# Calibration Report: Pyranometer

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ABSTRACT

Data were collected for the purpose of performing a calibration of pyranometer sensors using the LaRC 1250 High Bay Roof Calibration Facility from April through June of 1998. This calibration was performed to be in compliance with standards set in the Baseline Surface Radiation Network, (BSRN) Operations Manual V1.0, 1997. The type of pyranometer calibrated was the Eppley Laboratory, Inc. Precision Spectral Pyranometer (PSP). The serial numbers of the PSP's are as follows: 30798F3, 30847F3, 30676F3, 31560F3, 30851F3, 30806F3, 29472F3 and 30803F3. An Eppley Laboratory, Inc. Hickey-Frieden Absolute Cavity Pyrheliometer, AHF31041 was used as the radiometric standard in this calibration. The pyranometer sensitivity values were compared to manufacturer derived values. An uncertainty analysis was completed and included with the results of the pyranometer calibrations.

## 1. Introduction

Data were collected for the purpose of performing a calibration of eight pyranometer sensors at the LaRC 1250 High Bay Roof Calibration Facility. The calibration technique followed was that described in the Baseline Surface Radiation Network, (BSRN) Operations Manual, V1.0, 1997 (Ref 1). The BSRN document recommends the calibration technique described by Forgan (Ref 2). The calibrations were performed in two groups of four. The calibration data for the first set of instruments were collected on 28 April 1998, 14 May 1998 and 15 May 1998. Data for the second set were collected on 2 April 1998, 16 May 1998, 19 May 1998 and 3 June 1998. The type of pyranometer was the Eppley Laboratory, Inc. Precision Spectral Pyranometer (PSP). The serial numbers of the first set of PSP's are as follows: 30798F3, 30847F3, 30676F3, 31560F3. The serial numbers of the second set are 30851F3, 30806F3, 29472F3 and 30803F3. An Eppley Laboratory, Inc. Absolute Cavity Pyrheliometer, (ACP) (serial number AHF31041), was used as the standard in this calibration.

## 2. Preliminary Uncertainty Analysis

A preliminary Uncertainty Analysis was completed. This analysis was performed to determine the reasonable range in which the PSP calibration values should lie. If the combined uncertainty calculated at the end of the experiment is larger than that predicted by the preliminary uncertainty analysis, then either all suspected sources of error were not categorized or an anomaly exists in the measurement system.

The components of the measurement system included the ACP, the digital multimeter in the ACP control system, each PSP, a solar tracker and a microcomputer. All suspected sources of error within this system are listed and the magnitudes calculated or determined from manufacture's data or prior experience. All component error values are converted to or assumed to be a Standard Uncertainty (Ref 3), one standard deviation. The Standard Uncertainties of each component are converted to an Expanded Uncertainty by multiplying each Standard Uncertainty component by the coverage factor 2. This coverage factor implies that the probability of the mean value lies within the Combined Standard Uncertainty with a probability of 95%, (U95%). The Combined Expanded Standard Uncertainties are formed by the root sum square method. The results are shown in Table 1.

A. *Calibration Sensor Uncertainty*

The calibration unit used in this PSP calibration is the LaRC absolute cavity pyrheliometer, serial number AHF31041. This cavity pyrheliometer calibration has been linked to the current World Standard Group (WSG) of pyrheliometers kept in Davos, Switzerland at the Physikalisch-Meteorologisches Observatorium Davos (PMOD). The link is forged by way of a World Radiometric Reference (WRR) reduction factor assigned to pyrheliometer AHF31041 (Ref 4).

The WRR reduction factor is determined from measurements made by the World Standard Group, (WSG), of pyrheliometers at PMOD. As of the International Pyrheliometer Comparison VIII, (IPCVIII) (Ref 5), the Expanded Combined Uncertainty in the WSG measurement is 0.3% with respect to SI units at a 95% confidence level, U95%.

The U95% for any specific pyrheliometer conveys the expected statistical relationship that exists between individual measurements made by that pyrheliometer and a hypothetical co-located individual measurement made by the WSG. Any pyrheliometer with an associated WRR reduction factor makes a measurement that has a specific relationship with the WSG. This relationship is conveyed by the U95% metric. The U95% metric allows the investigator to expect the 95% confidence intervals formed by using measurements made by his/her radiometer and it's associated U95 would bound the WSG measurement 95% of the time.

The National Renewal Energy Laboratory (NREL) pyrheliometer standard group was linked to the WRR at IPCVIII (Ref 5). The LaRC pyrheliometer, AHF31041, was linked to the WRR through the NREL pyrheliometer standard group. The 1997 WRR reduction factor for this LaRC pyrheliometer is 0.99961 (Ref 4). Multiplying a measurement made by the LaRC pyrheliometer by 0.99961 will make the LaRC measurement equivalent to a WSG measurement within their combined uncertainty bounds.

The uncertainty bounds for the LaRC pyrheliometer AHF31041 are related to the path of links from the WSG uncertainty bounds. The transfer of the WRR to the NREL pyrheliometer group induced an additional Standard

Uncertainty of 0.104% as reported in NREL Pyrheliometer Comparisons NPC1996 (Ref 6). The transfer of the WRR to the LaRC ACP induced an additional Standard Uncertainty of 0.098% as reported in Results of NREL Pyrheliometer Comparisons NPC1997 (Ref 4). Therefore, the Expanded Combined Uncertainty for measurements made by the LaRC ACP is 0.42% (95% wrt SI).

B. *Data Acquisition Uncertainty*
The data logger bias is listed as 0.1% and is culled from an NREL uncertainty analysis shown at the Northwest Radiometry Conference (Ref 7).

C. *Data Reduction Uncertainty*
The standard uncertainties of the latitude and longitude, clock time, equation of time and the declination were taken from an NREL document presented at the Pacific Northwest Radiometer Workshop, Aug 1997 (Ref 7). These values are assumed to be Standard Uncertainties.

D. *PSP Sensor Uncertainty*
Limitations were placed on the Global PSP of 0.5% and on the diffuse PSP of 2%. This was done to reject periods of unstable atmosphere. The values were obtained through empirical examination for a very clear sky data collection period

Table 1
Preliminary Uncertainty Analysis

| Source | Type | Magnitude |
|---|---|---|
| Calibration Standard | | |
| ACP AHF31041 | WRR absolute | 0.42% (95%) |
| Data Acquisition | | |
| Data Logger Bias | non-random | 0.1% (1s) |
| Data Reduction | | |
| Latitude & Longitude | non-random | 0.02% (1s) |
| Clock time | non-random | 0.1% (1s) |
| Equation of Time | random | 0.2% (1s) |
| Declination | non-random | 0.2% (1s) |
| Global PSP | | 0.5% |
| Diffuse PSP | | 2.0% |
| TOTAL | Root-Sum-Square | 2.36% (95%) |

This preliminary uncertainty analysis indicates that a calculated measurement error of greater than 2.36% should be held suspect.

**3. Methodology**

The technique of this calibration was to make coincident PSP diffuse radiation measurements, PSP global radiation measurements and ACP direct beam measurements during clear sky conditions. In particular, make the coincident measurements in the morning, (A-period), then exchange the global sensors with the diffuse sensors and collect another set of coincident measurements in the afternoon, (B-period). Data collection periods are defined as solar zenith angles less than $75^o$. Perform this task over as many data collection periods as are appropriate.

Collect the following data:

VA1: PSP #1 sensor output during period A while shaded; Volts (Diffuse component)
VA2: PSP #2 sensor output during period A while un-shaded; Volts (Global Component)
VB1: PSP #1 sensor output during period B while un-shaded; Volts (Diffuse component)
VB2: PSP #2 sensor output during period B while shaded; Volts (Global Component)
$E_{dir}$: AHF31041 sensor output during both periods A and B, $W/m^2$ (Direct Component)

In this case four sensors are calibrated at a time. Two global PSP sensors were mounted with the signal connector pointed toward geometric north (+/- $5^o$). Two diffuse PSP sensors were mounted with their signal connectors pointed away from the sun (+/- $1^o$). All sensors were leveled to zero using the manufacturer installed bubble level (+/- $1^o$). The desiccant in each sensor was replaced before the calibration.

## 3. Data Analysis

Owing to the dearth of cloud free days in our operational area, and a variety of equipment failures, data collected on different days were used for each set of 4 sensors. In addition, a preliminary data rejection techniques was applied to each sensor's data prior to the application of the Forgan technique.

The PSP sensors are sampled at a frequency of 1Hz. A one-minute mean and a population standard deviation are formed from these measurements. If the population standard deviation of a measurement is greater than 0.02 $W/m^2$ the measurement is rejected. Additionally the population standard deviation as a percent of the measurement is calculated. If this value is greater than 2% for a diffuse PSP, or 0.5% for a global PSP, the measurement is rejected. A ratio of global signal to diffuse signal (G/D) was formed. If this ratio was less than 5.0 the data were excluded from the Forgan analysis. If the ratio of G/D to the cosine of the solar zenith angle was less than 9.0, the associated data were excluded from the Forgan analysis. These values were determined from an imperial analysis of our clearest observation period.

If the value of the standard deviation for an AHF31041 measurement is greater than 0.080 $W/m^2$, then the measurement is excluded from the Forgan analysis.

From the remaining data, form the two equations:

$$VA2(\theta) / R1 = Edir * COS(\theta) + VA1(\theta) / R2$$

$$VB1(\theta) / R1 = Edir * COS(\theta) + VB2(\theta) / R2$$

Where;

R1: Calibration coefficient for PSP #1; V/W/m$^2$

R2: Calibration coefficient for PSP #2; V/W/m$^2$

$q$ : solar zenith angle; degrees

Solve the two equations simultaneously for R1 and R2 at each coincident solar zenith angle. Perform statistical analyses on the resulting calibration coefficients to determine the coefficient and coefficient uncertainty for each sensor.

Since two PSP's were shaded and two were global, the calibration analysis was performed twice for each instrument. Results are presented for each sensor, and weighted mean results are presented for the combined results. Calibration results are presented in Table 2. Results for each sensor paired with each of the two others are displayed as well as a combination of the two comparisons.

## 4. Uncertainty Analysis

The uncertainty in the calibration factors is calculated with respect to SI units. The ACP used to calibrate the pyranometers, AHF31041, was connected to the WRR at NPC1997. The WRR determined at NPC1997 is 0.99961. The U95% of AHF31041 with respect to SI units is 0.42%.

The uncertainty of the PSP calibration factor is formed by combining the AHF31041 uncertainty and the PSP uncertainty in the following manner:

Form the mean of the PSP calibration coefficients as in Equation 1.

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n} \quad (1)$$

Then form the population standard deviation of the mean of the PSP calibration coefficients as in Equation 2.

$$s = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \bar{x})^2}{n-1}} \quad (2)$$

The final uncertainty of the PSP sensitivity factor is the sum of the ACP uncertainty, 0.042% (95%) and the uncertainty of the PSP measurements. In order to make the PSP measurement uncertainty equivalent to the ACP uncertainty, an expanded uncertainty of the PSP uncertainty must be formed.

Since the PSP uncertainty results from a precision error, the standard deviation of the measurements may be used. To make the confidence interval of the PSP measurements equal to the confidence interval of the ACP measurements, a coverage factor of two is used. This coverage factor of two multiplied by one standard deviation of the PSP measurement provides a 95-percent confidence interval. The combined experimental uncertainty (95%) was calculated using Equation 3.

$$U95\% = \sqrt{(0.42)^2 + (2 \times s)^2} \quad (3)$$

## 5. Results

The results of the analysis are presented in Table 2.

**Table 2**
**Calibration Results**

| Sensor | Compared With Sensor: | n | *s* | Forgan S V/W/m$^2$ | (U95,%) |
|---|---|---|---|---|---|
| 30798F3 | 30676F3 | 483 | 0.605 | 8.821E-6 | (1.282) |
| | 31560F3 | 483 | 0.595 | 8.846E-6 | (1.261) |
| | Both | 966 | 0.614 | 8.833E-6 | (1.298) |
| 30847F3 | 30676F3 | 483 | 0.593 | 8.776E-6 | (1.258) |
| | 31560F3 | 483 | 0.554 | 8.801E-6 | (1.185) |
| | Both | 966 | 0.590 | 8.789E-6 | (1.252) |
| 30676F3 | 30798F3 | 483 | 0.488 | 8.679E-6 | (1.063) |
| | 30847F3 | 483 | 0.510 | 8.694E-6 | (1.103) |
| | Both | 966 | 0.507 | 8.687E-6 | (1.097) |
| 31560F3 | 30798F3 | 483 | 0.438 | 9.518E-6 | (0.971) |
| | 30847F3 | 483 | 0.442 | 9.534E-6 | (0.979) |
| | Both | 966 | 0.448 | 9.526E-6 | (0.448) |
| 30851F3 | 29472F3 | 537 | 0.412 | 8.480E-6 | (0.926) |
| | 30803F3 | 537 | 0.384 | 8.495E-6 | (0.875) |
| | Both | 1074 | 0.406 | 8.487E-6 | (0.914) |
| 30806F3 | 29472F3 | 537 | 0.399 | 9.076E-6 | (0.902) |
| | 30803F3 | 537 | 0.405 | 9.092E-6 | (0.920) |
| | Both | 1074 | 0.409 | 9.084E-6 | (0.902) |
| 29472F3 | 30851F3 | 537 | 0.573 | 8.683E-6 | (1.220) |
| | 30806F3 | 537 | 0.513 | 8.704E-6 | (1.109) |
| | Both | 1074 | 0.556 | 8.693E-6 | (1.189) |
| 30803F3 | 30851F3 | 537 | 0.545 | 9.556E-6 | (1.169) |
| | 30806F3 | 537 | 0.513 | 9.579E-6 | (1.183) |
| | Both | 1074 | 0.561 | 9.567E-6 | (1.198) |

## 6. Discussion

The calibration of PSP sensors 30798F3, 30847F3, 30676F3, 31560F3, 30851F3, 30806F3, 29472F3 and 30803F3 using the Forgan method has been completed at LaRC. The sensor sensitivity coefficients and associated uncertainties resulting from the analysis of "Both" sets of sensors are defined as the current calibration values. The Eppley stated uncertainty of sensitivity is 5%. From this manufacturer baseline, all sensors calibrated with the Forgan technique are well within manufacturer calibration coefficient uncertainty specification except for sensor 30851F3.

Two of the sensors 30851F3 and 30803F3 were calibrated at NREL in July of 1996 in a Broadband Outdoor Radiometer Calibration Report (BORCAL) (Ref 8). The uncertainties determined at this calibration were on the order of 3%. Again sensor 30851F3 is outside the manufacturers uncertainty tolerances. The calibration history of the PSP sensors is presented in Table 3.

**Table 3**
**Calibration History**

| Sensor | Forgan S V/W/m$^2$ | (U95,%) | BORCAL96-2 S V/W/m$^2$ | (U95,%) | Eppley S V/W/m$^2$ | (U%) |
|---|---|---|---|---|---|---|
| 30798F3 | 8.821E-6 | (1.282) | n/a | | 9.01E-6 | (5) |
| 30847F3 | 8.801E-6 | (1.185) | n/a | | 8.96E-6 | (5) |
| 30676F3 | 8.679E-6 | (1.063) | n/a | | 8.74E-6 | (5) |
| 31560F3 | 9.534E-6 | (0.979) | n/a | | 9.51E-6 | (5) |
| 30851F3 | 8.480E-6 | (0.926) | 8.257E-6 | (3.3) | 9.68E-6 | (5) |
| 30806F3 | 9.076E-6 | (0.902) | n/a | | 9.22E-6 | (5) |
| 29472F3 | 8.683E-6 | (1.220) | n/a | | 8.76E-6 | (5) |
| 30803F3 | 9.556E-6 | (1.169) | 9.362E-6 | (3.2) | 9.46E-6 | (5) |

The results are well within the limitations determined during the preliminary uncertainty analysis. The sensors should be calibrated again using this Forgan technique. Sensor 30851F3 should continue to be calibrated but not used in the field until the change in sensitivity factors is understood.

A further step should be added to verify in the Forgan calibration results. That is, all sensors which have been calibrated using this technique, should be placed side-by-side, and the sensitivity factors applied to the measured data. The values all should be the same within their measured uncertainty.

## 7. Summary

The calibration and analysis of the Precision Spectral Pyranometer sensors has been completed at the LaRC 1250 Roof Calibration Site. The units of the sensitivity factors, S, are $V/W/m^2$. The sensitivity factors and their associated uncertainties (95%) are as follows:

| Sensor | S | (U95%) |
|---|---|---|
| 30798F3 | 8.833E-6 | (1.298) |
| 30847F3 | 8.789E-6 | (1.252) |
| 30676F3 | 8.687E-6 | (1.097) |
| 31560F3 | 9.526E-6 | (0.989) |
| 30851F3 | 8.487E-6 | (0.914) |
| 30806F3 | 9.084E-6 | (0.902) |
| 29472F3 | 8.693E-6 | (1.189) |
| 30803F3 | 9.567E-6 | (1.198) |

These values are valid for data collected from 28 June 1998. Sensor 30851F3 should NOT be used for science measurements until further notice.

REFERENCES

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