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Extensive validation of solar spectral irradiance meters at the World Radiation Center

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ABSTRACT

A comprehensive uncertainty analysis validates a Solar Spectral Irradiance Meter (SolarSIM) for accurately resolving the spectral and broadband direct normal irradiances (DNI), spectral aerosol optical depth (AOD), precipitable water vapour and atmospheric total column ozone amounts. The derivation of these parameters from four SolarSIMs were compared to reference instrumentation at the Physikalisch-Meteorologisches Observatorium Davos and World Radiation Center (PMOD/WRC) in Davos, Switzerland in September 2015. The SolarSIMs are the first instruments to ever simultaneously participate in the 12th WMO International Pyrheliometer Comparison, Fourth Filter Radiometer Comparison, and First Spectroradiometer Comparison. The SolarSIMs' DNI data were compared to the World Standard Group's PMO2 absolute cavity radiometer, with World Radiometric Reference factors ranging from 0.999674 to 0.994610 for the best and the worst performing devices, respectively. In addition, the SolarSIMs' spectral DNI data was compared against PMOD's Precision Spectral Radiometer. The mean difference of the spectral DNI was found to be less than 5% for wavelengths above 400 nm. The SolarSIMs' measurements of AOD data were compared against PMOD's Precision Filter Radiometer triad. The median AOD differences and their standard deviations were found to be 0.0046 ± 0.0044, 0.0016 ± 0.0034, 0.0018 ± 0.0026, and 0.0041 ± 0.0022 for 368 nm, 412 nm, 500 nm, and 865 nm, respectively. The SolarSIMs' measurements of precipitable water vapour were compared against PMOD's Cimel CE318 sun photometer. The median difference and the corresponding standard deviation averaged 1 ± 0.2 mm for all SolarSIMs. Furthermore, the SolarSIMs' measurements of total column atmospheric ozone were compared against PMOD's Brewer MkIII spectrophotometer. The median difference and the corresponding standard deviation averaged 6 ± 7 DU for all SolarSIMs.

1. Introduction

For decades now, measurements of sunlight have been vital for solar energy research, atmospheric science, and weather forecasting applications. Broadband direct normal irradiance (DNI) measurements, for example, have been extensively used for solar resource assessment and calibration of satellite-derived irradiance data sets (AlYahya and Irfan, 2016; Cebecauer and Suri, 2016). More recently, with the advent of concentrating photovoltaic technologies, spectral DNI measurements became critical for performance analysis of solar modules with high efficiency multi-junction solar cells (Núñez et al., 2016; Araki and Yamaguchi, 2003). Besides the spectral and broadband irradiance data, direct sun observations can quantify the aerosol optical depth (AOD), precipitable water vapor (PWV) and total column ozone contents of the atmosphere. The aerosols and water vapor impact earth's radiation budget and are key inputs into weather prediction models and climate studies (Holben et al., 2001; Liang et al., 2015; Karabatić et al., 2011), while the ozone layer is critical for protecting life on our planet, as it attenuates damaging ultraviolet radiation.

For over 50 years the Physikalisch-Meteorologisches Observatorium Davos and World Radiation Center (PMOD/WRC) in Davos, Switzerland has guaranteed the global homogenization of solar measurements by hosting quinquennial instrument inter-comparisons, such as the International Pyrheliometer Comparison (IPC) (Finsterle, 2016), the Filter Radiometer Comparison (FRC) (Kazadzis et al., 2016), and the Spectroradiometer Comparison (SRC) (Schmutz et al., 2016). A group of absolute cavity radiometers, known as the World Standard Group (WSG), is the manifestation of the World Radiometric Reference (WRR) with an estimated uncertainty to the International System of Units. The WRR is the world's primary standard for the DNI. During the IPC, the

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participating instruments are calibrated against the WSG and produce the new national or institutional DNI references with traceability to the WRR. Likewise, during the FRC, the measurements from a triad of Precision Filter Radiometers (PFRs) serve as the reference to the world's aerosol measuring community. More recently, the PMOD development of a Precision Solar Radiometer (PSR) has enabled spectral DNI comparisons to be performed (Gröbner et al., 2014). All these events at the WRC provide unique opportunities to assess the performance of novel devices against global references. Our solar spectral irradiance meter (SolarSIM) is a first instrument to participate in all three WRC comparisons.

The SolarSIM uses ground-based measurements to inform software algorithms for rapid resolution of the location-specific solar spectrum, total irradiance and atmospheric constituents. The SolarSIM works by measuring the solar spectral irradiance in six carefully chosen wavelength bands, using silicon photodiodes with rugged, hard coated bandpass filters,[1] to allow spectral reconstruction through parametrization of the major atmospheric processes, including aerosol extinction, ozone and water vapor absorptions (Tatsiankou et al., 2013; Tatsiankou et al., 2016). The direct sun version of the SolarSIM allows the user to resolve in the 280–4000 nm range the spectral AOD, PWV, atmospheric total column ozone, and ultimately compute the spectral and broadband DNI - thus providing data that typically requires five to seven commercial instruments. The ability to simultaneously obtain these solar and atmospheric parameters with only one instrument reduces cost, avoids diversity in data acquisition protocols and setup requirements, and so facilitates many research and commercial applications (Caballero et al., 2018; Rodrigo et al., 2017; Majumdar and Cunningham, 2017; Theristis et al., 2016; Fernández et al., 2016).

In this paper we perform a complete uncertainty analysis for all SolarSIM measurands. We first define the uncertainty of irradiance measurement for each of six SolarSIM channels, and then use these findings to derive the uncertainties of spectral and broadband DNI, spectral AOD, PWV and total column ozone. These results are compared to actual measurements from four SolarSIMs at the WRC during 28 September to 10 October 2015, which participated in the 12th IPC (DNI comparison), fourth FRC (AOD comparison), and first SRC (spectral DNI comparison). Additionally, the SolarSIMs' measurements of PWV content and total column ozone were compared against data from a co-located Cimel sun photometer and Brewer MkIII spectrophotometer, respectively.

2. Instrumentation setup

Four SolarSIMs with serial numbers SN102 and SN103 (D1 model), and SN112 and SN113 (D2 model), manufactured by Spectrafy Inc., were installed on the roof top of the WRC in Davos, Switzerland (46.81°N, 9.84°E) on 27 September 2015. The SolarSIM-D2 is a more rugged version of the SolarSIM-D1, designed to have an extended temperature range, lower power consumption, and improved internal humidity management. The SolarSIMs have a ± 2.5° field of view with a 1° slope angle, conforming to the World Meteorological Organization (WMO) standard for radiometric measurements of DNI (WMO, 2008). The instruments were mounted on a Brusag sun tracker with a custom aluminum plate and bracket, as shown in Fig. 1. They were aligned normal to the sun using a reference pinhole on each SolarSIM enclosure and a three point adjustment method. Each SolarSIM was interfaced to a laptop via Spectrafy's COMBOX accessory, which provides power and RS-485 communication to the instrument. A specialized graphical user interface on the laptop enables data acquisition from each instrument every five seconds. It takes 500 ms for a SolarSIM to acquire and send the current values, ambient temperature and pressure, and internal temperature and humidity to the host for analysis. Depending on the hardware specifications, it takes a typical laptop about 100 ms to process the raw data into spectral products. Throughout this paper, SolarSIMs SN102, SN103, SN112, and SN113 are referenced as SSIM 1, SSIM 2, SSIM 3, and SSIM 4, respectively.

Fig. 1. SolarSIMs, versions D1 and D2, installed on a Brusag tracker on the roof top at the World Radiation Center, Davos, Switzerland (white finish - SolarSIM-D1, silver finish - SolarSIM-D2). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3. Measurement methodology overview

The SolarSIM measures the calibrated irradiance in six optical bands centered at 420, 500, 610, 675, 880, and 940 nm with full widths at half maxima of 10 nm. It also senses the ambient temperature, atmospheric pressure, and the device's internal temperature. These measurements are fed into our radiative transfer model to derive the spectral DNI and AOD in the 280–4000 nm range (with a 1 nm resolution), broadband DNI, total column ozone and PWV (Tatsiankou et al., 2016). The atmospheric parameterization follows a methodology similar to a Simple Model of the Atmospheric Radiative Transfer of Sunshine (SMARTS) (Gueymard, 1995, 2006). SMARTS methodology was chosen because it has been demonstrated to have robust performance and fast computational speed (Gueymard, 2008), and, hence, it was adapted in our architecture. The procedure for parameterizing the atmosphere from the SolarSIM measurements consists of the following steps:

1. Calibrate an instrument:
    a. Determine the temperature coefficients for each channel.
    b. Perform on-sun calibration against a reference spectroradiometer or a reference SolarSIM.
2. Acquire the current from six optical channels, ambient temperature and pressure, and the internal temperature.
3. Use our radiative transfer model to derive the spectral irradiance, the spectral AOD, DNI, total column ozone and PWV content:
    a. Compute the zenith angle and the sun-earth distance using National Renewable Energy Laboratory's (NREL) solar position algorithm (Reda and Andreas, 2008).
    b. Apply the sun-earth distance correction on the extraterrestrial solar spectrum from Gueymard (2004).
    c. Calculate Rayleigh scattering and the transmittances from various atmospheric gases (CO_2, CH_4, O_2, NO_2) (Gueymard, 2006).
    d. Determine the spectral AOD and its transmittance from the 420, 500, 675, and 880 nm channels (Tatsiankou et al., 2013).
    e. Compute the total column ozone and its spectral transmittance from the 610 nm channel (Tatsiankou et al., 2013).
    f. Calculate the PWV content and its spectral transmittance from the 940 nm channel (Tatsiankou et al., 2013).

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[1] conform to MIL-C-48497A and MIL-STD-801F standards.