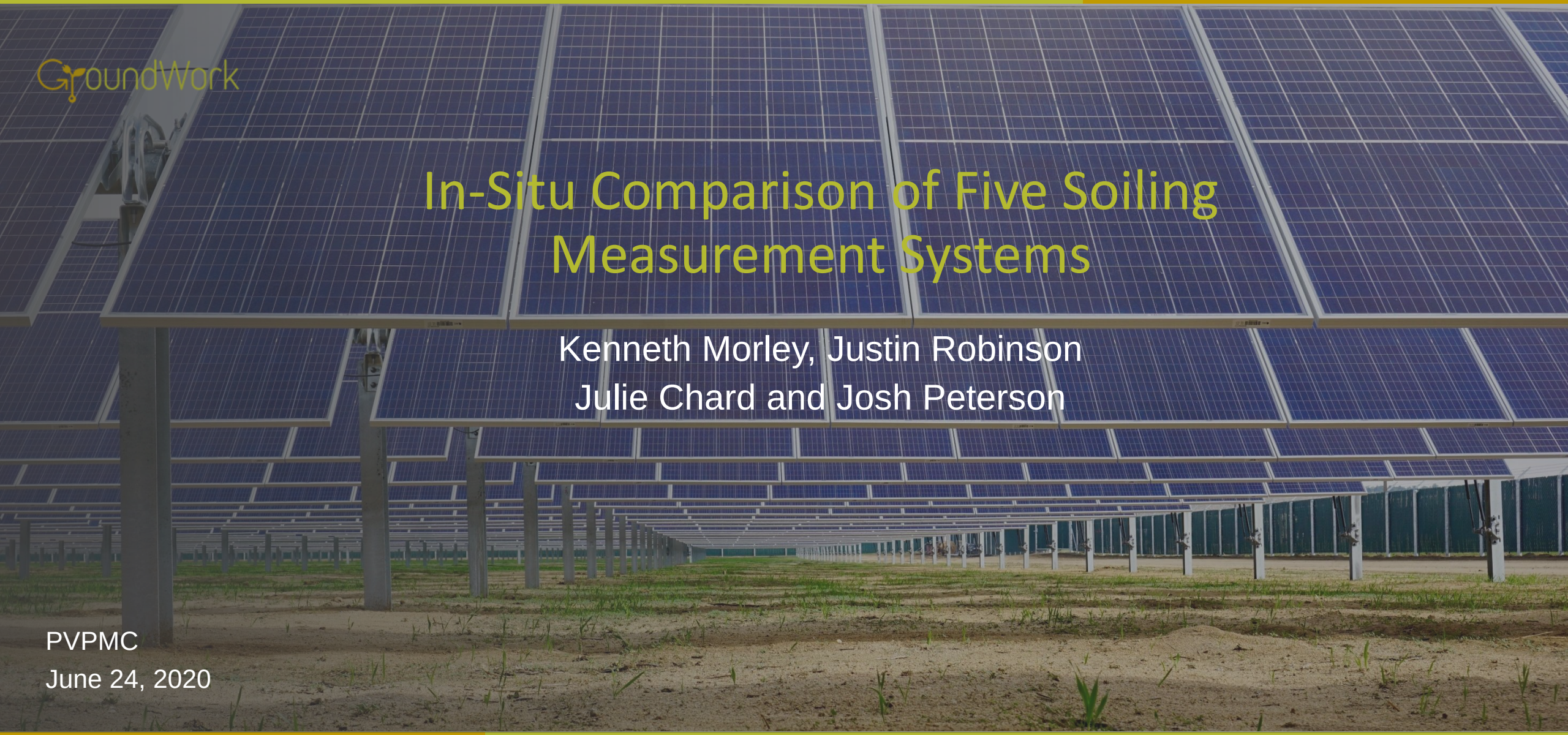


# In-Situ Comparison of Five Soiling Measurement Systems

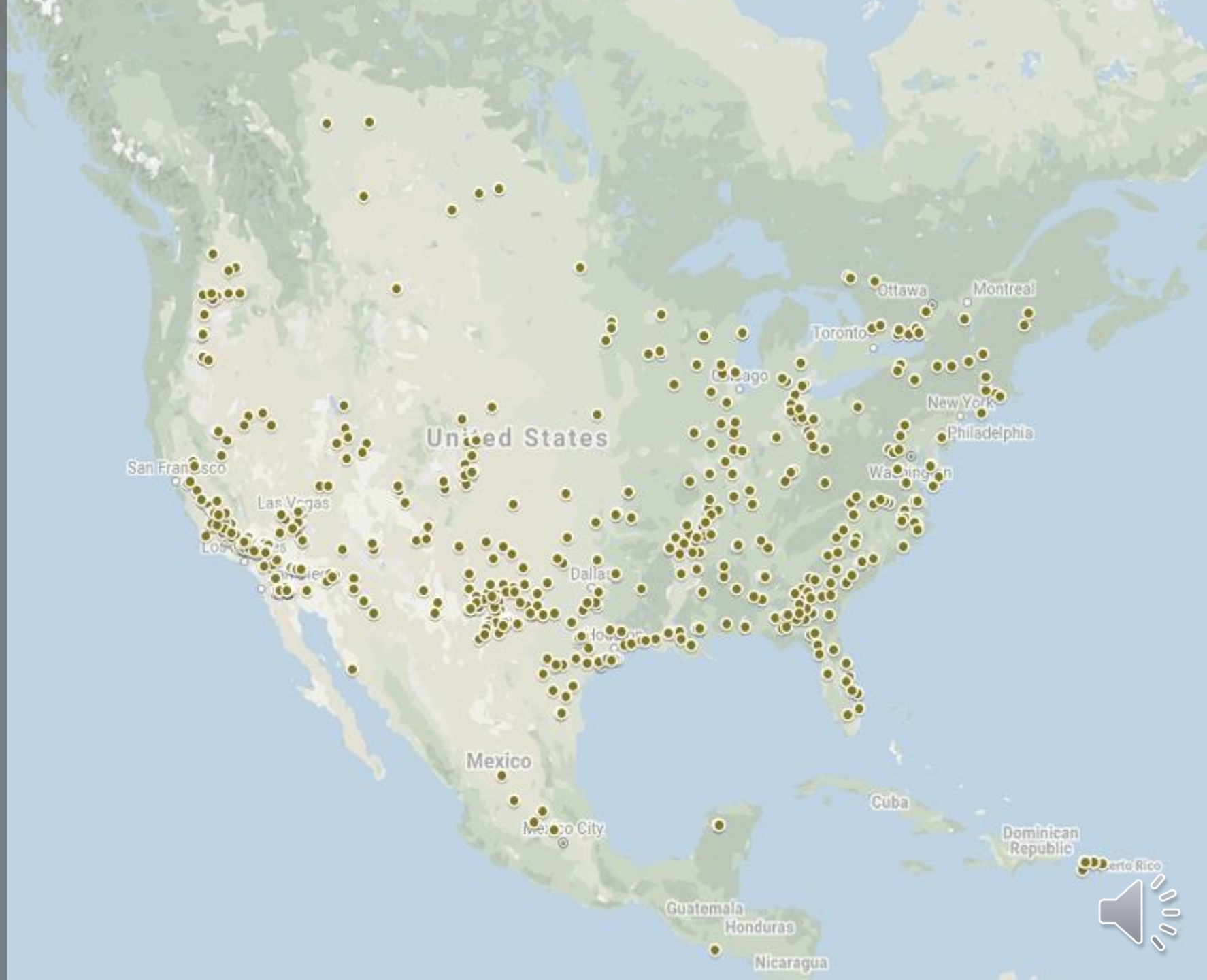
Kenneth Morley, Justin Robinson
Julie Chard and Josh Peterson

PVPMC
June 24, 2020

GroundWork

- Accelerate solar adoption by reducing solar resource uncertainty
- Solar industry leader for onsite reference measurements
- Contributed to over 25GW
- Early entrant working with NREL in 2008
- Outdoor R&D lab in operation since 2015
- US, Mexico, LatAM and Canada
- 39 staff + 140 technicians

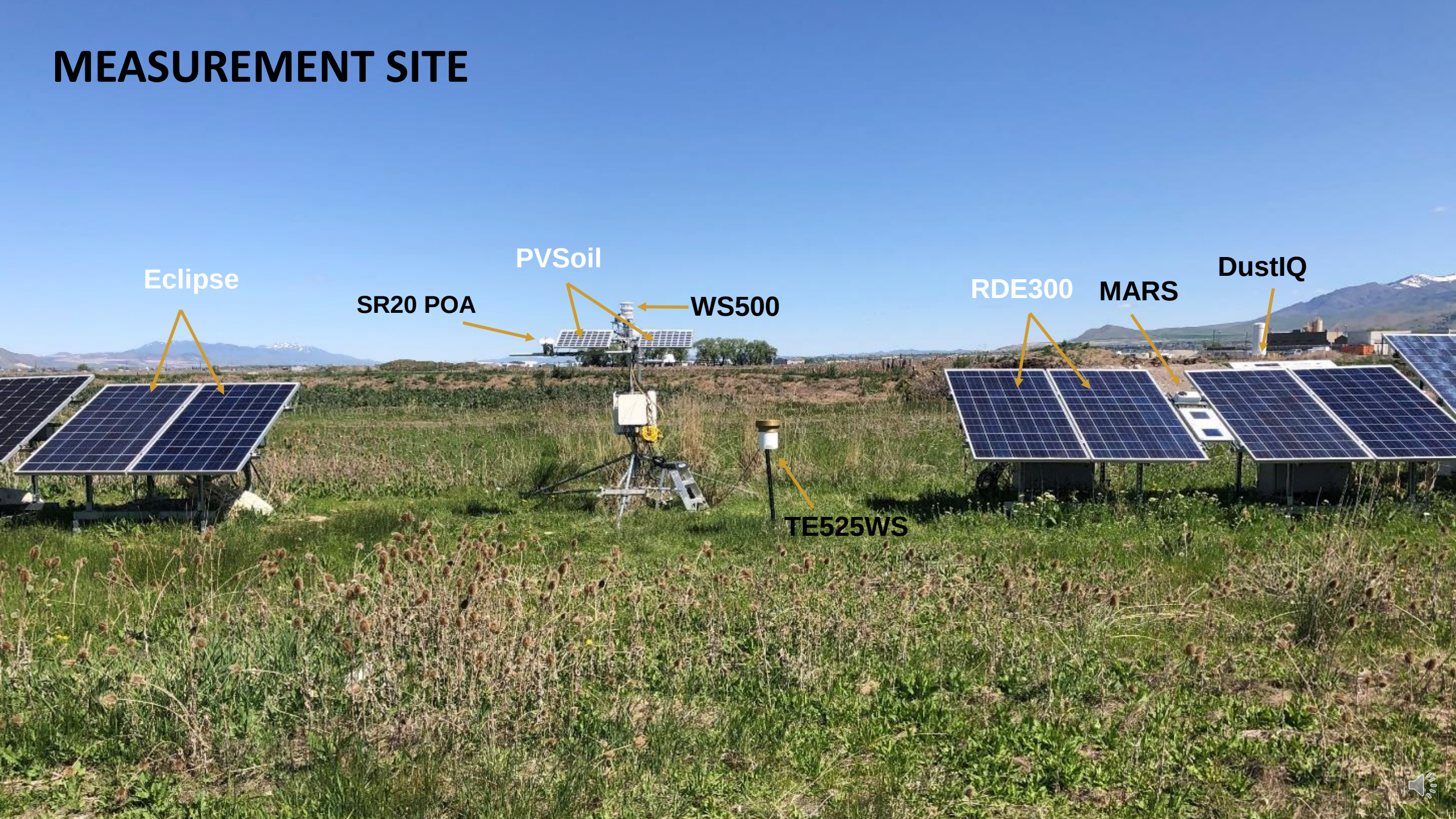




# PRESENTATION OUTLINE

- Introduce GroundWork Renewables (GR) R&D site
- Technology and data outputs
- GR soiling data processing methods
- Soiling measurement system data
- Next steps

# MEASUREMENT SITE



## SOILING MEASUREMENT DEVICES

| Device | Manufacturer | Method | Outputs | Measurement Rate | Data Collection Period |
|---|---|---|---|---|---|
| Eclipse | GroundWork | Short-circuit Current (Isc) | Isc, G, BOM Temp, SR, SLF | Three-second | May 2018 – May 2020 |
| PVSoil | GroundWork | Isc | Isc, G, BOM Temp, SR, SLF | Three-second | May 2018 – May 2020 |
| RDE300 | Atonometrics | Isc &<br>Max Power Point (MPP) | Isc, Voc, G, BOM Temp,<br>SR, $SR_{ISC}$, $SR_{Pmax}$ | One-minute | May 2018 – May 2020 |
| Mars | Atonometrics | Optical | TL, SR | Daily | May 2019 – May 2020 |
| Dust IQ | Kipp & Zonen | Optical | 2xTL, 2xSR, BOM Temp | Instantaneous | May 2019 – May 2020 |

## OTHER INSTRUMENTATION

| Sensor | Manufacturer | Measurement | Data Collection Period |
|---|---|---|---|
| SR20 | Hukseflux | Plane of Array Irradiance (26.5-degree tilt) | May 2018 – May 2020 |
| WS500 | Lufft | Wind speed & direction, ambient temperature, relative humidity, barometric pressure | May 2018 – May 2020 |
| TE525WS | Texas Instruments | Rainfall | May 2018 – May 2020 |

# MODULE-BASED SYSTEMS

## Eclipse

https://grndwork.com/eclipse-series-pv-soiling-measurement-system/

## PVSoil

https://grndwork.com/rey-series-secondary-standard-ghi-sms/

## RDE300

http://www.atonometrics.com/products/pv-power-plant-irradiance-measurement-system/

# OPTICAL SOILING SYSTEMS

## MARS


http://www.atonometrics.com/mars-optical-soiling-sensor-revolutionary-new-product/

## DustIQ


https://www.kippzonen.com/Product/419/DustIQ-Soiling-Monitoring-System#.Xu_28kVKhPY

# MEASUREMENT METHODS: PV MODULE-BASED SYSTEMS

- Two modules per measurement system: Clean and Soiled
- IEC 61724-1
  - Method 1 = Pmax
  - Method 2 = Isc
- Soiling ratio, *SR* = $\left(\frac{Soiled\ Module\ Output}{Clean\ Module\ Output}\right)$



*IEC 61724-1, "Photovoltaic system performance – Part 1: Monitoring," Edition 1.0, 2017-0*

# MEASUREMENT METHODS: OPTICAL SYSTEMS

- Measurements are based on transmission loss through a window due to the accumulation of soil
- Soiling ratio, *SR* = (*1 - Transmission Loss*)
- No regular cleaning
- The window should be cleaned (soiling system reset) when foreign substances block transmission

# METHODS

- Matched 72-cell modules
- Calibration or normalization was performed for all module-based systems
- Daily maintenance
  - Maintain clean module
  - Measure and log module angular displacement N/S & E/W
  - Reset as necessary
- All data aggregated on one logger to eliminate time offset issues

| 1. Maintenance Date | 2. Maintenance Time | Technician | 5. Comments | 6. Sky/Clouds | 7. Fence/Security | 8. Station Overview | 10. Lufft - Condition | 11. Rain Gauge - Condition | 12. POA SR20 - Condition Upon Arrival | 13. POA SR20 - Cleaned Dome | 14. POA SR20 - Bubble Position Upon Arrival | 15. POA SR2 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 5/8/2018 | 10:20:00 | Kenny Morley | | Scattered Clou | OK | OK | OK | OK | Dry - Light Dust | KJM | Is bubble centered over target (Horizontally leve | |
| 5/9/2018 | 13:51:00 | Kenny Morley | Installed CMP11 | Broken Clouds | | | | | | | | |
| 5/10/2018 | 11:08:00 | Kenny Morley | Late arriving due to morning rains | Overcast | NA | OK | OK | OK | Dry - Light Dust, Dry - Water Spots | KJM | Is bubble centered over target (Horizontally leve | |
| 5/14/2018 | 11:20:00 | Kenny Morley | | Scattered Clou | OK | OK | OK | OK | Dry - Light Dust | KJM | Is bubble centered over target (Horizontally leve | |
| 5/15/2018 | 10:35:00 | Kenny Morley | | Clear | NA | OK | OK | OK | Dry - Light Dust | KJM | Is bubble centered over target (Horizontally leve | |
| 5/16/2018 | 10:17:00 | Kenny Morley | | Clear | NA | OK | OK | OK | Clean/OK | KJM | Is bubble centered over target (Horizontally leve | |
| 5/17/2018 | 10:26:00 | Kenny Morley | | Clear | NA | OK | OK | Cleaned some cobwebs | Dry - Light Dust | KJM | Is bubble centered over target (Horizontally leve | |
| 5/18/2018 | 10:33:00 | Kenny Morley | | Overcast | NA | OK | OK | OK | Dry - Light Dust | KJM | Is bubble centered over target (Horizontally leve | |
| 5/21/2018 | 10:45:00 | Kenny Morley | | Clear | NA | OK | OK | OK | Dry - Light Dust | KJM | Is bubble centered over target (Horizontally leve | |
| 5/22/2018 | 10:43:00 | Kenny Morley | | Overcast | NA | OK | OK | OK | Dry - Light Dust | | Is bubble centered over target (Horizontally leve | |
| 5/23/2018 | 10:44:00 | Kenny Morley | | Broken Clouds | NA | OK | OK | OK | Clean/OK | KJM | Is bubble centered over target (Horizontally leve | |
| 5/24/2018 | 11:00:00 | Kenny Morley | | Clear | NA | | OK | OK | Dry - Light Dust | KJM | Is bubble centered over target (Horizontally leve | |
| 5/28/2018 | 11:00:00 | Kenny Morley | Reinstalling rde300 | Scattered Clou | NA | OK | OK | OK | Dry - Heavy Dust, Dry - Water Spots | KJM | Is bubble centered over target (Horizontally leve | |
| 5/29/2018 | 10:43:00 | Kenny Morley | | Scattered Clou | NA | OK | OK | OK | Wet, Dew | | Is bubble centered over target (Horizontally leve | |
| 5/30/2018 | 10:25:00 | Kenny Morley | | Scattered Clou | OK | OK | OK | OK | Dry - Light Dust | KJM | Is bubble centered over target (Horizontally leve | |
| 5/31/2018 | 10:48:00 | Kenny Morley | | Broken Clouds | OK | OK | OK | OK | Dry - Light Dust | KJM | Is bubble centered over target (Horizontally leve | |
| 6/1/2018 | 11:03:00 | Kenny Morley | | Broken Clouds | OK | OK | OK | OK | Dry - Light Dust | KJM | Is bubble centered over target (Horizontally leve | |
| 6/5/2018 | 10:43:00 | Kenny Morley | | Scattered Clou | OK | OK | OK | OK | Dry - Light Dust | KJM | Is bubble centered over target (Horizontally leve | |
| 6/6/2018 | 11:20:00 | Kenny Morley | | Scattered Clou | OK | OK | OK | OK | Dry - Light Dust | KJM | Is bubble centered over target (Horizontally leve | |
| 6/8/2018 | 11:43:00 | Kenny Morley | | Clear | OK | OK | OK | OK | Dry - Light Dust | KJM | Is bubble centered over target (Horizontally leve | |
| 6/11/2018 | 13:59:00 | Kenny Morley | | Clear | OK | OK | OK | OK | Dry - Light Dust | KJM | Is bubble centered over target (Horizontally leve | |
| 6/12/2018 | 11:04:00 | Kenny Morley | | Clear | OK | OK | OK | OK | Dry - Light Dust | KJM | Is bubble centered over target (Horizontally leve | |
| 6/13/2018 | 11:38:00 | Kenny Morley | | Clear | OK | OK | OK | OK | Clean/OK | KJM | Is bubble centered over target (Horizontally leve | |
| 6/14/2018 | 10:30:00 | Kenny Morley | Adding SMP10 back to station | Clear | OK | OK | OK | OK | Dry - Light Dust | KJM | Is bubble centered over target (Horizontally leve | |
| 6/15/2018 | 11:10:00 | Kenny Morley | | Scattered Clou | OK | OK | OK | OK | Dry - Light Dust | KJM | Is bubble centered over target (Horizontally leve | |
| 6/19/2018 | 0:18:00 | Kenny Morley | | Broken Clouds | OK | OK | OK | OK | Dry - Light Dust | KJM | Is bubble centered over target (Horizontally leve | |
| 6/20/2018 | 9:30:00 | Kenny Morley | Installed SPN1 experiment | Scattered Clou | OK | | OK | OK | Dry - Light Dust | KJM | Is bubble centered over target (Horizontally leve | |
| 6/21/2018 | 8:27:00 | Kenny Morley | | Scattered Clou | OK | OK | OK | OK | Dry - Light Dust | KJM | Is bubble centered over target (Horizontally leve | |
| 6/22/2018 | 10:02:00 | Kenny Morley | | Clear | OK | OK | OK | OK | Dry - Light Dust | KJM | Is bubble centered over target (Horizontally leve | |
| 6/25/2018 | 10:38:00 | Kenny Morley | | Clear | OK | OK | OK | OK | Dry - Light Dust | KJM | Is bubble centered over target (Horizontally leve | |
| 6/26/2018 | 11:08:00 | Kenny Morley | WS10 relocated previous day | Clear | OK | OK | OK | OK | Dry - Light Dust | KJM | Is bubble centered over target (Horizontally leve | |
| 6/27/2018 | 11:23:00 | Kenny Morley | | Clear | OK | OK | OK | OK | Dry - Light Dust | KJM | Is bubble centered over target (Horizontally leve | |
| 6/29/2018 | 12:10:00 | Justin Robinson | | Overcast | OK | Tall weeds lower ed | OK | OK | Clean/OK | JR | Is bubble centered over target (Horizontally leve | 26.3 husky |
| 7/2/2018 | 12:08:00 | Justin Robinso | Vegetation is starting to dry out and d | Clear | OK | OK | OK | OK | Dry - Light Dust | JR | Is bubble centered over target (Horizontally leve | |
| 7/5/2018 | 12:13:00 | Justin Robinson | | Scattered Clou | OK | OK | OK | OK | Dry - Light Dust, Dry - Dirty Water Spots | JR | Is bubble centered over target (Horizontally leve | |
| 7/6/2018 | 1:28:00 | Justin Robinso | Smoke haze from fires. | Scattered Clou | OK | OK | OK | OK | Dry - Light Dust | JR | Is bubble centered over target (Horizontally leve | |
| 7/9/2018 | 11:05:00 | Kenny Morley | Vegetation drying significantly | Scattered Clou | OK | OK | OK | OK | Dry - Light Dust | KJM | Is bubble centered over target (Horizontally leve | |
| 7/10/2018 | 11:26:00 | Kenny Morley | Quite a few wasps flying around. | Scattered Clou | OK | OK | OK | OK | Dry - Light Dust | KJM | Is bubble centered over target (Horizontally leve | |
| 7/11/2018 | 11:35:00 | Kenny Morley | | Scattered Clou | OK | Patch replacement | OK | OK | Dry - Light Dust | KJM | Is bubble centered over target (Horizontally leve | |
| 7/12/2018 | 11:10:00 | Kenny Morley | Modem overages. Shut down as of 0 | Scattered Clou | OK | OK | OK | OK | Dry - Light Dust | | Is bubble centered over target (Horizontally leve | |
| 7/16/2018 | 11:18:00 | Kenny Morley | Collecting data manually. Switched e | Broken Clouds | OK | OK | OK | OK | Dry - Light Dust | KJM | Is bubble centered over target (Horizontally leve | |
| 7/17/2018 | 11:20:00 | Kenny Morley | Added CMP11 | Clear | OK | OK | OK | OK | Dry - Light Dust | KJM | Is bubble centered over target (Horizontally leve | |

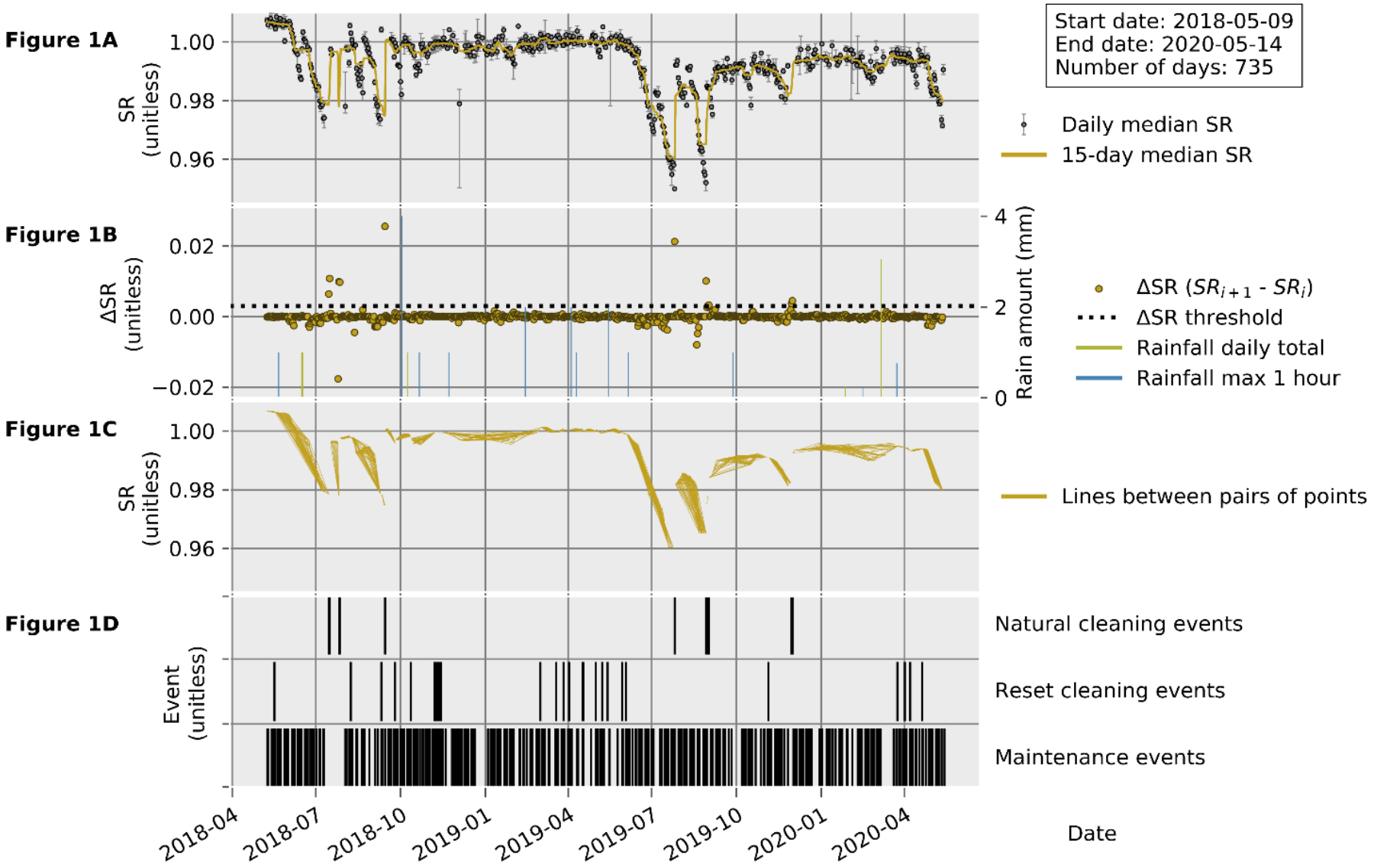
# DATA PROCESSING

- NREL Stochastic Rate and Recovery (SRR) Method*
  - Developed to quantify power loss due to PV degradation and soiling from PV yield data
  - Built into RdTools, an open source Python library for PV degradation analysis

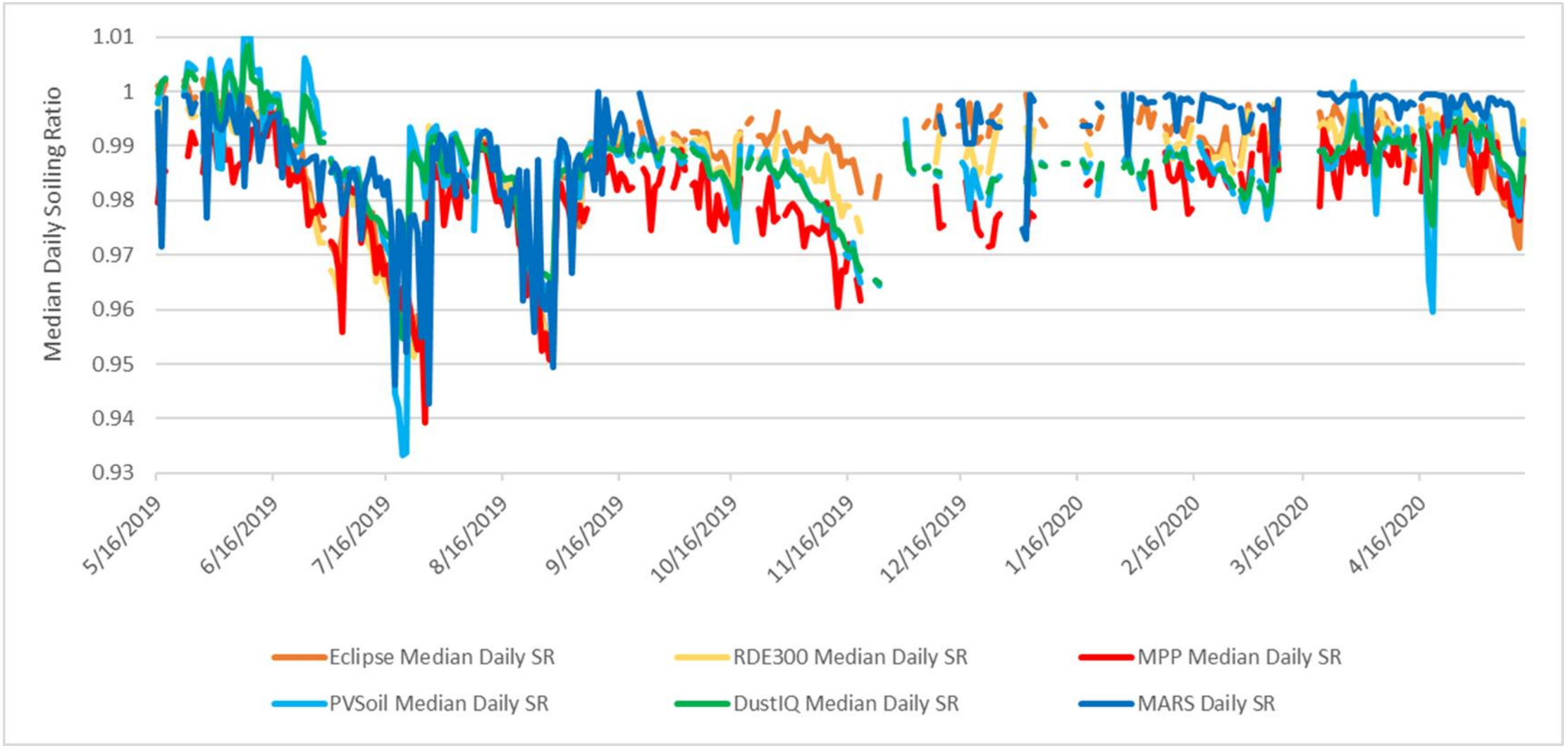
- GroundWork Data Processing Method
  - Rooted in the SRR method
  - Unique attributes of the GroundWork method:
    - Utilizes concurrent and co-located, ground-based irradiance measurements
    - “Turns the dials” to optimize the SRR method for soiling measurement system outputs
    - Sets a moving, site-specific and time-specific GHI irradiance threshold
    - Factors in soiling system reset events and overlays rain and regular maintenance events using high quality maintenance logs

*M. G. Deceglie, L. Micheli and M. Muller, "Quantifying Soiling Loss Directly From PV Yield," in IEEE Journal of Photovoltaics, vol. 8, no. 2, pp. 547-551, 2018-03*

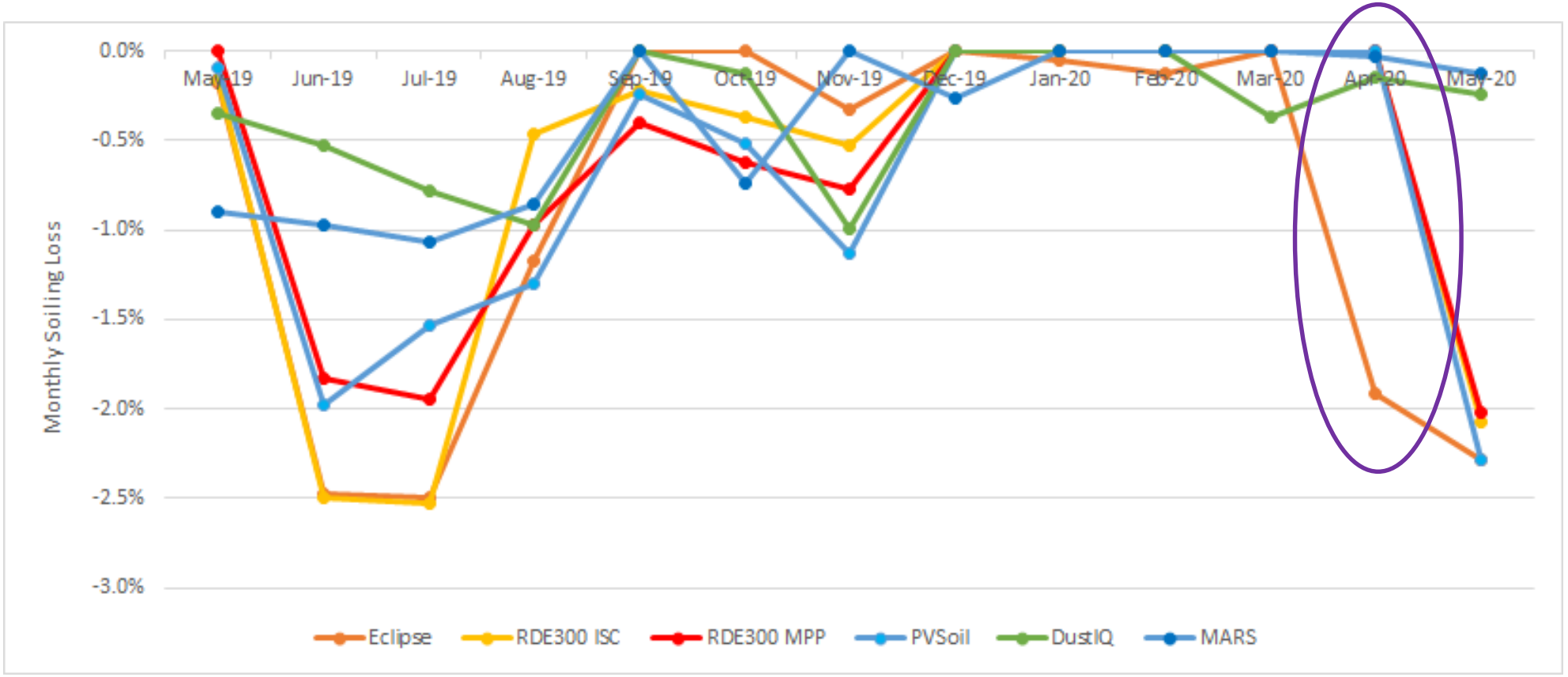
# GROUNDWORK DATA PROCESSING OUTPUT



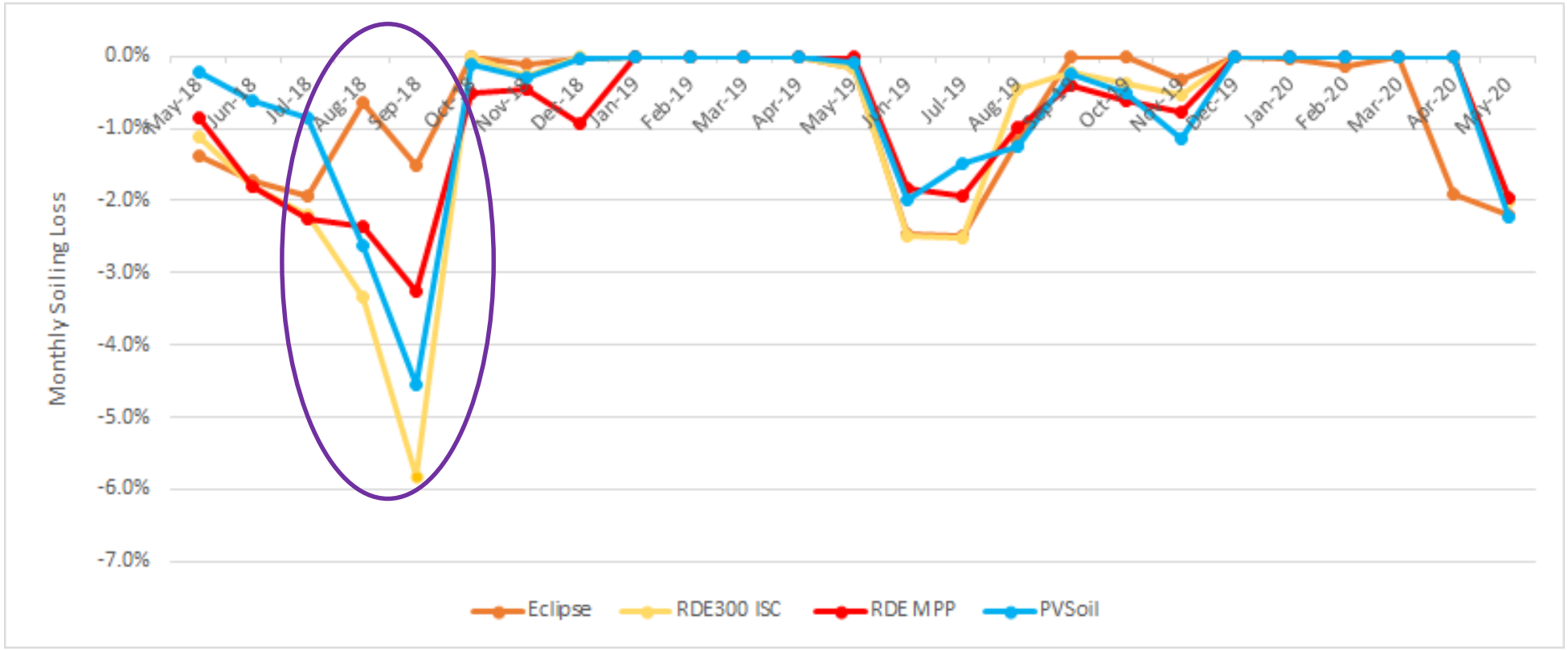
# TIME-SERIES COMPARISON: DAILY SOILING RATIO FROM ALL 5 DEVICES



# MONTHLY SOILING LOSS: ALL 5 DEVICES



# MONTHLY SOILING LOSS: PAIRED MODULE METHODS



# UDAQ PARTICULATE DATA

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
AIR QUALITY SYSTEM
RAW DATA MAX VALUES REPORT

(81102) PM10 Total 0-10um STP

## 2018

SITE ID: 49-005-0007 POC: 2
COUNTY: (005) Cache
CITY: (69640) Smithfield
SITE ADDRESS: 675 West 220 North
SITE COMMENTS:
MONITOR COMMENTS:

STATE: (49) Utah
AQCR: (219) UTAH
URBANIZED AREA: (0000) NOT IN AN URBAN AREA
LAND USE: RESIDENTIAL
LOCATION SETTING: RURAL

SUPPORT AGENCY: (1113) Utah Department Of Environmental Quality
MONITOR TYPE: SLAMS
COLLECTION AND ANALYSIS METHOD: (127) R - P Co Partisol Model 2025 Gravi
PQAO: (1113) Utah Department Of Environmental Quality

REPORT FOR: 2018

| Day | JANUARY | FEBRUARY | MARCH | APRIL | MAY | JUNE | JULY | AUGUST | SEPTEMBER | OCTOBER | NO |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | | 11 | | | | 7 | 15 | | | | |
| 2 | 23 | | | 13 | 5 | | | | | | |
| 3 | | | 5 | | | | | | | | |
| 4 | | | | | | | | | | | |
| 5 | | | | | | | | | 24 | 5 | |
| 6 | | | | | | | | 44 | | | |
| 7 | | 17 | | | | 31 | 29 | | | | |
| 8 | 11 | | | 2 | 17 | | | | | | |
| 9 | | | 45 | | | | | | | | |
| 10 | | | | | | | | | | | |
| 11 | | | | | | | | | 41 | 6 | |
| 12 | | | | | | | | 55 | | | |
| 13 | | 15 | | | | 28 | 29 | | | | |
| 14 | 11 | | | 7 | 6 | | | | | | |
| 15 | | | 2 | | | | | | | | |
| 16 | | | | | | | | | | | |
| 17 | | | | | | | | | 41 | 10 | |
| 18 | | | | | | | | 38 | | | |
| 19 | | 6 | | | | 10 | 31 | | | | |
| 20 | 4 | | | 17 | 9 | | | | | | |
| 21 | | | 7 | | | | | | | | |
| 22 | | | | | | | | | | | |
| 23 | | | | | | | | | 35 | 4 | |
| 24 | | | | | | | | 71 | | | |
| 25 | | 4 | | | | 17 | 43 | | | | |
| 26 | 8 | | | 20 | 21 | | | | | | |
| 27 | | | 4 | | | | | | | | |
| 28 | | | | | | | | | | | |
| 29 | | | | | | | | | 58 | 9 | |
| 30 | | | | | | | | 37 | | | |
| 31 | | | | | | | 45 | | | | |
| NO.: | 5 | 5 | 5 | 5 | 5 | 5 | 6 | 5 | 5 | 5 | |
| MAX: | 23. | 17. | 45. | 20. | 21. | 31. | 45. | 71. | 58. | 10. | |
| MEAN: | 11.4 | 10.6 | 12.6 | 11.8 | 11.6 | 18.6 | 32.0 | 49.0 | 39.8 | 6.8 | |

ANNUAL OBSERVATIONS: 60 ANNUAL MEAN: 20.1 ANNUAL MAX: 71.

Note: A plus sign ("+") following a value indicates that the computed average includes one or more raw data values effected by a special event.

AIR QUALITY SYSTEM
RAW DATA MAX VALUES REPORT

Mar. 10, 20

(81102) PM10 Total 0-10um STP

## 2019

SITE ID: 49-005-0007 POC: 2
COUNTY: (005) Cache
CITY: (69640) Smithfield
SITE ADDRESS: 675 West 220 North
SITE COMMENTS:
MONITOR COMMENTS:

STATE: (49) Utah
AQCR: (219) UTAH
URBANIZED AREA: (0000) NOT IN AN URBAN AREA
LAND USE: RESIDENTIAL
LOCATION SETTING: RURAL

CAS NUMBER:
LATITUDE: 41.84264
LONGITUDE: -111.852
UTM ZONE:
UTM NORTHING:
UTM EASTING:
ELEVATION-MSL: 1
PROBE HEIGHT:

SUPPORT AGENCY: (1113) Utah Department Of Environmental Quality
MONITOR TYPE: SLAMS
COLLECTION AND ANALYSIS METHOD: (127) R - P Co Partisol Model 2025 Gravi
PQAO: (1113) Utah Department Of Environmental Quality

REPORT FOR: 2019

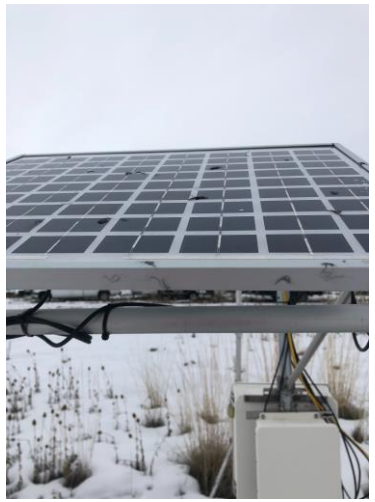
DURATION: 24 HOUR
UNITS: Micrograms/cubic meter (25 C)
MIN DETECTABLE: 4

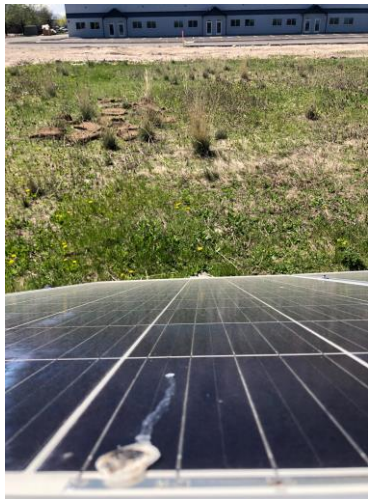
| Day | JANUARY | FEBRUARY | MARCH | APRIL | MAY | JUNE | JULY | AUGUST | SEPTEMBER | OCTOBER | NOVEMBER | DECEMBER |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | | | | | | | | | | | | |
| 2 | | | | | | 11 | 27 | | | | | |
| 3 | 26 | | | 2 | 14 | | | | | | | |
| 4 | | | 6 | | | | | | | | | |
| 5 | | | | | | | | | | | | 31 |
| 6 | | | | | | | | | 27 | 5 | | |
| 7 | | | | | | | | | | | | |
| 8 | | | | | | | | 32 | | | | |
| 9 | 41 | | | 4 | 3 | | | | | | | |
| 10 | | | | | | | | | | | | |
| 11 | | | | | | | | | | | 11 | 31 |
| 12 | | | | | | | | | 8 | 15 | | 13 |
| 13 | | | | | | | | 0 | | | | 3 |
| 14 | | 5 | | | | | | 21 | | | | 3 |
| 15 | 33 | | | 1 | 28 | | | | | | | 8 |
| 16 | | | 10 | | | | | | | | | 16 |
| 17 | | | | | | | | | | | 6 | 13 |
| 18 | | | | | | | | | 13 | 5 | | 29 |
| 19 | | | | | | | | 0 | | | | 47 |
| 20 | | 5 | | | | | | 26 | | | | 64 |
| 21 | 3 | | | 3 | 2 | | | | | | | 52 |
| 22 | | | 3 | | | | | | | | | 67 |
| 23 | | | | | | | | | | | 17 | 68 |
| 24 | | | | | | | | | 9 | 7 | | 11 |
| 25 | | | | | | | | 27 | | | | |
| 26 | | | | | | | | 36 | | | | |
| 27 | | | | 12 | 3 | | | | | | | |
| 28 | | | 5 | | | | | | | | | |
| 29 | | | | | | | | | | | | |
| 30 | | | | | | | | | 4 | 9 | | |
| 31 | | | | | | | | | | | | |
| NO.: | 4 | 2 | 4 | 5 | 5 | 1 | 5 | 3 | 5 | 5 | 3 | 15 |
| MAX: | 41. | 5. | 10. | 12. | 28. | 11. | 36. | 27. | 27. | 15. | 17. | 68. |
| MEAN: | 25.8 | 5.0 | 6.0 | 4.4 | 10.0 | 11.0 | 28.4 | 9.0 | 12.2 | 8.2 | 11.3 | 30.4 |

ANNUAL OBSERVATIONS: 57 ANNUAL MEAN: 17.2 ANNUAL MAX: 68.

Note: A plus sign ("+") following a value indicates that the computed average includes one or more raw data values effected by a special event.

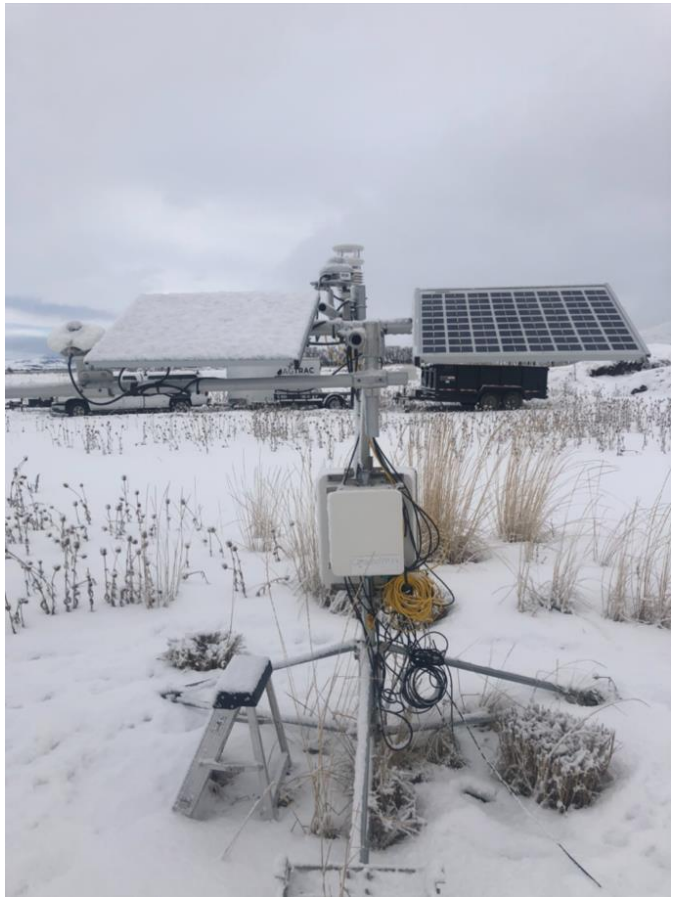
# REAL WORLD CHALLENGES



# SNOW TEST: PRE-CLEANING

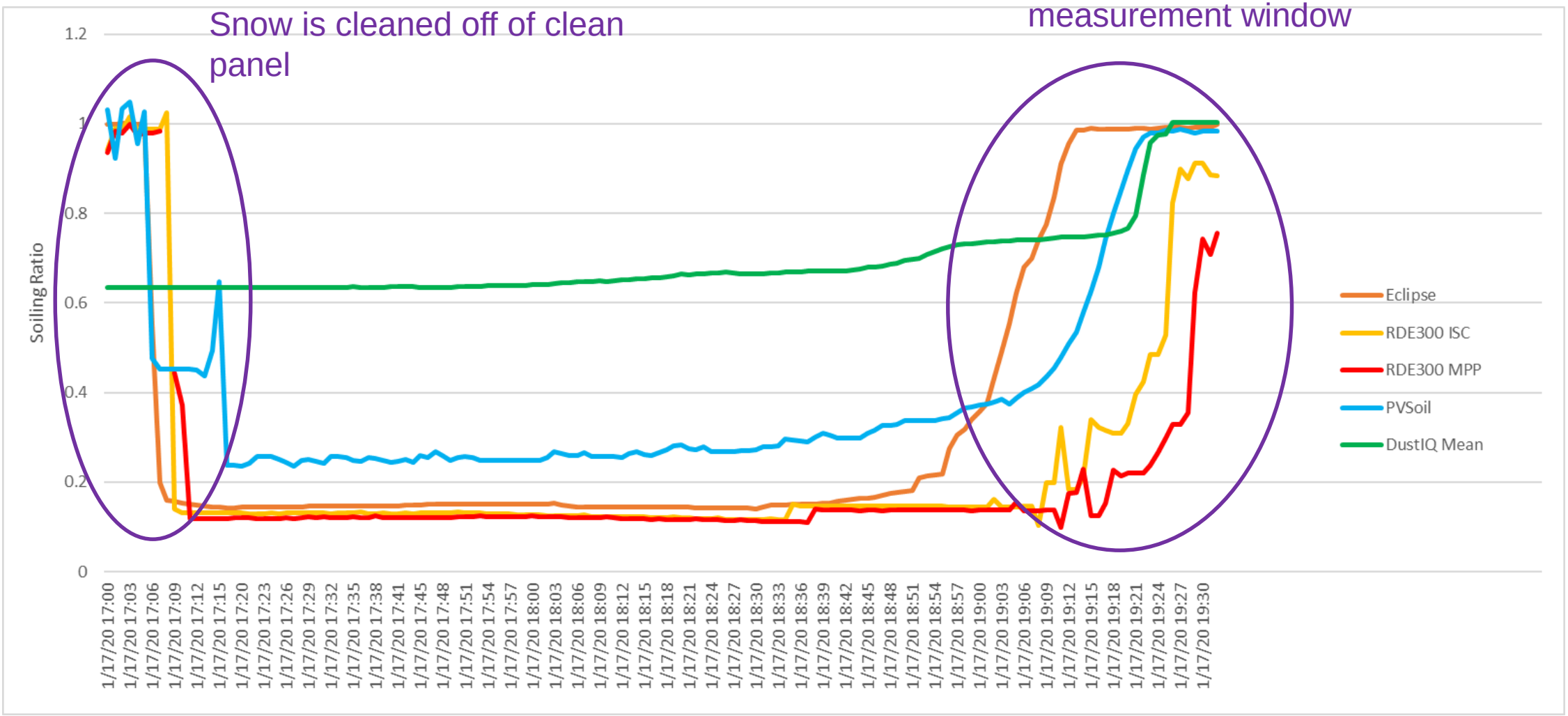
# SNOW TEST: POST-CLEANING



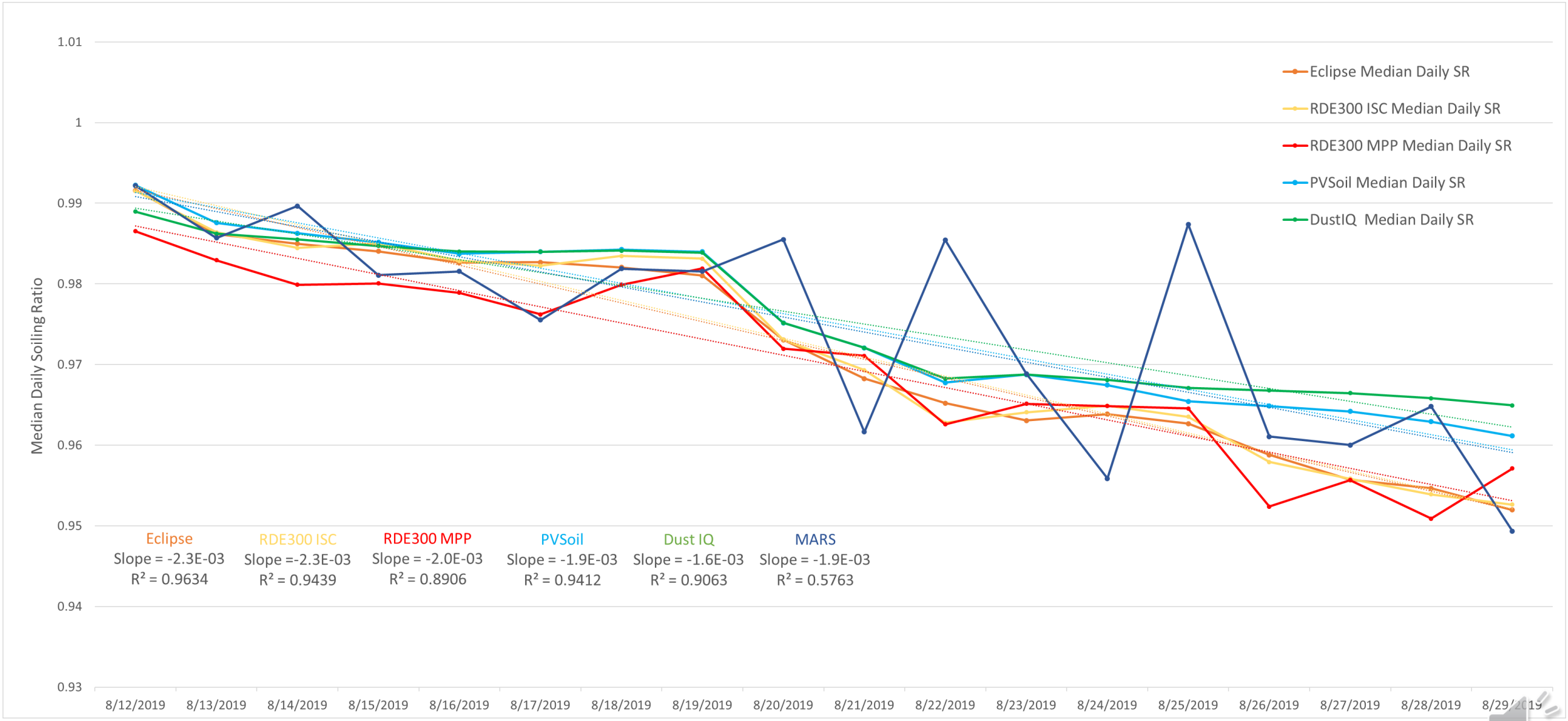
# EFFECTS OF SNOW ACCUMULATION AND MELTING

Snow is cleaned off of clean panel

Snow melts off of soiled panel or optical measurement window



# AUGUST 2019 SOILING EVENT: LINEAR REGRESSION ANALYSIS



# AUGUST 2019 SOILING EVENT: ANALYSIS COMPARISON

| | Eclipse | RDE Isc | RDE MPP | PVSoil | Dust IQ | Mars |
|---|---|---|---|---|---|---|
| Linear Regression Slope | -2.3E-03 | -2.3E-03 | -2.0E-03 | -1.9E-03 | -1.6E-03 | -1.0E-03 |
| Median Daily Soiling Rate | -2.3E-03 | -2.2E03 | -2.0E-03 | -1.7E-03 | -9.2E-04 | -1.9E-03 |

# CONCLUSIONS

- Variations in monthly soiling rate of module-based systems were on average < 1% while optical-based soiling rates were shown to deviate by a maximum of 2% when compared to the module-based data.
- The optical systems tended to underestimate the soiling at the Utah R&D site in the summer of 2019 as well as during snow events.
- The Eclipse and RD300 agree the best out of the 5 soiling measurement systems. This could be due to full-size high quality modules and similar measurement methods.
- The soiling tool results have a tight correlation with the linear regression calculation method. This helps to verify the accuracy of the soiling tool.
- Optical soiling measurement systems have promise due to the fact there is minimal maintenance and price but the measurements aren't quite as accurate as using the short circuit current method with full size modules.
- Interannual variability is hard to measure over smaller intervals. The Utah R&D site experienced different weather and environmental conditions over two years. These include, but are not limited to, a bad fire season causing increased particulates, a snowy winter, and bird migrations causing droppings and frequent resets in the spring months.


# WHAT'S NEXT?

- Uncertainty analysis
- Bifacial soiling
- Improved normalization techniques and optical sensor data processing
- Assess impact of light soak on normalization stability
- Historical dataset coupling
  - Rain