Calibration Report: Pyranometer

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Calibration date: 11 November 1999
Next Calibration due: 11 November 2001

The calibration and analysis of two Kipp & Zonen CM-31 pyranometer sensors has been completed at the CERES Ocean Validation Experiment, (COVE) BSRN site, Virginia. 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% $\mu V/W/m^2$	ECN
990004	12.133 ±0.739%	1882743
990005	11.748 ±0.753%	1882742

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 two pyranometer sensors at the CERES Ocean Validation Experiment, (COVE) BSRN site in Virginia on 11 November 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 Kipp & Zonen CM-31 pyranometers. The serial numbers of the pyranometers are as follows: 990004 and 990005. 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 two Kipp & Zonen CM-31 pyranometers at the CERES Ocean Validation Experiment, (COVE) BSRN site on 11 November 1999. The serial numbers of the two pyranometers are as follows: 990004 and 990005. 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 the two sensors.

2. Preliminary Uncertainty Analysis

A preliminary Uncertainty Analysis was performed to determine the reasonable range in which the CM-31 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 CM-31, 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. Combining each Expanded Uncertainty component using the root sum square method forms the Combined Expanded Uncertainty. 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 5).

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 5). These values are assumed to be Standard Uncertainties.

D. CM-31 Sensor Uncertainty

The manufacture stated uncertainty of each CM-31 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 CM-31	random	2.0%
Diffuse CM-31	random	2.0%
TOTAL	Summed	4.99% (95%)

This preliminary uncertainty analysis indicates that a calculated measurement error of greater than 4.99% should be held suspect.

3. Methodology

The Alternate method 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 CM-31 diffuse radiation measurements, CM-31 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 afternoon, (B-period). During the period 11 November 1999, data were collected for 2 sensors.

Collect the following data:

VA1: CM-31 #1 sensor output during period A while shaded; Volts (Diffuse component)
VA2: CM-31 #2 sensor output during period A while un-shaded; Volts (Global Component)
VB1: CM-31 #1 sensor output during period B while un-shaded; Volts (Diffuse component)
VB2: CM-31 #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)

One global CM-31 sensor mounted with the signal connector pointed toward geometric north (+/- 5^o), and one diffuse CM-31 sensor mounted with the signal connector 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 CM-31 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 (θ) / R1 = Edir * COS (θ) + VB2(θ) / R2

Where;
R1: Calibration coefficient for CM-31 #1; $\mu V/W/m^2$
R2: Calibration coefficient for CM-31 #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.

Calibration results are presented in Table 2.

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 CM-31 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 CM-31 calibration coefficient is a function of the ACP uncertainty, and the uncertainties of the CM-31 measurements. In order to make the CM-31 measurement uncertainty equivalent to the ACP uncertainty, the Expanded Uncertainty of the CM-31 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.

Table 2
Calibration Results

Sensor	Forgan S ±U95% $\mu V/W/m^2$
990004	12.133 ±0.739%
990005	11.748 ±0.753%

7. Discussion

The calibration of CM-31 sensors 90004 and 90005 using the Alternate method has been completed at COVE. The sensor calibration coefficients and associated uncertainties resulting from the analysis of all sets of data are defined as the current calibration values. The Kipp and Zonen stated uncertainty of sensitivity is 5% U99%.

From this manufacturer baseline, both sensors calibrated with the Alternate method technique are within manufacturer calibration coefficient uncertainty specification.

The calibration history of the CM-31 sensors is presented in Table 3.

Table 3
Calibration History

Sensor	1999 Forgan S ±U95% μV/W/m²	Original K&Z S ±U99% μV/W/m²
990004	12.133 ±0.739	8.76 ±5%
990005	11.748 ±0.753	8.74 ±5%

The results are well within the limitations determined during the preliminary uncertainty analysis. The sensors should be calibrated again using this Alternate method

A further step should be added to verify in the Alternate method 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 of two Kipp and Zonen CM-31 pyranometer sensors has been completed at the COVE BSRN site. The units of the sensitivity factors, S, are $\mu V/W/m^2$. The sensitivity factors and their associated uncertainties (95%) are as follows:

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S = calibration coefficient of the pyranometer
U95% = the 95 % confidence level

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