Calibration Report: Normal Incidence Pyrheliomters

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ABSTRACT

Calibration data from three Normal Incident Pyrheliometer sensors were collected at Mauna Loa Observatory, Hawaii on 16 February 1998. The sensor array included two Eppley Laboratory, Inc. sensors, 31375E6, 31376E6 and a Kipp and Zonen, Inc. sensor, 960133. The sensors were calibrated against an Eppley Laboratory, Inc. Absolute Cavity Radiometer with a World Radiation Factor of 0.99961. These calibration data were analyzed to produce sensitivity coefficients with 95-percent uncertainty bounds. These coefficients are compared to manufacturer derived values.

1. Introduction

Calibrations of three Normal Incident Pyrheliometers (NIP) sensors were made at Mauna Loa Observatory (MLO), Hawaii on 16 February 1998. The sensor array included two Eppley Laboratory, Inc. sensors, 31375E6, 31376E6 and a Kipp and Zonen, Inc. sensor, 960133. The sensors were calibrated against an Eppley Laboratory, Inc. Absolute Cavity Radiometer, (ACR), AHF31041. This radiometer has a World Radiometric Reference (WRR) factor of 0.99961 and a 95-percent uncertainty with respect to SI units (U95%) of 0.42%, as of the October 1997 NPC1997.

2. Preliminary Uncertainty Analysis

A preliminary uncertainty analysis was completed. This analysis was performed to determine the reasonable range in which the NIP calibration values should lie. Should the combined uncertainty of the experiment be 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 ACR, each NIP, the ACR 406 control box (more precisely the Digital Multimeter, (DMM) which displayed the measurements), a solar tracker and a PC. All suspected sources of error within this system were listed and the magnitudes calculated or determined from manufacture's data or prior experience. All values, no matter how derived, are converted to assumed to be a Standard Uncertainty so that they may be converted into an expanded uncertainty through the use of a coverage factor. A Standard Uncertainty is equivalent to a standard deviation of the measurements. These expanded uncertainties may then be combined to form an overall uncertainty estimation. The results are shown in Table 1.

A. *Calibration Unit Uncertainty*
The calibration unit used in this NIP calibration is LaRC ACR AHF31041. This ACR 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) ACR standard group was linked to the WRR at IPCVIII. The LaRC ACR AHF31041 was linked to WRR through the NREL ACR standard group. The WRR factor for this LaRC ACR is 0.99961. The transfer of the WRR to the NREL ACR group induced a standard uncertainty of 0.104% as reported in NREL Pyrheliometer Comparisons NPC1996. The transfer of the WRR to the LaRC ACR induced an additional standard uncertainty of 0.098% as reported in Results of NREL Pyrheliometer Comparisons NPC1997. Therefore, the Standard Uncertainty for measurements made by the LaRC ACR is 0.42% (U95% wrt SI).

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.

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. These values are assumed to be Standard Uncertainties.

Table 1
Preliminary Uncertainty Analysis

Source	Type	Magnitude
<u>Calibration Standard</u>		
ACR AHF31041	WRR absolute	0.42% (U95%)
<u>Data Acquisition</u>		
DMM voltage	random	0.023% (1*s*)
Tracker alignment	non-random	0.083% (1*s*)
<u>Data Reduction</u>		
Latitude & Longitude	non-random	0.02% (1*s*)
Clock time	non-random	0.1% (1*s*)
Equation of Time	random	0.2% (1*s*)
Declination	non-random	0.2% (1*s*)

TOTAL	Root-sum-square	0.75% (U95%)

The Root-sum-square total is formed as follows: the ACR uncertainty (U95%) is squared, each component is converted to an expanded uncertainty (U95%) using a coverage factor of 2 and squared, all squared components are summed, the square root of this sum is then taken to form the combined uncertainty. This preliminary uncertainty analysis indicates that a calculated measurement uncertainty of greater than 0.75% should be held suspect.

3. Methodology

Verify that the NIP desiccant was within the proper tolerance as necessary. Attach the ACR and NIP sensors to the solar tracker. Align the tracker to geometric N-S. Align the ACR and NIP sensors to the solar tracker. Make all ground connections and ground yourself. Connect the ACR and NIP sensors to the ACR controller and PC. Clean the NIP windows. Verify the ACR window and the ACR cover is off. Run the MULTNIPN.BAS program. Use the manufacturer's initial calibration factors for both the ACR and NIP sensors. Verify that sensor diopter alignments remain within tolerance throughout the data collection time period.

4. Data Analysis

The data used in this analysis are limited to those collected from about 7:10 am to about 12:55 pm in order to minimize the effects of turbulent afternoon atmosphere. Sensitivity factors for the 3 NIP sensors relative to the ACR were calculated. The ACR data used in this analysis are shown in Fig. 1

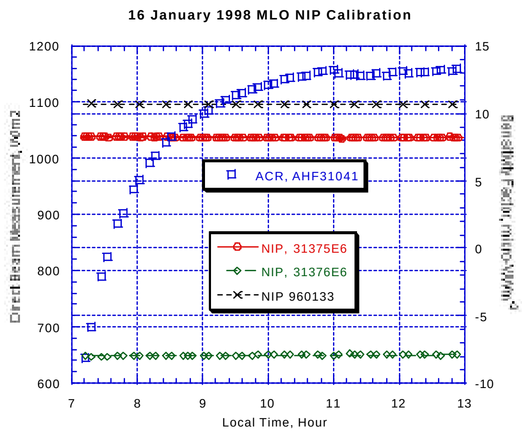

Figure 1

The NIP sensitivity factors shown in Fig. 1 were calculated by dividing the voltage output from the NIP by the non-WRR corrected ACR flux output. A mean of each NIP sensitivity factor was calculated as shown in Equation 1.

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

A population standard deviation about this mean was also calculated for each sensor as defined by Equation 2.

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

These NIP sensitivity factors were determined using the initial factory defined ACR correction factor of 1.99992. To correct the ACR measurements, (and therefore the NIP sensitivities) to the WRR, each NIP mean was corrected to WRR using Equation 3.

$$\text{WRRmean} = \bar{x} \,/\, 0.99961 \qquad (3)$$

The standard deviation was converted to percent of mean using Equation 4.

$$s\% = \frac{s}{WRRmean} \times 100 \qquad (4)$$

The final uncertainty of the NIP sensitivity factor is the sum of the ACR uncertainty, 0.042% (95%) and the uncertainty of the NIP measurements. In order to make the NIP measurement uncertainty equivalent to the ACR uncertainty, an expanded uncertainty of the NIP uncertainty must be formed. Since the NIP uncertainty results from a precision error, the standard deviation of the measurements may be used. To make the confidence interval of the NIP measurements equal to the confidence interval of the ACR measurements, a coverage factor of two is used. This coverage factor of two multiplied by one standard deviation of the NIP measurement provides a 95-percent confidence interval. The A combined uncertainty level was calculated using Equation 5.

$$U95\% = \sqrt{(0.42)^2 + (2 \times s\%)^2} \qquad (5)$$

Where
0.42% wrt SI is the NPC1997 U95% of ACR serial number AHF31041.

6. Results

The results are presented in Table 2.

Table 2

Manuf	sensor	mean	WRRmean	s	s %	U95%
Eppley	31375E6	8.2134	8.2166	0.029505	0.3591	0.8320
Eppley	31376E6	-7.9238	7.9269	0.046306	0.5842	1.2416
K&Z	960133	10.663	10.6672	0.025544	0.2391	0.6365

The number of significant figures was limited to 2 to the right of the decimal in the final results as the U95% of the ACR is limited to two digits. All mean sensitivity (S) values are in the units of micro-V/W/m^2. Table 3 presents the sensor sensitivity results of this analysis, the prior manufacturer sensitivity values and the percent difference between the two. The negative value reported for s/n 31376E6 is believed to be an artifact of manufacture, perhaps backward wiring. The sensitivity value (S) used is in fact positive.

Table 3

Sensor	S	%U95	Manufacturer S	%difference
31375E6	8.21	+/- 0.83%	8.24	-0.36%
31376E6	-7.92	+/- 1.17%	8.00	-1.00%
960133	10.66	+/- 0.64%	10.65	0.09%

8. Discussion

The calibration of NIP sensors 31375E6, 31376E6 and 960133 against an ACR AHF31041 has been completed at Mauna Loa Observatory, Hawaii. It appears that the cable used to NIP calibration has 2 wires backward and so the signals are flipped for NIP 31376E6. The Eppley sensors appear to have aged more than the Kipp and Zonen sensor. The Eppley stated uncertainty of "Manufacturer S" is 5%. The Kipp and Zonen stated uncertainty of "Manufacturer S" is 2%. From these manufacturer baselines, all three sensors are well within specification. The results of the preliminary uncertainty analysis would leave both Eppley instruments suspect. As the Eppley sensors are made by hand, and the Kipp & Zonen sensors are made by machine, one could describe the differences due to manufacturing technique and the incumbent stability. This does not explain the possible switched wiring in 31376E6. As such 31376E6 should be returned to the factory for repair.

9. Summary

The calibration and analysis of the Normal Incident Pyrheliometer sensors has been completed. The units of the sensitivity factors are micro-V/W/m^2. The sensitivity factors and their associated uncertainties (95%) are as follows:

31375E6	8.21	+/- 0.83%
31376E6	7.92	+/- 1.17%
960133	10.66	+/- 0.64%

These values are valid for data collected from 16 February 1998. If possible, do not use 31376E6 until it has been examined by the manufacturer.

REFERENCES

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