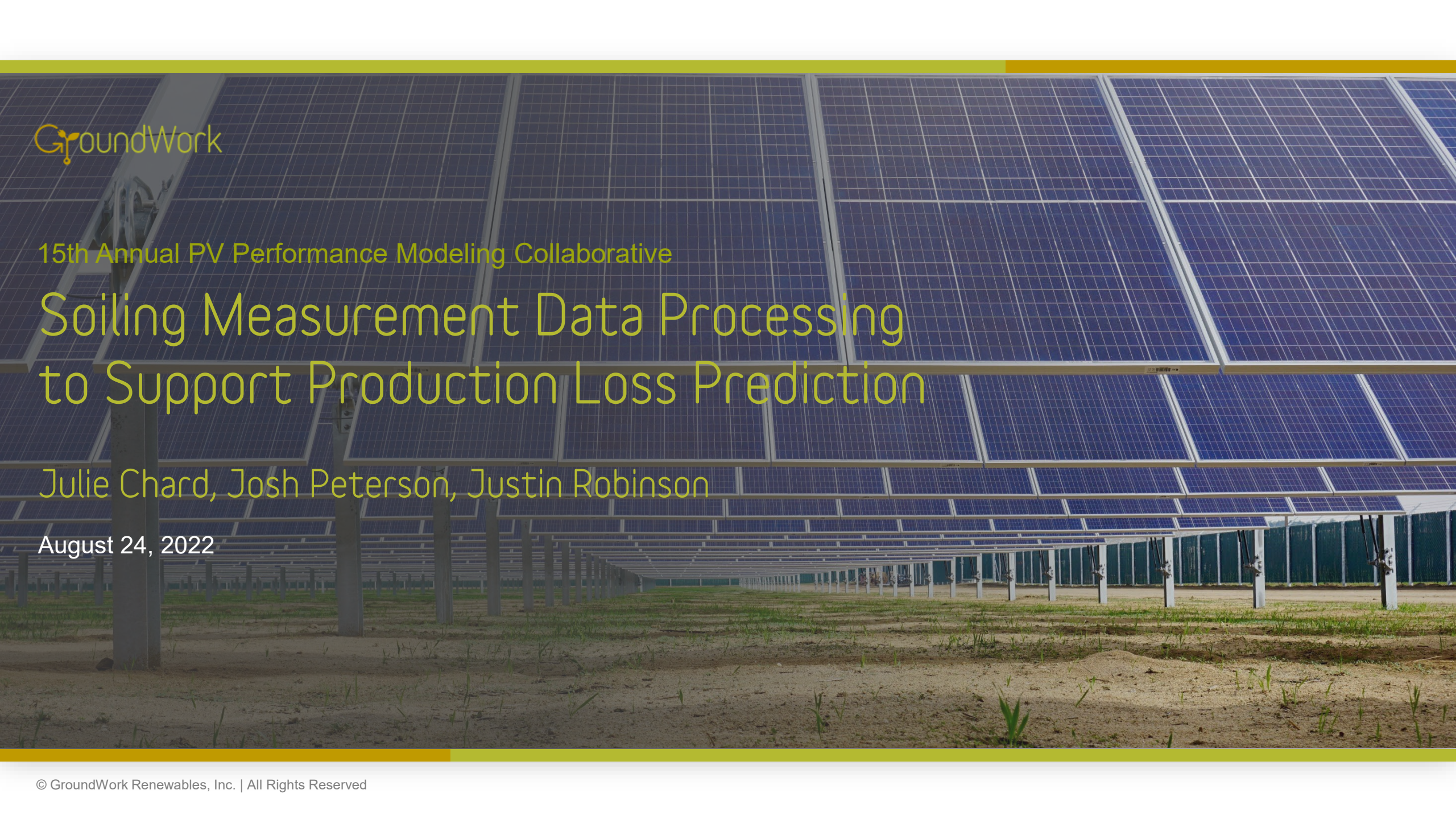


GroundWork

15th Annual PV Performance Modeling Collaborative

Soiling Measurement Data Processing to Support Production Loss Prediction

Julie Chard, Josh Peterson, Justin Robinson

August 24, 2022

GROUNDWORK IS...

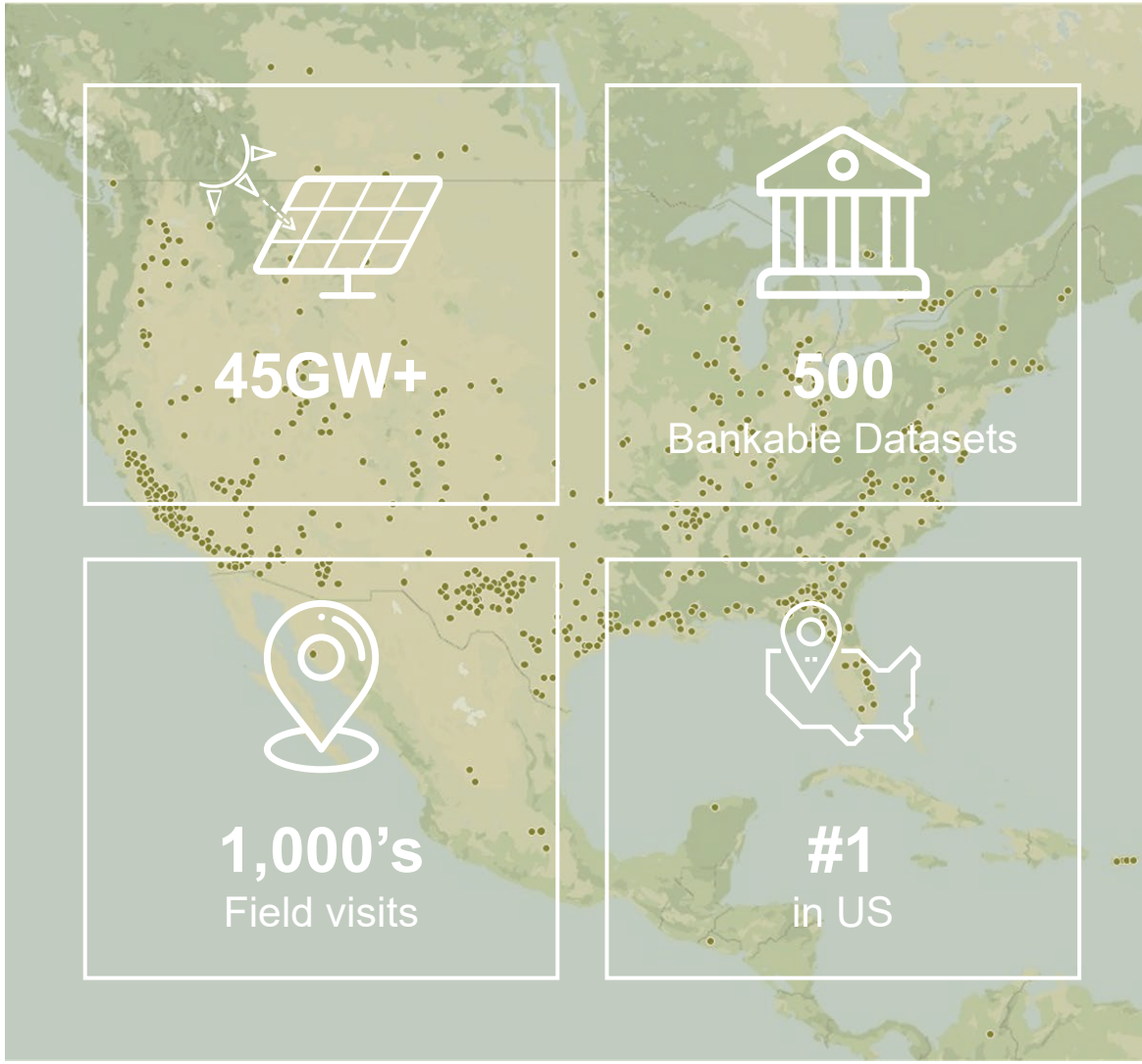
Mission Driven
To accelerate the success of solar in leading utility-scale energy production

Best in the World
At in situ, reference solar data acquisition and evaluation

The US-Market Leader
In reference to solar data through precision measurements and world-class services for the utility-scale solar industry

Founded in Values
Trustworthy & Caring | Knowledgeable & Trailblazing | Nimble & Meticulous

A Partner First



GROUNDWORKERS ARE REFERENCE SOLAR DATA EXPERTS

DEVELOPMENT
IPPs, Owners, Developers, Utilities

Resource Assessment (RA)

Offerings
- Design Engineering
- Systems
- Field Services
- GroundWatch®

CONSTRUCTION
EPCs

MET Equipment and Supply (EPC)

Offerings
- Design Engineering
- Systems
- Field Services

OPERATIONS
Owner/Operators

MET Support (Ops)

Offerings
- Equipment
- Calibration Management
- Extreme Weather Event Analysis
- Research and Development (R&D) Facilities

Soiling Measurement Data Processing to Support Production Loss Prediction

01 Soiling Measurement

02 Data Processing Challenges and Filtering Approaches

03 Soiling Rate Determination and Uncertainty

Paired PV Device Method [1]

Soiling Instrumentation

- Paired devices, mounted in the same plane
- One module is cleaned on a regular basis; the other module is allowed to naturally soil
- Soiling reduces the short circuit current (Isc) output of the soiled module relative to the clean control

Maintenance and Ancillary Measurements

- Weekly maintenance
- Manual and natural resets
- Concurrent rain measurement
- One-minute data

[1] IEC 61724-1:2021 *Photovoltaic system performance - Part 1: Monitoring*.
Available at https://webstore.iec.ch/publication/70170

SOILING MEASUREMENT: TERMINOLOGY

Soiling Ratio

- An instantaneous measure of the reduction in Isc due to soiling.

$$Soiling\ Ratio = \frac{Isc_{soiled}}{Isc_{clean}}$$

Soiling Rate

- A measure of how fast soiling is accumulating on the modules.

$$Soiling\ Rate = \frac{\Delta Soiling\ Ratio}{\Delta Time}$$

Soiling Loss

- A derate of power production due to soiling.
- In preconstruction, loss is predicted using models, where soiling rate is an input.
- In post-construction, loss is expressed as a function of the soiling ratio.
- Post-construction soiling rates can be calculated retrospectively, working backward from loss.

$$Soiling\ Loss\ (\%) \approx f(SRate, PM, Weather, ?)$$

$$Soiling\ Loss\ (\%) = (1 - SRatio) * 100$$

IEC 61724-1:2021 Photovoltaic system performance - Part 1: Monitoring, Annex C

IEC 61724-1:2021

- Data are filtered
- A daily average is computed
- A quality number is obtained

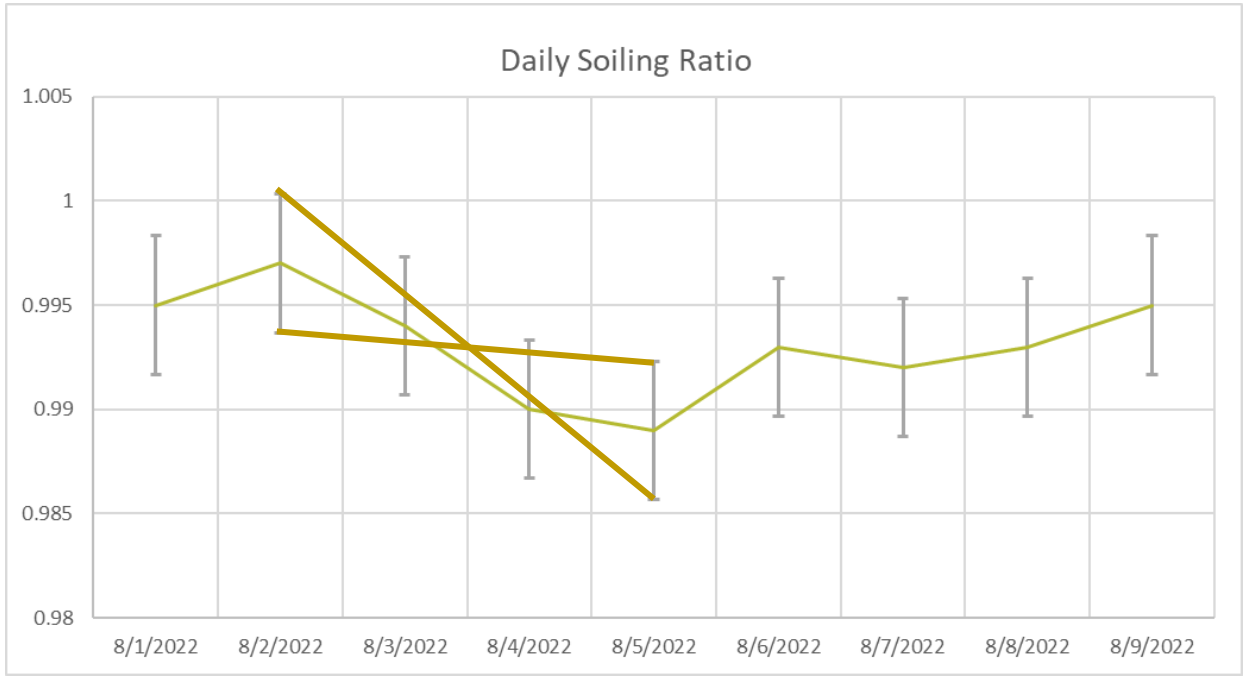
Published Filtering Approaches

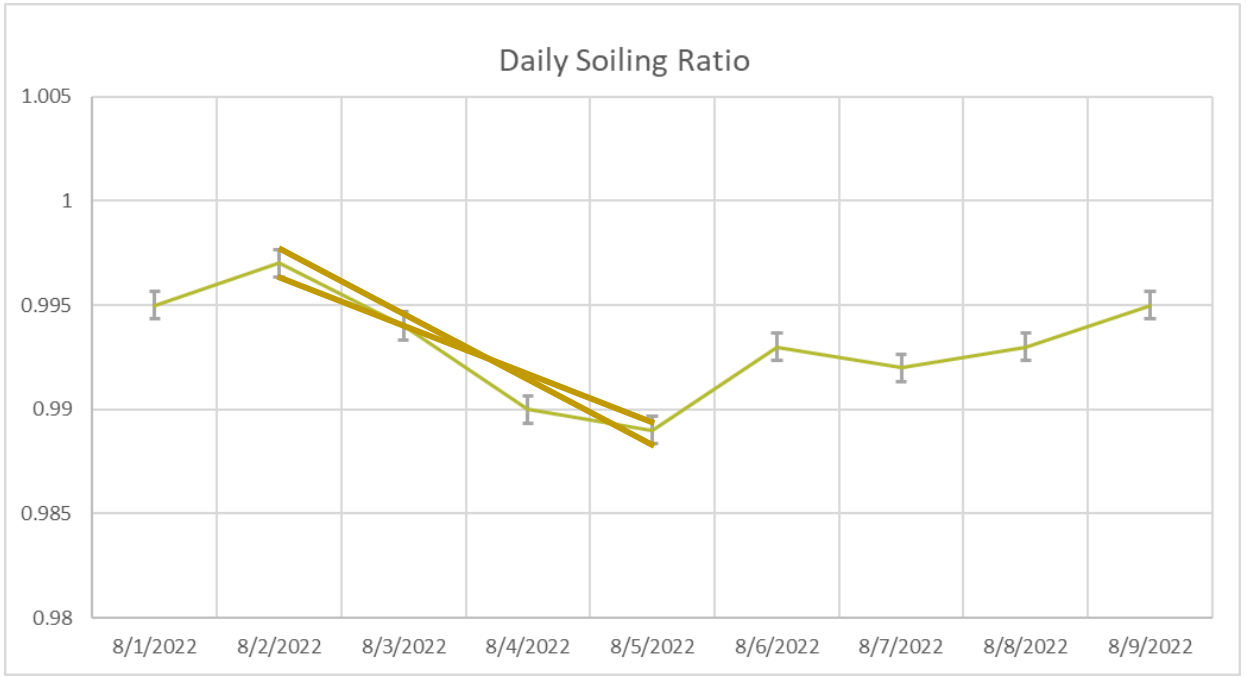
- Bessa et al., 2022. Estimation of photovoltaic soiling using environmental parameters: A comparative analysis of existing models. Advanced Sustainable Systems, 2100335.
- Deceglie et al., 2018. Quantifying soiling loss directly from PV yield. IEEE Journal of Photovoltaics, 8(2), 547-551.
- Skomedal et al., 2019. Endogenous soiling rate determination and detection of cleaning events in utility-scale PV plants. IEEE Journal of Photovoltaics, 9(3), 858-863.
- Micheli et al., 2021. Improved PV soiling extraction through the detection of cleanings and change points. IEEE Journal of Photovoltaics, 11(2), 519-526.
- Muller et al., 2022. Automated detection of photovoltaic cleaning events: A performance comparison of techniques as applied to a broad set of labeled photovoltaic data sets. Progress in Photovoltaics: Research and Applications, 30(5), 567-577.
- Peterson et al., 2022. Extraction of prevailing soiling rates from soiling measurement data. IEEE 49th Photovoltaic Specialists Conference, PVSC 2022.

“the instantaneously measured values shall be integrated to compute a daily average value… the data should first be filtered... the number of data points passing the filter should be recorded as a quality metric and calculation of the daily average should only be performed when a sufficient number of data points are valid”

DAY-TO-DAY CHANGES IN DAILY VALUES

A quality number is helpful. Error bars are more helpful.





Challenges with Soiling Data

Insufficient Irradiance
Soiling ratios are skewed when module outputs are smaller.

Inherent Noise
Variable sky conditions, variable module surface characteristics, birds flying over, etc.

Outliers
Anomalous instantaneous soiling ratios skew daily averages.

Angular Response
Data are less accurate when angles of incidence are larger.

Data are skewed across the solar noon window when modules aren't coplanar.

Clean Control
The clean module doesn't stay clean between maintenance events.

INSUFFICIENT IRRADIANCE

- Common irradiance threshold = 500 W/m^2
- Fixed thresholds are exceeded more often in summer than winter, and more often in equatorial than polar locations

  Limited irradiance = limited data
- Dynamic threshold, based on the modeled extraterrestrial GHI value (ETR):

G > Max(200 W/m^2, 50% ETR)

- G is the effective irradiance measured by the clean module
- G should be greater than 50% of ETR.
- Hard lower limit of 200 W/m^2 for extreme north/south locations

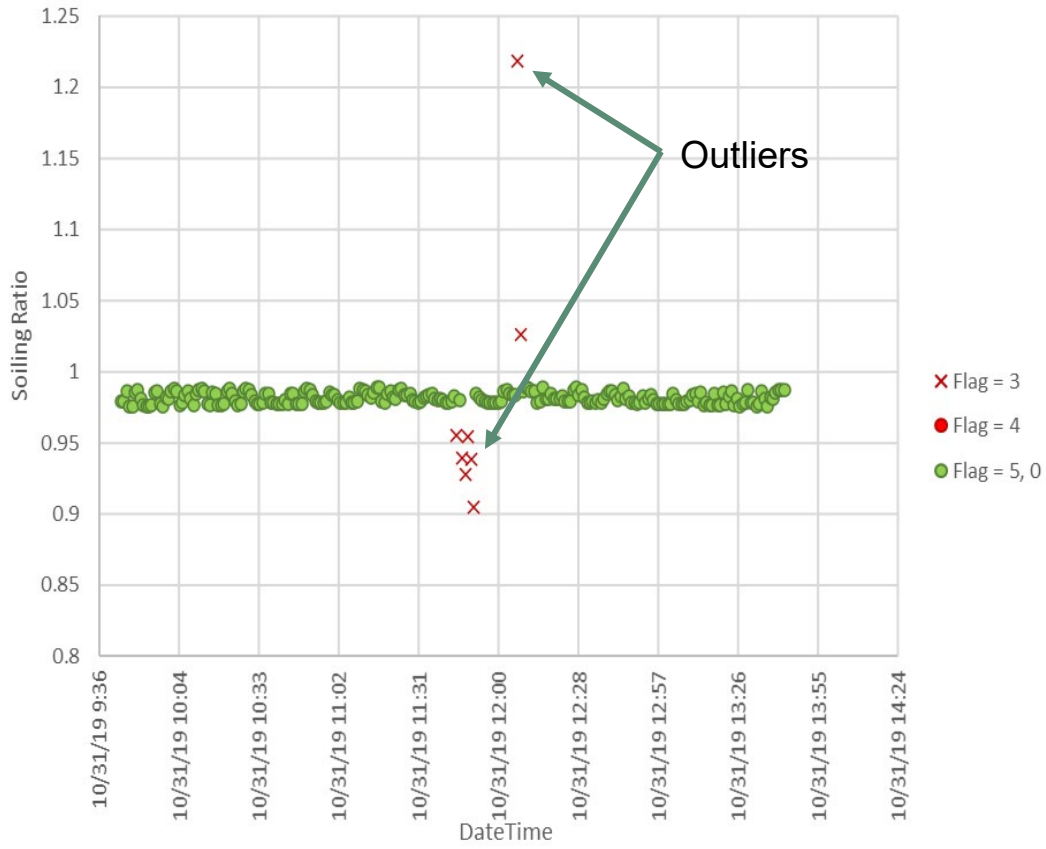
INHERENT NOISE AND OUTLIERS - INTRA-DAY VARIABILITY

Consider each day independently:

P50 – 2(P50 – P5) < SRatio < P50 + 2*(P95 – P50)*

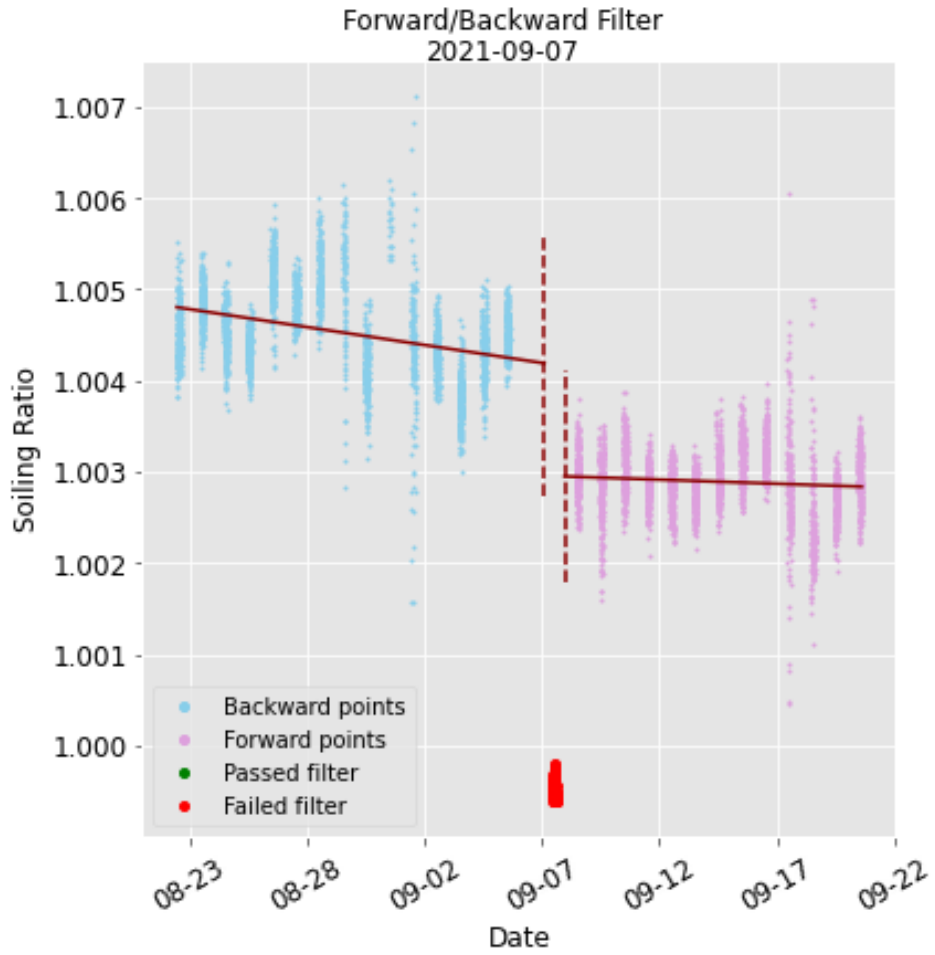
- Find the P5, P95, and median (P50) soiling ratio values
- Remove points that are less than twice the distance from the median to the P5
- Remove points that are more than twice the distance from the median to the P95

Remove outliers within the day

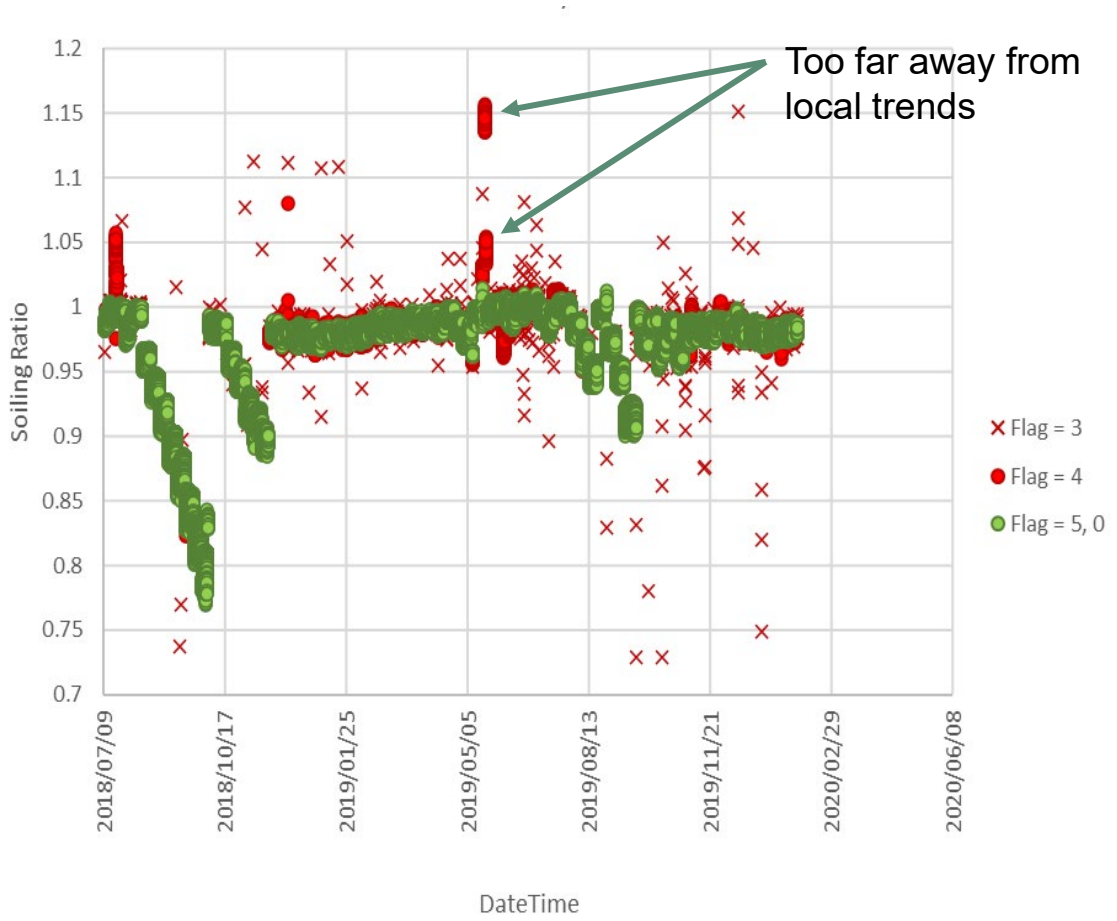


INHERENT NOISE AND OUTLIERS - INTER-DAY VARIABILITY

Trend should be continuous forward or backward



Soiling ratio should change slowly from day to day



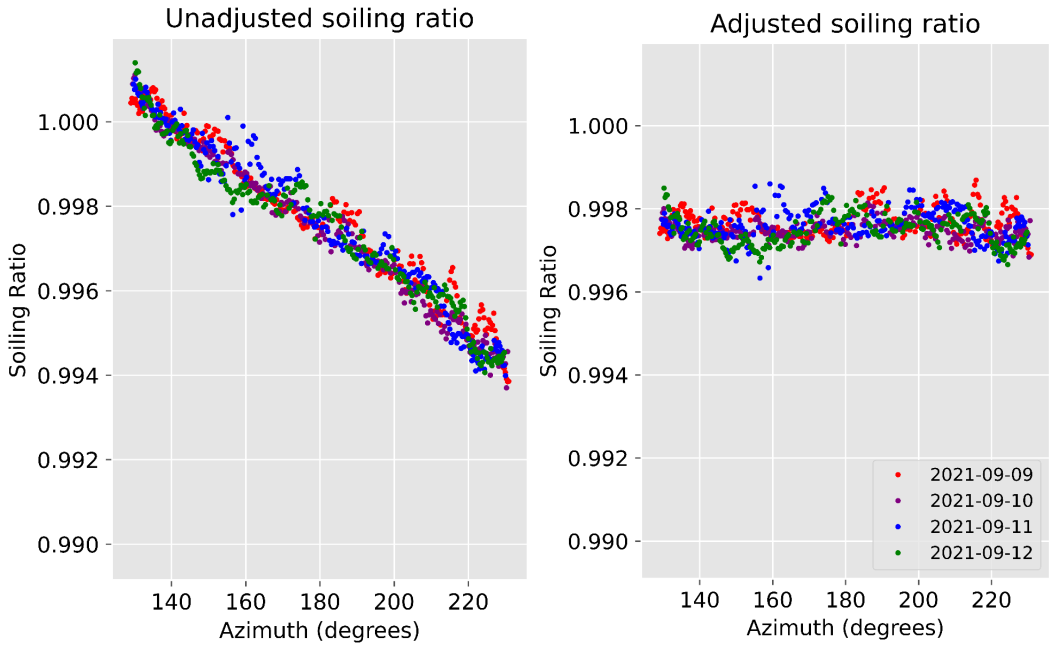
ANGULAR RESPONSE - MODULE MISALIGNMENT

Soiled Module Tilted To East

- Morning:
  - Larger Isc soiled
  - Larger soiling ratio
- Afternoon:
  - Smaller Isc soiled
  - Smaller soiling ratio
- Soiling ratio continually decreases over the solar noon window

Flattening Adjustment

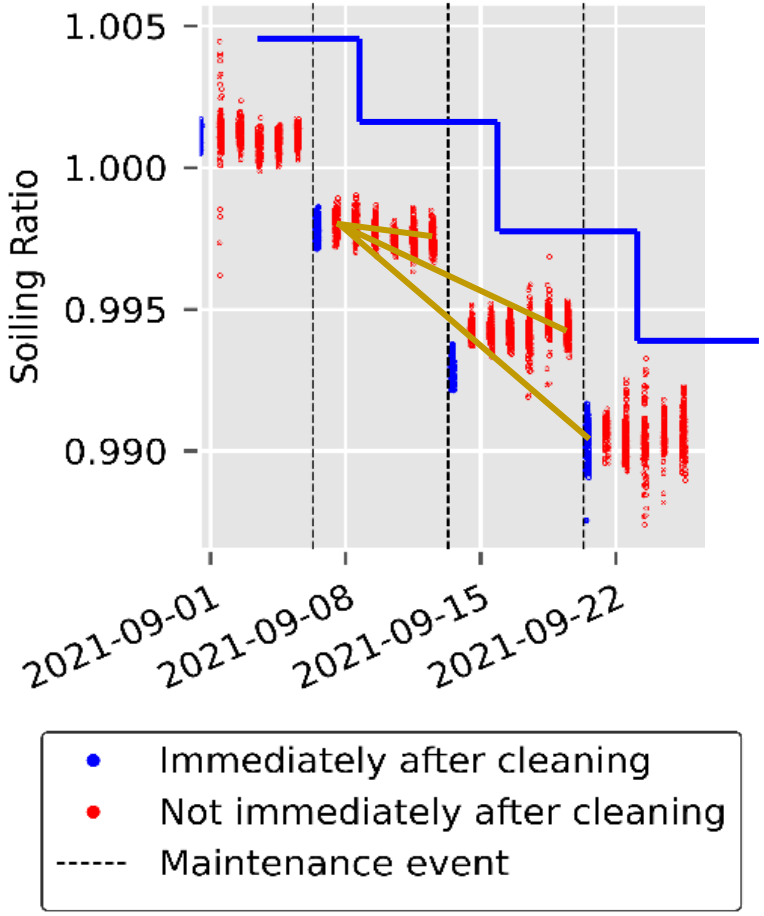
- Measured soiling ratios for a given day are adjusted to be more constant over the solar noon window
- Noise is preserved
- Reduced overall spread in soiling ratios = Reduced uncertainty



CLEAN CONTROL

- Between maintenance visits the “Clean” module accumulates dust at the same rate as the “Soiled” module.
- Because both modules accumulate dust at the same rate, the soiling ratio remains constant.
- When the “Clean” module is no longer clean, the soiling ratio is invalid.
- Only data immediately after a cleaning event should be selected for analysis.

Select data immediately after cleaning event



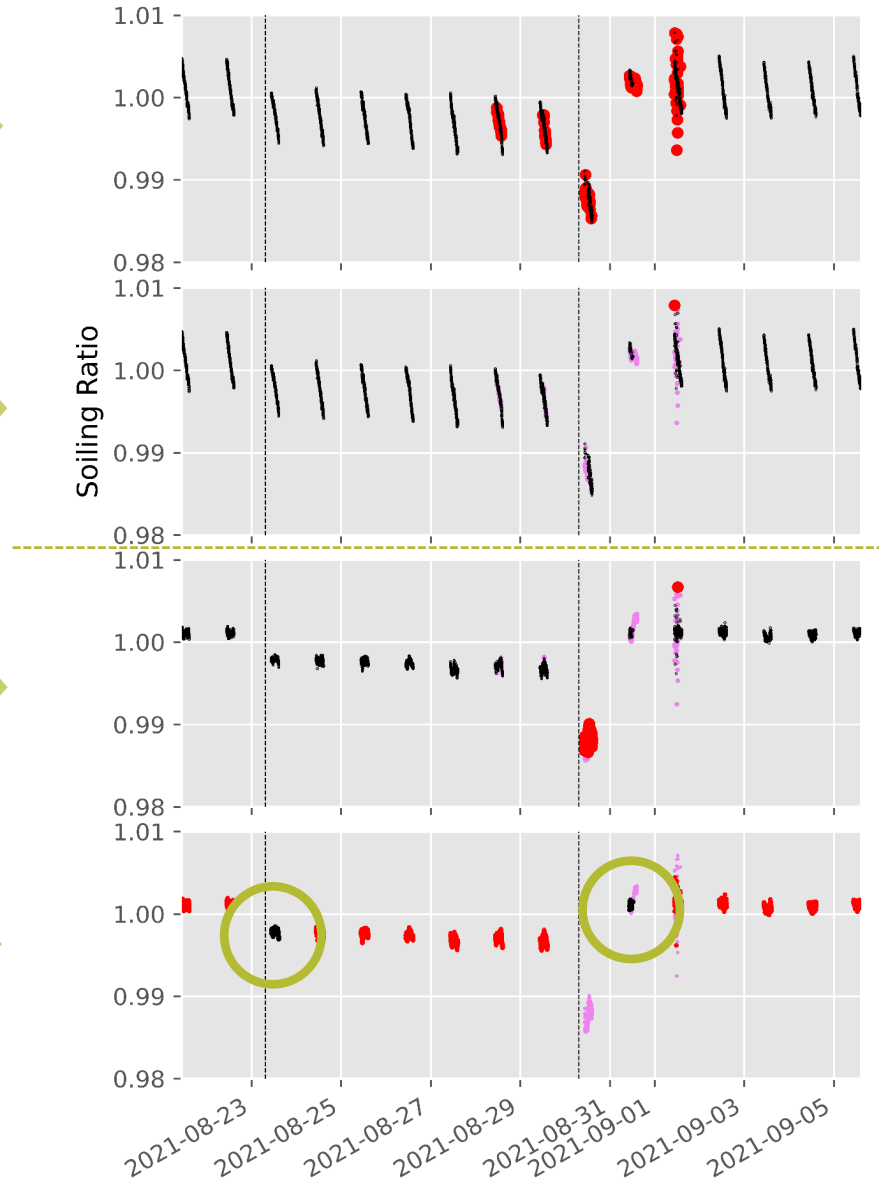
BENEFITS OF DATA FILTERING

Insufficient irradiance

Intra-day outliers

Inter-day outliers

Clean module clean?



Flattening adjustment

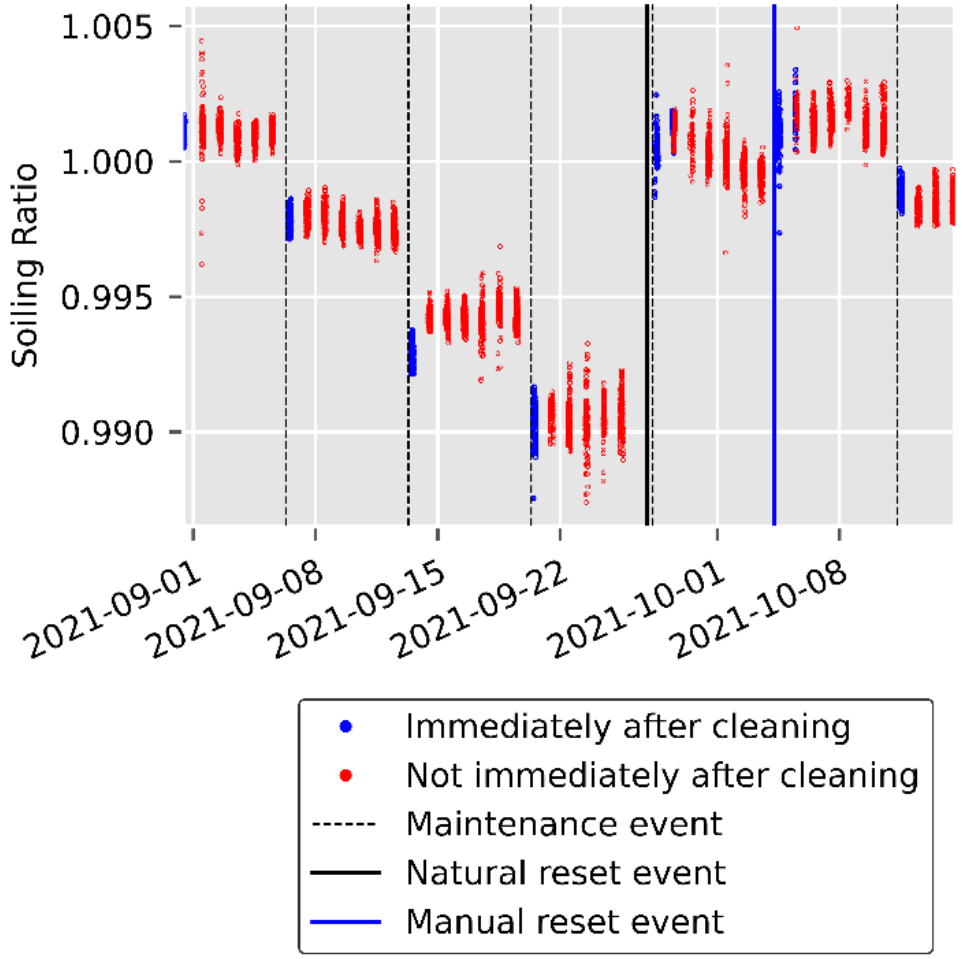
BREAKING THE DATA INTO SOILING PERIODS

Soiling periods are bracketed by reset cleaning events

- When the soiled module is cleaned, the soiling ratio jumps up. This resets the soiling period.

- Reset events may be manual or natural.
  - → Manual events are triggered by uncharacteristic localized soiling (e.g. bird droppings).
  - → Natural events include rain, wind and/or dew. Detected using the stochastic rate and recovery (SRR) method[1].

- When the soiled module is cleaned, the soiling ratio jumps up.



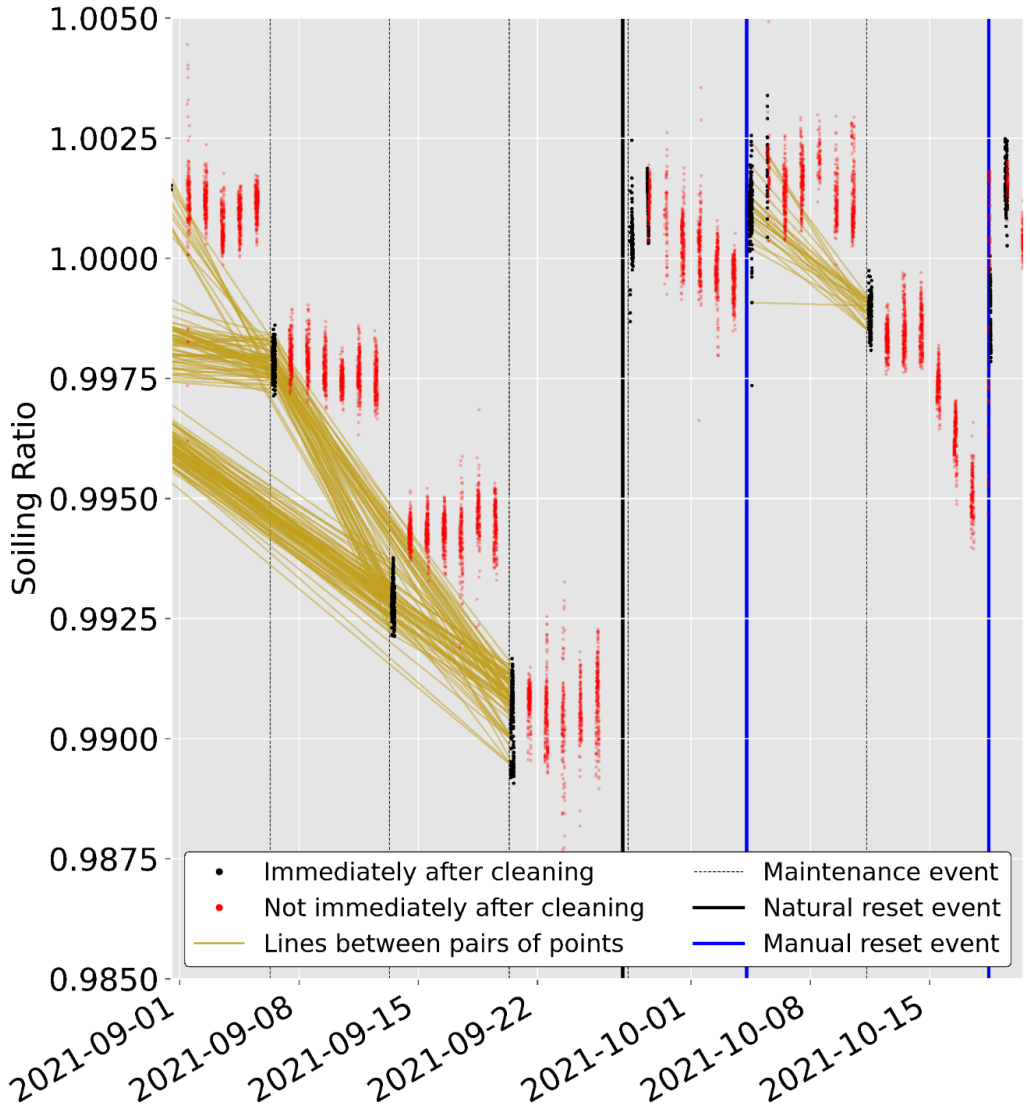
[1] Deceglie et al., 2018. *Quantifying soiling loss directly from PV yield.* IEEE Journal of Photovoltaics, 8(2), 547-551.

SOILING RATE DETERMINATION: SLOPES BETWEEN PAIRS OF POINTS

- The soiling rate between two points is the slope of the line connecting them.

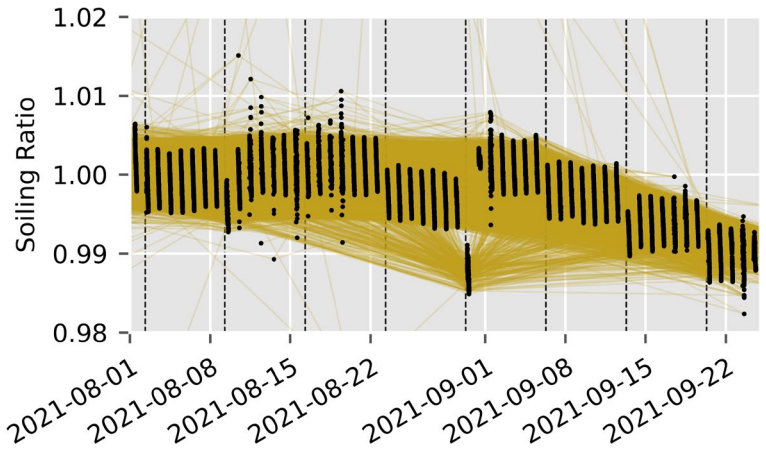
$$Soiling\ Rate = \frac{\Delta Soiling\ Ratio}{\Delta Time}$$

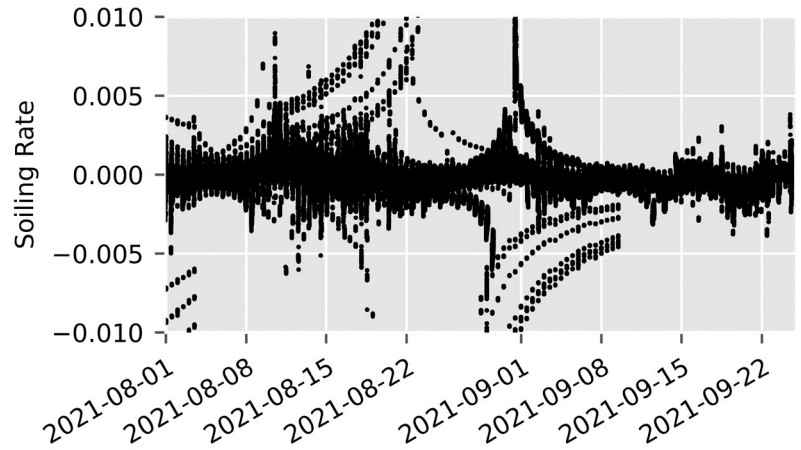
- Lines are drawn between all valid pairs of points and the corresponding slopes are computed.
  - → Pairs of points must fall within the same soiling period
  - → ~ 500K slopes/year with one-minute resolution data
- From the collection of slopes, the median soiling rate is determined for a given time period.
- An estimate of the soiling rate uncertainty is given by the range in the slope values for the specified time period.



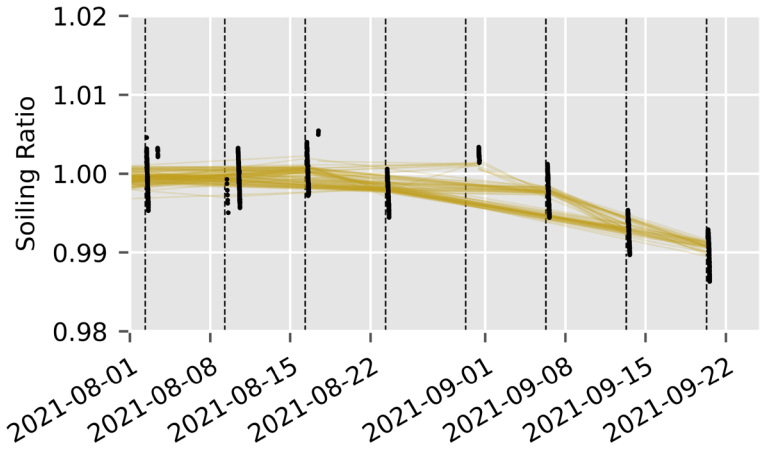
SOILING RATES WITH THE LOWEST POSSIBLE UNCERTAINTY

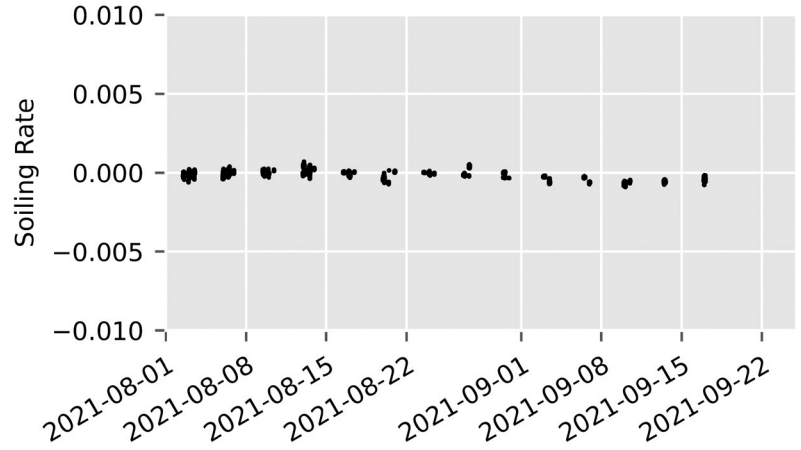
Proper filtering significantly improves the quality of soiling data.

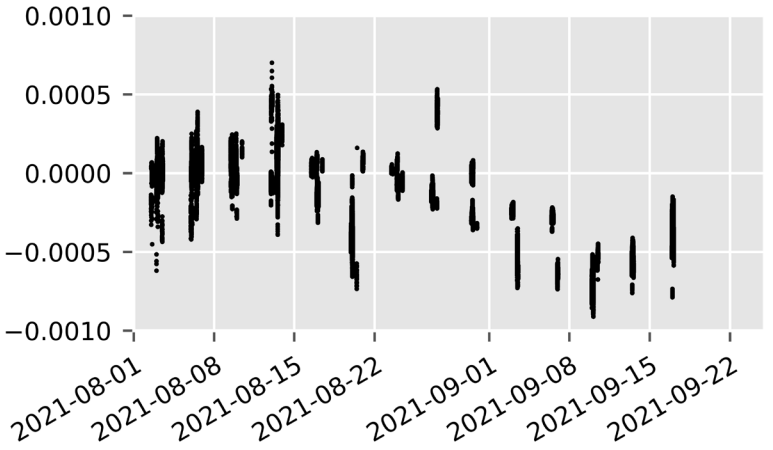




- Mean annualized soiling rate uncertainty for 32 GroundWork soiling measurement stations across the United States = 0.00083.







THANK YOU!

Q Questions?

A Contact me: jchard@grndwork.com