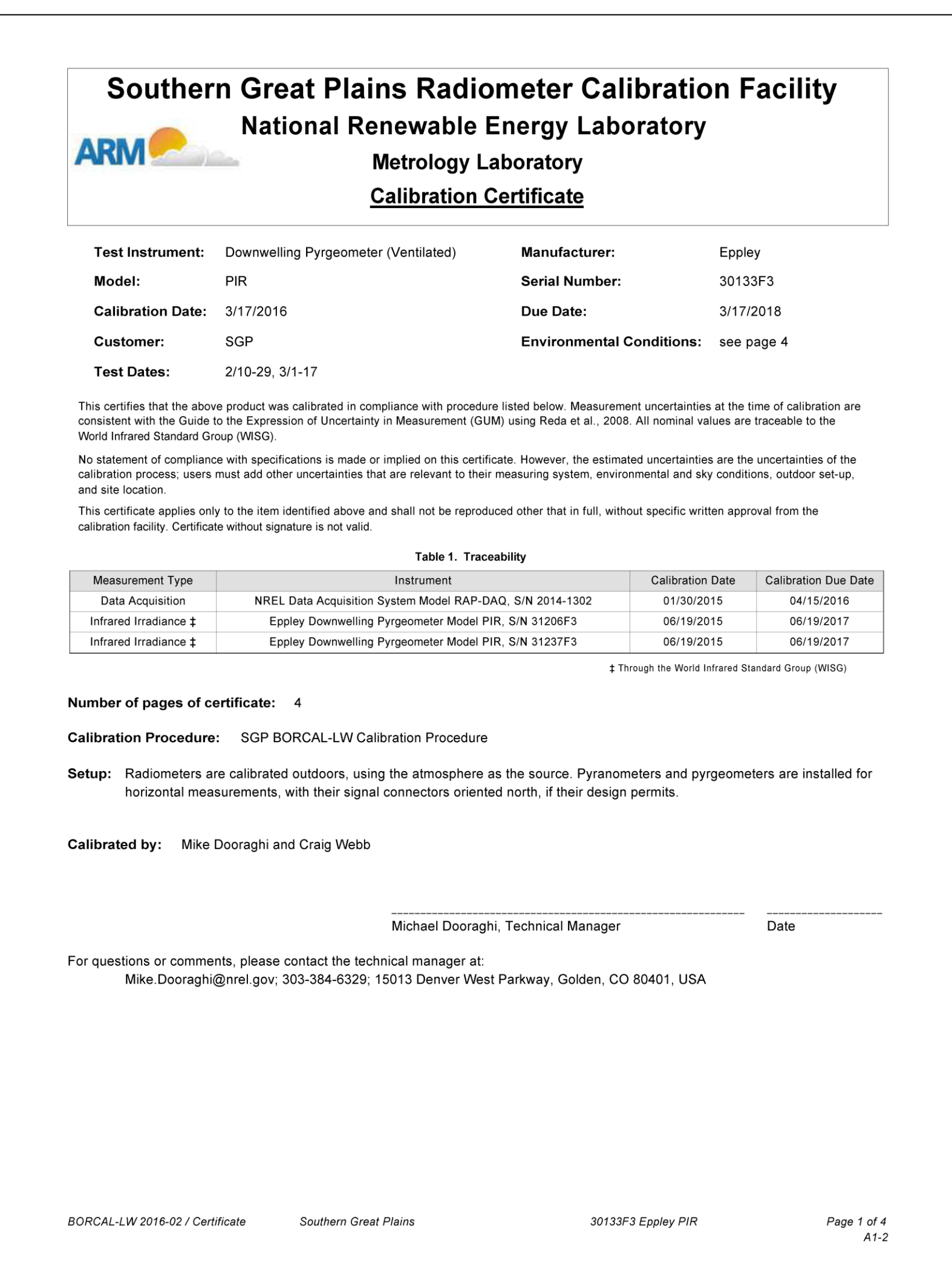


Traceable Pyrgeometer Calibrations

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SGP RCF: Craig Webb

Abstract: The Atmospheric Radiation Measurement (ARM) program provides high quality radiometric data from approximately 150 instruments deployed at Southern Great Plains (SGP), Eastern North Atlantic (ENA), North Slope of Alaska (NSA), Oliktok (OLI), and the ARM Mobile Facilities (AMF) sites. These instruments are deployed on the Solar Infrared Radiation Station (SIRS), SKYRAD, and GNDRAD instrument platforms. In addition to the operational radiometers, there are more than 200 other radiometers that are calibrated and used for instrument swaps and replacements. The National Renewable Energy Laboratory (NREL) and ARM, through the Radiometric Calibration Facility (RCF) at the Southern Great Plains (SGP) site, provides Broadband Outdoor Radiometer Calibrations (BORCAL) for all shortwave (SW) and longwave (LW) radiometers that are deployed by the ARM program. The BORCAL-SW is traceable to the International System of Units (SI), through the World Radiometric Reference (WRR). On the other hand, the SI standard is not yet established for longwave measurements. Both NREL and ARM continue to improve radiometric measurement through the introduction of new methods to reduce uncertainty in calibration and field measurements. A significant part of this effort is to establish the longwave traceability to SI units and deploy the BORCAL-LW using an interim World Infrared Standard Group (WISG) for traceability. Deployment of BORCAL-LW capability has been performed under ARM program ECO-00781, "Establish Pyrgometer Calibrations Traceable to the WISG". The stated purpose of the ECO is to adopt the consensus WISG for calibrating pyrgometers used by ARM for broadband longwave irradiance data collected from SIRS, SKYRAD, and GNDRAD instrument platforms. This poster presents the development, implementation, and operation of the LW-BORCAL system at the SGP RCF for the calibration of pyrgometers that provide traceability to WISG.

Calibration Certificate from BORCAL 2016-02 for PIR 30133F3



Southern Great Plains Radiometer Calibration Facility
National Renewable Energy Laboratory
Metrology Laboratory
Calibration Certificate

Test Instrument: Downwelling Pyrgometer (Ventilated) Manufacturer: Eppley
Model: PIR Serial Number: 30133F3
Calibration Date: 3/17/2016 Due Date: 3/17/2018
Customer: SGP Environmental Conditions: see page 4
Test Dates: 2/10-29, 3/1-17

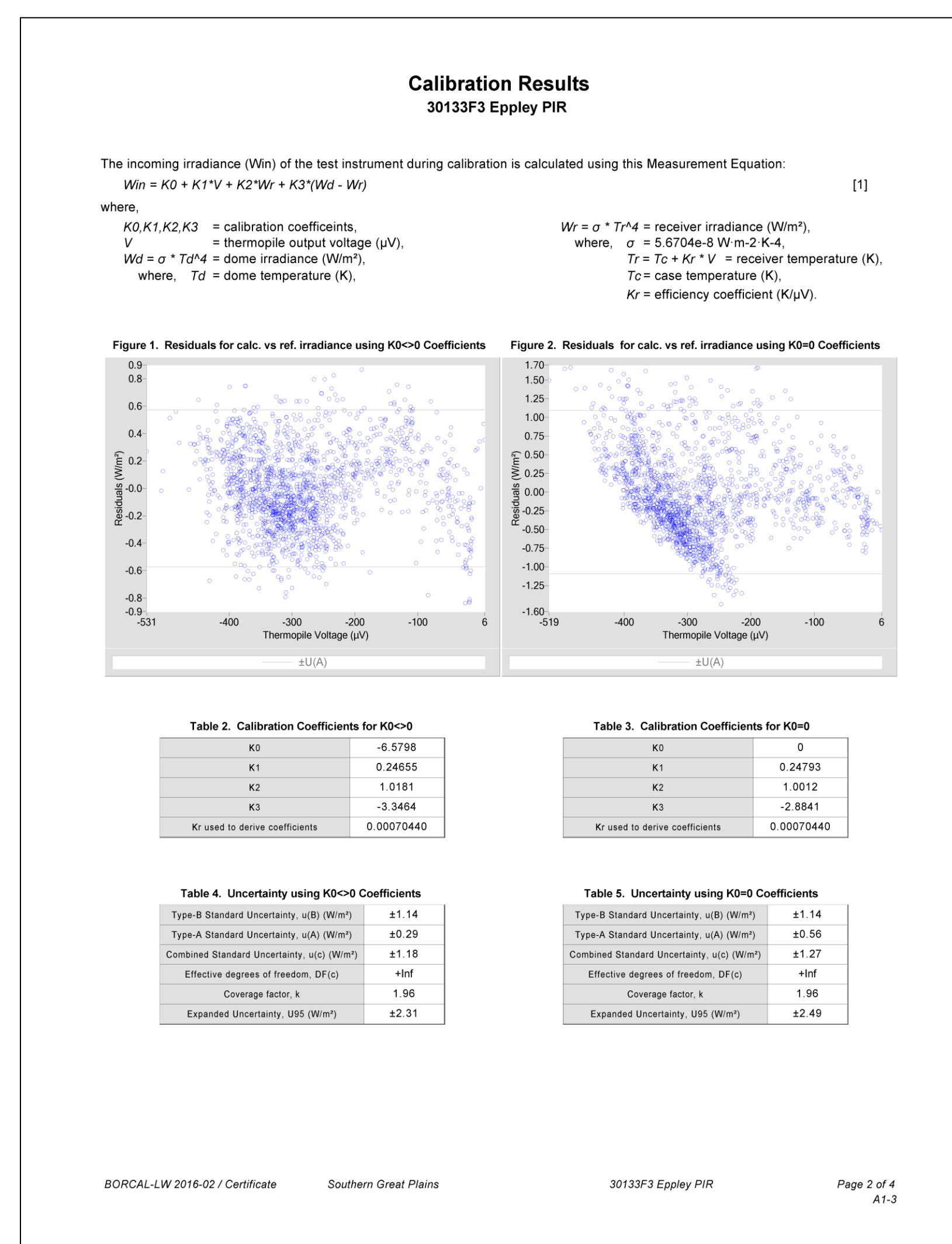
This certifies that the above product was calibrated in compliance with procedures listed below. Measurement uncertainties at the time of calibration are consistent with the Guide to the Expression of Uncertainty in Measurement (GUM) using Reda et al., 2009. All nominal values are traceable to the World 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 site conditions, outdoor setup, and site location.

This certificate applies only to the item identified above and shall not be reproduced other than in full, without specific written approval from the calibration facility. Certificate without signature is not valid.

| Measurement Type | Instrument | Calibration Date | Calibration Due Date |
|-----------------------|---|------------------|----------------------|
| Data Acquisition | NREL Data Acquisition System Model RSP-DAG, S/N 2016-1302 | 01/20/2015 | 04/15/2016 |
| Infrared Irradiance 1 | Eppley Downwelling Pyrgometer Model PIR, S/N 31208F3 | 06/18/2015 | 06/18/2017 |
| Infrared Irradiance 2 | Eppley Downwelling Pyrgometer Model PIR, S/N 31207F3 | 06/18/2015 | 06/18/2017 |

Number of pages of certificate: 4
Calibration Procedure: SGP BORCAL-LW Calibration Procedure
Setup: Radiometers are calibrated outdoors, using the atmosphere as the source. Pyranometers and pyrgometers are installed for horizontal measurements, with their signal connectors oriented north, if their design permits.
Calibrated by: Mike Dooraghi and Craig Webb
Michael Dooraghi, Technical Manager Date
For questions or comments, please contact the technical manager at: Mike.Dooraghi@nrel.gov; 303-384-6329; 15013 Denver West Parkway, Golden, CO 80401, USA



Calibration Results
30133F3 Eppley PIR

The incoming irradiance (W/m^2) of the test instrument during calibration is calculated using this Measurement Equation:

$$W_i = K_0 + K_1 V + K_2 W + K_3 (W - W_i) \quad [1]$$

where:

- K_0, K_1, K_2, K_3 = calibration coefficients
- V = thermopile output voltage (μV)
- $W_i = \sigma T_c^4 + T_c^4 \epsilon + W_{ref}$ = dome irradiance (W/m^2)
- T_c = dome temperature (K)
- T_c = case temperature (K)
- K_3 = efficiency coefficient (K 2 /V)

$W_i = \sigma T_c^4$ = receiver irradiance (W/m^2), where $\sigma = 5.6704 \times 10^{-8} W/m^2 K^{-4}$
 $T_c = \epsilon \sigma T_c^4 + W_{ref}$ = receiver temperature (K)
 T_c = case temperature (K)
 K_3 = efficiency coefficient (K 2 /V)

Figure 1. Residuals for calc. vs ref. irradiance using K0-K3 Coefficients

Figure 2. Residuals for calc. vs ref. irradiance using K0-K3 Coefficients

| Table 1. Calibration Coefficients for K0-K3 | Table 2. Calibration Coefficients for K0-K3 |
|---|---|
| K_0 : -5.7138 | K_0 : 0 |
| K_1 : 0.24655 | K_1 : 5.24753 |
| K_2 : 1.9391 | K_2 : 1.0012 |
| K_3 : -3.3464 | K_3 : -2.8841 |
| K used to derive coefficients: 0.00073440 | K used to derive coefficients: 0.00073440 |

| Table 4. Uncertainty using K0-K3 Coefficients | Table 5. Uncertainty using K0-K3 Coefficients |
|---|---|
| Type A Standard Uncertainty, u_A (W/m 2): 11.14 | Type A Standard Uncertainty, u_A (W/m 2): 17.14 |
| Type B Standard Uncertainty, u_B (W/m 2): 35.20 | Type B Standard Uncertainty, u_B (W/m 2): 65.56 |
| Combined Standard Uncertainty, u_C (W/m 2): 37.18 | Combined Standard Uncertainty, u_C (W/m 2): 71.27 |
| Effective Degrees of Freedom, ν_{eff} : 487 | Effective Degrees of Freedom, ν_{eff} : 487 |
| Coverage Factor, k : 1.96 | Coverage Factor, k : 1.96 |
| Expanded Uncertainty, U (W/m 2): 72.31 | Expanded Uncertainty, U (W/m 2): 139.49 |

Figure 1. Page 1 of the calibration certificate contains the customer and pyrgometer information. It also contains data acquisition and reference pyrgometer tractability information along with the calibration procedure and the technical manager's signature.

Figure 2. Page 2 of the calibration certificate contains the measurement equation with calibration coefficients and constants necessary to calculate the irradiance of the PIR to the sky. Page 2 also contains the residual graphs (as compared to the reference irradiance), calibration coefficients and uncertainty results for both $k=0$ and $k < 0$.

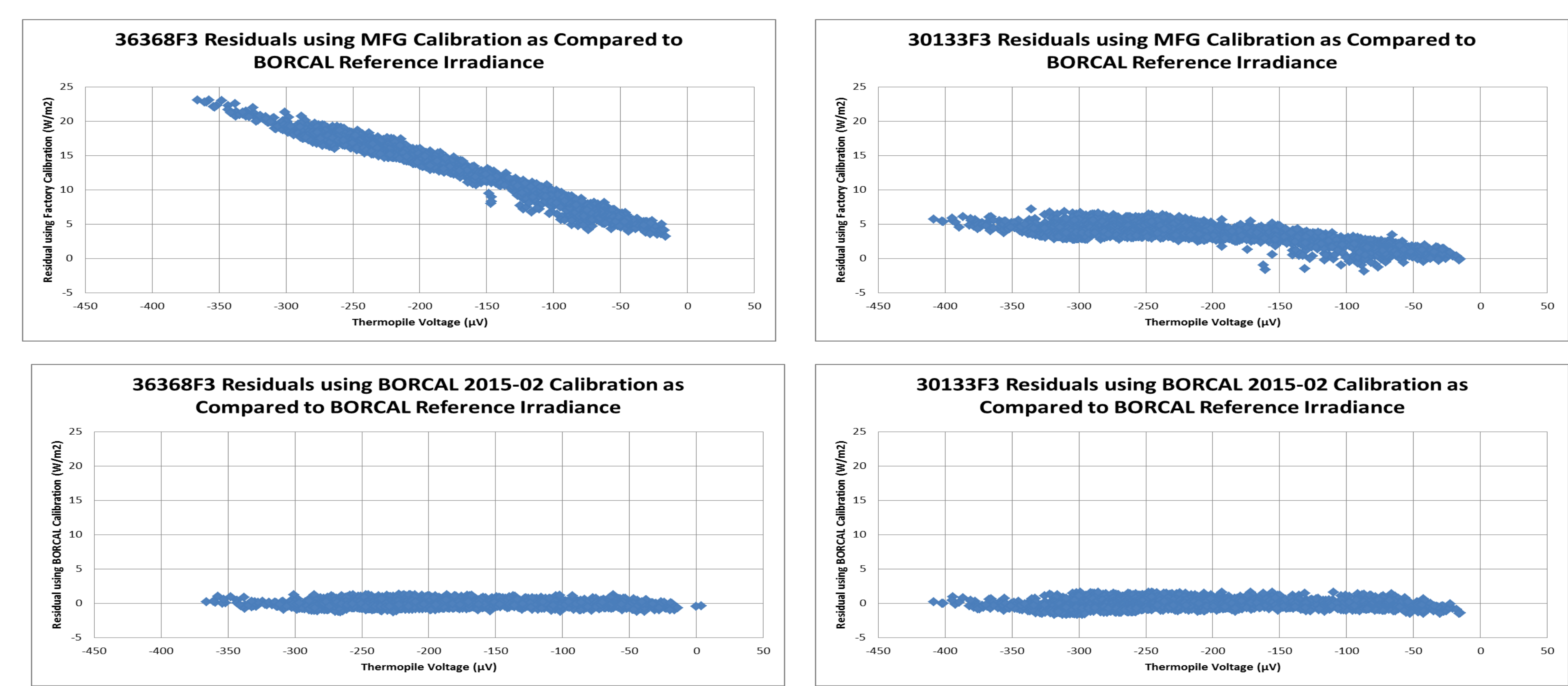


Figure 5. The residual in W/m^2 as compared to the reference instruments ranges from 3.2 to 23.1 for the control instrument (36368F3) and from -1.8 to 7.2 for the measurement assurance standard (30133F3) when using the manufacturer's calibration. The residual in W/m^2 as compared to the reference instruments ranges from -1.3 to 1.3 for the control instrument (36368F3) and from -1.6 to 1.6 for the measurement assurance standard (30133F3) when using the BORCAL-LW calibration.

Control Instrument History

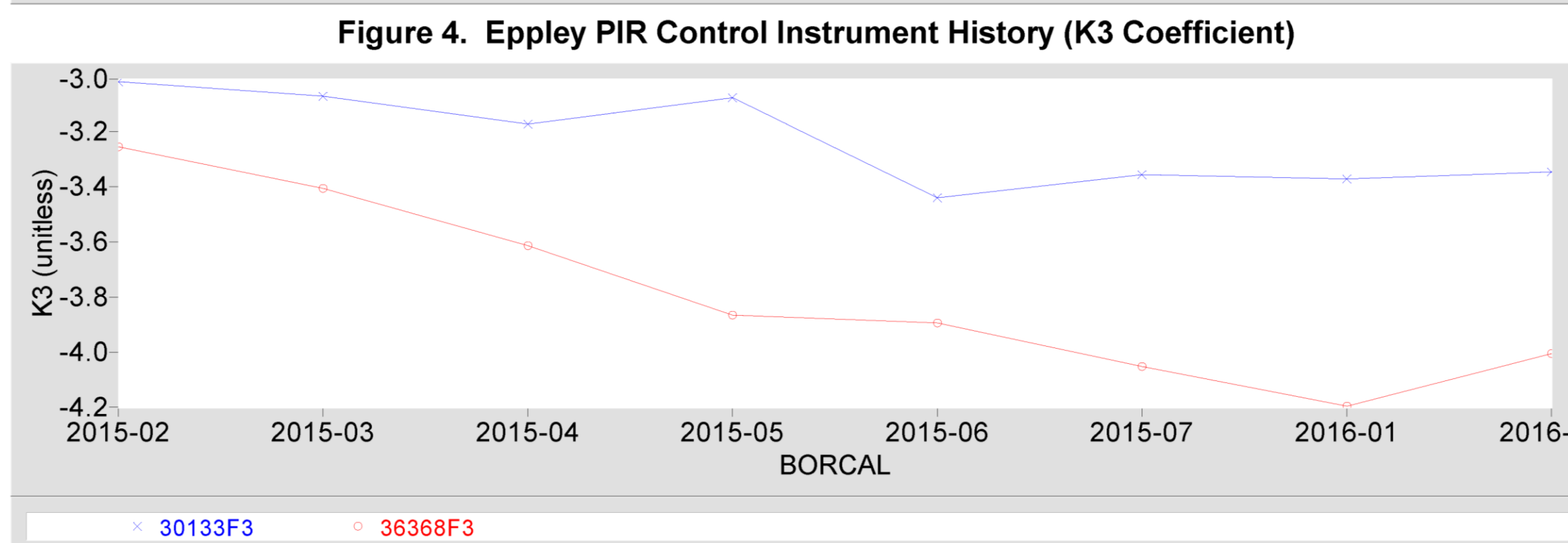
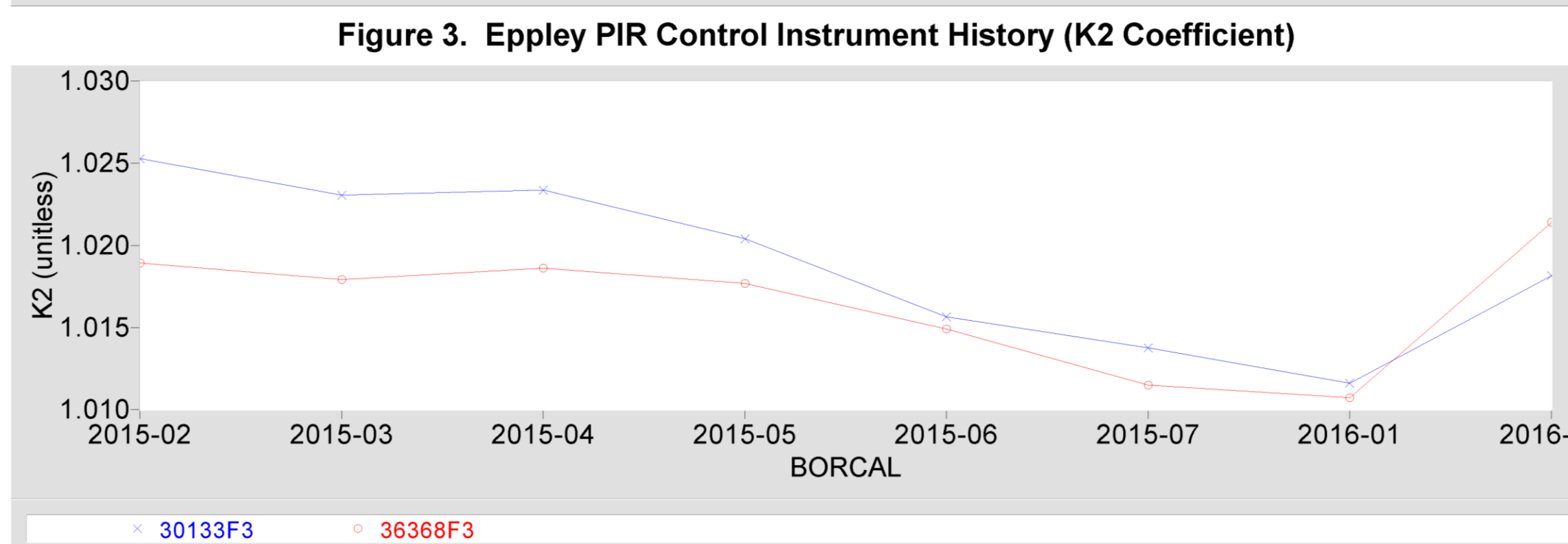
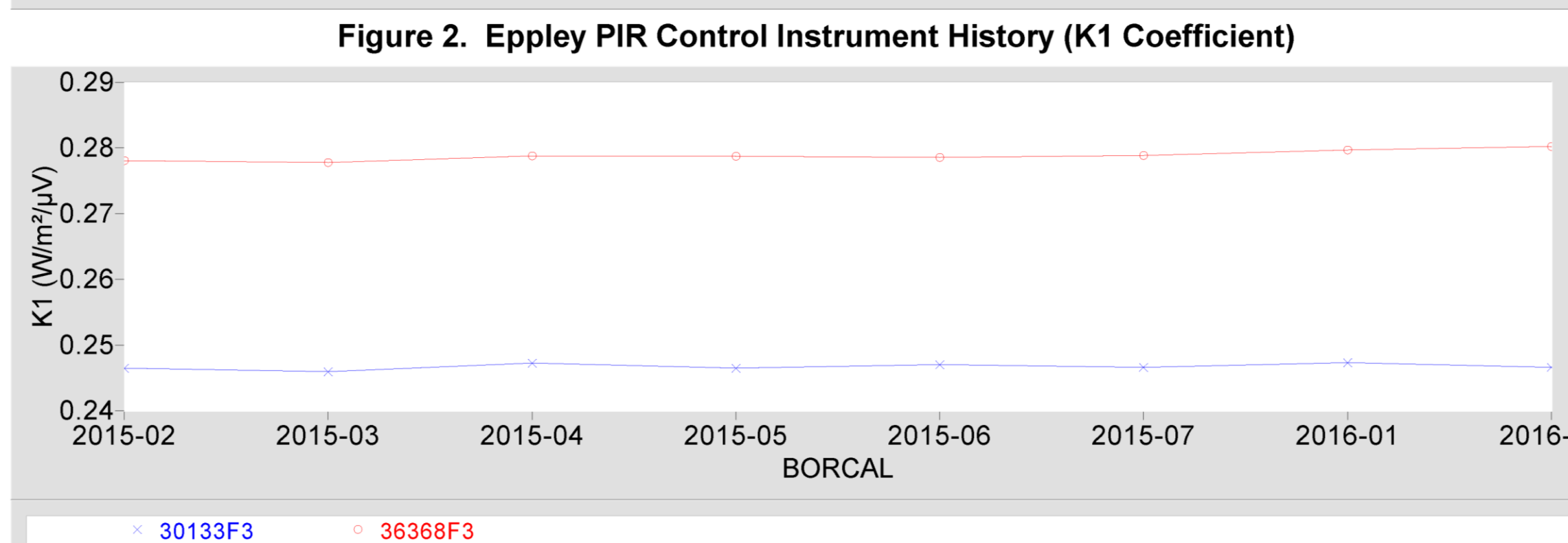
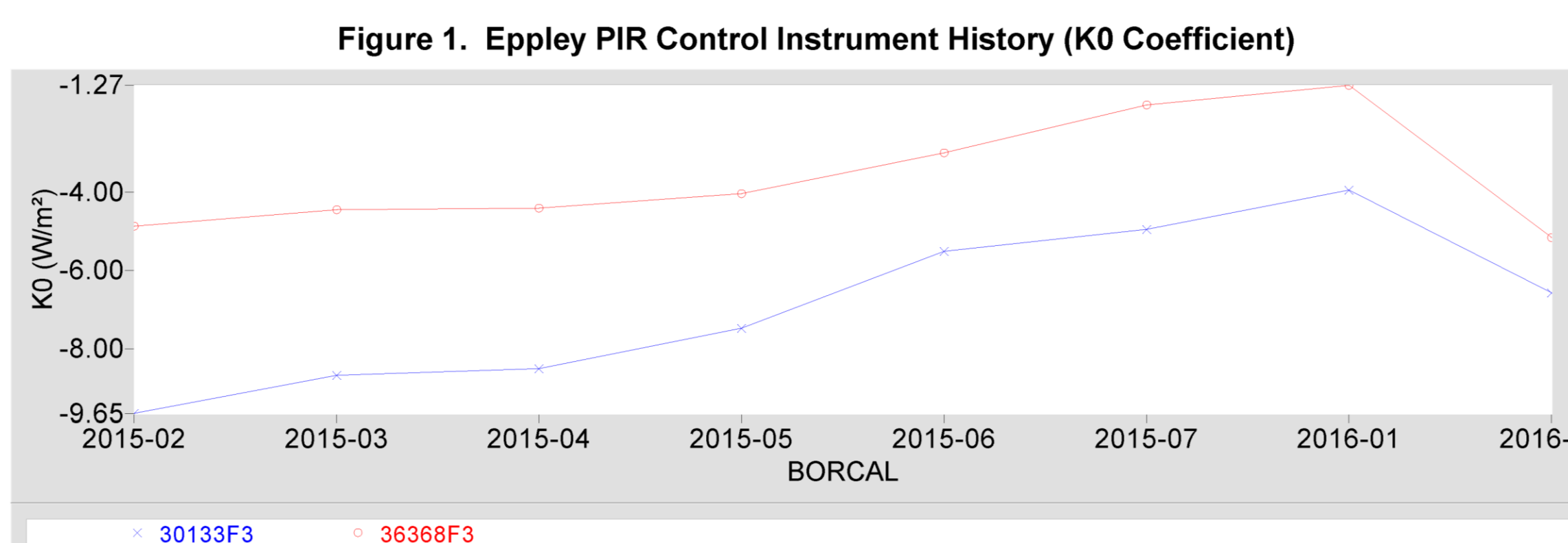


Figure 7. Results are from 8 LW BORCAL events for the control instrument (36368F3) and the Measurement Assurance Standard (30133F3) are shown above.



Figure 6. Craig Webb installing Pyrgometers on one of the LW trackers at the SGP RCF.

Metrics for LW calibrations from July 2015 to March 2016

- Total number of Instruments : 92
- Total individual Instruments : 81
- Total failed calibrations: 8 (Most of these were later linked to a failed channel)
- Average Uncertainty: $\pm 2.31 W/m^2$
- Highest Uncertainty: $\pm 2.59 W/m^2$
- Lowest Uncertainty: $\pm 2.26 W/m^2$
- Average number successful calibrations per session: 11.75
- Average length of time for BORCAL-LW to complete: 30.6 days
- Shortest BORCAL-LW event: 17 days
- Longest BORCAL-LW event: 44 days
- Current range of K0 values for all successfully calibrated instruments: -9.6467 to 4.0452
- Current range of K1 values for all successfully calibrated instruments: 0.2152 to 0.34601
- Current range of K2 values for all successfully calibrated instruments: 0.9929 to 1.0253
- Current range of K3 values for all successfully calibrated instruments: -5.1028 to 0.00087

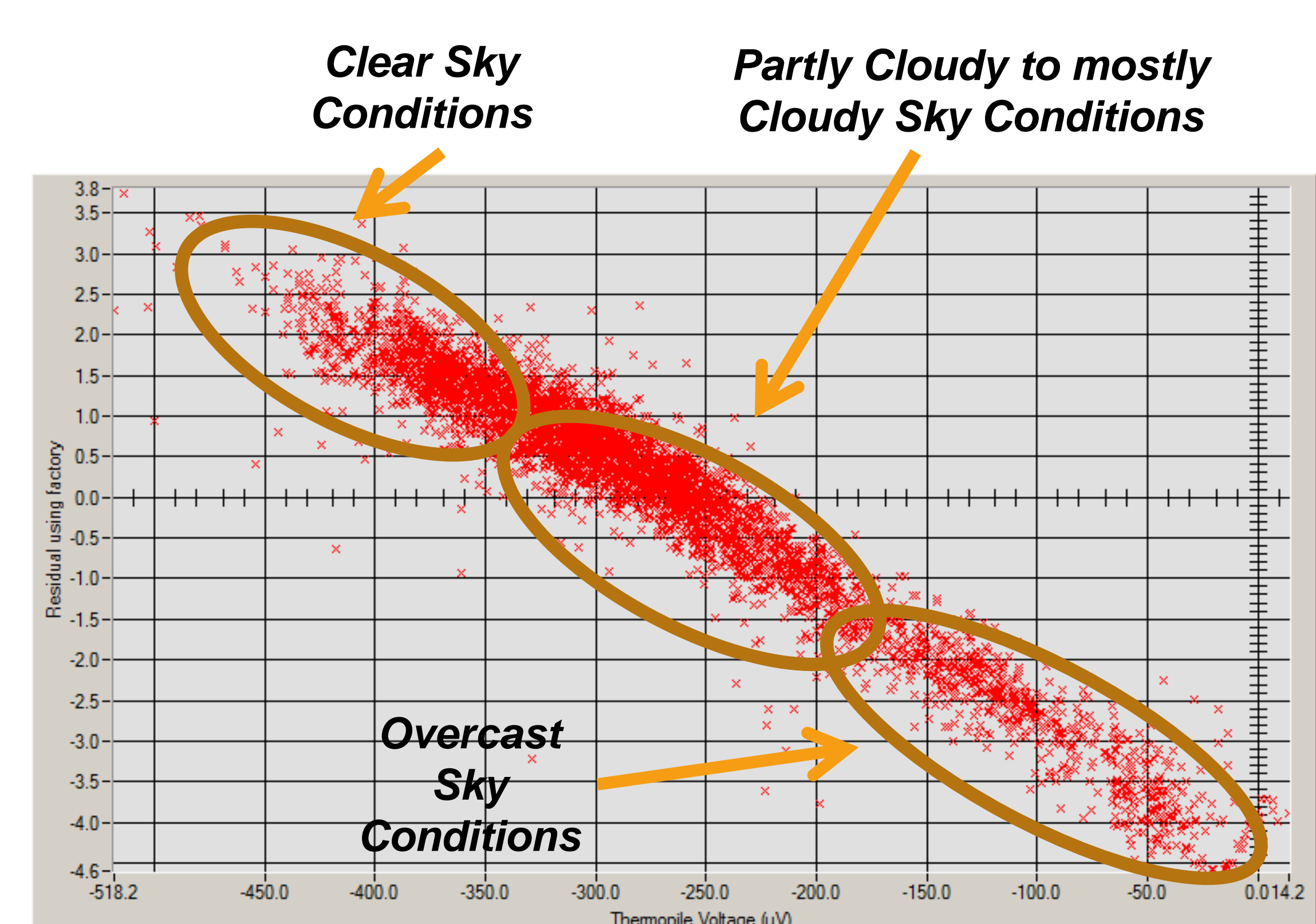
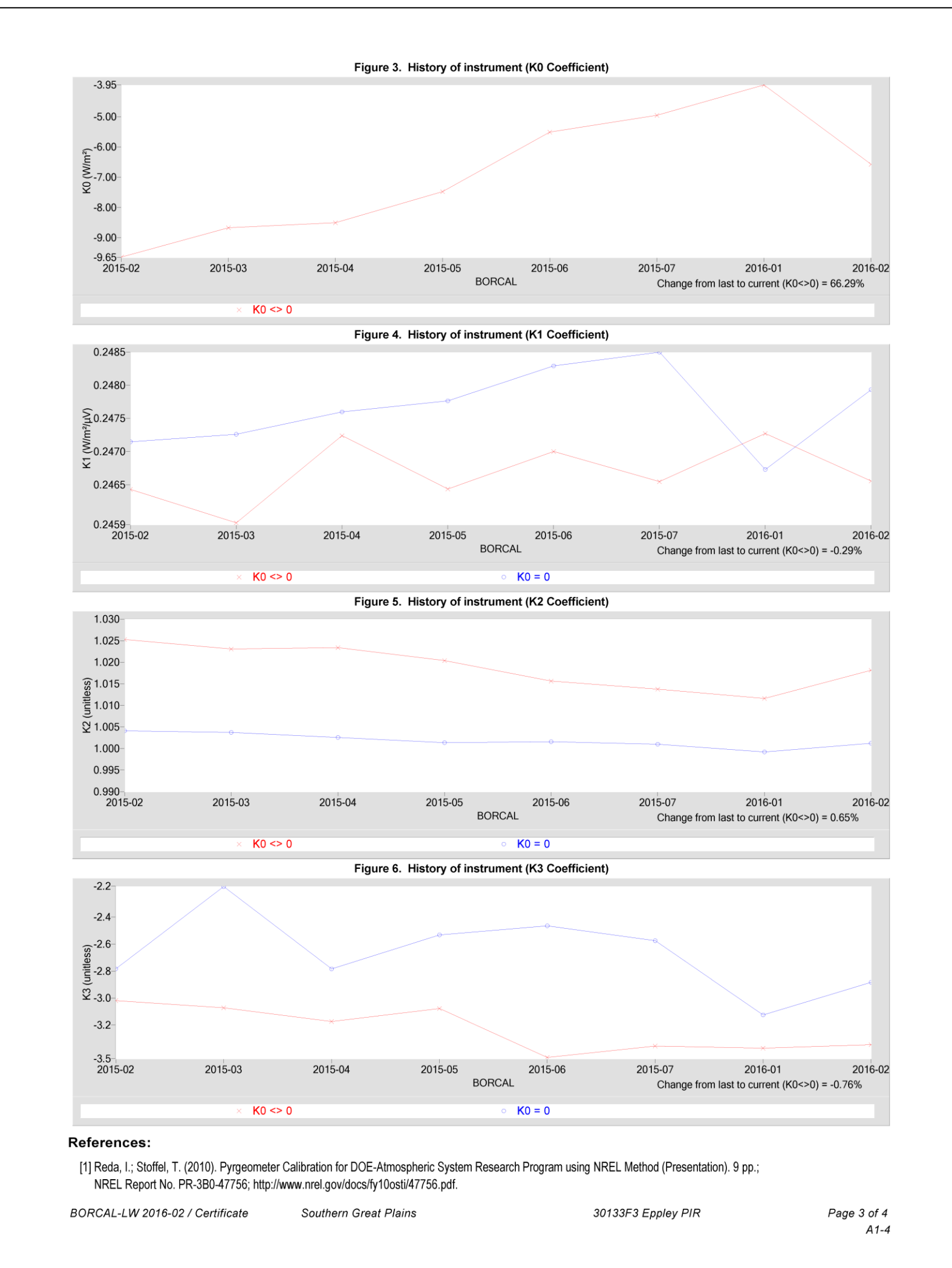


Figure 4. The LW BORCAL can be concluded once data has been collected under all sky conditions. This allows for calibration over the full voltage output range. The above graph shows the residuals in the between the reference irradiance and the instrument irradiance using the factory calibration.

Documentation of the longwave and shortwave BORCAL processes conducted at SGP can be found here: <http://www.nrel.gov/docs/fy15osti/65035.pdf>
Documentation of the Radiometer Calibration and Characterization (RCC) software can be found here: <http://www.nrel.gov/docs/fy16osti/65844.pdf>

This work was supported by Argonne National Laboratory MPO No. 2T-30084 and the U.S. Department of Energy under Contract No. DE-AC36-08-GO28308 with the National Renewable Energy Laboratory