Broadband Outdoor Radiometer Calibration Longwave

BORCAL-LW 2017-02

<u>Customer</u>

Craig Webb

Organization: ARM CRF SGP Site

Address: 109596 Coal Rd, Billings, OK 74630

Phone: 580-388-4053

<u>Calibration Facility</u>

Solar Radiation Research Laboratory

Latitude: 39.742°N

Longitude: 105.180°W

Elevation: 1828.8 meters AMSL

Time Zone: -7.0

Calibration date

04/25/2017 to 05/08/2017

Report Date

May 9, 2017

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 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 PIR Control Instrument History (K0 Coefficient)

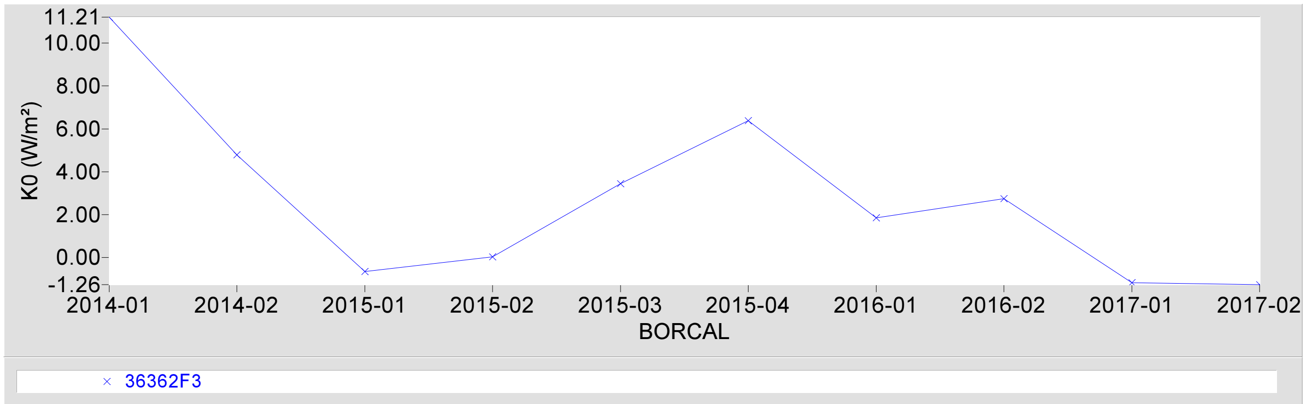


Figure 2. Eppley PIR Control Instrument History (K1 Coefficient)

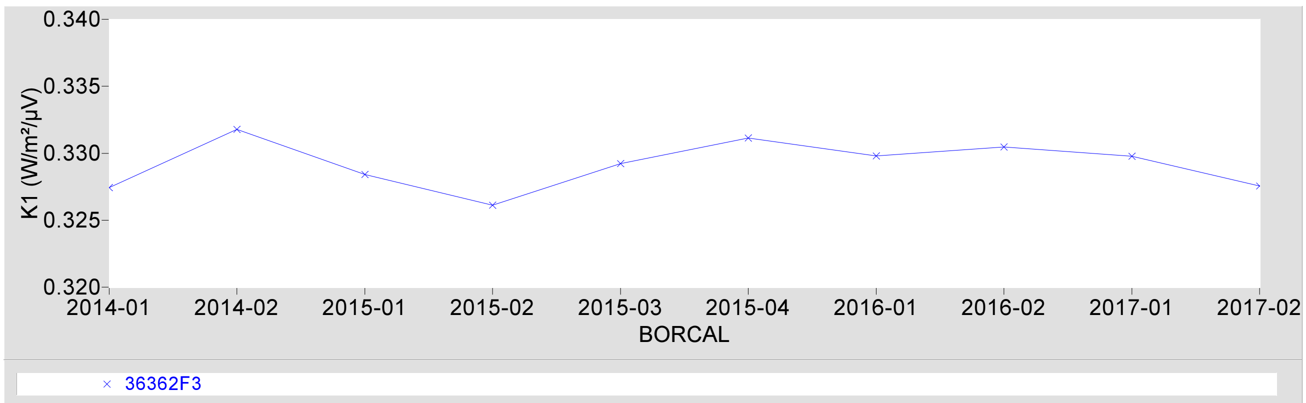


Figure 3. Eppley PIR Control Instrument History (K2 Coefficient)

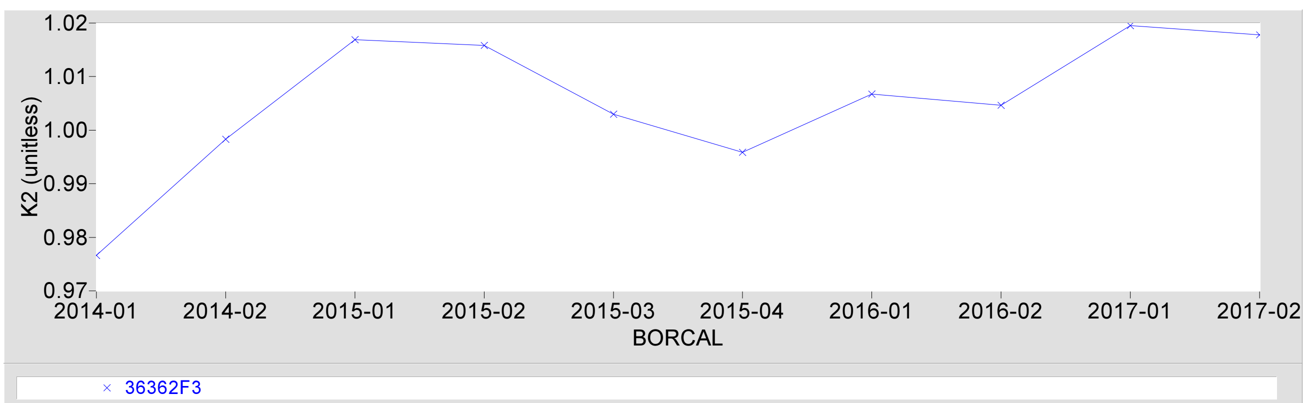
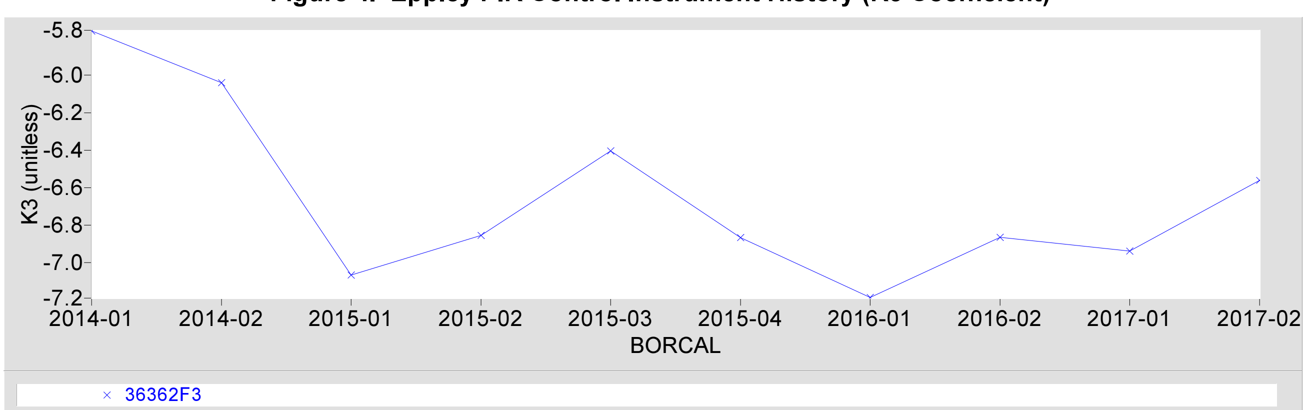


Figure 4. Eppley PIR Control Instrument History (K3 Coefficient)



Results Summary

Table 1. Results Summary

Instrument	K0 (W/m²)	K1 (W/m²/μV)	K2	K3	Kr * (K/μV)	U95 (W/m²)	Page
30020F3 Eppley PIR	-4.8711	0.25761	1.0175	1.0194	7.044e-4	±2.7	A1-2
30170F3 Eppley PIR	-5.1676	0.24040	1.0247	-3.8230	7.044e-4	±1.8	A1-5
30779F3 Eppley PIR	-5.6785	0.23849	1.0222	-3.4898	7.044e-4	±1.8	A1-8
30835F3 Eppley PIR	-6.3090	0.23009	1.0206	-3.4667	7.044e-4	±1.8	A1-11

Note: Environmental Conditions for BORCAL starts on page A1-14.

* Kr used to derive K0,K1,K2, and K3

Appendix 1
Instrument Details

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

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

National Renewable Energy Laboratory
Solar Radiation Research Laboratory
Metrology Laboratory
Calibration Certificate

Test Instrument:	Downwelling Pyrgeometer	**Manufacturer:**	Eppley
Model:	PIR	**Serial Number:**	30020F3
Calibration Date:	5/8/2017	**Due Date:**	5/8/2019
Customer:	Craig Webb	**Environmental Conditions:**	see page 4
Test Dates:	4/25-30, 5/1-8		

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 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	04/12/2017	04/12/2019
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	04/12/2017	04/12/2019
Infrared Irradiance ‡	Eppley Downwelling Pyrgeometer Model PIR, S/N 30557F3	01/29/2015	01/29/2020

‡ 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

__________________________________ ________________

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

30020F3 Eppley PIR

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

$$Win = K0 + K1 * V + K2 * Wr + K3 * (Wd - Wr) \quad [1]$$

where,

- $K0, K1, K2, K3$ = 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 calc. vs ref. irradiance using K0<>0 Coefficients

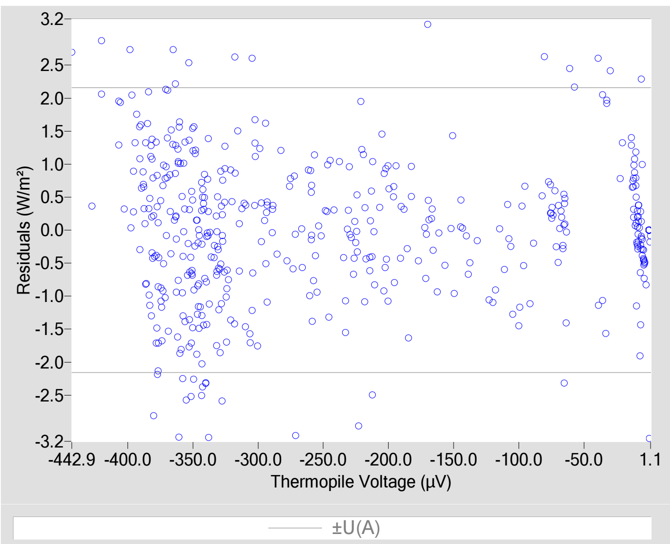


Figure 2. Residuals for calc. vs ref. irradiance using K0=0 Coefficients

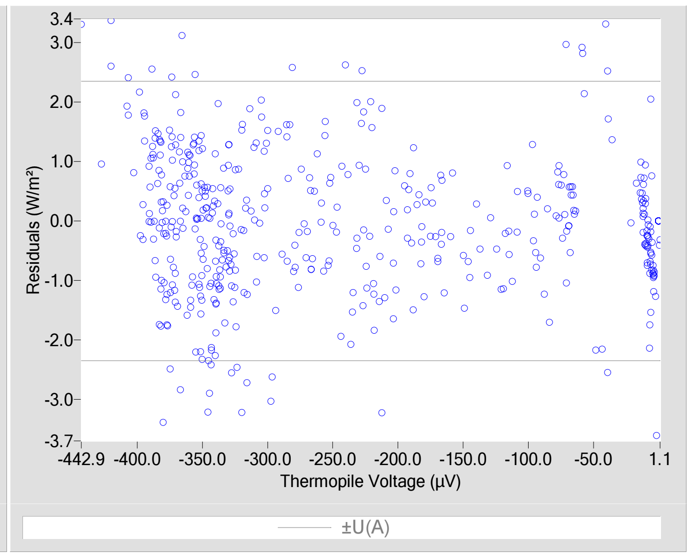


Table 2. Calibration Coefficients for K0<>0

K0	-4.8711
K1	0.25761
K2	1.0175
K3	1.0194
Kr used to derive coefficients	0.00070440

Table 3. Calibration Coefficients for K0=0

K0	0
K1	0.25646
K2	1.0028
K3	1.0011
Kr used to derive coefficients	0.00070440

Table 4. Uncertainty using K0<>0 Coefficients

Type-B Standard Uncertainty, u(B) (W/m²)	±0.87
Type-A Standard Uncertainty, u(A) (W/m²)	±1.1
Combined Standard Uncertainty, u(c) (W/m²)	±1.4
Effective degrees of freedom, DF(c)	+Inf
Coverage factor, k	1.96
Expanded Uncertainty, U95 (W/m²)	±2.7

Table 5. Uncertainty using K0=0 Coefficients

Type-B Standard Uncertainty, u(B) (W/m²)	±0.87
Type-A Standard Uncertainty, u(A) (W/m²)	±1.2
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 3. History of instrument (K0 Coefficient)

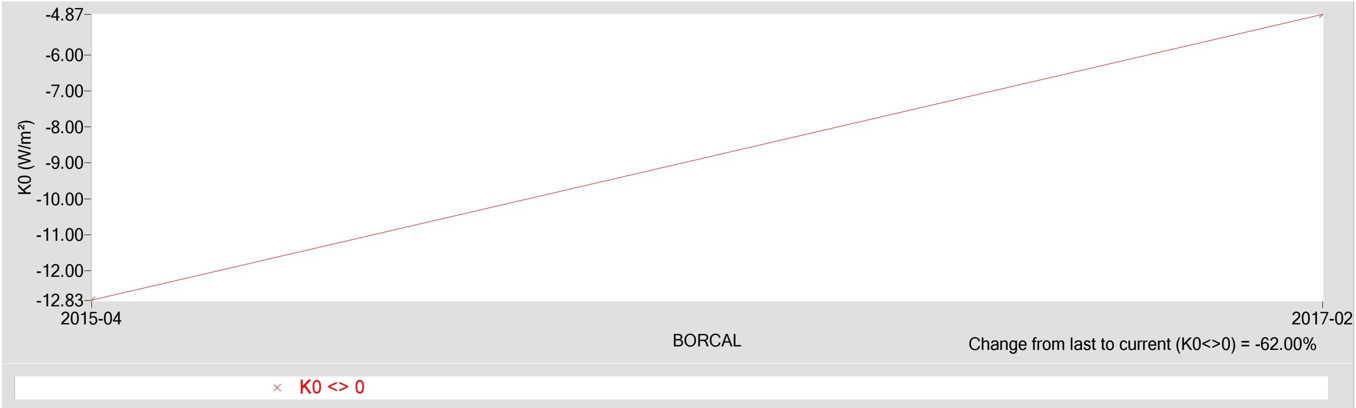


Figure 4. History of instrument (K1 Coefficient)

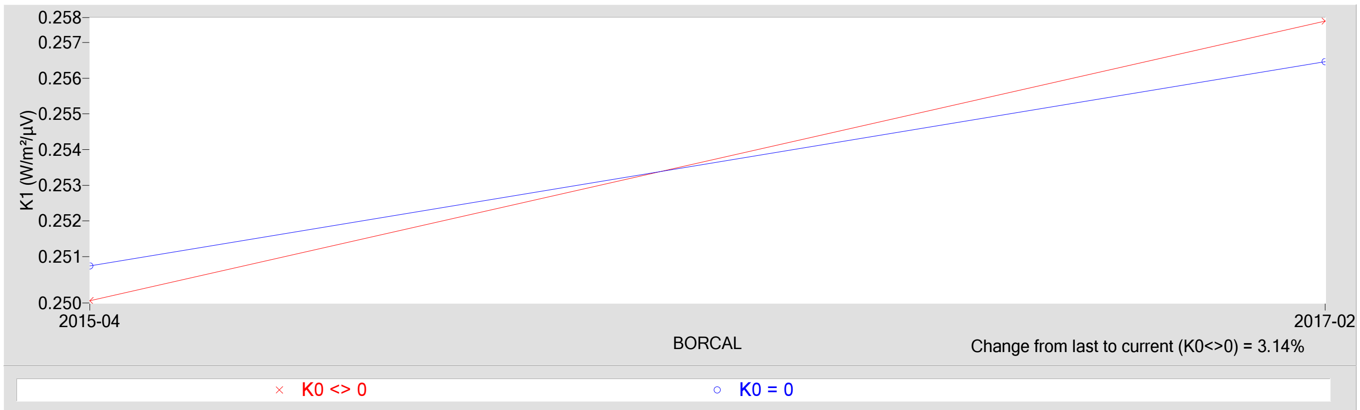


Figure 5. History of instrument (K2 Coefficient)

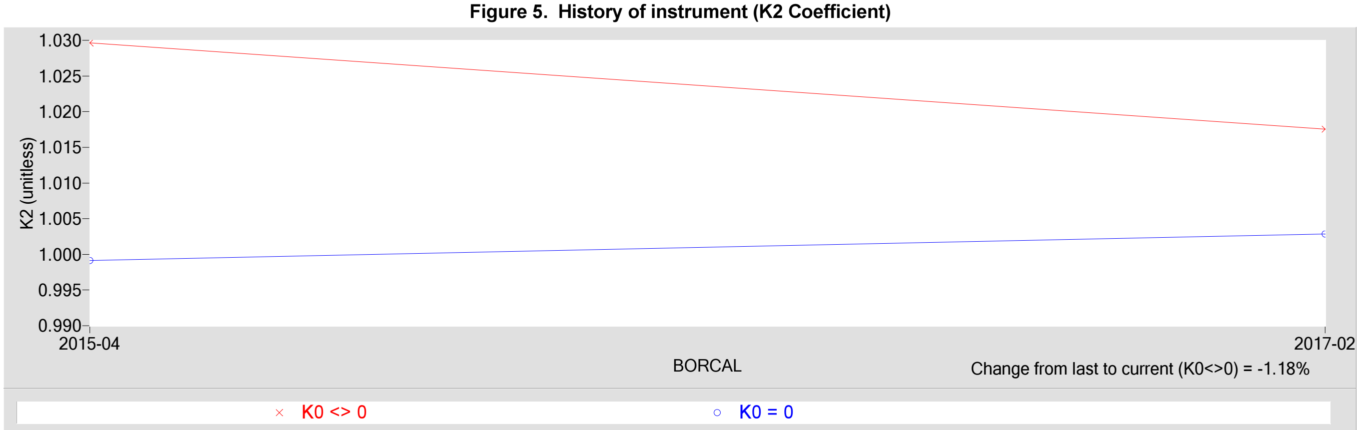
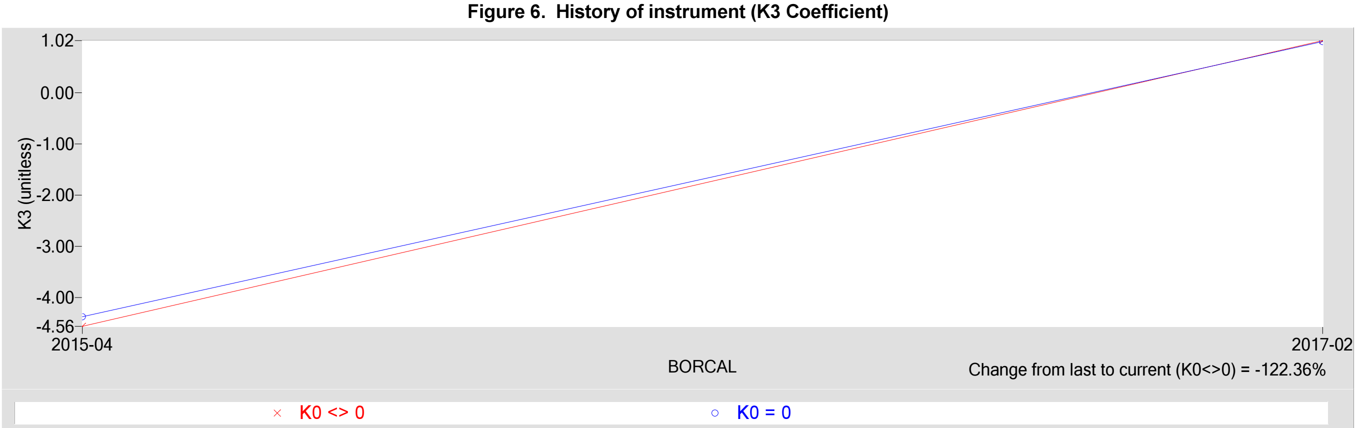


Figure 6. History of instrument (K3 Coefficient)



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

Test Instrument:	Downwelling Pyrgeometer	**Manufacturer:**	Eppley
Model:	PIR	**Serial Number:**	30170F3
Calibration Date:	5/8/2017	**Due Date:**	5/8/2019
Customer:	Craig Webb	**Environmental Conditions:**	see page 4
Test Dates:	4/25-30, 5/1-8		

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 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.

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Table 1. Traceability

Measurement Type	Instrument	Calibration Date	Calibration Due Date
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	04/12/2017	04/12/2019
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	04/12/2017	04/12/2019
Infrared Irradiance ‡	Eppley Downwelling Pyrgeometer Model PIR, S/N 30557F3	01/29/2015	01/29/2020

‡ 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

______________________________ ____________

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
30170F3 Eppley PIR

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

$$Win = K0 + K1*V + K2*Wr + K3*(Wd - Wr) \quad [1]$$

where,

K0,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 calc. vs ref. irradiance using K0<>0 Coefficients

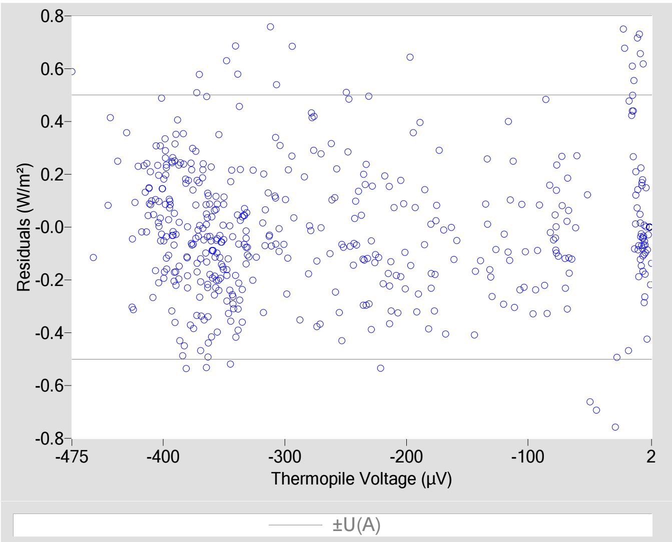


Figure 2. Residuals for calc. vs ref. irradiance using K0=0 Coefficients

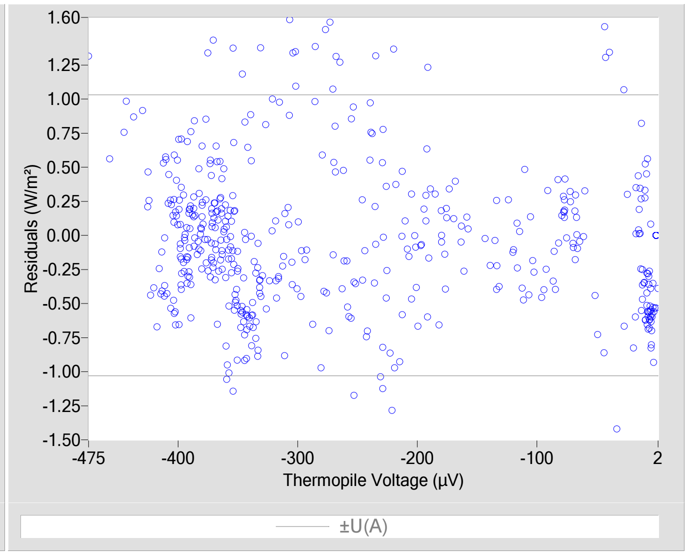


Table 2. Calibration Coefficients for K0<>0

K0	-5.1676
K1	0.24040
K2	1.0247
K3	-3.8230
Kr used to derive coefficients	0.00070440

Table 3. Calibration Coefficients for K0=0

K0	0
K1	0.23942
K2	1.0093
K3	-3.8759
Kr used to derive coefficients	0.00070440

Table 4. Uncertainty using K0<>0 Coefficients

Type-B Standard Uncertainty, u(B) (W/m²)	±0.87
Type-A Standard Uncertainty, u(A) (W/m²)	±0.26
Combined Standard Uncertainty, u(c) (W/m²)	±0.90
Effective degrees of freedom, DF(c)	+Inf
Coverage factor, k	1.96
Expanded Uncertainty, U95 (W/m²)	±1.8

Table 5. Uncertainty using K0=0 Coefficients

Type-B Standard Uncertainty, u(B) (W/m²)	±0.87
Type-A Standard Uncertainty, u(A) (W/m²)	±0.53
Combined Standard Uncertainty, u(c) (W/m²)	±1.0
Effective degrees of freedom, DF(c)	+Inf
Coverage factor, k	1.96
Expanded Uncertainty, U95 (W/m²)	±2.0

Figure 3. History of instrument (K0 Coefficient)

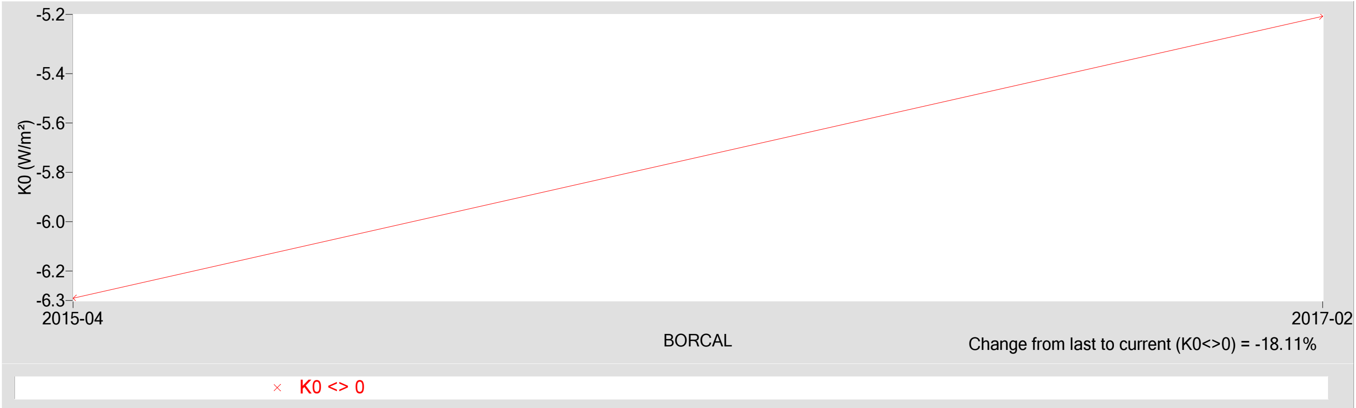


Figure 4. History of instrument (K1 Coefficient)

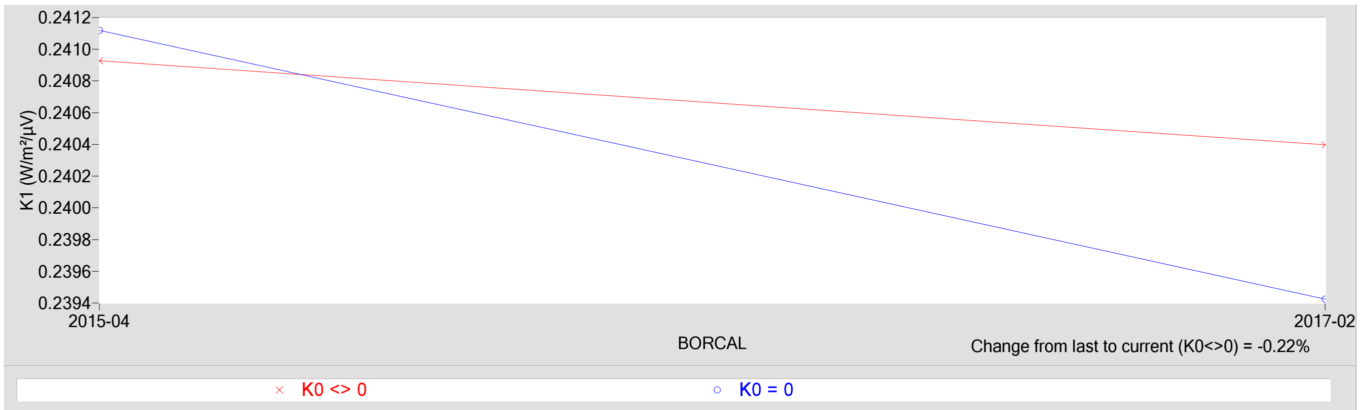


Figure 5. History of instrument (K2 Coefficient)

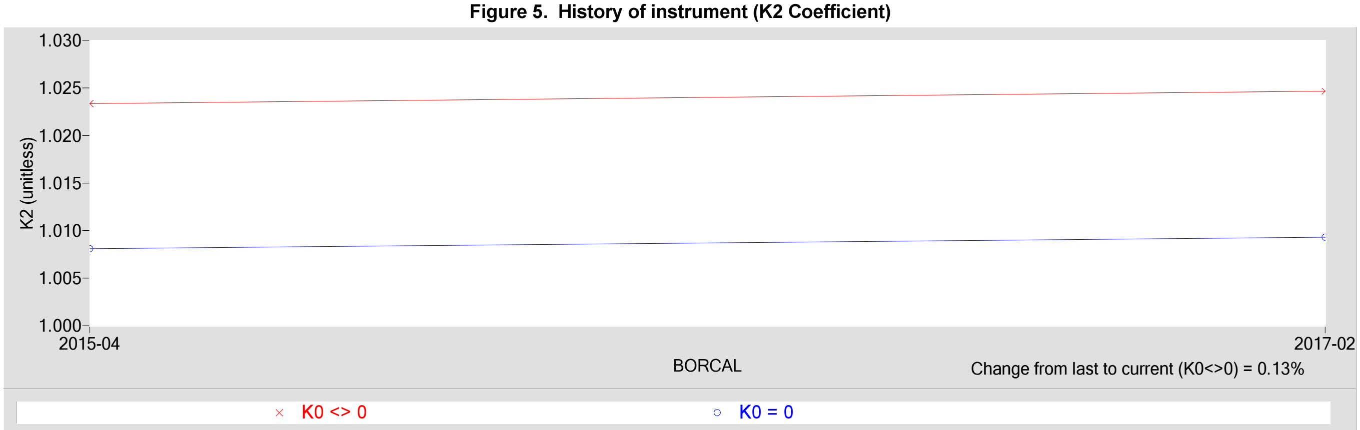
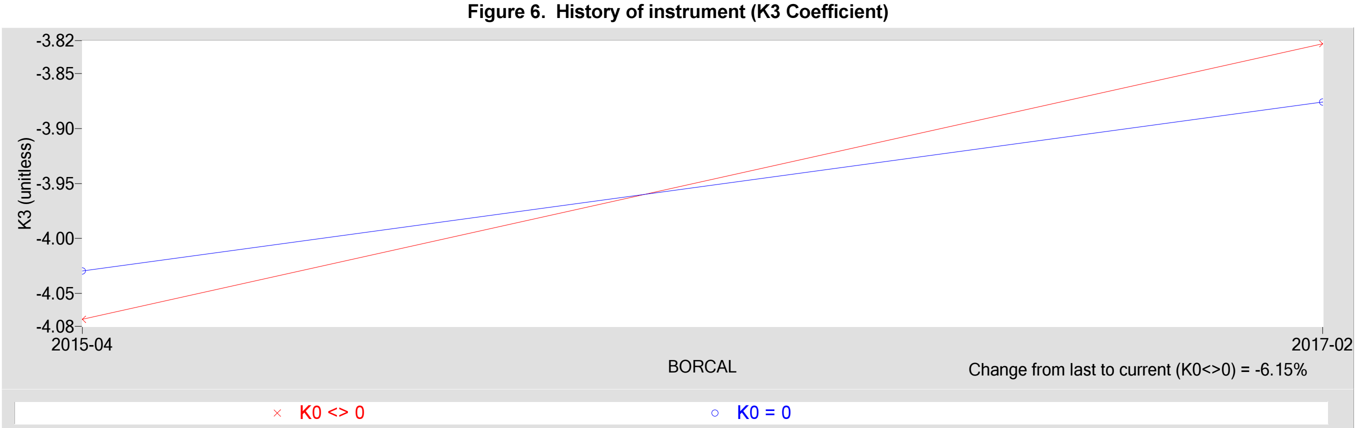


Figure 6. History of instrument (K3 Coefficient)



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

Test Instrument:	Downwelling Pyrgeometer	**Manufacturer:**	Eppley
Model:	PIR	**Serial Number:**	30779F3
Calibration Date:	5/8/2017	**Due Date:**	5/8/2019
Customer:	Craig Webb	**Environmental Conditions:**	see page 4
Test Dates:	4/25-30, 5/1-8		

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Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-998	04/12/2017	04/12/2019
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	04/12/2017	04/12/2019
Infrared Irradiance ‡	Eppley Downwelling Pyrgeometer Model PIR, S/N 30557F3	01/29/2015	01/29/2020

‡ 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

____________________________________ ________________

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

30779F3 Eppley PIR

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

*Win = K0 + K1*V + K2*Wr + K3*(Wd - Wr)* [1]

where,

K0,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 calc. vs ref. irradiance using K0<>0 Coefficients

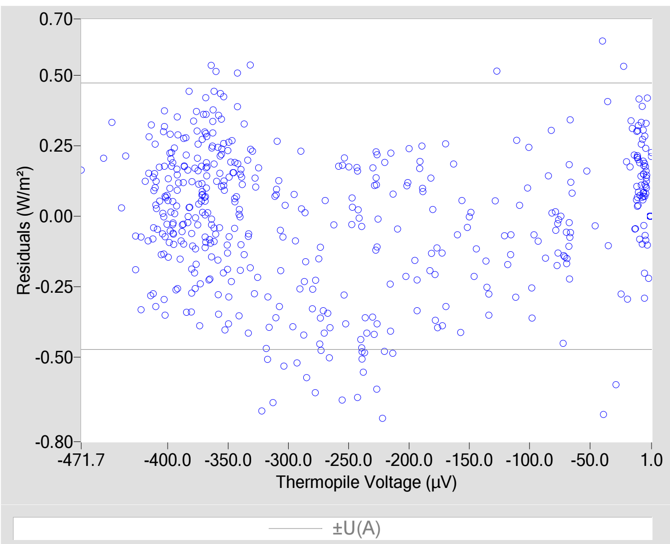


Figure 2. Residuals for calc. vs ref. irradiance using K0=0 Coefficients

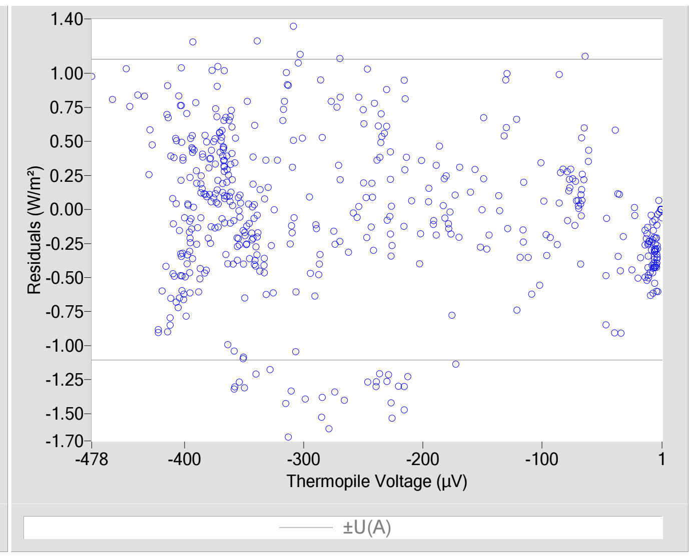


Table 2. Calibration Coefficients for K0<>0

K0	-5.6785
K1	0.23849
K2	1.0222
K3	-3.4898
Kr used to derive coefficients	0.00070440

Table 3. Calibration Coefficients for K0=0

K0	0
K1	0.23695
K2	1.0053
K3	-3.6799
Kr used to derive coefficients	0.00070440

Table 4. Uncertainty using K0<>0 Coefficients

Type-B Standard Uncertainty, u(B) (W/m²)	±0.87
Type-A Standard Uncertainty, u(A) (W/m²)	±0.24
Combined Standard Uncertainty, u(c) (W/m²)	±0.90
Effective degrees of freedom, DF(c)	+Inf
Coverage factor, k	1.96
Expanded Uncertainty, U95 (W/m²)	±1.8

Table 5. Uncertainty using K0=0 Coefficients

Type-B Standard Uncertainty, u(B) (W/m²)	±0.87
Type-A Standard Uncertainty, u(A) (W/m²)	±0.56
Combined Standard Uncertainty, u(c) (W/m²)	±1.0
Effective degrees of freedom, DF(c)	+Inf
Coverage factor, k	1.96
Expanded Uncertainty, U95 (W/m²)	±2.0

Figure 3. History of instrument (K0 Coefficient)

Figure 4. History of instrument (K1 Coefficient)

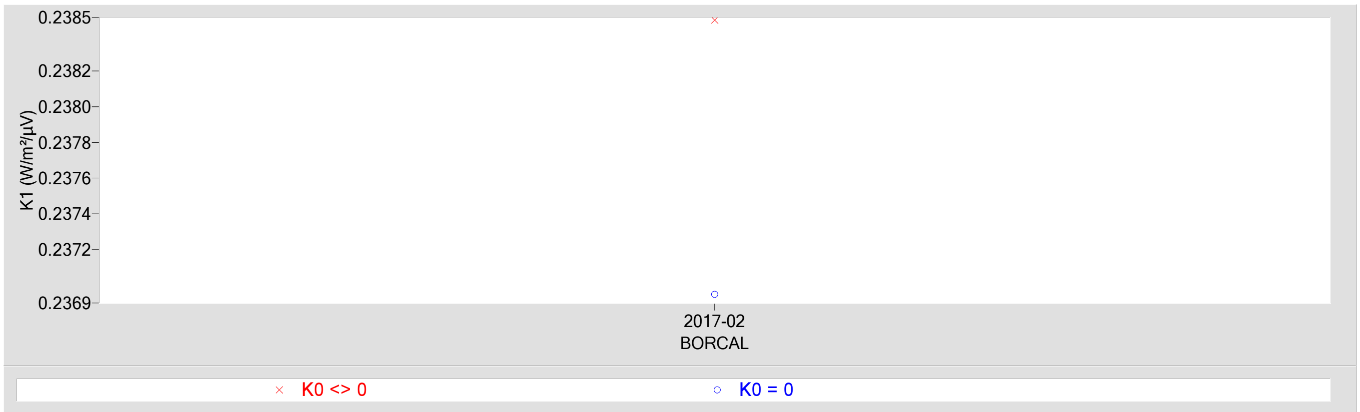


Figure 5. History of instrument (K2 Coefficient)

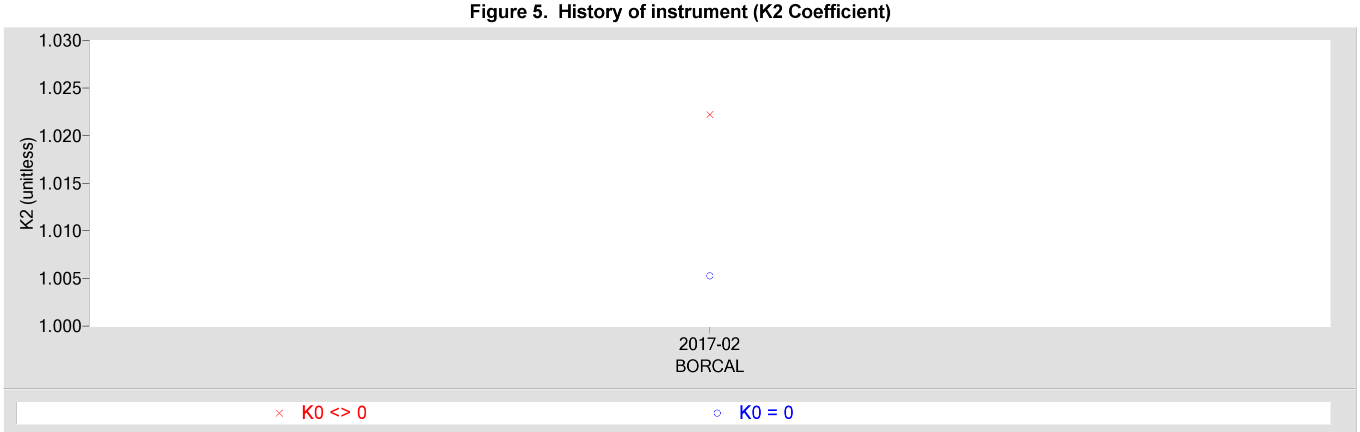
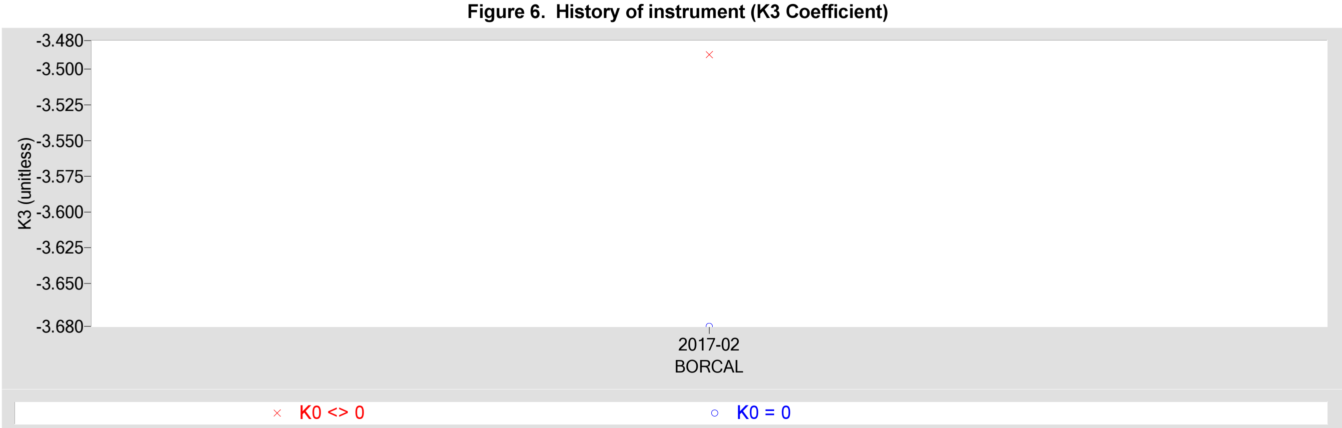


Figure 6. History of instrument (K3 Coefficient)



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[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

Test Instrument:	Downwelling Pyrgeometer	**Manufacturer:**	Eppley
Model:	PIR	**Serial Number:**	30835F3
Calibration Date:	5/8/2017	**Due Date:**	5/8/2019
Customer:	Craig Webb	**Environmental Conditions:**	see page 4
Test Dates:	4/25-30, 5/1-8		

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Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	04/12/2017	04/12/2019
Infrared Irradiance ‡	Eppley Downwelling Pyrgeometer Model PIR, S/N 30557F3	01/29/2015	01/29/2020

‡ 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

________________________________ ____________

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

30835F3 Eppley PIR

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

$$Win = K0 + K1*V + K2*Wr + K3*(Wd - Wr) \quad [1]$$

where,

K0,K1,K2,K3 = calibration coefficeints,
V = thermopile output voltage (µV),
$Wd = \sigma * Td^4$ = dome irradiance (W/m²),
where, *Td* = dome temperature (K),

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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 calc. vs ref. irradiance using K0<>0 Coefficients

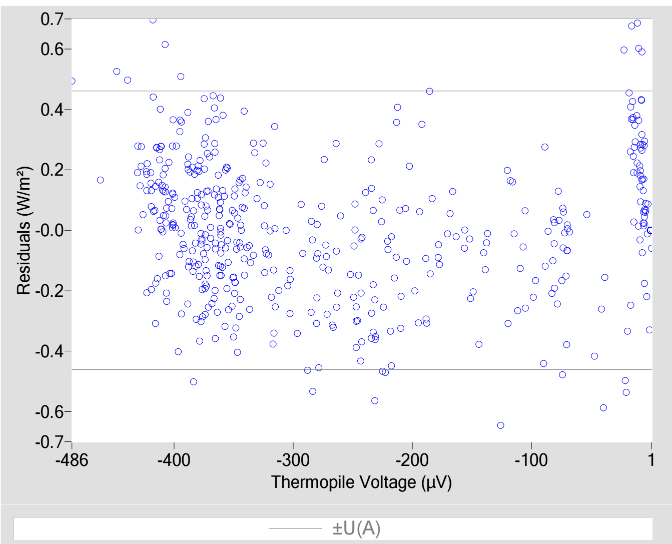


Figure 2. Residuals for calc. vs ref. irradiance using K0=0 Coefficients

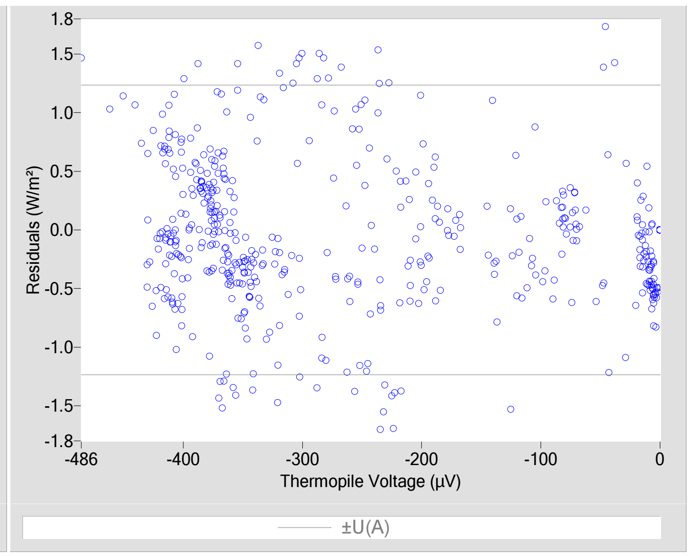


Table 2. Calibration Coefficients for K0<>0

K0	-6.3090
K1	0.23009
K2	1.0206
K3	-3.4667
Kr used to derive coefficients	0.00070440

Table 3. Calibration Coefficients for K0=0

K0	0
K1	0.22927
K2	1.0017
K3	-3.3611
Kr used to derive coefficients	0.00070440

Table 4. Uncertainty using K0<>0 Coefficients

Type-B Standard Uncertainty, u(B) (W/m²)	±0.87
Type-A Standard Uncertainty, u(A) (W/m²)	±0.24
Combined Standard Uncertainty, u(c) (W/m²)	±0.90
Effective degrees of freedom, DF(c)	+Inf
Coverage factor, k	1.96
Expanded Uncertainty, U95 (W/m²)	±1.8

Table 5. Uncertainty using K0=0 Coefficients

Type-B Standard Uncertainty, u(B) (W/m²)	±0.87
Type-A Standard Uncertainty, u(A) (W/m²)	±0.63
Combined Standard Uncertainty, u(c) (W/m²)	±1.1
Effective degrees of freedom, DF(c)	+Inf
Coverage factor, k	1.96
Expanded Uncertainty, U95 (W/m²)	±2.1

Figure 3. History of instrument (K0 Coefficient)

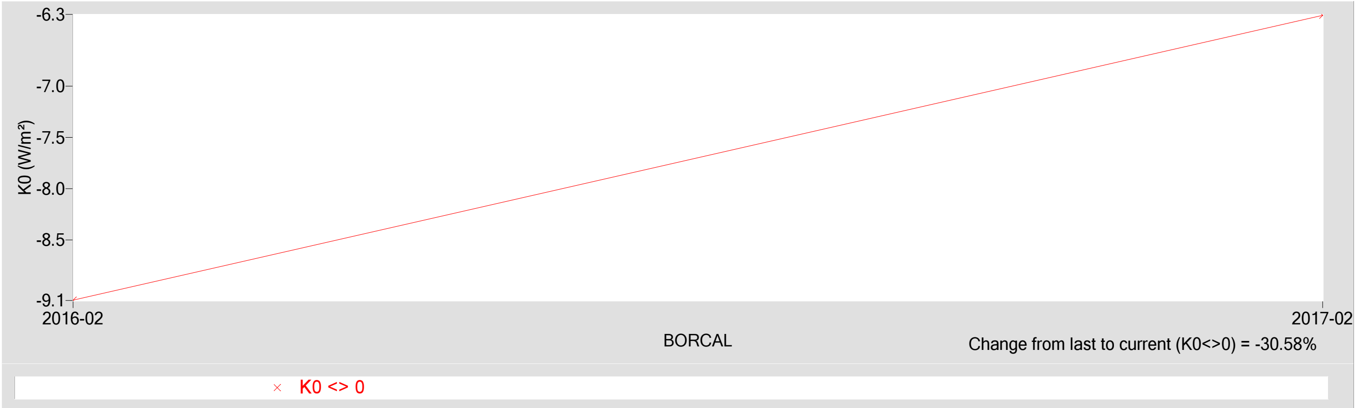


Figure 4. History of instrument (K1 Coefficient)

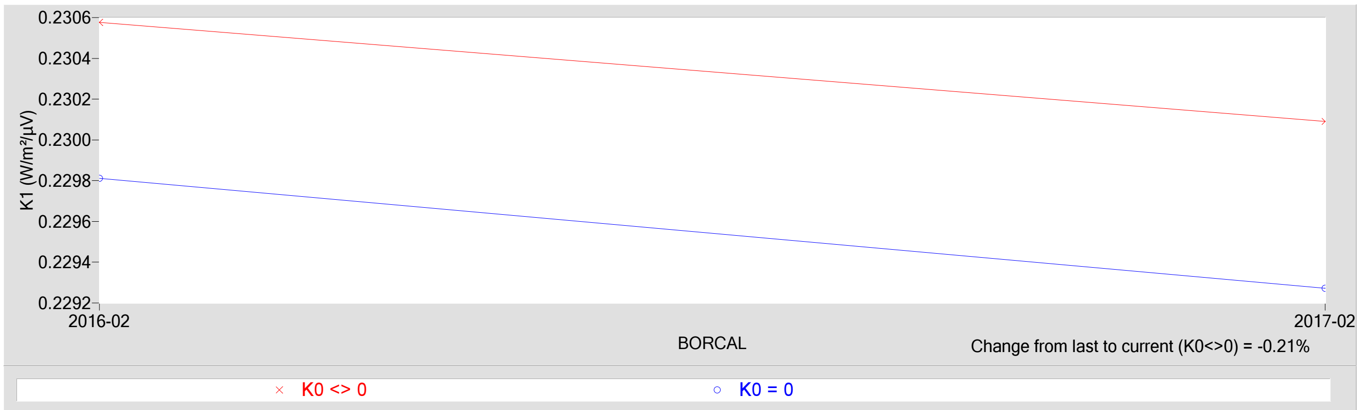


Figure 5. History of instrument (K2 Coefficient)

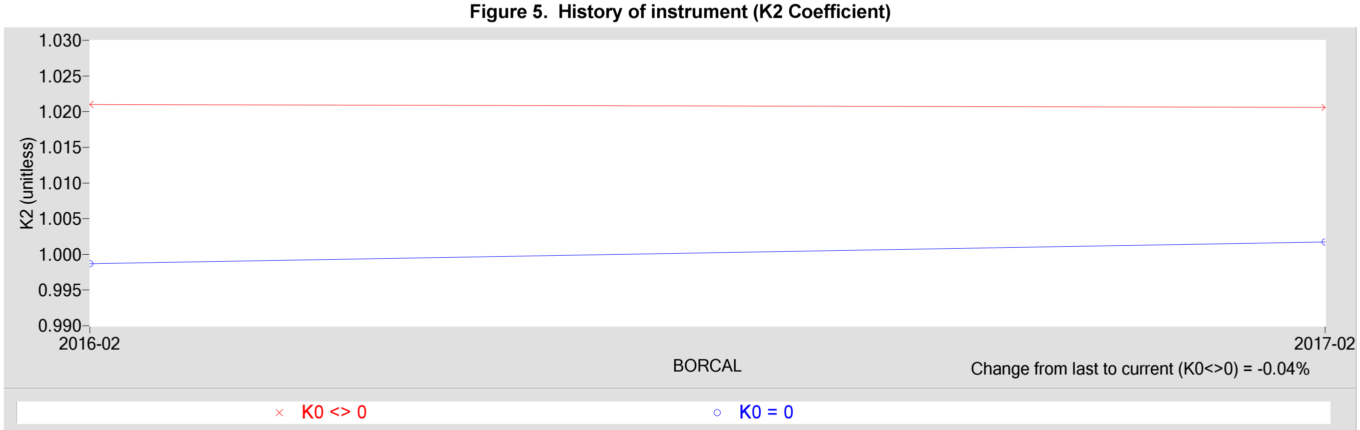
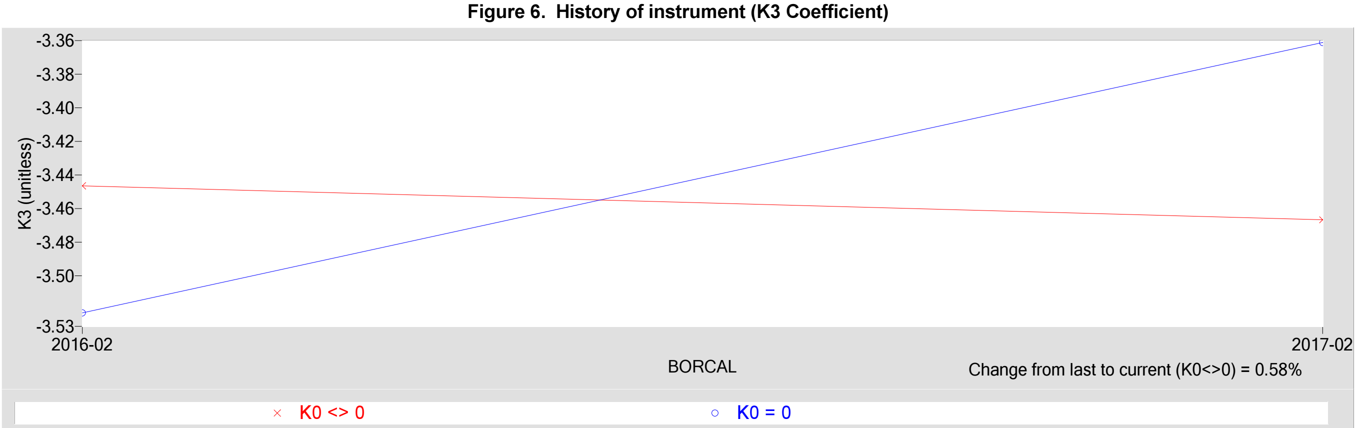


Figure 6. History of instrument (K3 Coefficient)



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.

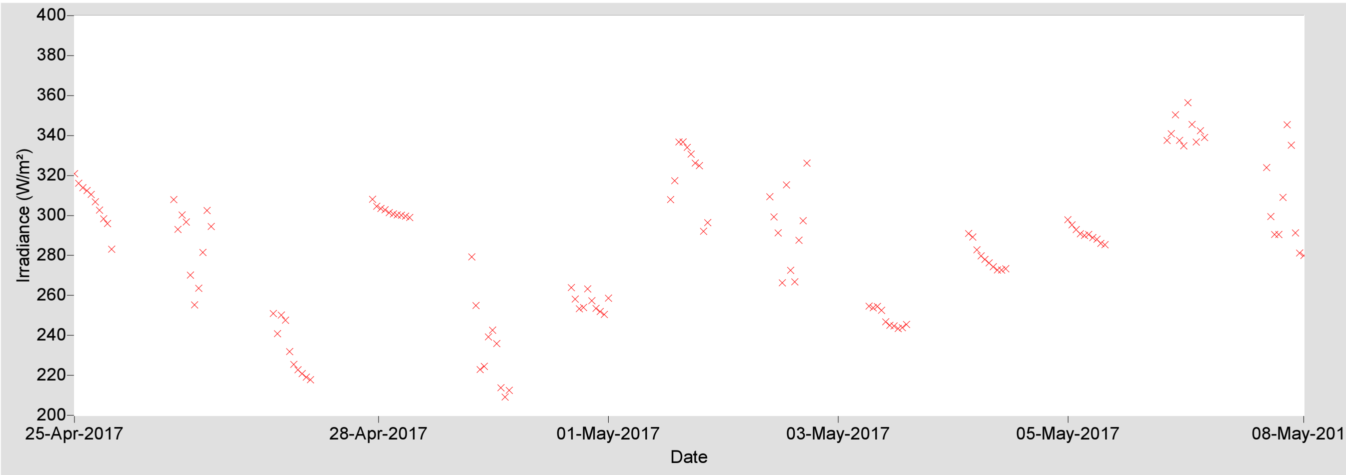
Environmental and Sky Conditions for BORCAL-LW 2017-02

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

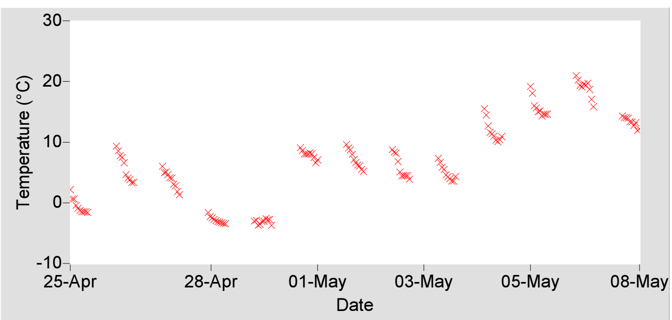


Figure 8. Humidity

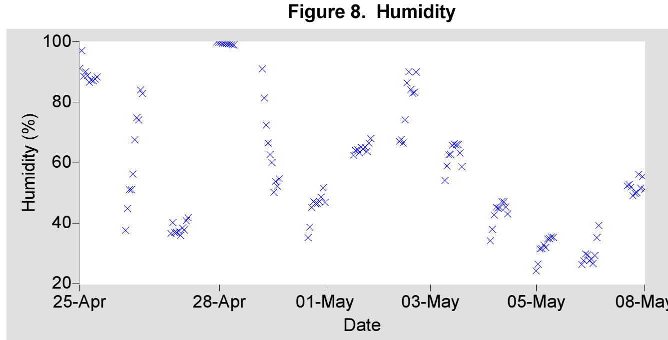


Figure 9. Pressure

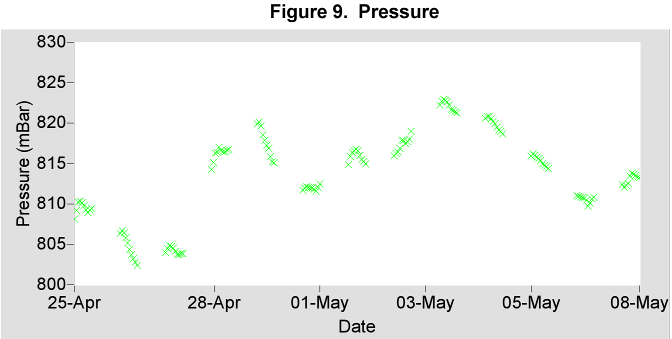


Figure 10. Estimated Precipitable Water Vapor (PWV)

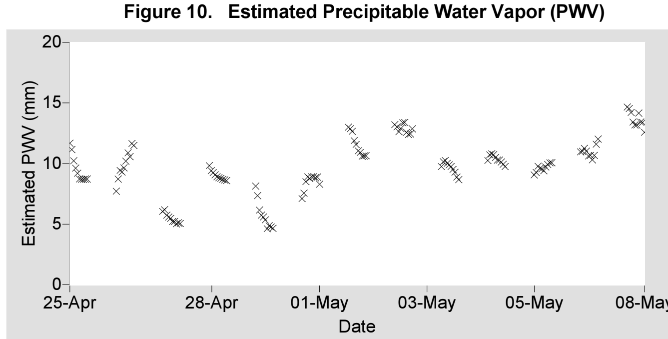


Table 6. Meteorological Observations

Observations	Mean	Min	Max
Temperature (°C)	6.74	-4.13	21.33
Humidity (%)	58.92	22.63	99.94
Pressure (mBar)	813.7	802.2	823.0
Est. Precipitable Water Vapor (mm)	9.7	4.4	15.2

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).