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Long Term Performance Analysis of Solar Spectral Irradiance Meters

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Abstract. Two generations of solar spectral irradiance meters (SolarSIMs), D1 and D2, are evaluated against reference instrumentation at the University of Ottawa SUNLAB outdoor test facility since their commissioning on September, 2014 and October, 2015, respectively. The average spectral direct normal irradiance (DNI) of the instruments was found to be well within ±1% at the six measured bands, centred at 420, 500, 610, 780, 880, and 940 nm, and mainly within ±2% for the remaining wavelengths in the 280-4000 nm range as compared to the reference SolarSIMs. The difference in cumulative energy densities as measured by the SolarSIMs and an Eppley model NIP pyrheliometer was found to be less than 0.5%. No degradation was observed during 19 months of operation.

INTRODUCTION

The solar spectrum is a key environmental factor affecting the performance of concentrating photovoltaic (CPV) modules, which are powered by over 40% efficient multi-junction solar cells (MJSCs) [1]. MJSCs are constructed with series-connected subcells of different bandgaps. As a result, these devices use the solar spectrum more efficiently, but their lowest current-generating subcell limits the performance of other subcells. For optimal performance, MJSC subcells are typically designed to be current matched for the AM1.5D spectrum from the ASTM G173 standard [2–4]. Under field conditions, however, the incident solar spectrum deviates from the reference one due to varying atmospheric conditions, which results in subcell current mismatch and consequently reduced CPV module performance [5–7]. Therefore, knowledge of the local solar spectrum is essential for a complete performance analysis of CPV systems.

Traditional ways of measuring the solar spectrum involves the use of expensive field spectroradiometers. The SolarSIM was designed as a cost-effective alternative to field spectroradiometers by using inexpensive silicon photodiodes with bandpass filters to measure the solar spectral irradiance in six narrow wavelength bands. The SolarSIM's software then uses these measurements to reconstruct the solar spectrum in the entire 280–4000 nm spectral range through estimation of the major atmospheric processes, such as air mass, Rayleigh scattering, aerosol extinction, ozone and water vapour absorptions [8].

In this paper, the performance of two SolarSIM generations, D1 and D2, at the University of Ottawa SUNLAB outdoor test facility is analyzed. SolarSIM-D1 (serial number SN101) has been in continuous operation since September 27, 2014, while SolarSIM-D2 (serial number SN115) has been in operation since October 23, 2015. SolarSIM-D2 builds upon the first generation with improved design, resulting in enhanced stray light rejection, increased durability,

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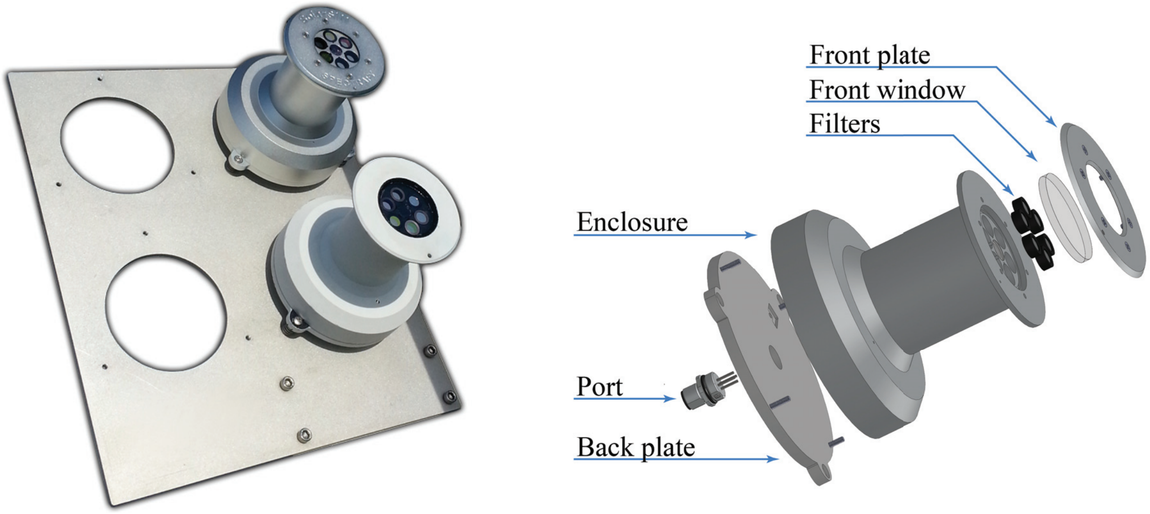


(a) (b)

FIGURE 1. a) SolarSIM-D1 SN101 (bottom) and SolarSIM-D2 SN115 (top) installed at the University of Ottawa outdoor test facility b) The exploded view of the main components of a SolarSIM-D2.

and improved electronics. The spectral irradiance and the DNI measured by both instruments is compared against reference SolarSIMs and an Eppley model NIP pyrheliometer, respectively.

SOLARSIM DESIGN FEATURES

The SolarSIM uses six silicon photodiodes coupled with six hard-coated bandpass filters to measure the spectral DNI within 10 nm full widths at half maximum. Each photodiode is situated within a collimation tube whose 5° field of view with 1° slope angle conforms to the World Meteorological Organization standard for radiometric measurements of DNI [9]. The aperture of each collimation tube is covered by a bandpass filter, which is situated under a BK-7 front window, as shown in Fig. 1. The internal humidity is kept at a low level with a desiccant. The data acquisition printed circuit board sequentially measures photodiode current from each channel, as well as ambient temperature and pressure. The photodiode current, ambient temperature and pressure data are sent via RS-485 communication protocol to a remote computer where specialized software driven by a graphical user interface implements spectral reconstruction over the 280-4000 nm range in real time [10].

The main design differences between SolarSIM-D1 and SolarSIM-D2 are presented in Table 1. To simplify the assembly procedure, the front window of SolarSIM-D2 is fastened between the enclosure and the front plate, as opposed to being glued to the enclosure. In addition, the collimation tube of D2 has a baffle to minimize stray light when the tracker goes off sun whereas the D1 version does not. SolarSIM-D2 also has a lower weight and lower power consumption as compared to D1, as a result of improved mechanical and electrical designs, respectively.

TABLE 1. SolarSIM-D1 and SolarSIM-D2 design features comparison

Design feature	SolarSIM-D1	SolarSIM-D2
Enclosure finish	Painted white	Clear anodized
Front plate	No	Yes
Frond window	Glued to an enclosure	Fastened via a front plate
Collimation tube	No baffles	One baffle
Instrument weight	1.2 kg	1 kg
Power consumption	1 W	0.7 W

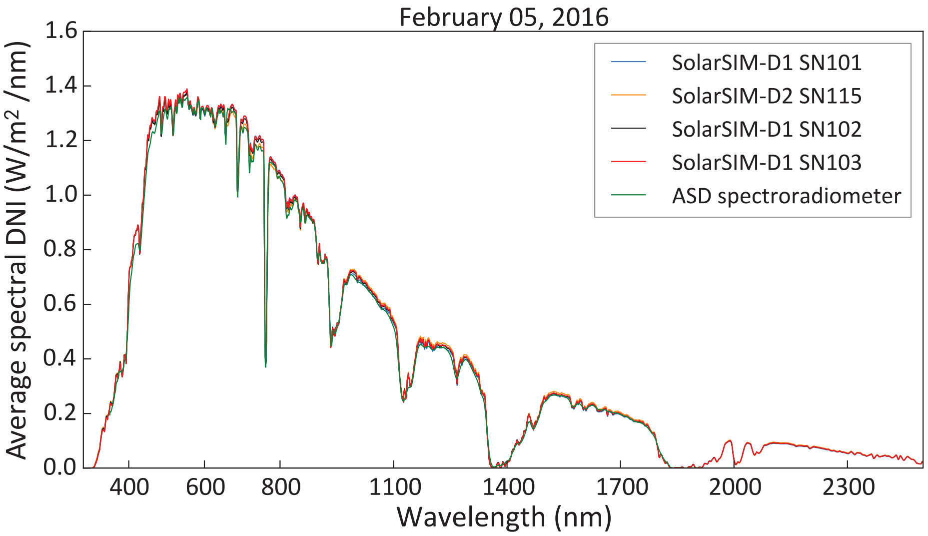
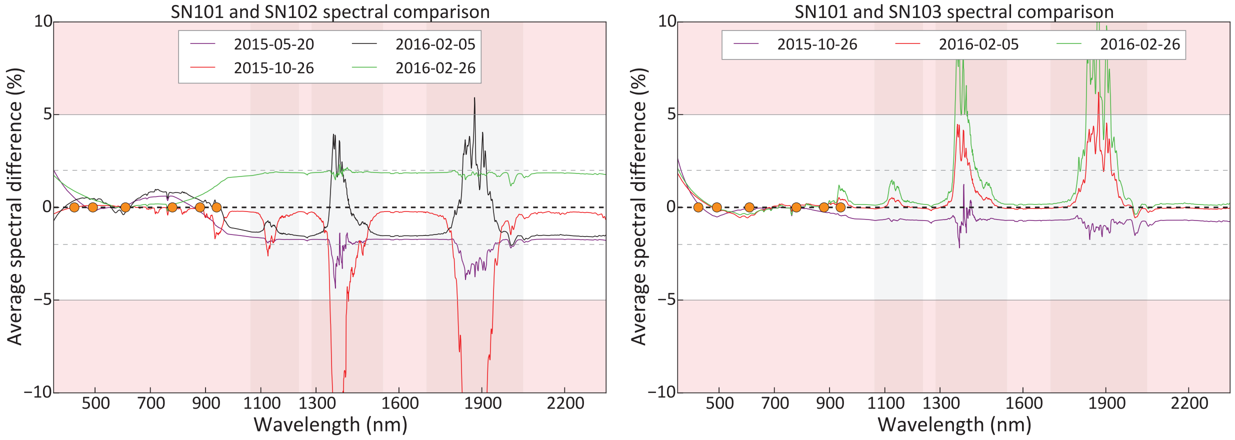


FIGURE 2. The average spectral DNI comparison between the SolarSIMs and the ASD spectroradiometer as measured at the University of Ottawa test facility on February 5, 2016 where the average geometric air mass over a one hour period was 2.1.

LONG TERM PERFORMANCE

Reference SolarSIMs SN102 and SN103 are primarily used to assess the spectral performance of SolarSIMs SN101 and SN115, as they were characterized and calibrated at the National Renewable Energy Laboratory in Golden, USA against secondary standard spectroradiometers and an absolute cavity radiometer [11]. The reference units are kept indoors and only occasionally brought outside for quick spectral comparisons on clear, sunny days. Fig. 2 shows the average spectral DNI comparison as measured by the reference SolarSIMs, SolarSIM-D1 SN101, SolarSIM-D2 SN115, and the ASD FieldSpec 3 spectroradiometer. The measurements were performed on February 5, 2016 where the average geometric air mass over a one hour period around the solar noon was 2.1. The spectral DNI from all instruments is mainly within ±5% of each other, albeit the ASD spectroradiometer slightly underestimates the spectral irradiance below 500 nm as compared to the SolarSIMs. Fig. 3a and 3b show the average spectral difference between SolarSIM SN101 and the reference SolarSIMs SN102 and SN103, respectively, on selected days for which the reference data was available. The orange circles in these figures are the locations of the six spectral bands measured by the instruments, centred at 420, 500, 610, 780, 880, and 940 nm. Agreement in these regions is critical since the spectral algorithm uses them to infer the spectral DNI in the 280–4000 nm range. The spectral irradiance inferred by SolarSIM SN101 is within ±1% in all six measured wavelength bands and is mainly within ±2% in all the other regions, except for the deep water bands centred at 1370 and 1870 nm. However, the spectral irradiance in those areas is close to zero, as apparent from Fig. 2. Evidently, no spectral degradation over the 19 month time period is observed.

The SolarSIM spectrum integral across the 280–4000 nm range yields the DNI in W/m^2. Over the course of a day, one can integrate the DNI versus time profile to compute the daily energy density in kWh/m^2. Furthermore, the summation of these quantities over time yields the cumulative or total energy density in MWh/m^2. These are the metrics used to evaluate long term SolarSIM performance against the Eppley pyrheliometer. The cumulative and daily energy densities from SolarSIMs SN101 and SN115 are compared to the corresponding values from the Eppley pyrheliometer over the September 27, 2014 to April 16, 2016, and October 23, 2015 to April 16, 2016 time periods, respectively, as demonstrated in Fig. 4. The daily energy density is computed from two minute time resolution data with DNI threshold of 50 W/m^2. Specific days were omitted from the analysis due to soiling from the snow. Cumulative energy densities from SolarSIM SN101 and the Eppley pyrheliometer are 1288.3 and 1283.4 MWh/m^2, respectively, for a difference of less than 0.5% over 19 months of operation. Cumulative energy densities from SolarSIM SN101 and the Eppley pyrheliometer are 247.9 and 246.8 MWh/m^2, respectively, for a difference of less than 0.5% over six months of operation. Over 50,000 and 9,000 data records were used to calculate the cumulative energy densities for SolarSIM SN101 and SN115, respectively, against the Eppley pyrheliometer.



(a) (b)

FIGURE 3. a) The average spectral difference between SolarSIM SN101 and SN102 and b) SN101 and SN103 on clear, sunny days. The orange circles represent the spectral bands measured by the instruments, centred at 420, 500, 610, 780, 880, and 940 nm. The spectral difference is mainly within ±2% limits, as represented by dashed lines, except for the deep water vapour bands, centred at 1370 and 1870 nm, as shown by grey, rectangular areas. No degradation is observed.

CONCLUSION

The long term performance of two generations of SolarSIMs is presented. SolarSIM-D1 has been in continuous operation at the University of Ottawa outdoor test facility for 19 months, while SolarSIM-D2 has been in operation for over for 6 months. The average spectral performance for both units was found to be well within ±1% for the six measured bands centred at 420, 500, 610, 780, 880, and 940 nm, and within ±2% for the entire 280-4000 nm range, except for deep water vapour absorption bands, through comparison with the reference SolarSIMs. The cumulative energy densities between the SolarSIMs and the Eppley model NIP pyrheliometer agreed to less than 0.5%, for both SolarSIM-D1 and D2. No degradation was observed during 19 months of operation. The SolarSIM's reduced size, cost and improved design with no internal moving components makes it a strong candidate for routine and dependable monitoring of solar spectral irradiance in multiple locations.

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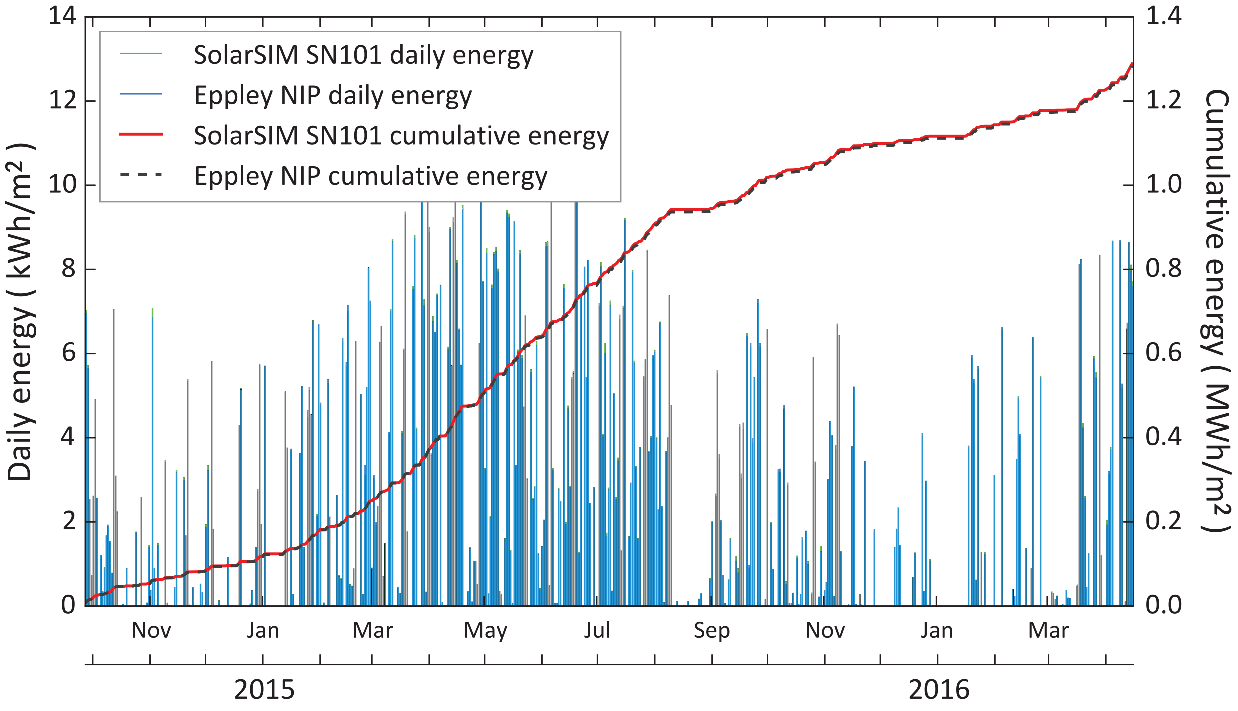

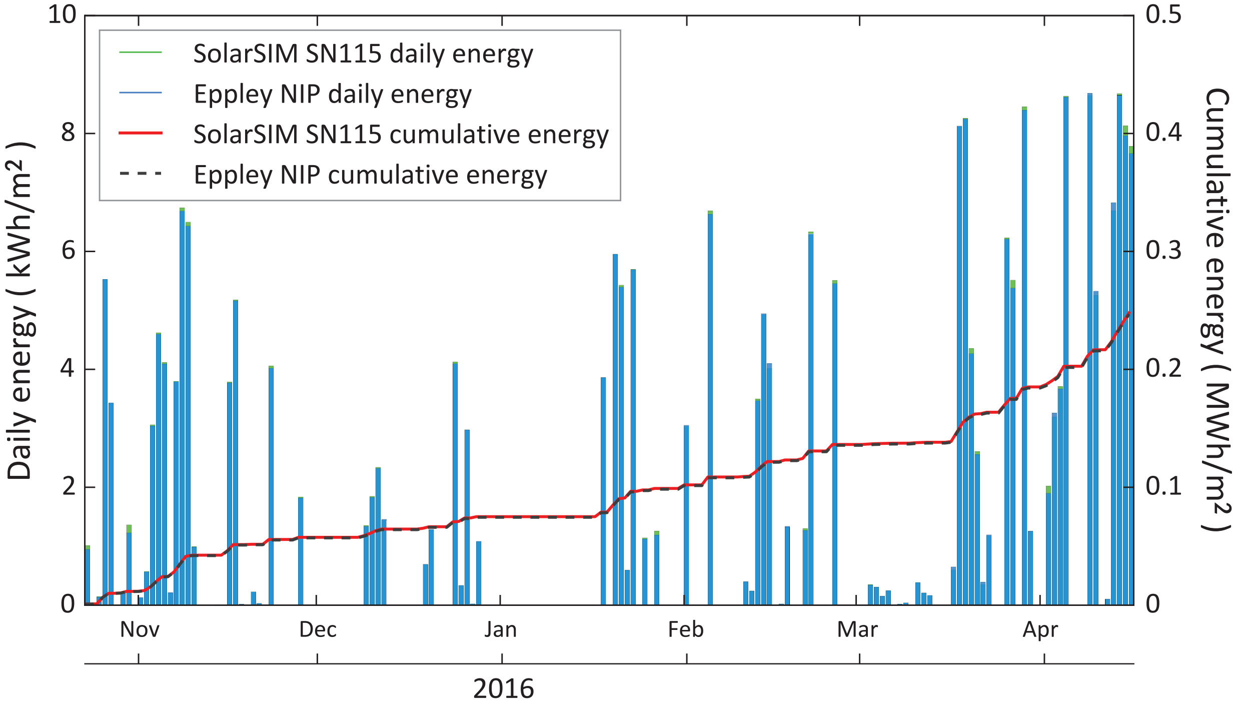

FIGURE 4. The cumulative and daily energy densities comparison between SolarSIM-D1 SN101 (top), SolarSIM-D2 SN115 (bottom) and the Eppley NIP pyrheliometer over 19 and 6 months, respectively. The cumulative energy density as measured by both SolarSIMs agrees to less than 0.5% of the corresponding values as reported by the Eppley pyrheliometer.

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