Measuring PV System Soiling Losses

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www.atonometrics.com

About Atonometrics

- **Test & measurement** equipment for the PV industry
- A leader in **soiling measurement systems**
- Provided **500 soiling stations** worldwide on **100 sites**
- Founded in 2007 and based in Austin, Texas, USA
- **Patents:** 5 issued, 6 pending

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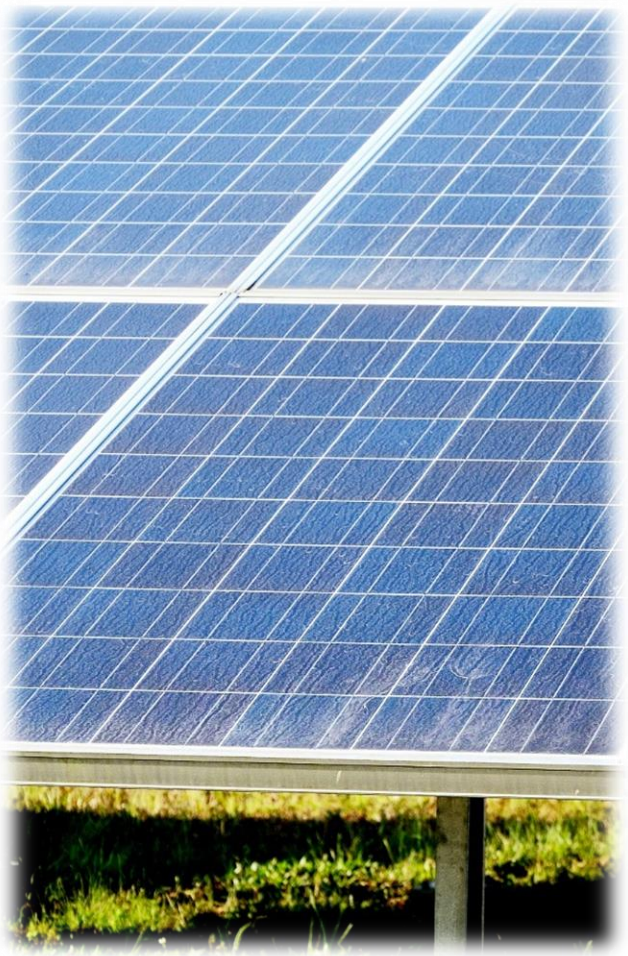
Why Measure Soiling?

Pre-construction site surveys:

1. **Predict** future plant performance

Operating PV plants:

2. **Assess** actual performance
3. **Optimize** washing schedule Return on Investment



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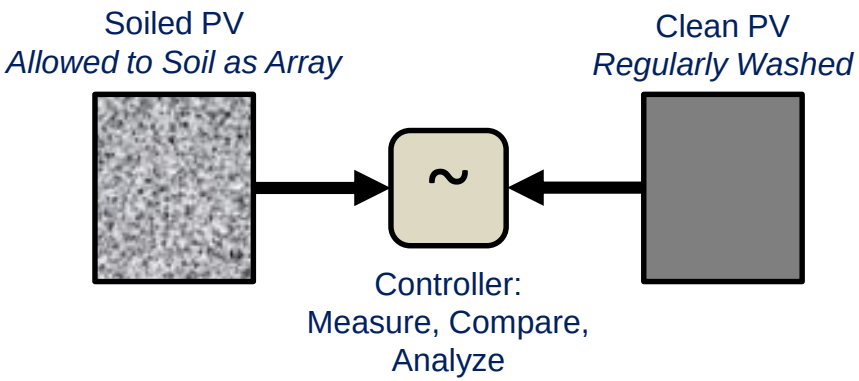
Basic Soiling Measurement Principle



$$\text{Soiling Ratio} = \frac{\text{Actual Output of Soiled PV}}{\text{Expected Output Based on Clean PV}}$$

$$\text{Soiling Loss} = SL = 1 - SR$$

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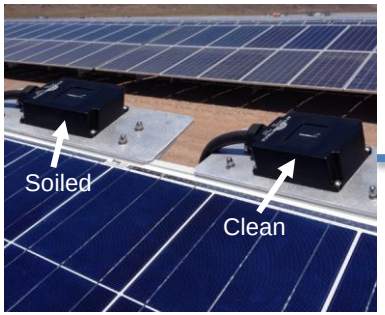
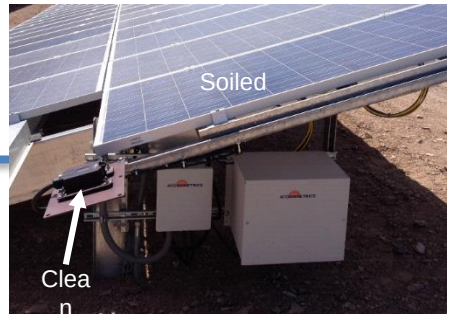
Many Configurations – Cost / Accuracy



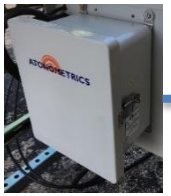
Cell-Cell

Module-Module



Cell-Module

Isc Only ——— **IV Curve and Pmax**



Measurement Only
Manual Wash

Measurement
+ Automatic Wash

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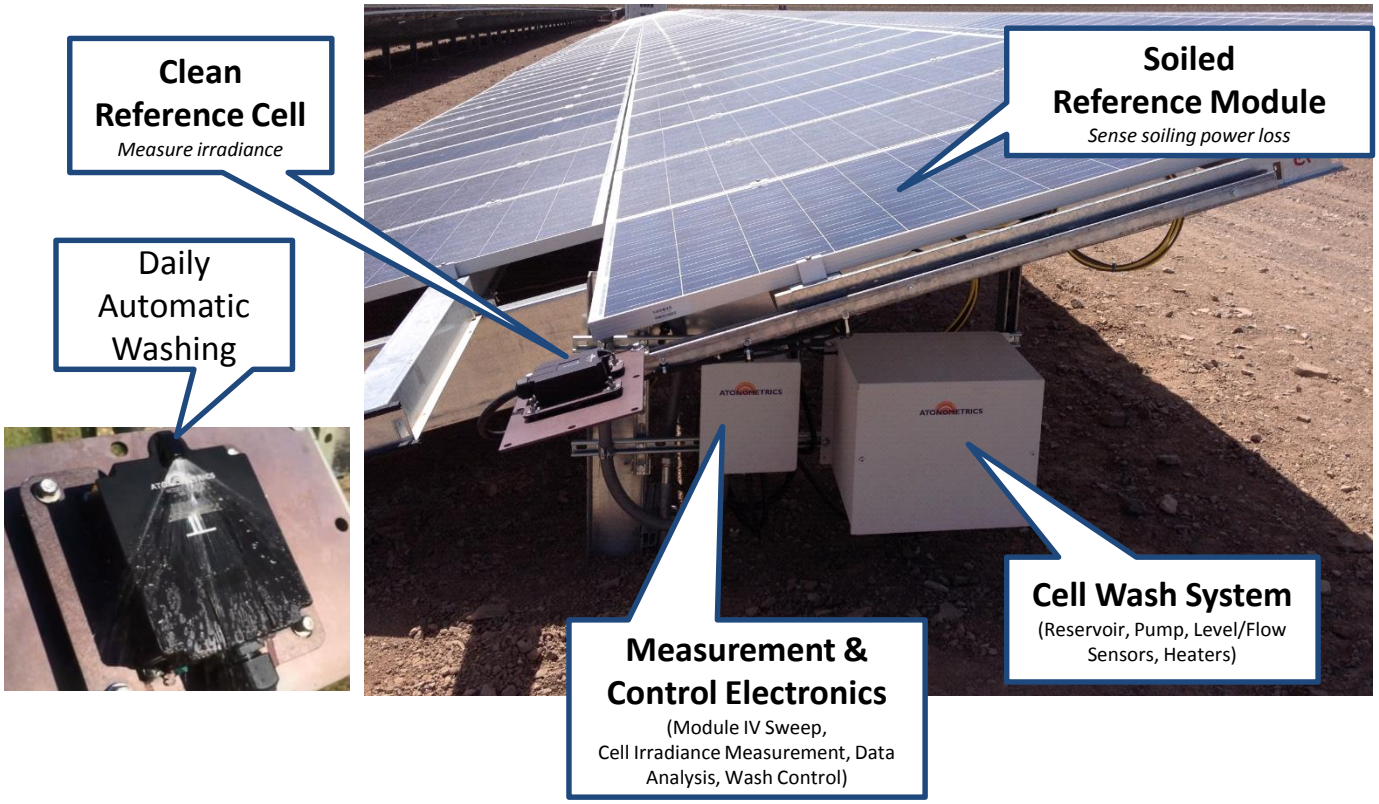
Example: Cell-Module, with I-V, & Auto Wash



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Example: On Tracking Array

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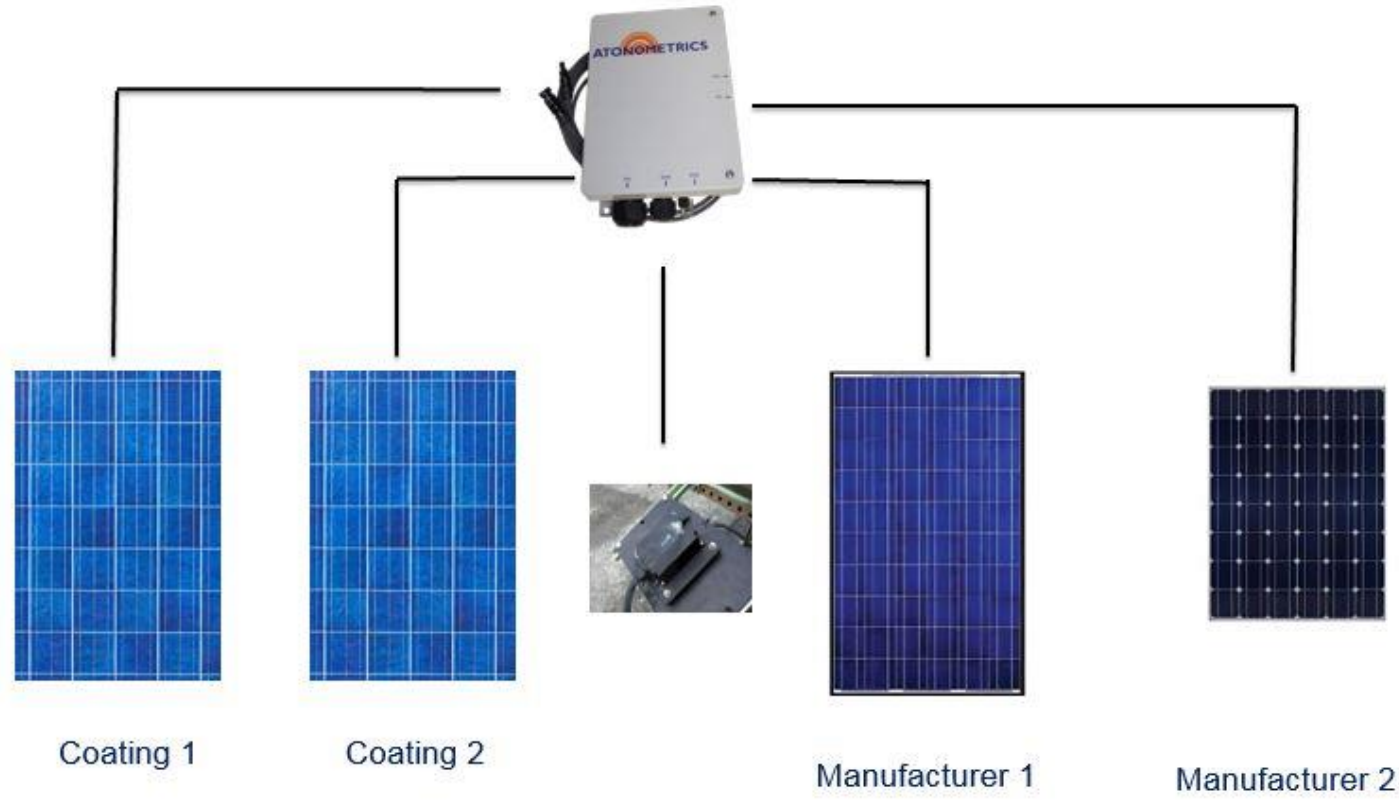
Example: Comparing Modules (Coatings, manufacturers, etc)



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Data Output

- **Raw Data**
  - Current
  - Voltage
  - Power
  - IV Curves
  - Temperature (RTD)
- **Analyzed Data**
  - Soiling
  - Irradiance (from a calibrated device)
  - Temperature (Voc)

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Choices: Cell or Module?

Cell	• **Less rack space**
Module	• **Captures true soiling effect** • (Same glass, coatings, frames, wind, rain, etc.)

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Choices: Isc or Pmax ?

Isc **(Short-Circuit Current)**	• **Simple** to measure • But not always proportional to output power
Pmax **(Max Power)**	• **Tracks actual power output** of modules in array

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Choices: Manual or Automated Washing?

Manual	• Lower **up-front cost** • **Lower accuracy** from weekly or fewer washings
Automated	• Lower **ongoing labor cost** • **Better accuracy** from daily washings

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Uniform & Non-Uniform Soiling

- **Uniform**
  - Dust **uniformly** distributed across module

- **Non-Uniform**
  - Dust **concentrated** on specific parts of the module
  - Typically at module **bottoms or edges**
  - **Rain, condensation, gravity,** wind,…

F. Brill, "EnviroPolitics Blog: PSEG building solar farms--and not just in New Jersey," 16-Nov-2012.

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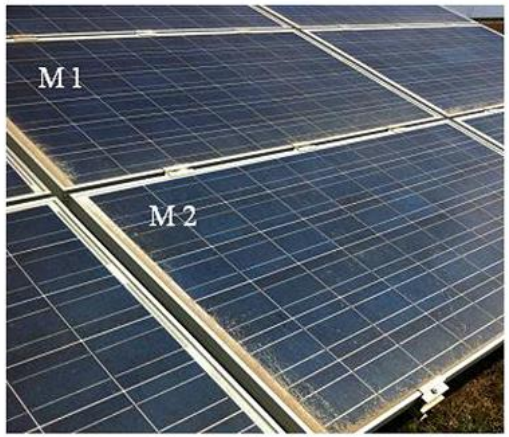
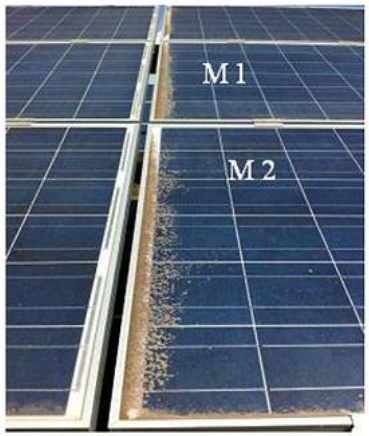
Non-Uniform Soiling





E. Lorenzo, R. Moretón, and I. Luque, Progress in Photovoltaics: Research and Applications, 2013.

F. Brill, "EnviroPolitics Blog: PSEG building solar farms--and not just in New Jersey," 16-Nov-2012.

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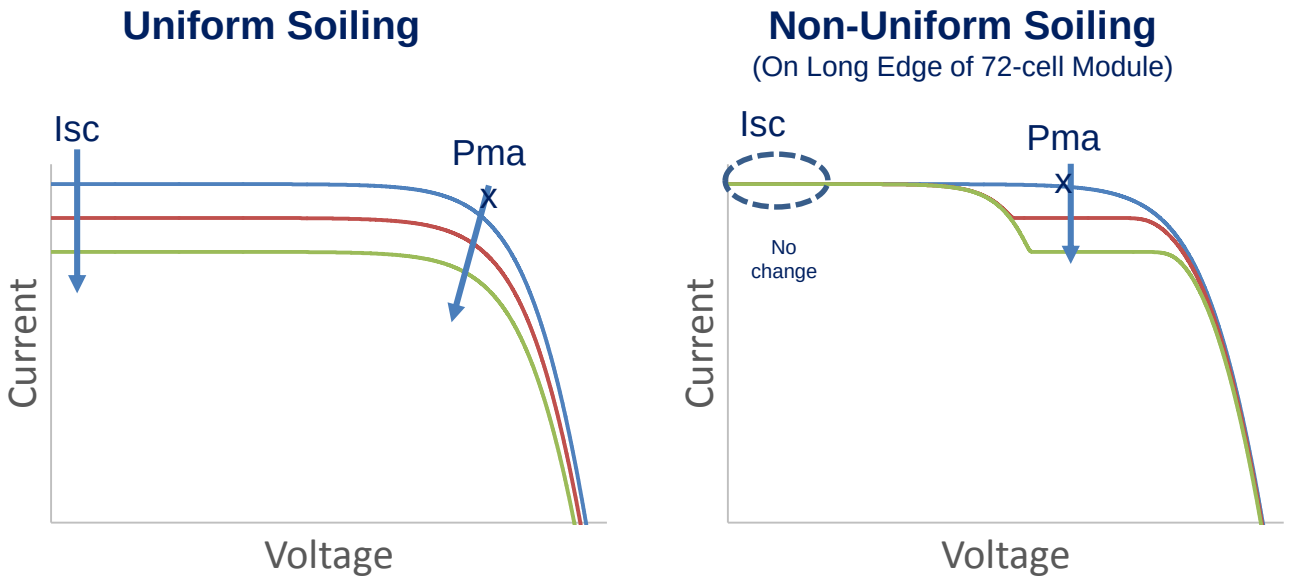
Uniform vs. Non-Uniform – Effect on IV Curve



For non-uniform soiling: **Isc may not track power loss**

→ **Pmax more accurate** for non-uniform cases

Gostein[1], Littmann[2], Caron[2], Dunn[1], IEEE PVSC 2013
[1]Atonometrics. [2]First Solar.

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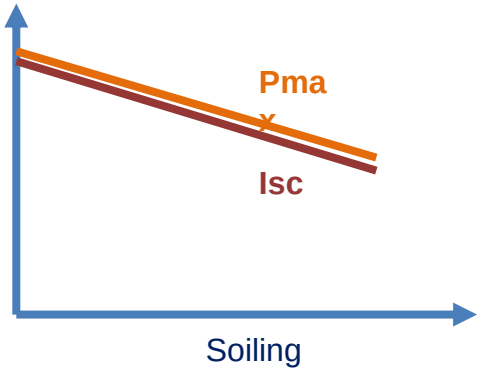
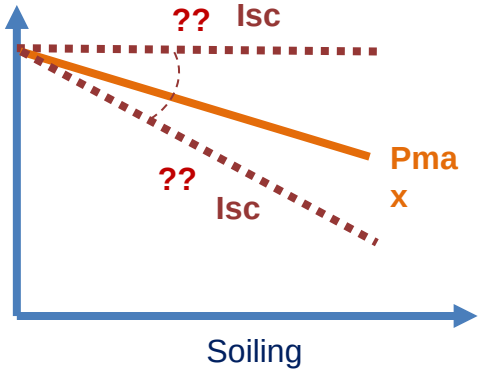
Uniform vs. Non-Uniform – Isc vs. Pmax

Uniform Soiling



Non-Uniform Soiling



Isc loss can **over- or under-predict** soiling, based on non-uniformity

→ **Pmax measurement more accurate** for non-uniform cases

Gostein[1], Littmann[2], Caron[2], Dunn[1], IEEE PVSC 2013
[1]Atonometrics. [2]First Solar.

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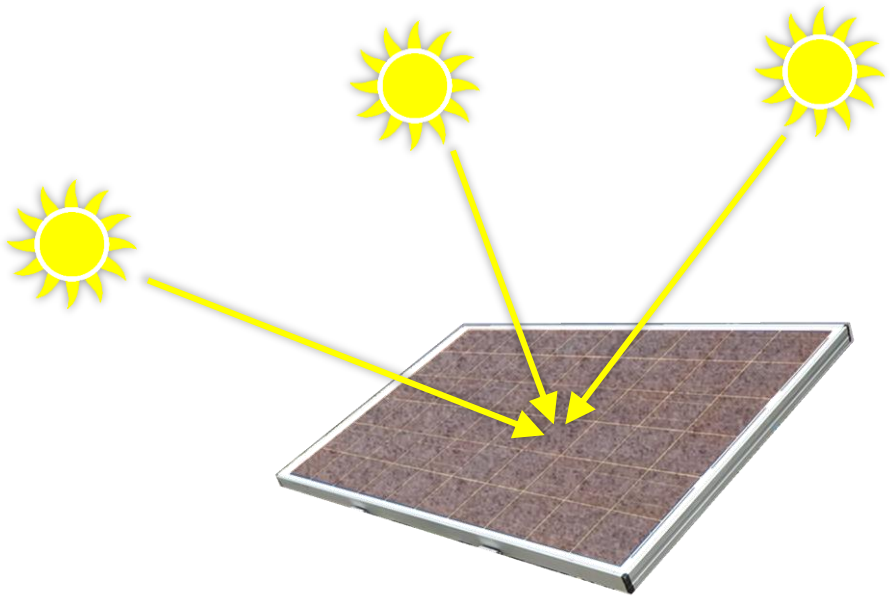
Incidence Angle Effect

Soiling loss can change by time of day



Soiling loss greater at **high incidence angles**

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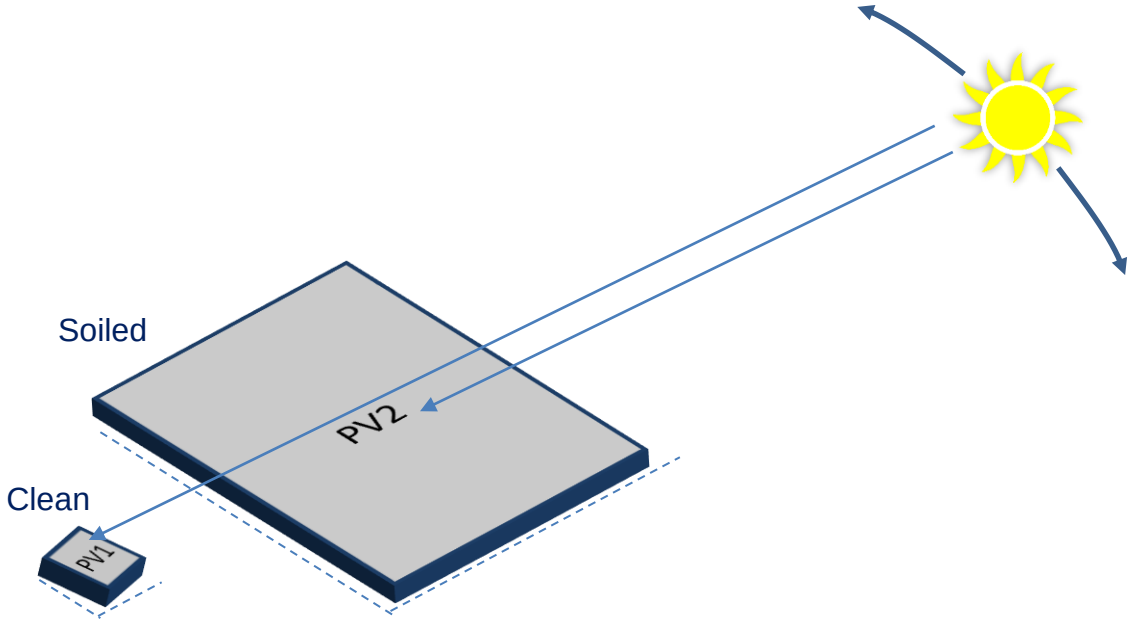
Misalignment Artifact



Misalignment (azimuth / tilt) causes measurement **artifact**
– apparent changes by time of day

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Analysis: Soiling Ratio Metric

Soiling Ratio, measured once per minute:

$$SR = \frac{Measured\ Output}{Expected\ Output}$$

Similar equation if using Isc instead of Pmax

$$SR = \frac{P_{max}^{soiled}}{P_{max,0}^{soiled} \cdot \left(1 + \gamma \cdot (T^{soiled} - T_0)\right) \cdot (G/G_0)}$$

Correct for temperature and irradiance

- $P_{max,0}^{soiled}$: STC power rating
- γ: Temp. coef.
- T_0: 25 °C
- G_0: 1000 W/m²
- G: Clean Device Irradiance

$$Soiling\ Loss = SL = 1 - SR$$

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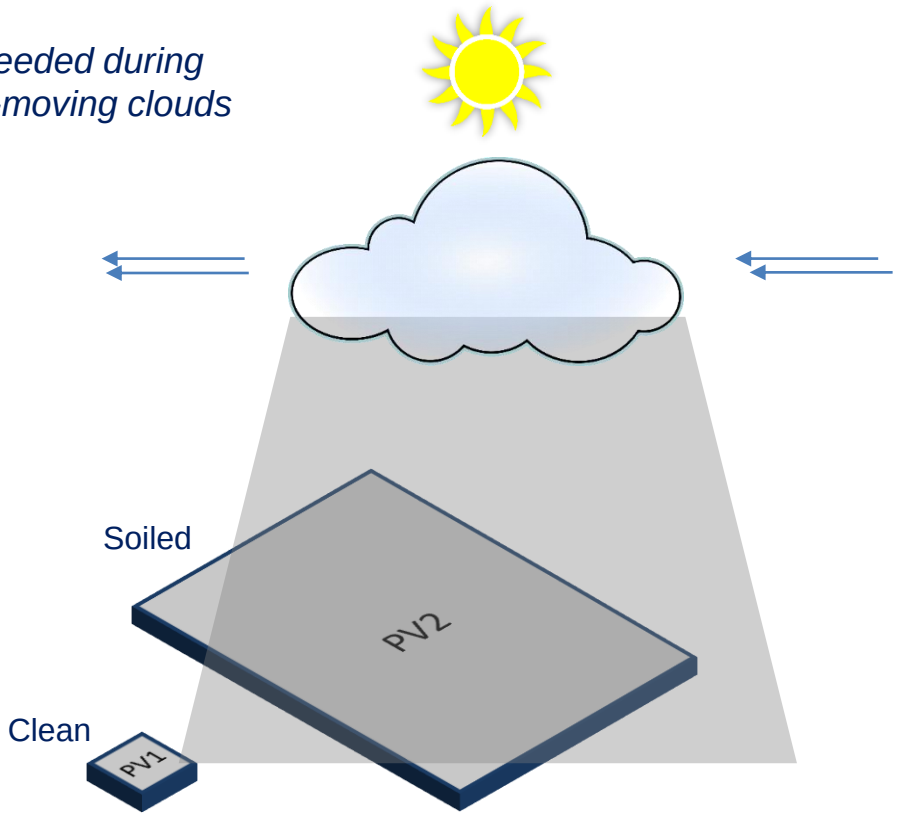
Irradiance Stability – Need Sophisticated Data Analysis

Data filtering needed during times with fast-moving clouds



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Analysis: Filtered Daily Average

Daily Irradiance-Weighted Average Soiling Ratio:

$$\langle SR \rangle_d = \frac{\sum SR \cdot G}{\sum G}$$

Correct for time-of-day variation

Filter points prior to average, to remove **outliers**

$$Soiling\ Loss = SL = 1 - SR$$

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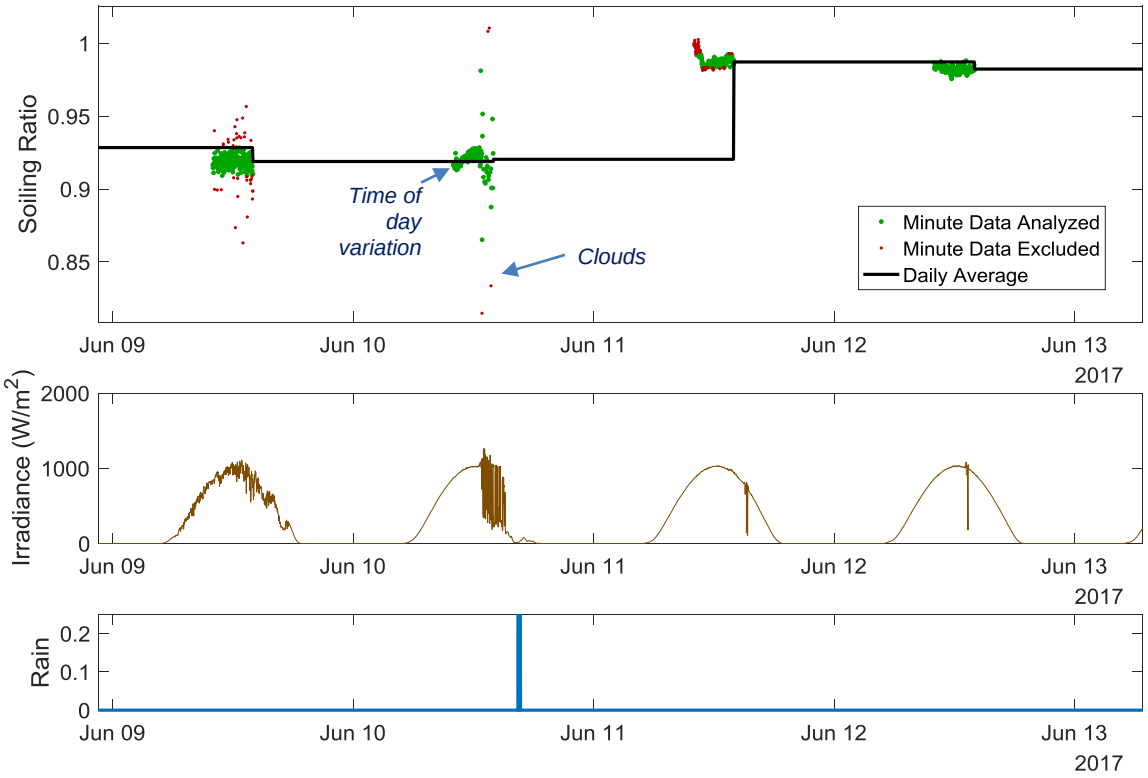
Analysis: Filtered Daily Average



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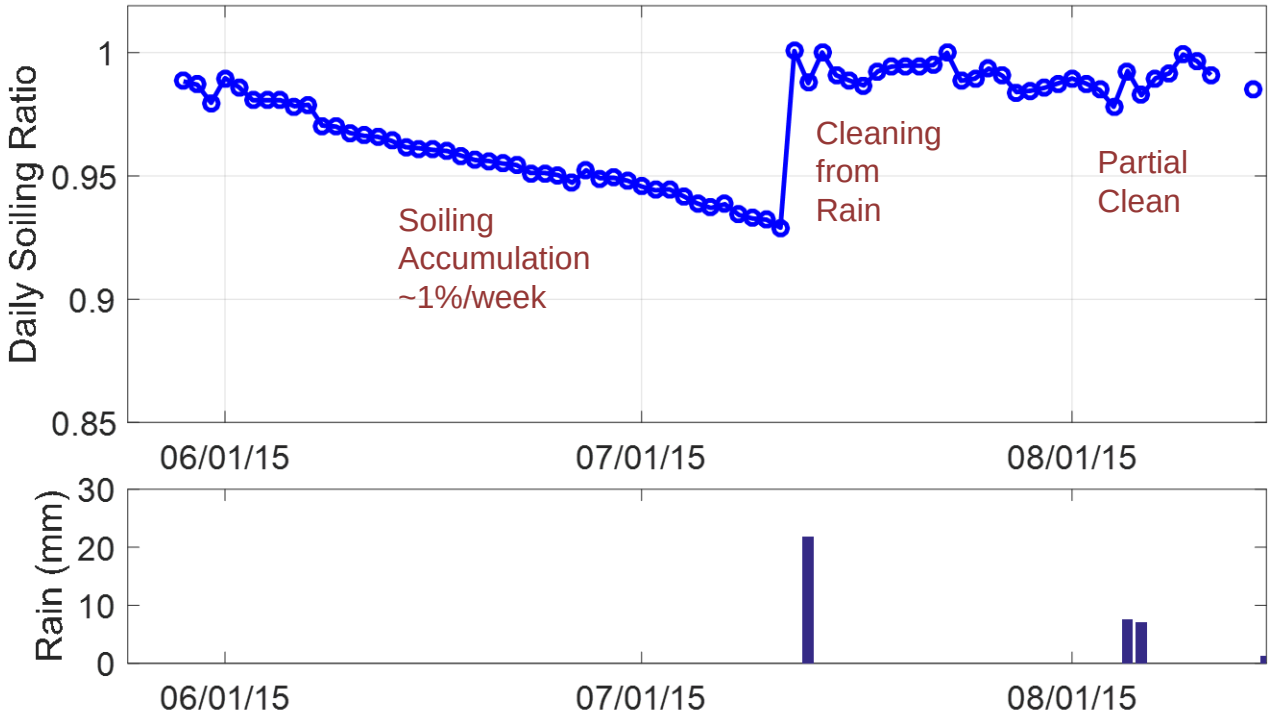
Typical Data Features



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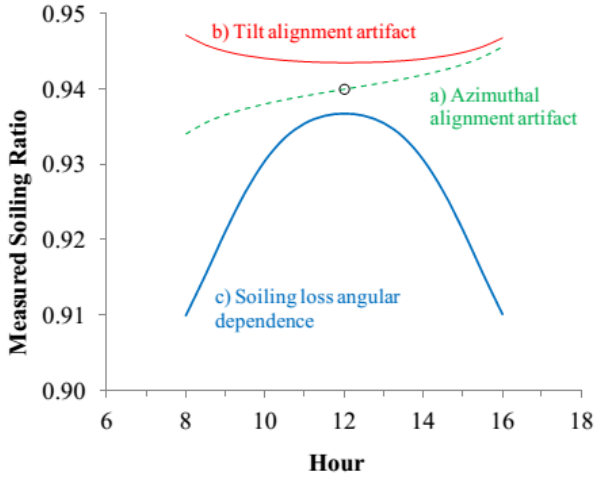
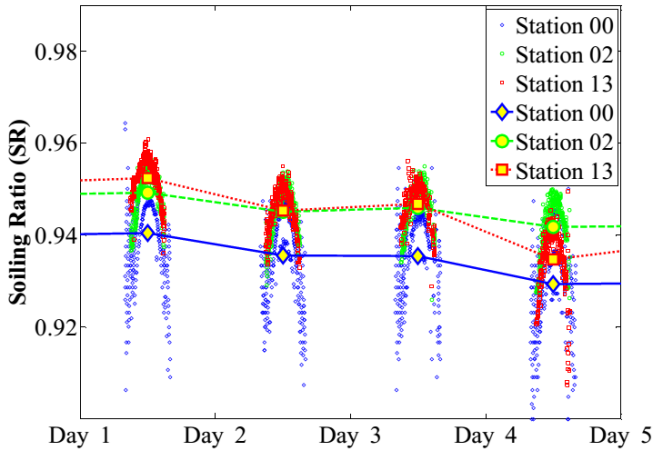
Incidence Angle & Alignment Effects





Gostein[1], Caron[2], Littmann[2], IEEE PVSC, 2014
[1]Atonometrics. [2]First Solar

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Long-Term Data Example – c-Si in U.S. Southwest

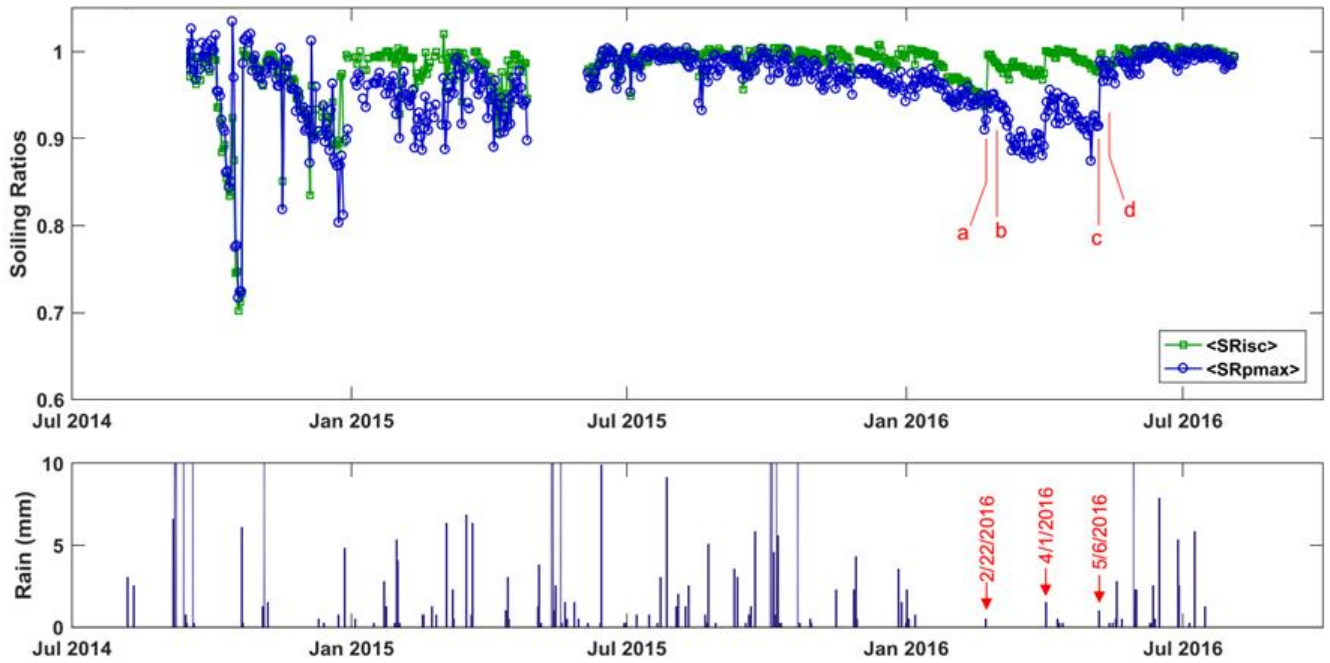

Fig. 2. Measured daily average values of the $SR^{I_{sc}}$ and $SR^{P_{max}}$ metrics (top) along with daily rainfall (bottom, y-axis limited to 10 mm) over a 24-month period. The four lettered arrows (a, b, c, d) indicate the days shown in the module photographs in Fig. 1.

Gostein[1], Stueve[1], Chan[2], 44th IEEE PVSC, 2017
[1]Atonometrics. [2]E-On Climate & Renewables

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Soiling Method Comparisons – Utility Scale Focus

System Type		Soiling Ratio Measurement Uncertainty
PV Configuration	Measured Parameter	
Cell-Module	Power	1-2%
Module-Module	Power	1-2%
Cell-Module	Current	3-5%
Module-Module	Current	3-5%
Cell-Cell	Current	4-7%

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Power Plant Correlation – 5 CdTe Plants Worldwide

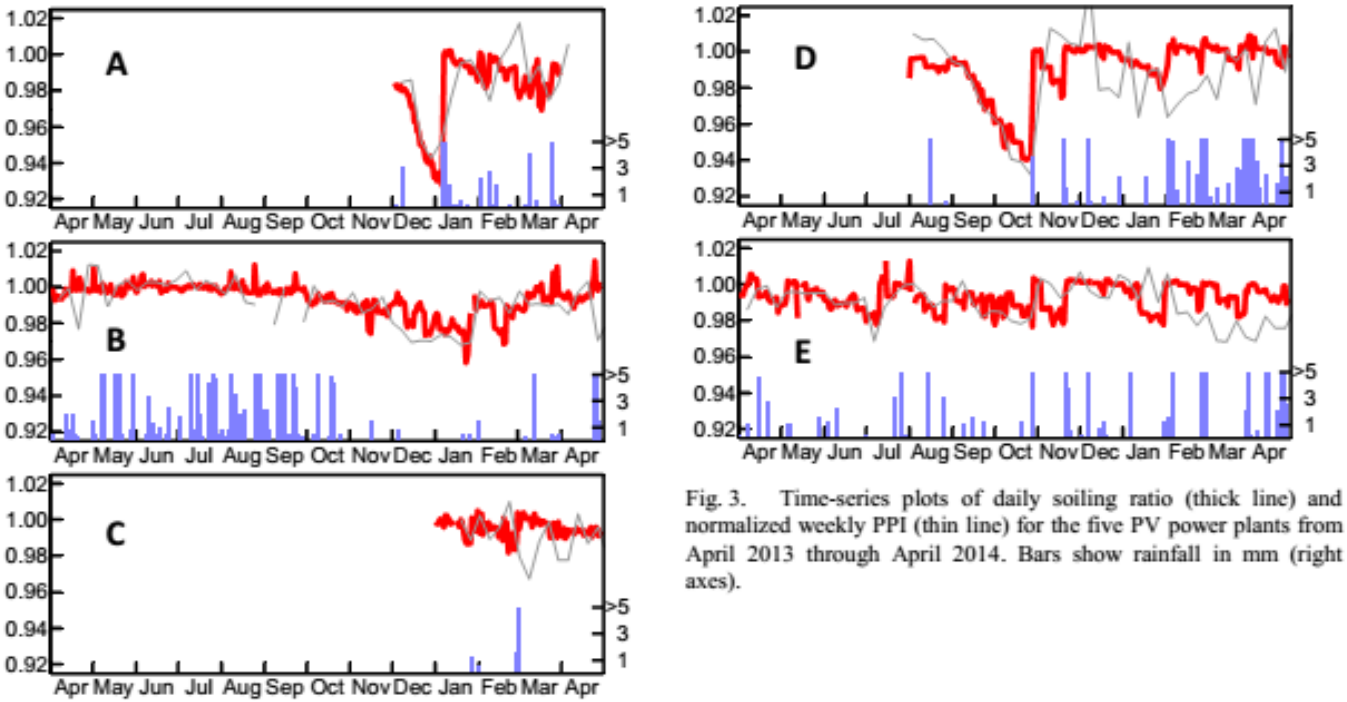

Fig. 3. Time-series plots of daily soiling ratio (thick line) and normalized weekly PPI (thin line) for the five PV power plants from April 2013 through April 2014. Bars show rainfall in mm (right axes).

Gostein[1], Caron[2], Littmann[2], IEEE PVSC, 2014
[1]Atonometrics. [2]First Solar

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Soiling Method Correlations – PV vs. Pyranometers

Fig. 1. Monitoring Station with SR20 (Left), LP02-1 (center), LP02-2 (right), self-cleaning reference cell (foreground), and reference module (back right)

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Soiling Method Correlations – PV vs. Pyranometers

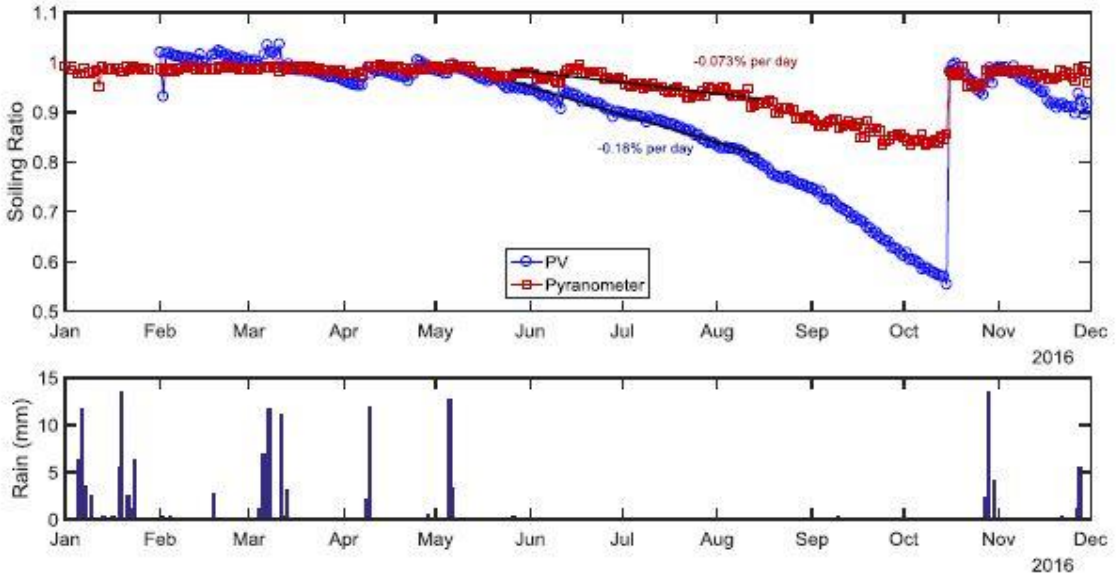

Fig. 2. Measured daily average values of the soiling ratios for the POA PV module and thermopile pyranometer and daily rainfall.

Waters[1], Tirumalai[1], Gostein[2], Stueve[2] IEEE PVSC, 2017
[1]Recurrent Energy, [2]Atonometrics

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Summary

- **Soiling measurements provide insight into plant performance**
- **Compare “soiled” reference to “clean” reference**
  - Note that modules/cells may soil differently
- **Wash the clean reference routinely**
- **Non-uniform soiling affects Isc & Pmax differently**
  - Measure both Isc & Pmax to get most complete information
- **Soiling loss measurement varies by time of day**
  - Perform daily average, filtering out cloud movements

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