# The Baseline Surface Radiation Network Pyrgeometer Round-Robin Calibration Experiment

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ABSTRACT

With the aim of improving the consistency of terrestrial and atmospheric longwave radiation measurements within the Baseline Surface Radiation Network, five Eppley Precision Infrared Radiometer (PIR) pyrgeometers and one modified Meteorological Research Flight (MRF) pyrgeometer were individually calibrated by 11 specialist laboratories. The round-robin experiment was conducted in a ''blind'' sense in that the participants had no knowledge of the results of others until the whole series of calibrations had ended. The responsivities $C(\mu V/W\ m^{-2})$ determined by 6 of the 11 institutes were within about 2% of the median for all five PIR pyrgeometers. Among the six laboratories, the absolute deviation around the median of the deviations of the five instruments is less than 1%. This small scatter suggests that PIR pyrgeometers were stable at least during the two years of the experiment and that the six different calibration devices reproduce the responsivity $C$ of PIR pyrgeometers consistently and within the precision required for climate applications. The results also suggest that the responsivity $C$ can be determined without simultaneous determination of the dome correction factor $k$, if the temperature difference between pyrgeometer body and dome is negligible during calibration. For field measurements, however, $k$ has to be precisely known. The calibration of the MRF pyrgeometer, although not performed by all institutes, also showed satisfactory results.

## 1. Introduction

Because of the important role of radiation in the climate system, the World Climate Research Programme (WMO 1990, 1991) proposed in 1990 the establishment of a worldwide Baseline Surface Radiation Network (BSRN) for continuous long-term measurements of the highest attainable quality of radiative fluxes at the earth's surface. About 30 stations located throughout the world are planned (two-thirds are collecting data at present) to measure upward and downward shortwave and longwave broadband irradiance. The objective of the BSRN is to provide surface radiation budget data for validating estimates inferred from satellite measurements, to verify the accuracy of radiation codes in climate models, and to detect possible long-term trends in radiative fluxes at the surface.

The performance and accuracy of broadband infrared instruments, such as pyrgeometers and pyrradiometers, to measure down- and upwelling longwave radiation has been an important issue for BSRN scientists. A number of questions were raised in this respect, especially because of conflicting information found in the literature and dithering views circulated within the scientific com-

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munity. Two field tests led by J. DeLuisi have been conducted, under BSRN auspices: the first was at Coffeyville, Kansas, during the First ISCCP (International Satellite Cloud Climatology Project) Regional Experiment (FIRE II) and the other was at Boulder, Colorado, to evaluate the performance of pyrgeometers and pyrradiometers. The objective was to determine the best method for measurement of broadband longwave irradiance for application in the BSRN network and to quantify the likely error in measurements. Various instruments used by participating BSRN groups were intercompared, and measurements were also compared with ''official'' estimates of the downwelling infrared irradiance provided by the Spectral Radiation Experiment, which also participated prominently in FIRE II as an adjunct experiment.

Results from the FIRE II intercomparisons (DeLuisi 1992) reinforced conclusions from earlier intercomparison results published by various authors (e.g., Weiss 1981; Alados-Arboledas et al. 1988; Field et al. 1992; Dehne et al. 1993), showing differences between downwelling longwave irradiance measurements from different instruments up to more than $\pm 10$ W m$^{-2}$. Two instrument calibrations were used—one the manufacturer provided with the instrument and an ice dome calibration. For the two calibrations, systematic differences of mean results between instruments of up to 13 W m$^{-2}$ were seen. This result particularly stressed the importance of a comparison of calibration procedures.

In this paper we report on the results of the round-robin calibration campaign, which was initiated by J. DeLuisi and A. Ohmura. The experiment was intended solely to test and compare presently available blackbody calibration devices. Problems related to pyrgeometer field measurements and to the absolute accuracy are not investigated. Five Eppley precision infrared radiometer (PIR) pyrgeometers and one pyrgeometer modified by Foot (1986) were supplied by different proprietors as test instruments. All PIRs had spent some time in the field and had proven to be reliable. Specialists and research laboratories of the radiation community from all over the world were invited to take part in the experiment, which involved calibration of the six pyrgeometers using their individual methods and apparatus. The round-robin experiment was conducted in a ''blind'' sense in that the participants had no knowledge of the results of others until the experiment ended. Calibration factors determined by the individual institutes were gathered at the World Radiation Center at Davos, Switzerland, and results from the analysis are presented on the following pages.

## 2. Pyrgeometers

PIR, a pyrgeometer developed by the Eppley Laboratory, is a development from their precision spectral pyranometer (PSP) but with a silicon rather than a glass dome. This instrument was first described by Drummond et al. (1970).

A pyrgeometer consists of a body, a thermopile, and a dome. Ideally, the dome should transmit all longwave radiation without attenuation and reflect all shortwave radiation. There should, therefore, be no thermal emission from the dome. In the perfect instrument, the voltage $U_{emf}$ from the thermopile is linearly related to the net gain of radiant power. The thermopile sensor surface absorbs and emits as a blackbody at a measured temperature $T_S$. For this idealized instrument the incoming irradiance $E_L$ is given by

$$E_L = \frac{U_{emf}}{C} + \varepsilon\sigma T_S^4, \tag{1}$$

where $C$ is the responsivity of the thermopile in $\mu$V/W m$^{-2}$ and $\sigma$ is the Stefan–Boltzmann constant. Here $T_S$ cannot directly be measured, but it can be derived from the body temperature $T_B$ measured at the cold junction of the thermopile, as shown by Albrecht et al. (1974) and Philipona et al. (1995). Also, in a real instrument, the emittance $\varepsilon$ of the thermopile surface has to be included; in practice, however, it is normally set to unity and implicitly included in the calibration.

In operation, research projects using aircraft-mounted pyrgeometers to determine up- and downwelling longwave radiation at high altitude revealed significant deficiencies in the accuracy of pyrgeometers. Unlike the Eppley PSP pyranometer that has a double glass dome, the PIR has only a single silicon dome. The transmittance of the silicon dome (Miskolczi and Guzzi 1993) with its vacuum-deposited low-pass interference filter has a cut-on at approximately 3–4 $\mu$m, and the transmission varies between 0.2 and 0.4 in the region of 4–50 $\mu$m; variations between different domes are significant. The large dome absorptance causes temperature differences between the dome and the body of the pyrgeometer, and hence, an additional thermal irradiance on the sensor surface, which is proportional to the difference between fourth power of the dome $T_D$ and the body temperature $T_B$. PIRs have since been equipped with a thermistor mounted at the lower rim to measure the temperature of the silicon dome. Albrecht et al. (1974) and Albrecht and Cox (1977) introduced an additional term in the pyrgeometer equation to correct for the exchange of radiant energy between the dome and the body in the form:

$$E_L = \frac{U_{emf}}{C} + \varepsilon\sigma T_B^4 - k\sigma(T_D^4 - T_B^4), \tag{2}$$

where $k$ is a ''correction factor.''

Tests conducted at the Meteorological Research Flight (MRF) of the U.K. Meteorological Office at Farnborough led Foot (1986) to conclude that the dome temperature cannot be measured satisfactorily at a single point and that within the body of the instrument there may be additional temperature gradients due to con-

TABLE 1. Round-robin participating laboratories and responsible scientists.

| | |
|---|---|
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| 3) CMDL, Boulder<br>Elsworth Dutton<br>dutton@cmdl1.cmdl.noaa.gov | NOAA/CMDL 3100 Marine St. Rm 310<br>Boulder, CO 80303<br>USA<br>Tel: 303-497-6994 Fax: 303-497-6546 |
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| 8) MRF, Farnborough<br>John H. Seymour<br>jhseymour@meto.govt.uk | Meteorological Research Flight<br>Building Y46, Defence Research Agency<br>Farnborough, Hampshire, GU14 6TD<br>UK<br>Tel: +44-252-395140 Fax: +44-252-376588 |
| 9) MRI, Tsukuba<br>Masataka Shiobara<br>shio@nipr.ac.jp | Meteorological Research Institute<br>1-1 Nagamine, Tsukuba 305<br>Japan<br>Tel: +81-298-53-8607 Fax: +81-298-55-2552 |
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| 11) NOAA/ARL, Boulder<br>John DeLuisi<br>deluisi@srrb.noaa.gov | NOAA/ARL<br>3100 Marine St. Rm 525<br>Boulder, CO 80303<br>USA<br>Tel: 303-497-6824 Fax: 303-497-6546 |
| 12) PMOD/WRC, Davos<br>Rolf Philipona<br>rphilipona@pmodwrc.ch | World Radiation Center<br>Dorfstrasse 33, CH-7260 Davos Dorf<br>Switzerland<br>Tel: +4181-417-5131 Fax: +4181-417-5100 |

duction and convection effects producing significant errors. MRF consequently adopted a modified design ''the MRF pyrgeometer,'' which minimizes the correction term by eliminating the influence of heat conduction and convection between dome and sensor surface. This is accomplished by arranging the gold cold junction and the black hot junction of the thermopile on the same surface so that both face the dome of the pyrgeometer and, therefore, are only sensitive to the radiation term. The correction factor $k$ of the MRF pyrgeometer is thus much reduced compared to a normal PIR, and the dome temperature measurement may be neglected. Equation (1) can then be used for computing the incoming irradiance with the reference temperature $T_B$; the remaining small dome correction term is ignored.

Pyrgeometers deployed to measure downwelling atmospheric radiation at the surface are usually operated with a shade disc. This prevents excessive heating of the dome by the sun and shields the sensor from receiving the infrared fraction of the solar beam, which,

TABLE 2. Description of blackbody and calibration apparatuses.

| | |
|---|---|
| AES, Toronto | Blackbody: Cone within a cylinder. Surrounding the outside of the cylinder is a heating coil, helically wound the entire length of the cylinder. A stirred synthetic oil bath conducts the heat from the walls of the cylinder to the cone. The cylinder is brass and the cone is copper. The interior of the cone is painted a flat black. Fins attached to the lid protrude into the oil bath to increase the turbulence of the fluid. The cone has an angle of 17°40′ and extends 56.5 cm. Beyond this is a cylindrical portion that extends another 18 cm with a diameter of 17.75 cm. The exit aperture is 12.7-cm diameter. Total emittance: 0.9987. |
| | General: The temperature of the oil is assumed constant throughout the vessel and is measured in the area approximately 3 cm below the impeller used to stir the liquid. |
| BoM, Melbourne | Blackbody: electrically heated aluminum cylinder (diameter 60 cm, height 60 cm) topped with a cone (base diameter 60 cm, height 60 cm) fitted with water-cooled aperture and shutter at the bottom entrance. Total emittance: 0.998. |
| | General: Sensor placed in a water-cooled enclosure by means of precision jig. Temperature of enclosure, shutter, and aperture maintained constant during calibration. Sensor alternatively exposed to the blackbody radiation by means of shutter. Thermopile output and dome and body temperature monitored by HP data acquisition system. Shutter movement automated; open/closed phase 180 s. Data collection automated. |
| CMDL, Boulder | Blackbody: Inverted brass cone with a diameter of about 10 cm and height of 14 cm (CSU's ''S. Cox cell''). Total emittance: 0.995. |
| | General: Blackbody is cooled to about −60°C and takes about 10 h to warm up to room temperature. During that time, multiple instruments are calibrated. The dome of the instrument is first heated and as it cools the $\Delta T = 0.0$ point is achieved. This allows the dome correction factor $k$ to be determined. Warming the cell to about 50°C gives similar results. |
| DWD/MOP, Potsdam | Blackbody: Stainless steel double-wall cylindrical device with a conical ceiling and air outlet at the top of the ceiling. Kipp & Zonen black for wall painting. Outer walls isolated. Eight temperature sensors (thermojunctions) at the wall surface. Thermostatted water flow from the bottom (four inlets) to the top (one outlet). Total emittance: 0.995. |
| | General: Two blackbodies hanging above the platform of a movable table. Two thermostats pumping water of 20° and 40°C, respectively, through the blackbodies. Ice water dewar for 0°C reference (thermojunction). Twenty-channel computer-controlled data acquisition system (Keithley DMM 195 and scanner). |
| EPLAB, Newport | Blackbody: Hemispherical blackbody cavity in temperature-controlled fluid bath with temperature circulator. Temperature measured by precision temperature gauge. Bath circulation is off when measuring at a plateau to allow bath to stabilize, no gradients or transients. Total emittance: 1. |
| | General: PIR inserted from below. Closing the opening of the blackbody cavity with the PIR itself raises the effective total emittance to very close to 1. |
| GIETHZ, Zurich | Blackbody: Ice cone from pure $H_2O$, 1-m high and base diameter of about 60 cm. Ice base plate with entrance hole of about 10 cm. Total emittance: 1. |
| | General: PIR is entered from below as well as oxygen inlet. |
| LANL, Los Alamos | Blackbody: Copper cone/cylinder cavity with base diameter of cylindrical part of 10.8-cm and 9-cm height, topped with cone of 16.5-cm height. Inside wall painted with specular black paint. Total emittance: >0.999. |
| | General: The blackbody is positioned horizontally and immersed in a very uniform (±1 mK) and very well stabilized (±1 mK) water bath. Pyrgeometer is in horizontal position during calibration. The pyrgeometer dome is precooled (preheated) for blackbody temperatures above (below) ambient temperature. Measurements during temperature drifts are used to determine the dome correction factor. |
| MRF, Farnborough | Blackbody: Copper cone of height 44 cm, base diameter 15 cm giving a half-angle of about 10°. Painted with Nextel 2010. Copper pipe for coolant on outside surface. Whole enclosure in cylinder with foam insulation. Hole at top for purging with dry air. Total emittance: 0.995. |
| | General: Coolant is supplied from low temperature circulating bath (Neslab ULT 80). Cone temperatures measured using thermocouples. PIR is supported on a jack stand with dome collar approximately level with base of cone. |
| MRI, Tsukuba | Blackbody: Conical blackbody source made of copper and painted black. The temperature of the blackbody is varied by alcohol circulation. The temperature is monitored at nine points by copper-constantan thermocouples soldered to the wall of the cone. Total emittance: 1. |
| | General: The blackbody is turned upside down and a PIR being calibrated is mounted facing downward to the base of the cone. It is possible to change the blackbody temperature from −25° to 25°C using the alcohol circulation system. A ring-shaped nozzle blows nitrogen gas onto the dome in order to change the dome temperature and maintain dryness inside the calibration device. |

TABLE 2. (*Continued*).

| | |
|---|---|
| NASA/ARC, Moffet Field | Blackbody: Curved cone made of thin copper, which is painted with black paint known to have very high total emittance in the infrared. This blackbody cone is immersed in a bath of alcohol, which can be chilled to very low temperatures and is monitored by a precision thermocouple. |
| | General: The instrument is placed on the blackbody cone at room temperature and the cone is chilled to about −50°C. The bath temperature is then increased in increments while the bath temperature and the instrument readings are recorded. The cone is purged by a gentle pure nitrogen gas stream to preclude condensation forming on the cone surface or on the instrument dome. |
| PMOD/WRC, Davos | Blackbody: Cylindrical aluminum cavity of height 60 cm and inner diameter of 18 cm, terminating in a bottom plate with central hole of 9 cm and a convex top plate. The cylindrical part has a helical groove that serves as a conduit for the cooling fluid. Similar grooves are in the bottom and top plates. Ten thermistors are used to measure the temperature of the inside wall and are weighted according to their specific viewing angle. Total emittance: 0.9985. |
| | General: A powerful circulation system pumps the temperature-stabilized fluid through the enclosure, maintaining and holding the temperature fixed between −30° and +60°C. PIR body temperature can be fixed and maintained between −10° and 30°C using a conduit wrapped around the pyrgeometer and a second temperature circulating system. Dome temperature can be increased with a heating coil around the collar of the pyrgeometer. Measurements are taken in stable thermal conditions. |

by definition, is not part of the atmospheric longwave radiation (Enz et al. 1975). Nevertheless, dome emission as a factor in the accuracy of PIR pyrgeometers is still being addressed. Shiobara and Asano (1992) control the dome temperature during the calibration with nitrogen gas ventilation. Philipona et al. (1995) reported large dome temperature gradients and introduced a new dome temperature measurement to provide an improved estimate of the average dome temperature using three thermistors separated by 120° and glued at 45° elevation. They also reevaluated the thermal flux balance of pyrgeometers and introduced a new equation with three correction factors $k_{1,2,3}$:

$$E_L = \frac{U_{\rm emf}}{C}(1 + k_1\sigma T_B^3) + k_2\sigma T_B^4 - k_3\sigma(T_D^4 - T_B^4). \quad (3)$$

The three $k$ values comprise dome characteristics such as absorptance, transmittance, and reflectance, as well as the emittance of the receiver surface of the thermopile.

## 3. The round-robin unit

S. Sandberg and J. Wendell prepared the round-robin instrumentation, which consisted of five standard PIR pyrgeometers (one dome thermistor at the rim) and one MRF pyrgeometer (no dome thermistor). They added a laptop computer, a Campbell Scientific data acquisition system for logging the pyrgeometer signals, and a nonintrudable computer program. This same autonomous measurement system was used by all participants for homogeneity, who otherwise used their own apparatus, calibration method, and equipment.

Climate Monitoring and Diagnostics Laboratory (CMDL) and the Applied Research Laboratory (ARL), both of the National Oceanic and Atmospheric Administration, organized the shipping of the equipment to the participating laboratories, which had agreed to calibrate the six pyrgeometers, and ARL periodically checked the entire unit. The first calibration was made at CMDL in 1993, and the same institution and ARL recalibrated the six instruments at the end of the round robin in 1996. The only problem encountered with the suite of equipment during the experiment was a malfunctioning instrument due to a ground pin that had been disconnected from the case by its owner. Eppley Laboratory, third in the round-robin sequence, discovered that the instrument (PIR 26181) had been modified and reconnected the ground pin. However, this did not appear to have significantly affected the results.

## 4. Participating laboratories and calibration devices

Eleven laboratories from seven countries participated in the round-robin calibration of the six pyrgeometers. Table 1 lists addresses of the laboratories in alphabetical order and the names and e-mail addresses of the responsible scientists. To learn more about the different calibration methods and devices used by the different institutes, and to get more insight into the parameter range in which the instruments were calibrated, a questionnaire was sent to the individual participants at the end of the experiment in 1995. Table 2 describes the blackbody radiation sources and gives a general description of the calibration apparatus. All the 11 blackbody radiation sources used are of different construction and shape. The emitted hemispherical radiation is computed from Planck's law using the mean temperature of the blackbody $T_{\rm bb}$ and the values of total emittance of the cavities, which range from 0.995 to 1.

Table 3 summarizes general characteristics of the calibration procedure and devices employed by the individual laboratories. Different pyrgeometer exposures were used during calibration, most of which were made with the pyrgeometer body temperature at around 20°C with extremes from −1° to 28°C. Blackbody temperatures varied in a wide range from −50° to +127°C. The

TABLE 3. Temperature range and general characteristics of calibration procedures and apparatus.

| Institute | Pyrgeometer position | Temperature body $T_B$ (°C) | Temperature blackbody $T_{bb}$ (°C) | $T_{dome} - T_{body}$ $T_B - T_{bb} = 25°C$ | Calibration points | Ventilation | Dome factor $k$ | Equation used |
|---|---|---|---|---|---|---|---|---|
| AES, Toronto | Upward | 25 | 70 | 0 | 1 | No | $k = 0$ | Eq. (1) |
| BoM, Melbourne | Upward | 27 | 127 | 0.1 | 1 | No | $k = 4$ | Eq. (2) |
| CMDL, Boulder | Downward | 23 | −50 to +15 | −1 | 10 | No | $k = \ldots$ | Eq. (2) |
| DWD/MOP, Potsdam | Upward | 20–25 | 20 and 40 | 0.6 | 3 | No | $k = 0$ | Special |
| EPLAB, Newport | Upward | 20–23 | +5 and +15 | 0 | 2 | No | $k = 0$ | Eq. (1) |
| GI-ETHZ, Zurich | Upward | 25–28 | 0 | −1.5 | 1 | Oxygen | $k = 4$ | Eq. (2) |
| LANL, Los Alamos | Sideward | 24 | 5, 15, 30, 45, 70 | 0.75 | 5 | No | $k = \ldots$ | Eq. (2) |
| MRF, Farnborough | Upward | 10–20 | −50–0 | −1.4 | 6 | No | $k = \ldots$ | Eq. (2) |
| MRI, Tsukuba | Downward | −1–18 | −25–20 | ±2 | Continuous | Nitrogen | $k = \ldots$ | Eq. (2) |
| NASA/ARC, Moffett Field | Downward | 10–20 | −50 to +10 | −2.5 | Continuous | Nitrogen | $k = 4$ | Eq. (2) |
| PMOD/WRC, Davos | Upward | 20, 10, 0 | $T_B - 12$ and $T_B - 25$ | −1.5 | 12 | No | $k = \ldots$ | Eq. (2) |

fifth column of Table 3 indicates that for a temperature difference of 25°C between pyrgeometer body and blackbody radiation source, maximum differences between the dome and the body temperature vary from 0° to 2.5°C for the different calibrations. The number of calibration points varied within a factor of 10. Only three laboratories used ventilation during the calibration.

## 5. Results

### *a. Calibration evaluation*

As pointed out in section 3, round-robin participants were free to adopt their own method of calibration. Five participants not only determined the responsivity $C$ but also an individual dome correction factor $k$ for the five PIRs (see the two last columns of Tables 3 and 6). In these cases, the pyrgeometer equation (2) was used in the evaluation. At three laboratories, a fixed dome correction factor of $k = 4$ was taken for all the instruments together with Eq. (2) for the evaluation. The remaining three laboratories ignored the dome correction by setting $k = 0$ and employed Eq. (1) with the body temperature $T_B$ as a reference for the pyrgeometer. The MRF pyrgeometer was calibrated by seven participants and Eq. (1) was used to calculate $C$. The responsivity $C$ is given in $\mu$V/W m$^{-2}$ and the individual correction factors $k$ range between about 2 and 5.

### *b. PIR responsivities C*

The responsivities of the five PIR pyrgeometers found by the 11 laboratories are shown in Table 4. The original responsivities given by the manufacturer and the value found by CMDL and ARL at the end of the round-robin experiment are also included at the end of the table. No distinction was made whether $C$ was determined with or without the dome correction factor $k$. The median of the 11 values was determined for each instrument and the minimum, maximum, and the absolute deviation of $C$ are given as percentages with respect to the median. (The median, rather than the arithmetic average, is likely to be nearer the average value of the non-Gaussian distribution expected from the 11 very different calibrations.) The difference $\Delta C$, between the individual $C$ values and the median of the respective instrument, is given as a percentage. Moreover, the median of the $\Delta C$ values of the five instruments was determined for each laboratory, and an absolute deviation of the five $\Delta C$ values from the median of the $\Delta C$'s is shown in the last column of Table 4.

The absolute deviation of $\Delta C$ to the median of the $\Delta C$'s of the five instruments best quantifies the calibrations of the individual laboratories. The small scatter demonstrates the reproducibility of the calibration result. Whether the median of the $\Delta C$'s is close to zero or not is less important, since a bias is related to a systematic error that could be corrected. Six out of the 11 laboratories determined the responsivity $C$ of the five PIRs within about 2% of the median, with an absolute deviation of $\Delta C$ less than 1%. Figure 1 represents the $\Delta C$'s from all the five instruments and the 11 laboratories and clearly shows the difference between the small scatter of the calibrations of 6 laboratories compared to the significantly larger scatter of the others. An error of 1% in $C$ corresponds to an error in the measured flux of about 1 W m$^{-2}$. Hence, the large errors found between individual pyrgeometer measurements of 10 or more W m$^{-2}$ are not explained with errors on the calibration contant. It is also worthwhile noting that the values of the original calibrations are within 2% of the median except for the oldest instrument (13678). Furthermore, the two CMDL calibrations made in 1993 and 1996 are almost identical.

### *c. MRF responsivity C*

The results from the MRF pyrgeometer calibrations are shown in Table 5. The responsivity found by the seven participants who calibrated the instrument are within 5% of the median, which is overall a better result than for the PIRs.

TABLE 4. Responsivity $C$ and deviation to median $\Delta C$ (%) of PIR pyrgeometers.

| Institute | PIR 13678 | | PIR 26181* | | PIR 28145 | | PIR 28631 | | PIR 29441 | | Median of $\Delta C$ (%) | AbsDev of $\Delta C$ (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $C$ | $\Delta C$ (%) | $C$ | $\Delta C$ (%) | $C$ | $\Delta C$ (%) | $C$ | $\Delta C$ (%) | $C$ | $\Delta C$ (%) | | |
| AES, Toronto | 4.01 | −0.2 | 3.49 | −9.1 | 3.72 | 0.3 | 3.52 | −5.4 | 3.59 | −1.4 | −1.37 | 2.90 |
| BoM, Melbourne | 4.29 | 6.7 | 3.85 | 0.3 | 4.01 | 8.1 | 3.80 | 2.2 | 3.87 | 6.3 | 6.32 | 2.48 |
| CMDL, Boulder | 4.02 | 0.0 | 3.84 | 0.0 | 3.71 | 0.0 | 3.71 | −0.3 | 3.69 | 1.4 | 0.00 | 0.33 |
| DWD/MOP, Potsdam | 3.95 | −1.7 | 3.89 | 1.3 | 3.74 | 0.8 | 3.78 | 1.6 | 3.71 | 1.9 | 1.30 | 0.89 |
| EPLAB, Newport | 4.04 | 0.5 | 3.84 | 0.0 | 3.72 | 0.3 | 3.72 | 0.0 | 3.63 | −0.3 | 0.00 | 0.21 |
| GI-ETHZ, Zurich | 4.60 | 14.4 | 4.25 | 10.7 | 4.15 | 11.9 | 4.05 | 8.9 | 4.40 | 20.9 | 11.86 | 3.15 |
| LANL, Los Alamos | 4.02 | 0.0 | 3.91 | 1.8 | 3.66 | −1.3 | 3.75 | 0.8 | 3.64 | 0.0 | 0.00 | 0.80 |
| MRF, Farnborough | 4.12 | 2.5 | 3.50 | −8.9 | 3.42 | −7.8 | 3.52 | −5.4 | 3.59 | −1.4 | −5.38 | 3.56 |
| MRI, Tsukuba | 3.99 | −0.7 | 3.85 | 0.3 | 3.71 | 0.0 | 3.77 | 1.3 | 3.65 | 0.3 | 0.26 | 0.47 |
| NASA/ARC, Moffett Field | 3.84 | −4.5 | 3.49 | −9.1 | 3.33 | −10.3 | 3.16 | −15.1 | 3.46 | −4.9 | −9.11 | 3.19 |
| PMOD/WRC, Davos | 3.95 | −1.7 | 3.74 | −2.6 | 3.69 | −0.5 | 3.67 | −1.3 | 3.62 | −0.5 | −1.34 | 0.65 |
| Median of $C$ | **4.020** | | **3.840** | | **3.710** | | **3.720** | | **3.640** | | | |
| AbsDev of $C$ (%) | 3.0 | | 4.0 | | 2.8 | | 2.6 | | 3.6 | | | |
| $\Delta C$ Minimum (%) | −4.5 | | −9.1 | | −10.3 | | −15.1 | | −4.9 | | | |
| $\Delta C$ Maximum (%) | 14.4 | | 10.7 | | 11.9 | | 8.9 | | 20.9 | | | |
| Original EPLAB Calibration | 4.13 | 2.7 | 3.77 | −1.8 | 3.70 | −0.3 | 3.75 | 0.8 | 3.72 | 2.2 | 0.81 | 1.41 |
| CMDL, 1996 End | 3.99 | −0.7 | 3.83 | −0.3 | 3.70 | −0.3 | 3.73 | 0.3 | 3.70 | 1.6 | −0.26 | 0.59 |

* This instrument had a bad ground connection when it was at EPLAB and the signal cycled when it was connected to the BSRN supplied data system.

### *d. PIR correction factor k*

Individual dome correction factors were determined by only five laboratories and are shown in Table 6. Generally speaking, the $k$ values were not as precisely determined as the $C$ values. Nevertheless, four out of the five participants found the correction factor $k$ of the five PIRs within 20% of the median. These four calibration laboratories are among the group of six with responsivity values $C$ close to the median.

## 6. Discussion of results

A first glance at the results of the round-robin calibration experiment shows notable differences of up to 20% from the median of the responsivities of the five PIR pyrgeometers. The maximum difference from the median of the MRF pyrgeometer is only about 5%. Unfortunately, only one instrument of this kind was included in the experiment and it was calibrated only by 7 of the 11 participants. Hence, it is difficult to compare the results obtained with the MRF pyrgeometer directly with the PIR calibrations.

However, looking more closely at the results, it becomes apparent that six laboratories determined the PIR responsivities $C$ with remarkably lower scatter around the median values than the other five participants (see also Fig. 1). The fact that among these six laboratories the absolute deviation of $\Delta C$ to the median of the $\Delta C$'s is less than 1% is strikingly good. At the outset, this provides a strong indication of the stability of PIR pyrgeometers, which is further underlined by the two calibrations made by CMDL (Dutton 1993), of the five PIRs, one at the beginning in 1993 and one at the end of the experiment in 1996, which are both almost identical and are within the 1% limit. Certainly, the instruments had very little exposure to the environment during the 3-yr time period. However, they had traveled to many different and distant locations.

A second important result is the good agreement found among results from very different calibration methods and apparatus. Among the six laboratories that achieved the good ''median'' results, pyrgeometer positioning during calibrations were upward, downward, and sideward. The body temperature was set between 0° and 25°C. Blackbody temperatures from −50° to +70°C were used. One participant used ventilation during calibration. For the evaluation, four laboratories determined $C$ and $k$ using Eq. (2), whereas two participants simply neglected the dome correction term and used Eq. (1). Despite of all these differences the good agreement between the responsivities suggests that blackbody radiation sources, although of very diverse construction, are capable of producing consistent results. Thus, the calibration procedure itself and, in particular, interchanging blackbody radiation sources, does not seem to be a matter of serious consequence.

Although it is not appropriate to judge individual lab-

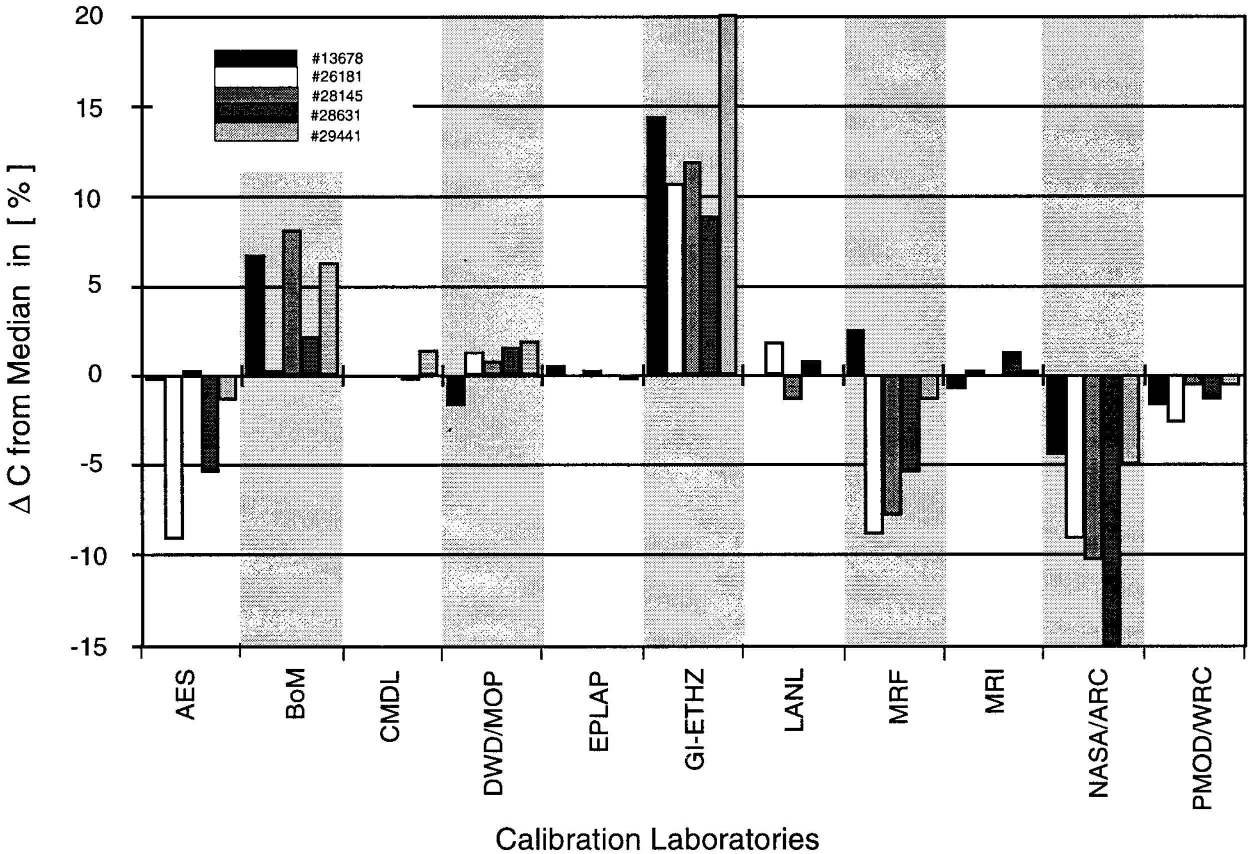


FIG. 1. Difference $\Delta C$ from the median in percent for the 5 PIRs of the 11 participants. Six out of the 11 groups determined $C$ within about 2% of the median, whereas the other groups have considerably larger deviations.

oratories and their calibration procedures and apparatus, we still feel that it is necessary to consider the reasons for the good "median" results of six participants and those for possible shortcomings of the other laboratories. Three of the participants [the Atmospheric Environment Service (AES), the Bureau of Meteorology (BoM), and Geographisches Institut ETH (GI-ETHZ)], which have a large scatter and are not among the six "median" results have only one calibration point and, thus, there is no indication of the internal consistency. AES and BoM calibrated with a blackbody temperature of 70° and 127°C, which is probably not the optimal temperature for pyrgeometers that rather measure thermal radiation corresponding to a temperature around or below 0°C. The three participants who evaluated their results using a fixed dome correction factor of $k = 4$ [BoM, GI-ETHZ, and National Aeronautics and Space Administration Applied Research Center (NASA/ARC)] are not among the six "median" results. The NASA/ARC calibration apparatus is designed to calibrate flight instruments that are not sensitive to dome temperature effects. During this calibration the dome temperature is not constant and drops to near the blackbody temperature, while the radiometer body remains at near room temperature. Dome correction factors determined by MRF have the largest scatter among the five laboratories that did determine the individual $k$ values, otherwise there is no obvious reason why MRF is not among the six.

TABLE 5. Responsivity $C$ and deviation to median $\Delta C$ (%) of MRF pyrgeometer.

| Institute | FOOT 127 | |
|---|---|---|
| | $C$ | $\Delta C$ (%) |
| AES, Toronto | 2.74 | −3.9 |
| BoM, Melbourne | — | — |
| CMDL, Boulder | — | — |
| DWD/MOP, Potsdam | 2.85 | 0.0 |
| EPLAB, Newport | 2.81 | −1.4 |
| GI-ETHZ, Zurich | — | — |
| LANL, Los Alamos | 2.96 | 3.9 |
| MRF, Farnborough | 2.82 | −1.1 |
| MRI, Tsukuba | — | — |
| NASA/ARC, Moffett Field | 2.95 | 3.5 |
| PMOD/WRC, Davos | 2.98 | 4.6 |
| Median of $C$ | **2.850** | |
| AbsDev of $C$ (%) | 2.6 | |
| $\Delta C$ Minimum (%) | −3.9 | |
| $\Delta C$ Maximum (%) | 4.6 | |

TABLE 6. PIR dome correction factors $k$ and deviations to median $\Delta k$ (%).

| Institute | PIR 13678 | | PIR 26181* | | PIR 28145 | | PIR 28631 | | PIR 29441 | | Median of $\Delta k$ (%) | AbsDev of $\Delta k$ (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $k$ | $\Delta k$ (%) | $k$ | $\Delta k$ (%) | $k$ | $\Delta k$ (%) | $k$ | $\Delta k$ (%) | $k$ | $\Delta k$ (%) | | |
| AES, Toronto | — | — | — | — | — | — | — | — | — | — | — | — |
| BoM, Melbourne | — | — | — | — | — | — | — | — | — | — | — | — |
| CMDL, Boulder | 3.80 | 4.4 | 3.20 | 1.9 | 3.00 | 10.3 | 2.90 | 6.2 | 3.50 | 0.0 | 4.40 | 2.92 |
| DWD/MOP, Potsdam | — | — | — | — | — | — | — | — | — | — | — | — |
| EPLAB, Newport | — | — | — | — | — | — | — | — | — | — | — | — |
| GI-ETHZ, Zurich | — | — | — | — | — | — | — | — | — | — | — | — |
| LANL, Los Alamos | 3.19 | −12.4 | 2.56 | −18.5 | 2.43 | −10.7 | 2.25 | −17.6 | 3.07 | −12.3 | −12.36 | 2.62 |
| MRF, Farnborough | 2.19 | −39.8 | 5.11 | 62.7 | 3.13 | 15.1 | 2.73 | 0.0 | 3.00 | −14.3 | 0.00 | 26.39 |
| MRI, Tsukuba | 3.81 | 4.7 | 3.14 | 0.0 | 2.63 | −3.3 | 2.45 | −10.3 | 3.70 | 5.7 | 0.00 | 4.79 |
| NASA/ARC, Moffett Field | — | — | — | — | — | — | — | — | — | — | — | — |
| PMOD/WRC, Davos | 3.64 | 0.0 | 2.71 | −13.7 | 2.72 | 0.0 | 2.74 | 0.4 | 3.52 | 0.6 | 0.00 | 2.93 |
| Median of $k$ | **3.64** | | **3.14** | | **2.72** | | **2.73** | | **3.50** | | | |
| AbsDev of $k$ (%) | 12.3 | | 19.4 | | 7.9 | | 6.9 | | 6.6 | | | |
| $\Delta C$ Minimum (%) | −39.8 | | −18.5 | | −10.7 | | −17.6 | | −14.3 | | | |
| $\Delta C$ Maximum (%) | 4.7 | | 62.7 | | 15.1 | | 6.2 | | 5.7 | | | |

* This instrument had a bad ground connection when it was at EPLAB and the signal cycled when it was connected to the BSRN supplied data system.

Dome correction factors are more difficult to determine and the almost 20% difference between the four participants whose results are nearest the ''median'' is large. The main reason for the large scatter is probably due to the dome temperature measurement, which seems to be influenced differently by the different calibration devices and, hence, that the dome thermistor at the rim does not indicate a representative dome temperature.

## 7. Conclusions

Six of the 11 participants of the round-robin pyrgeometer calibration experiment found very close responsivities $C$ around the median for the five pyrgeometers. This result shows that pyrgeometers are stable and that blackbody calibrations are reproducible. In this context the term stability is used to mean that the pyrgeometers consistently reproduce their calibration constants over long periods of time and after exposure to many environmental factors.

Participants were entirely free to use their own methods and calibration devices in this experiment and yet good results were achieved. However, there is no doubt within the BSRN community that a certain standardization of calibration procedures would improve the results even further. Therefore, for the BSRN, recommendations have been made with regard to the temperature range in which pyrgeometers are calibrated and the equation used for the evaluation of pyrgeometer calibrations. Although, for the thermopile, temperature compensation circuits are used (not in the MRF instrument), a certain enhancement of pyrgeometer performance might be achieved, if the body temperature during calibration could be set close to the annual mean of the ambient temperature of the site on which the pyrgeometer was to be deployed. Also, to simulate the downwelling atmospheric radiation as realistically as possible during calibration, the blackbody source temperature should be about 10°–25°C below the pyrgeometer's body temperature. It must be said, however, that calibrations made at more ''extreme,'' in particular lower temperatures, are not necessarily poorer performers. But the analysis clearly shows that a certain number of calibration points are necessary.

The good ''median'' results of the Deutscher Wetterdienst Meteorologisches Observatrium Potsdam, and the Eppley Laboratory, that did not determine and, therefore, did not use the correction factor $k$, carries an implication that the use of the dome correction term for the calibration may not be essential. However, this requires, that during calibration, the temperature difference between body and dome is very small. It is well known and accepted that the dome correction term and Eq. (2) must be used for accurate pyrgeometer measurements in the field. Hence, the dome correction factor $k$ has to be known accurately and should be determined during calibration. The unsatisfactory results with regard to the estimation of $k$ in this experiment is most likely connected to the dome temperature measurement at the rim, which does not provide a representative dome temperature. The new dome temperature measurement system described by Philipona et al. (1995), which uses three thermistors separated by 120° and glued at 45° elevation, to assess more exactly the representative dome temperature might be a solution to this problem.

The investigations presented in this paper are limited to calibration of pyrgeometers using a blackbody source and are therefore clearly separated from problems related to pyrgeometer field measurements. Results from the field test in Boulder, Colorado, using the round-robin instruments will be published in a separate paper. Encouraging results have been found with regard to the stability of pyrgeometers, the interchangability of blackbody radiation sources, and to the determination of the responsivity *C* of PIRs. However, further investigations are needed, in particular of the determination of the dome correction factor *k,* and a certain standardization of the pyrgeometer calibration procedures is inevitable for the future.

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