# Development and Comparative Performance of Clear-Sky and All-Sky Soiling Data Filters

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## ABSTRACT

Soiling of PV modules has a measurable impact on PV plant performance. Accurately modeling PV performance is important for plant capacity testing and operational monitoring and maintenance.

The 2017 update to the IEC 61724-1 standard for PV performance monitoring provided the first real guidance to the solar industry for making direct, real-time measurements of soiling losses. While IEC standard gives guidelines for equipment selection and methods for soiling measurement and data processing, measurement methodologies and data processing algorithms vary.

Two novel soiling data processing filters have been developed by GroundWork Renewables, Inc.: A Clear-Sky filter and an All-Sky filter. Both filters process high temporal resolution soiling data into irradiance-weighted average daily soiling ratios.

Here we present a short term evaluation of the two data filters utilizing the same data set from a single soiling measurement system located in Northern Utah with daily maintenance.

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## INTRODUCTION

The accumulation of surface debris on PV modules can significantly reduce energy production[1]. Soiling measurement systems are commonly deployed at utility-scale solar facilities before and after plant construction to accurately predict and quantify site-specific PV module soiling losses. Authors have presented work showing the time of day dependencies inherent in PV-module-based soiling measurement systems and the need for data filtering to calculate representative daily soiling ratios[2].

## OBJECTIVE

Research was conducted to validate data filter performance and compare the daily soiling values generated by the two discrete soiling data filtering methods.

The primary goal was to confirm that the two methods correlate well ($R^2$ >= 0.90) during clear sky periods at a single location to justify and inform the next phase of research; a 1-year, multi-site evaluation of the two soiling filters.

A secondary goal is to further the adoption of the All-Sky filter as it generates daily average soiling ratio even on cloudy days.

## METHODS

**Soiling Data Collection System:** Data to test the filters was collected using a GroundWork Eclipse soiling measurement system[3] deployed in Logan, Utah (Figure 1). Two 72-cell crystalline PV modules were mounted at a 26-degree fixed tilt at an azimuth of 180 degrees. The clean module was manually washed 5 days per week and the soiled module was left to foul. Data from June 2018 was selected as it included the greatest number of clear sky days for a given month.

## METHODS (Continued)

**Soiling Data Filters:** Two daily soiling filters were developed to automate the calculation of a daily irradiance weighted soiling ratio from near real-time soiling measurement data:

*Clear-Sky Filter*

The Clear-Sky filter was developed first, with direction from Ryan et al., 1989[4] based on the principle that only stable sky data, >500 W/m$^2$, within two hours of solar noon should be included in the irradiance-weighted daily soiling ratio calculation. Clear skies are determined using the method described in Reno et al., 2016[5] adapted to use modeled clear sky plane of array irradiance (POA) and effective irradiance (G) instead of modeled clear sky global horizontal irradiance (GHI) and measured GHI. G was calculated using equation three from Gostein et al., 2015[6] utilizing the soiling module measured short circuit current (Isc) and back of module temperature. The Ineichen clear sky model was used to estimate site-specific clear sky irradiance components using the optimized Linke turbidity coefficients[7, 8] and transposed[9, 10] to clear sky POA for clear period detection. The Clear-Sky filter outputs a daily irradiance-weighted average soiling ratio and a corresponding quality number which describes how many samples were included in the calculation. Values will only be generated if 10 or more clear sky samples are included in the daily calculation.

*All-Sky Filter*

The All-Sky filter is based upon methods described in [6, 11, 12] and calculates an irradiance-weighted daily average value using all data collected when G is greater than the set irradiance threshold of 500 W/m$^2$ regardless of time of day. Any data falling greater than one standard deviation away from the regression between clean and soiled is omitted from the daily average. The All-Sky filter outputs a daily irradiance-weighted average soiling ratio, sample count, and quality number when 10 or more all sky samples are included in the daily calculation.

## RESULTS

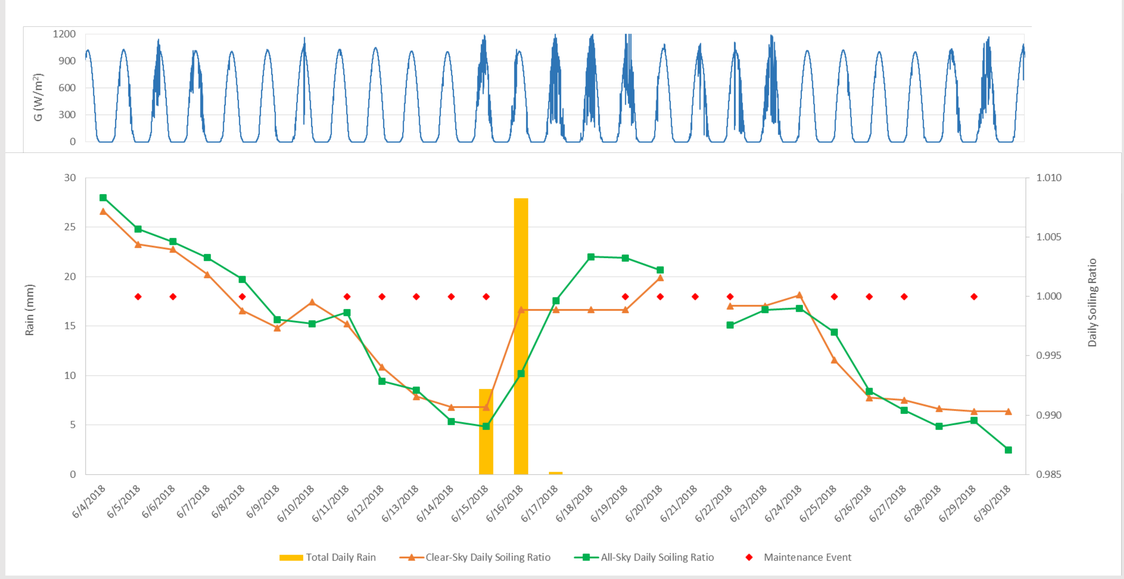


**Figure 2.** Top graph: Effective irradiance over time, as calculated from clean module Isc and back of module temperature.
Bottom Graph: Daily soiling ratios over time as calculated using the two filters. Washing of the clean module is indicated by "Maintenance Event."

| | Clear-Sky Filter | | All-Sky Filter | |
|---|---|---|---|---|
| | Daily Soiling Ratio | Sample Count | Daily Soiling Ratio | Sample Count |
| 6/6/2018 | 1.00397 | 42 | 1.00833 | 304 |
| 6/7/2018 | 1.00186 | 77 | 1.00568 | 330 |
| 6/8/2018 | 0.99879 | 102 | 1.00461 | 291 |
| 6/9/2018 | 0.99736 | 33 | 1.00326 | 283 |
| 6/10/2018 | 0.99952 | 40 | 1.00143 | 303 |
| 6/11/2018 | 0.99768 | 83 | 0.99806 | 291 |
| 6/12/2018 | 0.99407 | 102 | 0.99771 | 297 |
| 6/13/2018 | 0.99156 | 102 | 0.99866 | 289 |
| 6/14/2018 | 0.99067 | 102 | 0.99287 | 286 |
| 6/15/2018 | 0.99067 | 102 | 0.99213 | 309 |
| 6/16/2018 | 0.99886 | 68 | 0.98947 | 303 |
| 6/17/2018 | 0.99886 | 68 | 0.98904 | 336 |
| 6/18/2018 | 0.99886 | 68 | 0.99348 | 415 |
| 6/19/2018 | 0.99886 | 68 | 0.99966 | 370 |
| 6/20/2018 | 1.00159 | 46 | 1.00333 | 334 |

**Table 1.** Daily soiling ratios as calculated using the Clear-Sky and All-Sky filters, and the number of one-minute samples contributing to each.

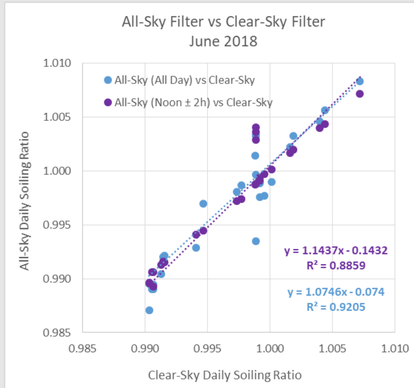


**Figure 3.** Regression comparison of daily soiling ratios as calculated using the two filters. Blue dots represent the All-Sky filter when data from the entire day are included. Purple dots represent the All-Sky filter when data from only the solar noon window are included.

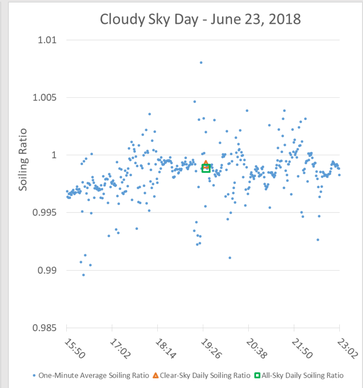


**Figure 4.** Time series of one-minute average soiling ratios with daily ratios calculated by the Clear-Sky and the All-Sky Filters superimposed.

| | Clear-Sky Filter | All-Sky Filter |
|---|---|---|
| **Irradiance Threshold** | >500 W/m$^2$, clear sky | >500 W/m$^2$, any sky |
| **Time period Included** | Solar noon ±2 h | Any |
| **Data not Included** | Any collected under unstable sky conditions | >1 standard deviation from clean vs soiled regression |

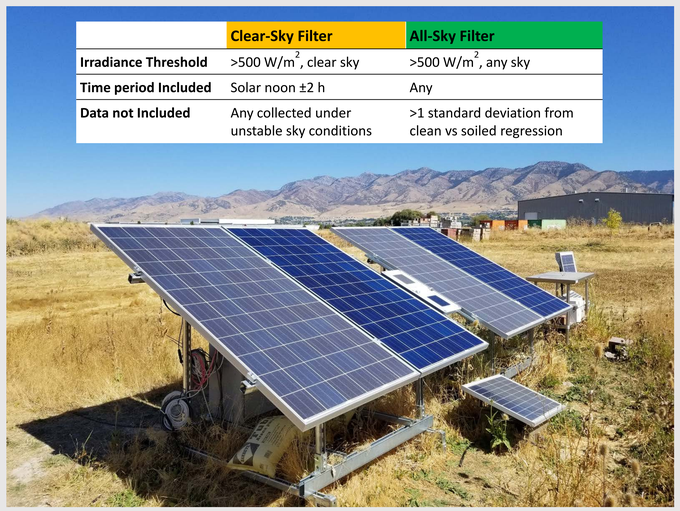

**Figure 1.** Soiling measurement system at the GroundWork research facility in Logan, Utah.

## CONCLUSION

Although clear-sky filters yield quality results, they only output daily average soiling ratios on clear sky days. An all-sky filter is required in order to reliably generate daily soiling ratios at locations with frequent cloudy weather. Preliminary results from the GroundWork All-Sky filter are very promising. Irradiance-weighted daily average soiling ratios calculated by the Clear-Sky and the All-Sky filter showed strong correlation across the month of June, particularly on stable clear sky days. The correlation improved from $R^2$ = 0.8859 to $R^2$ = 0.9964 when the All-Sky filter data processing window was narrowed from all day to ±2 hours of local solar noon to match the Clear-Sky filter window and comply with IEC 61724-1 fixed tilt recommendations. The All-Sky filter included on average more samples than the Clear-Sky filter in the daily average soiling ratio calculation. The All-Sky filter also generated daily values on cloudy days June 17, 18, 19 when the Clear-Sky filter did not. The All-Sky filter shows promise for locations with significant solar variability. Further testing is warranted to evaluate spatial and temporal performance.

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