Broadband Outdoor Radiometer Calibration

BORCAL
2010-03

Customer

NREL-SRRL-BMS

Organization: NREL
Address: BMS, SRRL, Golden, CO 80401 USA
Phone: 303-384-6326

Calibration Facility

Solar Radiation Research Laboratory

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

Calibration date
07/26/2010 to 07/27/2010

Report Date
August 3, 2010

NOTICE

This report was prepared as an account of work sponsored by an agency of the United States government. Neither the United States government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or any agency thereof.

Broadband Outdoor Radiometer Calibration Report

Table of contents

Introduction....3
Control Instrument history plots....4
Results summary....5
Appendix 1 Instrument Details....A1-1
Appendix 2 BORCAL Notes....A2-1

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 and application notes 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

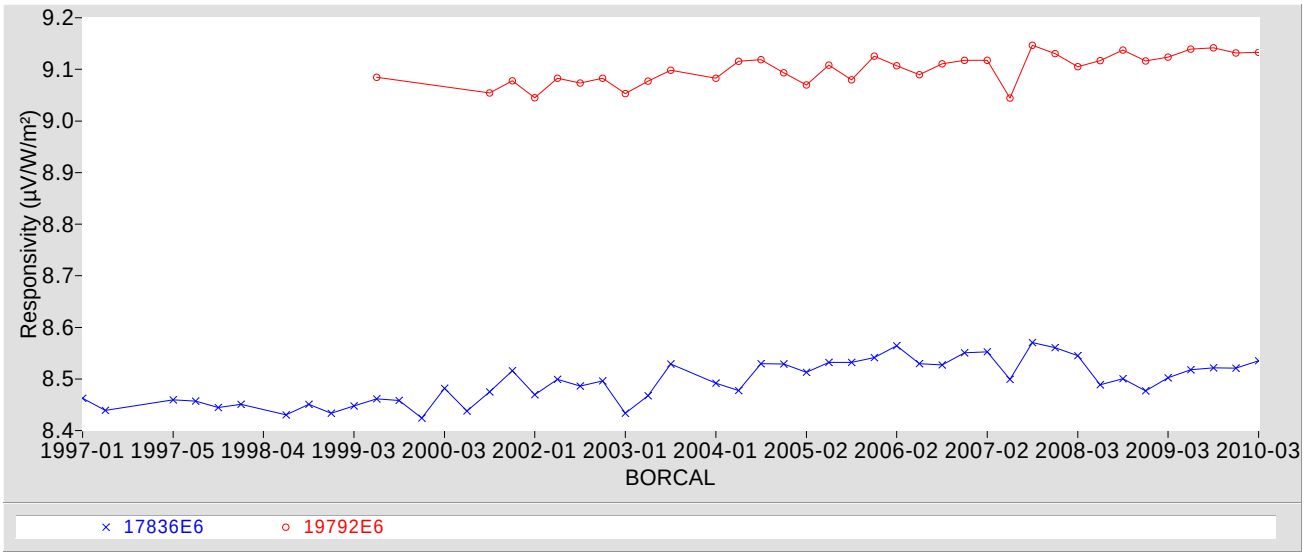
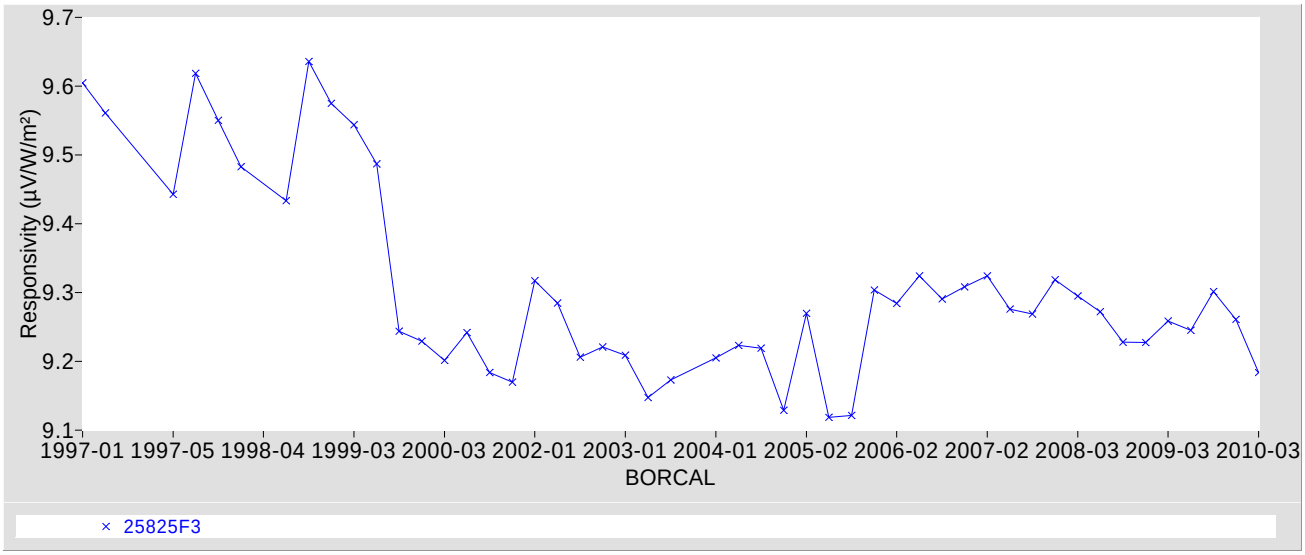


Figure 2. Eppley PSP Control Instrument History



Results Summary

Table 1. Results Summary

Instrument	R@45 [1] (µV/W/m²)	CF@45 [1] (W/m²/mV)	U [2] (%)	Rnet [3] (µV/W/m²)	Page
010034	10.867	92.018	+2.61 / -1.83	0	A1-2
PY28244	12.824	77.980	+1.36 / -2.45	0	A1-6
PY28247	12.665	78.961	+1.78 / -3.55	0	A1-10
PY28260	12.500	80.001	+1.37 / -2.61	0	A1-14

[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 A1-18.

Appendix 1
Instrument Details

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

Application Notes: 1 page for each radiometer

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	**Manufacturer:**	Kipp & Zonen
Model:	CM22	**Serial Number:**	010034
Calibration Date:	7/27/2010	**Due Date:**	7/27/2011
Customer:	NREL-SRRL-BMS	**Environmental Conditions:**	see page 4
Test Dates:	7/26		

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

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

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

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

This certificate applies only to the item identified above and shall not be reproduced other that in full, without specific written approval from the calibration facility. Certificate without signature is not valid.

Table 1. Traceability

Measurement Type	Instrument	Calibration Date	Calibration Due Date
Beam Irradiance †	Eppley Absolute Cavity Radiometer Model HF, S/N 29219	10/03/2009	10/03/2010
Diffuse Irradiance †	Eppley Black and White Pyranometer Model 8-48, S/N 32858	04/14/2010	04/14/2011
Diffuse Irradiance †	Eppley Black and White Pyranometer Model 8-48, S/N 32871	04/14/2010	04/14/2011
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	04/22/2009	04/22/2011
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	04/17/2009	04/17/2011

† 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 are installed for horizontal measurements, with their signal connectors oriented north, if their design permits. The shading disk for the reference diffuse measurement subtends a solid angle of 5°. Pyrheliometers are installed on solar trackers.

Calibrated by: RCC

_____ _____

Ibrahim Reda, Technical Manager Date

For questions or comments, please contact the technical manager at:
ibrahim.reda@nrel.gov; 303-384-6385; 1617 Cole Blvd, Golden, CO 80401, USA

Calibration Results

010034 Kipp & Zonen CM22

The responsivity of the test instrument during calibration is calculated using this Measurement Equation:

$$R = (V - Rnet * Wnet) / I \qquad [1]$$

where,

- R = radiometer responsivity (µV/W/m²),
- V = radiometer output voltage (microvolts),
- $Rnet$ = radiometer net infrared responsivity (µV/W/m²), see Table 3,
- $Wnet$ = effective net infrared measured by pyrgeometer (W/m²),
- I = reference irradiance (W/m²), beam (B) or global (G)
  where, $G = B * COS(Z) + D$,
  Z = zenith angle (degrees),
  D = reference diffuse irradiance (W/m²).

Figure 1. Responsivity vs Zenith Angle

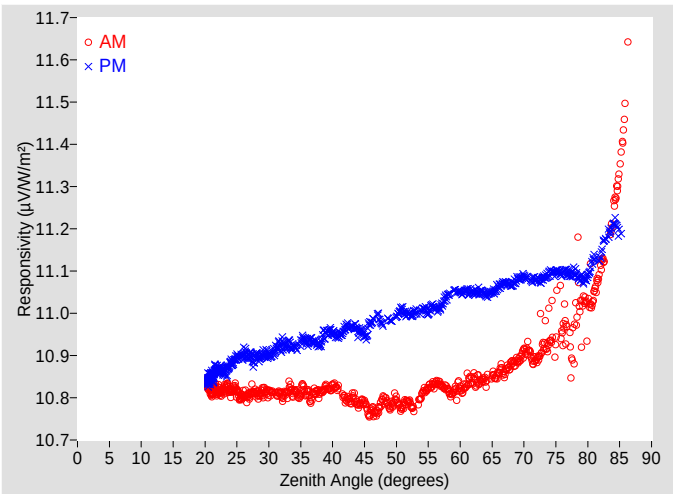


Figure 2. Responsivity vs Local Standard Time

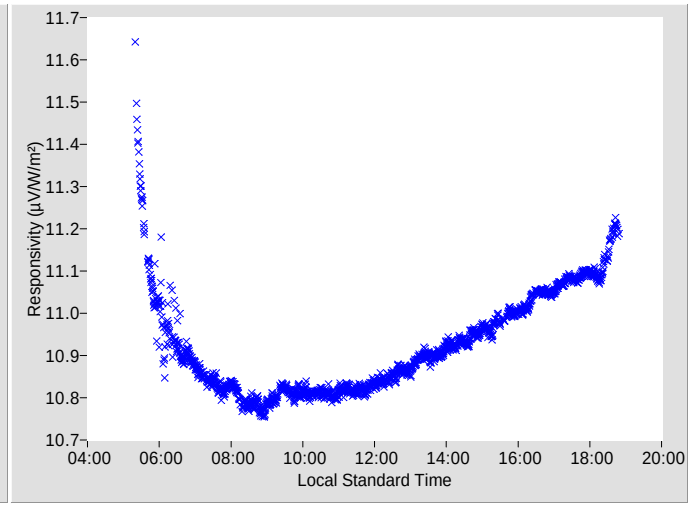


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)

Zenith	AM			PM			Zenith	AM			PM		
Angle	R	u(B)	Azimuth	R	u(B)	Azimuth	Angle	R	u(B)	Azimuth	R	u(B)	Azimuth
(deg.)	(µV/W/m²)	± (%)	Angle	(µV/W/m²)	± (%)	Angle	(deg.)	(µV/W/m²)	± (%)	Angle	(µV/W/m²)	± (%)	Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	10.769	0.39	101.73	10.978	0.41	258.15
2	N/A	N/A	N/A	N/A	N/A	N/A	48	10.797	0.39	99.70	10.972	0.42	259.99
4	N/A	N/A	N/A	N/A	N/A	N/A	50	10.797	0.39	97.75	10.994	0.42	262.23
6	N/A	N/A	N/A	N/A	N/A	N/A	52	10.790	0.40	95.88	10.999	0.43	264.00
8	N/A	N/A	N/A	N/A	N/A	N/A	54	10.807	0.41	94.07	11.007	0.44	265.86
10	N/A	N/A	N/A	N/A	N/A	N/A	56	10.833	0.41	92.31	11.013	0.45	267.57
12	N/A	N/A	N/A	N/A	N/A	N/A	58	10.819	0.42	90.60	11.042	0.46	269.29
14	N/A	N/A	N/A	N/A	N/A	N/A	60	10.824	0.43	88.97	11.050	0.48	270.94
16	N/A	N/A	N/A	N/A	N/A	N/A	62	10.845	0.45	87.32	11.049	0.49	272.55
18	N/A	N/A	N/A	N/A	N/A	N/A	64	10.842	0.46	85.70	11.044	0.51	274.16
20	N/A	N/A	N/A	N/A	N/A	N/A	66	10.859	0.48	84.11	11.064	0.53	275.76
22	10.816	0.36	155.41	10.865	0.37	204.55	68	10.881	0.50	82.53	11.067	0.56	277.34
24	10.815	0.37	144.07	10.880	0.37	215.86	70	10.909	0.53	80.97	11.086	N/A	278.91
26	10.804	0.37	136.20	10.901	0.37	223.65	72	10.892	0.57	79.40	11.080	N/A	280.49
28	10.811	0.37	130.24	10.899	0.37	229.62	74	10.940	N/A	77.81	11.095	N/A	282.05
30	10.811	0.37	125.39	10.900	0.38	234.56	76	10.969	N/A	76.23	11.095	N/A	283.64
32	10.804	0.37	121.20	10.924	0.38	238.76	78	10.969	N/A	74.55	11.097	N/A	285.24
34	10.813	0.37	117.53	10.921	0.39	242.34	80	11.005	N/A	72.99	11.088	N/A	286.85
36	10.813	0.37	114.31	10.931	0.39	245.68	82	11.113	N/A	71.25	11.137	N/A	288.53
38	10.812	0.37	111.33	10.925	0.39	248.53	84	11.242	N/A	69.60	11.215	N/A	290.31
40	10.827	0.38	108.68	10.955	0.40	251.18	86	11.533	N/A	67.90	N/A	N/A	N/A
42	10.799	0.38	106.21	10.966	0.40	253.67	88	N/A	N/A	N/A	N/A	N/A	N/A
44	10.783	0.38	103.91	10.958	0.40	255.97	90	N/A	N/A	N/A	N/A	N/A	N/A

N/A - Not Available

Figure 3. Type-B Standard Uncertainty vs Zenith Angle

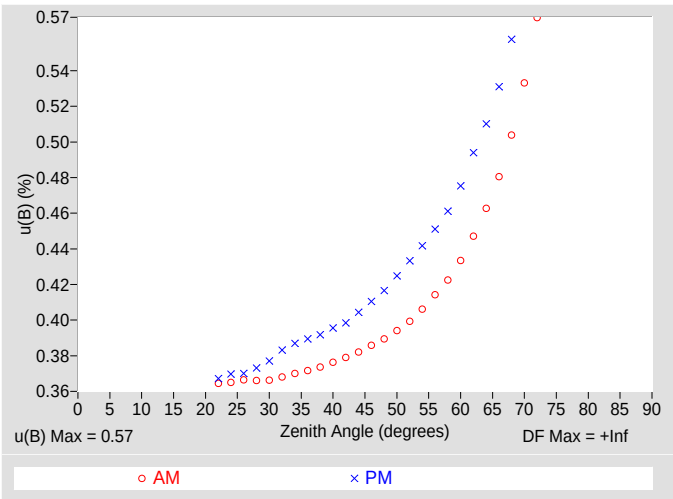


Figure 4. Residuals from Spline Interpolation

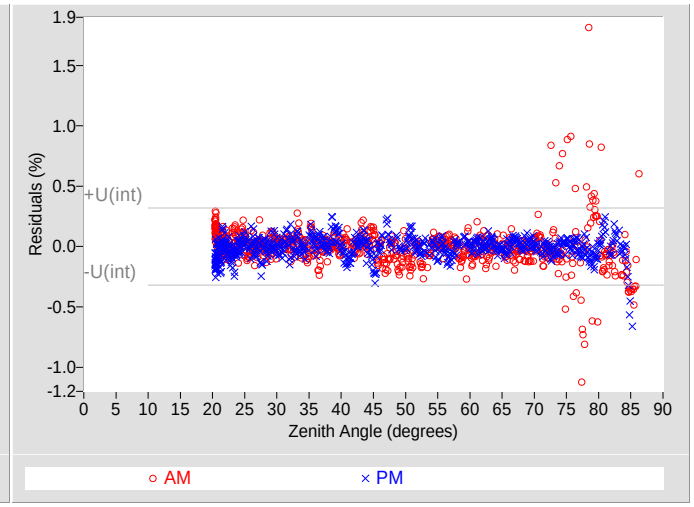


Table 3. Uncertainty using Spline Interpolation

Type-B Standard Uncertainty, u(B) (%)	±0.57
Type-A Interpolating Function, u(int) (%)	±0.16
Combined Standard Uncertainty, u(c) (%)	±0.59
Effective degrees of freedom, DF(c)	229760
Coverage factor, k	1.96
Expanded Uncertainty, U95 (%)	±1.16
AM Valid zenith angle range	22° to 72°
PM Valid zenith angle range	22° to 68°

Table 4. Calibration Label Values

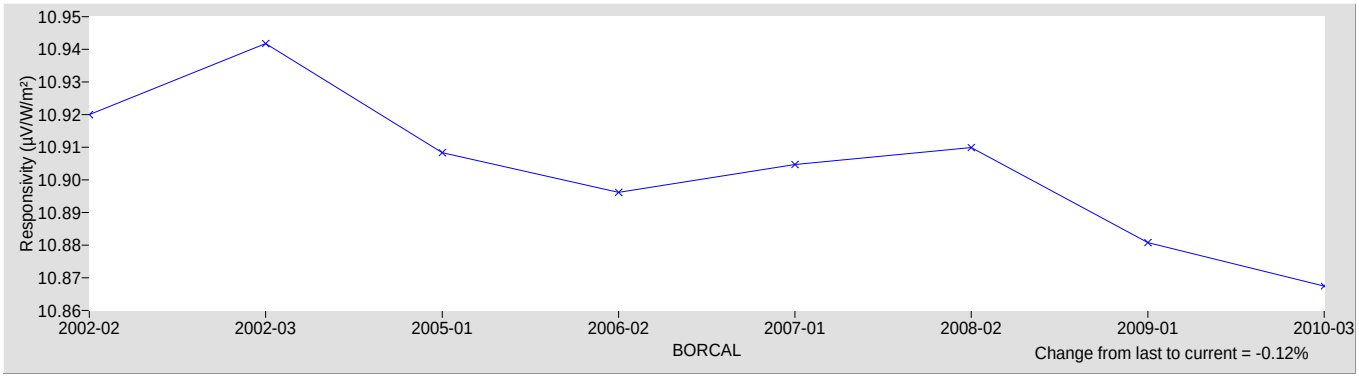
R @ 45° (µV/W/m²)	Rnet (µV/W/m²) †
10.867	0

† Rnet determination date: N/A

Table 5. Uncertainty using R @ 45°

Type-B Expanded Uncertainty, U(B) (%)	±0.93
Offset Uncertainty, U(off) (%)	+1.68 / -0.90
Expanded Uncertainty, U (%)	+2.61 / -1.83
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).

Application Notes for Calibration Results

010034 Kipp & Zonen CM22

Listed below are the results for the methods documented in "Improved Methods for Broadband Outdoor Radiometer Calibration (BORCAL)," Wilcox et al., Proceedings of the ARM Science Team Meeting, St. Petersburg, Florida, April 2002.

1. Two-degree Responsivities: Responsivities are obtained from Certificate Table 2.

2. The Single Responsivity: Responsivity is obtained from Certificate Table 3.

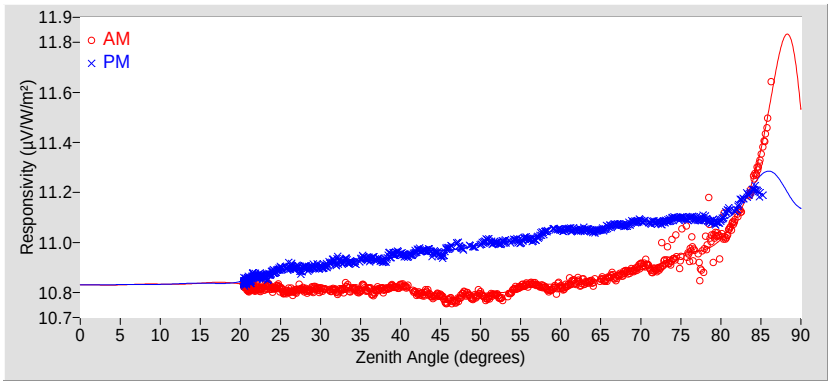
3. Spline Interpolated Responsivities: Responsivities are spline interpolated from Certificate Table 2.

4. AM and PM Responsivity Functions:

$$R_{AM} = \sum_{i=0}^{n} a_i \bullet \cos^i(Z) \quad ; \quad R_{PM} = \sum_{j=0}^{m} b_j \bullet \cos^j(Z)$$

where, Z = zenith angle (degrees) and the coefficients a_i and b_j are available upon request. [1]

Figure 1. Responsivity Function



The quality of the function fit to data is shown in Figure 1.

Table 1. Uncertainty using Responsivity Function

Type-B Standard Uncertainty, u(B) (%)	±0.57
Type-A Interpolating Function, u(int) (%)	±0.18
Combined Standard Uncertainty, u(c) (%)	±0.60
Effective degrees of freedom, DF(c)	158511
Coverage factor, k	1.96
Expanded Uncertainty, U95 (%)	±1.17
AM Valid zenith angle range	22° to 72°
PM Valid zenith angle range	22° to 68°

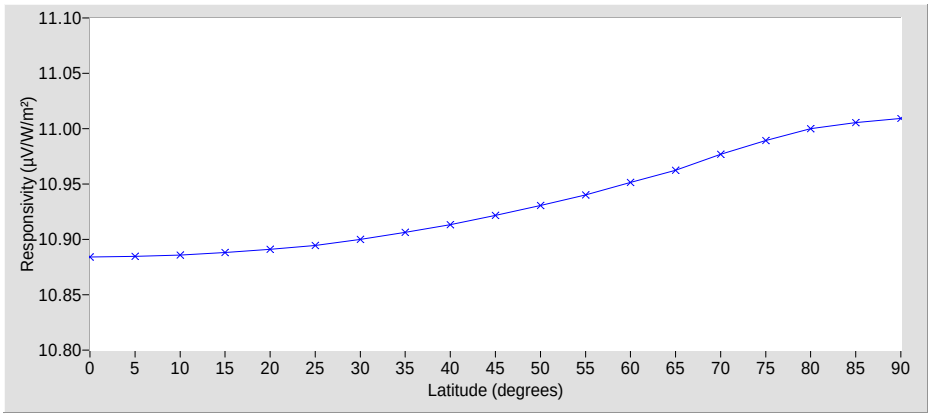
5. Latitude Optimized Responsivity:

Table 2. Latitude Optimized Responsivities

Latitude	RS (µV/W/m²)	Error estimate* (%)
0	10.884	+8.72 / -1.53
5	10.885	+8.72 / -1.53
10	10.886	+8.70 / -1.54
15	10.888	+8.68 / -1.55
20	10.891	+8.65 / -1.57
25	10.895	+8.62 / -1.59
30	10.900	+8.56 / -1.63
35	10.906	+8.50 / -1.67
40	10.913	+8.43 / -1.71
45	10.922	+8.35 / -1.77
50	10.931	+8.26 / -1.83
55	10.940	+8.17 / -1.90
60	10.951	+8.06 / -1.98
65	10.962	+7.95 / -2.06
70	10.977	+7.81 / -2.16
75	10.989	+7.69 / -2.10
80	11.000	+7.59 / -2.01
85	11.006	+7.53 / -1.98
90	11.009	+7.50 / -1.74

* Uncertainty is undefined

Figure 2. Latitude Optimized Responsivities



Application of the responsivities and uncertainties:

The responsivities above are applied according to Certificate equation [1]:

Example

Instrument responsivity (R) = 6.98 µV/W/m² +1.9/-2.7%
Instrument net infrared response (Rnet) = 0.64 µV/W/m²
Instrument output voltage (V) = 5930 µV
Measured effective net infrared (Wnet) = -133 W/m²
Irradiance (I) = (V - Rnet * Wnet) / R
= (5930 - 0.64*(-133)) / 6.98 = 861.8 W/m² (+1.9/-2.7)%

Thus, at the 95% confidence level, the irradiance lies between 838.5 and 878.2 W/m². (This only includes calibration uncertainty.)

National Renewable Energy Laboratory

Solar Radiation Research Laboratory

Metrology Laboratory

Calibration Certificate

Test Instrument:	Silicon Pyranometer	**Manufacturer:**	Licor
Model:	LI200	**Serial Number:**	PY28244
Calibration Date:	7/27/2010	**Due Date:**	7/27/2011
Customer:	NREL-SRRL-BMS	**Environmental Conditions:**	see page 4
Test Dates:	7/26		

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

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

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

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

This certificate applies only to the item identified above and shall not be reproduced other that in full, without specific written approval from the calibration facility. Certificate without signature is not valid.

Table 1. Traceability

Measurement Type	Instrument	Calibration Date	Calibration Due Date
Beam Irradiance †	Eppley Absolute Cavity Radiometer Model HF, S/N 29219	10/03/2009	10/03/2010
Diffuse Irradiance †	Eppley Black and White Pyranometer Model 8-48, S/N 32858	04/14/2010	04/14/2011
Diffuse Irradiance †	Eppley Black and White Pyranometer Model 8-48, S/N 32871	04/14/2010	04/14/2011
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	04/22/2009	04/22/2011
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	04/17/2009	04/17/2011

† 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 are installed for horizontal measurements, with their signal connectors oriented north, if their design permits. The shading disk for the reference diffuse measurement subtends a solid angle of 5°. Pyrheliometers are installed on solar trackers.

Calibrated by: RCC

_____ _____

Ibrahim Reda, Technical Manager Date

For questions or comments, please contact the technical manager at:
ibrahim.reda@nrel.gov; 303-384-6385; 1617 Cole Blvd, Golden, CO 80401, USA

Calibration Results

PY28244 Licor LI200

The responsivity of the test instrument during calibration is calculated using this Measurement Equation:

$$R = (V - Rnet * Wnet) / I \qquad [1]$$

where,

- R = radiometer responsivity (µV/W/m²),
- V = radiometer output voltage (microvolts),
- $Rnet$ = radiometer net infrared responsivity (µV/W/m²), see Table 3,
- $Wnet$ = effective net infrared measured by pyrgeometer (W/m²),
- I = reference irradiance (W/m²), beam (B) or global (G)
  - where, $G = B * COS(Z) + D$,
  - Z = zenith angle (degrees),
  - D = reference diffuse irradiance (W/m²).

Figure 1. Responsivity vs Zenith Angle

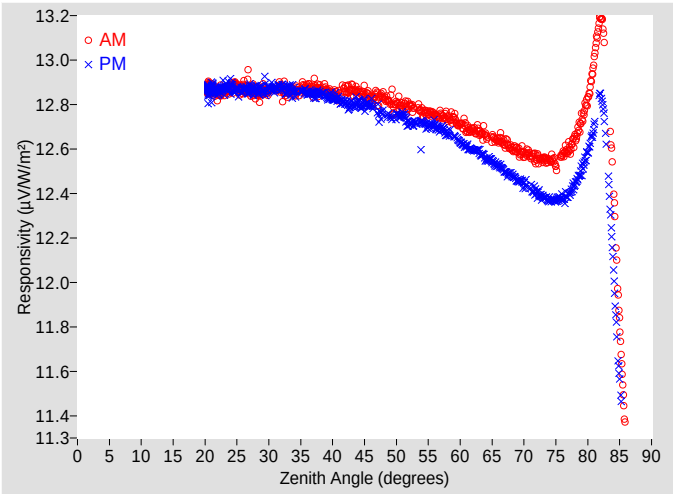


Figure 2. Responsivity vs Local Standard Time

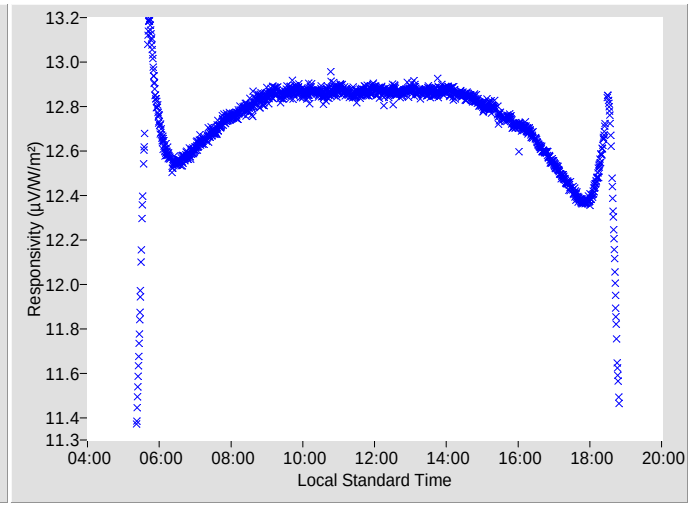


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)

Zenith	AM			PM			Zenith	AM			PM		
Angle	R	u(B)	Azimuth	R	u(B)	Azimuth	Angle	R	u(B)	Azimuth	R	u(B)	Azimuth
(deg.)	(µV/W/m²)	± (%)	Angle	(µV/W/m²)	± (%)	Angle	(deg.)	(µV/W/m²)	± (%)	Angle	(µV/W/m²)	± (%)	Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	12.819	0.39	101.74	12.797	0.41	258.16
2	N/A	N/A	N/A	N/A	N/A	N/A	48	12.834	0.39	99.71	12.765	0.42	260.01
4	N/A	N/A	N/A	N/A	N/A	N/A	50	12.806	0.39	97.72	12.751	0.42	262.23
6	N/A	N/A	N/A	N/A	N/A	N/A	52	12.797	0.40	95.85	12.715	0.43	264.01
8	N/A	N/A	N/A	N/A	N/A	N/A	54	12.764	0.41	94.04	12.722	0.44	265.85
10	N/A	N/A	N/A	N/A	N/A	N/A	56	12.756	0.41	92.32	12.705	0.45	267.58
12	N/A	N/A	N/A	N/A	N/A	N/A	58	12.743	0.42	90.61	12.669	0.46	269.30
14	N/A	N/A	N/A	N/A	N/A	N/A	60	12.712	0.43	88.97	12.629	0.47	270.95
16	N/A	N/A	N/A	N/A	N/A	N/A	62	12.688	0.45	87.33	12.596	0.49	272.55
18	N/A	N/A	N/A	N/A	N/A	N/A	64	12.659	0.46	85.71	12.555	0.51	274.17
20	N/A	N/A	N/A	N/A	N/A	N/A	66	12.639	0.48	84.12	12.525	0.53	275.77
22	12.854	0.36	155.44	12.860	0.37	204.58	68	12.604	0.50	82.55	12.484	0.56	277.31
24	12.867	0.36	143.97	12.881	0.37	215.89	70	12.577	0.53	80.97	12.442	N/A	278.91
26	12.872	0.37	136.22	12.865	0.37	223.68	72	12.557	0.57	79.38	12.399	N/A	280.46
28	12.854	0.37	130.26	12.869	0.37	229.64	74	12.547	N/A	77.81	12.370	N/A	282.05
30	12.859	0.37	125.41	12.872	0.38	234.58	76	12.574	N/A	76.21	12.379	N/A	283.65
32	12.862	0.37	121.13	12.877	0.38	238.77	78	12.645	N/A	74.61	12.441	N/A	285.25
34	12.856	0.37	117.55	12.862	0.39	242.36	80	12.826	N/A	72.96	12.587	N/A	286.86
36	12.879	0.37	114.32	12.850	0.39	245.62	82	13.185	N/A	71.30	12.837	N/A	288.52
38	12.864	0.37	111.34	12.847	0.39	248.54	84	12.439	N/A	69.61	12.055	N/A	290.24
40	12.849	0.38	108.69	12.832	0.40	251.19	86	11.379	N/A	68.05	N/A	N/A	N/A
42	12.864	0.38	106.22	12.811	0.40	253.68	88	N/A	N/A	N/A	N/A	N/A	N/A
44	12.856	0.38	103.92	12.808	0.40	255.98	90	N/A	N/A	N/A	N/A	N/A	N/A

N/A - Not Available

Figure 3. Type-B Standard Uncertainty vs Zenith Angle

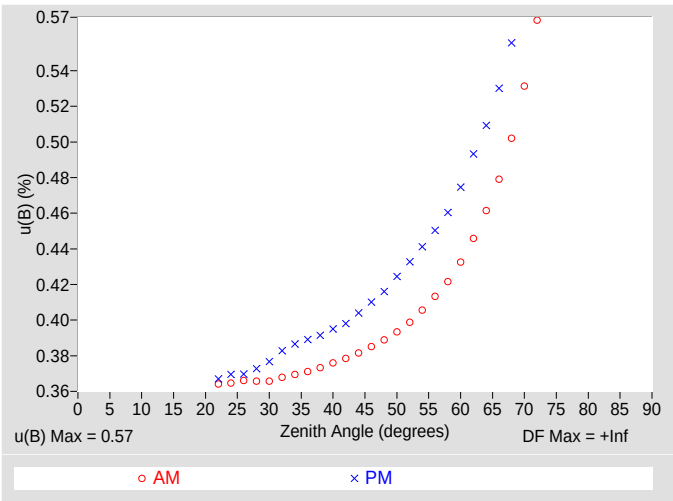


Figure 4. Residuals from Spline Interpolation

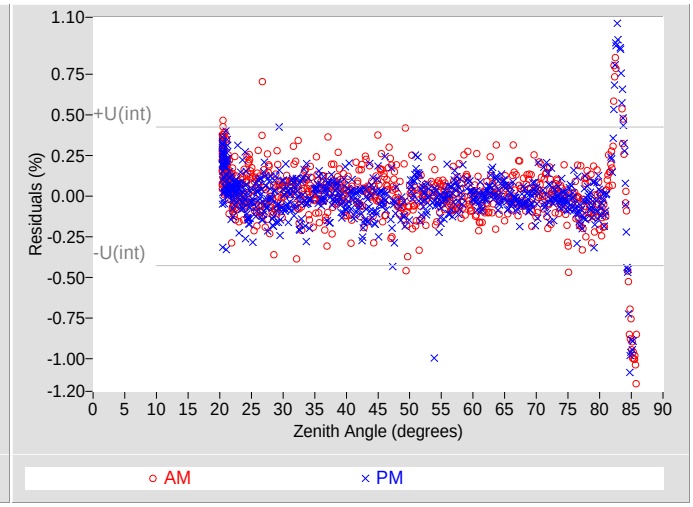


Table 3. Uncertainty using Spline Interpolation

Type-B Standard Uncertainty, u(B) (%)	±0.57
Type-A Interpolating Function, u(int) (%)	±0.21
Combined Standard Uncertainty, u(c) (%)	±0.61
Effective degrees of freedom, DF(c)	80536
Coverage factor, k	1.96
Expanded Uncertainty, U95 (%)	±1.19
AM Valid zenith angle range	22° to 72°
PM Valid zenith angle range	22° to 68°

Table 4. Calibration Label Values

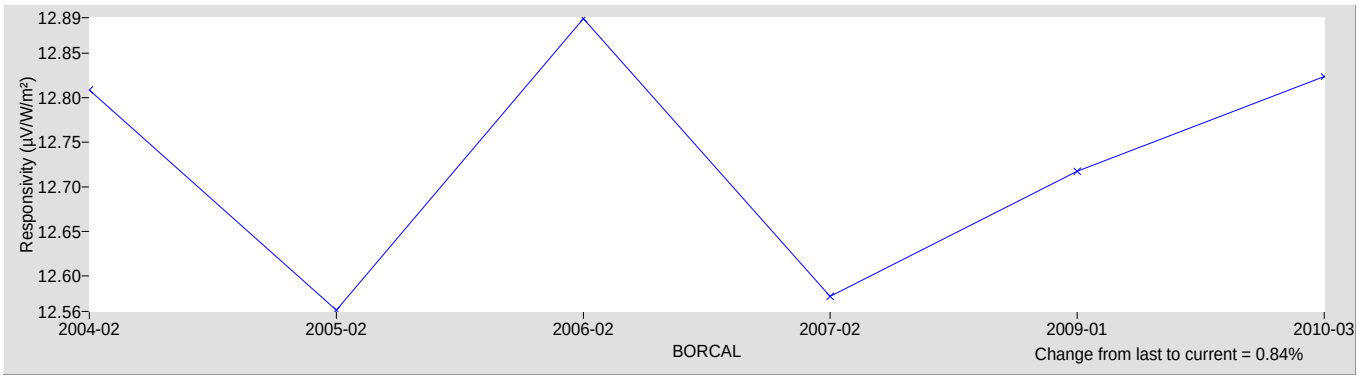
R @ 45° (µV/W/m²)	Rnet (µV/W/m²) †
12.824	0

† Rnet determination date: N/A

Table 5. Uncertainty using R @ 45°

Type-B Expanded Uncertainty, U(B) (%)	±0.93
Offset Uncertainty, U(off) (%)	+0.43 / -1.52
Expanded Uncertainty, U (%)	+1.36 / -2.45
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).

Application Notes for Calibration Results

PY28244 Licor LI200

Listed below are the results for the methods documented in "Improved Methods for Broadband Outdoor Radiometer Calibration (BORCAL)," Wilcox et al., Proceedings of the ARM Science Team Meeting, St. Petersburg, Florida, April 2002.

1. Two-degree Responsivities: Responsivities are obtained from Certificate Table 2.

2. The Single Responsivity: Responsivity is obtained from Certificate Table 3.

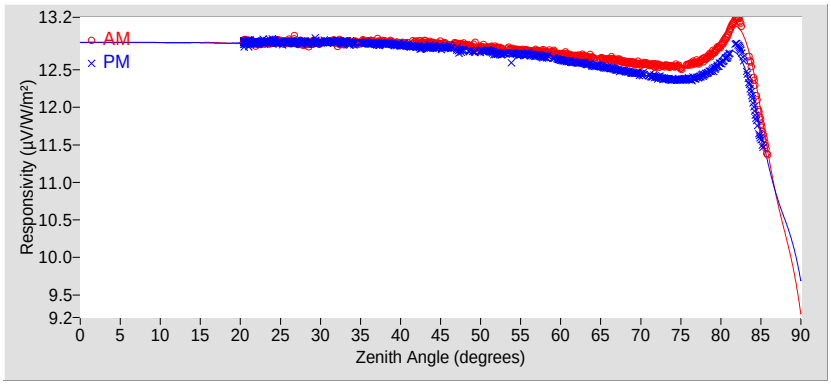
3. Spline Interpolated Responsivities: Responsivities are spline interpolated from Certificate Table 2.

4. AM and PM Responsivity Functions:

$$R_{AM} = \sum_{i=0}^{n} a_i \bullet \cos^i(Z) \quad ; \quad R_{PM} = \sum_{j=0}^{m} b_j \bullet \cos^j(Z)$$

where, Z = zenith angle (degrees) and the coefficients a_i and b_j are available upon request. [1]

Figure 1. Responsivity Function



The quality of the function fit to data is shown in Figure 1.

Table 1. Uncertainty using Responsivity Function

Type-B Standard Uncertainty, u(B) (%)	±0.57
Type-A Interpolating Function, u(int) (%)	±0.22
Combined Standard Uncertainty, u(c) (%)	±0.61
Effective degrees of freedom, DF(c)	75514
Coverage factor, k	1.96
Expanded Uncertainty, U95 (%)	±1.19
AM Valid zenith angle range	22° to 72°
PM Valid zenith angle range	22° to 68°

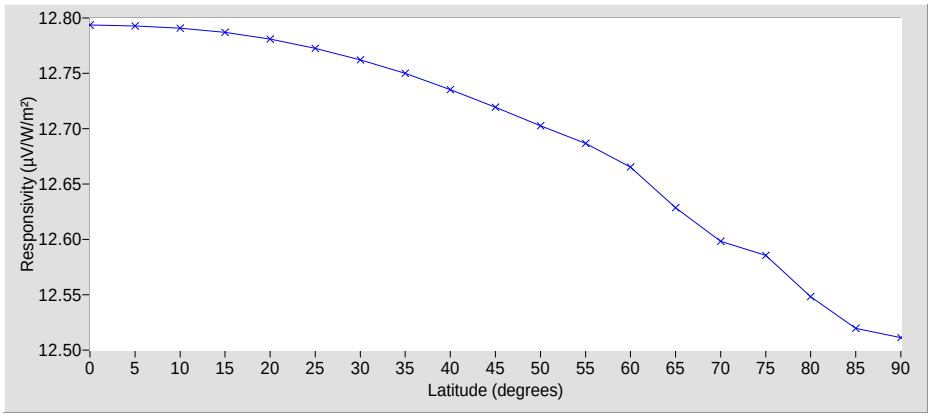
5. Latitude Optimized Responsivity:

Table 2. Latitude Optimized Responsivities

Latitude	RS (µV/W/m²)	Error estimate* (%)
0	12.793	+2.52 / -22.79
5	12.793	+2.52 / -22.79
10	12.791	+2.54 / -22.78
15	12.787	+2.57 / -22.75
20	12.781	+2.61 / -22.72
25	12.773	+2.67 / -22.67
30	12.762	+2.74 / -22.60
35	12.750	+2.83 / -22.53
40	12.735	+2.94 / -22.44
45	12.719	+3.06 / -22.34
50	12.703	+3.18 / -22.24
55	12.687	+3.30 / -22.14
60	12.665	+3.46 / -22.01
65	12.629	+3.75 / -21.79
70	12.598	+3.99 / -21.60
75	12.585	+4.09 / -21.52
80	12.548	+4.38 / -21.29
85	12.520	+4.61 / -21.11
90	12.511	+4.68 / -21.05

* Uncertainty is undefined

Figure 2. Latitude Optimized Responsivities



Application of the responsivities and uncertainties:

The responsivities above are applied according to Certificate equation [1]:

Example

Instrument responsivity (R) = 6.98 µV/W/m² +1.9/-2.7%
Instrument net infrared response (Rnet) = 0.64 µV/W/m²
Instrument output voltage (V) = 5930 µV
Measured effective net infrared (Wnet) = -133 W/m²
Irradiance (I) = (V - Rnet * Wnet) / R
= (5930 - 0.64*(-133)) / 6.98 = 861.8 W/m² (+1.9/-2.7)%

Thus, at the 95% confidence level, the irradiance lies between 838.5 and 878.2 W/m². (This only includes calibration uncertainty.)

National Renewable Energy Laboratory

Solar Radiation Research Laboratory

Metrology Laboratory

Calibration Certificate

Test Instrument:	Silicon Pyranometer	**Manufacturer:**	Licor
Model:	LI200	**Serial Number:**	PY28247
Calibration Date:	7/27/2010	**Due Date:**	7/27/2011
Customer:	NREL-SRRL-BMS	**Environmental Conditions:**	see page 4
Test Dates:	7/26		

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

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

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

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

This certificate applies only to the item identified above and shall not be reproduced other that in full, without specific written approval from the calibration facility. Certificate without signature is not valid.

Table 1. Traceability

Measurement Type	Instrument	Calibration Date	Calibration Due Date
Beam Irradiance †	Eppley Absolute Cavity Radiometer Model HF, S/N 29219	10/03/2009	10/03/2010
Diffuse Irradiance †	Eppley Black and White Pyranometer Model 8-48, S/N 32858	04/14/2010	04/14/2011
Diffuse Irradiance †	Eppley Black and White Pyranometer Model 8-48, S/N 32871	04/14/2010	04/14/2011
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	04/22/2009	04/22/2011
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	04/17/2009	04/17/2011

† 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 are installed for horizontal measurements, with their signal connectors oriented north, if their design permits. The shading disk for the reference diffuse measurement subtends a solid angle of 5°. Pyrheliometers are installed on solar trackers.

Calibrated by: RCC

_____ _____

Ibrahim Reda, Technical Manager Date

For questions or comments, please contact the technical manager at:
ibrahim.reda@nrel.gov; 303-384-6385; 1617 Cole Blvd, Golden, CO 80401, USA

Calibration Results

PY28247 Licor LI200

The responsivity of the test instrument during calibration is calculated using this Measurement Equation:

$$R = (V - Rnet * Wnet) / I \qquad [1]$$

where,

- R = radiometer responsivity (µV/W/m²),
- V = radiometer output voltage (microvolts),
- $Rnet$ = radiometer net infrared responsivity (µV/W/m²), see Table 3,
- $Wnet$ = effective net infrared measured by pyrgeometer (W/m²),
- I = reference irradiance (W/m²), beam (B) or global (G)
  - where, $G = B * COS(Z) + D$,
  - Z = zenith angle (degrees),
  - D = reference diffuse irradiance (W/m²).

Figure 1. Responsivity vs Zenith Angle

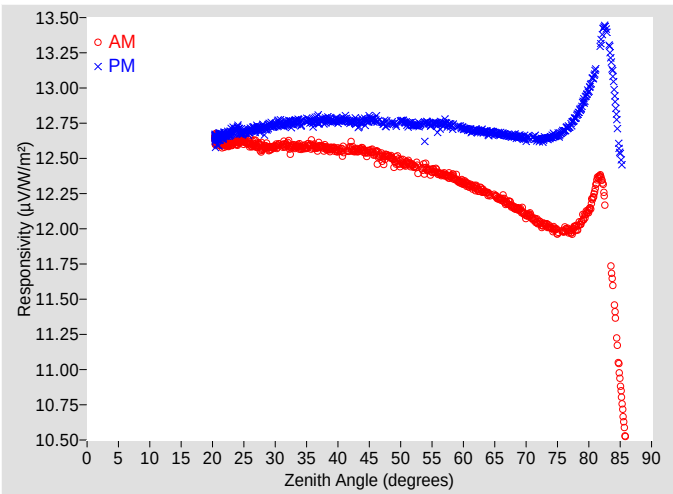


Figure 2. Responsivity vs Local Standard Time

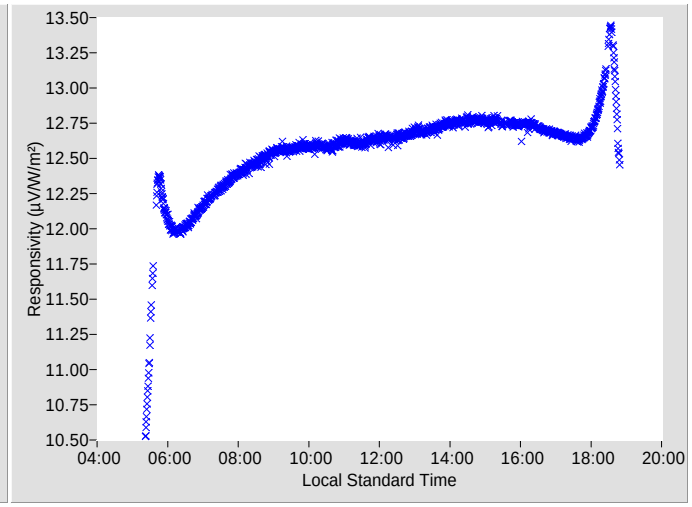


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)

Zenith	AM			PM			Zenith	AM			PM		
Angle	R	u(B)	Azimuth	R	u(B)	Azimuth	Angle	R	u(B)	Azimuth	R	u(B)	Azimuth
(deg.)	(µV/W/m²)	± (%)	Angle	(µV/W/m²)	± (%)	Angle	(deg.)	(µV/W/m²)	± (%)	Angle	(µV/W/m²)	± (%)	Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	12.539	0.39	101.79	12.771	0.41	258.16
2	N/A	N/A	N/A	N/A	N/A	N/A	48	12.518	0.39	99.71	12.754	0.42	260.01
4	N/A	N/A	N/A	N/A	N/A	N/A	50	12.469	0.39	97.72	12.765	0.42	262.23
6	N/A	N/A	N/A	N/A	N/A	N/A	52	12.449	0.40	95.85	12.735	0.43	264.01
8	N/A	N/A	N/A	N/A	N/A	N/A	54	12.426	0.41	94.04	12.756	0.44	265.85
10	N/A	N/A	N/A	N/A	N/A	N/A	56	12.398	0.41	92.32	12.739	0.45	267.61
12	N/A	N/A	N/A	N/A	N/A	N/A	58	12.375	0.42	90.61	12.731	0.46	269.30
14	N/A	N/A	N/A	N/A	N/A	N/A	60	12.333	0.43	88.97	12.713	0.47	270.95
16	N/A	N/A	N/A	N/A	N/A	N/A	62	12.294	0.45	87.33	12.697	0.49	272.55
18	N/A	N/A	N/A	N/A	N/A	N/A	64	12.248	0.46	85.71	12.678	0.51	274.17
20	N/A	N/A	N/A	N/A	N/A	N/A	66	12.213	0.48	84.12	12.674	0.53	275.77
22	12.608	0.36	155.44	12.665	0.37	204.58	68	12.154	0.50	82.55	12.662	0.56	277.31
24	12.616	0.36	143.97	12.705	0.37	215.89	70	12.093	0.53	80.97	12.645	N/A	278.91
26	12.604	0.37	136.22	12.694	0.37	223.68	72	12.048	0.57	79.38	12.632	N/A	280.46
28	12.575	0.37	130.26	12.721	0.37	229.54	74	12.002	N/A	77.81	12.651	N/A	282.05
30	12.584	0.37	125.41	12.735	0.38	234.58	76	11.987	N/A	76.21	12.695	N/A	283.65
32	12.596	0.37	121.13	12.754	0.38	238.77	78	12.007	N/A	74.61	12.799	N/A	285.25
34	12.580	0.37	117.55	12.755	0.39	242.36	80	12.132	N/A	72.96	12.991	N/A	286.86
36	12.592	0.37	114.32	12.751	0.39	245.62	82	12.352	N/A	71.30	13.352	N/A	288.52
38	12.575	0.37	111.34	12.771	0.39	248.54	84	11.496	N/A	69.61	12.991	N/A	290.24
40	12.558	0.38	108.69	12.772	0.40	251.19	86	10.527	N/A	68.05	N/A	N/A	N/A
42	12.574	0.38	106.22	12.760	0.40	253.68	88	N/A	N/A	N/A	N/A	N/A	N/A
44	12.562	0.38	103.92	12.770	0.40	255.98	90	N/A	N/A	N/A	N/A	N/A	N/A

N/A - Not Available

Figure 3. Type-B Standard Uncertainty vs Zenith Angle

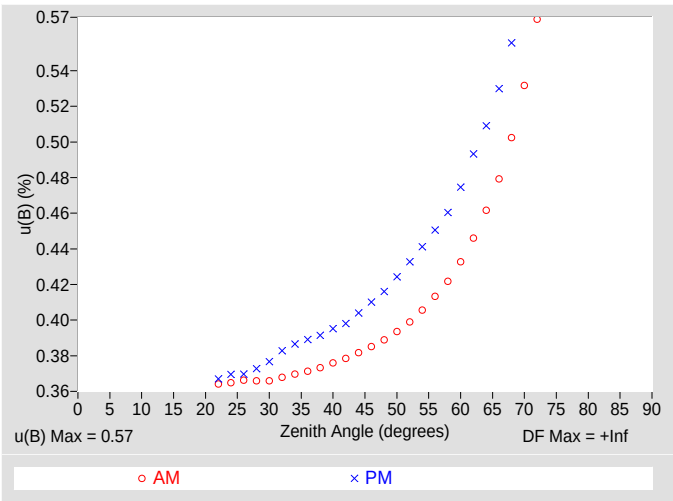


Figure 4. Residuals from Spline Interpolation

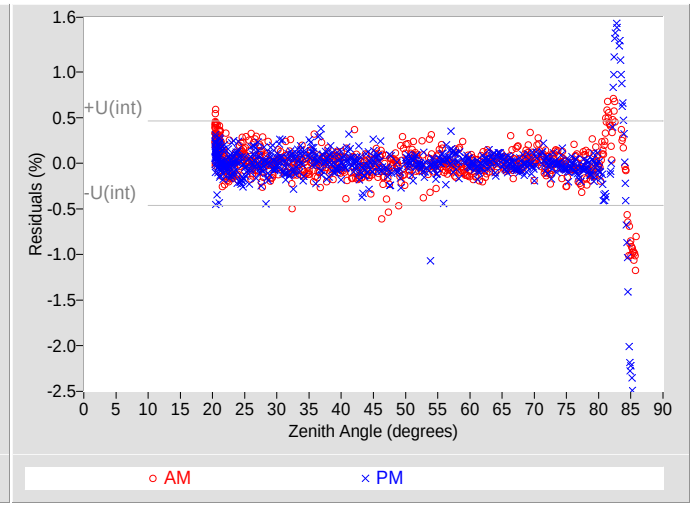


Table 3. Uncertainty using Spline Interpolation

Type-B Standard Uncertainty, u(B) (%)	±0.57
Type-A Interpolating Function, u(int) (%)	±0.23
Combined Standard Uncertainty, u(c) (%)	±0.61
Effective degrees of freedom, DF(c)	60082
Coverage factor, k	1.96
Expanded Uncertainty, U95 (%)	±1.20
AM Valid zenith angle range	22° to 72°
PM Valid zenith angle range	22° to 68°

Table 4. Calibration Label Values

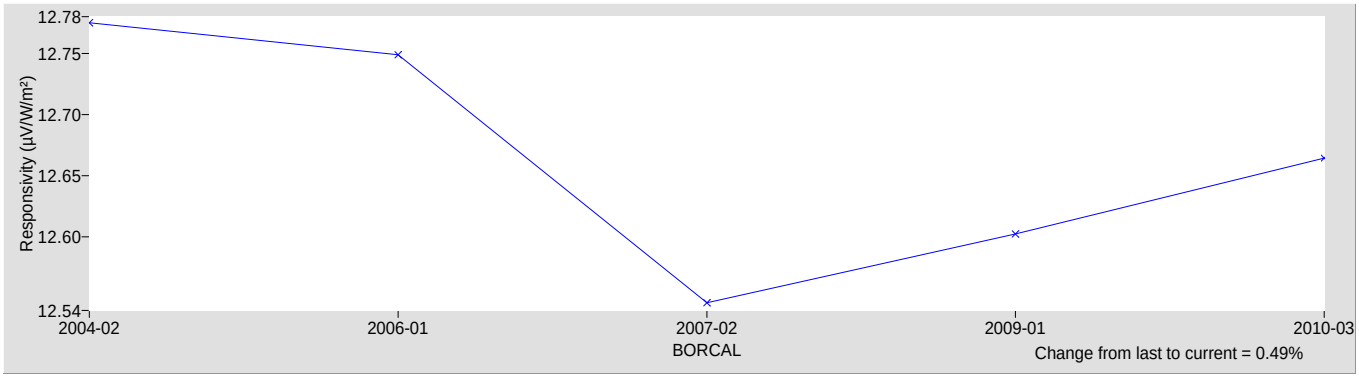
R @ 45° (µV/W/m²)	Rnet (µV/W/m²) †
12.665	0

† Rnet determination date: N/A

Table 5. Uncertainty using R @ 45°

Type-B Expanded Uncertainty, U(B) (%)	±0.93
Offset Uncertainty, U(off) (%)	+0.85 / -2.62
Expanded Uncertainty, U (%)	+1.78 / -3.55
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).

Application Notes for Calibration Results

PY28247 Licor LI200

Listed below are the results for the methods documented in "Improved Methods for Broadband Outdoor Radiometer Calibration (BORCAL)," Wilcox et al., Proceedings of the ARM Science Team Meeting, St. Petersburg, Florida, April 2002.

1. Two-degree Responsivities: Responsivities are obtained from Certificate Table 2.

2. The Single Responsivity: Responsivity is obtained from Certificate Table 3.

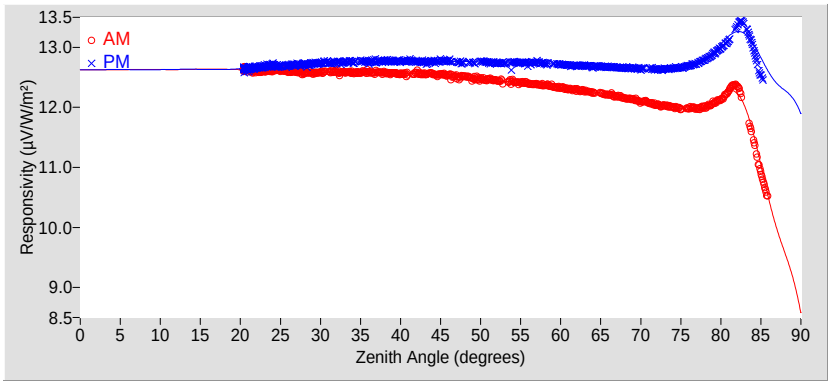
3. Spline Interpolated Responsivities: Responsivities are spline interpolated from Certificate Table 2.

4. AM and PM Responsivity Functions:

$$R_{AM} = \sum_{i=0}^{n} a_i \bullet \cos^i(Z) \quad ; \quad R_{PM} = \sum_{j=0}^{m} b_j \bullet \cos^j(Z)$$

where, Z = zenith angle (degrees) and the coefficients a_i and b_j are available upon request. [1]

Figure 1. Responsivity Function



The quality of the function fit to data is shown in Figure 1.

Table 1. Uncertainty using Responsivity Function

Type-B Standard Uncertainty, u(B) (%)	±0.57
Type-A Interpolating Function, u(int) (%)	±0.23
Combined Standard Uncertainty, u(c) (%)	±0.61
Effective degrees of freedom, DF(c)	58902
Coverage factor, k	1.96
Expanded Uncertainty, U95 (%)	±1.21
AM Valid zenith angle range	22° to 72°
PM Valid zenith angle range	22° to 68°

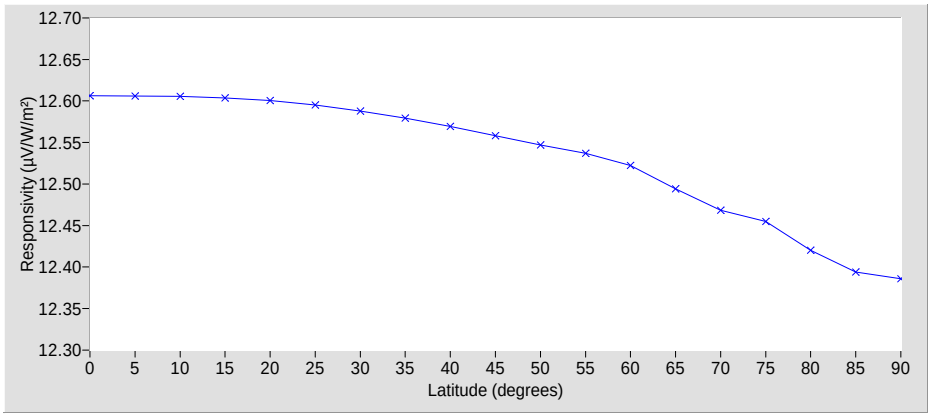
5. Latitude Optimized Responsivity:

Table 2. Latitude Optimized Responsivities

Latitude	RS (µV/W/m²)	Error estimate* (%)
0	12.607	+5.33 / -27.33
5	12.606	+5.33 / -27.33
10	12.606	+5.33 / -27.33
15	12.604	+5.35 / -27.32
20	12.600	+5.38 / -27.30
25	12.595	+5.42 / -27.27
30	12.588	+5.48 / -27.23
35	12.580	+5.55 / -27.18
40	12.569	+5.63 / -27.12
45	12.558	+5.72 / -27.06
50	12.547	+5.81 / -26.99
55	12.537	+5.90 / -26.93
60	12.522	+6.02 / -26.85
65	12.494	+6.25 / -26.68
70	12.468	+6.47 / -26.53
75	12.455	+6.58 / -26.45
80	12.420	+6.87 / -26.25
85	12.394	+7.10 / -26.09
90	12.386	+7.16 / -26.04

* Uncertainty is undefined

Figure 2. Latitude Optimized Responsivities



Application of the responsivities and uncertainties:

The responsivities above are applied according to Certificate equation [1]:

Example

Instrument responsivity (R) = 6.98 µV/W/m² +1.9/-2.7%
Instrument net infrared response (Rnet) = 0.64 µV/W/m²
Instrument output voltage (V) = 5930 µV
Measured effective net infrared (Wnet) = -133 W/m²
Irradiance (I) = (V - Rnet * Wnet) / R
= (5930 - 0.64*(-133)) / 6.98 = 861.8 W/m² (+1.9/-2.7)%

Thus, at the 95% confidence level, the irradiance lies between 838.5 and 878.2 W/m². (This only includes calibration uncertainty.)

National Renewable Energy Laboratory

Solar Radiation Research Laboratory

Metrology Laboratory

Calibration Certificate

Test Instrument:	Silicon Pyranometer	**Manufacturer:**	Licor
Model:	LI200	**Serial Number:**	PY28260
Calibration Date:	7/27/2010	**Due Date:**	7/27/2011
Customer:	NREL-SRRL-BMS	**Environmental Conditions:**	see page 4
Test Dates:	7/26		

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

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

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

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

This certificate applies only to the item identified above and shall not be reproduced other that in full, without specific written approval from the calibration facility. Certificate without signature is not valid.

Table 1. Traceability

Measurement Type	Instrument	Calibration Date	Calibration Due Date
Beam Irradiance †	Eppley Absolute Cavity Radiometer Model HF, S/N 29219	10/03/2009	10/03/2010
Diffuse Irradiance †	Eppley Black and White Pyranometer Model 8-48, S/N 32858	04/14/2010	04/14/2011
Diffuse Irradiance †	Eppley Black and White Pyranometer Model 8-48, S/N 32871	04/14/2010	04/14/2011
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	04/22/2009	04/22/2011
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	04/17/2009	04/17/2011

† 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 are installed for horizontal measurements, with their signal connectors oriented north, if their design permits. The shading disk for the reference diffuse measurement subtends a solid angle of 5°. Pyrheliometers are installed on solar trackers.

Calibrated by: RCC

_____ _____

Ibrahim Reda, Technical Manager Date

For questions or comments, please contact the technical manager at:
ibrahim.reda@nrel.gov; 303-384-6385; 1617 Cole Blvd, Golden, CO 80401, USA

Calibration Results

PY28260 Licor LI200

The responsivity of the test instrument during calibration is calculated using this Measurement Equation:

$$R = (V - Rnet * Wnet) / I \qquad [1]$$

where,

- R = radiometer responsivity (µV/W/m²),
- V = radiometer output voltage (microvolts),
- $Rnet$ = radiometer net infrared responsivity (µV/W/m²), see Table 3,
- $Wnet$ = effective net infrared measured by pyrgeometer (W/m²),
- I = reference irradiance (W/m²), beam (B) or global (G)
  - where, $G = B * COS(Z) + D$,
  - Z = zenith angle (degrees),
  - D = reference diffuse irradiance (W/m²).

Figure 1. Responsivity vs Zenith Angle

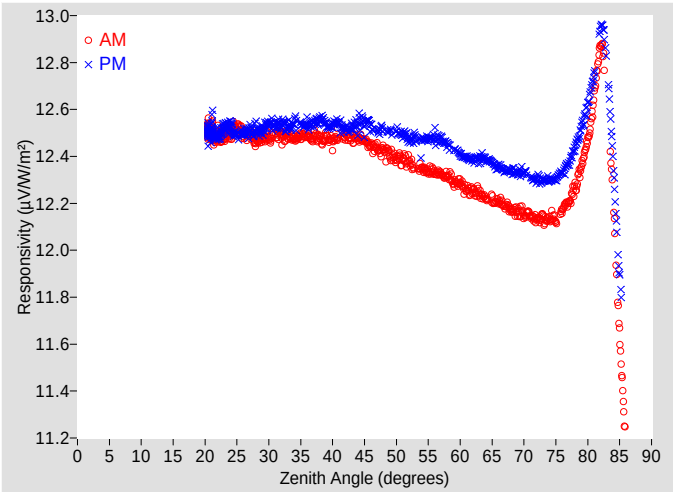


Figure 2. Responsivity vs Local Standard Time

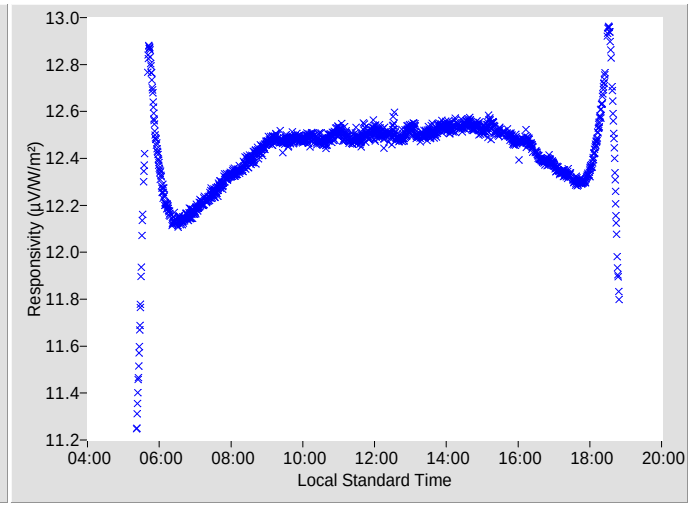


Table 2. Instrument Responsivity (R) and Calibration Type-B Standard Uncertainty, u(B)

Zenith	AM			PM			Zenith	AM			PM		
Angle	R	u(B)	Azimuth	R	u(B)	Azimuth	Angle	R	u(B)	Azimuth	R	u(B)	Azimuth
(deg.)	(µV/W/m²)	± (%)	Angle	(µV/W/m²)	± (%)	Angle	(deg.)	(µV/W/m²)	± (%)	Angle	(µV/W/m²)	± (%)	Angle
0	N/A	N/A	N/A	N/A	N/A	N/A	46	12.443	0.39	101.74	12.529	0.41	258.16
2	N/A	N/A	N/A	N/A	N/A	N/A	48	12.431	0.39	99.71	12.514	0.42	260.01
4	N/A	N/A	N/A	N/A	N/A	N/A	50	12.391	0.39	97.72	12.509	0.42	262.23
6	N/A	N/A	N/A	N/A	N/A	N/A	52	12.380	0.40	95.85	12.470	0.43	264.01
8	N/A	N/A	N/A	N/A	N/A	N/A	54	12.347	0.41	94.04	12.476	0.44	265.85
10	N/A	N/A	N/A	N/A	N/A	N/A	56	12.332	0.41	92.32	12.470	0.45	267.58
12	N/A	N/A	N/A	N/A	N/A	N/A	58	12.317	0.42	90.61	12.447	0.46	269.30
14	N/A	N/A	N/A	N/A	N/A	N/A	60	12.290	0.43	88.97	12.408	0.47	270.95
16	N/A	N/A	N/A	N/A	N/A	N/A	62	12.257	0.45	87.33	12.385	0.49	272.55
18	N/A	N/A	N/A	N/A	N/A	N/A	64	12.222	0.46	85.71	12.387	0.51	274.17
20	N/A	N/A	N/A	N/A	N/A	N/A	66	12.210	0.48	84.12	12.356	0.53	275.77
22	12.489	0.36	155.44	12.489	0.37	204.58	68	12.172	0.50	82.55	12.339	0.56	277.31
24	12.493	0.36	143.97	12.529	0.37	215.89	70	12.149	0.53	80.97	12.331	N/A	278.91
26	12.498	0.37	136.22	12.498	0.37	223.68	72	12.136	0.57	79.38	12.302	N/A	280.46
28	12.464	0.37	130.26	12.520	0.37	229.64	74	12.131	N/A	77.81	12.298	N/A	282.05
30	12.479	0.37	125.41	12.540	0.38	234.58	76	12.173	N/A	76.21	12.335	N/A	283.65
32	12.488	0.37	121.13	12.536	0.38	238.77	78	12.261	N/A	74.61	12.441	N/A	285.25
34	12.475	0.37	117.55	12.542	0.39	242.36	80	12.473	N/A	72.96	12.621	N/A	286.86
36	12.490	0.37	114.32	12.530	0.39	245.64	82	12.866	N/A	71.30	12.946	N/A	288.52
38	12.476	0.37	111.34	12.555	0.39	248.54	84	12.203	N/A	69.61	12.349	N/A	290.24
40	12.475	0.38	108.69	12.537	0.40	251.19	86	11.249	N/A	68.05	N/A	N/A	N/A
42	12.489	0.38	106.22	12.518	0.40	253.68	88	N/A	N/A	N/A	N/A	N/A	N/A
44	12.478	0.38	103.92	12.542	0.40	255.98	90	N/A	N/A	N/A	N/A	N/A	N/A

N/A - Not Available

Figure 3. Type-B Standard Uncertainty vs Zenith Angle

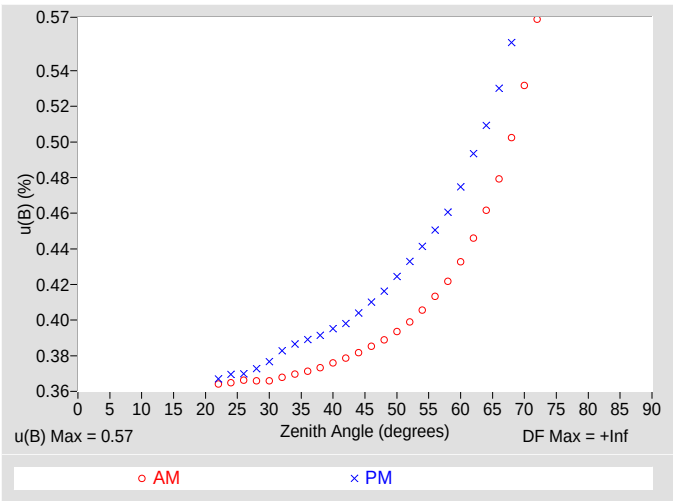


Figure 4. Residuals from Spline Interpolation

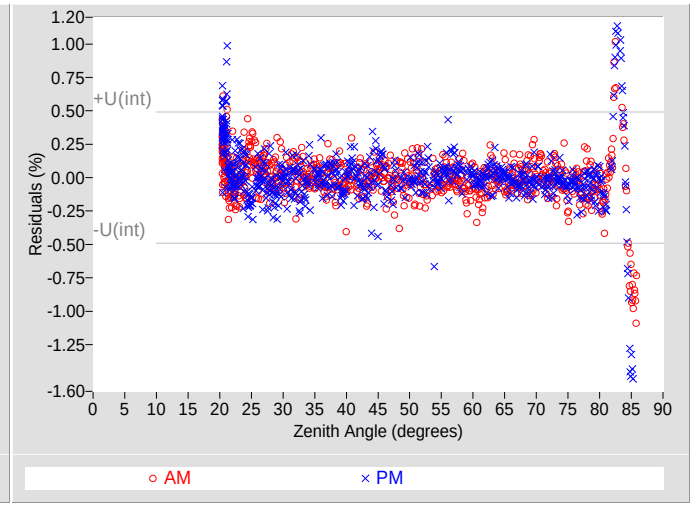


Table 3. Uncertainty using Spline Interpolation

Type-B Standard Uncertainty, u(B) (%)	±0.57
Type-A Interpolating Function, u(int) (%)	±0.25
Combined Standard Uncertainty, u(c) (%)	±0.62
Effective degrees of freedom, DF(c)	49438
Coverage factor, k	1.96
Expanded Uncertainty, U95 (%)	±1.21
AM Valid zenith angle range	22° to 72°
PM Valid zenith angle range	22° to 68°

Table 4. Calibration Label Values

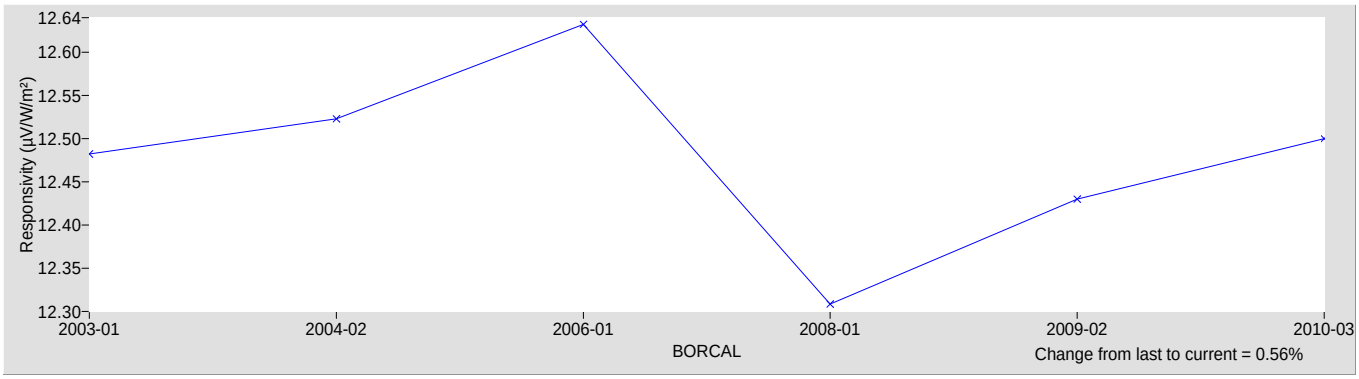
R @ 45° (µV/W/m²)	Rnet (µV/W/m²) †
12.500	0

† Rnet determination date: N/A

Table 5. Uncertainty using R @ 45°

Type-B Expanded Uncertainty, U(B) (%)	±0.93
Offset Uncertainty, U(off) (%)	+0.44 / -1.68
Expanded Uncertainty, U (%)	+1.37 / -2.61
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).

Application Notes for Calibration Results

PY28260 Licor LI200

Listed below are the results for the methods documented in "Improved Methods for Broadband Outdoor Radiometer Calibration (BORCAL)," Wilcox et al., Proceedings of the ARM Science Team Meeting, St. Petersburg, Florida, April 2002.

1. Two-degree Responsivities: Responsivities are obtained from Certificate Table 2.

2. The Single Responsivity: Responsivity is obtained from Certificate Table 3.

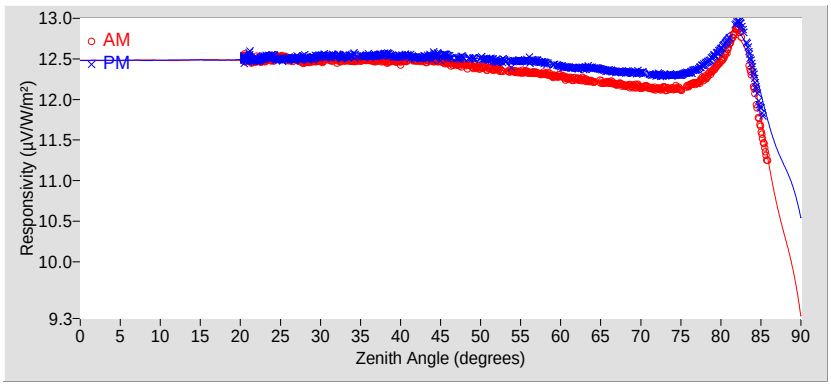
3. Spline Interpolated Responsivities: Responsivities are spline interpolated from Certificate Table 2.

4. AM and PM Responsivity Functions:

$$R_{AM} = \sum_{i=0}^{n} a_i \bullet \cos^i(Z) \quad ; \quad R_{PM} = \sum_{j=0}^{m} b_j \bullet \cos^j(Z)$$

where, Z = zenith angle (degrees) and the coefficients a_i and b_j are available upon request. [1]

Figure 1. Responsivity Function



The quality of the function fit to data is shown in Figure 1.

Table 1. Uncertainty using Responsivity Function

Type-B Standard Uncertainty, u(B) (%)	±0.57
Type-A Interpolating Function, u(int) (%)	±0.24
Combined Standard Uncertainty, u(c) (%)	±0.62
Effective degrees of freedom, DF(c)	53411
Coverage factor, k	1.96
Expanded Uncertainty, U95 (%)	±1.21
AM Valid zenith angle range	22° to 72°
PM Valid zenith angle range	22° to 68°

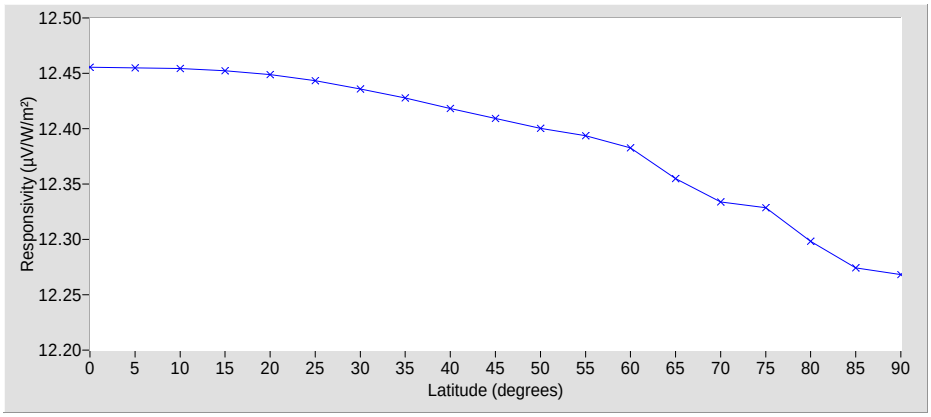
5. Latitude Optimized Responsivity:

Table 2. Latitude Optimized Responsivities

Latitude	RS (µV/W/m²)	Error estimate* (%)
0	12.456	+3.28 / -20.47
5	12.455	+3.29 / -20.47
10	12.454	+3.29 / -20.46
15	12.452	+3.31 / -20.45
20	12.449	+3.33 / -20.43
25	12.443	+3.38 / -20.39
30	12.436	+3.43 / -20.35
35	12.428	+3.50 / -20.29
40	12.418	+3.57 / -20.23
45	12.409	+3.64 / -20.18
50	12.400	+3.71 / -20.12
55	12.394	+3.76 / -20.08
60	12.383	+3.85 / -20.00
65	12.355	+4.07 / -19.83
70	12.334	+4.24 / -19.69
75	12.329	+4.29 / -19.65
80	12.298	+4.53 / -19.46
85	12.274	+4.73 / -19.30
90	12.268	+4.78 / -19.26

* Uncertainty is undefined

Figure 2. Latitude Optimized Responsivities



Application of the responsivities and uncertainties:

The responsivities above are applied according to Certificate equation [1]:

Example

Instrument responsivity (R) = 6.98 µV/W/m² +1.9/-2.7%
Instrument net infrared response (Rnet) = 0.64 µV/W/m²
Instrument output voltage (V) = 5930 µV
Measured effective net infrared (Wnet) = -133 W/m²
Irradiance (I) = (V - Rnet * Wnet) / R
= (5930 - 0.64*(-133)) / 6.98 = 861.8 W/m² (+1.9/-2.7)%

Thus, at the 95% confidence level, the irradiance lies between 838.5 and 878.2 W/m². (This only includes calibration uncertainty.)

Environmental and Sky Conditions for BORCAL 2010-03

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

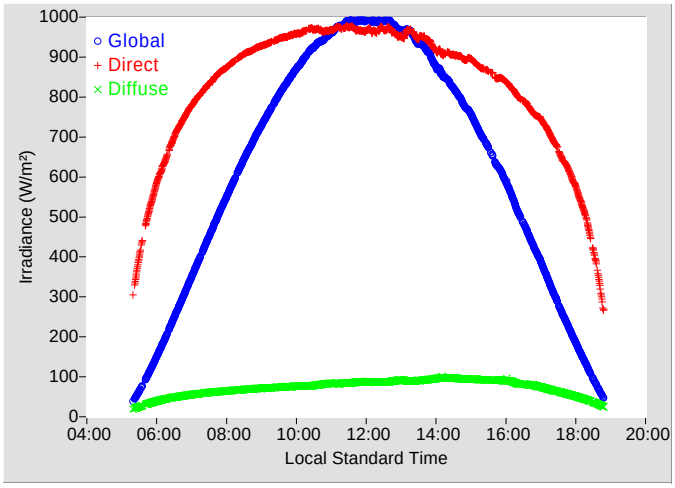
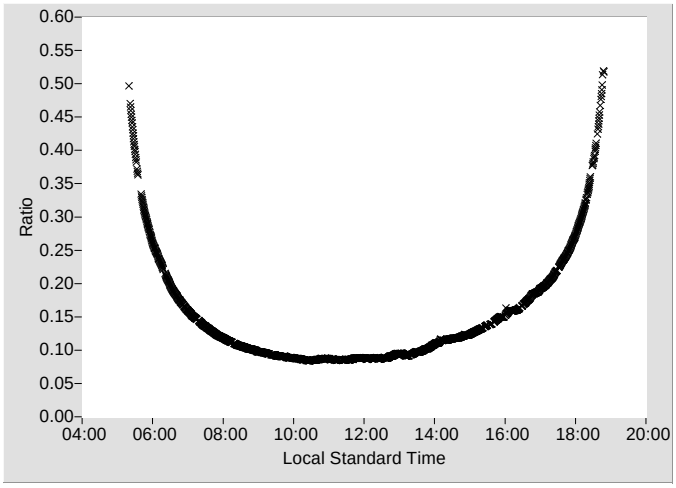


Figure 7. Diffuse / Global



Meteorological Observations:

Figure 8. Temperature

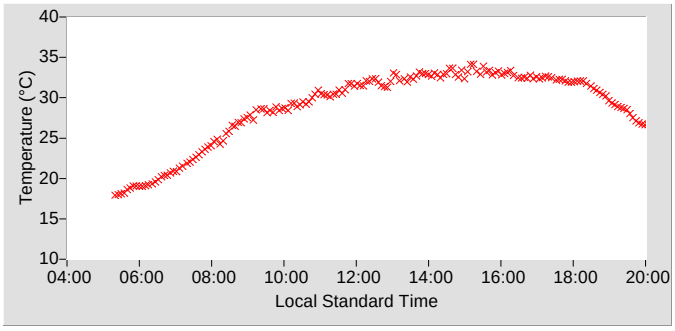


Figure 9. Humidity

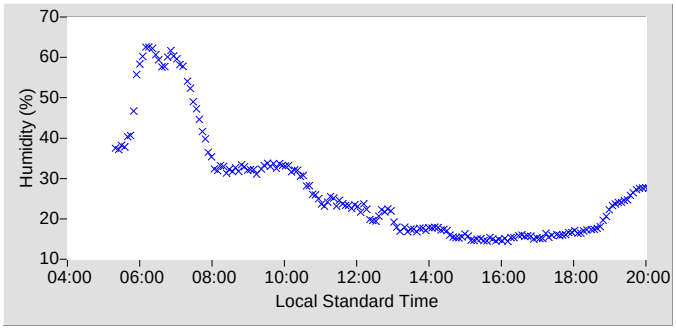


Figure 10. Pressure

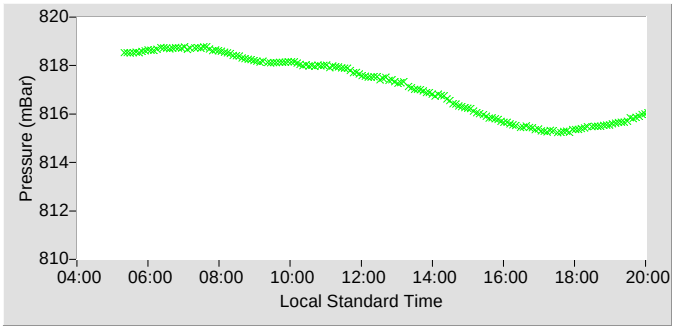


Figure 11. Effective Net Infrared

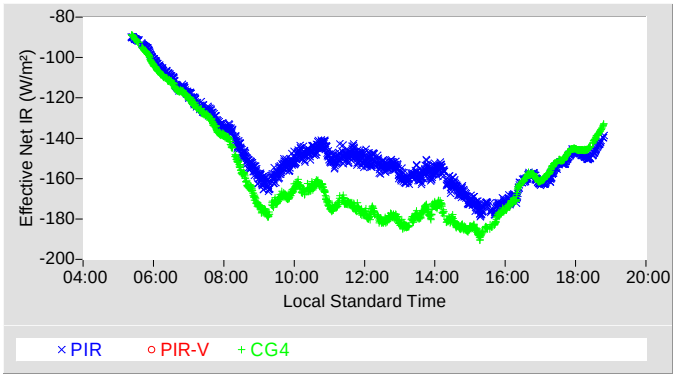


Figure 12. Estimated Broadband Aerosol Optical Depth

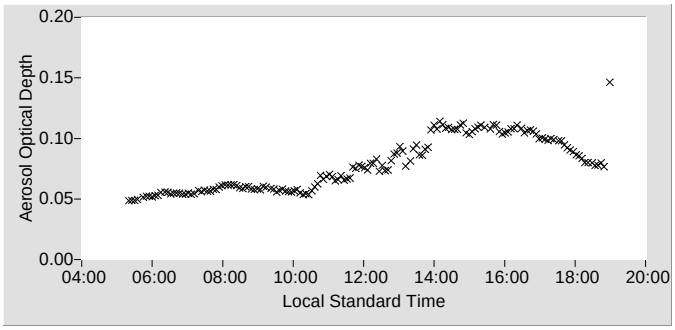


Table 6. Meteorological Observations

Observations	Mean
Temperature (°C)	28.66
Humidity (%)	27.37
Pressure (mBar)	817.1
Est. Aerosol Optical Depth (BB)	0.0780

For other information about the calibration facility visit: http://www.nrel.gov/solar_radiation/

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).