A Novel Instrument for Cost-Effective and Reliable Measurement of Solar Spectral Irradiance

Viktar Tatsiankou*, Karin Hinzer*, Henry Schriemer*, Joan Haysom*, and Richard Beal†

*University of Ottawa, Ottawa, Ontario, K1N 6N5, Canada
†COFOVO Energy Inc., Ottawa, Ontario, K1N 6N5, Canada

***Abstract*—A next generation solar spectral irradiance meter (SSIM) was installed at the University of Ottawa solar test site in September 2014, for ongoing collection of environmental and spectral data. The instrument's performance is compared against a commercial pyrheliometer and a spectroradiometer during an eight month study where ambient temperature fluctuates from -30°C to 30°C. The cumulative solar energy measured by the SSIM over the duration of the experiment agreed to within 0.5% as compared to the Eppley pyrheliometer. A good spectral agreement between the SSIM and the ASD FieldSpec 3 spectroradiometer is observed, with the integral of the spectral irradiance agreeing to within 1% for both instruments. No degradation is observed at any point during this investigation.**

***Index Terms*—solar spectral irradiance meter, SSIM, direct normal spectral irradiance, solar resource assessment, low cost spectral measurement**

I. INTRODUCTION

The solar spectrum is a primary environmental factor affecting the performance of concentrating photovoltaic (CPV) modules, which are equipped with optics to collect and concentrate the sunlight onto highly-efficient multi-junction solar cells (MJSCs). A MJSC consists of several subcells with different bandgaps, resulting in a more efficient harvest of the solar spectrum due to reduced thermalization and transmission losses. In this solar cell architecture the lowest current-generating subcell limits the performance of the other subcells. Therefore, for optimal performance MJSC subcells are designed to be current matched for a particular spectrum, such as for the AM1.5D reference spectrum, as defined in ASTM G173 [1–3]. Under field conditions, however, the solar spectrum deviates from this reference due to varying geographical and meteorological conditions, resulting in subcell current mismatch and with it - reduced CPV module performance [4, 5]. Therefore, the quantification of the solar spectrum is required for a complete performance analysis of CPV systems.

To date, a field spectroradiometer provided the most accurate way to reliably obtain solar spectra in a desired location. However, these measurements are rarely performed due to the prohibitive cost of the instrument. Therefore, a pyrheliometer is typically the only instrument used to assess the DNI, providing the total DNI power, but no information about spectral content. To address this problem, the solar spectral irradiance meter (SSIM) was designed to replace both a spectroradiometer and a pyrheliometer, at a fraction of the cost. The SSIM uses low-cost silicon photodiodes with bandpass filters to measure the solar spectral irradiance in several narrow wavelength bands. The SSIM's software then uses these measurements to resolve the solar spectrum through the calculation of the major atmospheric processes, such as air mass, Rayleigh scattering, aerosol extinction, ozone and water vapour absorptions [6].

The first iteration of the design led to a prototype deployment in 2013 with encouraging results, where the SSIM's DNI was on average within 1.5% of the Eppley pyrheliometer's DNI for nearly two months [7]. However, bandpass filter degradation and condensation limited the long term performance of this prototype. Recently, an improved, commercial-ready version of the SSIM was developed to address the aforementioned issues through the use of hard-coated bandpass filters and a custom aluminum enclosure.

In this paper, the performance of this next generation SSIM at the University of Ottawa solar test site is analyzed. An eight month comparative study with the Eppley pyrheliometer and the ASD FieldSpec 3 spectroradiometer is carried out to evaluate the reliability of the SSIM. The cumulative energy density difference and comparative daily plots between the aforementioned devices are presented.

II. SSIM INSTALLATION

The SSIM was installed in September, 2014 at the University of Ottawa solar test site (45.42°N, 75.68°W) [8]. The device is fastened to a mounting plate via three sets of screws and springs, which are manually adjusted to optimally orient the SSIM toward the sun. A pinhole on the instrument is used as a feedback to check the proper alignment. The SSIM is situated on the same mechanical assembly as the Eppley pyrheliometer and the ASD spectroradiometer, the latter measuring the spectral DNI within the range of 350–1830 nm. The dual-axis tracking system points these instruments normal to the sun with ±0.2° precision [9].

III. SSIM DESIGN

The next generation SSIM is pictured in Fig. 1a. The instrument uses six silicon photodiodes coupled with six bandpass filters to measure the spectral DNI in narrow wavelength bands with full widths at half maximum of 10 nm. Each photodiode is sensitive to the light distribution with slope and half angles of 1° and 2.5°, respectively, as defined by the World Meteorological Organization standard for radiometric measurements of the DNI [10]. This field of view is achieved by the geometric design of the SSIM's collimation tubes,

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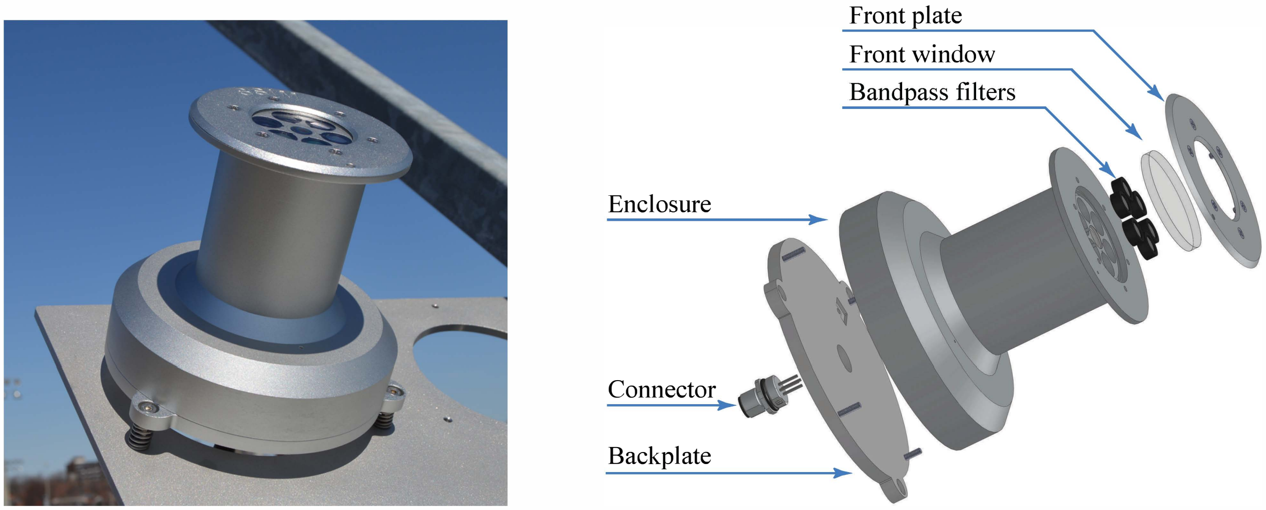

(a) (b)

Fig. 1. a) The solar spectral irradiance meter at the University of Ottawa solar test site. b) The exploded view of the main components of the solar spectral irradiance meter.

which are concentric with the photodiodes. The bandpass filters rest on the top of each collimation tube, while being protected by a front window from the ambient environment, as shown in Fig. 1b.

The data acquisition (DAQ) printed circuit board is housed inside the anodized aluminum enclosure. The DAQ sequentially measures the photodiode current from each channel as well as the ambient temperature and pressure. It takes a fraction of a second to perform these operations. The acquired measurements are sent via a RS-485 communication protocol to a remote computer, where specialized software with a graphical user interface processes it in real time. The photodiode current data, the ambient temperature, and pressure are fed into a model, which rapidly reconstructs the solar spectrum within the 280-4000 nm range [6]. The model also resolves air mass, Rayleigh scattering, aerosol extinction, ozone and water vapour absorptions.

IV. SSIM PERFORMANCE

The performance of the SSIM was evaluated against the Eppley pyrheliometer and the ASD spectroradiometer at the University of Ottawa solar test site over eight months. The ambient temperature fluctuates from -30°C to 30°C over this time period. Figure 2a shows the comparison of the DNI profiles as reported by the SSIM and the Eppley pyrheliometer for one partially cloudy day and one mainly clear day, occurring on September 28th, 2014 and May 17th, 2015, respectively. In both cases the SSIM is able to reproduce the DNI very accurately - on average it is within 1% of the Eppley pyrheliometer's DNI for clear sky conditions. This is likewise true for cloudy periods, although the DNI comparison is complicated due to differences in detector response times between the two instruments.

Furthermore, Fig. 2b shows the solar spectral irradiance for selected timestamps on September 28th, 2014 and May 17th, 2015 as reported by the SSIM and the ASD spectroradiometer. Overall, there is a good spectral agreement between both instruments, with the integral of the spectral irradiance agreeing to within 1%. However, the ASD spectroradiometer tends to systematically underestimate the solar spectrum in the near-UV range, as compared to the SSIM. A calibration error of the ASD spectroradiometer in this spectral range may be the cause of this discrepancy.

To validate the longterm reliability of the SSIM, its cumulative DNI energy was compared with a corresponding value from the Eppley pyrheliometer, as demonstrated in Fig. 3. Both datasets were filtered to eliminate DNI data below 50 W/m^2. In addition, days where the devices exhibited more than a 30 minute difference in availability were eliminated from the dataset. Days when sensors were obscured by snow have also been omitted. At the end of an eight month period the SSIM's and the Eppley pyrheliometer's cumulative energies are 549.1 and 546.5 kW·hr/m^2, respectively, or a difference of less than 0.5%.

V. CONCLUSION

The longterm performance validation of the SSIM is evaluated against the Eppley pyrheliometer and the ASD FieldSpec 3 spectroradiometer at the University of Ottawa solar test site between September, 2014 and May, 2015, during which ambient temperature fluctuations of -30°C to 30°C were observed. The SSIM accurately reproduces the solar spectrum and consequently the DNI under both clear-sky and cloudy conditions. The difference in the cumulative energy, as measured by the SSIM and the Eppley pyrheliometer, is within 0.5% over an eight month test period. A good spectral agreement between the SSIM and the ASD FieldSpec 3

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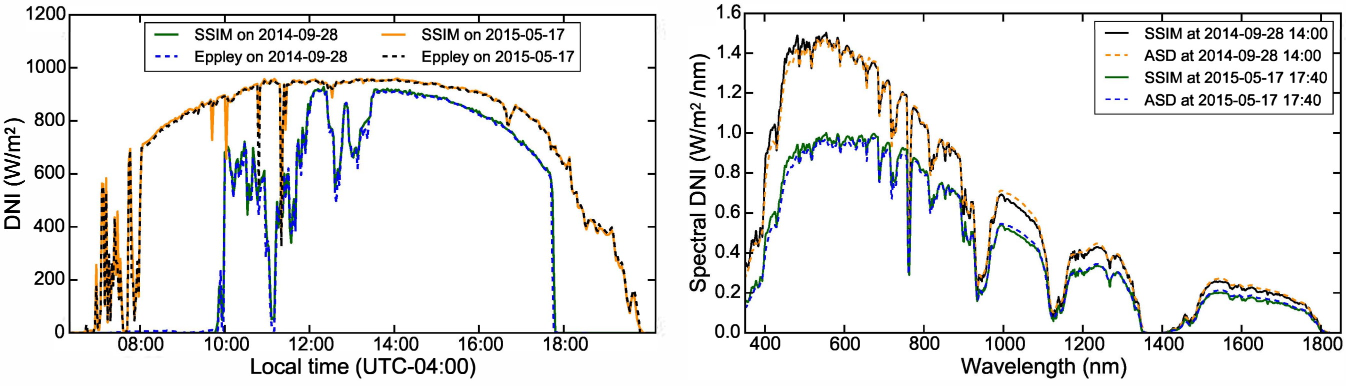

(a) (b)

Fig. 2. a) The comparison of the DNI between the Eppley pyrheliometer and the SSIM on partially cloudy and mostly clear sky days, occurring on September 28th, 2014 and May 17th, 2015, respectively. The SSIM is in an excellent agreement with the Eppley pyrheliometer, even under cloudy conditions. The data resolution is 2 min in both cases. b) The comparison of spectra as reported by the ASD spectroradiometer and the SSIM for selected timestamps on September 28th, 2014 and May 17th, 2015. The SSIM is in good spectral agreement between the SSIM and the ASD spectroradiometer is observed, with the integral of the spectral irradiance in both cases is less than 1%. Please note the SSIM's spectra are smoothed with central averaging to approximate the spectral resolution of the ASD spectroradiometer.

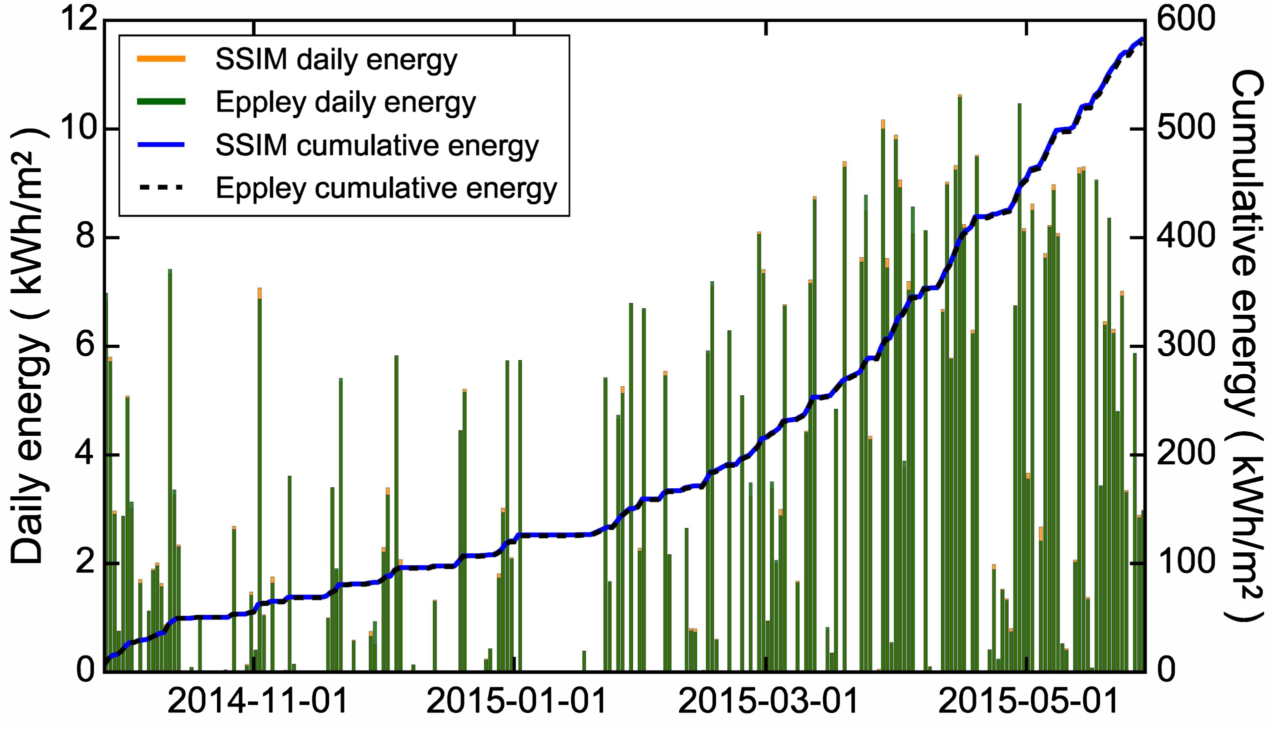

Fig. 3. The cumulative and daily energy densities comparison between the Eppley pyrheliometer and the SSIM over the six months. The cumulative energy density as measured by the SSIM agrees to within 0.5% of the corresponding value as reported by the Eppley pyrheliometer. The timestamps with the DNI less than 50 W/m^2 were omitted from the analysis.

spectroradiometer is also demonstrated, with the integral of the spectral irradiance agreeing to within 1% for both instruments for two timestamps, eight month apart. These results demonstrate that the SSIM is an accurate and reliable instrument for measuring the solar spectral irradiance and DNI over the entire solar range 280–4000 nm, containing 99.9% of the total power emitted by the sun. The reduced size, low cost and improved design with no moving components makes the SSIM a very attractive option for routine and dependable monitoring of solar irradiance in multiple locations.

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