Spectrafy™
solar spectral sensors

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

September 18th – October 6th, 2017

1. Executive Summary

In September 2017, two SolarSIM-G/UV reference units (RUs) (SN1010 and SN1011) underwent calibration and performance validation at NREL's Solar Radiation Research Laboratory. The SolarSIM RUs were calibrated on-sun, against NREL's reference UV spectroradiometers. UV-A/B/T, PAR and GHI measurement accuracy was then analysed over 17 days versus NREL's reference UV sensors, pyranometers and PAR sensors.

UV-Total measurements were shown to be comparable to NREL's UV-T reference sensors, with mean biases of ~0.2 W/m^2 and RMSE of 0.72 – 0.76 W/m^2 observed from over 10,000 data points analyzed.
UV-A measurements were shown to be comparable to NREL's UV-A reference sensors, with mean biases of -0.07 – 0.26 W/m^2 and RMSE of 0.61 – 1.98 W/m^2 observed from over 10,000 data points analyzed.
UV-B measurements were shown to be comparable to NREL's UV-B reference sensors, with mean biases of -0.07 – 0.02 W/m^2 and RMSE of 0.05 – 0.07 W/m^2 observed from over 10,000 data points analyzed.

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.

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

Overall, the test results serve as an important validation of the SolarSIM-UV as a highly accurate and reliable sensor for measuring UV-T/A/B/E, global irradiance and PAR.

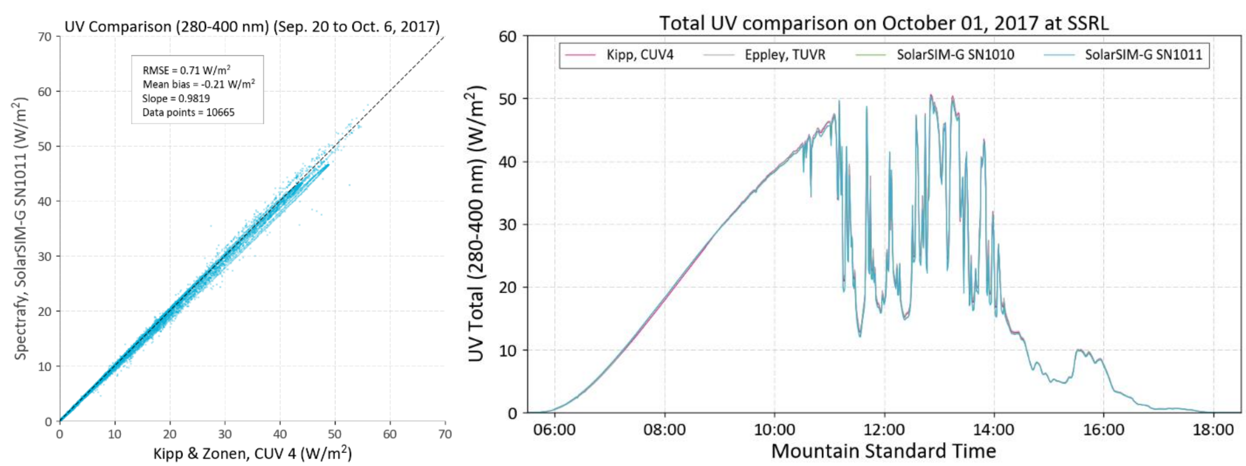

Figure 1. Scatter plot of UV-T data obtained from the SolarSIM RUs plotted against NREL reference UV sensors (LHS) and UV-T data obtained from the SolarSIM RUs compared to NREL's CUV4 and TUVR sensors for 1st October 2017.

2. Introduction

In September 2017, Spectrafy delivered two SolarSIM-G/UV 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/UV RUs against NREL's secondary standard spectroradiometers,
2. Validate the SolarSIM-UVs' UV-Total, UV-A, UV-B, UV-E, GHI and PAR measurement accuracy against NREL's reference UV sensors, pyranometers and PAR sensors, respectively.

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

3. SolarSIM-UV overview

The SolarSIM-UV 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-UV's software then uses these measurements, to accurately resolve the global solar spectral irradiance over the complete 280-4000 nm wavelength range, under all sky conditions. Broadband and partial band (i.e. GHI, UV-T, UV-A, UV-B, PAR) global irradiances are then obtained by integrating the spectra within the relevant wavelength range: 280-400nm for UV-T, 315-400nm for UV-A, 280-315nm for UV-B, 280-4000nm for GHI and 400-700nm for PAR.

4. SolarSIM-UV Specifications

Irradiance

UV-Total........280-400 nm
UV-A........315-400 nm
UV-B........280-315 nm
UV-E........per IEC 17166
PAR........400-700 nm
GHI........280-4000 nm
Spectral response........n/a - measurements integrated from spectra
Response Time (95%)........<0.5s
Directional Response........±3% at 80° zenith
Non-stability........<0.5%/yr
Non-linearity........<0.5%
Temperature Response........<0.1% (on-board temperature correction)
Calibration Uncertainty........1.1%
Max acquisition rate........0.5 Hz

General

Weight........1.1 kg
Dimensions........132 x 132 x 108 mm
Power supply and use........12 VDC, 1W
Communication........RS-485 ASCII, RS-485 Modbus, direct to PC, serial over ethernet or data logger
Operating Temperature........-30 to 65 °C
Humidity Range........0 to 100 % RH

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5. Calibration

Calibration of the SolarSIM 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 SolarSIMs' nine optical channels were calibrated for absolute irradiance against the reference spectroradiometers.

Figure 3. Calibration setup with the SolarSIM 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 RUs were compared, as shown in Figure 4. As expected, the spectral irradiance from the SolarSIM RUs matches the data from the reference spectroradiometers very well.

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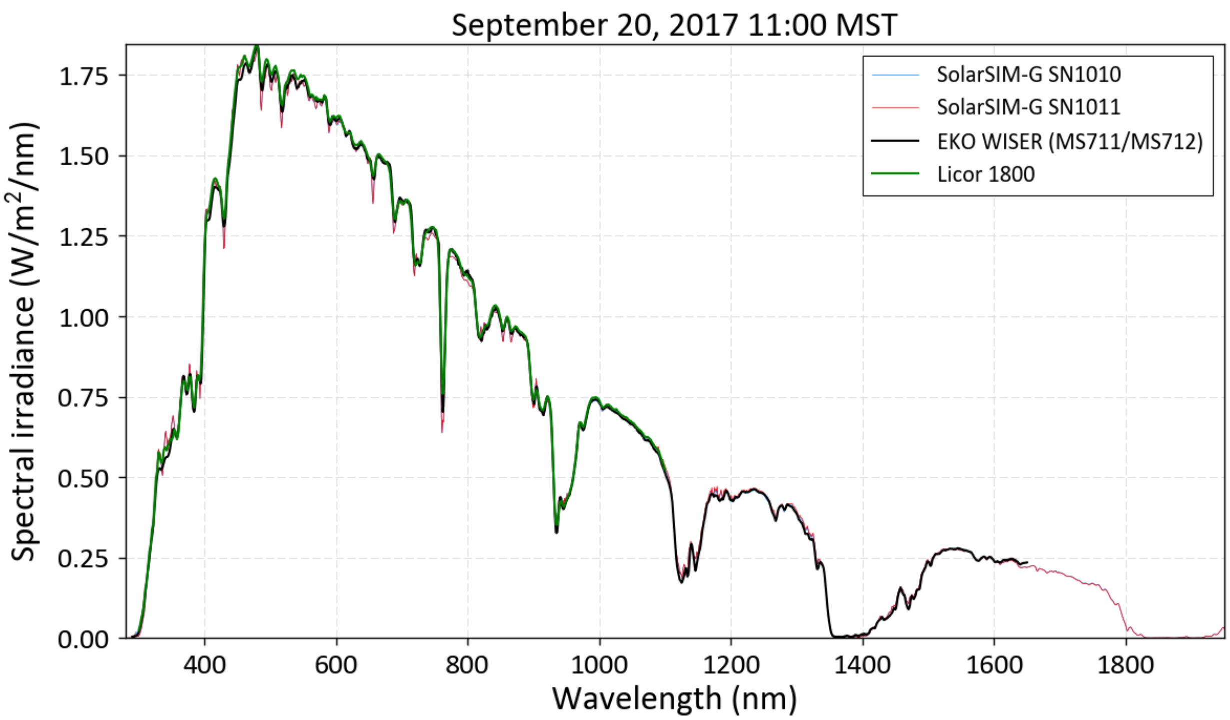

Figure 4. Spectral global normal irradiance as measured by the WISER, Licor-1800, and the SolarSIM RUs at 11:00 MST on September 20, 2017. To aid comparison, the spectra obtained from the SolarSIMs have been smoothed with 5 nm central averaging to approximate the lower measurement resolution of the reference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

6. UV-Total measurement performance

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

Figure 5 presents the daily UV-T profiles as measured by the SolarSIM-G/UV 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 RUs provide UV-T data that is highly comparable to the CUV4 and TUVR.

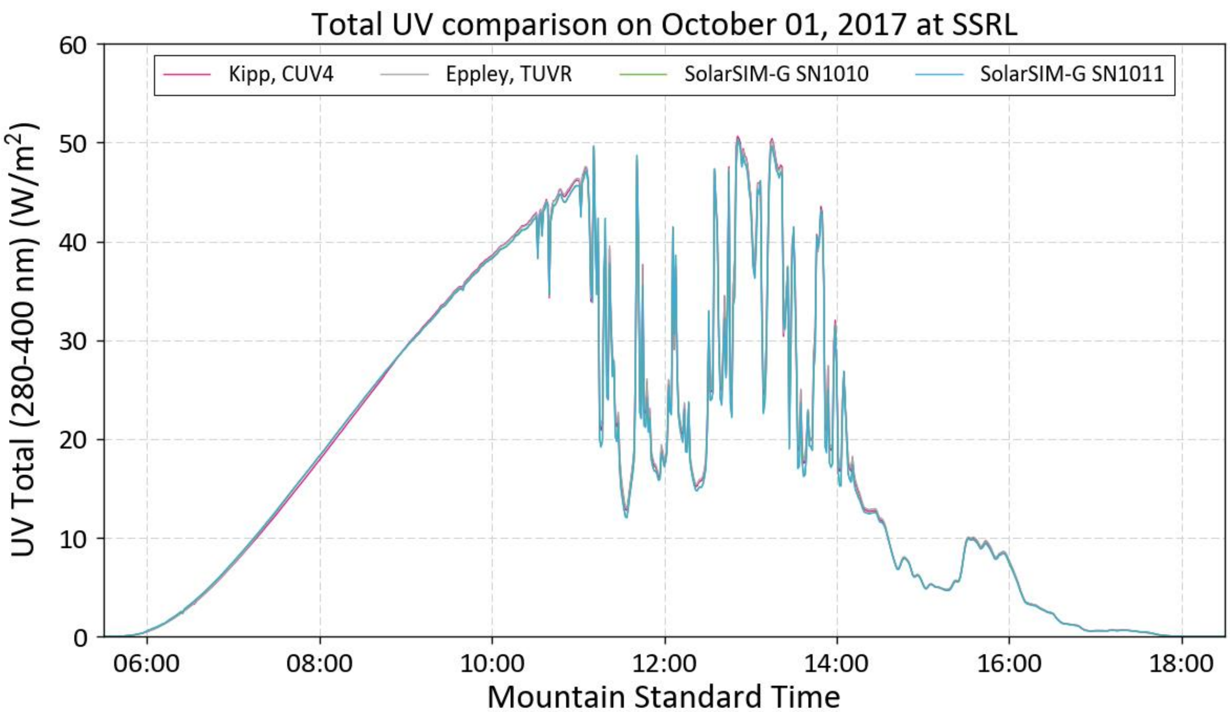

Figure 5. UV Total data obtained from the SolarSIM-G RUs, compared to NREL's CUV4 and TUVR sensors for the 1st October 2017.

A broader comparison is shown in Figures 6, which present comparative scatterplots for over two weeks of SN1010 UV-T data versus NREL's CUV-4 and TUVR data. As shown, the SolarSIM-UV produces 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 0.9830 were observed versus the CUV-4 and TUVR, respectively.

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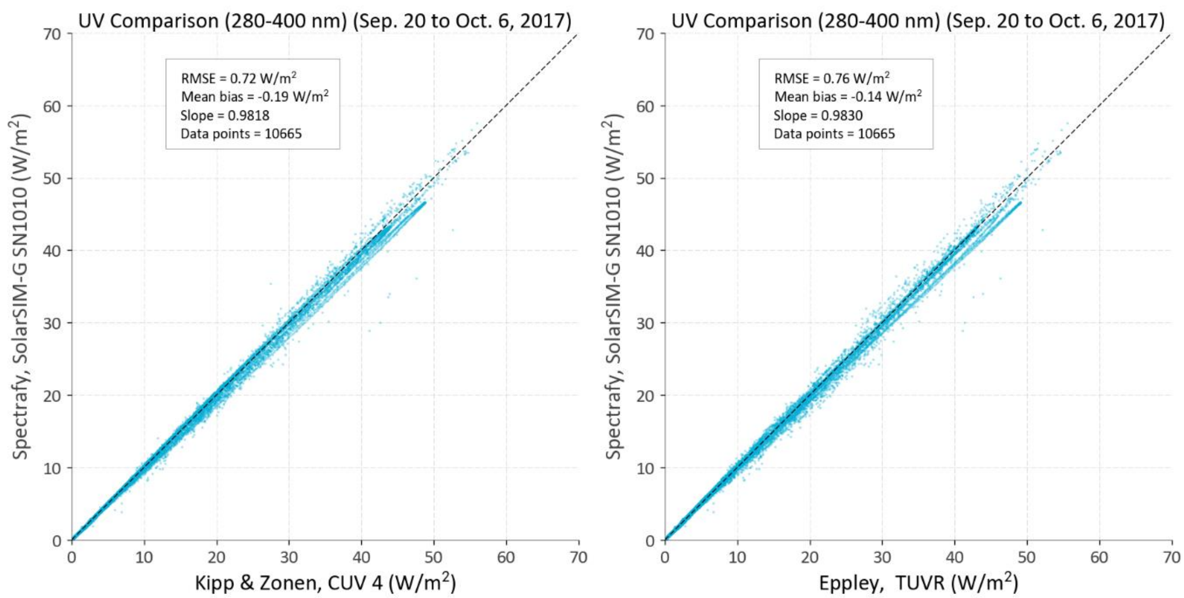

Figure 6. Scatter plots of the UV-T data obtained from the SolarSIM RU (SN1010) plotted against NREL's CUV-4 and TUVR UV-T data for the period 20th September to 6th October 2017. Over 10,000 data points were analyzed.

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7. UV-A measurement performance

The ability of the SolarSIM-UV to accurately resolve UV-A solar irradiance (UV-A) was compared against NREL's M501A-A and SUVA UV-A sensors and against the 315-400nm integral of NREL's MS711 spectroradiometer. The SolarSIM-UV's UV-A data is obtained directly from the wavelength integral of its spectral irradiance data between 315-400nm.

Figure 7 presents the daily UV-A profiles as measured by the SolarSIM RUs, for the 1st of October, with 1-minute time resolution. NREL's SUV-A and M501A-A data is also plotted for comparison. As shown, the SolarSIM RUs provide UV-A data that is highly comparable to the SUV-A and M501A-A.

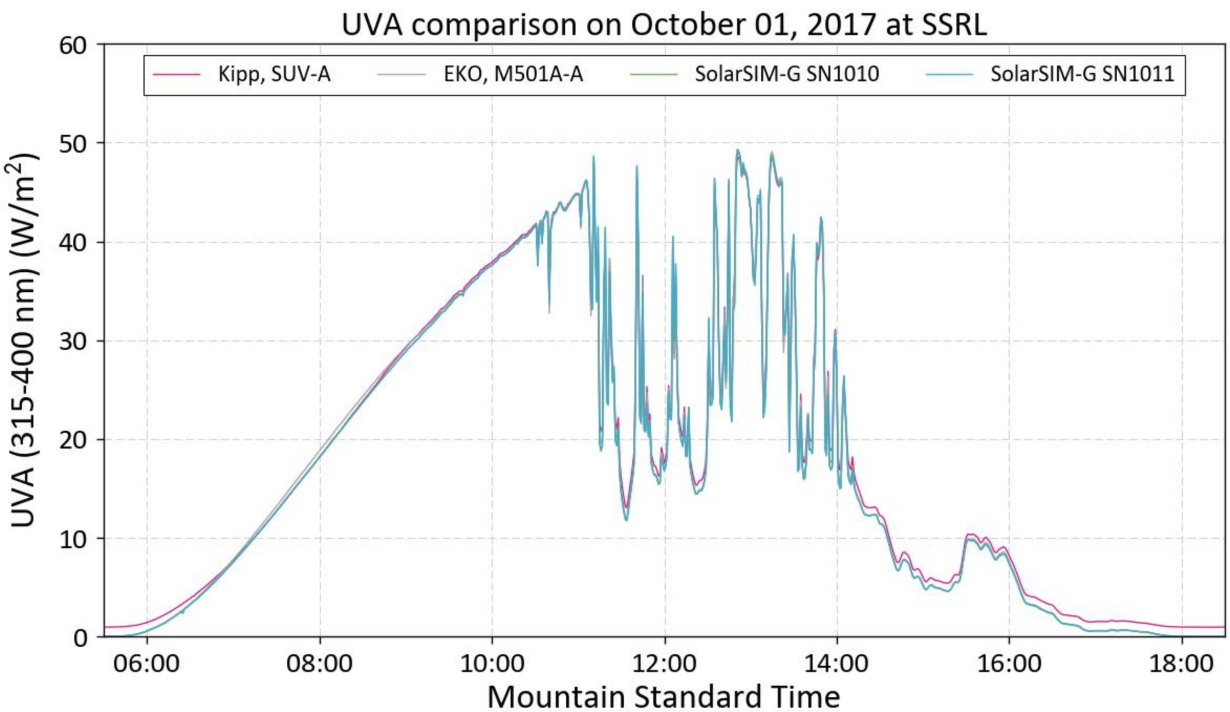

Figure 7. UV-A data obtained from the SolarSIM RUs, compared to NREL's M501A-A and SUV-A sensors for the 1st October 2017. Note the zero offset in the SUV-A data.

A broader comparison is shown in Figures 8, which present comparative scatterplots for over two weeks of SN1010 UV-A data versus NREL's M501A, SUV-A and MS711 data. As shown, the SolarSIM-UV produces highly comparable UV-A data under all sunlight conditions. Root mean square errors (RMSE) of approximately ±0.6 – 1.98 W/m^2 were observed with over 10,000 data points analyzed. Slope values of .9790 – 0.9931 were observed.

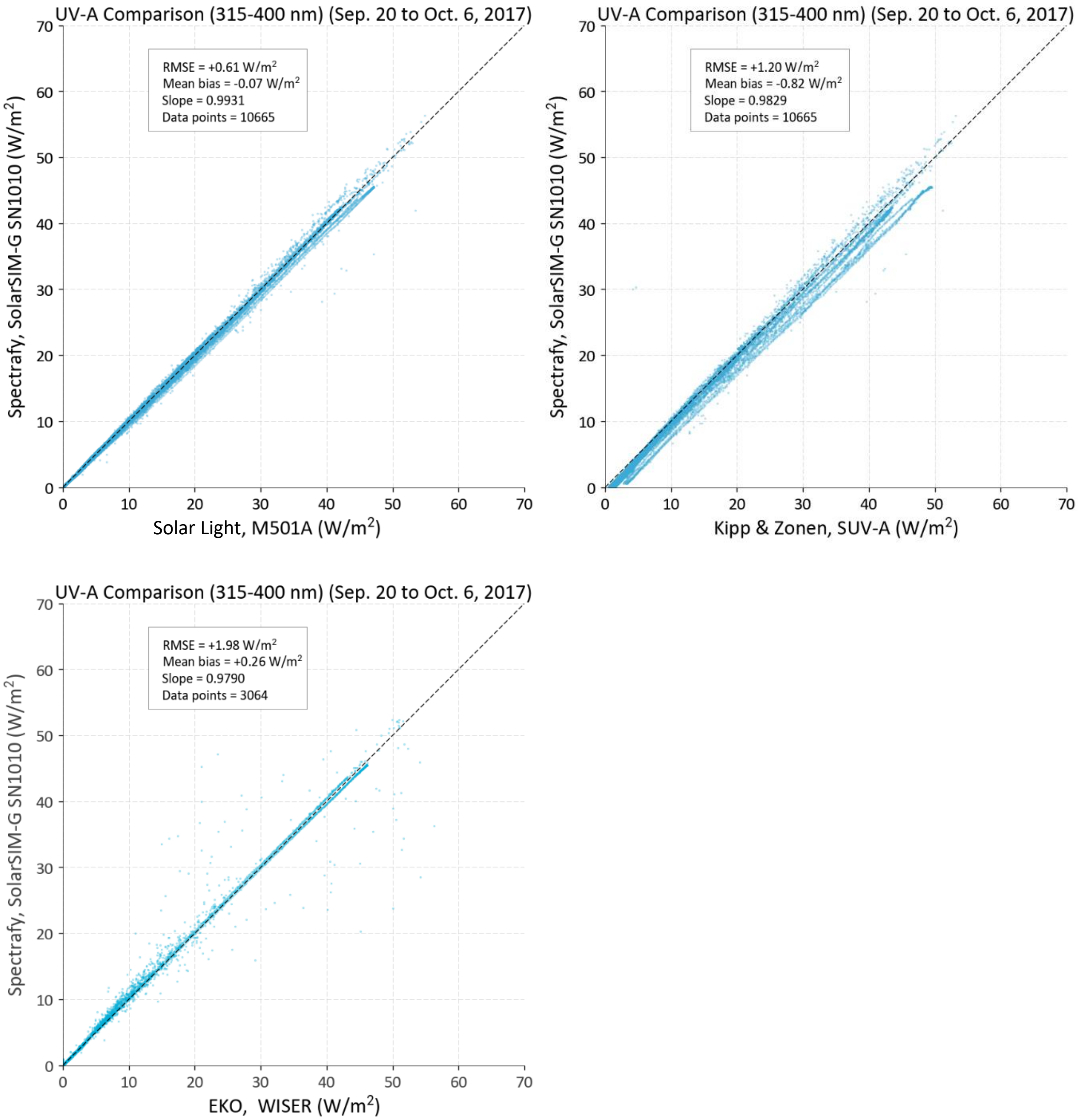

Figure 8. Scatter plots of the UV-A data obtained from the SolarSIM RU (SN1010) plotted against NREL's M501A (top left), SUV-A (top right) and MS711 (bottom left) for the period 20th September to 6th October 2017. Over 10,000 data points were analyzed. Note that the SUV-A suffered from a non-zero offset during the measurement period.

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8. UV-B measurement performance

The ability of the SolarSIM-UV to accurately resolve UV-B solar irradiance (UV-B) was compared against NREL's M501A, S210W, SUV-B and UVB1 UV-B sensors. The SolarSIM-UV's UV-B data is obtained directly from the wavelength integral of its spectral irradiance data between 315-400nm.

Figure 9 presents the daily UV-B profiles as measured by the SolarSIM RUs, for the 25th of September, with 1-minute time resolution. NREL's SUV-B, M501A-B, MS201W and UVB-1 data is also plotted for comparison. As shown, the SolarSIM RUs provide UV-B data that is highly comparable to the other UV-B sensors.

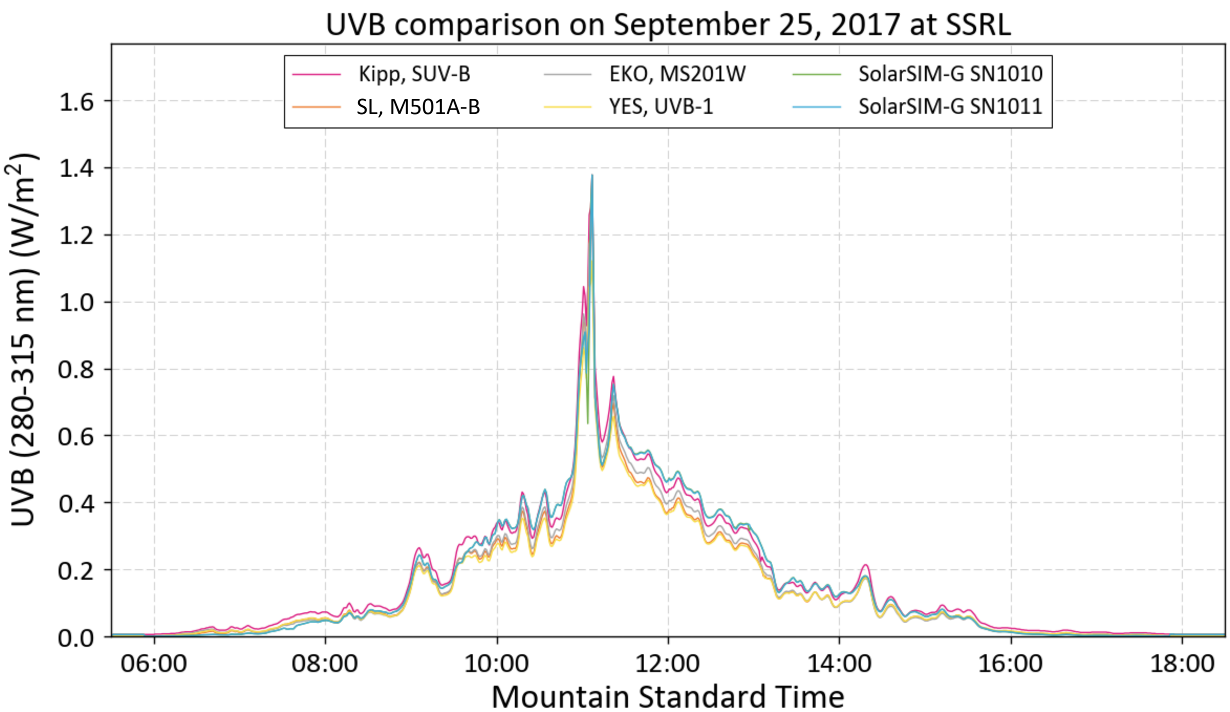

Figure 9. UV-B data obtained from the SolarSIM RUs, compared to NREL's M501A-B, SUV-B, MS201W and UVB-1 sensors for the 25th September 2017.

A broader comparison is shown in Figures 10, which present comparative scatterplots for over two weeks of SN1010 UV-B data versus NREL's UV-B sensor data. As shown, the SolarSIM produces comparable UV-B data under all sunlight conditions. Root mean square errors (RMSE) of approximately ±0.05-0.07 W/m^2 were achieved with over 10,000 data points analyzed. Slope values of 0.8312 – 0.8964 were observed.

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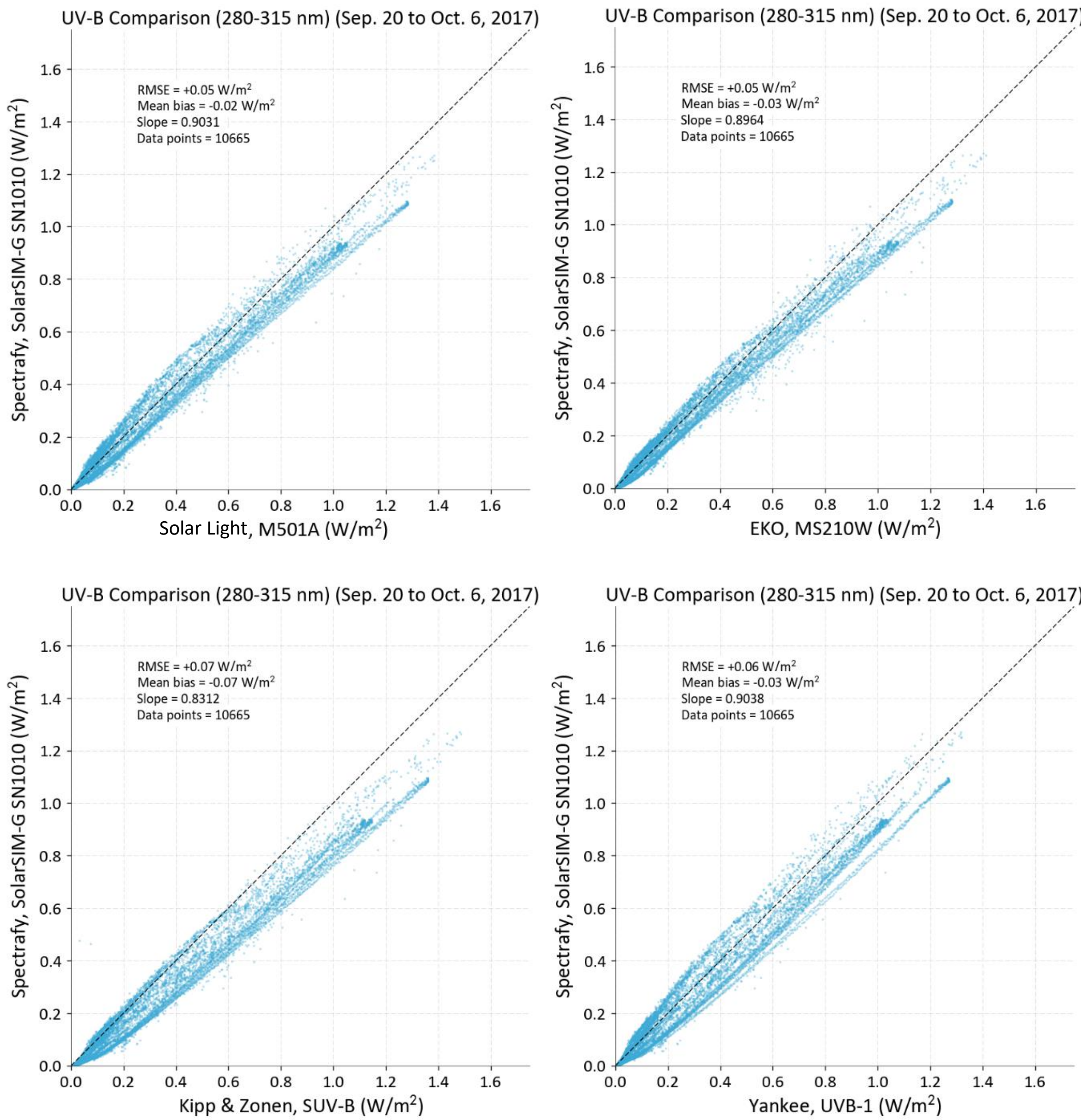

Figure 10. Scatter plots of the UV-B data obtained from the SolarSIM RU (SN1010) plotted against NREL's M501A-B (top left), MS210W (top right) SUV-A (bottom left) and UVB-1 (bottom right) for the period 20th September to 6th October 2017. Over 10,000 data points were analyzed.

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9. Global broadband measurement performance

Broadband performance of the SolarSIM 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-UV's GHI data is obtained directly from the wavelength integral of its spectral irradiance data over the 280-4000nm range.

Figures 11 and 12 present the daily GHI profiles as measured by the SolarSIM 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 RUs provide highly accurate measurements of GHI, well within the secondary standard limit of ± 10 W/m^2 (ISO-9060), versus the reference GHI.

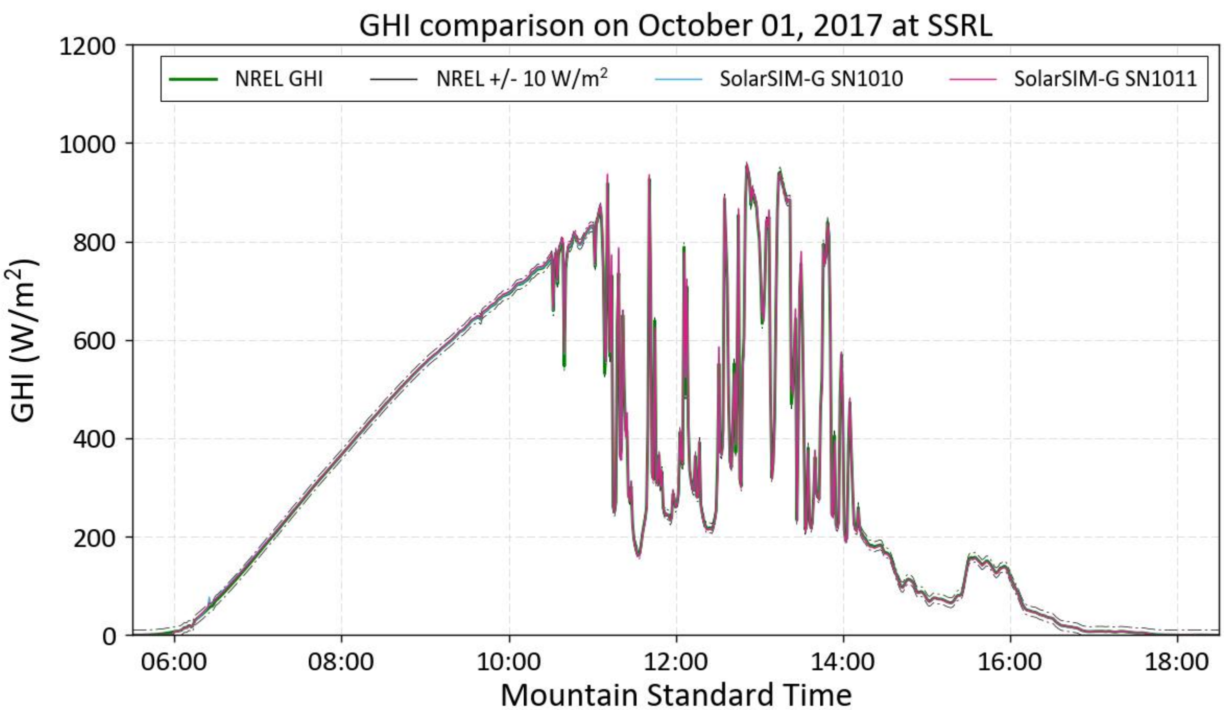

Figure 11. GHI data obtained from the SolarSIM RUs, compared to NREL's reference GHI data for the 1st October 2017. The SolarSIM data is consistently within ± 10 W/m^2 of the reference GHI data.

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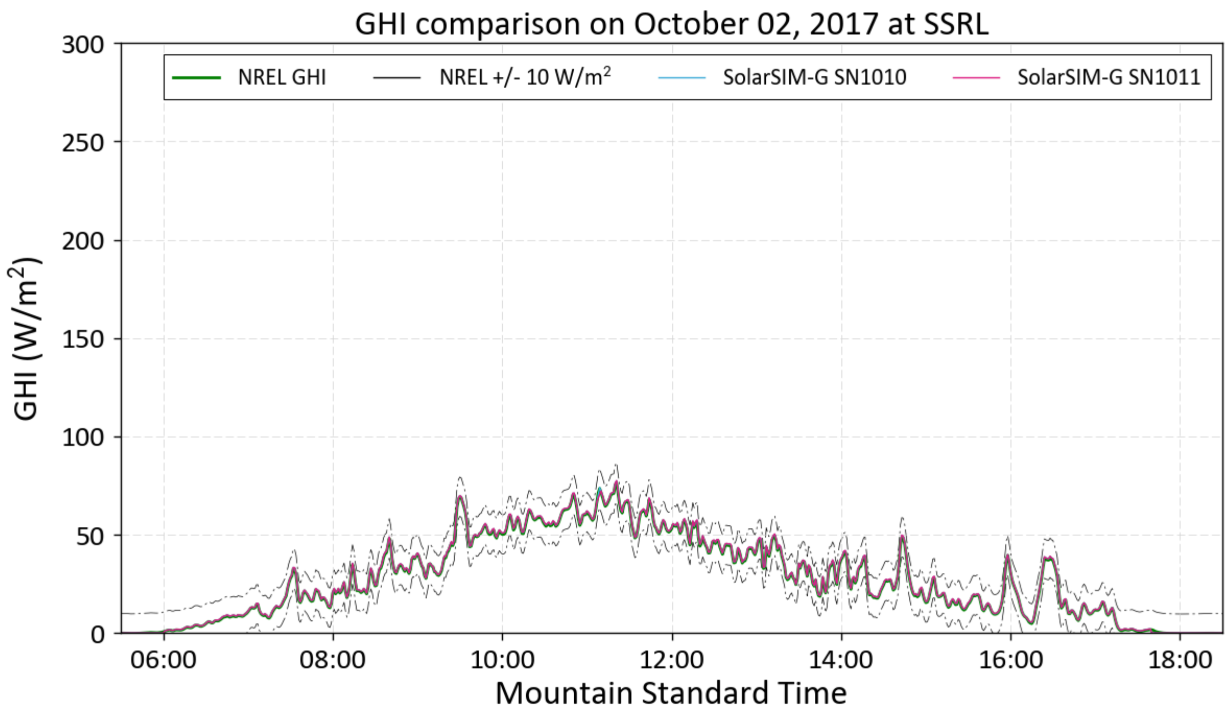

Figure 12. GHI data obtained from the SolarSIM RUs, compared to NREL's reference GHI data for the 2nd October 2017. The SolarSIM data is consistently within ± 10 W/m^2 of the reference GHI data.

A more holistic analysis of the SolarSIM RU's GHI performance is presented in Figure 13 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 observed for SolarSIM-G RUs SN1010 and SN1011, respectively.

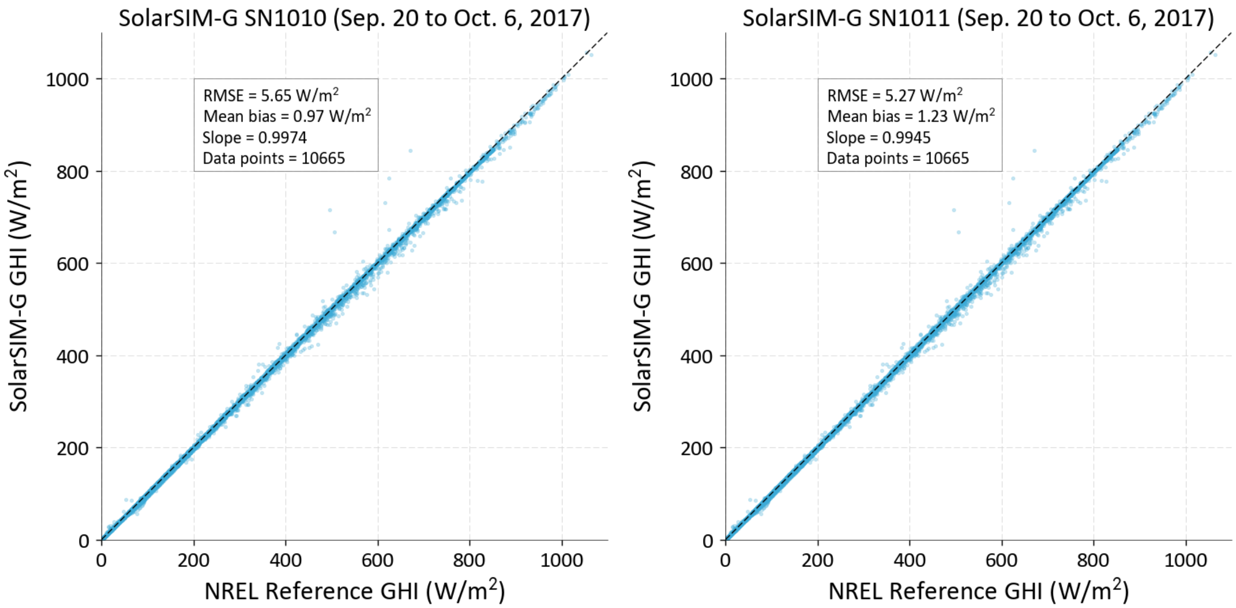

Figure 13. Scatter plots of the GHI data obtained from the SolarSIM RUs (SN1010 LHS, SN1011 RHS) plotted against NREL's reference GHI data for the period 20th September to 6th October 2017. The RMSEs for both instruments are well within ± 10 W/m^2 with over 10,000 data points analyzed per SolarSIM.

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10. PAR measurement performance

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

Figure 14 presents the daily PAR profiles as measured by the SolarSIM RUs, for the 1st of October, with 1-minute time resolution. NREL's PQS-1 PAR data is also plotted for comparison. The SolarSIM 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.

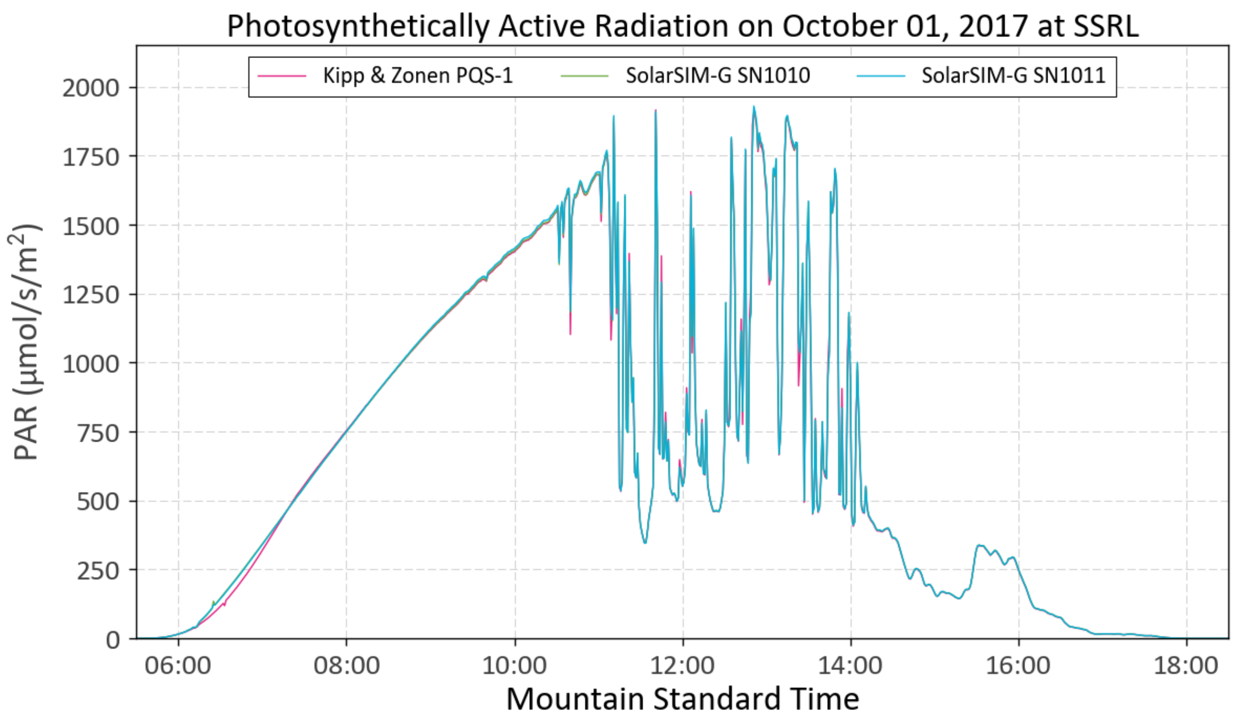

Figure 9. PAR data obtained from the SolarSIM RUs, compared to NREL's PSQ-1 PAR data for the 1st October 2017.

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 SolarSIMs produce highly accurate PAR data under all sunlight conditions. Root mean square errors (RMSE) were ±15 $\mu mol/s/m^2$ with over 10,000 data points analyzed. Slope values of .9993 and 1.0030 were obtained for SolarSIM 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.

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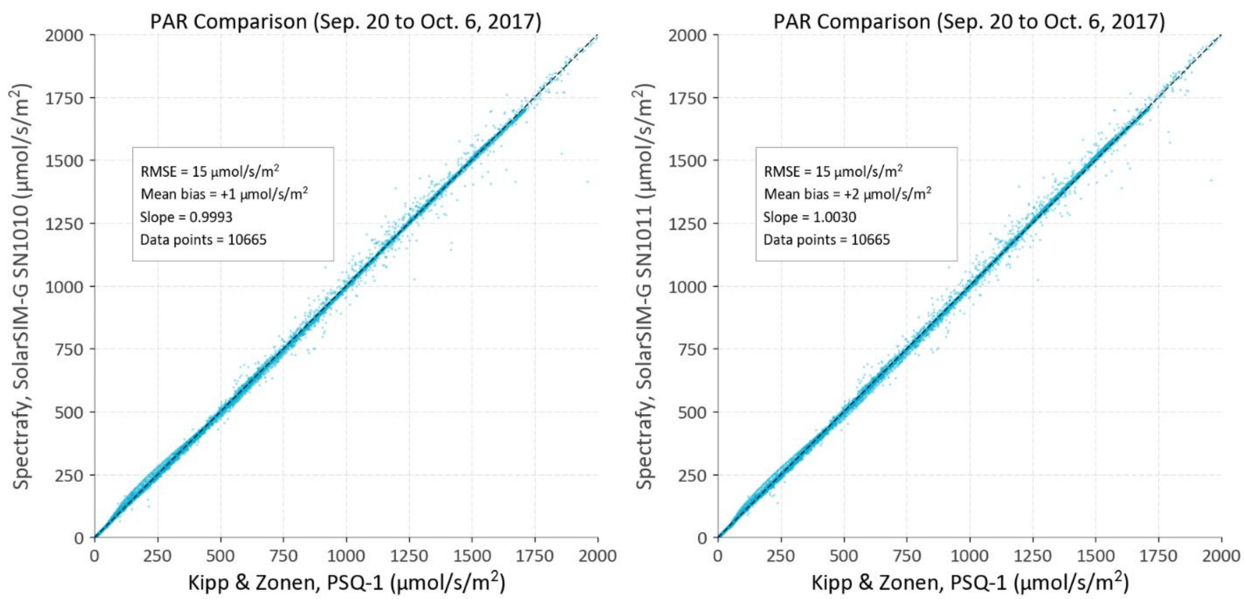

Figure 10. Scatter plots of the PAR data obtained from the SolarSIM RUs (SN1010 LHS, SN1011 RHS) plotted against NREL's PSQ-1 PAR data for the period 20th September to 6th October 2017. The RMSEs for both instruments are well within ± 15 μmol/s/m^2 with over 10,000 data points analyzed per SolarSIM.

11. Conclusions

Two SolarSIM-G/UV 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 SolarSIMs' 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, UV-A, UV-B and PAR from each RU have been compared against NREL's reference sensors, revealing accurate performance in all categories.

These results serve as an important validation of the SolarSIM-UV as a highly accurate, multi-functional sensor, capable of measuring solar UV-T/A/B/E, global irradiance and PAR under all sky conditions.