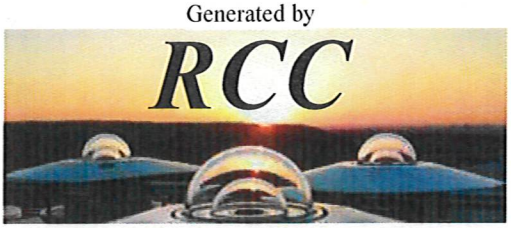
# Broadband Outdoor Radiometer Calibration
# Longwave

# BORCAL-LW
# 2024-01

Generated by




*Radiometer Calibration and Characterization*

Customer

Bryan Fabbri

Organization: NASA Langley Research Center
Address: Bldg. 1298/Room 147, Hampton, VA 23681 USA
Phone: 757-951-1639

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
02/19/2024 to 03/25/2024

Report Date
March 27, 2024

NREL

## NOTICE

# 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 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)**

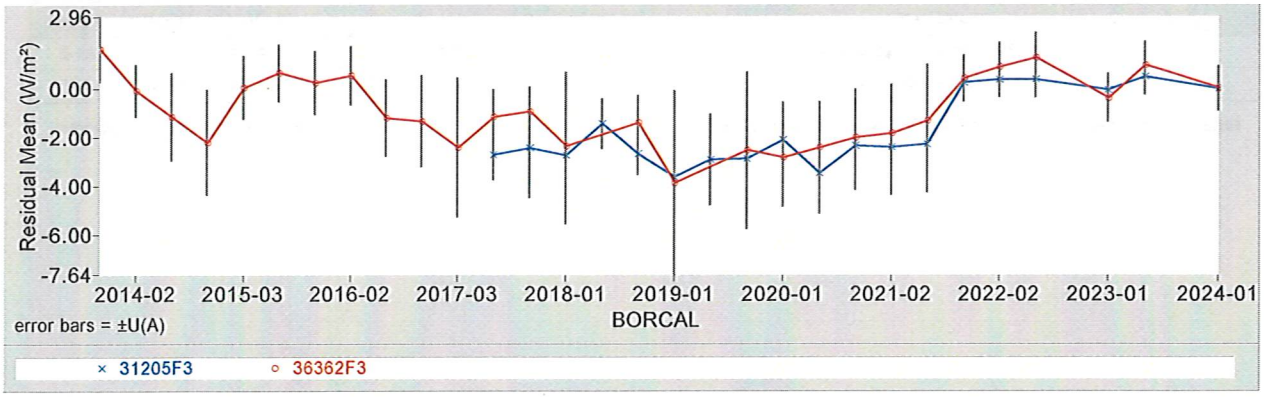



**Figure 2. Eppley PIR Control Instrument History (K1 Coefficient)**

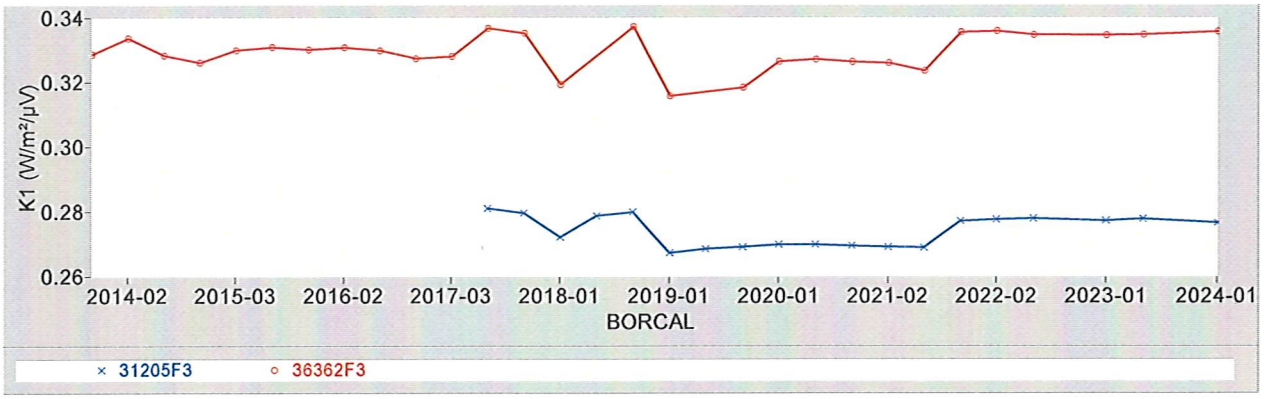



**Figure 3. Eppley PIR Control Instrument History (K2 Coefficient)**

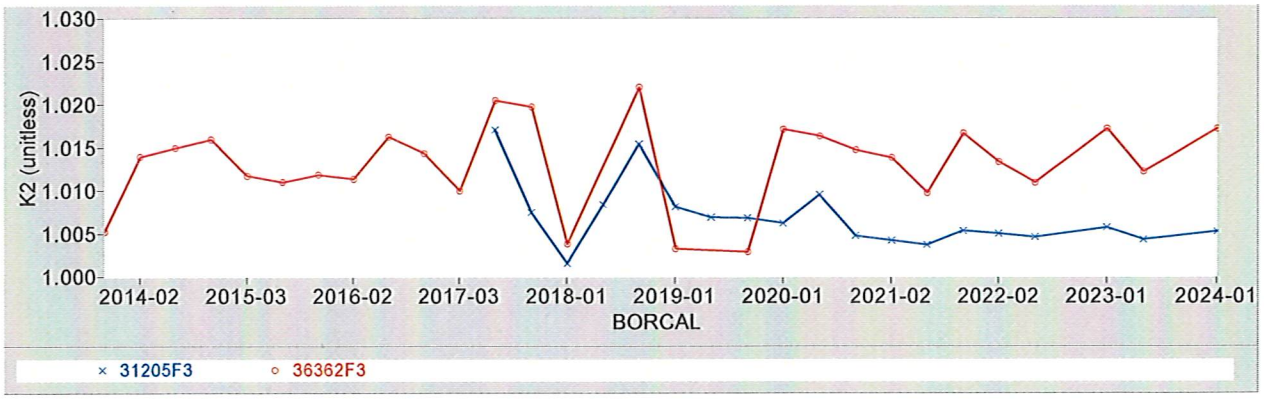
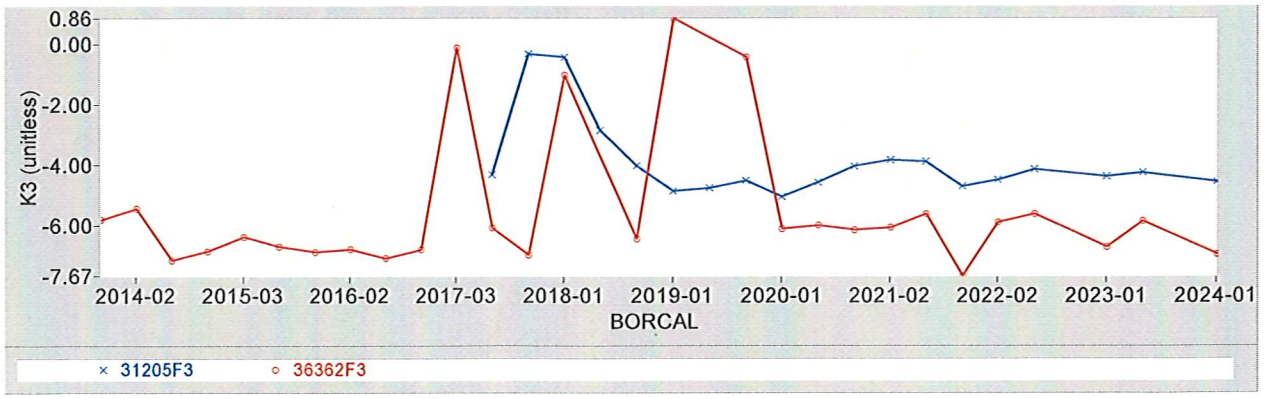



**Figure 4. Eppley PIR Control Instrument History (K3 Coefficient)**



# Results Summary

**Table 1. Results Summary**

| Instrument | K1 (W/m²/µV) | K2 | K3 | Kr * (K/µV) | U95 (W/m²) | Page |
|---|---|---|---|---|---|---|
| 180289 Kipp & Zonen CGR4 | 0.10194 | 0.9984 | 0.00 | 7.044e-4 | ±2.9 | A1-2 |
| 33974F3 Eppley PIR | 0.28300 | 1.0031 | -7.47 | 7.044e-4 | ±2.6 | A1-5 |

Note: Environmental Conditions for BORCAL starts on page A1-8.

* 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

NREL

ACCREDITED
Calibration CERT #1239.02

| | | | |
|---|---|---|---|
| **Test Instrument:** | Pyrgeometer | **Manufacturer:** | Kipp & Zonen |
| **Model:** | CGR4 | **Serial Number:** | 180289 |
| **Calibration Date:** | 3/25/2024 | **Due Date:** | 3/25/2027 |
| **Customer:** | Bryan Fabbri | **Environmental Conditions:** | see page 4 |
| **Test Dates:** | 2/19-29, 3/1-7, 3/9-12, 3/16-25 | | |

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 | 02/03/2023 | 02/03/2025 |
| 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 and Shawn Jaker

Ibrahim Reda, Technical Manager — Date: 4/1/24

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

## 180289 Kipp & Zonen CGR4

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, $\sigma$ = 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**

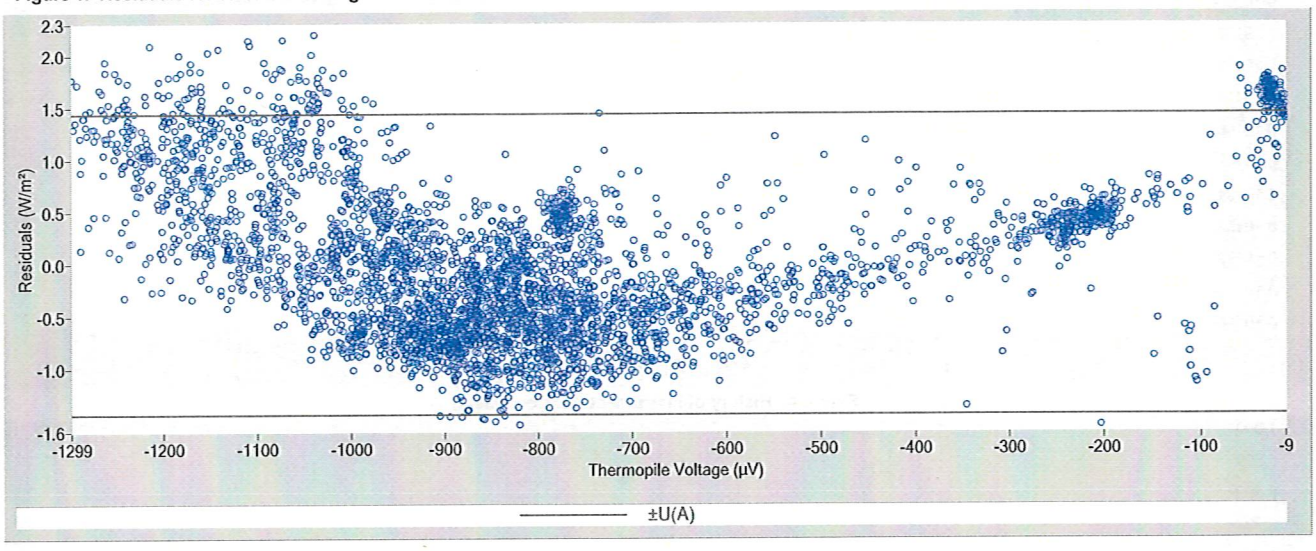



**Table 1. Calibration Coefficients**

| | |
|---|---|
| K1 | 0.10194 |
| K2 | 0.9984 |
| 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) | ±0.73 |
| Combined Standard Uncertainty, u(c) (W/m²) | ±1.5 |
| Effective degrees of freedom, DF(c) | +Inf |
| Coverage factor, k | 1.96 |
| Expanded Uncertainty, U95 (W/m²) | ±2.9 |

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

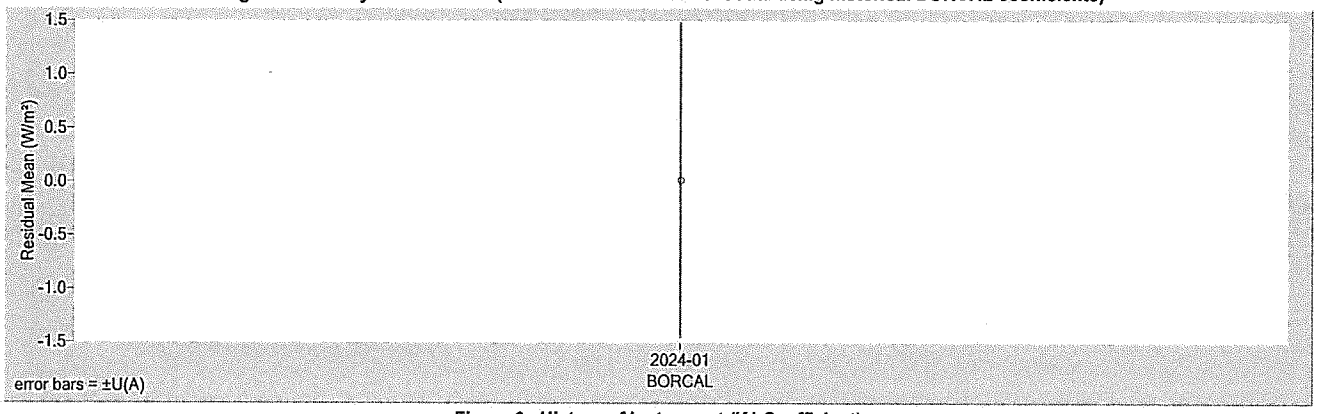



Figure 3. History of instrument (K1 Coefficient)

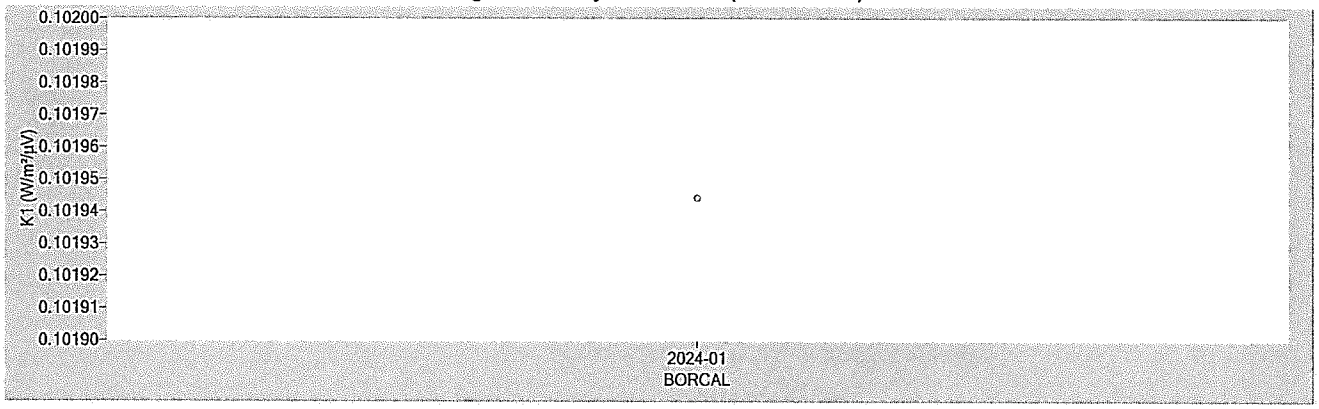
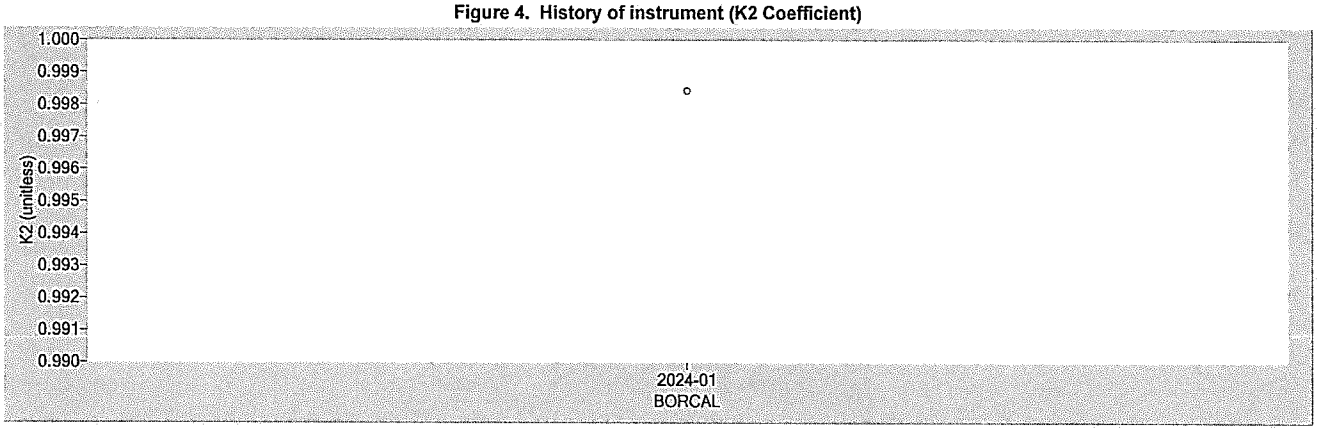



Figure 4. History of instrument (K2 Coefficient)




## 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

NREL

ACCREDITED
Calibration CERT #1239.02

| | | | |
|---|---|---|---|
| **Test Instrument:** | Downwelling Pyrgeometer | **Manufacturer:** | Eppley |
| **Model:** | PIR | **Serial Number:** | 33974F3 |
| **Calibration Date:** | 3/25/2024 | **Due Date:** | 3/25/2027 |
| **Customer:** | Bryan Fabbri | **Environmental Conditions:** | see page 4 |
| **Test Dates:** | 2/19-29, 3/1-7, 3/9-12, 3/16-25 | | |

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 | 02/03/2023 | 02/03/2025 |
| 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 and Shawn Jaker

R. J.

Ibrahim Reda, Technical Manager

4/1/24

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

## 33974F3 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),
$Wd = \sigma * Td\text{^}4$ = dome irradiance (W/m²),
where, $Td$ = dome temperature (K),

$Wr = \sigma * Tr\text{^}4$ = receiver irradiance (W/m²),
where, $\sigma$ = 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**

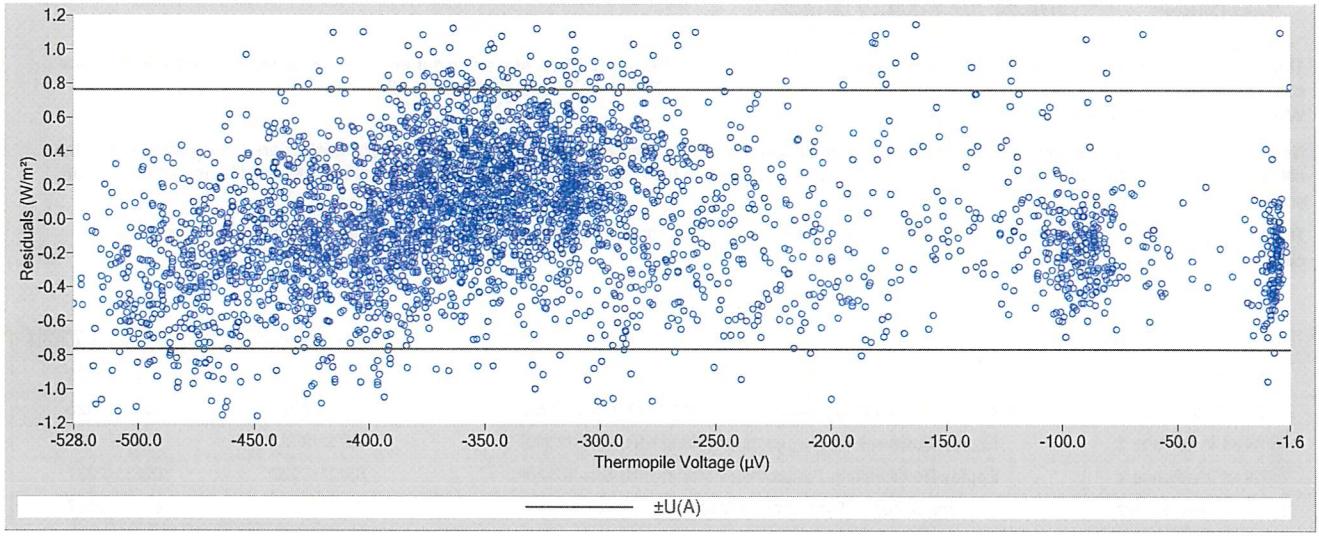



**Table 1. Calibration Coefficients**

| | |
|---|---|
| K1 | 0.28300 |
| K2 | 1.0031 |
| K3 | -7.47 |
| 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) | ±0.39 |
| 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)

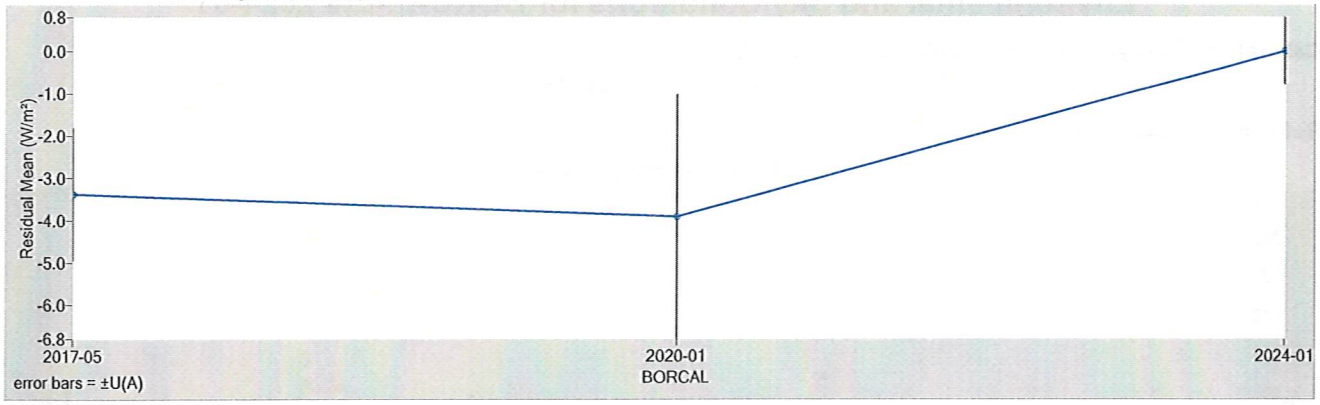



Figure 3. History of instrument (K1 Coefficient)

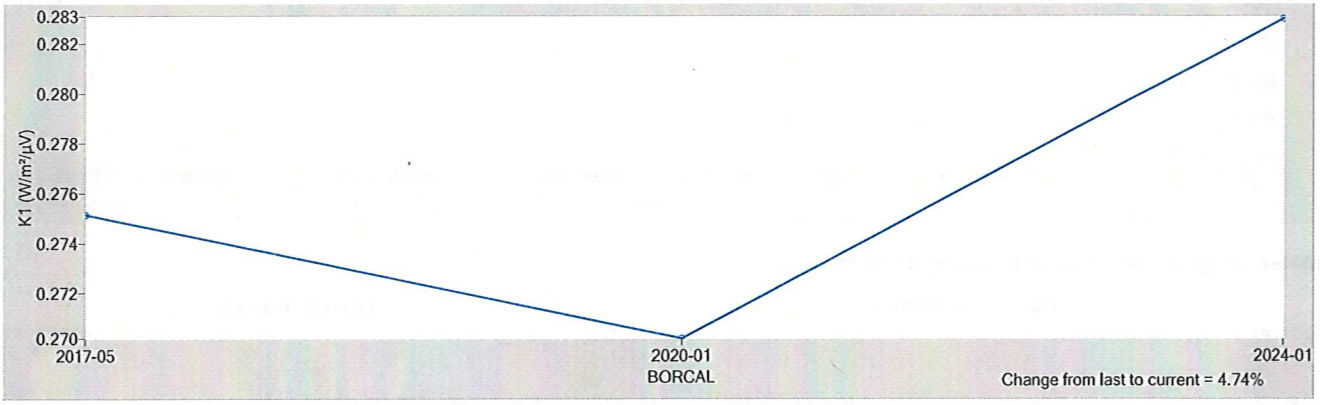



Figure 4. History of instrument (K2 Coefficient)

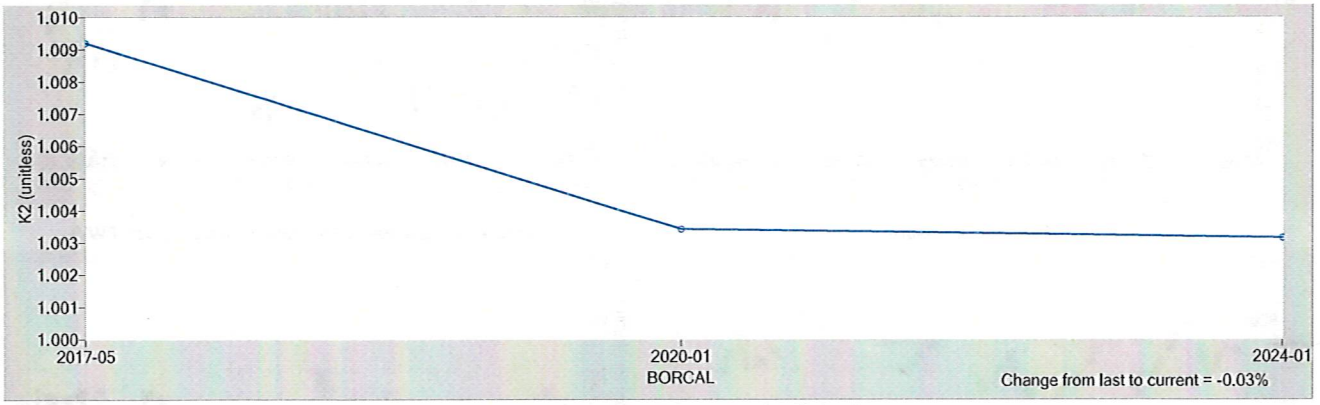
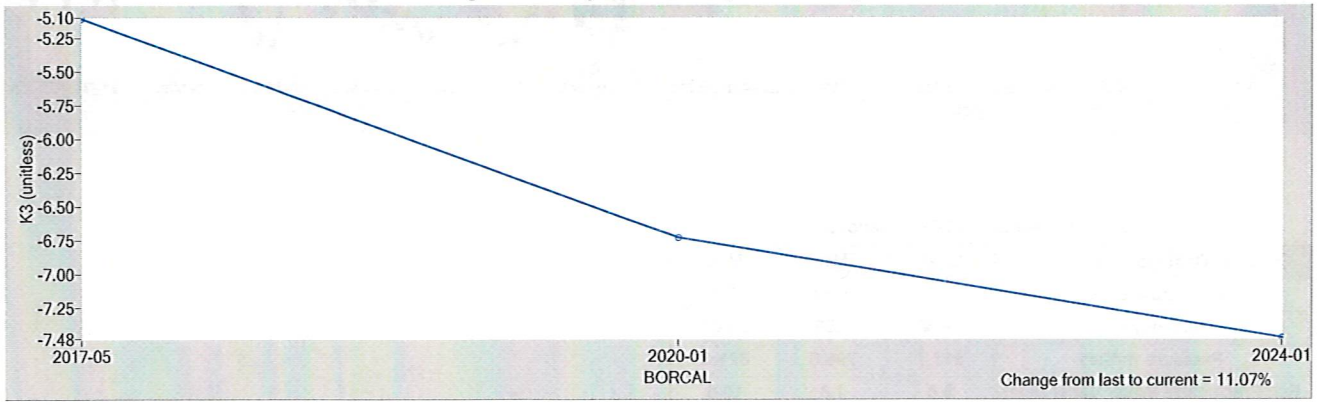



Figure 5. History of instrument (K3 Coefficient)




## 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.

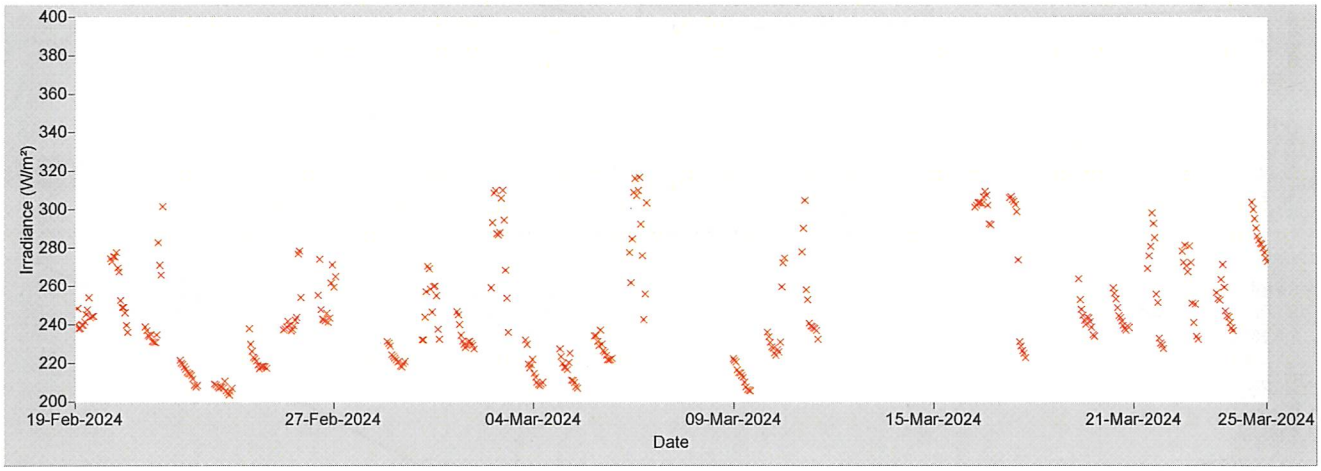
# Environmental and Sky Conditions for BORCAL-LW 2024-01

**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**

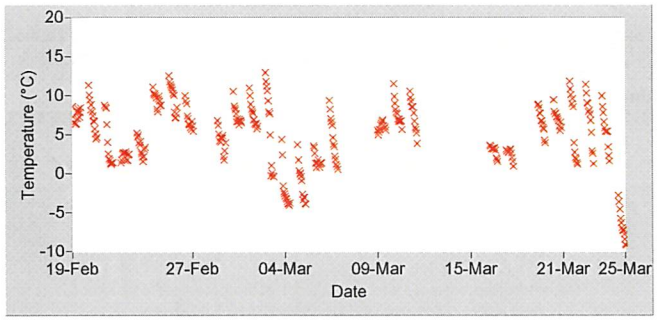



**Figure 8. Humidity**

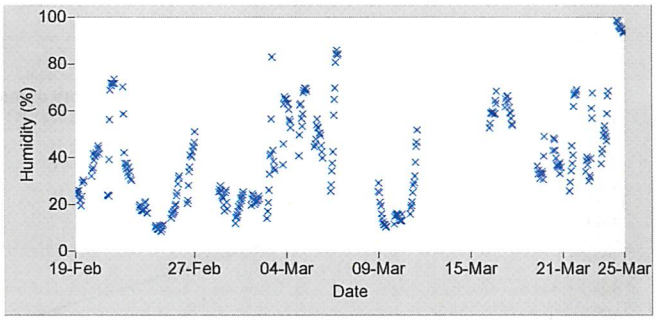



**Figure 9. Pressure**

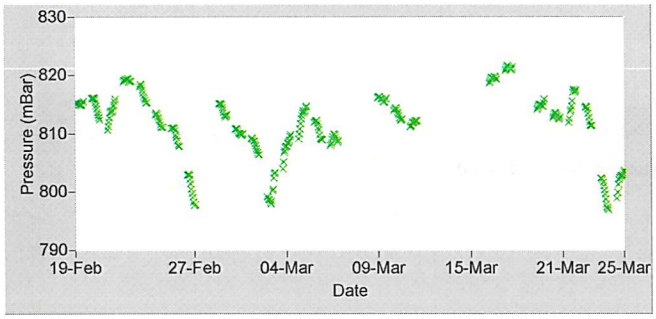



**Figure 10. Estimated Precipitable Water Vapor (PWV)**

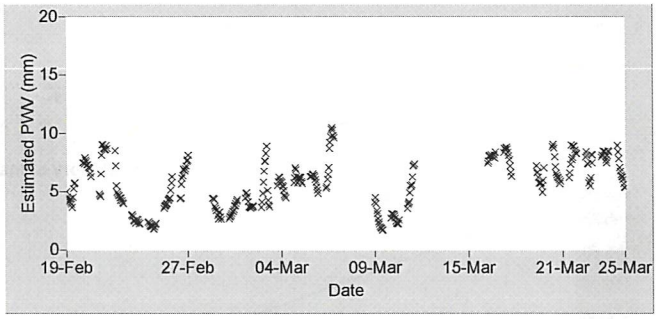



**Table 6. Meteorological Observations**

| Observations | Mean | Min | Max |
|---|---|---|---|
| Temperature (°C) | 4.89 | -9.34 | 13.35 |
| Humidity (%) | 39.58 | 7.59 | 99.01 |
| Pressure (mBar) | 811.7 | 796.9 | 821.8 |
| Est. Precipitable Water Vapor (mm) | 5.6 | 1.6 | 10.6 |

For other information about the calibration facility visit: https://www.nrel.gov/grid/solar-radiation-research-laboratory.html

# Appendix 2
# BORCAL Notes

Instrument, Configuration, and Session Notes for the BORCAL

# BORCAL Notes

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