Pyrgeometer Calibrations for the ARM Program

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Introduction

Pyrgeometers are used to measure the longwave radiation. Accurate measurements from these radiometers require regular calibration using temperature controlled blackbody radiators. The National Renewable Energy Laboratory (NREL) and The Eppley Laboratory, Inc. (EPLAB) are developing a new automated system for calibrating EPLAB Precision Infrared Radiometers (PIRs) for the Atmospheric Radiation Measurement (ARM) Program. Test results from the prototype system, now at NREL, will be used to develop a production version for deployment at the Southern Great Plains (SGP) Radiometer Calibration Facility (RCF).

Blackbody

The blackbody radiator is a copper hemisphere mounted in a fluid containing vessel, which is insulated. The geometry is such that the PIR will be in the up-looking position when it is inserted into the radiator. The surface of the hemispherical cavity is coated with Parson's black paint over a layer of Parson's black primer. This should yield a surface emissivity greater than 0.98. When the PIR is inserted in the hemispherical cavity the effective emissivity approaches 1.0, due to the cavitation and enhancement from reflection of its own radiation. Independent temperature-controlled circulators are used to set the blackbody hemisphere and the PIR case temperatures.

Measuring the Incoming Radiation Using the PIR

The incoming (sky) radiation is calculated using the following PIR primary measured parameters:

- the thermopile output signal in microvolts
- the case temperature in Kelvin
- the silicon hemisphere (dome) temperature in Kelvin.

To evaluate the calibration procedure using the prototype blackbody system, the following equation is adopted to calculate the incoming infrared radiation:

$$W_{sky} = K_0 + K_1 * V + K_2 * \sigma * T_c^{\,4} - K_3 * \sigma * \left(T_d^{\,4} - T_c^{\,4}\right) \qquad (1)$$

where W_{sky} = incoming (sky) radiation , in Watt/meter^2
$K_{i=0\text{-}3}$ = PIR calibration constants computed from blackbody measurements
V = PIR thermopile output voltage, in microvolts
σ = Stefan-Boltzmann Constant, 5.6697E^{-8} Watt/meter^2/Kelvin^{-4}
T_c = PIR case temperature, in Kelvin
T_d = PIR dome temperature, in Kelvin.

PIR Calibration

In this prototype blackbody system, the calibration is performed at six different temperature settings (plateaus). The temperature plateaus are shown in Table 1. For each plateau, the PIR parameters and the blackbody temperature are measured then substituted in Eq. (2). By substituting W_{sky} by W_{bb}, Eq. (1) can be rewritten for each plateau,

$$\left(T_{i,bb}\right)^4 = K_0 + K_1 * V_i + K_2 * \sigma * \left(T_{i,c}\right)^4 - K_3 * \sigma * \left[\left(T_{i,d}\right)^4 - \left(T_{i,c}\right)^4\right] \qquad (2)$$

where i = i^{th} plateau
$T_{i,bb}$ = blackbody temperature of the i^{th} plateau
W_{bb} = $\sigma * (T_{bb})^4$.

Table 1. Temperature plateaus.

Plateau Number	PIR Case Temperature, T_c, (°C)	Blackbody Temperature, T_{bb}, (°C)	Dome Temperature, T_d, (°C)
1	25	10	As Is
2	25	-5	As Is
3	10	-5	As Is
4	10	-20	As Is
5	-5	-20	As Is
6	-5	-35	As Is

Six equations will result from the PIR calibration, one for each plateau. The constants K_0, K_1, K_2, and K_3 are then calculated using matrices for the linear regression. The constants are then substituted in Eq. (1) to calculate the outdoor radiation using the calibrated PIR.

Calibration Results

Two PIRs were calibrated using the prototype blackbody system and plateaus described above. The calibration results are unique for each PIR as summarized in Table 2 for serial numbers 24055F3 and 30557F3.

Table 2. Calibration results.

	PIR Serial Number	
	24055F3	**30557F3**
K_0	-7.83729	-2.72748
K_1	0.23196	0.208681
K_2	1.014555	0.994501
K_3	0.403816	-1.50175
$\%\sigma_r^2$	1.01	0.05
$\%E_{max}$	±0.79	0.14
$\Delta T_{d\text{-}c}$ Range	-1.10 to -0.51 °C	-0.93 to -0.36 °C

where $K_{i=0\text{-}3}$ = PIR calibration constants computed from blackbody measurements
$\%\sigma_r^2$ = sum of the squared percentage errors of the regression
$\%E_{max}$ = maximum percentage error of the regression
$\Delta T_{d\text{-}c}$ = range of T_{dome} minus T_{case} noted during the calibration.

Outdoor Data Collection

The two PIRs that were calibrated at NREL, using the prototype blackbody system, are installed outdoors with three other PIRs that were calibrated at EPLAB. All PIRs were ventilated and unshaded. The data were sampled every 10 minutes. Incoming radiation measured by the two PIRs calibrated by the prototype blackbody system, is calculated using Eq. (1). The measurements from the PIRs calibrated at EPLAB were computed using the traditional equation,

$$W_{sky} = \frac{V}{RS} + \sigma * T_c^{\,4} - 4 * \sigma * \left(T_d^{\,4} - T_c^{\,4}\right) \tag{3}$$

where W_{sky} = measured incoming radiation, Watt/meter^2
V = measured thermopile output voltage, in microvolts
RS = PIR Responsivity, in microvolts/Watt/meter^2
4 = dome correction factor.

Due to its small regression error, PIR 30557F3 was used as a reference for comparing the outdoor measurements. The percentage errors of all other PIRs are calculated, $\%E_{sn}$,

$$\%E_{sn} = \frac{\left(W_{30557F3} - W_{sn}\right) * 100}{W_{30557F3}} \tag{4}$$

where $W_{30557F3}$ = measured incoming radiation of PIR 30557F3
W_{sn} = measured incoming radiation of PIR with serial number, sn

Conclusions

There are many lessons to be learned from this prototype blackbody system. Because there is no reference sources or detectors for outdoor infrared radiation measurement, it is difficult to evaluate pyrgeometer performance under field conditions. We hope the improved characterizations available from a production blackbody calibration system will improve longwave irradiance measurements for the ARM Program. Following blackbody characterization at the RCF, the PIRs will be installed outdoors in groups of 12 to 15 to evaluate the consistency of the calibration procedure.

The following are some preliminary conclusions from a very small data set, based on the calibration performed on February 21 and 22, 1999, and outdoor data from February 26, 1999:

- Consistency of calibration: PIR 24055F3 was calibrated using the prototype blackbody system, and its errors are calculated relative to 30557F3 (see Eq. [4]). The errors are within ±1%, within the maximum error of regression (see Figures 1 and 2).

- Temperature gradians between the PIR dome and case, ΔT_{d-c}: The differences are minimum for all PIRs when ΔT_{d-c} is approximately -0.4 °C (see Figures 1, 2, and 3). This suggests it is possible that the calibration at EPLAB introduces a similar temperature gradiance. At other ΔT_{d-c} than -0.4 °C, the errors can exceed ±6% for EPLAB calibrated PIRs but their errors from each other are less than ±1%. This suggests there may be a systematic error due to the change of ΔT_{d-c}. Figure 1 shows that ΔT_{d-c} ranges from -1.2 °C to +0.4 °C for data collected outdoor. This concludes that for proper regression, the new production blackbody system, if possible, must control ΔT_{d-c} from -1.5 °C to +1.5 °C.

To evaluate the accuracy of the system, a calibrated PIR at NREL should be compared with other pyrgeometers that are calibrated using other blackbody calibration systems from different organizations. Comparisons at NREL and the SGP RCF, involving a potentially new longwave radiation standard instrument now under development by the World Radiation Center, is planned for September 1999.

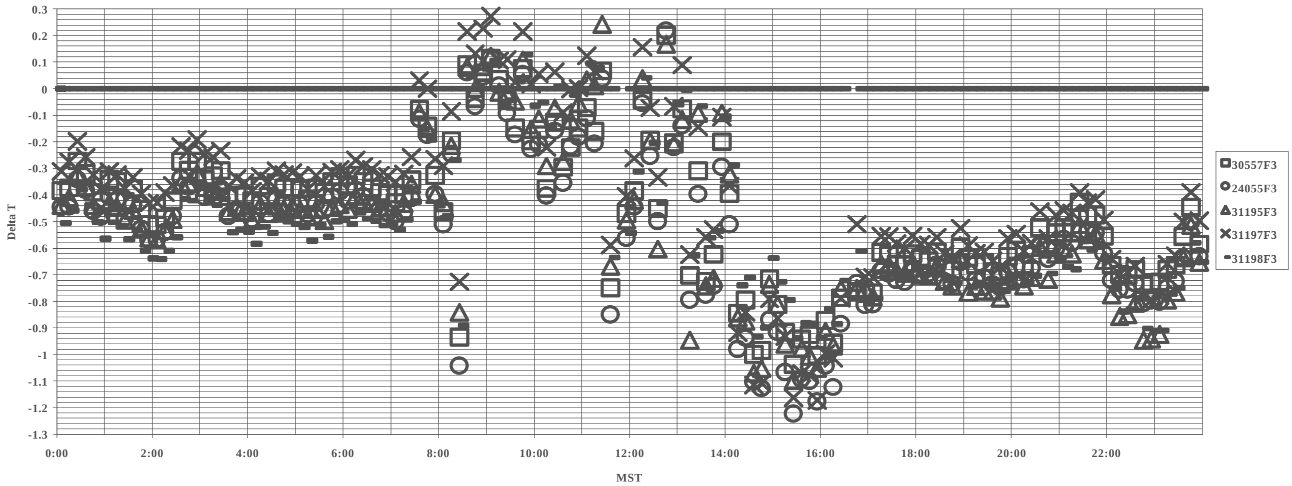

Figure 1. (Dome-Case) temperature, Delta T, versus Mountain Standard Time on 2/26/1999.

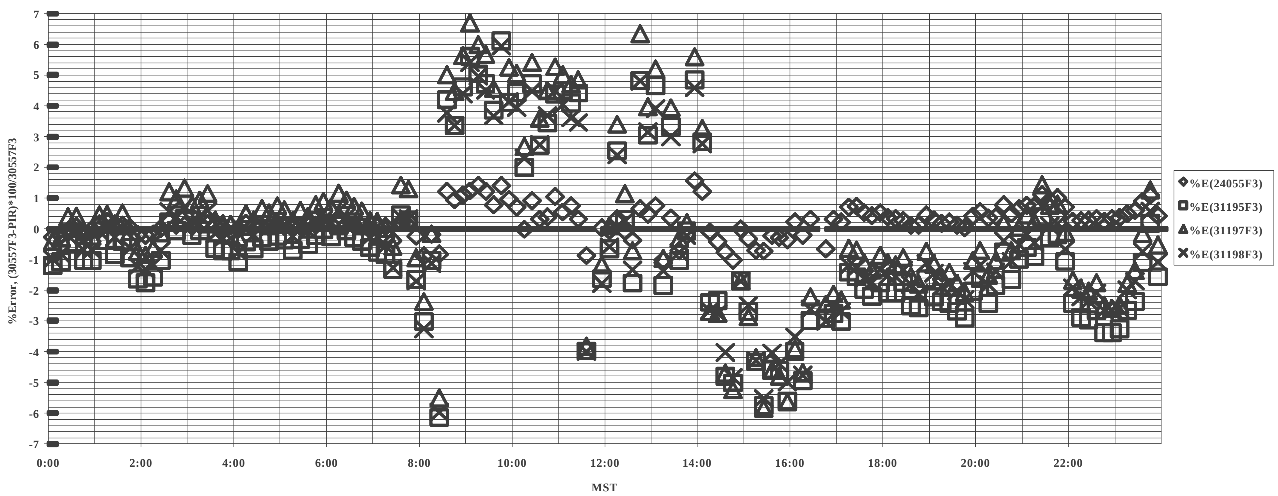

Figure 2. Percentage error of measured incoming radiation versus Mountain Standard Time.

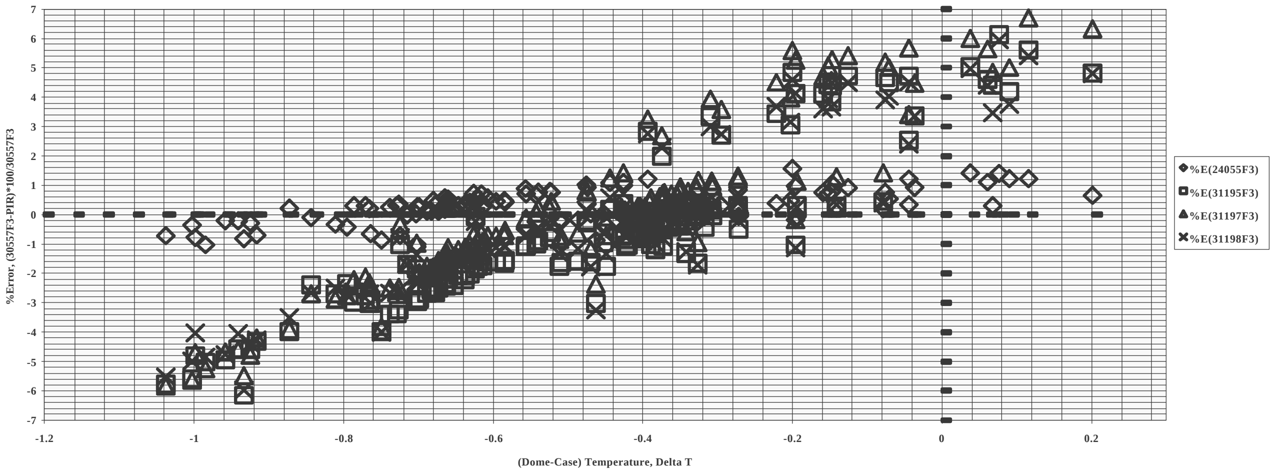

Figure 3. Percentage error of measured incoming radiation versus (dome-case) temperature, Delta T.