Calibration Report: Pyrheliometers

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SUMMARY

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

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

Pyrheliometer ECN	Serial Number	S (μV/W/m^2)	U95%
1610696	31375E6	8.14	+/- 1.06%
1610695	31376E6	7.88	+/- 1.00%
1611314	960132	11.06	+/- 0.73%
1611315	960133	10.53	+/- 0.73%

Application

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

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

ABSTRACT

Calibration data from four pyrheliometer sensors were collected at Mauna Loa Observatory, Hawaii during the period 7-12 February 1999. The sensor array included two Eppley Laboratory, Inc. sensors, 31375E6, 31376E6; two Kipp and Zonen, Inc. sensors, 960132, and 960133. The sensors were calibrated against an Eppley Laboratory, Inc. Absolute Cavity Radiometer (with a World Radiation Factor of 0.99833. 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 four pyrheliometer sensors were made at Mauna Loa Observatory (MLO), Hawaii on during the period 7-12 February 1999. The sensor array included two Eppley Laboratory, Inc. sensors, 31375E6, 31376E6, two Kipp and Zonen, Inc. sensors, 960132, and 960133, also referred to as pyrheliometers 1-4 respectively. The sensors were calibrated against the Eppley Laboratory, Inc. Absolute Cavity Radiometer, (ACR), AHF31041. This radiometer has a World Radiometric Reference (WRR) factor of 0.99833 and a 95-percent uncertainty with respect to SI units (U95%) of 0.37%, as of the October 1998 NPC1998.

2. Preliminary Uncertainty Analysis

A preliminary uncertainty analysis was completed. This analysis was performed to determine the reasonable range in which the pyrheliometer calibration values should lie. If the combined measured uncertainty of the experiment proves to 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, (which contains cavity radiometer and a 406 control box with a Digital Multimeter, (DMM)) each pyrheliometer, two solar trackers 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 an assumed 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 pyrheliometer calibration is the 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 resultant NPC1998 WRR factor for LaRC ACR AHF31041 is 0.99833, with an Uncertainty 0.37% (95% wrt SI).

Table 1
Preliminary Uncertainty Analysis

Source	Type	Magnitude
<u>Calibration Standard</u>		
ACR AHF31041	WRR absolute	0.37% (U95%)
<u>Data Acquisition</u>		
DMM voltage	random	0.023% (1σ)
Tracker alignment	non-random	0.083% (1σ)
Campbell data logger	random	0.2% (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)
<u>Previous calibration</u>		
Eppley	random	.59 (1σ)
Kipp and Zonen	random	.32 (1σ)
<u>TOTALS</u>		
Eppley	Root-sum-square	1.43% (U95%)
Kipp and Zonen	Root-sum-square	1.05% (U95%)

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.

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 1.43% for an Eppley or 1.05% for a Kipp and Zonen should be held suspect.

3. Methodology

Verify that the pyrheliometer desiccant was within the proper tolerance as necessary. Attach the ACR and pyrheliometer sensors to the solar trackers. Align the tracker to geometric N-S. Align the ACR and pyrheliometer sensors to the solar tracker. Make all ground connections. Connect the ACR to the ACR controller and the controller to the PC. Attach the pyrheliometers to the Campbell Scientific Inc. data logger system. Clean the pyrheliometer windows. Verify that the ACR window and the ACR cover are off. Use the Reda program supplied by NREL to operate the ACR. Use the Campbell data logger system to record voltages produced by the pyrheliometers. Use the manufacturer's initial as-manufactured sensitivity factors for both the ACR and pyrheliometer sensors in the data acquisition algorithms. 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 17:20 GMT (7:20 am LST) until about 23:00 GMT (1:00 PM LST) in order to minimize the effects of turbulent afternoon atmosphere. In practice, the data collection conditions were defined by 40mph winds and ambient temperatures ranging from about freezing to 12 deg C. A total of 1203 pyrheliometer data points were collected. ACR data was collected every two seconds and averaged over a one-minute interval, for each one-minute interval a mean and a standard deviation were obtained. The mean of these standard deviations was then calculated for the entire data set ($\sigma_{ACR\text{-}m}$). The pyrheliometer measurements were collected every second and averaged over a one-minute interval, for each one-minute interval a mean and a standard deviation were obtained. The mean of these standard deviations was calculated for the entire data set ($\sigma_{P\text{-}m}$). All standard deviations were converted to percent of mean using Equation 1.

$$s\ \% = \frac{s}{\text{WRRmean}} \times 100 \qquad (1)$$

Sensitivity factors for the 4 pyrheliometer sensors relative to the ACR were calculated by first dividing the voltage for each pyrheliometer by its respective as-manufactured sensitivity factor to obtain a pyrheliometer radiance value. The ratio of the ACR WRR corrected radiance divided by the pyrheliometer radiance is then calculated, the results of these calculations are shown for each pyrheliometer in figures 1-4. For each of the four pyrheliometer sensors (1-4) respective population means and standard deviations ($\sigma_{P(1\text{-}4)}$) were calculated. These three standard deviations were used along with the ACR U95 values to obtain a combined U95 value for each pyrheliometer. All standard deviations were converted to percent of mean.

The final uncertainty of the pyrheliometer sensitivity factor is a function of the ACR uncertainty, 0.37% (95%), the standard deviation of the one-minute ACR data, the standard deviation of the one-minute pyrheliometer data, and the standard deviation of the ratio of the ACR/pyrheliometer for each data set. In order to make the measurement uncertainty for each pyrheliometer equivalent to the ACR uncertainty, an expanded uncertainty for each pyrheliometer must be determined. Since the pyrheliometer uncertainty results from a precision error, two standard deviations of the measurements may be used to determine a 95-percent confidence interval. The combined experimental uncertainty (95%) was calculated using Equation 2.

$$\mathrm{U95\%} = \sqrt{0.37^2 + (2s_{\mathrm{P-m}})^2 + (2s_{\mathrm{P(1-4)}})^2 + (2s_{\mathrm{ACR-m}})^2} \quad (2)$$

Where 0.37% wrt SI is the NPC1998 U95% of ACR serial number AHF31041, and P(1-4) indicates one of the four pyrheliometers.

6. Results

The results are presented in Table 2.

Table 2

Pyrheliometer	Manuf	sensor	WRRmean	*s* %	U95%
1	Eppley	31375E6	8.15	0.3591	1.0602
2	Eppley	31376E6	7.88	0.5842	0.9951
3	K&Z	960132	11.06	0.2391	0.7306
4	K&Z	960133	10.53	0.2391	0.7271

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.

Table 3

Pyrhelio- Meter	Sensor	S1999	%U95	Manufacturer S	%difference
1	31375E6	8.14	+/- 1.06%	8.24	-1.21%
2	31376E6	7.88	+/- 1.00%	8.00	-1.50%
3	960132	11.06	+/- 0.73%	11.01	0.45%
4	960133	10.53	+/- 0.73%	10.65	-1.13%

8. Discussion

The calibration of pyrheliometer sensors 31375E6, 31376E6, 960132, and 960133 against ACR AHF31041 has been completed at Mauna Loa Observatory, Hawaii. 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. 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.

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

REFERENCES

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

Reda, I, Stoffel, T., Results of NREL Pyrheliometer Comparisons NPC1096, 1-5 October 1996, National Renewable Energy Laboratory, Golden, Colorado.

Reda, I., Stoffel, T., Treadwell, J., Results of NREL Pyrheliometer Comparisons NPC1997, National Renewable Energy Laboratory, Center for Renewable Energy Resources, Measurements & Instrumentation Team, 11 November 1997.

American National Standard for Expressing Uncertainty-U.S. Guide to the Expression of Uncertainty in Measurement, ANSI/NCSL Z540-2-1997. Reprinted 16 February 1998.

Reda, I results of NREL Pyrheliometer Comparisons NPC1998, National Renewable Energy Laboratory, Center for Renewable Energy Resources, Measurements & Instrumentation Team, 11 November 1997.

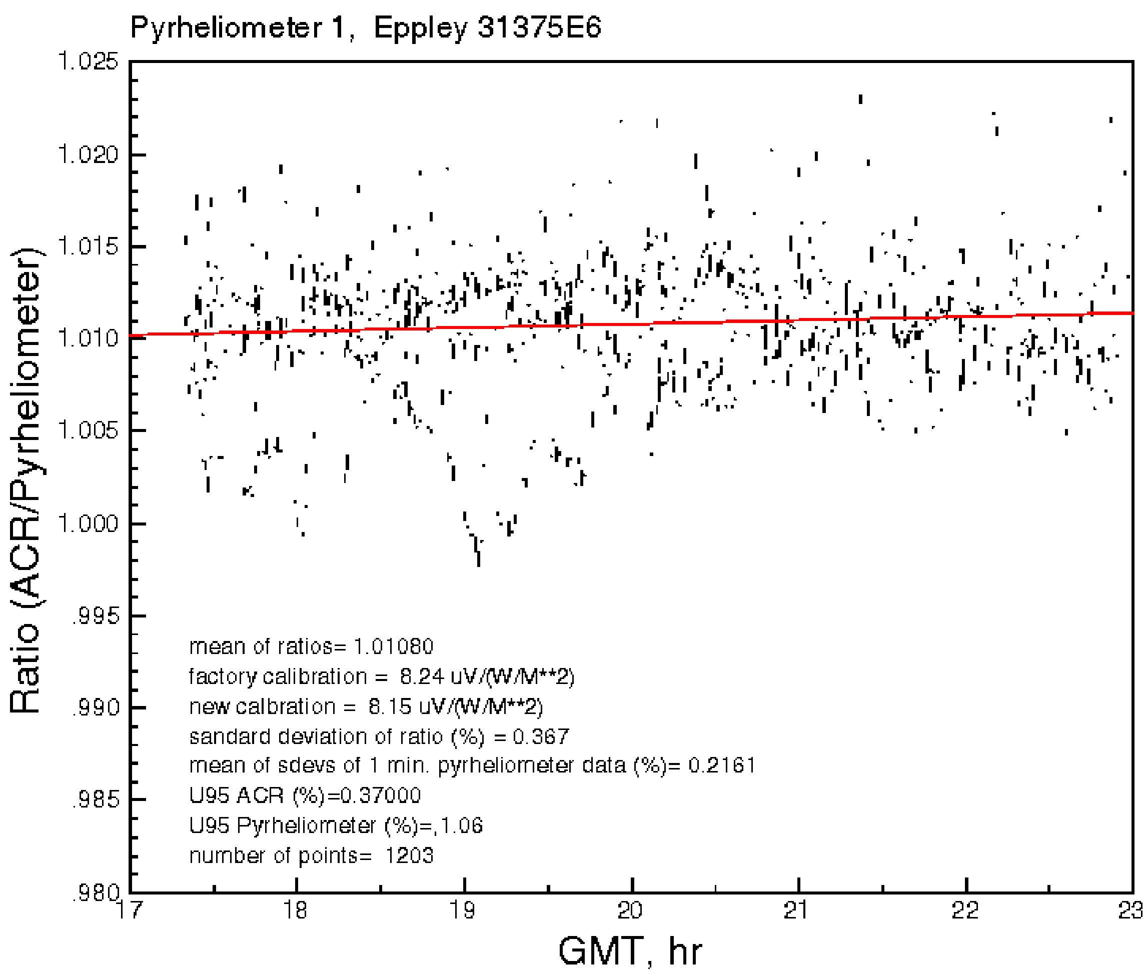

Figure 1. Absolute cavity Radiometer WRR corrected radiance values divided by the pyrheliometer radiance values for the Eppley 31375E6 unit. All data are one-minute averages.

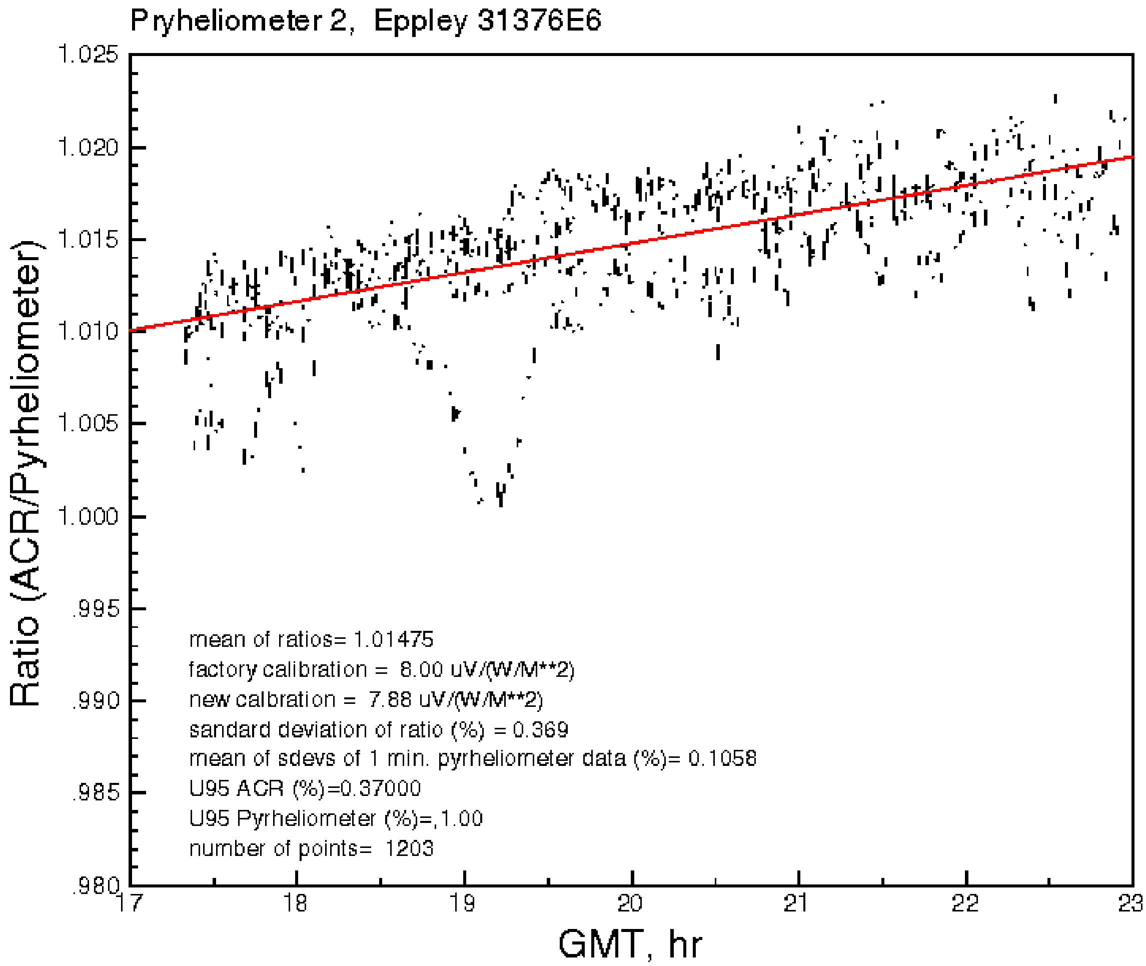

Figure 1. Absolute cavity Radiometer WRR corrected radiance values divided by the pyrheliometer radiance values for the Eppley 31376E6 unit. All data are one-minute averages.

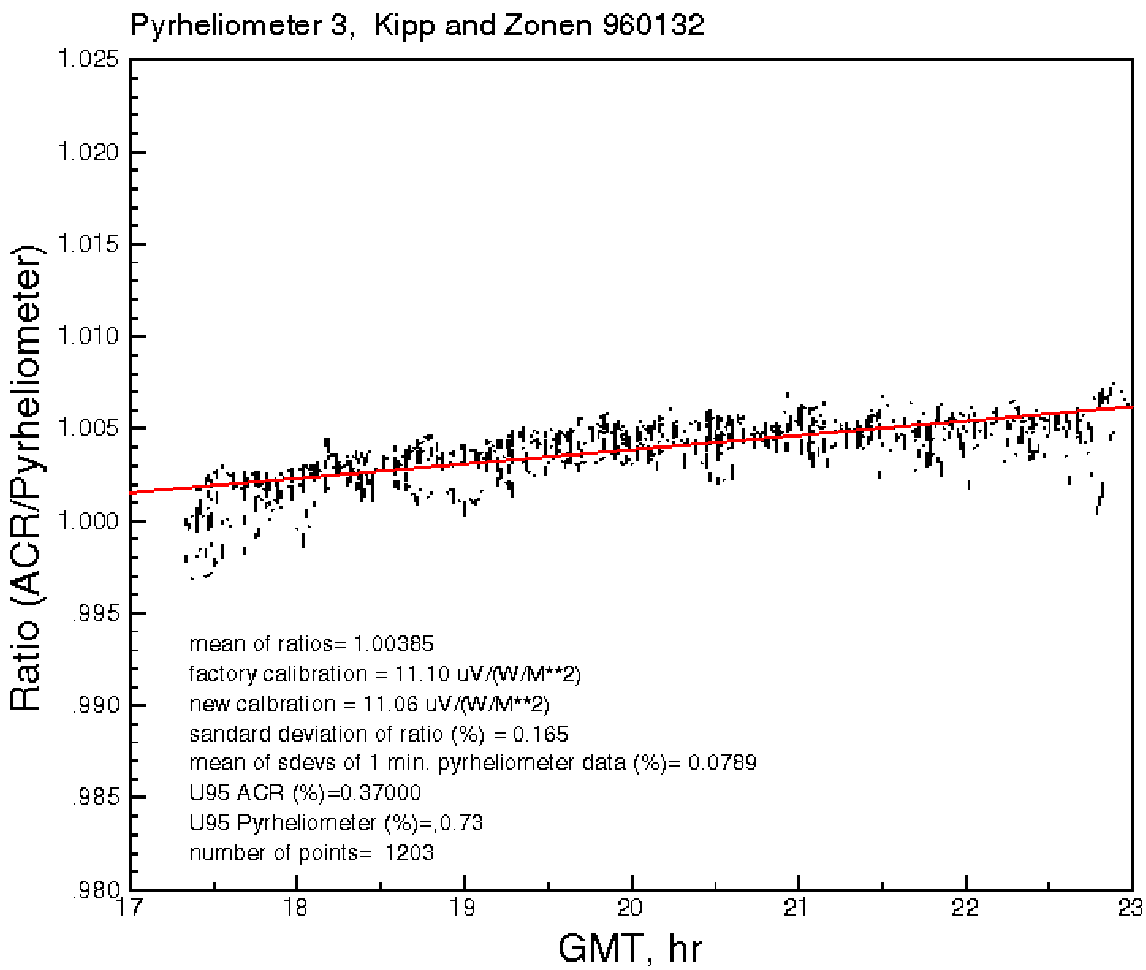

Figure 1. Absolute cavity Radiometer WRR corrected radiance values divided by the pyrheliometer radiance values for the Kipp and Zonen 960132 unit. All data are one-minute averages.

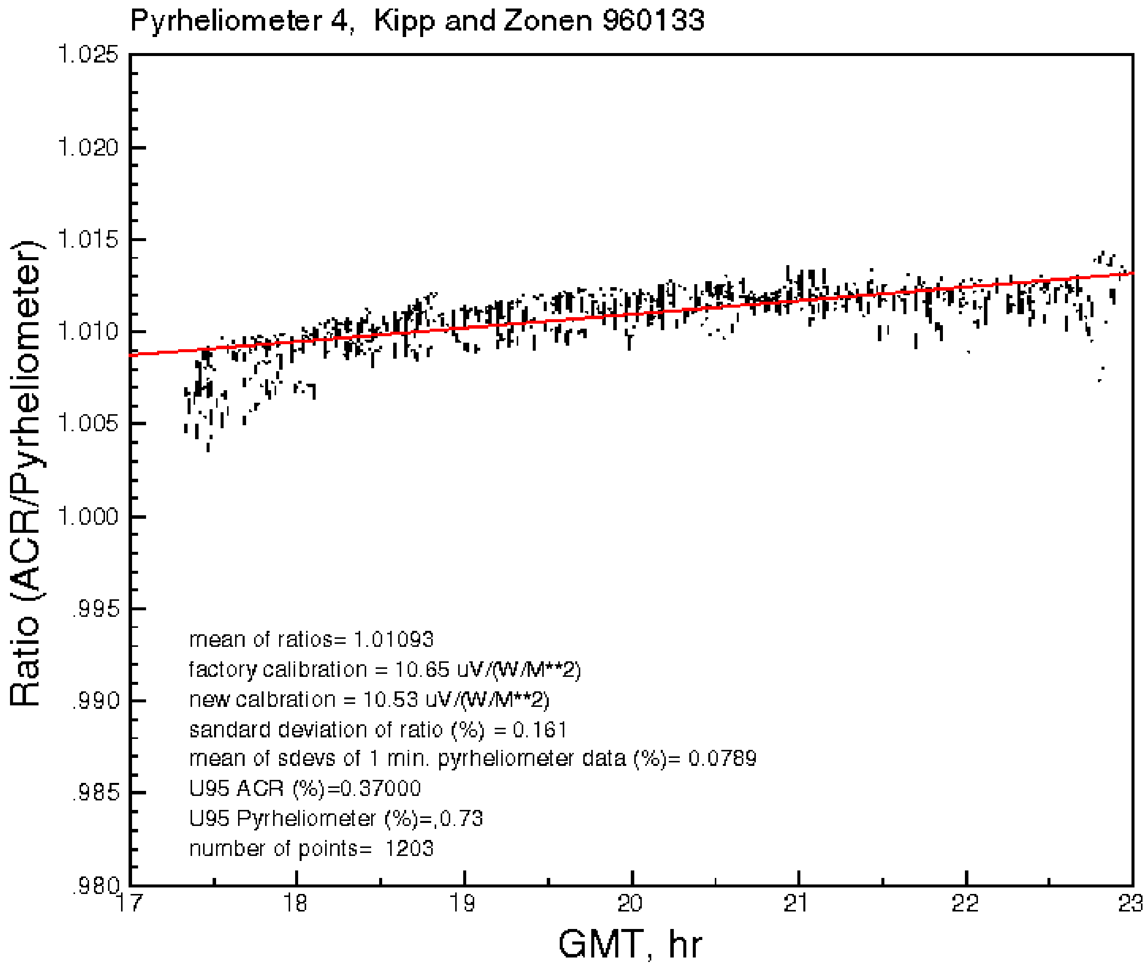

Figure 1. Absolute cavity Radiometer WRR corrected radiance values divided by the pyrheliometer radiance values for the Kipp and Zonen 960133 unit. All data are one-minute averages