MARS™ SOILING SENSOR

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ABSTRACT: We evaluate a new proprietary optical soiling measurement technology that does not require washing. The compact, water-free, and maintenance-free sensor technology is designed to permit PV system soiling measurement with lower cost and labor requirements compared to traditional soiling measurement systems using a clean/soiled pair of PV reference devices. These attributes make the sensor suitable for a wide range of sites including not only utility but also commercial-scale PV installations. Laboratory test results using soiled glass test coupons demonstrate excellent correlation between the optical sensor and a PV cell, and field testing is underway.

1 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 measurement systems compare the outputs 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 would lower the cost of soiling monitoring, and be 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 measurement concept developed by Atonometrics (Mars Soiling Sensor™, [4][5]), conceived as a solution for maintenance-free measurement of soiling loss. The Mars™ sensor is designed to be deployed at a PV installation site in plane-of-array and to operate unattended and without water. Soiling particles accumulate on the sensor window just as on any nearby PV modules and the sensor directly detects the soiling level on the sensor window.

2 OPTICAL MEASUREMENT OF SOILING

Consider a PV device covered by a transparent window upon which soiling particles have accumulated. The soiling particles block incident sunlight through reflection and absorption of light, and therefore result in lost power production by the PV device relative to a clean state of the window. The soiling loss *SL*, the fractional loss in power due to the soiling particles, can be expressed as

$$SL = 1 - T = R + A \quad (1)$$

where *T* is the fractional transmission of light through the layer of soiling particles, *R* is the fractional reflection (or scattering) of light, and *A* is the fractional absorption of light. Here we consider *T*, *R*, and *A* as properties of the layer of soiling particles only, neglecting any reflection or absorption by the glass, i.e. *SL* is only the additional loss due to the soiling particles. For simplicity, in eq. (1) we also neglect the spectral irradiance distribution of incident light, spectral transmissivity of the soiling layer, and spectral response of the PV device, although these can be considered in a more complete treatment.

Our aim is to determine *SL* or, equivalently, *T*.

Recently another optical soiling measurement device has been developed [6] which uses a reflection measurement to measure a signal proportional to the *R* term in eq. (1). A beam of light is directed from inside the sensor to the sensor window and light that is back-reflected/scattered by soiling particles is detected. The *A* term is neglected and *SL* is assumed to be proportional to the reflectance signal or *R* term. The device therefore requires separate calibrations for different colors of dust with different reflectance/absorbance. This is a significant difficulty since the type and color of dust encountered at a particular site are not necessarily known and may even change over time with weather conditions.

In contrast, our sensor concept directly measures both the *T* and *R* terms in eq. (1) using a microscopic imaging approach, similar to the soiling microscope used in [7] to study particle deposition dynamics, although with important differences.

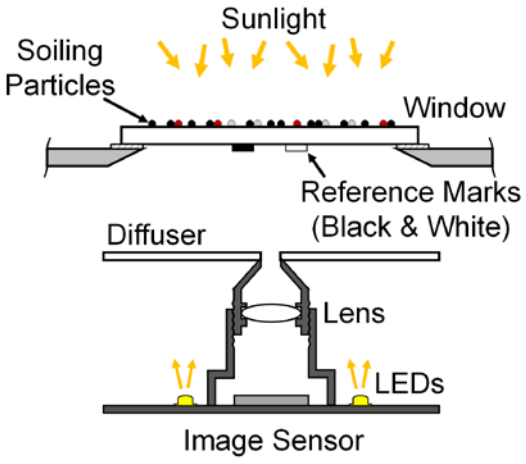


Figure 1: Mars Soiling Sensor™ concept. A microscope system captures an image of a soiling particle layer on a window using either external (sunlight) or internal (LED) illumination. Black and white reference marks provide calibration features for image analysis.



Figure 2: Mars Soiling Sensor™ measurement head, showing reference marks on inside of window.

3 MARS™ SENSOR CONCEPT

Fig. 1 illustrates the Mars Soiling Sensor™ concept. Soiling particles accumulate on a glass window mounted on the outside of the sensor enclosure. A camera assembly, consisting of a lens and image sensor, is focused on the outer layer of the window and captures a microscopic image of the soiling particle layer, which can be illuminated by sunlight and/or by internal LEDs. A diffuser spreads the LED illumination evenly across the window. Black and white reference marks screen-printed on the inside of the window are used as self-calibration features for image analysis, as well as for detection and rejection of invalid images. Note that the window edge is not covered, to prevent trapping moisture and dust. Fig. 2 is a photograph of the actual sensor head, which better shows the reference marks which are formed as two concentric circles. The sensor is focused to obtain images from a field of view on the window surface with diameter up to approximately 15 mm.

Fig. 3 shows an example acquired image when the sensor head is covered with a layer of ISO 12103-1, A2 fine test dust ("Arizona road dust"), which has a large silica content and is somewhat white and reflective. The sensor is illuminated externally by simulated diffuse sunlight. The dust particles, as well as both the black and white reference marks, appear dark, as they cast shadows blocking light entering from outside the sensor. To

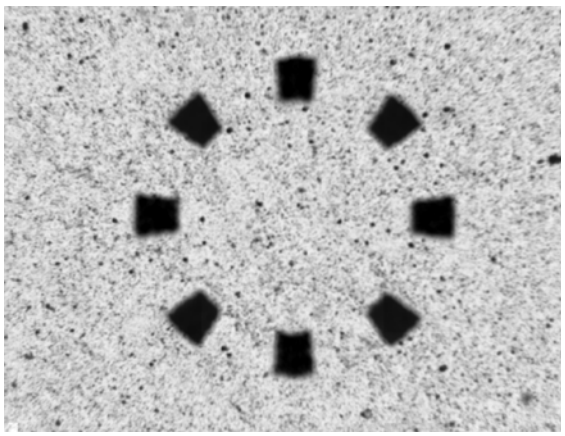


Figure 3: View through the sensor head with external illumination and a layer of dust on the sensor window.

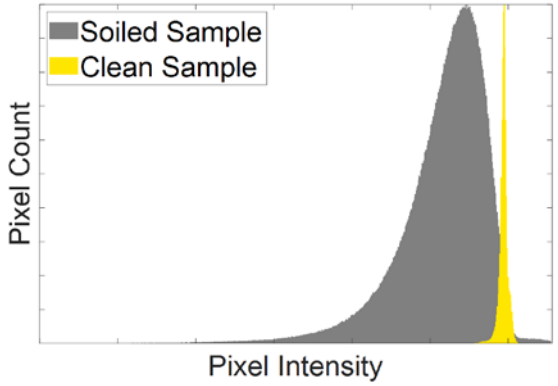


Figure 4: Pixel intensity distribution of Mars™ images of two samples, one clean and one soiled.

analyze the image, we use a proprietary background correction algorithm to correct for non-uniformities in illumination, identify a reference pixel brightness corresponding to local regions of maximum transmission, and then compute the average brightness of all pixels, excluding the reference marks, relative to the reference pixel brightness. The result directly yields the fractional transmission *T* and therefore *SL*. Note that this technique does not require that the camera resolve individual dust particles, unlike the method in [7], and that it does not assume any optical properties of the dust itself, which could be either opaque or partially translucent.

The image analysis method is further illustrated in Fig. 4, which shows pixel intensity histograms of Mars™ images, similar to that of Fig. 3, of two samples, one clean and one soiled by dust. Note that pixels corresponding to the circular reference mark pattern are not included in the histograms. For the clean sample the histogram distribution is very narrow, with most pixels having intensity near a value corresponding to clean glass and maximum light transmission. For the soiled sample, the histogram shows a wide range of pixel intensity values, indicating that many of the pixels have reduced light transmission. As described above, soiling loss is calculated by determining from each image a reference pixel brightness corresponding to clean glass and then comparing all pixels to the reference brightness to calculate average transmission and therefore soiling loss.

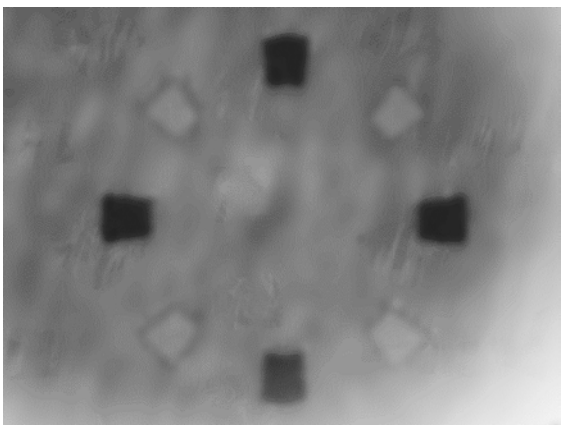


Figure 5: View through the sensor head with internal illumination and simulated snow on the sensor window.

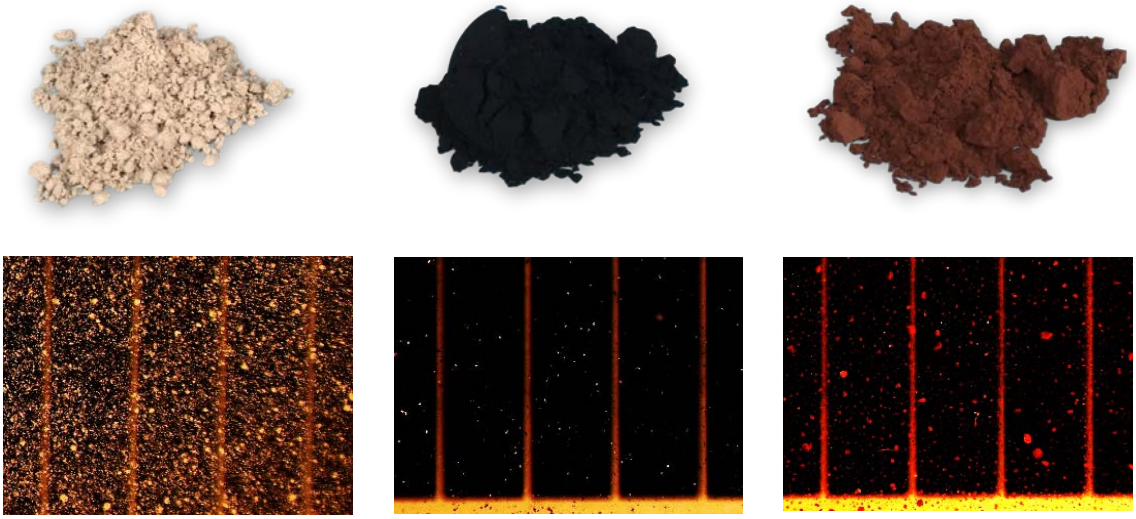


Figure 6: Dust powders (top) and microscope images (bottom) of representative soiled glass test coupons using each of the dust powders, Arizona road dust (left), carbon black (center), and red iron oxide (right). The clear glass soiled coupons were overlaid on a PV cell for the images; although appearance varies due to dust reflectivity, soil levels of each sample are similar (~12%). Image widths are 5 mm.

By using internal illumination from the LEDs, additional information can be gained. When illuminated from the inside (for example, at night), the camera captures an image of the reflection of material on the window. This mode of operation can be used to measure the *R* term in eq. 1, thus setting a lower limit on *SL* and providing an independent check. In addition, the measured reflectance can be used to provide a small correction to the external-illumination determination of *T* to account for daylight which enters the sensor, scatters upwards, and illuminates the particles from below. Thus analysis may combine both externally illuminated (i.e. daytime) and internally-illuminated (e.g. nighttime) images of the soiling layer.

Figure 5 shows another potential application of internal illumination, the detection of snow or other reflective substances (e.g. bird droppings) on the sensor which block external light. The image in Fig. 5 is taken with the sensor covered with simulated snow (a white foam sheet) and illuminated from the inside by LEDs. Note that the white reference marks reflect the internal illumination and that reflection from the simulated snow layer is also apparent in the image and can be referenced to the reflection from the white marks.

4 LABORATORY TESTING

Laboratory evaluation was performed using soiled test coupons. Coupons were prepared using three different dust materials, of different colors, representative

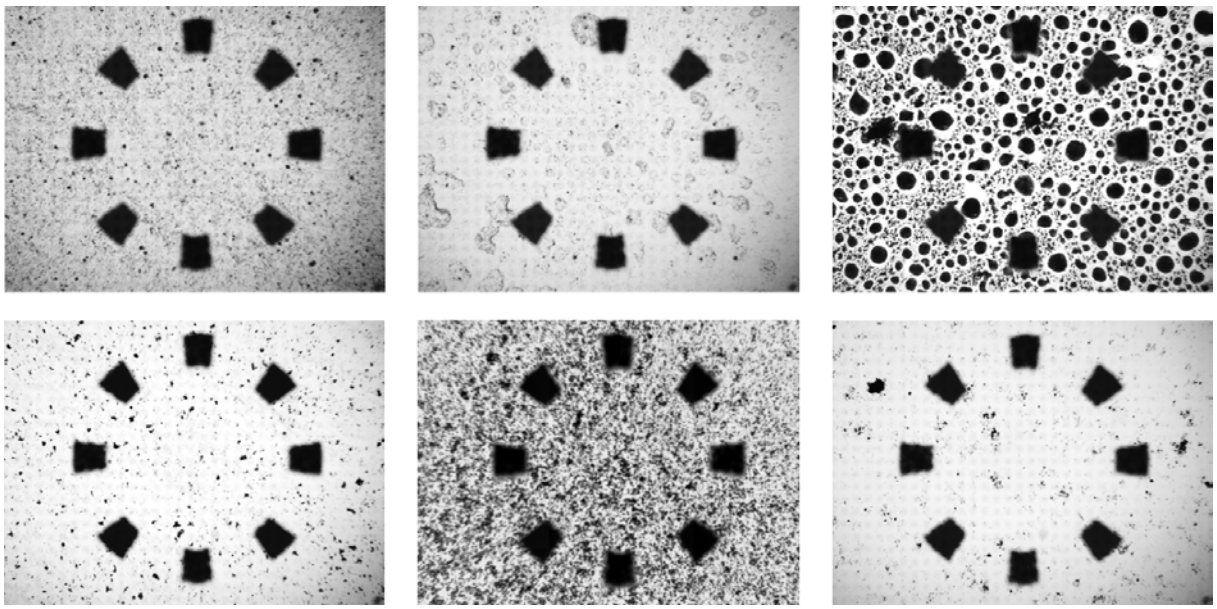


Figure 7: Mars™ images of representative soiled glass test coupons, illustrating the effects of varying deposition conditions. Each image has width ~11 mm.

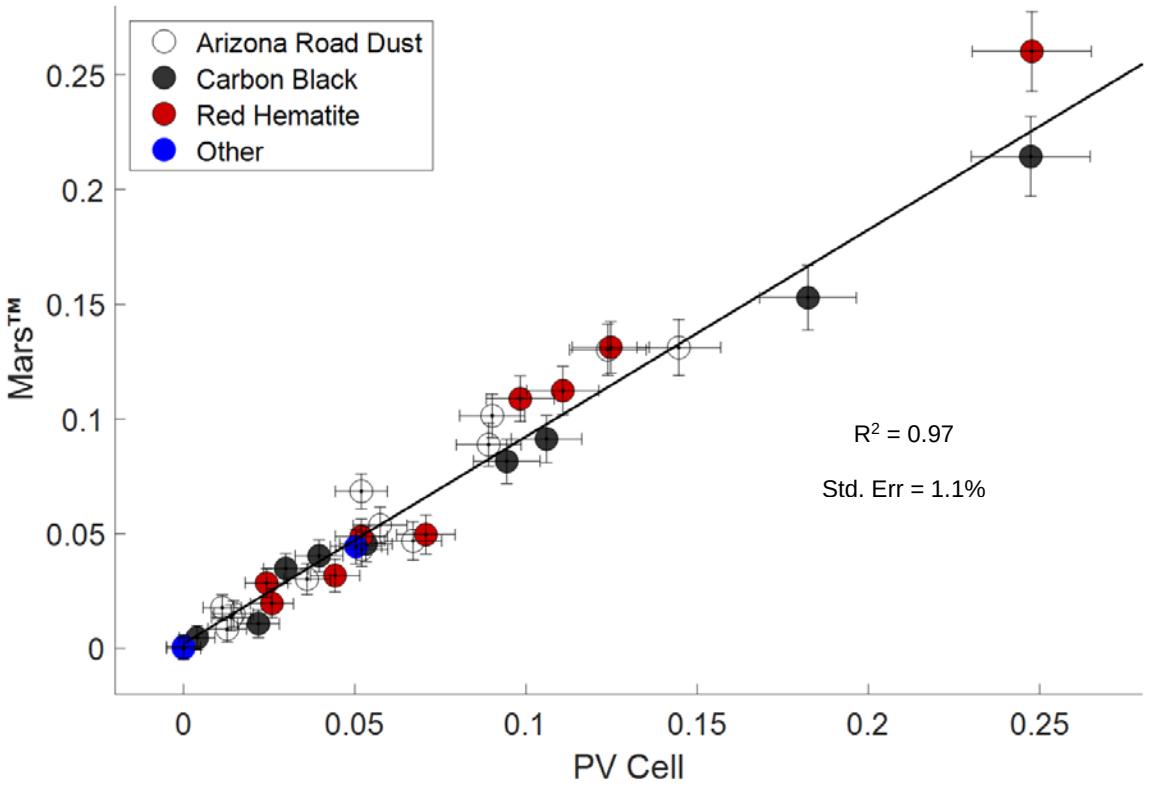


Figure 8: Correlation of soiling loss measured by the Mars Soiling Sensor™ versus results with a PV cell, for various representative dust materials including those with white, black, and red particles as indicated by the colored symbols.

of airborne soiling particles. These included fine Arizona road dust (ISO 12103-1, A2, Powder Technology), 30 um filtered carbon black (Inoxia), and 30 um filtered red iron oxide (Alpha Chemicals). The three materials are respectively white, black, and red in appearance, as shown in Fig. 6. The coupons consisted of 2" x 2" borosilicate glass slides. Dust was uniformly applied to the coupons by placing them, together with a selected dust material, in a custom-built dusting box, which uses a high speed recirculation fan to maintain a dust-laden air stream. Prior to dust exposure, the coupons were chilled to -10 °C to 5 °C, causing moisture condensation during exposure which promotes dust adhesion. Fig. 6 illustrates the varying appearance of the three different materials once applied to the coupons. The figure shows microscope images of coupons with each of the three materials in which the clear glass coupon is overlaid on a PV cell, simulating the appearance of a soiled PV device. Although all three coupons have similar soiling level of ~12% (measured as discussed below) their appearance is quite different: the white Arizona road dust particles are bright and reflective, while the carbon black is barely visible against the dark background and the red iron oxide has an intermediate appearance. This illustrates the difficulty of measuring particle coverage by appearance or by reflectivity.

By varying the deposition conditions, including pre-chilling temperature, exposure time, position within the dusting box, and other parameters, we achieved a wide variety of different dust coverages and morphologies, as illustrated in Fig. 7. The figure shows close-ups of images of various coupons as acquired with the Mars™ sensor, similar to Fig. 3, where each image is an image of the shadows of the dust particles against the external lighting. Note in some images that particles have agglomerated together into larger collections, due to the moisture level, which may be similar to natural soiling processes.

As a control, the soiling loss of each coupon was measured with a PV cell illuminated with a halogen lamp. A 10 mm diameter aperture was placed in front of the cell to limit the spot size of the measurement. The ratio of the PV cell short-circuit current for each coupon to its short-circuit current with clean glass was recorded, and one minus the ratio was logged as the soiling loss for the coupon. A small correction was performed to account for reflection of light from the multiple interfaces of the soiled coupons. The characteristic uniformity of soiling loss within the central region of the samples was estimated by translating selected samples across the PV cell aperture and measuring maximum and minimum soiling loss.

Following PV measurement, each sample was positioned on the window of the Mars™ sensor and images were acquired with both external and internal illumination. Images were processed as described above and the results were correlated with the control measurements using the PV cell.

Results are shown in Fig. 8. Error bars represent the uncertainty in the control measurements due to lamp instability as well as non-uniformity of the soiling in the central region of each sample. White, black, and red symbols indicate the white, black, and red dust particles. Blue symbols show other materials, which include salt, a mixture of the three dusts, and clean glass. The correlation between the optical soiling sensor and the PV cell is very good, with R^2 of 0.97 and standard error of correlation of 1.1%. Furthermore, all three different dust materials fall on the same trend line, suggesting a near-universal response of the sensor independent of dust

color.

The results presented in Fig. 8 are for soiling levels up to 25%, which is a practical range for PV system operation. Additional testing has been performed up to 75% soiling levels, showing adequate performance although with larger errors. Work is ongoing in this area.

5 OUTDOOR TESTING

Outdoor testing of the Mars™ sensor is underway, with several units deployed or in process of deployment at locations in Texas and California, together with traditional soiling measurement techniques for data correlation. Due to low soiling and frequent rains at the already installed test sites, data with significant soiling levels for correlation are not yet available, although initial results demonstrate the ability of the sensor to operate properly in the outdoor environment and in diffuse sunlight illumination. Further work is ongoing.

6 DISCUSSION AND CONCLUSIONS

Laboratory data show promising results for the new water-free and maintenance-free Mars Soiling Sensor™ concept. In particular, the results show very little, if any, dependence on dust color, in contrast to [6].

Note that the results presented in Fig. 8 do not include any arbitrary calibration constants. The slope of the best-fit line to all data points is 0.95, indicating that without calibration the technique already measures soiling loss close to the control method. By applying a calibration factor, the results can of course be improved. One potential reason for the non-unity slope of the correlation could be spectral mismatch between the PV cell and the image sensor. Further work is needed to assess this. Also, while to date we have processed acquired images in grayscale only, use of the color sensitivity of the image sensor could in the future allow automatic compensation for a spectral mismatch effect.

Our method for determining T does not depend on dust color, but it does depend on the morphology of the dust layer, since we must be able to observe some gaps between dust particles in order to determine reference intensities corresponding to local regions of clean glass. Therefore the method may be less effective for highly soiled samples with very small and highly uniformly distributed particles. However, in such cases our complementary method of determining R using internal illumination could provide a check and lower limit on SL.

Determining the accuracy of the Mars™ technique in actual practice will require long term outdoor testing with naturally-occurring soiling in a variety of conditions.

Finally, we note that our optical sensor measures soiling loss only at a relatively small region on the sensor itself, while PV module power loss can be significantly affected by the distribution pattern of dust across an entire module [8][9]. We envision potential extensions of the technique that could account for these effects [10].

Overall, the promising results obtained in laboratory testing so far suggest that the Mars Soiling Sensor™ concept could be an effective, compact, low-cost, and unattended soiling sensor practical not only for utility-scale but also commercial-scale PV projects.

7 ACKNOWLEDGEMENTS

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