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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, pyrheliometers, rotating shadowband radiometers (RSR),[1] 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-min, and hourly averages. Deviations from the reference irradiance measurements were calculated as a percent and W/m^2 of the reference value for solar zenith angles ranging from 17.5° to 85° (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°, differences of less than ±5% were observed among all GHI and DNI measurements when compared to the reference radiometers. For GHI these normalized differences increased up to ±17% under mostly-cloudy and clear-sky conditions when the solar zenith angle was greater than 60°. The normalized differences were greater yet under mostly-cloudy conditions (approaching ±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.
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Keywords: Global horizontal irradiance, GHI; Direct normal irradiance, DNI; Diffuse horizontal irradiance, DHI; Pyranometer; Pyrheliometer; Rotating shadowband radiometer, RSR

1. Introduction

Since 1981, the Solar Radiation Research Laboratory (SRRL) at the National Renewable Energy Laboratory in Golden, Colorado, USA has provided a continuous and quality controlled record of solar irradiance and surface meteorological conditions, improved methods for the calibration of radiometers and dissemination of solar

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

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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; 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, 1829 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 Tables 1 and 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 manufacturer-owned instruments, prior to the start of the evaluation period, the manufacturers were allowed to ensure that their instruments were installed and operating to their satisfaction. After the evaluation period began, the manufactures were not allowed any contact or interaction with the instruments. All data collected from the instruments for this study were downloaded directly to NREL computers. The Solar Millennium instrument (Solar-Mil.-CRADA-RSR) was set up by the manufacturer with special internal processing to take the place of the external processing that is usually provided by the manufacturer on corporate servers. As noted below, this necessitated the omission of the instrument's usual one-minute data output.

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

Data from 32 GHI and 19 DNI radiometers are presented in Tables 1 and 2. Reference values of GHI were calculated using a reference DNI and a reference DHI using the component sum method (Eq. (1)). The performance of each instrument was derived from time-series measurements relative to the corresponding reference irradiance. Reference DNI data were obtained using a Kipp and Zonen model CH1 pyrheliometer (serial number 010256), and reference DHI measurements were made by two Eppley Laboratory, Inc., model 8-48 pyranometers (serial number 21096 was replaced for re-calibration on May 26, 2011 by 32331). The 8-48 ("black and white") pyranometers were not ventilated. The DHI data for the two Eppley model 8-48 pyranometers were analyzed for any systematic shift in the reference DHI data. A comparison of one-minute measurements of GHI/DHI under clear sky conditions for five days prior to and five days after the instrument exchange suggested no significant shift between the two DHI reference pyranometers. Furthermore, 85% of the reference DHI data included in this paper came from the Eppley model 8-48, serial number 32331 (May 26, 2011 to March 31, 2012). The reference DNI and DHI instruments were mounted in an automatic solar tracker to provide accurate and continuous alignment of the pyrheliometer and the shading device for the pyranometer. Previous studies (Wilcox and Myers, 2008; Michalsky et al., 2011) and Broadband Outdoor Radiometer Calibration (BORCAL)[2] results from these instruments confirm that

[2] BORCAL reports are available from http://www.nrel.gov/aim/borcal.html.