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# Comparison of Historical Satellite-Based Estimates of Solar Radiation Resources with Recent Rotating Shadowband Radiometer Measurements

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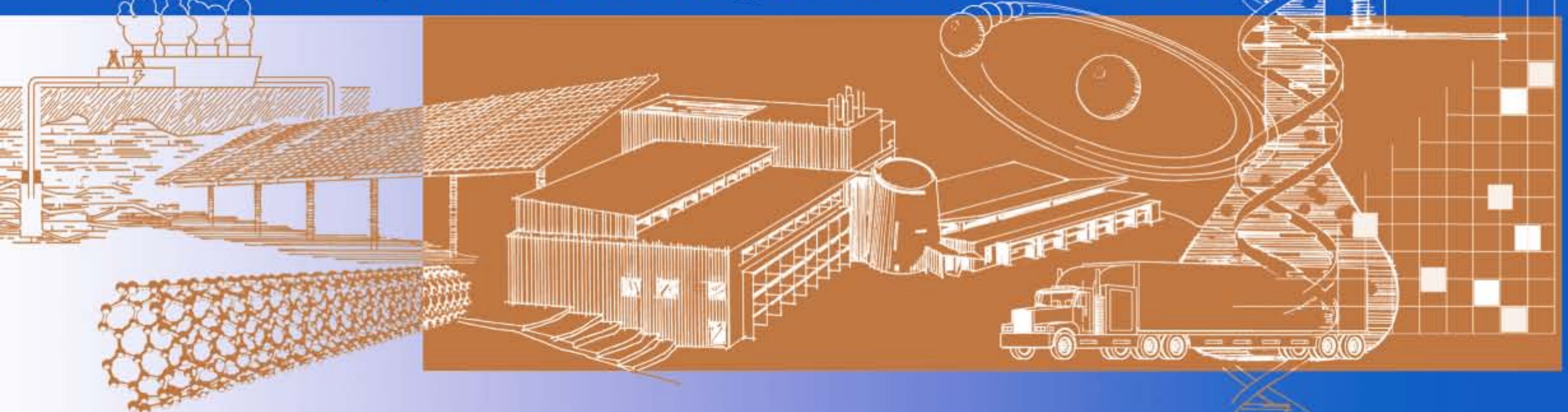

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# COMPARISON OF HISTORICAL SATELLITE-BASED ESTIMATES OF SOLAR RADIATION RESOURCES WITH RECENT ROTATING SHADOWBAND RADIOMETER MEASUREMENTS

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## ABSTRACT

Satellite-based solar radiation estimates have recently been incorporated into the 1990–2005 update to the 1961–1990 U.S. National Solar Radiation Database (NSRDB). The National Aeronautics and Space Administration (NASA) also supplies satellite-based estimates of solar radiation. The usefulness of such data with respect to solar resources for site selection and designing solar energy conversion systems is often questioned. The availability of rotating shadow band radiometer measurement data at several new stations provides an opportunity to compare historical satellite-based estimates of solar resources with measurements. We compare mean monthly daily total (MMDT) solar radiation data from eight years of NSRDB and 22 years of NASA hourly global horizontal and direct beam solar estimates with measured data from three stations, collected after the end of the available resource estimates. We compare the most recent shadowband radiometer MMDT with a complement of thermopile "first class" solar radiometers at one site. Quantitative analysis shows that in most cases, the long-term average MMDT and measured data are comparable, within 10% of each other for global, and 20% for direct-radiation MMDT.

## 1.0 INTRODUCTION

In 2007, the National Renewable Energy Laboratory (NREL) released the 1991–2005 update to the 1961–1990 National Solar Radiation Data Base (NSRDB), a 30-year data set of measured and modeled solar radiation and accompanying meteorological data. Solar estimates are based on the Meteorological/Statistical (METSTAT) solar radiation model developed at NREL [1,2]. From 1998 to 2005, geostationary satellite imagery could be used to estimate solar radiation resources on a 10-km grid [3]. The 10-km solar estimates were derived from the satellite model of Dr. R. Perez of the State University of New York (SUNY), Albany [4].

Since 2005, NREL has been developing a project to help the concentrating solar power industry deploy solar radiation measurement stations at prospective locations for system installations. There are two remote locations in addition to the NREL Solar Radiation Laboratory (SRRL), where a model 2 rotating shadowband radiometer (RSR2) has been deployed. Data for these sites are accessible over the Internet from the SRRL Measurement and Instrumentation Data Center at http://www.nrel.gov/midc. Besides the SRRL Baseline Measurement System (at http://www.nrel.gov/midc/srrl_bms), the other sites are the Lowery Range Solar Station (available at http://www.nrel.gov/midc/lrss/ and the Sunspot One, San Luis Valley (SS1) site, near Alamosa, Colorado, available at http://www.nrel.gov/midc/ss1. A wide complement of thermopile sensor instrumentation, considered to be of higher quality than the RSR2, is available at the SRRL. Figure 1 shows examples of the SRRL radiometers used in the study.

Fig. 1: Types of radiometers used in the study. Top left: RSR2; top right: thermopile pyranometer (global); bottom left: thermopile pyrheliometers (direct) at the NREL SRRL.

## 2.0 STATION INFORMATION

### 2.1 Station distribution

Figure 2 shows the geography of the radiometer deployment in Colorado.

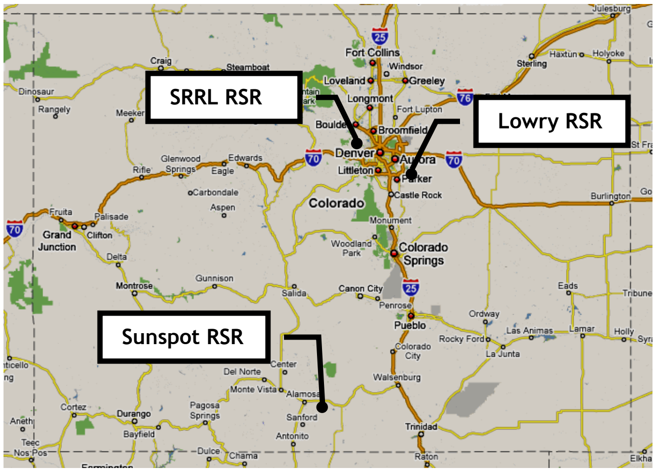


Fig. 2: Deployment sites for Irradiance RSR2 sensors in Colorado. The SSRL is located in Golden, Colorado.

Table 1 summarizes the locations and periods of record used to compare RSR2 measured and historical satellite-based estimates for the solar radiation data.

**TABLE 1: LOCATIONS AND ANALYSIS PERIOD**

| SITE | START DATE | END DATE | LAT-N | LONG-W | ELEV METER |
|---|---|---|---|---|---|
| SRRL | 1/1/2008 | 12/31/2008 | 39.75 | 105.18 | 1800 |
| | 7/1/2008 | 1/31/2009 | | | |
| Lowry | 7/1/2008 | 1/31/2009 | 39.61 | 104.58 | 1860 |
| Sunspot | 7/1/2008 | 1/31/2009 | 37.56 | 106.08 | 2335 |

### 2.2 Solar Measurements

The RSR2 data are collected once per minute. The band rotates at a high angular velocity from out of the view of the pyranometer, over the pyranometer, and back out of view. The band sweeps a shadow across the pyranometer as it blocks the sun during the rotation. Data logging software computes the difference between the shaded and unshaded signals of the pyranometer (Li-cor LI 200 SB, sensed across a 100-ohm ±0.1% low-temperature coefficient precision resistor), which is proportional to the vertical component of the direct beam radiation. The manufacturer's pyranometer calibration factor for global horizontal irradiance is used to compute "uncorrected" global and diffuse irradiance values [5].

From the local time and location coordinates, the zenith angle and the path length through the atmosphere (or air mass) are calculated. The uncorrected global and diffuse irradiances are corrected with functions that depend on the ambient temperature (also measured) and the air mass, as described elsewhere [6,7]. The corrected direct normal irradiance is then computed from the corrected global and diffuse data. All corrected and uncorrected irradiances are stored in the data logger memory for later download.

The SRRL broadband shortwave thermopile instrumentation (Kipp and Zonen CM22 Pyranometer, and CH1 Pyrheliometer) are estimated to have total uncertainties of ±2% in the direct beam irradiance, and ±5% in the global horizontal irradiance [8].

## 3.0 SATELLITE COMPARISON DATA

### 3.1 Perez/SUNY Satellite Estimates

Since 1992, NREL has made available and updated the NSRDB, which contains hourly solar radiation estimates derived from meteorological data. For 1961–1990, there are 239 stations [9,10]; for 1991–2005, 1440 sites, [11]. For 1998–2005, there is a 10-km gridded data set derived from geostationary satellite images for the entire United States (except Alaska) above 60° N latitude. The latter was developed by Perez [11].

The estimated uncertainty in the SUNY data under optimal conditions (e.g., clear skies, high view angles, and stable albedo conditions) is estimated at 8% for the global and diffuse irradiance, and 15% for the direct normal irradiance. These uncertainties grow depending on the need for time shifted corrections, high latitudes (grazing viewing angles), and influence of snow. Each hourly data point for the SUNY gridded data carries a source flag (1, K = satellite imagery; 2, indicating time shifting, and 3, indicating time shifting and predetermined lower diffuse limit) and uncertainty magnitude (8% and up, depending on factors mentioned above). Analysis by NREL [12] indicates that the SUNY model estimates are 2%–5% more accurate than the METSTAT-based estimates in the 1991–2005 NSRDB update; this explains our attention to comparing RSR2 and historical SUNY data.

### 3.2 NASA Surface Solar Energy Estimates

The National Aeronautics and Space Administration (NASA) has developed its own satellite-based estimates of solar radiation on a 1° × 1° latitude longitude grid, available through the NASA Surface Solar Energy website. [13]. Figure 3 shows the NASA SSE grid cells for the three sites.

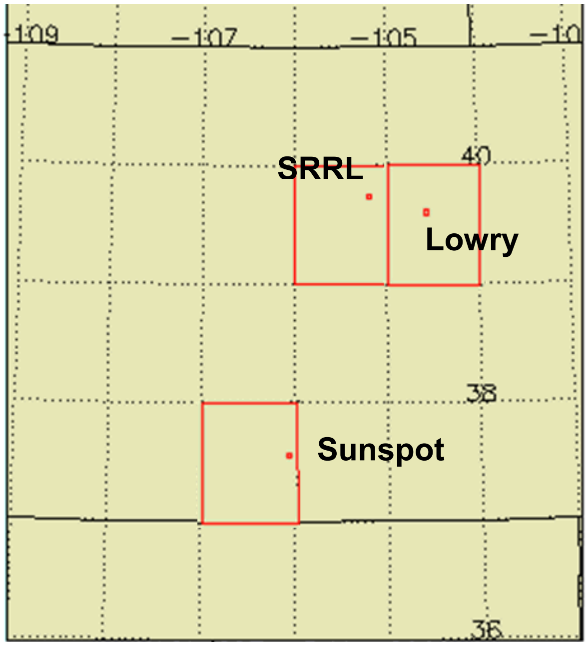


Fig. 3: NASA SSE grid cells for the three sites.

The SSE produces estimates of global horizontal, direct normal, and diffuse horizontal mean monthly daily total (MMDT) irradiances, as well as many other available parameters. The estimated accuracy of the SSE data sets is shown in Table 2 [14].

**TABLE 2: NASA SSE ACCURACY ESTIMATES**

| PARAMETER | METHOD | ROOT-MEAN-SQUARE (RMS) | MEAN BIAS (MBE) |
|---|---|---|---|
| Horizontal Insolation | SSE satellite Pinker | 13%–16% | +0.7%– –2% |
| Direct Normal | SSE/RETScreen SSE/Page | 15%~24% | –9%+2% |

Thus, we will be comparing RSR data with:

- SUNY data with uncertainty of ±8% in global horizontal, ±15% in direct beam data
- NASA SSE data with uncertainty of ±15% in global horizontal and ±20% in direct beam data
- SRRL thermopile data with uncertainty of ±5% in global horizontal and ±2% in direct beam data, as noted above.

The manufacturer's calibrations of the RSR2 pyranometer are claimed to be accurate to ±5% for global horizontal data. Uncorrected direct beam irradiance is expected to be accurate to ±10%, and corrected direct beam data slightly lower, perhaps ±8% after all corrections are applied.

3.3 Computing the MMDT

In our analysis, we compare MMDT irradiances. This is the average of the daily total irradiances computed for each day of the month, or the sum of daily totals divided by the number of days in the month. Many random errors contributing to the RMS errors will cancel out in the process of averaging the time series data.

The SUNY hourly data for the grid cells containing the three measurement sites were downloaded for the eight available years (1998–2005). An NREL Internet data access tool called the Solar Power Prospector (http://mercator.nrel.gov/csp) makes available the eight years of 10-km gridded data for a user-selected cell, with the addition of a "Typical Direct Year" or TDY for the cell. The TDY is analogous to the Typical Meteorological Year (TMY), but is derived from only the eight years of gridded satellite data estimates for solar radiation in combination with meteorological data assimilated from the National Oceanic and Atmospheric Administration meteorological reanalysis data [15], resampled to the 10-km grid of the solar data (see http://www.cdc.noaa.gov/data/reanalysis). The selection criteria produce slightly different TDY MMDT than the average of the eight years of SUNY radiation data.

The NASA SSE website produces MMDT representing the averages of the NASA 22-year period of record. Despite the fact that El Niño and La Niña year data can be selected or excluded, we used the all-inclusive 22-year average MMDT for each 1° × 1° latitude/longitude cell containing the measurement site in our analysis as the SSE MMDT.

4.0 RESULTS

4.1 SRRL One-Year Data Set Comparison

We begin with the most comprehensive comparison, that of the RSR2 data with the thermopile radiometers, long-term averaged SUNY and SSE for the SRRL location. Measured data for the year 2008 comprise the measurement sets. SUNY TDY and SSE data are averaged over 22 and 8 years, respectively. Tables 3 and 4 summarize the MMDT from each data set for global horizontal and direct normal radiation, respectively. Table 5 shows the percent error between measured thermopile and the corrected (C) and uncorrected (U) RSR2 global and direct MMDT irradiances over the year. Applying corrections apparently reduces the MMDT percent error by about 50%. The RSR2 corrected MMDT data are on average within 1% for global data and within 1.5% for direct data.

**TABLE 3: SRRL GLOBAL MMDT kWh/m$^2$/day**

| MONTH | CM22 | RSR2 C | RSR2 UN | SSE | SUNY TDY |
|---|---|---|---|---|---|
| 1 | 2.810 | 2.789 | 2.718 | 2.470 | 2.580 |
| 2 | 3.682 | 3.641 | 3.573 | 3.390 | 3.546 |
| 3 | 4.780 | 4.739 | 4.671 | 4.540 | 4.604 |
| 4 | 6.341 | 6.259 | 6.186 | 5.340 | 5.775 |
| 5 | 6.184 | 6.138 | 6.073 | 6.150 | 6.612 |
| 6 | 7.543 | 7.467 | 7.409 | 6.830 | 6.910 |
| 7 | 6.783 | 6.703 | 6.680 | 6.330 | 6.931 |
| 8 | 5.663 | 5.586 | 5.568 | 5.550 | 5.943 |
| 9 | 5.008 | 4.925 | 4.895 | 5.050 | 5.232 |
| 10 | 3.776 | 3.734 | 3.685 | 3.870 | 3.833 |
| 11 | 2.753 | 2.731 | 2.674 | 2.690 | 2.740 |
| 12 | 2.383 | 2.395 | 2.319 | 2.270 | 2.260 |

**TABLE 4: SRRL DIRECT-NORMAL MMDT kWh/m$^2$/day**

| MONTH | CH1 | RSR2 C | RSR2 UN | SSE | SUNY TDY |
|---|---|---|---|---|---|
| 1 | 5.258 | 5.145 | 5.355 | 4.950 | 4.714 |
| 2 | 5.133 | 5.022 | 5.257 | 5.570 | 5.602 |
| 3 | 5.417 | 5.329 | 5.574 | 6.040 | 6.196 |
| 4 | 6.959 | 6.796 | 7.091 | 5.740 | 6.344 |
| 5 | 5.438 | 5.324 | 5.586 | 6.170 | 6.999 |
| 6 | 7.900 | 7.789 | 8.159 | 7.050 | 7.537 |
| 7 | 6.742 | 6.662 | 7.032 | 6.300 | 7.241 |
| 8 | 5.952 | 5.900 | 6.233 | 5.710 | 6.596 |
| 9 | 6.178 | 6.107 | 6.420 | 6.420 | 6.522 |
| 10 | 5.671 | 5.624 | 5.896 | 6.060 | 5.555 |
| 11 | 4.375 | 4.393 | 4.619 | 5.070 | 5.095 |
| 12 | 4.213 | 4.266 | 4.429 | 4.980 | 4.792 |

In Table 6 we compare the SRRL measured thermopile MMDT for 2008 with the long-term averages from SSE and SUNY TDY. Although there are large differences between the long-term means in particular months, especially during the spring and fall, the mean differences in global and direct MMDT over the year for both long-term data sets is –7% to +5%. The computation is for measured minus long-term mean divided by measured, so positive values imply measured data greater than long-term means, and negative values imply the reverse. Figure 4 plots the data in Table 6.

These results show the deviations from long-term means (up to 30%) that can occur for a particular month or year.

**TABLE 5: PERCENT DIFFERENCE BETWEEN THERMOPILE , CORRECTED, AND UNCORRECTED RSR2 MMDT SRRL 2008 DATA**

| MONTH | % GLO C | %GLOR UN | % DIR C | %DIR UN |
|---|---|---|---|---|
| 1 | 0.7 | 3.3 | 2.2 | –1.9 |
| 2 | 1.1 | 3.0 | 2.2 | –2.4 |
| 3 | 0.8 | 2.3 | 1.6 | –2.9 |
| 4 | 1.3 | 2.4 | 2.3 | –1.9 |
| 5 | 0.7 | 1.8 | 2.1 | –2.7 |
| 6 | 1.0 | 1.8 | 1.4 | –3.3 |
| 7 | 1.2 | 1.5 | 1.2 | –4.3 |
| 8 | 1.3 | 1.7 | 0.9 | –4.7 |
| 9 | 1.7 | 2.3 | 1.1 | –3.9 |
| 10 | 1.1 | 2.4 | 0.8 | –4.0 |
| 11 | 0.8 | 2.9 | –0.4 | –5.6 |
| 12 | –0.5 | 2.7 | –1.3 | –5.1 |
| MEAN | 0.9 | 2.3 | 1.2 | –3.6 |

**TABLE 6: PERCENT DIFFERENCES BETWEEN SSE, SUNY, AND 2008 SRRL REFERENCE DATA MMDT**

| Month | CM22 SSE | CM22 SUNY | CH1 SSE | CH1 SUNY |
|---|---|---|---|---|
| 1 | 12.1 | 8.2 | 5.9 | 10.3 |
| 2 | 7.9 | 3.7 | –8.5 | –9.1 |
| 3 | 5.0 | 3.7 | –11.5 | –14.4 |
| 4 | 15.8 | 8.9 | 17.5 | 8.8 |
| 5 | 0.5 | –6.9 | –13.5 | –28.7 |
| 6 | 9.5 | 8.4 | 10.8 | 4.6 |
| 7 | 6.7 | –2.2 | 6.6 | –7.4 |
| 8 | 2.0 | –4.9 | 4.1 | –10.8 |
| 9 | –0.8 | –4.5 | –3.9 | –5.6 |
| 10 | –2.5 | –1.5 | –6.9 | 2.0 |
| 11 | 2.3 | 0.5 | –15.9 | –16.5 |
| 12 | 4.8 | 5.2 | –18.2 | –13.7 |
| MEAN | 5.3 | 1.5 | –2.8 | –6.7 |

The RSR2 and thermopile comparison data for 2008 show that the RSR2 corrected data and the SSE and SUNY long-term means would be within 1%–2% of these results. In the following sections we will compare both corrected and uncorrected RSR2 data with the satellite-derived long-term means, but only for the seven months of available data (July 2008 to January 2009).

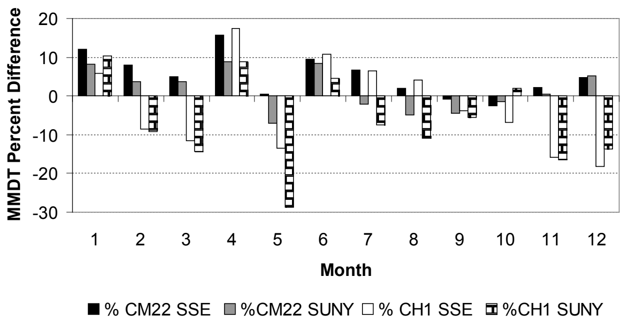

Fig. 4: Percent difference between SRRL 2008 thermopile radiometer measured global (CM22) and direct (CH1) MMDT with respect to long-term SSE and SUNY MMDT.

## 4.2 Lowry RSR2 Seven-Month Comparison

Tables 7 and 8 show MMDT for the RSR2 global horizontal and direct normal, respectively, and the SUNY TDY and SSE long-term mean MMDT at the Lowry site for July 2008 to January 2009.

### TABLE 7: LOWRY GLOBAL MMDT COMPARISON

| Month | RSR2 Corrected | RSR2 Uncorrected | SUNY TDY | SSE |
|---|---|---|---|---|
| 7 | 7.078 | 7.066 | 6.928 | 6.400 |
| 8 | 6.000 | 5.984 | 6.222 | 5.710 |
| 9 | 5.176 | 5.148 | 5.329 | 5.110 |
| 10 | 3.927 | 3.880 | 3.823 | 3.930 |
| 11 | 2.685 | 2.629 | 2.722 | 2.700 |
| 12 | 2.440 | 2.361 | 2.265 | 2.190 |
| 13 | 2.691 | 2.618 | 2.486 | 2.430 |

### TABLE 8. LOWRY DIRECT MMDT COMPARISON

| MTH | RSR2 CORRECTED | RSR2 UNCORRECTED | SUNY TDY | SSE |
|---|---|---|---|---|
| 7 | 7.550 | 7.814 | 7.076 | 6.430 |
| 8 | 6.994 | 7.228 | 7.606 | 6.020 |
| 9 | 6.765 | 6.982 | 7.763 | 6.550 |
| 10 | 6.104 | 6.284 | 6.529 | 6.220 |
| 11 | 4.337 | 4.487 | 6.366 | 5.090 |
| 12 | 4.745 | 4.836 | 6.132 | 4.630 |
| 13 | 4.699 | 4.812 | 5.004 | 4.780 |

Figure 5 plots the data in Table 7. Figure 6 shows the percent difference between global MMDT for the corrected and uncorrected RSR2 global data and the SUNY TDY and SSE long-term average MMDT. Figure 7 is for the direct.

Figure 5 indicates that the results for the measured and long-term means are relatively close, but Fig. 6 indicates that the percentage differences between the long-term means and measured data approach 10% for the SSE data set, 8% for the SUNY data set, measured data approach 10% for the SSE data set, and 8% for the SUNY data set.

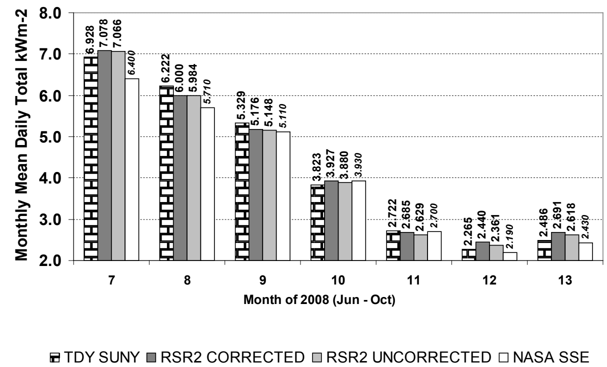

Fig. 5: RSR2 corrected and uncorrected and SUNY and SSE global horizontal MMDT for the Lowry site (from Table 7).

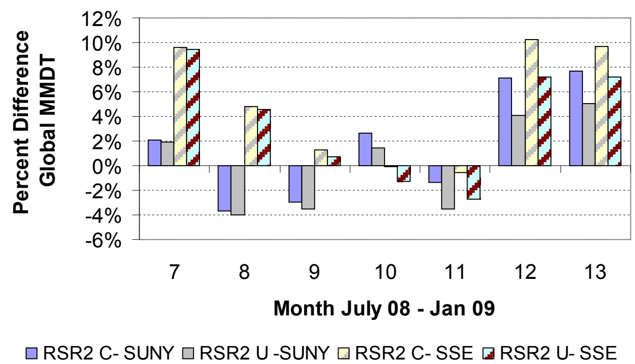

Fig. 6: Percent differences between RSR2 corrected and uncorrected and SUNY (solid) and SSE (hatch) global horizontal MMDT for Lowry site.

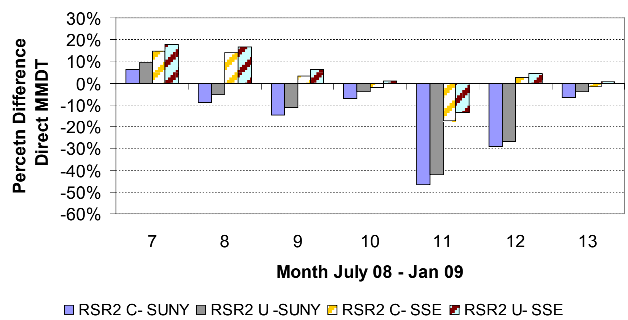

Fig. 7: Percent differences between RSR2 corrected and uncorrected and SUNY (solid) and SSE (hatch) direct beam MMDT for Lowry site.

The largest percentage differences occur in winter months, with lower total radiation (by almost a factor of 3). This is well within the quoted uncertainties discussed in section 3.2. This is excepting the direct beam in November 2008, when there were only about seven relatively clear days.

4.3 Sunspot RSR2, Alamosa, Colorado

As for the Lowry site, Tables 9 and 10 show measured global and direct MMDT with SUNY and SSE long-term average MMDT.

**TABLE 9: SUNSPOT GLOBAL MMDT kWh/m²/day**

| MTH | RSR2 CORRECTED | RSR2 UNCORRECTED | SUNY TDY | SSE |
|---|---|---|---|---|
| 7 | 7.234 | 7.165 | 7.180 | 6.310 |
| 8 | 6.216 | 6.166 | 6.537 | 5.590 |
| 9 | 5.881 | 5.830 | 5.643 | 5.200 |
| 10 | 4.492 | 4.420 | 4.400 | 4.090 |
| 11 | 3.268 | 3.183 | 3.568 | 2.970 |
| 12 | 2.854 | 2.747 | 2.720 | 2.560 |
| 13 | 3.416 | 3.292 | 2.816 | 2.800 |

Figure 8 plots the data in Table 10. Figures 9 and 10 show the percent difference between the Sunspot global and direct MMDT and long-term means, respectively.

**TABLE 10: SUNSPOT DIRECT MMDT kWh/m²/day**

| MTH | RSR2 CORRECTED | RSR2 UNCORRECTED | SUNY TDY | SSE |
|---|---|---|---|---|
| 7 | 7.658 | 7.775 | 7.861 | 6.150 |
| 8 | 6.839 | 6.960 | 7.161 | 5.600 |
| 9 | 7.930 | 8.054 | 7.430 | 6.440 |
| 10 | 7.204 | 7.292 | 6.608 | 6.190 |
| 11 | 5.796 | 5.914 | 5.624 | 5.410 |
| 12 | 4.923 | 4.924 | 5.969 | 5.390 |
| 13 | 6.462 | 6.430 | 5.561 | 5.480 |

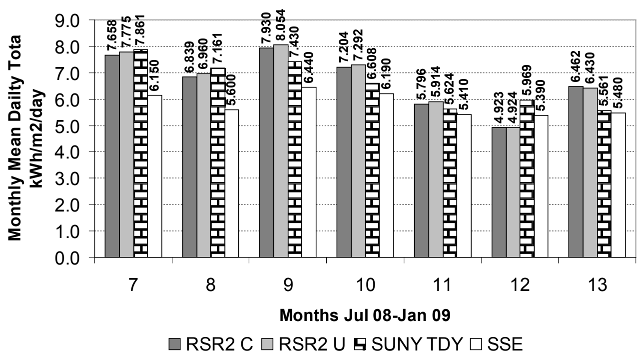


Fig. 8: RSR2 corrected (C), uncorrected (U), SUNY, and SSE direct beam MMDT for Sunspot site (from Table 10).

For this site, differences between measured MMDT and the long-term SSE means are larger and rather more constant, around 10% for global and 20% for direct (measured greater than SEE).

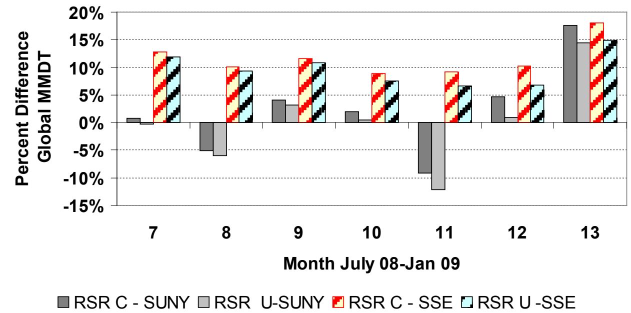


Fig. 9: Percent difference between RSR2 corrected and uncorrected and SUNY (solid) and SSE (hatch) global horizontal MMDT for Sunspot site.

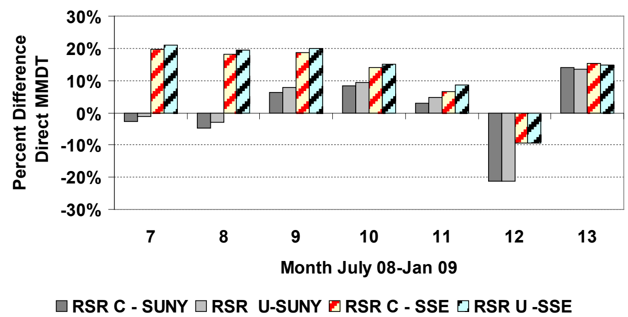


Fig. 10: Percent differences between RSR2 corrected and uncorrected and SUNY (solid) and SSE (hatch) direct beam MMDT for Sunspot site.

5.0 DISCUSSION

We compare 7 months of RSR2 measured and long-term (8 year and 22 year) estimated MMDT based on historical modeled estimates of MMDT. The long-term estimates are based on the NASA SSE (1983–2005) and SUNY (1998–2005) data sets. We have three sites with measured data available, all in Colorado, but in distinct NASA SSE (and SUNY) grid cells. Because the corrected RSR2 data are slightly better than the uncorrected data (see Table 5), we summarize the results for the 7 months common to all of the RSR2 data (July 2008 to January 2009) in Table 11. The entries are percent differences between measured and long-term MMDT computed as 100* (Measured-Mean)/ Measured. Recall from section 3.2 the estimated uncertainties in the long-term means:

SUNY **±8%** in global horizontal, **±15%** in direct beam. NASA SSE **±15%** in global horizontal and **±20%** in direct.

**TABLE 11: PERCENT DIFFERENCES BETWEEN RSR2-C MEASURED AND LONG-TERM MEAN MMDT BY SITE AND LONG-TERM SOURCE**

| **SUNY GLOBAL ±8%** | | | | |
|---|---|---|---|---|
| **MONTH** | **LOWRY** | **SUNSPOT** | **SRRL** | **AVG** |
| 7 | 2.1 | 0.7 | –3.4 | –0.2 |
| 8 | –3.7 | –5.2 | –6.4 | –5.1 |
| 9 | –3.0 | 4.1 | –6.2 | –1.7 |
| 10 | 2.6 | 2.0 | –2.7 | 0.7 |
| 11 | –1.4 | –9.2 | –0.3 | –3.6 |
| 12 | 7.1 | 4.7 | 5.6 | 5.8 |
| 13 | 7.6 | **17.6** | 7.5 | **10.9** |
| MEAN | **1.6** | **2.1** | **–0.8** | *1.0* |
| **SUNY Direct ±15%** | | | | |
| 7 | 6.3 | –2.6 | –8.7 | –1.7 |
| 8 | –8.8 | –4.7 | –11.8 | –8.4 |
| 9 | –14.8 | 6.3 | –6.8 | –5.1 |
| 10 | –7.0 | 8.3 | 1.2 | 0.8 |
| 11 | **–46.8** | 3.0 | **–16.0** | **–19.9** |
| 12 | **–29.2** | **–21.3** | **–12.3** | **–20.9** |
| 13 | –6.5 | 13.9 | 8.4 | 5.3 |
| MEAN | **–15.2** | **0.4** | **–6.6** | *–7.1* |
| **SSE Global ±15%** | | | | |
| 7 | 9.6 | 12.8 | 5.6 | 9.3 |
| 8 | 4.8 | 10.1 | 0.6 | 5.2 |
| 9 | 1.3 | 11.6 | –2.5 | 3.4 |
| 10 | –0.1 | 8.9 | –3.6 | 1.7 |
| 11 | –0.6 | 9.1 | 1.5 | 3.4 |
| 12 | 10.2 | 10.3 | 5.2 | 8.6 |
| 13 | 9.7 | **18.0** | 11.4 | 13.1 |
| MEAN | **5.0** | **11.5** | **2.6** | *6.4* |
| **SSE Direct ±20%** | | | | |
| 7 | 14.8 | 19.7 | 5.4 | 13.3 |
| 8 | 13.9 | 18.1 | 3.2 | 11.7 |
| 9 | 3.2 | 18.8 | –5.1 | 5.6 |
| 10 | –1.9 | 14.1 | –7.8 | 1.5 |
| 11 | –17.4 | 6.7 | –15.4 | –8.7 |
| 12 | 2.4 | –9.5 | –16.7 | –7.9 |
| 13 | –1.7 | 15.2 | 3.8 | 5.7 |
| MEAN | **1.9** | **11.9** | **–4.7** | *3.0* |

We examined how often the long-term means differ by an amount exceeding the estimated uncertainties in the long-term means, from the measured MMDT for the period. These cases are highlighted in Table 11 for various individual months and sites. For each long-term MMDT (SSE, SUNY), there are 21 possible site-months of data. For the SUNY global estimate, in only 1 case of 21 (5%) was the 8% uncertainty exceeded; and that was in January, at the Sunspot site near Alamosa, Colorado, where the global irradiance is around 3 kWh/m$^2$/day. The 18% difference represents ~500 Wh/m$^2$ in absolute terms.

The differences with the SUNY direct estimates at all sites in November and December are larger, representing the sensitivity of the direct beam to cloud and storm passage differences in these specific months, with respect to the average pattern over the years 1998–2005. However, the maximum mean percentage difference over the seven-month period is just 0.2% larger (at Lowry) than the estimated SUNY direct uncertainty. The differences for particular months (again, winter months with lower irradiance values) occurred 21% of the time.

For the SSE data set, performance appears somewhat better. Only 1 of the 21 (5%) months (Sunspot, January) showed a difference between the estimated and measured global MMDT greater than 15%. However, differences in individual months tend to be larger than those from the SUNY MMDT in most cases. In 11 of the 21 site-months, or 52% of the sample, the difference exceeds the 8% estimated uncertainty in the SUNY data. Most of the larger differences are seen at the Sunspot site, where the SSE 1° × 1°cell encloses a wide variety of terrain and elevations (mountains, valleys) that no doubt affect the model result (which averages about 12% low).

SSE direct results are similar to the global findings, including the fact that most of the larger differences occur at Sunspot. However only 8 of the 21 (38%) site months actually exceed the SUNY estimated uncertainty of ±8%.

Overall, in only 1 of the 12 (8%) estimates of overall mean differences (MEAN row in each table section) for both radiation components did the overall mean difference exceed the estimated uncertainty in the long-term mean (Lowry, direct MMDT mean), and then only by 0.2%. In all other cases, the mean difference between MMDT measured and estimated from the long-term means was half or less than the estimated uncertainties of the long-term means.

## 6.0 CONCLUSION

On the basis of global and direct beam MMDT over one year, we compared performance of the RSR2 with thermopile-based sensors (pyranometers, pyrheliometers). The RSR2 MMDT were on average within 2% of the thermopile data over 2008. Differences in individual monthly MMDT varied about ±2% for the corrected data, and ±5% for the uncorrected data (Table 5).

Thus the RSR2 radiometer, with corrections applied, is a reasonable substitute for complex thermopile sensors *for aggregated data on the scale of monthly averages*, to an accuracy of about 2%. This is a *relative performance* figure of merit only, not a measure of the absolute accuracy of either the thermopile sensors or the RSR2 radiometer, which is typically about 2% for pyrheliometers and 4%–5% for pyranometers [8,16].

Comparison of long-term estimates of MMDT for three sites for a common seven-month period shows that the long-term estimates are reasonably accurate *with respect to the estimated uncertainties associated with them and quoted for them.* That is, ±8% and ±15% for SUNY and SSE global MMDT, respectively, and 15% and ±20% for SUNY and SSE direct MMDT, respectively.

About 10% of the time for global, up to 25% of the time for direct in our sample of 21 site months, year-to-year variability in the weather will contribute to conditions resulting in "real" MMDT outside the bounds of the long-term estimate uncertainties. For our 21 site-month sample, *the long-term estimates were within their estimated uncertainty limits about 85% of the time for the SUNY data.* The SSE performance was "better" because the uncertainties were larger (41 of the 42 months, or 98%, were "within tolerance").

Fifty-seven percent (24 of 42) of the SSE estimates for both global and direct MMDT were within 10% of the measured MMDT; so about 50% of the SSE estimates may be "off" by 10% or more for sites similar to those used here.

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The availability of rotating shadow band radiometer measurement data at several new stations provides an opportunity to compare historical satellite-based estimates of solar resources with measurements. We compare mean monthly daily total (MMDT) solar radiation data from eight years of NSRDB and 22 years of NASA hourly global horizontal and direct beam solar estimates with measured data from three stations, collected after the end of the available resource estimates.

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