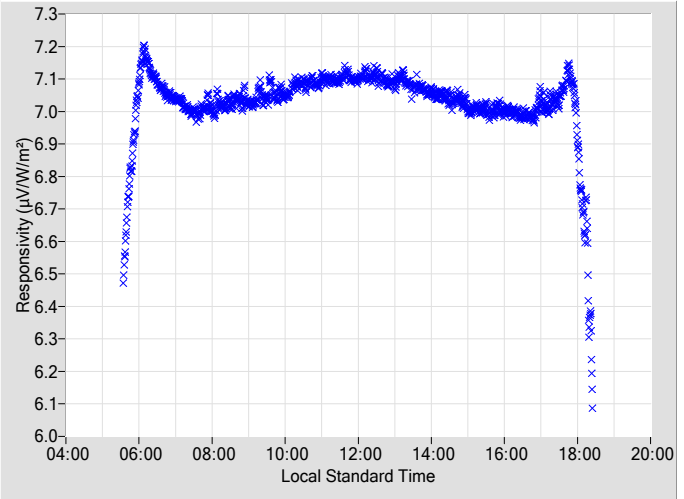
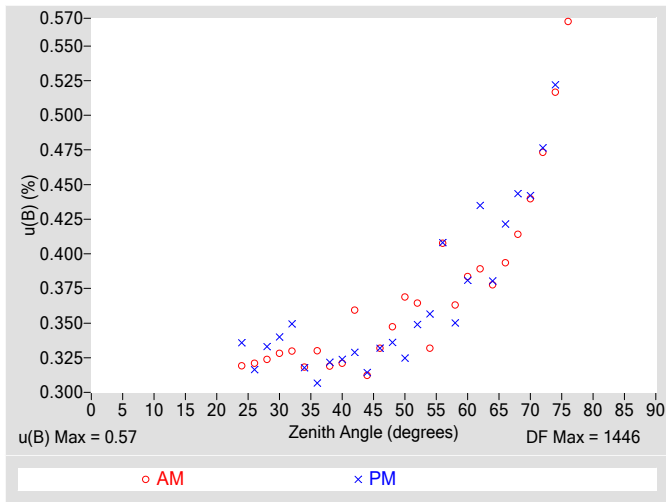


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty,  $u(B)$

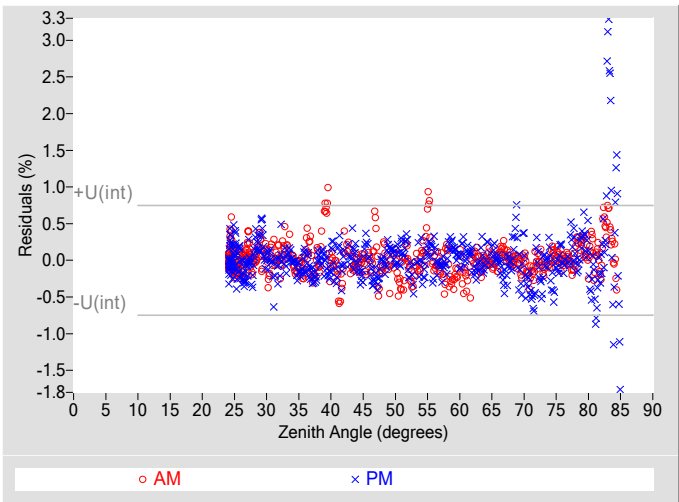
Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	AM $u(B)$ $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	PM $u(B)$ $\pm$ (%)	Azimuth Angle	Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	AM $u(B)$ $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	PM $u(B)$ $\pm$ (%)	Azimuth Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	7.0304	0.33	108.52	7.0194	0.33	251.62
2	N/A	N/A	N/A	N/A	N/A	N/A	48	7.0381	0.35	106.16	7.0139	0.34	253.97
4	N/A	N/A	N/A	N/A	N/A	N/A	50	7.0429	0.37	103.96	6.9973	0.32	256.16
6	N/A	N/A	N/A	N/A	N/A	N/A	52	7.0329	0.36	101.88	7.0058	0.35	258.19
8	N/A	N/A	N/A	N/A	N/A	N/A	54	7.0186	0.33	99.93	7.0025	0.36	260.24
10	N/A	N/A	N/A	N/A	N/A	N/A	56	6.9884	0.41	97.99	7.0113	0.41	262.13
12	N/A	N/A	N/A	N/A	N/A	N/A	58	7.0427	0.36	96.16	6.9987	0.35	263.96
14	N/A	N/A	N/A	N/A	N/A	N/A	60	7.0135	0.38	94.33	6.9895	0.38	265.75
16	N/A	N/A	N/A	N/A	N/A	N/A	62	7.0004	0.39	92.64	6.9940	0.43	267.46
18	N/A	N/A	N/A	N/A	N/A	N/A	64	7.0018	0.38	90.94	6.9854	0.38	269.19
20	N/A	N/A	N/A	N/A	N/A	N/A	66	7.0236	0.39	89.32	6.9799	0.42	270.85
22	N/A	N/A	N/A	N/A	N/A	N/A	68	7.0347	0.41	87.67	7.0155	0.44	272.49
24	7.0988	0.32	176.16	7.1073	0.34	184.39	70	7.0545	0.44	86.03	7.0334	0.44	274.12
26	7.1025	0.32	155.09	7.1045	0.32	204.91	72	7.0695	0.47	84.42	7.0412	0.48	275.74
28	7.0814	0.32	145.06	7.0891	0.33	215.19	74	7.0884	0.52	82.79	7.0395	0.52	277.35
30	7.0850	0.33	137.67	7.0859	0.34	222.47	76	7.1166	0.57	81.20	7.0690	N/A	278.99
32	7.0839	0.33	132.08	7.0801	0.35	227.99	78	7.1917	N/A	79.61	7.1244	N/A	280.58
34	7.0569	0.32	127.13	7.0667	0.32	232.75	80	7.0575	N/A	77.97	6.9870	N/A	282.22
36	7.0537	0.33	123.35	7.0638	0.31	236.82	82	6.8260	N/A	76.33	6.7017	N/A	283.87
38	7.0472	0.32	119.77	7.0556	0.32	240.39	84	6.5502	N/A	74.64	6.3540	N/A	285.57
40	7.0399	0.32	116.54	7.0486	0.32	243.53	86	N/A	N/A	N/A	N/A	N/A	N/A
42	7.0705	0.36	113.67	7.0284	0.33	246.40	88	N/A	N/A	N/A	N/A	N/A	N/A
44	7.0235	0.31	110.98	7.0415	0.31	249.14	90	N/A	N/A	N/A	N/A	N/A	N/A

N/A - Not Available

**Figure 3. Type-B Standard Uncertainty vs Zenith Angle**



**Figure 4. Residuals from Spline Interpolation**



**Table 3. Uncertainty using Spline Interpolation ‡**

Type-B Standard Uncertainty, $u(B)$ (%)	$\pm 0.57$
Type-A Interpolating Function, $u(int)$ (%)	$\pm 0.37$
Combined Standard Uncertainty, $u(c)$ (%)	$\pm 0.68$
Effective degrees of freedom, $DF(c)$	2346
Coverage factor, $k$	1.96
Expanded Uncertainty, $U95$ (%)	$\pm 1.3$
AM Valid zenith angle range	24° to 76°
PM Valid zenith angle range	24° to 74°

‡ 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**

$R @ 45^\circ$ ( $\mu V/W/m^2$ )	$R_{net}$ ( $\mu V/W/m^2$ ) †
7.0270	0

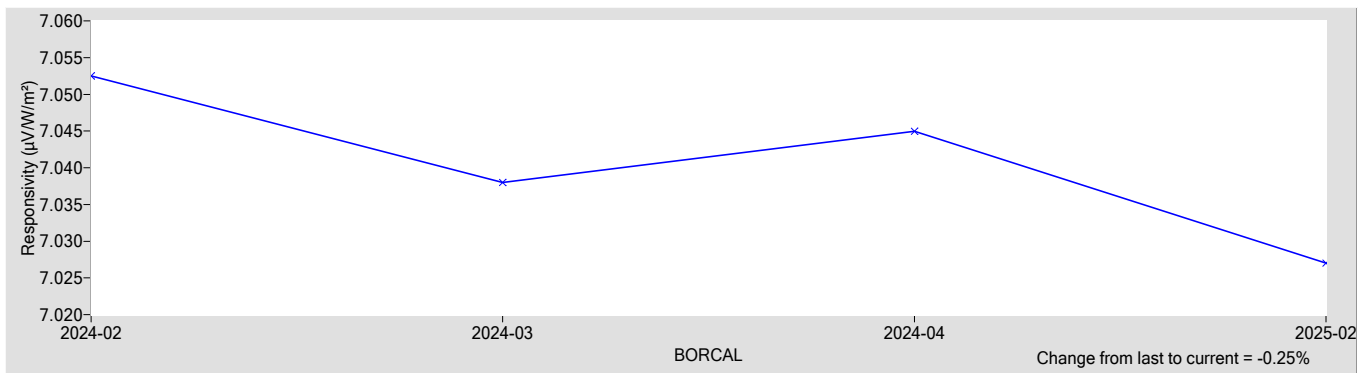
†  $R_{net}$  determination date: N/A

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

Type-B Expanded Uncertainty, $U(B)$ (%)	$\pm 0.80$
Offset Uncertainty, $U(off)$ (%)	+0.84 / -0.55
Expanded Uncertainty, $U$ (%)	+1.6 / -1.3
Effective degrees of freedom, $DF^*$	1994
Coverage factor, $k$	1.96
Valid zenith angle range	30.0° to 60.0°

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

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



**References:**

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



# National Renewable Energy Laboratory

## Solar Radiation Research Laboratory

### Metrology Laboratory

### Calibration Certificate



<b>Test Instrument:</b>	Pyranometer	<b>Manufacturer:</b>	Hukseflux
<b>Model:</b>	SR25	<b>Serial Number:</b>	2529
<b>Calibration Date:</b>	5/2/2025	<b>Due Date:</b>	5/2/2026
<b>Customer:</b>	NREL-SRRL-BMS	<b>Environmental Conditions:</b>	see page 4
<b>Test Dates:</b>	5/2		

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	09/27/2024	09/27/2025
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/21/2025	04/21/2026
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/21/2025	04/21/2026
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/07/2025	02/07/2027
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/07/2025	02/07/2027
Infrared Irradiance ‡	Kipp & Zonen Pyrgeometer Model CG4, S/N FT002	03/31/2022	03/31/2027

† Through the World Radiometric Reference (WRR)

‡ Through the World Infrared Standard Group (WISG)

**Number of pages of certificate:** 4

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

**Setup:** Radiometers are calibrated outdoors, using the sun as the source. Pyranometers and pyrgeometers are installed for horizontal measurements, with their signal connectors oriented north, if their design permits.

The shading disk for the reference diffuse subtends a solid angle of 5°. Pyrheliometers are installed on solar trackers.

**Calibrated by:** Afshin Andreas, RCC, and Shawn L. Jaker

-----  
Ibrahim Reda, Technical Manager

05/05/2025

-----  
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:

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

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 ( $\text{W}/\text{m}^2$ ),
  - =  $W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
  - where,  $W_{in}$  = incoming infrared ( $\text{W}/\text{m}^2$ ),  $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$ ,
  - $T_c$  = case temperature of pyrgeometer (K).
- $I$  = reference irradiance ( $\text{W}/\text{m}^2$ ), beam (B) or global (G)  
 where,  $G = B * \text{COS}(Z) + D$ ,  
 $Z$  = zenith angle (degrees),  
 $D$  = reference diffuse irradiance ( $\text{W}/\text{m}^2$ ).

Figure 1. Responsivity vs Zenith Angle

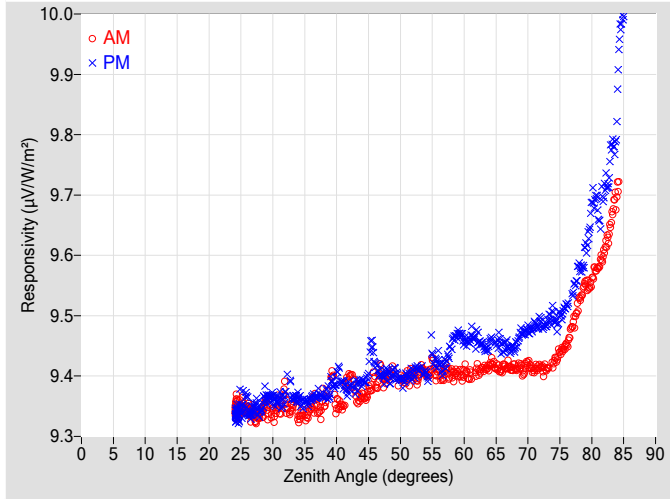


Figure 2. Responsivity vs Local Standard Time

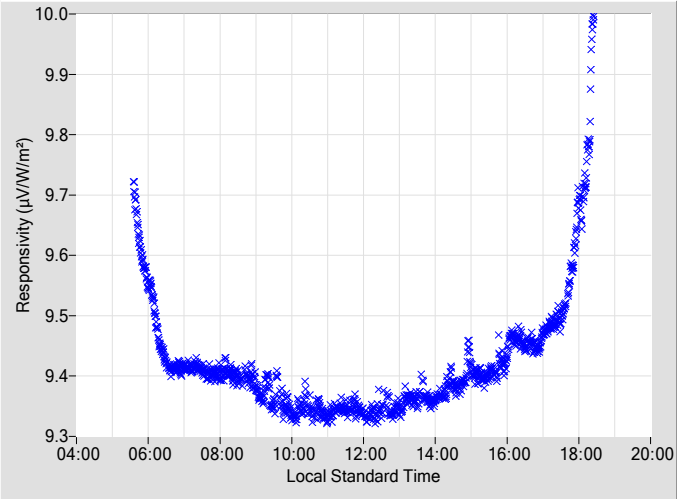
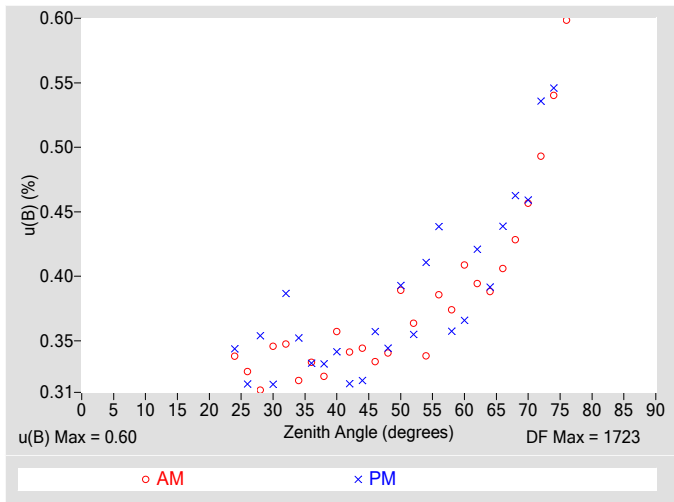


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)

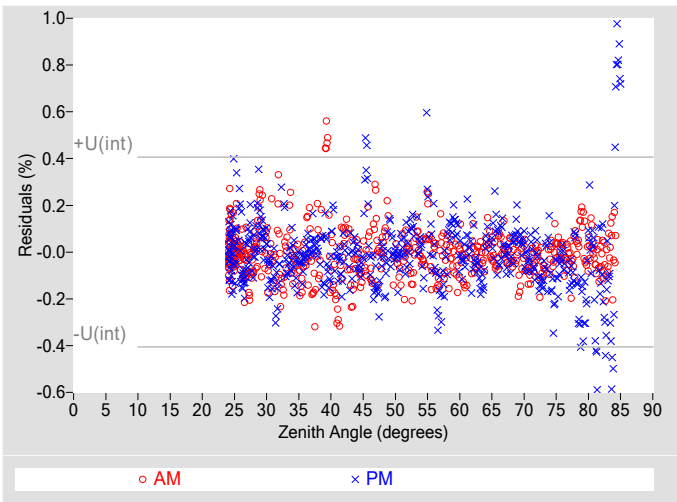
Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) $\pm$ (%)	Azimuth Angle	Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) $\pm$ (%)	Azimuth Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	9.3914	0.33	108.44	9.4239	0.36	251.62
2	N/A	N/A	N/A	N/A	N/A	N/A	48	9.3948	0.34	106.16	9.4078	0.34	253.97
4	N/A	N/A	N/A	N/A	N/A	N/A	50	9.3974	0.39	103.92	9.3947	0.39	256.15
6	N/A	N/A	N/A	N/A	N/A	N/A	52	9.4051	0.36	101.88	9.4019	0.35	258.24
8	N/A	N/A	N/A	N/A	N/A	N/A	54	9.4045	0.34	99.92	9.4029	0.41	260.24
10	N/A	N/A	N/A	N/A	N/A	N/A	56	9.4081	0.39	97.98	9.4235	0.44	262.12
12	N/A	N/A	N/A	N/A	N/A	N/A	58	9.4049	0.37	96.16	9.4534	0.36	263.97
14	N/A	N/A	N/A	N/A	N/A	N/A	60	9.4087	0.41	94.38	9.4600	0.37	265.74
16	N/A	N/A	N/A	N/A	N/A	N/A	62	9.4084	0.39	92.64	9.4617	0.42	267.48
18	N/A	N/A	N/A	N/A	N/A	N/A	64	9.4171	0.39	90.98	9.4556	0.39	269.18
20	N/A	N/A	N/A	N/A	N/A	N/A	66	9.4125	0.41	89.31	9.4446	0.44	270.84
22	N/A	N/A	N/A	N/A	N/A	N/A	68	9.4145	0.43	87.66	9.4487	0.46	272.49
24	9.3443	0.34	175.86	9.3339	0.34	183.98	70	9.4206	0.46	86.03	9.4762	0.46	274.12
26	9.3460	0.33	155.15	9.3492	0.32	205.26	72	9.4160	0.49	84.42	9.4920	0.54	275.74
28	9.3380	0.31	144.82	9.3418	0.35	215.41	74	9.4227	0.54	82.79	9.5026	0.55	277.34
30	9.3371	0.35	137.80	9.3641	0.32	222.47	76	9.4501	0.60	81.20	9.5165	N/A	278.98
32	9.3624	0.35	132.07	9.3793	0.39	228.09	78	9.5226	N/A	79.61	9.5805	N/A	280.58
34	9.3348	0.32	127.34	9.3625	0.35	232.74	80	9.5563	N/A	77.97	9.6819	N/A	282.22
36	9.3497	0.33	123.29	9.3628	0.33	236.82	82	9.6098	N/A	76.33	9.7098	N/A	283.87
38	9.3604	0.32	119.68	9.3653	0.33	240.38	84	9.7044	N/A	74.69	9.8544	N/A	285.52
40	9.3535	0.36	116.53	9.3996	0.34	243.60	86	N/A	N/A	N/A	N/A	N/A	N/A
42	9.3956	0.34	113.66	9.3818	0.32	246.47	88	N/A	N/A	N/A	N/A	N/A	N/A
44	9.3663	0.34	110.90	9.3895	0.32	249.27	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, $u(B)$ (%)	$\pm 0.60$
Type-A Interpolating Function, $u(int)$ (%)	$\pm 0.20$
Combined Standard Uncertainty, $u(c)$ (%)	$\pm 0.63$
Effective degrees of freedom, $DF(c)$	2094
Coverage factor, $k$	1.96
Expanded Uncertainty, $U95$ (%)	$\pm 1.2$
AM Valid zenith angle range	24° to 76°
PM Valid zenith angle range	24° to 74°

‡ 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**

$R @ 45^\circ$ ( $\mu V/W/m^2$ )	$R_{net}$ ( $\mu V/W/m^2$ ) †
9.3938	0.043000

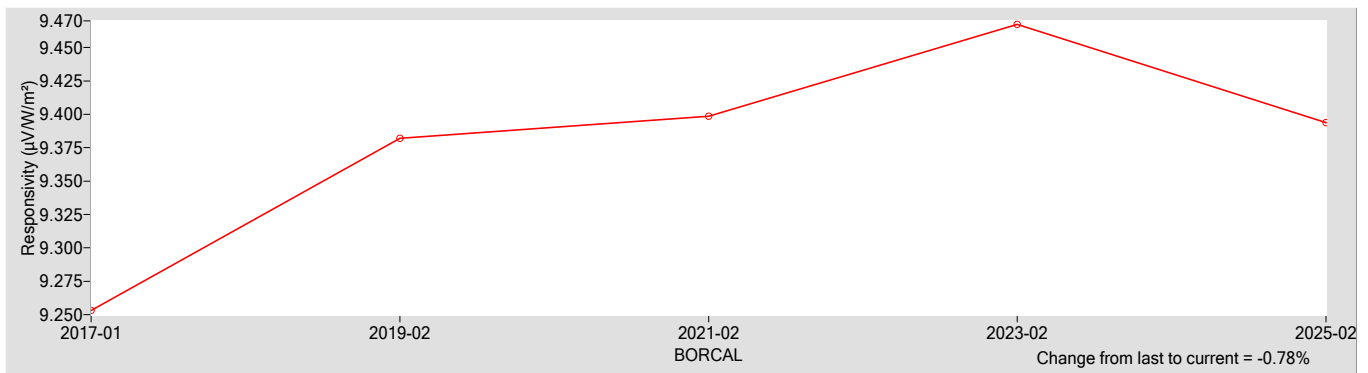
†  $R_{net}$  determination date: Estimated

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

Type-B Expanded Uncertainty, $U(B)$ (%)	$\pm 0.86$
Offset Uncertainty, $U(off)$ (%)	+0.70 / -0.63
Expanded Uncertainty, $U$ (%)	+1.6 / -1.5
Effective degrees of freedom, $DF^*$	2103
Coverage factor, $k$	1.96
Valid zenith angle range	30.0° to 60.0°

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

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



**References:**

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



# National Renewable Energy Laboratory

## Solar Radiation Research Laboratory

### Metrology Laboratory

### Calibration Certificate



<b>Test Instrument:</b>	Pyranometer (Ventilated)	<b>Manufacturer:</b>	Hukseflux
<b>Model:</b>	SR25	<b>Serial Number:</b>	2543
<b>Calibration Date:</b>	5/2/2025	<b>Due Date:</b>	5/2/2026
<b>Customer:</b>	NREL-SRRL-BMS	<b>Environmental Conditions:</b>	see page 4
<b>Test Dates:</b>	5/2		

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	09/27/2024	09/27/2025
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/21/2025	04/21/2026
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/21/2025	04/21/2026
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/07/2025	02/07/2027
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/07/2025	02/07/2027
Infrared Irradiance ‡	Eppley Downwelling Pyrgeometer Model PIR, S/N 38520F3	03/31/2022	03/31/2027

† Through the World Radiometric Reference (WRR)

‡ Through the World Infrared Standard Group (WISG)

**Number of pages of certificate:** 4

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

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

**Calibrated by:** Afshin Andreas, RCC, and Shawn L. Jaker

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Ibrahim Reda, Technical Manager

05/05/2025

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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 ( $\text{W}/\text{m}^2$ ),
  - =  $W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
  - where,  $W_{in}$  = incoming infrared ( $\text{W}/\text{m}^2$ ),  $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$ ,
  - $T_c$  = case temperature of pyrgeometer (K).
- $I$  = reference irradiance ( $\text{W}/\text{m}^2$ ), beam (B) or global (G)  
 where,  $G = B * \text{COS}(Z) + D$ ,  
 $Z$  = zenith angle (degrees),  
 $D$  = reference diffuse irradiance ( $\text{W}/\text{m}^2$ ).

Figure 1. Responsivity vs Zenith Angle

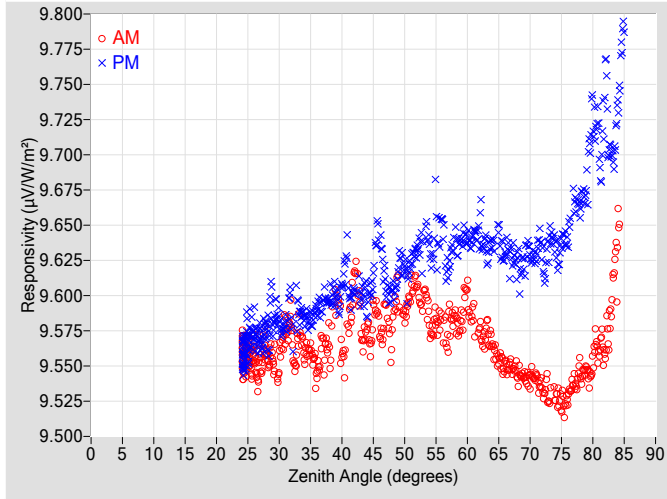


Figure 2. Responsivity vs Local Standard Time

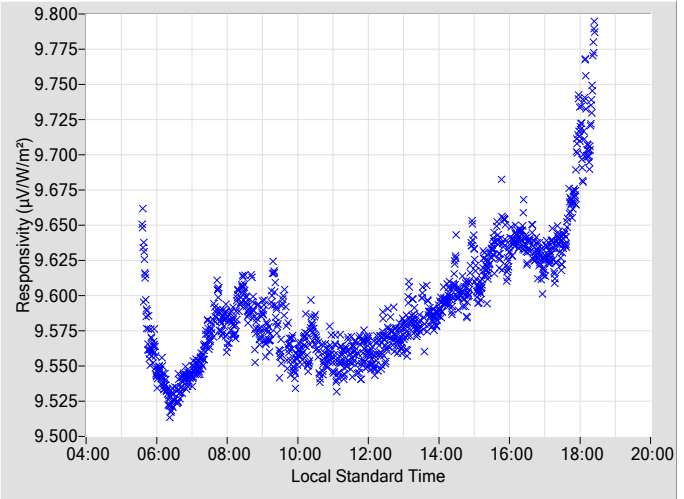
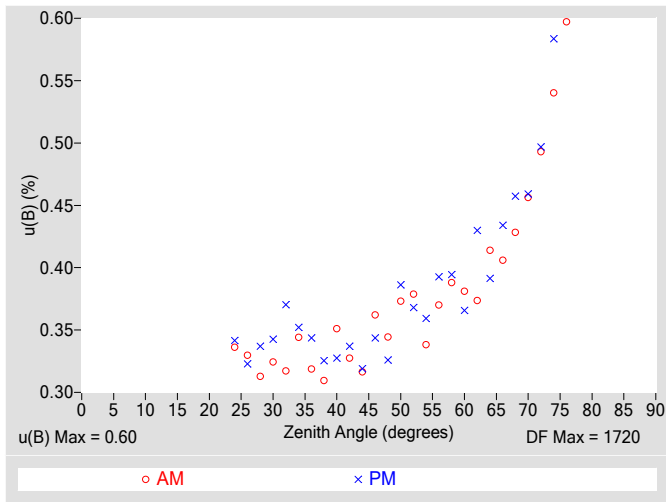


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)

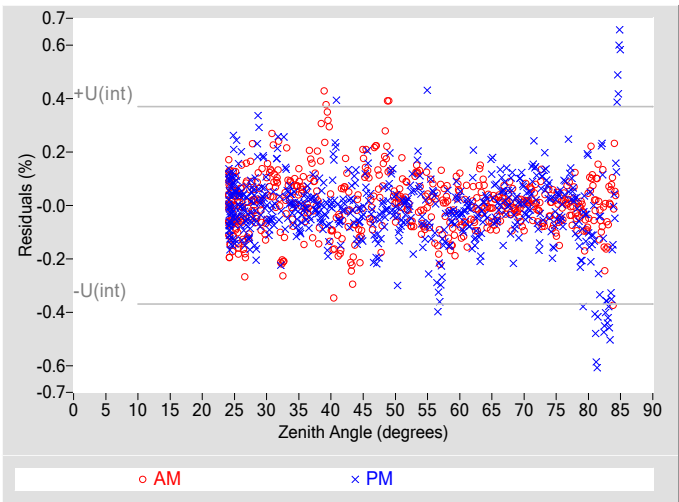
Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) $\pm$ (%)	Azimuth Angle	Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) $\pm$ (%)	Azimuth Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	9.5756	0.36	108.42	9.6418	0.34	251.65
2	N/A	N/A	N/A	N/A	N/A	N/A	48	9.5686	0.34	106.19	9.6021	0.33	254.01
4	N/A	N/A	N/A	N/A	N/A	N/A	50	9.5861	0.37	103.99	9.6210	0.39	256.19
6	N/A	N/A	N/A	N/A	N/A	N/A	52	9.6086	0.38	101.97	9.6338	0.37	258.27
8	N/A	N/A	N/A	N/A	N/A	N/A	54	9.5800	0.34	99.90	9.6325	0.36	260.22
10	N/A	N/A	N/A	N/A	N/A	N/A	56	9.5798	0.37	98.01	9.6505	0.39	262.16
12	N/A	N/A	N/A	N/A	N/A	N/A	58	9.5825	0.39	96.19	9.6435	0.39	264.02
14	N/A	N/A	N/A	N/A	N/A	N/A	60	9.5997	0.38	94.41	9.6408	0.37	265.77
16	N/A	N/A	N/A	N/A	N/A	N/A	62	9.5754	0.37	92.67	9.6490	0.43	267.51
18	N/A	N/A	N/A	N/A	N/A	N/A	64	9.5641	0.41	90.96	9.6367	0.39	269.21
20	N/A	N/A	N/A	N/A	N/A	N/A	66	9.5506	0.41	89.29	9.6297	0.43	270.87
22	N/A	N/A	N/A	N/A	N/A	N/A	68	9.5447	0.43	87.65	9.6209	0.46	272.52
24	9.5592	0.34	175.86	9.5571	0.34	184.03	70	9.5429	0.46	86.02	9.6288	0.46	274.15
26	9.5579	0.33	155.02	9.5725	0.32	204.98	72	9.5330	0.49	84.41	9.6230	0.50	275.76
28	9.5559	0.31	144.80	9.5756	0.34	215.22	74	9.5294	0.54	82.77	9.6358	0.58	277.37
30	9.5504	0.32	137.85	9.5816	0.34	222.26	76	9.5271	0.60	81.22	9.6415	N/A	278.97
32	9.5755	0.32	132.14	9.5814	0.37	228.09	78	9.5452	N/A	79.59	9.6660	N/A	280.60
34	9.5593	0.34	127.31	9.5851	0.35	232.71	80	9.5528	N/A	77.96	9.7267	N/A	282.20
36	9.5469	0.32	123.31	9.5904	0.34	236.78	82	9.5644	N/A	76.31	9.7460	N/A	283.89
38	9.5618	0.31	119.82	9.5980	0.33	240.43	84	9.6380	N/A	74.67	9.7351	N/A	285.55
40	9.5649	0.35	116.58	9.6070	0.33	243.57	86	N/A	N/A	N/A	N/A	N/A	N/A
42	9.6116	0.33	113.63	9.6030	0.34	246.37	88	N/A	N/A	N/A	N/A	N/A	N/A
44	9.5777	0.32	110.92	9.5972	0.32	249.18	90	N/A	N/A	N/A	N/A	N/A	N/A

N/A - Not Available

**Figure 3. Type-B Standard Uncertainty vs Zenith Angle**



**Figure 4. Residuals from Spline Interpolation**



**Table 3. Uncertainty using Spline Interpolation ‡**

Type-B Standard Uncertainty, $u(B)$ (%)	$\pm 0.60$
Type-A Interpolating Function, $u(int)$ (%)	$\pm 0.18$
Combined Standard Uncertainty, $u(c)$ (%)	$\pm 0.63$
Effective degrees of freedom, $DF(c)$	2034
Coverage factor, $k$	1.96
Expanded Uncertainty, $U95$ (%)	$\pm 1.2$
AM Valid zenith angle range	24° to 76°
PM Valid zenith angle range	24° to 74°

‡ 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**

$R @ 45^\circ$ ( $\mu V/W/m^2$ )	$R_{net}$ ( $\mu V/W/m^2$ ) †
9.5986	0.043000

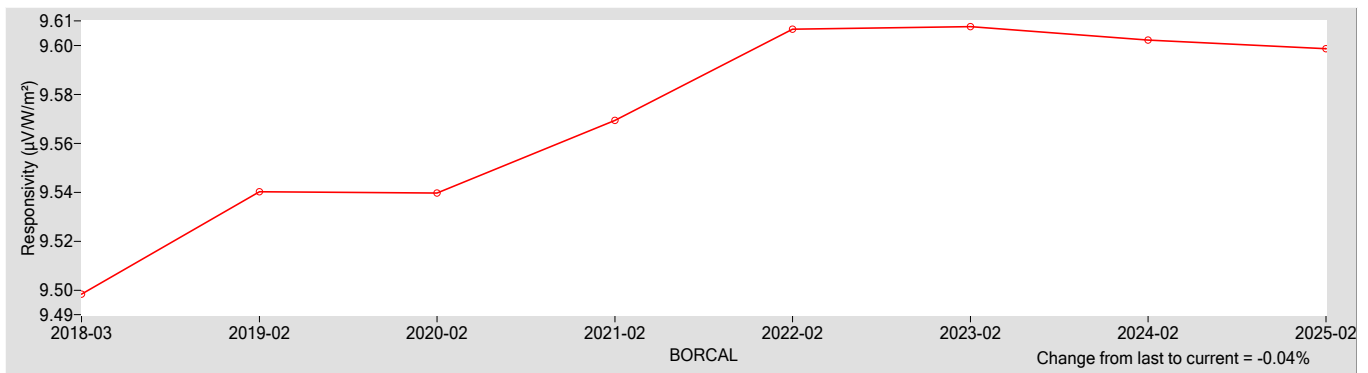
†  $R_{net}$  determination date: Estimated

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

Type-B Expanded Uncertainty, $U(B)$ (%)	$\pm 0.77$
Offset Uncertainty, $U(off)$ (%)	+0.54 / -0.54
Expanded Uncertainty, $U$ (%)	+1.3 / -1.3
Effective degrees of freedom, $DF^*$	2134
Coverage factor, $k$	1.96
Valid zenith angle range	30.0° to 60.0°

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

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



**References:**

- [1] Reda, I.; Hickey, J.; Long, C.; Myers, D.; Stoffel, T.; Wilcox, S.; Michalsky, J. J.; Dutton, E. G.; Nelson, D. (2005). "Using a Blackbody to Calculate Net Longwave Responsivity of Shortwave Solar Pyranometers to Correct for Their Thermal Offset Error During Outdoor Calibration Using the Component Sum Method." *Journal of Atmospheric and Oceanic Technology*, 2005; pp. 1531-1540; NREL Report No. JA-560-36646. doi:10.1175/JTECH1782.1
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- [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
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- [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



<b>Test Instrument:</b>	Precision Spectral Pyranometer	<b>Manufacturer:</b>	Eppley
<b>Model:</b>	PSP	<b>Serial Number:</b>	28402F3
<b>Calibration Date:</b>	5/2/2025	<b>Due Date:</b>	5/2/2026
<b>Customer:</b>	NREL-SRRL-BMS	<b>Environmental Conditions:</b>	see page 4
<b>Test Dates:</b>	5/2		

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	09/27/2024	09/27/2025
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/21/2025	04/21/2026
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/21/2025	04/21/2026
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/07/2025	02/07/2027
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/07/2025	02/07/2027
Infrared Irradiance ‡	Eppley Downwelling Pyrgeometer Model PIR, S/N 32309F3	03/31/2022	03/31/2027

† Through the World Radiometric Reference (WRR)

‡ Through the World Infrared Standard Group (WISG)

**Number of pages of certificate:** 4

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

**Setup:** Radiometers are calibrated outdoors, using the sun as the source. Pyranometers and pyrgeometers are installed for horizontal measurements, with their signal connectors oriented north, if their design permits.

The shading disk for the reference diffuse subtends a solid angle of 5°. Pyrheliometers are installed on solar trackers.

**Calibrated by:** Afshin Andreas, RCC, and Shawn L. Jaker

-----  
Ibrahim Reda, Technical Manager

05/05/2025

-----  
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 ( $\text{W}/\text{m}^2$ ),
  - =  $W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
  - where,  $W_{in}$  = incoming infrared ( $\text{W}/\text{m}^2$ ),  $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$ ,
  - $T_c$  = case temperature of pyrgeometer (K).
- $I$  = reference irradiance ( $\text{W}/\text{m}^2$ ), beam (B) or global (G)
  - where,  $G = B * \text{COS}(Z) + D$ ,
  - $Z$  = zenith angle (degrees),
  - $D$  = reference diffuse irradiance ( $\text{W}/\text{m}^2$ ).

Figure 1. Responsivity vs Zenith Angle

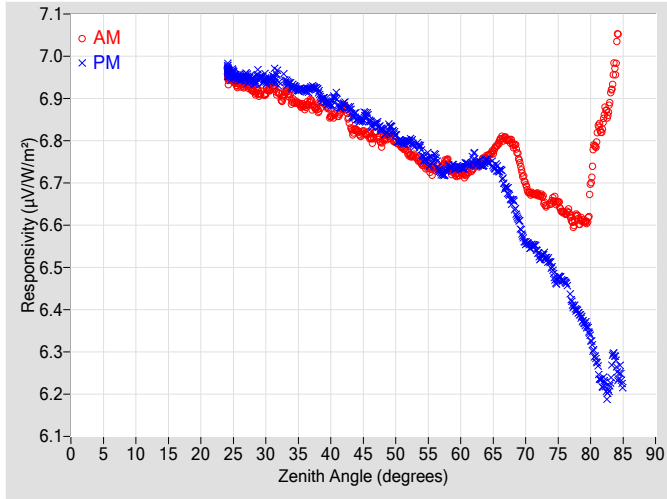


Figure 2. Responsivity vs Local Standard Time

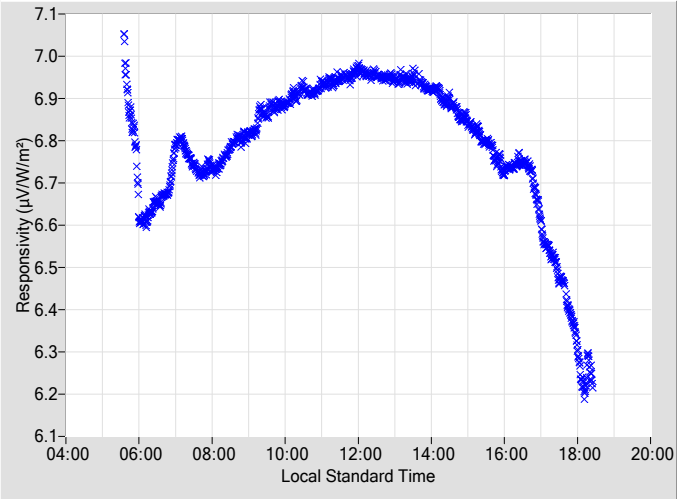
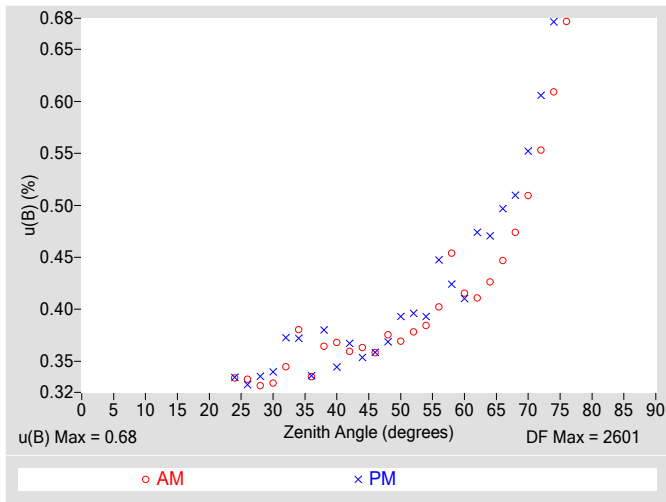


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty,  $u(B)$

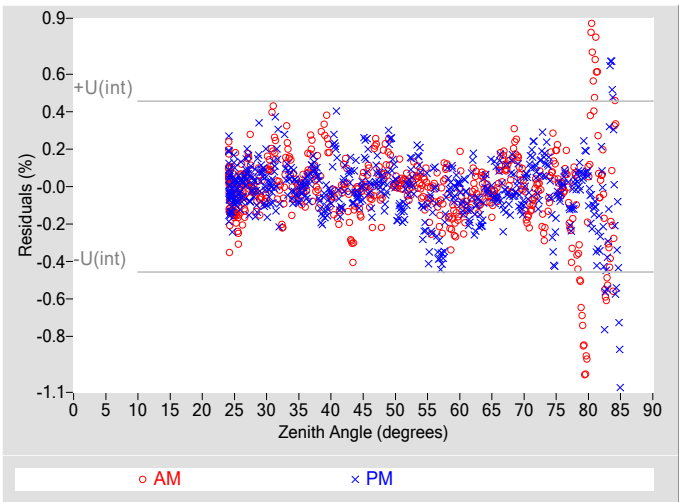
Zenith			AM			PM			Zenith			AM			PM		
Angle	R	u(B)	Azimuth	R	u(B)	Azimuth	Angle	R	u(B)	Azimuth	R	u(B)	Azimuth	R	u(B)	Azimuth	
(deg.)	( $\mu\text{V}/\text{W}/\text{m}^2$ )	$\pm$ (%)	Angle	( $\mu\text{V}/\text{W}/\text{m}^2$ )	$\pm$ (%)	Angle	(deg.)	( $\mu\text{V}/\text{W}/\text{m}^2$ )	$\pm$ (%)	Angle	( $\mu\text{V}/\text{W}/\text{m}^2$ )	$\pm$ (%)	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	6.8116	0.36	108.47	6.8471	0.36	251.65				
2	N/A	N/A	N/A	N/A	N/A	N/A	48	6.7987	0.38	106.19	6.8241	0.37	253.96				
4	N/A	N/A	N/A	N/A	N/A	N/A	50	6.7968	0.37	103.99	6.8119	0.39	256.19				
6	N/A	N/A	N/A	N/A	N/A	N/A	52	6.7696	0.38	101.91	6.7989	0.40	258.27				
8	N/A	N/A	N/A	N/A	N/A	N/A	54	6.7461	0.38	99.90	6.7719	0.39	260.21				
10	N/A	N/A	N/A	N/A	N/A	N/A	56	6.7331	0.40	97.93	6.7617	0.45	262.15				
12	N/A	N/A	N/A	N/A	N/A	N/A	58	6.7493	0.45	96.18	6.7364	0.42	263.98				
14	N/A	N/A	N/A	N/A	N/A	N/A	60	6.7262	0.42	94.40	6.7369	0.41	265.77				
16	N/A	N/A	N/A	N/A	N/A	N/A	62	6.7364	0.41	92.67	6.7606	0.47	267.50				
18	N/A	N/A	N/A	N/A	N/A	N/A	64	6.7606	0.43	90.96	6.7515	0.47	269.21				
20	N/A	N/A	N/A	N/A	N/A	N/A	66	6.7993	0.45	89.29	6.7290	0.50	270.87				
22	N/A	N/A	N/A	N/A	N/A	N/A	68	6.7924	0.47	87.64	6.6537	0.51	272.51				
24	6.9584	0.33	176.02	6.9653	0.33	184.26	70	6.6953	0.51	86.01	6.5584	0.55	274.14				
26	6.9442	0.33	155.01	6.9487	0.33	205.08	72	6.6717	0.55	84.40	6.5284	0.61	275.76				
28	6.9190	0.33	145.05	6.9443	0.34	215.31	74	6.6555	0.61	82.81	6.5005	0.68	277.36				
30	6.9128	0.33	137.84	6.9452	0.34	222.25	76	6.6289	0.68	81.22	6.4659	N/A	278.96				
32	6.9128	0.34	132.02	6.9450	0.37	227.75	78	6.6182	N/A	79.59	6.3947	N/A	280.60				
34	6.8961	0.38	127.40	6.9282	0.37	232.79	80	6.6907	N/A	77.95	6.3330	N/A	282.20				
36	6.8811	0.34	123.31	6.9199	0.34	236.77	82	6.8472	N/A	76.36	6.2253	N/A	283.89				
38	6.8755	0.36	119.81	6.9184	0.38	240.42	84	7.0086	N/A	74.66	6.2636	N/A	285.55				
40	6.8602	0.37	116.58	6.8872	0.34	243.57	86	N/A	N/A	N/A	N/A	N/A	N/A				
42	6.8778	0.36	113.63	6.8862	0.37	246.43	88	N/A	N/A	N/A	N/A	N/A	N/A				
44	6.8252	0.36	111.01	6.8533	0.35	249.17	90	N/A	N/A	N/A	N/A	N/A	N/A				

N/A - Not Available

**Figure 3. Type-B Standard Uncertainty vs Zenith Angle**



**Figure 4. Residuals from Spline Interpolation**



**Table 3. Uncertainty using Spline Interpolation ‡**

Type-B Standard Uncertainty, $u(B)$ (%)	$\pm 0.68$
Type-A Interpolating Function, $u(int)$ (%)	$\pm 0.23$
Combined Standard Uncertainty, $u(c)$ (%)	$\pm 0.71$
Effective degrees of freedom, $DF(c)$	3124
Coverage factor, $k$	1.96
Expanded Uncertainty, $U_{95}$ (%)	$\pm 1.4$
AM Valid zenith angle range	24° to 76°
PM Valid zenith angle range	24° to 74°

‡ 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**

$R @ 45^\circ$ ( $\mu V/W/m^2$ )	$R_{net}$ ( $\mu V/W/m^2$ ) †
6.8387	0.64000

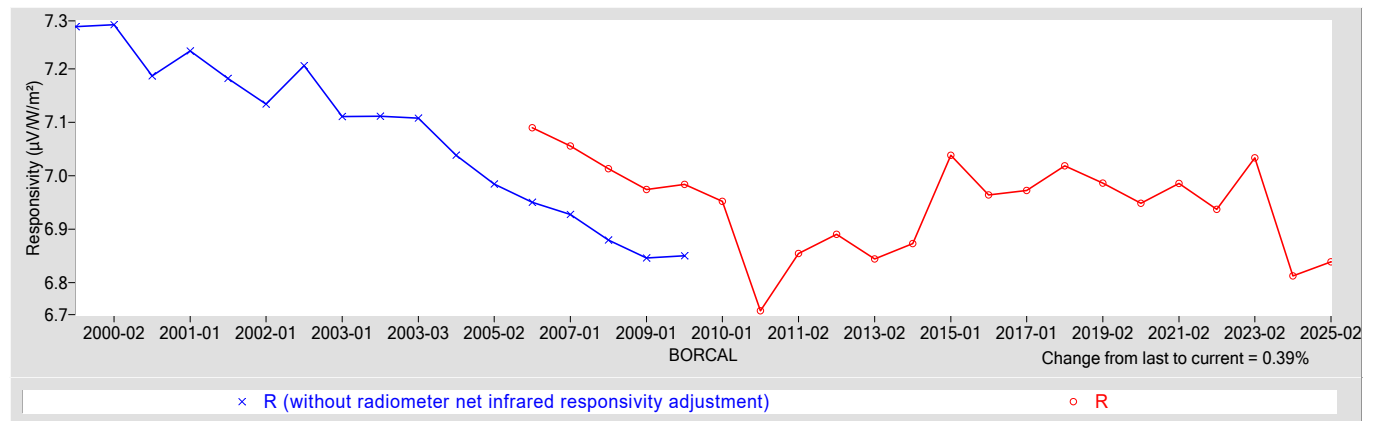
†  $R_{net}$  determination date: 02/28/2006

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

Type-B Expanded Uncertainty, $U(B)$ (%)	$\pm 0.89$
Offset Uncertainty, $U(off)$ (%)	+1.6 / -1.6
Expanded Uncertainty, $U$ (%)	+2.4 / -2.5
Effective degrees of freedom, $DF^*$	2233
Coverage factor, $k$	1.96
Valid zenith angle range	30.0° to 60.0°

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

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



**References:**

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



# National Renewable Energy Laboratory

## Solar Radiation Research Laboratory

### Metrology Laboratory

### Calibration Certificate



<b>Test Instrument:</b>	Normal Incidence Pyrheliometer	<b>Manufacturer:</b>	Eppley
<b>Model:</b>	NIP	<b>Serial Number:</b>	31137E6
<b>Calibration Date:</b>	5/2/2025	<b>Due Date:</b>	5/2/2026
<b>Customer:</b>	NREL-SRRL-BMS	<b>Environmental Conditions:</b>	see page 4
<b>Test Dates:</b>	5/2		

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	09/27/2024	09/27/2025
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/21/2025	04/21/2026
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/21/2025	04/21/2026
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/07/2025	02/07/2027
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/07/2025	02/07/2027

† 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, RCC, and Shawn L. Jaker

\_\_\_\_\_  
Ibrahim Reda, Technical Manager

05/05/2025

\_\_\_\_\_  
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 ( $\text{W}/\text{m}^2$ ),
  - =  $W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
  - where,  $W_{in}$  = incoming infrared ( $\text{W}/\text{m}^2$ ),  $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$ ,
  - $T_c$  = case temperature of pyrgeometer (K).
- $I$  = reference irradiance ( $\text{W}/\text{m}^2$ ), beam (B) or global (G)
  - where,  $G = B * \text{COS}(Z) + D$ ,
  - $Z$  = zenith angle (degrees),
  - $D$  = reference diffuse irradiance ( $\text{W}/\text{m}^2$ ).

Figure 1. Responsivity vs Zenith Angle

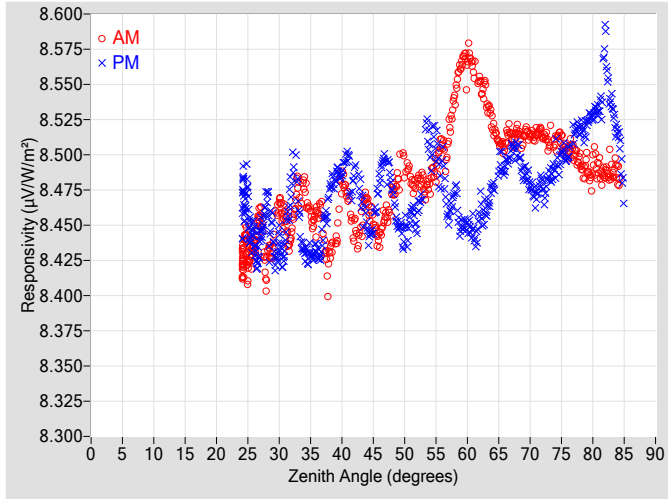


Figure 2. Responsivity vs Local Standard Time

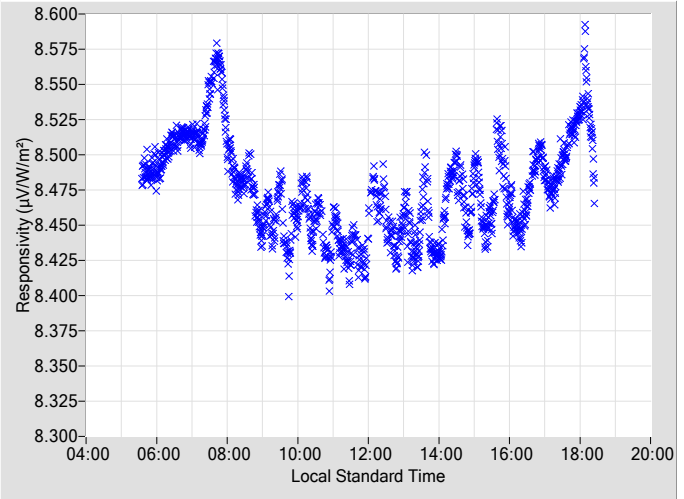
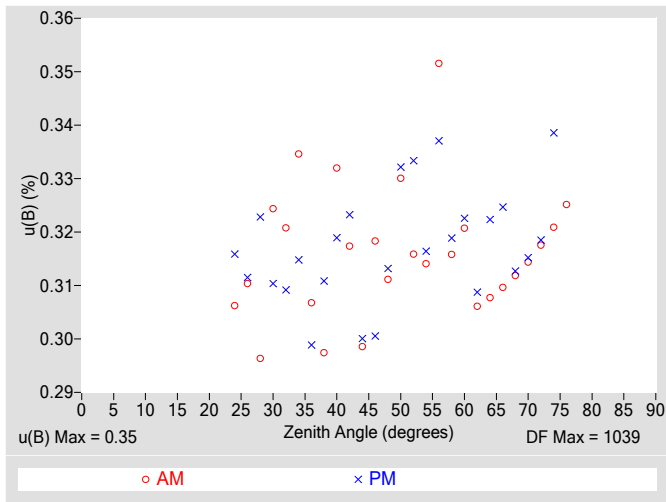


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)

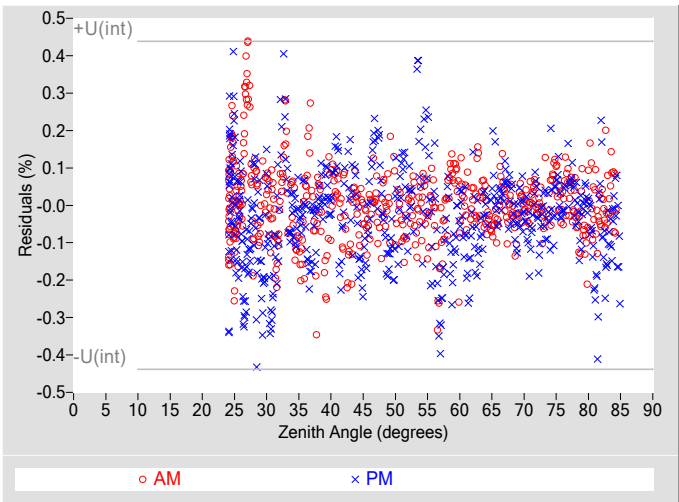
Zenith			AM			PM			Zenith			AM			PM		
Angle	R	u(B)	Azimuth	R	u(B)	Azimuth	Angle	R	u(B)	Azimuth	R	u(B)	Azimuth	R	u(B)	Azimuth	
(deg.)	( $\mu\text{V}/\text{W}/\text{m}^2$ )	$\pm$ (%)	Angle	( $\mu\text{V}/\text{W}/\text{m}^2$ )	$\pm$ (%)	Angle	(deg.)	( $\mu\text{V}/\text{W}/\text{m}^2$ )	$\pm$ (%)	Angle	( $\mu\text{V}/\text{W}/\text{m}^2$ )	$\pm$ (%)	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	8.4413	0.32	108.50	8.4830	0.30	251.67				
2	N/A	N/A	N/A	N/A	N/A	N/A	48	8.4711	0.31	106.09	8.4773	0.31	253.89				
4	N/A	N/A	N/A	N/A	N/A	N/A	50	8.4931	0.33	104.03	8.4460	0.33	256.20				
6	N/A	N/A	N/A	N/A	N/A	N/A	52	8.4821	0.32	101.87	8.4548	0.33	258.24				
8	N/A	N/A	N/A	N/A	N/A	N/A	54	8.4787	0.31	99.92	8.5031	0.32	260.23				
10	N/A	N/A	N/A	N/A	N/A	N/A	56	8.5075	0.35	98.03	8.4924	0.34	262.14				
12	N/A	N/A	N/A	N/A	N/A	N/A	58	8.5411	0.32	96.20	8.4745	0.32	264.01				
14	N/A	N/A	N/A	N/A	N/A	N/A	60	8.5703	0.32	94.39	8.4482	0.32	265.78				
16	N/A	N/A	N/A	N/A	N/A	N/A	62	8.5510	0.31	92.68	8.4615	0.31	267.47				
18	N/A	N/A	N/A	N/A	N/A	N/A	64	8.5222	0.31	90.97	8.4770	0.32	269.18				
20	N/A	N/A	N/A	N/A	N/A	N/A	66	8.5073	0.31	89.30	8.4919	0.32	270.89				
22	N/A	N/A	N/A	N/A	N/A	N/A	68	8.5171	0.31	87.66	8.5039	0.31	272.48				
24	8.4246	0.31	175.98	8.4707	0.32	184.28	70	8.5139	0.31	86.03	8.4787	0.32	274.11				
26	8.4348	0.31	154.88	8.4411	0.31	204.98	72	8.5137	0.32	84.42	8.4778	0.32	275.73				
28	8.4182	0.30	145.26	8.4662	0.32	215.29	74	8.5080	0.32	82.83	8.4934	0.34	277.38				
30	8.4635	0.32	137.73	8.4372	0.31	222.37	76	8.5019	0.33	81.19	8.4990	N/A	278.98				
32	8.4462	0.32	132.13	8.4812	0.31	227.92	78	8.4947	N/A	79.60	8.5189	N/A	280.57				
34	8.4792	0.33	127.36	8.4315	0.31	232.82	80	8.4920	N/A	77.96	8.5270	N/A	282.21				
36	8.4565	0.31	123.33	8.4310	0.30	236.80	82	8.4881	N/A	76.32	8.5745	N/A	283.86				
38	8.4242	0.30	119.75	8.4743	0.31	240.38	84	8.4847	N/A	74.63	8.5147	N/A	285.56				
40	8.4814	0.33	116.47	8.4872	0.32	243.51	86	N/A	N/A	N/A	N/A	N/A	N/A				
42	8.4463	0.32	113.58	8.4864	0.32	246.38	88	N/A	N/A	N/A	N/A	N/A	N/A				
44	8.4685	0.30	110.96	8.4481	0.30	249.19	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, $u(B)$ (%)	$\pm 0.35$
Type-A Interpolating Function, $u(int)$ (%)	$\pm 0.22$
Combined Standard Uncertainty, $u(c)$ (%)	$\pm 0.41$
Effective degrees of freedom, $DF(c)$	1735
Coverage factor, $k$	1.96
Expanded Uncertainty, $U95$ (%)	$\pm 0.81$
AM Valid zenith angle range	24° to 76°
PM Valid zenith angle range	24° to 74°

‡ 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**

$R @ 45^\circ$ ( $\mu V/W/m^2$ )	$R_{net}$ ( $\mu V/W/m^2$ ) †
8.4522	0

†  $R_{net}$  determination date: N/A

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

Type-B Expanded Uncertainty, $U(B)$ (%)	$\pm 0.69$
Offset Uncertainty, $U(off)$ (%)	+1.4 / -0.33
Expanded Uncertainty, $U$ (%)	+2.1 / -1.0
Effective degrees of freedom, $DF^*$	1039
Coverage factor, $k$	1.96
Valid zenith angle range	30.0° to 60.0°

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

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



**References:**

- [1] Reda, I.; Hickey, J.; Long, C.; Myers, D.; Stoffel, T.; Wilcox, S.; Michalsky, J. J.; Dutton, E. G.; Nelson, D. (2005). "Using a Blackbody to Calculate Net Longwave Responsivity of Shortwave Solar Pyranometers to Correct for Their Thermal Offset Error During Outdoor Calibration Using the Component Sum Method." Journal of Atmospheric and Oceanic Technology. , 2005; pp. 1531-1540; NREL Report No. JA-560-36646. doi:10.1175/JTECH1782.1
- [2] Reda, I.; Myers, D.; Stoffel, T. (2008). "Uncertainty Estimate for the Outdoor Calibration of Solar Pyranometers: A Metrologist Perspective." Measure. (NCSLI Journal of Measurement Science). Vol. 3(4), December 2008; pp. 58-66; NREL Report No. JA-581-4137
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- [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



<b>Test Instrument:</b>	Black and White Pyranometer	<b>Manufacturer:</b>	Eppley
<b>Model:</b>	8-48	<b>Serial Number:</b>	32331
<b>Calibration Date:</b>	5/2/2025	<b>Due Date:</b>	5/2/2026
<b>Customer:</b>	NREL-SRRL-BMS	<b>Environmental Conditions:</b>	see page 4
<b>Test Dates:</b>	5/2		

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	09/27/2024	09/27/2025
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/21/2025	04/21/2026
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/21/2025	04/21/2026
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/07/2025	02/07/2027
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/07/2025	02/07/2027

† 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, RCC, and Shawn L. Jaker

-----  
Ibrahim Reda, Technical Manager

05/05/2025

-----  
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:

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

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 ( $\text{W}/\text{m}^2$ ),
  - =  $W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
  - where,  $W_{in}$  = incoming infrared ( $\text{W}/\text{m}^2$ ),  $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$ ,
  - $T_c$  = case temperature of pyrgeometer (K).
- $I$  = reference irradiance ( $\text{W}/\text{m}^2$ ), beam (B) or global (G)  
 where,  $G = B * \text{COS}(Z) + D$ ,  
 $Z$  = zenith angle (degrees),  
 $D$  = reference diffuse irradiance ( $\text{W}/\text{m}^2$ ).

Figure 1. Responsivity vs Zenith Angle

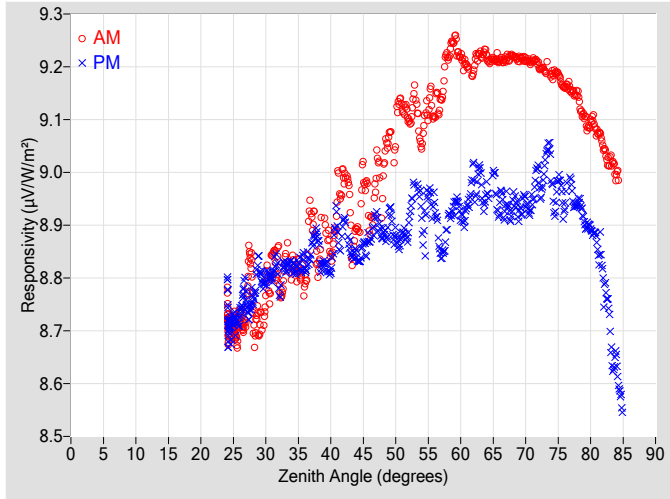


Figure 2. Responsivity vs Local Standard Time

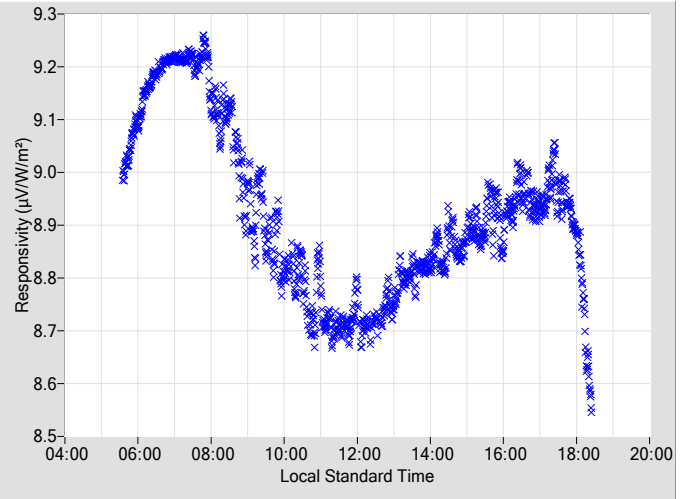
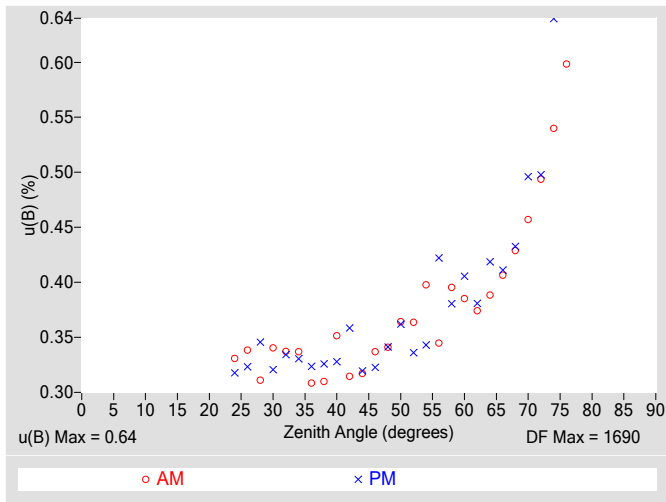


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)

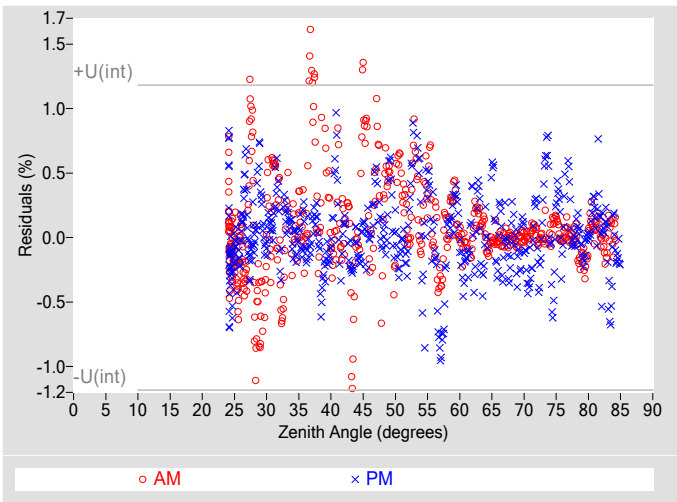
Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) $\pm$ (%)	Azimuth Angle	Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) $\pm$ (%)	Azimuth Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	8.9040	0.34	108.42	8.8701	0.32	251.63
2	N/A	N/A	N/A	N/A	N/A	N/A	48	8.9781	0.34	106.08	8.8821	0.34	253.96
4	N/A	N/A	N/A	N/A	N/A	N/A	50	9.0696	0.36	103.96	8.8765	0.36	256.20
6	N/A	N/A	N/A	N/A	N/A	N/A	52	9.1015	0.36	101.92	8.8964	0.34	258.23
8	N/A	N/A	N/A	N/A	N/A	N/A	54	9.0560	0.40	99.91	8.9118	0.34	260.22
10	N/A	N/A	N/A	N/A	N/A	N/A	56	9.1134	0.34	98.02	8.9325	0.42	262.17
12	N/A	N/A	N/A	N/A	N/A	N/A	58	9.2194	0.40	96.19	8.9091	0.38	264.01
14	N/A	N/A	N/A	N/A	N/A	N/A	60	9.2186	0.39	94.41	8.9197	0.41	265.78
16	N/A	N/A	N/A	N/A	N/A	N/A	62	9.1939	0.37	92.68	8.9840	0.38	267.52
18	N/A	N/A	N/A	N/A	N/A	N/A	64	9.2218	0.39	90.97	8.9607	0.42	269.17
20	N/A	N/A	N/A	N/A	N/A	N/A	66	9.2120	0.41	89.30	8.9416	0.41	270.88
22	N/A	N/A	N/A	N/A	N/A	N/A	68	9.2204	0.43	87.65	8.9379	0.43	272.53
24	8.7128	0.33	175.56	8.7290	0.32	184.05	70	9.2134	0.46	86.03	8.9448	0.50	274.16
26	8.7250	0.34	154.94	8.7279	0.32	205.05	72	9.2019	0.49	84.42	8.9883	0.50	275.73
28	8.7648	0.31	144.99	8.7601	0.35	215.14	74	9.1842	0.54	82.83	8.9840	0.64	277.37
30	8.7644	0.34	137.87	8.7987	0.32	222.60	76	9.1624	0.60	81.19	8.9348	N/A	278.98
32	8.8208	0.34	132.15	8.7888	0.33	228.13	78	9.1461	N/A	79.60	8.9414	N/A	280.57
34	8.8222	0.34	127.29	8.8233	0.33	232.82	80	9.0943	N/A	77.96	8.8944	N/A	282.21
36	8.7879	0.31	123.23	8.8239	0.32	236.79	82	9.0475	N/A	76.32	8.7942	N/A	283.85
38	8.8253	0.31	119.74	8.8774	0.33	240.36	84	8.9944	N/A	74.63	8.6349	N/A	285.56
40	8.8485	0.35	116.52	8.8161	0.33	243.51	86	N/A	N/A	N/A	N/A	N/A	N/A
42	8.9946	0.31	113.57	8.9026	0.36	246.45	88	N/A	N/A	N/A	N/A	N/A	N/A
44	8.8924	0.32	110.95	8.8420	0.32	249.19	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) (%)	±0.64
Type-A Interpolating Function, u(int) (%)	±0.59
Combined Standard Uncertainty, u(c) (%)	±0.87
Effective degrees of freedom, DF(c)	2644
Coverage factor, k	1.96
Expanded Uncertainty, U95 (%)	±1.7
AM Valid zenith angle range	24° to 76°
PM Valid zenith angle range	24° to 74°

‡ 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) †
8.9255	0

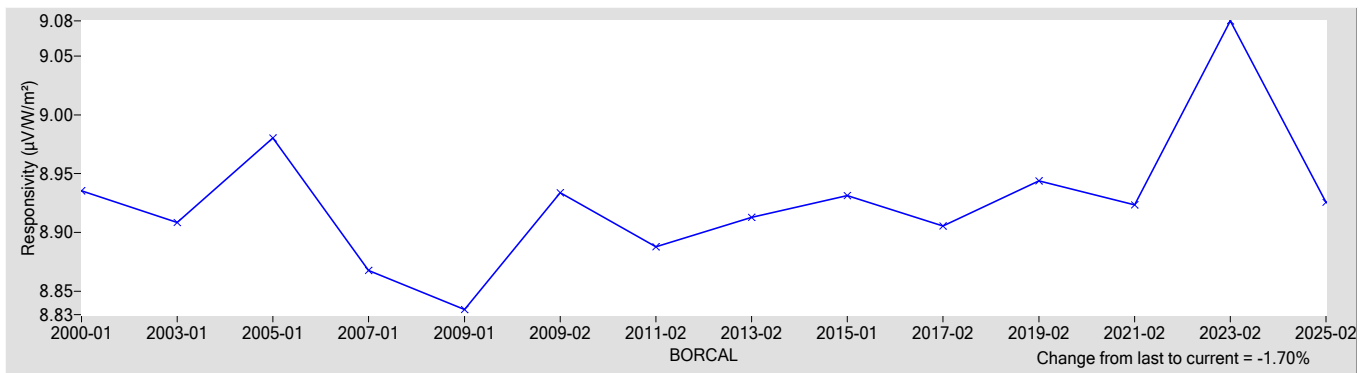
† Rnet determination date: N/A

**Table 5. Uncertainty using R @ 45°**

Type-B Expanded Uncertainty, U(B) (%)	±0.83
Offset Uncertainty, U(off) (%)	+3.3 / -1.8
Expanded Uncertainty, U (%)	+4.1 / -2.6
Effective degrees of freedom, DF *	2121
Coverage factor, k	1.96
Valid zenith angle range	30.0° to 60.0°

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

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



**References:**

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



# National Renewable Energy Laboratory

## Solar Radiation Research Laboratory

### Metrology Laboratory

### Calibration Certificate



<b>Test Instrument:</b>	Black and White Pyranometer	<b>Manufacturer:</b>	Eppley
<b>Model:</b>	8-48	<b>Serial Number:</b>	34718
<b>Calibration Date:</b>	5/2/2025	<b>Due Date:</b>	5/2/2026
<b>Customer:</b>	NREL-SRRL-BMS	<b>Environmental Conditions:</b>	see page 4
<b>Test Dates:</b>	5/2		

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	09/27/2024	09/27/2025
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/21/2025	04/21/2026
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/21/2025	04/21/2026
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/07/2025	02/07/2027
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/07/2025	02/07/2027

† 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, RCC, and Shawn L. Jaker

-----  
Ibrahim Reda, Technical Manager

05/05/2025

-----  
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:

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

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 ( $\text{W}/\text{m}^2$ ),
  - =  $W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
  - where,  $W_{in}$  = incoming infrared ( $\text{W}/\text{m}^2$ ),  $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$ ,
  - $T_c$  = case temperature of pyrgeometer (K).
- $I$  = reference irradiance ( $\text{W}/\text{m}^2$ ), beam (B) or global (G)  
 where,  $G = B * \text{COS}(Z) + D$ ,  
 $Z$  = zenith angle (degrees),  
 $D$  = reference diffuse irradiance ( $\text{W}/\text{m}^2$ ).

Figure 1. Responsivity vs Zenith Angle

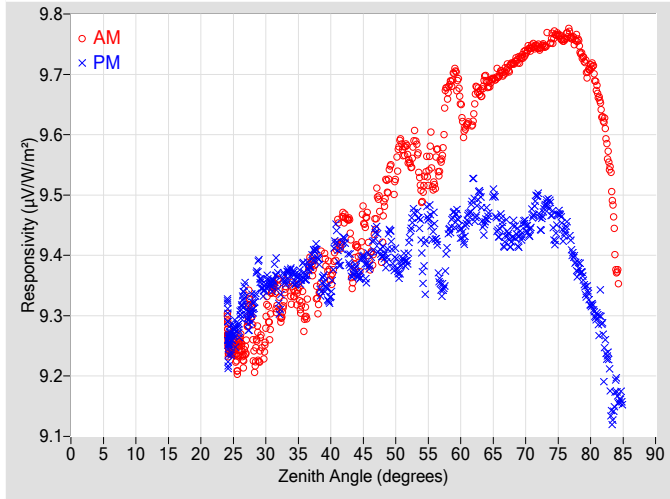


Figure 2. Responsivity vs Local Standard Time

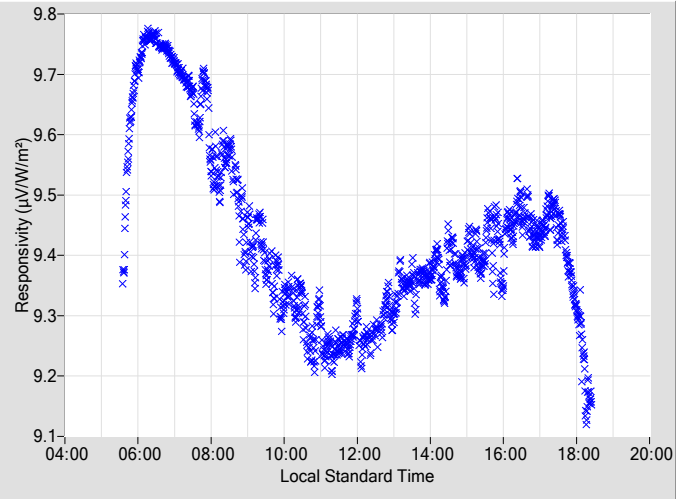
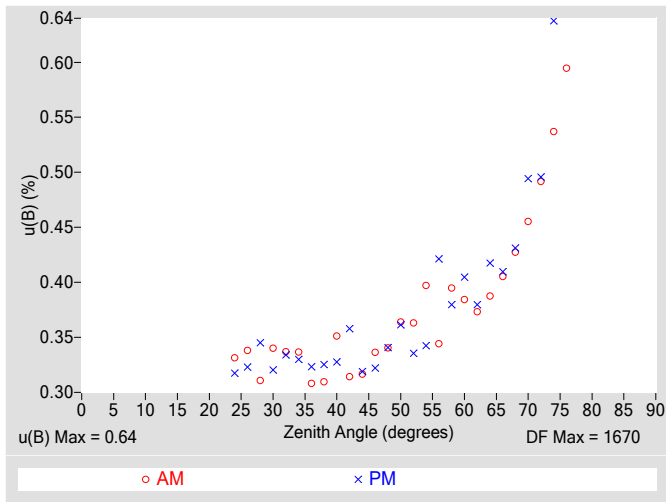


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)

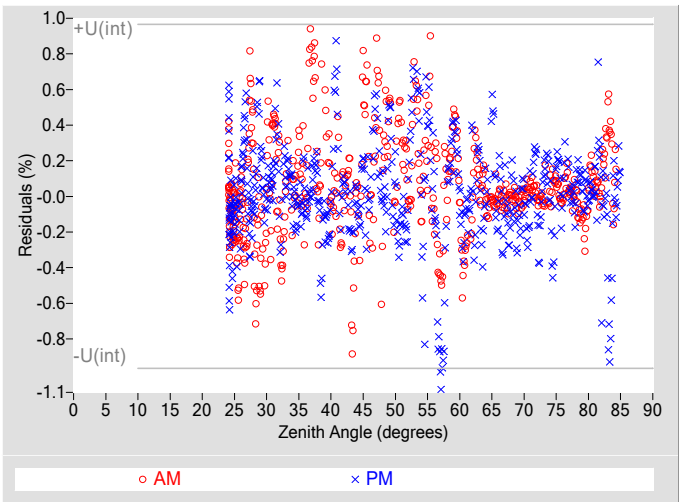
Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) $\pm$ (%)	Azimuth Angle	Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) $\pm$ (%)	Azimuth Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	9.3995	0.34	108.42	9.3850	0.32	251.63
2	N/A	N/A	N/A	N/A	N/A	N/A	48	9.4491	0.34	106.08	9.4009	0.34	253.96
4	N/A	N/A	N/A	N/A	N/A	N/A	50	9.5302	0.36	103.96	9.3882	0.36	256.20
6	N/A	N/A	N/A	N/A	N/A	N/A	52	9.5613	0.36	101.92	9.4121	0.34	258.23
8	N/A	N/A	N/A	N/A	N/A	N/A	54	9.5011	0.40	99.91	9.4030	0.34	260.22
10	N/A	N/A	N/A	N/A	N/A	N/A	56	9.5241	0.34	98.02	9.4401	0.42	262.17
12	N/A	N/A	N/A	N/A	N/A	N/A	58	9.6728	0.39	96.19	9.4278	0.38	264.01
14	N/A	N/A	N/A	N/A	N/A	N/A	60	9.6539	0.38	94.41	9.4385	0.40	265.78
16	N/A	N/A	N/A	N/A	N/A	N/A	62	9.6342	0.37	92.68	9.4931	0.38	267.52
18	N/A	N/A	N/A	N/A	N/A	N/A	64	9.6881	0.39	90.97	9.4640	0.42	269.17
20	N/A	N/A	N/A	N/A	N/A	N/A	66	9.7000	0.41	89.30	9.4472	0.41	270.88
22	N/A	N/A	N/A	N/A	N/A	N/A	68	9.7177	0.43	87.65	9.4380	0.43	272.53
24	9.2646	0.33	175.91	9.2688	0.32	184.05	70	9.7365	0.46	86.03	9.4498	0.49	274.16
26	9.2543	0.34	154.94	9.2923	0.32	205.05	72	9.7442	0.49	84.42	9.4792	0.50	275.73
28	9.2713	0.31	144.99	9.3136	0.35	215.14	74	9.7563	0.54	82.83	9.4679	0.64	277.37
30	9.2755	0.34	137.87	9.3539	0.32	222.60	76	9.7589	0.59	81.19	9.4370	N/A	278.98
32	9.3323	0.34	132.15	9.3308	0.33	228.13	78	9.7563	N/A	79.60	9.3778	N/A	280.57
34	9.3397	0.34	127.29	9.3700	0.33	232.82	80	9.7122	N/A	77.96	9.3193	N/A	282.21
36	9.2957	0.31	123.23	9.3677	0.32	236.79	82	9.6231	N/A	76.32	9.2569	N/A	283.85
38	9.3276	0.31	119.74	9.3997	0.33	240.36	84	9.3750	N/A	74.63	9.1765	N/A	285.56
40	9.3638	0.35	116.52	9.3341	0.33	243.51	86	N/A	N/A	N/A	N/A	N/A	N/A
42	9.4639	0.31	113.57	9.4231	0.36	246.45	88	N/A	N/A	N/A	N/A	N/A	N/A
44	9.4092	0.32	110.95	9.3742	0.32	249.19	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, $u(B)$ (%)	$\pm 0.64$
Type-A Interpolating Function, $u(int)$ (%)	$\pm 0.48$
Combined Standard Uncertainty, $u(c)$ (%)	$\pm 0.80$
Effective degrees of freedom, $DF(c)$	2695
Coverage factor, $k$	1.96
Expanded Uncertainty, $U_{95}$ (%)	$\pm 1.6$
AM Valid zenith angle range	24° to 76°
PM Valid zenith angle range	24° to 74°

‡ 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**

$R @ 45^\circ$ ( $\mu V/W/m^2$ )	$R_{net}$ ( $\mu V/W/m^2$ ) †
9.4242	0

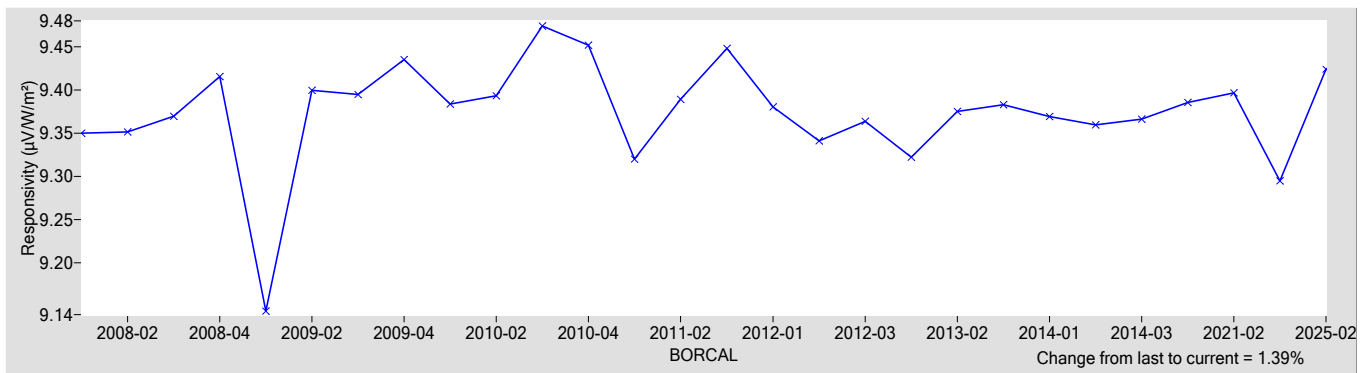
†  $R_{net}$  determination date: N/A

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

Type-B Expanded Uncertainty, $U(B)$ (%)	$\pm 0.83$
Offset Uncertainty, $U(off)$ (%)	+2.6 / -1.6
Expanded Uncertainty, $U$ (%)	+3.5 / -2.4
Effective degrees of freedom, $DF^*$	2109
Coverage factor, $k$	1.96
Valid zenith angle range	30.0° to 60.0°

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

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



**References:**

- [1] Reda, I.; Hickey, J.; Long, C.; Myers, D.; Stoffel, T.; Wilcox, S.; Michalsky, J. J.; Dutton, E. G.; Nelson, D. (2005). "Using a Blackbody to Calculate Net Longwave Responsivity of Shortwave Solar Pyranometers to Correct for Their Thermal Offset Error During Outdoor Calibration Using the Component Sum Method." *Journal of Atmospheric and Oceanic Technology*, 2005; pp. 1531-1540; NREL Report No. JA-560-36646. doi:10.1175/JTECH1782.1
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- [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.
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# National Renewable Energy Laboratory

## Solar Radiation Research Laboratory

### Metrology Laboratory

### Calibration Certificate



<b>Test Instrument:</b>	GPP Pyranometer	<b>Manufacturer:</b>	Eppley
<b>Model:</b>	GPP	<b>Serial Number:</b>	37831F3
<b>Calibration Date:</b>	5/2/2025	<b>Due Date:</b>	5/2/2026
<b>Customer:</b>	NREL-SRRL-BMS	<b>Environmental Conditions:</b>	see page 4
<b>Test Dates:</b>	5/2		

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	09/27/2024	09/27/2025
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/21/2025	04/21/2026
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/21/2025	04/21/2026
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/07/2025	02/07/2027
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/07/2025	02/07/2027
Infrared Irradiance ‡	Kipp & Zonen Pyrgeometer Model CG4, S/N FT002	03/31/2022	03/31/2027

† Through the World Radiometric Reference (WRR)

‡ Through the World Infrared Standard Group (WISG)

**Number of pages of certificate:** 4

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

**Setup:** Radiometers are calibrated outdoors, using the sun as the source. Pyranometers and pyrgeometers are installed for horizontal measurements, with their signal connectors oriented north, if their design permits.

The shading disk for the reference diffuse subtends a solid angle of 5°. Pyrheliometers are installed on solar trackers.

**Calibrated by:** Afshin Andreas, RCC, and Shawn L. Jaker

-----  
Ibrahim Reda, Technical Manager

05/05/2025

-----  
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 ( $\text{W}/\text{m}^2$ ),
  - =  $W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
  - where,  $W_{in}$  = incoming infrared ( $\text{W}/\text{m}^2$ ),  $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$ ,
  - $T_c$  = case temperature of pyrgeometer (K).
- $I$  = reference irradiance ( $\text{W}/\text{m}^2$ ), beam (B) or global (G)
  - where,  $G = B * \text{COS}(Z) + D$ ,
  - $Z$  = zenith angle (degrees),
  - $D$  = reference diffuse irradiance ( $\text{W}/\text{m}^2$ ).

Figure 1. Responsivity vs Zenith Angle

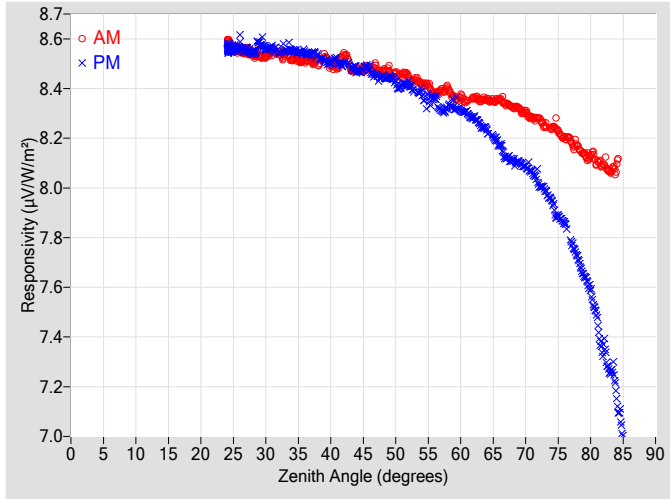


Figure 2. Responsivity vs Local Standard Time

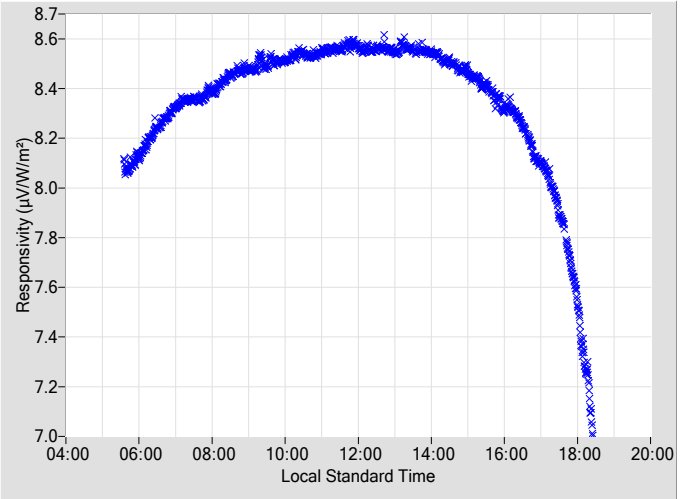
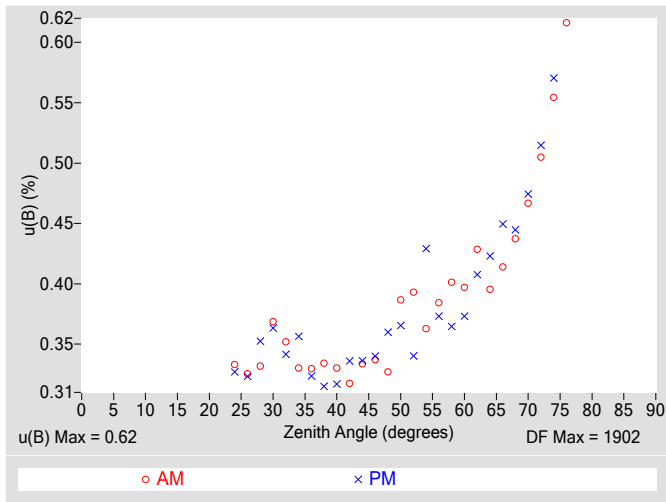


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)

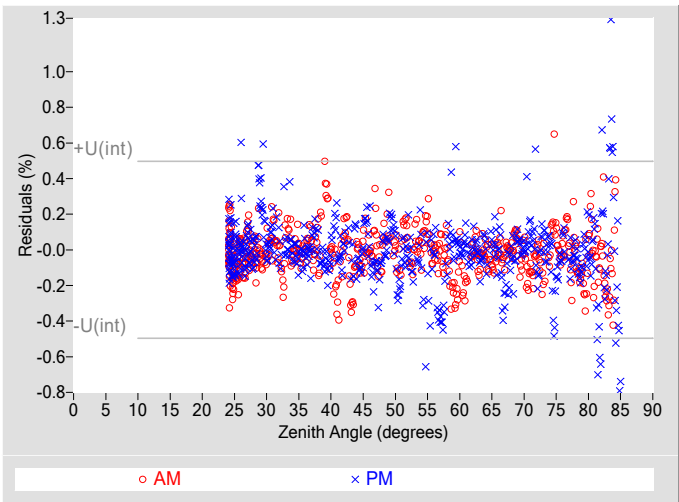
Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) $\pm$ (%)	Azimuth Angle	Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) $\pm$ (%)	Azimuth Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	8.4768	0.34	108.43	8.4743	0.34	251.67
2	N/A	N/A	N/A	N/A	N/A	N/A	48	8.4685	0.33	106.15	8.4475	0.36	254.02
4	N/A	N/A	N/A	N/A	N/A	N/A	50	8.4611	0.39	103.95	8.4232	0.37	256.15
6	N/A	N/A	N/A	N/A	N/A	N/A	52	8.4467	0.39	101.89	8.4146	0.34	258.24
8	N/A	N/A	N/A	N/A	N/A	N/A	54	8.4186	0.36	99.89	8.3792	0.43	260.20
10	N/A	N/A	N/A	N/A	N/A	N/A	56	8.3809	0.38	98.03	8.3622	0.37	262.12
12	N/A	N/A	N/A	N/A	N/A	N/A	58	8.4016	0.40	96.15	8.3282	0.36	264.03
14	N/A	N/A	N/A	N/A	N/A	N/A	60	8.3698	0.40	94.42	8.3114	0.37	265.74
16	N/A	N/A	N/A	N/A	N/A	N/A	62	8.3617	0.43	92.68	8.2823	0.41	267.47
18	N/A	N/A	N/A	N/A	N/A	N/A	64	8.3558	0.40	90.98	8.2327	0.42	269.18
20	N/A	N/A	N/A	N/A	N/A	N/A	66	8.3559	0.41	89.31	8.1719	0.45	270.84
22	N/A	N/A	N/A	N/A	N/A	N/A	68	8.3243	0.44	87.66	8.1134	0.44	272.49
24	8.5774	0.33	176.00	8.5575	0.33	184.17	70	8.3065	0.47	86.03	8.0831	0.47	274.12
26	8.5609	0.33	155.33	8.5641	0.32	205.14	72	8.2803	0.51	84.42	8.0237	0.51	275.73
28	8.5394	0.33	144.91	8.5444	0.35	215.36	74	8.2418	0.55	82.79	7.9468	0.57	277.38
30	8.5291	0.37	137.85	8.5602	0.36	222.37	76	8.2005	0.62	81.19	7.8550	N/A	278.98
32	8.5476	0.35	132.14	8.5470	0.34	228.12	78	8.1681	N/A	79.60	7.7202	N/A	280.57
34	8.5181	0.33	127.40	8.5537	0.36	232.77	80	8.1286	N/A	77.97	7.5829	N/A	282.21
36	8.5096	0.33	123.12	8.5452	0.32	236.81	82	8.0913	N/A	76.33	7.3551	N/A	283.86
38	8.5051	0.33	119.76	8.5299	0.31	240.37	84	8.0867	N/A	74.67	7.1531	N/A	285.56
40	8.4903	0.33	116.52	8.5060	0.32	243.52	86	N/A	N/A	N/A	N/A	N/A	N/A
42	8.5299	0.32	113.66	8.5003	0.34	246.46	88	N/A	N/A	N/A	N/A	N/A	N/A
44	8.4798	0.33	110.90	8.4766	0.34	249.20	90	N/A	N/A	N/A	N/A	N/A	N/A

N/A - Not Available

**Figure 3. Type-B Standard Uncertainty vs Zenith Angle**



**Figure 4. Residuals from Spline Interpolation**



**Table 3. Uncertainty using Spline Interpolation ‡**

Type-B Standard Uncertainty, $u(B)$ (%)	$\pm 0.62$
Type-A Interpolating Function, $u(int)$ (%)	$\pm 0.25$
Combined Standard Uncertainty, $u(c)$ (%)	$\pm 0.66$
Effective degrees of freedom, $DF(c)$	2449
Coverage factor, $k$	1.96
Expanded Uncertainty, $U95$ (%)	$\pm 1.3$
AM Valid zenith angle range	24° to 76°
PM Valid zenith angle range	24° to 74°

‡ 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**

$R @ 45^\circ$ ( $\mu V/W/m^2$ )	$R_{net}$ ( $\mu V/W/m^2$ ) †
8.4785	0.15000

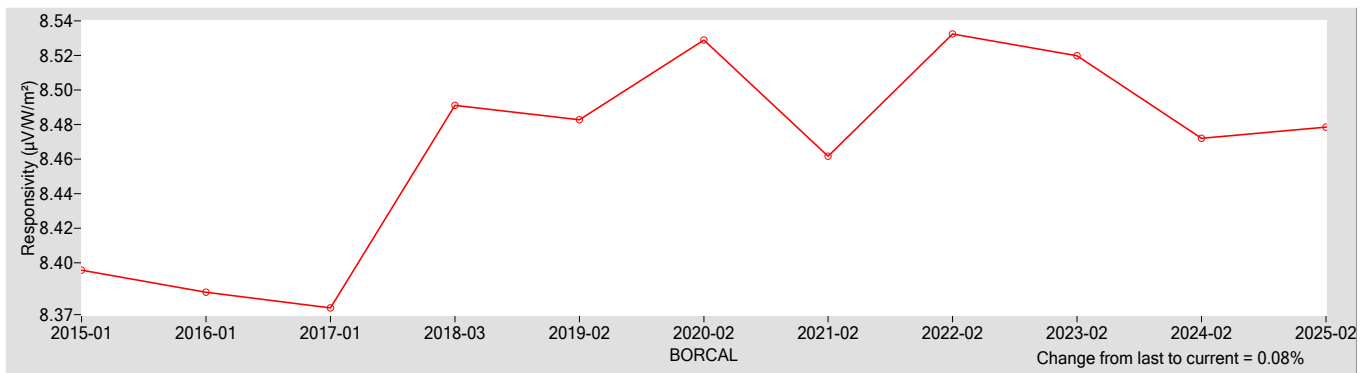
†  $R_{net}$  determination date: Estimated

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

Type-B Expanded Uncertainty, $U(B)$ (%)	$\pm 0.84$
Offset Uncertainty, $U(off)$ (%)	+0.96 / -2.0
Expanded Uncertainty, $U$ (%)	+1.8 / -2.8
Effective degrees of freedom, $DF^*$	2111
Coverage factor, $k$	1.96
Valid zenith angle range	30.0° to 60.0°

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

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



**References:**

[1] Reda, I.; Hickey, J.; Long, C.; Myers, D.; Stoffel, T.; Wilcox, S.; Michalsky, J. J.; Dutton, E. G.; Nelson, D. (2005). "Using a Blackbody to Calculate Net Longwave Responsivity of Shortwave Solar Pyranometers to Correct for Their Thermal Offset Error During Outdoor Calibration Using the Component Sum Method." *Journal of Atmospheric and Oceanic Technology*, 2005; pp. 1531-1540; NREL Report No. JA-560-36646. doi:10.1175/JTECH1782.1

[2] Reda, I.; Myers, D.; Stoffel, T. (2008). "Uncertainty Estimate for the Outdoor Calibration of Solar Pyranometers: A Metrologist Perspective." *Measure*. (NCSLI *Journal of Measurement Science*). Vol. 3(4), December 2008; pp. 58-66; NREL Report No. JA-581-4137

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

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

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

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

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



# National Renewable Energy Laboratory

## Solar Radiation Research Laboratory

### Metrology Laboratory

### Calibration Certificate



<b>Test Instrument:</b>	Standard Precision Pyranometer	<b>Manufacturer:</b>	Eppley
<b>Model:</b>	SPP	<b>Serial Number:</b>	37839F3
<b>Calibration Date:</b>	5/2/2025	<b>Due Date:</b>	5/2/2026
<b>Customer:</b>	NREL-SRRL-BMS	<b>Environmental Conditions:</b>	see page 4
<b>Test Dates:</b>	5/2		

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	09/27/2024	09/27/2025
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/21/2025	04/21/2026
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/21/2025	04/21/2026
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/07/2025	02/07/2027
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/07/2025	02/07/2027
Infrared Irradiance ‡	Eppley Downwelling Pyrgeometer Model PIR, S/N 32309F3	03/31/2022	03/31/2027

† Through the World Radiometric Reference (WRR)

‡ Through the World Infrared Standard Group (WISG)

**Number of pages of certificate:** 4

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

**Setup:** Radiometers are calibrated outdoors, using the sun as the source. Pyranometers and pyrgeometers are installed for horizontal measurements, with their signal connectors oriented north, if their design permits.

The shading disk for the reference diffuse subtends a solid angle of 5°. Pyrheliometers are installed on solar trackers.

**Calibrated by:** Afshin Andreas, RCC, and Shawn L. Jaker

-----  
Ibrahim Reda, Technical Manager

05/05/2025

-----  
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 ( $\text{W}/\text{m}^2$ ),
  - =  $W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
  - where,  $W_{in}$  = incoming infrared ( $\text{W}/\text{m}^2$ ),  $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$ ,
  - $T_c$  = case temperature of pyrgeometer (K).
- $I$  = reference irradiance ( $\text{W}/\text{m}^2$ ), beam (B) or global (G)
  - where,  $G = B * \text{COS}(Z) + D$ ,
  - $Z$  = zenith angle (degrees),
  - $D$  = reference diffuse irradiance ( $\text{W}/\text{m}^2$ ).

Figure 1. Responsivity vs Zenith Angle

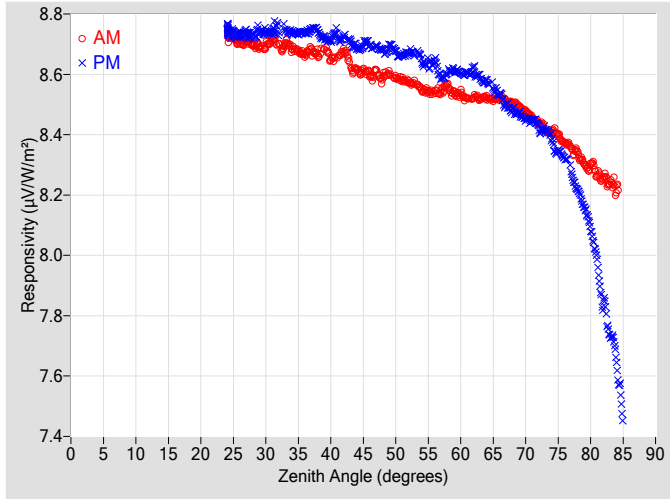


Figure 2. Responsivity vs Local Standard Time

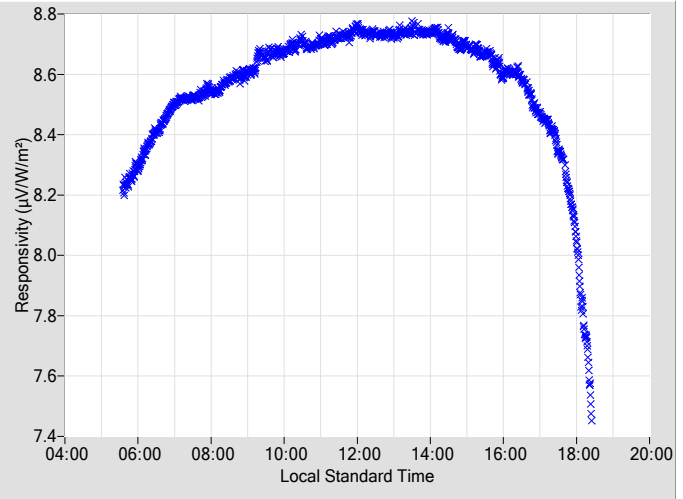
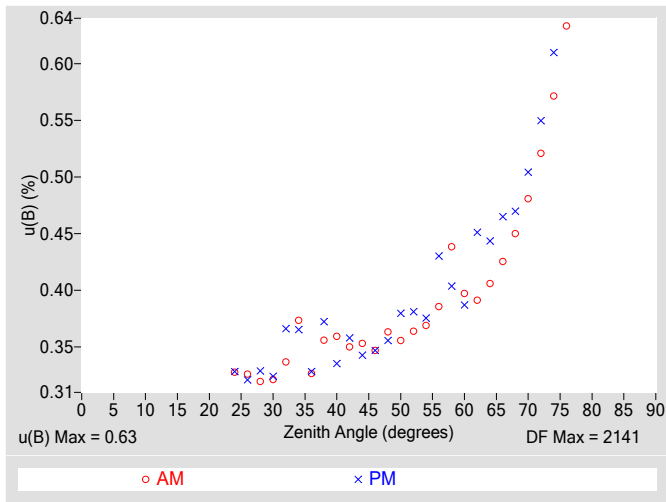


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty,  $u(B)$

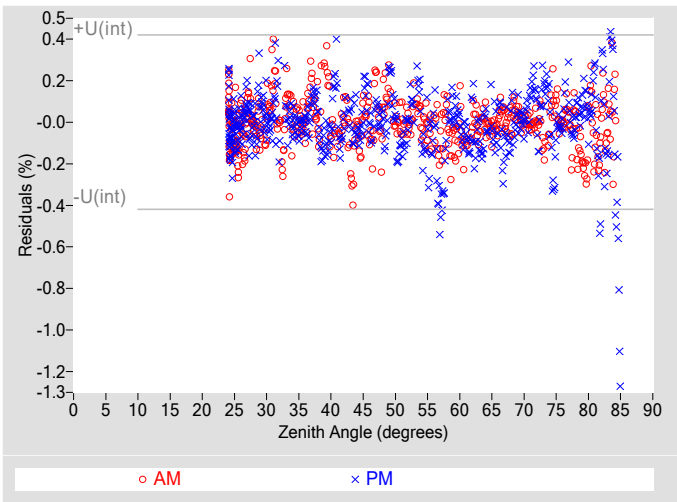
Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	$u(B)$ $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	$u(B)$ $\pm$ (%)	Azimuth Angle	Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	$u(B)$ $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	$u(B)$ $\pm$ (%)	Azimuth Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	8.6006	0.35	108.47	8.6961	0.35	251.65
2	N/A	N/A	N/A	N/A	N/A	N/A	48	8.5880	0.36	106.19	8.6789	0.36	253.96
4	N/A	N/A	N/A	N/A	N/A	N/A	50	8.5885	0.36	103.99	8.6752	0.38	256.19
6	N/A	N/A	N/A	N/A	N/A	N/A	52	8.5757	0.36	101.91	8.6719	0.38	258.27
8	N/A	N/A	N/A	N/A	N/A	N/A	54	8.5488	0.37	99.90	8.6460	0.38	260.21
10	N/A	N/A	N/A	N/A	N/A	N/A	56	8.5436	0.39	97.93	8.6432	0.43	262.15
12	N/A	N/A	N/A	N/A	N/A	N/A	58	8.5595	0.44	96.18	8.6091	0.40	263.98
14	N/A	N/A	N/A	N/A	N/A	N/A	60	8.5350	0.40	94.40	8.6046	0.39	265.77
16	N/A	N/A	N/A	N/A	N/A	N/A	62	8.5237	0.39	92.67	8.6145	0.45	267.50
18	N/A	N/A	N/A	N/A	N/A	N/A	64	8.5212	0.41	90.96	8.5769	0.44	269.21
20	N/A	N/A	N/A	N/A	N/A	N/A	66	8.5202	0.43	89.29	8.5340	0.46	270.87
22	N/A	N/A	N/A	N/A	N/A	N/A	68	8.5032	0.45	87.64	8.4804	0.47	272.51
24	8.7398	0.33	176.02	8.7464	0.33	184.26	70	8.4773	0.48	86.01	8.4513	0.50	274.14
26	8.7189	0.33	155.01	8.7313	0.32	205.08	72	8.4391	0.52	84.40	8.4205	0.55	275.76
28	8.6978	0.32	145.05	8.7311	0.33	215.31	74	8.4103	0.57	82.81	8.3849	0.61	277.36
30	8.6918	0.32	137.84	8.7372	0.32	222.29	76	8.3728	0.63	81.22	8.3214	N/A	278.96
32	8.7015	0.34	132.02	8.7461	0.37	227.75	78	8.3401	N/A	79.59	8.2149	N/A	280.60
34	8.6858	0.37	127.40	8.7385	0.37	232.79	80	8.2969	N/A	77.95	8.0897	N/A	282.20
36	8.6660	0.33	123.31	8.7396	0.33	236.77	82	8.2570	N/A	76.36	7.8391	N/A	283.89
38	8.6664	0.36	119.81	8.7426	0.37	240.42	84	8.2200	N/A	74.66	7.6401	N/A	285.55
40	8.6530	0.36	116.58	8.7150	0.34	243.57	86	N/A	N/A	N/A	N/A	N/A	N/A
42	8.6753	0.35	113.63	8.7249	0.36	246.43	88	N/A	N/A	N/A	N/A	N/A	N/A
44	8.6182	0.35	111.01	8.6878	0.34	249.17	90	N/A	N/A	N/A	N/A	N/A	N/A

N/A - Not Available

**Figure 3. Type-B Standard Uncertainty vs Zenith Angle**



**Figure 4. Residuals from Spline Interpolation**



**Table 3. Uncertainty using Spline Interpolation ‡**

Type-B Standard Uncertainty, $u(B)$ (%)	$\pm 0.63$
Type-A Interpolating Function, $u(int)$ (%)	$\pm 0.21$
Combined Standard Uncertainty, $u(c)$ (%)	$\pm 0.67$
Effective degrees of freedom, $DF(c)$	2571
Coverage factor, $k$	1.96
Expanded Uncertainty, $U95$ (%)	$\pm 1.3$
AM Valid zenith angle range	24° to 76°
PM Valid zenith angle range	24° to 74°

‡ 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**

$R @ 45^\circ$ ( $\mu V/W/m^2$ )	$R_{net}$ ( $\mu V/W/m^2$ ) †
8.6569	0.30000

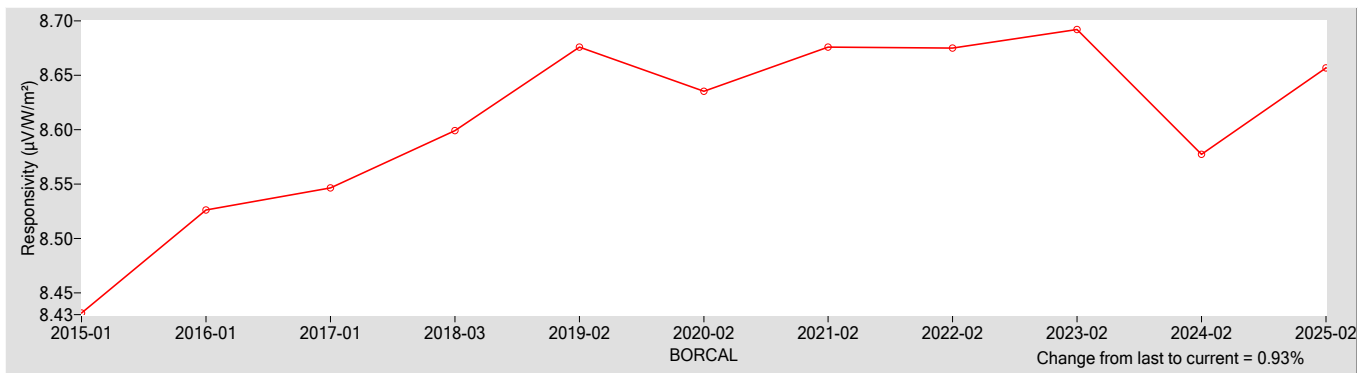
†  $R_{net}$  determination date: Estimated

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

Type-B Expanded Uncertainty, $U(B)$ (%)	$\pm 0.86$
Offset Uncertainty, $U(off)$ (%)	+1.0 / -1.4
Expanded Uncertainty, $U$ (%)	+1.9 / -2.3
Effective degrees of freedom, $DF^*$	2144
Coverage factor, $k$	1.96
Valid zenith angle range	30.0° to 60.0°

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

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



**References:**

- [1] Reda, I.; Hickey, J.; Long, C.; Myers, D.; Stoffel, T.; Wilcox, S.; Michalsky, J. J.; Dutton, E. G.; Nelson, D. (2005). "Using a Blackbody to Calculate Net Longwave Responsivity of Shortwave Solar Pyranometers to Correct for Their Thermal Offset Error During Outdoor Calibration Using the Component Sum Method." *Journal of Atmospheric and Oceanic Technology*, 2005; pp. 1531-1540; NREL Report No. JA-560-36646. doi:10.1175/JTECH1782.1
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- [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.
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# 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:** 5/2/2025      **Due Date:** 5/2/2026  
**Customer:** NREL-SRRL-BMS      **Environmental Conditions:** see page 4  
**Test Dates:** 5/2

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	09/27/2024	09/27/2025
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/21/2025	04/21/2026
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/21/2025	04/21/2026
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/07/2025	02/07/2027
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/07/2025	02/07/2027

† 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, RCC, and Shawn L. Jaker

Ibrahim Reda, Technical Manager

05/05/2025

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 ( $\text{W}/\text{m}^2$ ),
  - $= W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
  - where,  $W_{in}$  = incoming infrared ( $\text{W}/\text{m}^2$ ),  $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$ ,
  - $T_c$  = case temperature of pyrgeometer (K).
- $I$  = reference irradiance ( $\text{W}/\text{m}^2$ ), beam (B) or global (G)
  - where,  $G = B * \text{COS}(Z) + D$ ,
  - $Z$  = zenith angle (degrees),
  - $D$  = reference diffuse irradiance ( $\text{W}/\text{m}^2$ ).

Figure 1. Responsivity vs Zenith Angle

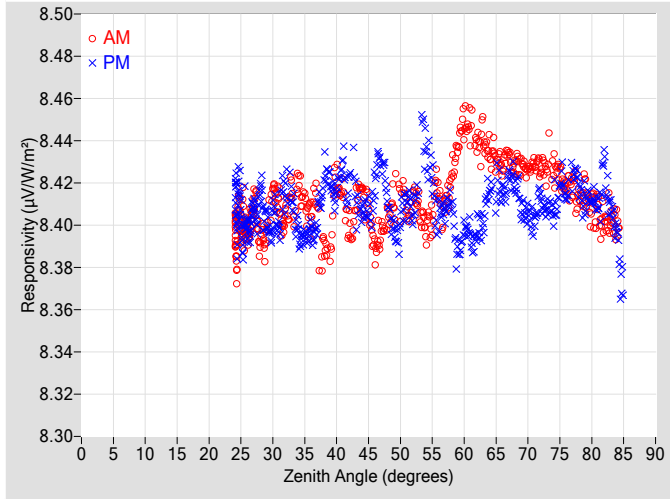


Figure 2. Responsivity vs Local Standard Time

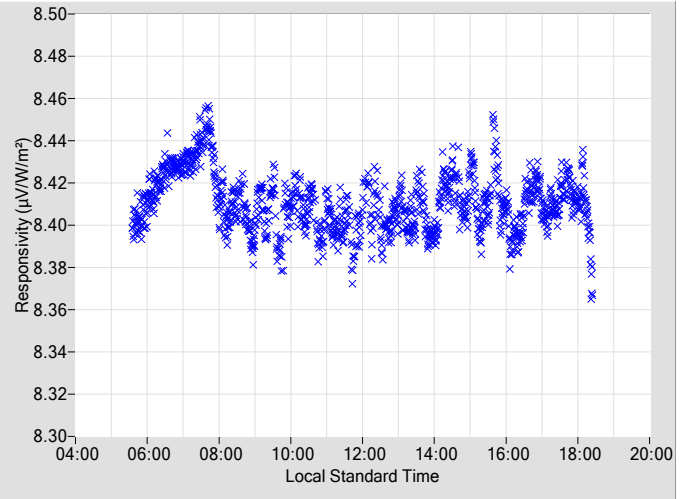
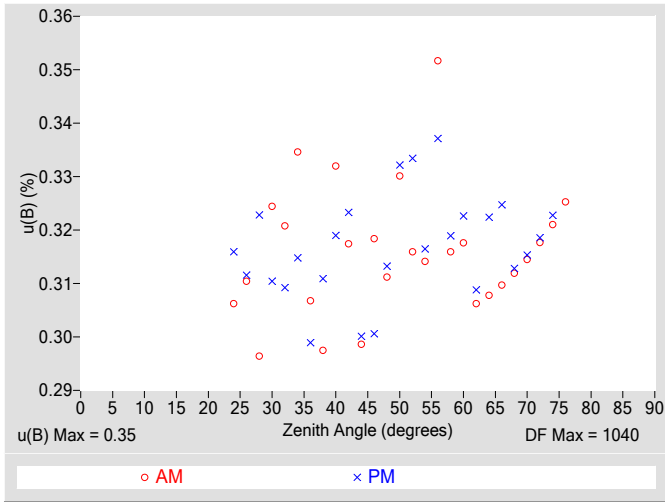


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)

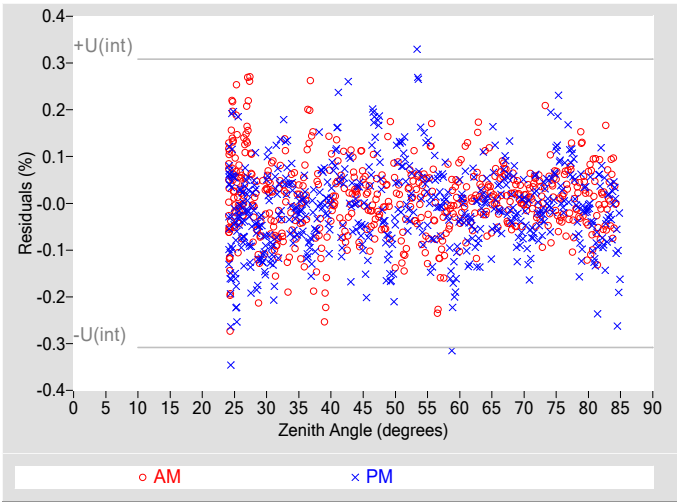
Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) $\pm$ (%)	Azimuth Angle	Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) $\pm$ (%)	Azimuth Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	8.3895	0.32	108.50	8.4193	0.30	251.67
2	N/A	N/A	N/A	N/A	N/A	N/A	48	8.4036	0.31	106.09	8.4123	0.31	253.89
4	N/A	N/A	N/A	N/A	N/A	N/A	50	8.4134	0.33	104.03	8.4027	0.33	256.20
6	N/A	N/A	N/A	N/A	N/A	N/A	52	8.4141	0.32	101.87	8.4053	0.33	258.24
8	N/A	N/A	N/A	N/A	N/A	N/A	54	8.3970	0.31	99.92	8.4340	0.32	260.23
10	N/A	N/A	N/A	N/A	N/A	N/A	56	8.4153	0.35	98.03	8.4032	0.34	262.14
12	N/A	N/A	N/A	N/A	N/A	N/A	58	8.4238	0.32	96.20	8.4101	0.32	264.01
14	N/A	N/A	N/A	N/A	N/A	N/A	60	8.4496	0.32	94.42	8.3980	0.32	265.78
16	N/A	N/A	N/A	N/A	N/A	N/A	62	8.4396	0.31	92.68	8.3985	0.31	267.47
18	N/A	N/A	N/A	N/A	N/A	N/A	64	8.4332	0.31	90.97	8.4160	0.32	269.18
20	N/A	N/A	N/A	N/A	N/A	N/A	66	8.4274	0.31	89.30	8.4155	0.32	270.89
22	N/A	N/A	N/A	N/A	N/A	N/A	68	8.4289	0.31	87.66	8.4196	0.31	272.48
24	8.3947	0.31	175.98	8.4166	0.32	184.28	70	8.4262	0.31	86.03	8.4054	0.32	274.11
26	8.3974	0.31	154.88	8.3991	0.31	204.98	72	8.4271	0.32	84.42	8.4132	0.32	275.73
28	8.3919	0.30	145.26	8.4160	0.32	215.29	74	8.4254	0.32	82.83	8.4046	0.32	277.36
30	8.4148	0.32	137.73	8.4030	0.31	222.37	76	8.4190	0.33	81.19	8.4131	N/A	278.98
32	8.4051	0.32	132.13	8.4165	0.31	227.92	78	8.4128	N/A	79.60	8.4190	N/A	280.57
34	8.4204	0.33	127.36	8.3958	0.31	232.82	80	8.4090	N/A	77.96	8.4111	N/A	282.21
36	8.4036	0.31	123.33	8.3977	0.30	236.80	82	8.4024	N/A	76.32	8.4262	N/A	283.86
38	8.3888	0.30	119.75	8.4223	0.31	240.38	84	8.3991	N/A	74.63	8.3946	N/A	285.56
40	8.4206	0.33	116.47	8.4148	0.32	243.51	86	N/A	N/A	N/A	N/A	N/A	N/A
42	8.3973	0.32	113.58	8.4195	0.32	246.38	88	N/A	N/A	N/A	N/A	N/A	N/A
44	8.4166	0.30	110.96	8.4055	0.30	249.19	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, $u(B)$ (%)	$\pm 0.35$
Type-A Interpolating Function, $u(int)$ (%)	$\pm 0.15$
Combined Standard Uncertainty, $u(c)$ (%)	$\pm 0.38$
Effective degrees of freedom, $DF(c)$	1424
Coverage factor, $k$	1.96
Expanded Uncertainty, $U_{95}$ (%)	$\pm 0.75$
AM Valid zenith angle range	24° to 76°
PM Valid zenith angle range	24° to 74°

‡ 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**

$R @ 45^\circ$ ( $\mu V/W/m^2$ )	$R_{net}$ ( $\mu V/W/m^2$ ) †
8.4075	0

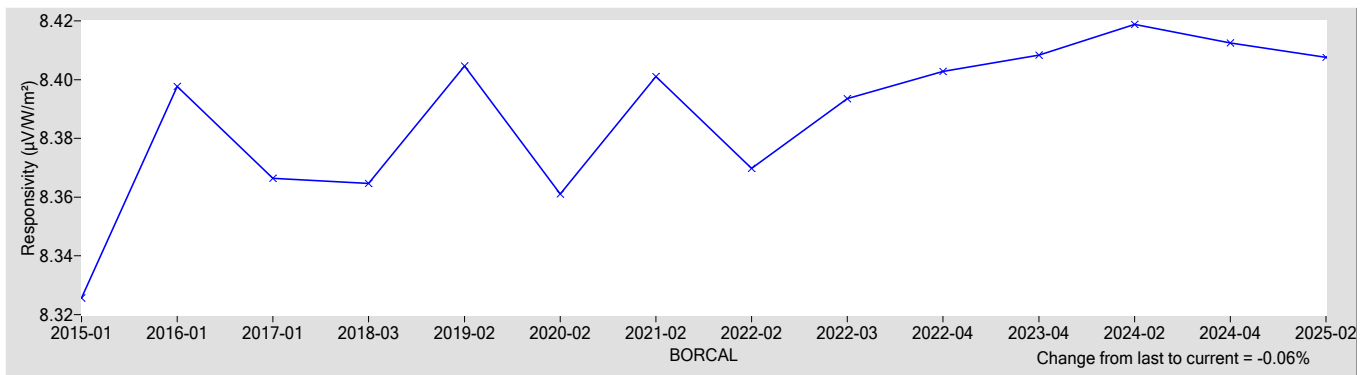
†  $R_{net}$  determination date: N/A

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

Type-B Expanded Uncertainty, $U(B)$ (%)	$\pm 0.69$
Offset Uncertainty, $U(off)$ (%)	+0.50 / -0.22
Expanded Uncertainty, $U$ (%)	+1.2 / -0.91
Effective degrees of freedom, $DF^*$	1040
Coverage factor, $k$	1.96
Valid zenith angle range	30.0° to 60.0°

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

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



**References:**

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



# National Renewable Energy Laboratory

## Solar Radiation Research Laboratory

### Metrology Laboratory

### Calibration Certificate



<b>Test Instrument:</b>	Si pyranometer	<b>Manufacturer:</b>	Apogee
<b>Model:</b>	SP-110	<b>Serial Number:</b>	40337
<b>Calibration Date:</b>	5/2/2025	<b>Due Date:</b>	5/2/2026
<b>Customer:</b>	NREL-SRRL-BMS	<b>Environmental Conditions:</b>	see page 4
<b>Test Dates:</b>	5/2		

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	09/27/2024	09/27/2025
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/21/2025	04/21/2026
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/21/2025	04/21/2026
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/07/2025	02/07/2027
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/07/2025	02/07/2027

† 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, RCC, and Shawn L. Jaker

\_\_\_\_\_  
Ibrahim Reda, Technical Manager

05/05/2025

\_\_\_\_\_  
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

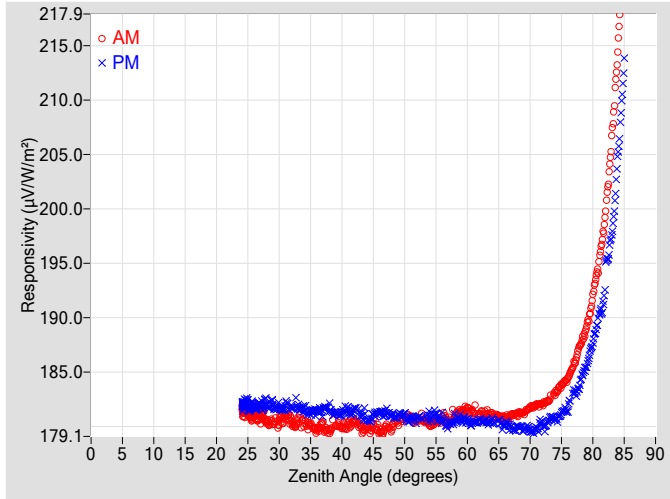
The responsivity ( $R$ ,  $\mu\text{V}/\text{W}/\text{m}^2$ ) of the test instrument during calibration is calculated using this Measurement Equation:

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

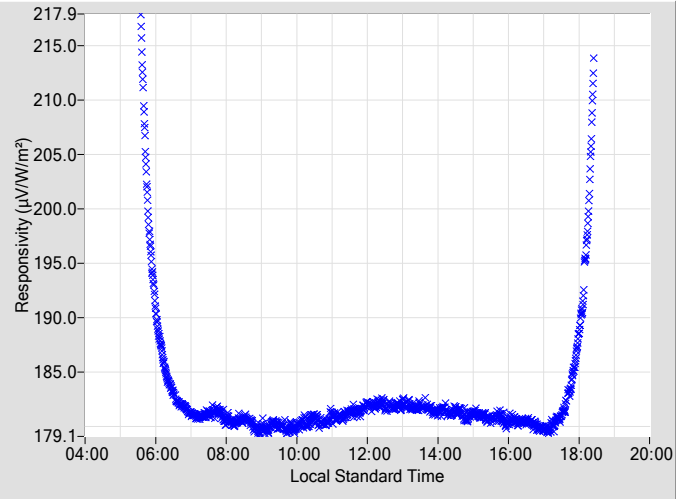
where,

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

**Figure 1. Responsivity vs Zenith Angle**



**Figure 2. Responsivity vs Local Standard Time**

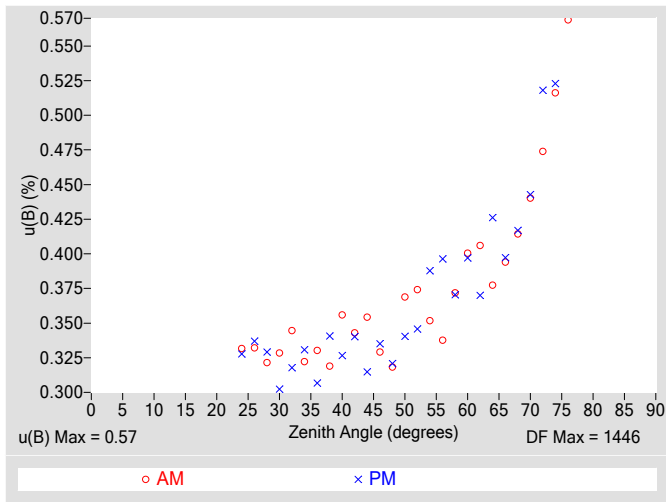


**Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)**

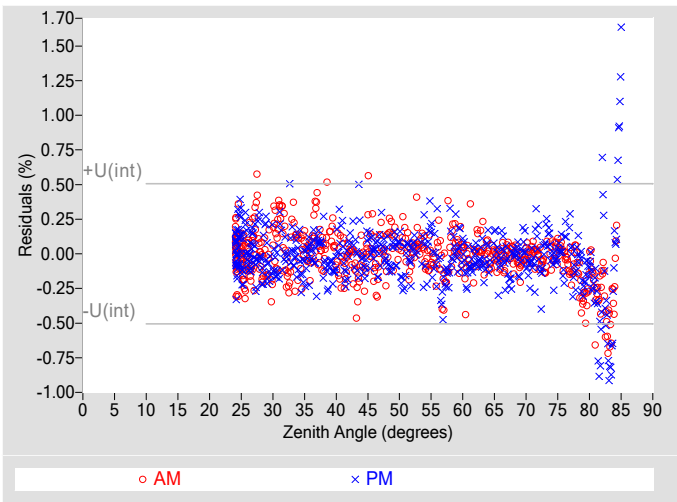
Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) $\pm$ (%)	Azimuth Angle	Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) $\pm$ (%)	Azimuth Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	179.64	0.33	108.48	181.32	0.34	251.66
2	N/A	N/A	N/A	N/A	N/A	N/A	48	179.94	0.32	106.08	181.01	0.32	253.95
4	N/A	N/A	N/A	N/A	N/A	N/A	50	180.65	0.37	103.94	180.98	0.34	256.20
6	N/A	N/A	N/A	N/A	N/A	N/A	52	180.66	0.37	101.92	180.70	0.35	258.23
8	N/A	N/A	N/A	N/A	N/A	N/A	54	180.18	0.35	99.91	180.91	0.39	260.16
10	N/A	N/A	N/A	N/A	N/A	N/A	56	180.82	0.34	98.02	180.70	0.40	262.05
12	N/A	N/A	N/A	N/A	N/A	N/A	58	180.87	0.37	96.16	180.62	0.37	263.99
14	N/A	N/A	N/A	N/A	N/A	N/A	60	181.65	0.40	94.41	180.51	0.40	265.77
16	N/A	N/A	N/A	N/A	N/A	N/A	62	181.13	0.41	92.67	180.59	0.37	267.51
18	N/A	N/A	N/A	N/A	N/A	N/A	64	181.09	0.38	90.96	180.51	0.43	269.21
20	N/A	N/A	N/A	N/A	N/A	N/A	66	180.88	0.39	89.30	180.19	0.40	270.87
22	N/A	N/A	N/A	N/A	N/A	N/A	68	181.17	0.41	87.65	180.01	0.42	272.52
24	181.55	0.33	175.48	182.02	0.33	184.20	70	181.74	0.44	86.02	179.67	0.44	274.15
26	181.00	0.33	154.87	181.73	0.34	205.10	72	182.11	0.47	84.41	180.16	0.52	275.76
28	180.47	0.32	144.87	182.11	0.33	215.26	74	183.08	0.52	82.82	180.71	0.52	277.37
30	180.49	0.33	137.62	181.83	0.30	222.76	76	184.38	0.57	81.23	181.73	N/A	278.97
32	180.45	0.34	132.14	181.77	0.32	228.12	78	187.51	N/A	79.59	184.14	N/A	280.61
34	180.37	0.32	127.42	181.64	0.33	232.77	80	192.04	N/A	77.95	187.90	N/A	282.24
36	179.70	0.33	123.31	181.36	0.31	236.78	82	199.61	N/A	76.31	193.61	N/A	283.85
38	179.59	0.32	119.73	181.66	0.34	240.43	84	215.08	N/A	74.63	204.77	N/A	285.55
40	179.99	0.36	116.46	181.23	0.33	243.58	86	N/A	N/A	N/A	N/A	N/A	N/A
42	180.52	0.34	113.63	181.55	0.34	246.44	88	N/A	N/A	N/A	N/A	N/A	N/A
44	179.93	0.35	110.95	180.60	0.31	249.32	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, $u(B)$ (%)	$\pm 0.57$
Type-A Interpolating Function, $u(int)$ (%)	$\pm 0.25$
Combined Standard Uncertainty, $u(c)$ (%)	$\pm 0.62$
Effective degrees of freedom, $DF(c)$	1966
Coverage factor, $k$	1.96
Expanded Uncertainty, $U95$ (%)	$\pm 1.2$
AM Valid zenith angle range	24° to 76°
PM Valid zenith angle range	24° to 74°

‡ 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**

$R @ 45^\circ$ ( $\mu V/W/m^2$ )	$R_{net}$ ( $\mu V/W/m^2$ ) †
180.63	0

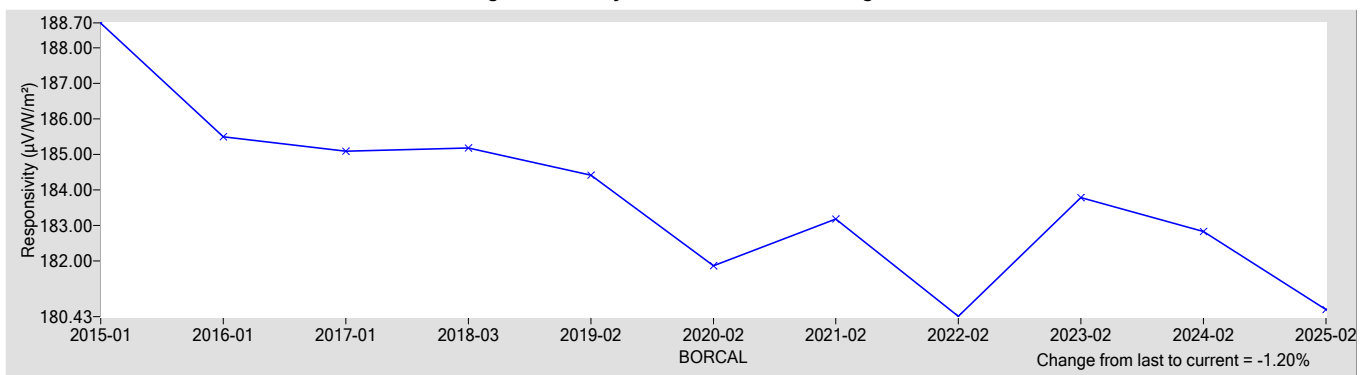
†  $R_{net}$  determination date: N/A

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

Type-B Expanded Uncertainty, $U(B)$ (%)	$\pm 0.79$
Offset Uncertainty, $U(off)$ (%)	+0.67 / -0.57
Expanded Uncertainty, $U$ (%)	+1.5 / -1.4
Effective degrees of freedom, $DF^*$	2002
Coverage factor, $k$	1.96
Valid zenith angle range	30.0° to 60.0°

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

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



**References:**

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

# National Renewable Energy Laboratory

## Solar Radiation Research Laboratory

### Metrology Laboratory

### Calibration Certificate



**Test Instrument:** Digital Pyranometer  
**Manufacturer:** Hukseflux  
**Model:** SR30  
**Serial Number:** 4246  
**Calibration Date:** 5/2/2025  
**Due Date:** 5/2/2026  
**Customer:** NREL-SRRL-BMS  
**Environmental Conditions:** see page 4  
**Test Dates:** 5/2

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	09/27/2024	09/27/2025
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/21/2025	04/21/2026
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/21/2025	04/21/2026
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/07/2025	02/07/2027
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/07/2025	02/07/2027

† 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, RCC, and Shawn L. Jaker

Ibrahim Reda, Technical Manager

05/05/2025

Date

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

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

# Calibration Results

## 4246 Hukseflux SR30

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

Figure 1. Responsivity vs Zenith Angle

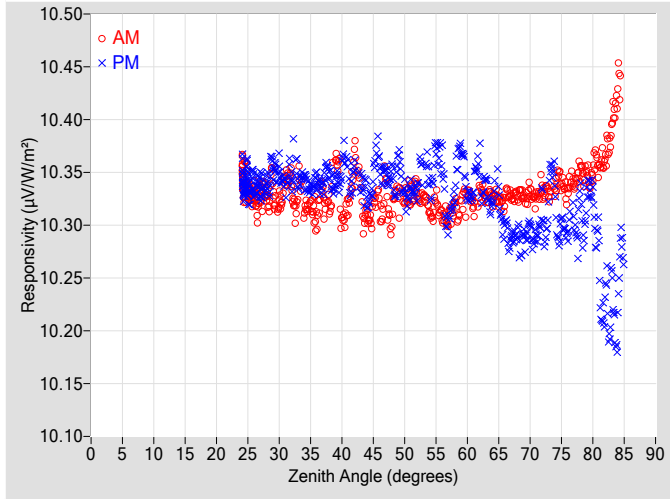


Figure 2. Responsivity vs Local Standard Time

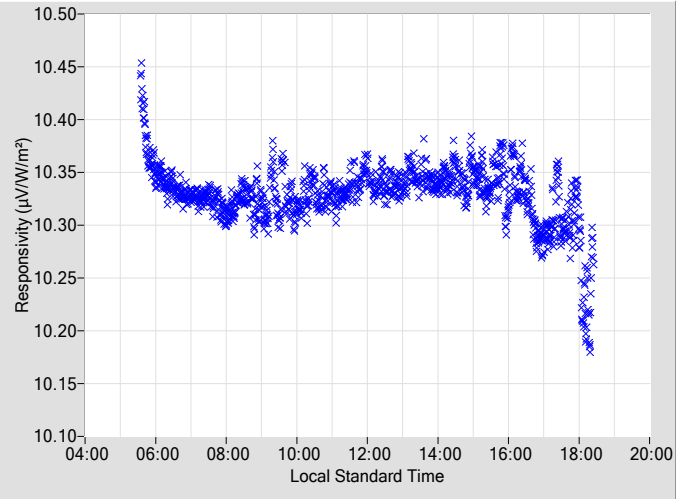
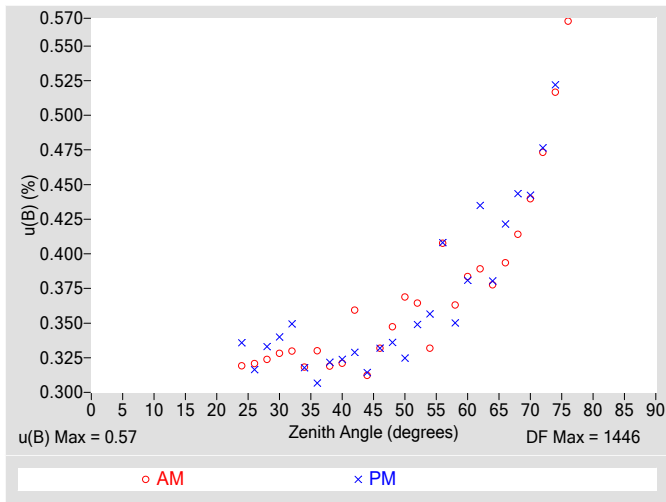


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)

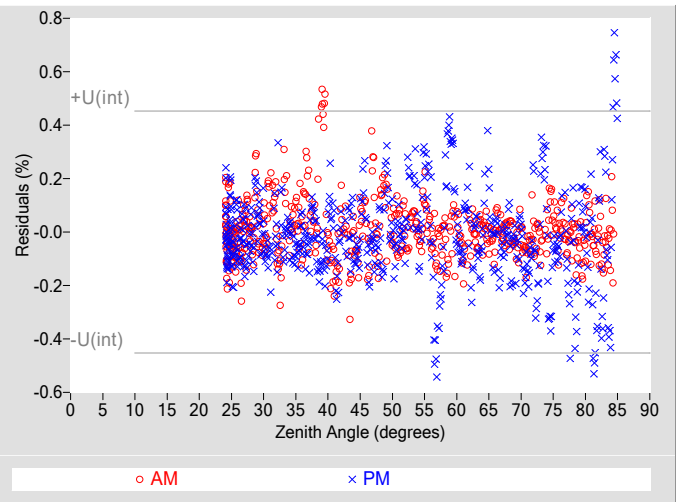
Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	AM u(B) $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	PM u(B) $\pm$ (%)	Azimuth Angle	Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	AM u(B) $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	PM u(B) $\pm$ (%)	Azimuth Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	10.323	0.33	108.52	10.362	0.33	251.62
2	N/A	N/A	N/A	N/A	N/A	N/A	48	10.308	0.35	106.16	10.348	0.34	253.97
4	N/A	N/A	N/A	N/A	N/A	N/A	50	10.326	0.37	103.96	10.330	0.32	256.16
6	N/A	N/A	N/A	N/A	N/A	N/A	52	10.333	0.36	101.88	10.335	0.35	258.19
8	N/A	N/A	N/A	N/A	N/A	N/A	54	10.312	0.33	99.93	10.338	0.36	260.24
10	N/A	N/A	N/A	N/A	N/A	N/A	56	10.308	0.41	97.99	10.354	0.41	262.13
12	N/A	N/A	N/A	N/A	N/A	N/A	58	10.319	0.36	96.16	10.336	0.35	263.96
14	N/A	N/A	N/A	N/A	N/A	N/A	60	10.325	0.38	94.33	10.328	0.38	265.75
16	N/A	N/A	N/A	N/A	N/A	N/A	62	10.331	0.39	92.64	10.352	0.43	267.46
18	N/A	N/A	N/A	N/A	N/A	N/A	64	10.326	0.38	90.94	10.323	0.38	269.19
20	N/A	N/A	N/A	N/A	N/A	N/A	66	10.325	0.39	89.32	10.300	0.42	270.85
22	N/A	N/A	N/A	N/A	N/A	N/A	68	10.328	0.41	87.67	10.289	0.44	272.49
24	10.347	0.32	176.16	10.342	0.34	184.39	70	10.332	0.44	86.03	10.298	0.44	274.12
26	10.330	0.32	155.09	10.340	0.32	204.91	72	10.334	0.47	84.42	10.310	0.48	275.74
28	10.326	0.32	145.06	10.340	0.33	215.19	74	10.336	0.52	82.79	10.329	0.52	277.35
30	10.321	0.33	137.67	10.352	0.34	222.47	76	10.332	0.57	81.20	10.294	N/A	278.99
32	10.336	0.33	132.08	10.348	0.35	227.99	78	10.353	N/A	79.61	10.323	N/A	280.58
34	10.315	0.32	127.13	10.344	0.32	232.75	80	10.353	N/A	77.97	10.326	N/A	282.22
36	10.307	0.33	123.35	10.342	0.31	236.82	82	10.364	N/A	76.33	10.232	N/A	283.87
38	10.319	0.32	119.77	10.347	0.32	240.39	84	10.430	N/A	74.64	10.223	N/A	285.57
40	10.307	0.32	116.54	10.354	0.32	243.53	86	N/A	N/A	N/A	N/A	N/A	N/A
42	10.364	0.36	113.67	10.354	0.33	246.40	88	N/A	N/A	N/A	N/A	N/A	N/A
44	10.309	0.31	110.98	10.327	0.31	249.14	90	N/A	N/A	N/A	N/A	N/A	N/A

N/A - Not Available

**Figure 3. Type-B Standard Uncertainty vs Zenith Angle**



**Figure 4. Residuals from Spline Interpolation**



**Table 3. Uncertainty using Spline Interpolation ‡**

Type-B Standard Uncertainty, $u(B)$ (%)	$\pm 0.57$
Type-A Interpolating Function, $u(int)$ (%)	$\pm 0.23$
Combined Standard Uncertainty, $u(c)$ (%)	$\pm 0.61$
Effective degrees of freedom, $DF(c)$	1875
Coverage factor, $k$	1.96
Expanded Uncertainty, $U_{95}$ (%)	$\pm 1.2$
AM Valid zenith angle range	24° to 76°
PM Valid zenith angle range	24° to 74°

‡ 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**

$R @ 45^\circ$ ( $\mu V/W/m^2$ )	$R_{net}$ ( $\mu V/W/m^2$ ) †
10.333	0

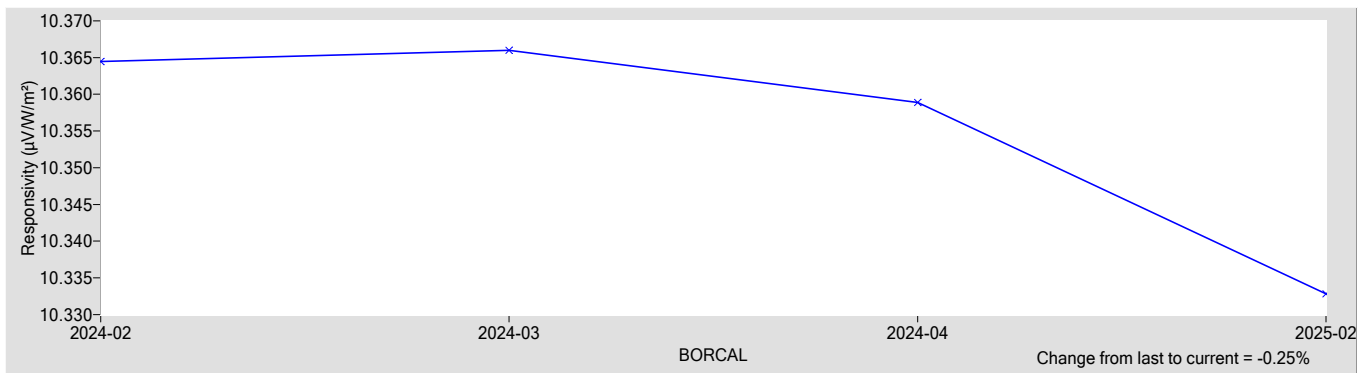
†  $R_{net}$  determination date: N/A

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

Type-B Expanded Uncertainty, $U(B)$ (%)	$\pm 0.80$
Offset Uncertainty, $U(off)$ (%)	+0.30 / -0.25
Expanded Uncertainty, $U$ (%)	+1.1 / -1.1
Effective degrees of freedom, $DF^*$	1994
Coverage factor, $k$	1.96
Valid zenith angle range	30.0° to 60.0°

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

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



**References:**

[1] Reda, I.; Hickey, J.; Long, C.; Myers, D.; Stoffel, T.; Wilcox, S.; Michalsky, J. J.; Dutton, E. G.; Nelson, D. (2005). "Using a Blackbody to Calculate Net Longwave Responsivity of Shortwave Solar Pyranometers to Correct for Their Thermal Offset Error During Outdoor Calibration Using the Component Sum Method." *Journal of Atmospheric and Oceanic Technology*, 2005; pp. 1531-1540; NREL Report No. JA-560-36646. doi:10.1175/JTECH1782.1

[2] Reda, I.; Myers, D.; Stoffel, T. (2008). "Uncertainty Estimate for the Outdoor Calibration of Solar Pyranometers: A Metrologist Perspective." *Measure*. (NCSLI Journal of Measurement Science). Vol. 3(4), December 2008; pp. 58-66; NREL Report No. JA-581-4137

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

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

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

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

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



# Calibration Results

## 65089 Hukseflux DR20-A1-T2

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 ( $\text{W}/\text{m}^2$ ),
  - =  $W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
  - where,  $W_{in}$  = incoming infrared ( $\text{W}/\text{m}^2$ ),  $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$ ,
  - $T_c$  = case temperature of pyrgeometer (K).
- $I$  = reference irradiance ( $\text{W}/\text{m}^2$ ), beam (B) or global (G)
  - where,  $G = B * \text{COS}(Z) + D$ ,
  - $Z$  = zenith angle (degrees),
  - $D$  = reference diffuse irradiance ( $\text{W}/\text{m}^2$ ).

Figure 1. Responsivity vs Zenith Angle

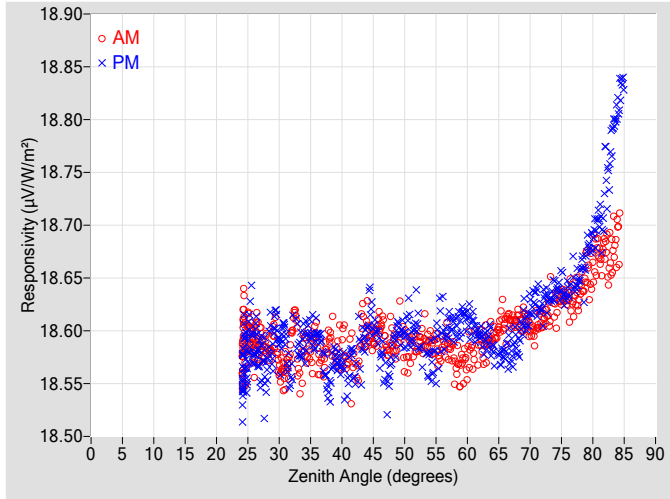


Figure 2. Responsivity vs Local Standard Time

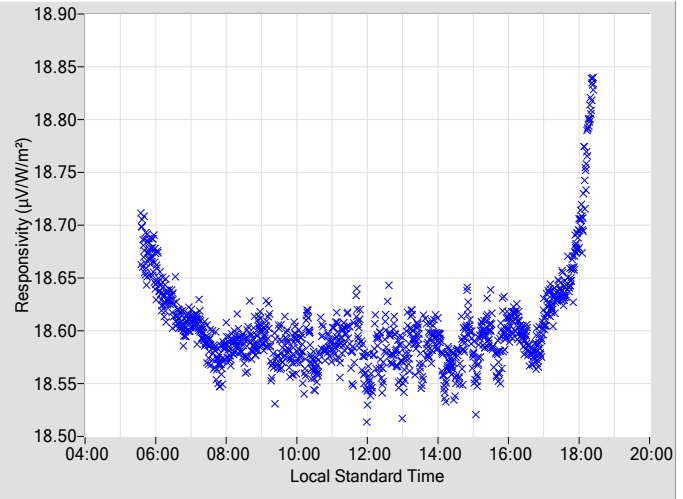
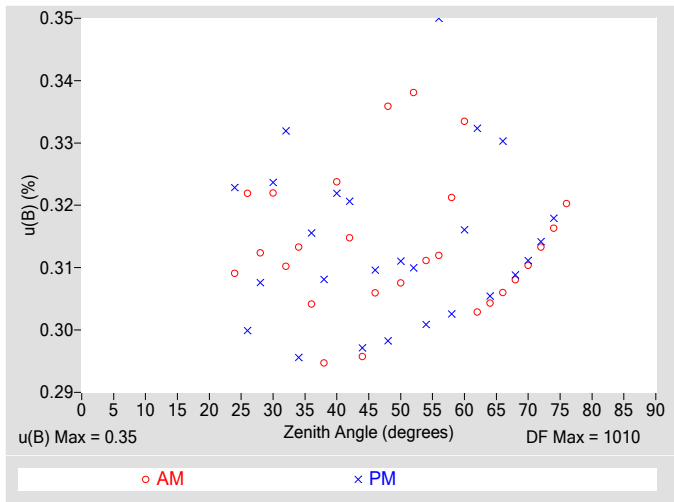


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)

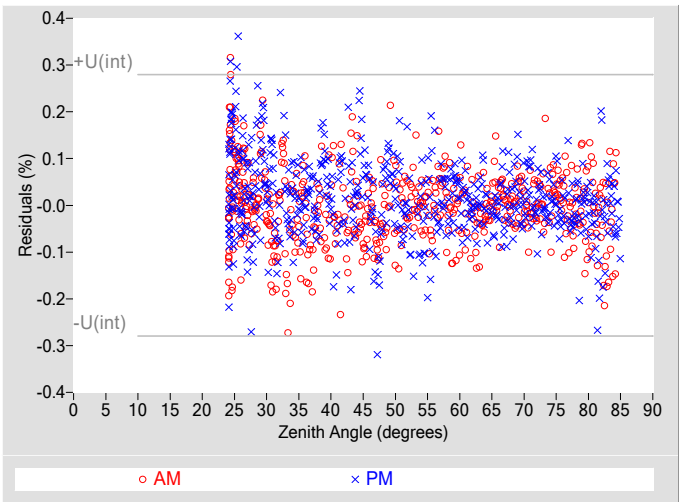
Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) $\pm$ (%)	Azimuth Angle	Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) $\pm$ (%)	Azimuth Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	18.607	0.31	108.50	18.582	0.31	251.67
2	N/A	N/A	N/A	N/A	N/A	N/A	48	18.594	0.34	106.15	18.578	0.30	253.90
4	N/A	N/A	N/A	N/A	N/A	N/A	50	18.585	0.31	103.95	18.592	0.31	256.15
6	N/A	N/A	N/A	N/A	N/A	N/A	52	18.585	0.34	101.91	18.609	0.31	258.24
8	N/A	N/A	N/A	N/A	N/A	N/A	54	18.590	0.31	99.92	18.571	0.30	260.23
10	N/A	N/A	N/A	N/A	N/A	N/A	56	18.584	0.31	98.03	18.603	0.35	262.14
12	N/A	N/A	N/A	N/A	N/A	N/A	58	18.568	0.32	96.15	18.601	0.30	263.95
14	N/A	N/A	N/A	N/A	N/A	N/A	60	18.573	0.33	94.37	18.609	0.32	265.74
16	N/A	N/A	N/A	N/A	N/A	N/A	62	18.592	0.30	92.64	18.598	0.33	267.47
18	N/A	N/A	N/A	N/A	N/A	N/A	64	18.597	0.30	90.98	18.582	0.31	269.18
20	N/A	N/A	N/A	N/A	N/A	N/A	66	18.604	0.31	89.31	18.579	0.33	270.84
22	N/A	N/A	N/A	N/A	N/A	N/A	68	18.612	0.31	87.66	18.584	0.31	272.48
24	18.580	0.31	176.01	18.552	0.32	183.79	70	18.601	0.31	86.03	18.620	0.31	274.11
26	18.585	0.32	154.86	18.582	0.30	205.07	72	18.609	0.31	84.42	18.623	0.31	275.73
28	18.587	0.31	144.95	18.563	0.31	215.27	74	18.621	0.32	82.83	18.637	0.32	277.36
30	18.564	0.32	137.65	18.587	0.32	222.37	76	18.627	0.32	81.19	18.637	N/A	278.98
32	18.596	0.31	132.14	18.568	0.33	227.93	78	18.638	N/A	79.60	18.655	N/A	280.57
34	18.588	0.31	127.40	18.591	0.30	232.86	80	18.664	N/A	77.97	18.689	N/A	282.21
36	18.589	0.30	123.34	18.599	0.32	236.81	82	18.681	N/A	76.33	18.738	N/A	283.86
38	18.592	0.29	119.76	18.543	0.31	240.39	84	18.689	N/A	74.64	18.815	N/A	285.56
40	18.584	0.32	116.60	18.568	0.32	243.60	86	N/A	N/A	N/A	N/A	N/A	N/A
42	18.571	0.31	113.70	18.562	0.32	246.50	88	N/A	N/A	N/A	N/A	N/A	N/A
44	18.601	0.30	110.97	18.599	0.30	249.13	90	N/A	N/A	N/A	N/A	N/A	N/A

N/A - Not Available

**Figure 3. Type-B Standard Uncertainty vs Zenith Angle**



**Figure 4. Residuals from Spline Interpolation**



**Table 3. Uncertainty using Spline Interpolation ‡**

Type-B Standard Uncertainty, $u(B)$ (%)	$\pm 0.35$
Type-A Interpolating Function, $u(int)$ (%)	$\pm 0.14$
Combined Standard Uncertainty, $u(c)$ (%)	$\pm 0.38$
Effective degrees of freedom, $DF(c)$	1324
Coverage factor, $k$	1.96
Expanded Uncertainty, $U_{95}$ (%)	$\pm 0.74$
AM Valid zenith angle range	24° to 76°
PM Valid zenith angle range	24° to 74°

‡ 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**

$R @ 45^\circ$ ( $\mu V/W/m^2$ )	$R_{net}$ ( $\mu V/W/m^2$ ) †
18.599	0

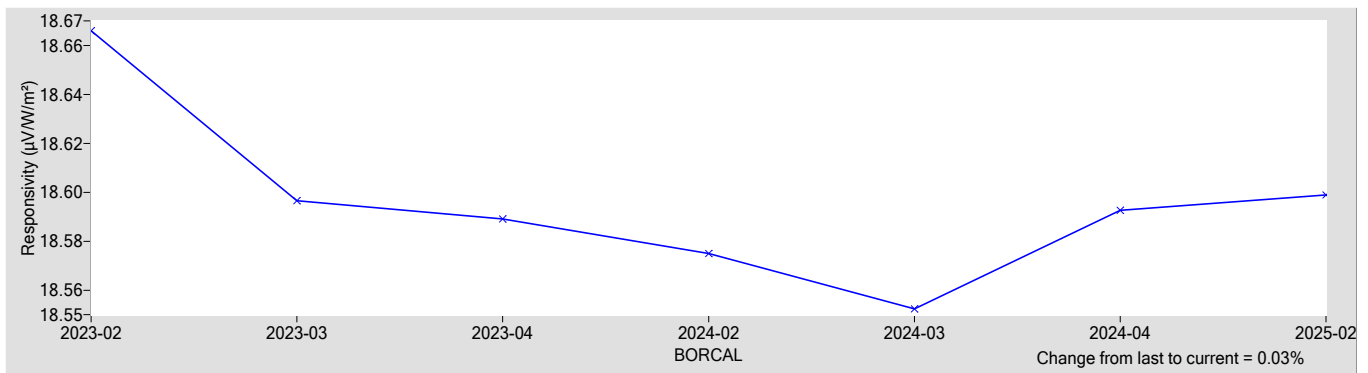
† Rnet determination date: N/A

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

Type-B Expanded Uncertainty, $U(B)$ (%)	$\pm 0.69$
Offset Uncertainty, $U(off)$ (%)	+0.055 / -0.30
Expanded Uncertainty, $U$ (%)	+0.74 / -0.99
Effective degrees of freedom, $DF^*$	1010
Coverage factor, $k$	1.96
Valid zenith angle range	30.0° to 60.0°

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

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



## References:

- [1] Reda, I.; Hickey, J.; Long, C.; Myers, D.; Stoffel, T.; Wilcox, S.; Michalsky, J. J.; Dutton, E. G.; Nelson, D. (2005). "Using a Blackbody to Calculate Net Longwave Responsivity of Shortwave Solar Pyranometers to Correct for Their Thermal Offset Error During Outdoor Calibration Using the Component Sum Method." *Journal of Atmospheric and Oceanic Technology*, 2005; pp. 1531-1540; NREL Report No. JA-560-36646. doi:10.1175/JTECH1782.1
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- [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.
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# National Renewable Energy Laboratory

## Solar Radiation Research Laboratory

### Metrology Laboratory

### Calibration Certificate



<b>Test Instrument:</b>	Pyrheliometer	<b>Manufacturer:</b>	Hukseflux
<b>Model:</b>	DR20-A1-T2	<b>Serial Number:</b>	70006
<b>Calibration Date:</b>	5/2/2025	<b>Due Date:</b>	5/2/2026
<b>Customer:</b>	NREL-SRRL-BMS	<b>Environmental Conditions:</b>	see page 4
<b>Test Dates:</b>	5/2		

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°
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**Table 1. Traceability**

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Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/21/2025	04/21/2026
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/21/2025	04/21/2026
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/07/2025	02/07/2027
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/07/2025	02/07/2027

† 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, RCC, and Shawn L. Jaker

\_\_\_\_\_  
Ibrahim Reda, Technical Manager

05/05/2025

\_\_\_\_\_  
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

## 70006 Hukseflux DR20-A1-T2

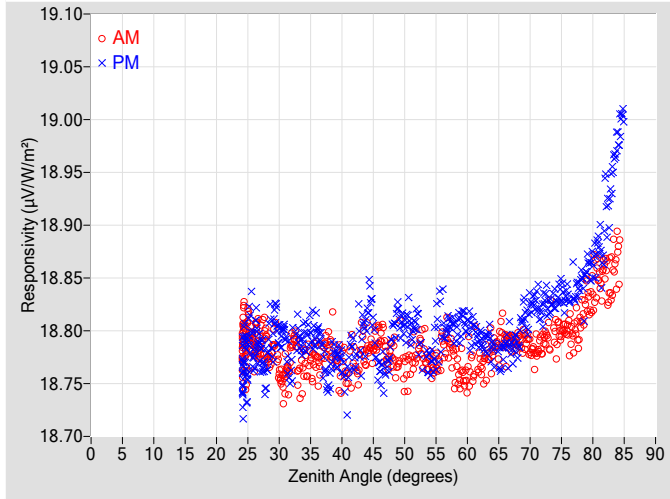
The responsivity ( $R$ ,  $\mu\text{V}/\text{W}/\text{m}^2$ ) of the test instrument during calibration is calculated using this Measurement Equation:

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

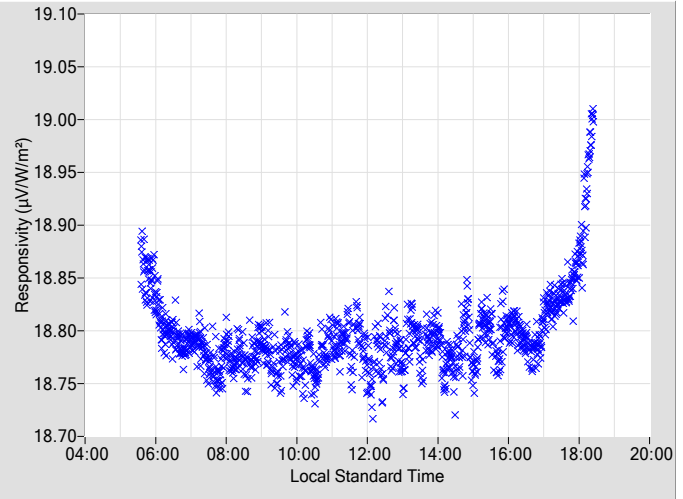
where,

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

**Figure 1. Responsivity vs Zenith Angle**



**Figure 2. Responsivity vs Local Standard Time**

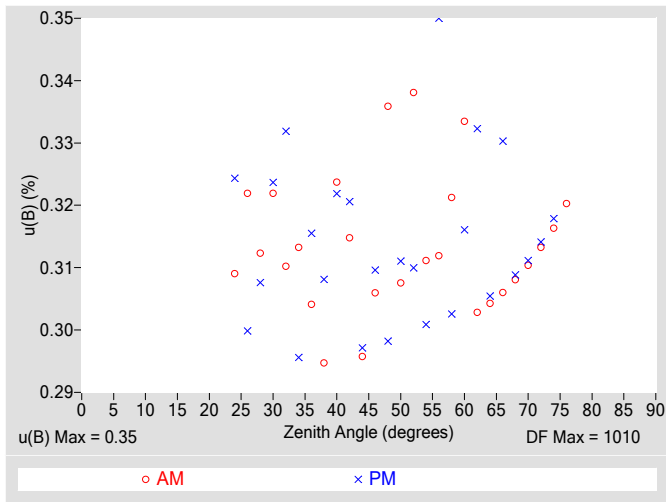


**Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)**

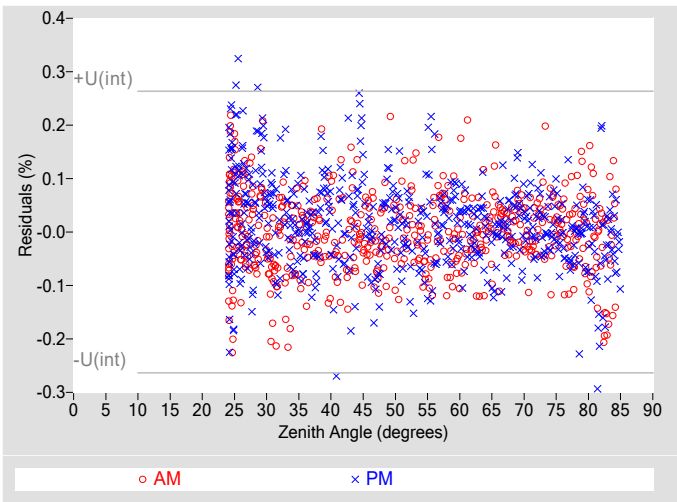
Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) $\pm$ (%)	Azimuth Angle	Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) $\pm$ (%)	Azimuth Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	18.795	0.31	108.50	18.762	0.31	251.67
2	N/A	N/A	N/A	N/A	N/A	N/A	48	18.780	0.34	106.15	18.796	0.30	253.90
4	N/A	N/A	N/A	N/A	N/A	N/A	50	18.763	0.31	103.95	18.801	0.31	256.15
6	N/A	N/A	N/A	N/A	N/A	N/A	52	18.778	0.34	101.91	18.807	0.31	258.24
8	N/A	N/A	N/A	N/A	N/A	N/A	54	18.772	0.31	99.92	18.769	0.30	260.23
10	N/A	N/A	N/A	N/A	N/A	N/A	56	18.787	0.31	98.03	18.805	0.35	262.14
12	N/A	N/A	N/A	N/A	N/A	N/A	58	18.767	0.32	96.15	18.798	0.30	263.95
14	N/A	N/A	N/A	N/A	N/A	N/A	60	18.761	0.33	94.37	18.803	0.32	265.74
16	N/A	N/A	N/A	N/A	N/A	N/A	62	18.768	0.30	92.64	18.792	0.33	267.47
18	N/A	N/A	N/A	N/A	N/A	N/A	64	18.783	0.30	90.98	18.783	0.31	269.18
20	N/A	N/A	N/A	N/A	N/A	N/A	66	18.787	0.31	89.31	18.786	0.33	270.84
22	N/A	N/A	N/A	N/A	N/A	N/A	68	18.790	0.31	87.66	18.785	0.31	272.48
24	18.787	0.31	176.01	18.756	0.32	183.95	70	18.783	0.31	86.03	18.820	0.31	274.11
26	18.786	0.32	154.86	18.782	0.30	205.07	72	18.786	0.31	84.42	18.820	0.31	275.73
28	18.787	0.31	144.95	18.766	0.31	215.27	74	18.795	0.32	82.83	18.827	0.32	277.36
30	18.761	0.32	137.65	18.796	0.32	222.37	76	18.797	0.32	81.19	18.835	N/A	278.98
32	18.786	0.31	132.14	18.768	0.33	227.93	78	18.805	N/A	79.60	18.847	N/A	280.57
34	18.772	0.31	127.40	18.794	0.30	232.86	80	18.839	N/A	77.97	18.865	N/A	282.21
36	18.772	0.30	123.34	18.802	0.32	236.81	82	18.862	N/A	76.33	18.909	N/A	283.86
38	18.789	0.29	119.76	18.753	0.31	240.39	84	18.870	N/A	74.64	18.984	N/A	285.56
40	18.762	0.32	116.60	18.768	0.32	243.60	86	N/A	N/A	N/A	N/A	N/A	N/A
42	18.773	0.31	113.70	18.775	0.32	246.50	88	N/A	N/A	N/A	N/A	N/A	N/A
44	18.782	0.30	110.97	18.807	0.30	249.13	90	N/A	N/A	N/A	N/A	N/A	N/A

N/A - Not Available

**Figure 3. Type-B Standard Uncertainty vs Zenith Angle**



**Figure 4. Residuals from Spline Interpolation**



**Table 3. Uncertainty using Spline Interpolation ‡**

Type-B Standard Uncertainty, $u(B)$ (%)	$\pm 0.35$
Type-A Interpolating Function, $u(int)$ (%)	$\pm 0.13$
Combined Standard Uncertainty, $u(c)$ (%)	$\pm 0.37$
Effective degrees of freedom, $DF(c)$	1290
Coverage factor, $k$	1.96
Expanded Uncertainty, $U_{95}$ (%)	$\pm 0.73$
AM Valid zenith angle range	24° to 76°
PM Valid zenith angle range	24° to 74°

‡ 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**

$R @ 45^\circ$ ( $\mu V/W/m^2$ )	$R_{net}$ ( $\mu V/W/m^2$ ) †
18.796	0

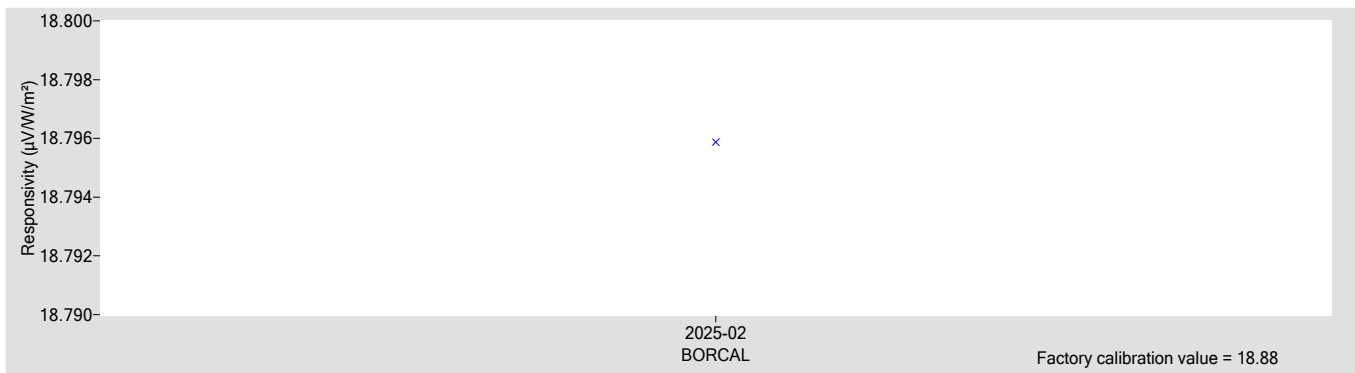
†  $R_{net}$  determination date: N/A

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

Type-B Expanded Uncertainty, $U(B)$ (%)	$\pm 0.69$
Offset Uncertainty, $U(off)$ (%)	+0.059 / -0.23
Expanded Uncertainty, $U$ (%)	+0.75 / -0.92
Effective degrees of freedom, $DF^*$	1010
Coverage factor, $k$	1.96
Valid zenith angle range	30.0° to 60.0°

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

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



**References:**

[1] Reda, I.; Hickey, J.; Long, C.; Myers, D.; Stoffel, T.; Wilcox, S.; Michalsky, J. J.; Dutton, E. G.; Nelson, D. (2005). "Using a Blackbody to Calculate Net Longwave Responsivity of Shortwave Solar Pyranometers to Correct for Their Thermal Offset Error During Outdoor Calibration Using the Component Sum Method." *Journal of Atmospheric and Oceanic Technology*, 2005; pp. 1531-1540; NREL Report No. JA-560-36646. doi:10.1175/JTECH1782.1

[2] Reda, I.; Myers, D.; Stoffel, T. (2008). "Uncertainty Estimate for the Outdoor Calibration of Solar Pyranometers: A Metrologist Perspective." *Measure*. (NCSLI *Journal of Measurement Science*). Vol. 3(4), December 2008; pp. 58-66; NREL Report No. JA-581-4137

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

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

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

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

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



# Calibration Results

## 9206 Hukseflux DR02

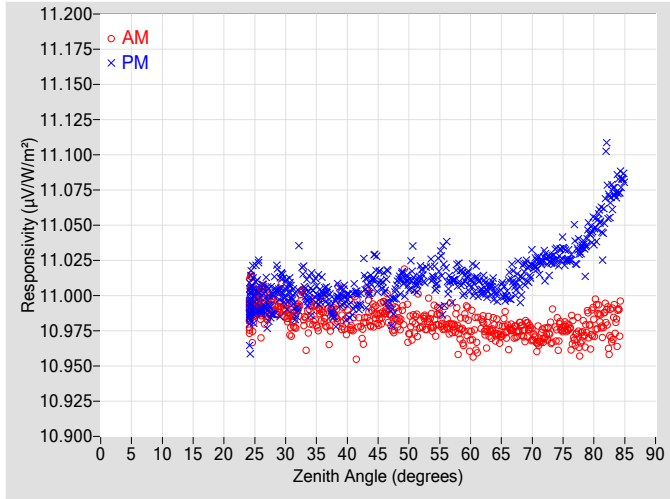
The responsivity ( $R$ ,  $\mu\text{V}/\text{W}/\text{m}^2$ ) of the test instrument during calibration is calculated using this Measurement Equation:

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

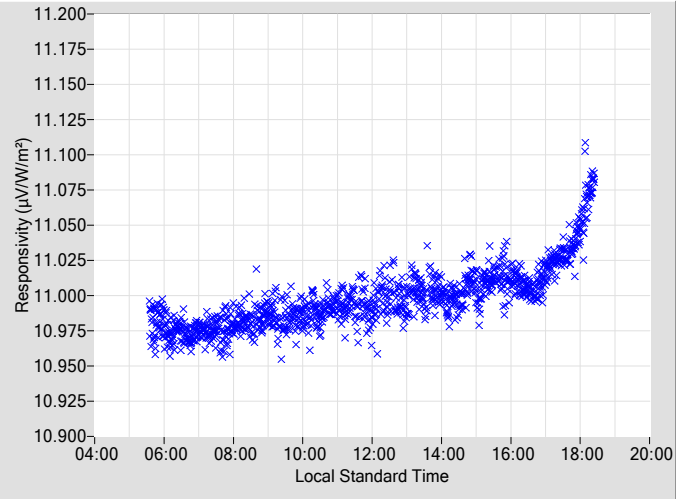
where,

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

**Figure 1. Responsivity vs Zenith Angle**



**Figure 2. Responsivity vs Local Standard Time**

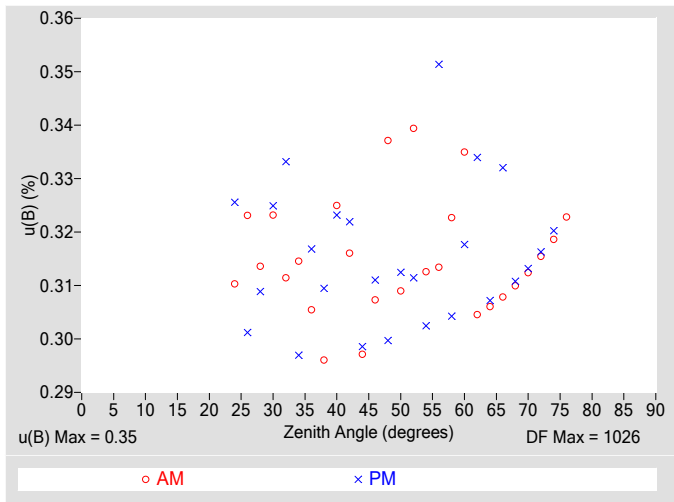


**Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)**

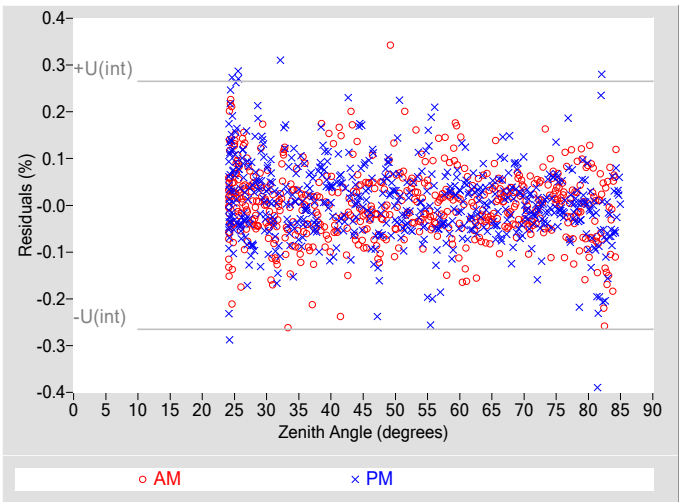
Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) ( $\pm$ %)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) ( $\pm$ %)	Azimuth Angle	Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) ( $\pm$ %)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) ( $\pm$ %)	Azimuth Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	10.991	0.31	108.50	11.005	0.31	251.67
2	N/A	N/A	N/A	N/A	N/A	N/A	48	10.986	0.34	106.15	11.005	0.30	253.90
4	N/A	N/A	N/A	N/A	N/A	N/A	50	10.978	0.31	103.95	11.008	0.31	256.15
6	N/A	N/A	N/A	N/A	N/A	N/A	52	10.979	0.34	101.91	11.016	0.31	258.24
8	N/A	N/A	N/A	N/A	N/A	N/A	54	10.981	0.31	99.92	11.013	0.30	260.23
10	N/A	N/A	N/A	N/A	N/A	N/A	56	10.982	0.31	98.03	11.015	0.35	262.14
12	N/A	N/A	N/A	N/A	N/A	N/A	58	10.975	0.32	96.15	11.015	0.30	263.95
14	N/A	N/A	N/A	N/A	N/A	N/A	60	10.973	0.33	94.37	11.008	0.32	265.74
16	N/A	N/A	N/A	N/A	N/A	N/A	62	10.981	0.30	92.64	11.007	0.33	267.47
18	N/A	N/A	N/A	N/A	N/A	N/A	64	10.977	0.31	90.98	11.002	0.31	269.18
20	N/A	N/A	N/A	N/A	N/A	N/A	66	10.973	0.31	89.31	11.005	0.33	270.84
22	N/A	N/A	N/A	N/A	N/A	N/A	68	10.977	0.31	87.66	11.009	0.31	272.48
24	10.990	0.31	176.01	10.990	0.33	183.95	70	10.972	0.31	86.03	11.021	0.31	274.11
26	10.989	0.32	154.86	10.995	0.30	205.07	72	10.971	0.32	84.42	11.028	0.32	275.72
28	10.993	0.31	144.95	10.997	0.31	215.27	74	10.973	0.32	82.83	11.027	0.32	277.36
30	10.989	0.32	137.65	11.002	0.32	222.37	76	10.974	0.32	81.19	11.027	N/A	278.98
32	10.991	0.31	132.14	11.001	0.33	227.93	78	10.970	N/A	79.60	11.034	N/A	280.57
34	10.989	0.31	127.40	11.003	0.30	232.86	80	10.983	N/A	77.97	11.047	N/A	282.21
36	10.988	0.31	123.34	11.003	0.32	236.81	82	10.987	N/A	76.33	11.077	N/A	283.86
38	10.989	0.30	119.76	10.988	0.31	240.39	84	10.984	N/A	74.64	11.079	N/A	285.56
40	10.983	0.32	116.60	10.997	0.32	243.60	86	N/A	N/A	N/A	N/A	N/A	N/A
42	10.980	0.32	113.70	10.996	0.32	246.50	88	N/A	N/A	N/A	N/A	N/A	N/A
44	10.987	0.30	110.97	11.011	0.30	249.13	90	N/A	N/A	N/A	N/A	N/A	N/A

N/A - Not Available

**Figure 3. Type-B Standard Uncertainty vs Zenith Angle**



**Figure 4. Residuals from Spline Interpolation**



**Table 3. Uncertainty using Spline Interpolation ‡**

Type-B Standard Uncertainty, $u(B)$ (%)	$\pm 0.35$
Type-A Interpolating Function, $u(int)$ (%)	$\pm 0.13$
Combined Standard Uncertainty, $u(c)$ (%)	$\pm 0.38$
Effective degrees of freedom, $DF(c)$	1311
Coverage factor, $k$	1.96
Expanded Uncertainty, $U_{95}$ (%)	$\pm 0.74$
AM Valid zenith angle range	24° to 76°
PM Valid zenith angle range	24° to 74°

‡ 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**

$R @ 45^\circ$ ( $\mu V/W/m^2$ )	$R_{net}$ ( $\mu V/W/m^2$ ) †
10.999	0

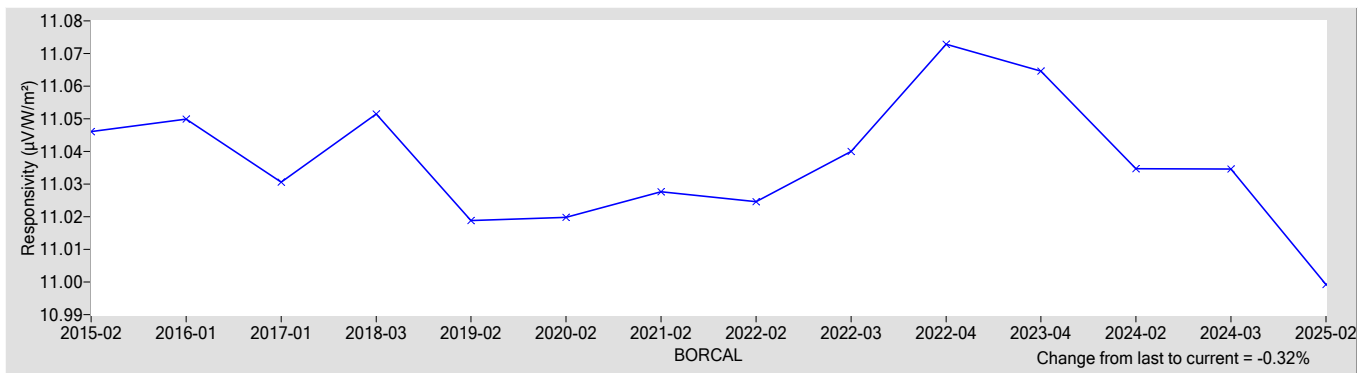
†  $R_{net}$  determination date: N/A

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

Type-B Expanded Uncertainty, $U(B)$ (%)	$\pm 0.69$
Offset Uncertainty, $U(off)$ (%)	+0.16 / -0.24
Expanded Uncertainty, $U$ (%)	+0.85 / -0.93
Effective degrees of freedom, $DF^*$	1026
Coverage factor, $k$	1.96
Valid zenith angle range	30.0° to 60.0°

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

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



**References:**

[1] Reda, I.; Hickey, J.; Long, C.; Myers, D.; Stoffel, T.; Wilcox, S.; Michalsky, J. J.; Dutton, E. G.; Nelson, D. (2005). "Using a Blackbody to Calculate Net Longwave Responsivity of Shortwave Solar Pyranometers to Correct for Their Thermal Offset Error During Outdoor Calibration Using the Component Sum Method." *Journal of Atmospheric and Oceanic Technology*, 2005; pp. 1531-1540; NREL Report No. JA-560-36646. doi:10.1175/JTECH1782.1

[2] Reda, I.; Myers, D.; Stoffel, T. (2008). "Uncertainty Estimate for the Outdoor Calibration of Solar Pyranometers: A Metrologist Perspective." *Measure*. (NCSLI *Journal of Measurement Science*). Vol. 3(4), December 2008; pp. 58-66; NREL Report No. JA-581-4137

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

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

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

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

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



# National Renewable Energy Laboratory

## Solar Radiation Research Laboratory

### Metrology Laboratory

### Calibration Certificate



<b>Test Instrument:</b>	Sunshine Pyranometer - Global Output	<b>Manufacturer:</b>	Delta-T
<b>Model:</b>	SPN1	<b>Serial Number:</b>	A360
<b>Calibration Date:</b>	5/2/2025	<b>Due Date:</b>	5/2/2026
<b>Customer:</b>	NREL-SRRL-BMS	<b>Environmental Conditions:</b>	see page 4
<b>Test Dates:</b>	5/2		

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	09/27/2024	09/27/2025
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/21/2025	04/21/2026
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/21/2025	04/21/2026
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/07/2025	02/07/2027
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/07/2025	02/07/2027

† 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, RCC, and Shawn L. Jaker

-----  
Ibrahim Reda, Technical Manager

05/05/2025

-----  
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 ( $\text{W}/\text{m}^2$ ),
  - =  $W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
  - where,  $W_{in}$  = incoming infrared ( $\text{W}/\text{m}^2$ ),  $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$ ,
  - $T_c$  = case temperature of pyrgeometer (K).
- $I$  = reference irradiance ( $\text{W}/\text{m}^2$ ), beam (B) or global (G)  
 where,  $G = B * \text{COS}(Z) + D$ ,  
 $Z$  = zenith angle (degrees),  
 $D$  = reference diffuse irradiance ( $\text{W}/\text{m}^2$ ).

Figure 1. Responsivity vs Zenith Angle

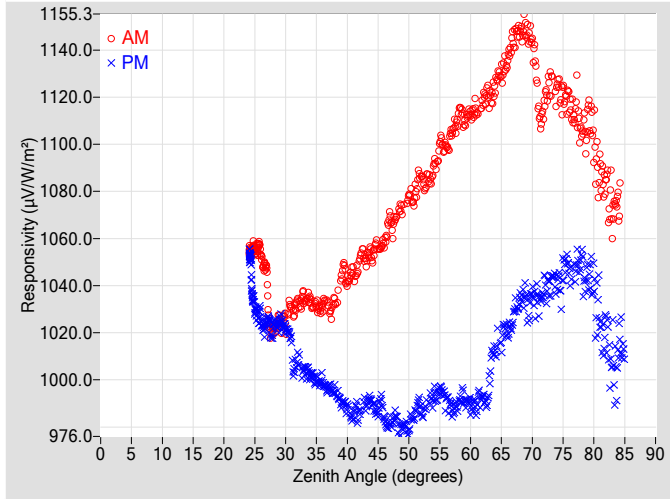


Figure 2. Responsivity vs Local Standard Time

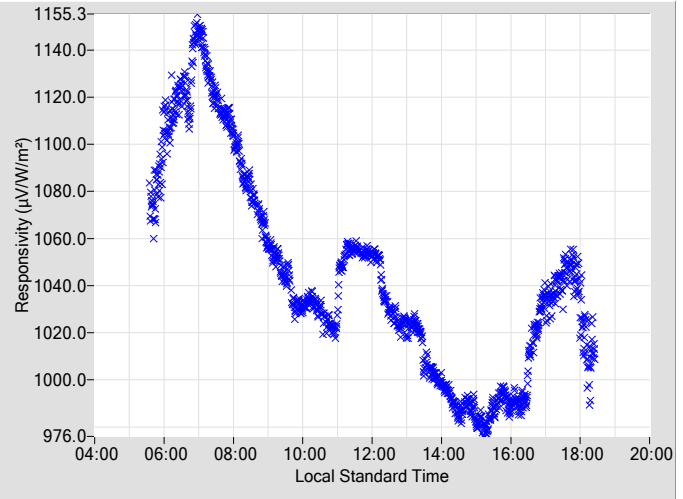
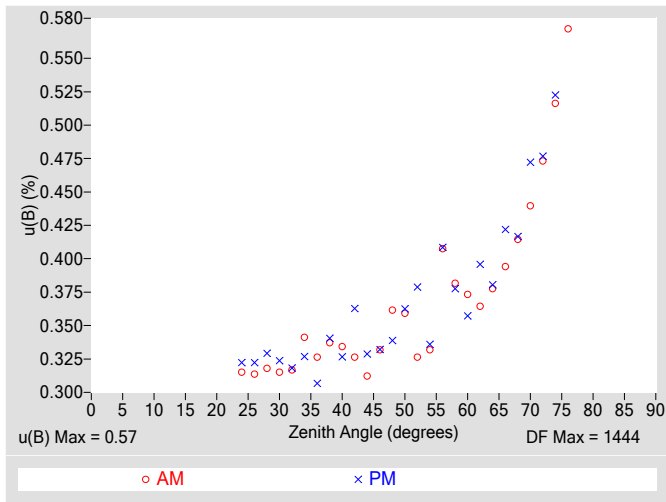


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty,  $u(B)$

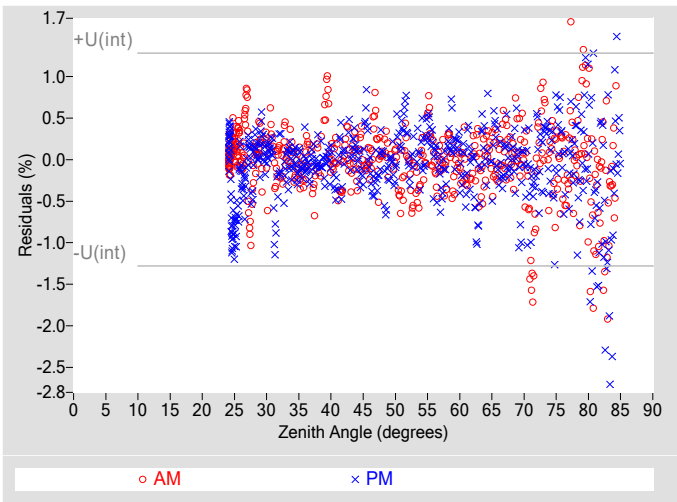
Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	$u(B)$ $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	$u(B)$ $\pm$ (%)	Azimuth Angle	Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	$u(B)$ $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	$u(B)$ $\pm$ (%)	Azimuth Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	1058.5	0.33	108.46	983.83	0.33	251.64
2	N/A	N/A	N/A	N/A	N/A	N/A	48	1068.4	0.36	106.30	983.55	0.34	253.95
4	N/A	N/A	N/A	N/A	N/A	N/A	50	1077.3	0.36	104.04	979.29	0.36	256.18
6	N/A	N/A	N/A	N/A	N/A	N/A	52	1086.1	0.33	101.87	986.15	0.38	258.26
8	N/A	N/A	N/A	N/A	N/A	N/A	54	1090.2	0.33	99.89	992.33	0.34	260.20
10	N/A	N/A	N/A	N/A	N/A	N/A	56	1099.0	0.41	98.00	991.43	0.41	262.14
12	N/A	N/A	N/A	N/A	N/A	N/A	58	1111.9	0.38	96.17	989.50	0.38	263.98
14	N/A	N/A	N/A	N/A	N/A	N/A	60	1113.1	0.37	94.39	989.06	0.36	265.76
16	N/A	N/A	N/A	N/A	N/A	N/A	62	1118.5	0.36	92.66	992.56	0.40	267.50
18	N/A	N/A	N/A	N/A	N/A	N/A	64	1124.5	0.38	90.95	1012.4	0.38	269.20
20	N/A	N/A	N/A	N/A	N/A	N/A	66	1135.9	0.39	89.28	1020.5	0.42	270.86
22	N/A	N/A	N/A	N/A	N/A	N/A	68	1148.5	0.41	87.64	1034.1	0.42	272.51
24	1053.7	0.32	175.53	1052.7	0.32	183.86	70	1143.0	0.44	86.05	1035.7	0.47	274.14
26	1053.8	0.31	155.22	1026.6	0.32	204.91	72	1117.4	0.47	84.44	1038.8	0.48	275.75
28	1021.2	0.32	144.87	1022.3	0.33	215.32	74	1123.3	0.52	82.81	1040.9	0.52	277.36
30	1025.1	0.32	138.01	1022.0	0.32	222.23	76	1119.2	0.57	81.22	1046.6	N/A	278.96
32	1033.0	0.32	132.39	1007.9	0.32	227.91	78	1105.5	N/A	79.58	1049.0	N/A	280.60
34	1033.4	0.34	127.41	1002.1	0.33	232.68	80	1103.0	N/A	77.99	1036.9	N/A	282.23
36	1031.4	0.33	123.29	998.88	0.31	236.85	82	1085.3	N/A	76.35	1022.0	N/A	283.88
38	1033.1	0.34	119.88	994.79	0.34	240.36	84	1075.2	N/A	74.66	1013.2	N/A	285.58
40	1041.6	0.33	116.56	988.05	0.33	243.48	86	N/A	N/A	N/A	N/A	N/A	N/A
42	1050.9	0.33	113.58	985.85	0.36	246.42	88	N/A	N/A	N/A	N/A	N/A	N/A
44	1053.2	0.31	111.00	990.55	0.33	249.16	90	N/A	N/A	N/A	N/A	N/A	N/A

N/A - Not Available

**Figure 3. Type-B Standard Uncertainty vs Zenith Angle**



**Figure 4. Residuals from Spline Interpolation**



**Table 3. Uncertainty using Spline Interpolation ‡**

Type-B Standard Uncertainty, $u(B)$ (%)	$\pm 0.57$
Type-A Interpolating Function, $u(int)$ (%)	$\pm 0.64$
Combined Standard Uncertainty, $u(c)$ (%)	$\pm 0.86$
Effective degrees of freedom, $DF(c)$	2279
Coverage factor, $k$	1.96
Expanded Uncertainty, $U_{95}$ (%)	$\pm 1.7$
AM Valid zenith angle range	24° to 76°
PM Valid zenith angle range	24° to 74°

‡ 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**

$R @ 45^\circ$ ( $\mu V/W/m^2$ )	$R_{net}$ ( $\mu V/W/m^2$ ) †
1022.2	0

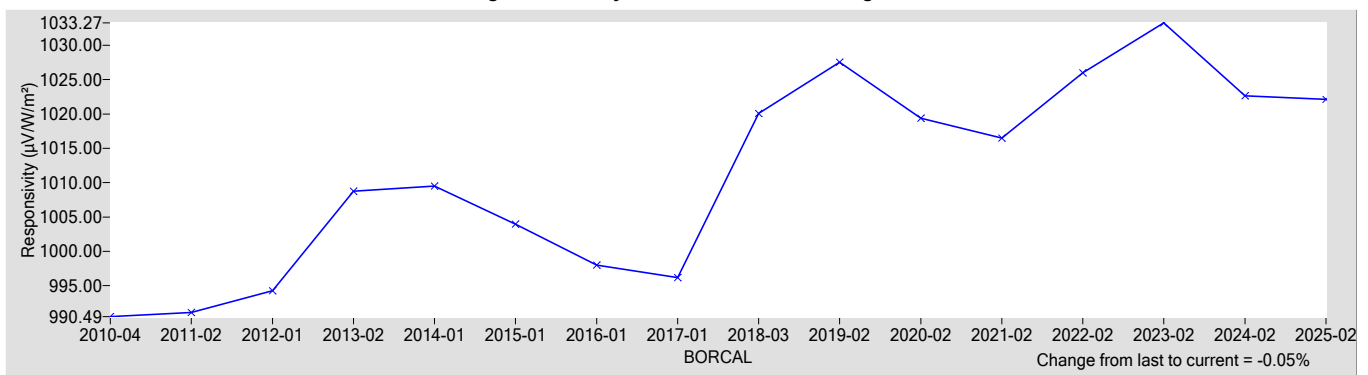
†  $R_{net}$  determination date: N/A

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

Type-B Expanded Uncertainty, $U(B)$ (%)	$\pm 0.80$
Offset Uncertainty, $U(off)$ (%)	+8.9 / -4.2
Expanded Uncertainty, $U$ (%)	+9.7 / -5.0
Effective degrees of freedom, $DF^*$	1995
Coverage factor, $k$	1.96
Valid zenith angle range	30.0° to 60.0°

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

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



**References:**

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



# National Renewable Energy Laboratory

## Solar Radiation Research Laboratory

### Metrology Laboratory

### Calibration Certificate



<b>Test Instrument:</b>	Pyranometer	<b>Manufacturer:</b>	EKO
<b>Model:</b>	MS-802	<b>Serial Number:</b>	F14077R
<b>Calibration Date:</b>	5/2/2025	<b>Due Date:</b>	5/2/2026
<b>Customer:</b>	NREL-SRRL-BMS	<b>Environmental Conditions:</b>	see page 4
<b>Test Dates:</b>	5/2		

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	09/27/2024	09/27/2025
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/21/2025	04/21/2026
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/21/2025	04/21/2026
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/07/2025	02/07/2027
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/07/2025	02/07/2027
Infrared Irradiance ‡	Kipp & Zonen Pyrgeometer Model CG4, S/N FT002	03/31/2022	03/31/2027

† Through the World Radiometric Reference (WRR)

‡ Through the World Infrared Standard Group (WISG)

**Number of pages of certificate:** 4

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

**Setup:** Radiometers are calibrated outdoors, using the sun as the source. Pyranometers and pyrgeometers are installed for horizontal measurements, with their signal connectors oriented north, if their design permits.

The shading disk for the reference diffuse subtends a solid angle of 5°. Pyrheliometers are installed on solar trackers.

**Calibrated by:** Afshin Andreas, RCC, and Shawn L. Jaker

-----  
Ibrahim Reda, Technical Manager

05/05/2025

-----  
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

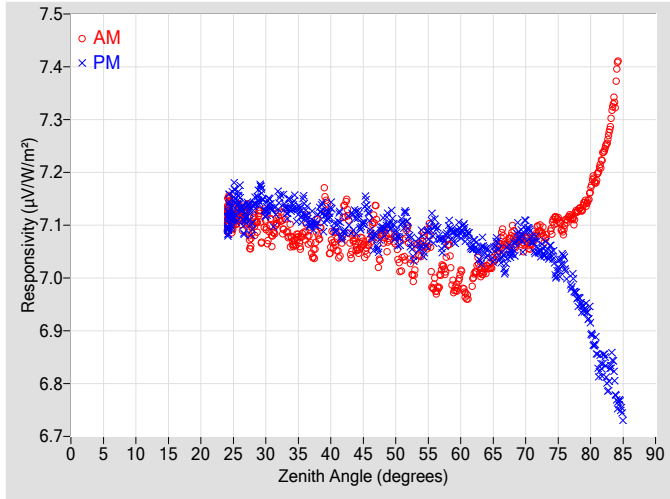
The responsivity ( $R$ ,  $\mu\text{V}/\text{W}/\text{m}^2$ ) of the test instrument during calibration is calculated using this Measurement Equation:

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

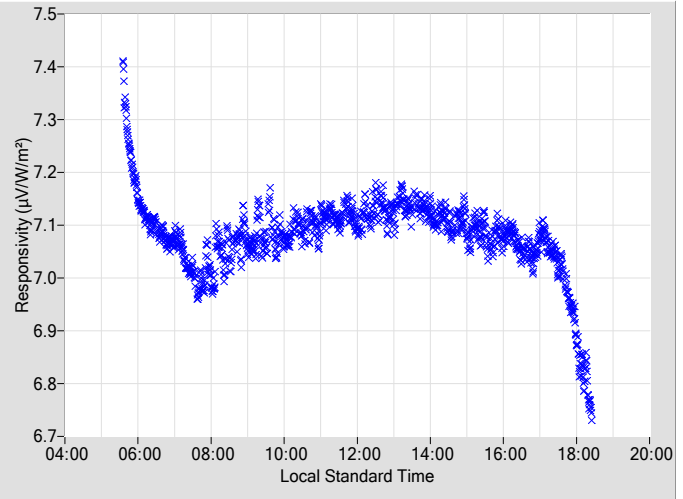
where,

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

**Figure 1. Responsivity vs Zenith Angle**



**Figure 2. Responsivity vs Local Standard Time**

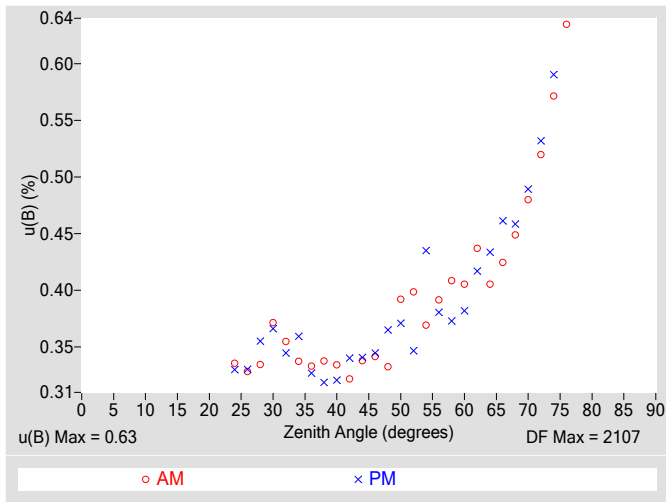


**Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)**

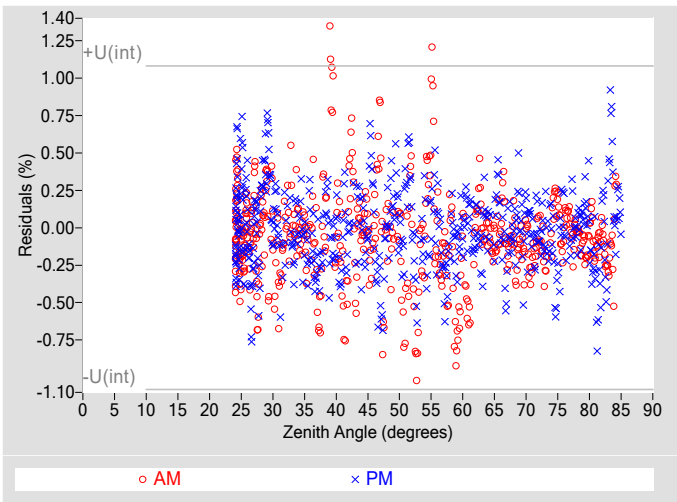
Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) $\pm$ (%)	Azimuth Angle	Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) $\pm$ (%)	Azimuth Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	7.0726	0.34	108.43	7.1006	0.34	251.67
2	N/A	N/A	N/A	N/A	N/A	N/A	48	7.0828	0.33	106.15	7.0953	0.36	254.02
4	N/A	N/A	N/A	N/A	N/A	N/A	50	7.0704	0.39	103.95	7.0840	0.37	256.15
6	N/A	N/A	N/A	N/A	N/A	N/A	52	7.0645	0.40	101.89	7.0838	0.35	258.24
8	N/A	N/A	N/A	N/A	N/A	N/A	54	7.0642	0.37	99.89	7.0657	0.44	260.20
10	N/A	N/A	N/A	N/A	N/A	N/A	56	6.9822	0.39	98.03	7.0904	0.38	262.12
12	N/A	N/A	N/A	N/A	N/A	N/A	58	7.0600	0.41	96.15	7.0930	0.37	264.03
14	N/A	N/A	N/A	N/A	N/A	N/A	60	7.0087	0.41	94.42	7.0896	0.38	265.74
16	N/A	N/A	N/A	N/A	N/A	N/A	62	7.0007	0.44	92.68	7.0617	0.42	267.47
18	N/A	N/A	N/A	N/A	N/A	N/A	64	7.0181	0.41	90.98	7.0490	0.43	269.18
20	N/A	N/A	N/A	N/A	N/A	N/A	66	7.0604	0.42	89.31	7.0425	0.46	270.84
22	N/A	N/A	N/A	N/A	N/A	N/A	68	7.0865	0.45	87.66	7.0532	0.46	272.49
24	7.1178	0.34	176.00	7.1044	0.33	184.17	70	7.0744	0.48	86.03	7.0952	0.49	274.12
26	7.1243	0.33	155.33	7.1439	0.33	205.14	72	7.0948	0.52	84.42	7.0536	0.53	275.73
28	7.0983	0.33	144.91	7.1200	0.36	215.36	74	7.0967	0.57	82.79	7.0504	0.59	277.38
30	7.1018	0.37	137.85	7.1248	0.37	222.37	76	7.0989	0.63	81.19	7.0227	N/A	278.98
32	7.1124	0.35	132.14	7.1494	0.34	228.12	78	7.1271	N/A	79.60	6.9607	N/A	280.57
34	7.0677	0.34	127.30	7.1337	0.36	232.77	80	7.1673	N/A	77.97	6.9105	N/A	282.21
36	7.0870	0.33	123.12	7.1325	0.33	236.81	82	7.2367	N/A	76.33	6.8425	N/A	283.86
38	7.0864	0.34	119.76	7.1150	0.32	240.37	84	7.3738	N/A	74.67	6.7685	N/A	285.56
40	7.0623	0.33	116.52	7.1292	0.32	243.52	86	N/A	N/A	N/A	N/A	N/A	N/A
42	7.1084	0.32	113.66	7.0865	0.34	246.46	88	N/A	N/A	N/A	N/A	N/A	N/A
44	7.0544	0.34	110.90	7.1141	0.34	249.20	90	N/A	N/A	N/A	N/A	N/A	N/A

N/A - Not Available

**Figure 3. Type-B Standard Uncertainty vs Zenith Angle**



**Figure 4. Residuals from Spline Interpolation**



**Table 3. Uncertainty using Spline Interpolation ‡**

Type-B Standard Uncertainty, $u(B)$ (%)	$\pm 0.63$
Type-A Interpolating Function, $u(int)$ (%)	$\pm 0.54$
Combined Standard Uncertainty, $u(c)$ (%)	$\pm 0.83$
Effective degrees of freedom, $DF(c)$	2995
Coverage factor, $k$	1.96
Expanded Uncertainty, $U_{95}$ (%)	$\pm 1.6$
AM Valid zenith angle range	24° to 76°
PM Valid zenith angle range	24° to 74°

‡ 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**

$R @ 45^\circ$ ( $\mu V/W/m^2$ )	$R_{net}$ ( $\mu V/W/m^2$ ) †
7.0858	0.18000

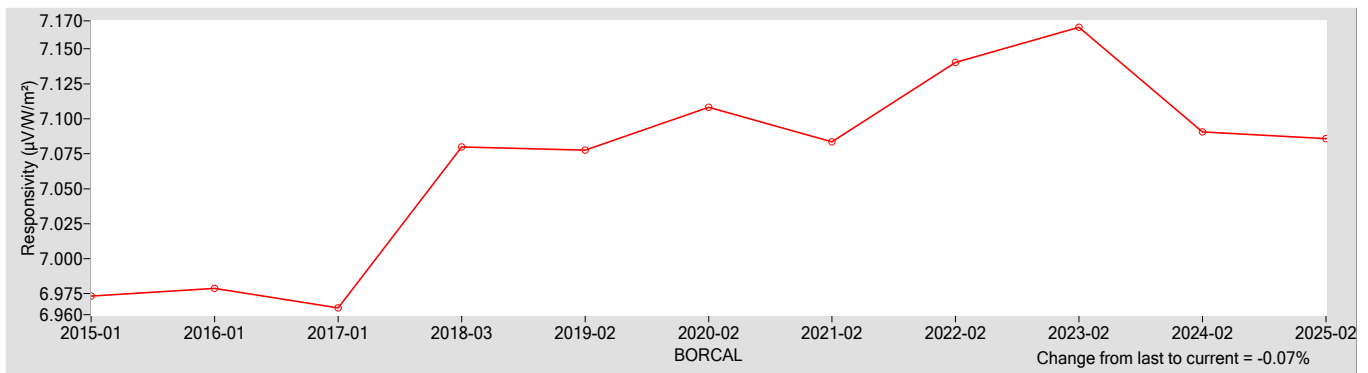
†  $R_{net}$  determination date: Estimated

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

Type-B Expanded Uncertainty, $U(B)$ (%)	$\pm 0.85$
Offset Uncertainty, $U(off)$ (%)	+0.90 / -1.5
Expanded Uncertainty, $U$ (%)	+1.8 / -2.3
Effective degrees of freedom, $DF^*$	2159
Coverage factor, $k$	1.96
Valid zenith angle range	30.0° to 60.0°

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

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



**References:**

- [1] Reda, I.; Hickey, J.; Long, C.; Myers, D.; Stoffel, T.; Wilcox, S.; Michalsky, J. J.; Dutton, E. G.; Nelson, D. (2005). "Using a Blackbody to Calculate Net Longwave Responsivity of Shortwave Solar Pyranometers to Correct for Their Thermal Offset Error During Outdoor Calibration Using the Component Sum Method." *Journal of Atmospheric and Oceanic Technology*, 2005; pp. 1531-1540; NREL Report No. JA-560-36646. doi:10.1175/JTECH1782.1
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- [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:** PY100360  
**Calibration Date:** 5/2/2025      **Due Date:** 5/2/2026  
**Customer:** NREL-SRRL-BMS      **Environmental Conditions:** see page 4  
**Test Dates:** 5/2

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	09/27/2024	09/27/2025
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/21/2025	04/21/2026
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/21/2025	04/21/2026
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/07/2025	02/07/2027
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/07/2025	02/07/2027

† 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, RCC, and Shawn L. Jaker

Ibrahim Reda, Technical Manager

05/05/2025

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 ( $\text{W}/\text{m}^2$ ),
  - =  $W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
  - where,  $W_{in}$  = incoming infrared ( $\text{W}/\text{m}^2$ ),  $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$ ,
  - $T_c$  = case temperature of pyrgeometer (K).
- $I$  = reference irradiance ( $\text{W}/\text{m}^2$ ), beam (B) or global (G)  
 where,  $G = B * \text{COS}(Z) + D$ ,  
 $Z$  = zenith angle (degrees),  
 $D$  = reference diffuse irradiance ( $\text{W}/\text{m}^2$ ).

Figure 1. Responsivity vs Zenith Angle

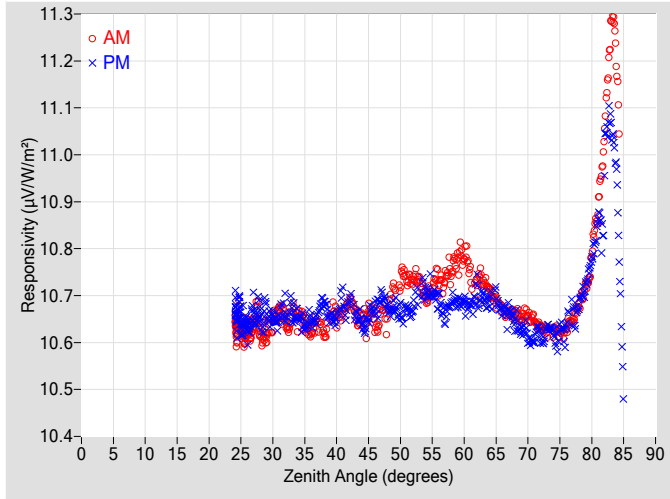


Figure 2. Responsivity vs Local Standard Time

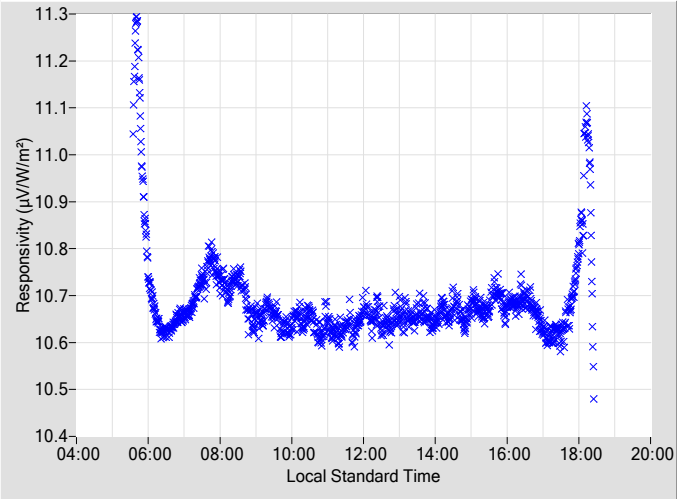
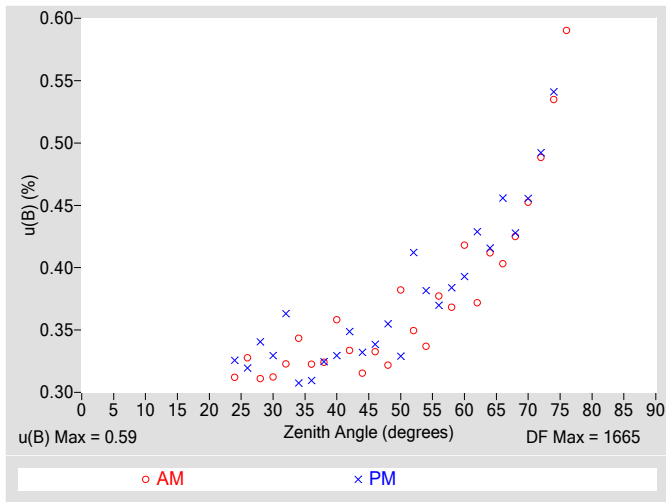


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)

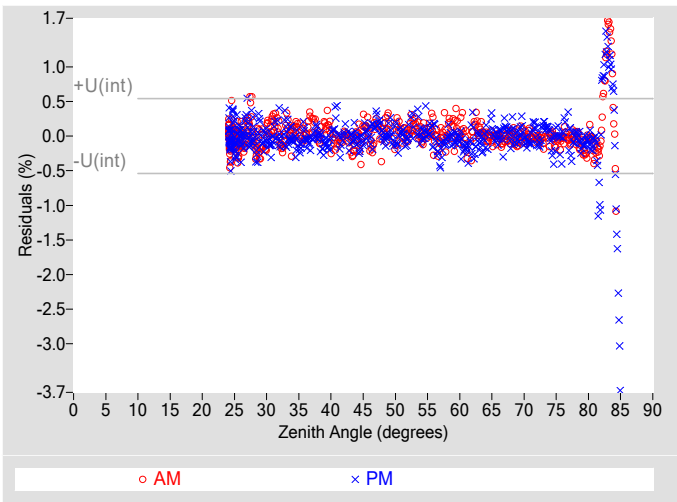
Zenith			AM			PM			Zenith			AM			PM		
Angle	R	u(B)	Azimuth	R	u(B)	Azimuth	Angle	R	u(B)	Azimuth	R	u(B)	Azimuth	R	u(B)	Azimuth	
(deg.)	( $\mu\text{V}/\text{W}/\text{m}^2$ )	$\pm$ (%)	Angle	( $\mu\text{V}/\text{W}/\text{m}^2$ )	$\pm$ (%)	Angle	(deg.)	( $\mu\text{V}/\text{W}/\text{m}^2$ )	$\pm$ (%)	Angle	( $\mu\text{V}/\text{W}/\text{m}^2$ )	$\pm$ (%)	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	10.645	0.33	108.52	10.673	0.34	251.64				
2	N/A	N/A	N/A	N/A	N/A	N/A	48	10.657	0.32	106.11	10.673	0.35	253.98				
4	N/A	N/A	N/A	N/A	N/A	N/A	50	10.732	0.38	103.91	10.664	0.33	256.17				
6	N/A	N/A	N/A	N/A	N/A	N/A	52	10.732	0.35	101.89	10.671	0.41	258.20				
8	N/A	N/A	N/A	N/A	N/A	N/A	54	10.693	0.34	99.88	10.706	0.38	260.25				
10	N/A	N/A	N/A	N/A	N/A	N/A	56	10.729	0.38	97.99	10.686	0.37	262.14				
12	N/A	N/A	N/A	N/A	N/A	N/A	58	10.749	0.37	96.17	10.689	0.38	263.97				
14	N/A	N/A	N/A	N/A	N/A	N/A	60	10.780	0.42	94.39	10.690	0.39	265.70				
16	N/A	N/A	N/A	N/A	N/A	N/A	62	10.726	0.37	92.65	10.709	0.43	267.49				
18	N/A	N/A	N/A	N/A	N/A	N/A	64	10.711	0.41	90.95	10.695	0.42	269.19				
20	N/A	N/A	N/A	N/A	N/A	N/A	66	10.674	0.40	89.32	10.670	0.46	270.86				
22	N/A	N/A	N/A	N/A	N/A	N/A	68	10.660	0.42	87.67	10.642	0.43	272.50				
24	10.641	0.31	176.08	10.670	0.33	184.13	70	10.658	0.45	86.05	10.611	0.46	274.13				
26	10.628	0.33	155.07	10.635	0.32	205.04	72	10.636	0.49	84.44	10.613	0.49	275.75				
28	10.626	0.31	145.12	10.663	0.34	215.10	74	10.627	0.53	82.80	10.619	0.54	277.35				
30	10.644	0.31	137.69	10.656	0.33	222.26	76	10.630	0.59	81.21	10.633	N/A	278.95				
32	10.645	0.32	132.09	10.661	0.36	228.00	78	10.679	N/A	79.61	10.684	N/A	280.59				
34	10.655	0.34	127.43	10.657	0.31	232.60	80	10.786	N/A	77.98	10.782	N/A	282.23				
36	10.618	0.32	123.27	10.646	0.31	236.84	82	11.045	N/A	76.34	10.958	N/A	283.88				
38	10.618	0.32	119.70	10.685	0.32	240.40	84	11.150	N/A	74.64	10.894	N/A	285.57				
40	10.658	0.36	116.60	10.653	0.33	243.53	86	N/A	N/A	N/A	N/A	N/A	N/A				
42	10.690	0.33	113.54	10.691	0.35	246.50	88	N/A	N/A	N/A	N/A	N/A	N/A				
44	10.656	0.32	110.99	10.640	0.33	249.15	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) (%)	±0.59
Type-A Interpolating Function, u(int) (%)	±0.27
Combined Standard Uncertainty, u(c) (%)	±0.65
Effective degrees of freedom, DF(c)	2270
Coverage factor, k	1.96
Expanded Uncertainty, U95 (%)	±1.3
AM Valid zenith angle range	24° to 76°
PM Valid zenith angle range	24° to 74°

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

**Table 4. Calibration Label Values**

R @ 45° (μV/W/m²)	Rnet (μV/W/m²) †
10.659	0

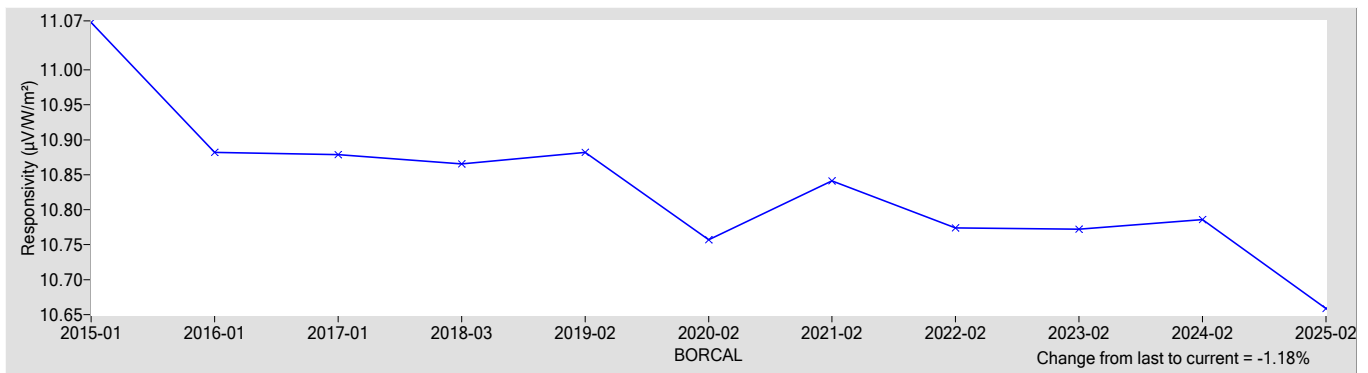
† Rnet determination date: N/A

**Table 5. Uncertainty using R @ 45°**

Type-B Expanded Uncertainty, U(B) (%)	±0.82
Offset Uncertainty, U(off) (%)	+1.1 / -0.39
Expanded Uncertainty, U (%)	+2.0 / -1.2
Effective degrees of freedom, DF *	2108
Coverage factor, k	1.96
Valid zenith angle range	30.0° to 60.0°

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

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



**References:**

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

# National Renewable Energy Laboratory

## Solar Radiation Research Laboratory

### Metrology Laboratory

### Calibration Certificate



<b>Test Instrument:</b>	Revised Silicon Pyranometer	<b>Manufacturer:</b>	Licor
<b>Model:</b>	LI200R	<b>Serial Number:</b>	PY102023
<b>Calibration Date:</b>	5/2/2025	<b>Due Date:</b>	5/2/2026
<b>Customer:</b>	NREL-SRRL-BMS	<b>Environmental Conditions:</b>	see page 4
<b>Test Dates:</b>	5/2		

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	09/27/2024	09/27/2025
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/21/2025	04/21/2026
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/21/2025	04/21/2026
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/07/2025	02/07/2027
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/07/2025	02/07/2027

† 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, RCC, and Shawn L. Jaker

\_\_\_\_\_  
Ibrahim Reda, Technical Manager

05/05/2025

\_\_\_\_\_  
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:

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

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 ( $\text{W}/\text{m}^2$ ),
  - =  $W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
  - where,  $W_{in}$  = incoming infrared ( $\text{W}/\text{m}^2$ ),  $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$ ,
  - $T_c$  = case temperature of pyrgeometer (K).
- $I$  = reference irradiance ( $\text{W}/\text{m}^2$ ), beam (B) or global (G)  
 where,  $G = B * \text{COS}(Z) + D$ ,  
 $Z$  = zenith angle (degrees),  
 $D$  = reference diffuse irradiance ( $\text{W}/\text{m}^2$ ).

Figure 1. Responsivity vs Zenith Angle

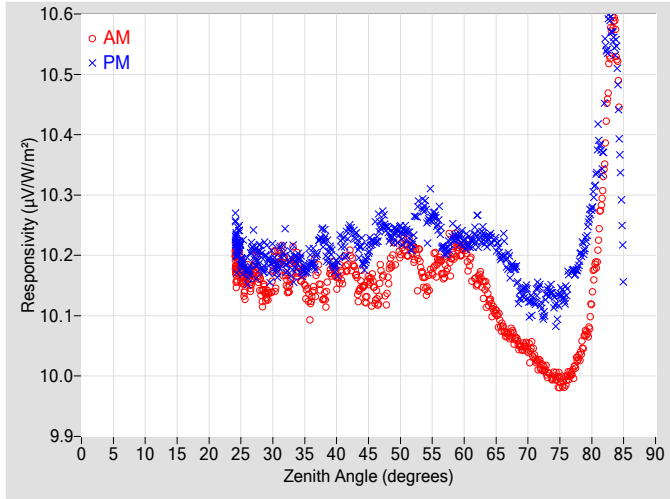


Figure 2. Responsivity vs Local Standard Time

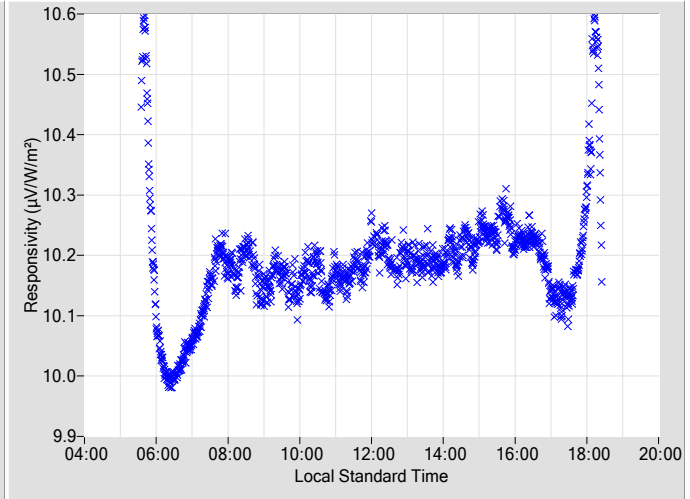
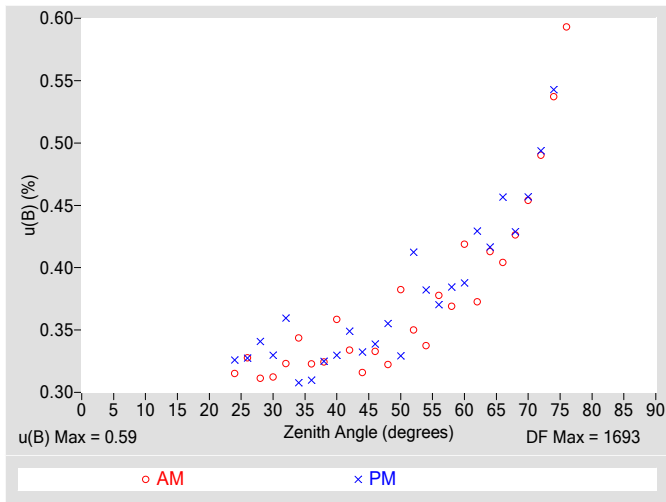


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)

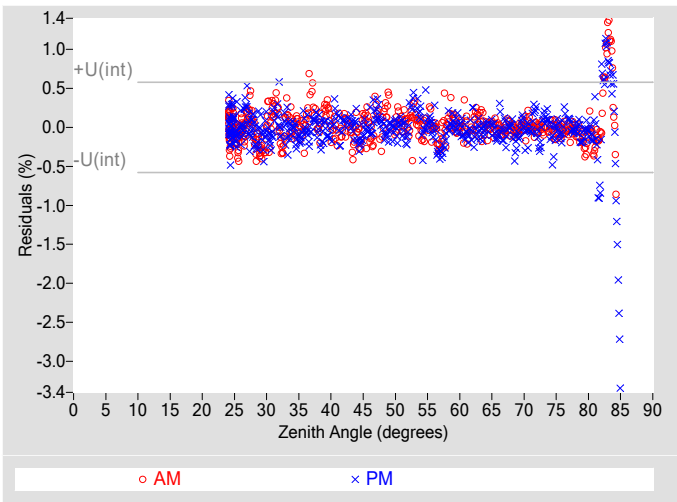
Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) $\pm$ (%)	Azimuth Angle	Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) $\pm$ (%)	Azimuth Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	10.140	0.33	108.52	10.229	0.34	251.64
2	N/A	N/A	N/A	N/A	N/A	N/A	48	10.150	0.32	106.11	10.240	0.36	253.98
4	N/A	N/A	N/A	N/A	N/A	N/A	50	10.207	0.38	103.91	10.239	0.33	256.17
6	N/A	N/A	N/A	N/A	N/A	N/A	52	10.203	0.35	101.89	10.230	0.41	258.20
8	N/A	N/A	N/A	N/A	N/A	N/A	54	10.149	0.34	99.88	10.265	0.38	260.25
10	N/A	N/A	N/A	N/A	N/A	N/A	56	10.191	0.38	97.99	10.253	0.37	262.14
12	N/A	N/A	N/A	N/A	N/A	N/A	58	10.192	0.37	96.17	10.232	0.38	263.97
14	N/A	N/A	N/A	N/A	N/A	N/A	60	10.212	0.42	94.39	10.220	0.39	265.75
16	N/A	N/A	N/A	N/A	N/A	N/A	62	10.156	0.37	92.65	10.241	0.43	267.49
18	N/A	N/A	N/A	N/A	N/A	N/A	64	10.123	0.41	90.95	10.229	0.42	269.19
20	N/A	N/A	N/A	N/A	N/A	N/A	66	10.080	0.40	89.32	10.208	0.46	270.86
22	N/A	N/A	N/A	N/A	N/A	N/A	68	10.062	0.43	87.67	10.175	0.43	272.50
24	10.187	0.32	175.90	10.231	0.33	184.13	70	10.043	0.45	86.05	10.128	0.46	274.13
26	10.167	0.33	155.07	10.173	0.33	205.64	72	10.018	0.49	84.44	10.125	0.49	275.75
28	10.155	0.31	145.12	10.202	0.34	215.10	74	9.9975	0.54	82.80	10.128	0.54	277.35
30	10.173	0.31	137.69	10.199	0.33	222.26	76	9.9944	0.59	81.21	10.141	N/A	278.95
32	10.171	0.32	132.09	10.184	0.36	228.04	78	10.031	N/A	79.61	10.189	N/A	280.59
34	10.179	0.34	127.43	10.196	0.31	232.60	80	10.130	N/A	77.98	10.281	N/A	282.23
36	10.121	0.32	123.27	10.188	0.31	236.84	82	10.357	N/A	76.34	10.473	N/A	283.88
38	10.129	0.32	119.70	10.230	0.32	240.40	84	10.514	N/A	74.64	10.489	N/A	285.57
40	10.163	0.36	116.60	10.181	0.33	243.53	86	N/A	N/A	N/A	N/A	N/A	N/A
42	10.192	0.33	113.54	10.242	0.35	246.50	88	N/A	N/A	N/A	N/A	N/A	N/A
44	10.154	0.32	110.99	10.203	0.33	249.15	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, $u(B)$ (%)	$\pm 0.59$
Type-A Interpolating Function, $u(int)$ (%)	$\pm 0.29$
Combined Standard Uncertainty, $u(c)$ (%)	$\pm 0.66$
Effective degrees of freedom, $DF(c)$	2373
Coverage factor, $k$	1.96
Expanded Uncertainty, $U_{95}$ (%)	$\pm 1.3$
AM Valid zenith angle range	24° to 76°
PM Valid zenith angle range	24° to 74°

‡ 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**

$R @ 45^\circ$ ( $\mu V/W/m^2$ )	$R_{net}$ ( $\mu V/W/m^2$ ) †
10.183	0

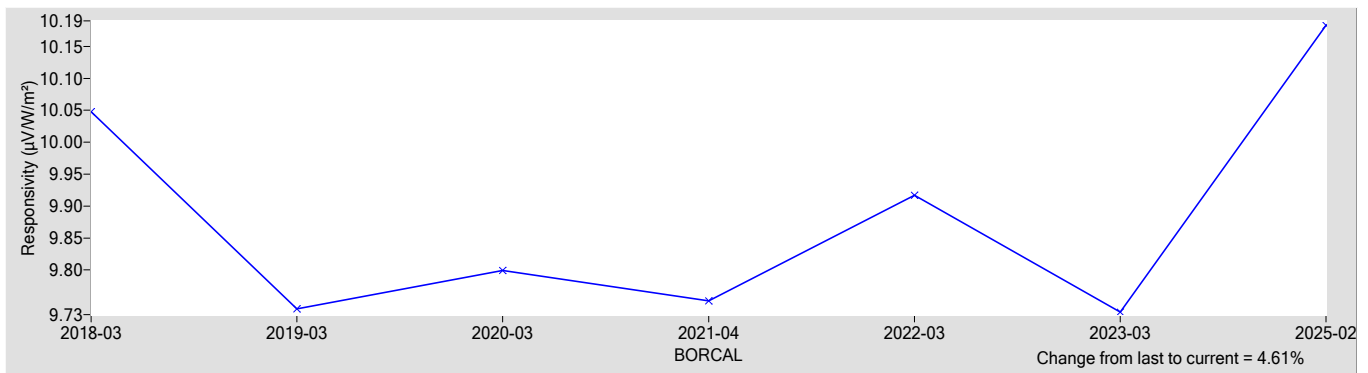
†  $R_{net}$  determination date: N/A

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

Type-B Expanded Uncertainty, $U(B)$ (%)	$\pm 0.82$
Offset Uncertainty, $U(off)$ (%)	+0.80 / -0.60
Expanded Uncertainty, $U$ (%)	+1.6 / -1.4
Effective degrees of freedom, $DF^*$	2120
Coverage factor, $k$	1.96
Valid zenith angle range	30.0° to 60.0°

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

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



**References:**

[1] Reda, I.; Hickey, J.; Long, C.; Myers, D.; Stoffel, T.; Wilcox, S.; Michalsky, J. J.; Dutton, E. G.; Nelson, D. (2005). "Using a Blackbody to Calculate Net Longwave Responsivity of Shortwave Solar Pyranometers to Correct for Their Thermal Offset Error During Outdoor Calibration Using the Component Sum Method." *Journal of Atmospheric and Oceanic Technology*, 2005; pp. 1531-1540; NREL Report No. JA-560-36646. doi:10.1175/JTECH1782.1

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

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[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:** Silicon Pyranometer      **Manufacturer:** Licor  
**Model:** LI200      **Serial Number:** PY28257  
**Calibration Date:** 5/2/2025      **Due Date:** 5/2/2026  
**Customer:** NREL-SRRL-BMS      **Environmental Conditions:** see page 4  
**Test Dates:** 5/2

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	09/27/2024	09/27/2025
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/21/2025	04/21/2026
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/21/2025	04/21/2026
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/07/2025	02/07/2027
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/07/2025	02/07/2027

† 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, RCC, and Shawn L. Jaker

Ibrahim Reda, Technical Manager

05/05/2025

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 ( $\text{W}/\text{m}^2$ ),
  - =  $W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
  - where,  $W_{in}$  = incoming infrared ( $\text{W}/\text{m}^2$ ),  $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$ ,
  - $T_c$  = case temperature of pyrgeometer (K).
- $I$  = reference irradiance ( $\text{W}/\text{m}^2$ ), beam (B) or global (G)  
 where,  $G = B * \text{COS}(Z) + D$ ,  
 $Z$  = zenith angle (degrees),  
 $D$  = reference diffuse irradiance ( $\text{W}/\text{m}^2$ ).

Figure 1. Responsivity vs Zenith Angle

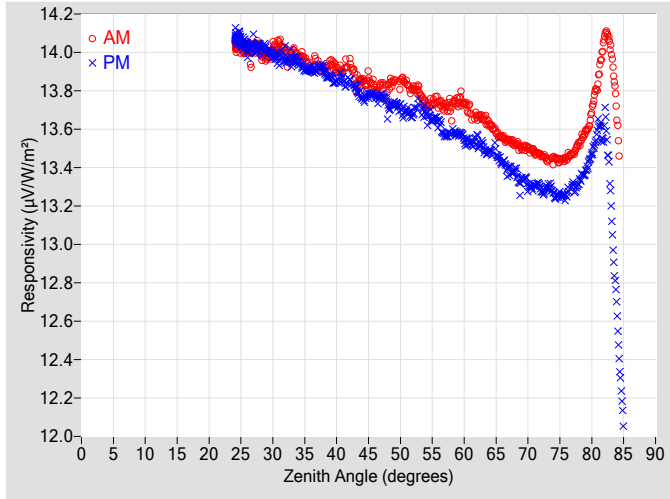


Figure 2. Responsivity vs Local Standard Time

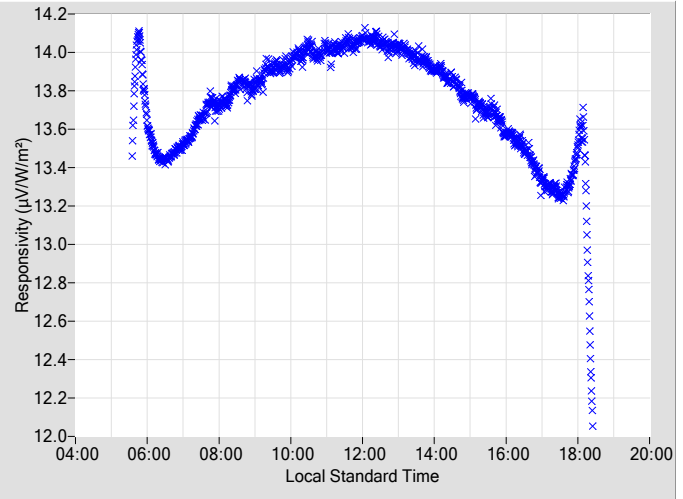
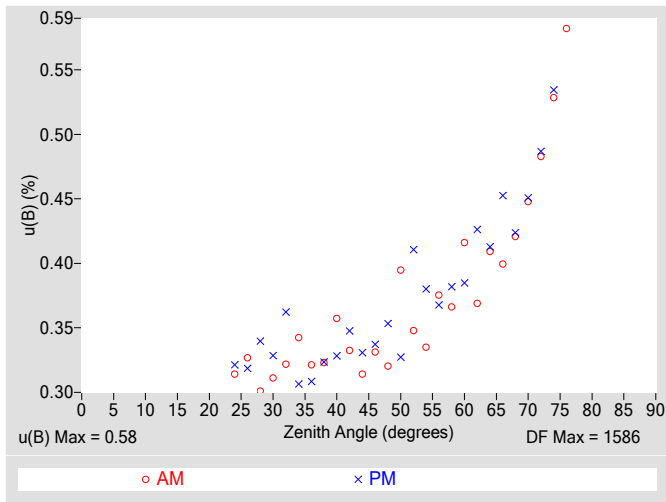


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty,  $u(B)$

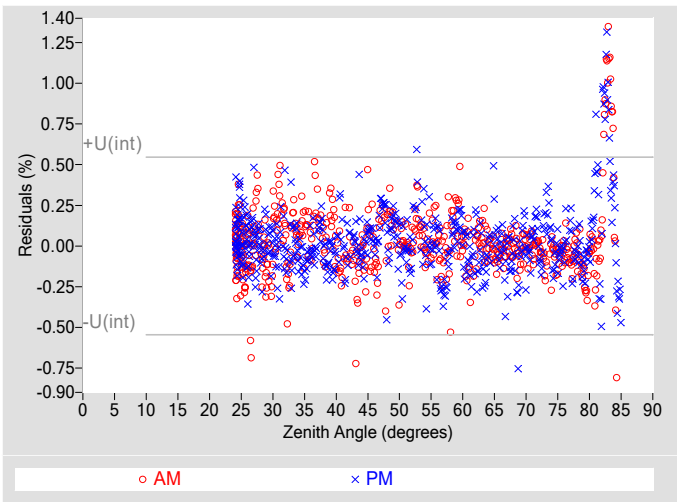
Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	AM $u(B)$ $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	PM $u(B)$ $\pm$ (%)	Azimuth Angle	Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	AM $u(B)$ $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	PM $u(B)$ $\pm$ (%)	Azimuth Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	13.818	0.33	108.52	13.774	0.34	251.64
2	N/A	N/A	N/A	N/A	N/A	N/A	48	13.802	0.32	106.11	13.714	0.35	253.98
4	N/A	N/A	N/A	N/A	N/A	N/A	50	13.858	0.39	103.88	13.710	0.33	256.17
6	N/A	N/A	N/A	N/A	N/A	N/A	52	13.809	0.35	101.89	13.679	0.41	258.20
8	N/A	N/A	N/A	N/A	N/A	N/A	54	13.729	0.33	99.88	13.677	0.38	260.25
10	N/A	N/A	N/A	N/A	N/A	N/A	56	13.739	0.38	97.99	13.633	0.37	262.14
12	N/A	N/A	N/A	N/A	N/A	N/A	58	13.715	0.37	96.17	13.582	0.38	263.97
14	N/A	N/A	N/A	N/A	N/A	N/A	60	13.735	0.42	94.39	13.540	0.38	265.75
16	N/A	N/A	N/A	N/A	N/A	N/A	62	13.669	0.37	92.65	13.543	0.43	267.49
18	N/A	N/A	N/A	N/A	N/A	N/A	64	13.626	0.41	90.95	13.487	0.41	269.19
20	N/A	N/A	N/A	N/A	N/A	N/A	66	13.559	0.40	89.32	13.428	0.45	270.86
22	N/A	N/A	N/A	N/A	N/A	N/A	68	13.523	0.42	87.67	13.379	0.42	272.50
24	14.049	0.31	175.90	14.072	0.32	184.16	70	13.501	0.45	86.05	13.310	0.45	274.13
26	14.029	0.33	155.07	14.024	0.32	205.04	72	13.466	0.48	84.44	13.288	0.49	275.75
28	13.991	0.30	144.76	14.031	0.34	215.10	74	13.451	0.53	82.79	13.263	0.53	277.35
30	14.010	0.31	137.69	13.987	0.33	222.26	76	13.449	0.58	81.21	13.260	N/A	278.95
32	13.992	0.32	132.09	13.967	0.36	228.00	78	13.522	N/A	79.61	13.323	N/A	280.59
34	13.980	0.34	127.43	13.956	0.31	232.60	80	13.692	N/A	77.98	13.474	N/A	282.23
36	13.908	0.32	123.27	13.908	0.31	236.84	82	14.070	N/A	76.34	13.612	N/A	283.88
38	13.909	0.32	119.70	13.907	0.32	240.40	84	13.629	N/A	74.64	12.587	N/A	285.57
40	13.915	0.36	116.60	13.852	0.33	243.53	86	N/A	N/A	N/A	N/A	N/A	N/A
42	13.938	0.33	113.54	13.850	0.35	246.50	88	N/A	N/A	N/A	N/A	N/A	N/A
44	13.856	0.31	110.99	13.766	0.33	249.15	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, $u(B)$ (%)	$\pm 0.58$
Type-A Interpolating Function, $u(int)$ (%)	$\pm 0.27$
Combined Standard Uncertainty, $u(c)$ (%)	$\pm 0.64$
Effective degrees of freedom, $DF(c)$	2195
Coverage factor, $k$	1.96
Expanded Uncertainty, $U95$ (%)	$\pm 1.3$
AM Valid zenith angle range	24° to 76°
PM Valid zenith angle range	24° to 74°

‡ 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**

$R @ 45^\circ$ ( $\mu V/W/m^2$ )	$R_{net}$ ( $\mu V/W/m^2$ ) †
13.819	0

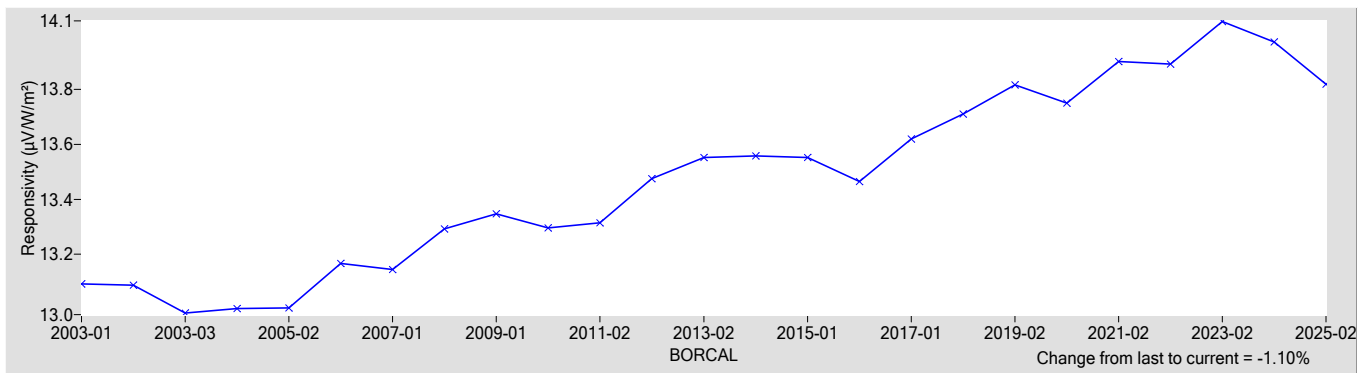
† Rnet determination date: N/A

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

Type-B Expanded Uncertainty, $U(B)$ (%)	$\pm 0.82$
Offset Uncertainty, $U(off)$ (%)	+1.4 / -2.0
Expanded Uncertainty, $U$ (%)	+2.2 / -2.8
Effective degrees of freedom, $DF^*$	2068
Coverage factor, $k$	1.96
Valid zenith angle range	30.0° to 60.0°

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

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



**References:**

- [1] Reda, I.; Hickey, J.; Long, C.; Myers, D.; Stoffel, T.; Wilcox, S.; Michalsky, J. J.; Dutton, E. G.; Nelson, D. (2005). "Using a Blackbody to Calculate Net Longwave Responsivity of Shortwave Solar Pyranometers to Correct for Their Thermal Offset Error During Outdoor Calibration Using the Component Sum Method." Journal of Atmospheric and Oceanic Technology. , 2005; pp. 1531-1540; NREL Report No. JA-560-36646. doi:10.1175/JTECH1782.1
- [2] Reda, I.; Myers, D.; Stoffel, T. (2008). "Uncertainty Estimate for the Outdoor Calibration of Solar Pyranometers: A Metrologist Perspective." Measure. (NCSLI Journal of Measurement Science). Vol. 3(4), December 2008; pp. 58-66; NREL Report No. JA-581-4137
- [3] Reda, I.; Andreas, A. (2004). "Solar Position Algorithm for Solar Radiation Applications." Solar Energy. Vol. 76(5), 2004; pp. 577-589; NREL Report No. JA-560-35518. doi:10.1016/j.solener.2003.12.003
- [4] Stoffel, T.; Reda, I. (2009). "NREL Pyrheliometer Comparisons: 22 September - 3 October 2008 (NPC-2008)." 54 pp.; NREL Report No. TP-550-45016.
- [5] Reda, I.; Stoffel, T.; Myers, D. (2003). "Method to Calibrate a Solar Pyranometer for Measuring Reference Diffuse Irradiance." Solar Energy. Vol. 74, 2003; pp. 103-112; NREL Report No. JA-560-35025. doi:10.1016/S0038-092X(03)00124-5
- [6] Reda, I. (1996). Calibration of a Solar Absolute Cavity Radiometer with Traceability to the World Radiometric Reference. 79 pp.; NREL Report No. TP-463-20619.
- [7] Reda, I.; Gröbner, J.; Stoffel, T.; Myers, D.; Forgan, B. (2008). Improvements in the Blackbody Calibration of 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:** PY66482  
**Calibration Date:** 5/2/2025      **Due Date:** 5/2/2026  
**Customer:** NREL-SRRL-BMS      **Environmental Conditions:** see page 4  
**Test Dates:** 5/2

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	09/27/2024	09/27/2025
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/21/2025	04/21/2026
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/21/2025	04/21/2026
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/07/2025	02/07/2027
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/07/2025	02/07/2027

† 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, RCC, and Shawn L. Jaker

Ibrahim Reda, Technical Manager

05/05/2025

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

## PY66482 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 ( $\text{W}/\text{m}^2$ ),
  - =  $W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
  - where,  $W_{in}$  = incoming infrared ( $\text{W}/\text{m}^2$ ),  $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$ ,
  - $T_c$  = case temperature of pyrgeometer (K).
- $I$  = reference irradiance ( $\text{W}/\text{m}^2$ ), beam (B) or global (G)  
 where,  $G = B * \text{COS}(Z) + D$ ,  
 $Z$  = zenith angle (degrees),  
 $D$  = reference diffuse irradiance ( $\text{W}/\text{m}^2$ ).

Figure 1. Responsivity vs Zenith Angle

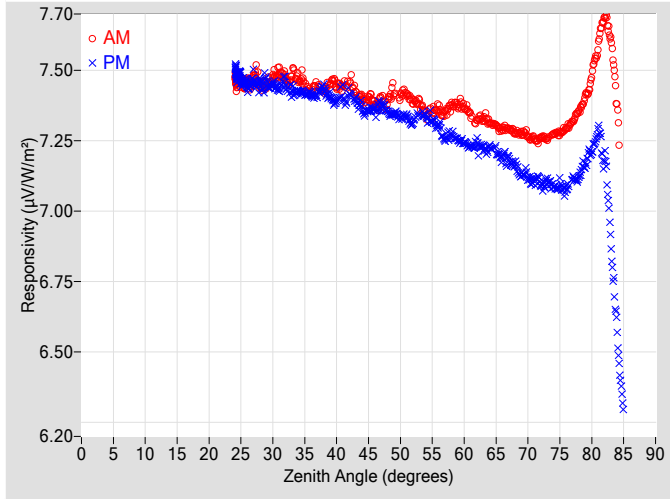


Figure 2. Responsivity vs Local Standard Time

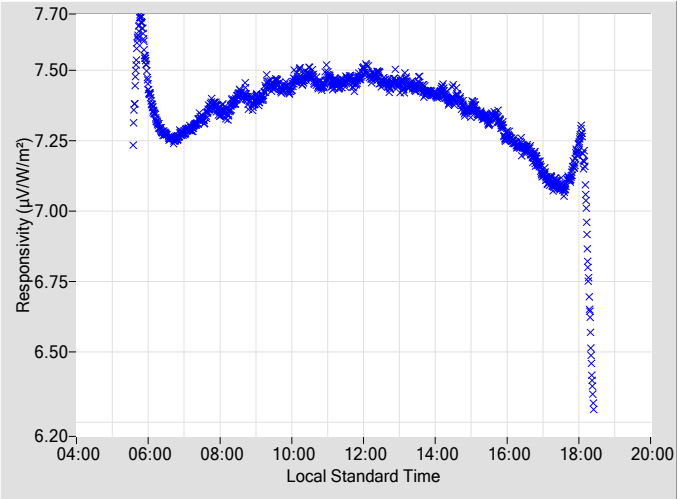
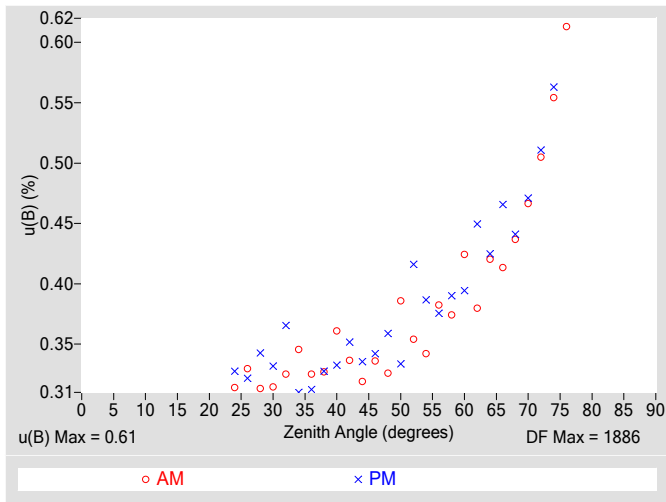


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)

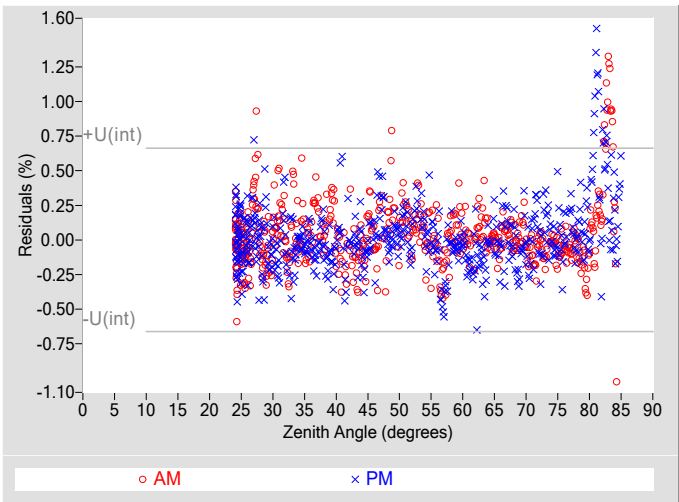
Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) $\pm$ (%)	Azimuth Angle	Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) $\pm$ (%)	Azimuth Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	7.3831	0.34	108.52	7.3565	0.34	251.64
2	N/A	N/A	N/A	N/A	N/A	N/A	48	7.3900	0.33	106.11	7.3522	0.36	253.98
4	N/A	N/A	N/A	N/A	N/A	N/A	50	7.4079	0.39	103.91	7.3320	0.33	256.17
6	N/A	N/A	N/A	N/A	N/A	N/A	52	7.3895	0.35	101.89	7.3153	0.42	258.20
8	N/A	N/A	N/A	N/A	N/A	N/A	54	7.3433	0.34	99.88	7.3330	0.39	260.25
10	N/A	N/A	N/A	N/A	N/A	N/A	56	7.3637	0.38	97.99	7.3051	0.38	262.14
12	N/A	N/A	N/A	N/A	N/A	N/A	58	7.3732	0.37	96.17	7.2713	0.39	263.97
14	N/A	N/A	N/A	N/A	N/A	N/A	60	7.3684	0.42	94.39	7.2419	0.39	265.75
16	N/A	N/A	N/A	N/A	N/A	N/A	62	7.3211	0.38	92.65	7.2446	0.45	267.44
18	N/A	N/A	N/A	N/A	N/A	N/A	64	7.3152	0.42	90.95	7.2274	0.42	269.19
20	N/A	N/A	N/A	N/A	N/A	N/A	66	7.2920	0.41	89.32	7.1912	0.47	270.86
22	N/A	N/A	N/A	N/A	N/A	N/A	68	7.2801	0.44	87.67	7.1627	0.44	272.50
24	7.4701	0.31	176.08	7.4980	0.33	184.13	70	7.2670	0.47	86.05	7.1201	0.47	274.13
26	7.4580	0.33	155.07	7.4458	0.32	205.04	72	7.2605	0.50	84.44	7.0950	0.51	275.75
28	7.4456	0.31	145.12	7.4536	0.34	215.10	74	7.2729	0.55	82.80	7.0879	0.56	277.35
30	7.4725	0.31	137.69	7.4517	0.33	222.26	76	7.2950	0.61	81.21	7.0773	N/A	278.95
32	7.4734	0.33	132.09	7.4443	0.37	228.00	78	7.3541	N/A	79.61	7.1216	N/A	280.59
34	7.4700	0.35	127.43	7.4255	0.31	232.60	80	7.4819	N/A	77.98	7.2122	N/A	282.23
36	7.4232	0.33	123.27	7.4125	0.31	236.84	82	7.6831	N/A	76.34	7.1764	N/A	283.88
38	7.4276	0.33	119.70	7.4353	0.33	240.40	84	7.3523	N/A	74.64	6.5493	N/A	285.57
40	7.4468	0.36	116.60	7.3917	0.33	243.53	86	N/A	N/A	N/A	N/A	N/A	N/A
42	7.4649	0.34	113.54	7.4179	0.35	246.50	88	N/A	N/A	N/A	N/A	N/A	N/A
44	7.4041	0.32	110.99	7.3665	0.34	249.15	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, $u(B)$ (%)	$\pm 0.61$
Type-A Interpolating Function, $u(int)$ (%)	$\pm 0.33$
Combined Standard Uncertainty, $u(c)$ (%)	$\pm 0.70$
Effective degrees of freedom, $DF(c)$	2718
Coverage factor, $k$	1.96
Expanded Uncertainty, $U95$ (%)	$\pm 1.4$
AM Valid zenith angle range	24° to 76°
PM Valid zenith angle range	24° to 74°

‡ 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**

$R @ 45^\circ$ ( $\mu V/W/m^2$ )	$R_{net}$ ( $\mu V/W/m^2$ ) †
7.3814	0

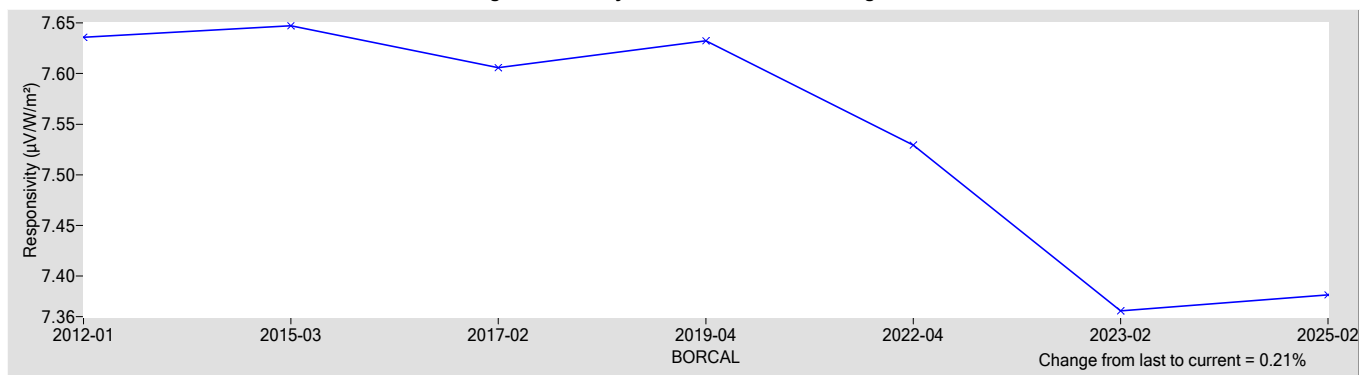
†  $R_{net}$  determination date: N/A

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

Type-B Expanded Uncertainty, $U(B)$ (%)	$\pm 0.83$
Offset Uncertainty, $U(off)$ (%)	+1.2 / -1.9
Expanded Uncertainty, $U$ (%)	+2.1 / -2.7
Effective degrees of freedom, $DF^*$	2222
Coverage factor, $k$	1.96
Valid zenith angle range	30.0° to 60.0°

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

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



## References:

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



# National Renewable Energy Laboratory

## Solar Radiation Research Laboratory

### Metrology Laboratory

### Calibration Certificate



<b>Test Instrument:</b>	Semiconductor Pyrheliometer	<b>Manufacturer:</b>	Licor
<b>Model:</b>	LI201SB	<b>Serial Number:</b>	PYHR101
<b>Calibration Date:</b>	5/2/2025	<b>Due Date:</b>	5/2/2026
<b>Customer:</b>	NREL-SRRL-BMS	<b>Environmental Conditions:</b>	see page 4
<b>Test Dates:</b>	5/2		

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	09/27/2024	09/27/2025
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/21/2025	04/21/2026
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/21/2025	04/21/2026
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/07/2025	02/07/2027
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/07/2025	02/07/2027

† 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, RCC, and Shawn L. Jaker

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Ibrahim Reda, Technical Manager

05/05/2025

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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 ( $\text{W}/\text{m}^2$ ),
- $= W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
- where,  $W_{in}$  = incoming infrared ( $\text{W}/\text{m}^2$ ),  $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$ ,
- $T_c$  = case temperature of pyrgeometer (K).
- $I$  = reference irradiance ( $\text{W}/\text{m}^2$ ), beam (B) or global (G)
- where,  $G = B * \text{COS}(Z) + D$ ,
- $Z$  = zenith angle (degrees),
- $D$  = reference diffuse irradiance ( $\text{W}/\text{m}^2$ ).

Figure 1. Responsivity vs Zenith Angle

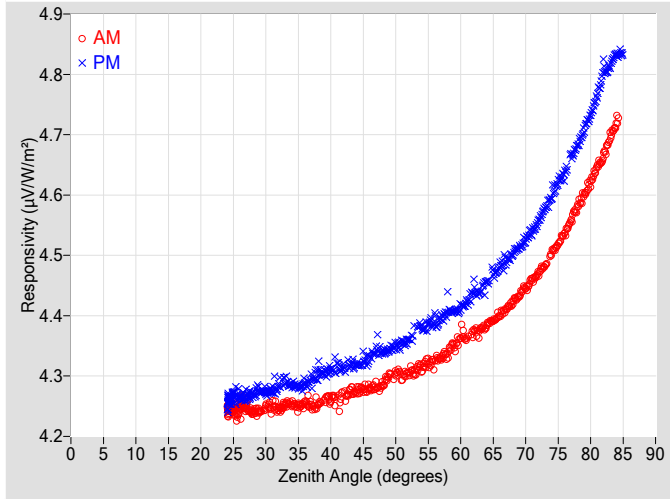


Figure 2. Responsivity vs Local Standard Time

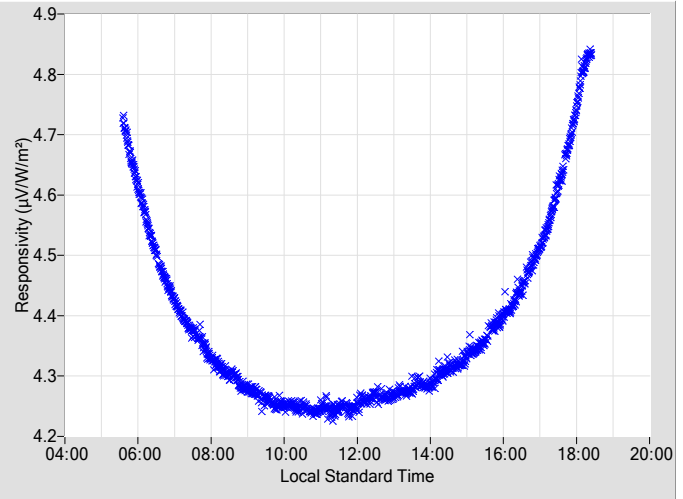
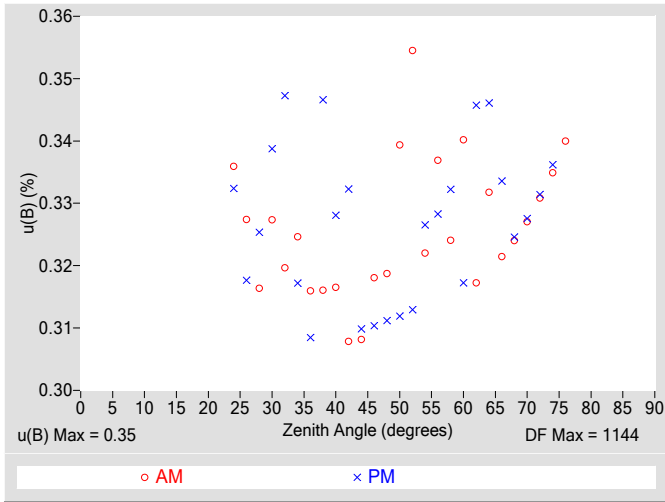


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty,  $u(B)$

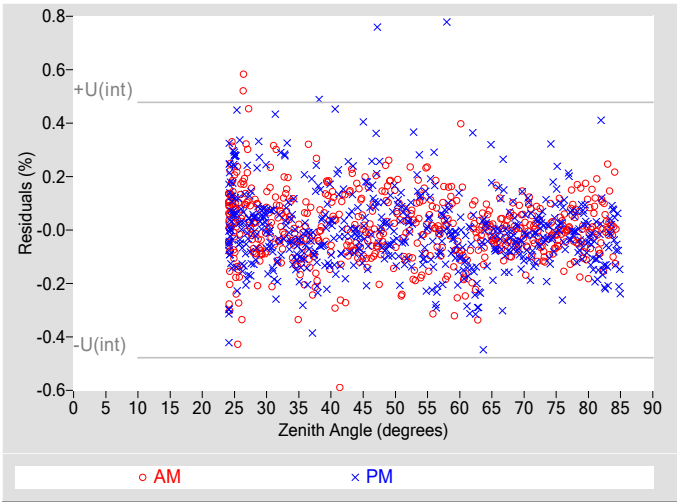
Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	$u(B)$ $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	$u(B)$ $\pm$ (%)	Azimuth Angle	Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	$u(B)$ $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	$u(B)$ $\pm$ (%)	Azimuth Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	4.2800	0.32	108.52	4.3279	0.31	251.60
2	N/A	N/A	N/A	N/A	N/A	N/A	48	4.2847	0.32	106.17	4.3400	0.31	253.99
4	N/A	N/A	N/A	N/A	N/A	N/A	50	4.3028	0.34	103.98	4.3491	0.31	256.17
6	N/A	N/A	N/A	N/A	N/A	N/A	52	4.3046	0.35	101.86	4.3593	0.31	258.20
8	N/A	N/A	N/A	N/A	N/A	N/A	54	4.3144	0.32	99.89	4.3791	0.33	260.25
10	N/A	N/A	N/A	N/A	N/A	N/A	56	4.3247	0.34	97.99	4.3921	0.33	262.14
12	N/A	N/A	N/A	N/A	N/A	N/A	58	4.3365	0.32	96.17	4.4050	0.33	263.97
14	N/A	N/A	N/A	N/A	N/A	N/A	60	4.3675	0.34	94.36	4.4143	0.32	265.76
16	N/A	N/A	N/A	N/A	N/A	N/A	62	4.3730	0.32	92.65	4.4440	0.35	267.49
18	N/A	N/A	N/A	N/A	N/A	N/A	64	4.3836	0.33	90.95	4.4559	0.35	269.19
20	N/A	N/A	N/A	N/A	N/A	N/A	66	4.4009	0.32	89.28	4.4813	0.33	270.86
22	N/A	N/A	N/A	N/A	N/A	N/A	68	4.4223	0.32	87.68	4.5031	0.32	272.50
24	4.2452	0.34	175.89	4.2570	0.33	184.01	70	4.4460	0.33	86.05	4.5269	0.33	274.13
26	4.2431	0.33	155.00	4.2655	0.32	205.16	72	4.4702	0.33	84.44	4.5574	0.33	275.75
28	4.2402	0.32	144.96	4.2700	0.33	215.35	74	4.5042	0.33	82.80	4.5992	0.34	277.35
30	4.2475	0.33	138.04	4.2726	0.34	222.35	76	4.5357	0.34	81.21	4.6367	N/A	278.95
32	4.2444	0.32	132.10	4.2853	0.35	228.05	78	4.5802	N/A	79.62	4.6836	N/A	280.59
34	4.2540	0.32	127.27	4.2861	0.32	232.61	80	4.6216	N/A	77.98	4.7337	N/A	282.23
36	4.2547	0.32	123.19	4.2877	0.31	236.84	82	4.6644	N/A	76.35	4.8073	N/A	283.88
38	4.2537	0.32	119.79	4.3031	0.35	240.40	84	4.7200	N/A	74.65	4.8322	N/A	285.57
40	4.2606	0.32	116.56	4.3106	0.33	243.55	86	N/A	N/A	N/A	N/A	N/A	N/A
42	4.2689	0.31	113.54	4.3138	0.33	246.53	88	N/A	N/A	N/A	N/A	N/A	N/A
44	4.2748	0.31	110.99	4.3190	0.31	249.15	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, $u(B)$ (%)	$\pm 0.35$
Type-A Interpolating Function, $u(int)$ (%)	$\pm 0.24$
Combined Standard Uncertainty, $u(c)$ (%)	$\pm 0.43$
Effective degrees of freedom, $DF(c)$	1965
Coverage factor, $k$	1.96
Expanded Uncertainty, $U_{95}$ (%)	$\pm 0.84$
AM Valid zenith angle range	24° to 76°
PM Valid zenith angle range	24° to 74°

‡ 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**

$R @ 45^\circ$ ( $\mu V/W/m^2$ )	$R_{net}$ ( $\mu V/W/m^2$ ) †
4.3024	0

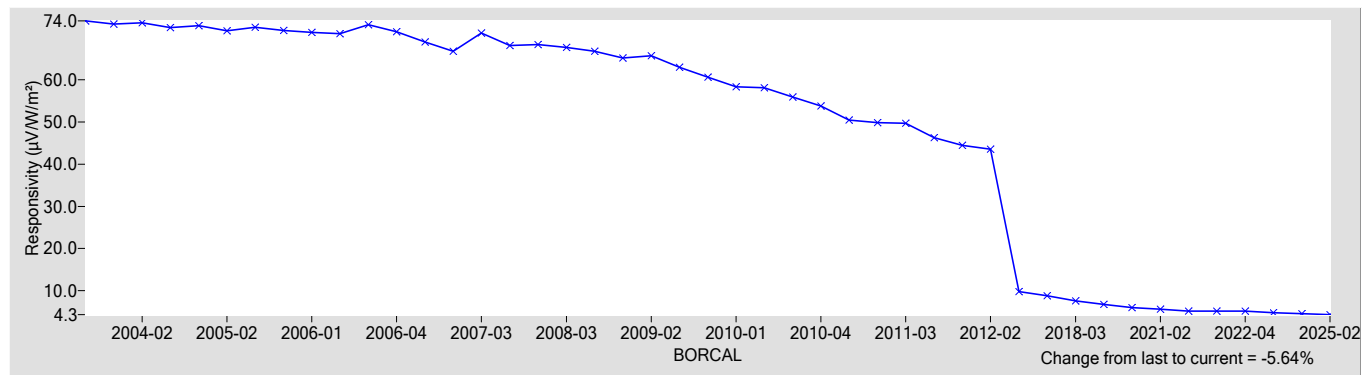
†  $R_{net}$  determination date: N/A

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

Type-B Expanded Uncertainty, $U(B)$ (%)	$\pm 0.70$
Offset Uncertainty, $U(off)$ (%)	+2.6 / -1.3
Expanded Uncertainty, $U$ (%)	+3.3 / -2.0
Effective degrees of freedom, $DF^*$	1144
Coverage factor, $k$	1.96
Valid zenith angle range	30.0° to 60.0°

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

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



**References:**

[1] Reda, I.; Hickey, J.; Long, C.; Myers, D.; Stoffel, T.; Wilcox, S.; Michalsky, J. J.; Dutton, E. G.; Nelson, D. (2005). "Using a Blackbody to Calculate Net Longwave Responsivity of Shortwave Solar Pyranometers to Correct for Their Thermal Offset Error During Outdoor Calibration Using the Component Sum Method." *Journal of Atmospheric and Oceanic Technology*, 2005; pp. 1531-1540; NREL Report No. JA-560-36646. doi:10.1175/JTECH1782.1

[2] Reda, I.; Myers, D.; Stoffel, T. (2008). "Uncertainty Estimate for the Outdoor Calibration of Solar Pyranometers: A Metrologist Perspective." *Measure*. (NCSLI Journal of Measurement Science). Vol. 3(4), December 2008; pp. 58-66; NREL Report No. JA-581-4137

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

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

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

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

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



# National Renewable Energy Laboratory

## Solar Radiation Research Laboratory

### Metrology Laboratory

### Calibration Certificate



<b>Test Instrument:</b>	Pyranometer	<b>Manufacturer:</b>	EKO
<b>Model:</b>	MS-602	<b>Serial Number:</b>	S13071483
<b>Calibration Date:</b>	5/2/2025	<b>Due Date:</b>	5/2/2026
<b>Customer:</b>	NREL-SRRL-BMS	<b>Environmental Conditions:</b>	see page 4
<b>Test Dates:</b>	5/2		

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	09/27/2024	09/27/2025
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/21/2025	04/21/2026
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/21/2025	04/21/2026
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/07/2025	02/07/2027
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/07/2025	02/07/2027
Infrared Irradiance ‡	Kipp & Zonen Pyrgeometer Model CG4, S/N FT002	03/31/2022	03/31/2027

† Through the World Radiometric Reference (WRR)

‡ Through the World Infrared Standard Group (WISG)

**Number of pages of certificate:** 4

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

**Setup:** Radiometers are calibrated outdoors, using the sun as the source. Pyranometers and pyrgeometers are installed for horizontal measurements, with their signal connectors oriented north, if their design permits.

The shading disk for the reference diffuse subtends a solid angle of 5°. Pyrheliometers are installed on solar trackers.

**Calibrated by:** Afshin Andreas, RCC, and Shawn L. Jaker

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Ibrahim Reda, Technical Manager

05/05/2025

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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:

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

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 ( $\text{W}/\text{m}^2$ ),
  - =  $W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
  - where,  $W_{in}$  = incoming infrared ( $\text{W}/\text{m}^2$ ),  $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$ ,
  - $T_c$  = case temperature of pyrgeometer (K).
- $I$  = reference irradiance ( $\text{W}/\text{m}^2$ ), beam (B) or global (G)  
 where,  $G = B * \text{COS}(Z) + D$ ,  
 $Z$  = zenith angle (degrees),  
 $D$  = reference diffuse irradiance ( $\text{W}/\text{m}^2$ ).

Figure 1. Responsivity vs Zenith Angle

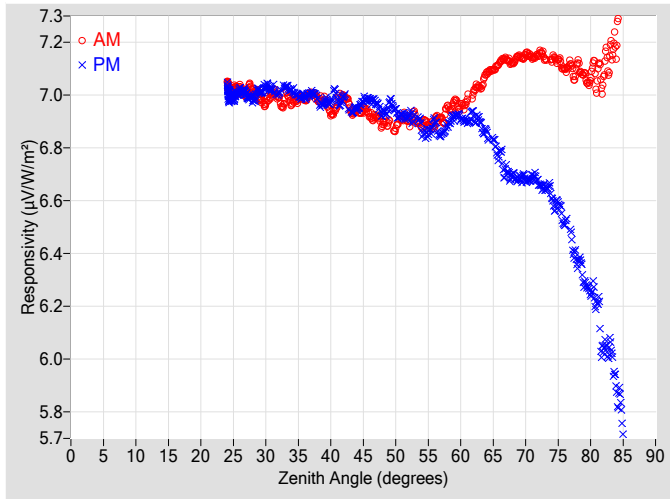


Figure 2. Responsivity vs Local Standard Time

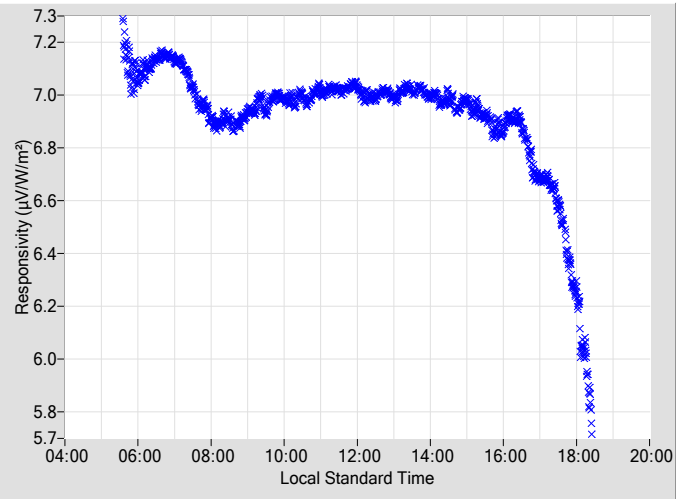
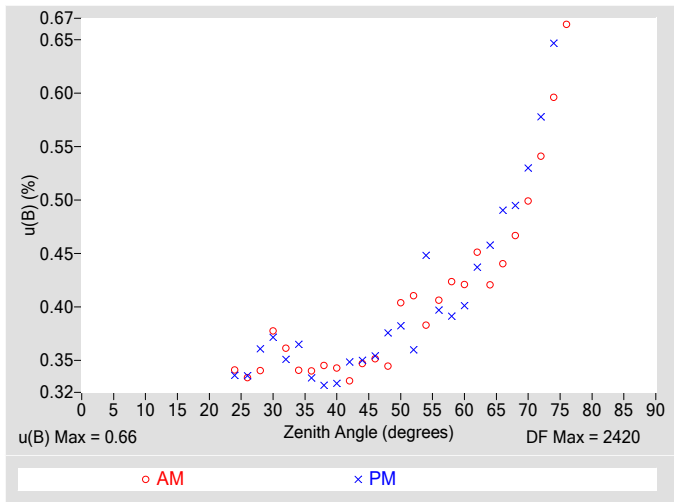


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)

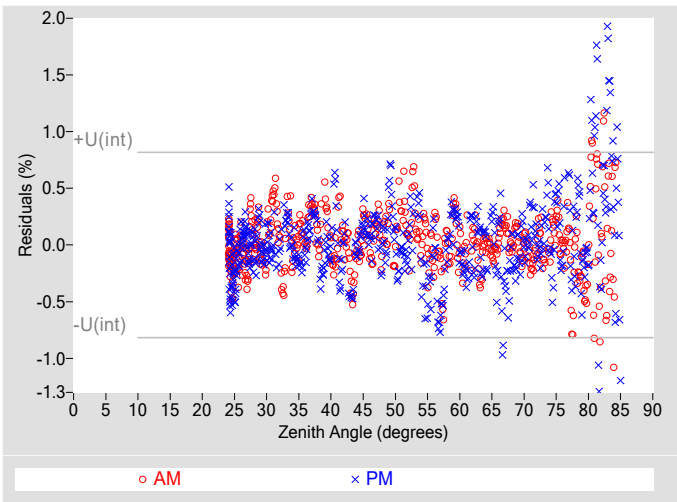
Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) $\pm$ (%)	Azimuth Angle	Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) $\pm$ (%)	Azimuth Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	6.9249	0.35	108.43	6.9810	0.35	251.67
2	N/A	N/A	N/A	N/A	N/A	N/A	48	6.8869	0.34	106.15	6.9334	0.38	254.02
4	N/A	N/A	N/A	N/A	N/A	N/A	50	6.8753	0.40	103.95	6.9382	0.38	256.15
6	N/A	N/A	N/A	N/A	N/A	N/A	52	6.8974	0.41	101.89	6.9192	0.36	258.24
8	N/A	N/A	N/A	N/A	N/A	N/A	54	6.8859	0.38	99.89	6.8740	0.45	260.20
10	N/A	N/A	N/A	N/A	N/A	N/A	56	6.8944	0.41	98.03	6.8998	0.40	262.12
12	N/A	N/A	N/A	N/A	N/A	N/A	58	6.9536	0.42	96.15	6.8898	0.39	264.03
14	N/A	N/A	N/A	N/A	N/A	N/A	60	6.9564	0.42	94.42	6.9142	0.40	265.74
16	N/A	N/A	N/A	N/A	N/A	N/A	62	7.0078	0.45	92.68	6.9220	0.44	267.47
18	N/A	N/A	N/A	N/A	N/A	N/A	64	7.0820	0.42	90.98	6.8557	0.46	269.18
20	N/A	N/A	N/A	N/A	N/A	N/A	66	7.1221	0.44	89.31	6.7757	0.49	270.84
22	N/A	N/A	N/A	N/A	N/A	N/A	68	7.1215	0.47	87.66	6.6997	0.49	272.49
24	7.0376	0.34	176.00	7.0126	0.34	184.17	70	7.1549	0.50	86.03	6.6811	0.53	274.12
26	7.0261	0.33	155.33	7.0143	0.34	205.14	72	7.1561	0.54	84.42	6.6679	0.58	275.73
28	7.0128	0.34	144.91	6.9881	0.36	215.36	74	7.1364	0.60	82.79	6.6135	0.65	277.38
30	6.9707	0.38	137.85	7.0339	0.37	222.37	76	7.0986	0.66	81.19	6.5163	N/A	278.98
32	6.9861	0.36	132.14	7.0104	0.35	228.12	78	7.1180	N/A	79.60	6.3655	N/A	280.57
34	6.9773	0.34	127.40	7.0201	0.36	232.77	80	7.0664	N/A	77.97	6.2528	N/A	282.21
36	6.9809	0.34	123.12	6.9950	0.33	236.81	82	7.0640	N/A	76.33	6.0491	N/A	283.86
38	6.9842	0.35	119.76	6.9835	0.33	240.37	84	7.2195	N/A	74.67	5.8705	N/A	285.56
40	6.9311	0.34	116.52	6.9752	0.33	243.52	86	N/A	N/A	N/A	N/A	N/A	N/A
42	6.9948	0.33	113.66	6.9934	0.35	246.46	88	N/A	N/A	N/A	N/A	N/A	N/A
44	6.9453	0.35	110.90	6.9504	0.35	249.20	90	N/A	N/A	N/A	N/A	N/A	N/A

N/A - Not Available

**Figure 3. Type-B Standard Uncertainty vs Zenith Angle**



**Figure 4. Residuals from Spline Interpolation**



**Table 3. Uncertainty using Spline Interpolation ‡**

Type-B Standard Uncertainty, $u(B)$ (%)	$\pm 0.66$
Type-A Interpolating Function, $u(int)$ (%)	$\pm 0.41$
Combined Standard Uncertainty, $u(c)$ (%)	$\pm 0.78$
Effective degrees of freedom, $DF(c)$	3427
Coverage factor, $k$	1.96
Expanded Uncertainty, $U_{95}$ (%)	$\pm 1.5$
AM Valid zenith angle range	24° to 76°
PM Valid zenith angle range	24° to 74°

‡ 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**

$R @ 45^\circ$ ( $\mu V/W/m^2$ )	$R_{net}$ ( $\mu V/W/m^2$ ) †
6.9633	0.30000

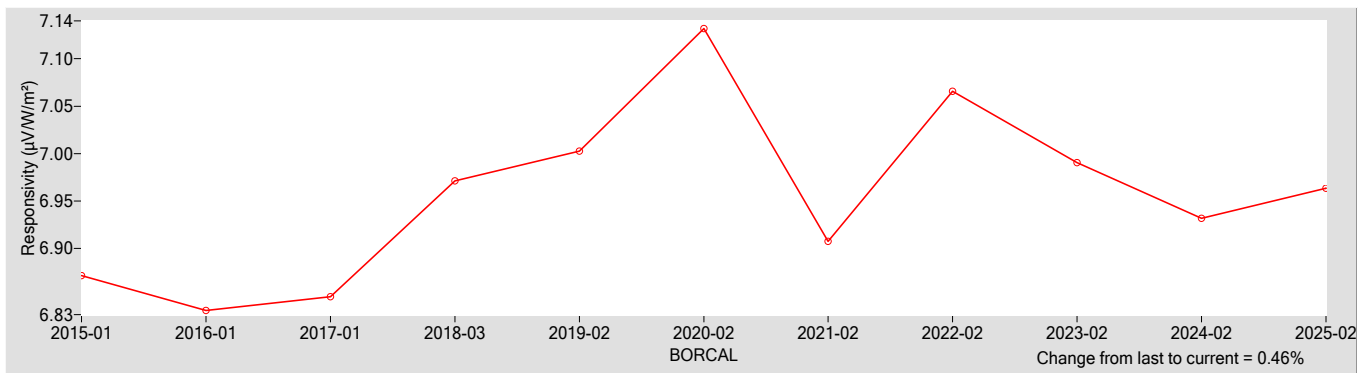
†  $R_{net}$  determination date: Estimated

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

Type-B Expanded Uncertainty, $U(B)$ (%)	$\pm 0.88$
Offset Uncertainty, $U(off)$ (%)	+1.0 / -1.3
Expanded Uncertainty, $U$ (%)	+1.9 / -2.2
Effective degrees of freedom, $DF^*$	2170
Coverage factor, $k$	1.96
Valid zenith angle range	30.0° to 60.0°

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

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



**References:**

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



# National Renewable Energy Laboratory

## Solar Radiation Research Laboratory

### Metrology Laboratory

### Calibration Certificate



<b>Test Instrument:</b>	Silicon Pyranometer	<b>Manufacturer:</b>	EKO
<b>Model:</b>	ML-01	<b>Serial Number:</b>	S13135063
<b>Calibration Date:</b>	5/2/2025	<b>Due Date:</b>	5/2/2026
<b>Customer:</b>	NREL-SRRL-BMS	<b>Environmental Conditions:</b>	see page 4
<b>Test Dates:</b>	5/2		

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	09/27/2024	09/27/2025
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/21/2025	04/21/2026
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/21/2025	04/21/2026
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/07/2025	02/07/2027
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/07/2025	02/07/2027

† 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, RCC, and Shawn L. Jaker

\_\_\_\_\_  
Ibrahim Reda, Technical Manager

05/05/2025

\_\_\_\_\_  
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:

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

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 ( $\text{W}/\text{m}^2$ ),
  - =  $W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
  - where,  $W_{in}$  = incoming infrared ( $\text{W}/\text{m}^2$ ),  $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$ ,
  - $T_c$  = case temperature of pyrgeometer (K).
- $I$  = reference irradiance ( $\text{W}/\text{m}^2$ ), beam (B) or global (G)  
 where,  $G = B * \text{COS}(Z) + D$ ,  
 $Z$  = zenith angle (degrees),  
 $D$  = reference diffuse irradiance ( $\text{W}/\text{m}^2$ ).

Figure 1. Responsivity vs Zenith Angle

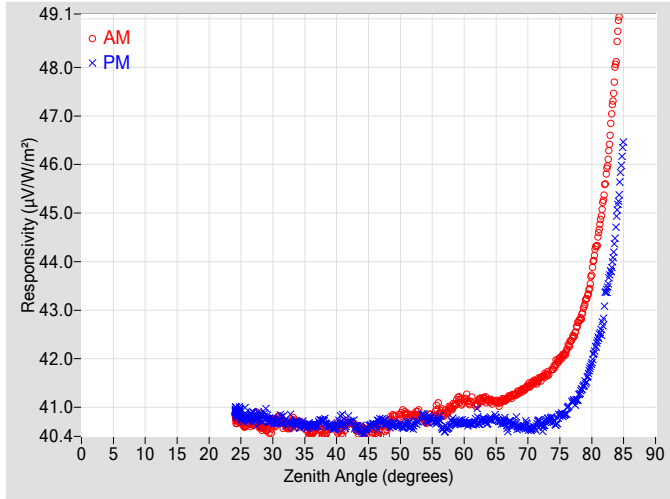


Figure 2. Responsivity vs Local Standard Time

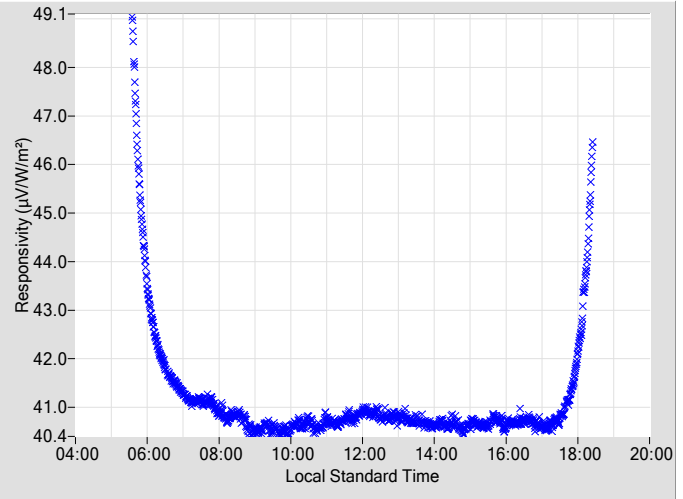
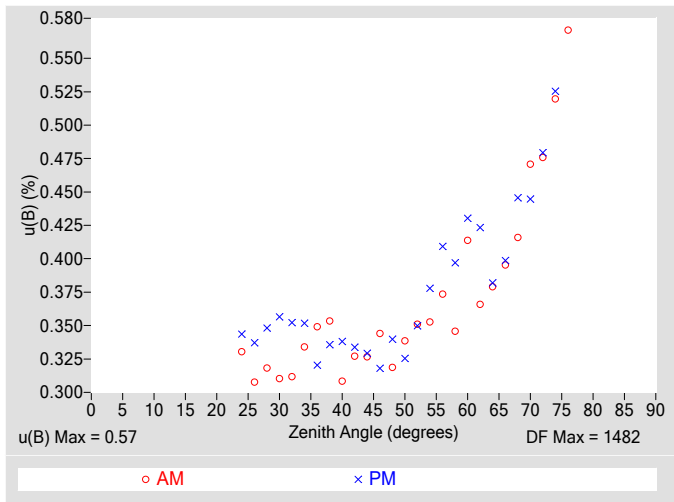


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty,  $u(B)$

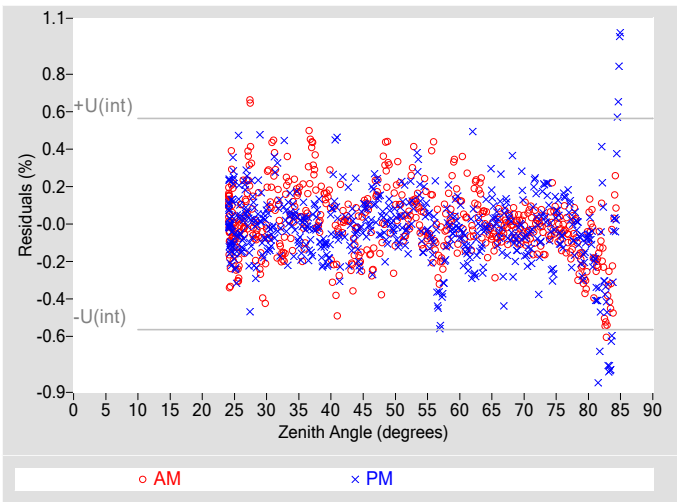
Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	$u(B)$ $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	$u(B)$ $\pm$ (%)	Azimuth Angle	Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	$u(B)$ $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	$u(B)$ $\pm$ (%)	Azimuth Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	40.518	0.34	108.51	40.650	0.32	251.64
2	N/A	N/A	N/A	N/A	N/A	N/A	48	40.577	0.32	106.11	40.668	0.34	253.99
4	N/A	N/A	N/A	N/A	N/A	N/A	50	40.807	0.34	103.96	40.616	0.33	256.17
6	N/A	N/A	N/A	N/A	N/A	N/A	52	40.832	0.35	101.83	40.616	0.35	258.20
8	N/A	N/A	N/A	N/A	N/A	N/A	54	40.707	0.35	99.93	40.747	0.38	260.24
10	N/A	N/A	N/A	N/A	N/A	N/A	56	40.914	0.37	97.99	40.740	0.41	262.13
12	N/A	N/A	N/A	N/A	N/A	N/A	58	40.992	0.35	96.16	40.695	0.40	263.97
14	N/A	N/A	N/A	N/A	N/A	N/A	60	41.137	0.41	94.38	40.679	0.43	265.75
16	N/A	N/A	N/A	N/A	N/A	N/A	62	41.072	0.37	92.65	40.772	0.42	267.49
18	N/A	N/A	N/A	N/A	N/A	N/A	64	41.139	0.38	90.94	40.754	0.38	269.19
20	N/A	N/A	N/A	N/A	N/A	N/A	66	41.141	0.40	89.32	40.689	0.40	270.85
22	N/A	N/A	N/A	N/A	N/A	N/A	68	41.265	0.42	87.67	40.658	0.45	272.50
24	40.822	0.33	176.23	40.919	0.34	184.33	70	41.436	0.47	86.05	40.596	0.44	274.13
26	40.692	0.31	155.28	40.772	0.34	204.85	72	41.600	0.48	84.43	40.646	0.48	275.74
28	40.600	0.32	144.84	40.819	0.35	215.29	74	41.813	0.52	82.80	40.722	0.53	277.35
30	40.640	0.31	137.68	40.732	0.36	222.34	76	42.164	0.57	81.21	40.903	N/A	278.95
32	40.639	0.31	132.09	40.681	0.35	227.91	78	42.763	N/A	79.61	41.246	N/A	280.58
34	40.642	0.33	127.21	40.651	0.35	232.85	80	43.768	N/A	77.98	41.948	N/A	282.23
36	40.444	0.35	123.27	40.629	0.32	236.83	82	45.473	N/A	76.34	43.128	N/A	283.88
38	40.416	0.35	119.76	40.726	0.34	240.39	84	48.578	N/A	74.64	45.086	N/A	285.57
40	40.573	0.31	116.59	40.607	0.34	243.54	86	N/A	N/A	N/A	N/A	N/A	N/A
42	40.668	0.33	113.67	40.731	0.33	246.48	88	N/A	N/A	N/A	N/A	N/A	N/A
44	40.568	0.33	110.98	40.506	0.33	249.15	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, $u(B)$ (%)	$\pm 0.57$
Type-A Interpolating Function, $u(int)$ (%)	$\pm 0.28$
Combined Standard Uncertainty, $u(c)$ (%)	$\pm 0.64$
Effective degrees of freedom, $DF(c)$	2110
Coverage factor, $k$	1.96
Expanded Uncertainty, $U95$ (%)	$\pm 1.2$
AM Valid zenith angle range	24° to 76°
PM Valid zenith angle range	24° to 74°

‡ 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**

$R @ 45^\circ$ ( $\mu V/W/m^2$ )	$R_{net}$ ( $\mu V/W/m^2$ ) †
40.573	0

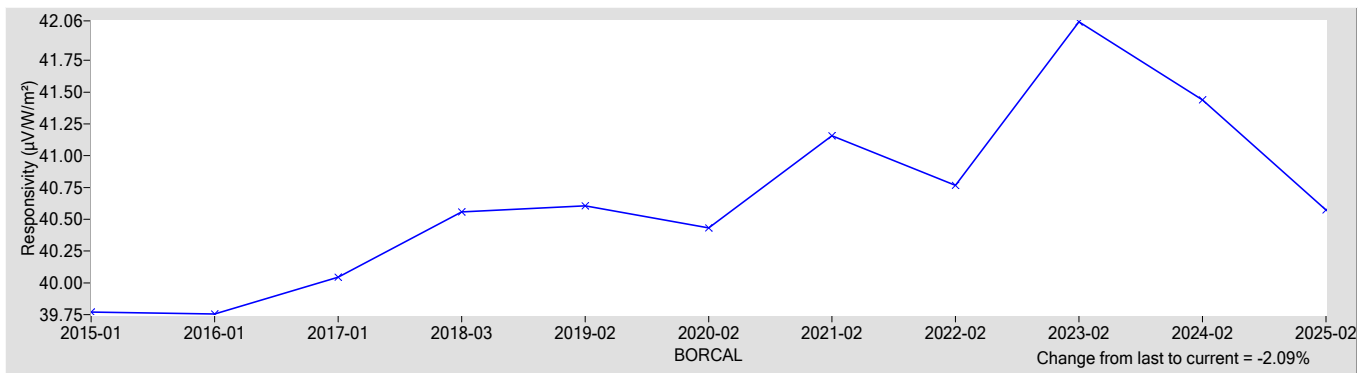
†  $R_{net}$  determination date: N/A

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

Type-B Expanded Uncertainty, $U(B)$ (%)	$\pm 0.84$
Offset Uncertainty, $U(off)$ (%)	+1.4 / -0.39
Expanded Uncertainty, $U$ (%)	+2.2 / -1.2
Effective degrees of freedom, $DF^*$	2015
Coverage factor, $k$	1.96
Valid zenith angle range	30.0° to 60.0°

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

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



**References:**

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



# National Renewable Energy Laboratory

## Solar Radiation Research Laboratory

### Metrology Laboratory

### Calibration Certificate



<b>Test Instrument:</b>	Pyranometer	<b>Manufacturer:</b>	EKO
<b>Model:</b>	MS-410	<b>Serial Number:</b>	S13144.085R
<b>Calibration Date:</b>	5/2/2025	<b>Due Date:</b>	5/2/2026
<b>Customer:</b>	NREL-SRRL-BMS	<b>Environmental Conditions:</b>	see page 4
<b>Test Dates:</b>	5/2		

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	09/27/2024	09/27/2025
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/21/2025	04/21/2026
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/21/2025	04/21/2026
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/07/2025	02/07/2027
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/07/2025	02/07/2027
Infrared Irradiance ‡	Kipp & Zonen Pyrgeometer Model CG4, S/N FT002	03/31/2022	03/31/2027

† Through the World Radiometric Reference (WRR)

‡ Through the World Infrared Standard Group (WISG)

**Number of pages of certificate:** 4

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

**Setup:** Radiometers are calibrated outdoors, using the sun as the source. Pyranometers and pyrgeometers are installed for horizontal measurements, with their signal connectors oriented north, if their design permits.

The shading disk for the reference diffuse subtends a solid angle of 5°. Pyrheliometers are installed on solar trackers.

**Calibrated by:** Afshin Andreas, RCC, and Shawn L. Jaker

-----  
Ibrahim Reda, Technical Manager

05/05/2025

-----  
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 ( $\text{W}/\text{m}^2$ ),
  - =  $W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
  - where,  $W_{in}$  = incoming infrared ( $\text{W}/\text{m}^2$ ),  $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$ ,
  - $T_c$  = case temperature of pyrgeometer (K).
- $I$  = reference irradiance ( $\text{W}/\text{m}^2$ ), beam (B) or global (G)
  - where,  $G = B * \text{COS}(Z) + D$ ,
  - $Z$  = zenith angle (degrees),
  - $D$  = reference diffuse irradiance ( $\text{W}/\text{m}^2$ ).

Figure 1. Responsivity vs Zenith Angle

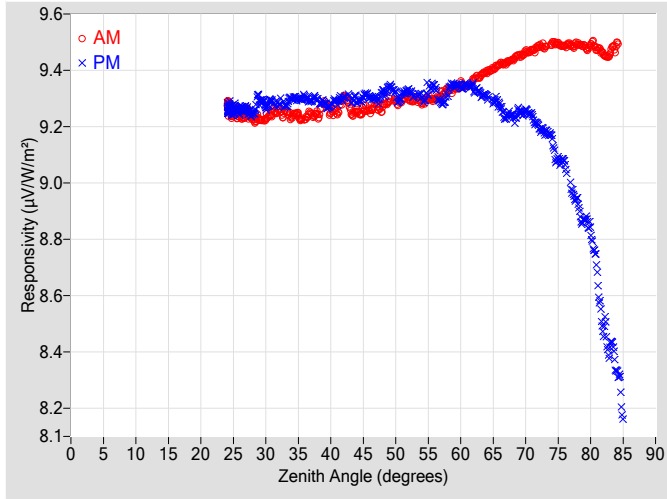


Figure 2. Responsivity vs Local Standard Time

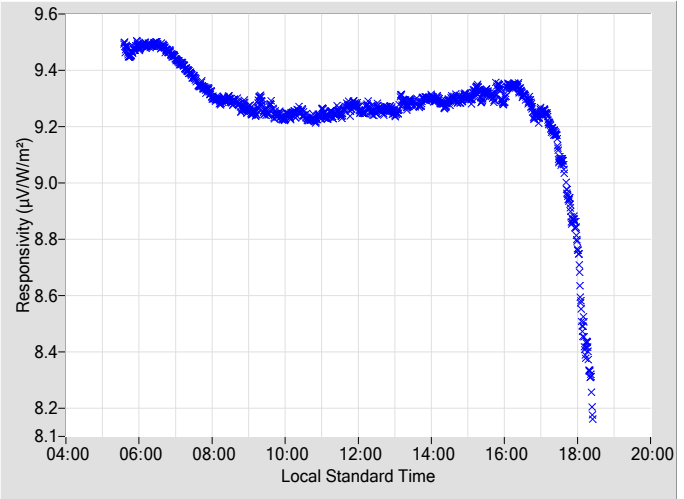
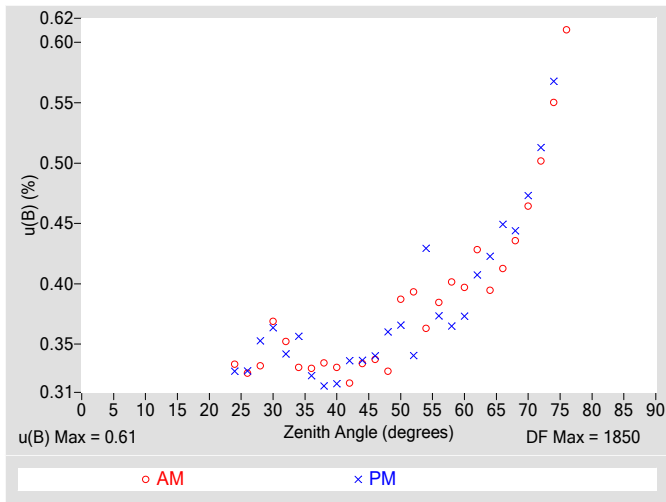


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty,  $u(B)$

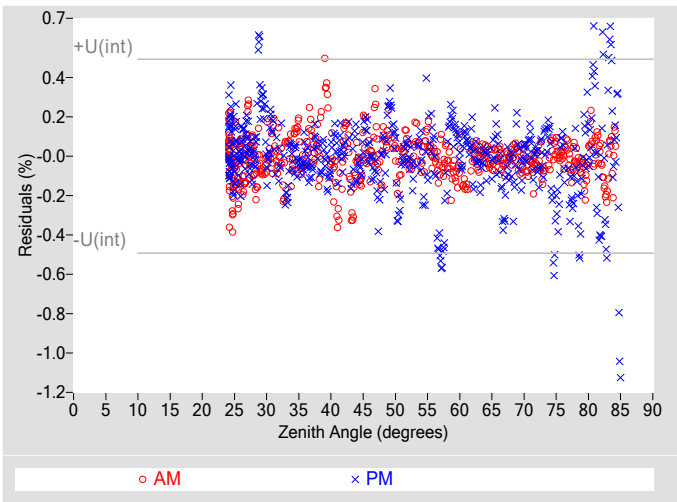
Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	AM u(B) $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	PM u(B) $\pm$ (%)	Azimuth Angle	Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	AM u(B) $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	PM u(B) $\pm$ (%)	Azimuth Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	9.2587	0.34	108.43	9.3028	0.34	251.67
2	N/A	N/A	N/A	N/A	N/A	N/A	48	9.2667	0.33	106.15	9.3224	0.36	254.02
4	N/A	N/A	N/A	N/A	N/A	N/A	50	9.2915	0.39	103.95	9.3145	0.37	256.15
6	N/A	N/A	N/A	N/A	N/A	N/A	52	9.2980	0.39	101.89	9.3266	0.34	258.24
8	N/A	N/A	N/A	N/A	N/A	N/A	54	9.2846	0.36	99.89	9.3052	0.43	260.20
10	N/A	N/A	N/A	N/A	N/A	N/A	56	9.2972	0.38	98.03	9.3404	0.37	262.12
12	N/A	N/A	N/A	N/A	N/A	N/A	58	9.3326	0.40	96.15	9.3248	0.36	264.03
14	N/A	N/A	N/A	N/A	N/A	N/A	60	9.3517	0.40	94.42	9.3408	0.37	265.74
16	N/A	N/A	N/A	N/A	N/A	N/A	62	9.3677	0.43	92.68	9.3372	0.41	267.47
18	N/A	N/A	N/A	N/A	N/A	N/A	64	9.3936	0.39	90.98	9.3087	0.42	269.18
20	N/A	N/A	N/A	N/A	N/A	N/A	66	9.4217	0.41	89.31	9.2741	0.45	270.84
22	N/A	N/A	N/A	N/A	N/A	N/A	68	9.4371	0.44	87.66	9.2399	0.44	272.49
24	9.2742	0.33	176.00	9.2562	0.33	184.17	70	9.4658	0.46	86.03	9.2582	0.47	274.12
26	9.2470	0.33	155.33	9.2601	0.33	205.14	72	9.4863	0.50	84.42	9.2016	0.51	275.73
28	9.2336	0.33	144.91	9.2474	0.35	215.36	74	9.4951	0.55	82.79	9.1550	0.57	277.38
30	9.2287	0.37	137.85	9.2728	0.36	222.37	76	9.4855	0.61	81.19	9.0648	N/A	278.98
32	9.2603	0.35	132.14	9.2836	0.34	228.12	78	9.4939	N/A	79.60	8.9342	N/A	280.57
34	9.2366	0.33	127.40	9.3013	0.36	232.77	80	9.4902	N/A	77.97	8.8249	N/A	282.21
36	9.2278	0.33	123.12	9.3036	0.32	236.81	82	9.4574	N/A	76.33	8.4870	N/A	283.86
38	9.2415	0.33	119.76	9.2927	0.32	240.37	84	9.4854	N/A	74.67	8.3288	N/A	285.56
40	9.2513	0.33	116.52	9.2760	0.32	243.52	86	N/A	N/A	N/A	N/A	N/A	N/A
42	9.2994	0.32	113.66	9.3016	0.34	246.46	88	N/A	N/A	N/A	N/A	N/A	N/A
44	9.2542	0.33	110.90	9.2957	0.34	249.20	90	N/A	N/A	N/A	N/A	N/A	N/A

N/A - Not Available

**Figure 3. Type-B Standard Uncertainty vs Zenith Angle**



**Figure 4. Residuals from Spline Interpolation**



**Table 3. Uncertainty using Spline Interpolation ‡**

Type-B Standard Uncertainty, $u(B)$ (%)	$\pm 0.61$
Type-A Interpolating Function, $u(int)$ (%)	$\pm 0.25$
Combined Standard Uncertainty, $u(c)$ (%)	$\pm 0.66$
Effective degrees of freedom, $DF(c)$	2385
Coverage factor, $k$	1.96
Expanded Uncertainty, $U95$ (%)	$\pm 1.3$
AM Valid zenith angle range	24° to 76°
PM Valid zenith angle range	24° to 74°

‡ 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**

$R @ 45^\circ$ ( $\mu V/W/m^2$ )	$R_{net}$ ( $\mu V/W/m^2$ ) †
9.2822	0.20000

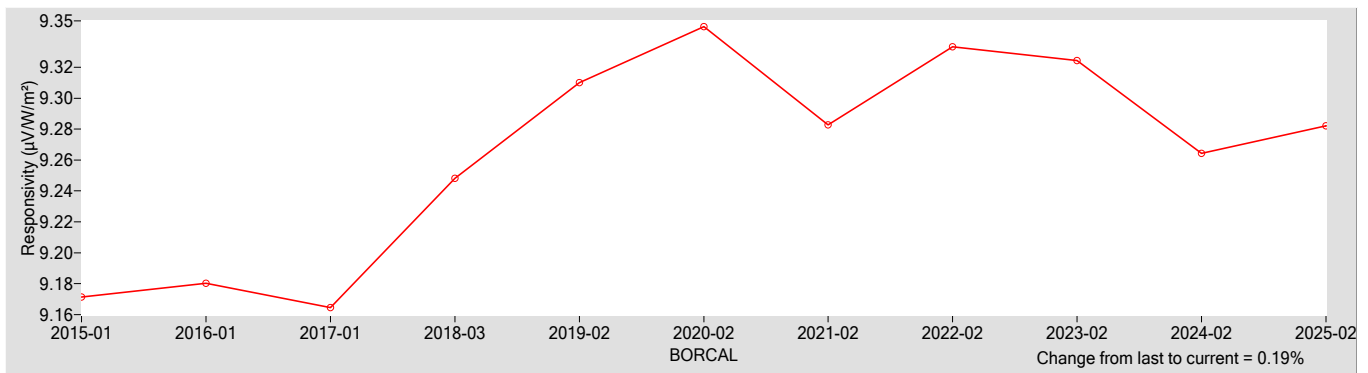
†  $R_{net}$  determination date: Estimated

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

Type-B Expanded Uncertainty, $U(B)$ (%)	$\pm 0.84$
Offset Uncertainty, $U(off)$ (%)	+0.75 / -0.59
Expanded Uncertainty, $U$ (%)	+1.6 / -1.4
Effective degrees of freedom, $DF^*$	2088
Coverage factor, $k$	1.96
Valid zenith angle range	30.0° to 60.0°

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

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



**References:**

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



# National Renewable Energy Laboratory

## Solar Radiation Research Laboratory

### Metrology Laboratory

### Calibration Certificate



<b>Test Instrument:</b>	Pyranometer	<b>Manufacturer:</b>	EKO
<b>Model:</b>	MS-80	<b>Serial Number:</b>	S17096005
<b>Calibration Date:</b>	5/2/2025	<b>Due Date:</b>	5/2/2026
<b>Customer:</b>	NREL-SRRL-BMS	<b>Environmental Conditions:</b>	see page 4
<b>Test Dates:</b>	5/2		

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	09/27/2024	09/27/2025
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/21/2025	04/21/2026
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/21/2025	04/21/2026
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/07/2025	02/07/2027
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/07/2025	02/07/2027
Infrared Irradiance ‡	Kipp & Zonen Pyrgeometer Model CG4, S/N FT002	03/31/2022	03/31/2027

† Through the World Radiometric Reference (WRR)

‡ Through the World Infrared Standard Group (WISG)

**Number of pages of certificate:** 4

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

**Setup:** Radiometers are calibrated outdoors, using the sun as the source. Pyranometers and pyrgeometers are installed for horizontal measurements, with their signal connectors oriented north, if their design permits.

The shading disk for the reference diffuse subtends a solid angle of 5°. Pyrheliometers are installed on solar trackers.

**Calibrated by:** Afshin Andreas, RCC, and Shawn L. Jaker

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Ibrahim Reda, Technical Manager

05/05/2025

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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 ( $\text{W}/\text{m}^2$ ),
  - =  $W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
  - where,  $W_{in}$  = incoming infrared ( $\text{W}/\text{m}^2$ ),  $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$ ,
  - $T_c$  = case temperature of pyrgeometer (K).
- $I$  = reference irradiance ( $\text{W}/\text{m}^2$ ), beam (B) or global (G)
  - where,  $G = B * \text{COS}(Z) + D$ ,
  - $Z$  = zenith angle (degrees),
  - $D$  = reference diffuse irradiance ( $\text{W}/\text{m}^2$ ).

Figure 1. Responsivity vs Zenith Angle

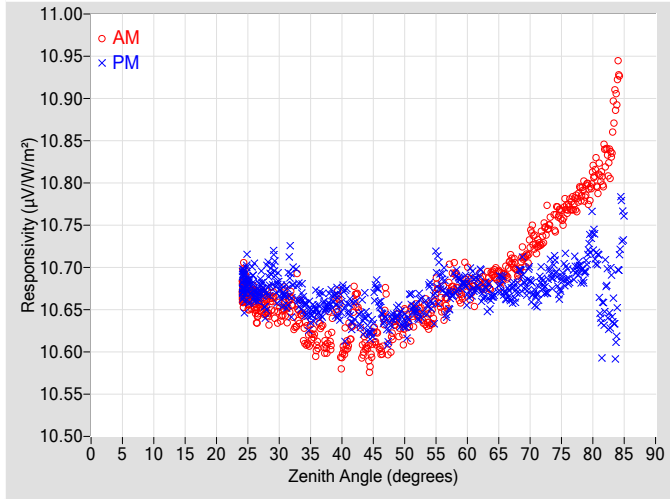


Figure 2. Responsivity vs Local Standard Time

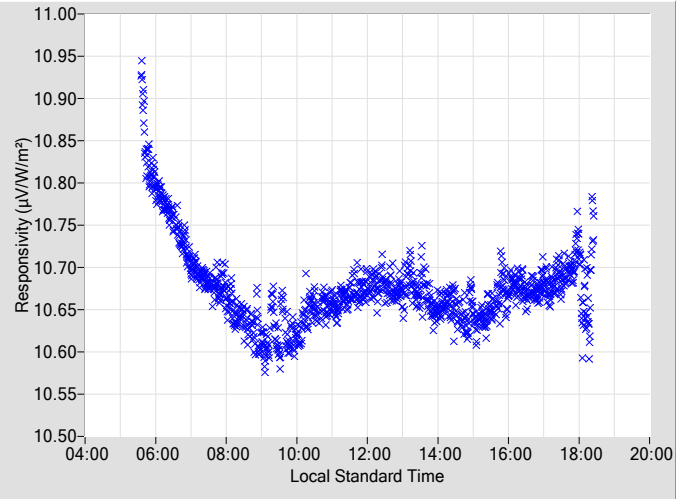
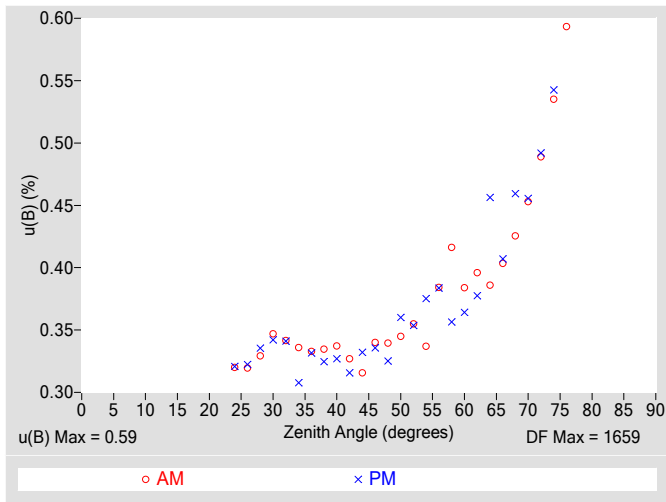


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)

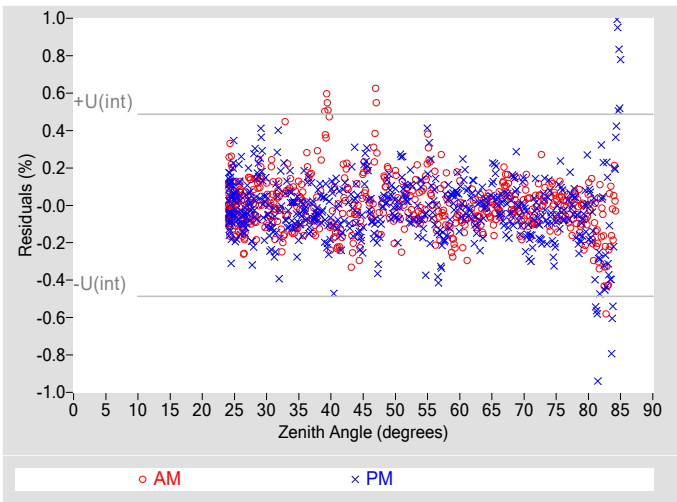
Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) $\pm$ (%)	Azimuth Angle	Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) $\pm$ (%)	Azimuth Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	10.601	0.34	108.30	10.658	0.34	251.67
2	N/A	N/A	N/A	N/A	N/A	N/A	48	10.618	0.34	106.15	10.640	0.33	253.96
4	N/A	N/A	N/A	N/A	N/A	N/A	50	10.631	0.34	104.06	10.636	0.36	256.15
6	N/A	N/A	N/A	N/A	N/A	N/A	52	10.648	0.35	101.81	10.646	0.35	258.23
8	N/A	N/A	N/A	N/A	N/A	N/A	54	10.636	0.34	99.91	10.667	0.38	260.23
10	N/A	N/A	N/A	N/A	N/A	N/A	56	10.656	0.38	98.04	10.684	0.38	262.11
12	N/A	N/A	N/A	N/A	N/A	N/A	58	10.688	0.42	96.14	10.687	0.36	264.03
14	N/A	N/A	N/A	N/A	N/A	N/A	60	10.686	0.38	94.37	10.669	0.36	265.78
16	N/A	N/A	N/A	N/A	N/A	N/A	62	10.684	0.40	92.68	10.684	0.38	267.52
18	N/A	N/A	N/A	N/A	N/A	N/A	64	10.692	0.39	90.97	10.665	0.46	269.17
20	N/A	N/A	N/A	N/A	N/A	N/A	66	10.694	0.40	89.30	10.666	0.41	270.83
22	N/A	N/A	N/A	N/A	N/A	N/A	68	10.693	0.43	87.66	10.680	0.46	272.48
24	10.671	0.32	175.78	10.680	0.32	184.39	70	10.731	0.45	86.02	10.685	0.46	274.11
26	10.665	0.32	155.15	10.677	0.32	205.28	72	10.738	0.49	84.41	10.685	0.49	275.73
28	10.652	0.33	144.79	10.673	0.34	215.43	74	10.757	0.54	82.78	10.701	0.54	277.38
30	10.646	0.35	137.83	10.678	0.34	222.28	76	10.770	0.59	81.19	10.689	N/A	278.97
32	10.659	0.34	132.12	10.683	0.34	228.07	78	10.788	N/A	79.60	10.698	N/A	280.61
34	10.627	0.34	127.43	10.656	0.31	232.73	80	10.807	N/A	77.96	10.741	N/A	282.21
36	10.610	0.33	123.24	10.653	0.33	236.80	82	10.837	N/A	76.32	10.674	N/A	283.90
38	10.617	0.33	119.75	10.660	0.32	240.34	84	10.920	N/A	74.67	10.676	N/A	285.56
40	10.605	0.34	116.59	10.667	0.33	243.59	86	N/A	N/A	N/A	N/A	N/A	N/A
42	10.656	0.33	113.65	10.648	0.32	246.45	88	N/A	N/A	N/A	N/A	N/A	N/A
44	10.608	0.32	110.96	10.635	0.33	249.19	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, $u(B)$ (%)	$\pm 0.59$
Type-A Interpolating Function, $u(int)$ (%)	$\pm 0.24$
Combined Standard Uncertainty, $u(c)$ (%)	$\pm 0.64$
Effective degrees of freedom, $DF(c)$	2165
Coverage factor, $k$	1.96
Expanded Uncertainty, $U_{95}$ (%)	$\pm 1.3$
AM Valid zenith angle range	24° to 76°
PM Valid zenith angle range	24° to 74°

‡ 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**

$R @ 45^\circ$ ( $\mu V/W/m^2$ )	$R_{net}$ ( $\mu V/W/m^2$ ) †
10.630	0.043000

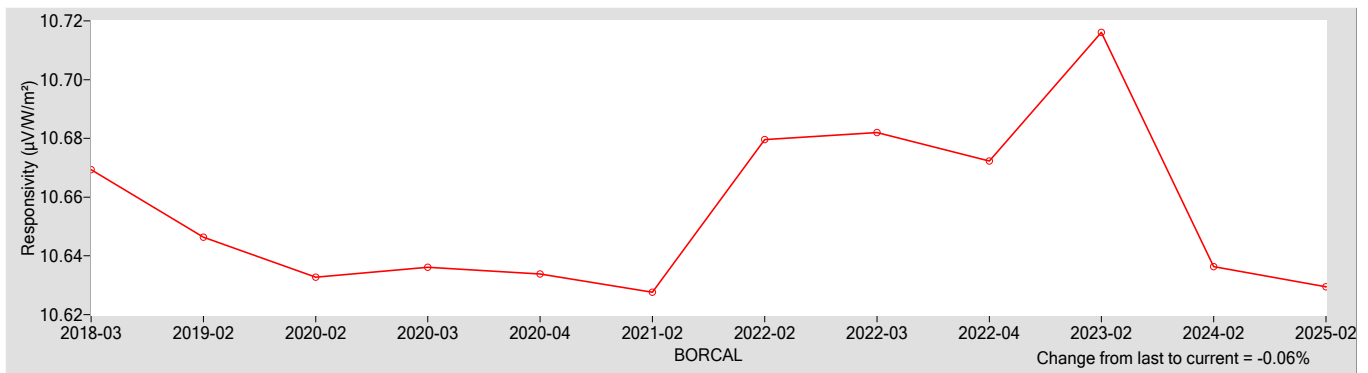
†  $R_{net}$  determination date: Estimated

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

Type-B Expanded Uncertainty, $U(B)$ (%)	$\pm 0.82$
Offset Uncertainty, $U(off)$ (%)	+0.55 / -0.26
Expanded Uncertainty, $U$ (%)	+1.4 / -1.1
Effective degrees of freedom, $DF^*$	2096
Coverage factor, $k$	1.96
Valid zenith angle range	30.0° to 60.0°

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

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



**References:**

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

# National Renewable Energy Laboratory

## Solar Radiation Research Laboratory

### Metrology Laboratory

### Calibration Certificate



<b>Test Instrument:</b>	Pyrheliometer	<b>Manufacturer:</b>	EKO
<b>Model:</b>	MS-57	<b>Serial Number:</b>	S18015.22
<b>Calibration Date:</b>	5/2/2025	<b>Due Date:</b>	5/2/2026
<b>Customer:</b>	NREL-SRRL-BMS	<b>Environmental Conditions:</b>	see page 4
<b>Test Dates:</b>	5/2		

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	09/27/2024	09/27/2025
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/21/2025	04/21/2026
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/21/2025	04/21/2026
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/07/2025	02/07/2027
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/07/2025	02/07/2027

† 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, RCC, and Shawn L. Jaker

\_\_\_\_\_  
Ibrahim Reda, Technical Manager

05/05/2025

\_\_\_\_\_  
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 ( $\text{W}/\text{m}^2$ ),
  - =  $W_{in} - W_{out} = W_{in} - \sigma * T_c^4$
  - where,  $W_{in}$  = incoming infrared ( $\text{W}/\text{m}^2$ ),  $\sigma = 5.6704\text{e-}8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$ ,
  - $T_c$  = case temperature of pyrgeometer (K).
- $I$  = reference irradiance ( $\text{W}/\text{m}^2$ ), beam (B) or global (G)
  - where,  $G = B * \text{COS}(Z) + D$ ,
  - $Z$  = zenith angle (degrees),
  - $D$  = reference diffuse irradiance ( $\text{W}/\text{m}^2$ ).

Figure 1. Responsivity vs Zenith Angle

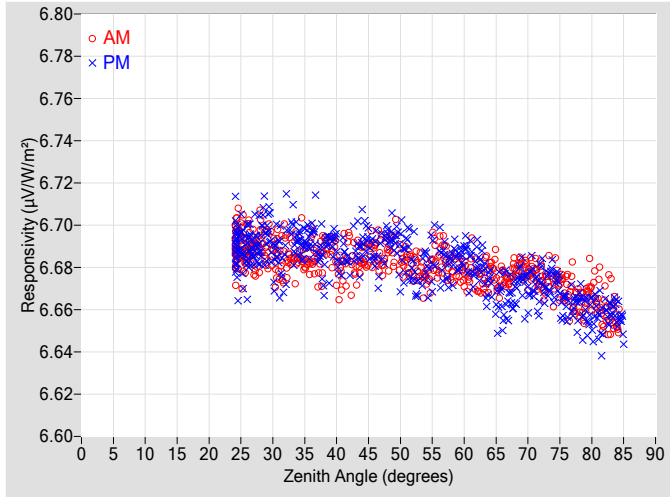


Figure 2. Responsivity vs Local Standard Time

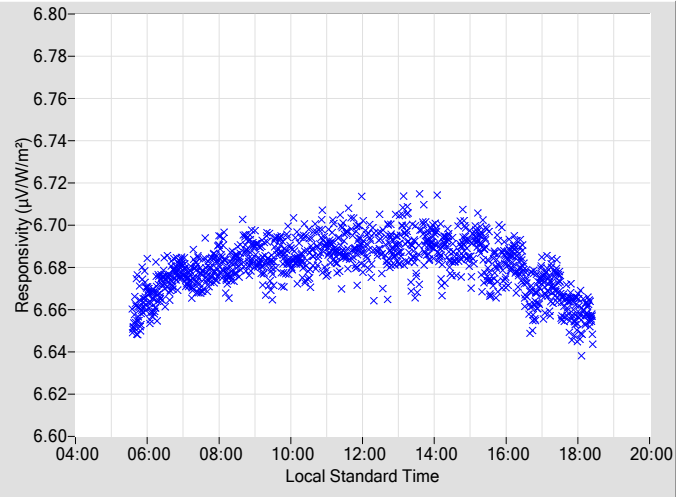
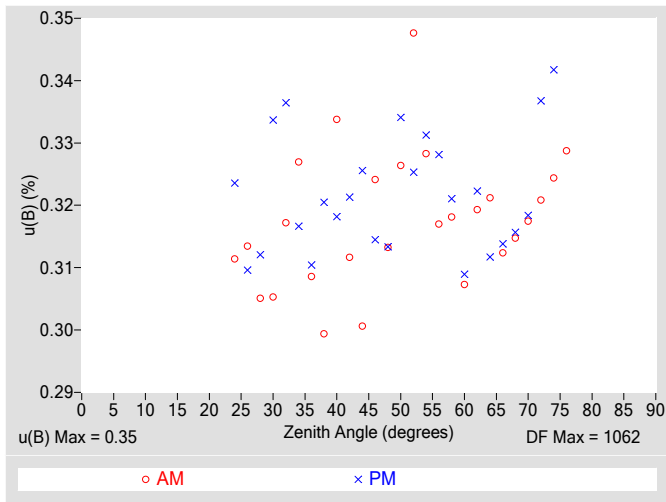


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)

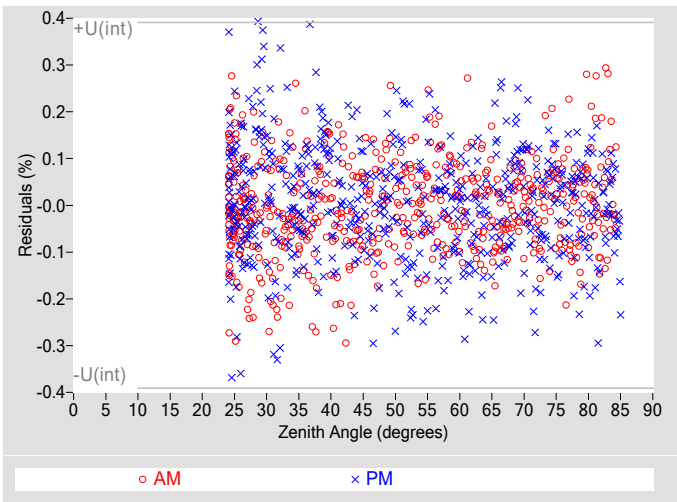
Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) $\pm$ (%)	Azimuth Angle	Zenith Angle (deg.)	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) $\pm$ (%)	Azimuth Angle	R ( $\mu\text{V}/\text{W}/\text{m}^2$ )	u(B) $\pm$ (%)	Azimuth Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	6.6887	0.32	108.42	6.6878	0.31	251.66
2	N/A	N/A	N/A	N/A	N/A	N/A	48	6.6872	0.31	106.08	6.6957	0.31	253.95
4	N/A	N/A	N/A	N/A	N/A	N/A	50	6.6846	0.33	103.88	6.6863	0.33	256.20
6	N/A	N/A	N/A	N/A	N/A	N/A	52	6.6793	0.35	101.92	6.6825	0.33	258.23
8	N/A	N/A	N/A	N/A	N/A	N/A	54	6.6759	0.33	99.91	6.6815	0.33	260.22
10	N/A	N/A	N/A	N/A	N/A	N/A	56	6.6836	0.32	98.02	6.6857	0.33	262.32
12	N/A	N/A	N/A	N/A	N/A	N/A	58	6.6801	0.32	96.19	6.6817	0.32	264.00
14	N/A	N/A	N/A	N/A	N/A	N/A	60	6.6775	0.31	94.41	6.6882	0.31	265.78
16	N/A	N/A	N/A	N/A	N/A	N/A	62	6.6747	0.32	92.67	6.6851	0.32	267.51
18	N/A	N/A	N/A	N/A	N/A	N/A	64	6.6775	0.32	90.97	6.6756	0.31	269.17
20	N/A	N/A	N/A	N/A	N/A	N/A	66	6.6768	0.31	89.30	6.6588	0.31	270.88
22	N/A	N/A	N/A	N/A	N/A	N/A	68	6.6794	0.31	87.65	6.6681	0.32	272.52
24	6.6897	0.31	176.01	6.6887	0.32	184.04	70	6.6769	0.32	86.02	6.6681	0.32	274.15
26	6.6889	0.31	155.15	6.6888	0.31	205.04	72	6.6764	0.32	84.41	6.6766	0.34	275.77
28	6.6938	0.31	145.15	6.6905	0.31	215.13	74	6.6708	0.32	82.82	6.6725	0.34	277.37
30	6.6886	0.31	137.83	6.6807	0.33	222.68	76	6.6706	0.33	81.19	6.6612	N/A	278.97
32	6.6887	0.32	132.11	6.6922	0.34	228.16	78	6.6640	N/A	79.60	6.6623	N/A	280.57
34	6.6858	0.33	127.38	6.6932	0.32	232.81	80	6.6658	N/A	77.96	6.6578	N/A	282.21
36	6.6861	0.31	123.32	6.6931	0.31	236.79	82	6.6589	N/A	76.32	6.6577	N/A	283.90
38	6.6897	0.30	119.74	6.6790	0.32	240.36	84	6.6529	N/A	74.63	6.6587	N/A	285.56
40	6.6813	0.33	116.53	6.6883	0.32	243.58	86	N/A	N/A	N/A	N/A	N/A	N/A
42	6.6867	0.31	113.61	6.6814	0.32	246.32	88	N/A	N/A	N/A	N/A	N/A	N/A
44	6.6854	0.30	110.97	6.6938	0.33	249.19	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, $u(B)$ (%)	$\pm 0.35$
Type-A Interpolating Function, $u(int)$ (%)	$\pm 0.20$
Combined Standard Uncertainty, $u(c)$ (%)	$\pm 0.40$
Effective degrees of freedom, $DF(c)$	1664
Coverage factor, $k$	1.96
Expanded Uncertainty, $U_{95}$ (%)	$\pm 0.78$
AM Valid zenith angle range	24° to 76°
PM Valid zenith angle range	24° to 74°

‡ 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**

$R @ 45^\circ$ ( $\mu V/W/m^2$ )	$R_{net}$ ( $\mu V/W/m^2$ ) †
6.6903	0

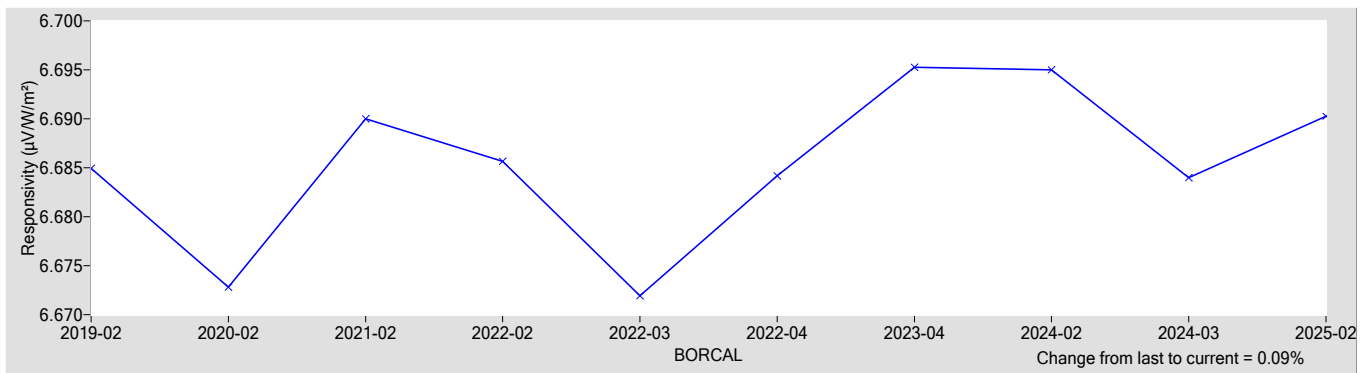
†  $R_{net}$  determination date: N/A

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

Type-B Expanded Uncertainty, $U(B)$ (%)	$\pm 0.68$
Offset Uncertainty, $U(off)$ (%)	+0.082 / -0.21
Expanded Uncertainty, $U$ (%)	+0.76 / -0.90
Effective degrees of freedom, $DF^*$	1062
Coverage factor, $k$	1.96
Valid zenith angle range	30.0° to 60.0°

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

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



**References:**

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



# National Renewable Energy Laboratory

## Solar Radiation Research Laboratory

### Metrology Laboratory

### Calibration Certificate



<b>Test Instrument:</b>	Digital Pyranometer	<b>Manufacturer:</b>	EKO
<b>Model:</b>	MS-80S	<b>Serial Number:</b>	S20066320
<b>Calibration Date:</b>	5/2/2025	<b>Due Date:</b>	5/2/2026
<b>Customer:</b>	NREL-SRRL-BMS	<b>Environmental Conditions:</b>	see page 4
<b>Test Dates:</b>	5/2		

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	09/27/2024	09/27/2025
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2541	04/21/2025	04/21/2026
Diffuse Irradiance †	Hukseflux Pyranometer Model SR25, S/N 2542	04/21/2025	04/21/2026
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/07/2025	02/07/2027
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/07/2025	02/07/2027

† 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, RCC, and Shawn L. Jaker

\_\_\_\_\_  
Ibrahim Reda, Technical Manager

05/05/2025

\_\_\_\_\_  
Date

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

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

# Calibration Results

## S20066320 EKO MS-80S

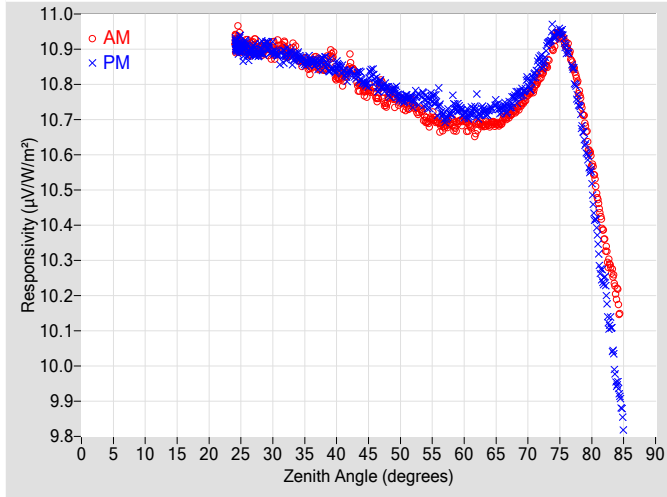
The responsivity ( $R$ ,  $\mu\text{V}/\text{W}/\text{m}^2$ ) of the test instrument during calibration is calculated using this Measurement Equation:

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

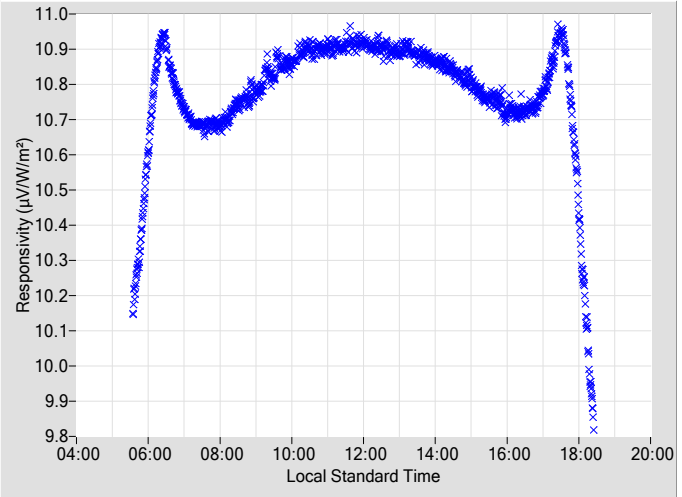
where,

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

**Figure 1. Responsivity vs Zenith Angle**



**Figure 2. Responsivity vs Local Standard Time**

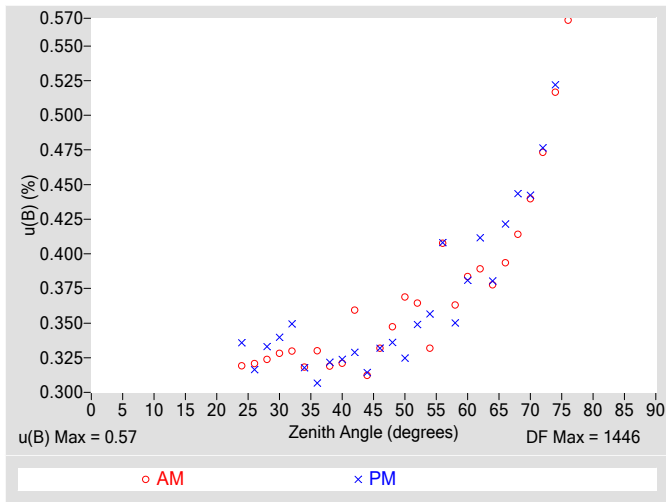


**Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)**

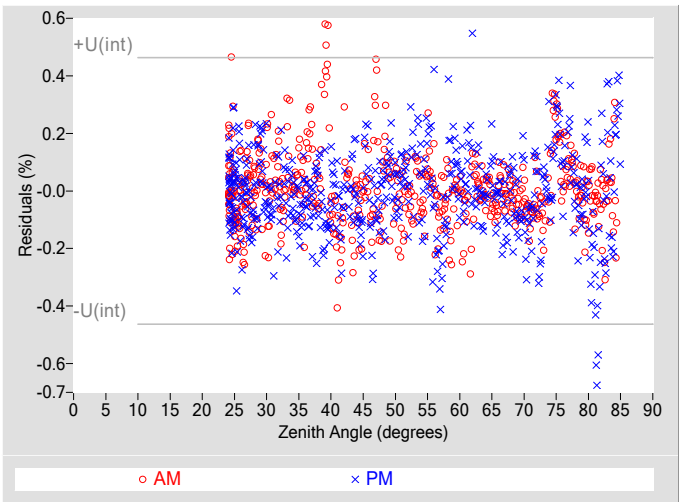
Zenith			AM			PM			Zenith			AM			PM		
Angle	R	u(B)	Azimuth	R	u(B)	Azimuth	Angle	R	u(B)	Azimuth	R	u(B)	Azimuth	R	u(B)	Azimuth	
(deg.)	( $\mu\text{V}/\text{W}/\text{m}^2$ )	$\pm$ (%)	Angle	( $\mu\text{V}/\text{W}/\text{m}^2$ )	$\pm$ (%)	Angle	(deg.)	( $\mu\text{V}/\text{W}/\text{m}^2$ )	$\pm$ (%)	Angle	( $\mu\text{V}/\text{W}/\text{m}^2$ )	$\pm$ (%)	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	10.774	0.33	108.52	10.820	0.33	251.62				
2	N/A	N/A	N/A	N/A	N/A	N/A	48	10.752	0.35	106.16	10.786	0.34	253.97				
4	N/A	N/A	N/A	N/A	N/A	N/A	50	10.754	0.37	103.96	10.761	0.32	256.16				
6	N/A	N/A	N/A	N/A	N/A	N/A	52	10.744	0.36	101.88	10.752	0.35	258.19				
8	N/A	N/A	N/A	N/A	N/A	N/A	54	10.699	0.33	99.93	10.751	0.36	260.24				
10	N/A	N/A	N/A	N/A	N/A	N/A	56	10.688	0.41	97.99	10.744	0.41	262.13				
12	N/A	N/A	N/A	N/A	N/A	N/A	58	10.693	0.36	96.16	10.728	0.35	263.96				
14	N/A	N/A	N/A	N/A	N/A	N/A	60	10.696	0.38	94.33	10.714	0.38	265.75				
16	N/A	N/A	N/A	N/A	N/A	N/A	62	10.680	0.39	92.64	10.713	0.41	267.45				
18	N/A	N/A	N/A	N/A	N/A	N/A	64	10.686	0.38	90.94	10.731	0.38	269.19				
20	N/A	N/A	N/A	N/A	N/A	N/A	66	10.697	0.39	89.32	10.732	0.42	270.85				
22	N/A	N/A	N/A	N/A	N/A	N/A	68	10.726	0.41	87.67	10.764	0.44	272.49				
24	10.917	0.32	176.16	10.914	0.34	184.39	70	10.773	0.44	86.03	10.804	0.44	274.12				
26	10.912	0.32	155.09	10.898	0.32	204.91	72	10.827	0.47	84.42	10.870	0.48	275.74				
28	10.898	0.32	145.06	10.899	0.33	215.19	74	10.910	0.52	82.79	10.944	0.52	277.35				
30	10.896	0.33	137.67	10.896	0.34	222.47	76	10.912	0.57	81.20	10.899	N/A	278.99				
32	10.900	0.33	132.08	10.882	0.35	227.99	78	10.783	N/A	79.61	10.742	N/A	280.58				
34	10.868	0.32	127.13	10.881	0.32	232.75	80	10.582	N/A	77.97	10.515	N/A	282.22				
36	10.848	0.33	123.35	10.866	0.31	236.82	82	10.360	N/A	76.33	10.234	N/A	283.87				
38	10.847	0.32	119.77	10.867	0.32	240.39	84	10.192	N/A	74.64	9.9425	N/A	285.57				
40	10.824	0.32	116.54	10.850	0.32	243.53	86	N/A	N/A	N/A	N/A	N/A	N/A				
42	10.857	0.36	113.67	10.836	0.33	246.40	88	N/A	N/A	N/A	N/A	N/A	N/A				
44	10.793	0.31	110.98	10.813	0.31	249.14	90	N/A	N/A	N/A	N/A	N/A	N/A				

N/A - Not Available

**Figure 3. Type-B Standard Uncertainty vs Zenith Angle**



**Figure 4. Residuals from Spline Interpolation**



**Table 3. Uncertainty using Spline Interpolation ‡**

Type-B Standard Uncertainty, $u(B)$ (%)	$\pm 0.57$
Type-A Interpolating Function, $u(int)$ (%)	$\pm 0.23$
Combined Standard Uncertainty, $u(c)$ (%)	$\pm 0.61$
Effective degrees of freedom, $DF(c)$	1891
Coverage factor, $k$	1.96
Expanded Uncertainty, $U95$ (%)	$\pm 1.2$
AM Valid zenith angle range	24° to 76°
PM Valid zenith angle range	24° to 74°

‡ 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**

$R @ 45^\circ$ ( $\mu V/W/m^2$ )	$R_{net}$ ( $\mu V/W/m^2$ ) †
10.799	0

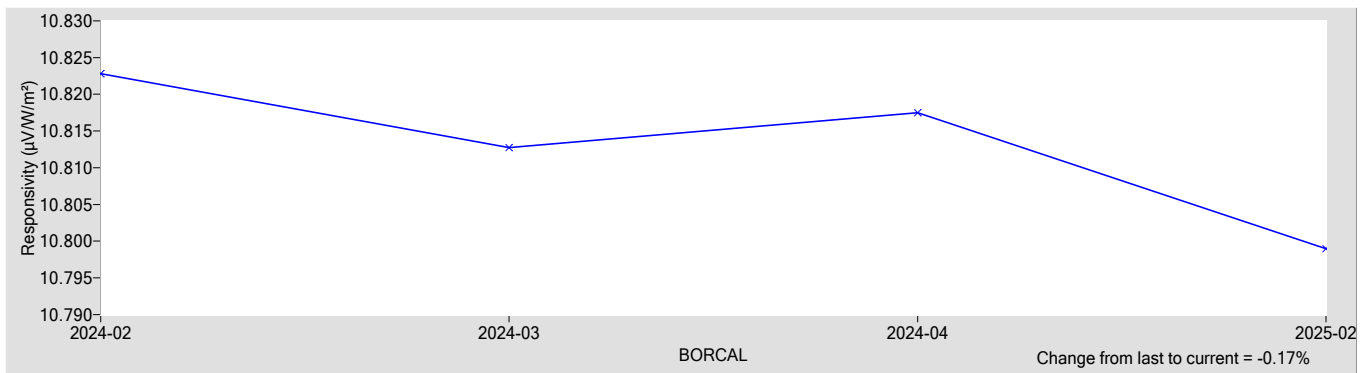
†  $R_{net}$  determination date: N/A

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

Type-B Expanded Uncertainty, $U(B)$ (%)	$\pm 0.80$
Offset Uncertainty, $U(off)$ (%)	+0.94 / -1.0
Expanded Uncertainty, $U$ (%)	+1.7 / -1.8
Effective degrees of freedom, $DF^*$	1994
Coverage factor, $k$	1.96
Valid zenith angle range	30.0° to 60.0°

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

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



**References:**

[1] Reda, I.; Hickey, J.; Long, C.; Myers, D.; Stoffel, T.; Wilcox, S.; Michalsky, J. J.; Dutton, E. G.; Nelson, D. (2005). "Using a Blackbody to Calculate Net Longwave Responsivity of Shortwave Solar Pyranometers to Correct for Their Thermal Offset Error During Outdoor Calibration Using the Component Sum Method." *Journal of Atmospheric and Oceanic Technology*, 2005; pp. 1531-1540; NREL Report No. JA-560-36646. doi:10.1175/JTECH1782.1

[2] Reda, I.; Myers, D.; Stoffel, T. (2008). "Uncertainty Estimate for the Outdoor Calibration of Solar Pyranometers: A Metrologist Perspective." *Measure*. (NCSLI *Journal of Measurement Science*). Vol. 3(4), December 2008; pp. 58-66; NREL Report No. JA-581-4137

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

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

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

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

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

# Environmental and Sky Conditions for BORCAL-SW 2025-02

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

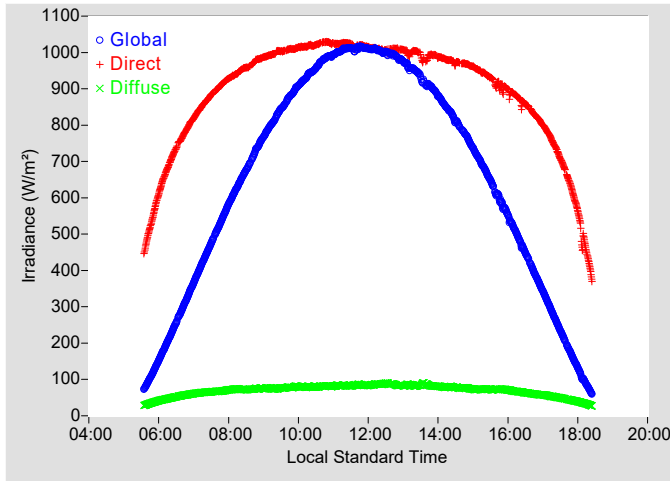
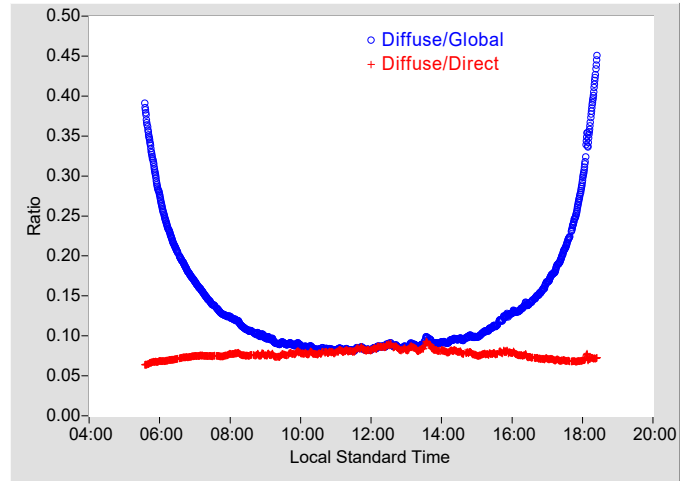


Figure 7. Diffuse Ratios



## Meteorological Observations:

Figure 8. Temperature

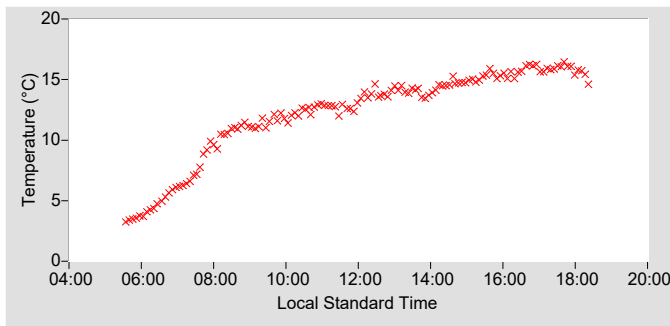


Figure 9. Humidity

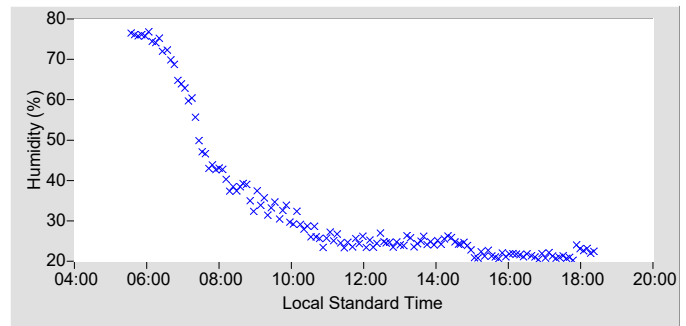


Figure 10. Pressure

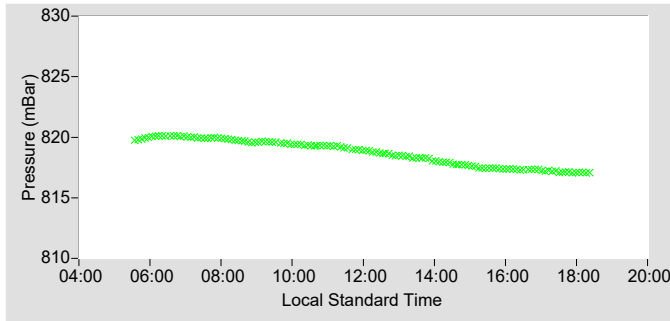


Figure 11. Effective Net Infrared

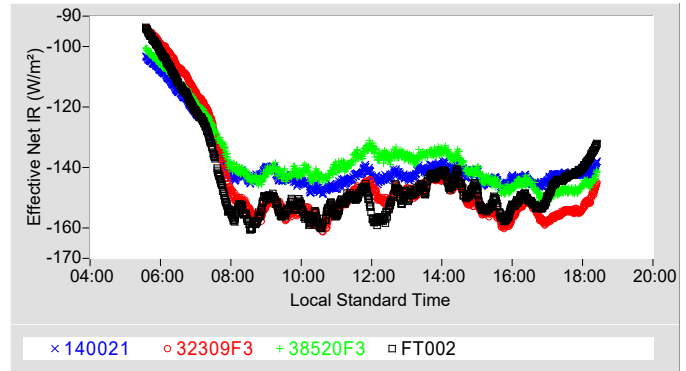


Figure 12. Estimated Broadband Aerosol Optical Depth

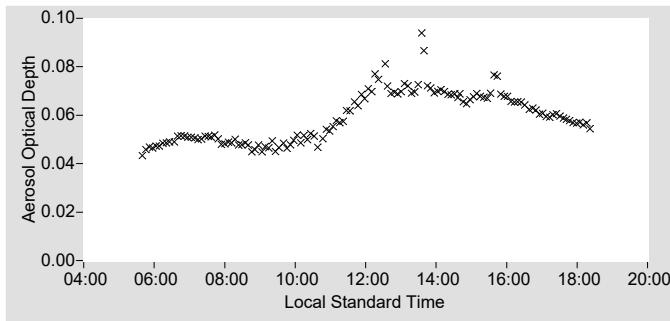


Table 6. Meteorological Observations

Observations	Mean	Min	Max
Temperature (°C)	12.22	3.26	16.45
Humidity (%)	33.28	20.27	76.83
Pressure (mBar)	818.7	817.0	820.1
Est. Aerosol Optical Depth (BB)	0.059	0.043	0.094

For other information about the calibration facility visit: <https://www.nrel.gov/grid/solar-radiation-research-laboratory.html>

# Appendix 2

## BORCAL Notes

Instrument, Configuration, and Session Notes for the BORCAL

# BORCAL Notes

---

Facility: Solar Radiation Research Laboratory

Comments:

Avg. Station Pressure & Temperature is for Denver, CO, which is used for the Solar Position Algorithm (SPA).

---

010284-UW-CM3 Kipp & Zonen CM3

Comments:

Retro-fitted from CNR1

---

Session Config: 15357 Hukseflux SR20-T2; Number: 2

Comments:

Hukseflux VU01 Ventilator

---

Session Config: 15366 Hukseflux SR20-T2; Number: 2

Comments:

Eppley Ventilator with mounting adapter