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Evaluation of Radiometers in Full-Time Use at the National Renewable Energy Laboratory Solar Radiation Research Laboratory

Technical Report
NREL/TP-550-44627
December 2008

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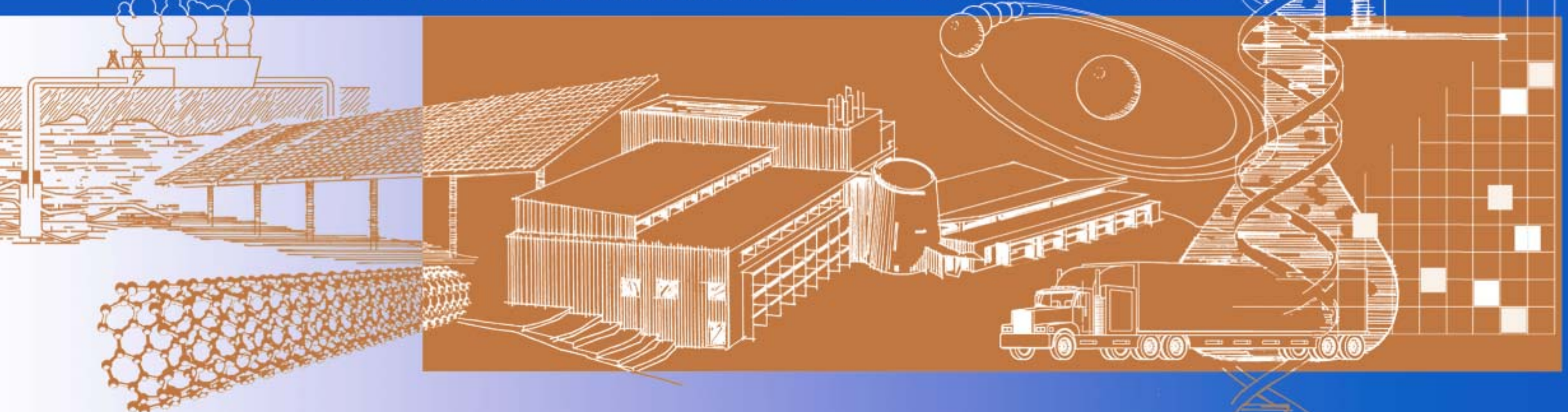

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Preface

This report describes the evaluation of the relative performance of the complement of solar radiometers deployed at the National Renewable Energy Laboratory (NREL) Solar Radiation Research Laboratory (SRRL). The evaluation represents a limited sample of instruments (usually one) from various manufacturers, and thus should not be viewed as representative of a specific manufacturer or model of instrument, but only of the instruments at hand for the evaluation. We report an analysis of 12 global (total hemispherical) horizontal radiometers three direct beam pyrheliometers, and two diffuse pyranometers in full-time use at SRRL. Data for 12 months were retrieved from the SRRL Baseline Measurement System and included the test instrument measurements and data for a computed reference data set. Not all test instruments had a full 12-month period of record as noted in the report. This report offers no explicit conclusion about instrument performance, as it is aimed at a very general array of applications with a wide range of instrumentation and accuracy requirements.

Acknowledgments

The continually scrupulous work of Afshin Andreas, Beverly Kay, Peter Gotseff, and Ibrahim Reda in maintaining the complement of instruments at the Solar Radiation Research Laboratory and performing exacting and demanding outdoor radiometer calibrations is gratefully acknowledged. The leadership of Thomas Stoffel, Resource Integration Group Manager, and David Mooney, Center Director, in setting the high standards for operations of the Solar Radiation Research Laboratory is appreciated. The United States Department of Energy Solar Energy Technology Program supported this work under DOE prime contract number DE-AC36-99-GO10337.

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1 Introduction

The Solar Radiation Research Laboratory (SRRL) at the National Renewable Energy Laboratory (NREL) regularly collects measurements from approximately 100 solar and metrological instruments as part of its Baseline Measurement System (BMS). These measurements are available to the public within a few seconds of logging via the NREL Measurement and Instrumentation Data Center (http://www.nrel.gov/midc/srrl_bms). Figure 1-1 shows the general configuration of SRRL and the instrument platform (to left, or west, of building) where the instruments are deployed.

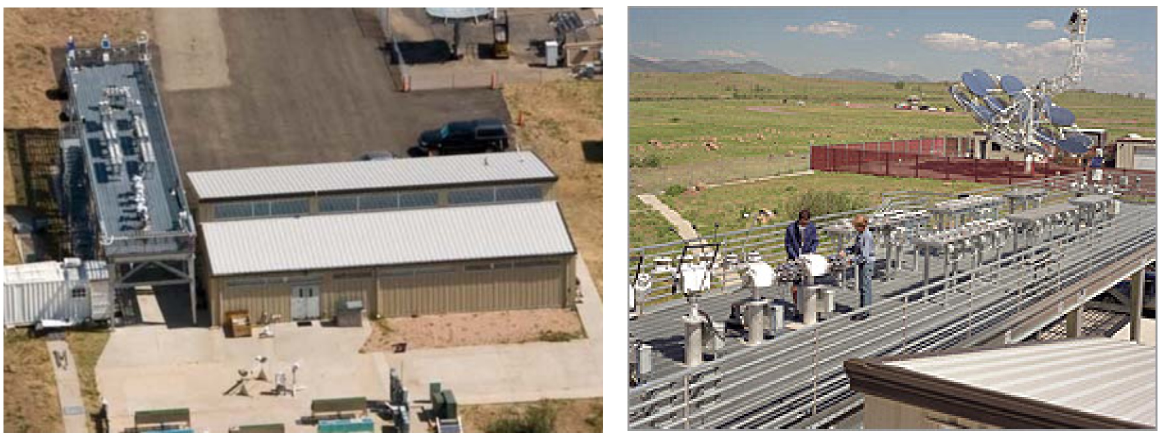

Figure 1-1. General SRRL configuration (left) with instrument platform (oriented north-south) located west of building. North is to the top, east to the right of the photograph. Instrument platform (right) with solar tracking instruments to the left (south) and horizontal instruments to right (north).

To support decision making for other projects, this report presents an analysis of 12 global (total hemispherical) horizontal radiometers, three direct beam pyrheliometers, and two diffuse pyranometers in full-time use at SRRL. Relative location of the radiometers is shown on the schematic layout of the SRRL instrument platform in Figure 1-2.

Data for 12 months were retrieved from SRRL's BMS and included the test instrument measurements and data for a reference data set computed from selected instruments. Not all test instruments had a full 12-month period of record as noted in the results. This report offers no explicit conclusion about instrument performance, as it is aimed at a very general array of applications with a wide range of instrumentation and accuracy requirements.

Note that the evaluation of these instruments represents a limited sample of instrument models (usually 1), and these results cannot be used with complete confidence to infer the same results or characteristics for all instruments of the same manufacturer and model. The evaluation used data from NREL's Solar Radiation Research Laboratory and results for instruments may be unique to the climate or geographical conditions at its Golden, Colorado, location (39.74 N latitude, 105.18 W longitude, and elevation 1829 m). Past experience indicates that many of these instruments respond to solar radiation to a different and usually unquantified degree in dissimilar physical environments.

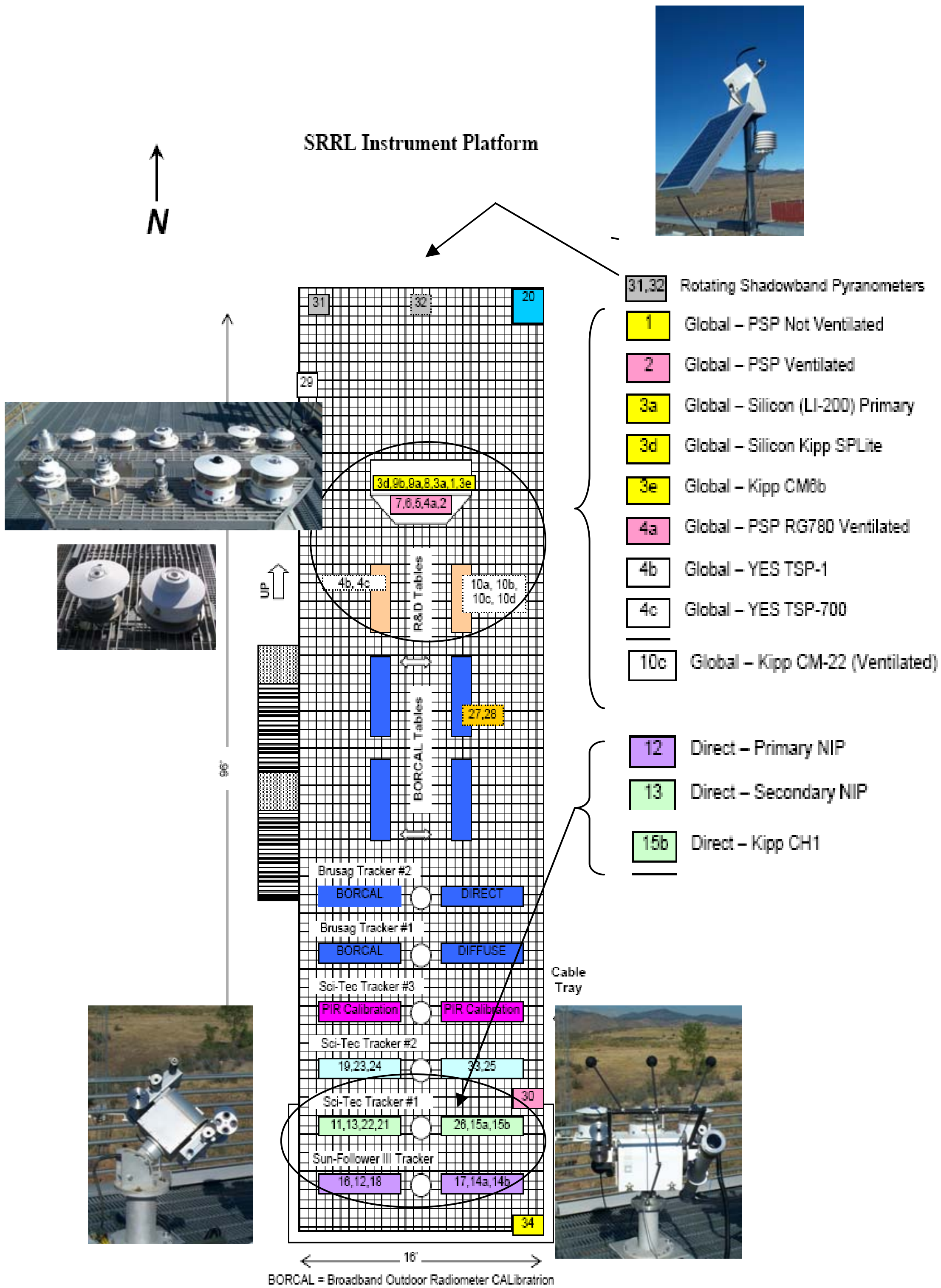

Figure 1-2. Schematic layout of relative positions of radiometers in the study, with representative photographs of the instruments as deployed.

The evaluation is subdivided into two sections: pyrheliometers (direct beam measurements) and pyranometers (global horizontal and diffuse horizontal measurements). The instruments evaluated are listed in Appendix A in Table A-1. The evaluation numerical results are summarized in Table 3-1. Detailed reports for each individual instrument are shown in Appendices B and C.

2 Approach

Two statistical summaries were prepared for each instrument, where sufficient data were available. Data for the 12 months from May 2006 to May 2007 were collected using the Solar Radiation Research Laboratory Baseline Measurement System. Data were recorded as 1-minute averages of 3 second (0.33 Hz, 20 samples per minute) sampled data using Campbell Scientific CR23X data loggers. This constituted the sub-hourly data set. Subsequently, the sub-hourly data sets were aggregated into hourly average data (mean of 60 1-minute averages), daily totals (sum of all sunup 1-minute data), and monthly mean daily totals (mean of the daily totals for all days in the month).

For the sub-hourly statistics, the values in the 80º to 90º bin are not included in the summary because of sensitivities to environmental error and general low irradiance conditions. The last three entries report the statistics for the Eppley Laboratories NIP 27592E6, 31137E6, and Kipp and Zonen CH1 010256 with respect to an absolute cavity radiometer [1], an Eppley Laboratories Automatic Hickey-Frieden (AHF) under clear sky conditions only. The monthly and annual statistics NA designation for the pyrheliometers are due to the limited duration data set (see section 2.2 on pyrheliometer evaluations).

2.1 Evaluation of Global Horizontal Pyranometers

Data for the portion of the study pertaining to pyranometers were collected under all sky conditions throughout a year (data quality filtering removed about 5% of the data, and some instruments as noted had a short period of record). Two independently evaluated instruments were used to create a computed global hemispherical irradiance data set against which the pyranometers' measured global hemispherical irradiance was compared. Two other independently evaluated instruments were used to validate and quality assess (QA) the reference data set and reject data inconsistent among those four instruments (computed global and QA instruments, respectively, see section 2.1.2). The computed global hemispherical (henceforth "Computed Global") and QA instruments are identified below.

2.1.1 Computed Global Irradiance

Computed from: Direct beam * COS(Z) + Diffuse

Direct Beam: Kipp & Zonen CH1 Serial No. 010256
Cal. Factor = 91.881 $W/m^2/mV$
Responsivity (Rs) @45°= 10.884 $\mu V/W/m^2$
CALIBRATION Uncertainty: +0.60% - 0.56% (for $30° \leq Z \leq 60°$)

Diffuse: Eppley 8-48 Serial No. 32331
Cal Factor = 112.77 $W/m^2/mV$
Responsivity (Rs) @45°= 8.868 $\mu V/W/m^2$
CALIBRATION Uncertainty: +1.95% -1.89% (for $30° \leq Z \leq 60°$)

2.1.2 Quality Assessment and Filtering of Reference Irradiance Data

The direct and diffuse irradiance measurements used to calculate the reference computed global irradiance data were evaluated against an independent global irradiance calculated from different direct beam and diffuse instruments listed below. SERI QC [2] was used to validate the measurements. SERI QC uses clearness index Kt for global, Kd for Diffuse, and Kn for direct beam (ratio of measured data to top of the atmosphere or extraterrestrial data of the same type, direct beam, and direct component on a horizontal) to check that the balance of the component sum equation Kt = Kn + Kd is "true" within a tolerance of ± 0.03 units. SERI QC generated flags for each data set. Any 1-minute data record without a SERI QC flag of 1 (zenith angle > 80°) or 3 (within the ± 0.03 tolerance limit) was rejected from the reference data set (approximately 5% of the data were rejected). In our experience, a flag of three indicates data from a well-maintained station.

QA Direct Beam = Eppley NIP Serial No. 31137E6

Period	Serial #	Cal Fac $W/m^2/mV$	RS@45 µV/W/m²	Uncertainty (30°≤Z≤60°)
16-05-2006 – 08-06-2007	31137E6	117.78	8.4905	+0.98/-0.92%
08-06-2007 - 18-06-2008	31137E6	117.59	8.5043	+1.11/-1.03%
18-07-2008 – 31-05-2008	31137E6	117.61	8.5024	+1.10/-1.00%

QA Diffuse = Kipp & Zonen CM22 (Shading ball) radiometers:

Period	Serial #	Cal Fac $W/m^2/mV$	RS@45 µV/W/m²	Uncertainty (30°≤Z≤60°)
01-06-2007 – 13-06-2007	010046	107.72	9.2832	+1.24/-1.14%
13-06-2007 – 23-05-2008	010034	91.704	10.905	+1.81/-1.50%
23-05-2008 – 31-05-2008	010046	107.56	9.2972	+1.45/-1.67%

The two diffuse instruments—8-48 and CM22—were chosen for the two roles of computing global irradiance and QA so as to remove the possibility of using the CM22 in computing reference irradiance for the global CM22.

2.1.3 Uncertainties of the Method

The evaluation data set was retrieved from the Solar Radiation Research Laboratory Baseline Measurement System recorded at 1-minute averages of 3 sec (0.33 Hz, 20 samples per minute) sampled data using Campbell Scientific CR23X data loggers:

01-06-2007 to 29-10-2007: CR23X s/n 3416 Factory Cal 01/25/2001
29-10-2007 to 31-05-2008: CR23X s/n 1162 Calibrated 01/19/2007

The manufacturer's specified accuracy is ±0.025% of Full Scale Range (FSR typically +/-50 mV, meaning FSR is 100 mV) 0°C to 40°C. So in the 50 mV range: accuracy: ±0.025 mV = 25 microvolts (µV) with 1.67 µV resolution. Thus, the data logger contribution to uncertainty is ~ ±25 µV ± 1.67 µV which is approximately ±26.7 µV.

Radiometer responsivities are generally <~ 5.0 to 10.0 μV/ Wm^{-2}, i.e., 1.0 Wm^{-2} generates 5 to 10 μV of signal. The 26.7 μV logger uncertainty equates to approximately 5 watts or 2.7 watts (absolute) in BOTH reference and TEST instruments, or ~ 1.0% to 0.5% of reading at midrange values of 500 Wm^{-2}, and 2% or 1% of 1000 Wm^{-2} readings. We will be conservative and select the average of the larger uncertainties, 1.5%, for the data logger contribution to overall uncertainty.

Combined uncertainty in the computed reference irradiance is estimated from the weighted contribution of the beam and diffuse components, ranging from ±1.0 % for extremely clear (nearly all direct beam) to ±2.5% overcast (all diffuse, or high zenith angles). The mean of the 250,981 1-minute reference uncertainties is 1.8% ±0.5%. Total uncertainty in the comparisons is determined from the square root of the mean squared uncertainties, plus twice the standard deviation squared, plus the logger uncertainty contribution squared or $(1.8^2+(2*0.5)^2 + 1.5^2) =$ ±2.5% . Thus reference and data irradiances within ±2.5% of each other are considered identical.

For each 1-minute data point, global irradiance from each test instrument was compared with the concurrent computed global irradiance, and the difference between them calculated as a percent (test irradiance minus computed irradiance divided by computed irradiance). The resulting data set was used to calculate "sub-hourly" percent mean bias differences and standard deviations. The computed global irradiance data and test instrument global irradiance data were summed into daily total irradiance, and monthly means of daily total, which were compared by calculating percent differences as for the 1-minute data.

Table A-1 in Appendix A lists the instruments evaluated. In the case of the Kipp & Zonen CM22 global horizontal measurement, because of calibration and deployment schedules, two physical instruments were used for this evaluation. The table also shows the uncertainty in the responsivity (Rs) derived from NREL's Broadband Outdoor Radiometer Calibration (BORCAL) Radiometer Calibration and Characterization (RCC) procedures [3]. Those uncertainties are assigned based on the range of responsivities computed during the BORCAL process between zenith angles of 30° and 60°. Since the Rs is specified at Z= 45° ±0.2°, the 30° to 60° Z angle range is used to indicate the variability in Rs over zenith angles with ±15° of the calibration point. Thus these uncertainties are a less comprehensive measure of performance than the results in this evaluation. The calibration results are represented as valid only for the environmental conditions existing on the day of the calibration, whereas this evaluation encompasses data and environmental conditions for an entire year. The calibration responsivity for each instrument was used to calculate irradiance for the instruments, but the calibration uncertainty of the test instruments was not used for this evaluation. It is provided to show the expected uncertainty in the determination of irradiances using the specified responsivity in the range of zenith angles from 30° to 60°.

2.1.4 Special Considerations

All data where the absolute value of the computed global irradiance was less than 10 Wm^{-2}, or differences between the computed irradiance and the test irradiance were > 100% were eliminated. This removed issues with computing the ratios of small irradiance values and transient effects from differing time constants which were seen to inordinately contribute to 'percentage difference' results. An additional 3% of the 250,000 data points were removed from the analysis using these criteria.

At the latitude of the SRRL, the minimum zenith angle in summer is 17 degrees, so there is no 0 to 10 degree zenith angle bin data.

The entire suite of instruments was maintained with daily cleaning five days per week by NREL staff. The effects of snow accumulation and frost in the wintertime may not have been completely removed from the data set. The QA process on the reference data set likely removed most snow effects for both the reference and test data set. But individual instruments may have accumulated snow at different rates under different conditions, and the effects of snow and frost may be present for some test instruments. Additionally, some instruments had the benefit of ventilators, which tends to mitigate frost and snow accumulation. These effects may show up as a negative or positive bias on certain days, increasing the scatter of data.

Zenith angle and thermal corrections for the Eppley PSP were developed by the National Renewable Energy Laboratory and are neither supplied by the manufacturer nor part of instrument output. The corrections require special calibrations and additional instrumentation (pyrgeometer) and were included in this study for consideration by the user. Corrections for the Irradiance Rotating Shadowband Radiometer (RSR2) are supplied by the manufacturer and corrected data are included as part of the instrument output.

2.2 Evaluation of Direct Normal Pyrheliometers

The absolute cavity radiometer (Eppley Automatic Hickey–Freidan) is the reference for NREL calibrations and for this work is presumed to be the pyrheliometer with the lowest uncertainty available [4]. Although a full year of data in varying conditions and seasons – such as that used for the pyranometer evaluations above – is desired, it is not practical to deploy the cavity full time because its aperture is open to the elements and internal components are subject to water or soiling.

For this evaluation we collected reference cavity radiometer data from all NREL calibration events from 2002 to 2007 and matched this reference data with three pyrheliometers from the SRRL baseline system (Eppley NIPs 25792E6 and 31137E6 and Kipp & Zonen CH1 010256). Because known and accepted uncertainties in the NREL calibrations are similar to expected differences among pyrheliometers, if there were different responsivities in use for an instrument in the different calibration events over the study period (e.g., see Table A-1), these responsivities were averaged. This removed noise effects of calibration uncertainty and also provided the opportunity to detect sensitivity drift with time (none were observed).

The portion of the study pertaining to pyrheliometers used only clear sky conditions (as mandated by the calibration events). Although the instruments are assumed to be linear in sensitivity with irradiance, overall performance could vary under different sky conditions. However, this may not detract from the usefulness of evaluation results presented here since performance under clear skies may be of greatest interest to solar power conversion applications.

2.2.1 Uncertainties for the Direct Normal Pyrheliometer Evaluation:

The NREL BORCAL process has a nominal uncertainty contribution from the cavity radiometer and low thermal and high precision data logging system (which is about five times more accurate than the routine monitoring data logger) of about 0.5%.

3 Results

3.1 Pyranometer Sub-Hourly 1-Minute Data

Table 3-1 and Figures 3-1 and 3-2 display a summary of the percent differences between the computed reference irradiances and the instrument data. The first two columns of Table 3-1 are for the sub-hourly (1-minute) data for each instrument or instrument configuration over all zenith angle ranges. The 3rd and 4th columns of Table 3-1 shows the percent bias error in monthly mean daily totals and annual average daily total data between the computed reference and the instrument data. Since the biases changed as a function of zenith angle (and hence as a function of the month of the year) a range of bias differences is shown, from minimum to maximum magnitude. Typically the minimum bias with respect to zenith angle is for the low zenith angle data (summer), and maximum bias occurs with the largest zenith angle bin (80 to 90 degrees) and winter data (highest average zenith angles for the year).

The majority of the pyranometers (9 of the 13) have a bias between ±1% to ±5% from the computed reference irradiance 1 minute data. These are the CM22 Ventilated, CM6B, PSP Ventilated and Corrected, TSP1 , TSP700, SP LITE, LI200, and RSR2 Corrected and Uncorrected. Of these, four have a bias error less than equal to ±2% in the 1-minute data. These are the RSR2 Corrected, CM6B, CM22 Ventilated, and SP LITE. The standard deviation of the differences from the 1-minute reference irradiance are less than ±6% for the CM22 Ventilated, TSP700, RSR2 Corrected and Uncorrected, PSP Ventilated and Corrected, and LI200.

Two of the instruments (RSR2 and SPN1), while strictly pyranometer-based, provide direct normal irradiance (DNI) through calculation from the measured global and diffuse irradiances. DNI values from these instruments are included in the pyranometer results.

3.2 Averaged Data: Monthly and Annual Average Daily Totals

Of the 13 pyranometers, all but two have a mean bias difference from the computed reference irradiance Monthly Mean Daily Totals (MMDT) of less than ±5% all year long. The two exceptions are the PSP Uncorrected and PSP Ventilated Uncorrected, which underestimate winter irradiances by more than 7% due to poor cosine response with respect to the 45° zenith angle responsivity for these instruments.

In terms of annual average daily total (AADT) irradiance, all instruments agree with the computed reference irradiance annual average daily total irradiance within ±3%, except the PSP Uncorrected, which has a mean bias of -3.9%. Eight of the instruments have less than ±2% bias from the computed reference irradiance AADT (CM22 Ventilated, SP Lite, TSP700, CM3, CM6B, LI200, RSR2 Corrected, and PSP Corrected.) Five of these have less than ±1% bias from the AADT of the computed reference irradiance (CM22 Ventilated, CM6B, LI200, RSR2 Corrected, and PSP Corrected).

Note there is insufficient coverage of the year by the Delta-T SPN1 radiometer to make an adequate comparison with the other pyranometers with respect to the annual daily totals. The MMDT for this instrument only span 4 months in the winter and spring seasons

Various combinations of mean bias error, standard deviation of the bias error, MMDT bias and AADT bias would result in different ‘rankings’ of the performance of the instruments with respect to the computed reference irradiance, which has an estimated uncertainty of ±2.5%.

Figure 3-1 shows that for zenith angles less than 60°, *all of the pyranometer mean bias errors are less than ±5%.* Figure 3-2 shows that for all but the CM3 pyranometer, the standard deviation of the differences from the computed reference irradiance is also *less than 5% for zenith angles less than 60°.*

Thus, it is imperative to note that the largest contribution to differences of all of the pyranometers with respect to the computed reference irradiance are due to issues with cosine response of the instruments for zenith angles greater than 60°.

Table 3-1. Instrument performance by zenith angle (sub-hourly; 1-minute), monthly mean daily total, and annual mean biases.

Instrument (see Table A1 in Appendix A)	Sub-hourly Uncertainty % (range of bins to 80° Zenith)		Mean Daily Total Uncertainty %	
	Bias % max / min	Standard Deviation %	Monthly Bias % (monthly bins) max / min	Annual Bias+ %
CM22_Vent	+0.6 to +0.4	2 to 3	+0.77 to +0.18	+0.48
CM6B	+0.8 to -0.3	4 to 7	+0.87 to -1.96	+0.15
CM3	+0.1 to -7.4	2 to 7	+0.37 to -1.84	-1.23
PSP_Vent_C	+0.0 to -3.1	2 to 6	-0.06 to -5.13	-2.08
PSP_C[1]	+5.7 to -0.3	2 to 11	+1.17 to -3.27	+0.79
PSP_Vent_U	+1.6 to -11.3	2 to 8	+0.01 to -8.38	-3.88
PSP_U	+2.5 to -7.5	2 to 9	+0.42 to -10.3	-2.78
TSP700	-0.8 to -2.5	4 to 6	+1.50 to -0.01	+1.09
TSP1	+3.2 to +0.4	2 to 12	+4.59 to -0.41	+2.32
SPN1 (Glo)*	-0.3 to -3.7	4 to 7	-0.67 to -6.04	*
SPN1 (Dir)*	+8.1 to +3.0	19 to 24	+15.4 to -7.90	*

[1] Infrared correction for unVentilated pyranometer using Ventilated pyrgeometer to measure net Infrared

SPN1 (Dif)*	-13.8 to -4.3	7 to 11	-12.9 to -10.4	*
SP_LITE	+1.4 to +0.8	4 to 7	+1.39 to +0.02	+1.35
LI200_TOT	+2.8 to -2.0	3 to 8	+1.92 to -2.01	+0.93
RSR2_C (Glo)**	+1.0 to -1.2	4 to 6	+0.53 to -2.54	-0.73
RSR2_C (Dir)**	-3.5 to -7.5	16 to 19	-0.59 to -8.81	-6.60
RSR2_C (Dif)	-0.2 to +3.0	5 to 6	-1.06 to +3.03	+1.00
RSR2_U (Glo)**	-0.8 to -2.5	4 to 6	-0.81 to -3.59	-2.17
RSR2_U (Dir)**	+1.3 to +0.5	17 to 20	-2.07 to +3.37	+1.04
RSR2_U (Dif)**	-12.0 to -15.0	13 to 16	-19.3 to -19.6	-14.1
NIP 31137 DNI**	-0.2 to +0.4	1.7 to 2.1	-0.30 to +1.20	+0.10
NIP 25792E6/Cav	+0.79 to -0.28	0.5 to 0.7	N/A	N/A
NIP 31137E6/Cav	+0.46 to -0.53	0.4 to 0.6	N/A	N/A
CH1 010256/Cav	+0.23 to +0.10	0.4 to 0.5	N/A	N/A

* Partial period of record (4 months); ** Partial period of record (11 months); + Average % difference in annual daily totals

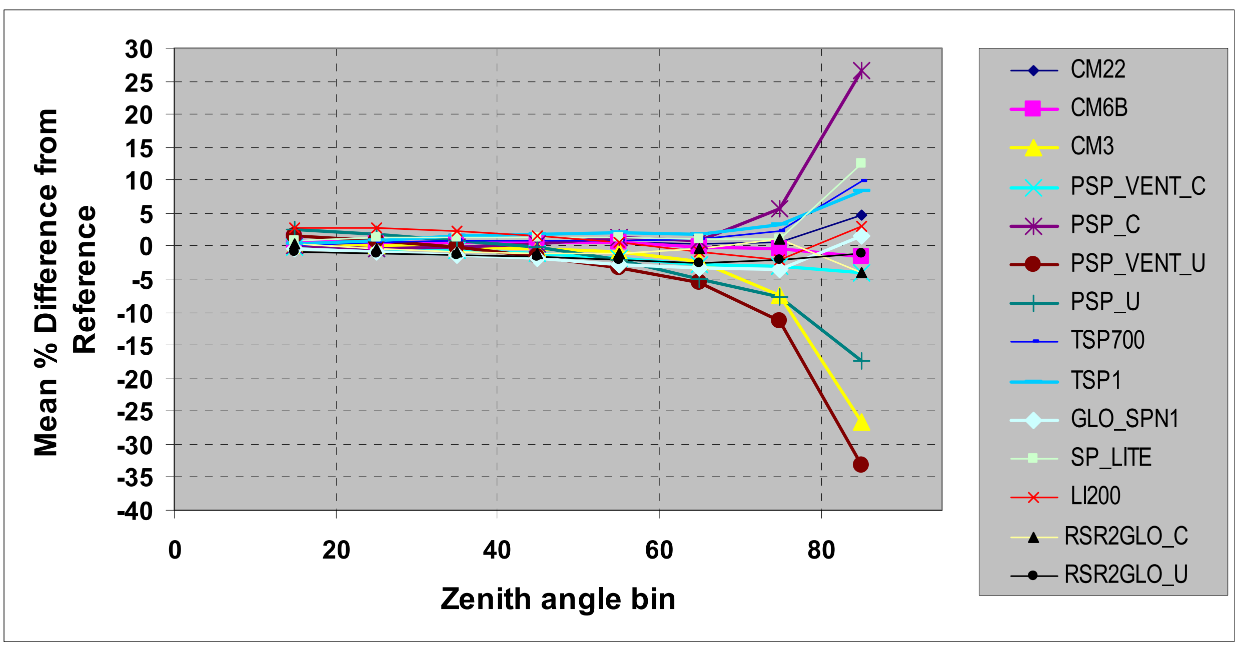

Figure 3-1. Mean percent differences from reference global irradiance for pyranometers as function of zenith angle. See Appendix A, Table A-1 for instrument list.

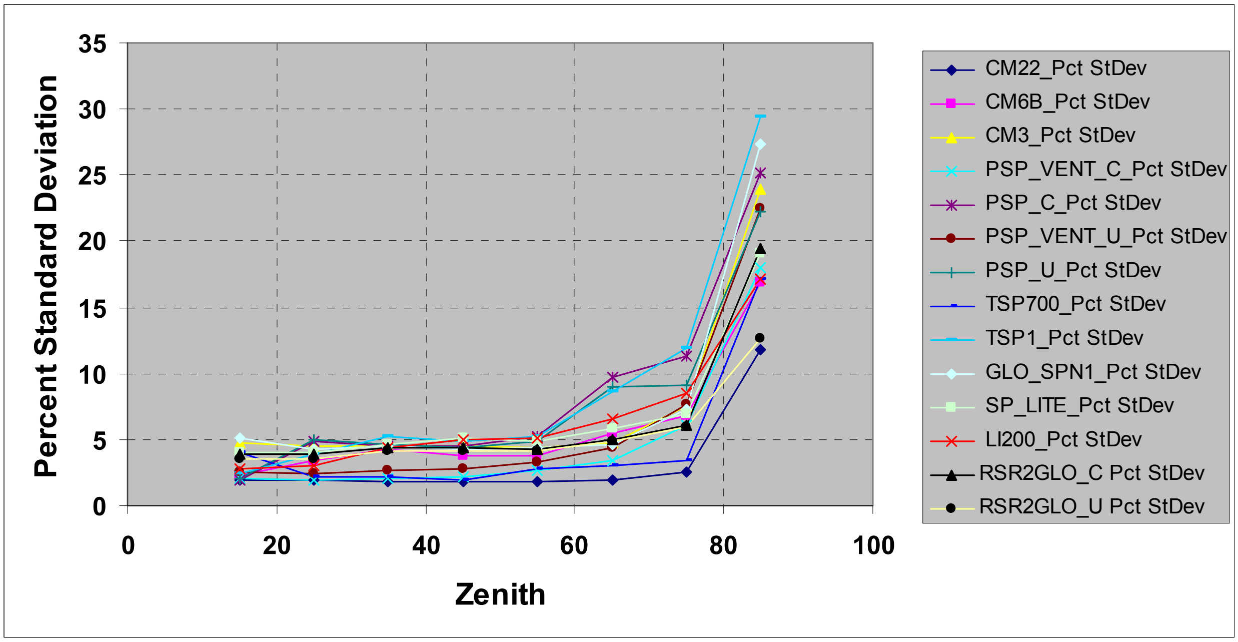

Figure 3-2. Percent standard deviations of differences from reference global irradiance for pyranometers as function of zenith angle. See Appendix A, Table A-1 for instrument list.

Figure 3-3 is a bar chart of the mean difference between the MMDT of test and computed reference global (and the SPN1 Direct and Diffuse with respect to the CH1 direct and CM22 diffuse MMDT) irradiances. The error bars represent the standard deviation of the MMDT differences in percent of the mean irradiance.

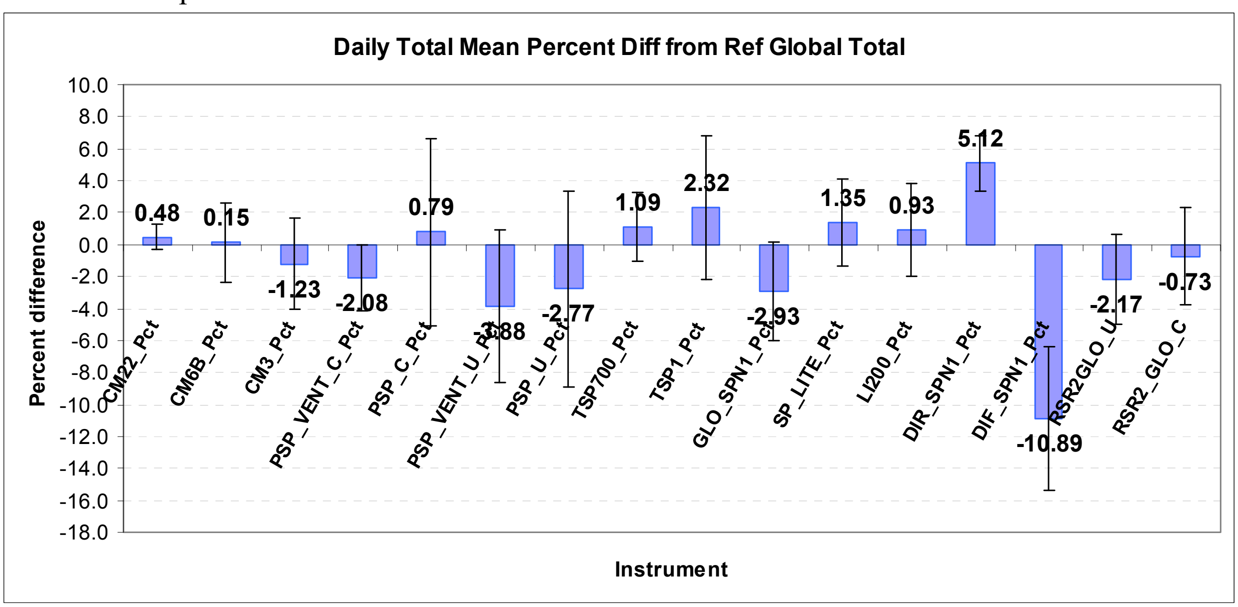

Figure 3-3. Summary of means and standard deviations of differences (in percent) between test radiometers and reference irradiance Monthly Mean Daily Total. See Appendix A, Table A-1 for instrument list.

Table 3-2 shows the data of Figure 3-3 in tabular form, as well as the range of differences in MMDT in percent.

Table 3-2. Table of statistics for percent differences in daily total irradiances versus reference irradiance.

	Count (N)	**Mean**	**StDev (sd)**	Maximum	Minimum	Range
CM22_VENT_Pct	366	**0.480**	**0.788**	5.8	-4.6	10.4
CM6B_Pct	366	**0.151**	**2.495**	9.3	-23.8	33.1
CM3_Pct	366	**-1.230**	**2.854**	5.3	-39.3	44.6
PSP_VENT_C_Pct	366	**-2.081**	**2.098**	3.2	-12.2	15.4
PSP_C_Pct	366	**0.792**	**5.856**	45.3	-55.5	100.8
PSP_VENT_U_Pct	366	**-3.880**	**4.759**	1.2	-58.3	59.5
PSP_U_Pct	366	**-2.775**	**6.096**	8.3	-59.8	68.1
TSP700_Pct	366	**1.086**	**2.177**	7.1	-35	42.1
TSP1_Pct	366	**2.320**	**4.467**	27.2	-31.6	58.8
GLO_SPN1_Pct	152	**-2.928**	**3.121**	6.8	-14.7	21.5
SP_LITE_Pct	366	**1.352**	**2.714**	15.6	-20.8	36.4
LI200_Pct	366	**0.928**	**2.935**	12.2	-23.9	36.1
DIR_SPN1_Pct*	144	**4.197**	**17.79**	91.0	-66.8	157.8
RSR2_U (Glo)**	341	**-2.174**	**2.812**	11.5	-35.7	47.2
RSR2_U (Dir)**	329	**1.043**	**9.269**	39.0	-82.7	121.7
RSR2_C (Glo)**	341	**-0.733**	**3.015**	14.2	-47.4	47.7
RSR2_C (Dir)**	330	**-4.626**	**10.48**	65.4	-97.8	163.2

* Only 4 months of valid data (Feb 2008-May 2008); ** 11 months of data (July 07 to May 08)

Figure 3-3 and Table 3-2 summarize results for the aggregated months in the study. Figure 3-4 and Table 3-3 show the month to month variability of the differences in MMDT for the global hemispherical irradiances. Six units, the SPN1 Global, Corrected PSP, Corrected Ventilated PSP, Uncorrected PSP, Uncorrected Ventilated PSP, and TSP1 pyranometers exceed +/-2% difference for one or more months of the year, typically in the winter (month 7 is December, 2007) months. The TSP1 MMDT are 4% too high in the spring (Feb, Mar, Apr) months. The Corrected PSP MMDT difference is -3% only for one month (Dec). Note that the SPN1 Global data was present for January (month 8) to May (month 12).

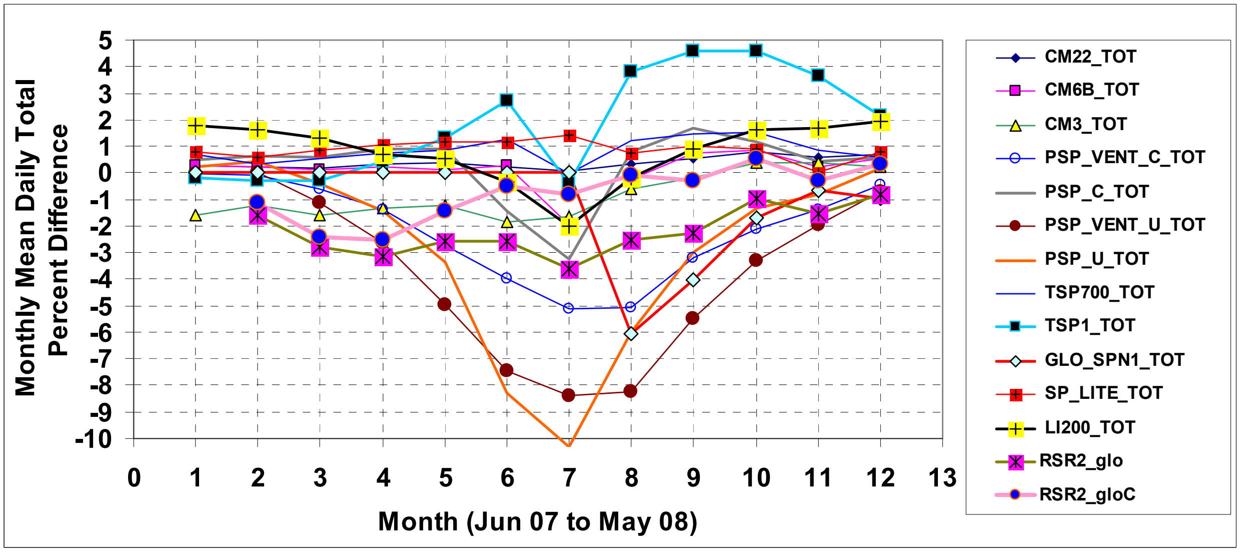

Figure 3-4. Percent difference between Monthly Mean Daily Totals of test radiometers and reference irradiance.. See Appendix A, Table A1 for instrument list.

Table 3-3 shows the tabular data presented in Figure 3.4. Shaded cells highlight MMDT differences that exceed +/- 2.5%.

Table 3-3. Monthly Mean Daily Total Percent differences from Ref Global Horizontal (CH1 + Diff)

	JUN 2007	JUL 2007	AUG 2007	SEP 2007	OCT 2007	NOV 2007	DEC 2007	JAN 2008	FEB 2008	MAR 2008	APR 2008	MAY 2008
GLO_REF Wh/m^{-2}	**6749**	**6473**	**5386**	**4503**	**3881**	**2306**	**2211**	**2500**	**3467**	**4597**	**6133**	**6001**
CM22_Vent	0.266	0.203	0.184	0.319	0.372	0.205	0.064	0.317	0.527	0.771	0.612	0.687
CM6B	0.293	0.230	0.117	0.246	0.138	0.264	-1.960	-0.241	0.753	0.870	0.227	0.554
CM3	-1.606	-1.244	-1.585	-1.342	-1.207	-1.843	-1.638	-0.581	-0.195	0.386	0.355	0.233
PSPVENC	-0.034	-0.061	-0.626	-1.394	-2.740	-4.002	-5.129	-5.083	-3.226	-2.099	-1.379	-0.475
PSP_C	0.509	0.665	0.611	0.904	0.897	-1.461	-3.268	0.802	1.696	1.173	0.454	0.569
PSPVENTU	-0.036	0.007	-1.110	-2.647	-4.977	-7.465	-8.380	-8.222	-5.467	-3.322	-1.932	-0.692
PSPU	0.214	0.423	-0.419	-1.446	-3.355	-8.293	-10.314	-5.995	-3.011	-1.354	-0.833	0.180
TSP700	0.670	0.305	0.544	0.755	0.831	1.253	-0.010	1.201	1.488	1.500	0.858	0.571
TSP1	-0.209	-0.313	-0.270	0.423	1.337	2.719	-0.411	3.793	4.589	4.597	3.657	2.169
GLO_SPN1	----	----	----	----	----	----	----	-6.040	-4.043	-1.705	-0.668	-0.979
RSR_UNCOR	---	-1.58	-2.76	-3.14	-2.59	-2.56	-3.59	-2.5	-2.27	-0.99	-1.55	-0.81
RSR_Corr	---	-1.13	-2.42	-2.54	-1.42	-0.48	-0.78	0.08	-0.32	0.53	-0.30	0.34
SP_LITE	0.798	0.569	0.823	1.039	1.182	1.182	1.393	0.743	0.982	0.921	0.021	0.809
LI200	1.802	1.639	1.308	0.686	0.524	-0.350	-2.011	-0.208	0.893	1.628	1.701	1.918

As mentioned earlier, the largest contribution to the differences in the winter months is the deviation in response of the instruments as a function of the high zenith angles (greater than 60°) in the winter at the location of the Solar Radiation Research Laboratory.

The diffuse measurements provided by the RSR and SPN1 radiometers were evaluated separately for their relationship to the reference diffuse as shown in Table 3-4 and Figure 3-5.

Table 3-4. Diffuse Horizontal RSR and SPN1 (Mean % difference in monthly mean daily totals)*

	JUN 2007	JUL 2007	AUG 2007	SEP 2007	OCT 2007	NOV 2007	DEC 2007	JAN 2008	FEB 2008	MAR 2008	APR 2008	MAY 2008
DIFFUSE REF Wh/m^{-2}		1992	1770	1365	1055	838	814	762	1214	1681	1842	2260
RSR DIF U %	----	**-13.22**	**-13.42**	**-16.10**	**-19.35**	**-18.82**	**-16.19**	**-17.88**	**-13.14**	**-10.85**	**-11.61**	**-6.35**
RSR DIF C %	----	**-0.64**	**-1.06**	**-0.40**	**1.31**	**1.47**	**0.12**	**2.02**	**1.44**	**2.05**	**2.88**	**3.03**
SPN1 DIF %	----	----	----	----	----	----	----	----	**-12.9**	**-11.9**	**-11.57**	**-10.24**

* Month 1 = July 2007; Month 11 = May 2008

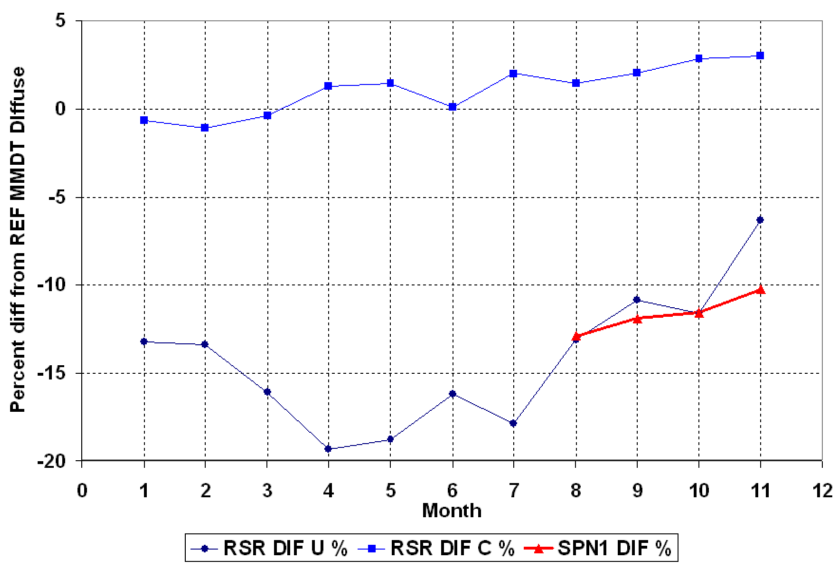

Figure 3-5. Difference between MMDT of Corrected and Uncorrected RSR and SPN1 Diffuse and reference diffuse. Note SPN1 data available only for months 8 to11.

The Corrected RSR Diffuse is typically within 3% of the reference Diffuse, however the Uncorrected RSR and SPN1 Diffuse readings are significantly low (more than -10%) for all months.

3.3 Pyrheliometer and Cavity Pyrheliometer Comparisons

3.3.1 Cavity pyrheliometer and test pyrheliometer comparison

The following plots and tables indicate the relative bias and scatter of the data among direct normal measuring instruments with respect to an absolute cavity radiometer reference during scheduled clear-sky calibration events. The uncertainty of the reference instrument (AHF Cavity radiometer) data is nominally ±0.5%, meaning that the bias plots could move up or down by that magnitude and not be significant. Scatter in individual instrument plots within ±0.5% could be due as much to the reference instrument as the test instrument itself. However, movements in biases relative to other test instruments hold greater significance since each instrument was compared against the same reference cavity radiometer data set. All zenith bins are 10 deg wide and the center of bin is the independent variable in plots. Units are percent (%) deviation from reference irradiance. Tables 3-5, 3-6, and 3-7 show statistics within each zenith angle bin for the differences between the test pyrheliometers and the reference cavity pyrheliometer.

Table 3-5. Kipp & Zonen 010256 CH1 Z angle statistics

Zenith Angle Bin	Count (N)	Mean %	StDev %	Maximum %	Minimum %	Range %
15	879	0.234	0.396	1.241	-0.97	2.22
25	2107	0.115	0.419	1.442	-0.98	2.42
35	2107	0.115	0.419	1.442	-0.98	2.42
45	2166	0.183	0.434	1.316	-1.51	2.82
55	1847	0.150	0.441	1.342	-2.30	3.64
65	1978	0.101	0.461	1.222	-4.18	5.40
75	1815	0.185	0.452	1.348	-3.12	4.47
85	1698	0.222	0.479	1.780	-4.96	6.74

Table 3-6. Eppley Nip 25792 Z angle statistics

Zenith Angle Bin	Count (N)	Mean %	StDev %	Maximum %	Minimum %	Range %
15	879	-0.284	0.494	1.230	-1.66	2.90
25	2107	-0.168	0.478	1.197	-1.81	3.00
35	2166	-0.134	0.473	1.089	-2.94	4.03
45	1847	0.0081	0.535	1.517	-1.64	3.16
55	1978	0.1316	0.542	1.781	-3.92	5.70
65	1815	0.3935	0.562	2.469	-1.35	3.82
75	1697	0.7858	0.702	3.297	-1.79	5.09
85	456	1.0388	0.799	2.828	-1.21	4.04

Table 3-7. Eppley Nip 31137 Z angle statistics

Zenith Angle Bin	Count (N)	Mean %	StDev %	Maximum %	Minimum %	Range %
15	879	-0.528	0.351	0.422	-2.46	2.88
25	2106	-0.440	0.415	0.951	-1.78	2.73
35	2166	-0.218	0.473	1.400	-1.93	3.33
45	1847	-0.055	0.547	1.454	-2.33	3.79
55	1978	0.058	0.554	1.936	-4.69	6.62
65	1815	0.266	0.561	2.573	-2.20	4.78
75	1698	0.458	0.603	2.665	-4.42	7.09
85	456	0.475	0.821	2.976	-1.48	4.46

Units of all comparisons are percent deviation from the absolute cavity (AHF) reference irradiance

The Direct Normal Irradiance (DNI) comparison was made with only values of the CH1 & NIP greater than 10 watts to remove very large percentage errors caused by ratios of small numbers.

Figures 3-6 and 3-7 show that the CH1 demonstrates flat zenith angle response with respect to the reference cavity radiometer and smaller standard deviation over the entire range of zenith angles. The two NIPs have significantly larger mean deviations, which vary by zenith angle; being minimal at low zenith angles and increasing at high zenith angles. The standard deviations of the two NIPs are comparable, and only slightly (0.1%) greater then the CH1 standard deviation.

Figure 3-6 shows the individual deviations from the reference absolute cavity pyrheliometer. The normal baseline monitored data was merged with the cavity radiometer reference data during the clear sky calibration events, and percentage differences between the reference and test irradiances were computed.

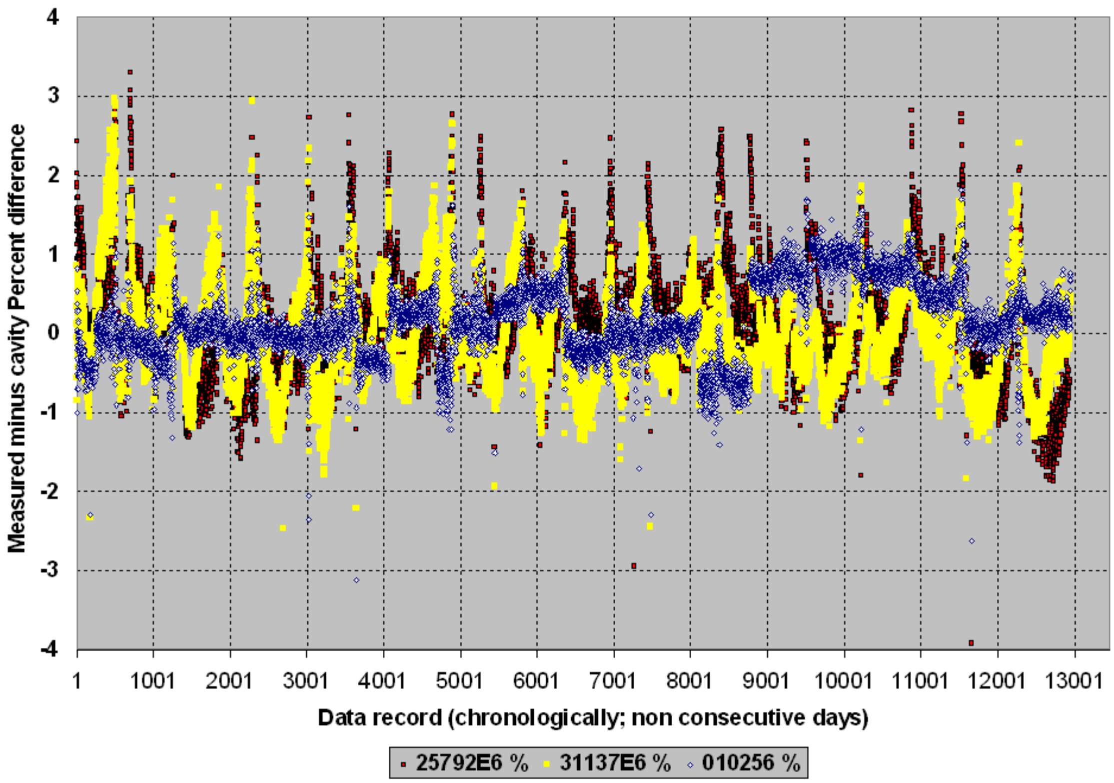

Figure 3-6. Pseudo time series plot of differences between reference AHF cavity radiometer and K&Z CH1 010256, Eppley NIP 31173E6, and Eppley NIP 257926E6. (Data in chronological order from individual calibration days which may be separated by periods from a week to many months; sometimes indicated by discontinuities.)

Figure 3-7 is the same data as Figure 3-6, but plotted versus time of day for all of the days in Figure 3-6. Note the 'smile' in the NIP data, and rather flatter CH1 curve in Figure 3-7. Figure 3-

8 shows the variation of the mean percent difference (solid lines) between the reference cavity pyrheliometer and the test pyrheliometers (installed in the baseline monitoring system) as a function of zenith angle bin. The standard deviations of the differences as a function of the zenith angle bin are also shown with the dashed lines. The CH1 data are almost flat with respect to zenith angle, and the NIP data have increasing differences and standard deviations at increasing zenith angles. The apparent correlation with zenith angle may not be a first-order relationship. There is possibly some other factor causing varying differences in instrument output that also correlates with zenith angle.

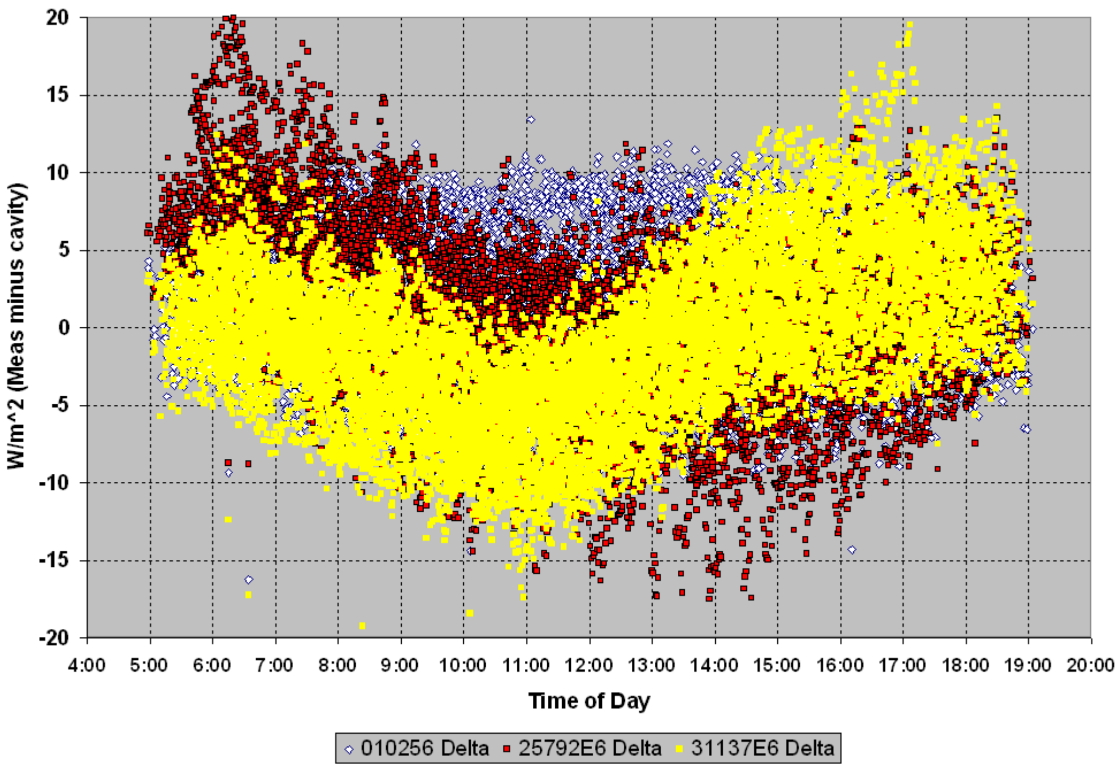

Figure 3-7. Differences in W/m^2 between reference AHF cavity radiometer and Kipp CH1 010256, Eppley NIP 31173E6, and Eppley NIP 25792E6 during broadband calibrations as function of time of day.

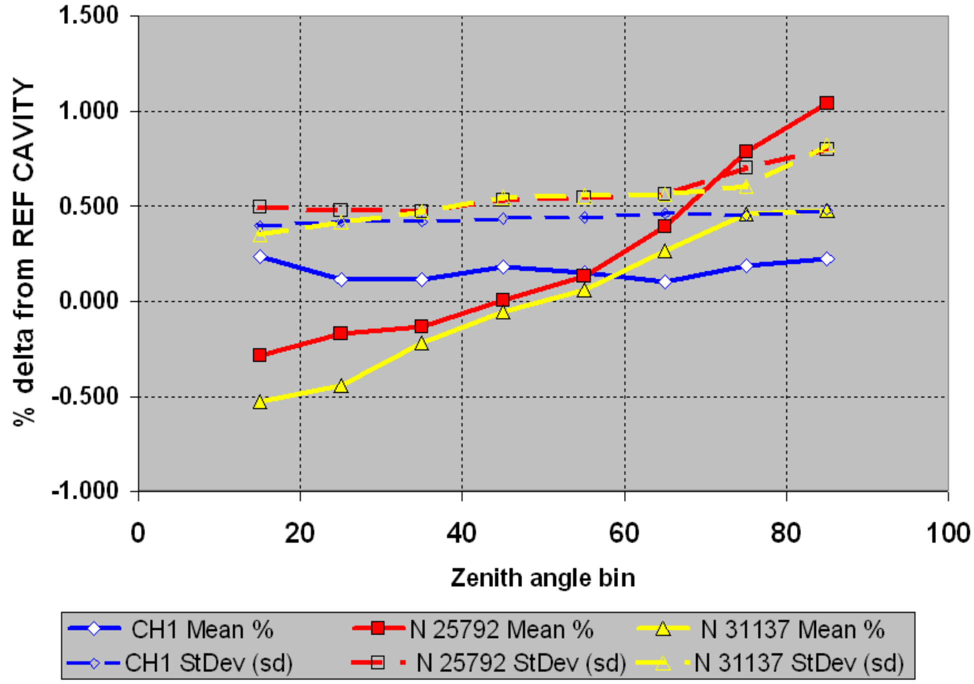

Figure 3-8. Percent differences between the three test instruments and reference cavity pyrheliometer as function of zenith angle bins during BORCAL. Means and standard deviations (1 sigma, also in percent) for each 10° zenith angle bin shown at center of bin.

3.3.2 Test Direct Normal Data Comparison with CH1 Pyrheliometer

We conducted a separate study of the relationship between the Eppley, Kipp and Zonen, and three other direct beam irradiances derived from two other instruments over the period from June 2007 to May 2008. This study used the 1 minute monitored data. Eppley NIP 31137, Kipp and Zonen CH1 010256, direct beam from an Irradiance, Inc. rotating shadowband radiometer (RSR), and a Delta-T, Inc. SPN1 radiometer were studied. The RSR data is provided in two forms, with and without corrections for spectral and cosine effects. The correction scheme is provided by the manufacturer. The SPN1 direct beam data is computed from shaded (Diffuse) and unshaded (global) sensors mounted in the SPN1 instrument, using the manufacturer's calibration factor. The following table 3.8 and Figure 3.9 show percent differences from the CH1 data in monthly mean daily totals (MMDT) for the other DNI instruments

Table 3-8. Direct Normal Comparison Eppley NIP, RSR and SPN1 with CH1 (mean percent difference in MMDT) by month; month 1 = JULY 2007; month 11 = MAY 2008

	JUN 2007	JUL 2007	AUG 2007	SEP 2007	OCT 2007	NOV 2007	DEC 2007	JAN 2008	FEB 2008	MAR 2008	APR 2008	MAY 2008
DIRECT CH1 MMDT Whm^{-2}	7063	6109	5540	5322	5936	5021	4072	4922	4799	5140	6648	5189
Eppley NIP % Δ	**-0.33**	**1.15**	**-0.28**	**-0.18**	**-0.03**	**0.42**	**0.05**	**-0.21**	**0.27**	**0.39**	**-0.33**	**----**
RSR DIR U % Δ	**----**	**3.37**	**2.74**	**1.46**	**1.47**	**0.45**	**0.76**	**2.99**	**-2.07**	**-1.46**	**-0.64**	**1.80**
RSR DIR C % Δ	**----**	**-0.59**	**-3.74**	**-4.58**	**-4.19**	**-5.13**	**-3.86**	**-3.90**	**-7.28**	**-8.81**	**-4.60**	**-4.00**
SPN1 DIR %Δ	**----**	**----**	**----**	**----**	**----**	**----**	**----**	**----**	**-7.59**	**+3.89**	**+15.42**	**+6.00**

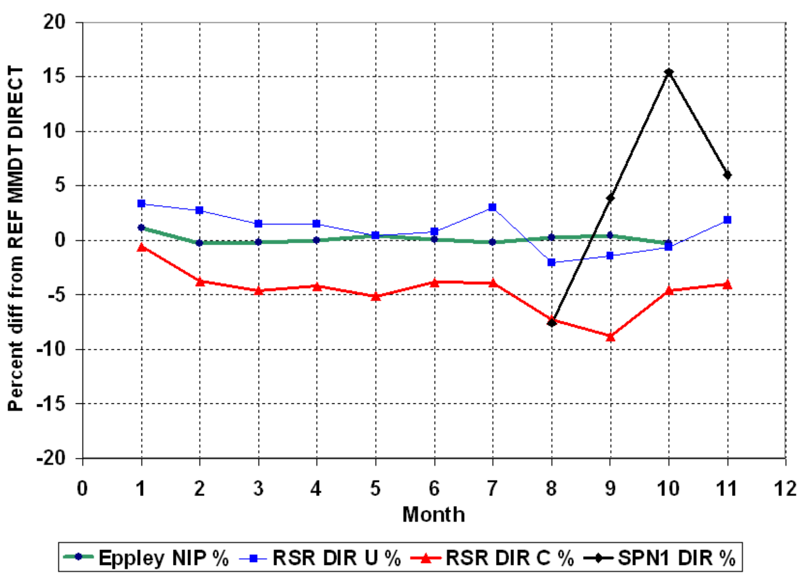

Figure 3-9. Percent difference in Monthly Mean Daily Totals for NIP, SPN1, RSR Corrected and Uncorrected from the Kipp and Zonen CH1 010256.

Table 3-9. Average percent differences between NIP 1 and CH 1 one-minute data by 10 degree zenith angle bin over 11 months (169538 pts) Month 1 = JULY 2007; Month 11 = MAY 2008

Zenith angle bin	Count (N)	Mean %	StDev (sd)	Maximum %	Minimum %	Range
15	4447	-0.20	1.71	9.93	-3.91	13.84
25	14162	0.01	2.21	10.00	-80.10	90.10
35	17701	0.11	2.13	10.00	-26.89	36.89
45	21586	0.14	1.91	9.99	-13.86	23.85
55	28766	0.23	1.96	10.00	-62.44	72.44
65	36135	0.33	2.06	10.00	-60.12	70.12
75	27069	0.37	1.83	10.00	-14.41	24.41
85	19672	0.06	1.83	9.98	-41.68	51.67

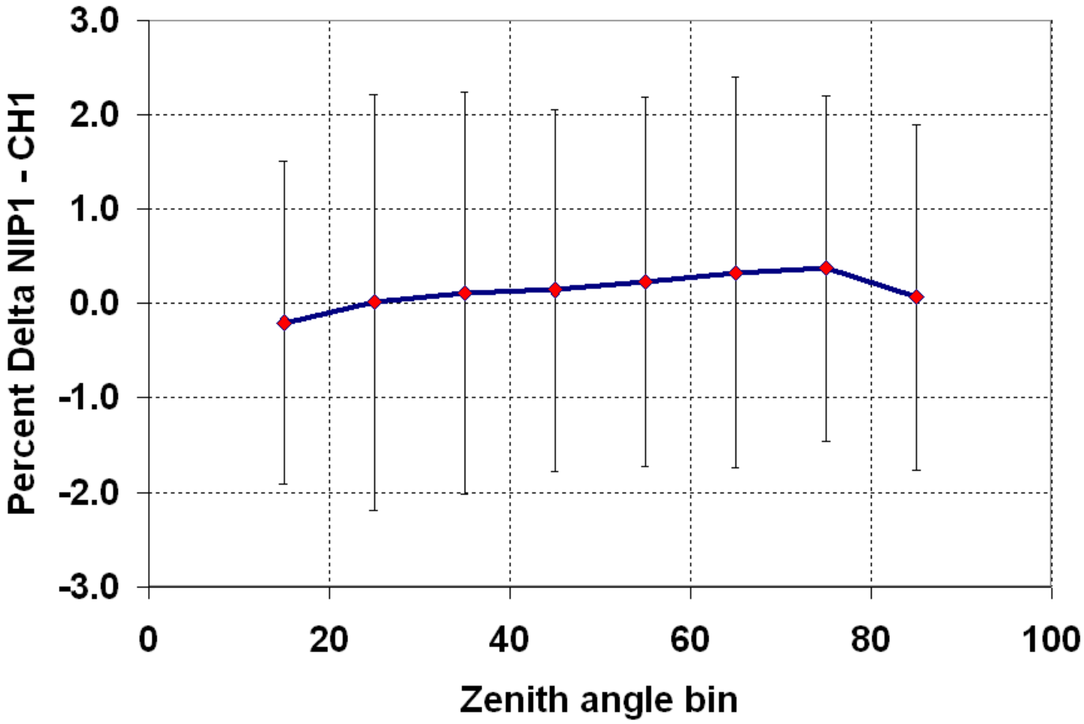

Figure 3-10. Average (dots) and standard deviation (1 sigma error bars) of percent difference between NIP 31137 and CH1 by zenith angle over 11 months (169538 pts).

Figure 3-11 shows a histogram of the percent difference between the NIP 31137 and the CH1 pyrheliometers for the 1-minute sub-hourly data over the 11 month period from July 2007 to May 2008. The mean difference is 0.2% with a standard deviation of ±1.98%. This implies that over the year, the NIP and CH1 produce nearly identical average irradiances, but with a variation through the year of about ± 2% (1 sigma) between the two. Figures 3.6 and 3.7 suggest the variation is mostly due to responsivity variations in the NIP instruments.

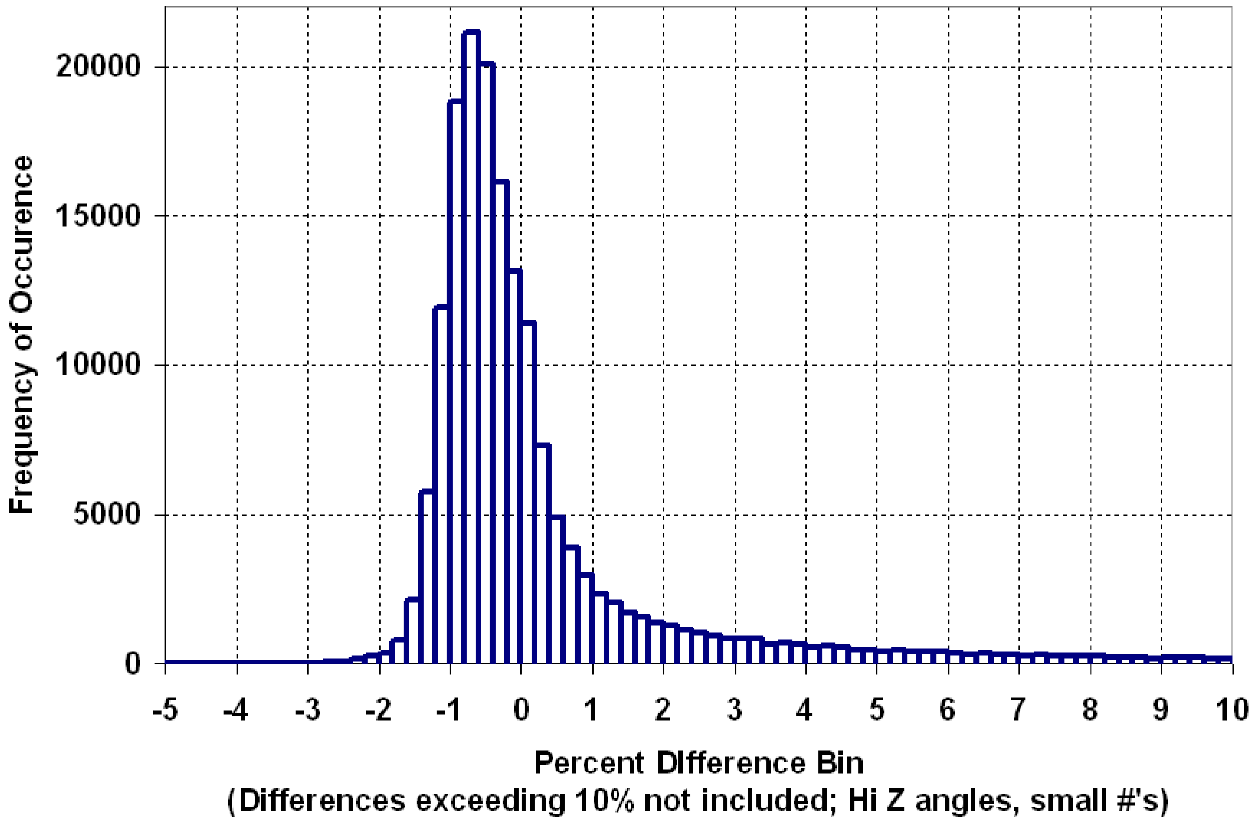

Figure 3-11. Histogram of percent differences between NIP 31137E6 and CH1 over all Zenith angles. Mean value of percent difference is 0.20%, standard deviation of 1.98%

4 Summary

This study shows that at the NREL SRRL location, for pyranometer data based on a single calibration factor (sometimes in combination with corrections for cosine response and infrared offsets) there is agreement to better than 5% for all of pyranometers for zenith angles in the range of 30° to 60° on a minute by minute basis. However, the various different cosine response curves for the radiometers, in conjunction with a single responsivity assignment (at 45° zenith angle ±0.2°) leads to lack of agreement, exceeding 10% or 20% at 70° zenith angle, and more than 20% at 80° zenith angles. Correction and ventilation techniques applied to the data or instruments may not always improve the situation, but rather may add additional sources of uncertainty to the data. The ±5% range of agreement observed for zenith angles less than 60° is typical of the quoted uncertainty in sub-hourly pyranometer data over the past 30 years. Averaging (hourly, daily totals and averages, monthly mean and annual mean daily totals) may help cancel out some of the random variability between instruments. However, as Figure 3.4 demonstrates, there is still the possibility of differences exceeding 5% among this family of instruments. There are differences (up to ±2%) in the responsivity of pyrheliometers from the two different manufacturers' instruments evaluated here. An investigation is ongoing as to the sources of these differences. The design of the instruments and susceptibility to environmental influences are being studied. The ±2% differences observed among thermopile pyrheliometers, including with respect to an absolute cavity pyrheliometer (basic uncertainty ±0.5%) is in accordance with the long standing quote of ±2% uncertainty in direct normal irradiance instruments.

5 References

[1] WMO (1996). *International Pyrheliometer Comparison VIII*. World Meteorological Organization, Geneva, Switzerland.

[2], Maxwell, E.; Wilcox, S.; Rymes, M. (1993). Users Manual for SERI_QC Software: Assessing the Quality of Solar Radiation Data. NREL/TP-463-5608. Golden CO: National Renewable Energy Laboratory.

[3] Myers, D. R.; Stoffel, T. L.; Reda, I.; Wilcox, S. M.; Andreas, A. M. (2002). "Recent Progress in Reducing the Uncertainty in and Improving Pyranometer Calibrations." *ASME Journal of Solar Energy Engineering* (124:1); pp. 44-50.

[4] Reda, I.; Stoffel, T. L.; Myers, D. R. (1996). Calibration of a Solar Absolute Cavity Radiometer with Traceability to the World Radiometric Reference. NREL/TP-463-20619. Golden CO: National Renewable Energy Laboratory.

6 Appendices

Appendix A—Instrument List

Table A-1. The instruments evaluated and calibration uncertainties.

Model	Manufacturer	Serial #	Installation Period	Rs @45 υV/W/m^2	CALIBRATION Uncertainty % [30° ≤ Z ≤ 60°]
CM22 (AC Ventilated)	Kipp & Zonen	010034	06-01-07 to 06-13-07	10.896	+1.85/-1.37%
		010046	06-13-07 to 05-23-08	9.3009	+1.92/-1.17%
		010034	05-23-08 to 05-31-08	10.904	+1.81/-1.50%
CM6B	Kipp & Zonen	015189	06-01-07 to 06-08-07	10.871	+2.53/-1.09%
			06-08-07 to 05-31-08	10.912	+1.98/-1.59%
CM3	Kipp & Zonen	010284	06-01-07 to 05-31-08	9.234	±5% (?)
PSP	Eppley Laboratory	25782F3	06-01-07 to 06-13-07	8.8793	+3.30/-4.49%
			06-13-07 to 05-23-08	8.8568	+2.98/-5.38%
			05-23-08 to 05-31-08	8.7834	+3.16/-5.67%
PSP Corrected[1]	Eppley Laboratory	25782F3	06-01-07 to 06-13-07	9.0368	+2.87/-3.92%
Zenith correction and			06-13-07 to 05-23-08	9.0005	+2.68/-4.71%
*Vc = V - Wnet * RSnet*			05-23-08 to 05-31-08	8.9422	+2.78/-4.65%
PSP (AC Ventilated)	Eppley Laboratory	28402F3	06-01-07 to 06-13-07	6.9504	+2.24/-2.85%
			06-13-07 to 05-23-08	6.9276	+2.37/-2.88%
			05-23-08 to 05-31-08	6.8796	+2.09/-4.43%
PSP (AC Ventilated) Corrected	Eppley Laboratory	28402F3	06-01-07 to 06-13-07	7.0901	+1.87/-2.29%
Zenith correction and			06-13-07 to 05-23-08	7.0557	+2.05/-2.03%
*Vc = V - Wnet * RSnet*			05-23-08 to 05-31-08	7.0131	+1.72/-3.56%
TSP700 (AC Ventilated)	YES, Inc.	0212-02	06-01-07 to 06-13-07	2876.5	+1.40/-1.04%
			06-13-07 to 05-23-08	2908.5	+1.22/-1.37%
			05-23-08 to 05-31-08	2919.2	+1.53/-1.66%
TSP1	YES, Inc.	940703	06-01-07 to 06-13-07	2004.1	+1.91/-1.76%
			06-13-07 to 05-23-08	2000.1	+1.68/-2.44%
			05-23-08 to 05-31-08	2026.7	+1.93/-2.58%
SPN1	Delta-T	A168	08-23-07 to 05-23-08	1000.0	±4% (?)
(GLO/DIR/DIF)			05-23-08 to 05-31-08	976.01	+4.30/-2.37%

Model	Manufacturer	Serial #	Installation Period	Rs @45 υV/W/m^2	CALIBRATION Uncertainty % [30° ≤ Z ≤ 60°]
SP_LITE	Kipp & Zonen	970003	06-01-07 to 06-13-07	85.298	+1.21/-1.96%
			06-13-07 to 05-23-08	85.304	+1.80/-1.75%
			05-23-08 to 05-31-08	84.948	+1.63/-2.05%
LI-200	Li-Cor	PY28257	06-01-07 to 06-13-07	13.144	+3.06/-4.50%
			06-13-07 to 05-31-08	13.292	+3.11/-5.51%
RSR2 Uncorrected	Irradiance, Inc.	PY37627	Jun 07-May08	10.35	+/- 5% (not stated)
RSR2 Corrected	(GLO/DIR/DIF)	PY37627	Jun 07-May08	10.35	+/-5% (not stated)

[1]Non-standard correction using ventilated pyrgeometer

Appendix B—Global and Diffuse Radiometer Evaluation Detailed Results

The following plots and tables indicate the relative bias and scatter of the data among instruments. The uncertainty of the reference instrument data is stated in this report as nominally ±2.5%, meaning that the bias plots could move up or down by that magnitude and not be significant. Scatter in individual instrument plots within ±2.5% could be due as much to the reference instruments as the test instrument itself. However, movements in biases relative to other test instruments hold greater significant since each instrument was compared against the same reference data set.

The section below contains a statistical summary for each instrument, one instrument per page. For each instrument:

- Sub-hourly (1-minute) percent differences versus zenith angle, average and standard deviation percent differences in 10° wide zenith angle bins and percent differences in daily total irradiance between the reference (computed) global irradiance and test instrument data are shown as a function of zenith angle, zenith angle bin, and date, respectively. Error bars represent the standard deviations of the means. No data where the difference exceeded 100% in absolute value is included in the statistics mainly to avoid issues with small irradiance values. These time scale measurements are useful for many applications requiring analysis of the resource throughout the entire day.
- Table presenting the numerical data in the first graph.
- A presentation of the entire 1 minute data set of differences between measured and reference irradiances as a function of zenith angles (within plot limits of ±25% for graph clarity).
- Time series presentation of the daily total data as percent difference between test and reference instruments. This measurement is useful for applications requiring measurements on a daily time scale without regard to hourly or sub-hourly variations.

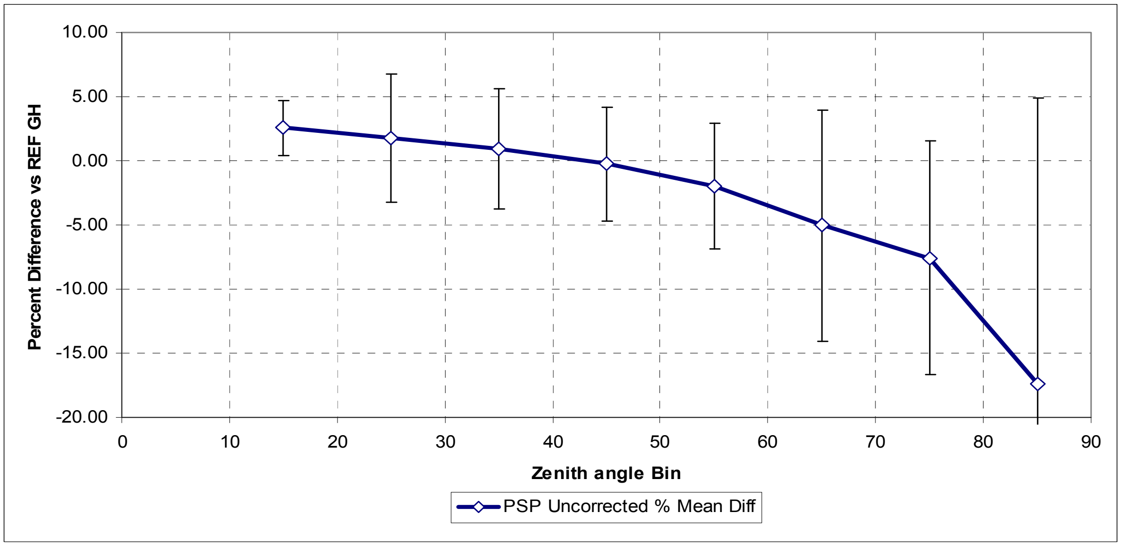

Figure B-1. Uncorrected Eppley PSP: PSP 25782F3

Table B-1. Statistical summary 1-minute data by zenith angle bin PSP 25782F3

PSP_U	Count (N)	PSP Uncorrected % Mean Diff	StDev (sd)	Maximum	Minimum	Range
15	5497	2.572	2.109	41.9	-28.4	70.3
25	19111	1.729	4.995	32.4	-72.6	105.0
35	24260	0.921	4.657	70.1	-77.5	147.5
45	30018	-0.232	4.410	29.9	-77.1	107.0
55	39487	-1.997	4.895	66.3	-75.4	141.8
65	50754	-5.047	8.973	69.3	-79.9	149.2
75	40634	-7.567	9.139	63.5	-80.4	143.9
85	39182	-17.357	22.251	99.8	-99.9	199.7

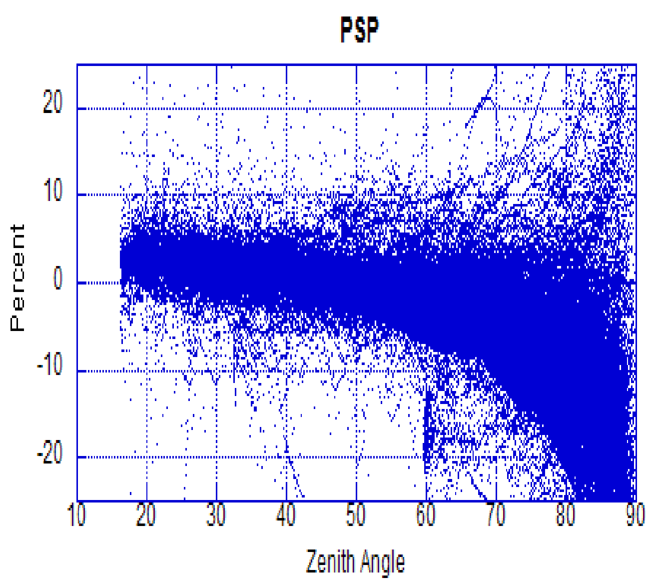

Figure B-1(a). One-minute data set percent differences; PSP Uncorrected

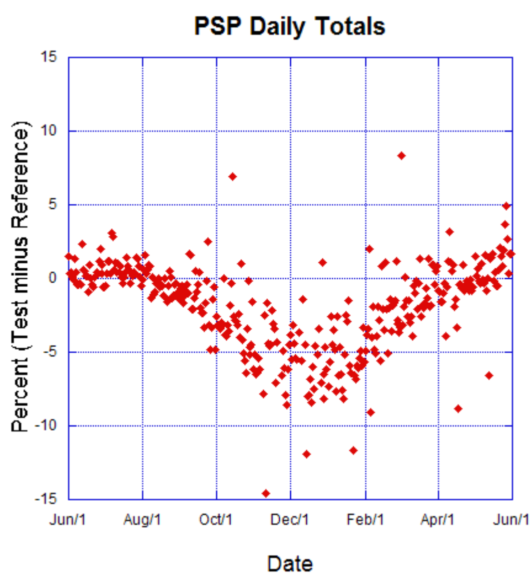

Figure B-1(b). Daily total percent difference; PSP Uncorrected

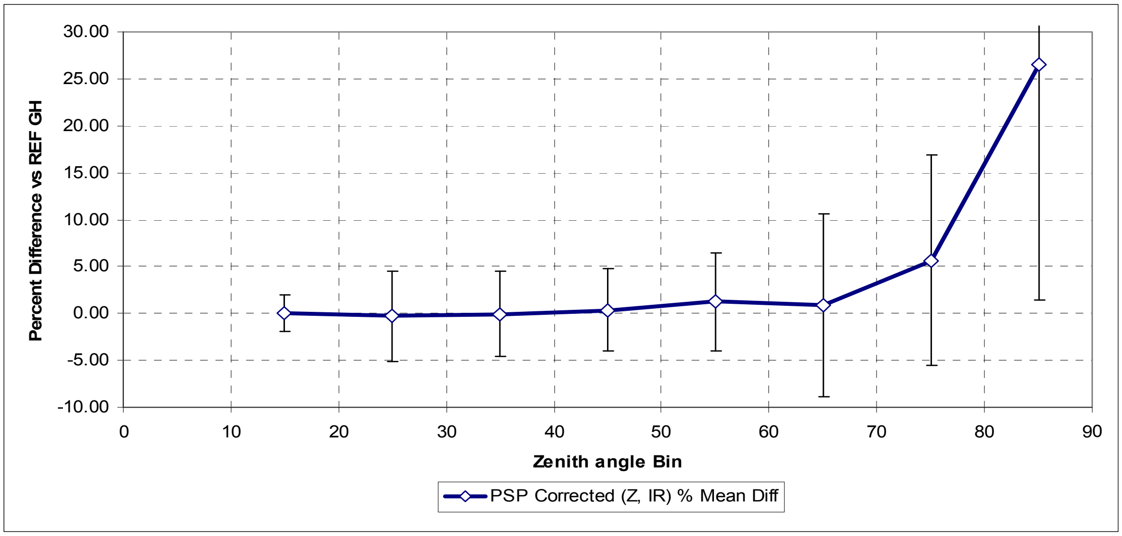

Figure B-2. Corrected Eppley PSP (Corrected for Z angle response and IR offset) PSP_C 25782F3

Table B-2. Statistical summary 1-minute data by zenith angle bin PSP 25782F3 (Corrected)

PSP_C	Count (N)	PSP Corrected (Z, IR) % Mean Diff	StDev (sd)	Maximum	Minimum	Range
15	5497	0.069	1.958	39.0	-29.7	68.7
25	19111	-0.284	4.822	30.4	-73.1	103.5
35	24260	-0.060	4.527	72.2	-77.7	149.9
45	30018	0.372	4.443	32.6	-77.2	109.8
55	39487	1.221	5.168	68.7	-73.1	141.8
65	50753	0.877	9.774	79.2	-76.5	155.7
75	40634	5.679	11.251	86.0	-76.5	162.5
85	36205	26.580	25.118	100.0	-96.1	196.0

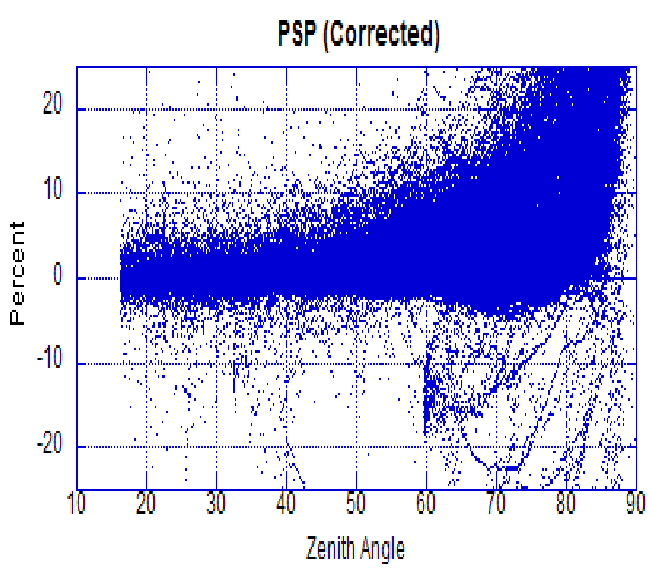

Figure B-2(a). One-minute data set percent differences. PSP, Corrected.

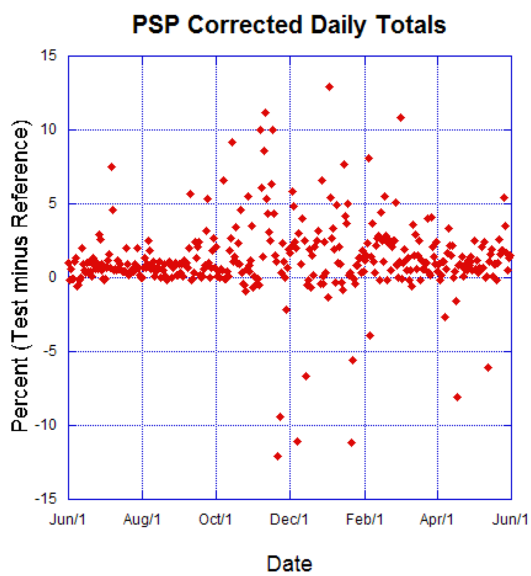

Figure B-2(b). Daily total percent difference; PSP, Corrected.

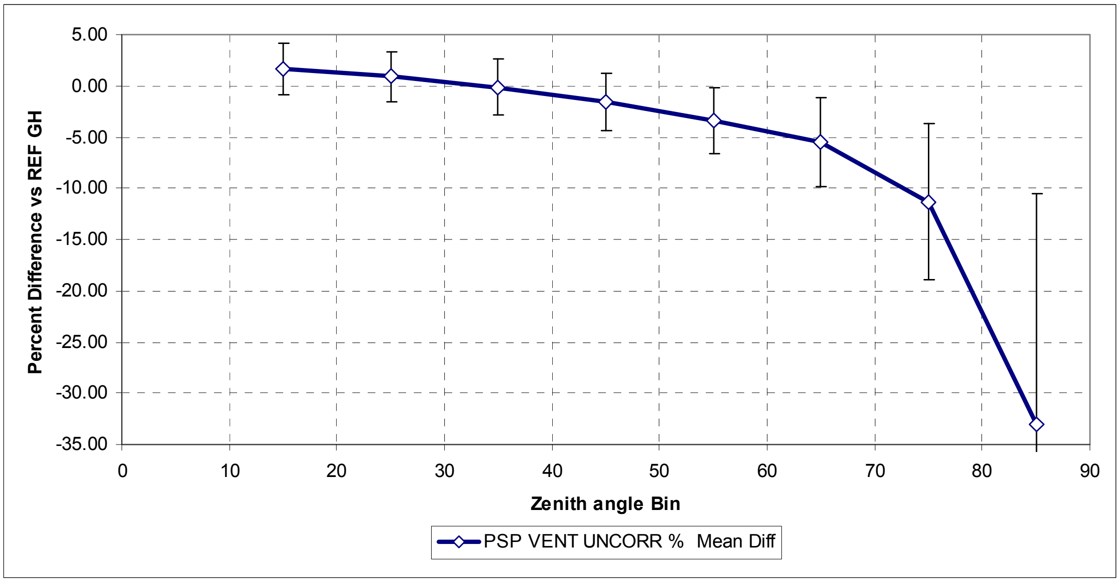

Figure B-3. PSP Ventilated Uncorrected 28402F3

Table B-3. Statistical summary 1-minute data by zenith angle bin PSP 28402F3 (Ventilated, Uncorrected)

PSP_V_U	Count (N)	PSP VENT UNCOR% Mean Diff	StDev (sd)	Maximum	Minimum	Range
15	5497	1.603	2.503	39.1	-28.1	67.2
25	19111	0.912	2.429	29.6	-24.1	53.7
35	24260	-0.148	2.711	64.3	-28.0	92.3
45	30018	-1.564	2.768	27.0	-38.8	65.8
55	39487	-3.390	3.229	62.5	-53.5	116.0
65	50754	-5.490	4.340	65.8	-73.2	139.0
75	40614	-11.305	7.629	19.0	-99.6	118.5
85	33743	-33.084	22.538	99.2	-99.9	199.2

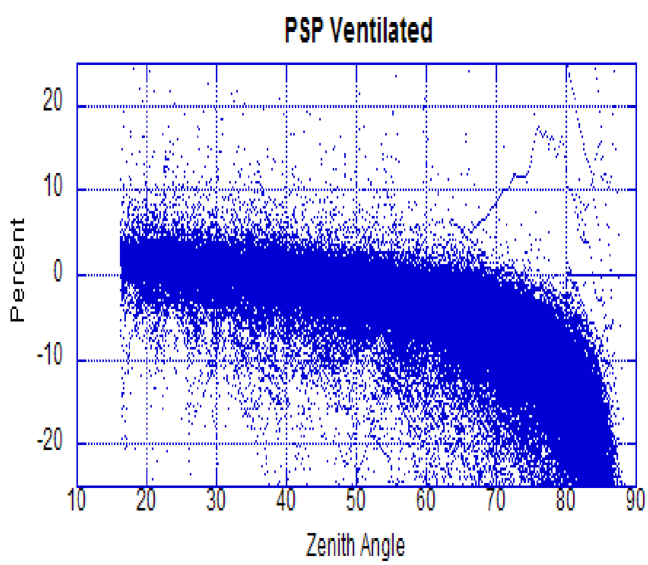

Figure B-3(a). One-minute data set percent differences; PSP, Ventilated, Uncorrected.

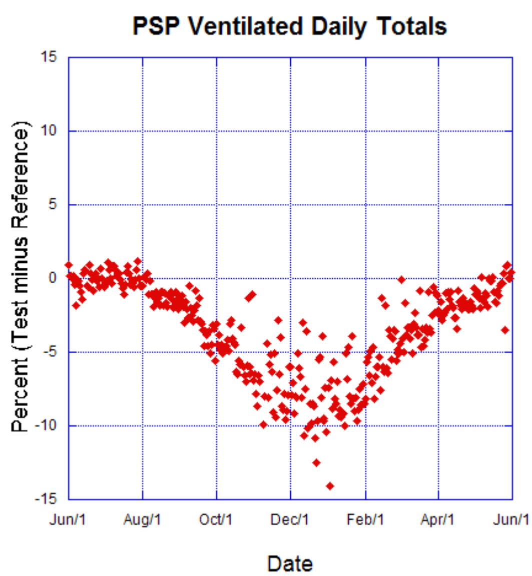

Figure B-3(b). Daily total percent difference; PSP, Ventilated, Uncorrected.

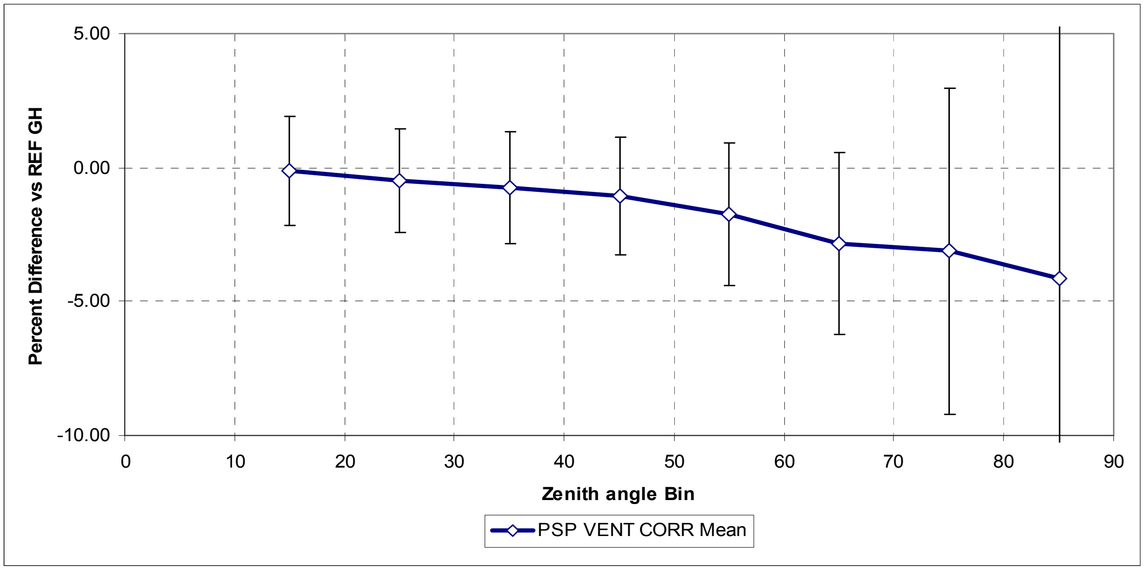

Figure B-4. PSP Ventilated and Corrected PSP_V_C 28402F3

Table B-4. Statistical summary 1-minute data by zenith angle bin PSP 28402F3 (Ventilated, Corrected)

PSP_V_C	Count (N)	Sum	PSP VENT CORR Mean	StDev (sd)	Maximum	Minimum	Range
15	5497	-621.3	-0.113	2.039	36.9	-29.0	65.9
25	19111	-9083.12	-0.475	1.943	28.5	-25.3	53.9
35	24260	-18038.3	-0.744	2.077	67.3	-27.0	94.3
45	30018	-32552.2	-1.084	2.191	30.2	-34.7	65.0
55	39487	-69002.7	-1.747	2.679	64.9	-44.3	109.2
65	50753	-144207	-2.841	3.416	67.4	-55.0	122.4
75	40632	-126642	-3.117	6.090	33.6	-99.5	133.1
85	38887	-160636	-4.131	17.940	100.0	-99.9	199.9

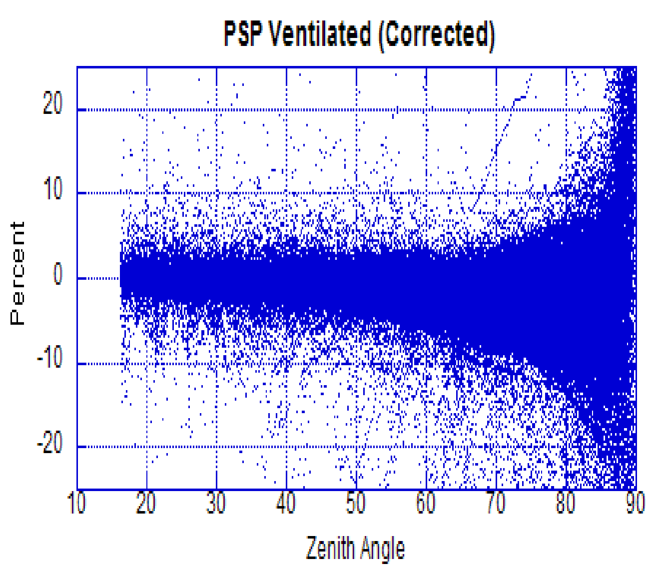

Figure B-4(a). One-minute data set percent differences; PSP, Ventilated, Corrected.

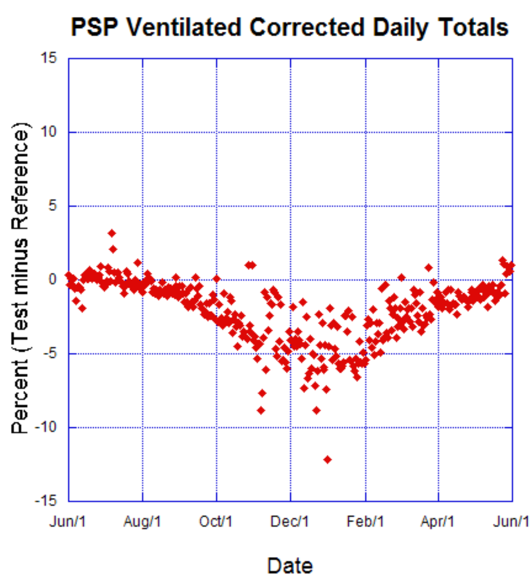

Figure B-4(b). Daily total percent difference; PSP, Ventilated, Corrected.

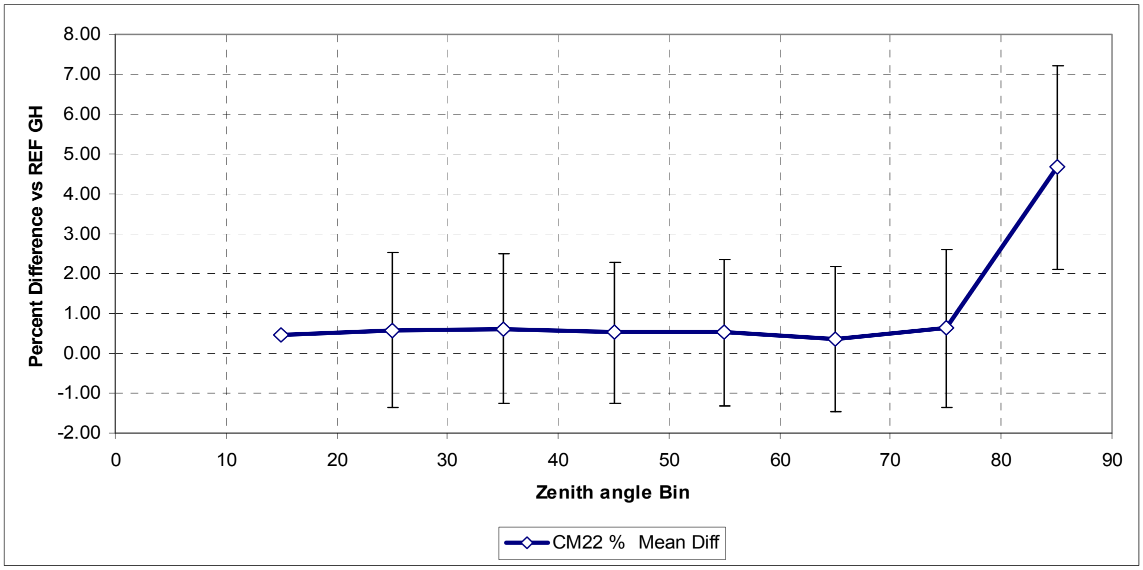

Figure B-5. Kipp & Zonen CM22 (Ventilated) 010034

Table B-5. Statistical summary 1-minute data by zenith angle bin CM22 010034 (Ventilated)

CM22	Count (N)	Sum	CM22 % Mean Diff	StDev (sd)	Maximum	Minimum	Range
15	5497	2455.4	0.447	1.947	30.1	-28.2	58.3
25	19111	11212.96	0.587	1.887	26.6	-22.4	48.9
35	24260	15068.77	0.621	1.769	51.6	-25.8	77.4
45	30018	15568.67	0.519	1.842	43.7	-33.1	76.9
55	39487	20603.2	0.522	1.823	51.3	-30.5	81.8
65	50754	18704.81	0.369	1.972	65.3	-49.7	115.0
75	40634	25611.97	0.630	2.548	56.9	-28.8	85.7
85	40339	188401.9	4.670	11.835	99.9	-99.3	199.2

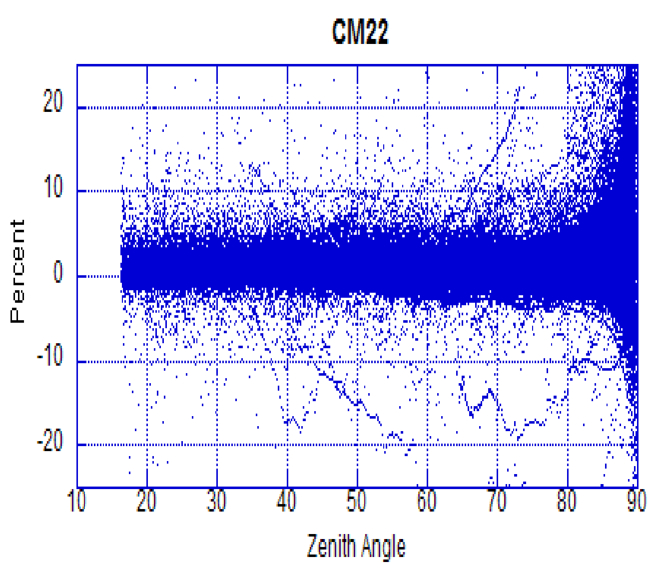

Figure B-5(a). One-minute data set percent difference; CM22, Ventilated.

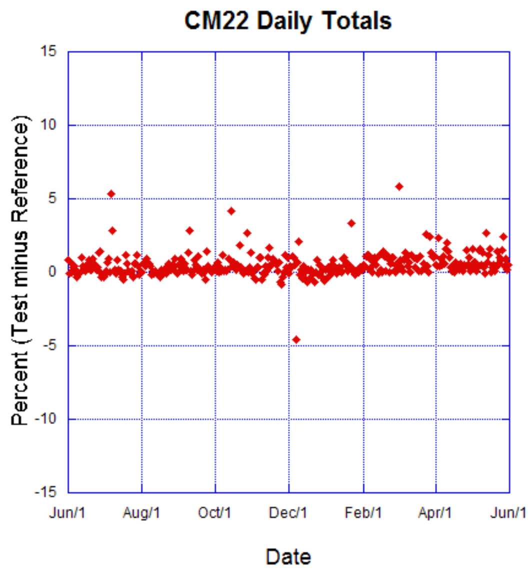

Figure B-5(b). Daily total percent difference; CM22, Ventilated.

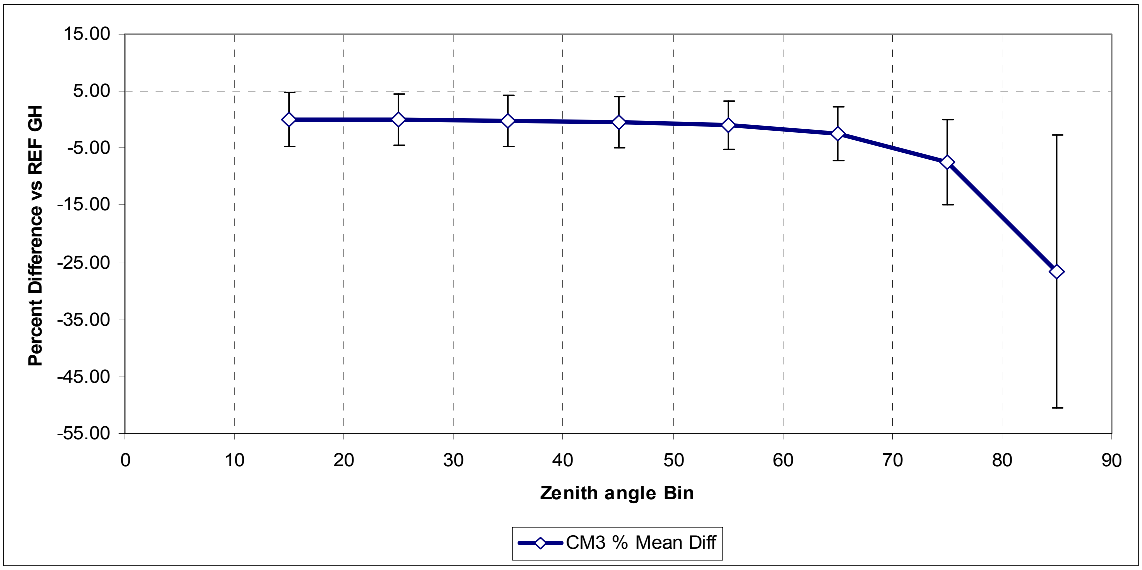

Figure B-6. Kipp & Zonen CM3 010284

Table B-6. Statistical summary 1-minute data by zenith angle bin CM3 010284

CM3	Count (N)	CM3 % Mean Diff	StDev (sd)	Maximum	Minimum	Range
15	5495	0.101	4.799	77.5	-58.5	136.0
25	19111	0.085	4.554	93.0	-56.5	149.5
35	24260	-0.140	4.523	71.1	-53.9	125.0
45	30018	-0.365	4.521	70.4	-71.6	142.0
55	39487	-0.967	4.315	54.8	-56.1	110.8
65	50754	-2.374	4.703	94.0	-57.6	151.5
75	40633	-7.415	7.491	59.0	-70.4	129.4
85	34843	-26.587	23.896	99.5	-99.9	199.4

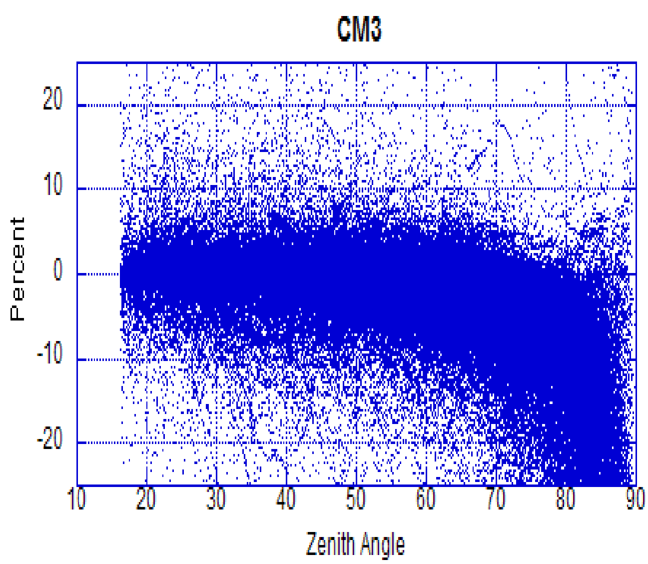

Figure B-6(a). One-minute data set percent differences; CM3.

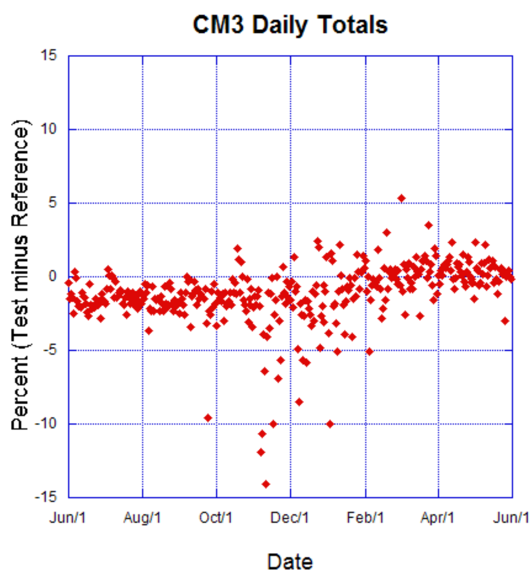

Figure B-6(b). Daily total percent difference; CM3.

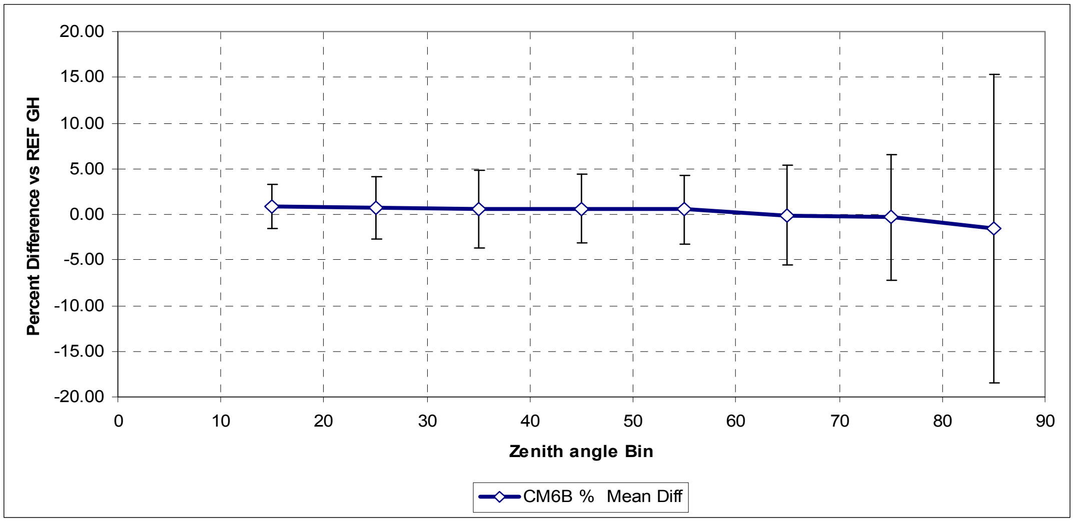

Figure B-7. Kipp & Zonen CM6B 015189

Table B-7. Statistical summary 1-minute data by zenith angle bin CM6B 015189

CM6B	Count (N)	CM6B % Mean Diff	StDev (sd)	Maximum	Minimum	Range
15	5497	0.852	2.346	40.6	-28.1	68.7
25	19111	0.685	3.414	34.2	-53.4	87.6
35	24260	0.574	4.209	78.2	-70.0	148.3
45	30018	0.627	3.746	36.3	-69.8	106.1
55	39487	0.515	3.736	72.1	-62.0	134.1
65	50754	-0.087	5.511	74.7	-70.6	145.4
75	40634	-0.338	6.831	63.2	-71.9	135.1
85	40155	-1.551	16.920	99.7	-99.6	199.3

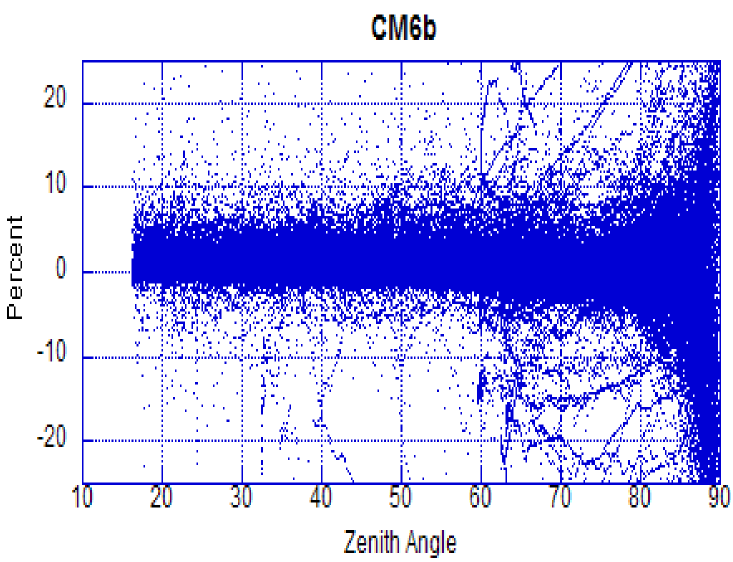

Figure B-7(a). One-minute data set percent differences; CM6B.

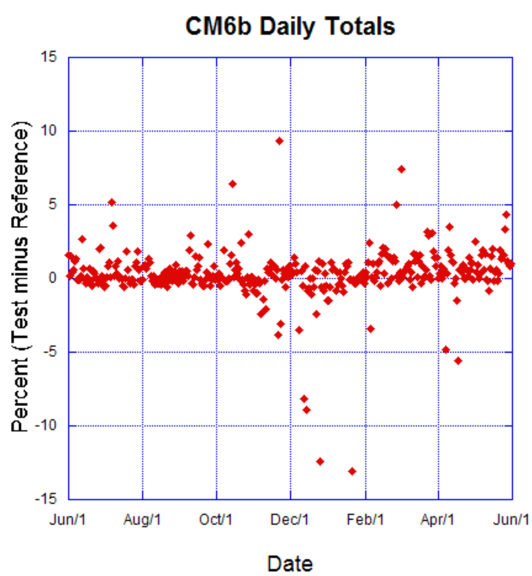

Figure B-7(b). Daily total percent difference; CM6B.

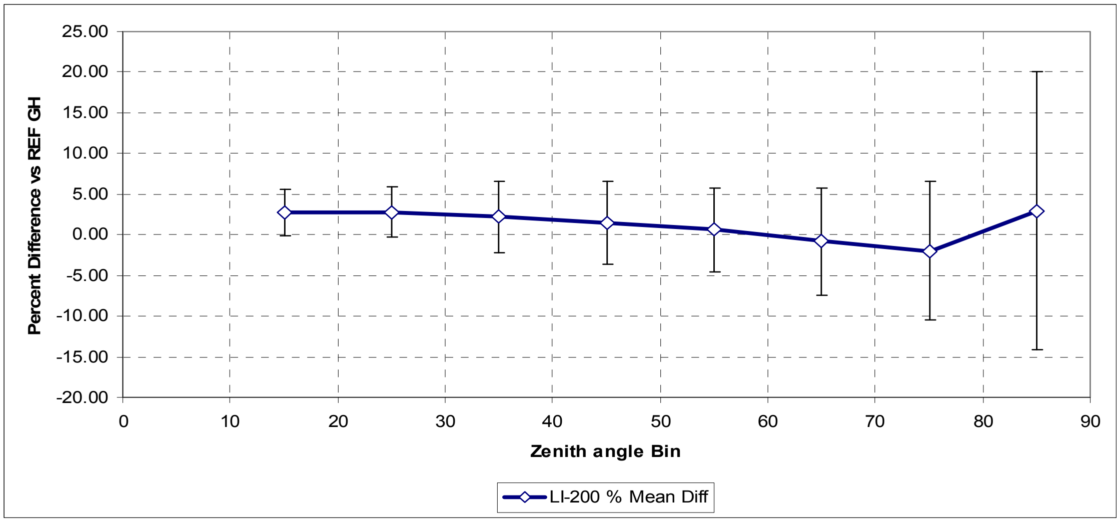

Figure B-8. Li-Cor LI 200 PY28257

Table B-8. Statistical summary 1-minute data by zenith angle bin Li-200 PY28257

LI-200	Count (N)	LI-200 % Mean Diff	StDev (sd)	Maximum	Minimum	Range
15	5497	2.783	2.850	37.8	-33.4	71.2
25	19111	2.799	3.086	28.4	-30.5	58.9
35	24260	2.221	4.342	53.1	-60.8	113.9
45	30018	1.474	5.017	29.7	-64.0	93.7
55	39487	0.610	5.135	63.8	-68.9	132.7
65	50754	-0.801	6.601	61.6	-74.3	135.9
75	40634	-1.975	8.495	69.9	-74.4	144.2
85	39972	2.906	17.091	99.9	-98.8	198.8

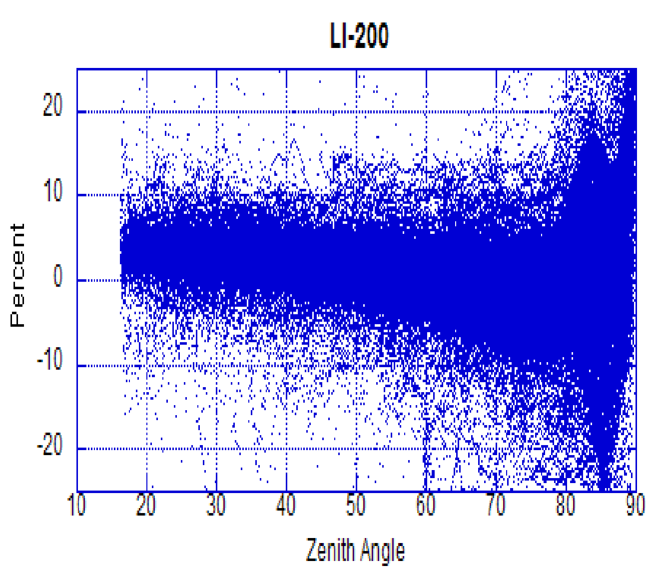

Figure B-8(a). One-minute data set percent diccerens; LI-200 PY.

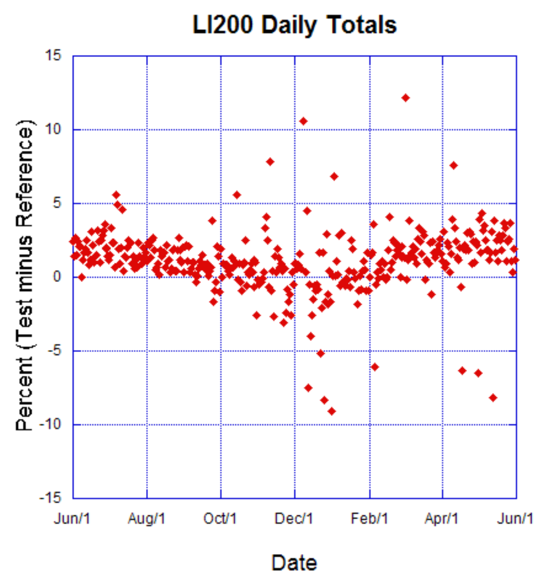

Figure B-8(b). Daily total percent difference Li-200.

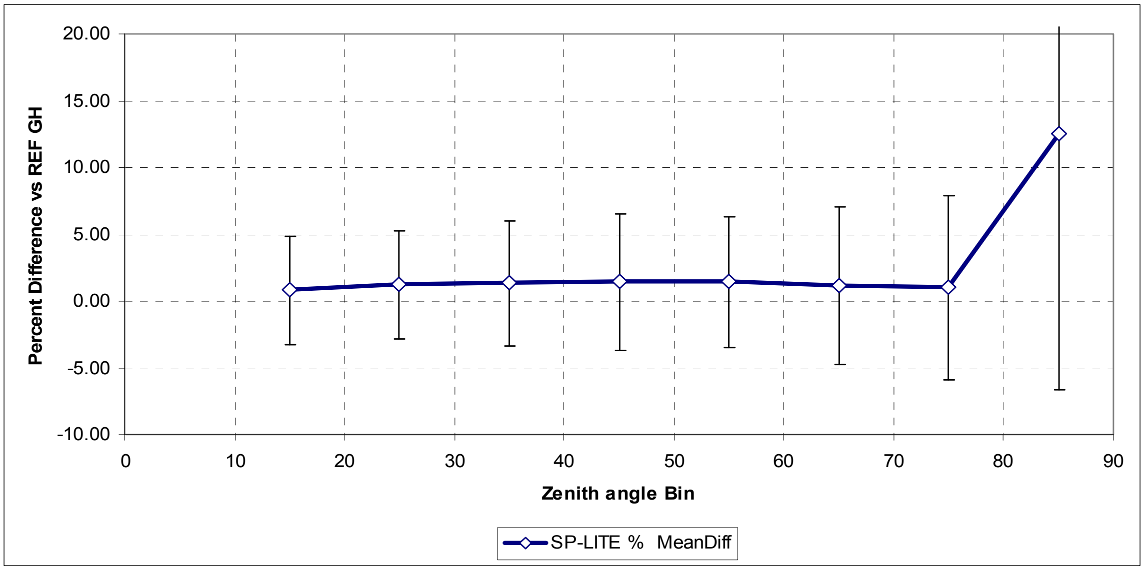

Figure B-9. SP-LITE 970003

Table B-9. Statistical summary 1-minute data by zenith angle bin SP-LITE 970003

SPLITE	Count (N)	SP-LITE % MeanDiff	StDev (sd)	Maximum	Minimum	Range
15	5497	0.829	4.057	32.6	-35.1	67.7
25	19111	1.214	4.019	32.3	-31.7	64.0
35	24260	1.346	4.662	49.9	-65.8	115.6
45	30018	1.429	5.146	34.6	-66.5	101.2
55	39487	1.435	4.873	56.2	-65.0	121.2
65	50754	1.147	5.864	68.5	-78.8	147.3
75	40634	1.018	6.925	75.7	-79.4	155.1
85	39685	12.479	19.067	100.0	-58.3	158.2

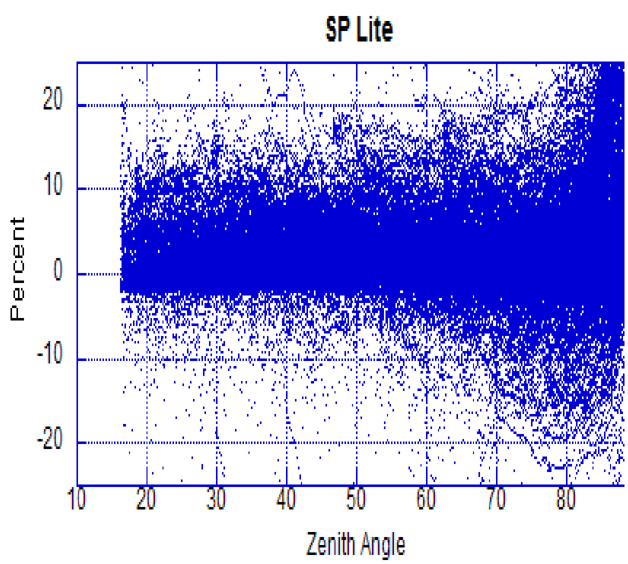

Figure B-9(a). One-minue data set percent differences; SP Lite Global.

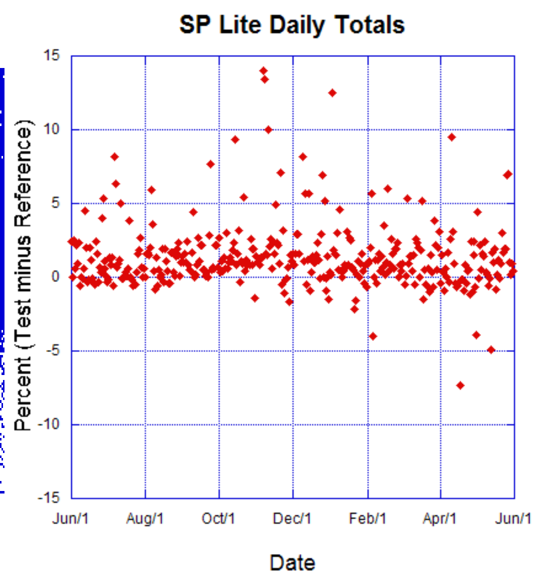

Figure B-9(b). Daily total percent difference; SP Lite Global.

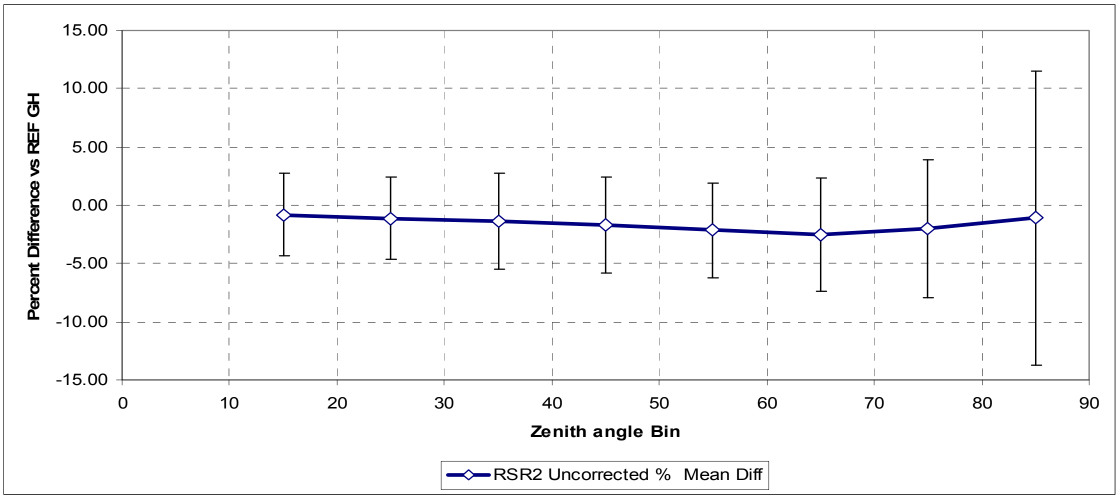

Figure B-10. Irradiance, Inc. RSR2 –Global Uncorrected PY37627 (11 months Jul 2007 -May 2008)

Table B-10. Statistical summary 1-minute data by zenith angle bin RSR2 Global Uncorrected

RSR2_U_G	Count (N)	RSR2 Uncorrected % Mean Diff	StDev (sd)	Maximum	Minimum	Range
15	3007	-0.808	3.543	27.6	-21.4	49.0
25	15555	-1.135	3.526	28.2	-60.0	88.3
35	21172	-1.399	4.129	48.9	-73.5	122.5
45	27137	-1.703	4.125	27.6	-79.9	107.5
55	37364	-2.132	4.078	24.0	-66.7	90.7
65	48789	-2.539	4.831	38.6	-51.4	89.9
75	38434	-1.986	5.906	67.1	-58.5	125.6
85	37203	-1.090	12.613	99.6	-96.4	196.0

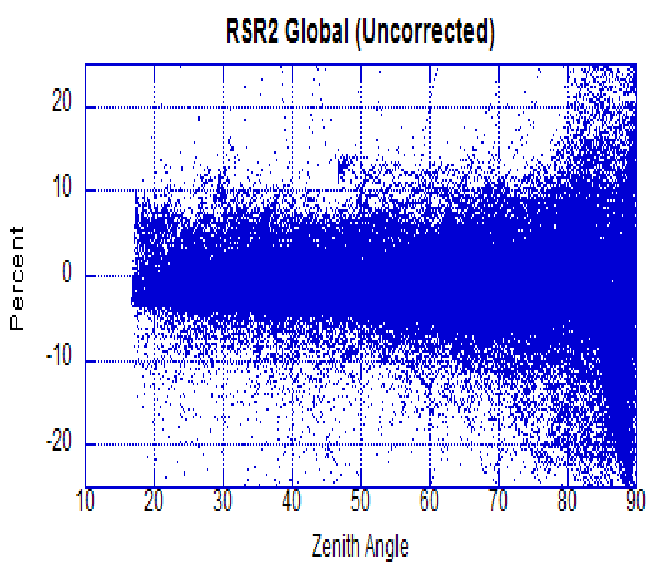

Figure B-10(a). One-minute data set percent differences; RSR2 Global Uncorrected.

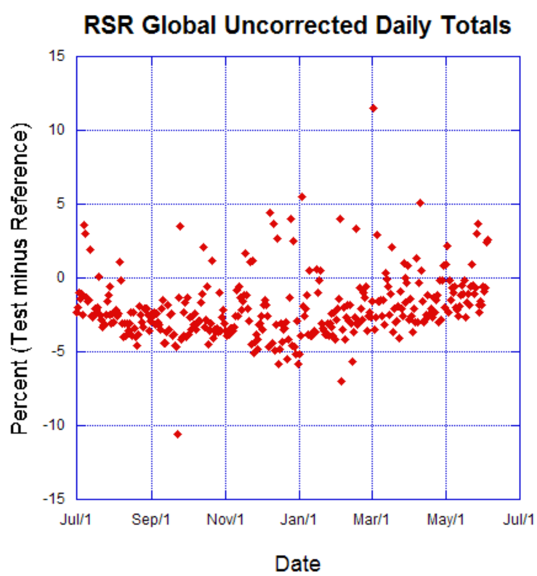

Figure B-10(b). Daily total percent difference; RSR2 Global Uncorrected.

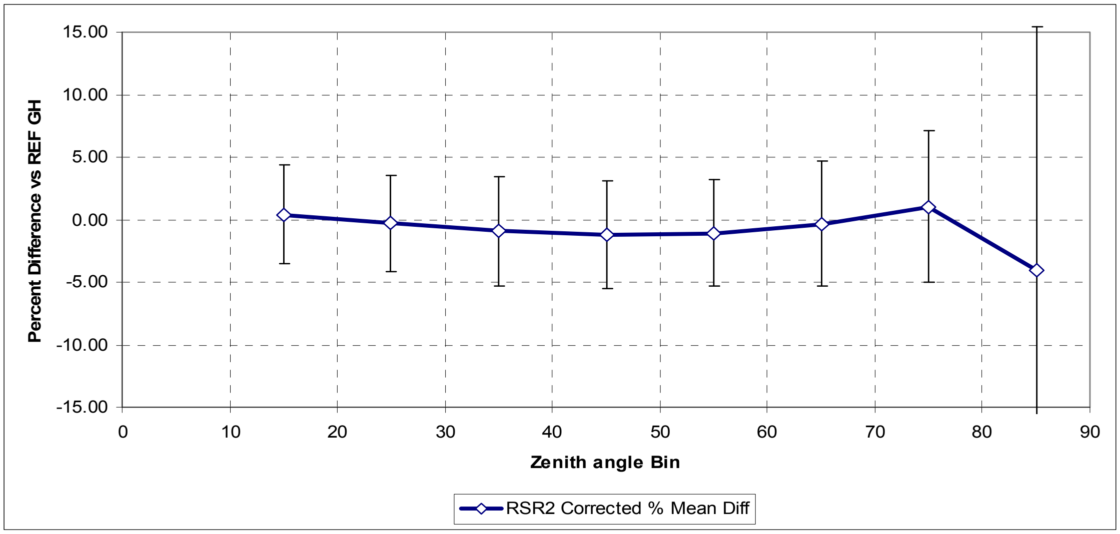

Figure B-11. Irradiance, Inc. RSR2 global Corrected PY37627 (11 months Jul 2007 -May 2008)

Table B-11. Statistical summary 1-minute data by zenith angle bin RSR2 Global Corrected

RSR2_C_G	Count (N)	RSR2 Corrected % Mean Diff	StDev (sd)	Maximum	Minimum	Range
15	3007	0.409	3.946	29.6	-20.8	50.4
25	15555	-0.312	3.863	30.8	-60.0	90.8
35	21172	-0.934	4.404	49.1	-73.6	122.6
45	27137	-1.221	4.350	28.2	-79.9	108.1
55	37364	-1.080	4.260	24.5	-66.0	90.5
65	48789	-0.351	5.008	41.6	-49.6	91.2
75	38434	1.034	6.080	67.4	-57.5	124.9
85	37287	-4.035	19.442	99.4	-98.7	198.1

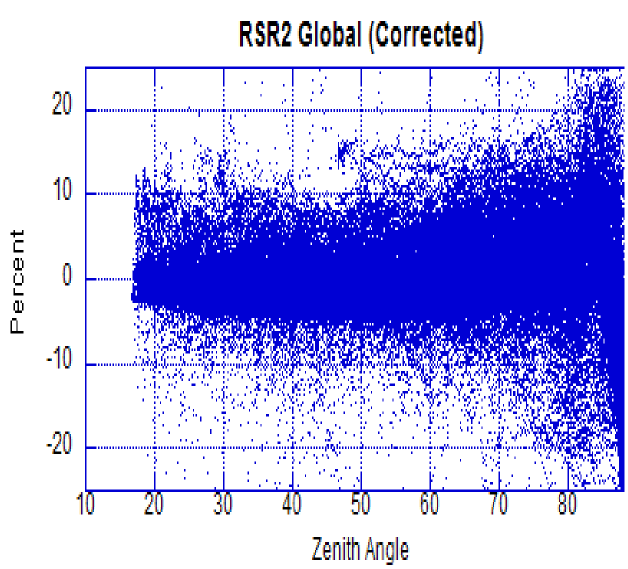

Figure B-11(a). One-minute data set percent differences. RSR2 Global Corrected.

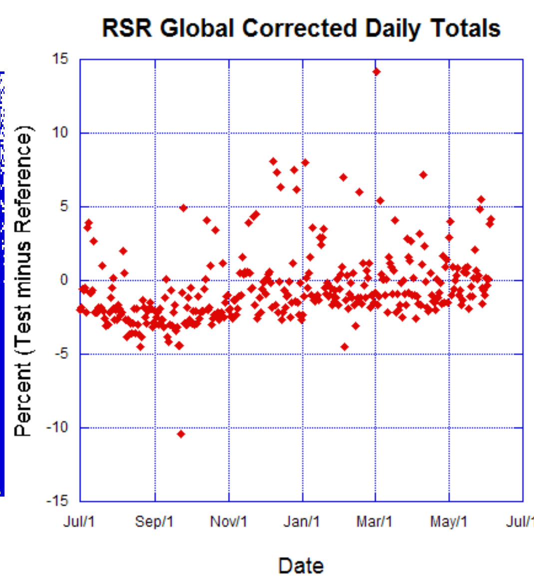

Figure B-11(b). Daily total percent difference RSR2 Global Corrected.

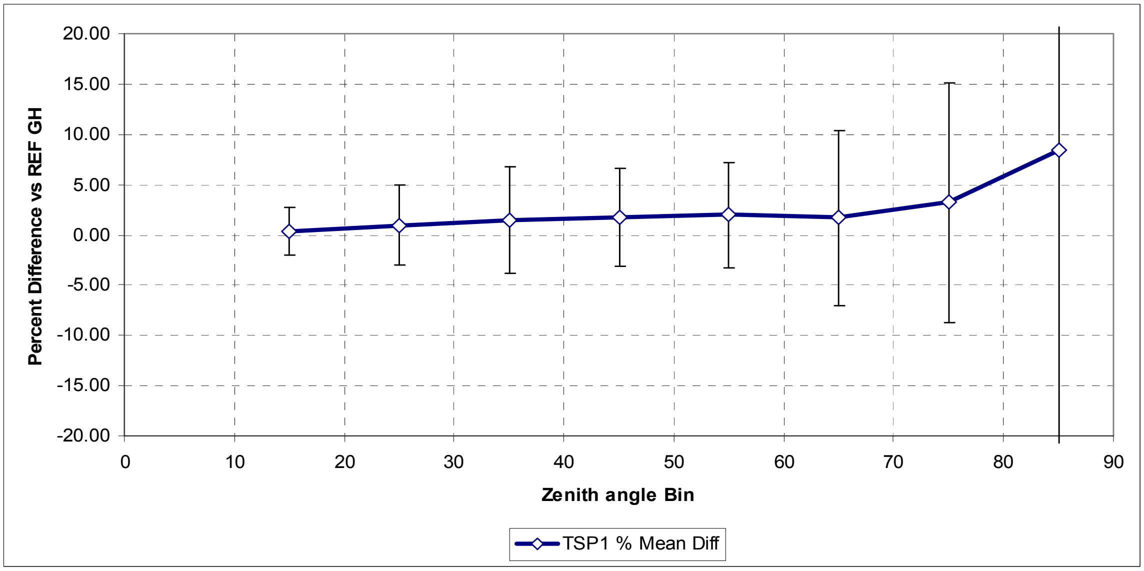

Figure B-12. TSP1 - 940703

Table B-12. Statistical summary 1-minute data by zenith angle bin TSP1 Global

TSP1	Count (N)	TSP1 % Mean Diff	StDev (sd)	Maximum	Minimum	Range
15	5497	0.357	2.387	31.2	-24.4	55.6
25	19111	0.952	3.949	30.7	-67.3	98.0
35	24260	1.489	5.267	53.1	-74.2	127.3
45	30018	1.757	4.898	36.5	-74.0	110.4
55	39487	1.977	5.189	60.3	-64.6	124.9
65	50754	1.693	8.685	73.8	-100.0	173.8
75	40613	3.250	11.927	90.2	-100.0	190.1
85	36888	8.469	29.463	100.0	-100.0	200.0

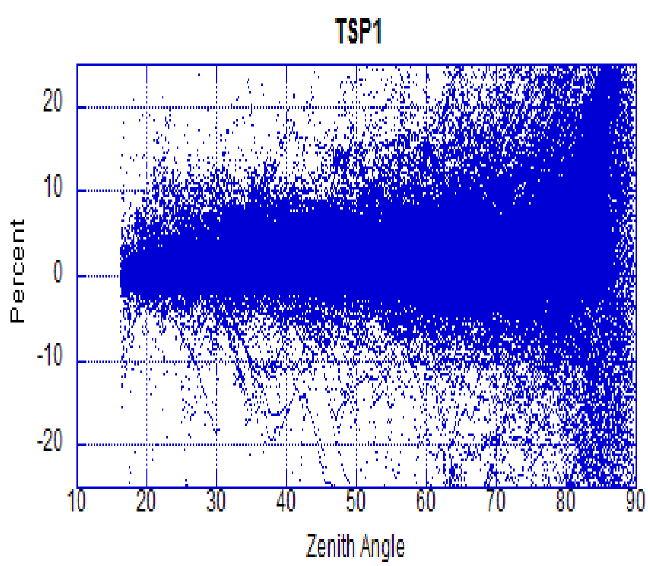

Figure B-12(a). One-minute data set percent differences; TSP1 Global.

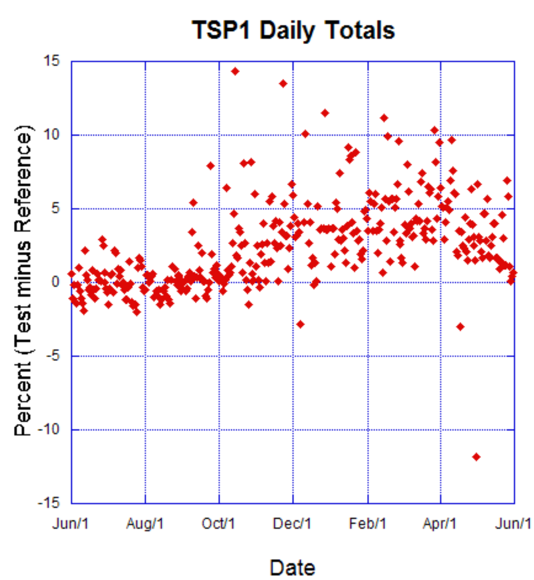

Figure B-12(b). Daily total percent difference TSP1 Global.

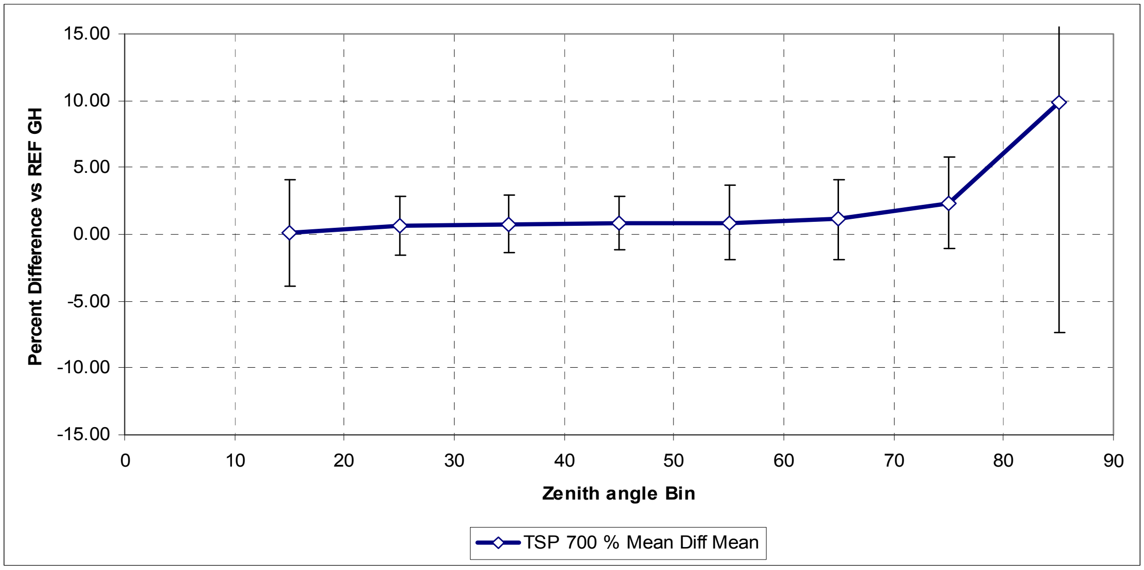

Figure B-13. TSP700 0212-02 (Ventilated)

Table B-13. Statistical summary 1-minute data by zenith angle bin TSP700 Global

TSP700	Count (N)	TSP 700 % Mean Diff	StDev (sd)	Maximum	Minimum	Range
15	5497	0.058	3.990	29.9	-51.9	81.8
25	19111	0.610	2.234	27.8	-32.6	60.3
35	24260	0.750	2.146	49.4	-44.1	93.4
45	30018	0.853	1.990	33.3	-32.8	66.1
55	39487	0.867	2.756	52.9	-73.9	126.8
65	50680	1.104	2.992	68.5	-100.0	168.5
75	40564	2.358	3.432	69.8	-95.1	164.9
85	39651	9.873	17.194	100.0	-99.6	199.6

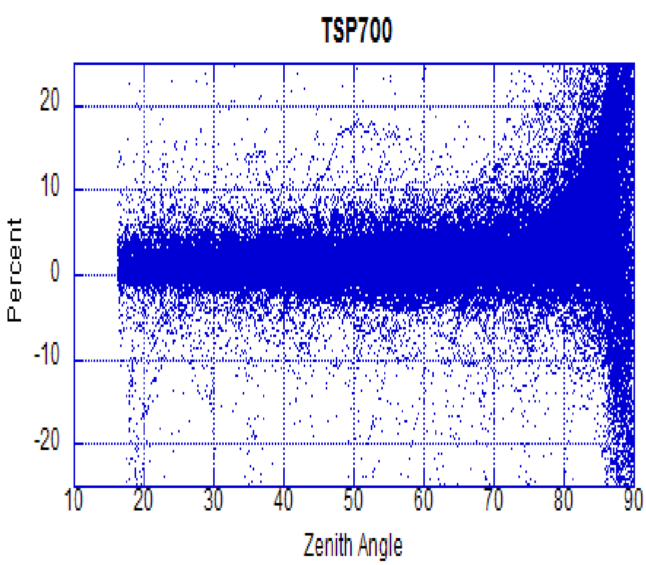

Figure B-13(a). One-minute data set percent difference; TSP700 Global, Ventilated

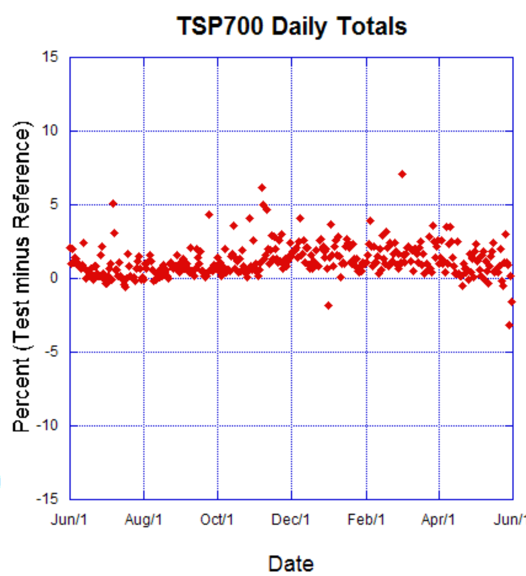

Figure B-13(b). Daily total percent difference; TSP7000 Global, Ventilated.

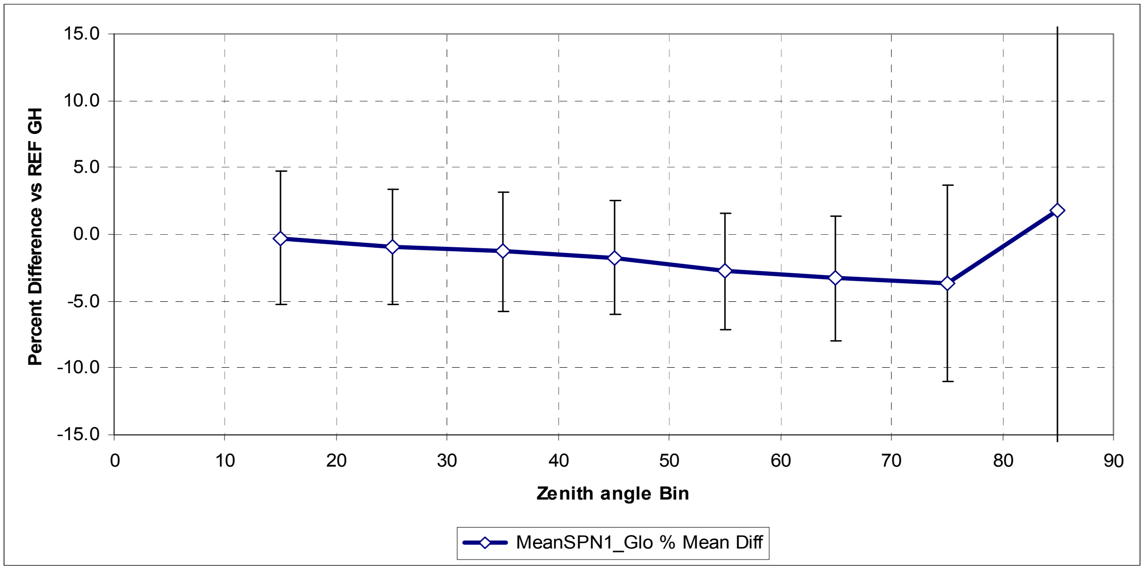

Figure B-14. SPN1 GLOBAL A168 (4 months of data Feb 2008 -May 2008)

Table B-14. Statistical summary 1-minute data by zenith angle bin SPN1 Global

SPN1_G	Count (N)	MeanSPN1_Glo % Mean Diff	StDev (sd)	Maximum	Minimum	Range
15	862	-0.308	4.983	15.4	-15.7	31.1
25	7049	-0.981	4.307	25.1	-18.4	43.5
35	10244	-1.297	4.489	23.7	-91.9	115.6
45	13518	-1.760	4.246	23.9	-100.0	123.9
55	18292	-2.733	4.354	54.4	-100.0	154.4
65	20881	-3.269	4.667	55.7	-39.9	95.6
75	16840	-3.656	7.362	67.4	-35.8	103.3
85	15621	1.747	27.431	99.9	-100.0	199.9

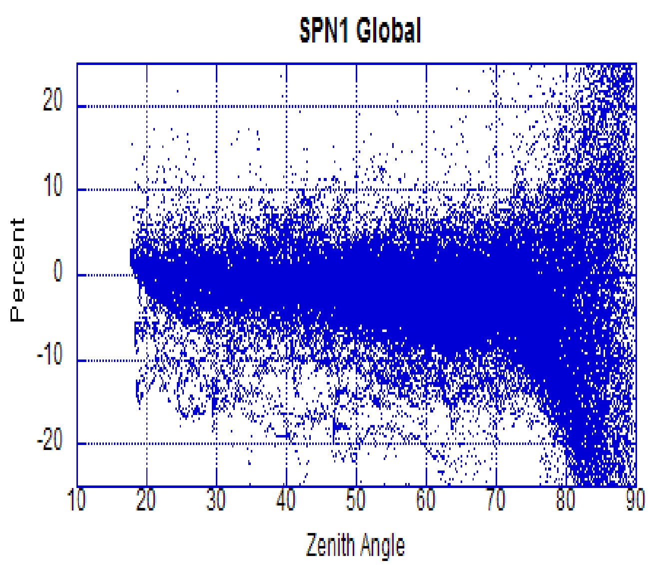

Figure B-14(a). One-minute data set percent differences; SPNI Global.

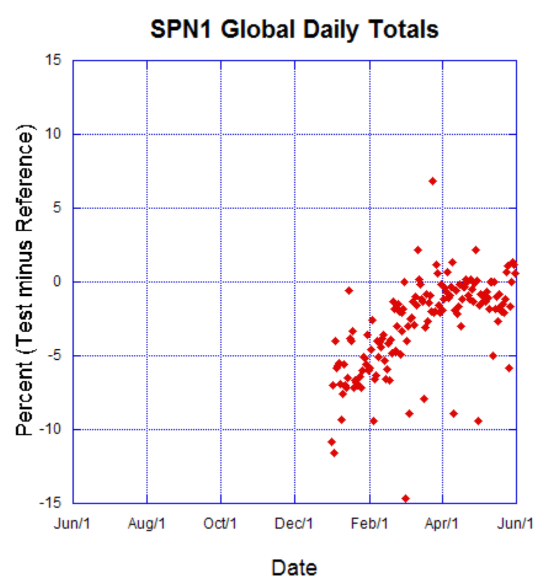

Figure B-14(b). Daily total percent difference; SPN1 Global.

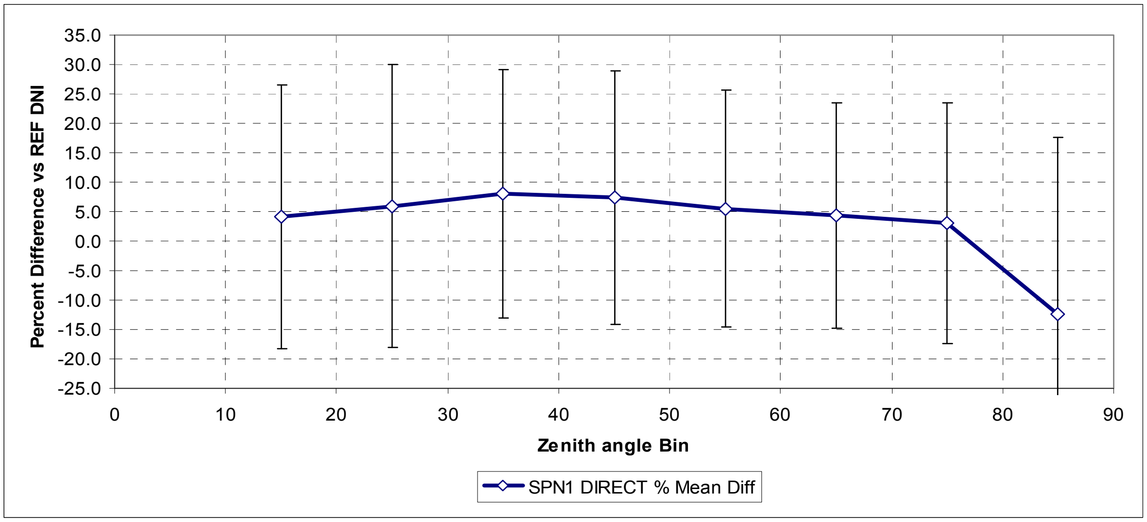

Figure B-15. SPN1 DIRECT A168 (4 months of data Feb 2008 -May 2008)

Table B-15. Statistical summary 1-minute data by zenith angle bin SPN1 Direct

SPN1_DIR	Count (N)	SPN1 DIRECT % Mean Diff	StDev (sd)	Maximum	Minimum	Range
15	672	4.143	22.4	99.25	-99.99	199.24
25	5732	5.905	24.0	98.5	-99.99	198.49
35	7996	8.057	21.1	99.82	-99.99	199.81
45	10530	7.343	21.5	99.99	-99.99	199.98
55	14304	5.489	20.1	99.81	-99.99	199.8
65	16324	4.419	19.2	99.91	-99.99	199.9
75	12410	3.024	20.4	99.71	-99.99	199.7
85	9259	-12.472	30.1	99.1	-99.99	199.09

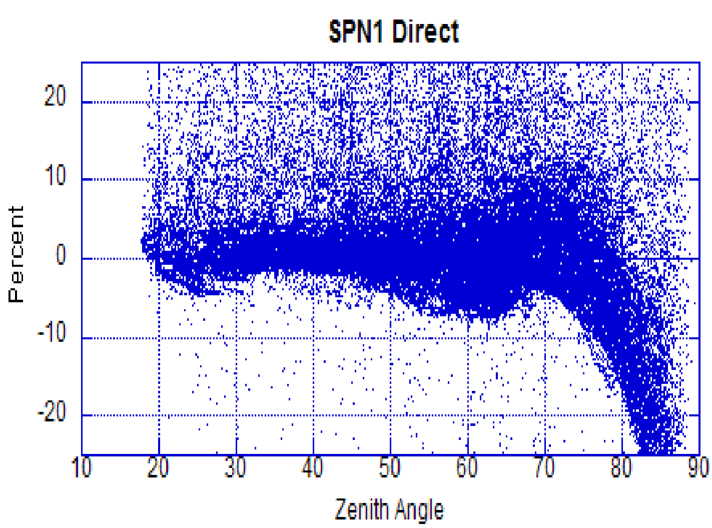

Figure B-15(a). One-minute data set percent differences; SPN1 Direct.

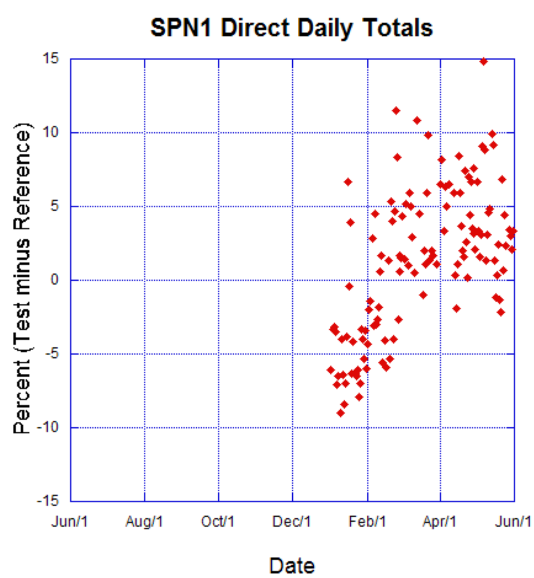

Figure B-15(b). Daily total percent difference; SPN1 Direct.

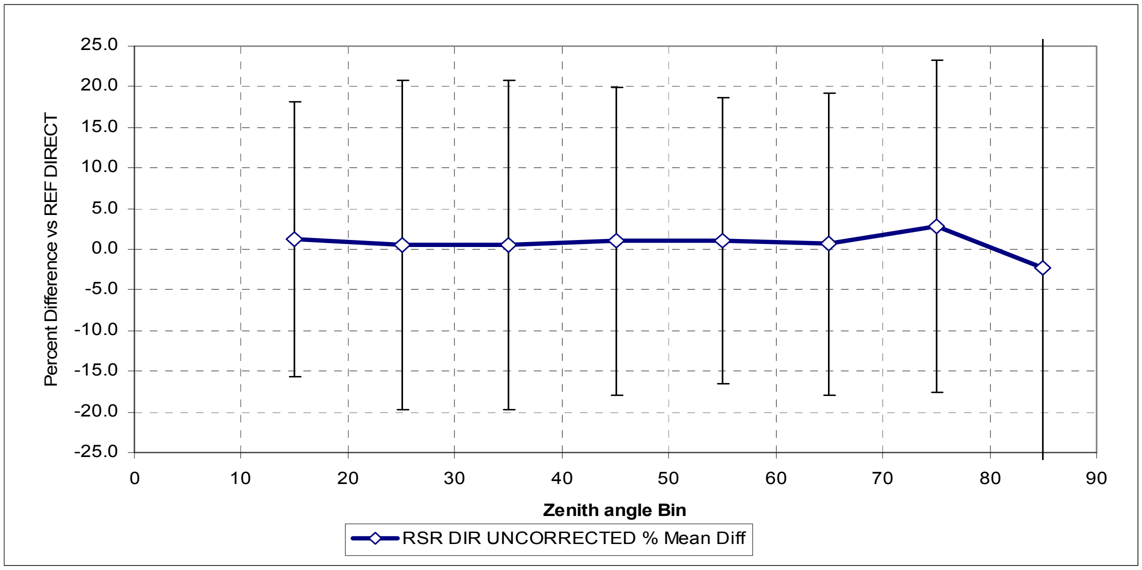

Figure B-16. RSR2 Direct Uncorrected (11 months of data Jul 2007 -May 2008)

Table B-16. Statistical summary 1-minute data by zenith angle bin RSR2 Direct Uncorrected

RSR DIR U	Count (N)	RSR DIR UNCORRECTED % Mean Diff	StDev (sd)	Maximum	Minimum	Range
15	2599	1.251	16.8	99.09	-98.08	197.17
25	17944	0.499	20.2	99.88	-99.99	199.87
35	17944	0.499	20.2	99.88	-99.99	199.87
45	22645	0.976	18.9	99.85	-99.99	199.84
55	31499	1.022	17.6	99.64	-99.99	199.63
65	40494	0.627	18.6	99.81	-99.99	199.8
75	30449	2.875	20.4	99.74	-99.99	199.73
85	22925	-2.235	33.0	99.86	-99.99	199.85

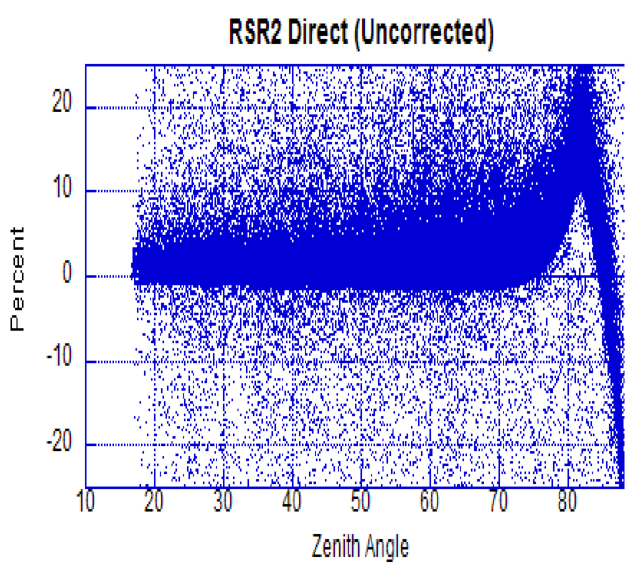

Figure B-16(a). One-minute data set percent differences: RSR2 Direct Uncorrected.

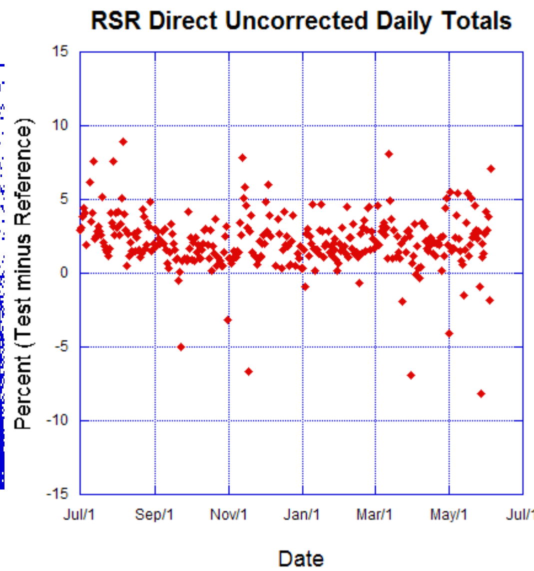

Figure B-16(b). Daily total percent difference RS2 Direct Uncorrected.

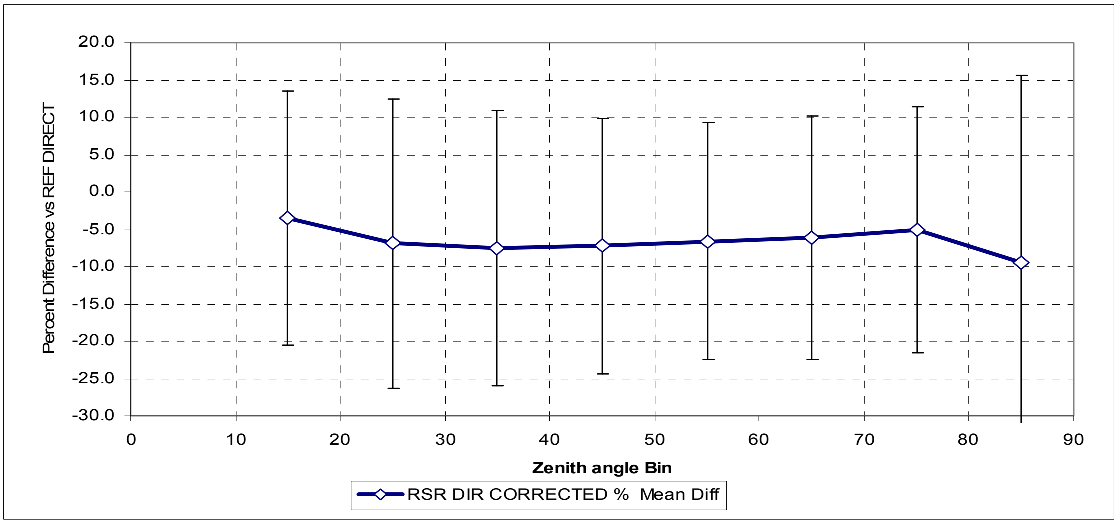

Figure B-17. RSR Direct Corrected (11 months of data Jul 2007 – May 2008)

Table B-17. Statistical summary 1-minute data by zenith angle bin RSR2 Direct Corrected

RSR DIR C	Count (N)	RSR DIR CORRECTED % Mean Diff	StDev (sd)	Maximum	Minimum	Range
15	2504	-3.507	17.0	97.41	-99.51	196.92
25	12387	-6.899	19.4	95.29	-99.99	195.28
35	16643	-7.509	18.4	92.79	-99.99	192.78
45	20957	-7.255	17.1	99.67	-99.97	199.64
55	29369	-6.606	15.9	94.73	-99.99	194.72
65	37428	-6.189	16.3	94.61	-99.97	194.58
75	27961	-5.025	16.5	86.66	-99.98	186.64
85	18818	-9.558	25.1	99.62	-99.99	199.61

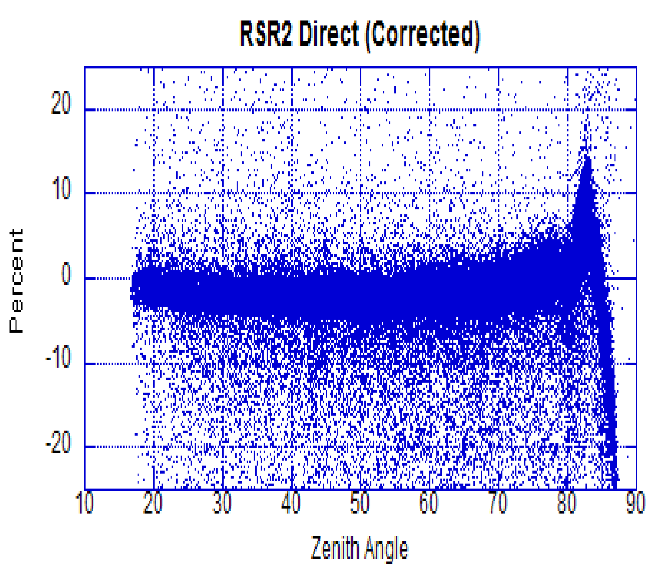

Figure B-17(a). One-minute data set percent differences; RSR2 Direct Corrected.

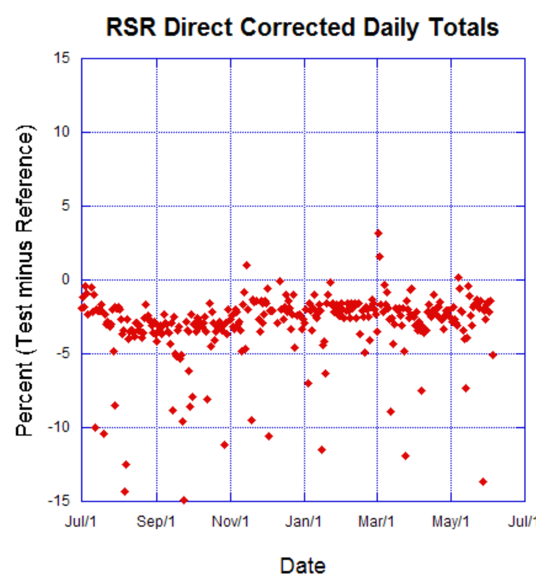

Figure B-17(b). Daily total percent difference; RSR2 Direct Corrected.

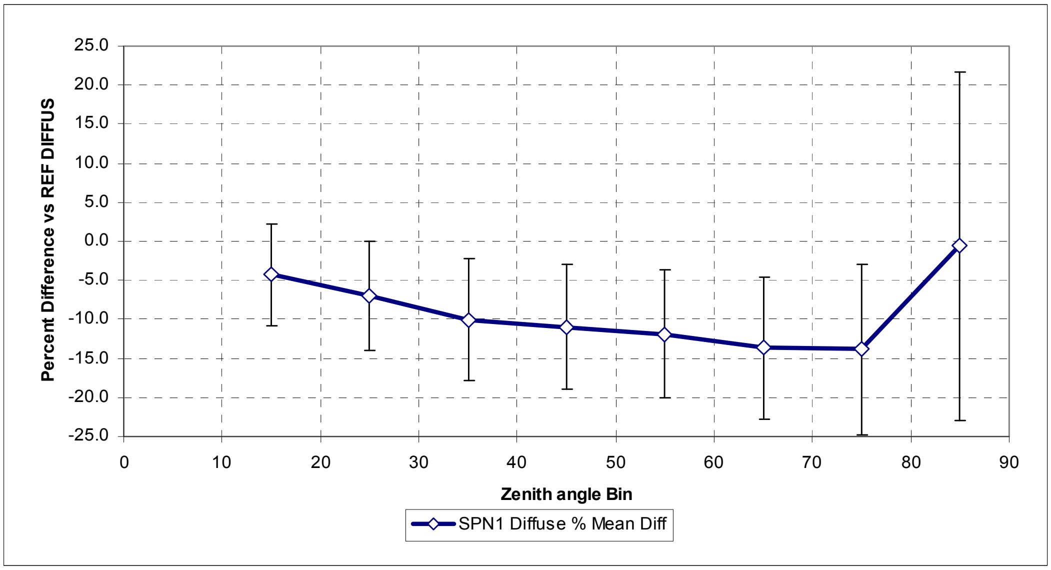

Figure B-18. SPN1 Diffuse A168 (4 months of data Feb 2008 -May 2008)

Table B-18. Statistical summary 1-minute data by zenith angle bin SPN1 Diffuse

SPN1 DIF	Count (N)	SPN1 Diffuse % Mean Diff	StDev (sd)	Maximum	Minimum	Range
15	862	-4.277	6.5	20.43	-30.08	50.51
25	7049	-6.911	7.0	23.23	-37.16	60.39
35	10244	-10.039	7.7	16.03	-88.52	104.55
45	13517	-10.966	8.0	22.6	-47.6	70.2
55	18291	-11.910	8.2	44.86	-39.34	84.2
65	20881	-13.658	9.1	48.6	-57.41	106.01
75	16840	-13.873	10.9	27.11	-49.79	76.9
85	15959	-0.635	22.3	99.96	-96.68	196.64

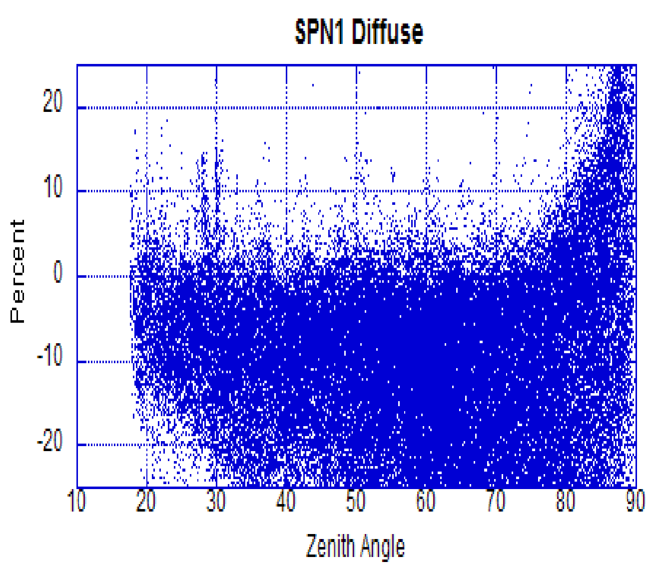

Figure B-18(a). One-minute data set percent differences; SPN1 Diffuse.

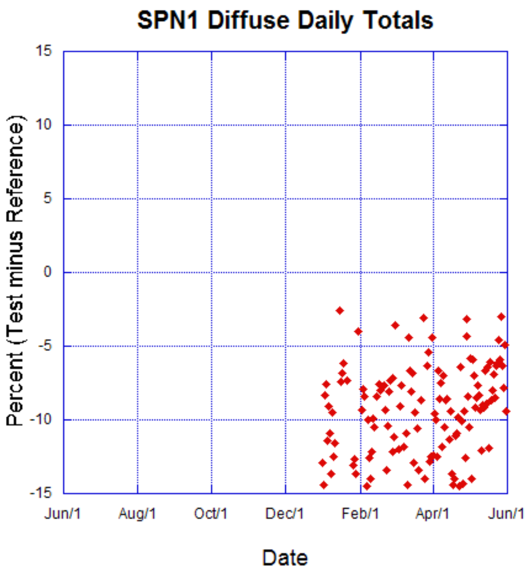

Figure B-18(b). Daily total percent difference; SPN1 Diffuse.

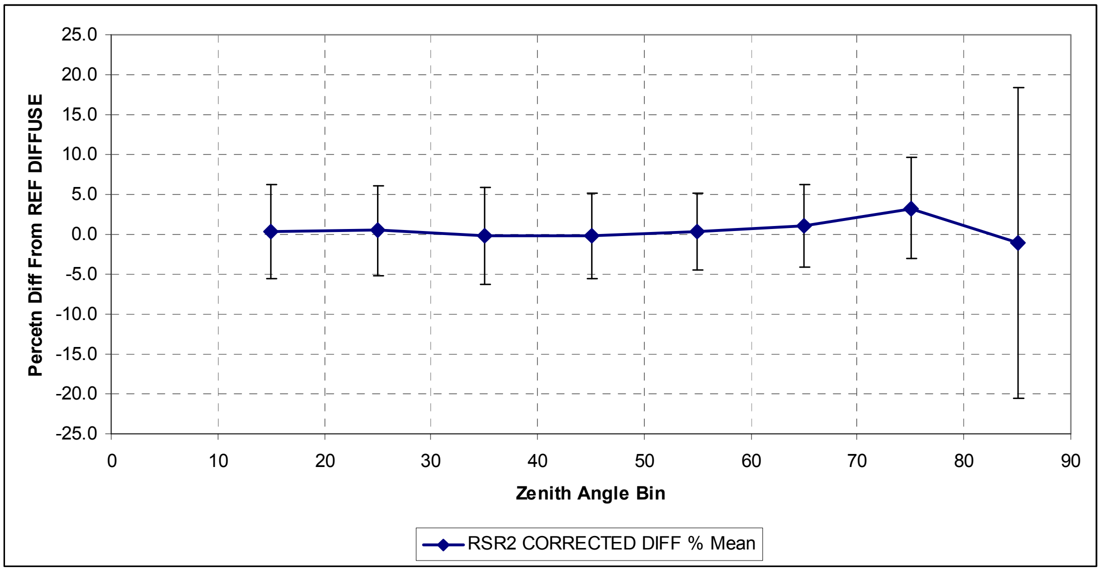

Figure B-19. RSR2 Diffuse Corrected (11 months of data Jul 2007-May 2008)

Table B-19. Statistical summary 1-minute data by zenith angle bin RSR2 Diffuse Corrected

RSR DIFF C	Count (N)	RSR DIFF CORRECTED % Mean Diff	StDev (sd)	Maximum	Minimum	Range
15	2997	0.37	5.95	39.63	-78.50	118.13
25	15534	0.46	5.68	99.89	-90.08	189.97
35	21144	-0.23	6.10	93.37	-98.45	191.82
45	27098	-0.19	5.40	74.27	-99.11	173.38
55	37353	0.33	4.77	61.93	-92.93	154.86
65	48783	1.09	5.23	99.94	-96.01	195.95
75	38433	3.23	6.32	61.74	-68.33	130.07
85	37406	-1.06	19.47	99.47	-100.00	199.47

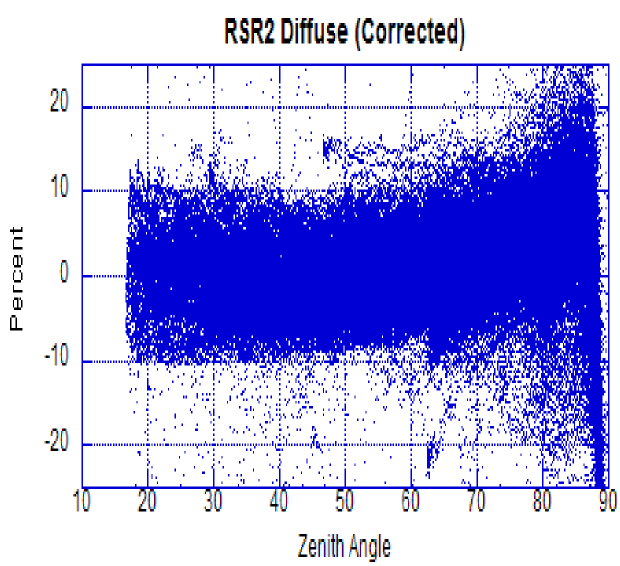

Figure B-19(a). One-minute data set percent differences; RSR2 Diffuse Corrected.

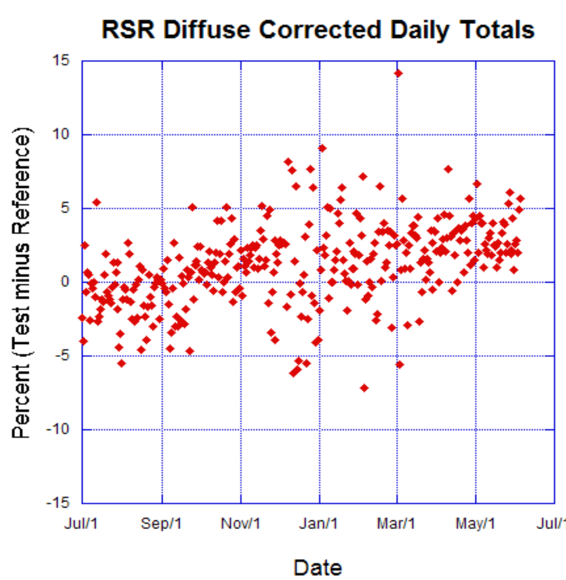

Figure B-19(b). Daily total percent difference RSR2 Diffuse Corrected.

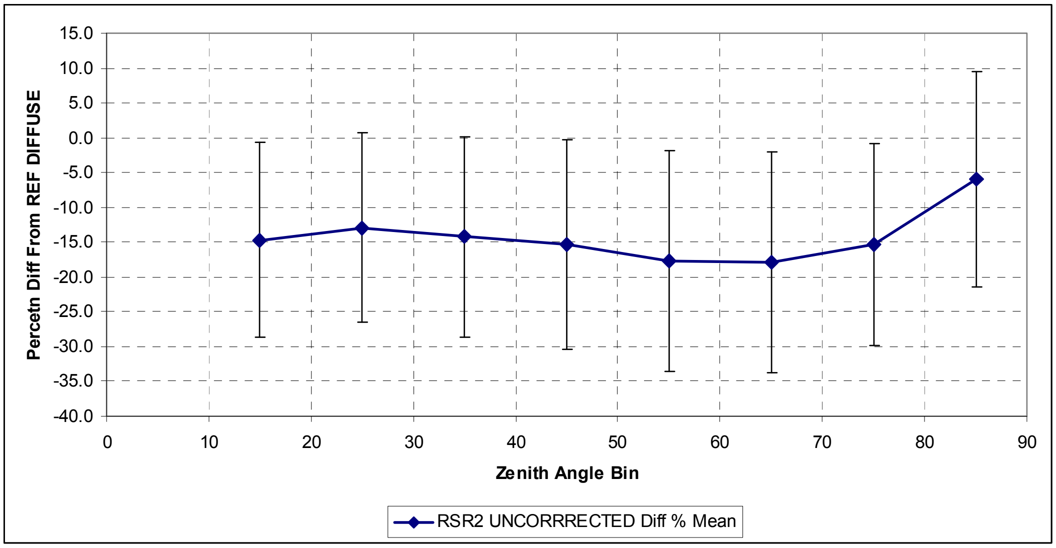

Figure B-20. RSR2 Diffuse Uncorrected (11 months of data Jul 2007 -May 2008)

Table B-20. Statistical summary 1-minute data by zenith angle bin RSR2 Diffuse Uncorrected.

RSR DIF U	Count (N)	RSR DIFF UNCORRECTED % Mean Diff	StDev (sd)	Maximum	Minimum	Range
15	2996	-14.69	13.96	20.71	-92.50	113.21
25	15526	-12.96	13.61	98.08	-92.68	190.76
35	21129	-14.19	14.38	81.66	-99.58	181.24
45	27087	-15.31	15.12	91.72	-99.29	191.01
55	37349	-17.75	15.82	32.48	-99.10	131.58
65	48783	-17.89	15.94	98.54	-82.18	180.72
75	38432	-15.34	14.57	56.72	-94.77	151.49
85	37227	-5.90	15.48	99.72	-99.64	199.36

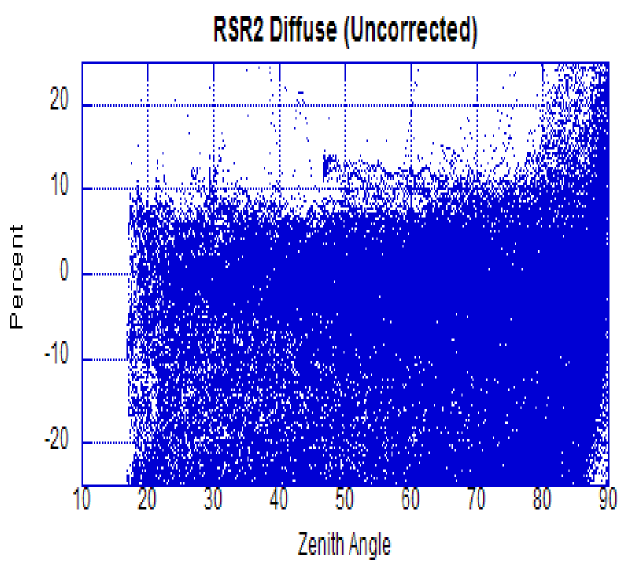

Figure B-20(a). One-minute data set percent differences; RSR2 Diffuse Uncorrected.

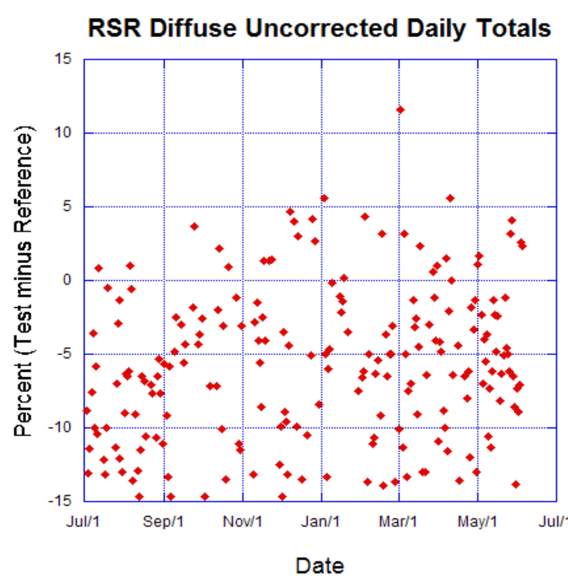

Figure B-20(b). Daily total percent difference RSR2 Diffuse Uncorrected.

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14. ABSTRACT *(Maximum 200 Words)*
This report describes the evaluation of the relative performance of the complement of solar radiometers deployed at the National Renewable Energy Laboratory (NREL) Solar Radiation Research Laboratory (SRRL). This report presents an analysis of 12 global (total hemispherical) horizontal radiometers, three direct beam pyrheliometers, and two diffuse pyranometers in full-time use at SRRL. Data for 12 months were retrieved from the SRRL Baseline Measurement System and included the test instrument measurements and data for a computed reference data set. This report offers no explicit conclusion about instrument performance, as it is aimed at a very general array of applications with a wide range of instrumentation and accuracy requirements.

15. SUBJECT TERMS
SRRL, Solar Radiation Research Laboratory, radiometers, pyrheliometers, pyranometers; Baseline Measurement System; BSM

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