Efficient, Real-Time Global Spectral and Broadband Irradiance Acquisition

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***Abstract* — Two global solar spectral irradiance meters (SolarSIM-Gs) were deployed and tested at the National Renewable Energy Laboratory in Golden, USA from 18 September to 6 October 2017. The instruments were installed in the global horizontal orientation at the Solar Radiation Research Laboratory and their measurements were compared against co-located secondary reference spectroradiometers and secondary standard pyranometers. The SolarSIM-Gs' spectral global horizontal irradiance (GHI) accuracy was shown to be < 5% on average per wavelength in the 290-1650 nm range for over 1,900 analyzed spectra. The broadband GHI measurement accuracy for two instruments was shown to have mean bias and standard deviation of 0.97, 1.23 W/m^2 and 5.27, 5.65 W/m^2, respectively, for over 10,000 analyzed data points.**

***Index Terms* — global solar spectral irradiance meter, SolarSIM-G, solar spectrum, GHI, global horizontal spectral irradiance, spectral irradiance, solar sensors, solar instrumentation**

I. INTRODUCTION

Photovoltaic (PV) module performance is specified for Standard Testing Conditions (STC) under the ASTM G-173 reference solar spectrum with integrated irradiance of 1000 W/m^2 and an air mass of 1.5 [1]. During field operation, the air mass, aerosols, precipitable water vapour and pollutants modify the spectral distribution as seen by solar panels, hence their performance deviates from the STC. For example, in the continental USA depending on the PV module technology and location, the spectral irradiance variation cause anywhere between -0.6% to +2.6% change in predicted annual energy yield with and without spectral correction [2]. In other locations, such as India and China, the solar spectrum fluctuations are expected to affect PV performance even more [3]. Unarguably, the knowledge of the local global horizontal or plane of array spectral irradiance as opposed to just the broadband irradiance improves the accuracy of instantaneous characterization and reduces the long-term performance uncertainty of PV power plants.

Historically, field spectroradiometers have been the only way to acquire the local solar spectrum, but, due to high instrument costs, the routine spectral measurements are almost non-existent, except for a few, well-funded national labs, such as the Solar Radiation Research Facility (SRRL) at the National Renewable Energy Laboratory (NREL) in the USA [4]. With this challenge in mind, the global solar spectral irradiance meter (SolarSIM-G) was designed as a cost-effective alternative to a spectroradiometer with the added function of providing the broadband global horizontal or tilted irradiance, as typically acquired by a pyranometer. This novel instrument was made to provide PV community with an affordable tool for solar resource assessment, module characterization and power plant performance monitoring.

In this abstract, we describe SolarSIM-G's general design and then assess the instrument's ability of resolving the spectral and broadband global horizontal irradiances (GHI). To do so, we perform a comparative analysis from the datas gathered by two SolarSIM-Gs deployed at the SRRL during 18 September to 6 October 2017 against co-located secondary reference spectroradiometers and secondary standard pyranometers.

II. DESIGN AND OPERATION

The SolarSIM-GFig 1 measures the global spectral irradiance with seven silicon and two indium gallium arsenide photodetectors combined with nine hard-coated narrow bandpass filters; the instrument also senses ambient pressure, relative humidity, air temperature, as well as device's internal humidity and temperature. These parameters are fed into a radiative transfer model to derive in real-time the spectral and broadband GHIs. The software and hardware of the SolarSIM-G is partially based on the SolarSIM-D2, our six-channel sensor which resolves the spectral and broadband direct normal irradiance, spectral aerosol optical depth, precipitable water vapour and total ozone column amount in the 280-4000 nm range [5]. However, compared to the direct beam irradiance, the reconstruction of global sunlight is more involved because one must also consider the diffuse irradiance, arising mainly from the atmospheric scattering, clouds, and ground albedo. Hence, the SolarSIM-G has three additional channels as compared to the D2, which aids in the reconstruction of the diffuse irradiance – one channel is in the ultraviolet and two channels are in the infrared ranges.

The SolarSIM-G couples sunlight with a 180º field of view through a bulk diffuser into a cylindrical integrating cavity, which is coated with a near-Lambertian, high-reflectance coating. The integrating cavity and diffuser combination have been designed to optimize the cosine

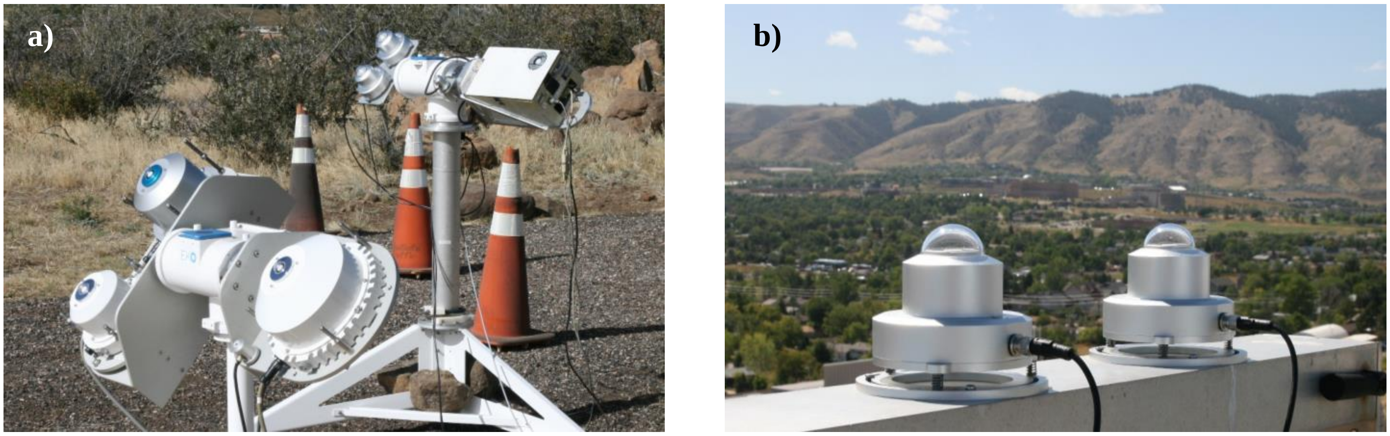

Fig 1. a) Two SolarSIM-Gs were calibrated against the EKO WISER and LICOR Li-1800 spectroradiometers in the global normal orientation at the Solar Radiation Research Laboratory (SRRL). b) Two SolarSIM-Gs were deployed in the global horizontal orientation post-calibration at the SRRL to assess their broadband and spectral performance against NREL's pyranometers and spectroradiometers, respectively.

response which complies with a secondary standard for a pyranometer (±10 W/m^2 as per ISO-9060). The diffuse light then exits the cavity via nine collimation tubes, with each having a bandpass filter and a photodiode below it. The aperture and field stop geometries of the collimation tubes ensure that the light passing through bandpass filters has angular divergence of less than 10º to maintain their stated performance.

Analogous to the D2, the SolarSIM-G data acquisition printed circuit board is housed inside the anodized aluminum enclosure. The electronics sequentially measure the current from each photodiode and digitizes it with a 22-bit analog-to-digital converter. The converted values, along with meteorological measurands are sent via a RS-485 communication protocol to a computer, where a graphical user interface reconstructs in real-time the spectra and broadband GHI in the 280-4000 nm range with a frequency of up to 1 Hz.

III. PERFORMANCE

The SolarSIM-Gs were installed in the global horizontal orientation to assess their spectral and broadband GHI performance against NREL's reference instruments, as shown in Fig. 1b. The integral of the SolarSIM-G's spectrum in the 280-4000 nm range yields the broadband GHI, which was compared against NREL's calculated reference GHI. The reference values are computed from the direct normal irradiance, as measured by first class pyrheliometers (average of the two Kipp & Zonen CHP-1s), CMP-22s, one Huksenflux SR-25, and one Eppley-848). This method of obtaining the GHI values has less uncertainty than the data measured by the unshaded pyranometer alone, because the cosine errors are minimized. Fig. 2 shows the daily GHI profile as measured by two SolarSIM-Gs on 1 October 2017 with a one-minute resolution. This day presents a mix of atmospheric conditions, varying from clear sky in the morning to heavy cloudy in the afternoon. The SolarSIM-Gs' data stays within ±10 W/m^2 of the reference NREL GHI throughout this

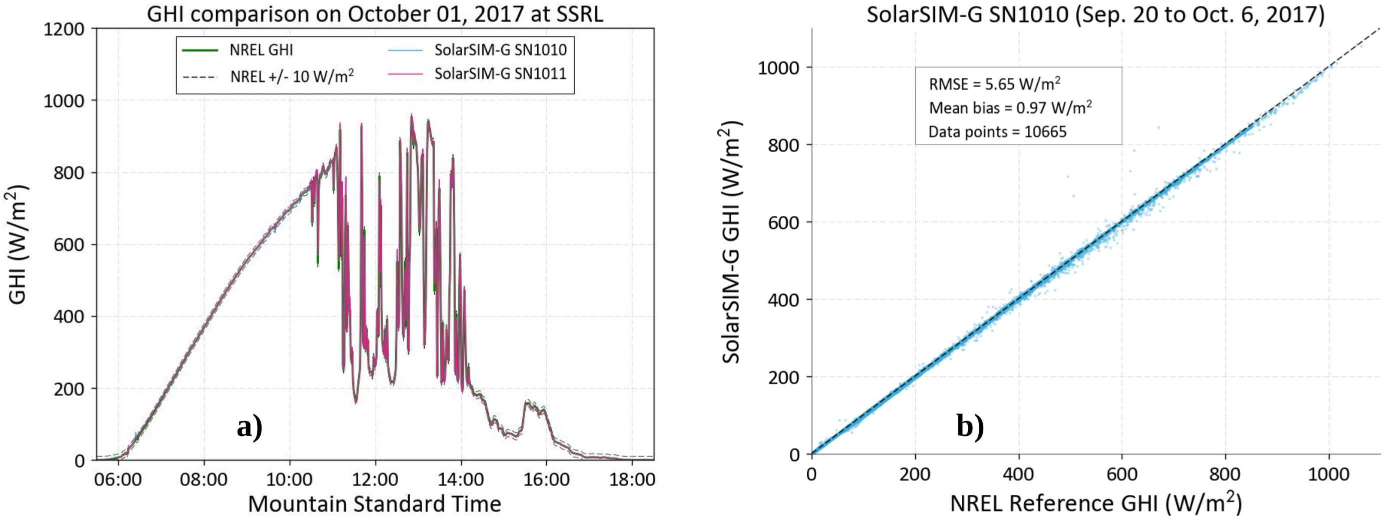

Fig. 2. a) GHI data from the SolarSIM-Gs, as compared to NREL's reference GHI data on 1 October 2017. The dashed black lines represent the ±10 W/m^2 limits from the reference GHI. b) Scatter plot of the GHI data from SolarSIM-G SN1010 versus NREL's reference GHI data from 20 September to 6 October 2017. The mean bias and RMSE of the dataset are 0.97 W/m^2 and 5.65 W/m^2, respectively.

day. We then aggregate the GHI data for the SolarSIM-G SN1010 and SN1010 from 20 September to October 6 into a scatter plot, as presented for SN1010 in Fig. 3. The mean bias and the root mean square error (RMSE) of the SN1010 data set was found to be 0.97 W/m^2 and 5.65 W/m^2, respectively, for over 10,000 data points analyzed. Similarly, for the SN1011 data set, the mean bias and RMSE were 1.23 W/m^2 and 5.27 W/m^2, respectively. Note, the scatter plot for SN1011 is not shown because it's near identical to SN1010's one.

We then compared the spectral measurement performance of the SolarSIM-Gs against the NREL's WISER spectroradiometer in the global horizontal orientation. Fig. 4a shows the mean spectral GHI of the aforementioned instruments from 20 to 24 September 2017, during which 1,929 spectra per instrument were gathered. Note, the spectra with integrated total irradiance of less than 50 W/m^2 were excluded from the analysis. The plot suggests that the mean spectral irradiance of the SolarSIM-Gs is well within the combined uncertainty of the WISER spectroradiometer. For more detail, Fig. 4b shows the mean difference and the standard deviation between the SolarSIM-G SN1010 and WISER's spectral GHI data sets is mainly within 5%, except for areas with oxygen and water vapour absorption bands (vertical gray bands). Increased standard deviation is observed below 350 nm and above 1600 nm, which can be partially attributed to higher temperature dependence and/or stray light limitation of the WISER spectroradiometers.

IV. CONCLUSION

Two SolarSIM-Gs SN1010 and SN1011 were deployed and validated at the SRRL against NREL's reference instrumentation. The SolarSIM-Gs' broadband and spectral performances in the global horizontal orientation were assessed against co-located secondary standard pyranometers and secondary reference spectroradiometers, respectively, from 20 September to 6 October 2017. Over this period, the mean bias and the RMSE of the SolarSIM-Gs' as compared to reference GHI data sets were 0.97 W/m^2 and 5.65 W/m^2 for SN1010, respectively, and 1.23 W/m^2 and 5.27 W/m^2, for SN1011, respectively. Over 10,000 data points per instrument were used in our GHI comparative analysis. Furthermore, the mean difference and the standard deviation of the spectral GHI data set between the SolarSIM-Gs and the WISER spectroradiometer were mainly within ±5%, not including the oxygen and water vapour absorption bands. Over 1,900 spectra per instrument was gathered from 20 to 24 September 2017 and used in our spectral GHI performance analysis. These results indicate the SolarSIM-G can perform very accurate spectral and broadband GHI measurements. In addition, its compact size, low cost, and rugged design makes the SolarSIM-G a capable instrument for performing solar resource assessment, module characterization studies, certification, operation and maintenance of PV power plants.

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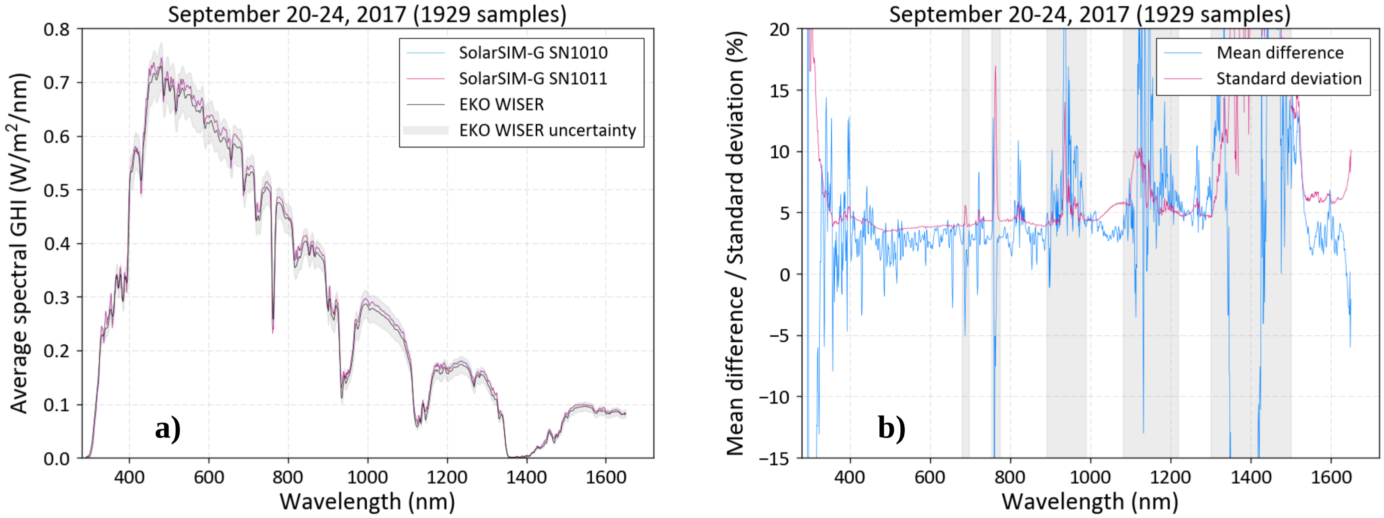

Fig. 3. a) The mean spectral GHI as measured by the SolarSIM-G SN1010 and SN1011 versus the spectral GHI from the WISER spectroradiometer. The mean spectra were calculated from 1,929 measurements, per instrument during the period of 20 to 24 September 2017. The gray band represents the estimated combined uncertainty of the WISER. Note, the SolarSIM-G spectra was smoothed with 5 nm central averaging to approximate the lower measurement resolution of the spectroradiometer. b) The mean difference and standard deviation between the SolarSIM-G's (SN1010) and WISER's spectral GHI data sets. The vertical gray bands are areas with oxygen and water vapour absorption.