

Broadband Outdoor Radiometer Calibration Shortwave

BORCAL-SW 2019-04

Generated by



Radiometer Calibration and Characterization

Customer

Aron Habte

Organization: NREL

Address: 15013 Denver West Parkway, Golden, CO 80401 USA

Calibration Facility

Solar Radiation Research Laboratory

Latitude: 39.742°N

Longitude: 105.180°W

Elevation: 1828.8 meters AMSL

Time Zone: -7.0

Calibration date

07/19/2019 to 07/29/2019

Report Date

July 30, 2019



NOTICE

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Broadband Outdoor Radiometer Calibration Report

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Introduction

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

This report includes these sections:

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

Control Instrument History

Figure 1. Eppley NIP Control Instrument History

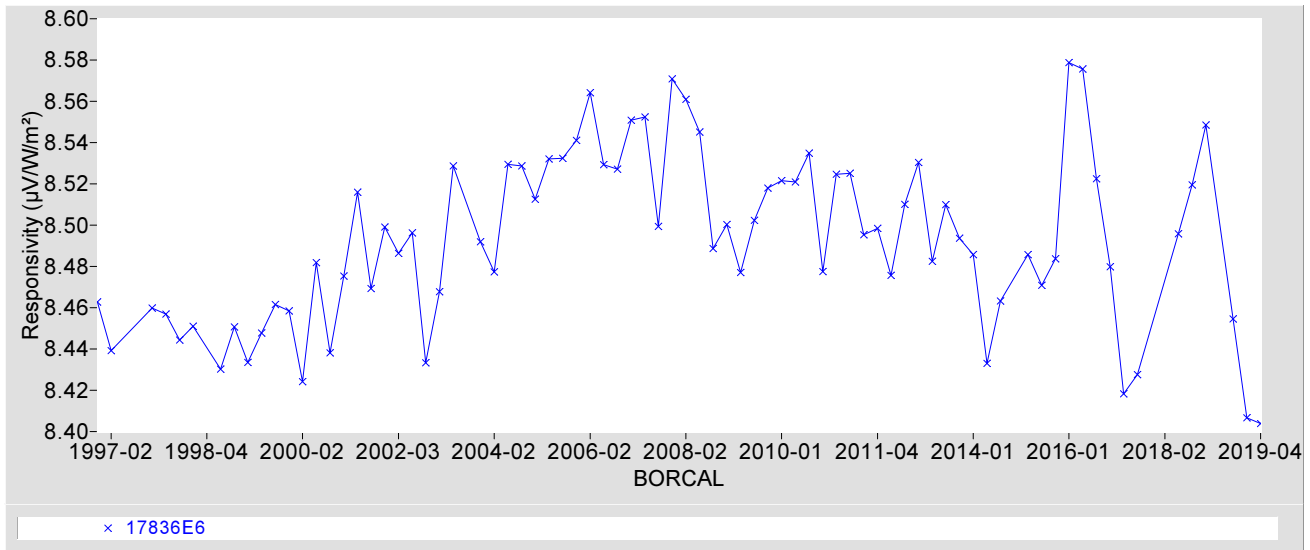
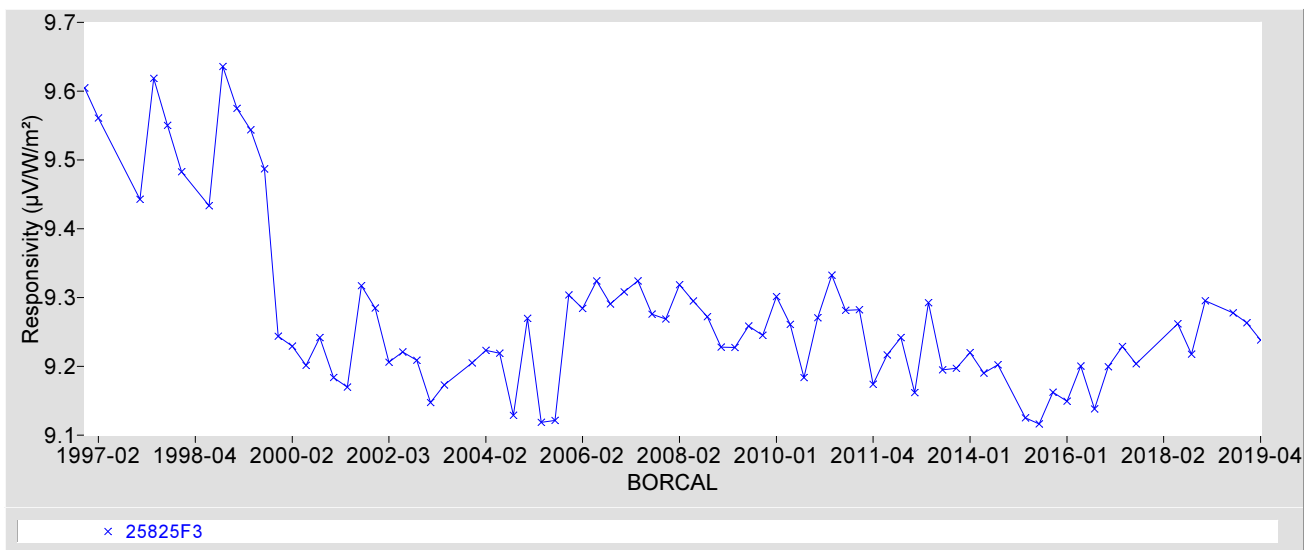


Figure 2. Eppley PSP Control Instrument History



Results Summary

Table 1. Results Summary

| Instrument | R@45 ¹ ($\mu\text{V}/\text{W}/\text{m}^2$) | CF@45 ¹ ($\text{W}/\text{m}^2/\text{mV}$) | U ² (%) | Rnet ³ ($\mu\text{V}/\text{W}/\text{m}^2$) | Page |
|---------------------------|--|---|-----------------------|--|------|
| 080018 Kipp & Zonen CMP22 | 9.9466 | 100.54 | +1.4 / -1.7 | 0.087000 | A1-2 |
| 080033 Kipp & Zonen CH1 | 9.0104 | 110.98 | +0.94 / -1.0 | 0 | A1-5 |
| 35243 Eppley 8-48 | 8.9568 | 111.65 | +4.3 / -3.4 | 0 | A1-8 |

¹ CF = 1000 / R

² See certificate for valid zenith angle range

³ Instrument's Effective Net IR Response

Note: Environmental Conditions for BORCAL starts on page A1-11.

Appendix 1

Instrument Details

Calibration Certificates: 3 pages for each radiometer (4 including Environmental Conditions)

Environmental Conditions for BORCAL: Last Page of a Calibration Certificate. Note: This appears only once, at the end of Appendix 1.



National Renewable Energy Laboratory

Solar Radiation Research Laboratory

Metrology Laboratory

Calibration Certificate



| | | | |
|--------------------------|--------------------------|----------------------------------|--------------|
| Test Instrument: | Pyranometer (Ventilated) | Manufacturer: | Kipp & Zonen |
| Model: | CMP22 | Serial Number: | 080018 |
| Calibration Date: | 7/29/2019 | Due Date: | 7/29/2020 |
| Customer: | Aron Habte | Environmental Conditions: | see page 4 |
| Test Dates: | 7/19, 7/29 | | |

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

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

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

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

This certificate applies only to the item identified above and shall not be reproduced other 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 | 09/24/2018 | 09/24/2019 |
| Diffuse Irradiance † | Hukseflux Pyranometer Model SR25, S/N 2541 | 04/19/2019 | 04/19/2020 |
| Diffuse Irradiance † | Hukseflux Pyranometer Model SR25, S/N 2542 | 04/19/2019 | 04/19/2020 |
| Data Acquisition | NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998 | 02/14/2019 | 02/14/2021 |
| Data Acquisition | NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999 | 02/14/2019 | 02/14/2021 |
| Infrared Irradiance ‡ | Kipp & Zonen Pyrgeometer Model CGR4, S/N 140021 | 04/02/2019 | 04/02/2023 |

† Through the World Radiometric Reference (WRR)

‡ Through the World Infrared Standard Group (WISG)

Number of pages of certificate: 4

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

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

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

Calibrated by: Afshin Andreas, Aron Habte, Ibrahim Reda, Peter Gotseff, and RCC

Ibrahim Reda, Technical Manager

Date

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

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

Calibration Results

080018 Kipp & Zonen CMP22

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

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

where,

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

Figure 1. Responsivity vs Zenith Angle

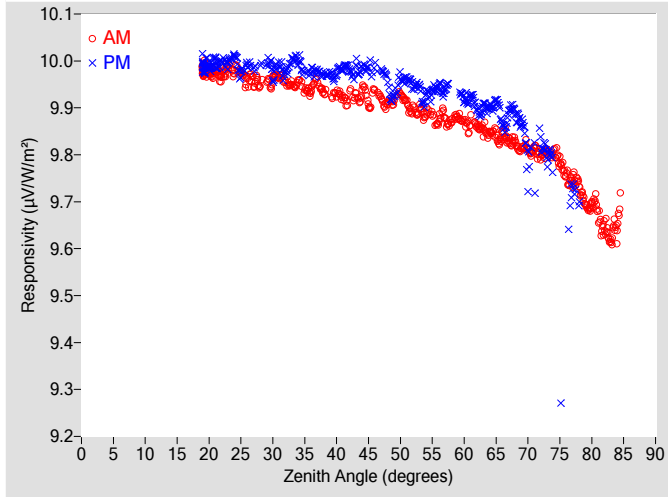


Figure 2. Responsivity vs Local Standard Time

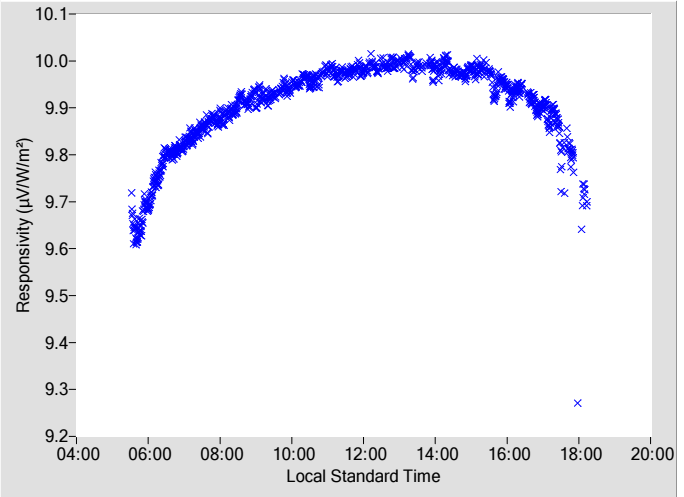


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)

| Zenith Angle (deg.) | R ($\mu\text{V}/\text{W}/\text{m}^2$) | 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 | 9.9389 | 0.36 | 103.03 | 9.9906 | 0.37 | 260.62 |
| 2 | N/A | N/A | N/A | N/A | N/A | N/A | 48 | 9.9072 | 0.36 | 100.79 | 9.9592 | 0.39 | 262.58 |
| 4 | N/A | N/A | N/A | N/A | N/A | N/A | 50 | 9.9296 | 0.37 | 98.73 | 9.9637 | 0.39 | 264.53 |
| 6 | N/A | N/A | N/A | N/A | N/A | N/A | 52 | 9.8959 | 0.38 | 96.98 | 9.9448 | 0.40 | 266.34 |
| 8 | N/A | N/A | N/A | N/A | N/A | N/A | 54 | 9.8864 | 0.39 | 95.08 | 9.9244 | 0.42 | 268.02 |
| 10 | N/A | N/A | N/A | N/A | N/A | N/A | 56 | 9.8718 | 0.40 | 93.29 | 9.9469 | 0.43 | 269.74 |
| 12 | N/A | N/A | N/A | N/A | N/A | N/A | 58 | 9.8719 | 0.41 | 91.58 | N/A | N/A | N/A |
| 14 | N/A | N/A | N/A | N/A | N/A | N/A | 60 | 9.8698 | 0.42 | 89.88 | 9.9171 | 0.46 | 273.01 |
| 16 | N/A | N/A | N/A | N/A | N/A | N/A | 62 | 9.8612 | 0.44 | 88.19 | 9.8971 | 0.48 | 274.61 |
| 18 | N/A | N/A | N/A | N/A | N/A | N/A | 64 | 9.8473 | 0.46 | 86.57 | 9.9025 | 0.51 | 276.18 |
| 20 | 9.9786 | 0.32 | 158.69 | 9.9879 | 0.32 | 200.96 | 66 | 9.8400 | 0.49 | 85.00 | 9.8656 | 0.54 | 277.74 |
| 22 | 9.9700 | 0.32 | 145.93 | 10.001 | 0.32 | 214.14 | 68 | 9.8263 | 0.52 | 83.41 | 9.8841 | N/A | 279.30 |
| 24 | 9.9796 | 0.31 | 137.32 | 10.011 | 0.32 | 222.92 | 70 | 9.8134 | 0.55 | 81.83 | 9.7761 | N/A | 280.82 |
| 26 | 9.9553 | 0.32 | 130.83 | 9.9907 | 0.33 | 229.15 | 72 | 9.7982 | 0.60 | 80.22 | 9.8253 | N/A | 282.44 |
| 28 | 9.9446 | 0.32 | 125.62 | 9.9930 | 0.33 | 234.82 | 74 | 9.8026 | N/A | 78.68 | 9.7781 | N/A | 283.81 |
| 30 | 9.9582 | 0.33 | 127.34 | 9.9749 | 0.33 | 238.84 | 76 | 9.7563 | N/A | 77.06 | N/A | N/A | N/A |
| 32 | 9.9535 | 0.33 | 123.03 | 9.9792 | 0.34 | 242.65 | 78 | 9.7323 | N/A | 75.45 | 9.6955 | N/A | 287.18 |
| 34 | 9.9558 | 0.33 | 119.22 | 9.9990 | 0.34 | 245.96 | 80 | 9.6913 | N/A | 73.83 | N/A | N/A | N/A |
| 36 | 9.9356 | 0.34 | 115.85 | 9.9807 | 0.34 | 249.06 | 82 | 9.6455 | N/A | 72.18 | N/A | N/A | N/A |
| 38 | 9.9339 | 0.34 | 112.73 | 9.9721 | 0.35 | 251.50 | 84 | 9.6491 | N/A | 70.47 | N/A | N/A | N/A |
| 40 | 9.9307 | 0.34 | 110.04 | 9.9755 | 0.35 | 254.19 | 86 | N/A | N/A | N/A | N/A | N/A | N/A |
| 42 | 9.9271 | 0.35 | 107.48 | 9.9822 | 0.36 | 256.38 | 88 | N/A | N/A | N/A | N/A | N/A | N/A |
| 44 | 9.9319 | 0.35 | 105.14 | 9.9843 | 0.36 | 258.43 | 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

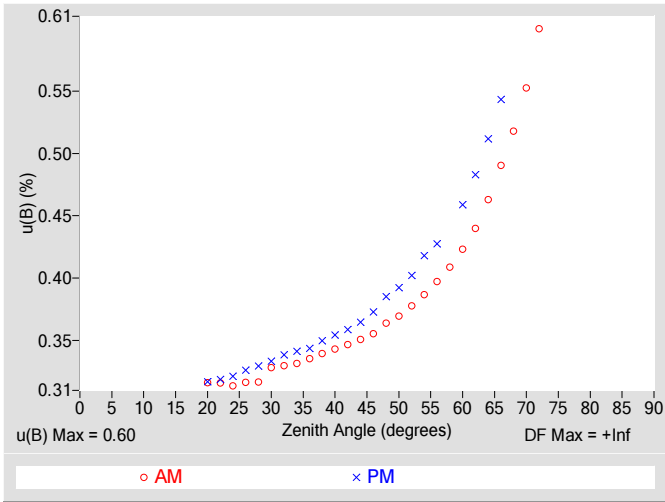


Figure 4. Residuals from Spline Interpolation

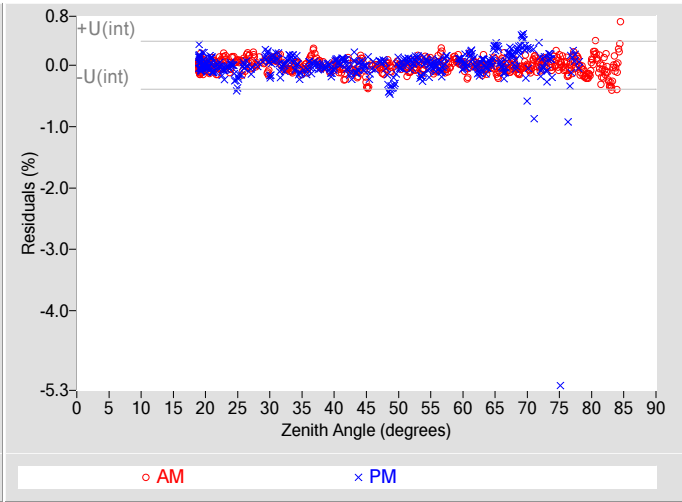


Table 3. Uncertainty using Spline Interpolation ‡

| | |
|---|------------|
| Type-B Standard Uncertainty, $u(B)$ (%) | ± 0.60 |
| Type-A Interpolating Function, $u(int)$ (%) | ± 0.20 |
| Combined Standard Uncertainty, $u(c)$ (%) | ± 0.63 |
| Effective degrees of freedom, $DF(c)$ | 94271 |
| Coverage factor, k | 1.96 |
| Expanded Uncertainty, $U95$ (%) | ± 1.2 |
| AM Valid zenith angle range | 20° to 72° |
| PM Valid zenith angle range | 20° to 66° |

‡ 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

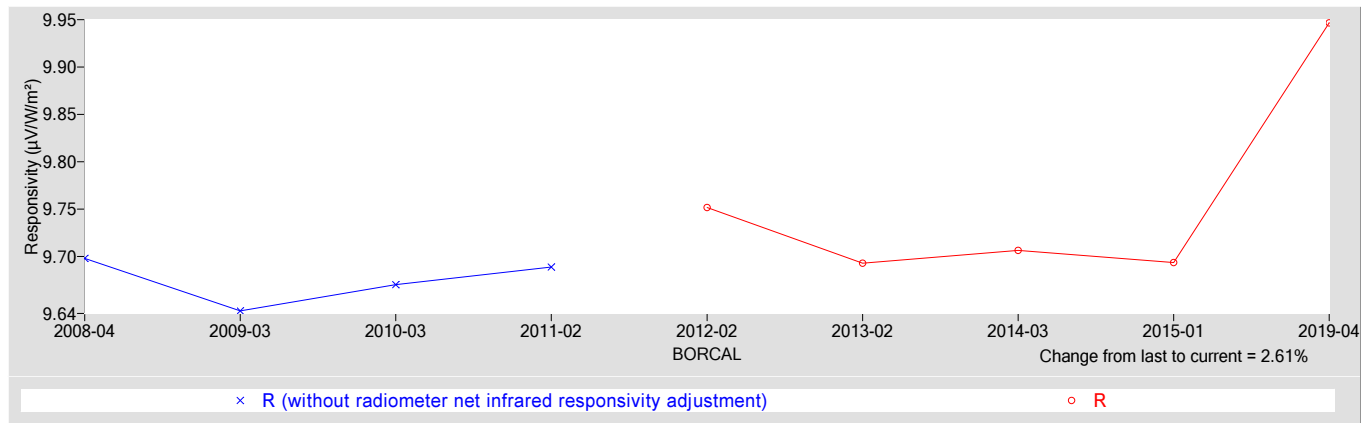
| | |
|----------------------------------|-------------------------------|
| $R @ 45^\circ$ ($\mu V/W/m^2$) | R_{net} ($\mu V/W/m^2$) † |
| 9.9466 | 0.087000 |

† R_{net} determination date: Estimated

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

| | |
|---|----------------|
| Type-B Expanded Uncertainty, $U(B)$ (%) | ± 0.90 |
| Offset Uncertainty, $U(off)$ (%) | +0.53 / -0.77 |
| Expanded Uncertainty, U (%) | +1.4 / -1.7 |
| Effective degrees of freedom, DF | +Inf |
| Coverage factor, k | 1.96 |
| Valid zenith angle range | 30.0° to 60.0° |

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



References:

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

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

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

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

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

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

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



National Renewable Energy Laboratory

Solar Radiation Research Laboratory

Metrology Laboratory

Calibration Certificate



| | | | |
|--------------------------|---------------|----------------------------------|--------------|
| Test Instrument: | Pyrheliometer | Manufacturer: | Kipp & Zonen |
| Model: | CH1 | Serial Number: | 080033 |
| Calibration Date: | 7/29/2019 | Due Date: | 7/29/2020 |
| Customer: | Aron Habte | Environmental Conditions: | see page 4 |
| Test Dates: | 7/19, 7/29 | | |

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

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

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

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

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Table 1. Traceability

| Measurement Type | Instrument | Calibration Date | Calibration Due Date |
|----------------------|--|------------------|----------------------|
| Beam Irradiance † | Eppley Absolute Cavity Radiometer Model HF, S/N 29219 | 09/24/2018 | 09/24/2019 |
| Diffuse Irradiance † | Hukseflux Pyranometer Model SR25, S/N 2541 | 04/19/2019 | 04/19/2020 |
| Diffuse Irradiance † | Hukseflux Pyranometer Model SR25, S/N 2542 | 04/19/2019 | 04/19/2020 |
| Data Acquisition | NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998 | 02/14/2019 | 02/14/2021 |
| Data Acquisition | NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999 | 02/14/2019 | 02/14/2021 |

† Through the World Radiometric Reference (WRR)

Number of pages of certificate: 4

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

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

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

Calibrated by: Afshin Andreas, Aron Habte, Ibrahim Reda, Peter Gotseff, and RCC

Ibrahim Reda, Technical Manager

Date

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

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

Calibration Results

080033 Kipp & Zonen CH1

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

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

where,

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

Figure 1. Responsivity vs Zenith Angle

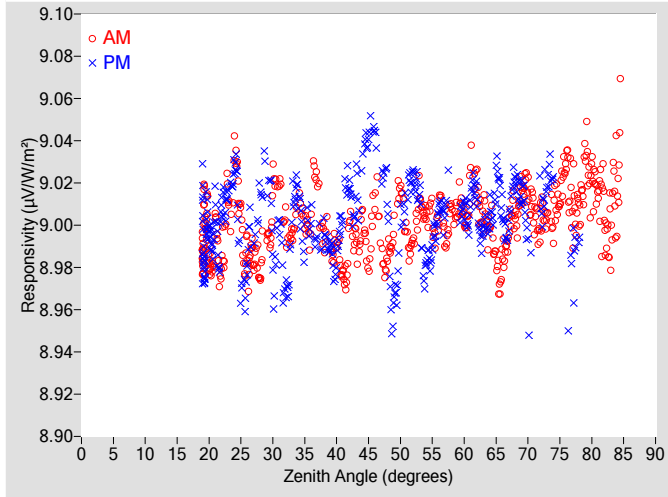


Figure 2. Responsivity vs Local Standard Time

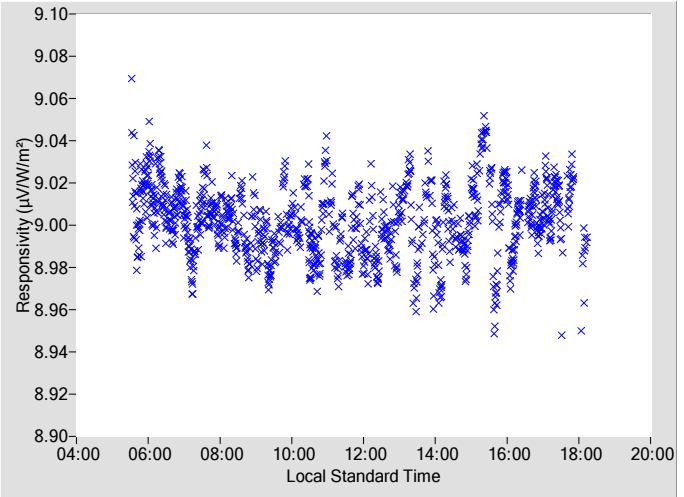


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)

| Zenith Angle (deg.) | R ($\mu\text{V}/\text{W}/\text{m}^2$) | u(B) \pm (%) | Azimuth Angle | R ($\mu\text{V}/\text{W}/\text{m}^2$) | u(B) \pm (%) | Azimuth Angle | Zenith Angle (deg.) | R ($\mu\text{V}/\text{W}/\text{m}^2$) | u(B) \pm (%) | Azimuth Angle | R ($\mu\text{V}/\text{W}/\text{m}^2$) | u(B) \pm (%) | Azimuth Angle |
|---------------------|---|----------------|---------------|---|----------------|---------------|---------------------|---|----------------|---------------|---|----------------|---------------|
| 0 | N/A | N/A | N/A | N/A | N/A | N/A | 46 | 9.0113 | 0.28 | 102.85 | 9.0432 | 0.29 | 260.64 |
| 2 | N/A | N/A | N/A | N/A | N/A | N/A | 48 | 8.9854 | 0.28 | 100.80 | 9.0040 | 0.29 | 262.65 |
| 4 | N/A | N/A | N/A | N/A | N/A | N/A | 50 | 9.0158 | 0.29 | 98.77 | 8.9986 | 0.29 | 264.47 |
| 6 | N/A | N/A | N/A | N/A | N/A | N/A | 52 | 8.9924 | 0.29 | 96.93 | 9.0224 | 0.29 | 266.32 |
| 8 | N/A | N/A | N/A | N/A | N/A | N/A | 54 | 9.0052 | 0.29 | 95.10 | 8.9795 | 0.29 | 268.04 |
| 10 | N/A | N/A | N/A | N/A | N/A | N/A | 56 | 9.0056 | 0.29 | 93.27 | 9.0064 | 0.29 | 269.72 |
| 12 | N/A | N/A | N/A | N/A | N/A | N/A | 58 | 9.0079 | 0.29 | 91.63 | N/A | N/A | N/A |
| 14 | N/A | N/A | N/A | N/A | N/A | N/A | 60 | 9.0027 | 0.29 | 89.86 | 9.0090 | 0.30 | 273.03 |
| 16 | N/A | N/A | N/A | N/A | N/A | N/A | 62 | 9.0187 | 0.29 | 88.25 | 9.0124 | 0.30 | 274.57 |
| 18 | N/A | N/A | N/A | N/A | N/A | N/A | 64 | 8.9978 | 0.29 | 86.67 | 9.0035 | 0.30 | 276.18 |
| 20 | 8.9898 | 0.28 | 159.26 | 8.9982 | 0.28 | 200.62 | 66 | 8.9822 | 0.29 | 85.02 | 9.0058 | 0.30 | 277.73 |
| 22 | 8.9826 | 0.28 | 145.91 | 9.0091 | 0.28 | 214.50 | 68 | 9.0047 | 0.30 | 83.43 | 9.0213 | N/A | 279.28 |
| 24 | 9.0296 | 0.28 | 136.90 | 9.0268 | 0.28 | 222.93 | 70 | 9.0173 | 0.30 | 81.89 | 8.9834 | N/A | 280.79 |
| 26 | 8.9839 | 0.28 | 130.65 | 8.9808 | 0.28 | 229.16 | 72 | 9.0028 | 0.30 | 80.24 | 9.0090 | N/A | 282.46 |
| 28 | 8.9771 | 0.28 | 125.39 | 9.0167 | 0.28 | 234.54 | 74 | 9.0057 | N/A | 78.68 | 9.0222 | N/A | 283.83 |
| 30 | 9.0099 | 0.28 | 127.51 | 8.9832 | 0.28 | 238.80 | 76 | 9.0305 | N/A | 77.04 | 8.9500 | N/A | 285.79 |
| 32 | 9.0006 | 0.28 | 123.03 | 8.9703 | 0.28 | 242.72 | 78 | 9.0079 | N/A | 75.47 | 8.9930 | N/A | 287.16 |
| 34 | 9.0119 | 0.28 | 119.26 | 9.0146 | 0.28 | 245.93 | 80 | 9.0193 | N/A | 73.82 | N/A | N/A | N/A |
| 36 | 8.9964 | 0.28 | 115.93 | 9.0029 | 0.28 | 248.81 | 82 | 9.0053 | N/A | 72.16 | N/A | N/A | N/A |
| 38 | 8.9940 | 0.28 | 112.78 | 8.9965 | 0.28 | 251.79 | 84 | 9.0152 | N/A | 70.45 | N/A | N/A | N/A |
| 40 | 8.9911 | 0.28 | 110.03 | 8.9818 | 0.28 | 254.09 | 86 | N/A | N/A | N/A | N/A | N/A | N/A |
| 42 | 8.9981 | 0.28 | 107.47 | 9.0168 | 0.29 | 256.50 | 88 | N/A | N/A | N/A | N/A | N/A | N/A |
| 44 | 9.0024 | 0.28 | 105.23 | 9.0298 | 0.29 | 258.62 | 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

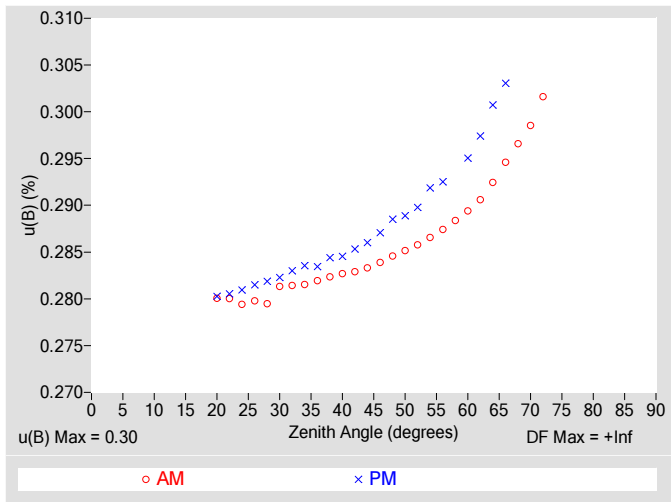


Figure 4. Residuals from Spline Interpolation

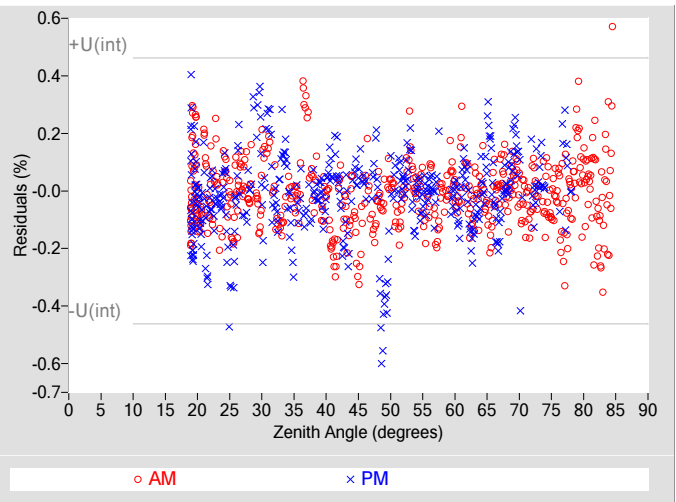


Table 3. Uncertainty using Spline Interpolation ‡

| | |
|---|------------|
| Type-B Standard Uncertainty, $u(B)$ (%) | ± 0.30 |
| Type-A Interpolating Function, $u(int)$ (%) | ± 0.23 |
| Combined Standard Uncertainty, $u(c)$ (%) | ± 0.38 |
| Effective degrees of freedom, $DF(c)$ | 6429 |
| Coverage factor, k | 1.96 |
| Expanded Uncertainty, U_{95} (%) | ± 0.75 |
| AM Valid zenith angle range | 20° to 72° |
| PM Valid zenith angle range | 20° to 66° |

‡ 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

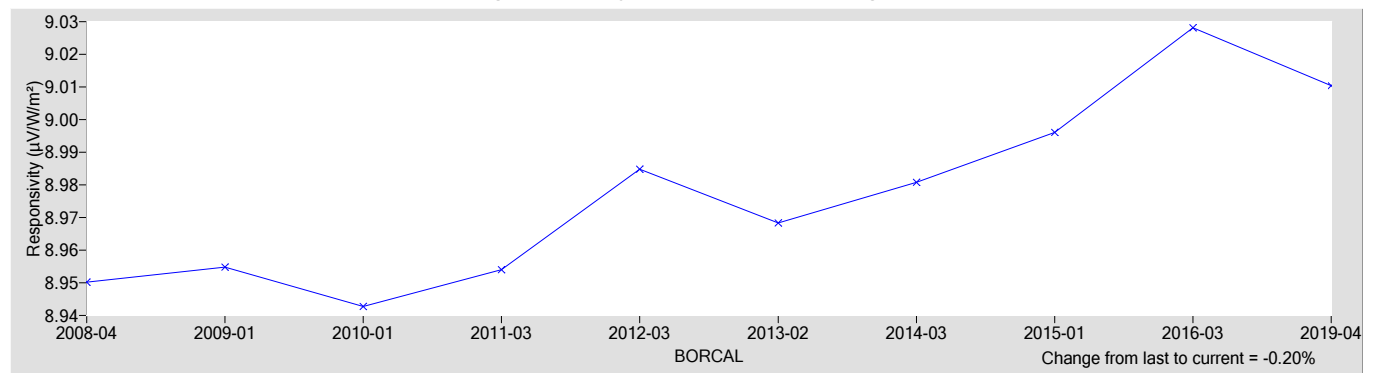
| $R @ 45^\circ$ ($\mu V/W/m^2$) | R_{net} ($\mu V/W/m^2$) † |
|----------------------------------|-------------------------------|
| 9.0104 | 0 |

† R_{net} determination date: N/A

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

| | |
|---|----------------|
| Type-B Expanded Uncertainty, $U(B)$ (%) | ± 0.58 |
| Offset Uncertainty, $U(off)$ (%) | +0.36 / -0.44 |
| Expanded Uncertainty, U (%) | +0.94 / -1.0 |
| Effective degrees of freedom, DF | +Inf |
| Coverage factor, k | 1.96 |
| Valid zenith angle range | 30.0° to 60.0° |

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



References:

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



National Renewable Energy Laboratory

Solar Radiation Research Laboratory

Metrology Laboratory

Calibration Certificate



| | | | |
|--------------------------|-----------------------------|----------------------------------|------------|
| Test Instrument: | Black and White Pyranometer | Manufacturer: | Eppley |
| Model: | 8-48 | Serial Number: | 35243 |
| Calibration Date: | 7/29/2019 | Due Date: | 7/29/2020 |
| Customer: | Aron Habte | Environmental Conditions: | see page 4 |
| Test Dates: | 7/19, 7/29 | | |

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

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

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

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

This certificate applies only to the item identified above and shall not be reproduced other 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 | 09/24/2018 | 09/24/2019 |
| Diffuse Irradiance † | Hukseflux Pyranometer Model SR25, S/N 2541 | 04/19/2019 | 04/19/2020 |
| Diffuse Irradiance † | Hukseflux Pyranometer Model SR25, S/N 2542 | 04/19/2019 | 04/19/2020 |
| Data Acquisition | NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998 | 02/14/2019 | 02/14/2021 |
| Data Acquisition | NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999 | 02/14/2019 | 02/14/2021 |

† Through the World Radiometric Reference (WRR)

Number of pages of certificate: 4

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

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

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

Calibrated by: Afshin Andreas, Aron Habte, Ibrahim Reda, Peter Gotseff, and RCC

Ibrahim Reda, Technical Manager

Date

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

Calibration Results

35243 Eppley 8-48

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

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

where,

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

Figure 1. Responsivity vs Zenith Angle

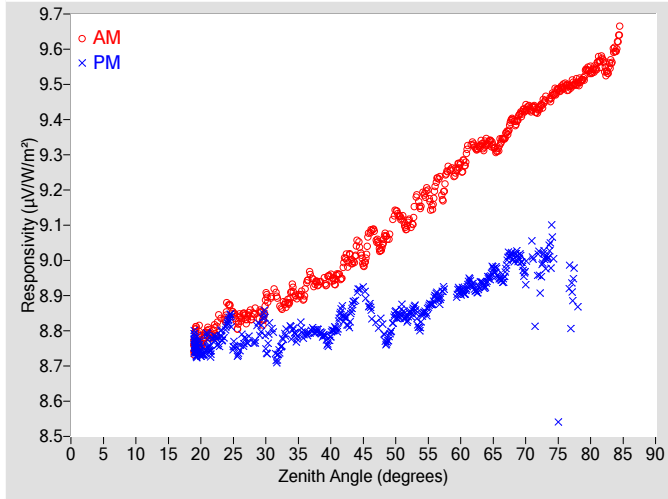


Figure 2. Responsivity vs Local Standard Time

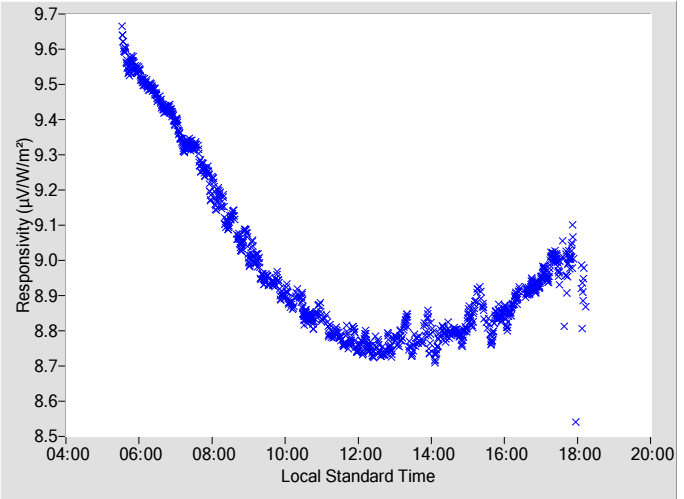


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)

| Zenith Angle (deg.) | R ($\mu\text{V}/\text{W}/\text{m}^2$) | u(B) \pm (%) | Azimuth Angle | R ($\mu\text{V}/\text{W}/\text{m}^2$) | u(B) \pm (%) | Azimuth Angle | Zenith Angle (deg.) | R ($\mu\text{V}/\text{W}/\text{m}^2$) | u(B) \pm (%) | Azimuth Angle | R ($\mu\text{V}/\text{W}/\text{m}^2$) | u(B) \pm (%) | Azimuth Angle |
|---------------------|---|----------------|---------------|---|----------------|---------------|---------------------|---|----------------|---------------|---|----------------|---------------|
| 0 | N/A | N/A | N/A | N/A | N/A | N/A | 46 | 9.0787 | 0.36 | 102.86 | 8.8624 | 0.37 | 260.73 |
| 2 | N/A | N/A | N/A | N/A | N/A | N/A | 48 | 9.0479 | 0.36 | 100.78 | 8.7996 | 0.39 | 262.77 |
| 4 | N/A | N/A | N/A | N/A | N/A | N/A | 50 | 9.1365 | 0.37 | 98.75 | 8.8465 | 0.39 | 264.42 |
| 6 | N/A | N/A | N/A | N/A | N/A | N/A | 52 | 9.1096 | 0.38 | 96.96 | 8.8420 | 0.40 | 266.30 |
| 8 | N/A | N/A | N/A | N/A | N/A | N/A | 54 | 9.1649 | 0.39 | 95.11 | 8.8381 | 0.42 | 268.07 |
| 10 | N/A | N/A | N/A | N/A | N/A | N/A | 56 | 9.1926 | 0.40 | 93.28 | 8.8936 | 0.43 | 269.71 |
| 12 | N/A | N/A | N/A | N/A | N/A | N/A | 58 | 9.2544 | 0.41 | 91.61 | N/A | N/A | N/A |
| 14 | N/A | N/A | N/A | N/A | N/A | N/A | 60 | 9.2632 | 0.42 | 89.85 | 8.9128 | 0.46 | 273.01 |
| 16 | N/A | N/A | N/A | N/A | N/A | N/A | 62 | 9.3290 | 0.44 | 88.24 | 8.9222 | 0.48 | 274.63 |
| 18 | N/A | N/A | N/A | N/A | N/A | N/A | 64 | 9.3342 | 0.46 | 86.61 | 8.9381 | 0.51 | 276.14 |
| 20 | 8.7746 | 0.32 | 159.68 | 8.7446 | 0.32 | 200.19 | 66 | 9.3281 | 0.49 | 85.01 | 8.9500 | 0.54 | 277.71 |
| 22 | 8.7981 | 0.32 | 145.46 | 8.7789 | 0.32 | 214.43 | 68 | 9.3992 | 0.52 | 83.43 | 9.0099 | N/A | 279.27 |
| 24 | 8.8519 | 0.31 | 137.26 | 8.8192 | 0.32 | 223.03 | 70 | 9.4305 | 0.55 | 81.83 | 8.9632 | N/A | 280.78 |
| 26 | 8.8336 | 0.32 | 130.64 | 8.7571 | 0.33 | 229.39 | 72 | 9.4293 | 0.60 | 80.27 | 8.9734 | N/A | 282.43 |
| 28 | 8.8418 | 0.32 | 125.48 | 8.7651 | 0.33 | 234.83 | 74 | 9.4646 | N/A | 78.67 | 9.0379 | N/A | 283.95 |
| 30 | 8.8794 | 0.33 | 127.32 | 8.7834 | 0.33 | 238.77 | 76 | 9.4952 | N/A | 77.07 | N/A | N/A | N/A |
| 32 | 8.8814 | 0.33 | 123.00 | 8.7367 | 0.34 | 242.60 | 78 | 9.5033 | N/A | 75.46 | 8.8684 | N/A | 287.18 |
| 34 | 8.9134 | 0.33 | 119.12 | 8.8025 | 0.34 | 245.91 | 80 | 9.5370 | N/A | 73.80 | N/A | N/A | N/A |
| 36 | 8.8987 | 0.34 | 115.93 | 8.7889 | 0.34 | 248.74 | 82 | 9.5597 | N/A | 72.15 | N/A | N/A | N/A |
| 38 | 8.9355 | 0.34 | 112.76 | 8.7999 | 0.35 | 251.67 | 84 | 9.6040 | N/A | 70.47 | N/A | N/A | N/A |
| 40 | 8.9530 | 0.34 | 110.00 | 8.7898 | 0.35 | 254.20 | 86 | N/A | N/A | N/A | N/A | N/A | N/A |
| 42 | 8.9824 | 0.35 | 107.52 | 8.8433 | 0.36 | 256.48 | 88 | N/A | N/A | N/A | N/A | N/A | N/A |
| 44 | 9.0310 | 0.35 | 105.21 | 8.9046 | 0.36 | 258.64 | 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

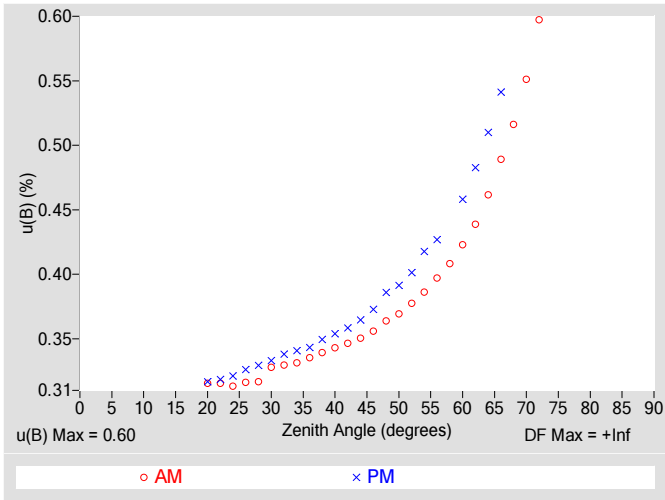


Figure 4. Residuals from Spline Interpolation

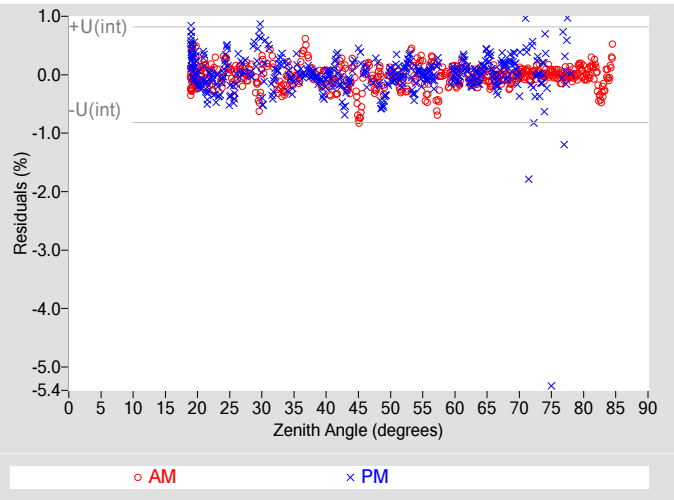


Table 3. Uncertainty using Spline Interpolation ‡

| | |
|---|------------|
| Type-B Standard Uncertainty, $u(B)$ (%) | ± 0.60 |
| Type-A Interpolating Function, $u(int)$ (%) | ± 0.41 |
| Combined Standard Uncertainty, $u(c)$ (%) | ± 0.72 |
| Effective degrees of freedom, $DF(c)$ | 8400 |
| Coverage factor, k | 1.96 |
| Expanded Uncertainty, $U95$ (%) | ± 1.4 |
| AM Valid zenith angle range | 20° to 72° |
| PM Valid zenith angle range | 20° to 66° |

‡ 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

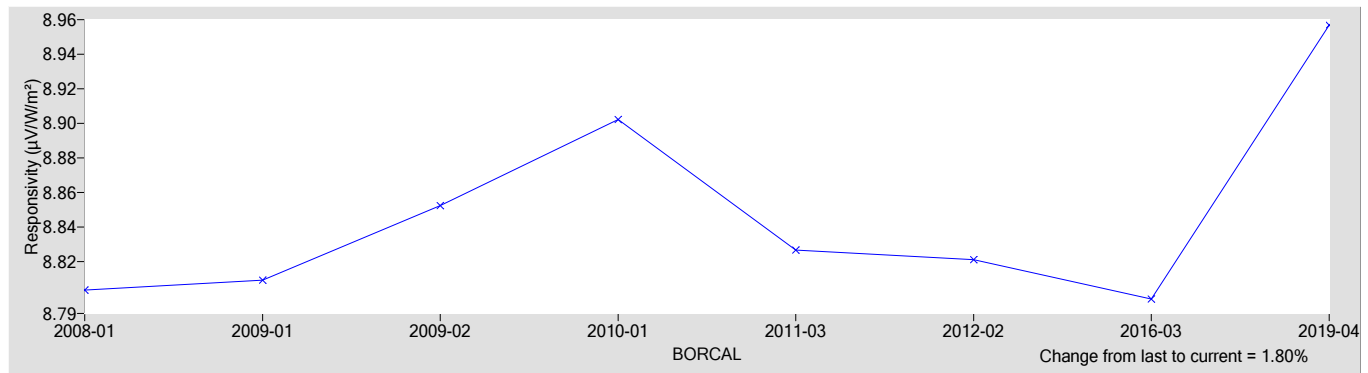
| | |
|----------------------------------|-------------------------------|
| $R @ 45^\circ$ ($\mu V/W/m^2$) | R_{net} ($\mu V/W/m^2$) † |
| 8.9568 | 0 |

† R_{net} determination date: N/A

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

| | |
|---|----------------|
| Type-B Expanded Uncertainty, $U(B)$ (%) | ± 0.90 |
| Offset Uncertainty, $U(off)$ (%) | +3.4 / -2.5 |
| Expanded Uncertainty, U (%) | +4.3 / -3.4 |
| Effective degrees of freedom, DF | +Inf |
| Coverage factor, k | 1.96 |
| Valid zenith angle range | 30.0° to 60.0° |

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



References:

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

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

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

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

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

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

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

Environmental and Sky Conditions for BORCAL-SW 2019-04

Calibration Facility: Solar Radiation Research Laboratory

Latitude: 39.742°N

Longitude: 105.180°W

Elevation: 1828.8 meters AMSL

Time Zone: -7.0

Reference Irradiance:

Figure 6. Reference Irradiance

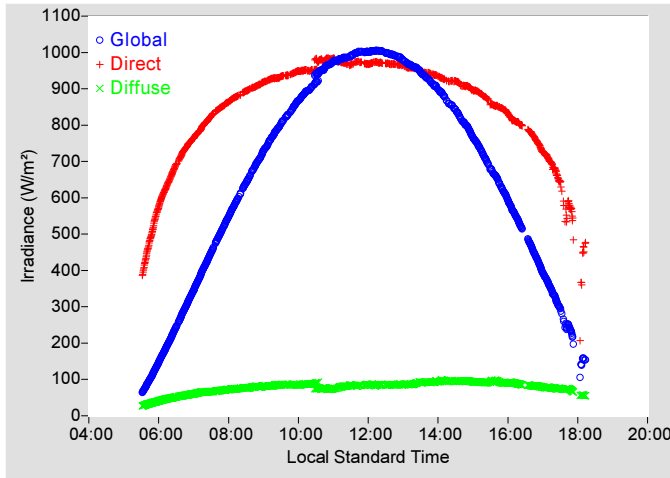
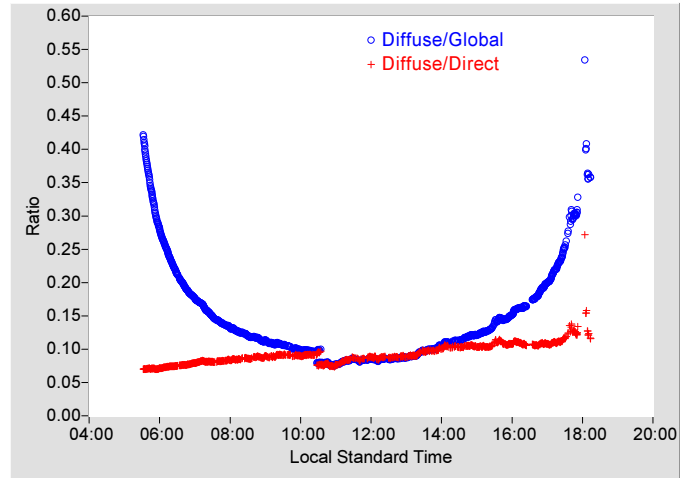


Figure 7. Diffuse Ratios



Meteorological Observations:

Figure 8. Temperature

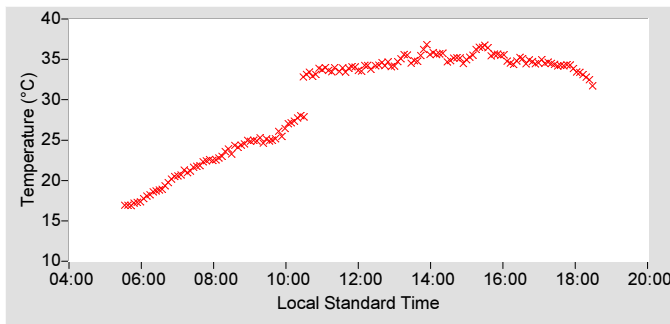


Figure 9. Humidity

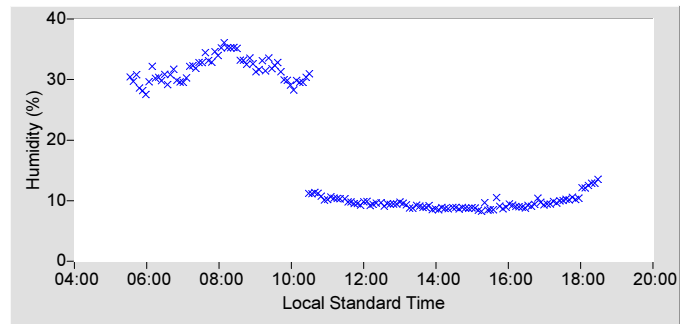


Figure 10. Pressure

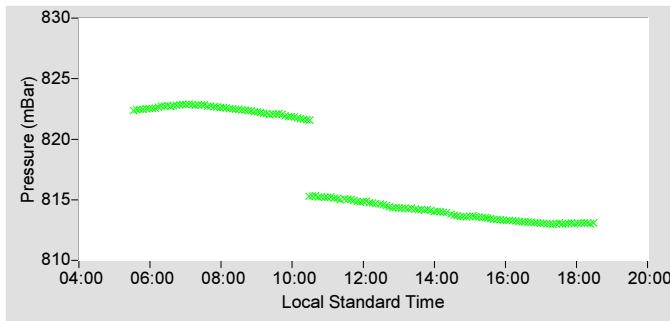


Figure 11. Effective Net Infrared

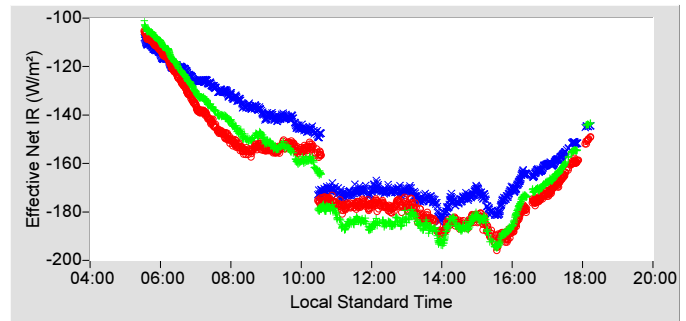


Figure 12. Estimated Broadband Aerosol Optical Depth

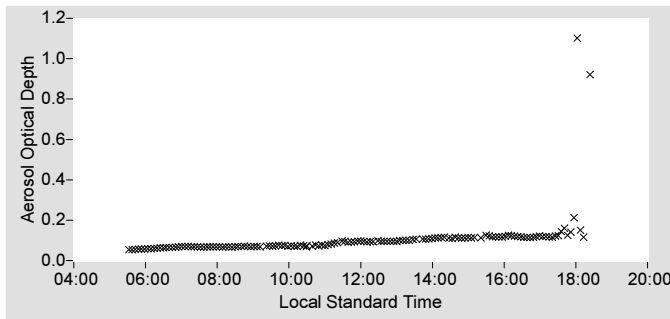


Table 6. Meteorological Observations

| Observations | Mean | Min | Max |
|---------------------------------|-------|-------|-------|
| Temperature (°C) | 29.84 | 16.88 | 36.82 |
| Humidity (%) | 18.22 | 8.27 | 36.11 |
| Pressure (mBar) | 817.2 | 813.0 | 822.9 |
| Est. Aerosol Optical Depth (BB) | 0.105 | 0.054 | 1.101 |

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

Appendix 2

BORCAL Notes

Instrument, Configuration, and Session Notes for the BORCAL

BORCAL Notes

Facility: Solar Radiation Research Laboratory

Comments:

Avg. Station Pressure & Temperature is for Denver, CO, which is used for the Solar Position Algorithm (SPA).