Field Evaluations of Mars™ Optical Soiling Sensor

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***Abstract* — We report on field evaluations of the new Mars™ optical soiling sensor technology. The Mars™ soiling sensor was specifically 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 two test locations in California, including a solar test field and a commercial-scale PV parking canopy. Each site also included a reference soiling measurement system employing a washed/unwashed reference cell pair. Results to date demonstrate good overall correlation between the Mars™ sensor and the washed/unwashed reference cells.**

***Index Terms* — photovoltaic systems, performance analysis, solar power generation, solar energy, soiling, soil measurement**

I. Introduction

Soiling of PV modules is one of the principal energy loss factors for PV systems. Accordingly, in recent years there has been a growing interest in measuring PV soiling at both pre-production prospecting and operational sites [1]. 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 cleaned to serve as a reference [1][2]. Daily or weekly cleaning is performed either manually by onsite personnel or by an automated [3] washing system.

Eliminating the requirement for washing a reference device in order to measure soiling lowers the cost of soiling monitoring, and is especially favorable for commercial-scale PV sites that typically have smaller budgets and no onsite personnel.

In this work we evaluate a new proprietary all-optical soiling sensor concept developed by Atonometrics (Mars™ soiling sensor, [4]), conceived as a solution for compact, low-cost, water-free and maintenance-free measurement of soiling loss.

II. Mars™ Sensor Concept

The Mars™ soiling sensor concept has been previously described [5][6]. Briefly, the sensor includes a dust collection window configured to be in the same plane as the PV modules to be monitored and uses an internal microscopic imaging system to detect dust particles on the window, coupled with proprietary image analysis techniques which accurately quantify the fraction of light blocked by the dust particles. The sensor directly measures losses in transmission of sunlight through the glass – rather than reflectance of the particles



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



Fig. 2. Site 2: Mars™ soiling sensor at PV parking canopy.

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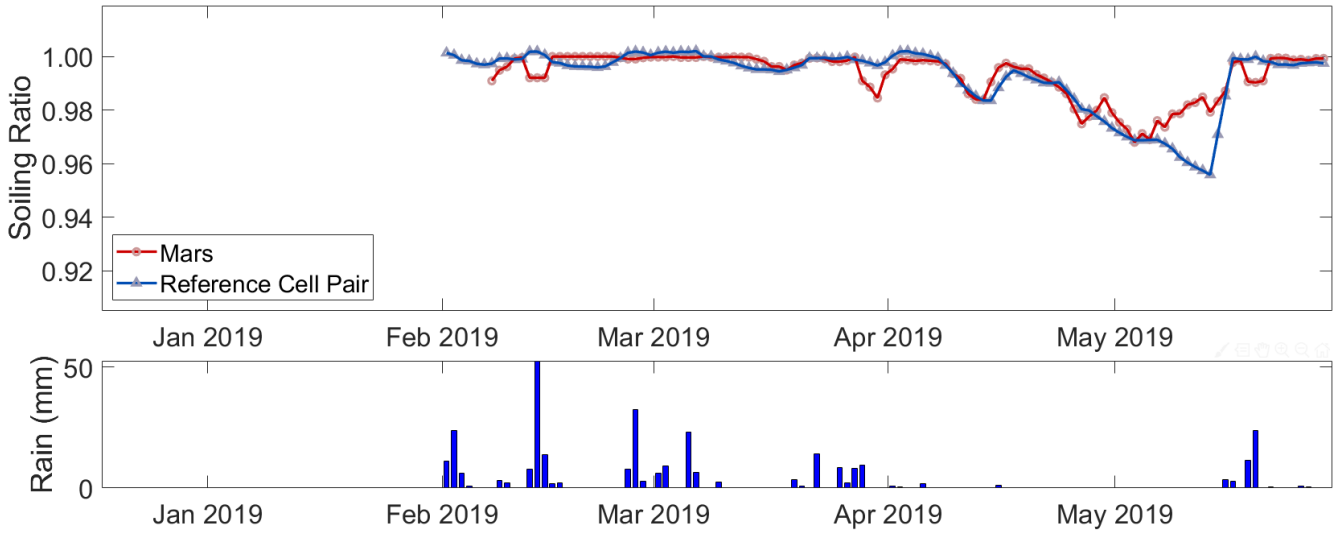


Fig. 3. Results for Site 1

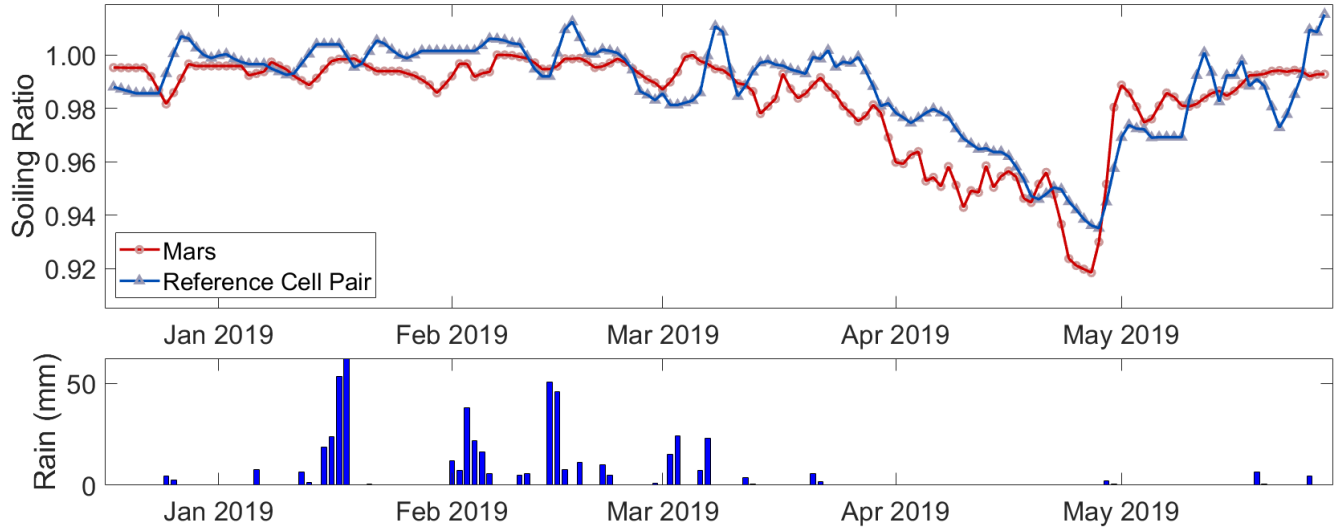


Fig. 4. Results for Site 2

themselves. It therefore does not depend on dust color and does not require on-site, dust-specific calibration [5][6].

III. Experiment

We report data from two test sites, both in California. Site 1, 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 two reference cells are identical and are mounted side by side as shown in Fig. 1. The Mars™ sensor and both cells are mounted at a tilt angle of 20°, facing south. The washed cell was washed 3 times per week. In addition, rain data is collected on-site. Site 2, shown in Fig. 2, is a 120 kW PV parking canopy structure in southern California. In addition to the Mars™ sensor, the site also includes a washed/unwashed reference cell pair for comparison to Mars™. The two reference cells, not shown in Fig. 2, are different models provided by different manufacturers. The washed reference cell is washed daily by automated equipment (RDE300), and is located approximately 16 meters from the Mars™ unit, and the unwashed reference cell is located approximately 4 meters further away. The Mars™ and both reference cells are mounted co-planar with modules of the PV array at a tilt angle of 7°, facing south. Rain data are not collected on-site, so for this site we have used NOAA rain data from a station approximately 7 miles away. At each site, the irradiance readings of each cell are averaged for each day and the ratio of the daily averages from the unwashed cell to the washed cell is used as a measure of soiling ratio [1][2][3]. Each

Mars™ unit operates daily at sunset and measures the transmission loss through its sensor window. Data collection began at Site 2 in December 2018 and at Site 1 in February 2019.

IV. Results and Discussion

A. Soiling Ratio Data

Fig. 3 and Fig. 4 show the results from Site 1 and Site 2, respectively. In each figure, the upper panel compares the soiling ratio measured by the Mars™ sensor to that measured with the reference cell pair, while the lower panel shows the daily rain total. In this context, soiling ratio is equivalent to the fraction of incident sunlight that passes through the accumulated dust layer on the sensor or reference cell glass.

Soiling ratios for the reference cell pair were calculated by dividing the daily average irradiance measured by the unwashed reference cell by that of the washed reference cell. For Site 2, because the washed and unwashed reference cells were located some distance apart and were measured by two different data acquisition systems on asynchronous timing, the reference cell soiling data show noise related to irradiance fluctuations that affect the two cells differently. Low-irradiance (cloudy) days were therefore excluded from the reference cell analysis on Site 2, and missing days were filled with soiling ratios from the previous valid day. For both Site 1 and Site 2, the reference cell soiling ratios were normalized such the average of the soiling ratios on days following rainfall, when both reference cells in a pair are assumed to be clean, is equal to 1.00.

Soiling ratios for the Mars™ sensors were determined by the Mars™ analysis algorithm [4] which quantifies transmission loss from the acquired images of the sensor windows.

In Fig. 3 and Fig. 4, a 3-day rolling average was applied to both the Mars™ and reference cell pair soiling ratio data.

The data sets for both sites show a soiling buildup rate of ~0.15%/day during the dry periods, which is within typical ranges for their respective regions in California.

B. Data Comparison

The overall level of agreement at each site between the Mars™ sensor and the reference cell pair is good. Each site shows a similar trend, with little to no soiling loss in the winter and early spring months due to frequent rains, then accumulation of soiling loss from late March through late April, followed by rains that clean the sites and reset the soiling ratio readings. The peak soiling loss measured at each site by the Mars™ sensor and reference cell pair is in good agreement.

However, there are differences between the results of the two measurements at each site which merit discussion.

Some of the variance in the data sets is due to measurement noise related to each of the techniques. The reference cell pair data are especially affected by irradiance fluctuations. As noted above, spatial and temporal fluctuations in irradiance can degrade the correlation of nearby reference cells on cloudy days. Additional factors, including angular misalignment [1] and temperature effects can also degrade the correlation. These effects are more significant in the reference cell pair data for Site 2 than for Site 1, due to the greater distance between the cells in the pair and the non-simultaneity of measurements. The Mars™ data also likely exhibit some daily random error due to variations in sky conditions and to analysis limitations. In addition, raindrops on the Mars™ sensor can be perceived as a soiling loss, which affects several days in the data sets (e.g. Feb. 13 and May 19 for Site 1).

However, another source of variance between the Mars™ and reference cell data sets is temporary variations in the actual soiling of the Mars™ sensor vs. the unwashed reference cell. For example, around March 29 at Site 1, some large particulate matter was observed to cloud the Mars™ sensor and reduce its soiling ratio reading, although the unwashed reference cell at the site remained nearly clean. Differences in soiling deposition and self-cleaning related to dew and/or wind may also explain the differences between the Mars™ and reference cell pair readings in early May at Site 1. These types of differences are not necessarily related to the Mars™ technology but could be expected to occur when comparing any two soiling measurement devices on a single site, especially when using compact small-area sensors, since soiling has a spatially random component.

Despite the differences between the Mars™ and reference cell pair data discussed above, overall the data sets show good correlation when evaluated over long periods. The standard error of correlation for the data in Fig. 3 and Fig. 4 is 0.44% for Site 1 and 1.02% for Site 2, indicating the ability of Mars™ to detect soiling level differences on the order of 1% or better, which is qualitatively supported by the graphs in Fig. 3 and Fig. 4.

C. Implications for PV System Monitoring

The data presented above compare the soiling-induced transmission loss measured by Mars™ to that measured by a washed/unwashed reference cell pair, although ultimately the goal of soiling measurement is to estimate soiling-related power losses of full size PV modules in a PV array. The reference cell pair method is widely used as a proxy for module soiling estimation because of its simplicity and it provides reasonable agreement to module soiling under many conditions. However, it is known that soiling-related power losses on full-size PV modules can also exhibit significant effects due to characteristic soiling non-uniformity patterns [7][8][9] under specific weather conditions, and these effects are not detectable by the reference cell pair method. Furthermore, PV modules may soil differently than PV cells (or a Mars™ sensor) due to differences in glass type, coatings, and module construction. To investigate the impact of these effects on the correlation with Mars™ and potential extensions of the Mars™ technology, data collection

is underway at Site 2 using an additional system (RDE300) which measures the soiling-induced power loss of a PV module deployed within the array.

An additional 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 [10].

V. Conclusions

Field test data of the Mars™ soiling sensor has shown good correlation to traditional soiling measurements using a washed/unwashed reference cell pair, demonstrating the validity of the Mars™ technique. The results are promising for providing a low-cost, compact, maintenance-free soiling sensor that can be more widely deployed than traditional solutions. Further investigation at the test sites used in this study is ongoing and we expect to publish additional results.

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