Field Testing of Mars™ Soiling Sensor

Michael Gostein
Atonometrics
Austin, USA

Ben Bourne
SunPower Corporation
Richmond, USA

Fabrizio Farina
SunPower Corporation
Richmond, USA

Bill Stueve
Atonometrics
Austin, USA

***Abstract*—We report on an ongoing field evaluation of the Mars™ optical soiling sensor technology. The Mars™ soiling sensor was developed to provide a compact, low-cost, water-free and maintenance-free method to measure soiling at PV power plants, especially for small utility or commercial-scale sites where more complex solutions can be prohibitive. In this study, a Mars™ soiling sensor was deployed at a test site in California starting in February 2019. The site also includes a reference soiling measurement system employing a washed/unwashed PV reference cell pair. We review the correlation between the Mars™ and reference cell pair soiling results over a 13-month period.**

***Index Terms*—photovoltaic (PV) systems, resource assessment, soiling, system performance, monitoring**

I. Introduction

Soiling of PV modules is one of the principal energy loss factors for PV systems. Accordingly, there is a strong interest in measuring PV soiling at both pre-production prospecting and operational sites. Motivations include performance prediction, monitoring of plant operations, verifying compliance with performance guarantees, and optimizing wash schedules for best return-on-investment of washing expense.

Traditional soiling sensors compare the output of two PV devices, one of which is allowed to soil naturally and the other of which is routinely washed to serve as a reference [1] [2]. Daily or weekly washing is performed either manually by on-site personnel or by an automated [3] washing system. The most complete measurement is achieved by using a full-size PV module identical to those on the PV array as the soiled reference device and measuring the module's maximum power output [4] [5] relative to expectations from a washed module or washed cell. A simpler approach, often used as an approximation, is to compare the outputs of washed/unwashed PV reference cells.

However, eliminating the requirement for washing a reference device could significantly lower the cost of soiling monitoring and would be especially favorable for commercial-scale PV sites that typically have smaller budgets and no on-site personnel.

In this work we report on our continued field evaluation of an all-optical soiling sensor concept developed by Atonometrics (Mars™ soiling sensor, [6]), conceived as a solution for compact, low-cost, water-free and maintenance-free measurement of soiling loss. We previously reported on this field evaluation [7] [8] and in this will paper provide the latest results from over a year of testing.

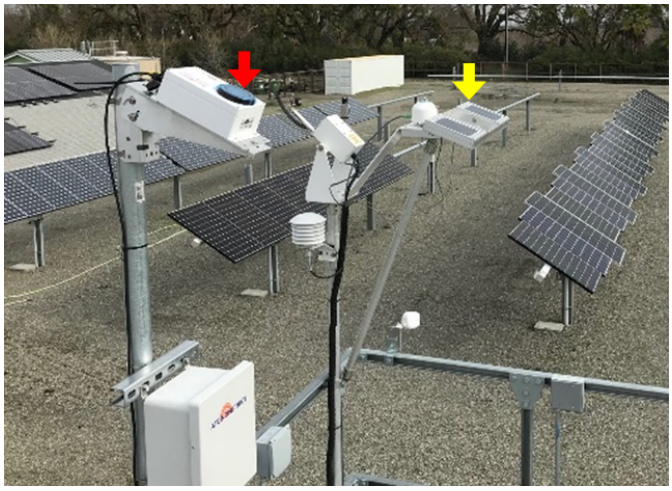


Fig. 1. Mars™ sensor (red arrow) at test field with washed/unwashed reference cell pair (yellow arrow).

II. Mars™ Sensor Concept

The Mars™ soiling sensor concept has been previously described [6] [9]. Briefly, the sensor includes a dust collection window configured to be in the same plane as the PV modules to be monitored and uses a microscopic imaging system to detect dust particles on the window coupled with image analysis which quantifies the fraction of light blocked by the dust particles, without requiring local dust calibration.

III. Experiment

The test site, shown in Fig. 1, is a solar test field near Sacramento in the Central Valley. In addition to the Mars™ sensor, the setup includes a washed/unwashed reference cell pair that is used as a reference for comparison to Mars™. The Mars™ unit operates daily at sunset and measures the transmission loss (TL) through its sensor window, from which a soiling ratio is calculated ($SR = 1 - TL$). The two reference cells are identical and are mounted side by side as shown in Fig. 1. The washed cell is washed 3 times per week. The irradiance readings of each cell are averaged on an hourly basis and the ratio of the average from the unwashed cell to the washed cell is used as a measure of soiling ratio (SR) [1] [2] [3] after normalization by a constant chosen such that soiling ratio is unity on days following significant rain. The Mars™ sensor and both cells are mounted at a tilt angle of 20° facing south. Rain data are collected on-site.

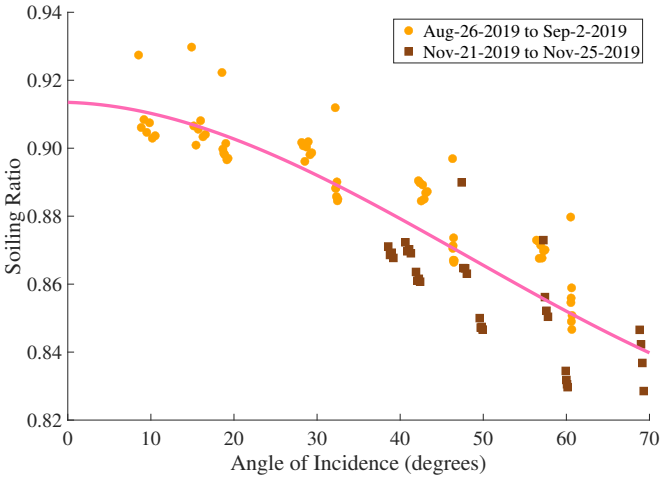


Fig. 2. Hourly PV reference cell pair soiling ratio versus angle of incidence for selected days.

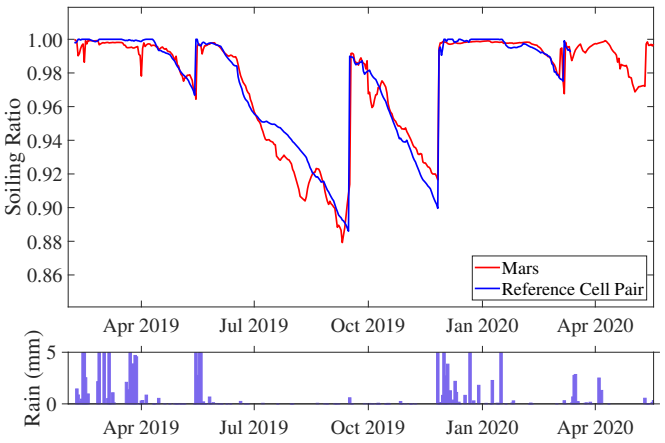


Fig. 3. Upper: comparison of Mars™ soiling ratio results to soiling measurements with a washed/unwashed reference cell pair corrected to 0° incidence angle. Lower: daily rain.

IV. Results and Discussion

A. Angle of Incidence Effect

Measurements of PV soiling loss with washed/unwashed PV device pairs are known to show variation with solar angle of incidence [1] [10] because transmission loss through a layer of dust increases at high incidence angle due to microscopic shadowing. This is commonly observed as a time-of-day dependence in PV device pair soiling ratio data, as shown in [1], and is one factor leading to the recommendation in IEC 61724-1 to limit such measurements to angles of incidence less than 35° [2].

As expected we observed an angle-of-incidence dependence in our PV reference cell soiling data as shown in Fig. 2. In the figure each data point is the hourly soiling ratio measured by the washed/unwashed reference cell pair. The figure includes data from two short date ranges, one in summer and one in fall, during which soiling ratios were similar and near the minima for the entire data set (i.e. highest soiling losses). The summer data (Aug-26 to Sep-2) span a large range of incidence angles from sunrise to sunset and the fall data (Nov-21 to Nov-25) span only a limited subset of these angles due to lower sun elevation. The pink curve is a polynomial fit to all the points shown. The soiling loss $(1 - SR)$ is seen to increase from $\sim 9\%$ at low incidence angle to $\sim 16\%$ at 70°. This is similar to the trend observed in [10] where a factor of ~ 1.7 increase was found between 0° and 70° angle of incidence for a similar level of soiling and the results were explained by a ray-tracing model accounting for angle-dependent dust shadowing and reflection [10].

Therefore, in order to provide a consistent basis for comparison across the year-long data set, in calculating daily soiling ratios for the PV reference cell pair we used only data measured during the noon hour (highest solar elevation) and in addition corrected each PV reference cell pair soiling ratio by a function of the solar angle of incidence to translate the measured soiling loss to its equivalent at 0° incidence based on the trend corresponding to the polynomial fit in Fig. 2.

B. Soiling Ratio Results

Fig. 3 shows the soiling ratio results from the test site. The upper panel compares the daily soiling ratio measured by the Mars™ sensor to that measured with the reference cell pair, while the lower panel shows the daily rain total. Raw data acquired from each of the sensors were processed with a smoothing algorithm that preserves sharp steps corresponding to rain and cleaning events and the reference cell pair data were then also normalized by the average value following rain events, as described above. The resulting data are shown as the traces in the figure. The reference cell pair data for each day includes only the noon hour and were corrected for angle of incidence, as described above, while no such correction was performed for the Mars™ sensor due to the different measurement principle. Data for the reference cell pair are shown only through early March 2020, after which washing of the clean reference cell was temporarily suspended due to on-site work stoppages resulting from the coronavirus pandemic; however, the Mars™ sensor continued operating unattended during this time.

Fig. 3 demonstrates similar soiling ratio trends for both the Mars™ sensor and the PV reference cell pair, indicating good agreement. Soiling losses were largest during the long dry months in the summer and fall of 2019 and decreased sharply after rain events, including the light rain in mid September. Data from the Mars™ sensor have more day-to-day fluctuation than data from the PV reference cell pair, although they still show the same overall soiling trend and of course have the advantage of being automatically collected without any labor.

C. Soiling Rates

In Fig. 4 we show the soiling rates determined by fitting the data in Fig. 3 during extended dry periods. The linear fits were performed using the robust Thiel-Sen estimator together with bootstrapping to determine 95% confidence intervals of the slope results [11] [12].

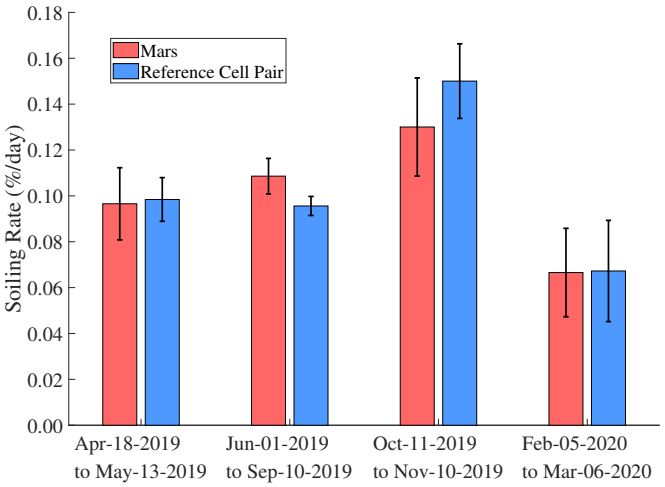


Fig. 4. Soiling rates determined from Mars™ and reference cell pairs.

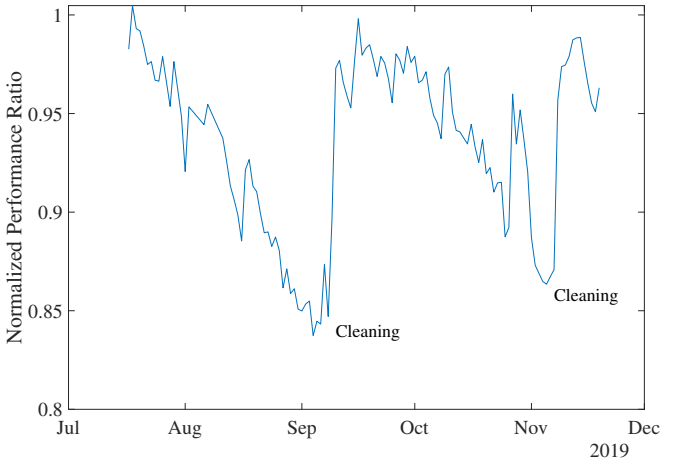


Fig. 5. Normalized average performance ratio of two roof-top PV arrays near the soiling measurement station.

Both the Mars™ sensor and the reference cell pair measurements show similar soiling rates, with values agreeing within the fit uncertainties. Soiling rates ranged from ∼0.06%/day in winter (Feb-Mar) up to ∼0.15%/day in late fall (Oct-Nov) and are in the typical range for the region [13] [14] [12] [15]. The higher soiling rates in the fall time period could be expected due to activity at farms adjacent to the test site. In particular, dust clouds originating from adjacent fields were observed at the test site on Oct. 21 and Oct. 31 due to soil tilling. Note that if the angle-of-incidence correction described above was not performed, the soiling rate for the reference cell pair would appear approximately 40% higher for the fall period.

D. Comparison to PV Array

Two PV arrays are mounted on opposite-facing roofs of a building near the soiling measurement station and their performance is monitored as part of the test center operations. Fig. 5 shows the average of the daily non-temperature-corrected performance ratios of the two arrays, calculated per [2]), for the summer and fall months. The arrays were cleaned on Sep. 10 and Nov. 7. Losses in the performance ratio for the dates shown in the figure are dominated by soiling losses – as evidenced by the performance ratio recoveries after cleaning – although other factors may also be important, especially for the long-term variations. The performance ratio plot is consistent with the soiling ratios shown in Fig. 3. Note that the data in Fig. 5 are not corrected to 0° angle of incidence, so a greater loss in November is expected relative to that in Fig. 3. However, it is also important to note that power losses due to soiling on PV arrays can deviate from soiling losses measured on soiling sensors due to the effects of non-uniform soiling accumulation [4] [5].

E. Discussion

Due to the effect of incidence angle on soiling losses, care should be taken when defining and comparing soiling ratios between various sensors and PV array performance losses and when comparing soiling rates across different seasons. In Fig. 3 and Fig. 4 we have corrected PV reference cell pair soiling ratio data to 0° angle of incidence in order to provide a consistent basis for comparison. However, the non-corrected data represent the actual losses measured by the reference cell pair, which are indeed higher when sun elevation is lower. So the non-corrected data would be a better representation of nearby PV array performance, assuming the sensors and array are mounted at the same orientation. For the Mars™ sensor, the results could also be scaled by a correction factor to account for additional losses experienced by a PV array due to its orientation, using the relation shown by the fit in Fig. 2 or similar, if desired.

The soiling measurement study at the site is ongoing. In order to explore the possibility that different soiling sensors and reference cells could soil differently due to their size, glass characteristics, mounting, or other factors, we plan to install an additional washed/unwashed reference cell pair at the test site soon. Comparing the soiling rates of both the existing and the new reference cell pair will help provide insight on the correlation to be expected from adjacent soiling measurement sensors.

A potential benefit of the Mars™ technology, especially for utility-scale sites, is the ability to deploy more sensors around a site at lower cost in order to measure within-plant non-uniformity of soiling, which can be significant for large sites that border local sources of particulates such as farms or other operations [12].

V. Conclusions

Overall the data clearly show the ability of the Mars™ sensor to track trends in soiling data and demonstrate good agreement between the Mars™ sensor and a washed/unwashed reference cell pair. The results are promising for providing a low-cost, compact, maintenance-free soiling sensor that can be more widely deployed than traditional solutions.

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