Low-Cost Sensor for Solar Resource Assessment and Microclimate Monitoring

Cooperative Research and Development Final Report

CRADA Number: CRD-17-686

NREL Technical Contact: Aron Habte

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
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Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-5D00-76509
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Cooperative Research and Development Final Report

Report Date: 3/27/20

In accordance with requirements set forth in the terms of the CRADA agreement, this document is the final CRADA report, including a list of subject inventions, to be forwarded to the DOE Office of Scientific and Technical Information as part of the commitment to the public to demonstrate results of federally funded research.

Parties to the Agreement: Arable Labs

CRADA number: CRD-17-686

CRADA Title: Low-Cost Sensor for Solar Resource Assessment and Microclimate Monitoring

Joint Work Statement Funding Table showing DOE commitment:

Estimated Costs	NREL Shared Resources a/k/a Government In-Kind
Year 1	$140,000.00
TOTALS	$140,000.00

Abstract of CRADA Work:

Under this Agreement, NREL will work with Arable Labs, Inc. to improve the instrumentation and measurement systems available for measuring and monitoring solar radiation elements needed by electric utilities and solar power system integrators to adequately characterize the spatial and temporal variations of the renewable energy resources. The Arable Labs' low-cost system contains a combination of fast response detectors that will provide meteorological and trending information of significantly improved accuracy for solar resource assessment and forecasting in solar energy projects. The proposed work includes utilizing NREL's SRRL ISO-17025 accredited calibration facility and expertise to perform accurate spectral and broadband calibration and characterization of the fast response detectors in the Arable Labs' system, and, assisting Arable Labs' in developing a published methodology that will enable implementation of the results into their production pipe resulting in more accurate solar resource measurements for end-user organizations.

Summary of Research Results:

Evaluating photovoltaic (PV) cells, modules, and arrays, and systems performance relies on accurate and traceable measurement of the available solar radiation resources for conversion. NREL's solar radiation Research Laboratory (SRRL) is known in providing research and development of solar resource measurement and calibration and research and the development of standards and best practices for dissemination. The SRRL is located on the top of South Table Mountain on the north side of NREL's Campus in Golden, Colorado where it has excellent solar access because of its unrestricted view of the horizon from sunrise to sunset throughout the year. The SRRL contains a collection of radiometers in continuous operation, high-quality, long-term and has measurements going back to 1981. The experience gathered at SRRL from operating instruments, developing standards, and testing models is shared quickly and easily across the solar energy industry. For this reason NREL SRRL was chosen by Arable Labs to work on U.S. Department of Energy-funded project through a Small Business Voucher to assist Arable Labs to gain the knowledge and expertise needed to evaluate and improve the Arable Labs device to be used for solar energy applications. The calibration and characterization process provided an understanding of the quality of the Arable Labs device when compared to high quality SRRL radiometers. The characterization process provided an understanding of the variability between the Arable device and essentially providing an understanding of the manufacturing quality of the device. These calibrations and characterization were carried out in collaboration with Arable Labs. The results were published in a comprehensive technical report that allow the solar energy industry to understand the performance of the device and make informed decisions regarding their deployment of the use of data collected by those devices.

The Arable Lab's Mark low-cost, multiparameter sensor system was installed at SRRL by following best practices for measuring global horizontal irradiance and other meteorological parameters. The device data was compared with reference irradiance determined by a Kipp & Zonen model CHP1 pyrheliometer and a shaded Eppley Laboratory 8-48 pyranometer. The study characterized the output data from the instruments under clear condition and also analyzed the data under varying sky conditions. Source of errors were identified and a methodology to mitigate such errors were recommended and implemented.

Task 1: Perform outdoor calibration and characterization

Shortwave calibration

As stated in [1 &2], the calibration was carried out using the NREL Broadband Outdoor Radiometer Calibration (BORCAL) method where the Arable Labs device output signals were recorded every one minute and compared with reference irradiance determined by a Kipp & Zonen model CHP1 pyrheliometer and a shaded Eppley Laboratory 8-48 pyranometer. The radiometers produce an electrical signal proportional to global irradiance. The signal to irradiance ratio is the responsivity (RS) of the instrument in µV/W/m2. Both reference radiometers are traceable to the World Radiometric Reference (WRR) by means of the NREL Transfer Standard Group and the NREL Broadband Outdoor Radiometer Calibration (BORCAL). The study characterized the output data from the instruments under clear condition and also characterized the data under varying sky conditions. The instruments' response could vary depending on the time of the year, sky condition and solar zenith angle.

The responsivity of the test instrument is calculated using the following equation

$$RS = \frac{V}{I} \qquad \text{Eq. 1}$$

where,

RS = radiometer responsivity (μV/W/m²),
V = radiometer output voltage (microvolt),
I = reference irradiance (W/m²), global (G),
where, $G = B * COS(Z) + DHI$

B = direct normal irradiance
Z = zenith angle (degrees),
DHI = reference diffuse irradiance (W/m²).

Calibration of the Arable Labs Mark Device Diffuser

As stated in [1], the measurement of the absolute spectral transmission was carried indoors using a stable light source at normal incidence. The same procedure was implemented outdoors at different orientations (Figure 1). [1] contains details about the methodology.

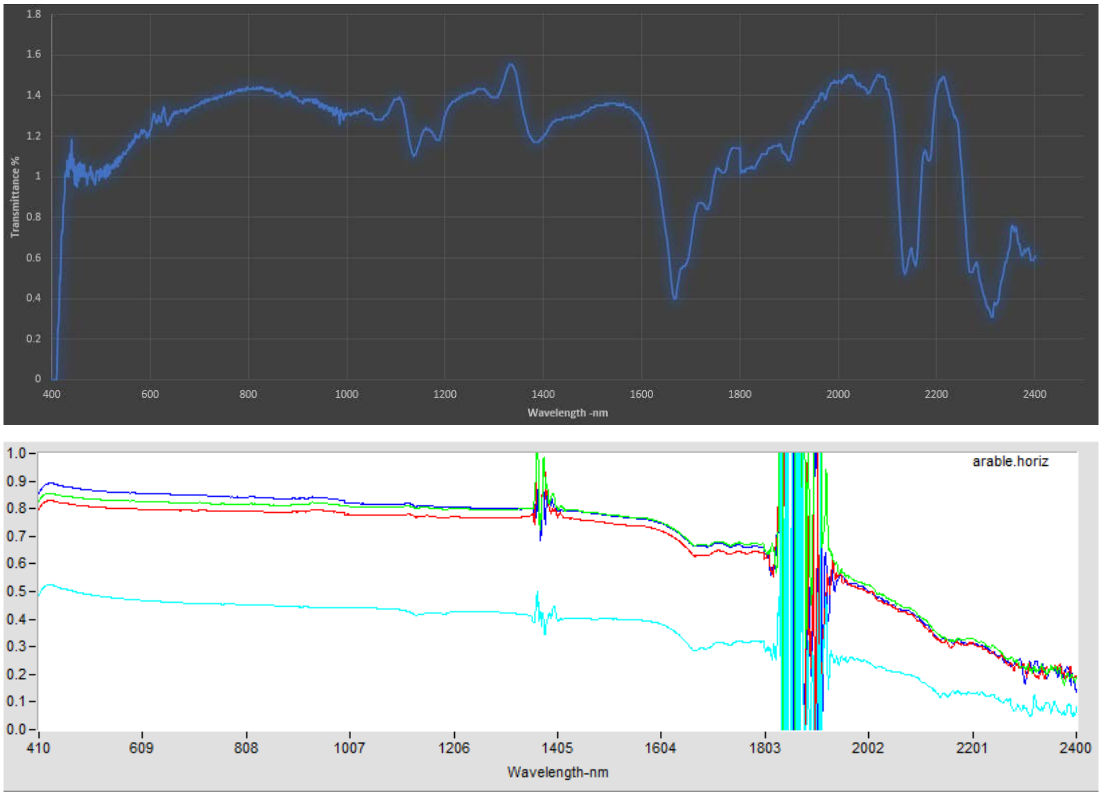

Figure 1. Top – Arable's Mark indoor diffuser transmission and Bottom – Dark blue: diffuser mounted horizontal in the typical orientation (diffuser pointed south); red and green: diffuser mounted horizontal but rotated -90 or 90°; light blue: diffuser mounted near sunrise or sunset (simulated), rotated to the side and then tilted to the north to imitate the solar ray incident at an oblique angle to the surface of the diffuser. Obtained from [1]

Spectral Calibration

Spectral calibration of the narrowband spectrometers of the Arable Labs Mark device was also carried out using the EKO WISER spectroradiometers system that is deployed full-time at NREL SRRL. Calibration factors for each spectrometer was developed (Table 1).

Table 1. Computed Calibration Factors for the Mark spectral sensors on September 22, 2018 (Obtained from [1])

Wavelength	Calibration Factor (W/m^2/nm/V)
475 nm	3.68
530 nm	2.038
580 nm	2.405
645 nm	2.084
715 nm	1.741
860 nm	3.75
950 nm	0.927

Task 2: Develop Correction Methodologies

Correction methodologies for shortwave and spectral irradiance measurement were developed. The corrections were required because the device demonstrated directional response error. The first attempt to correct this error was to implement an azimuthal correction which was implemented as a function of solar azimuth. A polynomial fit of the solar azimuth was applied using Eq. 2.

$$E_{cor} = E_{raw} - \sum_0^6 a_i\, A^i \qquad \text{Eq. 2}$$

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.

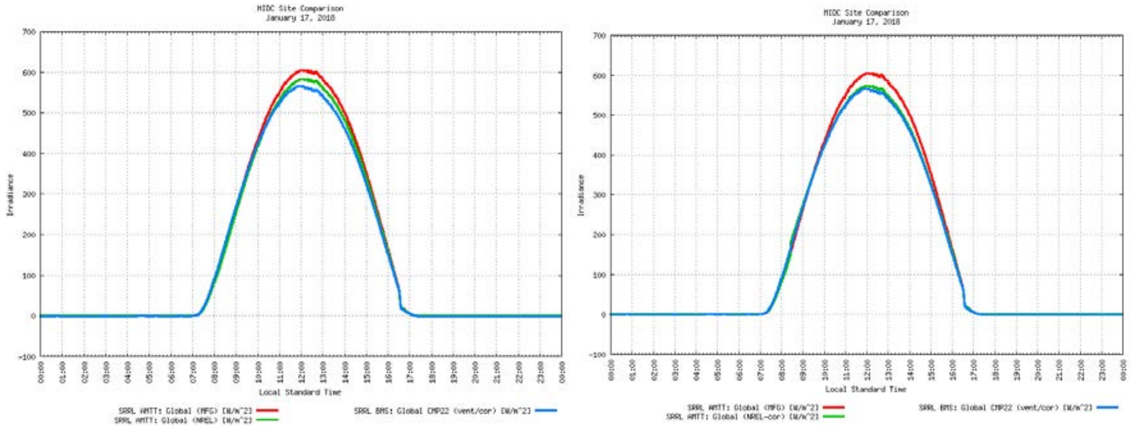

Figure 2. Shortwave Irradiance of the manufacturer calibrated device data (red), NREL calibrated data (green) and Reference NREL data (blue). Note: the green color line (before correction – left and after correction – right).

[1] contains more detail analysis of the result of the correction methodologies under all sky conditions. However, the above method of correction works for certain time of the year; therefore a more robust methodology was developed that encompasses both the cosine and tilt correction. This method is described in detail in [1], and the method was adopted from [3&4]. As shown the correction was employed using Eq. 3 & 4

$$Rel\_units = \frac{Signal\ (\Theta)}{Signal(0) * \cos\ (\Theta)} \qquad \text{Eq. 3}$$

where the signal is the voltage readings (V), and Θ is SZA in degrees. To obtain the signal reading at zero degree (denominator), the signal is plotted versus SZA and then an estimated voltage reading for zero SZA is taken from the curve ($V_0 = \sim 0.65$ V) (Figure 13 in [1]). The result of Eq. 3 is illustrated in Figure 14 in [1] and used to assist in generating the power function using curve fitting (*d*) as described in Eq. 4 and illustrated in Figure 14 in [1] by the red dashed line.

$$d = (a + offset) * (\Theta^{b}) + c \qquad \text{Eq. 4}$$

where, a, b, c are coefficients. Two specific offset values are applied for the morning and afternoon for each device. Solar azimuth angle was used to differentiate between morning and afternoon, where solar azimuth angle less than 180 in the morning and greater in the afternoon. Further, the cosine and tilt error correction was applied only for SZAs less than 70° because the cosine error correction becomes uncertain at SZAs greater than 70°.

Figure 3 shows results after correction where the Arable Labs Mark device demonstrate good relationship with the NREL SRRL reference radiometer.

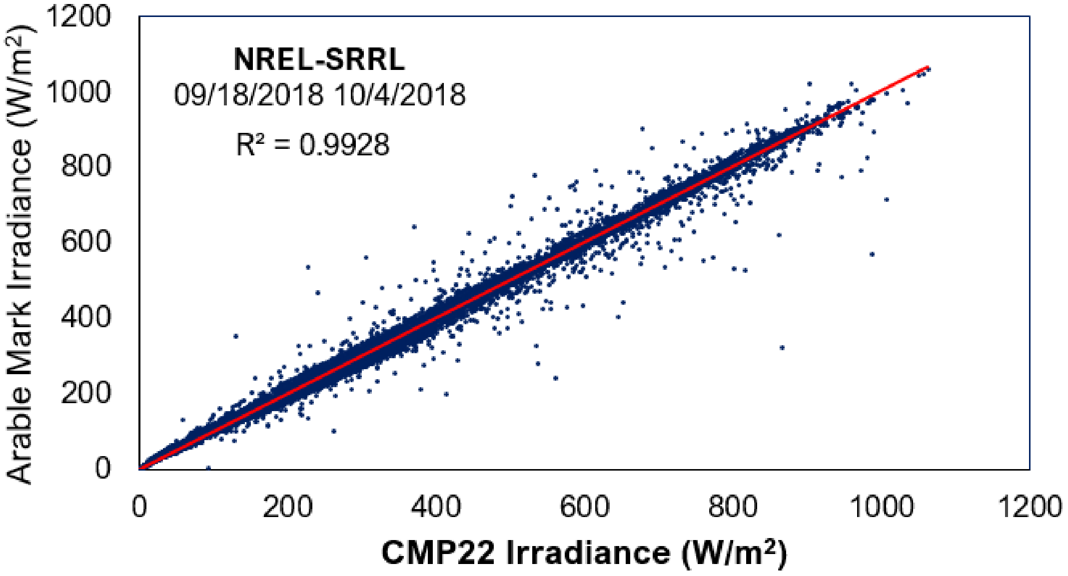

Figure 3. One-minute GHI comparison between Arable's Mark and a reference CMP22 thermopile pyranometer after implementing the cosine and tilt correction methodology (obtained from [1]).

Similarly, a correction methodology was also implemented for the spectral data obtained from the Arable Labs Mark device. The result showed significant improvement (Figure 4).

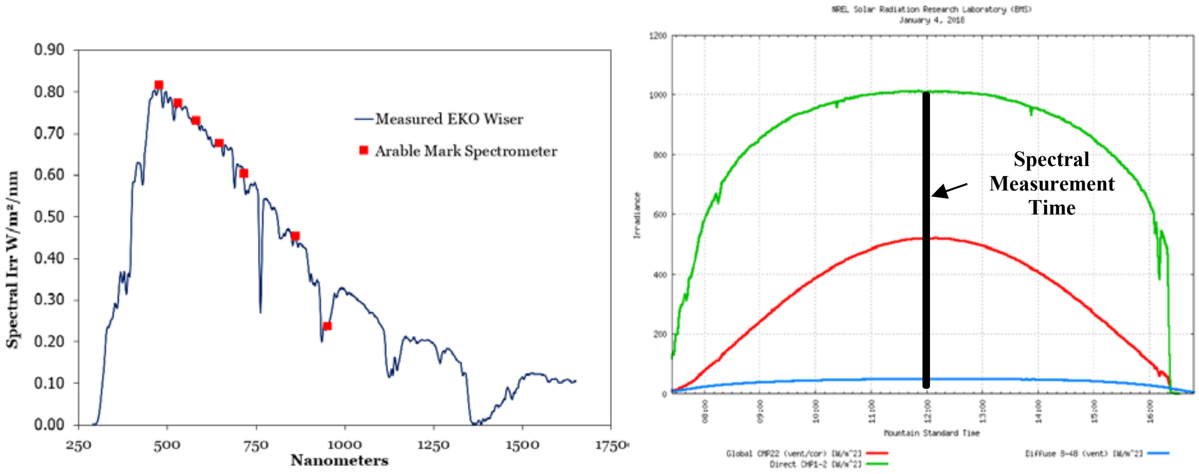

Figure 4. Spectral comparison between the WISER and Arable's Mark for January 4, 2018, at 12:00 p.m. Local Sidereal Time (left); broadband direct (green), global (red), and diffuse (blue) irradiance measured with thermopile radiometers for that clear day (right). Obtained from [1]

Task 3: Publication and implementation of calibration and characterization methodology

NREL published the results of this project. Readers are encouraged to check references [1&2] for details. Further, NREL in collaboration with Arable Labs made some improvements for the Mark device which contained shortwave sensor that only sees the power of electromagnetic radiation in the spectral range that is used by plants for photosynthesis (400–700 nm). Most of Photovoltaic (PV) modules see 400–1000 nm. Therefore, to make the sensor more beneficial for solar energy applications, we swapped the existed sensor (400–700 nm) with a new sensor (400–1000 nm). Details about this upgrade can be found in [1]. Arable Labs will consider this change in future production line.

Also, NREL designed an external leveling apparatus for the Mark device, this will assist field personnel to easily level the device during installation and regular field operation (Figure 5).

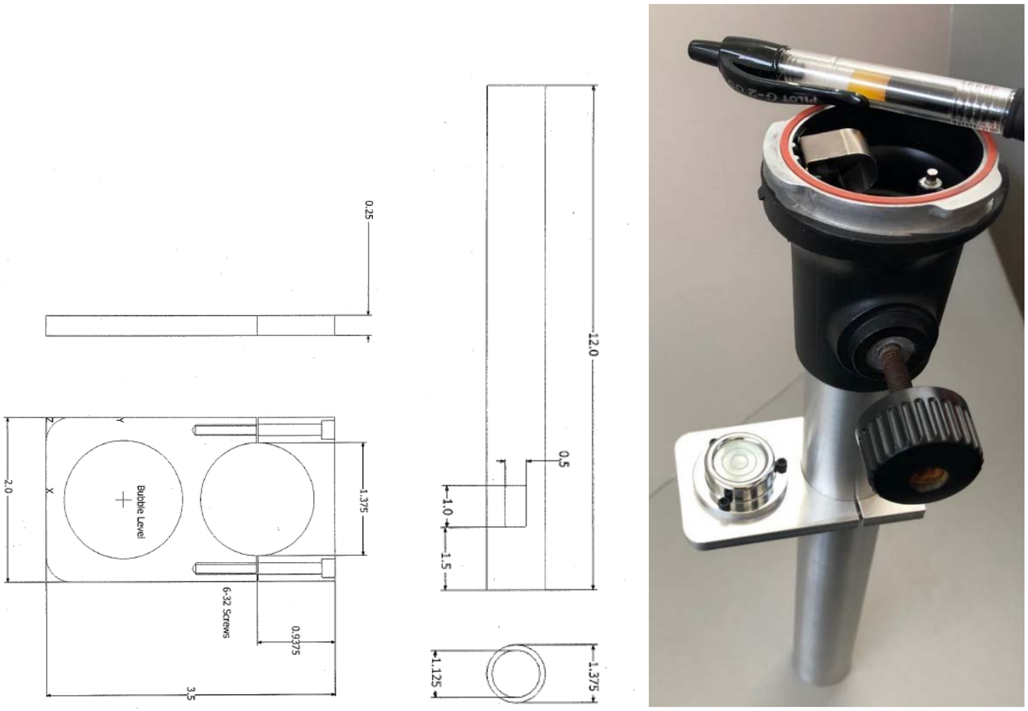

Figure 5. Design and image of Arable's new Mark leveling apparatus. Obtained from [1]

References

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Subject Inventions Listing:

None

ROI #:

None

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