Calibration Report: Pyranometer

F. M. Denn, K. T. Larman
Analytical Services & Materials, Inc., Hampton, Virginia

Calibration date: 12 February 1999
Next Calibration due: 12 February 2001

The calibration and analysis of nine Eppley Laboratory, Inc. Precision Spectral Pyranometer sensors has been completed at the Mauna Loa Observatory, Hawaii. The units of the sensitivity factors, S, are $\mu V/W/m^2$. The sensitivity factors and their associated uncertainties (95%) are as follows:

Sensor	S ±U95% $\mu V/W/m^2$
29472F3	8.49 ±4.51%
30676F3	8.49 ±2.98%
30798F3	8.45 ±5.23%
30803F3	9.26 ±4.35%
30806F3	8.72 ±5.47%
30847F3	8.75 ±3.14%
30851F3	8.37 ±1.61%
31560F3	9.23 ±4.20%
31561F3	8.42 ±1.84%

Application

$$I = (\text{mV output})/S \pm U95\%$$

Where: I = the radiance measured by the pyrheliometer
(mV output) = micro-volt output of the pyranometer
S = calibration coefficient of the pyranometer
U95% = the 95 % confidence level

ABSTRACT

Data were collected for the purpose of calibrating nine pyranometer sensors at the Mauna Loa Observatory, Hawaii during the period 7-12 February 1999. This calibration was performed to be in compliance with standards set in the Baseline Surface Radiation Network, (BSRN) Operations Manual V1.0, 1997. The calibrated sensors were Eppley Laboratory, Inc. Precision Spectral Pyranometers (PSPs). The serial numbers of the

PSP's are as follows: 29472F3, 30676F3, 30798F3, 30803F3, 30806F3, 30847F3, 30851F3, 31560F3, and 31561F3. An Eppley Laboratory, Inc. Hickey-Frieden Absolute Cavity Pyrheliometer, AHF31041 was used as the radiometric standard in this calibration. The pyranometer calibration coefficients were compared to manufacturer derived values. An uncertainty analysis was completed and included with the results of the pyranometer calibrations.

1. Introduction

Calibration data were collected for nine Eppley Laboratory, Inc. Precision Spectral pyranometers (PSPs), at the Mauna Loa Observatory (MLO), Hawaii during the period 7-12 February 1999. The serial numbers of the nine of PSP's are as follows: 29472F3, 30676F3, 30798F3, 30803F3, 30806F3, 30847F3, 30851F3, 31560F3, and 31561F3. An Eppley Laboratory, Inc. Absolute Cavity Pyrheliometer, (ACP) (serial number AHF31041), was used as the standard in this calibration. The calibration technique followed is 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 calibration data were collected for groups of four sensors. The PSPs were calibrated at this site because it has very clear sky and stable atmospheric conditions. Knowledge of sensor characteristics under these pristine conditions is quite useful during subsequent field deployment. The second reason was to get a full range of solar zenith angles, in order to study the zenith angle response of a PSP. This is difficult if not impossible in the Hampton, Virginia area.

2. Preliminary Uncertainty Analysis

A preliminary Uncertainty 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, (which contains the cavity radiometer and a 406 control box with a Digital Multimeter, (DMM)), each PSP, a solar tracker, a Campbell Scientific Inc. data logger and a microcomputer. All suspected sources of error within this system are listed and the magnitudes are calculated, determined from manufacture's data or based on prior experience.

All component error values are converted to, or assumed to be a Standard Uncertainty (Ref 3), of one standard deviation. The Standard Uncertainties of each component are converted to an Expanded Uncertainty component by multiplying each Standard Uncertainty component by the coverage factor of 2. The true value of each measurement component lies within the range of the Expanded Uncertainty component with a probability of 95% (U95%). The overall system uncertainty is the Combined Expanded

Uncertainty. The Combined Expanded Uncertainty is formed by combining each Expanded Uncertainty component using the root sum square method. The root-sum-square is defined as follows: the ACP uncertainty (U95%) is squared, each Expanded Uncertainty (U95%), (2 standard deviations) is squared, all squared components are summed, the square root of this sum is then taken to form the Combined Uncertainty. The results are shown in Table 1.

A. Calibration Sensor Uncertainty

The calibration unit used was the LaRC ACP AHF31041. The ACP calibration has been linked to the current World Radiation Reference (WRR) kept in Davos, Switzerland at the Physikalisch-Meteorologisches Observatorium Davos (PMOD). The defined magnitude of the WRR standard uncertainty is 0.3%, (U95% wrt SI units) reported from the latest International Pyrheliometer Comparison IPCVIII. The National Renewal Energy Laboratory (NREL) ACP standard group was linked to the WRR at IPCVIII. The LaRC ACP AHF31041 was linked to WRR through the NREL ACP standard group. The resultant NPC1998 WRR factor for LaRC ACP AHF31041 is 0.99833, with an Uncertainty 0.37% (95% wrt SI). The link is forged by way of a World Radiometric Reference (WRR) reduction factor assigned to pyrheliometer AHF31041 (Ref 4).

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 World Standard Group (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.

B. Data Acquisition Uncertainty

The data acquisition uncertainty is determined by the manufacturer uncertainty of the Digital Multi-meter (DMM). In the 20mV range, the 1-year standard uncertainty is 0.023%. The tracker alignment was controlled using diopter feedback. The maximum diopter error accepted during the measurement was 0.30 degrees. Convert this to a percentage by dividing by 360 and multiplying by 100, or 0.083%. This is assumed to be a Standard 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

The manufacture stated uncertainty of each PSP sensor is 5%.

Table 1
Preliminary Uncertainty Analysis

Source	Type	Magnitude
<u>Calibration Standard</u>		
ACP AHF31041	WRR absolute	0.37% (95%)
<u>Data Acquisition</u>		
Data Logger Bias	non-random	0.1% (1σ)
<u>Data Reduction</u>		
Latitude & Longitude	non-random	0.02% (1σ)
Clock time	non-random	0.1% (1σ)
Equation of Time	random	0.2% (1σ)
Declination	non-random	0.2% (1σ)
Global PSP	random	5.0%
Diffuse PSP	random	5.0%
TOTAL	Root-Sum-Square	10.05% (95%)

This preliminary uncertainty analysis indicates that a calculated measurement error of greater than 10.05% should be held suspect.

3. Methodology

The Forgan calibration methodology was used to calibrate these sensors. This methodology is as described in the BSRN Operations Manual V1.0, 1997. 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 of one day, (A-period), then exchange the global sensors with the diffuse sensors and collect another set of coincident measurements in the morning of another day, (B-period). During the period 7-12 February 1999, data were collected each day for a set of 4 sensors.

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)

Measurements were taken from four instruments at a time. Two global PSP sensors mounted with the signal connector pointed toward geometric north (+/- 5^o), and two diffuse PSP sensors 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 checked and replaced as necessary before the calibration.

4. Data Analysis

The PSP sensors were sampled at a frequency of 1Hz, one-minute means and standard deviations were determined, and used in the uncertainty analysis.

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

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

Where;
R1: Calibration coefficient for PSP #1; $\mu V/W/m^2$
R2: Calibration coefficient for PSP #2; $\mu V/W/m^2$
θ : solar zenith angle; degrees

Solve the two equations simultaneously for R1 and R2, at coincident solar zenith angles. Perform statistical analyses on the resulting calibration coefficients to determine the means and standard deviations of the calibration coefficients for each sensor.

Since two PSP's were shaded and two were global, the calibration could be twice for each sensor, additional calibration opportunities occurred because the sensors were mounted in several different combinations. Calibration results are presented in Table 2. Figures 1 – 9 show the results of the calibration analysis, for each PSP, for the February 1999 calibration data. A subset of the May – June 1998 calibration data is also displayed for comparison.

5. 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 NPC1998. The WRR value determined at NPC1998 is 0.99833, with a U95 0.37%. The 0.37% value occurs twice in the uncertainty analysis because the cavity is used for each set of measurements in a paired set of measurements.

For each set of PSP data the one minute means and standard deviations of the one Hz data were formed, additionally the mean of the standard deviations of the one minute data values for a each calibration set were determined. These means were used in the calculation of the combined uncertainty.

The final uncertainty of the PSP calibration coefficient is a function of the ACP uncertainty, and the uncertainties of the PSP measurements. In order to make the PSP measurement uncertainty equivalent to the ACP uncertainty, the Expanded Uncertainty of the PSP measurements (two standard deviations) is used. The combined experimental uncertainty (95%) was calculated using Equation 1.

$$U95\% = \sqrt{(2*0.37)^2 + (2\sigma_{GA})^2 + (2\sigma_{DA})^2 + (2\sigma_{GB})^2 + (2\sigma_{DB})^2 + (2\sigma_R)^2} \qquad (1)$$

where:

0.37 ≡ U95% uncertainty of the ACP, used twice because two measurements were made. σ_{GA} ≡ mean of the standard deviations of the global 1 minute means for period A σ_{DA} ≡ mean of the standard deviations of the diffuse 1 minute means for period A σ_{GB} ≡ mean of the standard deviations of the global 1 minute means for period B σ_{DB} ≡ mean of the standard deviations of the diffuse 1 minute means for period B σ_R ≡ standard deviations of the calibration coefficients for a given period.

6. Results

The results of the analysis are presented in Table 2. Plots of the calibration coefficients, for each sensor, for the February 1999 calibrations appear in figures 1-9. A subset of the May-June calibration points are included in the figures for comparison.

Table 2
Calibration Results

Sensor	Forgan S ±U95% μV/W/m^2
29472F3	8.49 ±4.51%
30676F3	8.49 ±2.98%
30798F3	8.45 ±5.23%
30803F3	9.26 ±4.35%
30806F3	8.72 ±5.47%
30847F3	8.75 ±3.14%
30851F3	8.37 ±1.61%
31560F3	9.23 ±4.20%
31561F3	8.42 ±1.84%

7. Discussion

The calibration of PSP sensors 29472F3, 30676F3, 30798F3, 30803F3, 30806F3, 30847F3, 30851F3, 31560F3, and 31561F3 using the Forgan method has been completed at MLO. The sensor calibration coefficients and associated uncertainties resulting from the analysis of all sets of data are defined as the current calibration values. The Eppley stated uncertainty of sensitivity is 5%.

From this manufacturer baseline, six sensors calibrated with the Forgan technique are within manufacturer calibration coefficient uncertainty specification. The other three sensors 30798F3, 30806F3, and 30851F3 exhibit changes in calibration coefficient outside the original manufacturers range. Although the change exhibited by sensor 30851F3 is outside the range of the original calibration, it has shown the greatest consistency between 1998 and 1999, also its calibration coefficients show a small solar zenith angle dependence.

For most of the sensors a calibration coefficient, determined as a function of the solar zenith angle, would result in better irradiance values. Another method which might provide better overall calibration values would be to weight the individual calibration coefficients by the sine of the solar zenith angle thereby giving more consideration to periods of greater incident energy.

A major cause of the increase in the uncertainty of the PSP calibration coefficients is the increase their range. This range increase appears to be the result of a solar zenith angle dependence in response of the sensor. All of the calibration coefficient plots show a spike in 60-70 deg solar zenith angle range, the cause of this spike is unknown although it may have been a reflection or a shadow.

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 was outside the range of the manufactures original calibration. The calibration history of the PSP sensors is presented in Table 3.

Table 3
Calibration History

Sensor	1999 Forgan S ±U95% μV/W/m^2	1998 Forgan S ±U95% μV/W/m^2	1996 BORCAL96-2 S ±U95% μV/W/m^2	Original Eppley S ±U95% μV/W/m^2
29472F3	8.49 ±4.51%	8.68 ±1.22%	N/A	8.76 ±5%
30676F3	8.49 ±2.98%	8.66 ±1.06%	N/A	8.74 ±5%
30798F3	8.45 ±5.23%	8.82 ±1.28%	N/A	9.01 ±5%
30803F3	9.26 ±4.35%	9.55 ±1.17%	9.362 ±3.2%	9.46 ±5%
30806F3	8.72 ±5.47%	9.07 ±0.90%	N/A	9.22 ±5%
30847F3	8.75 ±3.14%	8.80 ±1.19%	N/A	8.96 ±5%
30851F3	8.37 ±1.61%	8.48 ±0.93%	8.257 ±3.3%	9.68 ±5%
31560F3	9.23 ±4.20%	9.53 ±0.98%	N/A	9.51 ±5%
31561F3	8.42 ±1.84%	N/A	N/A	8.52 ±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.

8. Summary

The calibration and analysis nine Eppley Laboratory, Inc. Precision Spectral Pyranometer sensors has been completed at the Mauna Loa Observatory, Hawaii. The units of the sensitivity factors, S, are $\mu V/W/m^2$. The sensitivity factors and their associated uncertainties (95%) are as follows:

Sensor	S ±U95% $\mu V/W/m^2$
29472F3	8.49 ±4.51%
30676F3	8.49 ±2.98%
30798F3	8.45 ±5.23%
30803F3	9.26 ±4.35%
30806F3	8.72 ±5.47%
30847F3	8.75 ±3.14%
30851F3	8.37 ±1.61%
31560F3	9.23 ±4.20%
31560F3	8.42 ±1.84%

Application

$$I = (\text{mV output})/S \pm U95\%$$

Where: I = the radiance measured by the pyranometer
(mV output) = micro-volt output of the pyrheliometer
S = calibration coefficient of the pyranometer
U95% = the 95 % confidence level

REFERENCES

(1) McArthur, L.J.B., Baseline Surface Radiation Network (BSRN) Operations Manual V1.0, World Climate Research Programme, June 1997.

(2)Forgan, B.W.,"A New Method for Calibrating Reference and Field Pyranometers" The Journal of Atmospheric and Oceanic Technology, Vol 13, pp 638-645, June 1996.

(3)American National Standard for Expressing Uncertainty-U.S. Guide to the Expression of Uncertainty in Measurement, ANSI/NCSL Z540-2-1997. Reprinted February 1998

(4)Reda, I., Stoffel, T., Treadwell, J., Results of NREL Pyrheliometer Comparisons NPC1998, National Renewable Energy Laboratory, Center for Renewable Energy Resources, Measurements & Instrumentation Team, 11 November 1998.

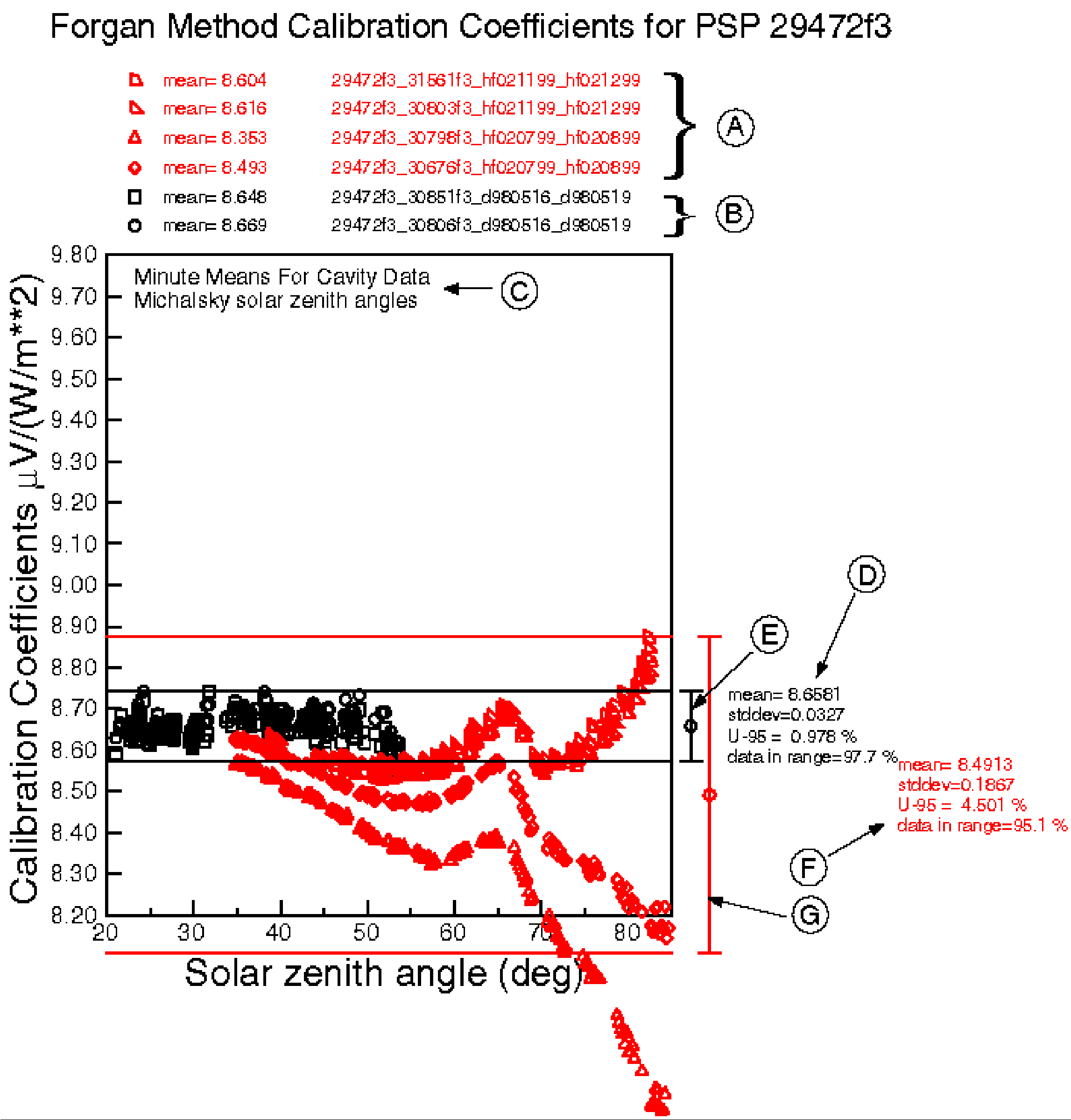
(5) Swiss Meteorological Institute, (May 1996) “International Pyrheliometer Comparison IPC VIII,” Working Report No. 188, Davos and Zurich.

(6) Reda, Ibrahim, Stoffel, Tom, “Results of the NREL Pyrheliometer Comparsions NPC1096, 1-5 October 1996”, National Renewable Energy Laboratory, Renewable Energy Resources Center, Measurements and Instrumentation Team.

(7)Pacific Northwest Radiometer Workshop, National Renewable Energy Laboratory, University of Oregon Solar Monitoring Lab, Eugene, Oregon, Aug 6-8 1997.

(8)NREL, “Broadband Outdoor Radiometer Calibration Report”, BORCAL 96-2, 23 July 1996.

(9)Michalsky, J., 1988: The Astronomical Almanac's algorithm for approximate solar position (1950-2050), Solar Energy 40, 227-235 (but the version of this program in the Appendix contains errors and should not be used)



<u>Figure 1.</u> Plot of calibration coefficients as a function of solar zenith angle for PSP 29472f3. Each labeled part of the plot will be described. These descriptions will also apply to plots 2 through 9. Each line, of section “A”, displays a symbol used on the plot for a given pair of sensors, the mean calibration coefficient over the full range of solar zenith angles (e.g. 8.604), the PSP which is being calibrated (e.g. 29472f3) the sensor to which it is being compared (e.g. 31561f3), the date on which one set of data was taken (e.g. hf021199) the hf refers to the Hickey Frieden Absolute Cavity Pyrheliometer, and is in the form mmddyy, the last entry on a line (e.g. hf021299) is the date of the second set of data. Section “B” is for year 1998 and is similar to section “A” except dates are represented differently (e.g. d980515) is data for yymmdd. Section “C” indicates the 2 second ACP data has been averaged into 1 minute values, and the solar zenith angles were calculated using an algorithm developed by Michalsky (Ref 9). Section “D” summerizes the 1998 calibration data. The mean and standard deviation over all sensor combinations

and solar zenith angles are presented, (e.g. 8.6581, and 0.0327 respectively) as well as the 95% confidence interval (0.978%). As a final check the fraction of the data which fall within the limits of the 95% confidence interval is displayed on the forth line of this section (e.g. 97.7%). Section "E" is a graphical representation of the mean and standard deviation presented in section "D". Sections "F" and "G" are the same as "D" and "E" except the calibration year is 1999.

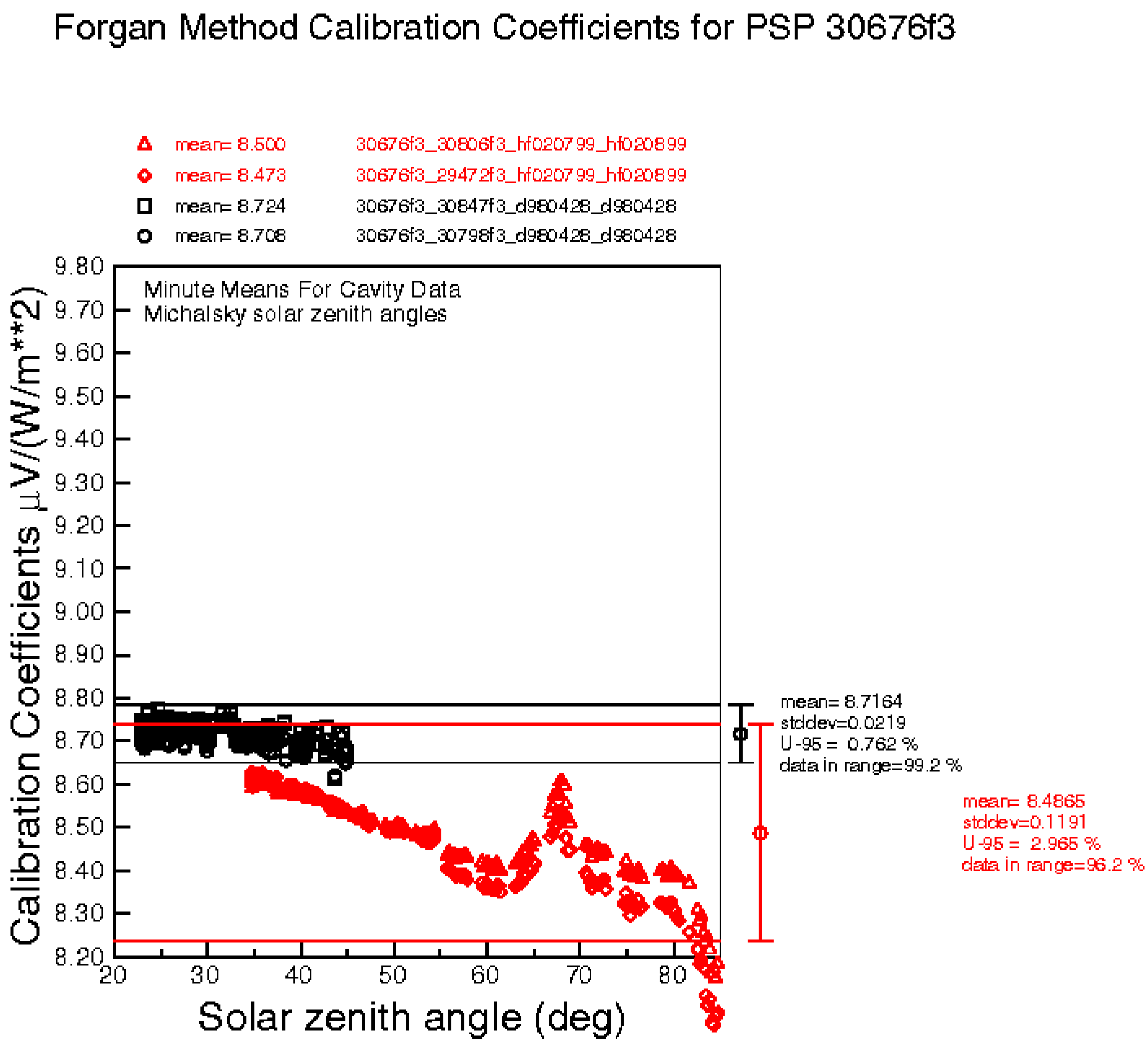


Figure 2. Same as figure 1 except for PSP 30676f3.

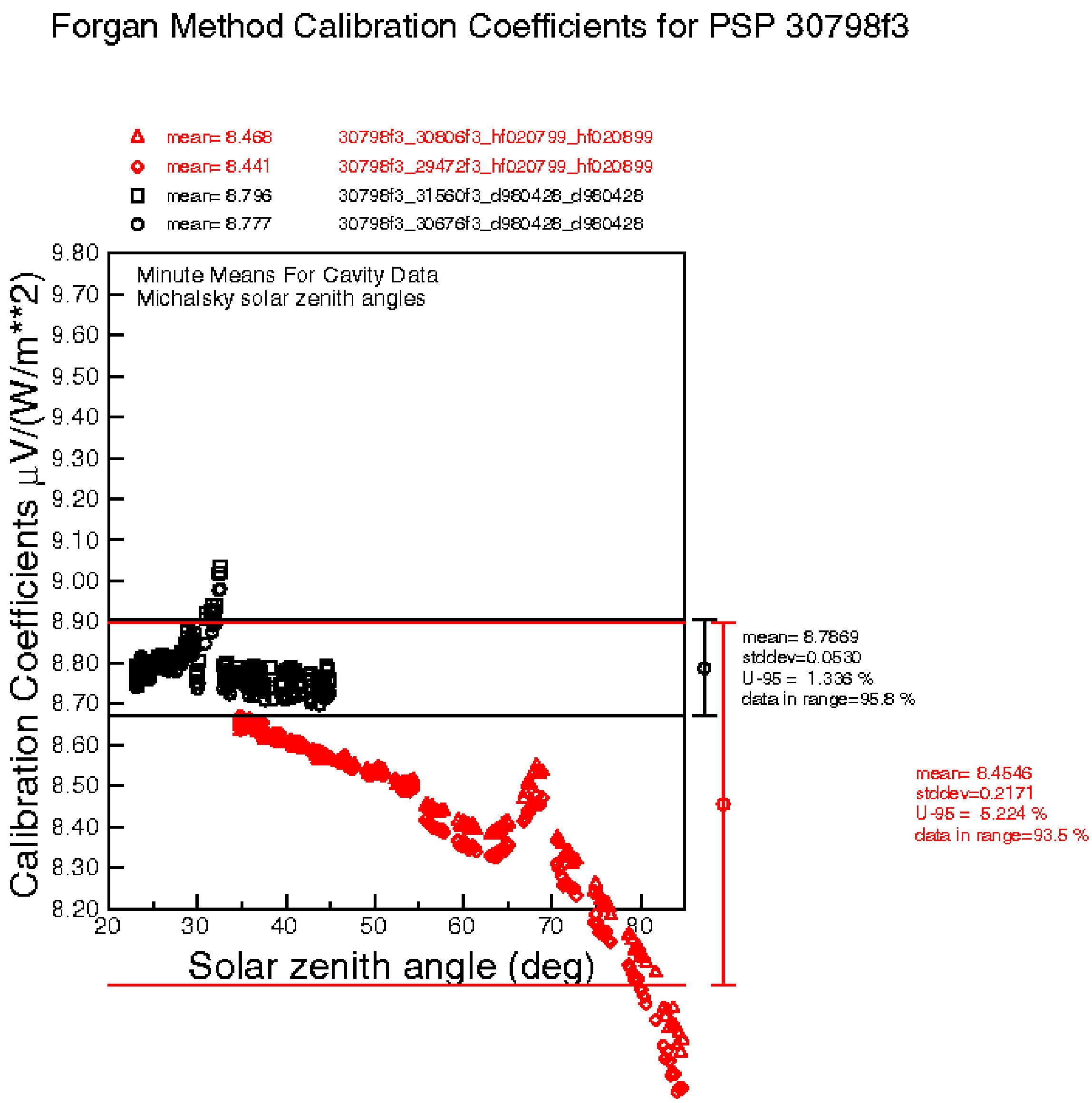


Figure 3. Same as figure 1 except for PSP 30798f3.

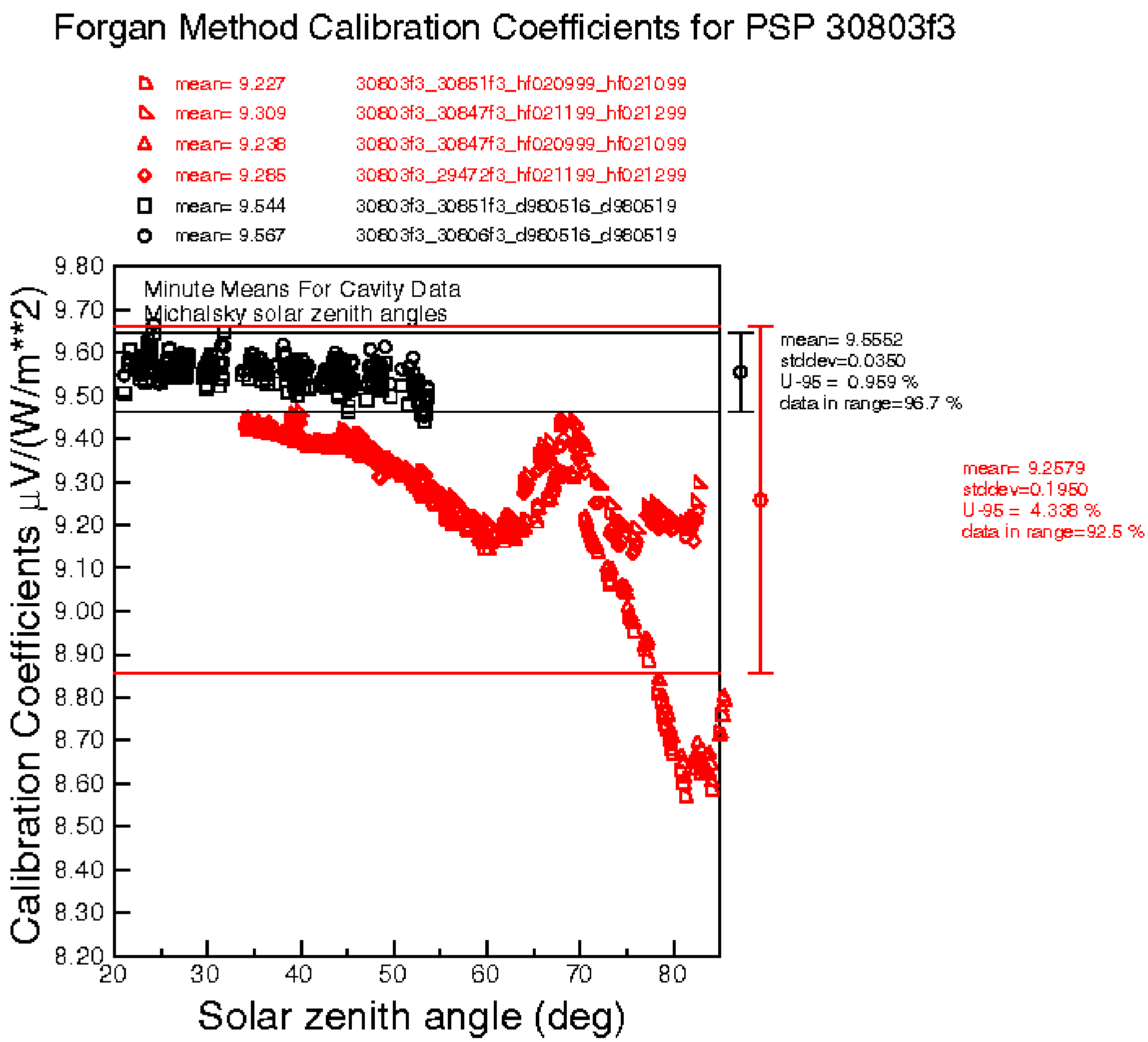


Figure 4. Same as figure 1 except for PSP 30803f3.

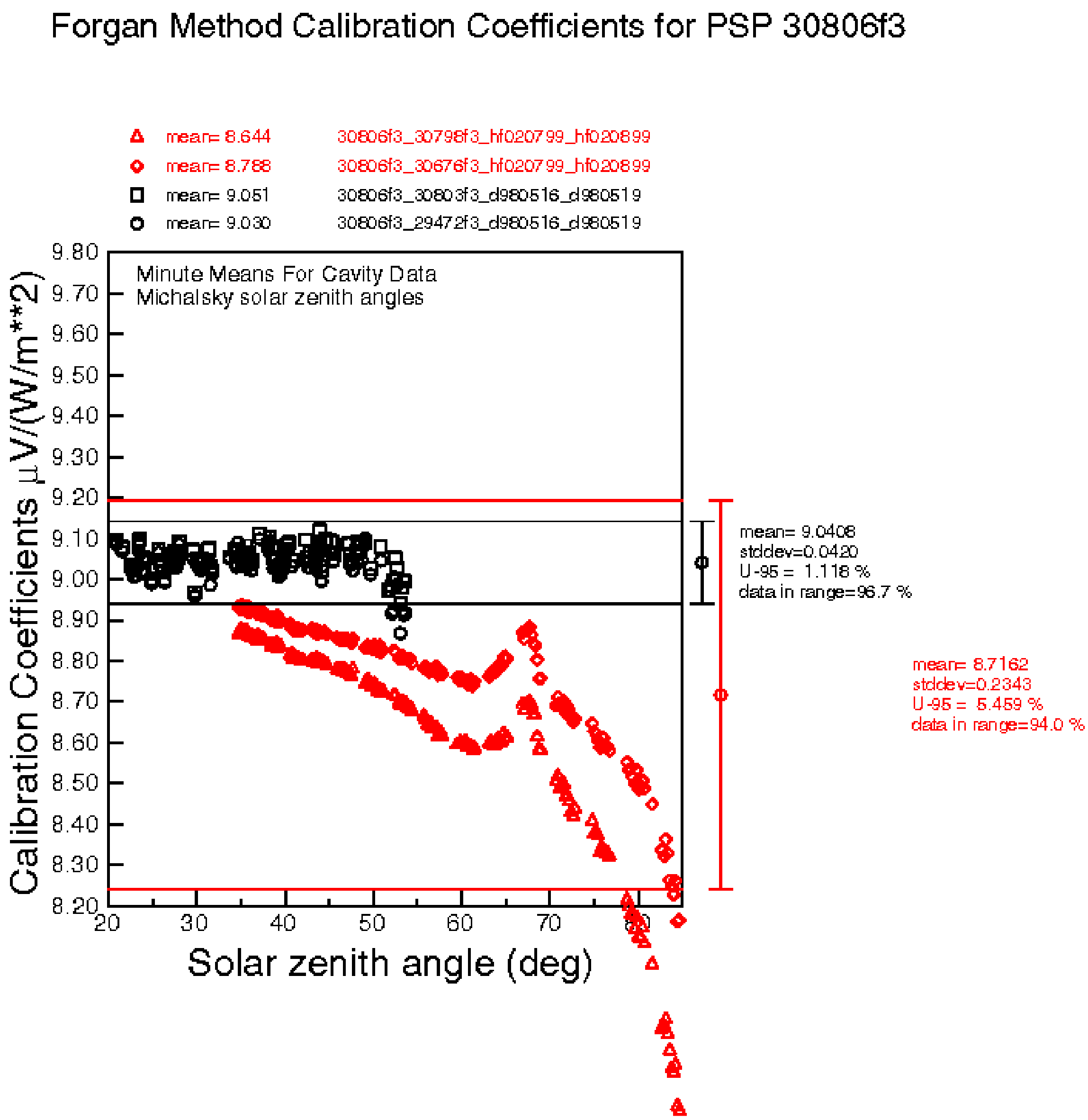


Figure 5. Same as figure 1 except for PSP 30806f3.

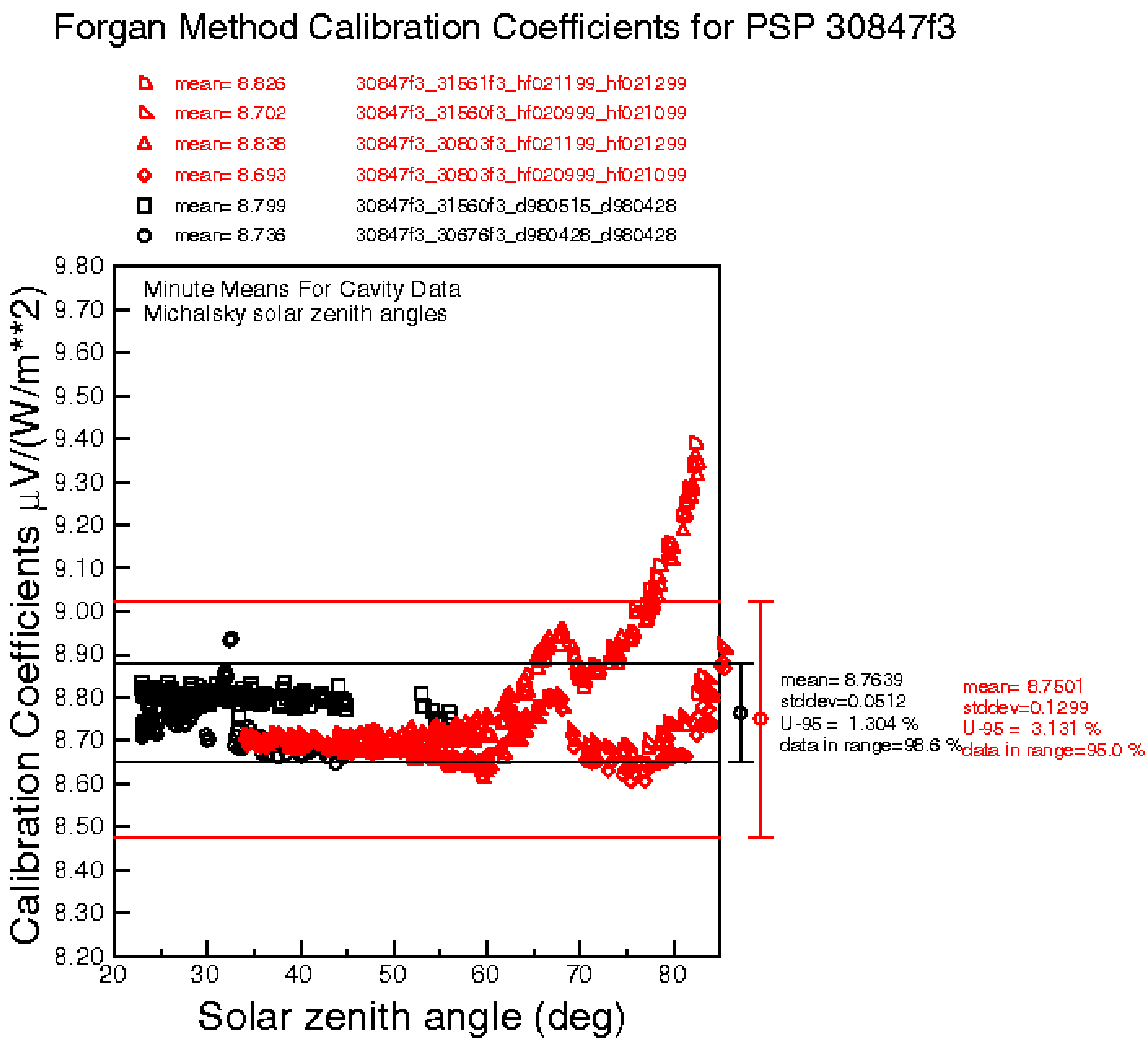


Figure 6. Same as figure 1 except for PSP 30847f3.

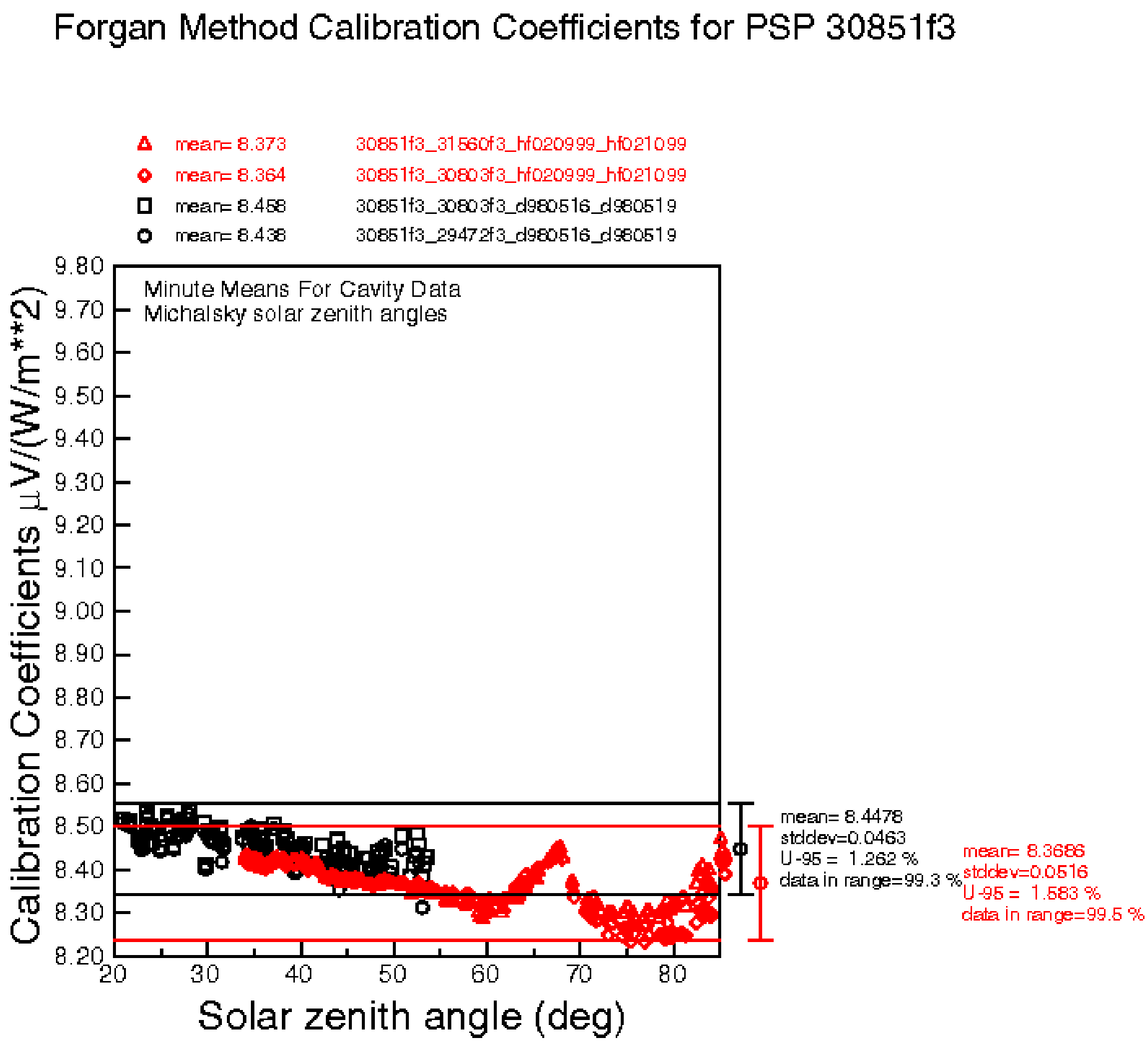


Figure 7. Same as figure 1 except for PSP 30851f3.

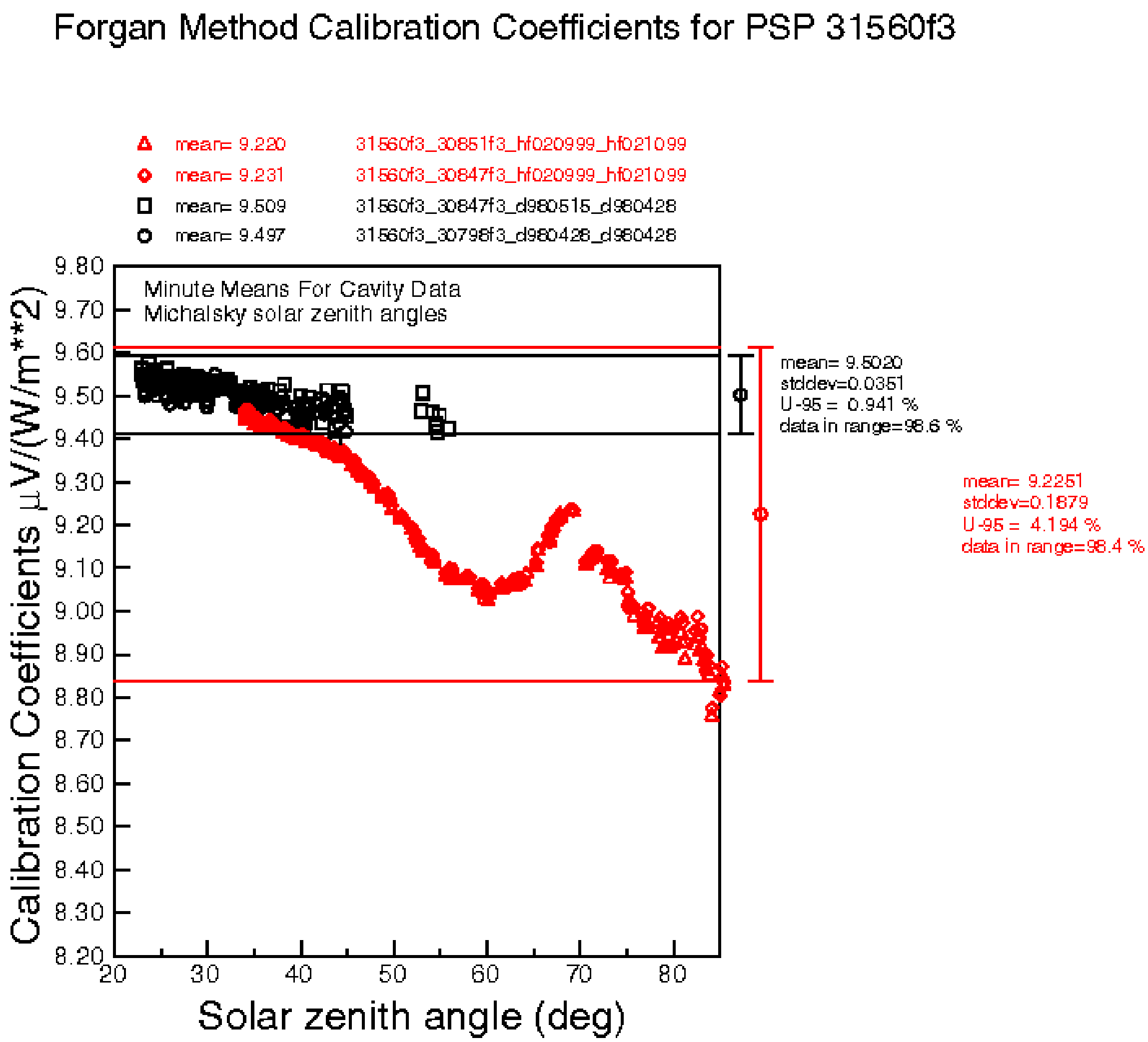


Figure 8. Same as figure 1 except for PSP 31560f3.

Forgan Method Calibration Coefficients for PSP 31561E3

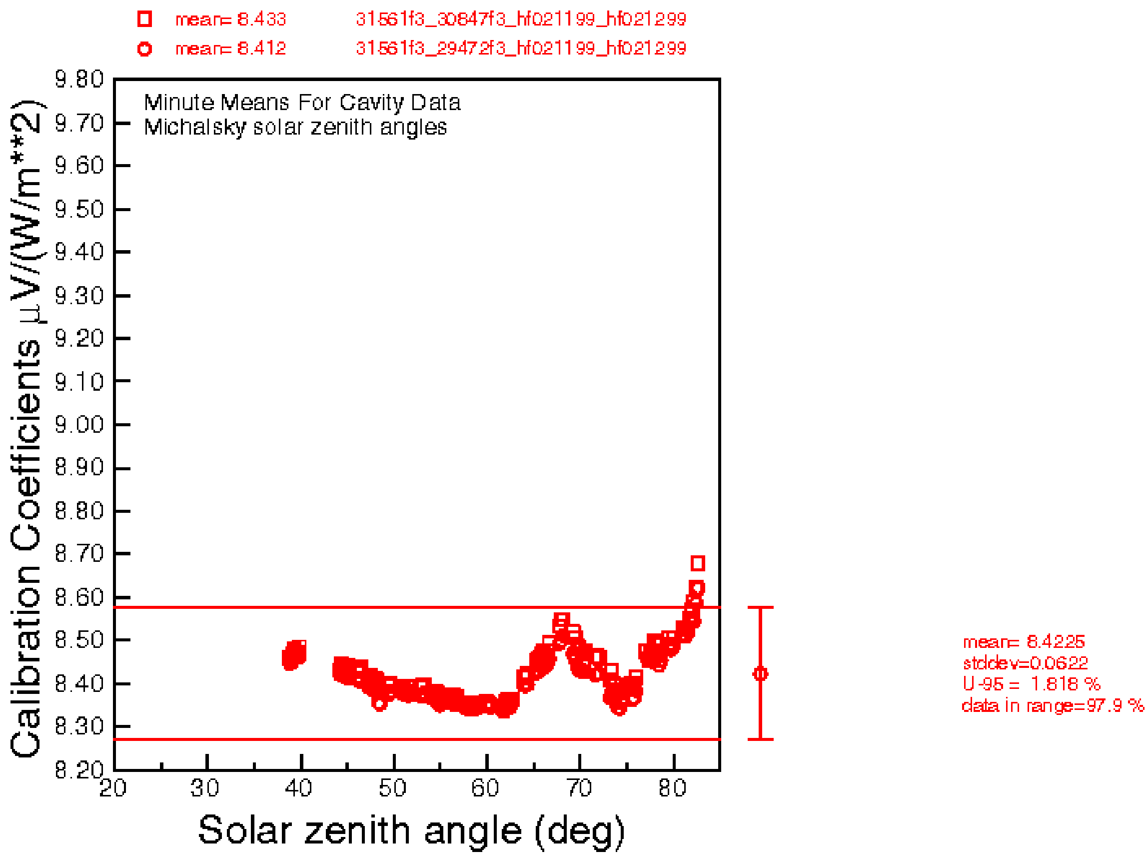


Figure 9. Same as figure 1 except for PSP 31561f3.