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Characterization of a Low-Cost Multi-Parameter Sensor for Solar Resource Applications

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***Abstract* — Low-cost multi-parameter sensing and measurement devices enable cost-effective monitoring of the functional, operational reliability, efficiency, and resiliency of the electrical grid. The National Renewable Research Laboratory (NREL) Solar Radiation Research Laboratory (SRRL), in collaboration with Arable Labs Inc., deployed Arable Lab's Mark multi-parameter sensor system. The unique suite of system sensors measures the downwelling and upwelling shortwave solar resource and longwave radiation, humidity, air temperature, and ground temperature. This study describes the shortwave calibration, characterization, and validation of measurement accuracy of this instrument by comparison with existing instruments that are part of NREL-SRRL's Baseline Measurement System.**

I. Introduction

The National Renewable Research Laboratory (NREL) is working with Arable Labs, Inc. to calibrate and characterize Arable's Mark low-cost multi-parameter sensor. This instrument is perceived as having a lot of potential applications, such as measuring and monitoring solar radiation elements needed by electric utilities and solar power system integrators to adequately characterize the spatial and temporal variations of solar energy generation. The Mark system consists of a combination of fast-response detectors that can provide meteorological and trending information for solar resource assessment and forecasting in solar energy projects. Further, the system is equipped with six downward- and upward-facing narrow-band spectrometer channels that measure spectral radiation and surface spectral reflectance. Among other applications, these spectrometers could be used to monitor the operational reliability of bifacial photovoltaic modules, which convert solar resource captured on both the front and back sides of the module into electrical power.

The Arable Mark uses cellular, Wi-Fi, and Bluetooth communication systems to ensure real-time availability of the data, and it includes a GPS for synchronizing time and identifying its location. Additional features include an embedded solar panel, innovative mounting options, highly simplified connectors, and minimal user configuration for easy installation in remote areas.

The present work involves using the NREL SRRL ISO-17025 accredited calibration facility and expertise to perform accurate calibration and characterization of the fast-response detectors of the instrument. One specimen of the multi-parameter system (Fig. 1) is now deployed at the NREL-SRRL Baseline Measurement System (BMS). The data are accessible through the Measurement Instrumentation Data Center [1].

In this study, the shortwave detection part of the Arable Mark sensor is characterized, and an improved calibration methodology is implemented.

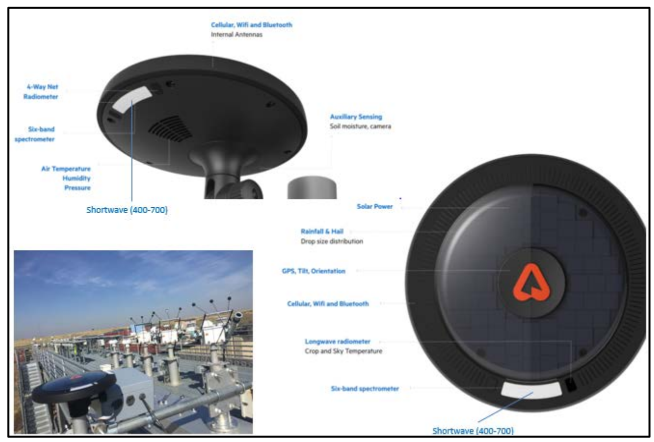

Fig. 1. Arable's Mark low-cost multi-parameter system at NREL -SRRL.

II. Method

The Arable Mark shortwave sensor measures the broadband global horizontal irradiance (GHI). The shortwave sensor is initially calibrated in the factory before shipment. Nevertheless, after installation at the NREL-SRRL, biases were noticed in the irradiance data. This necessitated recalibration using NREL-SRRL's outdoor calibration methodology. The calibration was carried out using the NREL-SRRL reference direct normal irradiance (DNI) and diffuse horizontal irradiance (DHI) radiometers. According to best practice [2], the reference GHI (GHI_{ref}) is obtained using the component-sum methodology. The data from these reference radiometers are traceable to the System International units through the World Radiation Reference scale [2]. Both reference radiometers—a Kipp & Zonen model CHP1 pyrheliometer and a shaded Eppley Laboratory 8-48 pyranometer—were chosen because of their low combined uncertainty [2], [3], [4].

Photodiode sensors can be calibrated using the NREL-SRRL procedure by following one of two options: (i) calibration as a function of solar zenith angle (SZA), or (ii) calibration at a fixed SZA of 45° [3]. For the specific sensor under scrutiny here, however, an optimum calibration SZA of 37.5° was selected, and the calibration factor was derived using:

$$R = \frac{V}{GHI_{ref}} \quad (1)$$

where R is the instrument's responsivity, in μV/(W m^{-2}) and V is the instrument's sensor output voltage (μV).

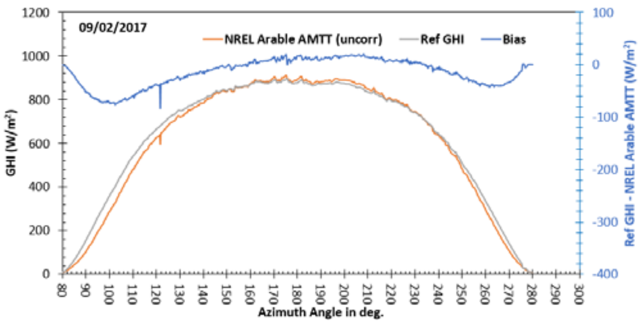

Fig. 2. Measured irradiance from the reference dataset and the UUT, and directional bias. The data from 09/02/2017 are used to calibrate the UUT using Eq. 1.

III. Results and Discussion

A. Shortwave data analysis and result

During the measurement period, some directional dependency of the shortwave sensor was noticed (Fig. 2). One of these directional dependencies is because of the azimuthal orientation of the detector with respect to the incoming solar radiation. To correct for this dependency, a correction was applied as a function of solar azimuth. In order to remove this error, a polynomial function of the solar azimuth was implemented using the bias line, as follows:

$$E_{cor} = E_{raw} - \sum_0^6 a_i \, A^i \quad (2)$$

where E_{cor} is the corrected irradiance for the unit under test (UUT), E_{raw} is the uncorrected (raw) irradiance, A is the solar azimuth, and a_i are numerical coefficients obtained by least-squares fitting:

a_0 = 10671.15
a_1 =-401.84
a_2 =6.06
a_3 = −4.74E-2
a_4 =2.038E−04
a_5 = −4.57E−07
a_6 = 4.19E−10.

The above equation was implemented only for SZA < 80° and for any clearness index (K_t or K_n) greater than 0.3. (As usual, K_t is defined as the ratio between GHI and its extraterrestrial counterpart; similarly, K_n is defined as the ratio between DNI and its extraterrestrial counterpart.) Outside of these ranges, the uncorrected UUT irradiance was used. This is because of the limitations of Eq. (2), which is imprecise at low sun elevation or under overcast conditions.

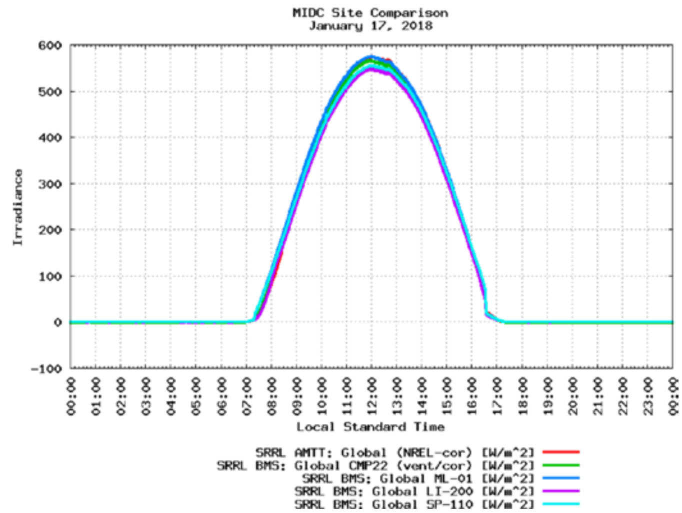

Fig. 3. GHI measured with the Arable Mark (labeled "SRRL AMTT: Global (NREL-cor)") or with usual thermopile or photodiode radiometers during a clear day at NREL-SRRL.

Preliminary tests have shown that the azimuthal correction described above was more appropriate than a more conventional zenithal correction; however, more elaborate and complete correction methods are now being evaluated.

Fig. 3 shows a comparison of the corrected data using the method described here with a thermopile pyranometer (Kipp & Zonen model CMP22) and photodiode sensors (LICOR's model LI-200, EKO's model ML-01, and Apogee's model SP110). After correction, the UUT appears to compare well with these more conventional instruments.

To understand the difference better, 1-min dataset clear-sky data (K_n > 0.7) from Aug. 18 to Nov. 28, 2017) from the photodiode pyranometers (UUT, EKO ML-01, LICOR LI-200, and SP110) were compared to the reference data. As shown in Fig. 4, the radiometers labeled "1" and "2" (X-axis) both actually represent the UUT. UUT-1 is corrected according to Eq. 1 (NREL-corrected), whereas UUT-2 refers to the original factory calibration. The NREL correction method shows ±2% bias compared to 2%–8% when just using only the factory methodology. Further, the NREL-corrected UUT shows a comparable or better result, with average bias of less than ±1% in comparison with the three conventional photodiode sensors. The NREL-corrected UUT also contains less directional error compared to the LICOR LI-200 unit. However, the interquartile range is larger for the NREL-corrected UUT compared to the three sensors. This is due to more variability and noise in the signal, apparently caused by the imperfect correction method.

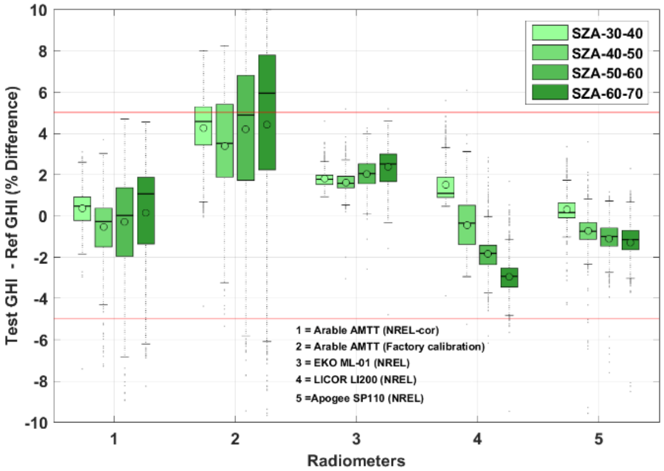

Fig. 4. Irradiance comparison of photodiode sensors relative to the reference data (1-min dataset from 8/18/2017 to 11/28/2017). Each green box represents a 10° bin of the interquartile range of the data in each bin. The circle in each box is a mean, and the black line indicates the median value Ninety-five percent off the dataset is within the whiskers; data points outside the whiskers are plotted with a symbol (dots).

Further, a long-term analysis included an all-sky comparison at 1-minute temporal resolution over a 3-month period (8/18/2017 to 11/28/2017). The results show good agreement with an R-square value of ~0.99 compared with the reference CMP22 instrument (Fig. 5).

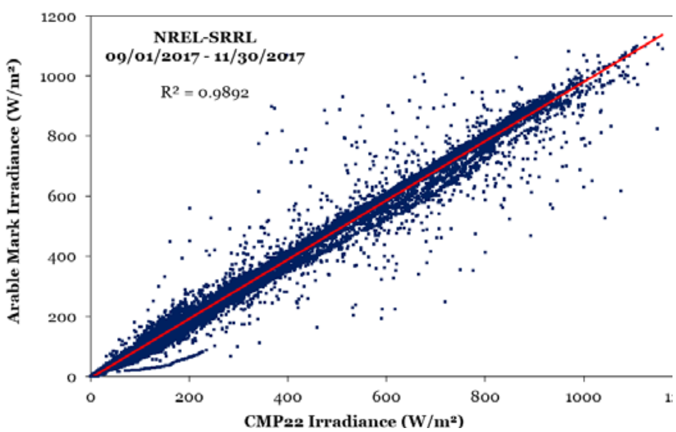

Fig. 5. one-minute GHI comparison between Arable Mark and a reference CMP22 thermopile pyranometer.

B. Spectral data analysis and results

In addition to the broadband sensor discussed above, the Arable Mark device is equipped with a six-band spectrometer (Fig. 6). These bands cover the range 400–950 nm and were calibrated at SRRL against an EKO WISER model MS-711 spectroradiometer, which is itself regularly lamp calibrated, with traceability to NIST standard. The Arable Mark spectrometer contains similar azimuthal error as the broadband sensor. A similar polynomial function as above is used here to correct this error. After correction, the Mark and WISER instruments show good agreement under clear-sky conditions (Fig. 6).

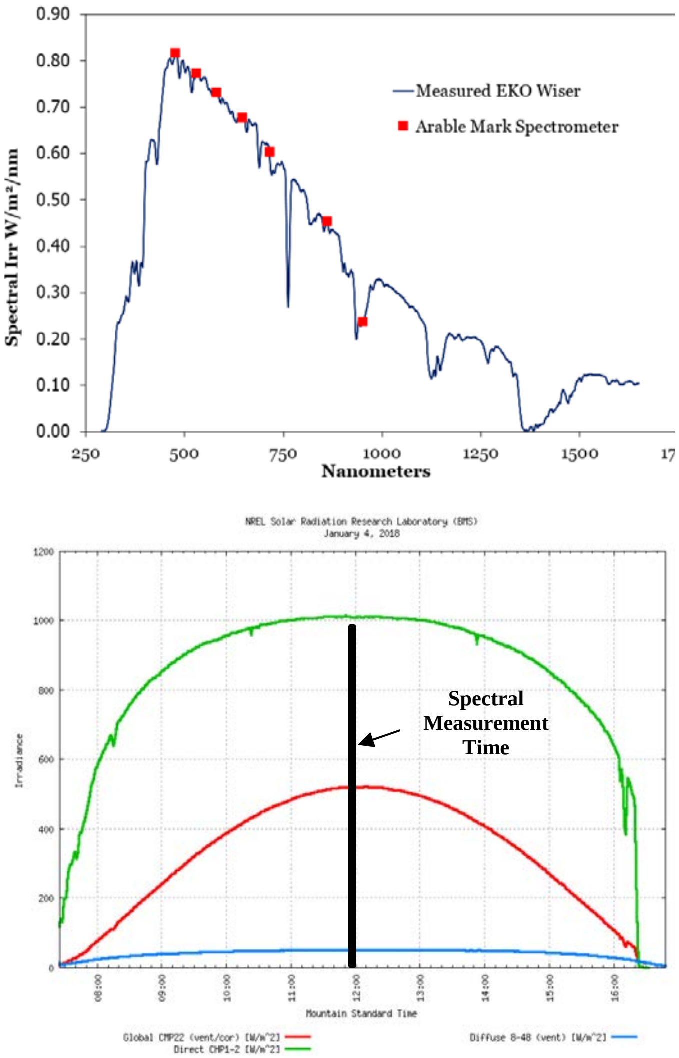

Fig. 6. (Top) Spectral comparison between the WISER and Arable Mark for 01/04/2018 @ 12:00 LST; (bottom) broadband direct (green), global (red) and diffuse (blue) irradiance measured with thermopile radiometers for that clear day.

Under partly cloudy skies, however, the difference in spectral global irradiance sensed by the two instruments is significant. This can be partly attributed to the difference in scan rate, because the WISER scans every 5 minutes, whereas the spectrometer scans each minute. Sky conditions and atmospheric transmittance can change rapidly under cloudy situations, hence triggering rapid variations in the solar spectrum (Fig. 7). The Mark's rapid scan time can be an advantage in, e.g., applications involving PV spectral effects.

Note here that the present results represent only the location, data period, and instruments specifically used for this study. It is known that different specimens of the same radiometer model may have differing characteristics, and that silicon sensors are affected by spectral variations in the incident spectrum, which depend on atmospheric conditions, and thus on location [5], [6]. Work is underway to better characterize these spectral effects and to reduce the measurement uncertainty of the Arable Mark with more advanced corrections.

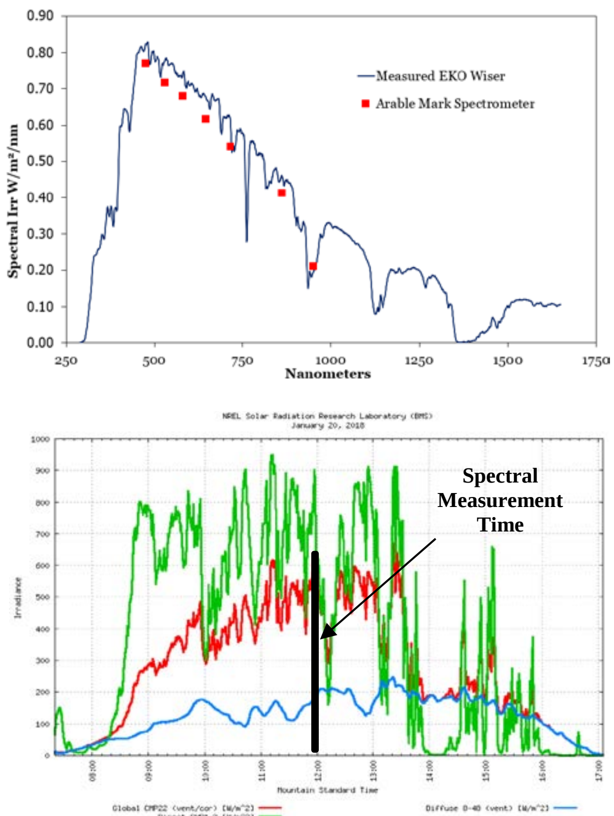

Fig. 7. (Top) spectral comparison between the WISER and Arable Mark for 01/20/2018 @ 12:00 PM; bottom - broadband direct (green), global (red) and diffuse (blue) irradiance for the partly cloudy day.

III. Conclusion

The comparison of the Arable Mark device demonstrated good agreement with the existing photodiode pyranometers, such as the LI-200 sensor from LICOR. The calibration and characterization methodologies employed by NREL result in ±2% bias compared to the reference GHI data obtained with a thermopile pyranometer over a 3-month period. In parallel, the comparison of the Mark broadband sensor with three conventional photodiode sensors demonstrated almost equivalent results during the same period, with an average bias of less than ±1%.

After recalibration, the spectral capabilities of the Mark instrument were found satisfying in comparison with a reference spectroradiometer, at least under clear-sky conditions. More research is needed to evaluate the spectral accuracy under partly cloudy and rapidly changing conditions.

The present characterization and results apply only to the UUT, location, and data period discussed here. It is too early to evaluate the instrument's uncertainty, and it is not possible to infer a broad conclusion based on the results of only one specimen.

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