Broadband Outdoor Radiometer Calibration

BORCAL
2006-01

Customer:

NREL-SRRL-BSRN

Calibration Facility:

Solar Radiation Research Laboratory

Latitude: 39.740°N

Longitude: 105.180°W

Elevation: 1829.0 meters AMSL

Avg. Station Pressure: 835.0 mBar

Time Zone: -7.0

Calibration date

05/15/2006 to 05/16/2006

Report Date

June 5, 2006

Broadband Outdoor Radiometer Calibration Report

Table of contents

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 World Radiometric Reference and to the National Institute of Standards and Technology.

This report includes these sections:

- Calibration Environment - meteorological conditions and irradiance reference data encountered during the event.
- 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 suggested methods of applying results for each instrument.

The BORCAL process is described in "Improved Methods for Broadband Outdoor Radiometer Calibration (BORCAL)," Wilcox, S., Andreas, A., Reda, I., and Myers, D., Proceedings of the ARM Science Team Meeting, St. Petersburg, Florida, April 2002.

Reference Irradiance

0.0° / 0.0° Tilt / Azm

Figure 1. Reference Irradiance

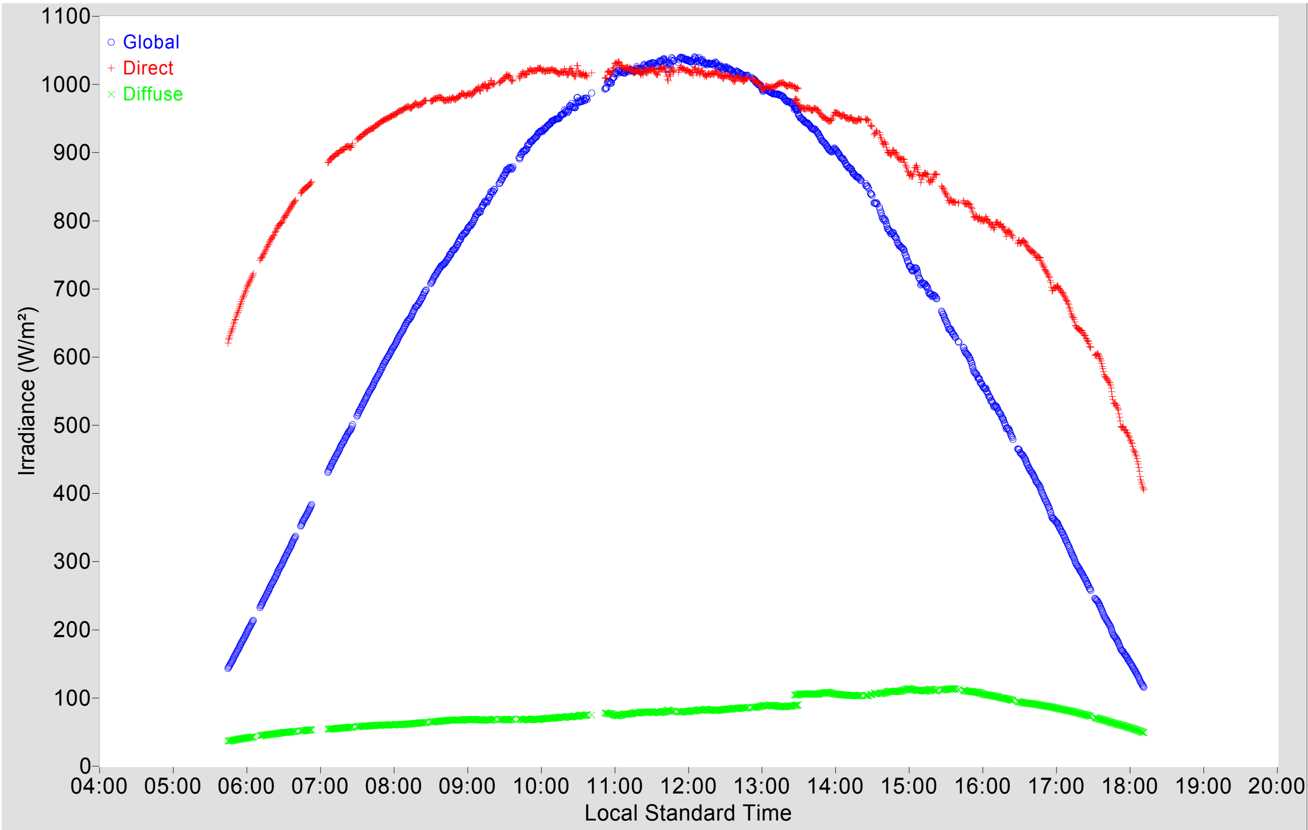
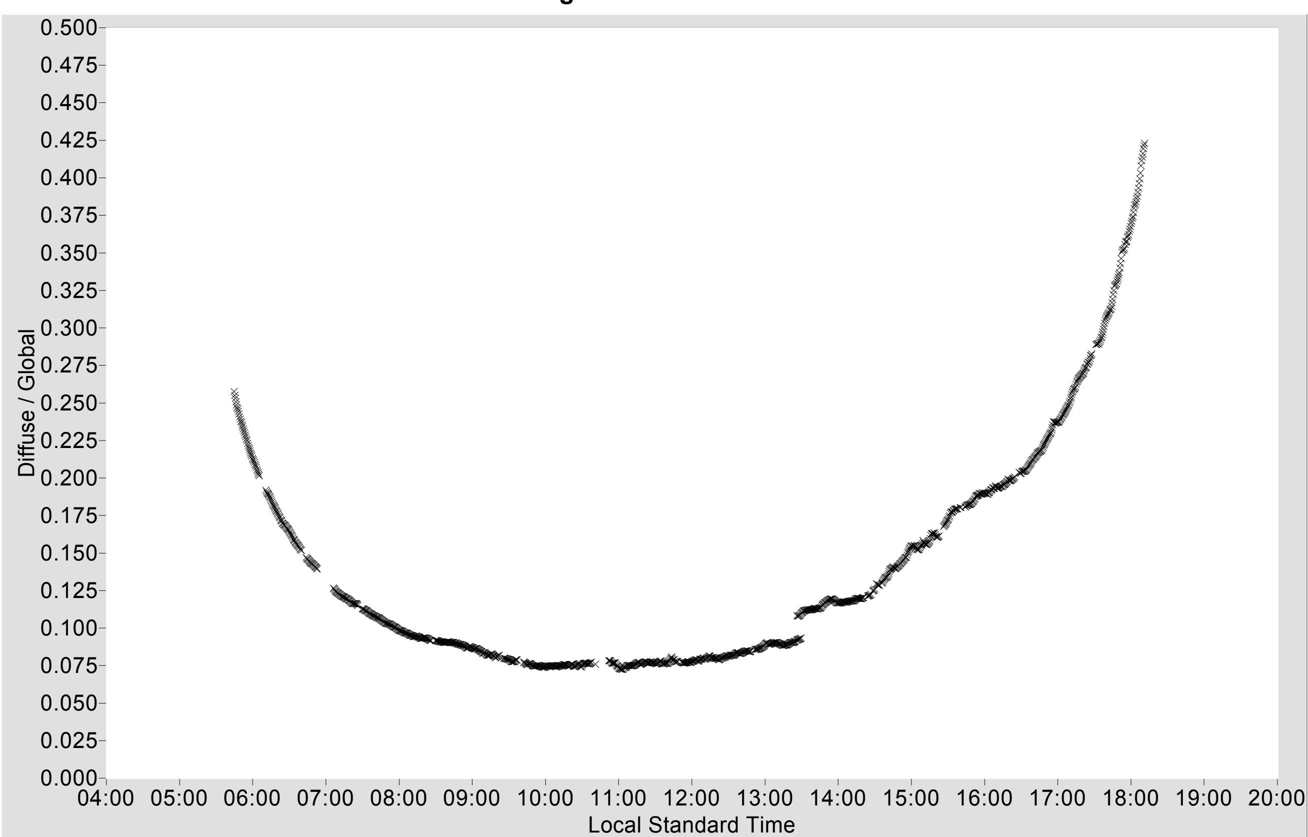


Figure 2. Diffuse / Global



Meteorological Observations

Table 1. Meteorological Observations

Observations	Mean
Temperature (°C)	20.23
Humidity (%)	32.39
Pressure (mBar)	823.8
Est. Aerosol Optical Depth (BB)	0.0646

Figure 3. Effective Net Infrared

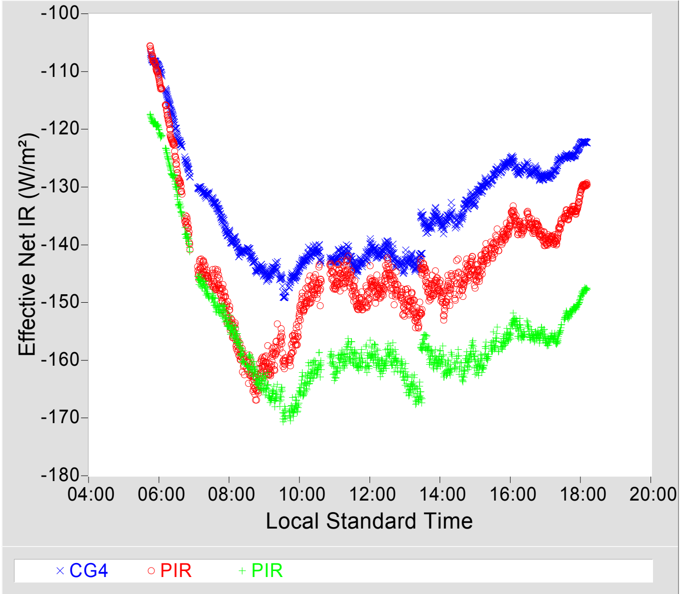


Figure 4. Temperature

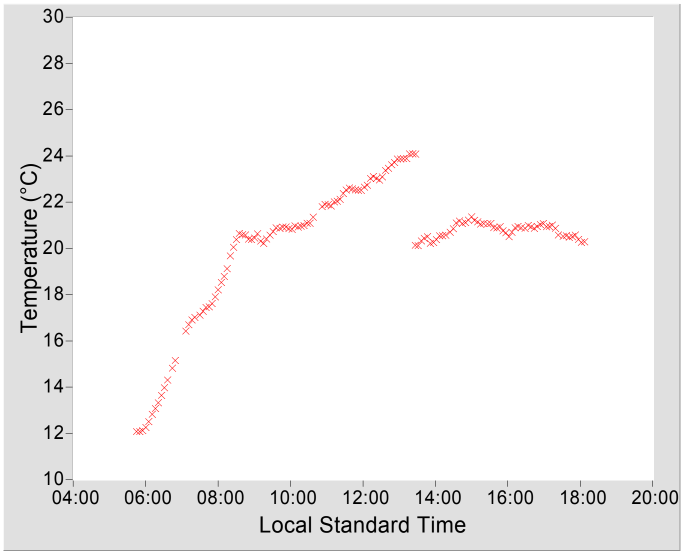


Figure 5. Humidity

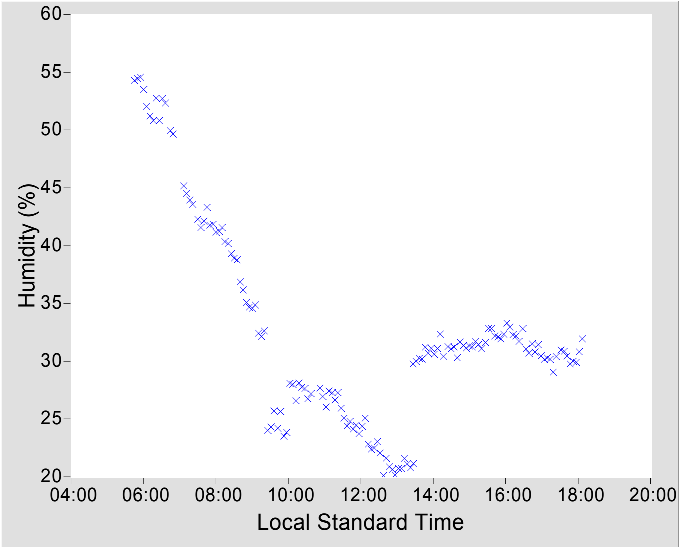


Figure 6. Pressure

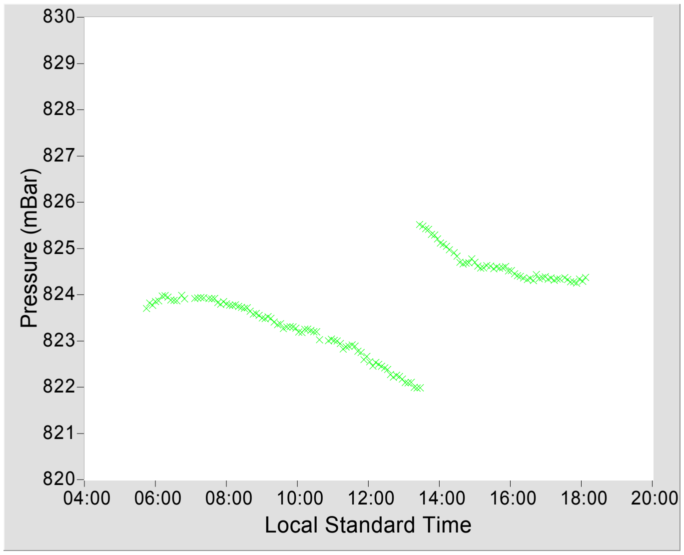
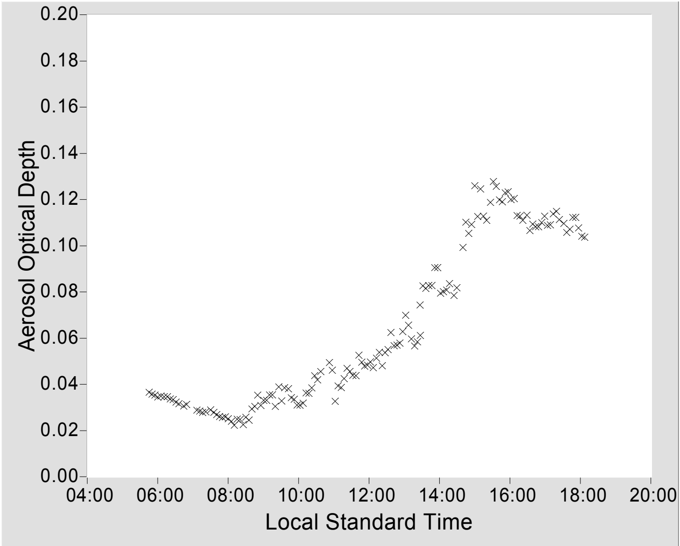


Figure 7. Estimated Broadband Aerosol Optical Depth



Control Instrument History

Figure 8. Eppley FPP Control Instrument History

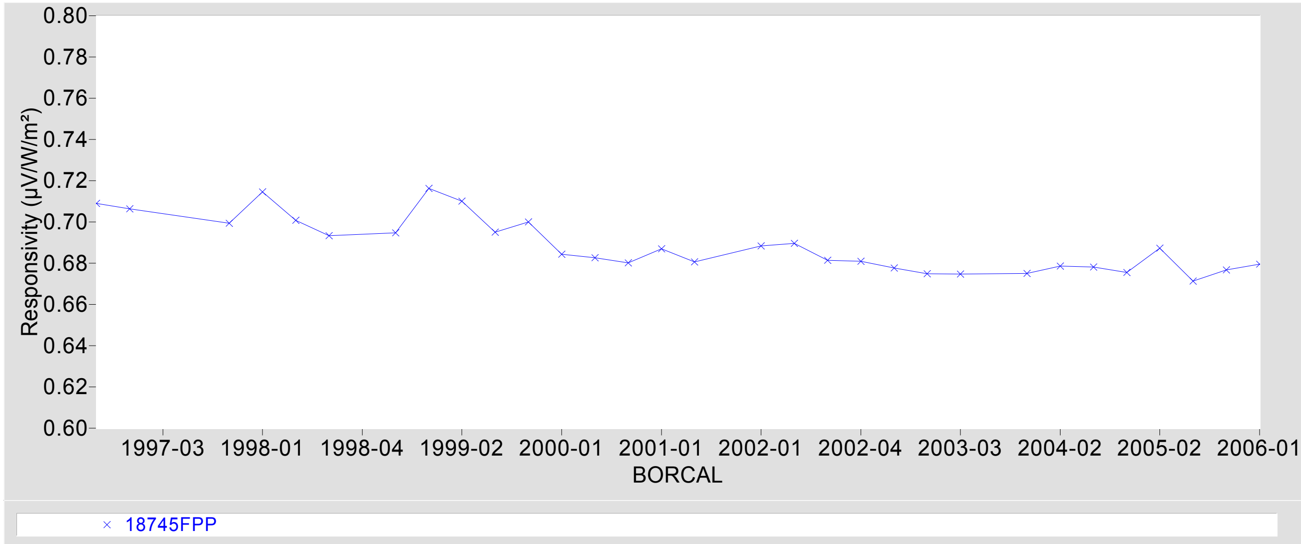


Figure 9. Eppley NIP Control Instrument History

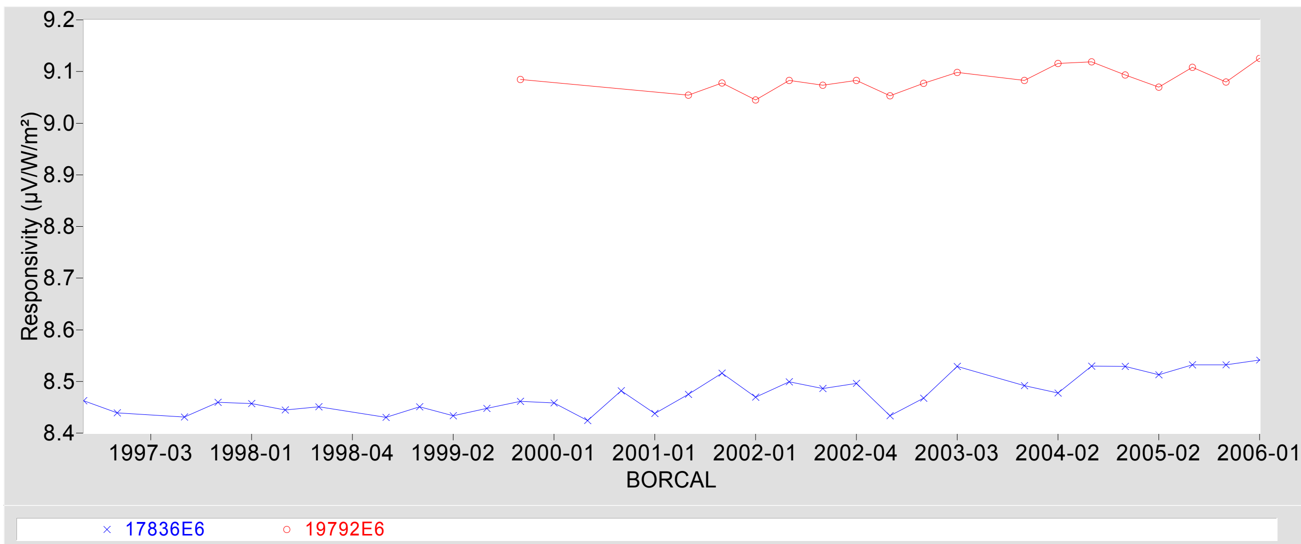
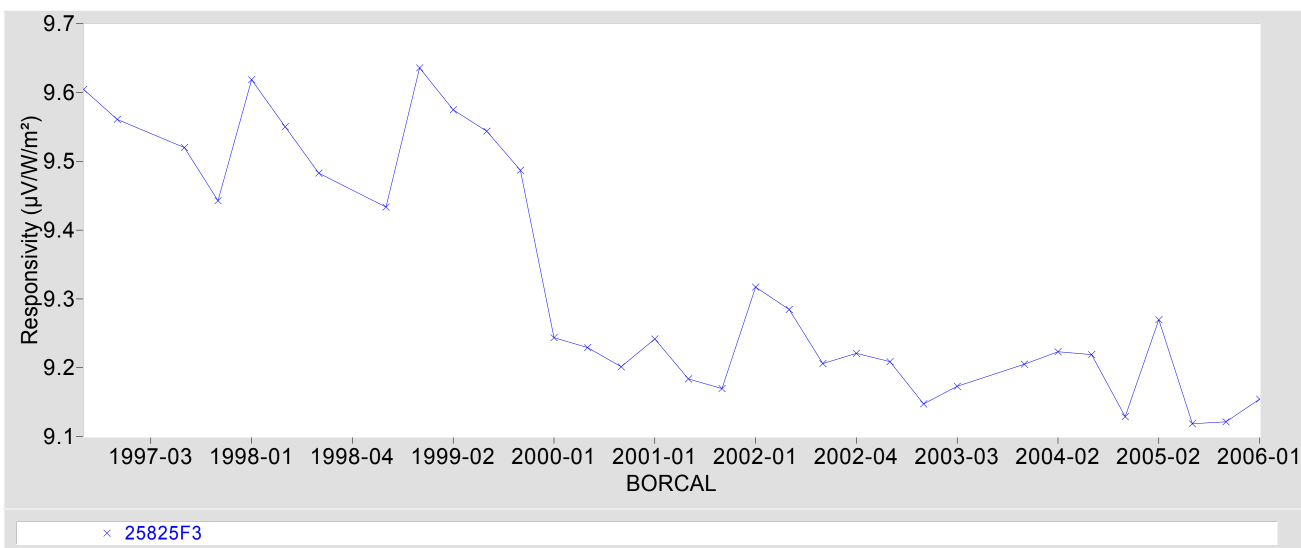
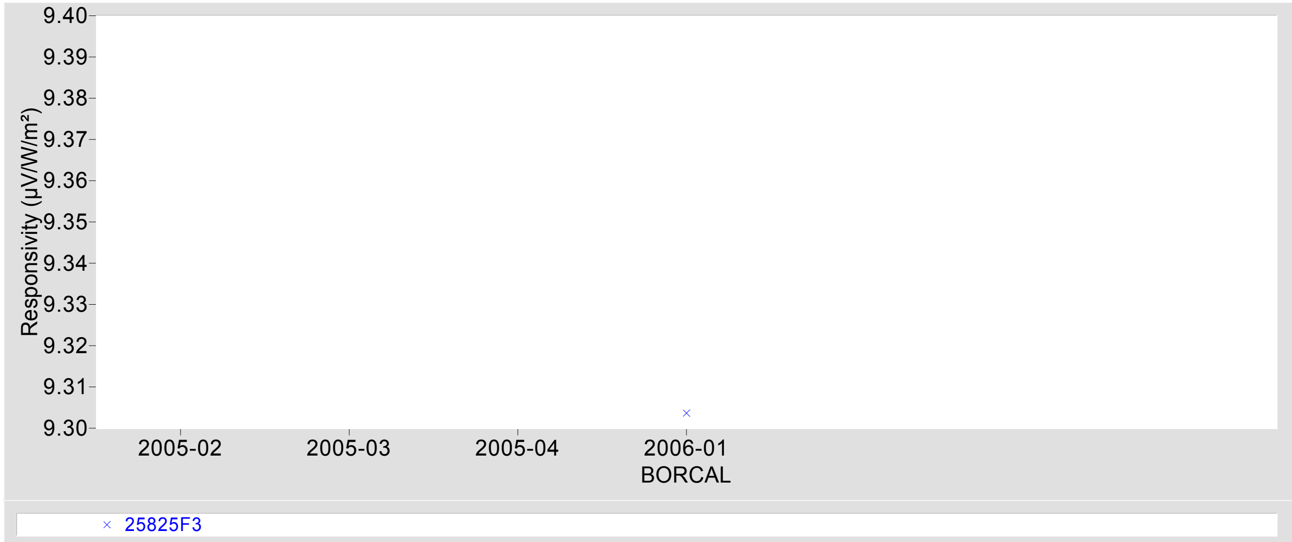


Figure 10. Eppley PSP Control Instrument History



Control Instrument History

Figure 11. Eppley PSP Control Instrument History (Effective Net IR Corrected)



Results Summary

Table 2. Results Summary

Instrument	RS@45 (μV/W/m²)	CF@45 [1] (W/m²/mV)	U95 (%)	RSc@45 [2] (μV/W/m²)	CFc@45 [12] (W/m²/mV)	U95 corr. [2] (%)	RS net [3] (μV/W/m²)	Page
31399F3	7.6663	130.44	+2.90 / -4.04	n/a	n/a	n/a	n/a	A1-2

Note: Ancillary Data for BORCAL starts on page A1-7.

[1] CF = 1000 / Rs [2] Effective Net IR Corrected

[3] Instrument's Effective Net IR Response

Appendix 1
Instrument Details

Calibration Certificates: Page 1 and 2 for each instrument
Suggested Methods: 1 Page for each Pyrheliometer/Shaded Pyranometer and 2 Pages for each Unshaded Pyranometer
Ancillary Data for BORCAL: Page 3 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:	Precision Spectral Pyranometer	**Manufacturer:**	Eppley
Model:	PSP	**Serial Number:**	31399F3
Calibration Date:	5/16/2006	**Due Date:**	5/16/2007
Customer:	NREL-SRRL-BSRN	**Calibration Site Parameters:**	see Ancillary Data

Environmental Conditions: Outdoors, under natural sunlight (see Ancillary Data)

Data Acquisition Dates: 5/15-16

Table 1. Traceability

Measurement Type	Instrument	Calibration Date	Calibration Due Date
Beam Irradiance †	Eppley Absolute Cavity Radiometer Model HF, S/N 31104	10/01/2004	10/01/2006
Diffuse Irradiance †	Eppley Black and White Pyranometer Model 8-48, S/N 32858	04/05/2006	04/05/2007
Diffuse Irradiance †	Eppley Black and White Pyranometer Model 8-48, S/N 32871	04/05/2006	04/05/2007
Data Acquisition ‡	NREL Data Proof Scanner System Model RAP-DAQ, S/N 2005-998	11/22/2005	11/22/2006
Data Acquisition ‡	NREL Data Proof Scanner System Model RAP-DAQ, S/N 2005-999	11/22/2005	11/22/2006

† Traceable to the World Radiometric Reference
‡ Traceable to the National Institute of Standards and Technology

Number of pages of certificate: 4

Calibration Procedure:

[1] Myers, D., Stoffel, T., Reda, I., Wilcox, S., and Andreas, A., 2002, "Recent Progress in Reducing the Uncertainty in and Improving Pyranometer Calibrations." Journal of Solar Energy Engineering, vol. 124, pp. 44-50. The American Society of Mechanical Engineers, Transactions of the ASME.
[2] "Improved Methods for Broadband Outdoor Radiometer Calibration (BORCAL)," Wilcox, S., Andreas, A., Reda, I., and Myers, D., Proceedings of the ARM Science Team Meeting, St. Petersburg, Florida, April 2002. Available upon request.

Calibrated by: Afshin Andreas and Ibrahim Reda

Certified by:

____
Ibrahim Reda

Title: Senior Scientist II

Date: __________________

Quality Assured by:

____
Daryl Myers

Title: Senior Scientist II

Date: __________________

Calibration Results

31399F3 Eppley PSP

Figure 1. Responsivity vs Incident Angle

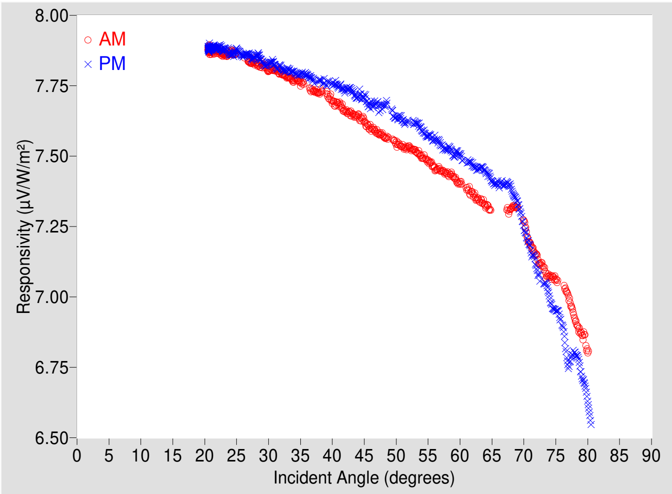


Figure 2. Responsivity vs Local Standard Time

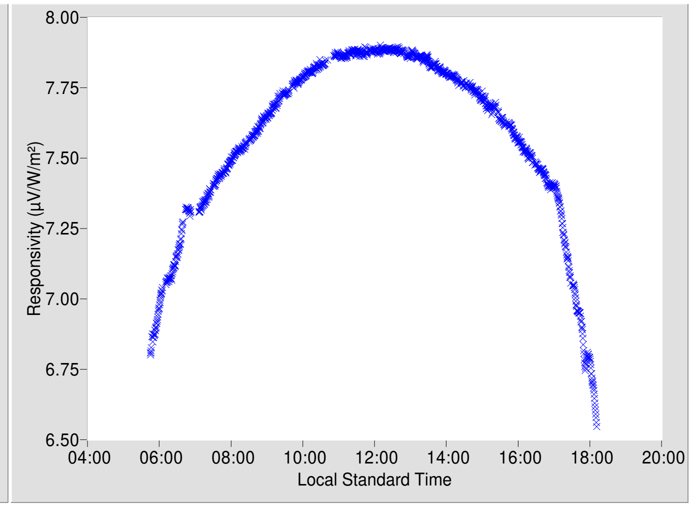


Table 2. Calibration Label Values

RS @ 45° (µV/W/m²) ‡	U95 (%) †	Tilt / Azm
7.6663	+2.90 / -4.04	0.0° / 0.0°

† Valid incident angle range: 30.0° to 60.0°

‡ Estimated thermal offset error during calibration = -20.000 W/m²

Table 3. Instrument Responsivity (RS) and Calibration Uncertainty (U95)

Inc. Angle†	AM			PM			Inc. Angle†	AM			PM		
	RS (µV/W/m²)	U95 ± (%)	Azm. Angle‡	RS (µV/W/m²)	U95 ± (%)	Azm. Angle‡		RS (µV/W/m²)	U95 ± (%)	Azm. Angle‡	RS (µV/W/m²)	U95 ± (%)	Azm. Angle‡
0	N/A	N/A	N/A	N/A	N/A	N/A	46	7.5985	0.56	102.05	7.6827	0.72	257.65
2	N/A	N/A	N/A	N/A	N/A	N/A	48	7.5711	0.52	100.00	7.6785	0.71	259.72
4	N/A	N/A	N/A	N/A	N/A	N/A	50	7.5452	0.54	98.05	7.6345	0.74	261.69
6	N/A	N/A	N/A	N/A	N/A	N/A	52	7.5313	0.54	96.17	7.6215	0.72	263.42
8	N/A	N/A	N/A	N/A	N/A	N/A	54	7.4970	0.61	94.36	7.5928	0.81	265.39
10	N/A	N/A	N/A	N/A	N/A	N/A	56	7.4584	0.61	92.64	7.5595	0.80	267.17
12	N/A	N/A	N/A	N/A	N/A	N/A	58	7.4372	0.59	90.91	7.5255	0.81	268.87
14	N/A	N/A	N/A	N/A	N/A	N/A	60	7.4046	0.65	89.23	7.5021	0.83	270.55
16	N/A	N/A	N/A	N/A	N/A	N/A	62	7.3674	0.69	87.65	7.4657	0.86	272.24
18	N/A	N/A	N/A	N/A	N/A	N/A	64	7.3248	0.70	86.02	7.4448	0.93	273.79
20	N/A	N/A	N/A	N/A	N/A	N/A	66	N/A	N/A	N/A	7.4004	0.94	275.36
22	7.8759	0.49	156.51	7.8826	0.48	203.65	68	7.3138	0.76	82.83	7.3863	1.09	276.96
24	7.8682	0.47	144.70	7.8632	0.50	215.38	70	7.2600	1.20	81.18	7.2451	1.47	278.57
26	7.8489	N/A	136.02	7.8568	0.51	223.29	72	7.1431	1.01	79.68	7.1021	1.39	280.14
28	7.8305	0.50	130.74	7.8533	0.52	229.33	74	7.0745	0.99	78.13	6.9980	1.43	281.73
30	7.8048	0.48	125.80	7.8292	0.54	233.57	76	7.0409	N/A	76.29	6.8969	2.06	283.34
32	7.7936	0.50	121.58	7.8132	0.56	237.90	78	6.9229	1.49	74.93	6.7990	1.71	284.95
34	7.7692	0.46	117.97	7.7979	0.55	241.57	80	6.8125	1.49	73.36	6.6250	2.31	286.56
36	N/A	N/A	N/A	7.7890	0.57	244.85	82	N/A	N/A	N/A	N/A	N/A	N/A
38	7.7270	0.48	111.69	7.7685	0.56	247.90	84	N/A	N/A	N/A	N/A	N/A	N/A
40	7.6983	0.58	109.06	7.7558	0.60	250.66	86	N/A	N/A	N/A	N/A	N/A	N/A
42	7.6604	0.57	106.57	7.7357	0.63	253.11	88	N/A	N/A	N/A	N/A	N/A	N/A
44	7.6428	0.52	104.26	7.7130	0.67	255.44	90	N/A	N/A	N/A	N/A	N/A	N/A

† Angle of incidence (degrees)

‡ Average azimuth angle for ±0.3° of incidence angle

N/A - Not Available

Effective Net Infrared Corrected Calibration Results

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Figure 3. Responsivity vs Incident Angle

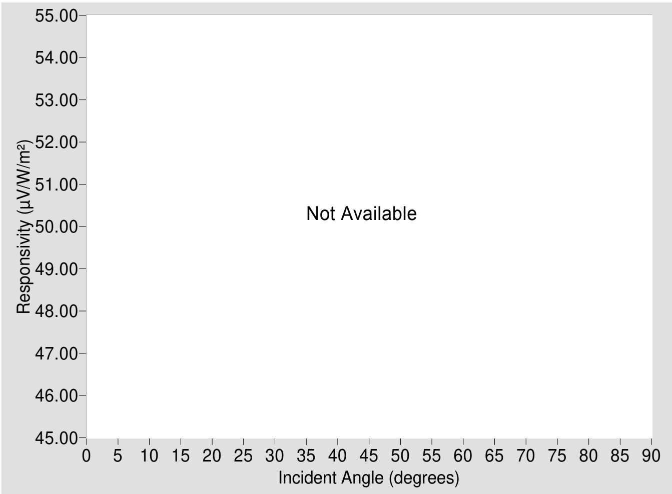

Figure 4. Responsivity vs Local Standard Time

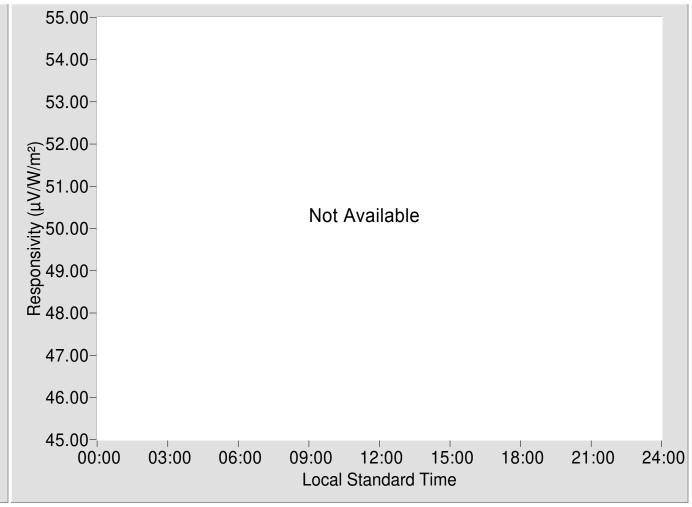

Table 4. Calibration Label Values

RS @ 45° (μV/W/m²) ‡	U95 (%) †	Tilt / Azm
N/A	N/A	0.0° / 0.0°

† Valid incident angle range: N/A

‡ RSnet = N/A

Table 5. Instrument Responsivity (RS) and Calibration Uncertainty (U95)

	AM			PM				AM			PM		
Inc. Angle†	RS (μV/W/m²)	U95 ± (%)	Azm. Angle‡	RS (μV/W/m²)	U95 ± (%)	Azm. Angle‡	Inc. Angle†	RS (μV/W/m²)	U95 ± (%)	Azm. Angle‡	RS (μV/W/m²)	U95 ± (%)	Azm. Angle‡
0	N/A	N/A	N/A	N/A	N/A	N/A	46	N/A	N/A	N/A	N/A	N/A	N/A
2	N/A	N/A	N/A	N/A	N/A	N/A	48	N/A	N/A	N/A	N/A	N/A	N/A
4	N/A	N/A	N/A	N/A	N/A	N/A	50	N/A	N/A	N/A	N/A	N/A	N/A
6	N/A	N/A	N/A	N/A	N/A	N/A	52	N/A	N/A	N/A	N/A	N/A	N/A
8	N/A	N/A	N/A	N/A	N/A	N/A	54	N/A	N/A	N/A	N/A	N/A	N/A
10	N/A	N/A	N/A	N/A	N/A	N/A	56	N/A	N/A	N/A	N/A	N/A	N/A
12	N/A	N/A	N/A	N/A	N/A	N/A	58	N/A	N/A	N/A	N/A	N/A	N/A
14	N/A	N/A	N/A	N/A	N/A	N/A	60	N/A	N/A	N/A	N/A	N/A	N/A
16	N/A	N/A	N/A	N/A	N/A	N/A	62	N/A	N/A	N/A	N/A	N/A	N/A
18	N/A	N/A	N/A	N/A	N/A	N/A	64	N/A	N/A	N/A	N/A	N/A	N/A
20	N/A	N/A	N/A	N/A	N/A	N/A	66	N/A	N/A	N/A	N/A	N/A	N/A
22	N/A	N/A	N/A	N/A	N/A	N/A	68	N/A	N/A	N/A	N/A	N/A	N/A
24	N/A	N/A	N/A	N/A	N/A	N/A	70	N/A	N/A	N/A	N/A	N/A	N/A
26	N/A	N/A	N/A	N/A	N/A	N/A	72	N/A	N/A	N/A	N/A	N/A	N/A
28	N/A	N/A	N/A	N/A	N/A	N/A	74	N/A	N/A	N/A	N/A	N/A	N/A
30	N/A	N/A	N/A	N/A	N/A	N/A	76	N/A	N/A	N/A	N/A	N/A	N/A
32	N/A	N/A	N/A	N/A	N/A	N/A	78	N/A	N/A	N/A	N/A	N/A	N/A
34	N/A	N/A	N/A	N/A	N/A	N/A	80	N/A	N/A	N/A	N/A	N/A	N/A
36	N/A	N/A	N/A	N/A	N/A	N/A	82	N/A	N/A	N/A	N/A	N/A	N/A
38	N/A	N/A	N/A	N/A	N/A	N/A	84	N/A	N/A	N/A	N/A	N/A	N/A
40	N/A	N/A	N/A	N/A	N/A	N/A	86	N/A	N/A	N/A	N/A	N/A	N/A
42	N/A	N/A	N/A	N/A	N/A	N/A	88	N/A	N/A	N/A	N/A	N/A	N/A
44	N/A	N/A	N/A	N/A	N/A	N/A	90	N/A	N/A	N/A	N/A	N/A	N/A

† Angle of incidence (degrees)

‡ Average azimuth angle for ±0.3° of incidence angle

N/A - Not Available

Suggested Methods of Applying Calibration Results

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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. Computing the net infrared corrected solar irradiance is documented in "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," Reda et al., American Meteorological Society (pp. 1531-1540), October 2005.

In all cases, the solar irradiance is calculated from the instrument responsivity using one of these equations:

$$IRR = V / RS \quad [1]$$

$$IRR\ (corr.) = (V - Wnet * RSnet) / RSc \quad [2]$$

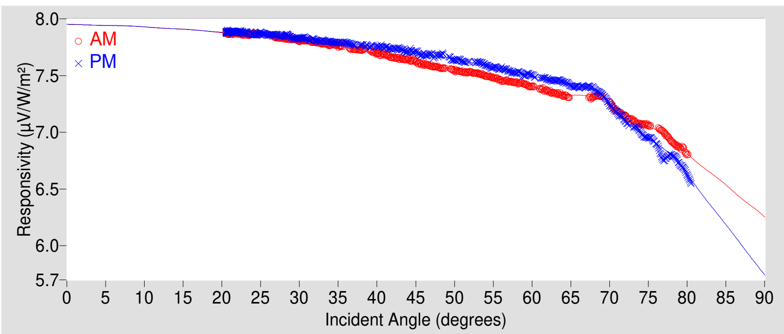
where,

- *IRR* = solar irradiance (Watts per square meter),
- *V* = radiometer output voltage (microvolts),
- *RS* = responsivity of the radiometer (μV/W/m²),
- *IRR (corr.)* = net infrared corrected solar irradiance (W/m²),
- *Wnet* = effective net infrared measured by pyrgeometer (W/m²)
- *RSnet* = pyranometer net infrared response (μV/W/m²), see Table 4,
- *RSc* = net infrared corrected responsivity (μV/W/m²).

1. Two-degree Responsivities: Responsivities are obtained from Certificate Table 3 or 5. See Note 1 on next page.

2. AM and PM Responsivity Functions: See Note 1 on next page.

Figure 1. Responsivity Function



$$RS\ (am) = \sum_{i=0}^{n} a_i \cdot \cos^i(I)$$

$$RS\ (pm) = \sum_{j=0}^{m} b_j \cdot \cos^j(I) \quad [3]$$

where the coefficients a_i and b_j are available upon request.

The quality of the function fit to data is shown in Figure 1 and 2.

Figure 2. Net IR Corrected Responsivity Function

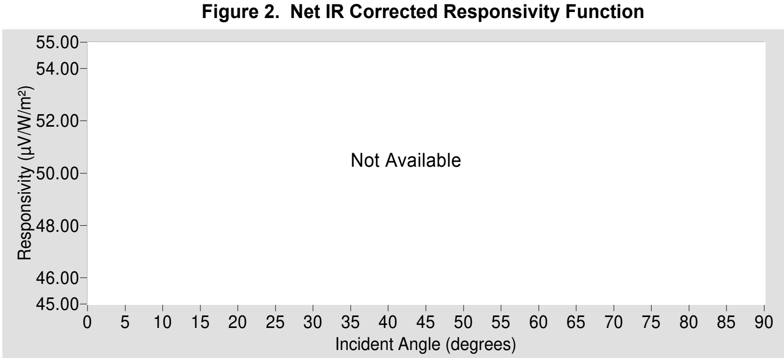


Table 1. Function Validity

	AM	PM
Uncertainty U95 (%)	±1.17	±1.17
R²	0.9999993	0.9999993
Valid incidence angle range	20.5° to 80.1°	20.5° to 80.5°
Net IR corr. uncert. U95 (%)	N/A	N/A
Net IR corrected R²	N/A	N/A
Corr. valid inc. angle range	N/A	N/A

3. Nine-degree Bin Responsivity: See Note 1 on next page.

Table 2. Nine-degree responsivities

Inc. Angle	Responsivity AM RS (μV/W/m²)	Responsivity AM U95 (%)	Responsivity PM RS (μV/W/m²)	Responsivity PM U95 (%)	Responsivity Combined RS (μV/W/m²)	Responsivity Combined U95 (%)	Net IR Corr. Responsivity AM RS (μV/W/m²)	Net IR Corr. Responsivity AM U95 (%)	Net IR Corr. Responsivity PM RS (μV/W/m²)	Net IR Corr. Responsivity PM U95 (%)	Net IR Corr. Responsivity Combined RS (μV/W/m²)	Net IR Corr. Responsivity Combined U95 (%)
0-9	7.9435	*	7.9434	*	7.9434	*	N/A	N/A	N/A	N/A	N/A	N/A
9-18	7.9148	*	7.9147	*	7.9148	*	N/A	N/A	N/A	N/A	N/A	N/A
18-27	7.8720	*	7.8744	*	7.8732	*	N/A	N/A	N/A	N/A	N/A	N/A
27-36	7.7971	±1.29	7.8210	±1.24	7.8090	±1.47	N/A	N/A	N/A	N/A	N/A	N/A
36-45	7.6914	±1.42	7.7499	±1.27	7.7206	±1.91	N/A	N/A	N/A	N/A	N/A	N/A
45-54	7.5584	±1.39	7.6514	±1.35	7.6049	±2.19	N/A	N/A	N/A	N/A	N/A	N/A
54-63	7.4283	±1.51	7.5248	±1.46	7.4765	±2.55	N/A	N/A	N/A	N/A	N/A	N/A
63-72	7.2942	±1.61	7.3524	±2.38	7.3233	±3.22	N/A	N/A	N/A	N/A	N/A	N/A
72-81	6.9927	*	6.8718	*	6.9323	*	N/A	N/A	N/A	N/A	N/A	N/A
81-90	6.5053	*	6.1408	*	6.3230	*	N/A	N/A	N/A	N/A	N/A	N/A

* The responsivity is based on extrapolated data and the corresponding uncertainty is undefined.

4. The Single Responsivities:

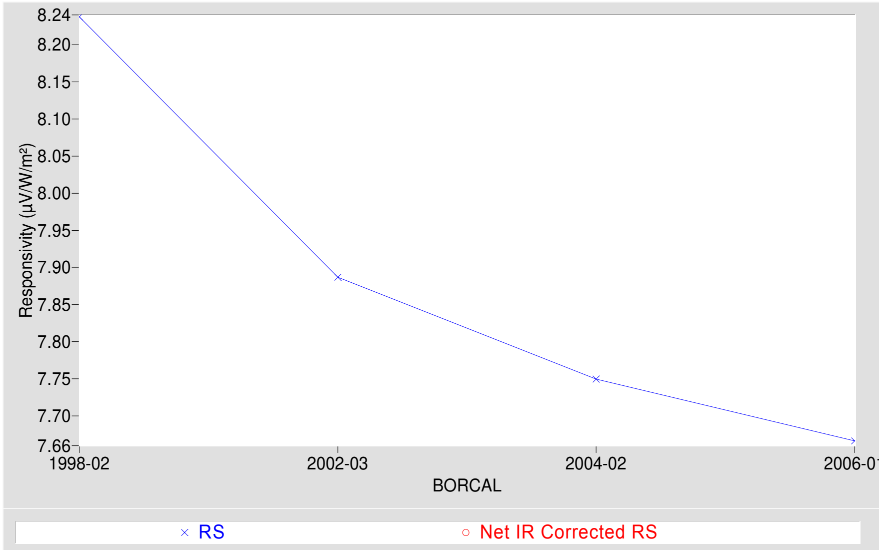
Table 3. Single Responsivities

Responsivity Characterization	RS (µV/W/m²)	U95 † (%)
45°	7.6663	+2.90 / -4.04
45° - 55°	7.5944	±1.87
Composite	7.7191	+2.36 / -14.73
45° (Net IR Corr.)	N/A	N/A
45° - 55° (Net IR Corr.)	N/A	N/A
Composite (Net IR Corr.)	N/A	N/A

† Valid incident angle ranges:
45°: 30.0° to 60.0°
45° - 55°: 45.0° to 55.0°
Composite: 20.5° to 80.1°

The instrument responsivity at I = 45° may be used to monitor instrument stability. The instrument's history at I = 45° is shown in Figure 2.

Figure 2. History of instrument at I = 45°



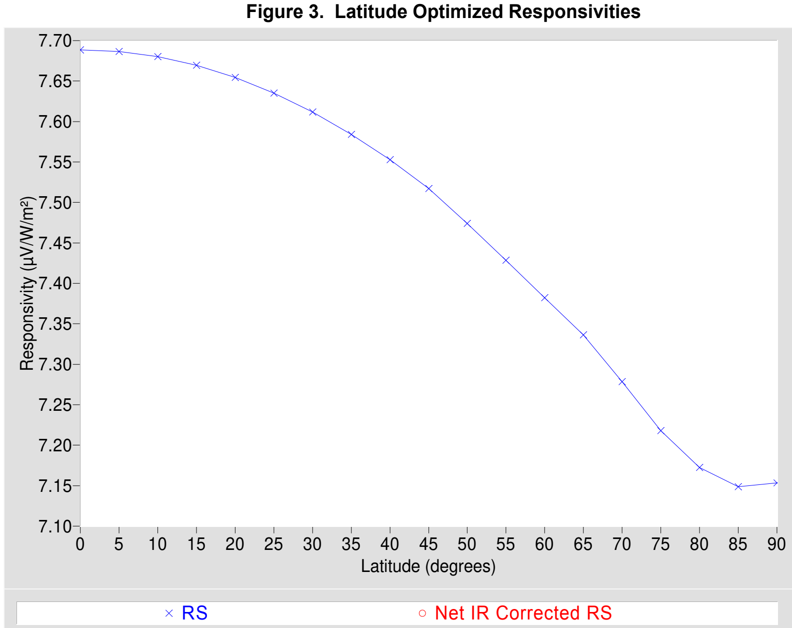
5. Latitude Optimized Responsivity:

Table 4. Latitude Optimized Responsivities

Latitude	RS (µV/W/m²)	Error estimate* (%)	RS (µV/W/m²) Net IR Corr.	Error estimate* (%) Net IR Corr.
0	7.6884	+3.62 / -24.18	N/A	N/A
5	7.6864	+3.64 / -24.16	N/A	N/A
10	7.6802	+3.72 / -24.10	N/A	N/A
15	7.6697	+3.86 / -24.00	N/A	N/A
20	7.6545	+4.06 / -23.85	N/A	N/A
25	7.6350	+4.30 / -23.65	N/A	N/A
30	7.6116	+4.47 / -23.42	N/A	N/A
35	7.5841	+4.64 / -23.14	N/A	N/A
40	7.5526	+4.81 / -22.82	N/A	N/A
45	7.5172	+4.93 / -22.46	N/A	N/A
50	7.4740	+5.30 / -22.01	N/A	N/A
55	7.4286	+5.44 / -21.53	N/A	N/A
60	7.3820	+5.57 / -21.04	N/A	N/A
65	7.3363	+5.73 / -20.55	N/A	N/A
70	7.2785	+5.73 / -19.91	N/A	N/A
75	7.2179	+5.87 / -19.24	N/A	N/A
80	7.1725	+5.54 / -18.73	N/A	N/A
85	7.1489	+4.76 / -18.47	N/A	N/A
90	7.1533	+3.92 / -18.52	N/A	N/A

* Uncertainty is undefined

Figure 3. Latitude Optimized Responsivities



Application of the responsivities and uncertainties:

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

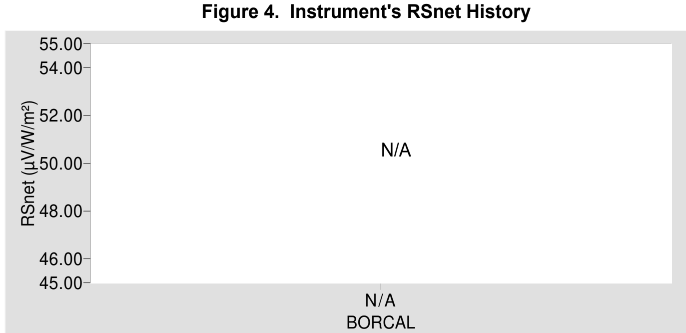
Example

Instrument responsivity (RS) = 7.34 µV/W/m² ±2.7%
Instrument output voltage (V) = 0.00624 V (6240 µV)
Irradiance (IRR) = V / RS = 6240 / 7.34 = 850.1 W/m² ±2.7%

Thus, at the 95% confidence level, the irradiance lies between 827.1 and 873.1 W/m²

Instrument's Effective Net Infrared History (RSnet):

Figure 4. Instrument's RSnet History



Note 1:

The above methods, in conjunction with knowledge of the net infrared and sky irradiance distribution, may be used to compute the effective instrument responsivity with less uncertainties.

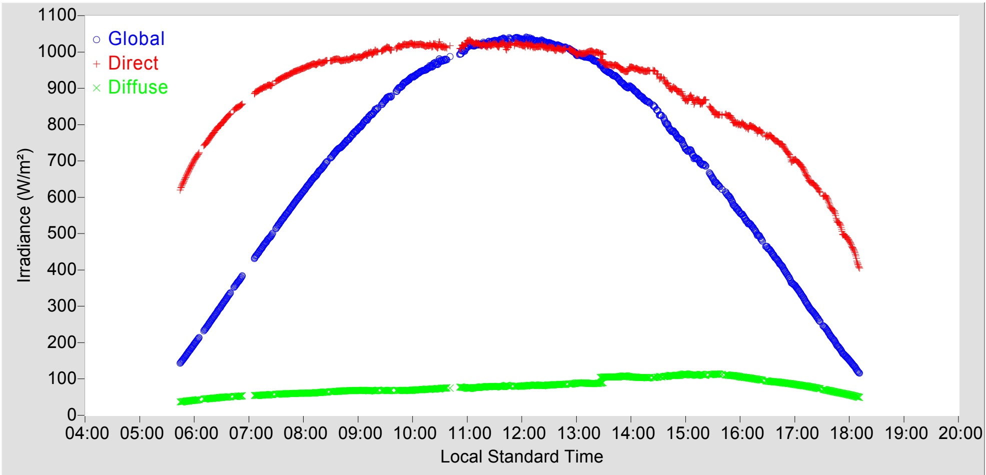
Ancillary Data for BORCAL 2006-01

Calibration Facility: Solar Radiation Research Laboratory

Latitude: 39.740°N   Longitude: 105.180°W   Elevation: 1829.0 meters AMSL   Avg. Station Pressure: 835.0 mBar   Time Zone: -7.0

Reference Irradiance: 0.0° / 0.0° Tilt / Azm

Figure 1. Reference Irradiance



The reference global irradiance (G) is calculated using: G = B * Cos (I) + D, where I is the refraction-corrected solar incidence angle.

Meteorological Observations:

Figure 2. Temperature

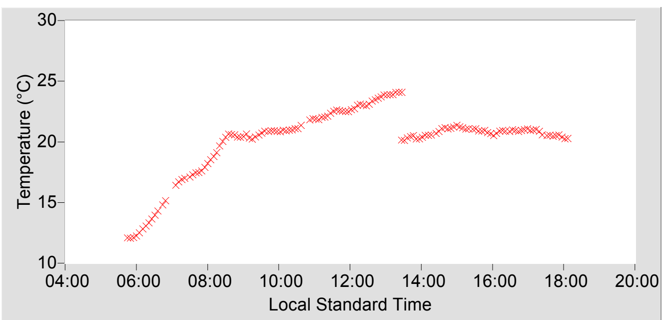


Figure 3. Humidity

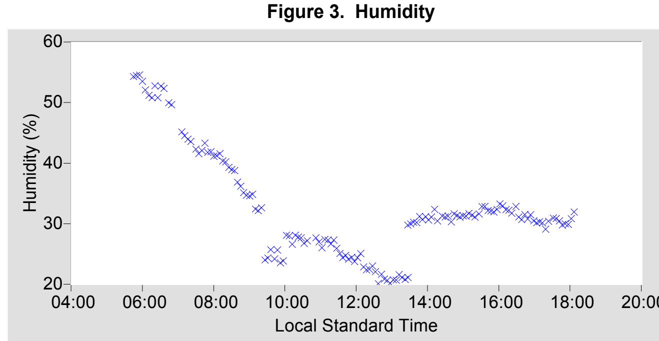


Figure 4. Pressure

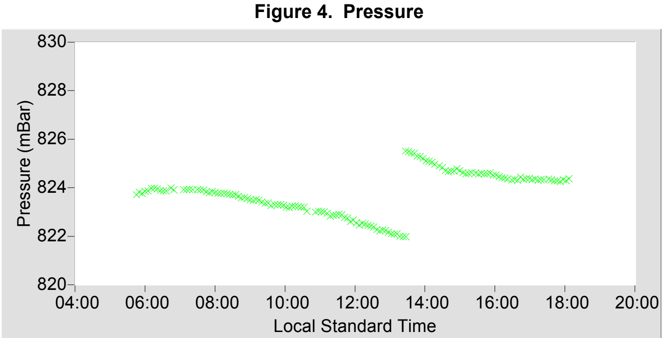


Figure 5. Effective Net Infrared

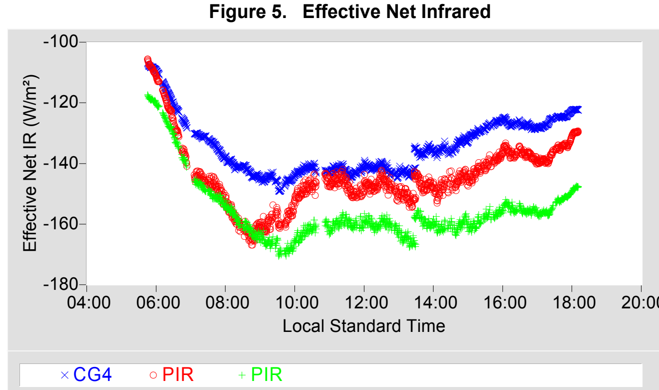


Figure 6. Estimated Broadband Aerosol Optical Depth

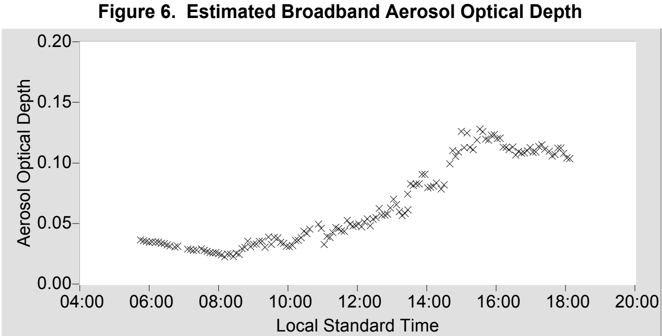


Table 1. Meteorological Observations

Observations	Mean
Temperature (°C)	20.23
Humidity (%)	32.39
Pressure (mBar)	823.8
Est. Aerosol Optical Depth (BB)	0.0646

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

Appendix 2
BORCAL Notes

Instrument, Configuration, and Session Notes for the BORCAL

BORCAL Notes

BORCAL: 2006-01
Comments:
After data collection, the cavity WRR factor was updated, prior to generating responsivities and report:
OLD WRR: 9.999010e-01
NEW WRR: 9.987550e-01

Facility: Solar Radiation Research Laboratory
Comments:
Avg. Station Pressure & Temperature is for Denver, CO, which is used for the Solar Position Algorithm (SPA).