National Renewable Energy Laboratory

A national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy

Innovation for Our Energy Future

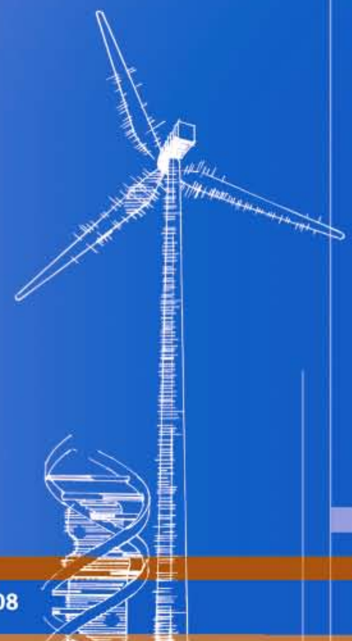
# Relative Accuracy of 1-Minute and Daily Total Solar Radiation Data for 12 Global and 4 Direct Beam Solar Radiometers

## Preprint

D.R. Myers and S.M. Wilcox
*National Renewable Energy Laboratory*

*To be presented at the American Solar Energy Society Annual Conference*
*Buffalo, New York*
*May 11–16, 2009*

***Conference Paper***
**NREL/CP-550-45374**
**March 2009**



NREL is operated for DOE by the Alliance for Sustainable Energy, LLC    Contract No. DE-AC36-08-GO28308

Available electronically at http://www.osti.gov/bridge

Available for a processing fee to U.S. Department of Energy
and its contractors, in paper, from:
U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone: 865.576.8401
fax: 865.576.5728
email: mailto:reports@adonis.osti.gov

Available for sale to the public, in paper, from:
U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
phone: 800.553.6847
fax: 703.605.6900
email: orders@ntis.fedworld.gov
online ordering: http://www.ntis.gov/ordering.htm

Printed on paper containing at least 50% wastepaper, including 20% postconsumer waste

# RELATIVE ACCURACY OF 1-MINUTE AND DAILY TOTAL SOLAR RADIATION DATA FOR 12 GLOBAL AND 4 DIRECT BEAM SOLAR RADIOMETERS

Daryl Myers
National Renewable Energy Laboratory
1617 Cole Boulevard, Golden CO
daryl.myers@nrel.gov

Stephen M. Wilcox
National Renewable Energy Laboratory
1617 Cole Boulevard Golden, CO 80401
stephen.wilcox@nrel.gov

ABSTRACT

We evaluated the relative performance of 12 global and four direct beam solar radiometers deployed at a single site over a 12-month period. Test radiometer irradiances were compared with a reference irradiance consisting of either an absolute cavity radiometer (during calibrations) or a low uncertainty thermopile pyrheliometer (during the evaluation period) for pyrheliometers; and for pyranometers a reference global irradiance computed from the reference pyrheliometer and diffuse irradiance from a shaded pyranometer. One minute averages of 3-second data for 12 months from the test instrument measurements were compared with the computed reference data set. Combined uncertainty in the computed reference irradiance is 1.8% ±0.5%. Total uncertainty in the pyranometer comparisons is ±2.5%. We show mean percent difference between reference global irradiance and test pyranometer 1 minute data as a function of zenith angle, and percent differences between daily totals for the reference and test irradiances as a function of day number. We offer no explicit conclusion about the performance of instrument models, as a general array of applications with a wide range of instrumentation and accuracy requirements could be addressed with any of the radiometers.

## 1. BACKGROUND

The National Renewable Energy Laboratory (NREL) Solar Radiation Research Laboratory (SRRL) has a complement of 12 solar radiometers of various designs for measuring global horizontal irradiance, and four radiometers which report direct beam irradiance[1]. The 12 pyranometers for measuring global horizontal radiation are installed in various configurations (unventilated and ventilated) and some have empirical corrections applied for cosine response [1, 2] and thermal offsets [3, 4] to produce engineering corrected data. Table 1 lists radiometer designations, manufacturers[2], whether any empirical corrections are applied, and the sensor type. Eight pyranometers and all of the pyrheliometers use thermopile sensors. Two Yankee Environmental System (YES) radiometers use platinum resistance thermal detectors (RTD). The remaining radiometers, including an Irradiance, Inc. RSR-2 Model rotating shadowband radiometer (RSR2), have silicon diode sensors. The RSR2 global (unshaded) and diffuse (shaded) irradiances were reported as uncorrected, and with corrections for cosine and spectral effects described elsewhere [5, 6]. The evaluation is subdivided into two sections: pyrheliometers (direct beam measurements) and pyranometers (global horizontal and diffuse horizontal measurements). Unless otherwise noted in table 1, the instruments listed measure global horizontal radiation; or are designed for Diffuse (Dif) or Direct (Dir) radiation sensing.

## 2. UNCERTAINTY IN EVALUATION

The evaluation data set was retrieved from the SRRL Baseline Measurement System recorded at 1-minute averages of 3 sec (0.33 Hz, 20 samples per minute) sampled data using two Campbell Scientific CR23X data loggers with factory calibrations. The manufacturer's specified accuracy is ±0.025% of Full Scale Range (FSR).

[1] See http://www.nrel.gov/midc/srrl_bms

[2] No endorsement of manufacturers mentioned is implied

**TABLE 1: TEST INSTRUMENTS CONFIGURATION**

| *Instrument* | *Manufacturer* | *Configuration* | *Sensor* |
|---|---|---|---|
| CM22_V | Kipp & Zonen | Ventilated | Thermopile |
| CM6B | Kipp & Zonen | Unventilated | Thermopile |
| CM3 | Kipp & Zonen | Unventilated | Thermopile |
| PSP_V_C | Eplab Model PSP pyranometer | Ventilated thermal offset; cosine corrected | Thermopile |
| PSP_C | Eplab | Unventilated thermal offset; cosine corrected | Thermopile |
| PSP_V_U | Eplab | PSP Ventilated Uncorrected | Thermopile |
| PSP_U | Eplab | Uncorrected | Thermopile |
| TSP700 | YES | Ventilated | RTD |
| TSP1 | YES | Ventilated | RTD |
| SPN1 (Glo)* | Delta-T | Uncorrected | Multiple Thermopiles |
| SPN1 (Dir)* | | | |
| SPN1 (Dif)* | | | |
| SP_LITE | Kipp & Zonen | Uncorrected | Silicon (Si) |
| LI200_TOT | Licor | Uncorrected | Si diode |
| RSR2_C (Glo)** | Irradiance Licor | Corrected Global | Si diode |
| RSR2_C (Dir)** | | Computed from corrected Glo & Diffuse | |
| RSR2_C (Dif) | | Corrected | |
| RSR2_U (Glo)** | | Uncorrected | |
| RSR2_U (Dir)** | | Computed from uncorrected Glo & Dif | |
| RSR2_U (Dif)** | | Uncorrected | |
| 31137E6 | Eplab NIP DIR | Uncorrected | Thermopile |
| 25792E6 | Eplab NIP DIR | Uncorrected | Thermopile |
| CH1 010256 | Kipp Zonen DIR | Uncorrected | Thermopile |

*period of record (4 months) ** period of record (11 months)
*** Unventilated pyranometer corrected using ventilated pyrgeometer

FSR is typically ±50 mV, meaning FSR is 100 mV. So in the 50 mV range accuracy is ±0.025 mV or 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 about 5.0 µV/ $Wm^{-2}$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 to 2.7 watts (absolute) in both reference and test instrument data, 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 to be 1.5%, for the data logger 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 was 1.8% ±0.5%. Total uncertainty in the comparisons is the square root of the mean squared uncertainties, plus twice the standard deviation squared, plus the logger uncertainty contribution squared or $(1.8^2+(2*0.5)^2 + 1.5^2)^{0.5}$ = ±2.5% . Thus reference and data irradiances within ±2.5% of each other are considered identical.

## 3. EVALUATION OF PYRHELIOMETERS

The absolute cavity radiometer (Eppley Automatic Hickey –Freidan, AHF) is the reference for NREL calibrations. For this work the AHF is presumed to be the pyrheliometer with the lowest uncertainty of ±0.4% [1, 7, 8]. Although a full year of data 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. We collected reference cavity radiometer data from all NREL calibration events from 2002 to 2007 and merged this reference data with three pyrheliometers from the SRRL baseline system (Eppley NIPs 25792E6 and 31137E6 and Kipp & Zonen CH1 010256). Known and accepted uncertainties in the NREL calibrations are similar to expected differences among pyrheliometers, so if there were different responsivities in use for an instrument in the different calibration events over the study period, these responsivities were averaged. This removed noise effects of calibration uncertainty and also provided the opportunity to detect sensitivity drift with time (none was observed).

The first portion of the pyrheliometer study used only clear sky conditions as mandated by the calibration events. Then RSR2 and NIP 1-minute direct beam data were compared to the CH1 beam data for the whole year.

3.1 Results for Pyrheliometer Cavity Comparisons

Figure 1 shows a composite of all deviations, in percent, of test pyrheliometers from the AHF reference cavity during calibrations in the period from 2002 to 2007. Note the CH1 deviations in the lowest layer of the plot are relatively flat, while the NIP deviations show a greater deviation throughout a day.

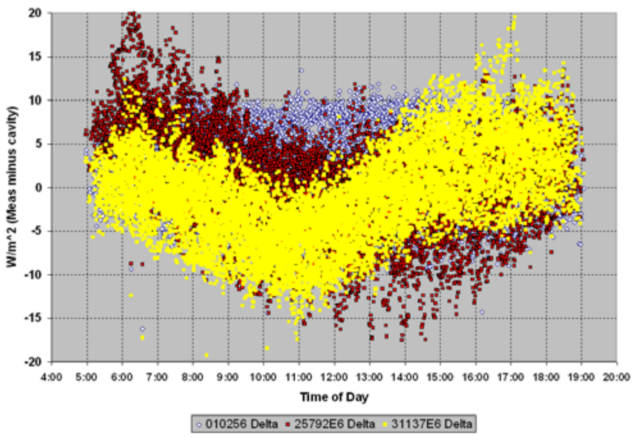



**Fig. 1**. Percent difference from AHF Pyrheliometer for three test pyrheliometers during clear sky calibrations

Table 2 summarizes the mean percent difference of each of the three pyrheliometers from the reference cavity pyrheliometer and standard deviation (in percent) as a function of zenith angle. The zenith angle numbers represent the center of 10° wide zenith angle bins. The smaller values at 45° Z result because the responsivity at Z=45° is used to convert the pyrheliometer signal to irradiance. The larger deviation of the NIP pyrheliometer at higher zenith angles as opposed to the relatively constant CH1 response is apparent. Figure 2 plots the data in table 2.

**TABLE 2: AVERAGE PERCENT DIFFERENCE AND STANDARD DEVIATION BETWEEN TEST AND CAVITY PYRHELIOMETERS**

| Zenith Bin | CH1 Avg% | σ % | 25792E6 Avg % | σ % | 31137E6 Avg% | σ % |
|---|---|---|---|---|---|---|
| 15 | 0.24 | 0.40 | -0.29 | 0.49 | -0.53 | 0.35 |
| 25 | 0.12 | 0.42 | -0.17 | 0.48 | -0.44 | 0.42 |
| 35 | 0.12 | 0.42 | -0.13 | 0.47 | -0.22 | 0.47 |
| 45 | 0.18 | 0.43 | 0.01 | 0.54 | -0.06 | 0.55 |
| 55 | 0.15 | 0.44 | 0.13 | 0.54 | 0.06 | 0.55 |
| 65 | 0.10 | 0.46 | 0.39 | 0.56 | 0.27 | 0.56 |
| 75 | 0.18 | 0.45 | 0.79 | 0.70 | 0.46 | 0.60 |
| 85 | 0.22 | 0.48 | 1.04 | 0.80 | 0.48 | 0.82 |

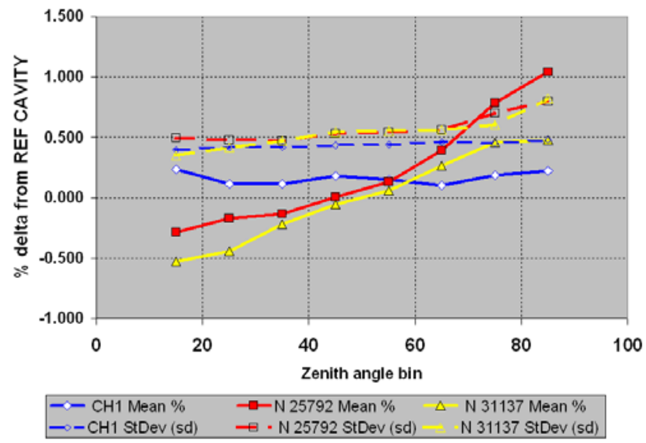



**Fig 2.** Zenith angle dependence of pyrheliometer percent differences and standard deviations with respect to reference AHF pyrheliometer.

3.2 Direct Comparison with CH1 Pyrheliometer

This study used the 1-minute monitored data for all sky conditions over a year. Eppley NIP 31137, Kipp and Zonen CH1 010256, direct beam from the RSR2 and direct beam from a Delta-T, Inc. SPN1 radiometer were studied. The RSR2 data is provided in two forms, with and without corrections for spectral and cosine effects. The correction scheme is provided by the manufacturer based on published results [5, 6]. 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. Table 3 shows the difference between the CH1 and NIP pyrheliometer 25792E6 1-minute data over the year, as a function of zenith angle. Table 4 summarizes the mean percent difference and standard deviation for the corrected and uncorrected RSR2 computed 1-minute direct beam data.

**TABLE 3: AVERAGE PERCENT DIFFERENCE BETWEEN CH 1 AND NIP 25792E6 ONE MINUTE DATA BY ZENITH ANGLE**

| Zenith bin | Count (N) | Mean % | σ % |
|---|---|---|---|
| 15 | 4447 | -0.20 | 1.71 |
| 25 | 14162 | 0.01 | 2.21 |
| 35 | 17701 | 0.11 | 2.13 |
| 45 | 21586 | 0.14 | 1.91 |
| 55 | 28766 | 0.23 | 1.96 |
| 65 | 36135 | 0.33 | 2.06 |
| 75 | 27069 | 0.37 | 1.83 |
| 85 | 19672 | 0.06 | 1.83 |

**TABLE 4: UNCORRECTED (U) AND CORRECTED (C) PERCENT DIFFERENCE BETWEEN RSR2 and CH1 DIRECT BEAM VERSUS Z.**

| *Zenith Angle* | *Count (N)* | *RSR2 U Mean* | *StDev (sd) %* | *Count (N)* | *RSR2 C Mean* | *StDev (sd) %* |
|---|---|---|---|---|---|---|
| 15 | 2599 | 1.25 | 16.8 | 2504 | -3.51 | 17.0 |
| 25 | 17944 | 0.50 | 20.2 | 12387 | -6.90 | 19.4 |
| 35 | 17944 | 0.50 | 20.2 | 16643 | -7.51 | 18.4 |
| 45 | 22645 | 0.98 | 18.9 | 20957 | -7.25 | 17.1 |
| 55 | 31499 | 1.02 | 17.6 | 29369 | -6.61 | 15.9 |
| 65 | 40494 | 0.63 | 18.6 | 37428 | -6.19 | 16.3 |
| 75 | 30449 | 2.87 | 20.4 | 27961 | -5.02 | 16.5 |
| 85 | 22925 | -2.24 | 33.0 | 18818 | -9.56 | 25.1 |

Next, monthly mean daily totals (MMDT) for the reference pyrheliometers and the test direct beam data were computed. Table 5 shows the percent difference between the reference (CH1) MMDT and NIP 25792E6, the RSR2 corrected (C) and uncorrected (U) beam data, and the SPN1 beam data for the months available.

**TABLE 5: NIP, RSR2, AND SPN1 MMDT PERCENT DIFFERENCE FROM CH1 MMDT**

| **Month** | **CH1 MMDT Whm$^{-2}$** | **NIP % Δ** | **RSR2 U % Δ** | **RSR2 C % Δ** | **SPN1 DIR % Δ** |
|---|---|---|---|---|---|
| Jun-07 | 7063 | -0.33 | ---- | ---- | ---- |
| Jul-07 | 6109 | 1.15 | 3.37 | -0.59 | ---- |
| Aug-07 | 5540 | -0.28 | 2.74 | -3.74 | ---- |
| Sep-07 | 5322 | -0.18 | 1.46 | -4.58 | ---- |
| Oct-07 | 5936 | -0.03 | 1.47 | -4.19 | ---- |
| Nov-07 | 5021 | 0.42 | 0.45 | -5.13 | ---- |
| Dec-07 | 4072 | 0.05 | 0.76 | -3.86 | ---- |
| Jan-08 | 4922 | -0.21 | 2.99 | -3.90 | ---- |
| Feb-08 | 4799 | 0.27 | -2.07 | -7.28 | -7.6 |
| Mar-08 | 5140 | 0.39 | -1.46 | -8.81 | 3.9 |
| Apr-08 | 6648 | -0.33 | -0.64 | -4.60 | 15.4 |
| May-08 | 5189 | ---- | 1.80 | -4.00 | 6.0 |

These results show that the basic accuracy of pyrheliometers under the very best of conditions (clear sky calibration conditions) can be less than 0.5% with respect to an absolute cavity radiometer. Under general conditions, bias errors may be around 0.5% between thermopile instruments, but the standard deviation of differences can approach 2%, and total uncertainty about 2.5%. The RSR2 computed direct beam irradiances are on the order of 3% to 6% different. The larger RSR2 standard deviations (~ 15% to 20%) may be due to the orders of magnitude difference in time response of the silicon detectors (milliseconds) and the thermopile reference unit (1 to 2 seconds) under variable sky conditions. MMDT for thermopile pyrheliometers are comparable to better than 1%; however the RSR2 MMDT difference with the reference pyrheliometer was 3 to 9 times larger. The SPN1 direct data could be off by as much as 15%.

## 4. PYRANOMETER COMPARISONS

Data for the pyranometer study 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. A second set of two 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)[9]. The reference irradiance was computed from direct beam * cos(Z) + diffuse, with Direct Beam from Kipp & Zonen CH1 Serial No. 010256 (uncertainty +0.60% - 0.56% for 30°≤ Z ≤60°) and for diffuse: Eppley 8-48 Serial No. 32331 (Uncertainty: +1.95% -1.89% for 0°≤ Z ≤60°).

### 4.1 Pyranometer 1-minute and MMDT Results

Table 6 is a summary of the percent difference between the computed reference irradiances and the instrument 1 minute and MMDT data. The first two columns of Table 6 are for the 1-minute data for each instrument or instrument configuration over all zenith angle ranges. Columns 3 and 4 of Table 6 show the range of percent bias error in MMDT (over 12 possible months) and the annual average daily total with respect to the computed reference irradiance. Since the bias and standard deviation changed as a function of zenith angle (and hence by the month of the year) ranges are shown, from minimum to maximum magnitude. Note the RSR2 direct and diffuse, and SPN1 diffuse data are also included in this table. 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 (winter) data.

The majority of the pyranometers (9 of the 13, counting RSR2 as 1 radiometer) have a bias between ±1% and ±5% from the reference irradiance. These are the CM22 Ventilated, CM6B, PSP Ventilated and Corrected, TSP1, TSP700, SP LITE, LI200, and RSR2 Corrected and Uncorrected. Standard deviation of the differences from the 1-minute reference irradiance is less than ±6% for 6 units:

ventilated CM22, TSP700, RSR2 corrected and uncorrected, and PSP ventilated and corrected.

**TABLE 6: ONE MINUTE AND MMDT MEAN % DIFFERENCE AND STANDARD DEVIATIONS**

| Unit | 1-min Mean % Δ | 1-min Sigma % | Monthly % Bias Range | Annual Mean % Bias |
|---|---|---|---|---|
| **CM22_V** | +0.6<br>+0.4 | 2 to 3 | +0.8<br>+0.2 | +0.5 |
| **CM6B** | +0.8<br>-0.3 | 4 to 7 | +0.9<br>-2.0 | +0.2 |
| **CM3** | +0.1<br>-7.4 | 2 to 7 | +0.4<br>-1.8 | -1.2 |
| **PSPV_C** *** | +0.0<br>-3.1 | 2 to 6 | -0.1<br>-5.1 | -2.1 |
| **PSP_C** | +5.7<br>-0.3 | 2 to 11 | +1.2<br>-3.3 | +0.8 |
| **PSP_V_U** | +1.6<br>-11.3 | 2 to 8 | +0.0<br>-8.4 | -3.8 |
| **PSP_U** | +2.5<br>-7.5 | 2 to 9 | +0.4<br>-10.3 | -2.8 |
| **TSP700** | -0.8<br>-2.5 | 4 to 6 | +1.5<br>-0.0 | +1.1 |
| **TSP1** | +3.2<br>+0.4 | 2 to 12 | +4.6<br>-0.4 | +2.3 |
| **SPN1 (Glo)*** | -0.3<br>-3.7 | 4 to 7 | -0.7<br>-6.0 | N/A |
| **SPN1 (Dif)*** | -13.8<br>-4.3 | 7 to 11 | -12.9<br>-10.4 | N/A |
| **SP_LITE** | +1.4<br>+0.8 | 4 to 7 | +1.4<br>+0.0 | +1.4 |
| **LI200_TOT** | +2.8<br>-2.0 | 3 to 8 | +1.9<br>-2.0 | +0.9 |
| **RSR2_C (Glo)**** | +1.0<br>-1.2 | 4 to 6 | +0.5<br>-2.5 | -0.7 |
| **RSR2_C (Dif)** | -0.2<br>+3.0 | 5 to 6 | -1.1<br>+3.0 | +1.0 |
| **RSR2_U (Glo)**** | -0.8<br>-2.5 | 4 to 6 | -0.8<br>-3.6 | -2.2 |
| **RSR2_U (Dif)**** | -12.0<br>-15.0 | 13 to 16 | -19.3<br>-19.6 | -14.1 |
| **25792E6** | +0.8<br>-0.3 | 0.5 to 0.7 | N/A (wrt Cavity) | |
| **31137E6** | +0.5<br>-0.5 | 0.4 to 0.6 | N/A (wrt Cavity) | |
| **CH1 10256** | +0.2<br>+0.1 | 0.4 to 0.5 | N/A (wrt Cavity) | |

*period of record (4 months) ** period of record (11 months)
*** Unventilated pyranometer corrected using ventilated pyrgeometer

We compared the daily total global irradiance for the reference irradiance, and 14 test global irradiances. The percent mean difference and standard deviations of the differences are shown in Table 7. Note the RSR and SPN1 direct beam data are also shown, with respect to the CH1 daily totals.

**TABLE 7: PERCENT DFFERENCES BETWEEN TEST AND REFERENCE DAILY IRRADIANCE TOTALS**

| Unit | N | Mean % Bias | Sigma % |
|---|---|---|---|
| CM22_V | 366 | **0.5** | **0.8** |
| CM6B | 366 | **0.2** | **2.8** |
| CM3 | 366 | **-1.2** | **2.8** |
| PSP_V_C | 366 | **-2.1** | **2.1** |
| PSP_C | 366 | **0.8** | **5.9** |
| PSP_V_U | 366 | **-3.9** | **4.8** |
| PSP_U | 366 | **-2.8** | **6.1** |
| TSP700 | 366 | **1.1** | **2.2** |
| TSP1 | 366 | **2.3** | **4.5** |
| GLO_SPN1 | 152 | **-2.9** | **3.1** |
| SP_LITE | 366 | **1.3** | **2.7** |
| LI200_TOT | 366 | **0.9** | **2.9** |
| DIR_SPN1* | 144 | **4.1** | **17.8** |
| RSR2_U (Glo)** | 341 | **-2.2** | **2.8** |
| RSR2_U (Dir)** | 329 | **1.0** | **9.3** |
| RSR2_C (Glo)** | 341 | **-0.7** | **3.0** |
| RSR2_C (Dir)** | 330 | **-4.6** | **10.5** |

*period of record (4 months) ** period of record (11 months)

Example plots of individual instrument percent differences between 1 minute data from the reference irradiance as a function of zenith angle and the percent difference in daily totals as a function of day of the year are shown in Figure 3. Comparable plots for each radiometer are provided in the NREL technical report which is the basis of this paper [10].

Table 8 shows the percent difference between monthly daily totals for each global radiometer with respect to the reference irradiance by month. Those cells highlighted in gray are where the difference between the test and reference monthly daily total exceeds 2.5%, the assumed uncertainty in our evaluation process from section 2. 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 and table 8 demonstrate, there is still the possibility of systematic deviations from the best measurements exceeding 5% by members of this family of instruments.

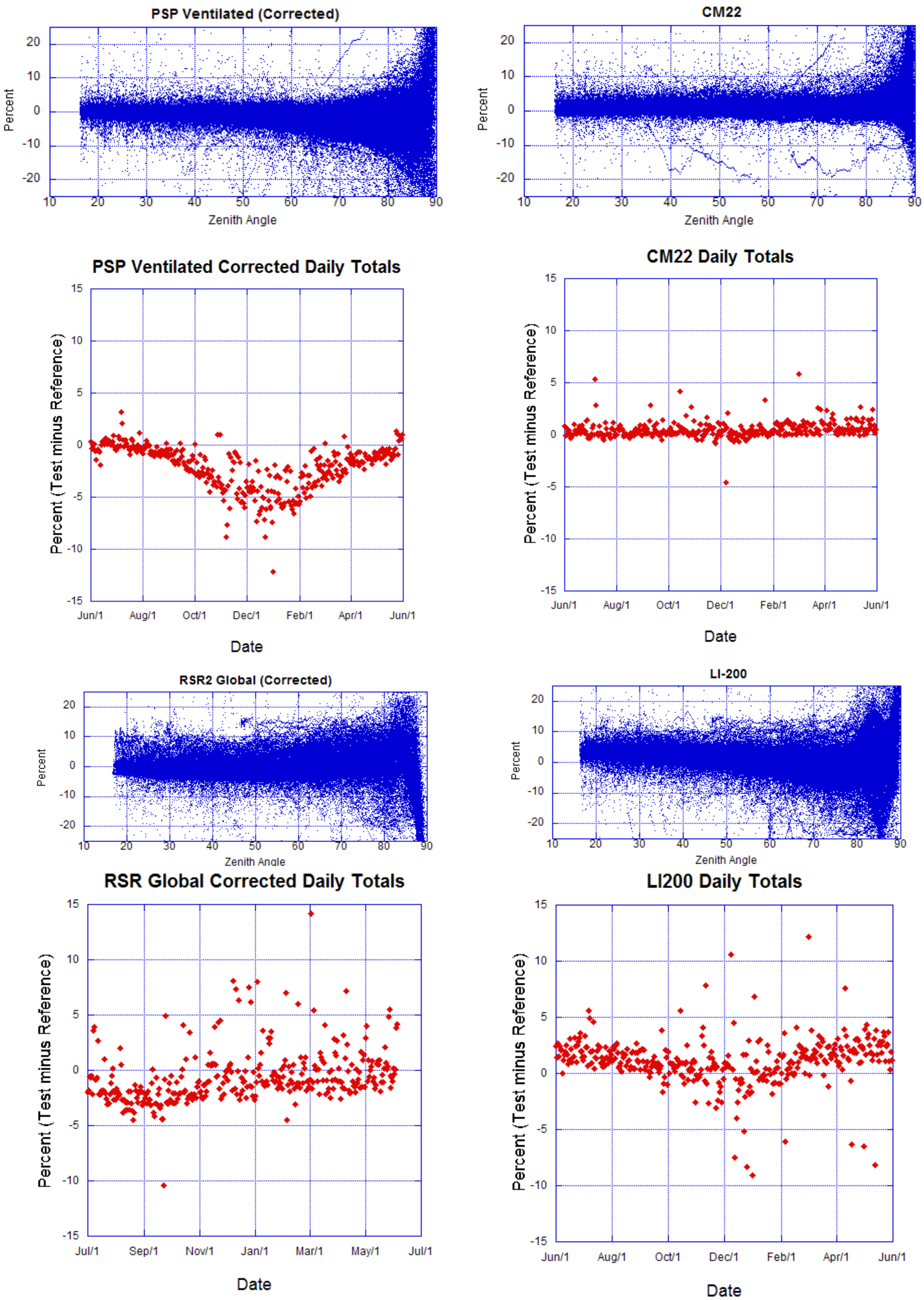



**Fig. 3.** Example plots of percent difference between 1-minute reference irradiance and test instrument irradiance as a function of zenith angle and monthly daily total percent differences as a function of day of the year.

**TABLE 8: 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 | 0.27 | 0.20 | 0.18 | 0.32 | 0.37 | 0.20 | 0.06 | 0.32 | 0.53 | 0.77 | 0.61 | 0.69 |
| CM6B | 0.29 | 0.23 | 0.12 | 0.25 | 0.14 | 0.26 | -1.96 | -0.24 | 0.75 | 0.87 | 0.23 | 0.55 |
| CM3 | -1.61 | -1.24 | -1.58 | -1.34 | -1.21 | -1.84 | -1.64 | -0.58 | -0.19 | 0.39 | 0.35 | 0.23 |
| PSP_V_C | -0.03 | -0.06 | -0.63 | -1.39 | **-2.74** | **-4.00** | **-5.13** | **-5.08** | **-3.23** | -2.10 | -1.38 | -0.47 |
| PSP_C | 0.51 | 0.66 | 0.61 | 0.90 | 0.90 | -1.46 | **-3.27** | 0.80 | 1.70 | 1.17 | 0.45 | 0.57 |
| PSP_V_U | -0.04 | 0.01 | -1.11 | **-2.65** | **-4.98** | **-7.46** | **-8.38** | **-8.22** | **-5.47** | **-3.32** | -1.93 | -0.69 |
| PSP_U | 0.21 | 0.42 | -0.42 | -1.45 | **-3.35** | **-8.29** | **-10.31** | **-5.99** | **-3.01** | -1.35 | -0.83 | 0.18 |
| TSP700 | 0.67 | 0.30 | 0.54 | 0.75 | 0.83 | 1.253 | -0.01 | 1.20 | 1.49 | 1.50 | 0.86 | 0.57 |
| TSP1 | -0.21 | -0.31 | -0.27 | 0.42 | 1.34 | **2.72** | -0.41 | **3.79** | **4.59** | **4.60** | **3.66** | 2.16 |
| GLO_SPN1 | **----** | **----** | **----** | **----** | **----** | **----** | **----** | **-6.04** | **-4.04** | -1.70 | -0.67 | -0.98 |
| 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 | 0.79 | 0.57 | 0.82 | 1.04 | 1.18 | 1.18 | 1.39 | 0.74 | 0.98 | 0.92 | 0.02 | 0.81 |
| LI200_TOT | 1.81 | 1.65 | 1.31 | 0.69 | 0.52 | -0.35 | -2.01 | -0.21 | 0.89 | 1.63 | 1.70 | 1.92 |

## 5. SUMMARY

At the NREL SRRL location, all pyranometer data based on a single calibration factor (sometimes in combination with corrections for cosine response and infrared offsets) agree to within 5% for zenith angles in the range of 30° to 60° on a minute by minute basis. Various cosine responses for the radiometers, in conjunction with a single responsivity (at 45° zenith angle ±0.2°) may lead to lack of agreement, exceeding 20% at Z=70°, and more than 20% at Z=80°. Correction and ventilation techniques applied to the data or instruments may not always improve the situation, but may add additional sources of uncertainty. The ±5% range of agreement observed for zenith angles less than 60° is typical of the historically quoted uncertainty in sub-hourly pyranometer data over the past 30 years. Averaging may cancel some of the random variability between instruments, but differences exceeding 5%, especially in winter, are possible among this family of instruments. Pyrheliometers differ by up to ±2% on a 1 minute and averaged data basis.±2% differences observed among thermopile pyrheliometers is typical of often quoted uncertainties in direct beam data.

## 6. ACKNOWLEDGMENTS

The physical measurement capability and data quality at the NREL SRRL is maintained by A. Andreas, P. Gotseff, B. Kay, I. Reda, T. Stoffel, and S. Wilcox. This work was supported by the U.S. Department of Energy under Contract No. DE-AC36-99GO10337 with the National Renewable Energy Laboratory.

## 7. REFERENCES

1. Michalsky, J.J.; Harrison, L.C.; and Berkheiser, W.E., "Cosine Response of some Radiometric and Photometric Sensors", *Solar Energy* Vol. 54 No. 6, pp. 397-402, 1995.
2. Myers, D. R.; Stoffel, T. L.; Reda, I.; Wilcox, S. M.; Andreas, A. M., "Recent Progress in Reducing the Uncertainty in and Improving Pyranometer Calibrations", *ASME Journal of Solar Energy Engineering* (124:1), pp. 44-50, 2002.
3. Reda, I.; Hickey, J.; Long, C.; Myers, D.; Stoffel, T.; Wilcox, S.; Michalsky, J.J.; Dutton, E.G.; and Nelson, D., **"**Using a Blackbody to Calculate Net Longwave Responsivity of Shortwave Solar Pyranometers to Correct for Their Thermal Offset Error during Outdoor Calibration Using the Component Sum *Method", Journal of Atmospheric and Oceanic Technology,* Vol 22, pp. 1531-1540, 2005.
4. Gulbrandsen, A., "On the Use of Pyranometers in the Study of Spectral Solar Radiation and Atmospheric Aerosols", *Journal of Applied Meteorology*, Vol 17, pp. 899-904, 1978.

5. Zhou, C.; Michalsky, J.; Harrison, L., "Comparison of Irradiance Measurements Made With the Multi-filter Rotating Shadowband Radiometer and First Class Thermopile Radiometers", *Solar Energy,* Vol. 55; No. 6, pp. 487-491, 1995.
6. Vignola, F., "Removing Systematic Errors from Rotating Shadowband Pyranometer Data", paper A090.pdf in Proceedings of Solar 2006, July 9-13 Denver, CO. (CD-ROM), American Solar Energy Society, Boulder, CO.
7. WMO (1996), *International Pyrheliometer Comparison VIII,* World Meteorological Organization, Geneva, Switzerland.
8. Reda, I.; Stoffel, T. L.; Myers, D. R., "Calibration of a Solar Absolute Cavity Radiometer with Traceability to the World Radiometric Reference", NREL/TP-463-20619, Golden CO: National Renewable Energy Laboratory, 1996.
9. Maxwell, E.; Wilcox, S.; Rymes, M. (1993), Users Manual for SERI_QC Software: Assessing the Quality of Solar Radiation Data, NREL Report No. TP-463-5608, Golden, CO: National Renewable Energy Laboratory.
10. Wilcox, S. M.; Myers, D. R. (2008), Evaluation of Radiometers in Full-Time Use at the National Renewable Energy Laboratory Solar Radiation Research Laboratory, pp. 57; NREL Report No. TP-550-44627, Golden, CO: National Renewable Energy Laboratory.

| **REPORT DOCUMENTATION PAGE** | | *Form Approved*<br>*OMB No. 0704-0188* |
|---|---|---|



| **1. REPORT DATE** *(DD-MM-YYYY)* | **2. REPORT TYPE** | **3. DATES COVERED** *(From - To)* |
|---|---|---|
| March 2009 | Conference Paper | |

**4. TITLE AND SUBTITLE**
Relative Accuracy of 1-Minute and Daily Total Solar Radiation Data for 12 Global and 4 Direct Beam Solar Radiometers

**5a. CONTRACT NUMBER**
DE-AC36-08-GO28308

**5b. GRANT NUMBER**

**5c. PROGRAM ELEMENT NUMBER**

**6. AUTHOR(S)**
D.R. Myers and S.M. Wilcox

**5d. PROJECT NUMBER**
NREL/CP-550-45374

**5e. TASK NUMBER**
PVD93110

**5f. WORK UNIT NUMBER**

**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401-3393

**8. PERFORMING ORGANIZATION REPORT NUMBER**
NREL/CP-550-45374

**9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)**

**10. SPONSOR/MONITOR'S ACRONYM(S)**
NREL

**11. SPONSORING/MONITORING AGENCY REPORT NUMBER**

**12. DISTRIBUTION AVAILABILITY STATEMENT**
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

**13. SUPPLEMENTARY NOTES**

**14. ABSTRACT** *(Maximum 200 Words)*
This report evaluates the relative performance of 12 global and four direct beam solar radiometers deployed at a single site over a 12-month period. Test radiometer irradiances were compared with a reference irradiance consisting of either an absolute cavity radiometer (during calibrations) or a low uncertainty thermopile pyrheliometer (during the evaluation period) for pyrheliometers; and for pyranometers a reference global irradiance computed from the reference pyrheliometer and diffuse irradiance from a shaded pyranometer.

**15. SUBJECT TERMS**
NREL; National Renewable Energy Laboratory; Solar Radiation Laboratory; SRRL; radiometer; pyrheliometer; pyranometer

| **16. SECURITY CLASSIFICATION OF:** | | | **17. LIMITATION OF ABSTRACT** | **18. NUMBER OF PAGES** | **19a. NAME OF RESPONSIBLE PERSON** |
|---|---|---|---|---|---|
| **a. REPORT** | **b. ABSTRACT** | **c. THIS PAGE** | | | |
| Unclassified | Unclassified | Unclassified | UL | | **19b. TELEPHONE NUMBER** *(Include area code)* |

**Standard Form 298** (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

F1147-E(10/2008)