Performance Validation of the SolarSIM-G at NREL's Solar Radiation Research Laboratory

September 18th – October 6th, 2017

1. Executive Summary

In September 2017, Spectrafy's two SolarSIM-G reference units (RUs) (SN1010 and SN1011) underwent calibration and performance validation at NREL's Solar Radiation Research Laboratory. The SolarSIM-G RUs were calibrated on-sun, against NREL's reference spectroradiometers. Broadband, narrowband and spectral measurement accuracy was then analysed over 17 days versus NREL's reference pyranometers, UV sensors, PAR sensors and spectroradiometers.

Broadband GHI measurement accuracy was shown to be within secondary standard limits with a mean bias of 0.97 – 1.23 W/m^2 and RMSE of 5.27 – 5.65 W/m^2 for 10,665 data points analyzed.

UV-Total measurements were shown to be highly comparable to NREL's UV-T sensors, with mean biases of ~0.2 W/m^2 observed from over 10,000 ata points analyzed.

Photosynthetic Photon Flux Density (PPFD) measurements were shown to be highly comparable to NREL's reference PAR sensor, with mean biases of ≤2 μmol/s/m^2 observed from over 10,000 data points analyzed.

Spectral GHI measurement accuracy was shown to be similarly impressive, with average mean differences of <5% per wavelength for 1,929 data points analyzed – well within the measurement uncertainty of NREL's reference spectroradiometer.

Overall, the test results serve as an important validation of the SolarSIM-G as a highly accurate and reliable sensor for measuring global broadband, narrowband and global spectral irradiance, under all sky conditions.

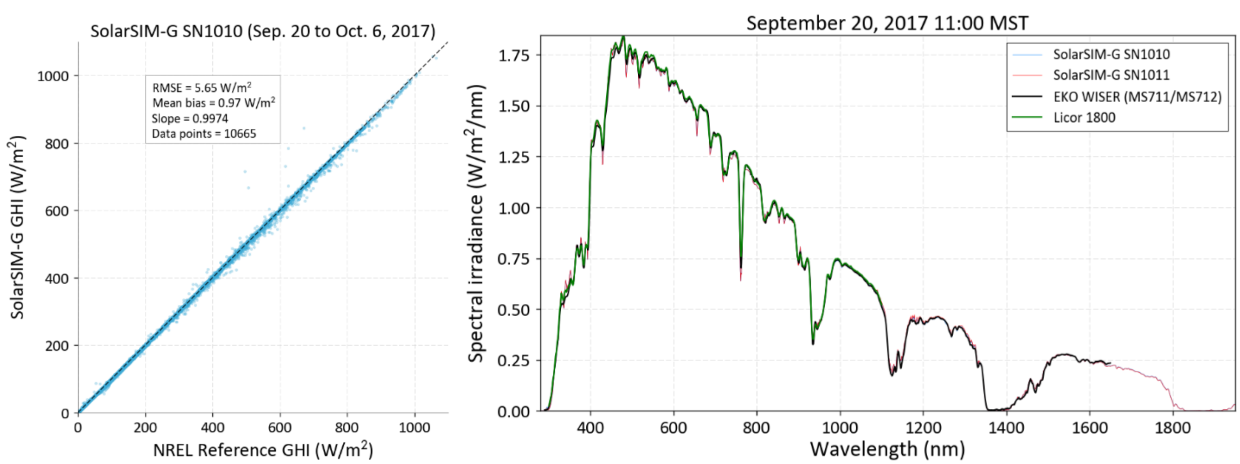

Figure 1. GHI scatter plot versus reference GHI data for SolarSIM-G RU SN1010 (LHS) and spectra GHI plot versus reference spectroradiometer data for both SolarSIM-G RUs (RHS).

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2. Introduction

In September 2017, Spectrafy delivered two SolarSIM-G reference units (RUs) (SN1010 and SN1011) to the Solar Radiation Research Laboratory (SRRL) at the National Renewable Energy Laboratory (NREL) for calibration and evaluation (see Figure 2). The evaluation period covered September 18 – October 6, 2017. The purpose of the tests was to:

1. Calibrate the SolarSIM-G RUs against NREL's secondary standard spectroradiometers,
2. Validate the SolarSIM-Gs' spectral measurement accuracy against NREL's reference spectroradiometers.
3. Validate the SolarSIM-Gs' broadband measurement accuracy against NREL's reference pyranometers, and;
4. Validate the SolarSIM-Gs' UV-Total and PAR measurement accuracy against NREL's UV-T and PAR sensors, respectively.

Figure 2. The SolarSIM-G reference units in operation at NREL's Solar Radiation Research Laboratory, October 2017.

3. SolarSIM-G overview

The SolarSIM-G uses silicon and InGaAS photodiodes coupled with hard-coated bandpass filters to make precise measurements of the solar spectrum in nine narrow wavelength bands, in addition to measuring ambient temperature, pressure and relative humidity. The SolarSIM-G's software then uses these measurements, to accurately resolve the global solar spectral irradiance over the complete 280-4000 nm wavelength range, as well as broadband and partial band (i.e. UV-A, UV-B, PAR) global irradiances, under all sky conditions.

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4. SolarSIM-G Specifications

Broadband Irradiance

Spectral Range	280-4000 nm
Custom Range Selection	Yes
Spectral Range	280-4000 nm
Maximum Irradiance	2000 W/m^2
Response Time (95%)	<0.5s
Zero offset A	n/a
Zero offset B	n/a
Non-stability	<0.2%/yr
Non-linearity	<0.5%
Spectral Selectivity	n/a
Temperature Response	<0.1% (on-board temperature correction)
Directional Response	<10W/m^2 0° - 80°
Tilt Response	n/a
Calibration Uncertainty	1.1%
ISO 9060 equivalence	Secondary Standard*

Spectral Irradiance

Wavelength Range	280-4000 nm
Spectral Resolution (FWHM)	1 nm
Wavelength Accuracy	±0.1 nm
Spectral Measurement Uncertainty	<5% per wavelength
Exposure Time	<1 ms
Acquisition Rate	<1 s
Temperature Dependency	<0.1% (on-board temperature correction)

General

Weight	1.3 kg
Dimensions	132 x 132 x 110 mm
Power Supply	12 VDC
Power Consumption	<1W
Communication	2-wire RS-485, direct to PC, serial over ethernet or data logger
Operating Temperature	-30 to 65 °C
Humidity Range	0 to 100 % RH

*Because the SolarSIM-G measures only several narrow spectral bands, it does not meet the 'spectrally flat' criteria of ISO 9060. Nonetheless, the SolarSIM-G does eliminate spectral selectivity errors, because all broadband irradiance values are calculated directly from the integrals of spectra. The SolarSIM-G meets or exceeds all other 9060 requirements.

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5. Calibration

Calibration of the SolarSIM-G RUs was performed on-sun, against NREL's reference spectroradiometers (1 x EKO WISER (MS711/MS712) and 1 x Licor-1800) in the global normal orientation, mounted on STR-32G trackers, as shown in
Figure 3. The calibration was performed in the global normal orientation to minimize any cosine errors.

The calibration took place on the 18th and 20th of September, between 10:00 and 14:00 MST, under clear-sky conditions. During the calibration process, the irradiances measured in the SolarSIM-Gs' nine optical channels were calibrated for absolute irradiance against the reference spectroradiometers.

Figure 3. Calibration setup with the SolarSIM-G RUs and Licor 1800 spectroradiometer (background) and the EKO WISER (MS711/MS712) spectroradiometers (foreground).

After the calibration, the global normal spectral irradiance resolved by the reference spectroradiometers and the SolarSIM-G RUs were compared, as shown in Figure 4. As expected, the spectral irradiance from the SolarSIM-G RUs matches the data from the reference spectroradiometers very well.

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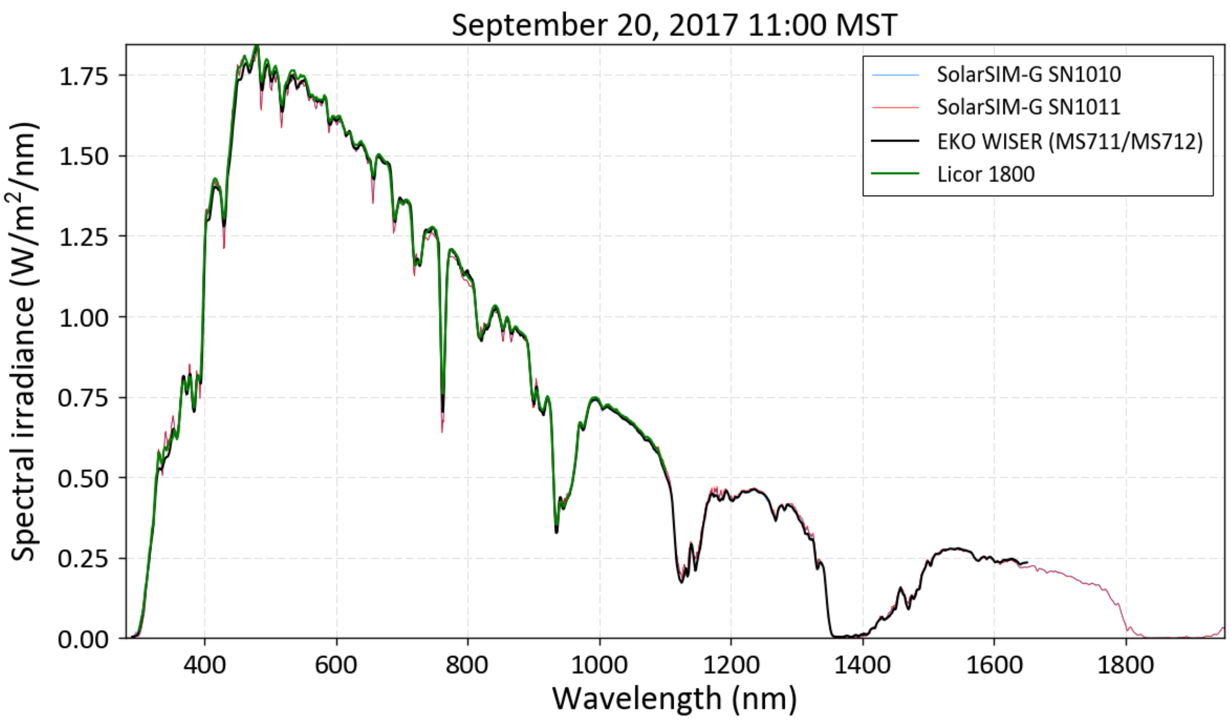

Figure 4. Spectral global normal irradiance as measured by the WISER, Licor-1800, and the SolarSIM-G RUs at 11:00 MST on September 20, 2017. To aid comparison, the spectra obtained from the SolarSIMs have been smoothed with 5 nm central averaging to approximate the lower measurement resolution of the reference spectroradiometers.

6. Global broadband measurement performance

Broadband performance of the SolarSIM-G RUs was compared against NREL's calculated reference global horizontal irradiance (GHI). NREL's reference GHI is calculated from measurements of direct normal irradiance, as measured by first class pyrheliometers (average of two Kipp & Zonen CHP1s) and diffuse horizontal irradiance, as measured by secondary standard pyranometers (the average of two Kipp & Zonen CMP22s, one Eppley-848, and one Hukseflux SR25). The calculated reference GHI has a lower uncertainty than GHI measured by an unshaded pyranometer alone. The SolarSIM-G's GHI data is obtained directly from the wavelength integral of its spectral irradiance data over the 280-4000nm range.

Figures 5 and 6 present the daily GHI profiles as measured by the SolarSIM-G RUs, for the 1st and 2nd of October, with 1-minute time resolution. NREL's reference GHI is also plotted for comparison. The 1st of October presented a mix of atmospheric conditions, varying from clear-sky in the morning to intermittent and heavy cloudy in the afternoon. Data from October 2nd indicates a completely overcast day. In all cases, the SolarSIM-G RUs provide highly accurate measurements of GHI, well within the secondary standard limit of ± 10 W/m^2 (ISO-9060), versus the reference GHI.

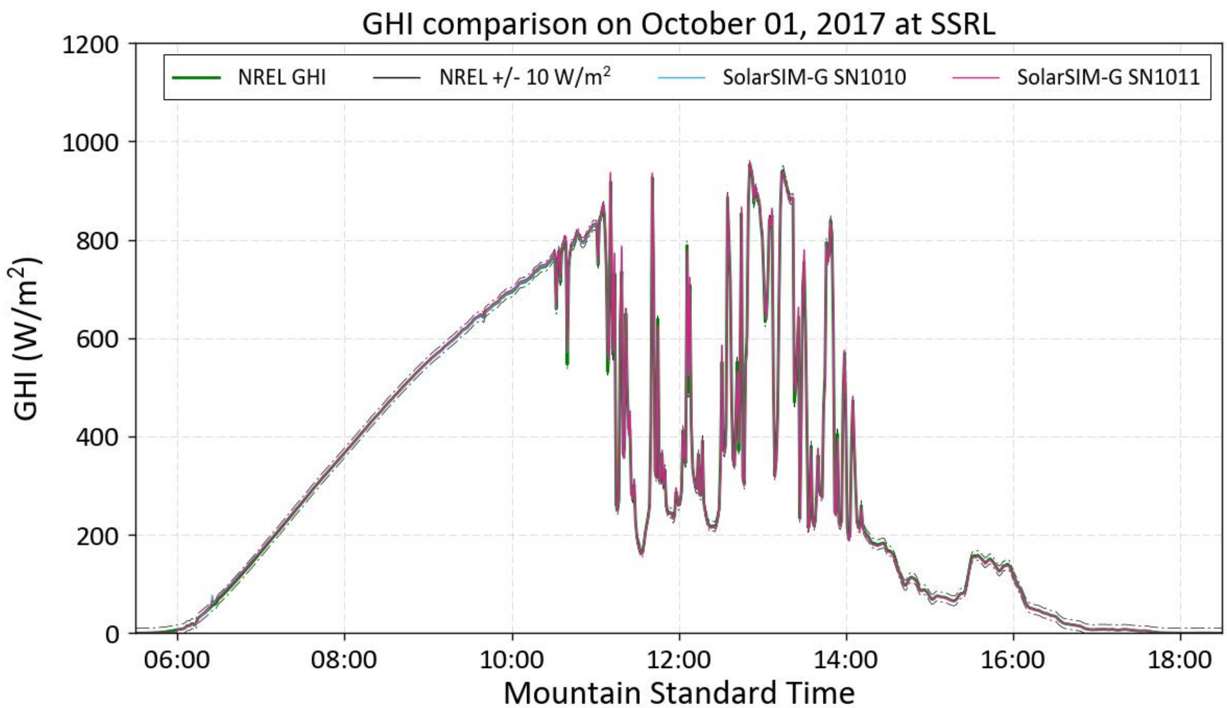

Figure 5. GHI data obtained from the SolarSIM-G RUs, compared to NREL's reference GHI data for the 1st October 2017. The SolarSIM-G data is consistently within ± 10 W/m^2 of the reference GHI data.

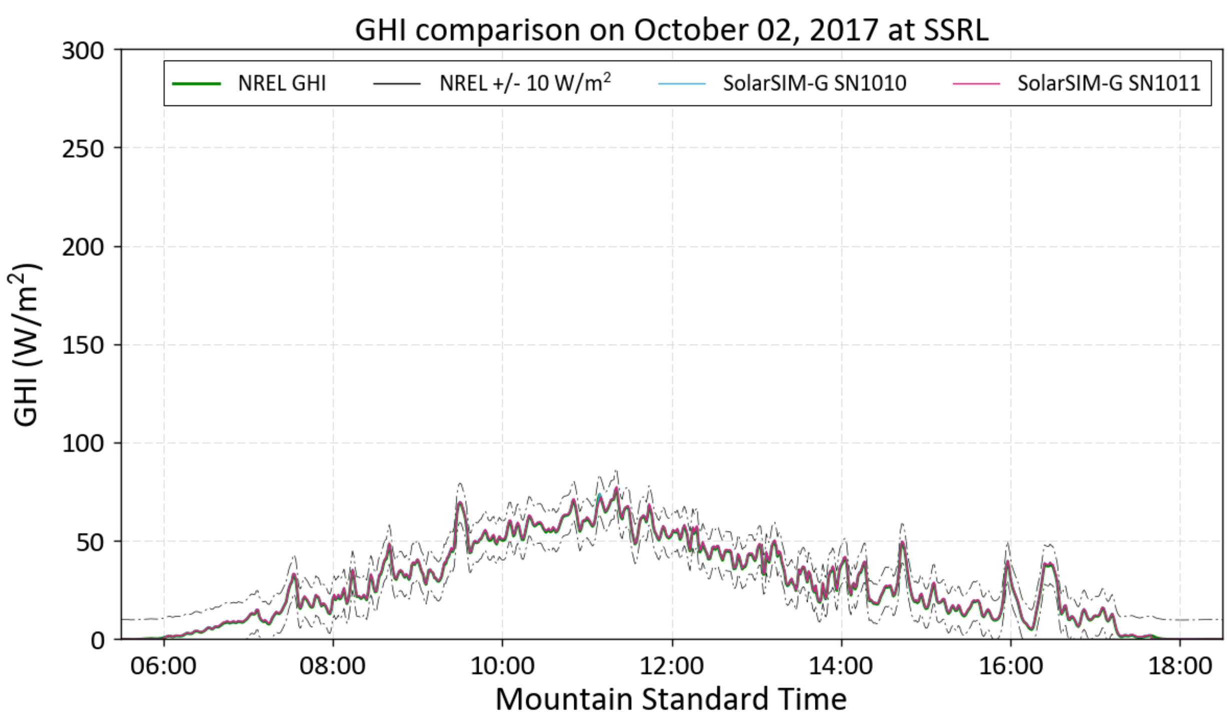

Figure 6. GHI data obtained from the SolarSIM-G RUs, compared to NREL's reference GHI data for the 2nd October 2017. The SolarSIM-G data is consistently within ± 10 W/m^2 of the reference GHI data.

A more holistic analysis of the SolarSIM-Gs' GHI performance is presented in Figure 7 via scatter plots of the SN1010 and SN1011 GHI data versus NREL's reference GHI data. As shown, the root mean square errors (RMSE) are well below 10 W/m^2, with over 10,000 data points analyzed. Slope values of 0.9974 and 0.9945 were obtained for SolarSIM-G RUs SN1010 and SN1011, respectively.

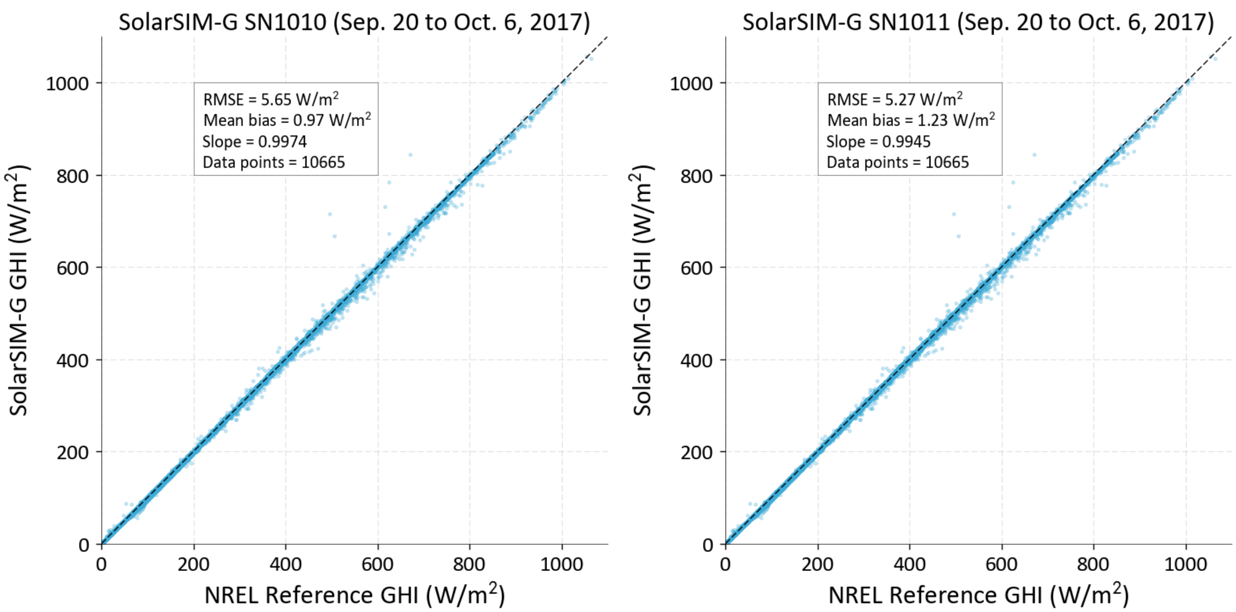

Figure 7. Scatter plots of the GHI data obtained from the SolarSIM RUs (SN1010 LHS, SN1011 RHS) plotted against NREL's reference GHI data for the period 20th September to 6th October 2017. The RMSEs for both instruments are well within ± 10 W/m^2 with over 10,000 data points analyzed per SolarSIM.

7. Spectral irradiance measurement performance

The spectral measurement performance of the SolarSIM-G RUs was evaluated against the NREL's EKO WISER spectroradiometers. Both instruments were mounted on the southern end of the SRRL deck in the global horizontal orientation (see Figure 8). The data analysis was limited to the 20th – 24th of September due to the availability of the WISER spectroradiometers.

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Figure 8. The SolarSIM-G RUs in global horizontal mode on the SRRL deck, alongside NREL's WISER(711/712) spectroradiometers.

Figure 9 presents the average spectral GHI of the SolarSIM-G RUs and the WISER spectroradiometers for the 20th - 24th of September 2017. 1,929 data points per instrument are included in the analysis. Note: spectra with integrated irradiance < 50W/m^2 were excluded.

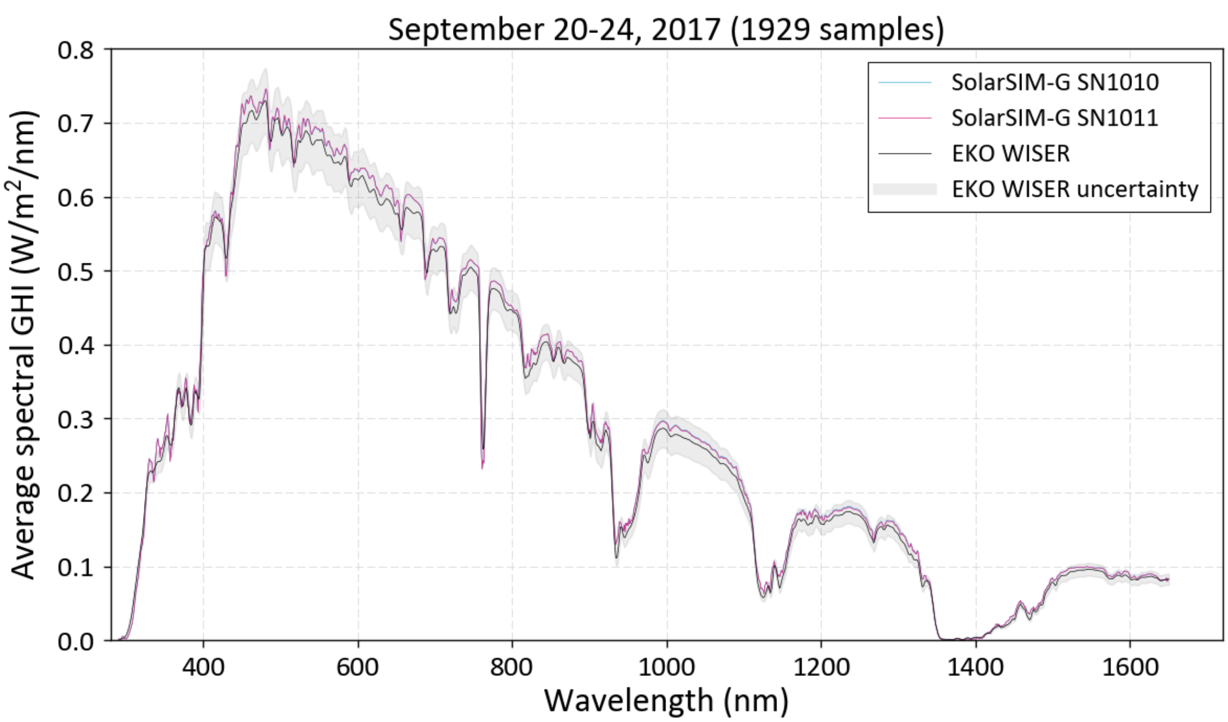

Figure 9. The mean spectral GHI as measured by the SolarSIM-G RUs and WISER spectroradiometers for the period of the 20th to the 24th of September. The spectra presented here represent the mean spectra calculated from 1,929 measurements, per instrument. The grey

band represents the combined uncertainty of the WISER spectroradiometer measurements. Note: to aid comparison, the spectra obtained from the SolarSIM-G RUs have been smoothed with 5 nm central averaging to approximate the lower measurement resolution of the WISER spectroradiometers.

Figure 9 shows that the mean spectra from the SolarSIM-G RUs and the WISER spectroradiometers match well (both relatively and absolutely), with the SolarSIMs measuring slightly higher values on average, but well within the uncertainty limits of the reference spectroradiometers.

For more detail, Figure 10 presents the mean difference and standard deviation thereof between the SolarSIM-G (SN1010) and WISER spectral data sets. Note that the data for SolarSIM-G RU SN1011 is nearly identical to SN1010 and has been omitted for clarity.

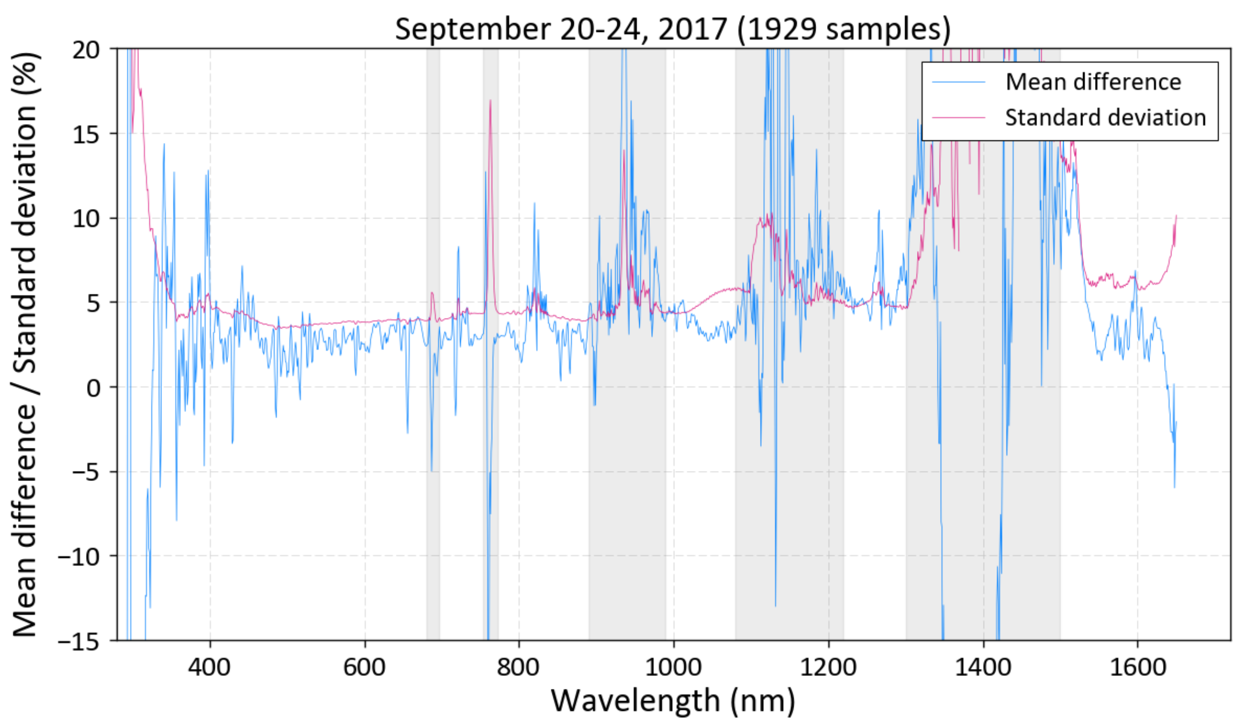

Figure 10. The mean difference and standard deviation thereof between the SolarSIM-G (SN1010) and WISER spectral GHI data sets for the period 20th - 24th of September. The data set contains over 1900 spectra per instrument. Note: the SolarSIM-G spectra have not been smoothed in this analysis.

Figure 10 shows that the mean difference and standard deviation are broadly below 5%, within the 300-1650 nm spectral range – excluding wavelength ranges characterized by sharp oxygen and water vapor absorption features (vertical gray bands). Furthermore, for wavelengths below 350 nm and above 1600 nm the standard deviations are shown to increase.

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Given that the SolarSIM-G has been shown to generate highly accurate broadband GHI data from the integral of its spectral GHI data (as detailed in Section 6 above), we can be confident in the cosine response and absolute accuracy of the SolarSIM-G's spectral GHI data. As such, it is plausible that the 2%-5% difference in spectral GHI observed between the SolarSIM-G RUs and the WISER spectroradiometers can be largely attributed to the cosine error of the WISER (which can be as high as 7% between zenith angles of 0° and 80°). For comparison, a typical cosine response for the SolarSIM-G is presented in Figure 11, showing <2% error at 80°.

In addition, the increased deviations below 350 nm and above 1600 nm are likely due to the higher temperature dependence and/or stray light limitations of the WISER spectroradiometers within these regions. Broadly speaking, the spectral irradiance variations seen between the SolarSIM-G RUs and the WISER spectroradiometers are within the limits typically seen for state-of-the-art spectroradiometer intercomparisons.

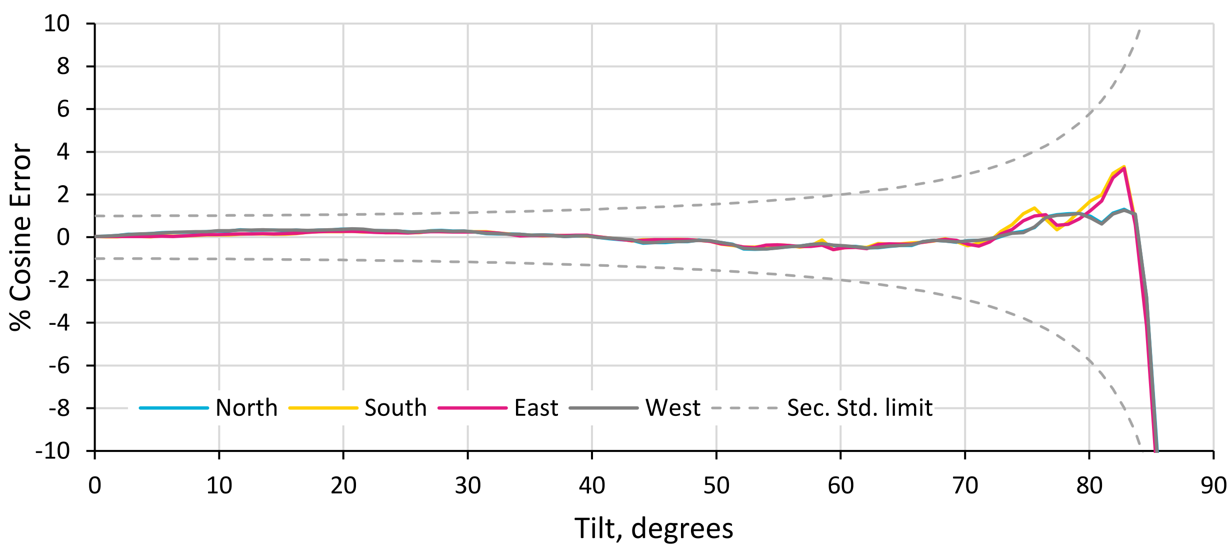

Figure 11. Typical cosine error for the SolarSIM-G. Note, the cosine error curves shown here represent the average of all nine SolarSIM-G measurement channels, weighted to the AM1.5G solar spectrum. The dotted grey lines represent the secondary standard cosine error limits, as defined in ISO-9060.

8. UV-Total measurement performance

The ability of the SolarSIM-G to accurately resolve total UV solar irradiance (UV-T) was compared against NREL's CUV4 and TUVR total UV sensors. The SolarSIM-G's UV-T data is obtained directly from the wavelength integral of its spectral irradiance data between 280-400nm.

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Figure 12 presents the daily UV-T profiles as measured by the SolarSIM-G RUs, for the 1st of October, with 1-minute time resolution. NREL's CUV4 and TUVR UV-T data is also plotted for comparison. As shown, the SolarSIM-G RUs provide UV-T data that is highly comparable to the CUV4 and TUVR.

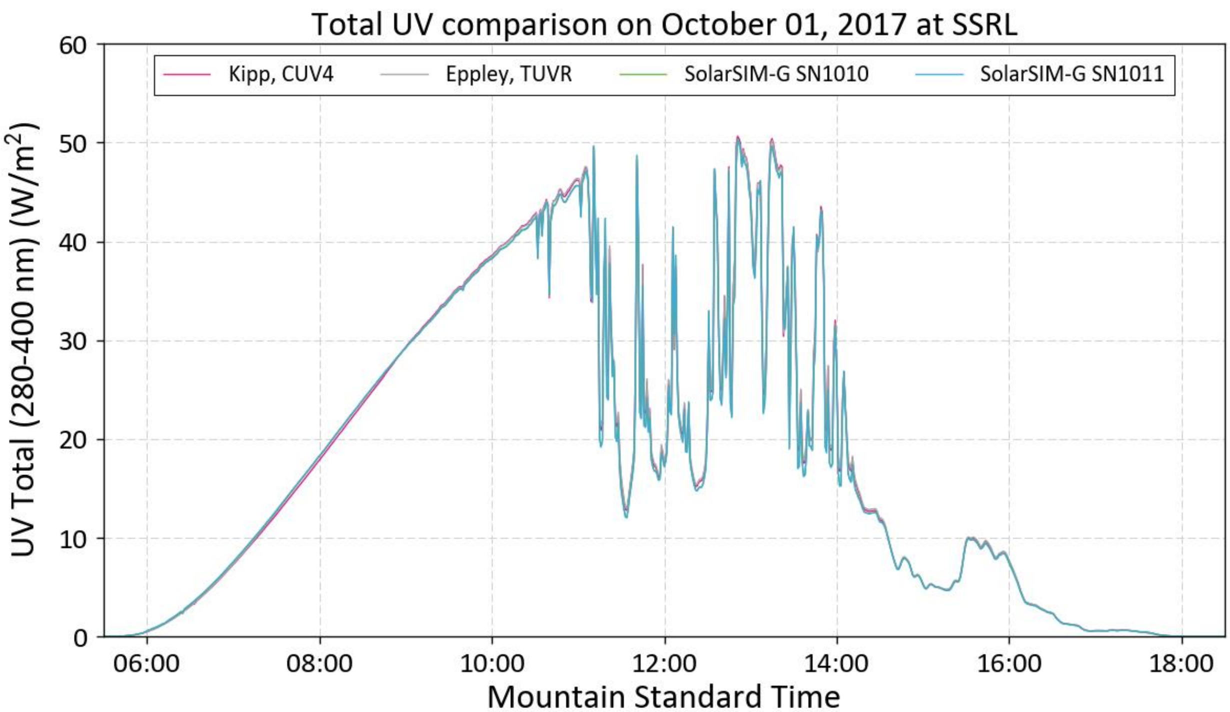

Figure 12. UV Total data obtained from the SolarSIM-G RUs, compared to NREL's CUV4 and TUVR sensors for the 1st October 2017.

A broader comparison is shown in Figures 13, which present comparative scatterplots for over two weeks of SN1010 and SN1011 UV-T data versus NREL's CUV4 data. As shown, the SolarSIM-Gs produce highly comparable UV-T data under all sunlight conditions. Root mean square errors (RMSE) of approximately ±0.7 W/m^2 were achieved with over 10,000 data points analyzed. Slope values of .9818 and 0.9819 were observed for SolarSIM-G RUs SN1010 and SN1011, respectively.

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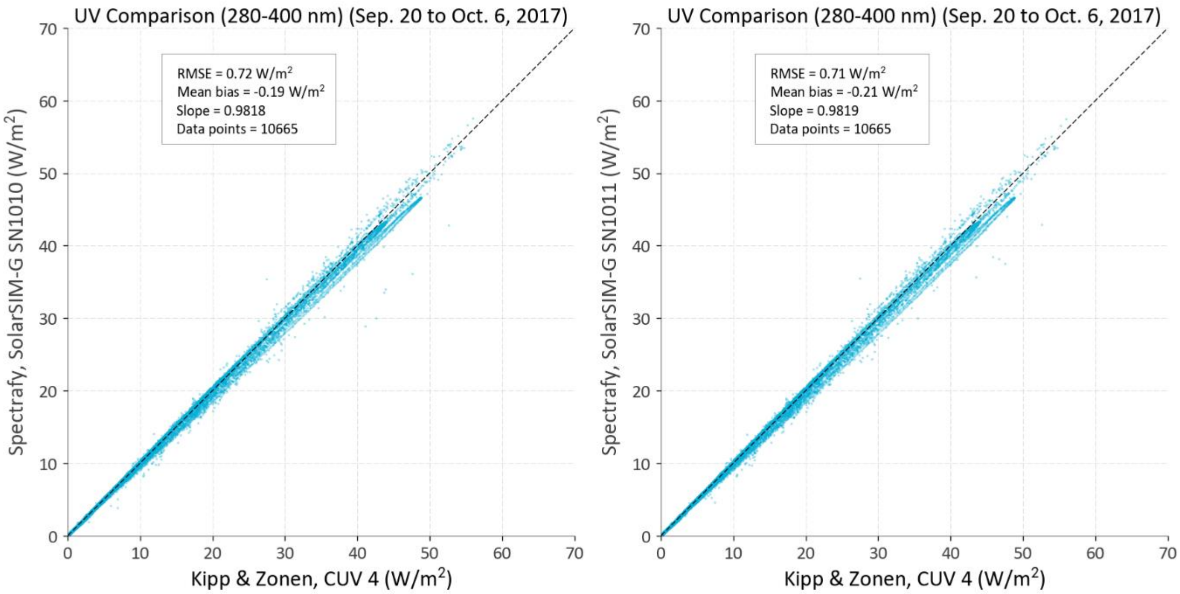

Figure 13. Scatter plots of the UV-T data obtained from the SolarSIM RUs (SN1010 LHS, SN1011 RHS) plotted against NREL's CUV-4 UV-T data for the period 20th September to 6th October 2017. Over 10,000 data points were analyzed.

9. PAR measurement performance

The ability of the SolarSIM-G to accurately resolve photosynthetically active radiation (PAR) was compared against NREL's PQS-1 PAR sensor. The SolarSIM-G's PAR data is obtained directly from the wavelength integral of its spectral irradiance data between 400-700nm.

Figures 14 presents the daily PAR profiles as measured by the SolarSIM-G RUs, for the 1st of October, with 1-minute time resolution. NREL's PQS-1 PAR data is also plotted for comparison. The SolarSIM-G RUs provide highly comparable measurements of PAR, well within the measurement uncertainty of the PQS-1. The divergence observed around 7:00AM can be attributed to the relatively poor cosine response of the PQS-1.

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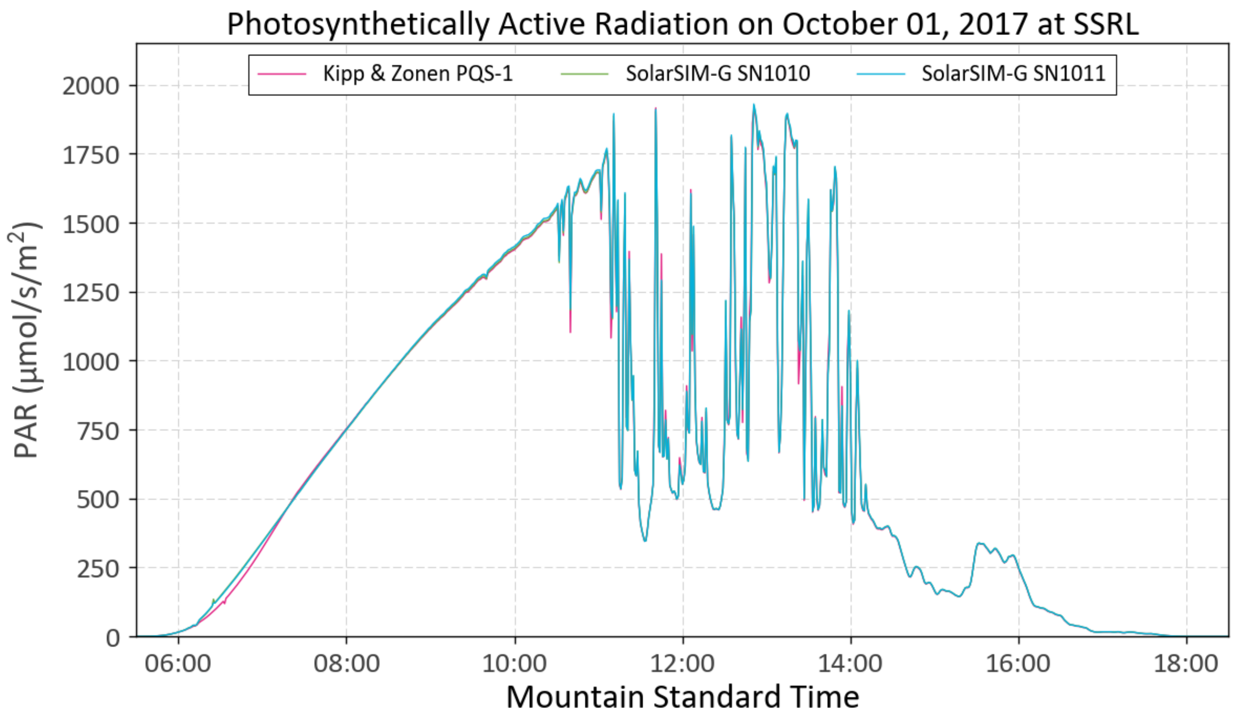

Figure 14. PAR data obtained from the SolarSIM-G RUs, compared to NREL's PSQ-1 PAR data for the 1st October 2017.

A broader comparison is shown in Figure 15, which presents comparative scatterplots for over two weeks of SN1010 and SN1011 PAR data versus NREL's PQS-1 data. As shown, the SolarSIM-Gs produce highly accurate PAR data under all sunlight conditions. Root mean square errors (RMSE) were ±15 μmol/s/m^2 with over 10,000 data points analyzed. Slope values of .9993 and 1.0030 were obtained for SolarSIM-G RUs SN1010 and SN1011, respectively. The slight bulge in the dataset observable at low irradiance levels can be attributed to the relatively poor cosine response of the PQS-1.

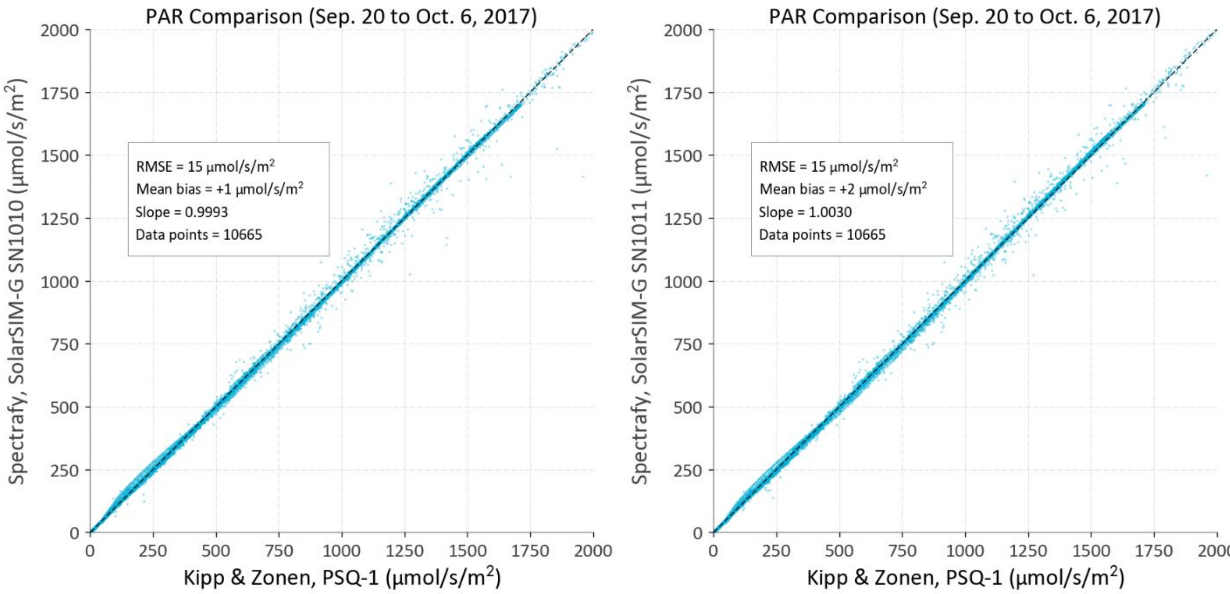

Figure 15. Scatter plots of the PAR data obtained from the SolarSIM RUs (SN1010 LHS, SN1011 RHS) plotted against NREL's PSQ-1 PAR data for the period 20th September to 6th October 2017. The RMSEs for both instruments are well within ± 15 μmol/s/m^2 with over 10,000 data points analyzed per SolarSIM.

10. Conclusions

Two SolarSIM-G reference units (SN1010 and SN1011) were calibrated at NREL's Solar Radiation Research Laboratory against NREL's reference spectroradiometers (WISER and LI-1800 spectroradiometers) in the global normal orientation. The SolarSIM-Gs' spectral, broadband and narrowband irradiance measurement performance was then assessed in the global horizontal orientation from 20th September to 6th October 2017. For that time period, over 10,000 measurements of GHI, UV-Total and PAR from each RU have been compared against NREL's reference sensors, revealing accurate performance in all three categories.

Furthermore, the SolarSIM-Gs' spectral GHI data has been compared against NREL's WISER spectroradiometers for the same time period. 1,929 spectra were analyzed per device, revealing mean differences and standard deviations that were largely within 5% for the 300-1650nm spectral range - excluding areas with sharp oxygen absorption peaks and water vapour bands. The minor differences in spectral irradiance measurement that are observed can plausibly be contributed to the cosine, temperature response and stray light limitations of the WISER spectroradiometers.

These results serve as an important validation of the SolarSIM-G as a highly accurate, multi-functional sensor, capable of measuring global broadband, narrowband and global spectral irradiance, under all sky conditions.

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