Calibration Report: Pyranometer

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Calibration date: 2010 January 01.
Next calibration: 2012 January 01.
Reference standard: AHF-31041

Four radiometers were calibrated at the Chesapeake Ocean Validation (COVE) site. The results of these Calibrations are included in this box. Earlier calibrations appear below in the CALIBRATION HISTORIES section. 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 ($\mu V/(W/m^2)$) ± U95%	Method
CM22-000025	9.246 ± 1.14%	shade/unshade
CM22-040100	9.00 ± 1.25%	relative to CM22-000025
CM31-990004	12.08 ± 0.77%	relative to CM31-000506
CM31-000506	11.64 ± 0.71%	shade/unshade
CM31-000507	11.69 ± 0.63%	shade/unshade
BW-32953	8.636 ± 0.82%	shade/unshade

Application

$$I = (\mu V\ \text{output})/S \pm \text{sqrt}(2)*U95\%$$

Where: I = the irradiance measured by the pyranometer
(μV output) = microvolt output of the pyranometer
S = calibration coefficient of the pyranometer
U95% = the 95 % confidence level

INTRODUCTION

The following sections contain, a brief executive summary, a set of figures, a summary of past calibrations, and a description of the calibration process.

SUMMARY

REFERENCE STANDARD.

The reference pyrheliometer was the Eppley Laboratories Inc. Absolute Cavity Radiometer serial number AHF-31041 with its associated Agilent 34970A control unit. The cavity is traceable to the World Standard Group (WSG) of pyrheliometers at the Physikalisch-Meteorologisches Observatorium in Davos, Switzerland. The cavity participated in the International Pyrheliometer Comparison (IPC) in years 2000 and 2005. It is traceable directly to the World Standard Group (WSG) through the IPCs. In other years, 1997 through 2009, the cavity is traceable to the WSG through the National Renewable Energy Laboratory (NREL) working group in Golden Colorado.

TEST INSTRUMENTATION.

The six test pyranometers were are listed below along with their calibration method.

CM22-000025	9.246	±	1.14%	shade/unshade
CM22-040100	9.00	±	1.25%	relative to CM22-000025
CM31-990004	12.08	±	0.77%	relative to CM31-000506
CM31-000506	11.64	±	0.71%	shade/unshade
CM31-000507	11.69	±	0.63%	shade/unshade
BW-32953	8.636	±	0.82%	shade/unshade

NOTE: The BW-32953 is a model 848 black and white.

All pyranometers were wired for differential measurements. Shade/unshade is referenced directly to the absolute cavity radiometer AHF-31041

FIGURES.

Figures are included which show an example of raw pyranometer global and diffuse measurements, and cavity irradiance measurements. Plots are also included of calibration value histories, for each instrument included in this calibration event.

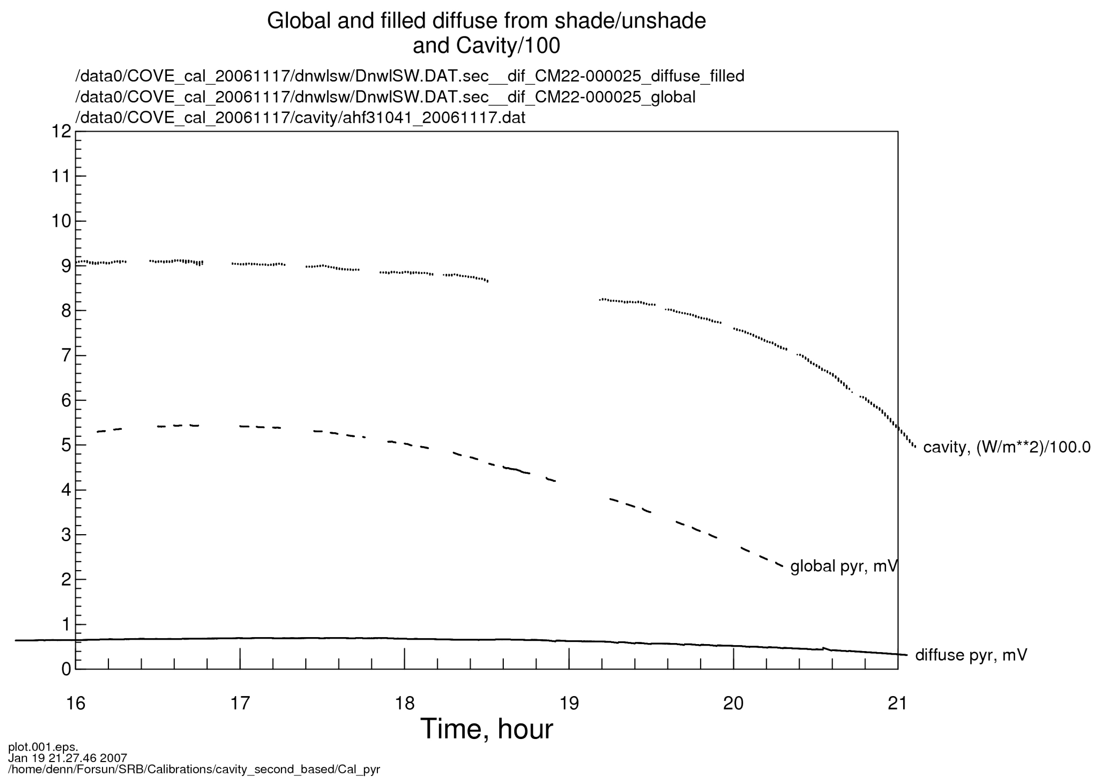

Figure 1. A historical example of calibration measurements for a pyranometer is presented. Cavity, global pyranometer, and diffuse pyranometer measurements are shown separately. The diffuse measurements have been interpolated over their missing data periods.

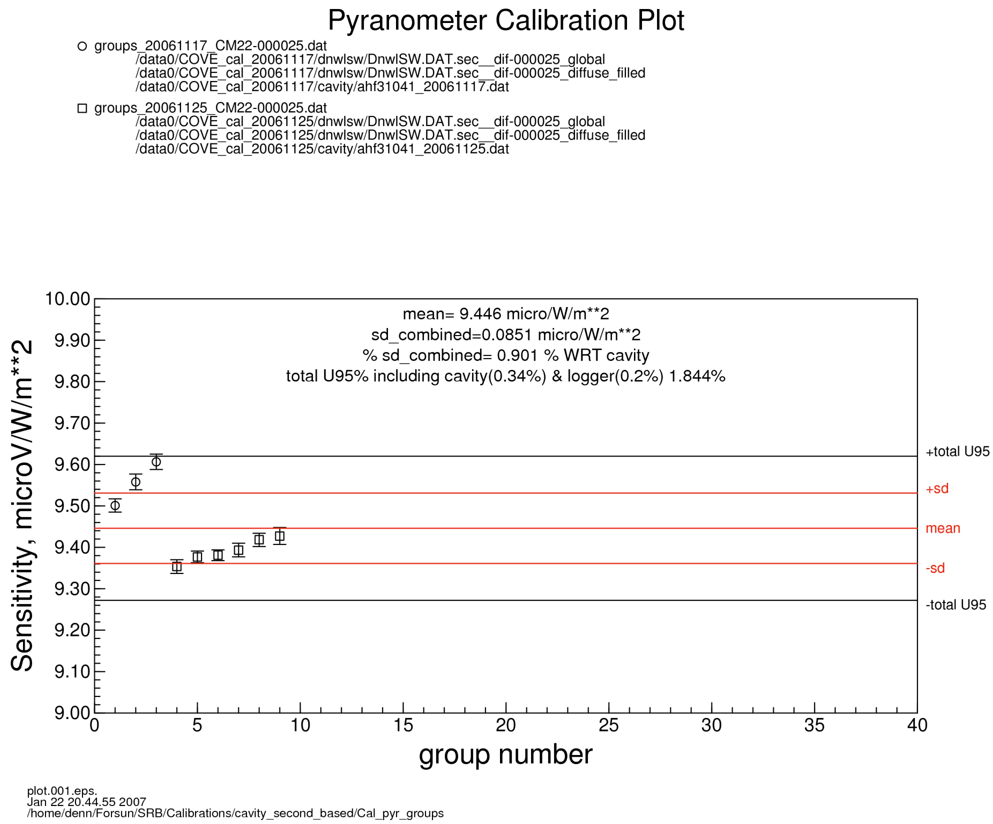

Figure 2. A historical example of grouped shade/unshade calibration data is shown. A data group consists of a cavity run which is about 30 minutes long. The mean and standard deviation of the grouped data are also shown.

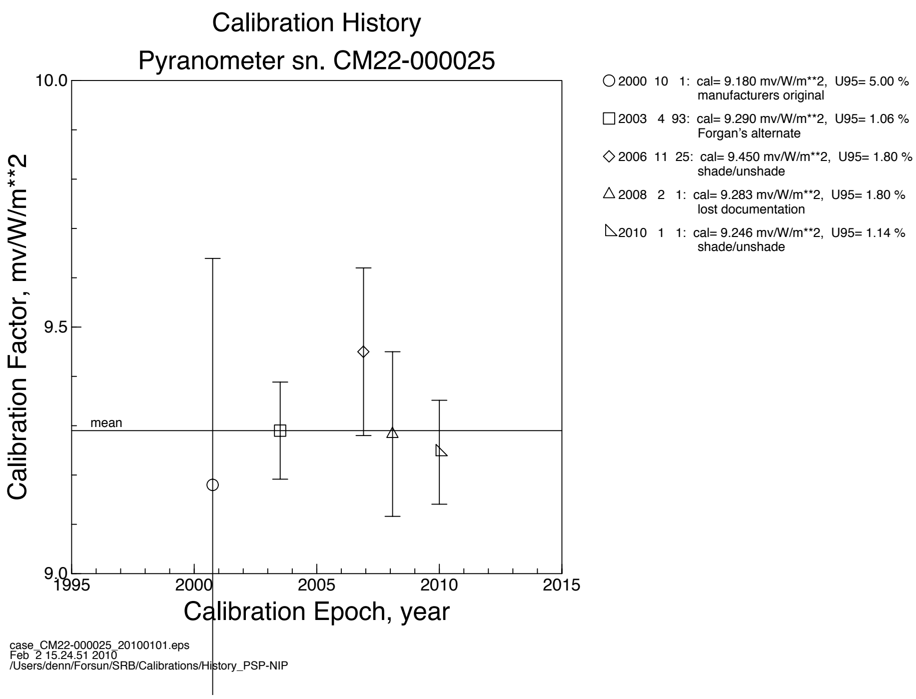

Figure 3a. Calibration history for pyranometer CM22-000025 is presented. The solid horizontal line represents the mean value. The symbols and their error bars represent the mean and U95 of each calibration event. The column on the right presents numerical values for each calibration event and a brief description of the calibration method used.

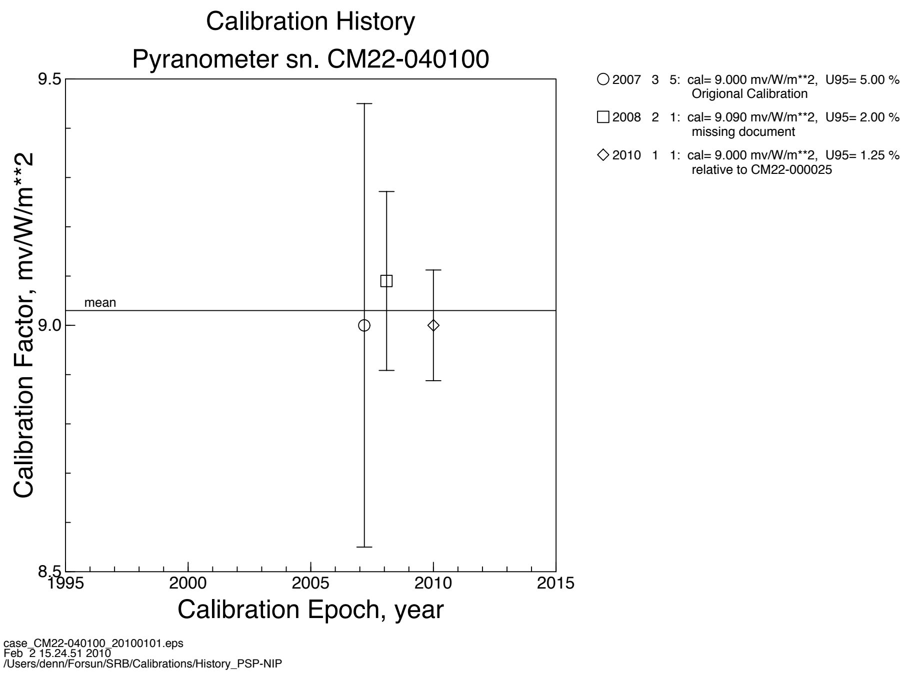

Figure 3b. Calibration history for pyranometer CM22-040100 is presented. The solid horizontal line represents the mean value. The symbols and their error bars represent the mean and U95 of each calibration event. The column on the right presents numerical values for each calibration event and a brief description of the calibration method used.

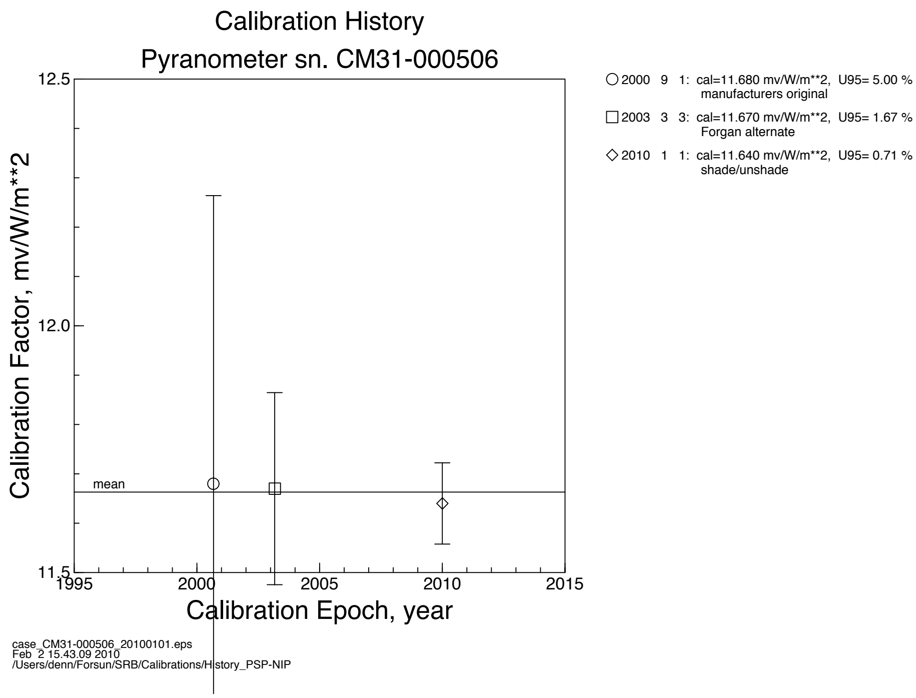

Figure 3c. Calibration history for pyranometer CM31-000506 is presented. The solid horizontal line represents the mean value. The symbols and their error bars represent the mean and U95 of each calibration event. The column on the right presents numerical values for each calibration event and a brief description of the calibration method used.

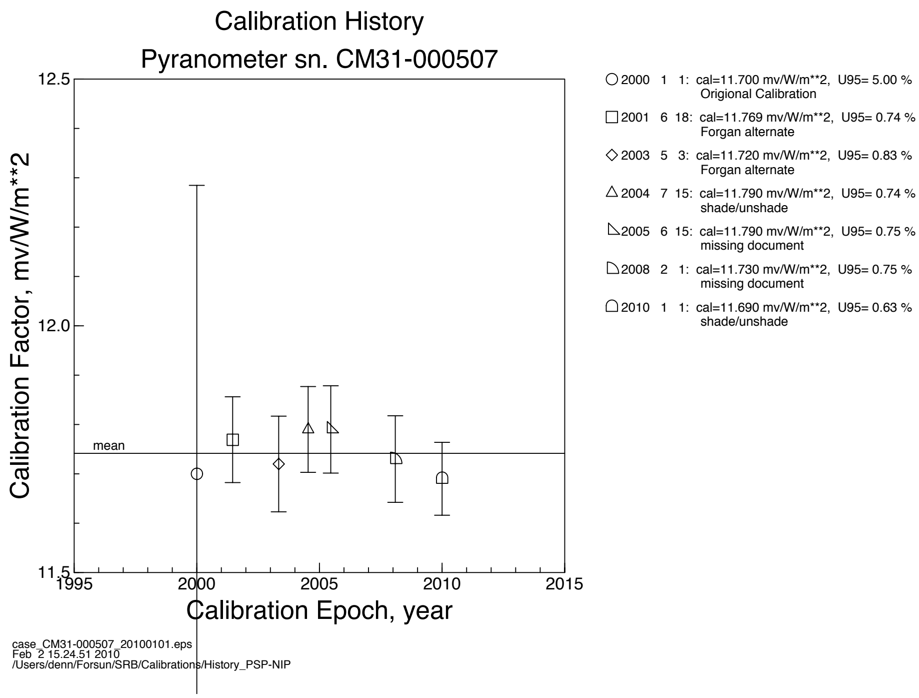

Figure 3d. Calibration history for pyranometer CM31-000507 is presented. The solid horizontal line represents the mean value. The symbols and their error bars represent the mean and U95 of each calibration event. The column on the right presents numerical values for each calibration event and a brief description of the calibration method used.

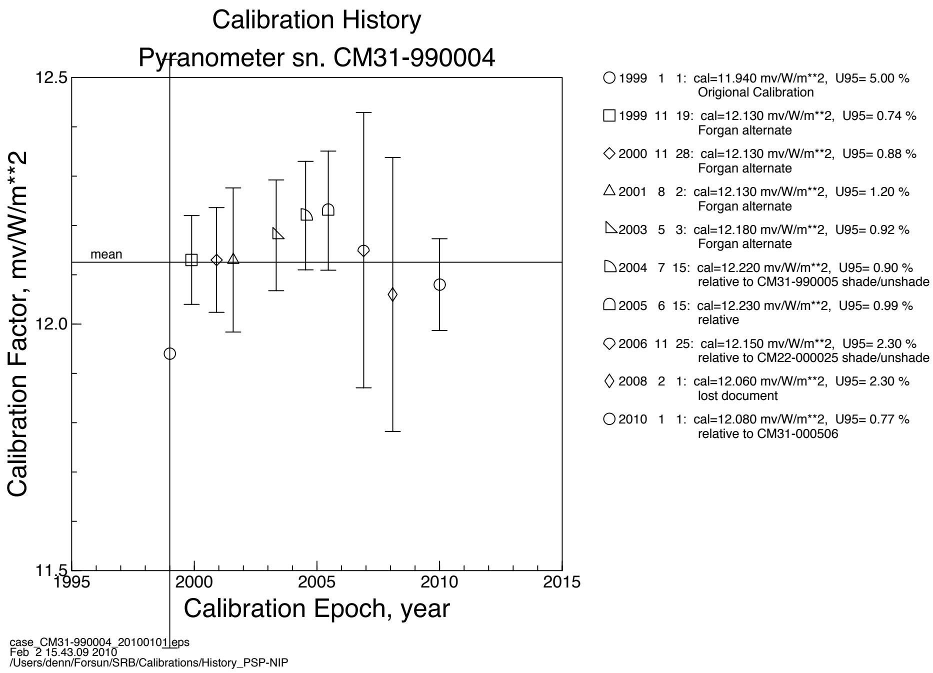

Figure 3e. Calibration history for pyranometer CM31-990004 is presented. The solid horizontal line represents the mean value. The symbols and their error bars represent the mean and U95 of each calibration event. The column on the right presents numerical values for each calibration event and a brief description of the calibration method used.

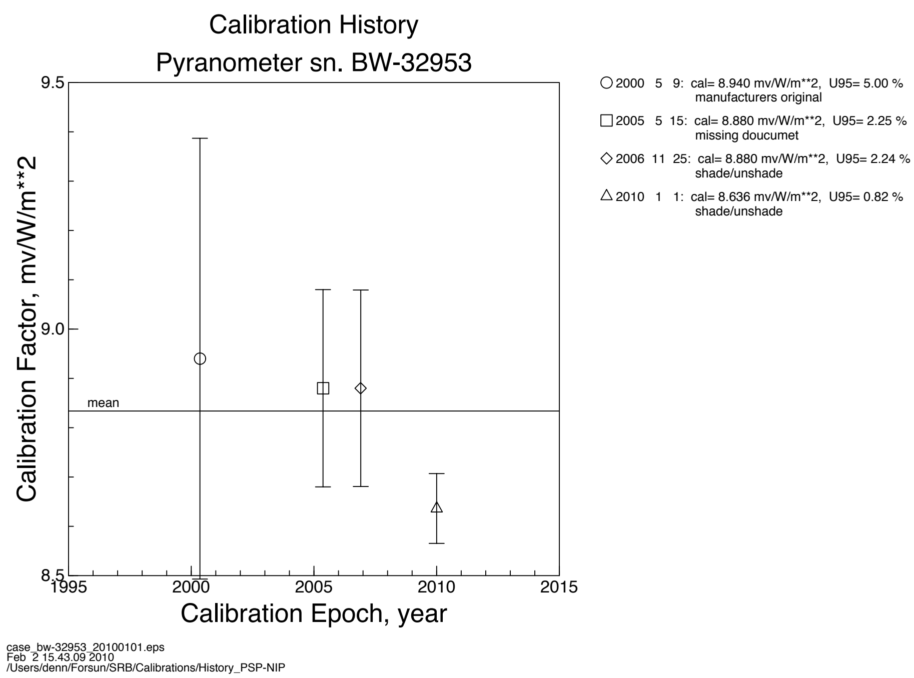

Figure 3f. Calibration history for pyranometer BW-32953 is presented. The solid horizontal line represents the mean value. The symbols and their error bars represent the mean and U95 of each calibration event. The column on the right presents numerical values for each calibration event and a brief description of the calibration method used.

CALIBRATION HISTORIES
(doy = day of year)

Pyranometer: Kipp and Zonen CM22-000024

date	doy	S ($\mu V/W/m^2$)	U95 (%)	calibration type
2003 Apr 03	093	9.19	1.16	Forgan's alternate
2001 Jun 18	169	9.214	1.013	Forgan's alternate
2000 Oct 01	275	9.16	5.00	manufacturers original

Pyranometer: Kipp and Zonen CM22-000025

date	doy	S ($\mu V/W/m^2$)	U95 (%)	calibration type
2010 Jan 01	001	9.25	1.14	shade/unshade
2008 Feb 02	033	9.28	1.8	lost document, shade/unshade
2006 Nov 25	329	9.45	1.85	shade/unshade
2006 May 17	----	-----	-----	bad cavity data, removed
2003 Apr 03	093	9.29	1.06	Forgan's alternate
2000 Oct 01	275	9.18	5.00	manufacturers original

Pyranometer: Kipp and Zonen CM22-000030

date	doy	S ($\mu V/W/m^2$)	U95 (%)	calibration type
2001 Jun 18	169	8.40	1.316	Forgan's alternate
2000 Jan 01	001	8.40	5.00	manufacturers original

Pyranometer: Kipp and Zonen CM31-990004

date	doy	S ($\mu V/W/m^2$)	U95 (%)	calibration type
2010 Jan 01	001	12.08	0.77	relative to CM31-000506
2008 Feb 01	031	12.06	2.3	relative
2006 Nov 25	329	12.15	2.30	relative
2006 May 17	----	------	-----	bad cavity data, removed
2005 June 15	165	12.23	0.99	relative
2004 Jul 15	197	12.22	0.90	relative
2003 Apr 03	093	12.18	0.92	Forgan's alternate
2002 Mar 31	90	12.26	1.8	Intercomparison (do not use)
2001 Aug 02	214	12.130	1.2	Forgan's alternate
2000 Nov 28	333	12.132	0.88	Forgan's alternate
1999 Nov 11	315	12.133	0.74	Forgan's alternate
1999 Jan 01	001	11.94	5.00	manufacturers original

Pyranometer: Kipp and Zonen CM31-990005

date	doy	S ($\mu V/W/m^2$)	U95 (%)	calibration type
2006 Nov 29	329	11.87	2.50	relative
2006 May 10	----	------	-----	bad cavity data, removed
2005 June 15	165	11.87	0.78	shade/unshade
2004 Jul 15	197	11.86	0.85	shade/unshade
2003 Apr 03	093	11.83	1.5	Forgan's alternate
2001 Aug 02	214	11.813	1.1	Forgan's alternate
2000 Nov 28	333	11.852	0.96	Forgan's alternate
1999 Nov 11	315	11.748	0.75	Forgan's alternate
1999 Jan 01	001	11.67	5.00	manufacturers original

Pyranometer: Kipp and Zonen CM31-000506

date	doy	S ($\mu V/W/m^2$)	U95 (%)	calibration type
2010 Jan 01	001	11.64	0.71	shade/unshade
2003 Apr 03	093	11.67	1.64	Forgan's alternate
2000 Sep 01	245	11.68	5.00	manufacturers original

Pyranometer: Kipp and Zonen CM31-000507

date	doy	S ($\mu V/W/m^2$)	U95 (%)	calibration type
2010 Jan 01	001	11.69	0.63	shade/unshade
2008 Feb 01	032	11.73	0.75	lost document
2006 May 10	----	------	-----	bad cavity data, removed
2004 Jul 03	197	11.79	0.74	shade/unshade
2003 Apr 03	093	11.72	0.83	Forgan's alternate
2001 Jun 18	169	11.769	0.74	Forgan's alternate
2000 Jan 01	001	11.70	5.00	manufacturers original

Pyranometer: Kipp and Zonen CM31-000508

date	doy	S ($\mu V/W/m^2$)	U95 (%)	calibration type
2004 Jul 03	197	11.86	0.91	relative
2003 Apr 03	093	11.78	1.9	Forgan's alternate
2002 Mar 31	90	12.08	1.63	intercomparison (do not use)
2001 Aug 02	214	11.59	1.63	intercomparison[1] (do not use)
2001 Jun 18	169	11.866	0.932	Forgan's alternate
2000 Jan 01	001	11.81	5.00	manufacturers original

Pyranometer: Eppley PSP-29472F3

date	doy	S ($\mu V/W/m^2$)	U95 (%)	calibration type
2003 Apr 03	093	8.53	1.80	Forgan's alternate
2002 Mar 31	090	8.52	2.95	intercomparison (do not use)
2001 Jun 18	169	8.57	2.63	Forgan's alternate
1999 Feb 12	043	8.49	4.51	Forgan's alternate
1998 Jun 03	154	8.68	1.22	Forgan's alternate
1993 Apr 16	106	8.76	5.00	manufacturers original

Pyranometer: Eppley PSP-30676F3

date	doy	S ($\mu V/W/m^2$)	U95 (%)	calibration type
1999 Feb 12	043	8.49	2.98	Forgan's alternate
1998 Jun 03	154	8.66	1.06	Forgan's alternate
1995 Jun 16	167	8.74	5.00	manufacturers original

Pyranometer: Eppley PSP-30798F3

date	doy	S ($\mu V/W/m^2$)	U95 (%)	calibration type
1999 Feb 12	043	8.45	5.23	Forgan's alternate
1998 Jun 03	154	8.82	1.28	Forgan's alternate
1995 Aug 07	219	9.01	5.00	manufacturers original

Pyranometer: Eppley PSP-30803F3

date	doy	S ($\mu V/W/m^2$)	U95 (%)	calibration type
1999 Feb 12	043	9.26	4.35	Forgan's alternate
1998 Jun 03	154	9.55	1.17	Forgan's alternate
1996 Jul 23	205	9.362	3.2	BORCAL
1995 Aug 07	219	9.46	5.00	manufacturers original

Pyranometer: Eppley PSP-30806F3

date	doy	S ($\mu V/W/m^2$)	U95 (%)	calibration type
2003 Apr 03	093	8.70	2.92	Forgan's alternate
2002 Mar 31	090	8.76	1.81	Intercomparison (do not use)
2001 Jun 18	169	8.95	1.22	Forgan's alternate
1999 Feb 12	043	8.72	5.47	Forgan's alternate
1998 Jun 03	154	9.07	0.90	Forgan's alternate
1995 Aug 07	219	9.22	5.00	manufacturers original

Pyranometer: Eppley PSP-30847F3

date	doy	S ($\mu V/W/m^2$)	U95 (%)	calibration type
1999 Sep 24	267	8.37	3.24	Forgan's alternate
1999 Feb 12	043	8.75	3.14	Forgan's alternate
1998 Jun 03	154	8.80	1.19	Forgan's alternate
1995 Aug 07	219	8.96	5.00	manufacturers original

Pyranometer: Eppley PSP-30851F3

Date	doy	S ($\mu V/W/m^2$)	U95 (%)	calibration type
1999 Feb 12	043	8.37	1.61	Forgan's alternate
1998 Jun 03	154	8.48	0.93	Forgan's alternate
1996 Jul 23	205	8.257	3.3	BORCAL
1995 Aug 07	219	9.68	5.00	manufacturers original

Pyranometer: Eppley PSP-31560F3

date	doy	S ($\mu V/W/m^2$)	U95 (%)	calibration type
1999 Sep 24	267	8.85	9.07	Forgan's alternate (poor)
1999 Feb 12	043	9.23	4.20	Forgan's alternate
1998 Jun 03	154	9.53	0.98	Forgan's alternate
1997 May 05	125	9.51	5.00	manufacturers original

Pyranometer: Eppley PSP-31561F3

date	doy	S ($\mu V/W/m^2$)	U95 (%)	calibration type
1999 Feb 12	043	8.42	1.84	Forgan's alternate
1997 May 05	125	8.52	5.00	manufacturers original

Pyranometer: Eppley PSP-33028F3

date	doy	S ($\mu V/W/m^2$)	U95 (%)	calibration type
2003 Apr 03	093	8.53	1.01	Forgan's alternate
2000 Jul 01	183	8.65	5.00	manufacturers original

Pyranometer: Eppley black and white 848-32953 (BW-32953)

date	doy	S ($\mu V/W/m^2$)	U95 (%)	calibration type
2010 Jan 01	001	8.64	0.82	shade/unshade
2006 Nov 25	329	8.88	2.24	shade/unshade
2000 May 09	128	8.94	5.00	manufacturers original

1) The Pyranometer was mounted as a global sensor. An intercomparison with the COVE derived global irradiance was performed. The uncertainty was determined using the root sum square method and previously determined uncertainties for the 3 sensors, COVE direct, COVE diffuse, and the sensor being analyzed (CM31-000508).

ABSTRACT

Data have been collected for the purpose of calibrating pyranometers. The current data sets were collected at the CERES Ocean Validation Experiment (COVE) site. COVE is located at the Chesapeake Light Station approximately 25 km east of Virginia Beach, Virginia. Pyranometers included are those which measure global and diffuse downwelling shortwave radiation. In the past, calibration data have been collected at COVE, NASA Langley in Hampton Virginia, and Mauna Loa Observatory Hawaii. These historical data are used to create a time history of calibration coefficients. The radiometric reference used for the current calibration measurements was the Eppley Laboratory Inc. absolute cavity radiometer serial number AHF-31041. During past calibration events the absolute cavity AHF-31105 has also been used. For more information about the cavity radiometers see the Absolute Cavity Radiometer calibration entries on the COVE web site. An uncertainty analysis is preformed and included with the pyranometer calibrations. During this calibration session data were collected for the pyranometers listed in the box at the beginning of the document. These calibration values are traceable to the World Radiometric Reference (WRR), at the Physikalisch-Meteorologisches Observatorium in Davos, Switzerland.

DISCUSSION

REFERENCE STANDARD.

The reference pyrheliometer was the Eppley Laboratories Inc. Absolute Cavity Radiometer (ACR) serial number AHF-31941 with its associated Agilent 34970A control unit. The NASA Langley owned Eppley Laboratories Inc Absolute cavity radiometers AHF-31041 and AHF-31105 can be traced to the World Radiation Reference (WRR). Direct linkage was obtained at the ninth and tenth International Pyrheliometer Comparisons (IPC-IX and IPC-X) in October of 2000 and 2005 respectively. Other years starting in 1997 they were linked to the WRR through the National Standard Group (NSG) at the National Renewable Energy Laboratories in Golden, Colorado. The NSG is also linked to the WRR at the IPCs. The WRR is an average of the World Standard Group (WSG) of pyrheliometers which is kept at the Physikalisch-Meteorologisches Observatorium in Davos, Switzerland. The uncertainty of the WSG is 0.3% (U95% with respect to SI units). After each cavity intercomparison is completed, new WRR correction values and their U95 uncertainties, with respect to SI, are determined for each participant cavity. The raw irradiances as measured by a given ACR are multiplied by its WRR correction value to get the final ACR determined direct beam irradiance values. See the cavity calibration documents for greater detail.

The Agilent 34970As, used as cavity controllers, contain the following 3 optional boards: 34901A 20 channel multiplexer; 34904A matrix switch; and a 34907A multi function module. It is operated with a Windows computer using a LabView based program supplied by Ibrahim Reda of The National Renewable Energy Laboratory (NREL) located in Golden Colorado.

SHADE/UNSHADE METHOD, CONFIGURATION AND METHODOLOGY.

The pyranometers, calibrated using the shade/unshade, are those ordinarily used to measure diffuse irradiance. All pyranometers remain in their original positions. The only exception would be if the normally downlooking pyranometer is to be calibrated. In that case it would be moved to an uplooking global position. The nut on the lowest link of the shading ball system is removed. This allows the normally diffuse pyranometers to be operated alternately in the diffuse and global mode. The ACR is mounted on a tracker and aligned with the sun. Pyranometer measurements, in millivolts are recorded by Campbell Scientific Inc. model 23x data loggers. The data logger programs are modified to store 1 HZ data. All pyranometers are leveled using the manufacturer installed bubble level (+/- 1^{o}). The desiccant in each sensor was checked and replaced as necessary.

During a pyranometer calibration session the following process is repeated as long as sky conditions permit. The ACR self calibration process is performed, this takes about 3 minutes. The program is then instructed to take 400 measurements, one every 4 seconds, this is considered to be a run. (Before January 2006, a run consisted of 300 measurements taken at intervals of 3-4 seconds). During a run the pyranometers are operated alternately in the shaded (diffuse) configuration and then in the unshaded (global) configuration for periods of about 5 minutes each. This is accomplished by rotating the shading balls towards the tracker until they rest on the long arms attached to the zenith axes of the tracker. A run is about 30 minutes, about 2 runs per hour can be made.

SHADE/UNSHADE METHOD, DATA ANALYSIS.

In the shade/unshade method, the data collected from a pyranometer during shaded and unshaded periods is separated into global and diffuse components. The missing periods of the diffuse component are filled in, in this case by linear interpolation. The difference in millivolts between the interpolated shaded values and the measured global values is determined for each global value. Some of the pyranometer data is only sampled every 2 seconds due to limitations in the data logger system, this data is then interpolated to fill in the missing seconds. If this is not done the pyranometer measurements may or may not line up temporally with the ACR data. The pyranometer and ACR points are matched to the closest second. A WRR adjusted horizontal component of the direct beam irradiance, in watts/meter**2, is calculated for each ACR measurement. This is accomplished by multiplying the ACR measured irradiance by the cosine of the solar zenith angle at the time of the measurement. The calibration coefficient, for each second of matching data, is then determined by dividing the pyranometer millivolt reading by the appropriate ACR determined horizontal irradiance. The resulting data are edited to remove periods of unacceptable sky conditions. For a run to be considered valid 66% of the maximum number of points are required. A mean and standard deviation are determined for each run. These run values and standard deviations are then used to calculate a calibration event mean and standard deviation. Ideally a calibration event would consist of at least 3 non-identical clear sky days during which measurements are taken. This makes the calibration value more representative of an ‘average’ day. Due to poor site access this is generally not possible. Up to the 4 most recent calibration measurement events may used to obtain a final calibration value. The calibration event mean is the mean of the run values. A standard deviation of these means is then calculated, as well as the mean of the individual standard deviations. These two standard deviations are converted into U95 values by multiplying them by 2.0 and used in the uncertainty analysis below. The Final result is then converted to microvolt/(W/m**2).

SHADE/UNSHADE, UNCERTAINTY ANALYSIS.

The uncertainties presented here are the U95 values. A measured value with its U95 uncertainty has a 95% probability of including the ‘true value’. The U95 uncertainty is twice the standard deviation. Four uncertainties are used there to determine a resultant uncertainty they are, 1) reference standard uncertainty, 2) mean of the uncertainty of the individual data points, 3) uncertainty of the mean of the data points and, 4) data logger uncertainty. The cavity uncertainty determined at the 2004 National Pyrheliometer Comparison at NREL was 0.34%. The final uncertainty is taken to be the root sum square of the components. The measured uncertainty is twice the root sum square of the mean of the standard deviations of the individual calibration values with the with the standard deviation of

$$U95_{total} = \mathrm{sqrt}((U95_{reference})^2 + (U95_{mean})^2 + (U95_{SDs})^2 + (U95_{logger})^2)$$

Where:
$U95_{total}$ is the total U95 for the test pyranometer.
$U95_{reference}$ is the U95 of the reference with respect to the WRR
$U95_{mean}$ is the U95 of the test pyranometers mean.
$U95_{SDs}$ is the U95 of the mean of the standard deviations of the calibration points.
$U95_{logger}$ is the expected U95 of the of the test pyranometer data logger (0.2%).

Relative Measurement Method.

RELATIVE METHOD, CONFIGURATION AND DATA ANALYSIS.

In the relative comparison method, the global pyranometer measurements obtained by a normally diffuse pyranometer (reference pyranometer) are compared to the standard global pyranometers (test pyranometers) measurements. Clear sky data is selected from the available data. The data is then grouped by ACR run. For each run 66% of the data must be present or the group is rejected. For each data point within a group the irradiance determined by the reference pyranometer is determined. The calibration value of the test pyranometer is then determined by dividing the millivolt output of the test pyranometer by the irradiance of the reference pyranometer. For each group a mean and standard deviation are then determined. The mean of the group means and the standard deviation of the group means is then determined. This mean is taken as the calibration value. The final results are presented in terms of microvolts/(Watts/Meter**2).

Uncertainty Analysis, Relative Method.

The three principal components of uncertainty used in this analysis are; 1) the mean of the standard deviations of the individual groups; 2) the standard deviation of the individual group means and; 3) the U95 uncertainty of the reference pyranometer. The two standard deviations are placed in terms of U95 by multiplying them by 2.0. The total U95 is then determined by the root sum sq method.

$$U95_{total} = \mathrm{sqrt}((U95_{reference})^2 + (U95_{mean})^2 + (U95_{sd})^2)$$

Where:
$U95_{total}$ is the total U95 for the test pyranometer.
$U95_{reference}$ is the U95 of the reference with respect to the WRR
$U95_{mean}$ is the U95 of the group mean of the test pyranometer sensitivities.
$U95_{sd}$ is the mean of the group U95 values.

Summary

Calibration of pyranometers has been completed. A set of calibration coefficients along with their associated U95 uncertainties have been determined. These values for each pyranometer are displayed at the beginning of this document. Historical calibration values are included for each pyranometer in the body of the document.

USEFULL REFERENCES

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

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

NREL, "Broadband Outdoor Radiometer Calibration Report", BORCAL 96-2, 23 July 1996.

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

Bruce W. Forgan, "A New Method for Calibrating Reference and Field Pyranometers", Journal of Atmospheric and Oceanic Technology, Volume 13, Pages 638-645.

Pyrheliometer calibration document, 2001 Aug 2, http://www-svg.larc.nasa.gov/cal/indes.html

International Pyrheliometer Comparison – 10 (IPC-X). IOM report No. 91. WMO/TD No. 1320. (Contact PMOD WRC for more information)