INTERCOMPARISON OF 51 RADIOMETERS FOR DETERMINING GLOBAL HORIZONTAL IRRADIANCE AND DIRECT NORMAL IRRADIANCE MEASUREMENTS

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ABSTRACT

Accurate solar radiation measurements require properly installed and maintained radiometers with calibrations traceable to the World Radiometric Reference (WRR). This study analyzes the performance of 51 commercially available and prototype radiometers used for measuring global horizontal irradiances (GHI) or direct normal irradiances (DNI). These include pyranometers, pyrhemimeters, rotating shadowband radiometers (RSR)², and a pyranometer with an internal shading mask deployed at the National Renewable Energy Laboratory's (NREL) Solar Radiation Research Laboratory (SRRL). The radiometers in this study were deployed for one year (from April 1, 2011, through March 31, 2012) and their measurements were compared under clear sky, partly cloudy, and mostly cloudy conditions to reference values of low estimated measurement uncertainties. Mean Bias Difference (MBD) and Root Mean Square Difference (RMSD) statistics were used as metrics to compare the GHI and DNI values from individual instruments with concurrent measurements using the reference instruments over time intervals of one-minute, 10-minute, and hourly averages. Deviations from the reference irradiance measurements were calculated as a percent and W/m² of the reference value 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 $\pm 5\%$ were observed among all GHI and DNI measurements when compared to the reference radiometers. For GHI these normalized differences increased up to $\pm 17\%$ under mostly-cloudy and clear-sky conditions when the solar zenith angle was greater than 60 degrees. The normalized differences were greater yet under mostly- cloudy conditions (approaching $\pm 40\%$) for few DNI data sets at higher solar zenith angles. The intent of this paper is to present a general overview of each radiometer's performance based on the instrumentation and environmental conditions available at NREL.

Keywords: Global Horizontal Irradiance; GHI; Direct Normal Irradiance; DNI; Diffuse Horizontal Irradiance; DHI; Pyranometer; Pyrhemimeter; Rotating Shadowband Radiometer; RSR;

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² In 2011, IEA Task 46 activity B1 adopted the name Rotating Shadowband Irradiometers (RSI) to categorize this type of measurement systems

1. INTRODUCTION

Accurate solar radiation measurement is essential for reducing the risks associated with the increased deployment of solar energy conversion systems on a variety of generation scales throughout the world (Habte et al., 2015). For instance, in order to finance these systems through a power purchase agreement (PPA), banks demand assurances that these systems will produce the energy predicted through performance models. Failing to meet the minimum energy performance requirements can result in large financial penalties requiring expensive risk mitigation measures. Since 1981, the Solar Radiation Research Laboratory (SRRL) at the National Renewable Energy Laboratory in Golden, Colorado, USA has provided a continuous record of solar irradiance and surface meteorological conditions, improved methods for the calibration of radiometers and dissemination of solar resource data through the Measurement and Instrumentation Data Center (MIDC) (Andreas and Stoffel, 1981). MIDC provides historical solar data from multiple radiometers with calibration traceability to the Système International d'Unités through the World Radiometric Reference (WRR) (Fröhlich 1977 and Fröhlich 1991, Stoffel and Reda, 2013). This paper provides a comprehensive estimation of differences associated with radiometric data obtained from various radiometers under a wide range of sky conditions with respect to a measurement reference demonstrating low estimated measurement uncertainty. Some of the variables contributing to the observed differences include radiometer calibrations and each instrument's unique response characteristics to variations in solar zenith angle, solar and atmospheric spectral irradiance distributions, temperature, installation (e.g., sensor tilt), aging, nonlinearity, and other environmental conditions. The solar measurements from the radiometers were quality assessed to minimize erroneous data used in our analyses. However, our results are presented with some caveats: (1) A sufficient number of radiometers for each model were not available to provide representative sample data for each manufacturer's product. (2) In our professional experience, we have found that each instrument responds differently under various climatic/weather conditions; thus, these results are specific to the conditions encountered at SRRL in Golden, Colorado, USA (39.742° N, 105.18° W, 1,829 m AMSL) during the period of analysis (April 1, 2011 through March 31, 2012). (3) Solar irradiance at the Earth's surface is extremely variable over space and time, and the reference and test instruments have different inherent responses to changes in solar and atmospheric radiation, spectral radiation distribution, incidence angle of the incoming radiation (e.g., pyranometer cosine response), thermal offset and temperature sensitivities. Thus, while some instrument performance characteristics may be similar in other operational environments, the limited data set and specific location used for this study should not be used to infer comprehensive conclusions of radiometer performance beyond the context of the evaluations. This paper intends to provide the reader with a general understanding about how each radiometer behaves under specific documented conditions when compared to the selected reference data.

2. MATERIALS AND METHODS

Most of the instruments in this study are owned by NREL as part of our ongoing Baseline Measurement System (BMS). For this study, additional instruments were provided by the manufacturers at the request of NREL or as part of a Cooperative Research and Development Agreement (CRADA). A complete list of instruments is provided as Table 1 and Table 2. The manufacturers were allowed to select the instruments they provided, and NREL made no effort to ensure that they were representative of typical production units. In the case of

1 manufacturer-owned instruments, prior to the start of the evaluation period, the manufacturers were allowed to
2 ensure that their instruments were installed and operating to their satisfaction. After the evaluation period began, the
3 manufactures were not allowed any contact or interaction with the instruments. All data collected from the
4 instruments for this study were downloaded directly to NREL computers. The Solar Millennium instrument (Solar-
5 Mil.-CRADA-RSR) was set up by the manufacturer with special internal processing to take the place of the external
6 processing that is usually provided by the manufacturer on corporate servers. As noted below, this necessitated the
7 omission of the instrument's usual one-minute data output.

8 The performance of each test instrument relative to the reference instrument was analyzed using the Mean
9 Bias Difference (MBD) and Root Mean Square Difference (RMSD) statistics. One-minute reference global
10 horizontal irradiance (GHI) data were calculated using the reference direct normal irradiance (DNI) and diffuse
11 horizontal irradiance (DHI) instruments. The reference GHI and DNI data and unit under test (UUT) GHI and DNI
12 data were then averaged to obtain 10-minute and hourly data. The 10-minute data were averaged from the observed
13 one-minute data—except for the Solar-Mil.-CRADA-RSR, which recorded the data as 10-minute averages. The
14 hourly data for all radiometers were averaged from the 10-minute data sets.

15 Data from 32 GHI and 19 DNI radiometers are presented in Table 1 and Table 2. Reference values of GHI
16 were calculated using a reference DNI and a reference DHI using the component sum method (Equation 1). The
17 performance of each instrument was derived from time-series measurements relative to the corresponding reference
18 irradiance. Reference DNI data were obtained using a Kipp and Zonen model CH1 pyrheliometer (serial number
19 010256), and reference DHI measurements were made by two Eppley Laboratory, Inc., model 8-48 pyranometers
20 (serial number 21096 was replaced for re-calibration on May 26, 2011 by 32331). The 8-48 (“black and white”)
21 pyranometers were not ventilated. The DHI data for the two Eppley model 8-48 pyranometers were analyzed for
22 any systematic shift in the reference DHI data. . A comparison of one-minute measurements of GHI/DHI under
23 clear sky conditions for five days prior to and five days after the instrument exchange suggested no significant shift
24 between the two DHI reference pyranometers. Furthermore, 85% of the reference DHI data included in this paper
25 came from the Eppley model 8-48, serial number 32331 (May 26, 2011 to March 31, 2012). The reference DNI and
26 DHI instruments were mounted in an automatic solar tracker to provide accurate and continuous alignment of the
27 pyrheliometer and the shading device for the pyranometer. Previous studies (Wilcox and Myers 2008, Michalsky et
28 al. 2011) and Broadband Outdoor Radiometer Calibration (BORCAL)³ results from these instruments confirm that
29 the CH1 exhibits relatively lower calibration and measurement uncertainty compared to others in the sample. For
30 consistency with our previous study, the model 8-48 pyranometer for the diffuse measurement was selected instead
31 of an available model CM22 pyranometer to minimize a possible systematic design bias that might favor the
32 evaluation of the CM22 global instrument. Each GHI instrument under test was then compared to the calculated
33 reference GHI values.

³ BORCAL reports are available from <http://www.nrel.gov/aim/borcal.html>

2.1 Data Logging

The irradiance measurements were recorded as one-minute averages of three-second samples for most radiometers. The ATI radiometer was recording two-second samples, the TSR radiometers were recording every 15 seconds and the Hukseflux radiometers recorded one second samples. For these radiometers the data were recorded using Campbell Scientific, Inc., data loggers. The exceptions are the Solar-Mil.-CRADA-RSR where the data were collected every 10 minutes using a Campbell Scientific, Inc., data logger. The TSRs reported data every one-minute using a proprietary YES Inc., data acquisition system based on a 15 second sample rate. All the one-minute data were averaged to produce the 10-minute and hourly data used in our evaluations. The differing sample rates among instruments will have some effect on the representativeness of the averages, but these differences are not considered significant at the ten minute and hourly level.

2.2 Reference Data

The reference radiometers were calibrated with an absolute cavity radiometer traceable to the World Radiometric Reference (WRR) using NREL's Broadband Outdoor Radiometer Calibration process (Myers et al., 2001). This method provides the lowest calibration and measurement uncertainties for both GHI and DNI irradiances (Myers, 2013, Michalsky et al., 2011, Wilcox and Myers 2008). The reference GHI was computed from measurements by the reference DNI and DHI radiometers as shown in Equation 1:

$$GHI = DNI * \cos(\text{Solar Zenith Angle}) + DHI \quad (1)$$

2.1.1 Correcting Reference Data for Temperature Dependence

The manufacturer specifications state the temperature dependencies of the reference radiometers (Figure 1). The temperature dependency function from Figure 1 was used to correct the reference irradiance data obtained from the reference radiometers based on the coincident meteorological measurements of air temperature.

Figure 1. Temperature dependencies for the Kipp and Zonen model CH1 (left) and (right) the Eppley Laboratory, Inc., model 8-48 reference radiometers.

This correction process resulted in an approximate $\pm 0.08\%$ difference on average for both DNI and calculated GHI (reference GHI) dataset compared to the uncorrected data.

2.3 Measurement Uncertainty

Each instrument, including the reference instruments, had its own estimated measurement uncertainty based on the design and performance specifications. The measurement uncertainty analysis and estimation is beyond the scope of this paper⁴. Previous work by Reda et al., 2011 and Habte et al., 2014 describe the methodology of radiometric measurement uncertainty estimation using the *Guide to the Expression of Uncertainty in Measurement* (GUM; JCGM, 2008). The calibration and measurement uncertainty estimates of the reference and test radiometers are essential to properly interpret the reported differences obtained in this study. That is, observed differences among the radiometers must be greater than the uncertainty estimates to be considered measurable. Habte et al., 2015 reported about $\pm 2.1\%$ uncertainty for the GHI reference data and about $\pm 1\%$ for the reference DNI data. The percent uncertainties are obtained from the average irradiance reading of the study period and include the calibration uncertainties of the reference radiometers. Further the CR23X Campbell Scientific data logger used to acquire the study data contributes to the overall uncertainty. Wilcox and Myers, 2008 reported around $\pm 1.5\%$ uncertainty from the data logger to the average reference irradiance. Therefore, the expanded or overall uncertainties (coverage factor = 1.96) of the reference data would be the root sum of the squares of the irradiance and the data logger uncertainty, resulting in $\pm 2.6\%$ and $\pm 1.8\%$ for reference GHI and DNI, respectively. Hence, in this paper the reported differences between the reference data and the unit under test (UUT) would be statistically significant if the difference is greater than the overall reference data uncertainty.

2.4 Data Quality

Multiple post-measurement data quality schemes were applied to the radiometric data. Some of these schemes target detecting equipment and operational related errors and data issues as a result of contaminated optics.

2.4.1 SERI_QC

A data quality assessment software tool (SERI_QC) was applied to each data point (Maxwell, et al., 1993). Using an empirical approach, the process combines three-component redundancy (i.e., Equation 1) with acceptable physical limits of the measurements for a specific measurement location and assigns a data quality value, or flag, for each data point based upon a normalization process involving the dimensionless (clearness index (K_t), effective diffuse horizontal transmittance (K_d) and direct beam transmittance (K_n)) derived from the corresponding extraterrestrial radiation. This data quality assessment tool was applied to the reference and UUT data in this study. Data that were outside of the physical limits previously developed for SRRL measurements were excluded from the analysis.

2.5 Operation and Maintenance

Proper installation, operation and maintenance of the instruments are critical for measuring accurate solar resources. The installation of all instruments at SRRL is consistent with current best practices (Sengupta et al., 2015). Cleaning radiometer optical surfaces on a regular basis minimizes the attenuation of the signals by

⁴ A tool for estimating radiometer measurement uncertainties is available from http://www.nrel.gov/midc/radiometer_uncert.xlsx

contaminates. However, in some cases, accumulation of snow or frost could create greater statistical differences between the reference and unit under test (UUT) because some instruments tend to accumulate more snow or frost than others. To minimize the effect of this accumulation, some of the pyranometers are equipped with ventilators as noted in Table 1. Proper leveling of the pyranometers is essential to avoiding any asymmetric responses by these radiometers throughout the day. Checking desiccants, when part of the radiometer design, is important for preventing condensation inside the optical surfaces, which would affect the signal. Further, regularly checking the signal cable condition can help to prevent data loss or signal contamination. However, these problems might not have been completely detected and removed by the SERI_QC software.

Some instruments have built-in post-measurement correction algorithms that are applied by the onboard data logger for known instrument response characteristics. These corrections are applied by the manufacturer during routine data acquisition and were available in the instrument output data set used for this study. Further, the Eppley model Precision Spectral Pyranometer (PSP) used in this study has correction algorithms developed and applied by NREL (Andreas and Stoffel, 1981; Reda, 1998). A thermal correction to GHI data using coincident measurements of infrared irradiance by a collocated pyrgeometer and a correction to the GHI pyranometer responsivity as a function of the solar zenith angle were implemented in the study. Results for both the uncorrected PSP (as typically deployed) and the NREL-corrected PSP are included in our study. The three Yankee model TSR instruments had experimental post-processing applied to test research algorithms under development (Michalsky et. al., 1987). The same instruments were used for measurements, and the sensor data were replicated into three different data streams, each treated as independent instruments by the study (e.g., TSR-59x, TSR-59x-LH and TSR-59x-JM).

2.6 Data Filtering

Selected data points were excluded from the analysis to maintain a consistent comparison among instruments for the 12-month period. If data were excluded from one instrument, data from the same period were excluded from all instruments. The exception was the Yankee model Thermopile Shadowband Radiometer 591 (TSR-591), which had incorrect or no data for the month of November 2011. To minimize the loss of data in the analysis from all the UUT, we did not include data from TSR-591, TSR-591-LH and TSR-591-JM in the filtering process for the November 2011.

The study included only daytime data (e.g., solar zenith angles less than or equal to 85 degrees). Some data points at solar zenith angles approaching 85 degrees (i.e., periods with typically low solar irradiance levels) were excluded from the analysis to avoid the effects of large relative differences during the low absolute magnitude of irradiance near sunrise and sunset. Therefore, differences greater than $\pm 100\%$ were excluded from the final analysis for all UUT radiometers. This criterion is consistent with a previous study (Wilcox and Myers 2008).

Furthermore, concurrent data from a Yankee Environmental Systems, Inc., total sky imager (TSI) model TSI-880 were used to categorize irradiance data from all the instruments according to clear, partly-cloudy, and mostly-cloudy sky conditions. The total cloud cover percentage from the TSI-880 instrument was used for this classification. The instrument provides high-resolution, one-minute data that coincide with the radiometric data. In our experience, the instrument tends to underestimate cloud cover, and for this reason a simple criterion that mitigates the problem was developed to distinguish cloud cover ranges. Sky condition categories were determined as

follows: Clear sky conditions when TSI total cloud cover data were less than 1.2%; partly- cloudy from 1.2% to 60%; and mostly-cloudy when TSI total cloud cover data were greater than 60%.

2.7 Data Normalization

To remove potential instrument calibration biases and to better isolate the environmental effects, the annual radiometric data from the test instruments were normalized to the reference irradiance data. Normalization was done by isolating the irradiance data under all sky conditions for the study period (April 1, 2011, through March 31, 2012) between 44- and 46-degree solar zenith angles and summing all the data in this solar zenith angle range for each radiometer. The specified solar zenith angle range was selected to conform to the NREL convention of reporting all broadband radiometer calibrations at a 45-degree solar zenith angle (Myers et al., 2000). A ratio was then obtained by dividing each test radiometer summation by the sum of the reference data derived using the same criterion. The ratio for each test radiometer was then used to acquire the new normalized irradiance value by dividing each test irradiance value for the time interval by the normalization ratio (Equation 2):

$$Normalization\ Factor = \frac{\sum I_{UUT\ 44^{\circ}\ to\ 46^{\circ}}}{\sum I_{Ref\ 44^{\circ}\ to\ 46^{\circ}}} \quad (2)$$

where $I_{UUT\ 44^{\circ}\ to\ 46^{\circ}}$ is the irradiance data under all sky condition for the UUT within the two-degree solar zenith angle bin and $I_{Ref\ 44^{\circ}\ to\ 46^{\circ}}$ 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 (Equation 3):

$$I_{UUT(New)} = \frac{I_{UUT}}{Normalization\ Factor} \quad (3)$$

The adjustments used to normalize the data for each instrument are included in Table 1 and Table 2 as the Normalization Factor column. Comparing calibration methods is beyond the scope of this paper, but the factors listed in the two tables will provide users with an indication of possible variances among calibration techniques that could affect the accuracy of their measurements. A normalization factor greater than one indicated that the UUT data were higher than the reference radiometer measurement. A normalization factor lower than one meant that the UUT was underestimating irradiance relative to reference data.

Overall, as shown by the values in Table 1 and Table 2, the data normalization process presented an approximate range of $\pm 5\%$ compared to the un-normalized data for both the GHI and DNI data sets. This statistic should not be interpreted or included as a quantified uncertainty for each instrument, as it is intentionally independent of the results presented here. It is included to educate the user of possible calibration bias in field measurements and to convey a full understanding of the study method. Note that most of the normalizations for NREL-calibrated instruments are within $\pm 1\%$, indicating a consistency at the study location. However, instruments calibrated at NREL have demonstrated a shift in calibration when moved to another location and environment. The same may be true for instruments calibrated at other locations using other methods, which may be in part revealed by the normalization statistic. This underscores our assertion that these results cannot be used to infer instrument behavior at all locations.

Table 1: GHI Instrument List

Inst. #	Instrument Type	Model	Normalization Factor	Manufacturer and Comment	Inst. #	Instrument Type	Model	Normalization Factor	Manufacturer and Comment
1	Thermopile	CM22 ^a	1.01	Kipp & Zonen -DC Ventilated - Clear glass domes	17	Semiconductor	LI-200	0.99	Irradiance, Inc./ LI-COR - Diffuser - LICOR secondary sensor sitting outside of the RSR2 unit
2	Thermopile	CM6b ^a	1.01	Kipp & Zonen - Clear glass dome	18	Thermopile	TSR-590	0.96	YES, Inc. - Diffuser
3	Thermopile	CM3- CNR1 ^a	1.01	Kipp & Zonen - Does not have a relatively clear view of the sky (current location) - Clear glass dome	19	Thermopile	TSR-591	0.95	YES, Inc. - Diffuser
4	Thermopile	PSP ^a	1.00	Eppley Laboratory, Inc. - AC Ventilated, thermal, and zenith corrected - Clear glass domes	20	Thermopile	TSR-592	0.96	YES, Inc. - Diffuser
5	Thermopile	PSP ^a	1.00	Eppley Laboratory, Inc. - Thermal, and zenith corrected - Clear glass domes	21	Thermopile	TSR-590-LH ^b	0.97	YES, Inc. - Correction applied - Diffuser
6	Thermopile	PSP ^a	0.99	Eppley Laboratory, Inc.	22	Thermopile	TSR-591-LH ^b	0.97	YES, Inc. - Correction applied - Diffuser
7	Thermopile	PSP ^a	1.00	Eppley Laboratory, Inc. - Clear glass dome	23	Thermopile	TSR-592-LH ^b	0.97	YES, Inc. - Correction applied - Diffuser
8	Thermopile	TSP-700 ^a	1.01	YES, Inc.	24	Thermopile	TSR-590-JM ^c	0.99	YES, Inc. - Correction applied - Diffuser
9	Thermopile	TSP-1 ^a	1.00	YES, Inc.	25	Thermopile	TSR-591-JM ^c	0.99	YES, Inc. - Correction applied - Diffuser
10	Thermopile	SPN1 ^a	1.03	Delta-T - Clear glass dome - Fixed shade band geometry	26	Thermopile	TSR-592-JM ^c	0.98	YES, Inc. - Correction applied - Diffuser
11	Semiconductor	SPLite ^a	1.01	Kipp & Zonen - Diffuser	27	Thermopile	SR11-7196	0.97	Hukseflux - Clear glass dome
12	Semiconductor	SP-110 ^a	1.06	Apogee - Diffuser	28	Thermopile	SR11-7242	0.98	Hukseflux - Clear glass dome
13	Semiconductor	LI-200 ^a	1.01	LI-COR - Diffuser	29	Thermopile	LP02-41120	0.99	Hukseflux - Clear glass dome
14	Semiconductor	P007	1.00	David Brooks - Experimental sensor - Diffuser	30	Thermopile	LP02-41272	0.97	Hukseflux - Clear glass dome
15	Semiconductor	ATI/ LI- 200	1.00	Ascension Technology, Inc., RSR /LI-COR - Obsolete, replaced by RSR2 - Diffuser	31	Semiconductor	NREL- CRADA- RSR2/ LI-200	0.98	Irradiance Inc./LI-COR - Experimental instrument; not for sale - Diffuser
16	Semiconductor	RSR2/ LI-200	0.98	Irradiance, Inc./ LI- COR - Diffuser	32	Semiconductor	Solar-Mil.- CRADA-RSR/ LI-200	1.00	Solar Millennium AG./Reichert GmbH/LI-COR - Not available (Solar Millennium, Inc., is out of business) - Diffuser

^a Current NREL calibration factor used during the period of the evaluation

^b Empirical Radiometric Correction applied by Lee Harrison (Michalsky et. al., 1987)

^c Empirical Radiometric Correction applied by Joseph Michalsky (Michalsky et. al., 1987)

Table 2: DNI Instrument List

Inst. #	Instrument Type	Model	Normalization Factor	Manufacturer/Comment
1	Thermopile	NIP ^a	0.99	Eppley Laboratory, Inc. - Glass window (Normal Incidence Pyrheliometer, sample 2)
2	Thermopile	NIP ^a	0.99	Eppley Laboratory, Inc. - Glass window (Normal Incidence Pyrheliometer, sample 1)
3	Semiconductor	LI-201 ^a	0.94	LI-COR - Experimental instrument; not for sale - Diffuser
4	Semiconductor	ATI/ LI-COR ^b	1.04	Ascension Technology Inc./LI-COR - Obsolete, replaced by RSR2 - Diffuser
5	Semiconductor	RSR2/ LI-COR ^b	0.98	Irradiance Inc./LI-COR - Diffuser
6	Thermopile	TSR-590 ^b	0.99	YES, Inc. - Diffuser
7	Thermopile	TSR-591 ^b	0.97	YES, Inc. - Diffuser
8	Thermopile	TSR-592 ^b	0.99	YES, Inc. - Diffuser
9	Thermopile	TSR-590LH ^b	0.99	YES, Inc. - Diffuser
10	Thermopile	TSR-591LH ^b	0.98	YES, Inc. - Diffuser
11	Thermopile	TSR-592LH ^b	0.99	YES, Inc. - Diffuser
12	Thermopile	TSR-590JM ^b	0.98	YES, Inc. - Diffuser
13	Thermopile	TSR-591JM ^b	0.97	YES, Inc. - Diffuser
14	Thermopile	TSR-592JM ^b	0.97	YES, Inc. - Diffuser
15	Semiconductor	NREL-CRADA-RSR2/LI-COR ^b	0.98	Irradiance Inc./LI-COR - Experimental instrument. Not for sale. - Diffuser
16	Thermopile	SPN1 ^{ab}	1.05	Delta-T - Clear glass dome
17	Thermopile	DR018066	0.97	Hukseflux - Glass window
18	Thermopile	DR018068	0.98	Hukseflux - Glass window
19	Semiconductor	Solar-Mil.-CRADA-RSR/ LI-COR ^b	1.00	Solar Millennium AG./Reichert GmbH/LI-COR - Not available (Solar Millennium, Inc., is out of business)

^a Current NREL calibration factor used during the period of the evaluation

^b Calculated using global and diffuse measurements

3. RESULTS AND DISCUSSION

3.1 Comparison Result for Global Horizontal Irradiance Radiometers

The figures and tables discussed in the results section show the performance of each unit under test (UUT) instrument relative to the reference instrument under various sky conditions. Mean Bias Difference (MBD) and Root Mean Square Difference (RMSD) statistics were used as the basic set of performance measures to assess the performance of each UUT relative to the reference instruments. MBD calculations both in percent and power density in watts per square meter square (W/m^2) were used to assess radiometer performance (Equation 4). Further, supplemental meteorological measurements such as temperature and wind speed from the collocated instruments were used to assist in the analysis. Each radiometric data value from the test instruments demonstrated systematic differences as a function of solar zenith angle, temperature, and wind speed.

$$MBD(\text{W/m}^2) = \frac{1}{n} \sum_{i=1}^n (I_{UUT(New)_i} - I_{Ref_i}) \quad \text{and} \quad MBD(\%) = \left(\frac{1}{n} \sum_{i=1}^n \frac{(I_{UUT(New)_i} - I_{Ref_i})}{I_{Ref_i}} \right) * 100 \quad (4)$$

where, $I_{UUT(New)}$ is the irradiance value for the UUT in W/m^2 and I_{Ref} is the irradiance value for the reference instrument in W/m^2 .

RMSD demonstrates the randomness in the data, and the calculation was performed in percent differences using Equation 5.

$$RMSD(\%) = \sqrt{\left(\frac{1}{n} \sum_{i=1}^n \left(\frac{I_{UUT(New)_i} - I_{Ref_i}}{I_{Ref_i}} \right)^2 \right)} * 100 \quad (5)$$

Figure 2 and Figure 3 demonstrate the 10-minute and hourly average GHI data comparison, respectively, for all instruments under test. The ranges of MBD and RMSD in percent are shown for each instrument. These plots demonstrate the relative tendencies or performance of each instrument with respect to the references used in our study. As shown in the figures, the plots are bounded by $\pm 20\%$ MBD for GHI. Data points outside of these bounds were not included in the statistical analyses. These criteria helped limit the contribution of outlying high-percentage differences that could have resulted from time response differences among the instruments, performance disruptions during routine cleaning events, and/or erroneous observations for unknown reasons. Further, Figure 2 and Figure 3 illustrate the skewness of the differences when the MBD (%) tended to the positive on some of the instruments and negative on others. These characteristic differences assisted in identifying the overestimation or underestimation of irradiance by each UUT instrument. Under clear-sky conditions, the relative difference appeared to exhibit less bias and the mean differences (red line) for most UUT tended to have less variability than the partly-cloudy or mostly-cloudy sky condition. One important aspect to note from Figure 2 and Figure 3 is that the sizes of the 95% confidence interval indicated by the black boxes, provide valuable information about the scatter of the differences between the reference instrument and the UUT. Smaller/larger ranges of the 95% confidence intervals depict smaller/larger differences in the comparative data. Further, UUT instruments that showed higher variability above

the confidence interval box, either to the positive or negative trend, tended to have relatively lower performance characteristics in the higher zenith angle ranges. (See Appendix - [Table A.1](#). for individual instrument performance.)

Figure 2. MBD in percent for the 10-minute average GHI data under study ((A) all sky, (B) clear sky, (C) mostly-cloudy sky, and (D) partly-cloudy sky). The red line signifies the mean value of the MBD for the 95% confidence level (black color - box). See [Table 1](#) for the instrument number, name and model.

The 10-minute average data showed more scatter than found in the hourly-averaged results. (Compare the ranges among the 10-minute plots in [Figure 2](#) and the hourly plots in [Figure 3](#)). In general, the average MBD (%) for GHI data from all zenith angles (17 degrees to 85 degrees) appeared to fall within $\pm 5\%$ for almost all instruments using the 95% confidence coverage for the 10-minute and hourly averaging time.

Figure 3. MBD in percent for the hourly averaged GHI data under study ((A) all sky, (B) clear sky, (C) mostly cloudy sky, and (D) partly cloudy sky). The red line signifies the mean value of the MBD for the 95% confidence level (black color - box). See [Table 1](#) for the instrument number, name and model.

The MBD values shown in Appendix - [Table A.1](#). present all differences within a $\pm 100\%$ data exclusion range. There could have been outliers that were close to the data exclusion range that might have affected the overall MBD average in each bin of the higher solar zenith angle and mostly-cloudy conditions. These two situations included irradiance values of a very small magnitude, and ratios of two small irradiance numbers will produce high MBD in percent (the yellow highlighted values in Appendix - [Table A.1](#)).

[Figure 4](#) presents the RMSD results for GHI in percent. As can be expected during stable atmospheric conditions, all instruments had relatively low RMSD values during clear-sky conditions than during partly- and mostly-cloudy sky conditions. These results can be largely attributed to the differing instrument response characteristics (e.g., time-response, spectral response, and etc.) invoked under changing sky conditions ([Vignola, Stoffel, and Michalsky 2012](#)). The fast responding photodiode instruments may exhibit greater RMSD than the slower response thermopile instruments. Some of this may be a false representation of where the measurement difference originates (i.e., with the reference instrument rather than the UUT).

Further, both the MBD and RMSD values should be taken into consideration (e.g., Figure 2 through Figure 4) to understand the performance of each instrument relative to the reference instrument. For instance, one instrument could have less bias but higher RMSD; therefore, an instrument with less bias and less RMSD would perform similarly to the reference data. This also applies to the DNI data set comparison, which is discussed in Section 3.2.

Figure 4. RMSD in percent for the hourly average GHI data under study ((A) all sky, (B) clear sky, (C) mostly cloudy sky, and (D) partly cloudy sky). The red line signifies the mean value of the RMSD for the 95% confidence level. Refer to Table 1 for the instrument number, name and model.

3.1.1 Photodiode Pyranometer Characteristics

The fast responding photodiode instruments could also exhibit large differences due to the design impacts of detector time response, having optical diffusers versus glass domes above the detectors, higher temperature sensitivity in some wavelength ranges relative to thermopile pyranometers, and the limited spectral response range of the photodiode detectors compared to the black thermopile detectors. Figure 5 illustrates a GHI solar spectral distribution at 1.5 Airmass and the relative spectral response characteristics of silicon photodiode radiometers from 400 nm to 1,100 nm (e.g., the LI-COR Model LI-200) and the typical spectral response of single-black detectors

used in thermopile-based radiometers. Photodiode detectors are fast-responding sensors (e.g., less than 1 μsec for 1/e) and are calibrated to a thermopile spectral range (300 nm to 4,000 nm).

Figure 5. GHI solar spectrum with thermopile and silicon photodiode pyranometers spectral response (modified from Myers 2011 and Myers 2013).

Silicon photodiode pyranometers tend to have reasonable accuracy under the calibration conditions, but have spectral, angular, and temperature sensitivity characteristics that contribute to significant differences under measurement conditions differing from the calibration conditions. Post-measurement correction methods have been developed for pyranometers based on photodiode detectors (Myers 2011, Vignola 2006, King and Myers 1997). The NREL-CRADA-RSR2 instrument has a built-in correction algorithm in the data acquisition system supplied by the manufacturer (Irradiance, Inc.). These algorithms apply different correction methods to minimize the above-mentioned issues. It appears that the application of such algorithms in the NREL-CRADA-RSR2 minimized the deviation of the data relative to the reference instrument (Refer to Appendix - Table A.1. for NREL CRADA RSR2). The NREL-CRADA-RSR2 uses a LI-COR model LI-200 pyranometer; Figure 6 demonstrates the comparison results between the NREL-CRADA-RSR2 (instrument # 31 in Table 1) and the stand-alone LI-200 (instrument # 13 in Table 1) sensors for GHI irradiance relative to the reference instrument data. The stand-alone LI-200 instrument does not have spectral, angular, or temperature sensitivity corrections. Between the two instruments, there was a clear shift of the probability distribution for the clear-sky condition from negative differences for the LI-200 (Figure 6 – C) to less and relatively normally distributed differences in GHI from the NREL-CRADA-RSR2 (Figure 6 – F). However, in the mostly-cloudy sky condition, the probability distribution differences shifted more to the positive MBD for the NREL-CRADA-RSR2.

Figure 6. Comparison relative to reference data between the uncorrected silicon photodiode pyranometer LI-200 (top) and corrected silicon photodiode NREL-CRADA-RSR2 (bottom) by solar zenith angle (A&D) and ambient air temperature (B&E), and probability distribution differences (C&F).

As a result of the post-measurement corrections, the temperature and zenith dependencies appeared to be less in the NREL-CRADA-RSR2 (Figure 6 – D) than the stand-alone LI-200 (Figure 6 – A). However, these improvements were more conspicuous for the clear-sky condition than the partly- or mostly-cloudy conditions. Under clear-sky conditions, the NREL-CRADA-RSR2 tended to have better temperature sensitivity (Figure 6 – E) performance than the stand-alone LI-200 (Figure 6 – B). This is likely due to the temperature correction algorithm applied in the NREL-CRADA-RSR2 system. Under mostly-cloudy sky conditions, NREL-CRADA-RSR2 did not show much improvement. This could be related to the spectral sensitivity of the sensors in which the instrument is susceptible to changes of broadband spectral distribution by changes of air mass, humidity, clouds, and aerosols (Vignola 2006). The angular response corrections inherent to the NREL-CRADA-RSR2 instrument (Augustyn et al., 2004) appear to correct the so-called “cat ear error” when compared with data from the uncorrected, stand-alone LI-200.

3.1.2 Effect of Ventilators on Eppley Model PSP Pyranometer

In general, the Earth’s surface temperature is higher than the sky temperature. Likewise, thermopile radiometers equilibrate to ambient air temperature, which is typically higher than the effective sky temperature. This creates an infrared energy imbalance between the all-black thermopile radiometer and the sky, producing a thermal energy exchange in which the thermopile detector emits energy to the sky (Myers 2013). This was evident in the data as a negative output signal by the all-black thermopile radiometers in the absence of solar radiation. For

this reason, some of the data from thermopile pyranometers have infrared corrections applied to offset this thermal imbalance using coincident infrared or longwave ($4\text{ }\mu\text{m} - 50\text{ }\mu\text{m}$) irradiance measurements from a collocated pyrgeometer. (Note: By design, the Eppley Model 8-48, also called a “black and white” pyranometer, does not exhibit significant thermal offset behaviors. The black (hot) and white (cold) junctions of the thermopile are exposed equally to the effective sky temperature. The absence of a significant thermal offset is reason to use this pyranometer for accurate measurements of DHI.)

Figure 7. Pyranometer thermal offset characteristics with corrections for ventilated and unventilated compared to reference GHI for selected nighttime solar zenith angle bins under all sky conditions (A) and normalized differences (UUT minus reference GHI) versus temperature for ventilated (B) and unventilated (C) Eppley Laboratory, Inc., model PSP pyranometers under clear-sky conditions (one-minute data).

One of the Eppley model PSP radiometers in this study is equipped with AC powered ventilator (Figure 7-B) to reduce accumulation of dust, snow, frost, dew, etc., from the dome of the radiometers and to discourage the presence of insects. Although both the Eppley ventilated and unventilated pyranometers were corrected for thermal offset, 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. This scenario was more apparent during cold ambient temperatures by comparing the number and extent of negative differences in GHI (%) at air temperatures near

freezing (Figure 7-B). Usually during overcast skies, the ambient air and sky temperatures are near equilibrium. However, the ventilator was heating the radiometer, which we postulated created an additional exchange of energy between the radiometer and the sky. Kutchenreiter et al., 2014, reported similar claim of pyranometers with AC powered ventilators. This situation ultimately increased the negative bias within the pyranometer. Further, this condition could be exacerbated if the ventilator filter is uncleaned for some time and airflow is restricted. The ventilator effect appeared to be particularly noticeable during nighttime (as shown in Figure 7-A). However, a couple important observations are worth mentioning here. The thermal offset correction for the ventilated PSP was performed using a ventilated Eppley model Precision Infrared Radiometer (PIR). The PSP and PIR share the same case and detector construction details and differ only by the placement of small thermistors for sensing dome and case temperatures and by the use of different domes protecting the thermopile detector. The thermal properties of the two instruments are similar when estimating their heat exchange while ventilated or unventilated. But if the ventilator airflow in both the PIR and the PSP is not equivalent—for example, because of a difference in the amount of filter obstruction—then the results as shown in Figure 7-B could be due to such an imbalance. On the other hand, we used a ventilated Eppley PIR to correct the unventilated PSP (as shown in Figure 7-C). This correction method stipulates that like ventilation be used to correct both the PIR and the PSP. This could be the reason for an overestimation of irradiance for the unventilated Eppley PSP.

3.1.3 Asymmetric Installation of Photodiode Detector

As mentioned above, in addition to routine maintenance of the radiometers, proper installation is critical for accurate solar irradiance measurements. Imprecise leveling of the instrument or imprecise manufacturing when mounting the detector within the instrument body parallel with the optical plane could cause asymmetric responsivity in a radiometer's output throughout the day. This situation is noticeable in the Ascension Technology (ATI) GHI data (Figure 8). Here, the instrument bubble level had been maintained during installation and routine maintenance, so the performance of this UUT could have been affected by an imprecise mounting of the detector itself within the radiometer.

Figure 8. Asymmetric morning and afternoon clear-sky results from the ATI radiometer may be caused by an unlevelled detector.

3.1.4 Improper Calibration and Instrument Malfunction

During the study period, the SPN1 (Delta-T) and SP-110 (Apogee) pyranometers were possibly affected by errors associated with improper calibration and water incursion through the diffuser, respectively.

According to Delta-T, to implement proper calibration for the SPN1 pyranometer, all seven thermopile detectors should be calibrated in unison to be accurately matched so that they give the same output under the same irradiance levels. Further, the manufacturer recommends correlating the SPN1 output to a reference pyranometer. The correlation equation is then used as the pyranometer calibration. However, for this study, we left the internal shading mask in place during BORCAL for comparison with the computed reference irradiance at a solar zenith angle equal to 45°. As a result, only two of the seven thermopile output responsivities were averaged and compared with the BORCAL reference irradiance. This approach results in an adjustment to all sensors based on the calibration average of a subset, and it is possible that dissimilar aging of the seven sensors could account for some of the differences seen in this report.

The Apogee model SP-110 was observed to have occasional water incursions, a situation discussed with the manufacturer. The separation of the diffuser from the main body allows the water droplets to intrude into the detector and instrument interior resulting in erroneous readings for those periods. As a result of these discussions, the manufacturer replaced the original sample with an improved model, but the replacement instrument exhibited the same highly variable sensitivity. For this reason, NREL left the replacement instrument in place as possibly representative of the model in outdoor use. For the study period, we did not try to remove anomalous data points.

Therefore, the higher MBD and RMSD obtained for these pyranometers and calculated DNI from the SPN1 should be read in the context of the above performance limitations.

3.2 Comparison Result for Direct Normal Irradiance Radiometers

The reference DNI measurements were taken by a Kipp & Zonen Model CH1 pyrheliometer traceable to the World Radiometric Reference (WRR) by means of the NREL Transfer Standard Group of electrically self-calibrating absolute cavity radiometers and the Broadband Outdoor Radiometer Calibration (BORCAL) process. As shown in previous studies (Michalsky et al., 2011, Wilcox and Myers 2008), this reference pyrheliometer has less calibration and measurement uncertainty (+1.8%) than the other pyrheliometers described in this report. For this reason, the instrument was chosen as the DNI reference pyrheliometer for our study. The SERI-QC data quality assessment tool was applied to the DNI data set as stated in previous sections by comparing it to other reference diffuse and global measurements. Appendix - Table A.2. contains result statistics of individual DNI radiometers included in the report.

Nineteen DNI data sets were included in this analysis. Some of the instruments calculate the DNI value from measurements of GHI and DHI and others had a direct measurement of DNI. For instance the RSR and SPN1 instruments have a calculated DNI based on measurements of GHI, and DHI. The calculation of DNI was obtained from these two data sets using Equation 1 and solving for DNI. However, Myers (2011) described that the computed DNI from photodiode, such as the RSR instruments produces an approximate $\pm 7\%$ difference because these instruments are susceptible to spectral sensitivity and the spectral distribution from GHI and DHI. These conditions

carry forth the greater differences in GHI and DHI to provide larger differences for the calculated DNI when compared with pyrheliometer data.

Figure 9 and Figure 10 show the 10-minute and hourly average comparison results respectively, using MBD for the DNI instruments partitioned into the four categories of sky condition. As shown in the figures, the plots are bounded by $\pm 50\%$ MBD for DNI. Data points outside of these bounds were not included in the statistical analyses. The black boxes in each figure illustrate a 95% confidence interval coverage, and the red line is the mean point for the 95% confidence interval area. The MBD differences tended to decrease with the increase of the averaging time for the same reasons as those described for the GHI instruments.

The clear-sky conditions demonstrated smaller differences among the instruments than the other sky conditions. The two Eppley model Normal Incidence Pyrheliometers (NIP) and the two Hukseflux model “DR” types had less MBD than others under clear-sky conditions. As expected, the variability of the DNI was much higher than the GHI under partly- or mostly-cloudy sky conditions.

Figure 9. MBD in percent for the 10-minute average for all DNI data under study ((A) all sky, (B) clear sky, (C) mostly cloudy sky, and (D) partly cloudy sky). The red line signifies the mean value of the MBD for the 95% confidence level. See Table 2 to obtain the instrument name and model by using the instrument number (x-axis).

Figure 10. MBD in percent for the hourly average for all DNI data under study ((A) all sky, (B) clear sky, (C) mostly cloudy sky, and (D) partly cloudy sky). The red line signifies the mean value of the MBD for the 95% confidence level. See Table 2 to obtain the instrument name and model by using the instrument number (x-axis).

Appendix - Table A.2. demonstrates the MBD for all the DNI instruments under clear and mostly-cloudy conditions. The differences were divided in various solar zenith angle ranges. Solar zenith angle dependence is not likely for pyrheliometers (Wilcox, 2008) and data in the table for those radiometers may not be significant; however, rotating shadowband instruments that calculate DNI from GHI and DHI will demonstrate a difference correlation with zenith angle. As described in the GHI section, some of the outliers that were close to the $\pm 100\%$ MBD limit might have skewed the outcome in Appendix - Table A.2., especially data from the high solar zenith angle and partly- or mostly-cloudy conditions. These higher deviations could have been a result of fast-moving clouds accompanied by differing fields of view (Vignola et al., 2012), for example calculated DNI for the RSR and the reference pyrheliometer. Further, the RSR radiometers with computed DNI from DHI and GHI are susceptible to spectral effects relating to the optical transmittance of the diffusers as well as the limited spectral range of the detectors. Therefore, temperature dependency, differing fields of view, differing instrument response characteristics, and solar zenith angle dependency can cause disagreements between the UUT and the reference pyrheliometer.

Note: In Appendix - Table A.2., yellow highlighted values are MBD greater than $\pm 5\%$ and the data exclusion threshold was $\pm 100\%$ MBD.

The RMSD results suggest that under clear-sky conditions, all the DNI data from the UUT radiometers agreed relatively well with the reference instruments (Figure 11). However, under partly- and mostly-cloudy sky conditions, factors such as temporal responsivity and field of view of the radiometers can result in higher RMSD%. Also consider that much of the DNI data in the mostly-cloudy conditions had a small magnitude, resulting in unrealistically large ratios while the actual difference in solar irradiance is quite small. This can be confirmed by noting in Appendix - Table A.2. that most of the highlighted percent values (outside of $\pm 5\%$) are associated with small irradiance values, typically less than 5 W/m^2 . Users should take this into account when considering the mostly-cloudy conditions presented in Appendix - Table A.2.

Figure 11. RMSD in percent for the hourly average for all DNI data under study ((A) all sky, (B) clear sky, (C) mostly cloudy sky, and (D) partly cloudy sky). The red line signifies the mean value of the RMSD for the 95% confidence level. See Table 2 to obtain the instrument name and model by using the instrument number (x-axis).

3.2.1 Effect of Ambient Temperature on the Sensitivity of the Pyrheliometers

The DNI thermopile radiometers (pyrheliometers) have temperature dependencies similar to the GHI thermopile pyranometers. For instance, one-minute data from the Hukseflux radiometer model number DR108068

had relatively more evident temperature dependency than model number DR108066 (Figure 12). The two Eppley model NIP radiometers tended to have less temperature dependency, especially at ambient air temperatures below 20°C. The two NIPs and the two Hukseflux radiometers did not have the temperature correction applied in this study. However, a previous study that included the Hukseflux pyrhemliometers showed that the manufacturer's temperature correction curve for these instruments reduced temperature error to a much lower magnitude which allowed the pyrhemliometers to perform among the top non-cavity pyrhemliometers (Michalsky et al., 2011).

Figure 12. Effect of temperature on DNI measurement (A) Hukseflux radiometer serial number DR108066, (B) Hukseflux radiometer serial number DR108068, (C) Eppley Laboratory, Inc. NIP (Table 2 Instrument #2) and (D) Eppley Laboratory, Inc. NIP (Table 2 Instrument #1)

3.3 Thermopile versus Photodiode Radiometers

The design of commercially available pyranometers and pyrhemliometers for measuring broadband solar irradiance is generally based on the principles of thermoelectric or photoelectric detectors. The cost/performance characteristics of these radiometers must meet user needs consistent with the intended application and the desired data uncertainty limits. As previously introduced, the inherent measurement performance characteristics of these radiometers differ according to various response characteristics. Thermopile-based radiometers have a wide-band thermopile detector (280 nm to 2,800 nm) with flat spectral response for most of the solar spectrum and they are equipped with precision-ground glass or sapphire domes to protect the detector. They also exhibit thermal offsets

1 due to prevailing net infrared radiation conditions at time of measurement and their measurements can be corrected
2 for temperature, and thermal offset response characteristics. On the other hand, photodiode-based radiometers have
3 limited spectral response ranges; typically about 75 % of the full solar spectrum, non-uniform spectral response, and
4 varying temperature and angular response characteristics, depending on their design. Photodiode-based radiometers
5 have the fastest time responses, exhibit no thermal offsets, and their measurements can be corrected for spectral,
6 angular, and temperature response characteristics. Furthermore, the characteristics of photodiode radiometers will
7 have an effect on the spectral power distribution of the total global horizontal and diffuse horizontal irradiance
8 which in-turn can impact the calculated direct normal irradiance data. Various methods are available for correcting
9 known measurement performance limitations of photodiode-based radiometers. Additionally, the responsivity of
10 each thermopile or photodiode radiometer of the same model could differ depending on the environmental
11 conditions. Each instrument, whether a photodiode or thermopile model, should be treated independently based on
12 the instrument's performance and/or the manufacturer's specifications. In general terms, the results here show that
13 the best of the thermopile instruments performed better than the best of the silicon instruments, but there were some
14 silicon instruments that performed better than some of thermopile instruments. Actual instrument choice should take
15 these results into consideration, along with acquisition and installation costs, desired measurement uncertainty, and
16 availability of resources for maintenance.

3.4 Recent Advances in Radiometry

17 The historically small commercial market for radiometers has limited the manufacturers' interests to
18 significantly improve their products. The increasing number and size of solar energy conversion systems has now
19 created more opportunities and demands for improvements to radiometry. In these new circumstances, there are
20 various groups including the manufacturers of radiometers, working to improve measurement performance and
21 harmonize the methodology for acquiring radiometric data. These improvements will be based on customer
22 feedback, government research (NREL, National Oceanic and Atmospheric Administration (NOAA), National
23 Institute of Standards and Technology (NIST), et al.), international standard development groups such as, the
24 International Organization for Standardization (ISO), American Society for Testing Materials (ASTM -
25 International), the International Energy Agency (IEA – Task 46), and the needs/requirements of the solar and utility
26 industries. The focus to improve radiometer design will require identifying the more significant contributors to
27 measurement uncertainty and change their instrument design and manufacturing accordingly. Although
28 improvements in instrumentation are an important focus in the long term, environmental or operational issues
29 (soiling, precipitation, tracking errors, and inadequate maintenance) are usually a far greater contributor to solar
30 measurement error than instrument design. This makes improvements in operational protocols an immediate
31 candidate for reducing measurement uncertainty.

4. SUMMARY

32 Accurate solar resource measurements are essential for determining system efficiencies of solar energy
33 conversion installations, developing improved satellite-based models for estimating solar resources, and validating
34 solar radiation forecasts. An intercomparison of 51 radiometric measurements used to determine global horizontal

and direct normal irradiance (GHI and DNI) was made based upon measurements for the period 1 April 2011 through 31 March 2012 at the Solar Radiation Research Laboratory (SRRL) in Golden, Colorado, USA. This report helps differentiate the similarities and differences among DNI and GHI radiometers when compared to the reference data set with the lowest estimated measurement uncertainties of the corresponding measurement type. As a whole, the instruments were most similar when the solar zenith angle was below 60 degrees and there was a clear-sky condition. The comparisons with reference data showed that the differences among the measurement data from the participating instruments were within $\pm 5\%$ for both GHI and DNI. At higher solar zenith angles (greater than 60 degrees), the GHI differences under mostly- and clear-sky conditions went up to $\pm 17\%$. Further, at higher solar zenith angles, mostly-cloudy conditions demonstrated higher percentage differences, up to $\pm 40\%$ for DNI on very few instruments. Some of these differences are a result of varying time response, spectral irradiance distribution responses, angular response, thermal offset, and temperature sensitivity. Further, the ventilators (especially AC powered) used on some of the instruments exacerbated the differences between the reference and the test instruments. Post-measurement corrections applied to some instruments, such as zenith and temperature correction, appeared to lessen the differences with respect to the reference irradiance, e.g. the NREL-CRADA-RSR2 LICOR GHI data shown a reduction by as much as $\pm 2\%$. Previous studies and NREL calibration reports shown individual radiometer responsivity ($\mu\text{V}/\text{Wm}^{-2}$) varies with the range of solar zenith angles achieved at SRRL. Therefore, applying responsivity as a function of solar zenith angle could show significant reduction in the differences from the reference value. One important note is that data from all radiometers were normalized to minimize effects attributed to differing calibration methods and results, and the normalization factor is not intended to modify results reported elsewhere. Further, this approach did not address differences in calibration methods and the specific calibration factors used for each instrument; there is on-going investigation to address this issue. We also tried to investigate the measurement differences versus various environmental parameters, such as temperature and wind speed. There were noticeable temperature correlation events for some of the radiometers, but wind speed did not show significant correlation as a result of the analyses. Overall, the interpretation of the differences (MBD and/or RMSD) should be read in the context that reference instrument and data logger uncertainties were not included in the reported values; therefore, the differences among the reference and test instruments could move up and down by the uncertainty magnitude ($\pm 2.6\%$ and $\pm 1.8\%$ for reference GHI and DNI, respectively) and may not be significant within these uncertainty intervals.

Furthermore, through research and development, instrument manufacturer and research institutions continue to improve radiometer measurement performance by tackling the major sources of uncertainty to the radiometric data. The sources of uncertainties differ by radiometer type and model. Therefore, users are advised to understand the context of the results described in this paper when choosing radiometers for their specific application.

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