Broadband Outdoor Radiometer Calibration
Longwave

BORCAL-LW
2023-02

Generated by

Radiometer Calibration and Characterization

Customer

NREL-SRRL-BMS

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

Calibration Facility

Solar Radiation Research Laboratory

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

Calibration date
06/24/2023 to 07/18/2023

Report Date
July 18, 2023

NREL

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 World Infrared Standard Group (WISG).

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 PIR Control Instrument (Residual means of current data using historical coefficients)

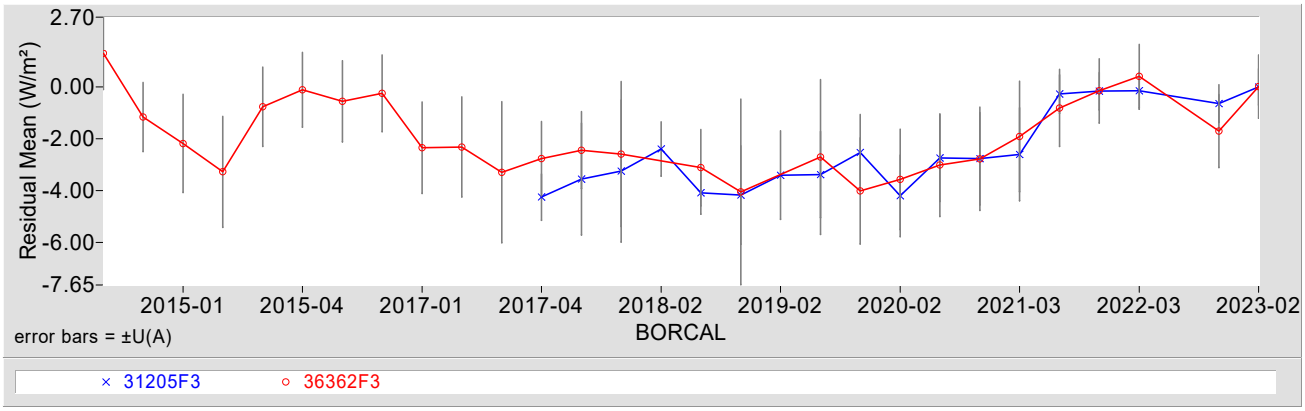


Figure 2. Eppley PIR Control Instrument History (K1 Coefficient)

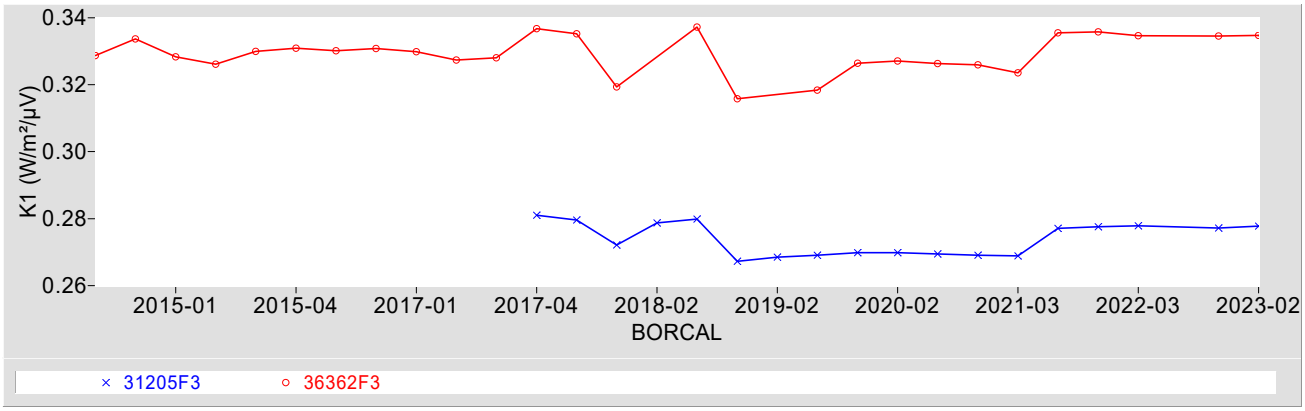


Figure 3. Eppley PIR Control Instrument History (K2 Coefficient)

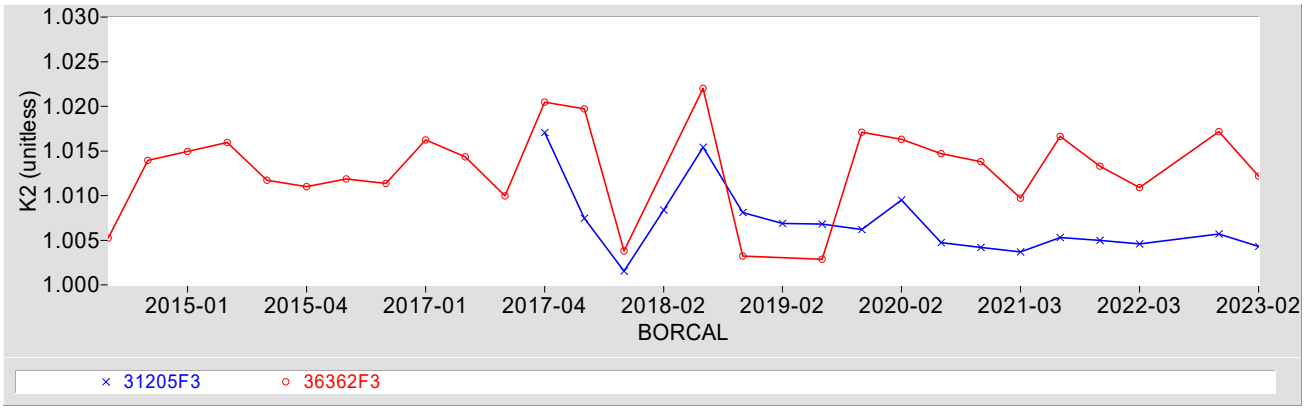
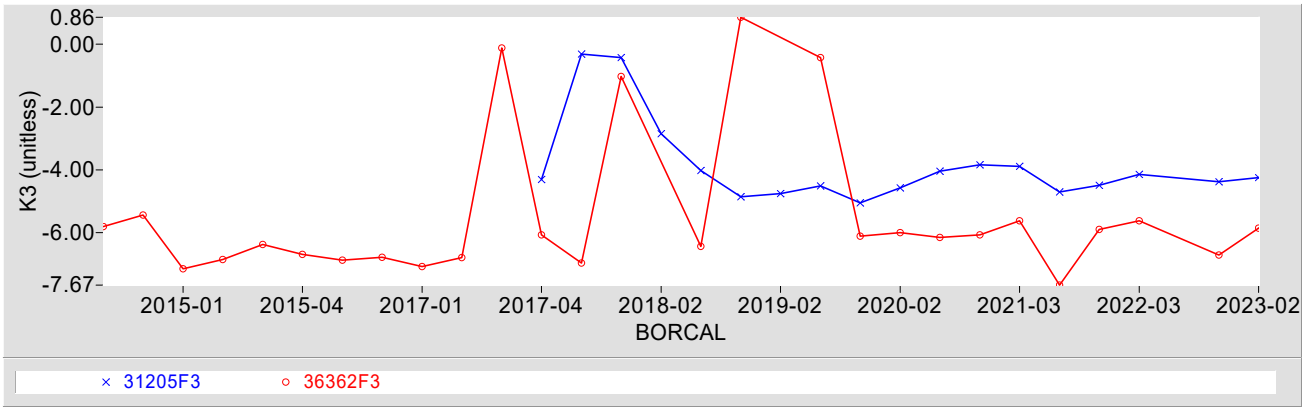


Figure 4. Eppley PIR Control Instrument History (K3 Coefficient)



Results Summary

Table 1. Results Summary

Instrument	K1 (W/m²/µV)	K2	K3	Kr * (K/µV)	U95 (W/m²)	Page
010284-UW-CG3 Kipp & Zonen CG3	0.090806	1.0002	0.00	7.044e-4	±3.1	A1-2
010548 Kipp & Zonen CG4	0.076460	1.0004	0.00	7.044e-4	±2.6	A1-5
31193F3 Eppley PIR	0.27344	0.9990	-3.52	7.044e-4	±2.5	A1-8
31198F3 Eppley PIR	0.27188	0.9959	-3.70	7.044e-4	±2.5	A1-11

Note: Environmental Conditions for BORCAL starts on page A1-14. * Kr used to derive coefficients

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

Calibration CERT #1239.02

Test Instrument:	Pyrgeometer	**Manufacturer:**	Kipp & Zonen
Model:	CG3	**Serial Number:**	010284-UW-CG3
Calibration Date:	7/18/2023	**Due Date:**	7/18/2025
Customer:	NREL-SRRL-BMS	**Environmental Conditions:**	see page 4
Test Dates:	6/24-30, 7/1-4, 7/6-7, 7/9-18		

This certifies that the above product was calibrated in compliance with ISO/IEC 17025:2017. Measurement uncertainties at the time of calibration are consistent with the Guide to the Expression of Uncertainty in Measurement (GUM) using Reda et al., 2008. All nominal values are traceable to the World Infrared Standard Group (WISG).

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.

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
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/03/2023	02/03/2025
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/08/2023	02/08/2025
Infrared Irradiance ‡	Eppley Downwelling Pyrgeometer Model PIR, S/N 32309F3	03/31/2022	03/31/2027
Infrared Irradiance ‡	Eppley Downwelling Pyrgeometer Model PIR, S/N 38520F3	03/31/2022	03/31/2027
Infrared Irradiance ‡	Kipp & Zonen Pyrgeometer Model CG4, S/N FT002	03/31/2022	03/31/2027

‡ Through the World Infrared Standard Group (WISG)

Number of pages of certificate: 4

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

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

Calibrated by: Afshin Andreas, Jaemo Yang, and Shawn Jaker

_____ _____

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

010284-UW-CG3 Kipp & Zonen CG3

The incoming irradiance (Win, W/m²) of the test instrument during calibration is calculated using this Measurement Equation:

$$Win = K1*V + K2*Wr + K3*(Wd - Wr) \quad [1]$$

where,

K1,K2,K3 = calibration coefficeints,
V = thermopile output voltage (μV),
$Wd = \sigma * Td^4$ = dome irradiance (W/m²),
where, *Td* = dome temperature (K),

$Wr = \sigma * Tr^4$ = receiver irradiance (W/m²),
where, σ = 5.6704e-8 W·m-2·K-4,
$Tr = Tc + Kr * V$ = receiver temperature (K),
Tc = case temperature (K),
Kr = efficiency coefficient (K/μV).

Figure 1. Residuals for calculated using coefficients vs reference irradiance

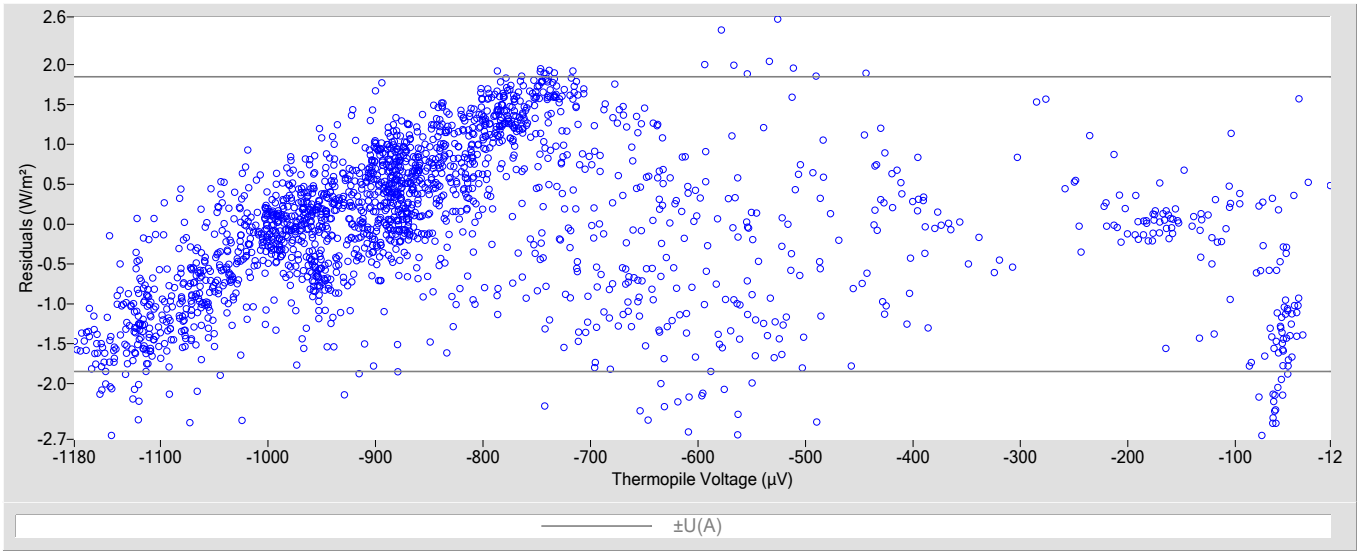


Table 1. Calibration Coefficients

K1	0.090806
K2	1.0002
K3	0.00
Kr used to derive coefficients	7.044e-4

Table 2. Uncertainty using coefficients

Type-B Standard Uncertainty, u(B) (W/m²)	±1.3
Type-A Standard Uncertainty, u(A) (W/m²)	±0.94
Combined Standard Uncertainty, u(c) (W/m²)	±1.6
Effective degrees of freedom, DF(c)	+Inf
Coverage factor, k	1.96
Expanded Uncertainty, U95 (W/m²)	±3.1

Figure 2. History of instrument (Residual means of current data using historical BORCAL coefficients)

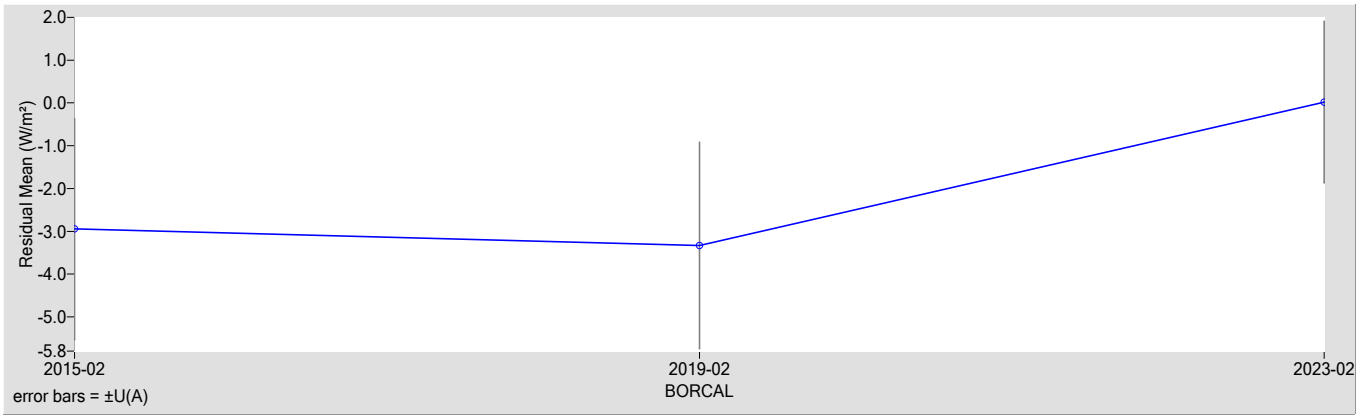


Figure 3. History of instrument (K1 Coefficient)

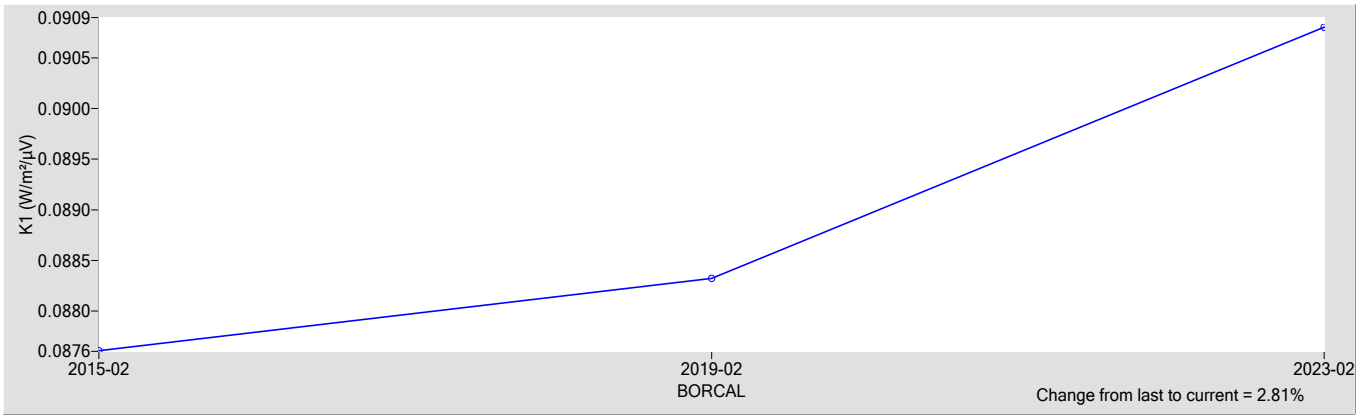
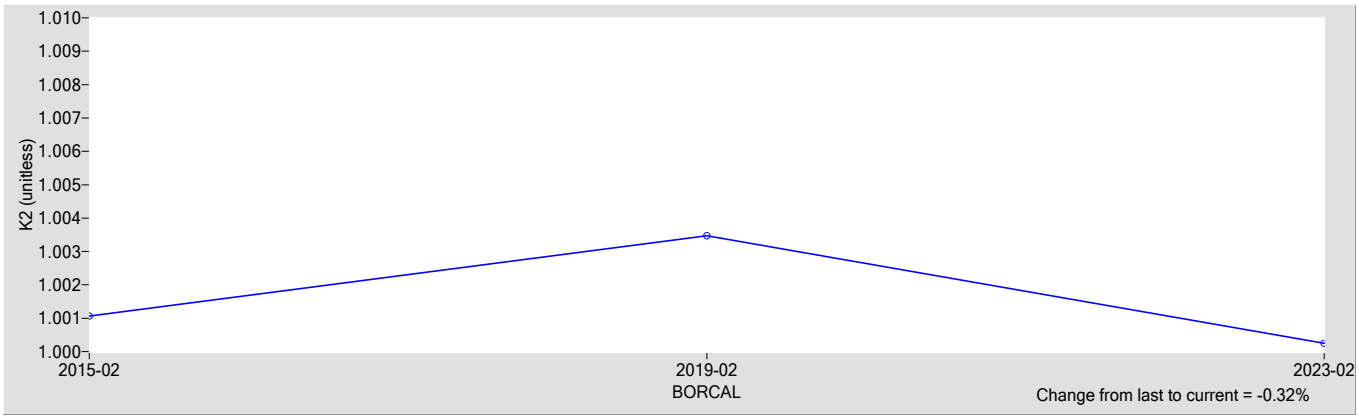


Figure 4. History of instrument (K2 Coefficient)



References:

[1] Reda, I.; Stoffel, T. (2010). Pyrgeometer Calibration for DOE-Atmospheric System Research Program using NREL Method (Presentation). 9 pp.; NREL Report No. PR-3B0-47756; http://www.nrel.gov/docs/fy10osti/47756.pdf.

National Renewable Energy Laboratory

Solar Radiation Research Laboratory

Metrology Laboratory

Calibration Certificate

Calibration CERT #1239.02

Test Instrument:	Pyrgeometer	**Manufacturer:**	Kipp & Zonen
Model:	CG4	**Serial Number:**	010548
Calibration Date:	7/18/2023	**Due Date:**	7/18/2025
Customer:	NREL-SRRL-BMS	**Environmental Conditions:**	see page 4
Test Dates:	6/24-30, 7/1-4, 7/6-7, 7/9-18		

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Measurement Type	Instrument	Calibration Date	Calibration Due Date
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/03/2023	02/03/2025
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/08/2023	02/08/2025
Infrared Irradiance ‡	Eppley Downwelling Pyrgeometer Model PIR, S/N 32309F3	03/31/2022	03/31/2027
Infrared Irradiance ‡	Eppley Downwelling Pyrgeometer Model PIR, S/N 38520F3	03/31/2022	03/31/2027
Infrared Irradiance ‡	Kipp & Zonen Pyrgeometer Model CG4, S/N FT002	03/31/2022	03/31/2027

‡ Through the World Infrared Standard Group (WISG)

Number of pages of certificate: 4

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

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

Calibrated by: Afshin Andreas, Jaemo Yang, and Shawn Jaker

_____ _____

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

010548 Kipp & Zonen CG4

The incoming irradiance (Win, W/m²) of the test instrument during calibration is calculated using this Measurement Equation:

*Win = K1*V + K2*Wr + K3*(Wd - Wr)* [1]

where,

K1,K2,K3 = calibration coefficeints,
V = thermopile output voltage (μV),
*Wd = σ * Td^4* = dome irradiance (W/m²),
where, *Td* = dome temperature (K),

*Wr = σ * Tr^4* = receiver irradiance (W/m²),
where, *σ* = 5.6704e-8 W·m-2·K-4,
*Tr = Tc + Kr * V* = receiver temperature (K),
Tc = case temperature (K),
Kr = efficiency coefficient (K/μV).

Figure 1. Residuals for calculated using coefficients vs reference irradiance

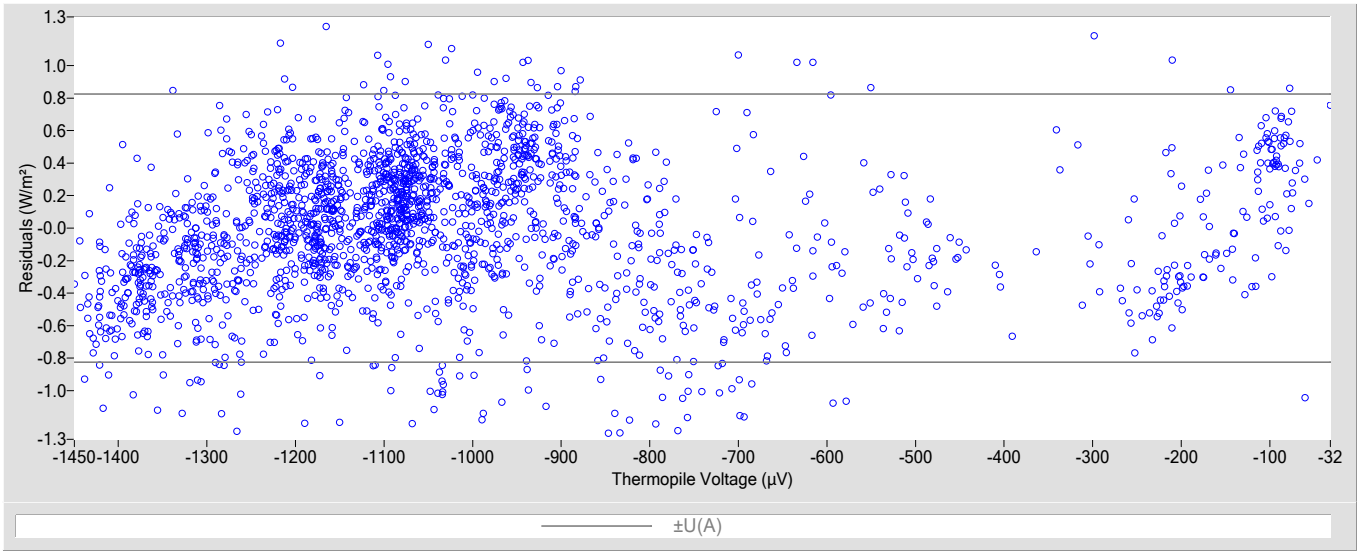


Table 1. Calibration Coefficients

K1	0.076460
K2	1.0004
K3	0.00
Kr used to derive coefficients	7.044e-4

Table 2. Uncertainty using coefficients

Type-B Standard Uncertainty, u(B) (W/m²)	±1.3
Type-A Standard Uncertainty, u(A) (W/m²)	±0.42
Combined Standard Uncertainty, u(c) (W/m²)	±1.3
Effective degrees of freedom, DF(c)	+Inf
Coverage factor, k	1.96
Expanded Uncertainty, U95 (W/m²)	±2.6

Figure 2. History of instrument (Residual means of current data using historical BORCAL coefficients)

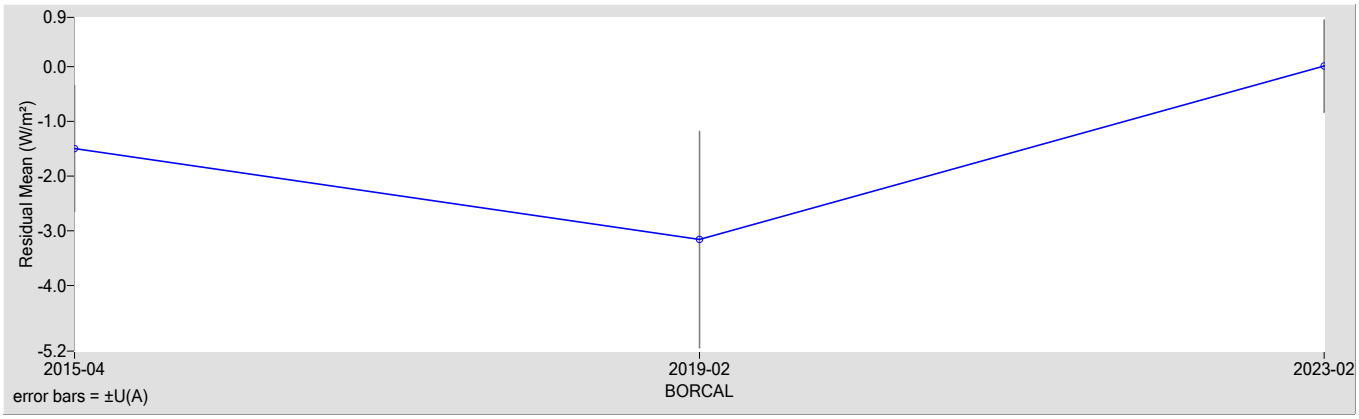


Figure 3. History of instrument (K1 Coefficient)

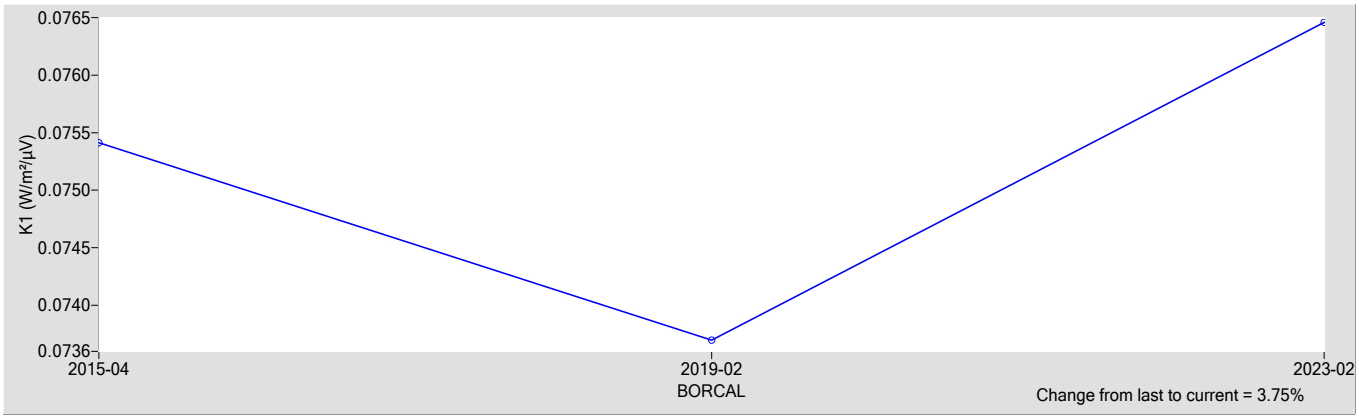
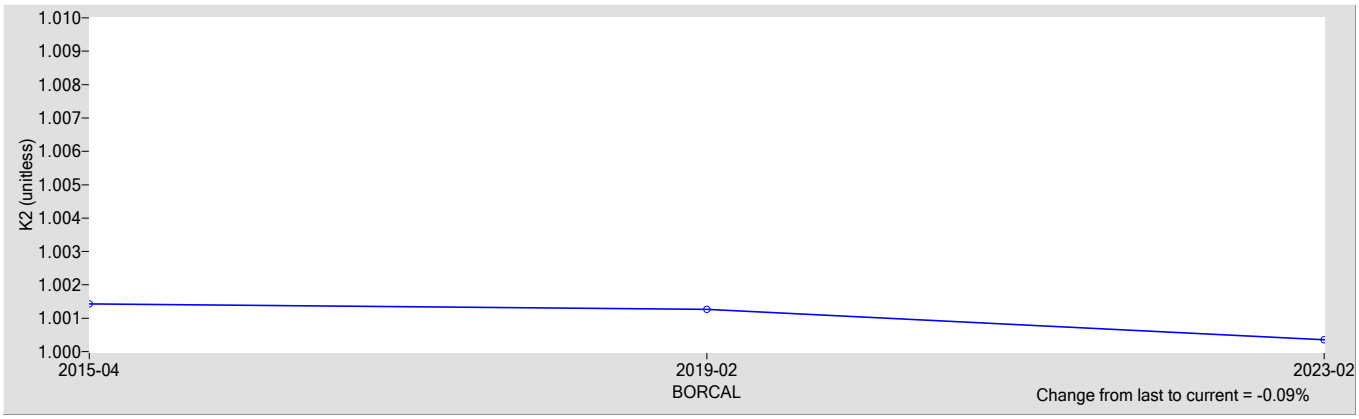


Figure 4. History of instrument (K2 Coefficient)



References:

[1] Reda, I.; Stoffel, T. (2010). Pyrgeometer Calibration for DOE-Atmospheric System Research Program using NREL Method (Presentation). 9 pp.; NREL Report No. PR-3B0-47756; http://www.nrel.gov/docs/fy10osti/47756.pdf.

National Renewable Energy Laboratory

Solar Radiation Research Laboratory

Metrology Laboratory

Calibration Certificate

Calibration CERT #1239.02

Test Instrument:	Downwelling Pyrgeometer	**Manufacturer:**	Eppley
Model:	PIR	**Serial Number:**	31193F3
Calibration Date:	7/18/2023	**Due Date:**	7/18/2025
Customer:	NREL-SRRL-BMS	**Environmental Conditions:**	see page 4
Test Dates:	6/24-30, 7/1-4, 7/6-7, 7/9-18		

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Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/08/2023	02/08/2025
Infrared Irradiance ‡	Eppley Downwelling Pyrgeometer Model PIR, S/N 32309F3	03/31/2022	03/31/2027
Infrared Irradiance ‡	Eppley Downwelling Pyrgeometer Model PIR, S/N 38520F3	03/31/2022	03/31/2027
Infrared Irradiance ‡	Kipp & Zonen Pyrgeometer Model CG4, S/N FT002	03/31/2022	03/31/2027

‡ Through the World Infrared Standard Group (WISG)

Number of pages of certificate: 4

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

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

Calibrated by: Afshin Andreas, Jaemo Yang, and Shawn Jaker

_____ _____

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

31193F3 Eppley PIR

The incoming irradiance (Win, W/m²) of the test instrument during calibration is calculated using this Measurement Equation:

$$Win = K1*V + K2*Wr + K3*(Wd - Wr) \quad [1]$$

where,

K1,K2,K3 = calibration coefficeints,
V = thermopile output voltage (μV),
$Wd = \sigma * Td^4$ = dome irradiance (W/m²),
where, *Td* = dome temperature (K),

$Wr = \sigma * Tr^4$ = receiver irradiance (W/m²),
where, σ = 5.6704e-8 W·m-2·K-4,
$Tr = Tc + Kr * V$ = receiver temperature (K),
Tc = case temperature (K),
Kr = efficiency coefficient (K/μV).

Figure 1. Residuals for calculated using coefficients vs reference irradiance

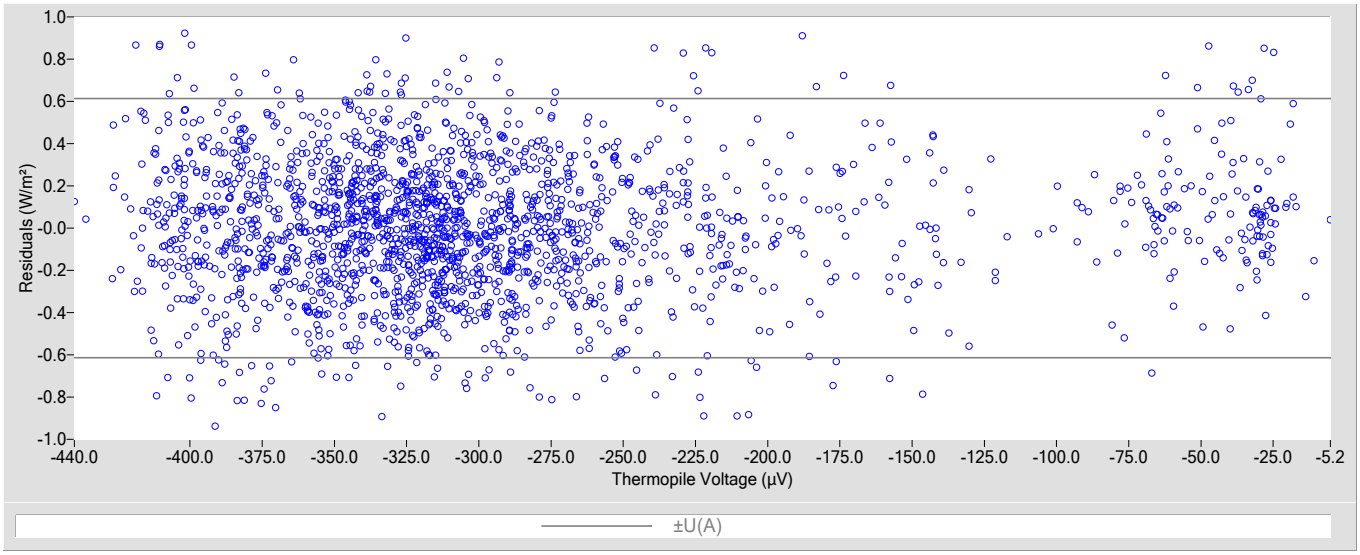


Table 1. Calibration Coefficients

K1	0.27344
K2	0.9990
K3	-3.52
Kr used to derive coefficients	7.044e-4

Table 2. Uncertainty using coefficients

Type-B Standard Uncertainty, u(B) (W/m²)	±1.3
Type-A Standard Uncertainty, u(A) (W/m²)	±0.31
Combined Standard Uncertainty, u(c) (W/m²)	±1.3
Effective degrees of freedom, DF(c)	+Inf
Coverage factor, k	1.96
Expanded Uncertainty, U95 (W/m²)	±2.5

Figure 2. History of instrument (Residual means of current data using historical BORCAL coefficients)

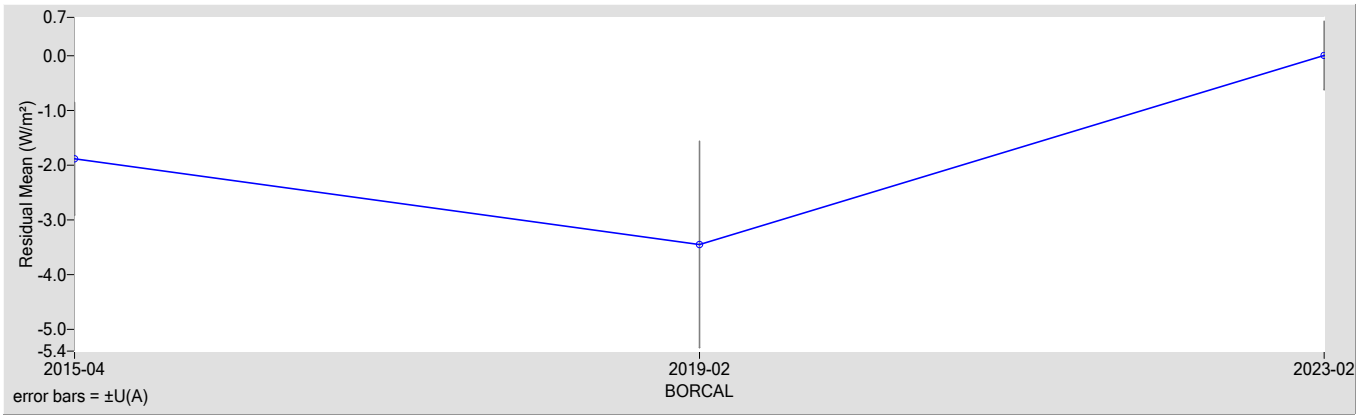


Figure 3. History of instrument (K1 Coefficient)

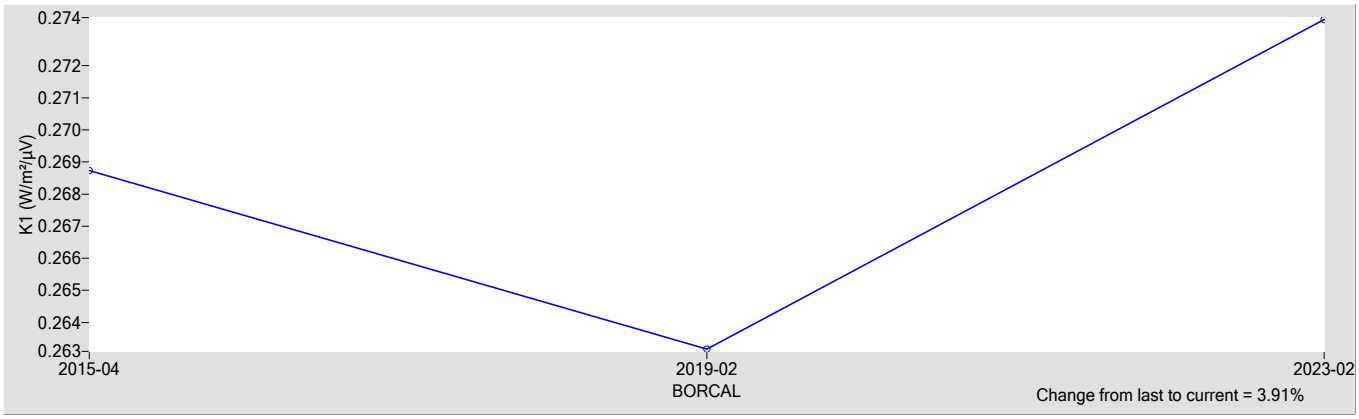


Figure 4. History of instrument (K2 Coefficient)

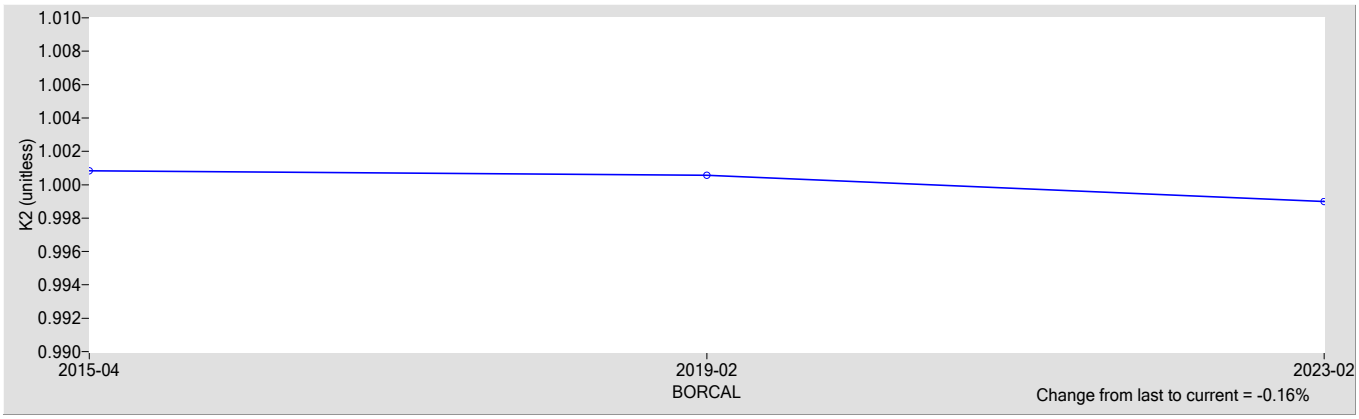
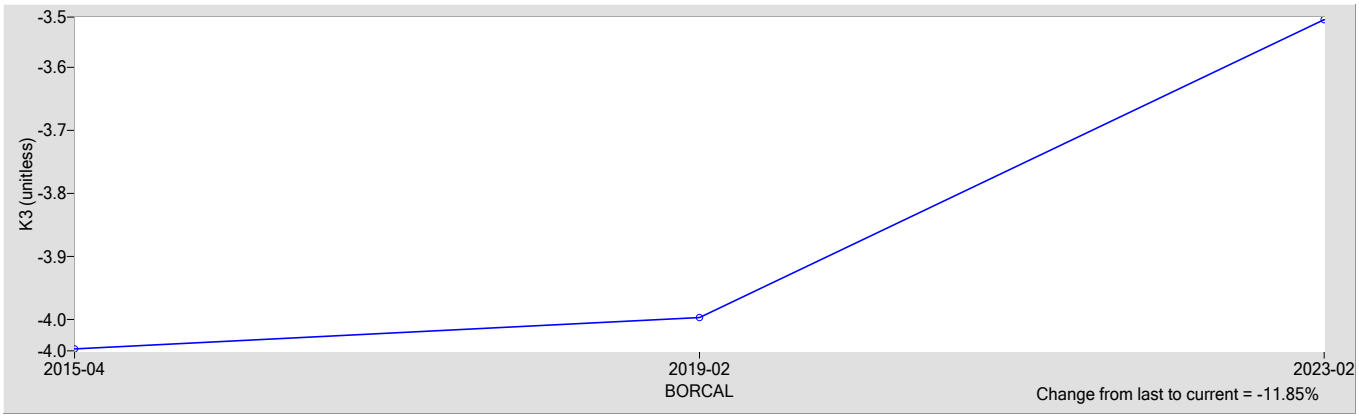


Figure 5. History of instrument (K3 Coefficient)



References:

[1] Reda, I.; Stoffel, T. (2010). Pyrgeometer Calibration for DOE-Atmospheric System Research Program using NREL Method (Presentation). 9 pp.; NREL Report No. PR-3B0-47756; http://www.nrel.gov/docs/fy10osti/47756.pdf.

National Renewable Energy Laboratory

Solar Radiation Research Laboratory

Metrology Laboratory

Calibration Certificate

Calibration CERT #1239.02

Test Instrument:	Downwelling Pyrgeometer	**Manufacturer:**	Eppley
Model:	PIR	**Serial Number:**	31198F3
Calibration Date:	7/18/2023	**Due Date:**	7/18/2025
Customer:	NREL-SRRL-BMS	**Environmental Conditions:**	see page 4
Test Dates:	6/24-30, 7/1-4, 7/6-7, 7/9-18		

This certifies that the above product was calibrated in compliance with ISO/IEC 17025:2017. Measurement uncertainties at the time of calibration are consistent with the Guide to the Expression of Uncertainty in Measurement (GUM) using Reda et al., 2008. All nominal values are traceable to the World Infrared Standard Group (WISG).

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Measurement Type	Instrument	Calibration Date	Calibration Due Date
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	02/03/2023	02/03/2025
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/08/2023	02/08/2025
Infrared Irradiance ‡	Eppley Downwelling Pyrgeometer Model PIR, S/N 32309F3	03/31/2022	03/31/2027
Infrared Irradiance ‡	Eppley Downwelling Pyrgeometer Model PIR, S/N 38520F3	03/31/2022	03/31/2027
Infrared Irradiance ‡	Kipp & Zonen Pyrgeometer Model CG4, S/N FT002	03/31/2022	03/31/2027

‡ Through the World Infrared Standard Group (WISG)

Number of pages of certificate: 4

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

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

Calibrated by: Afshin Andreas, Jaemo Yang, and Shawn Jaker

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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

31198F3 Eppley PIR

The incoming irradiance (Win, W/m²) of the test instrument during calibration is calculated using this Measurement Equation:

$$Win = K1*V + K2*Wr + K3*(Wd - Wr) \quad [1]$$

where,

K1,K2,K3 = calibration coefficeints,
V = thermopile output voltage (μV),
$Wd = \sigma * Td^4$ = dome irradiance (W/m²),
where, *Td* = dome temperature (K),

$Wr = \sigma * Tr^4$ = receiver irradiance (W/m²),
where, σ = 5.6704e-8 W·m-2·K-4,
$Tr = Tc + Kr * V$ = receiver temperature (K),
Tc = case temperature (K),
Kr = efficiency coefficient (K/μV).

Figure 1. Residuals for calculated using coefficients vs reference irradiance

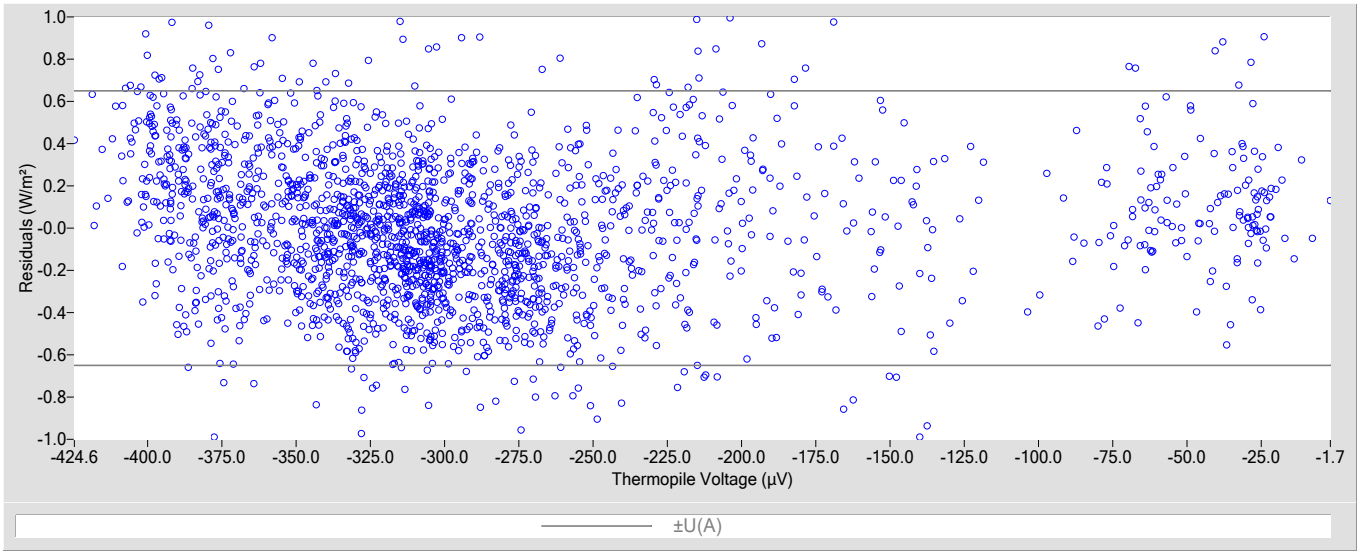


Table 1. Calibration Coefficients

K1	0.27188
K2	0.9959
K3	-3.70
Kr used to derive coefficients	7.044e-4

Table 2. Uncertainty using coefficients

Type-B Standard Uncertainty, u(B) (W/m²)	±1.3
Type-A Standard Uncertainty, u(A) (W/m²)	±0.33
Combined Standard Uncertainty, u(c) (W/m²)	±1.3
Effective degrees of freedom, DF(c)	+Inf
Coverage factor, k	1.96
Expanded Uncertainty, U95 (W/m²)	±2.5

Figure 2. History of instrument (Residual means of current data using historical BORCAL coefficients)

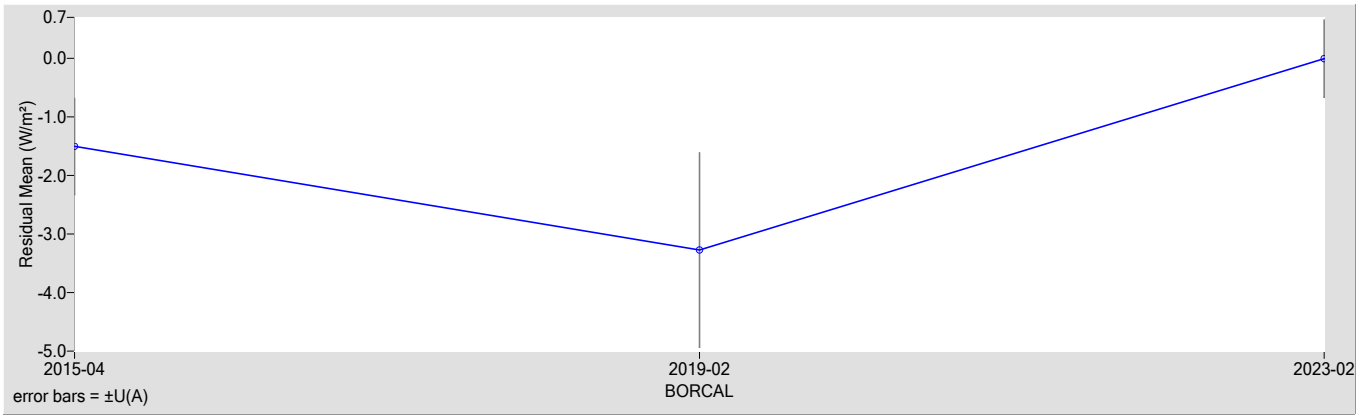


Figure 3. History of instrument (K1 Coefficient)

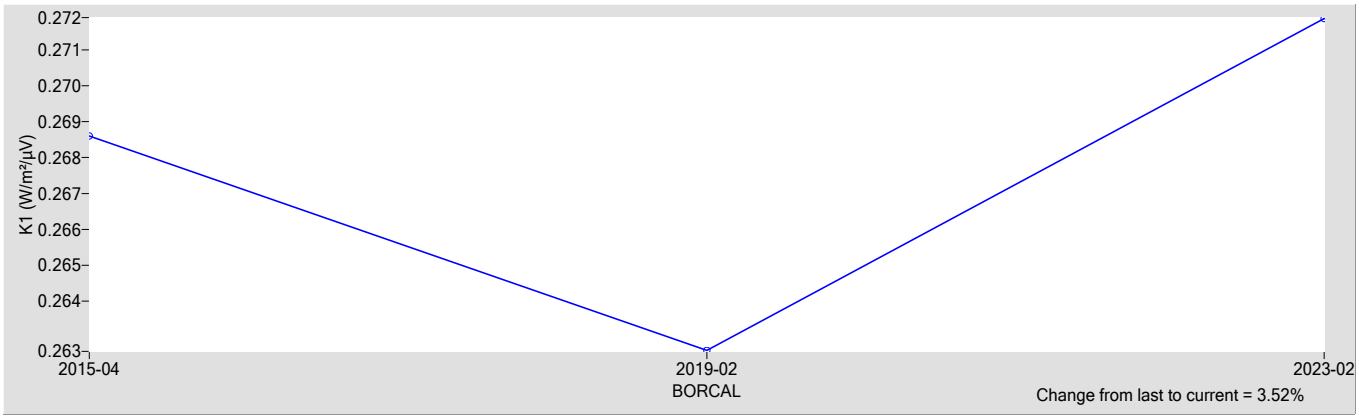


Figure 4. History of instrument (K2 Coefficient)

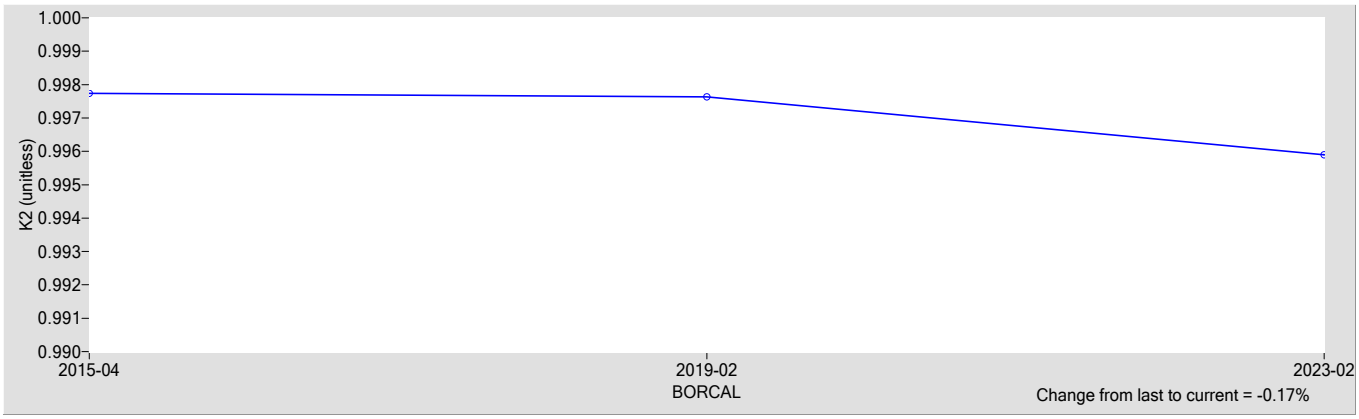
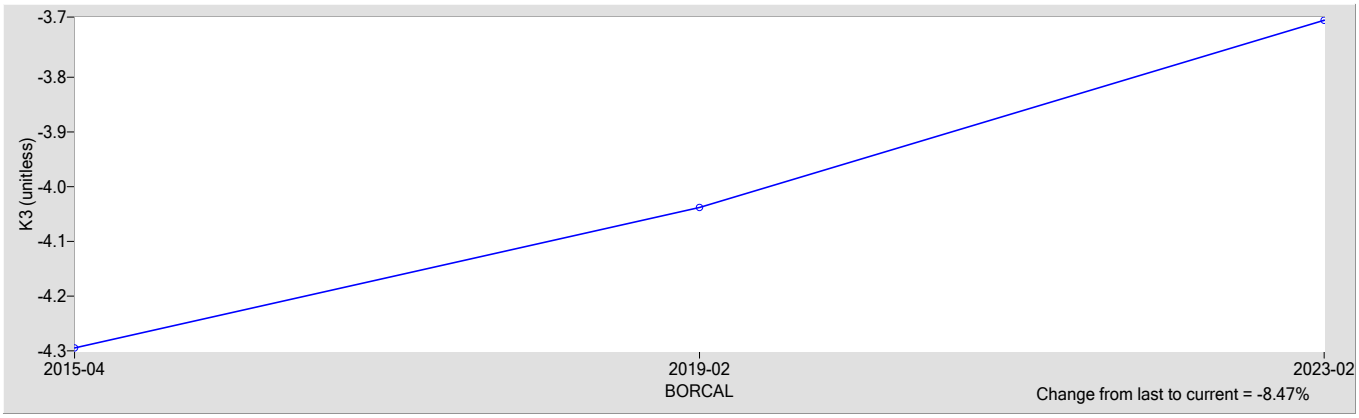


Figure 5. History of instrument (K3 Coefficient)



References:

[1] Reda, I.; Stoffel, T. (2010). Pyrgeometer Calibration for DOE-Atmospheric System Research Program using NREL Method (Presentation). 9 pp.; NREL Report No. PR-3B0-47756; http://www.nrel.gov/docs/fy10osti/47756.pdf.

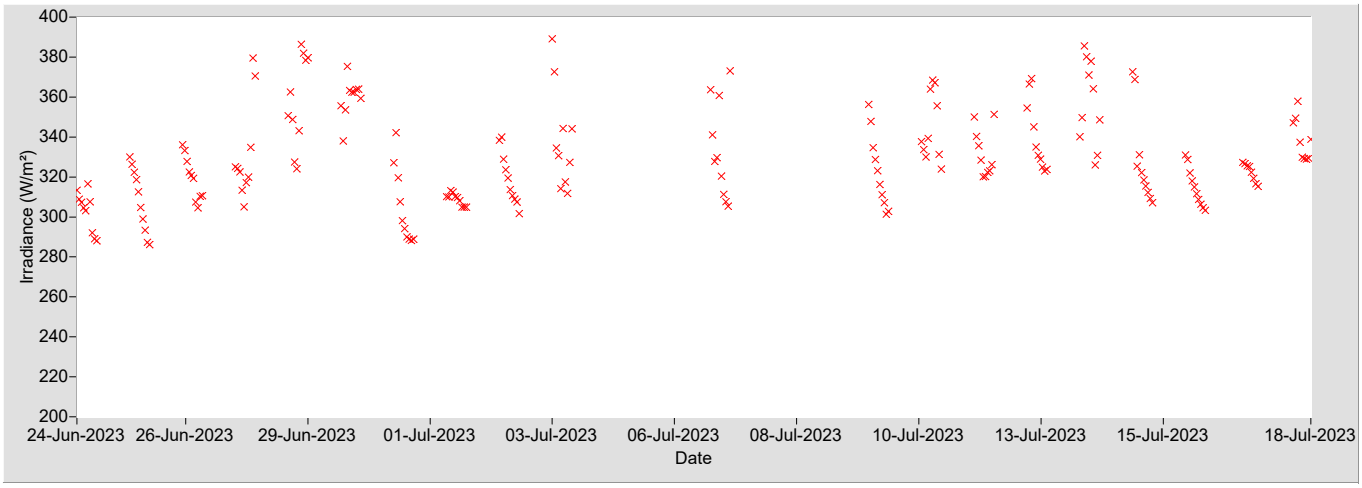
Environmental and Sky Conditions for BORCAL-LW 2023-02

Calibration Facility: Solar Radiation Research Laboratory

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

Reference Irradiance (hourly averages):

Figure 6. Reference Irradiance



Meteorological Observations (hourly averages):

Figure 7. Temperature

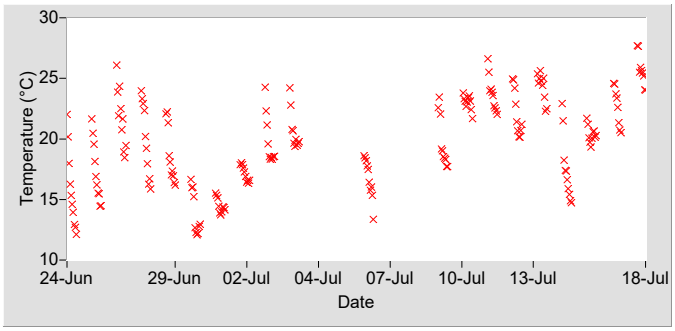


Figure 8. Humidity

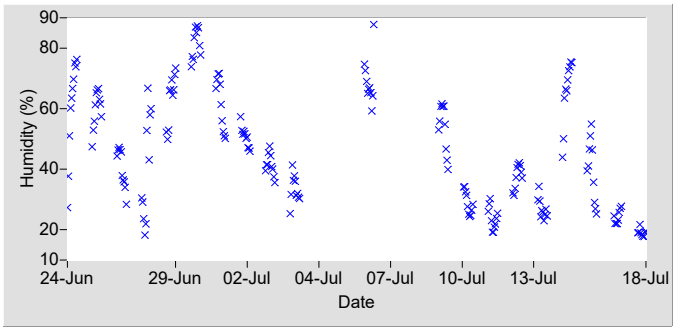


Figure 9. Pressure

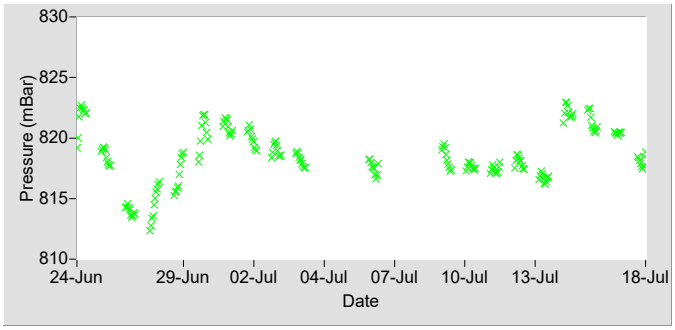


Figure 10. Estimated Precipitable Water Vapor (PWV)

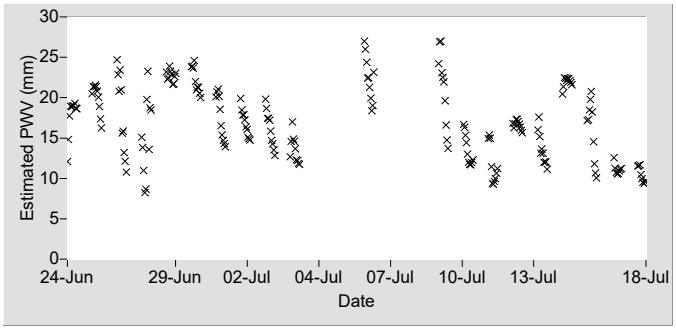


Table 6. Meteorological Observations

Observations	Mean	Min	Max
Temperature (°C)	19.55	11.95	27.96
Humidity (%)	46.73	16.21	94.38
Pressure (mBar)	818.6	812.4	823.1
Est. Precipitable Water Vapor (mm)	16.9	7.2	30.5

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).

010284-UW-CG3 Kipp & Zonen CG3
Comments:
Retro-fitted from CNR1