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EVALUATING SOLAR RESOURCE DATA OBTAINED FROM MULTIPLE RADIOMETERS DEPLOYED AT THE NATIONAL RENEWABLE ENERGY LABORATORY

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ABSTRACT: Solar radiation resource measurements from radiometers are used to predict and evaluate the performance of photovoltaic and concentrating solar power systems, validate satellite-based models for estimating solar resources, and advance research in solar forecasting and climate change. This study analyzes the performance of various commercially available radiometers used for measuring global horizontal irradiances (GHI) and direct normal irradiances (DNI). The radiometers in this study were deployed for one year (from April 1, 2011, through March 31, 2012) and compared to measurements from radiometers with the lowest values of estimated measurement uncertainties for producing reference GHI and DNI. The differences were calculated as a percent of reading for solar zenith angles ranging from 17.5 degrees to 85 degrees (the range of available solar zenith angles throughout the year at SRRL, excluding data near sunrise and sunset). Under clear-sky conditions when the solar zenith angle was less than 60 degrees, differences of less than 5% were observed for both GHI and DNI measurements when they were compared to the reference radiometers. These normalized differences increased during partly cloudy sky conditions and when the solar zenith angle was greater than 60 degrees. The intent of this paper is to present a general overview of each radiometer's performance. The National Renewable Energy Laboratory made no effort to ensure that the radiometers presented here were representative units; therefore, this paper does not guarantee the same results for all radiometers from the same manufacturer or model.

Method and Experimental Design:

Location:

- Solar Radiation Research Laboratory, Golden, Colorado USA

Deployment:

- The radiometers in this study were deployed for one year (from April 1, 2011, through March 31, 2012)

Reference Data:

- A Kipp and Zonen CH1 (DNI) instrument and an Eppley Laboratory, Inc., black-and-white model 8-48 (diffuse horizontal irradiance, or DHI) instrument

Test Instruments:

- 32 instruments measuring GHI data set
- 19 instruments measuring DNI data set. Some of the instruments had a calculated DNI value.

Data Quality:

- SERI_QC—a data quality assessment tool was applied to the radiometric data

Best practices for the operations and maintenance of the instruments were followed.

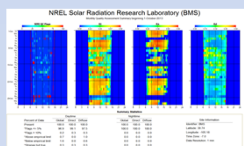

Fig. 1: Example of data quality plot developed using NREL SERI-QC software

Data Normalization:

- The solar irradiance data from the radiometers were normalized to the reference data to remove potential instrument calibration biases.

$$Ratio = \frac{\sum I_{UUT\,44^\circ\,to\,46^\circ}}{\sum I_{Ref\,44^\circ\,to\,46^\circ}}$$

where $I_{UUT\,44^o\,to\,46^o}$ is the irradiance data for the UUT within the 2-degree solar zenith angle bin and $I_{Ref\,44^o\,to\,46^o}$ is the irradiance data of the reference instrument within the same solar zenith angle range.

The new normalized irradiance data from the UUT were then computed as

$$I_{UUT(New)} = \frac{I_{UUT}}{Ratio}$$

Data Filtering for sky condition was carried out using TSI-880.

Fig.2: Example of instrument types under test

GHI Instrument List:

Instrument Number	Instrument Type	Model	Manufacturer	Instrument Number	Instrument Type	Model	Manufacturer
1	Thermopile	CM22	Kipp & Zonen	17	Semiconductor	RSP (secondary)	LI-Cor
2	Thermopile	CM6b	Kipp & Zonen	18	Thermopile	TSR-590	YES, Inc.
3	Thermopile	CM3-CNR1	Kipp & Zonen	19	Thermopile	TSR-591	YES, Inc.
4	Thermopile	PSP	Eppley Laboratory, Inc.	20	Thermopile	TSR-592	YES, Inc.
5	Thermopile	PSP	Eppley Laboratory, Inc.	21	Thermopile	TSR-590-LH[a]	YES, Inc.
6	Thermopile	PSP	Eppley Laboratory, Inc.	22	Thermopile	TSR-591-LH	YES, Inc.
7	Thermopile	PSP	Eppley Laboratory, Inc.	23	Thermopile	TSR-592-LH	YES, Inc.
8	Thermopile	TSP-700	YES, Inc.	24	Thermopile	TSR-590-JM[b]	YES, Inc.
9	Thermopile	TSP-1	YES, Inc.	25	Thermopile	TSR-591-JM	YES, Inc.
10	Thermopile	SPN1	Delta-T	26	Thermopile	TSR-592-JM	YES, Inc.
11	Semiconductor	SPLite	Kipp & Zonen	27	Thermopile	SR11-7196	Hukseflux
12	Semiconductor	SP-110	Apogee	28	Thermopile	SR11-7242	Hukseflux
13	Semiconductor	LI-200	LI-Cor	29	Thermopile	LP02-41120	Hukseflux
14	Semiconductor	P007	David Brooks	30	Thermopile	LP02-41272	Hukseflux
15	Semiconductor	ATI	Ascension Technology, Inc. RSR/LI-Cor	31	Semiconductor	NREL-CRADA-RSR2	Irradiance Inc./LI-Cor
16	Semiconductor	RSP	LI-Cor	32	Semiconductor	Solar-Mil.-CRADA-RSR	Solar Millennium AG./LI-Cor

DNI Instrument List:

Instrument Number	Instrument Type	Model	Manufacturer
1	Thermopile	NIP2	Eppley Laboratory, Inc.
2	Thermopile	NIP1	Eppley Laboratory, Inc.
3	Semiconductor	LI-201	LI-Cor
4	Semiconductor	ATI/LI-Cor	Ascension Technology Inc./LI-Cor
5	Semiconductor	RSP/LI-Cor	Irradiance Inc./LI-Cor
6	Thermopile	TSR-590	YES, Inc.
7	Thermopile	TSR-591	YES, Inc.
8	Thermopile	TSR-592	YES, Inc.
9	Thermopile	TSR-590LH	YES, Inc.
10	Thermopile	TSR-591LH	YES, Inc.
11	Thermopile	TSR-592LH	YES, Inc.
12	Thermopile	TSR-590JM	YES, Inc.
13	Thermopile	TSR-591JM	YES, Inc.
14	Thermopile	TSR-592JM	YES, Inc.
15	Semiconductor	NREL-CRADA-RSR2/LI-Cor	Irradiance Inc./LI-Cor
16	Thermopile	SPN1	Delta-T
17	Thermopile	DR018066	Hukseflux
18	Thermopile	DR018068	Hukseflux
19	Semiconductor	Solar-Mil.-CRADA-RSR/LI-Cor	Solar Millennium AG./LI-Cor

Reference:

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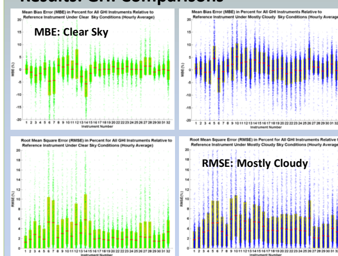
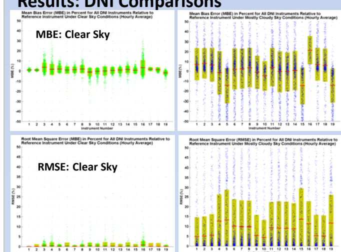
Results: GHI Comparisons



- The average mean bias error (MBE, %) appeared to fall within ±5% for almost all instruments using the 95% confidence coverage.
- Under clear-sky conditions, the relative difference appeared to exhibit less bias, and the mean differences (red line) for most test instruments tended to have less variability than they did under the mostly-cloudy sky condition.
- The average root mean square error (RMSE, %) appeared to fall within 4% for most of the instruments using the 95% confidence coverage.

Fig.3: Clear and mostly cloudy sky condition: (top) MBE and (bottom) RMSE in percent for the hourly average for all GHI data under study. The red line signifies the mean value of the differences for the 95% confidence level.

Results: DNI Comparisons



- Under mostly cloudy sky conditions, some factors, such as temporal responsivity and field of view of the radiometers, become an influence for the higher RMSE in percent.
- The clear-sky conditions demonstrated tighter differences among the instruments than the rest of the sky conditions. The two Eppley normal incidence pyrheliometers (NIP) and the two Hukseflux model "DR" types had less MBE than others under clear-sky conditions. However, the sensitivity of the DNI was much higher than the GHI under partly or mostly cloudy sky conditions.

Fig.4: Clear- and mostly cloudy sky condition: (top) MBE and (bottom) RMSE in percent for the hourly average for all DNI data under study.

Rotating Shadowband Radiometer Correction Algorithm Outcome

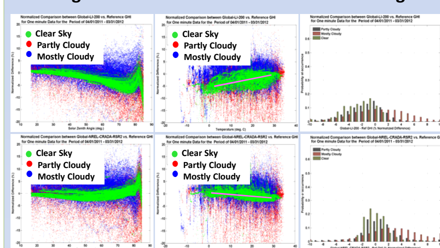


Fig.5: (Top) Comparison between the uncorrected silicon photodiode sensor and (bottom) corrected silicon photodiode—RSR2

- The temperature and zenith dependence appeared to be smaller in the NREL-CRADA-RSR2 than the LI-200. The NREL-CRADA-RSR2 instrument has a built-in correction algorithm in the data acquisition system supplied by the manufacturer that minimizes spectral, angular, and temperature sensitivity issues.
- A clear shift of the probability distribution for the clear-sky condition from negative errors for the LI-200 to smaller and relatively normally distributed errors for the RSR2 was observed.

Eppley PSP Ventilator Effect on Thermal Offset

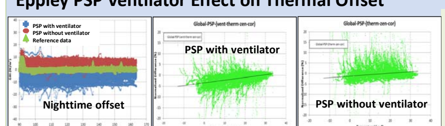
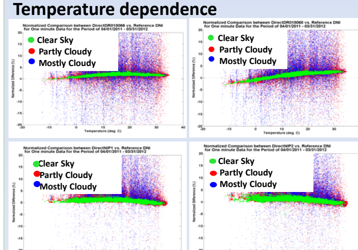


Fig.6: Understanding nighttime thermal offset (left) under all sky conditions and normalized differences (UUT minus reference) versus temperature for (middle) ventilated and (right) unventilated Eppley Laboratory, Inc., PSP radiometers under clear-sky conditions (1-minute data).

- The negative output of irradiance is due to a thermal energy exchange in which the thermopile emits energy to the sky.
- The ventilator on the ventilated PSP tended to affect the irradiance by creating an additional temperature imbalance between the case and dome of the instrument.
- More apparent thermal offset during winter or cold ambient temperatures was observed.
- The condition could be exacerbated if the ventilator filter of the PSP is not cleaned for some time and airflow is restricted.

Temperature dependence



- The Hukseflux radiometer model number DR108068 had relatively more evident temperature dependence than model number DR108066.
- The two Eppley NIP radiometers tended to have less temperature dependence, especially at temperatures below 20°C.

Fig.7: Effect of temperature on DNI measurement

Summary:

- **Under clear-sky conditions when the solar zenith angle was less than 60 degrees, differences of less than 5% were observed for both GHI and DNI measurements when compared to the reference radiometers.**
- **For data during periods when the solar zenith angle was greater than 60 degrees, differences in GHI under mostly cloudy and clear-sky conditions increased to 17%. Differences of up to 40% in DNI measurements on a few instruments were found for high solar zenith angles under mostly cloudy sky conditions.**
- **Some of these differences were expected from the various instrument design characteristics for time response, spectral response, angular (cosine) response, field of view, and temperature response.**

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