Pyrgeometer Calibrations for the Atmospheric Radiation Measurement Program: Updated Approach

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Introduction

Accurate measurements of the broadband longwave irradiance at wavelengths between 3.5 and 50 microns are important for understanding the total energy balance at the earth's surface. Atmospheric Radiation Measurement (ARM) Program has acquired more than 100 pyrgeometers, a type of radiometer used for these measurements, for deployment in the Solar and Infrared Stations, SKYRAD, GNDRAD, and METRAD platforms at the Southern Great Plains (SGP), Tropical Western Pacific, ARM Mobile Facility installations, and the Unmanned Aerospace Vehicle program. Proper calibration of these pyrgeometers is essential for producing accurate measurements of downwelling and upwelling longwave irradiance consistent with ARM research goals.

The calibration of ARM pyrgeometers continues to be a topic of intense research to achieve the goal of accurate field measurements that are traceable to a recognized reference standard. The original EPLAB factory calibrations were used for all initial ARM pyrgeometer deployments. Between 2002 and 2004, all SKYRAD, GNDRAD, Solar and Infrared Stations, and BRS pyrgeometers were calibrated using the then newly-developed National Renewable Energy Laboratory (NREL) Pyrgeometer Blackbody Calibration System. Recent results of data analyses by the Broadband Heating Rate Profile, including the Longwave Quality Measurement Experiment comparisons involving the Atmospheric Emitted Radiation Interferometer (AERI), indicated a significant and consistent pyrgeometer measurement bias of about -12 $Wm^{-2} \pm 5$ Wm^{-2} under clear-sky conditions. By March 2006, the resulting BCR-01162, *Remove Pyrgeometer Calibration Bias*, returned all pyrgeometer calibration values for field measurements to the original EPLAB thermopile sensitivities and dome correction factors set to 4.0 as originally deployed until the pyrgeometer calibration issues could be resolved.

Here, we provide some background, present examples of recent research results, and suggest a modification to our original approach for pyrgeometer calibration (Reda et al. 1999, Reda et al. 2003).

Pyrgeometer Calibration Basics

As shown in Figure 1, pyrgeometers are designed to measure the net longwave irradiance between about 3.5 and 50 microns at the detector surface. The net longwave irradiance (W_{net}) in Watts per square meter can be determined from pyrgeometer outputs:

$$W_{net} = W_{in} - W_{out} + \Delta W \quad [1]$$

where,

W_{in} = Incoming irradiance = $\varepsilon_{sky}\, \sigma\, T^4_{sky}$
W_{out} = Outgoing irradiance = $\varepsilon_{receiver}\, \sigma\, T^4_{receiver}$
ΔW = Pyrgeometer dome effect,
= $\varepsilon_{case}\, \sigma\, T^4_{case} - \varepsilon_{dome}\, \sigma\, T^4_{dome}$

and,

ε = emissivity
T = temperature (K)
σ = Stefan-Boltzmann Constant 5.67 E-08 (Wm^{-2}/K^{-4})

Rearranging equation (1) using the pyrgeometer calibration coefficients (K) and available measurement parameters (thermopile output voltage, V_{tp} and temperatures of the instrument case, T_{case}, and interference filter, T_{dome}) the incoming longwave irradiance (W_{in}) can be computed in several ways (Reda et al. 2002, Reda et al. 2003):

Traditional (2-coefficients)

$$W_{in} = K_1\, V_{tp} + \sigma T^4_{case} + K_3\, \sigma\, (T^4_{dome} - T^4_{case}) \quad [2]$$

Albrecht & Cox (3-coefficients)

$$W_{in} = K_1\, V_{tp} + K_2\, \sigma T^4_{case} + K_3\, \sigma\, (T^4_{dome} - T^4_{case}) \quad [3]$$

Figure 1a. Three Eppley Model precision infrared radiometer (PIR) pyrgeometers mounted in ventilators on a solar tracker to provide shading of direct shortwave (solar) radiation. Each PIR has a thermopile detector under a protective hemispheric interference filter transparent to longwave radiation (3.5 to 50 microns).

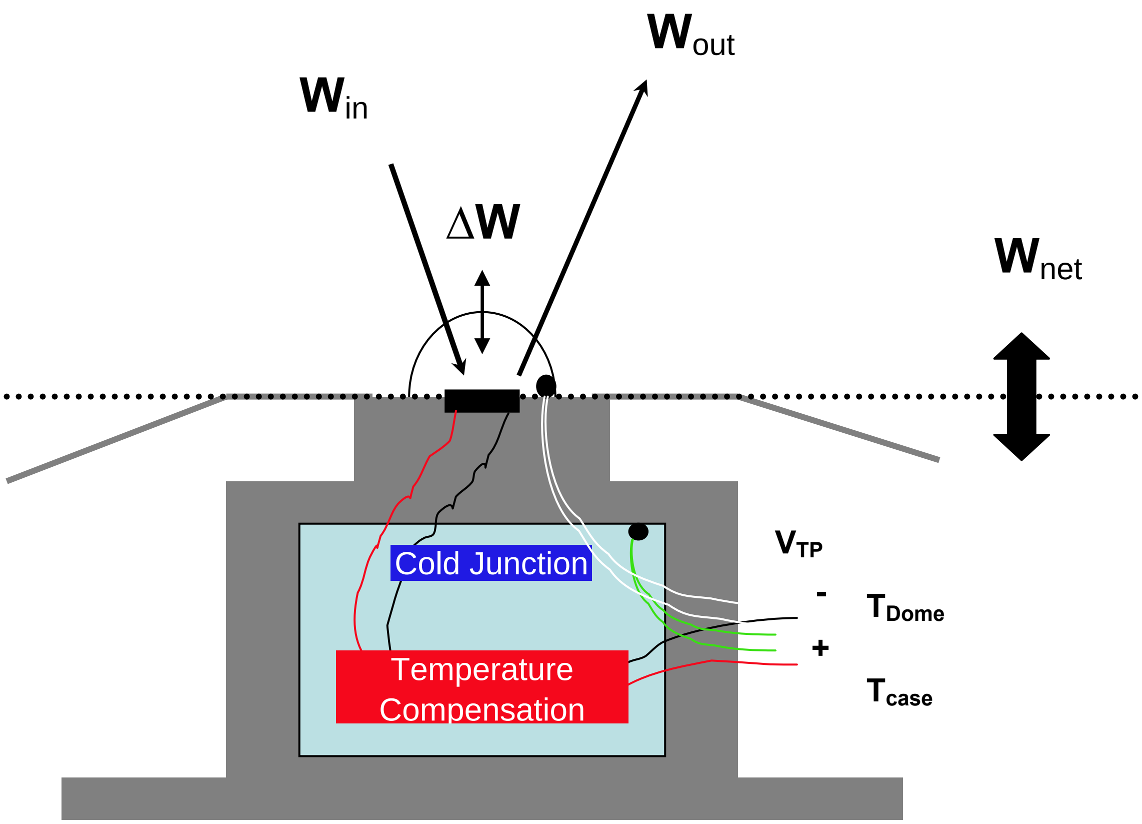

Figure 1b. Concept of infrared flux balance at the pyrgeometer thermopile detector and locations of thermistors used to measure case and dome temperatures.

Philipona et al. (3-coefficients)

$$W_{in} = K_1 V_{tp} + \sigma T^4_{case} + K_3 \sigma (T^4_{dome} - T^4_{case}) + K_4 \sigma V_{tp} T^3_{case} \quad [4]$$

Reda et al. (4-coefficients)

$$W_{in} = K_0 + K_1 V_{tp} + K_2 \sigma T^4_{receiver} + K_3 \sigma (T^4_{dome} - T^4_{receiver}) \quad [5]$$

where,

$$T_{receiver} = T_{case} + 0.0007044 V_{tp}$$

Determining the pyrgeometer thermopile detector sensitivity (K_1) and dome correction factor (K_3) are common to all methods. The case emissivity is assumed to be 1.0 or included with K_2 or K_4 depending on the approach. A general offset term (K_0) is included in equation 5 to capture any transducer output signals in the absence of longwave irradiance stimulation. Equations 4 and 5 also include approximations to account for possible differences between case temperature (a pyrgeometer output signal) and the effective receiver temperature (the basis for measuring net irradiance).

Prior to the International Pyrgeometer and Absolute Sky-scanning Radiometer Comparisons (IPASRC-I & II) in 1999 and 2002 [Philipona et al. 2001 and Marty et al. 2003] low-temperature blackbody sources were used to calibrate pyrgeometers. With the advent of an Absolute Sky-scanning Radiometer, outdoor measurements are now part of the World Infrared Standard Group (WISG) development (see Figure 2).

The method of calibration and data reduction determines the types of pyrgeometer calibration coefficients. Pyrgeometer blackbody calibrations present two major challenges:

1. The blackbody radiance field viewed by the pyrgeometer should match spectral and angular distributions of the natural sky, and

2. The effective blackbody temperature must be known accurately and account for any thermal exchange between the blackbody and the pyrgeometer that could affect the accuracy of determining the blackbody (source) reference temperature.

The first challenge is addressed by the blackbody design, e.g., relative size, shape, and materials used in the blackbody construction to achieve proper emissivity and temperature field characteristics. See Figure 3 for the ARM design features.

The second challenge can be addressed by operational considerations. Varying the blackbody temperature while maintaining constant pyrgeometer case and dome temperatures provides an opportunity to compute thermopile detector sensitivity (K_1). EPLAB procedures require the PIR remain at room temperature for at least 24 hours prior to rapid exposures (a few minutes to acquire stable measurements) at two fixed blackbody temperatures (15°C and 5°C) (Kirk 2005). National Oceanic and Atmospheric Administration (NOAA) also uses a "transient" pyrgeometer exposure method that includes data collection during the warming of a large cylindrical blackbody copper mass from -50°C to room temperature (Dutton 1995). The NREL system used for ARM pyrgeometer calibrations is designed to collect calibration data during controlled temperatures of the blackbody and pyrgeometer case (Reda et al. 2003).

Figure 2a. WISG under development at the World Radiation Center in Davos, Switzerland.

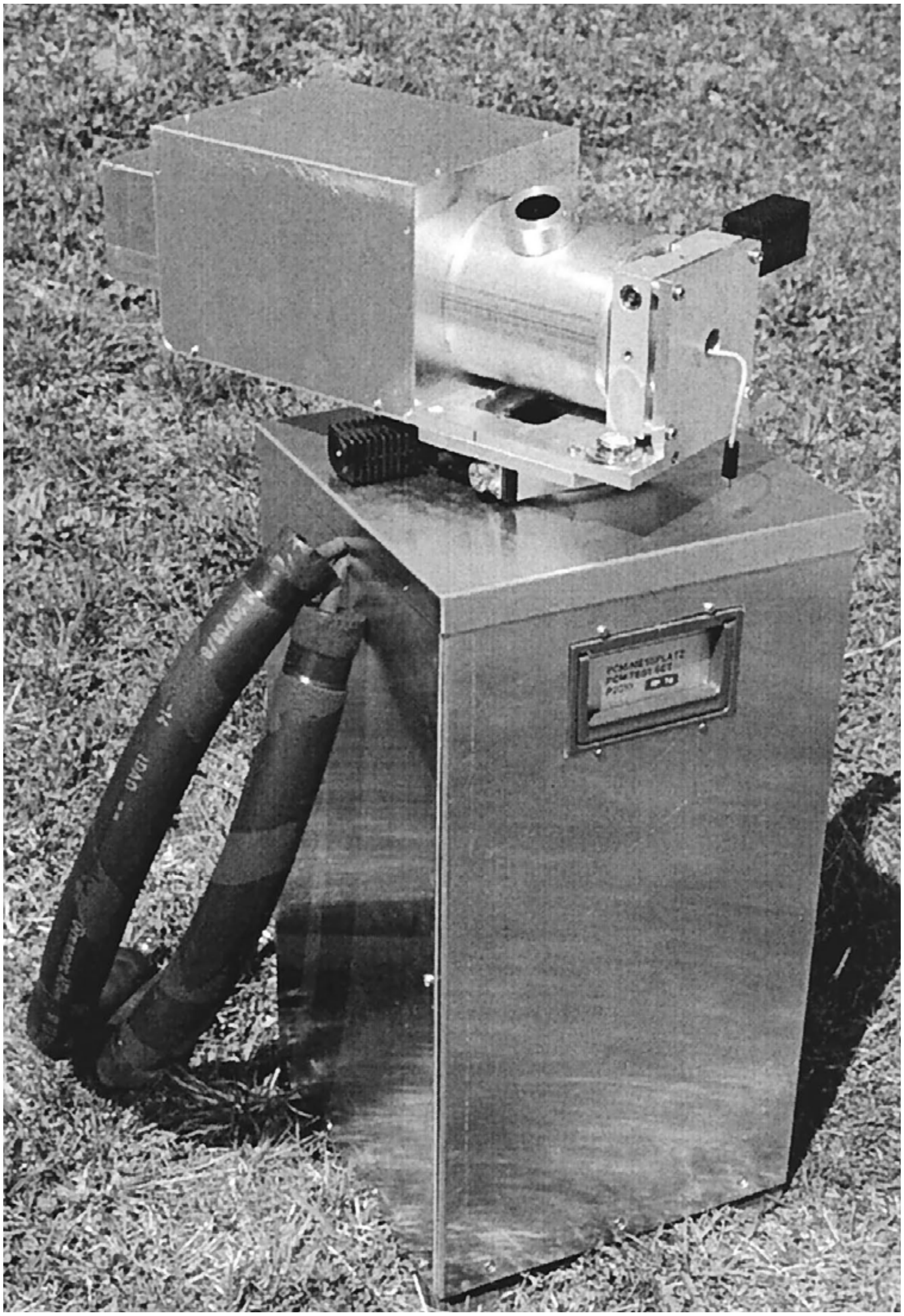

Figure 2b. Absolute Sky-scanning Radiometer developed by Rolf Philipona and others at the World Radiation Center in Davos, Switzerland.

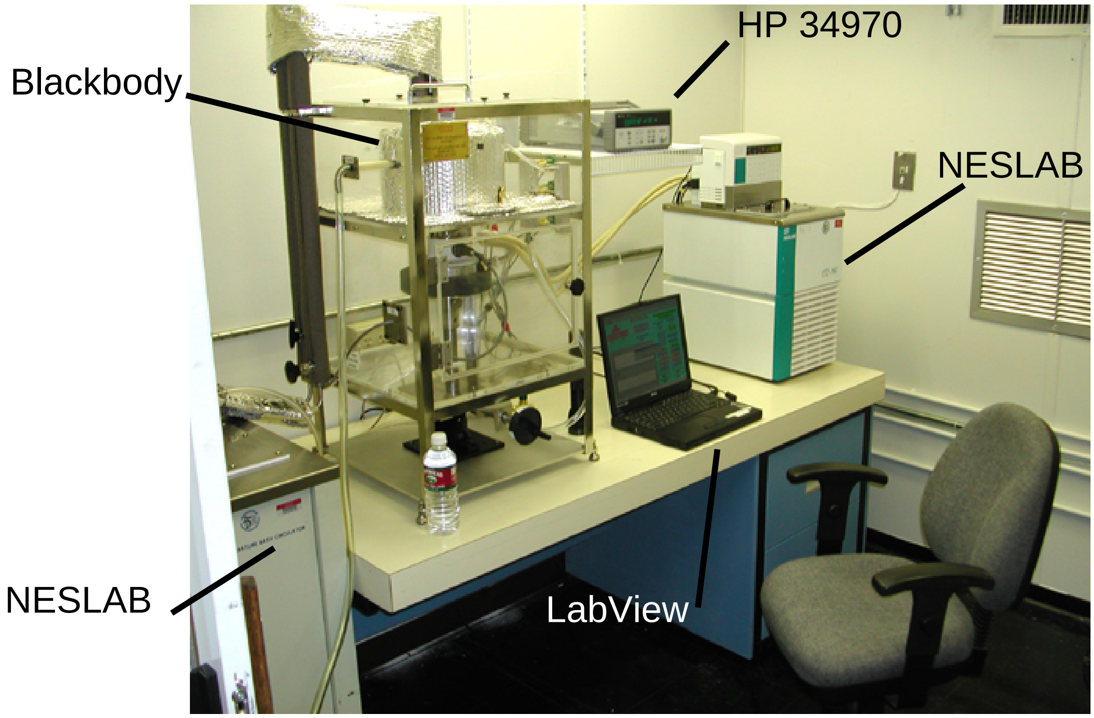

Figure 3a. Pyrgeometer Blackbody Calibration System installed at the SGP Radiometer Calibration Facility. Two temperature-controlled Neslab circulators are used to maintain pyrgeometer case and blackbody source temperatures during calibration. A dry air generator (not shown) maintains low moisture levels within the blackbody enclosure to prevent dew and frost accumulation on the pyrgeometer.

Figure 3b. Close-up of PIR beneath blackbody completion hemisphere. PIR dome is fully inserted during calibration data acquisition.

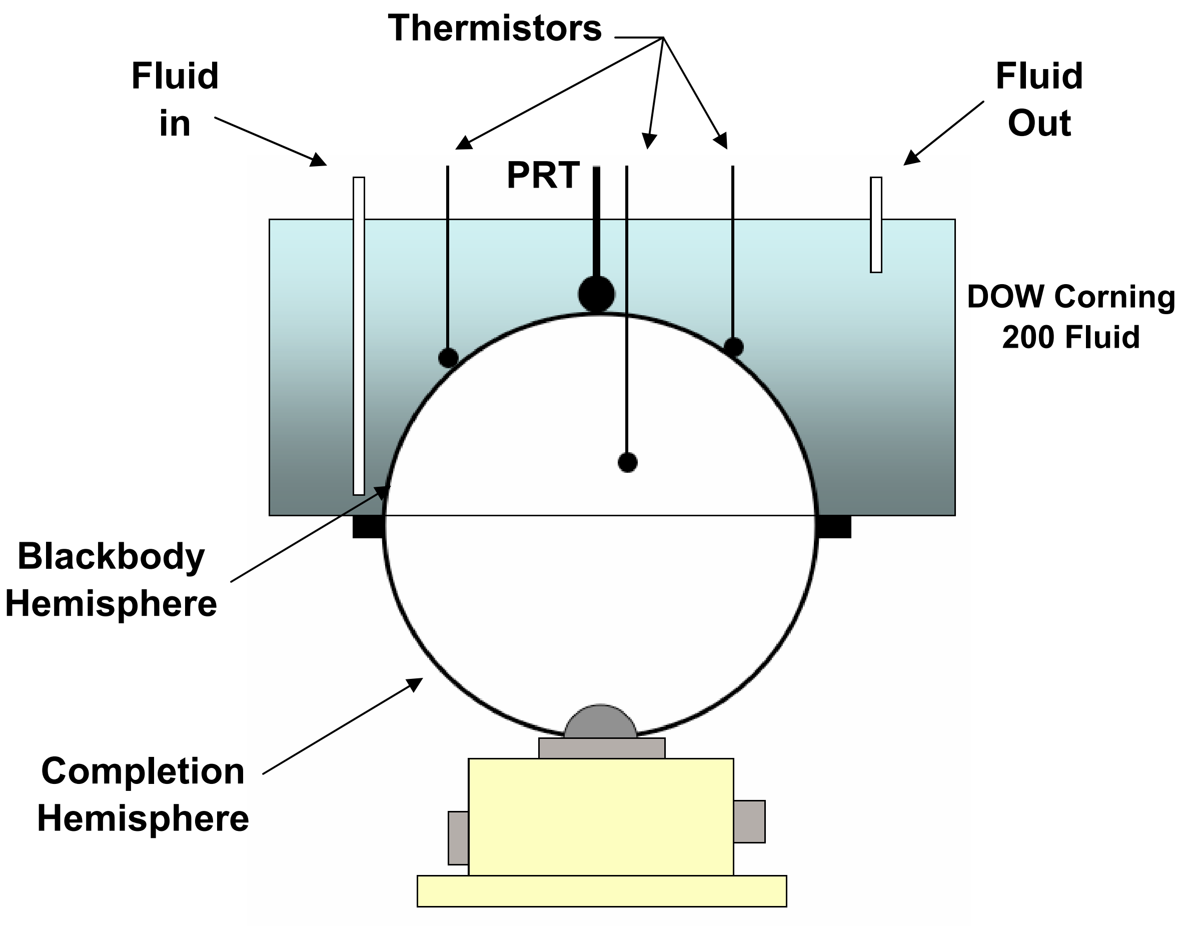

Figure 3c. Blackbody operation schematic showing location of platinum resistance thermometer, thermistor temperature probes, and other key components including a pyrgeometer at the base of the system.

Current Research Issues

The outdoor measurement precision with respect to a group mean was improved for 12 ARM pyrgeometers calibrated with the NREL blackbody system (see Figure 4), but the calibration method introduced a significant clear-sky bias compared with AERI and longwave Quality Measurement Experiment data (see Figure 5). This discrepancy has prompted additional research at our collective facilities and the calibration of several pyrgeometers belonging to ARM, NREL, and NOAA at the World Radiation Center (WRC).

At NREL, temperature gradients of 1°C to 2°C have been measured between the top and middle of the blackbody in the NREL system for fluid operating temperatures below -15°C. The addition of a mechanical stirring device reduced the blackbody vertical temperature gradient to an average of less than 0.2°C, but adversely effected the outdoor measurement precision as shown in Figure 6. These comparisons are based on outdoor data collected at the WRC from July 29 to November 21, 2005 as part of the calibration of NREL references. Applying the original 4-coeffients determined from the stirred blackbody calibration to the WRC data reduces the clear-sky bias when compared with WSIG references, but introduces a 15 Wm^{-2} scatter in irradiances for partly-cloudy to overcast conditions. Results of applying various calibration coefficients (Equation 5) based on the method for determining the blackbody reference temperature (T_{bb}) are also presented in Figure 6. Clear-sky biases appear from these data to range from nearly +20 Wm^{-2} for T_{bb} based on the platinum resistance thermometer (PRT) at the top of the blackbody hemisphere to +5 Wm^{-2} for T_{bb} based on the maximum of the four blackbody temperature probes (fluid not stirred).

Figure 7 shows the differences between a CG4 calibrated by the WRC and PIR 31196F3 deployed outdoors at NREL in January 2006. The NREL calibration results for this PIR were based on a combination of sources. NREL blackbody system measurements (fluid not stirred and T_{bb} computed from the average of four probes) were used to determine K_0 and K_3 for the PIR. K_1 and K_2 were modified to match outdoor comparisons at NREL with a CG4 previously calibrated at the WRC. Both pyrgeometers were ventilated and shaded from direct solar radiation. The comparison data shown in Figure 7 were based on equation 5 for the PIR and equation 4 for the CG4. The results suggest such a hybrid calibration approach (blackbody and outdoor comparisons with the WISG) can produce +/-2.5 Wm^{-2} agreement by a field pyrgeometer.

EPLAB has been studying the effects of transient vs. controlled, steady state plateaus for blackbody and pyrgeometer case temperatures during the calibration process. The time-response of PIR 13985F3 is shown in Figure 8.

NOAA has been studying the outdoor performance of a number of pyrgeometers, including some recently calibrated at the WRC, when deployed with and without ventilation or sun shading. The benefits of three dome thermistors in a PIR were also investigated. Selected data presentations are shown in Figures 9 and 10.

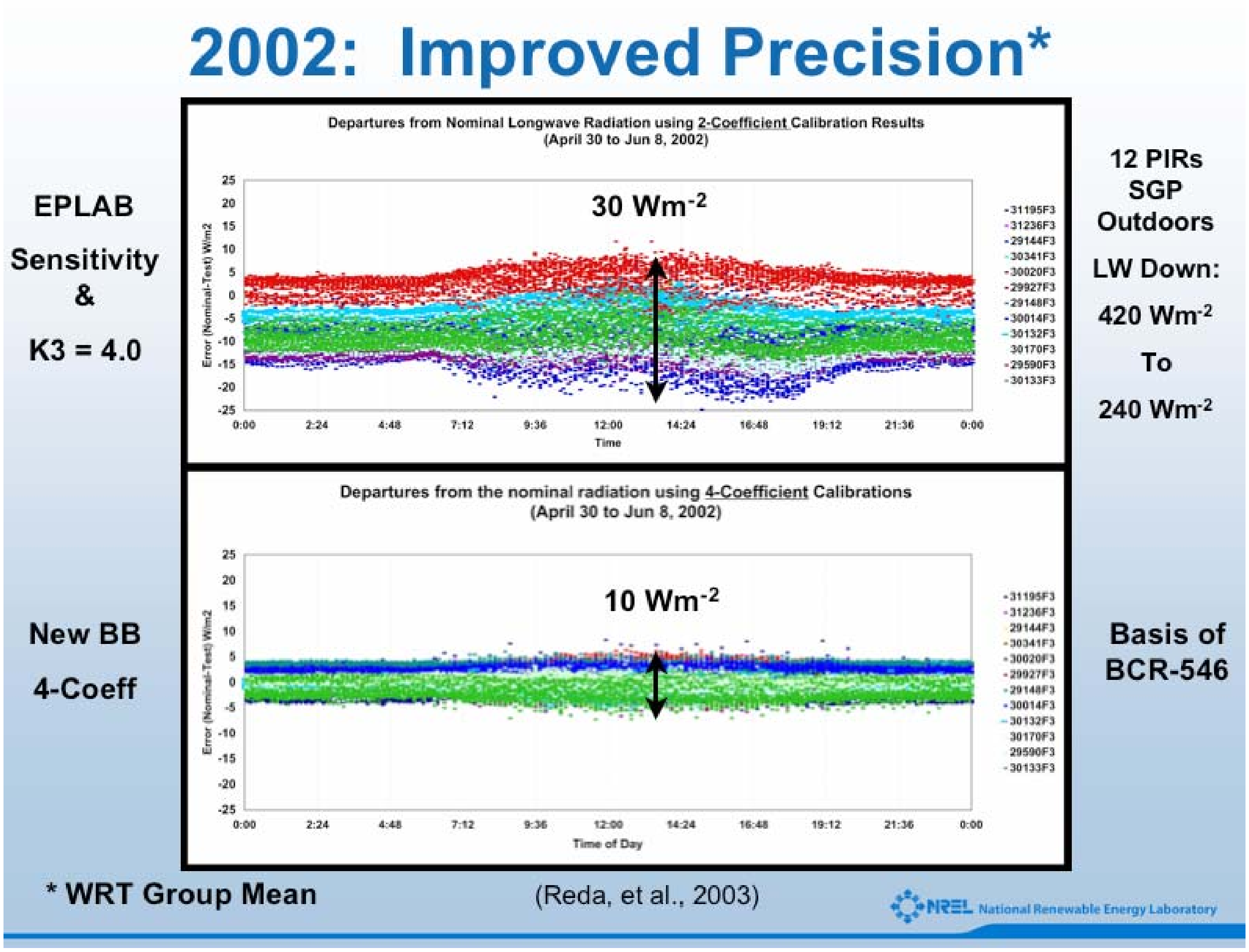

Figure 4. Outdoor comparison of 12 PIRs deployed at the SGP Radiometer Calibration Facility from April 30 to June 8, 2002. Diurnal comparisons of factory calibration and fixed dome correction factor (K3) applied to measurements (upper plot) and NREL coefficients determined from new blackbody system (lower plot) resulted in BCR-00546 implementing four-coefficient PIR calibrations for the ARM Program.

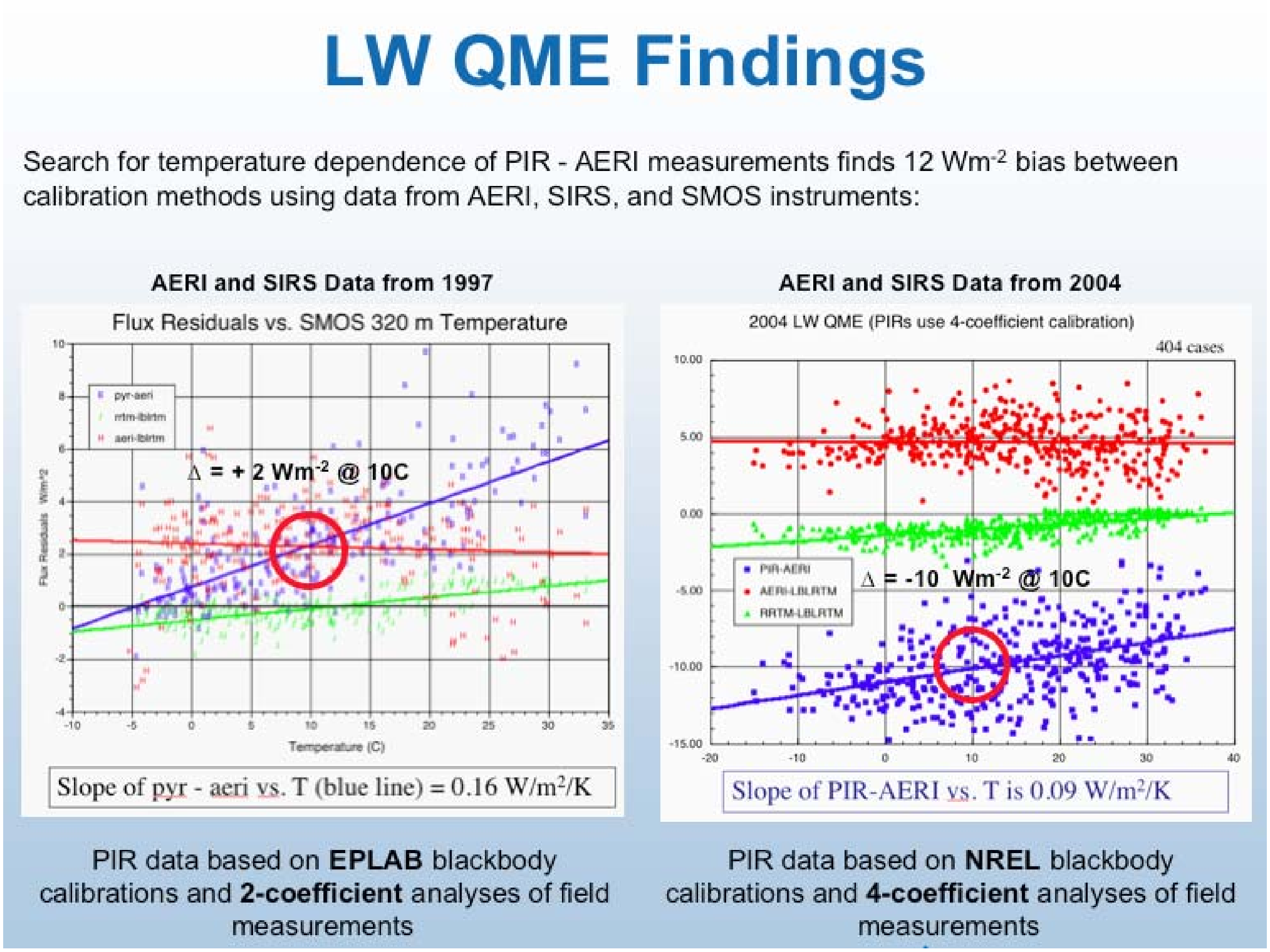

Figure 5. Comparing the effects of original factory calibrations used prior to 2003 (left plot) and new four-coefficient calibrations (right) on comparisons with AERI instrument indicates a 12 Wm^{-2} measurement bias.

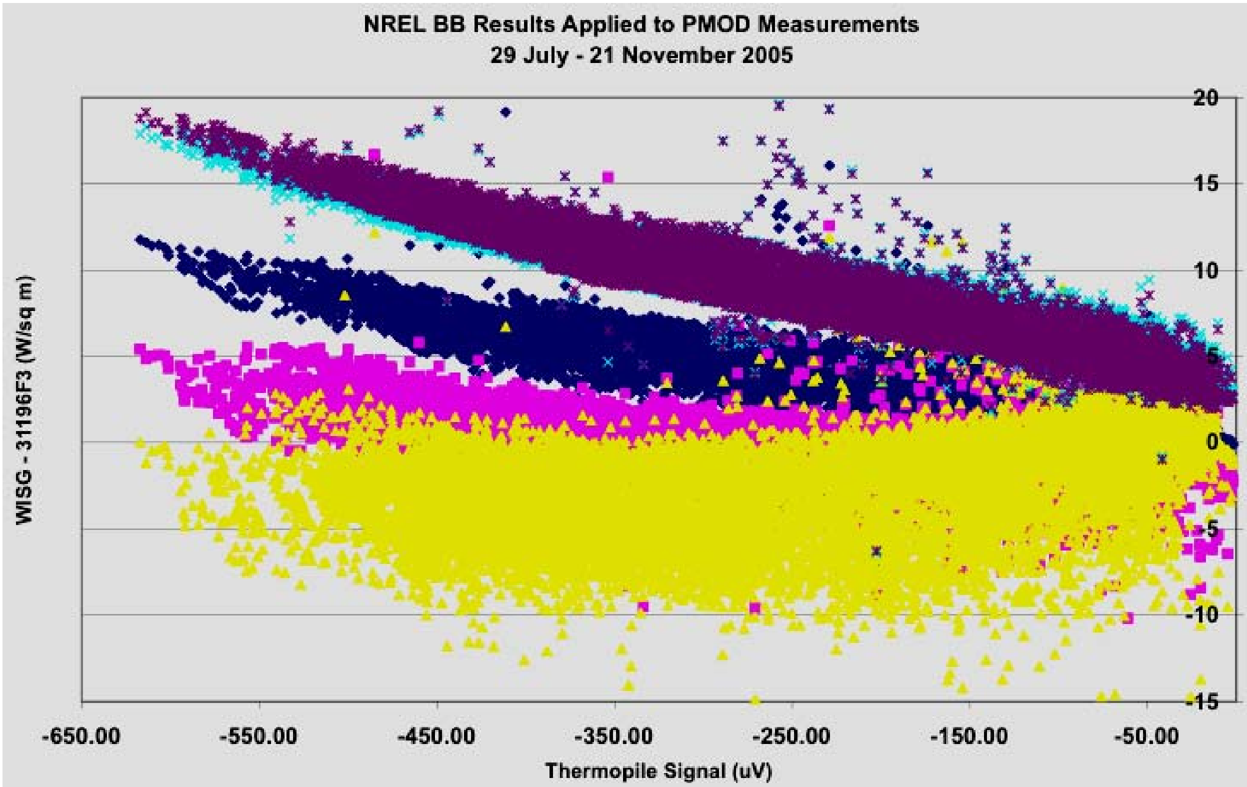

Figure 6. Applying various NREL blackbody system calibration results for PIR 31196F3 to outdoor data collected at the World Radiation Center from July 29 to November 21, 2005. Blackbody reference irradiance computed from (top to bottom groupings): PRT at top of blackbody hemisphere; average of four temperature probes; maximum temperature from the four probes; average of four probes with mechanical mixing of bath fluid surrounding blackbody hemisphere.

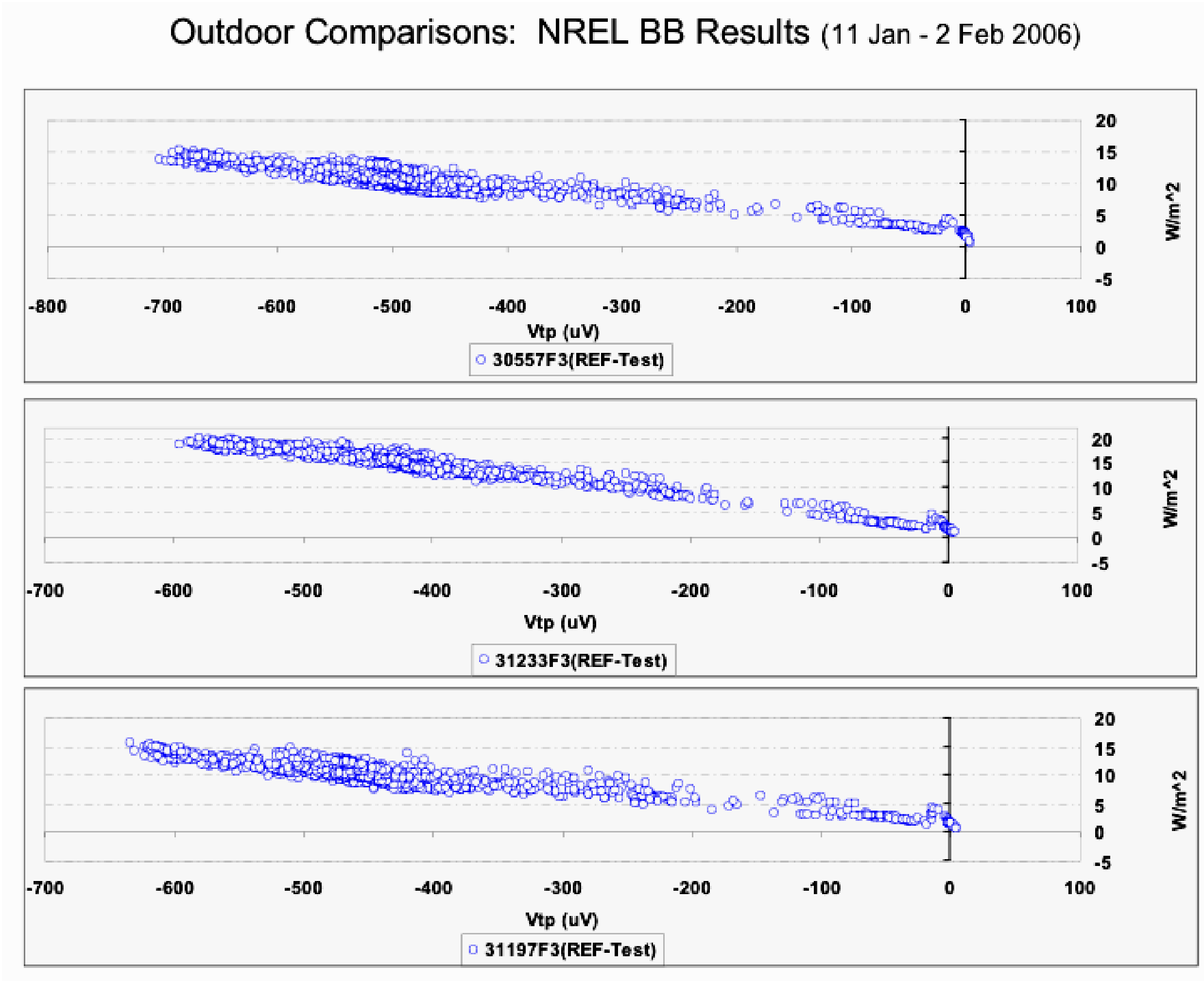

Figure 7a. Comparison of outdoor measurement differences as a function of thermopile voltage (microvolts) at NREL in January/February 2006 from three PIRs calibrated in NREL blackbody to determine K_0, K_1, K_2, and K_3 (in Equation 5) and a CG4 directly traceable to the WISG (using Equation 4). Data show consistent clear-sky bias (left portion of horizontal axis) similar to previous findings.

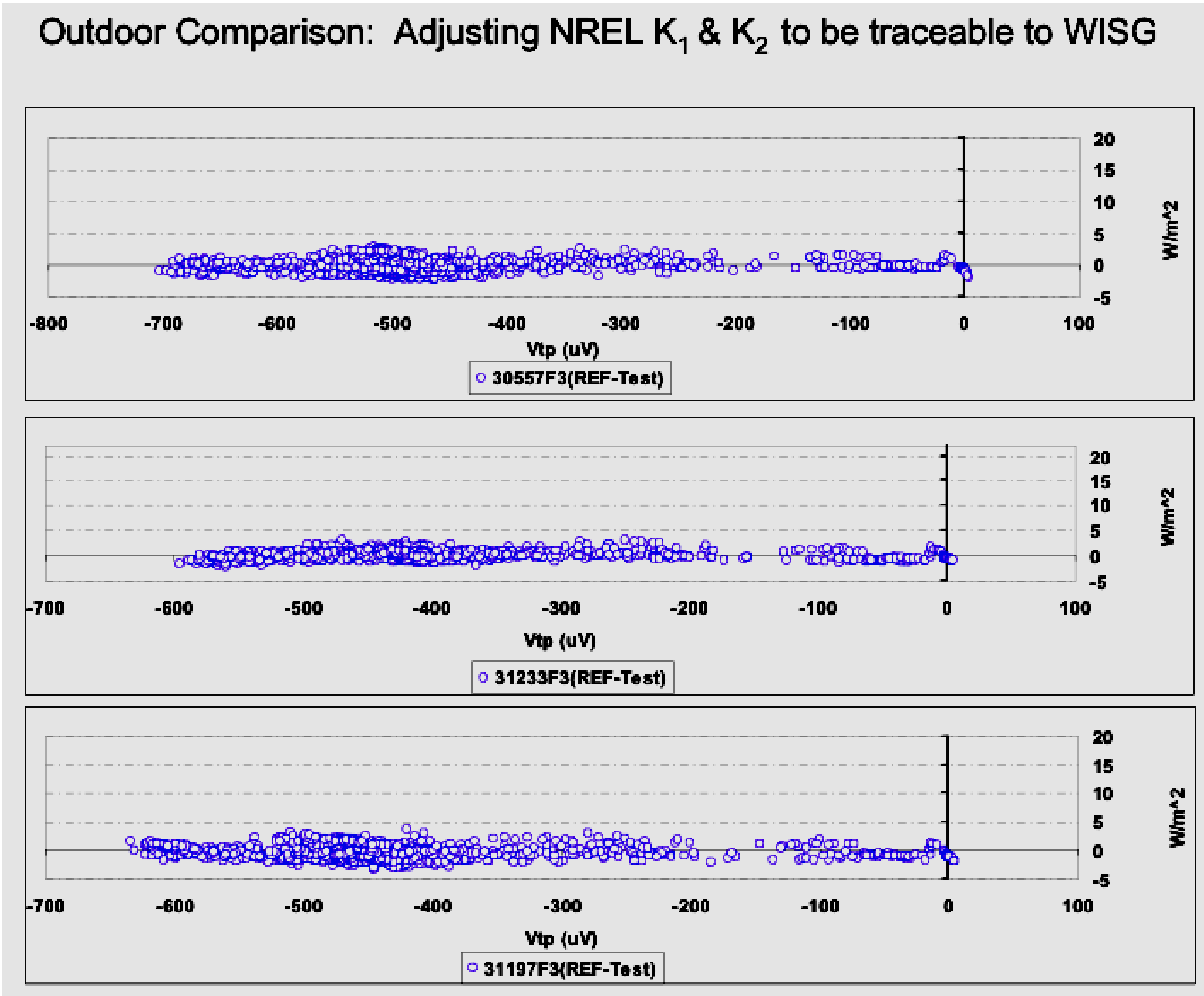

Figure 7b. Comparison of outdoor measurements at NREL in January/February 2006 from three PIR calibrated in NREL blackbody with K_1 and K_2 coefficients adjusted to agree with a CG4 directly traceable to the WISG. Measurements agree for all sky conditions to within +/- 5 Wm^{-2}.

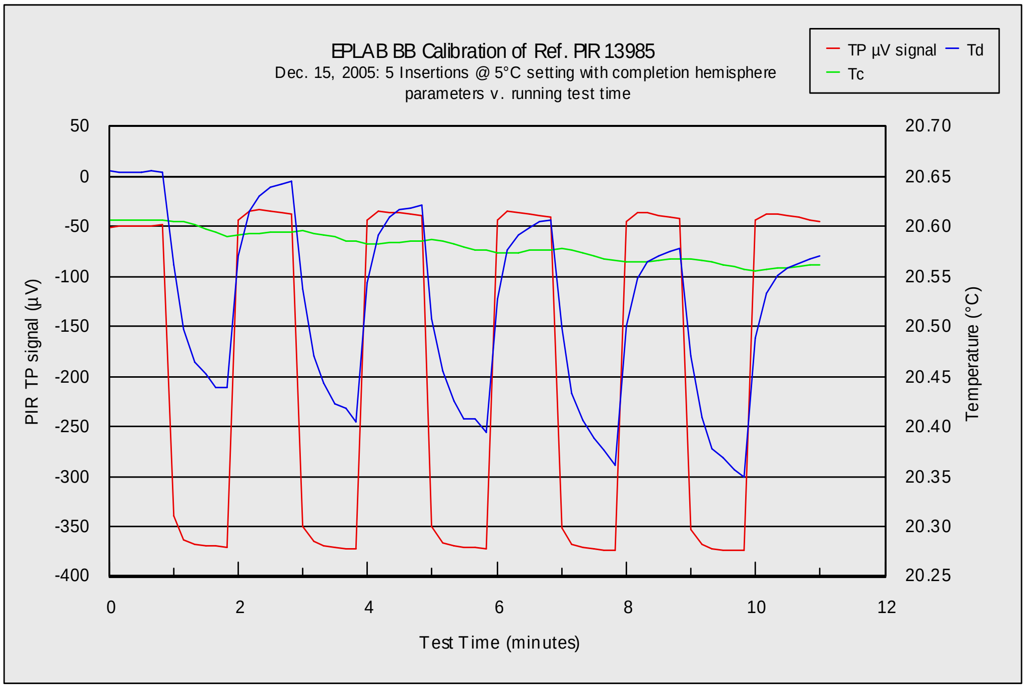

Figure 8. Preliminary results of time-response studies at EPLAB using their production pyrgeometer blackbody calibration system to address transient vs. steady state exposures to blackbody reference radiance.

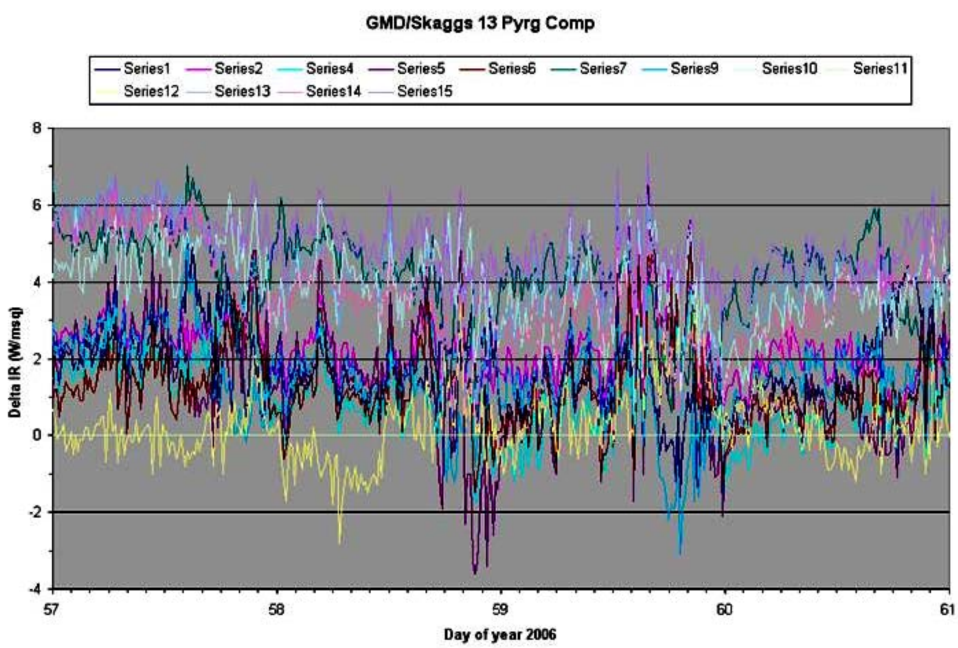

Figure 9. Outdoor comparison of 13 pyrgeometers at NOAA/Geophysical Monitoring Division in Boulder, Colorado for several days in February 2006 show maximum differences of 10 Wm^{-2}.

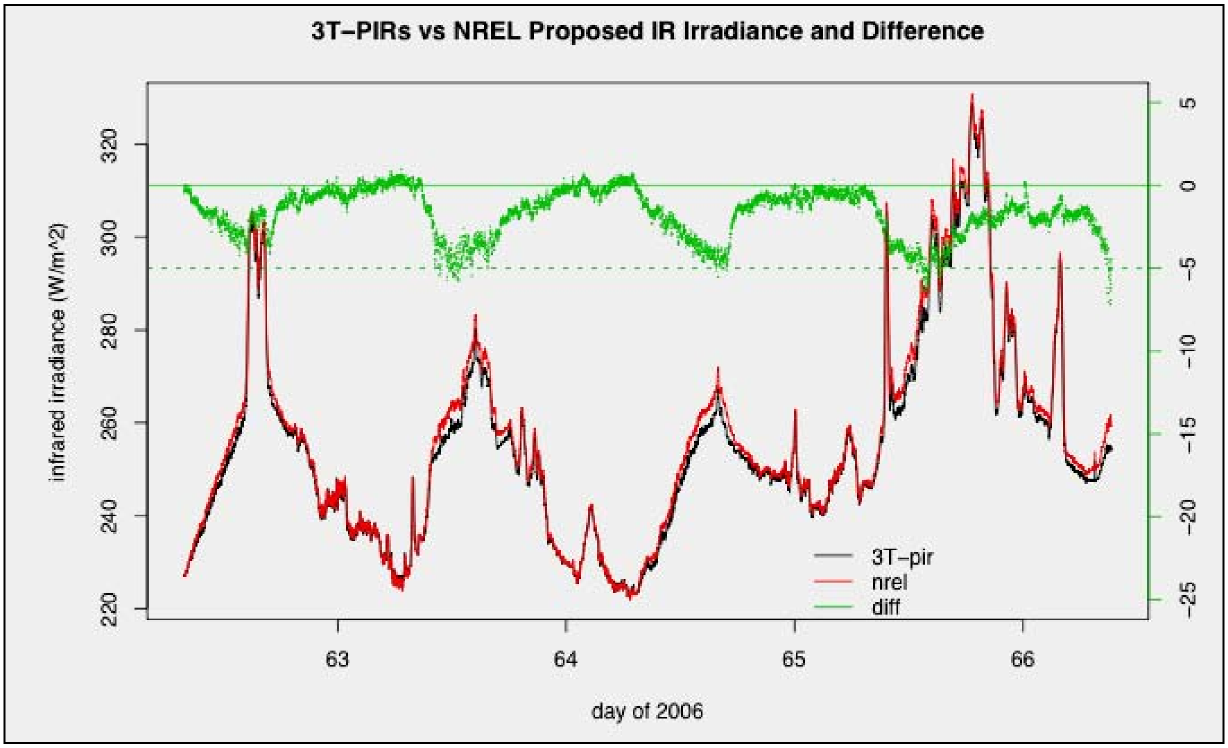

Figure 10. Comparison of outdoor measurements at NOAA/Geophysical Monitoring Division made by PIRs with three dome thermistors and a conventional single dome thermistor show a 0 Wm^{-2} to 5 Wm^{-2} agreement (upper trace). All PIRs were calibrated by the WRC in the previous six months.

Conclusions

Longwave irradiance data precision and accuracy depends on the method of calibration and the availability of a recognized measurement reference. As originally suggested by NREL (Reda et al. 1999) and verified by recent access to the interim WISG, all ARM pyrgeometers should be characterized by an accurate blackbody and compared outdoors with ventilation and sun shade under a variety of non-precipitating sky conditions. Figure 11 presents a diagram of such an implementation.

The existing NREL pyrgeometer blackbody calibration system needs modification to eliminate the 1°C to 1.5°C temperature gradients in the reference blackbody at fluid temperatures below -15°C.

ARM needs to complete the development of calibration references traceable to the interim and final implementations of the WISG with continued cooperation among researchers at EPLAB, NOAA, NREL, and WRC. This includes the development of additional Absolute Sky-scanning Radiometers needed to establish the next implementation of the WISG.

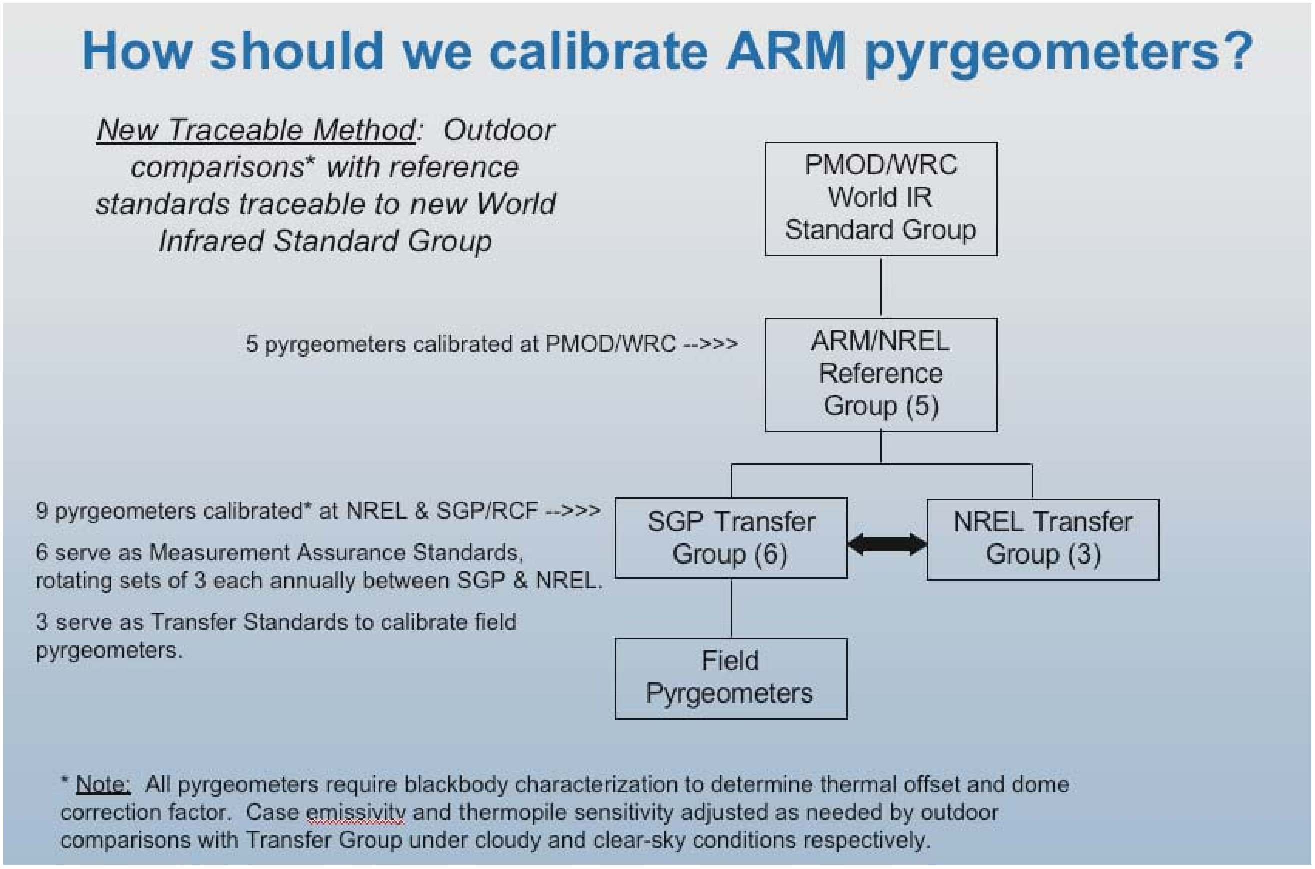

Figure 11. Instrument Mentor recommendation for ARM pyrgeometer calibrations provides traceability to the international measurement standard, involves blackbody characterizations, and establishes calibration reference and transfer standard groups.

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