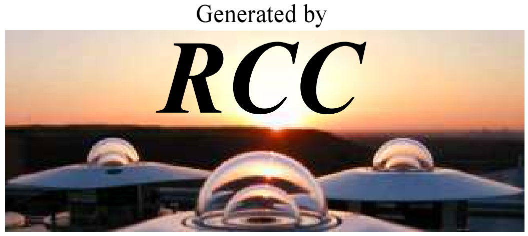
Broadband Outdoor Radiometer Calibration
Longwave

BORCAL-LW
2019-02

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
05/24/2019 to 07/30/2019

Report Date
July 30, 2019

NREL

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 History (K0 Coefficient)

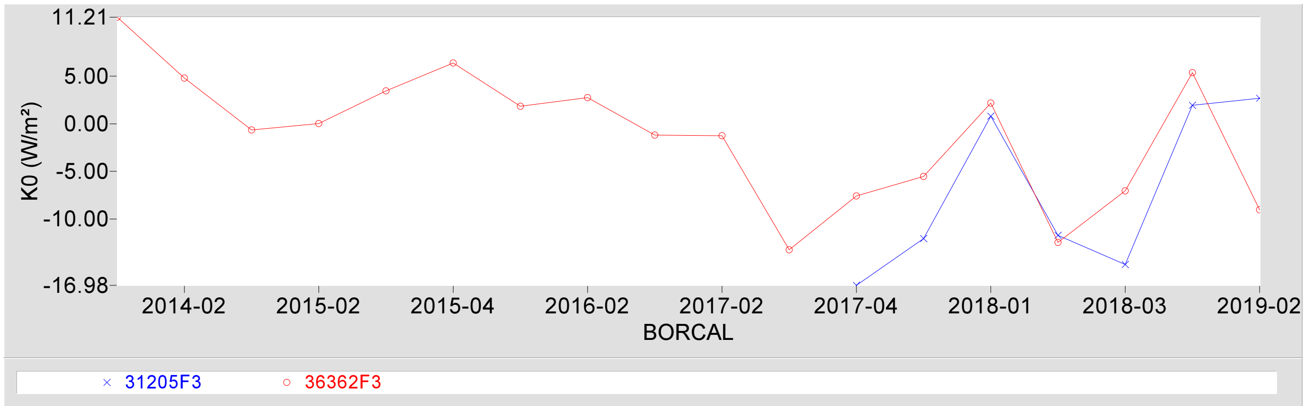


Figure 2. Eppley PIR Control Instrument History (K1 Coefficient)

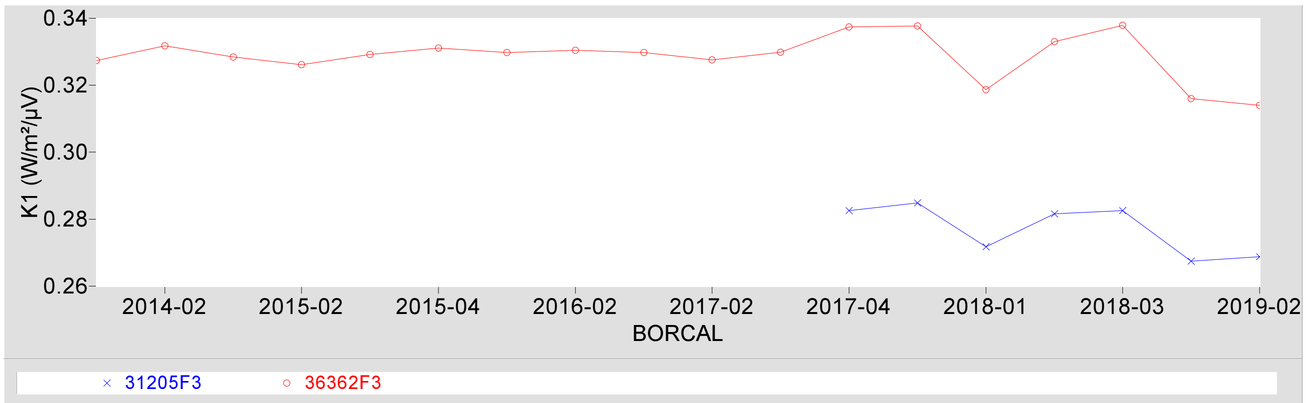


Figure 3. Eppley PIR Control Instrument History (K2 Coefficient)

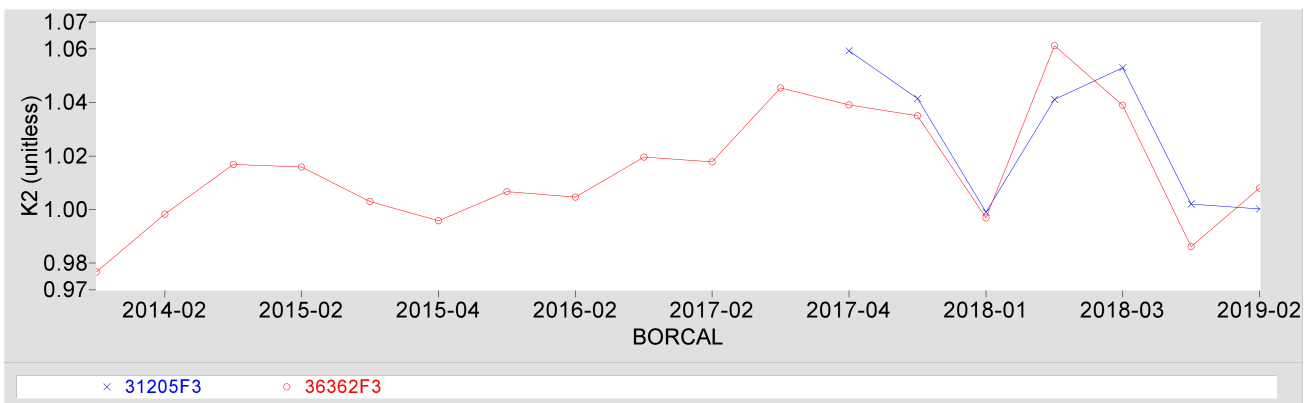
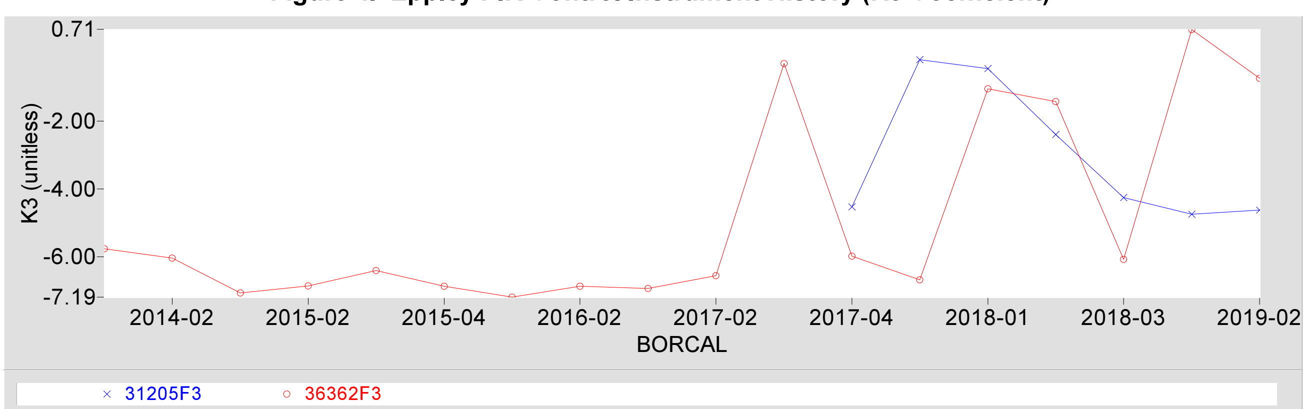


Figure 4. Eppley PIR Control Instrument History (K3 Coefficient)



Results Summary

Table 1. Results Summary

Instrument	K0 (W/m²)	K1 (W/m²/μV)	K2	K3	Kr * (K/μV)	U95 (W/m²)	Page
010284-UW-CG3 Kipp & Zonen CG3	7.5	0.088759	0.9857	0.00	7.044e-4	±3.2	A1-2
010548 Kipp & Zonen CG4	5.7	0.073838	0.9874	0.00	7.044e-4	±2.8	A1-5
1060 Apogee SL-510	-45.2	0.0035490	1.1115	0.00	7.044e-4	±3.8	A1-8
31193F3 Eppley PIR	2.5	0.26342	0.9945	-3.89	7.044e-4	±2.7	A1-11
31198F3 Eppley PIR	0.2	0.26266	0.9971	-4.03	7.044e-4	±2.7	A1-14

Note: Environmental Conditions for BORCAL starts on page A1-17. * 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:	Pyrgeometer	**Manufacturer:**	Kipp & Zonen
Model:	CG3	**Serial Number:**	010284-UW-CG3
Calibration Date:	7/30/2019	**Due Date:**	7/30/2021
Customer:	NREL-SRRL-BMS	**Environmental Conditions:**	see page 4

Test Dates: 5/24-31, 6/1-3, 6/6-7, 6/9-11, 6/13-16, 6/19-21, 6/23-30, 7/2-4, 7/6-20, 7/23-30

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	02/14/2019	02/14/2021
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/14/2019	02/14/2021
Infrared Irradiance ‡	Eppley Downwelling Pyrgeometer Model PIR, S/N 32309F3	08/02/2017	08/02/2022

‡ 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

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 = 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

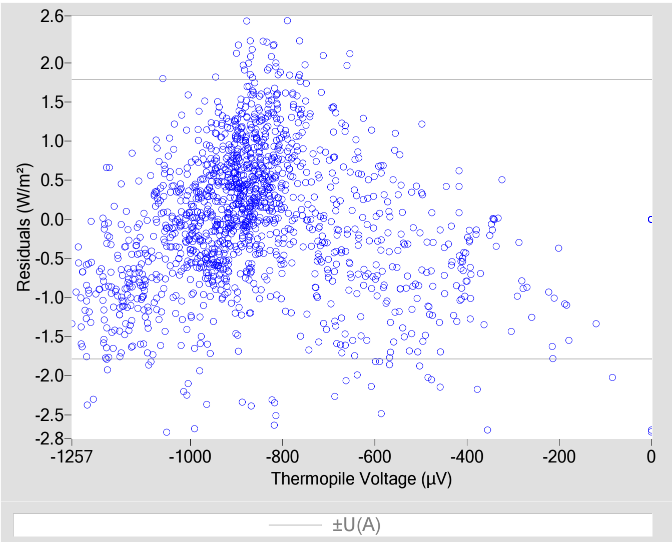


Figure 2. Residuals for calc. vs ref. irradiance using K0=0 Coefficients

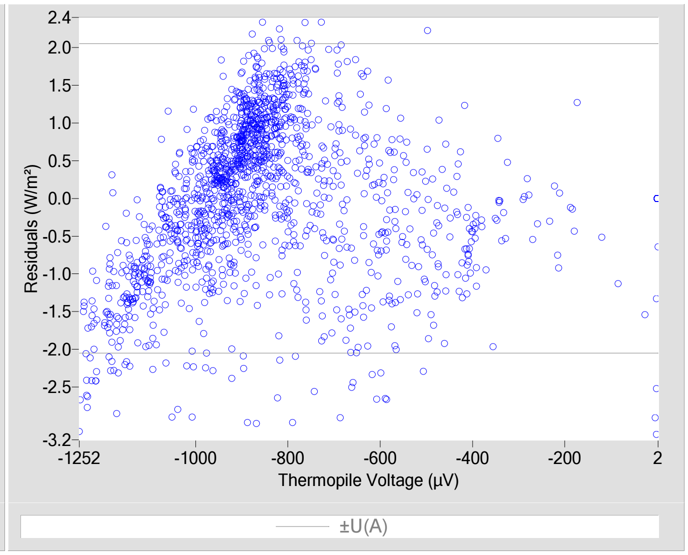


Table 2. Calibration Coefficients for K0<>0

K0	7.5
K1	0.088759
K2	0.9857
K3	0.00
Kr used to derive coefficients	7.044e-4

Table 3. Calibration Coefficients for K0=0

K0	0.0
K1	0.088320
K2	1.0035
K3	0.00
Kr used to derive coefficients	7.044e-4

Table 4. Uncertainty using K0<>0 Coefficients

Type-B Standard Uncertainty, u(B) (W/m²)	±1.3
Type-A Standard Uncertainty, u(A) (W/m²)	±0.91
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)	±3.2

Table 5. Uncertainty using K0=0 Coefficients

Type-B Standard Uncertainty, u(B) (W/m²)	±1.3
Type-A Standard Uncertainty, u(A) (W/m²)	±1.0
Combined Standard Uncertainty, u(c) (W/m²)	±1.7
Effective degrees of freedom, DF(c)	+Inf
Coverage factor, k	1.96
Expanded Uncertainty, U95 (W/m²)	±3.3

Figure 3. History of instrument (K0 Coefficient)

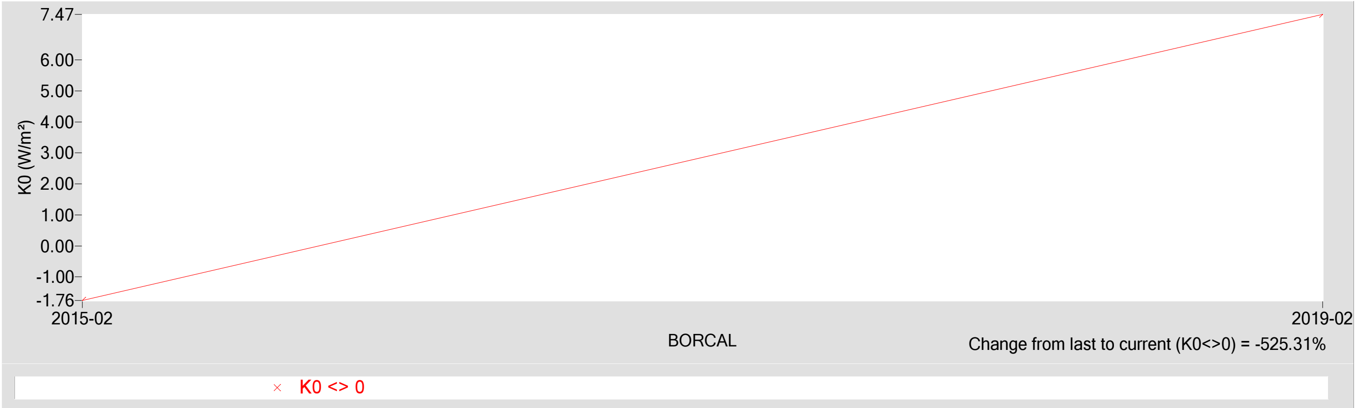


Figure 4. History of instrument (K1 Coefficient)

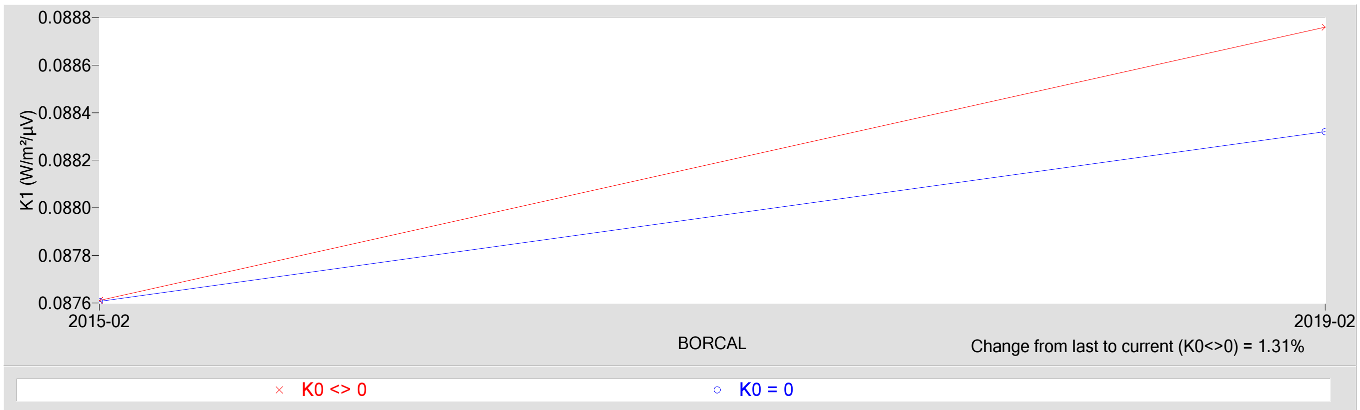
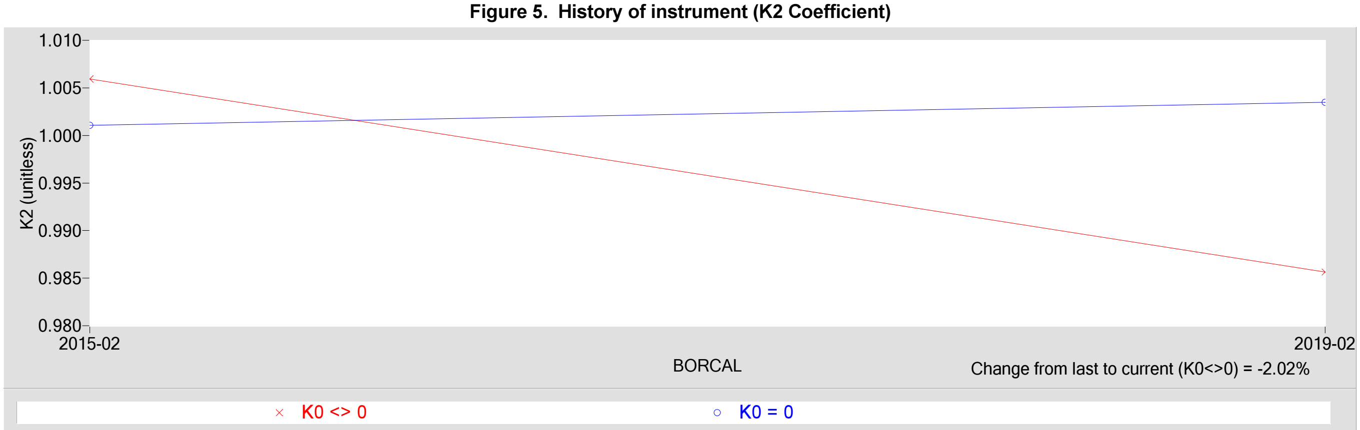


Figure 5. History of instrument (K2 Coefficient)



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

Test Instrument:	Pyrgeometer	**Manufacturer:**	Kipp & Zonen
Model:	CG4	**Serial Number:**	010548
Calibration Date:	7/30/2019	**Due Date:**	7/30/2021
Customer:	NREL-SRRL-BMS	**Environmental Conditions:**	see page 4

Test Dates: 5/24-31, 6/1-3, 6/6-7, 6/9-11, 6/13-16, 6/19-21, 6/23-30, 7/2-4, 7/6-20, 7/23-30

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	02/14/2019	02/14/2021
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/14/2019	02/14/2021
Infrared Irradiance ‡	Eppley Downwelling Pyrgeometer Model PIR, S/N 32309F3	08/02/2017	08/02/2022

‡ 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

010548 Kipp & Zonen CG4

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 = *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

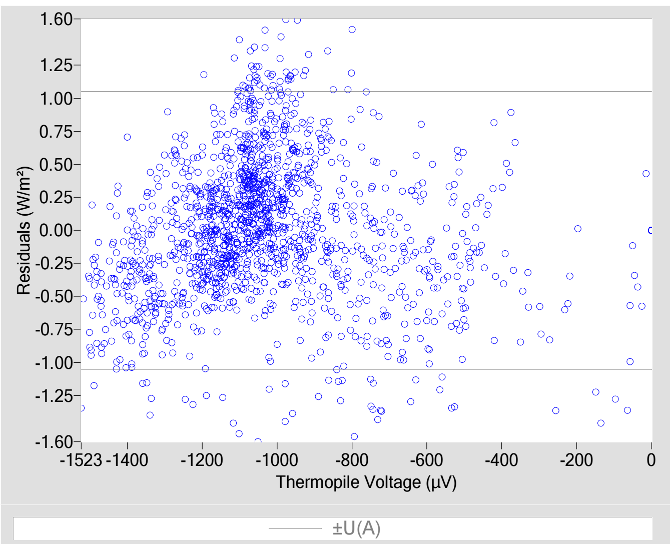


Figure 2. Residuals for calc. vs ref. irradiance using K0=0 Coefficients

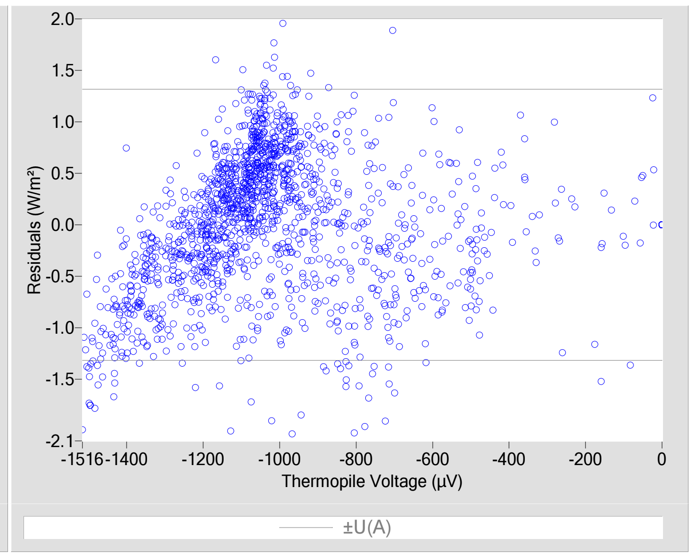


Table 2. Calibration Coefficients for K0<>0

K0	5.7
K1	0.073838
K2	0.9874
K3	0.00
Kr used to derive coefficients	7.044e-4

Table 3. Calibration Coefficients for K0=0

K0	0.0
K1	0.073698
K2	1.0013
K3	0.00
Kr used to derive coefficients	7.044e-4

Table 4. Uncertainty using K0<>0 Coefficients

Type-B Standard Uncertainty, u(B) (W/m²)	±1.3
Type-A Standard Uncertainty, u(A) (W/m²)	±0.54
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)	±2.8

Table 5. Uncertainty using K0=0 Coefficients

Type-B Standard Uncertainty, u(B) (W/m²)	±1.3
Type-A Standard Uncertainty, u(A) (W/m²)	±0.67
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)

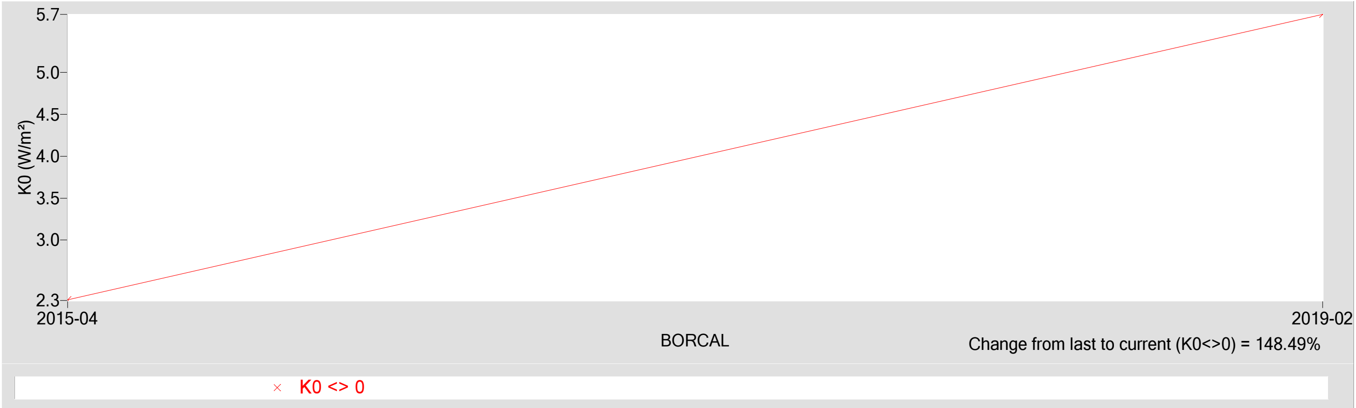


Figure 4. History of instrument (K1 Coefficient)

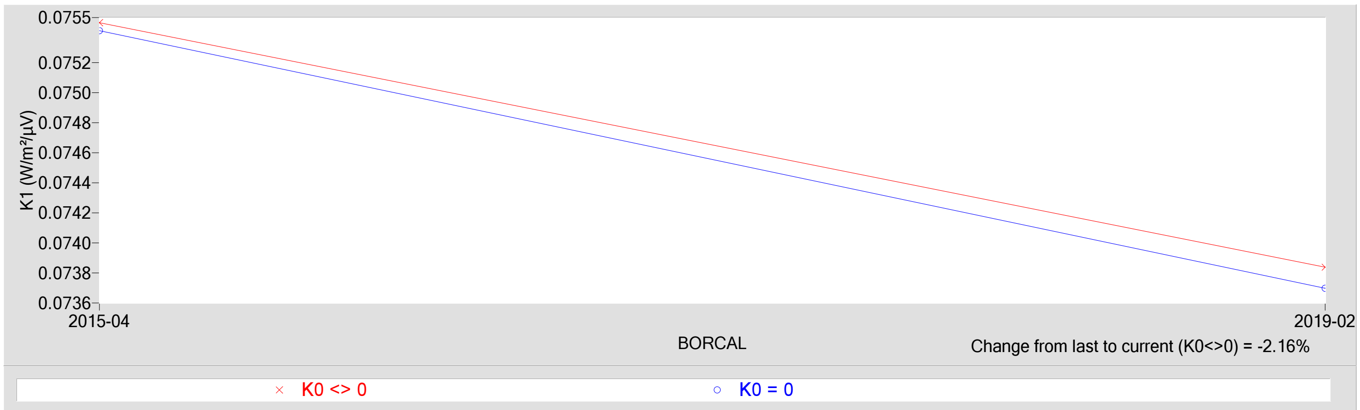
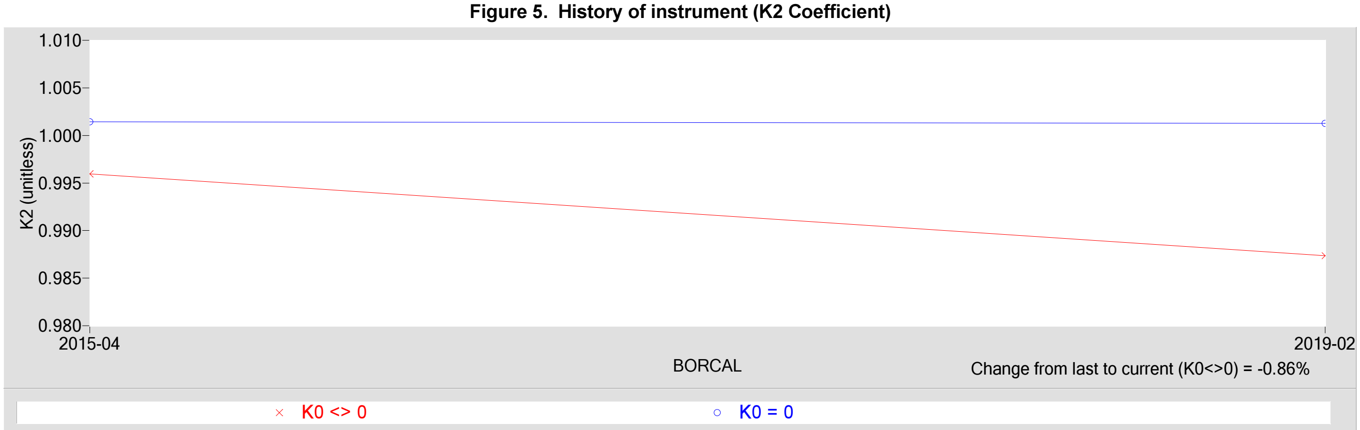


Figure 5. History of instrument (K2 Coefficient)



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:	Pyrgeometer	**Manufacturer:**	Apogee
Model:	SL-510	**Serial Number:**	1060
Calibration Date:	7/30/2019	**Due Date:**	7/30/2021
Customer:	NREL-SRRL-BMS	**Environmental Conditions:**	see page 4

Test Dates: 5/24-31, 6/1-3, 6/6-7, 6/9-11, 6/13-16, 6/19-21, 6/23-30, 7/2-4, 7/6-20, 7/23-30

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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	02/14/2019	02/14/2021
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/14/2019	02/14/2021
Infrared Irradiance ‡	Eppley Downwelling Pyrgeometer Model PIR, S/N 32309F3	08/02/2017	08/02/2022

‡ 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

1060 Apogee SL-510

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

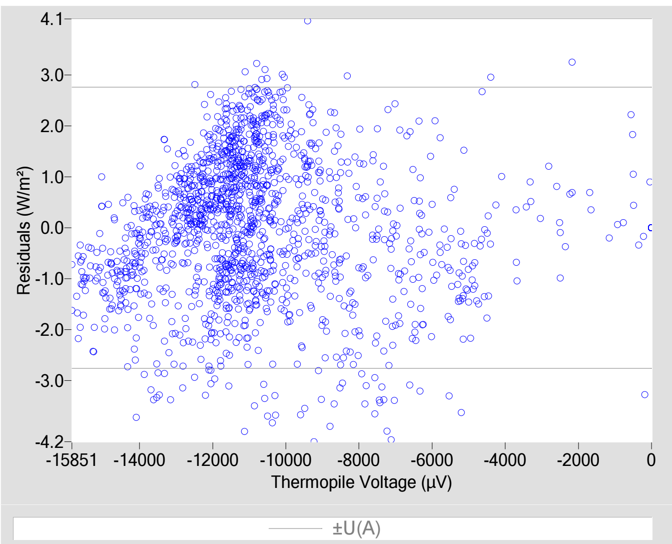


Figure 2. Residuals for calc. vs ref. irradiance using K0=0 Coefficients

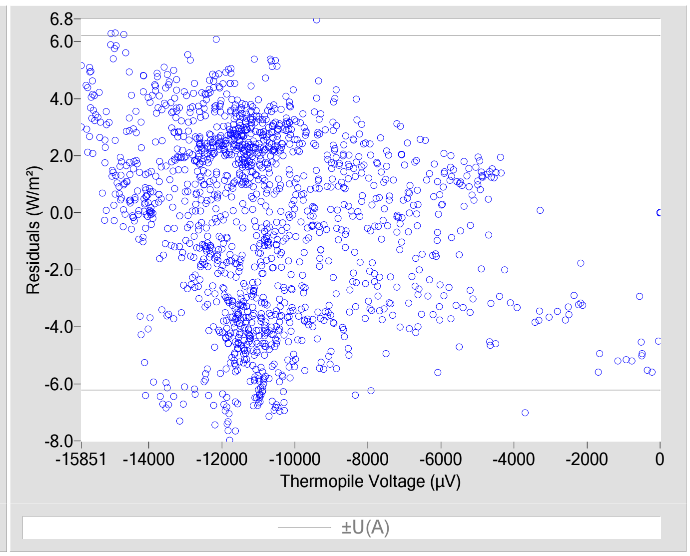


Table 2. Calibration Coefficients for K0<>0

K0	-45.2
K1	0.0035490
K2	1.1115
K3	0.00
Kr used to derive coefficients	7.044e-4

Table 3. Calibration Coefficients for K0=0

K0	0.0
K1	0.0038970
K2	0.9980
K3	0.00
Kr used to derive coefficients	7.044e-4

Table 4. Uncertainty using K0<>0 Coefficients

Type-B Standard Uncertainty, u(B) (W/m²)	±1.3
Type-A Standard Uncertainty, u(A) (W/m²)	±1.4
Combined Standard Uncertainty, u(c) (W/m²)	±1.9
Effective degrees of freedom, DF(c)	+Inf
Coverage factor, k	1.96
Expanded Uncertainty, U95 (W/m²)	±3.8

Table 5. Uncertainty using K0=0 Coefficients

Type-B Standard Uncertainty, u(B) (W/m²)	±1.3
Type-A Standard Uncertainty, u(A) (W/m²)	±3.2
Combined Standard Uncertainty, u(c) (W/m²)	±3.4
Effective degrees of freedom, DF(c)	+Inf
Coverage factor, k	1.96
Expanded Uncertainty, U95 (W/m²)	±6.7

Figure 3. History of instrument (K0 Coefficient)

Figure 4. History of instrument (K1 Coefficient)

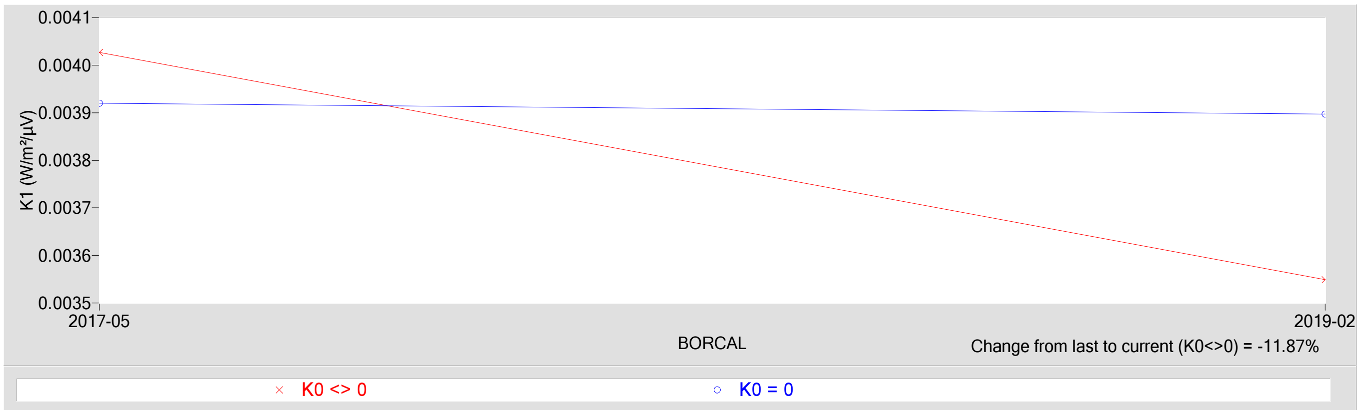
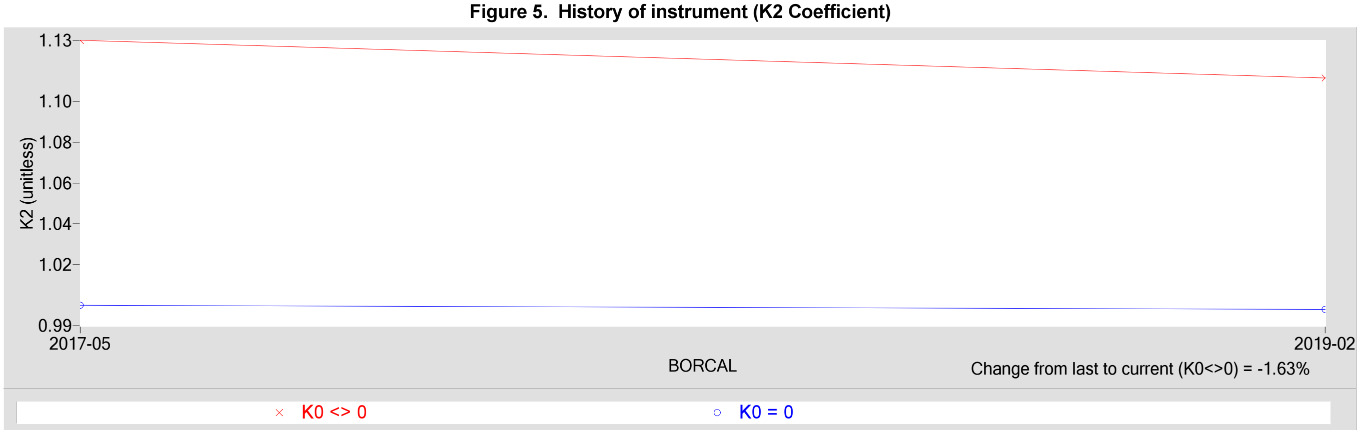


Figure 5. History of instrument (K2 Coefficient)



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

Test Instrument:	Downwelling Pyrgeometer	**Manufacturer:**	Eppley
Model:	PIR	**Serial Number:**	31193F3
Calibration Date:	7/30/2019	**Due Date:**	7/30/2021
Customer:	NREL-SRRL-BMS	**Environmental Conditions:**	see page 4
Test Dates:	5/24-31, 6/1-3, 6/6-7, 6/9-11, 6/13-16, 6/19-21, 6/23-30, 7/2-4, 7/6-20, 7/23-30		

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).

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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	02/14/2019	02/14/2021
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/14/2019	02/14/2021
Infrared Irradiance ‡	Eppley Downwelling Pyrgeometer Model PIR, S/N 32309F3	08/02/2017	08/02/2022

‡ 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

31193F3 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

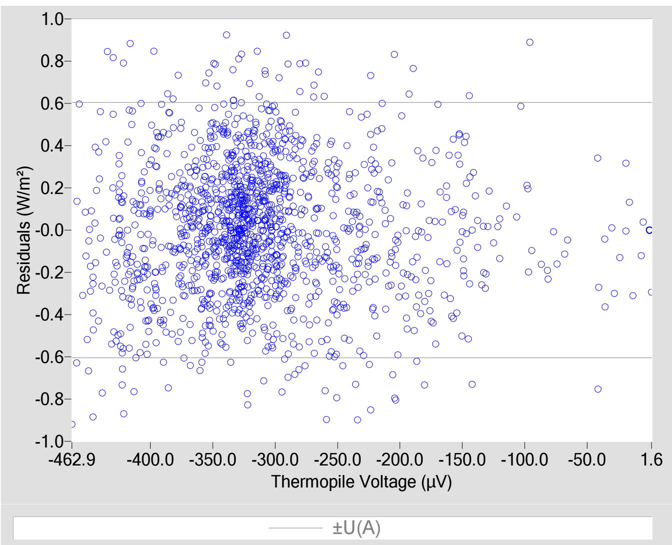


Figure 2. Residuals for calc. vs ref. irradiance using K0=0 Coefficients

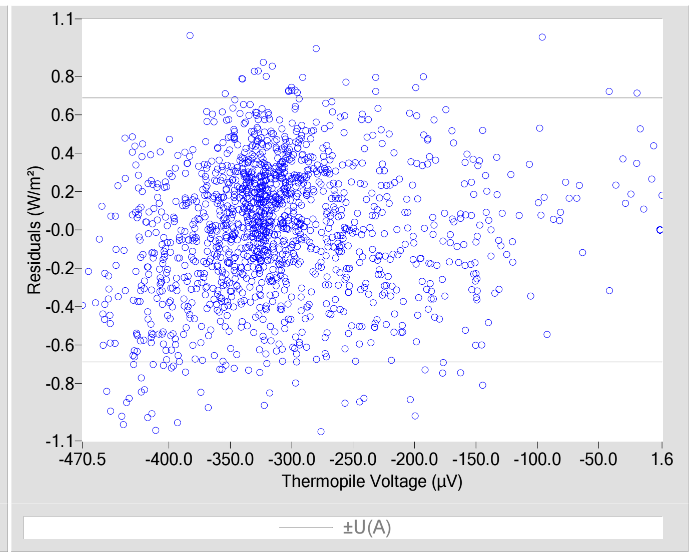


Table 2. Calibration Coefficients for K0<>0

K0	2.5
K1	0.26342
K2	0.9945
K3	-3.89
Kr used to derive coefficients	7.044e-4

Table 3. Calibration Coefficients for K0=0

K0	0.0
K1	0.26317
K2	1.0006
K3	-4.00
Kr used to derive coefficients	7.044e-4

Table 4. Uncertainty using K0<>0 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)	±1.4
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)	±1.3
Type-A Standard Uncertainty, u(A) (W/m²)	±0.35
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

Figure 3. History of instrument (K0 Coefficient)

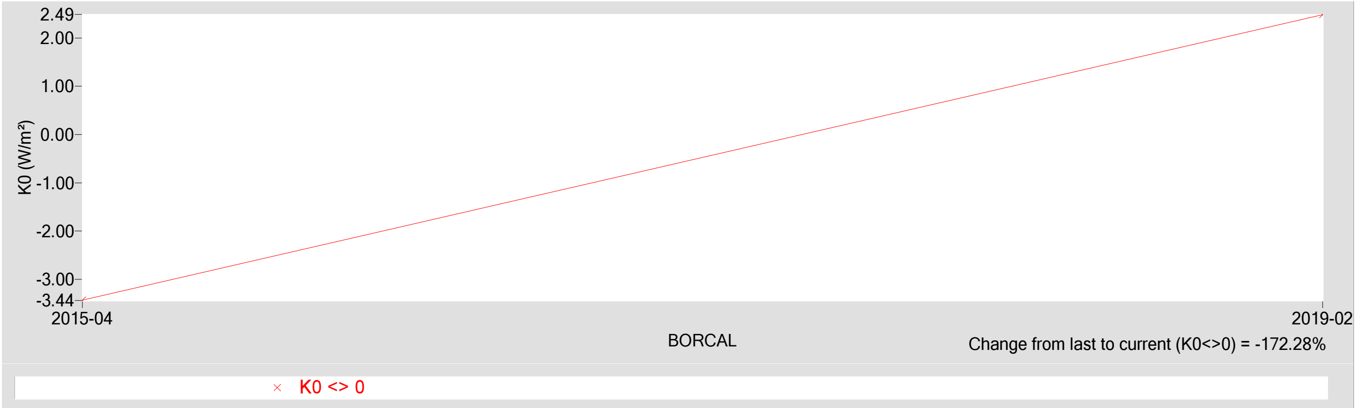


Figure 4. History of instrument (K1 Coefficient)

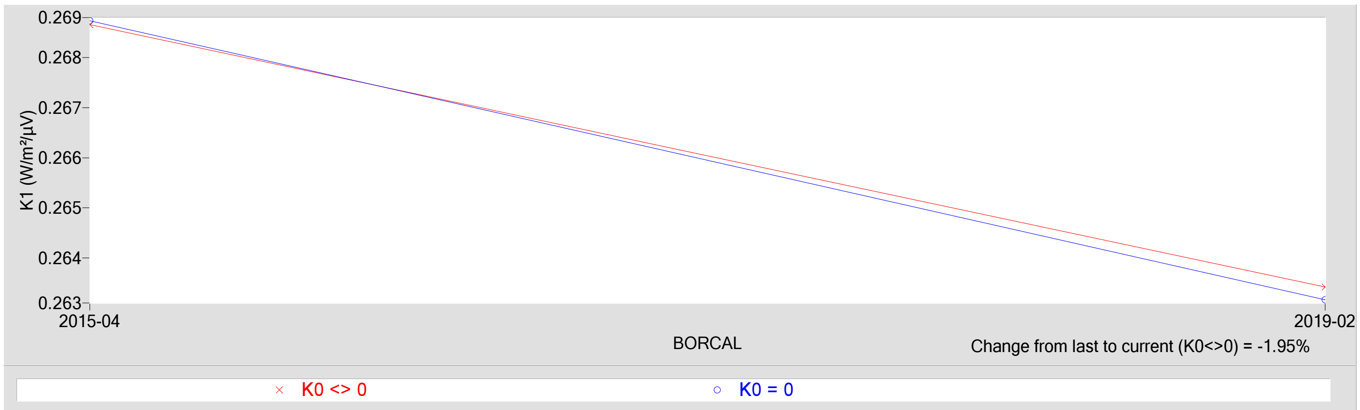


Figure 5. History of instrument (K2 Coefficient)

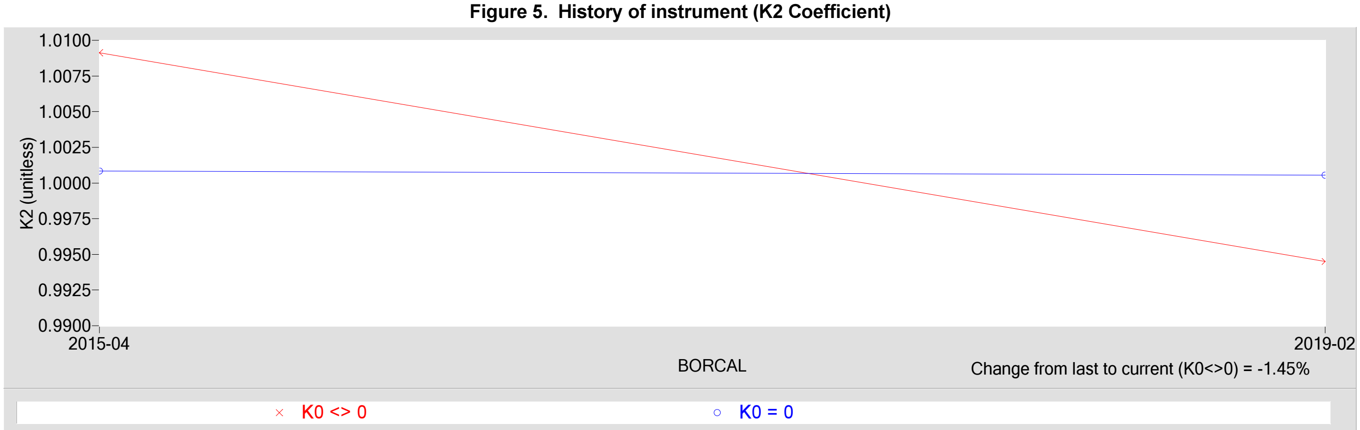
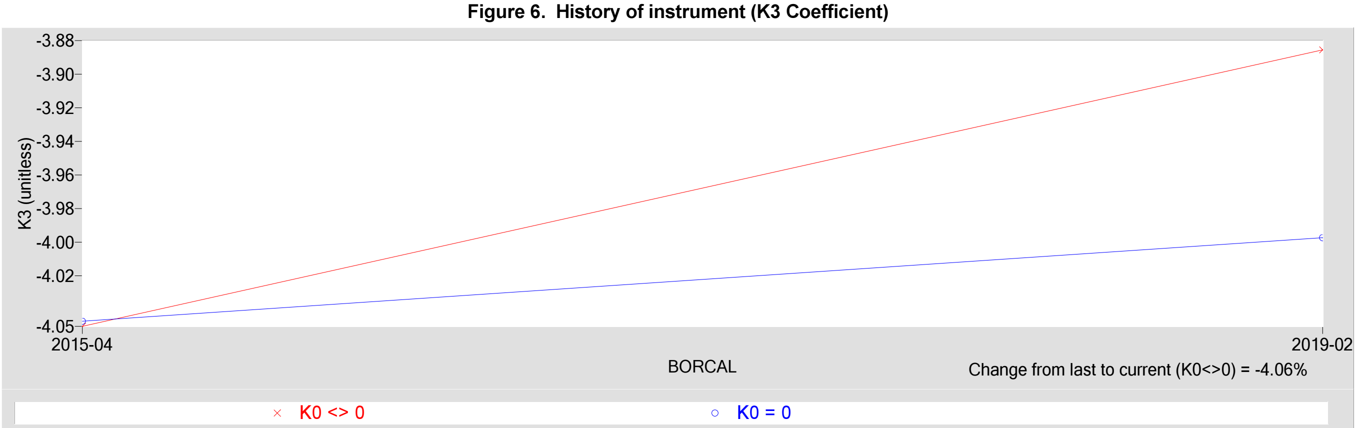


Figure 6. History of instrument (K3 Coefficient)



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:**	31198F3
Calibration Date:	7/30/2019	**Due Date:**	7/30/2021
Customer:	NREL-SRRL-BMS	**Environmental Conditions:**	see page 4
Test Dates:	5/24-31, 6/1-3, 6/6-7, 6/9-11, 6/13-16, 6/19-21, 6/23-30, 7/2-4, 7/6-20, 7/23-30		

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	02/14/2019	02/14/2021
Data Acquisition	NREL Data Acquisition System Model RAP-DAQ, S/N 2005-999	02/14/2019	02/14/2021
Infrared Irradiance ‡	Eppley Downwelling Pyrgeometer Model PIR, S/N 32309F3	08/02/2017	08/02/2022

‡ 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

31198F3 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 = 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

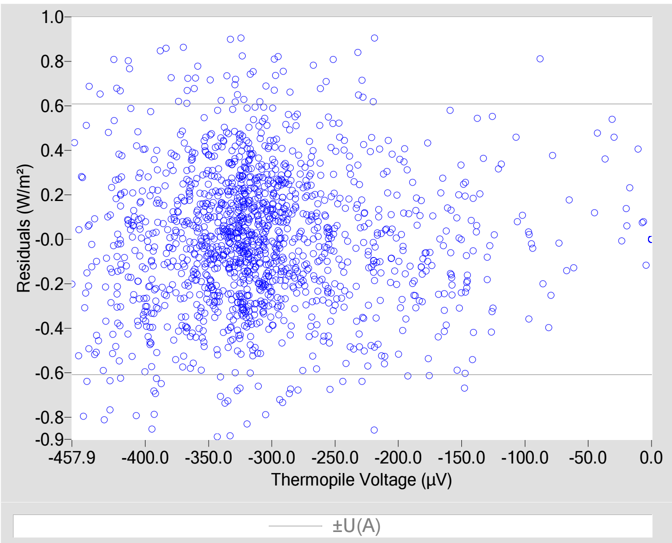


Figure 2. Residuals for calc. vs ref. irradiance using K0=0 Coefficients

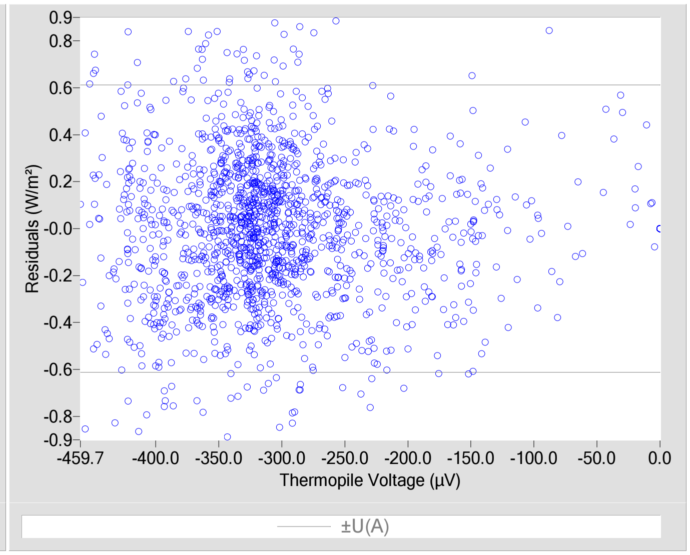


Table 2. Calibration Coefficients for K0<>0

K0	0.2
K1	0.26266
K2	0.9971
K3	-4.03
Kr used to derive coefficients	7.044e-4

Table 3. Calibration Coefficients for K0=0

K0	0.0
K1	0.26262
K2	0.9976
K3	-4.04
Kr used to derive coefficients	7.044e-4

Table 4. Uncertainty using K0<>0 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)	±1.4
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)	±1.3
Type-A Standard Uncertainty, u(A) (W/m²)	±0.31
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

Figure 3. History of instrument (K0 Coefficient)

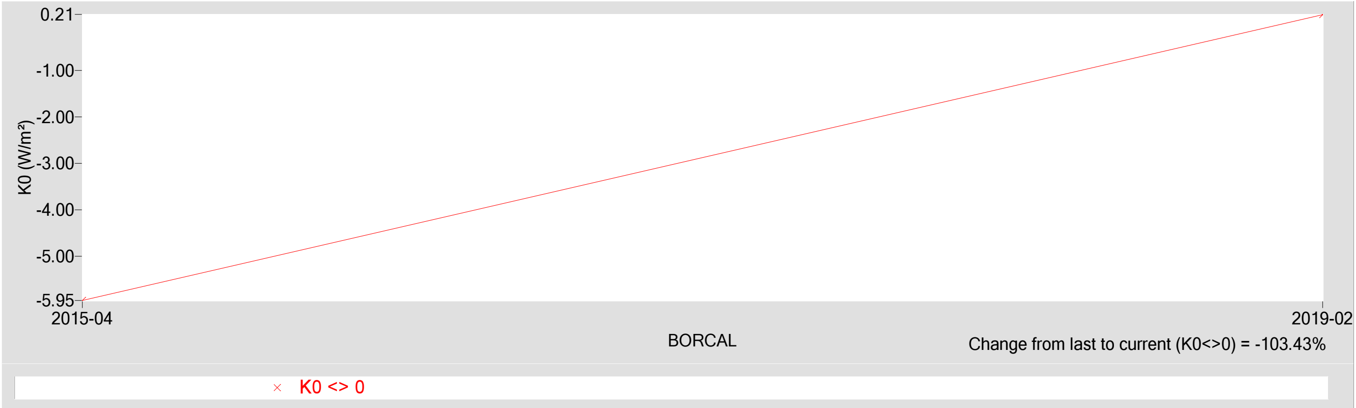


Figure 4. History of instrument (K1 Coefficient)

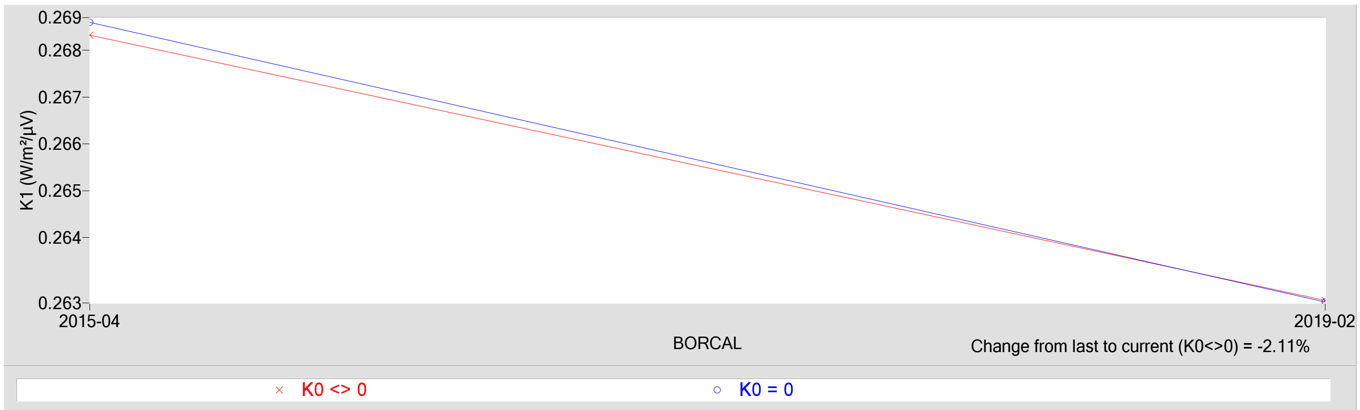


Figure 5. History of instrument (K2 Coefficient)

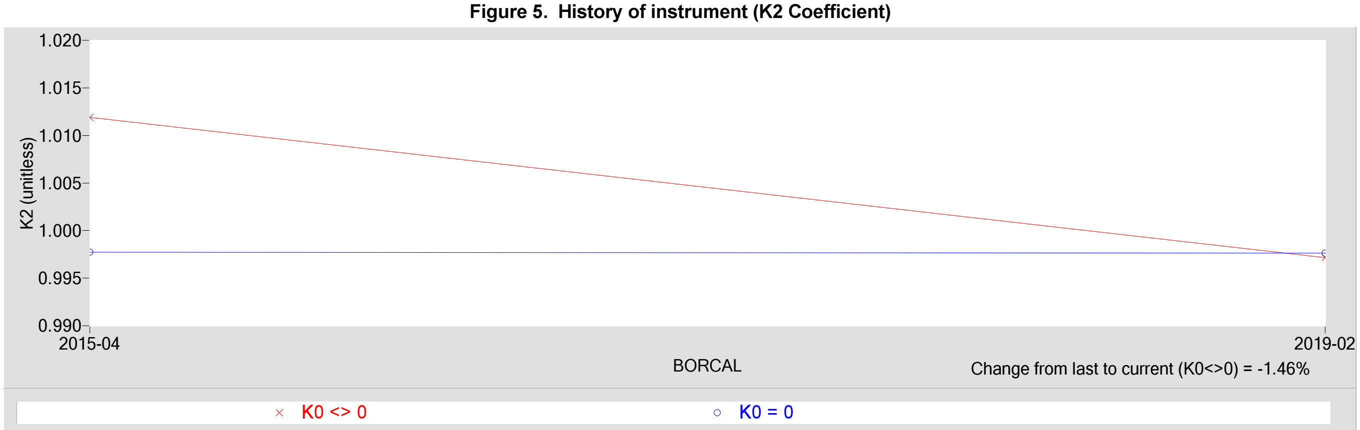
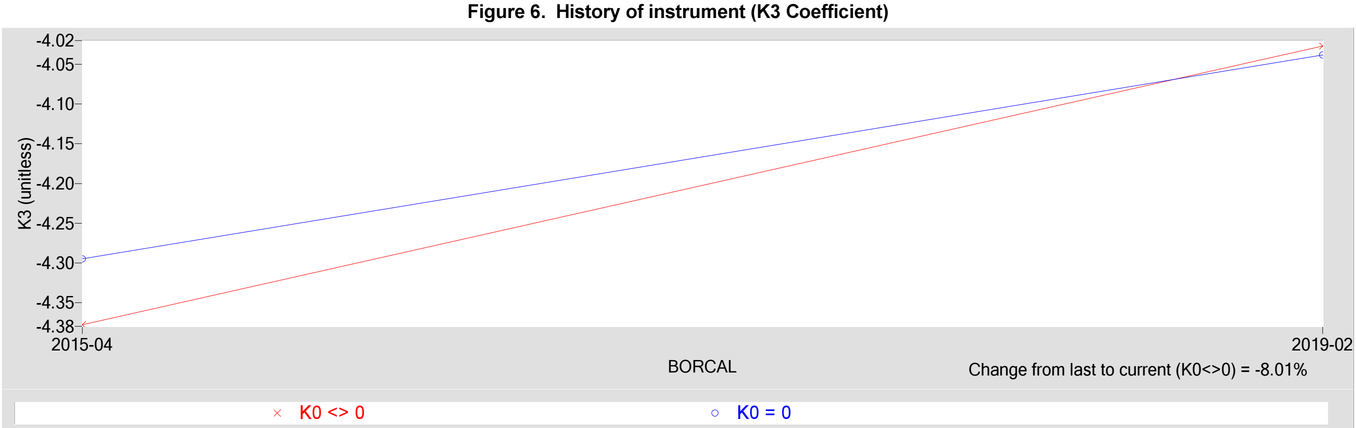


Figure 6. History of instrument (K3 Coefficient)



References:

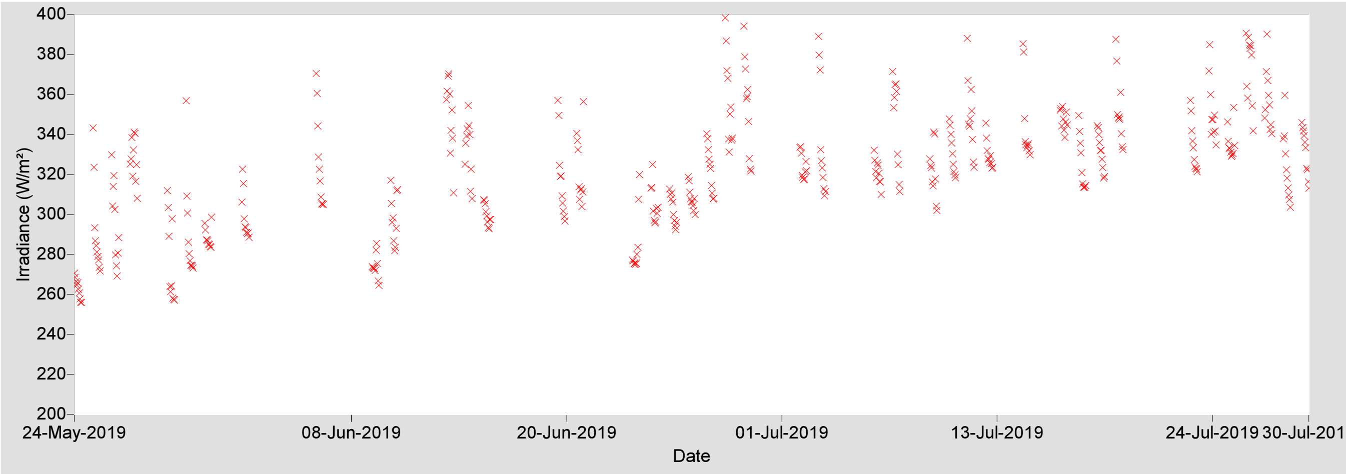
[1] Reda, I.; Stoffel, T. (2010). Pyrgeometer Calibration for DOE-Atmospheric System Research Program using NREL Method (Presentation). 9 pp.; NREL Report No. PR-3B0-47756; http://www.nrel.gov/docs/fy10osti/47756.pdf.

Environmental and Sky Conditions for BORCAL-LW 2019-02

Calibration Facility: Solar Radiation Research Laboratory

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

Figure 6. Reference Irradiance



Meteorological Observations (hourly averages):

Figure 7. Temperature

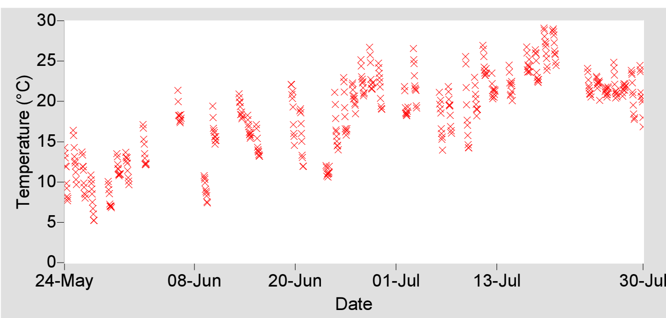


Figure 8. Humidity

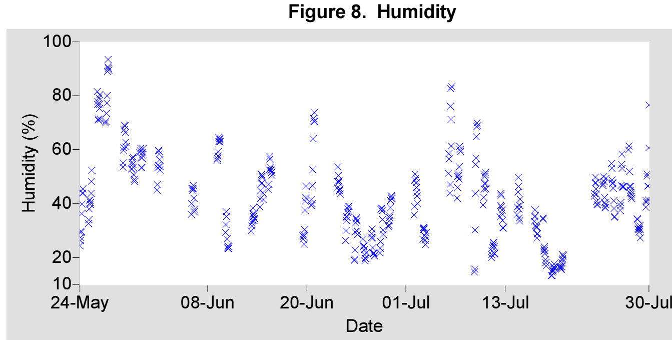


Figure 9. Pressure

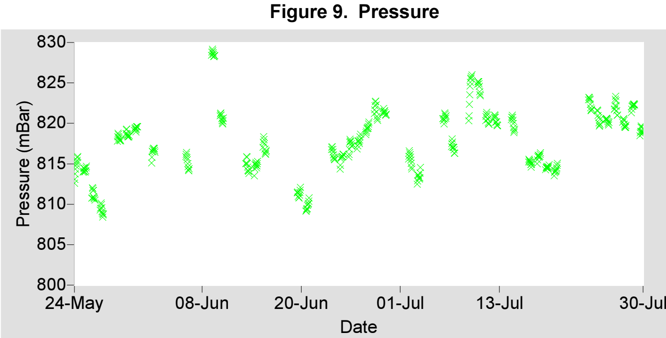


Figure 10. Estimated Precipitable Water Vapor (PWV)

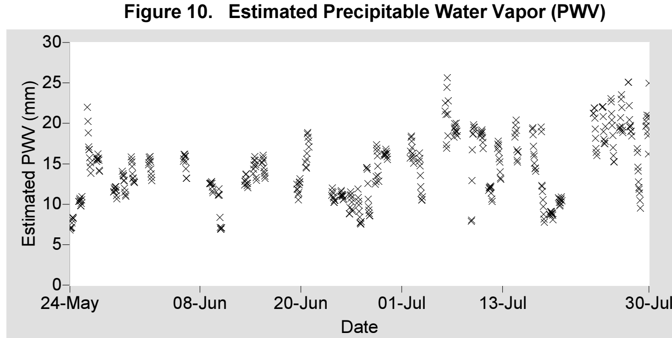


Table 6. Meteorological Observations

Observations	Mean	Min	Max
Temperature (°C)	18.22	4.33	29.39
Humidity (%)	42.75	12.42	96.25
Pressure (mBar)	817.9	808.0	829.2
Est. Precipitable Water Vapor (mm)	14.5	6.6	26.0

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