NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Exploring Sources of Uncertainties in Solar Resource Measurements

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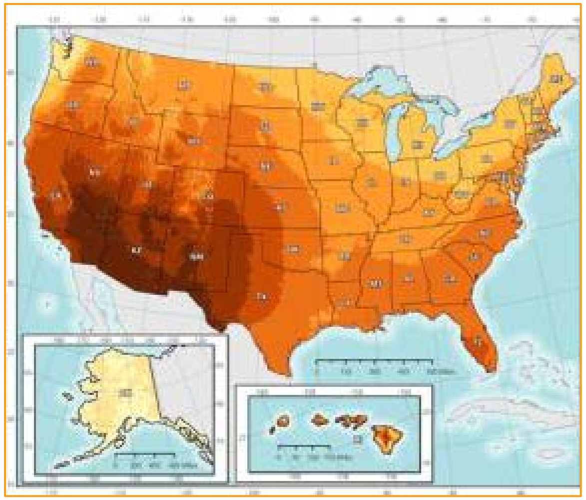
2016 6th PV Performance and Monitoring Workshop

Freiburg, Germany (October 24-25, 2016)

NREL/PR-5D00-67320

Sensing, Measurement, and Forecasting

Provide high-quality meteorological and power data for energy yield assessment, resource characterization, and grid integration

Measurements	Modeling	Standards
		
The right observations of wind and solar resources	Targeted predictions of resources and plant performance	Raising everyone to the same level and enabling dialog

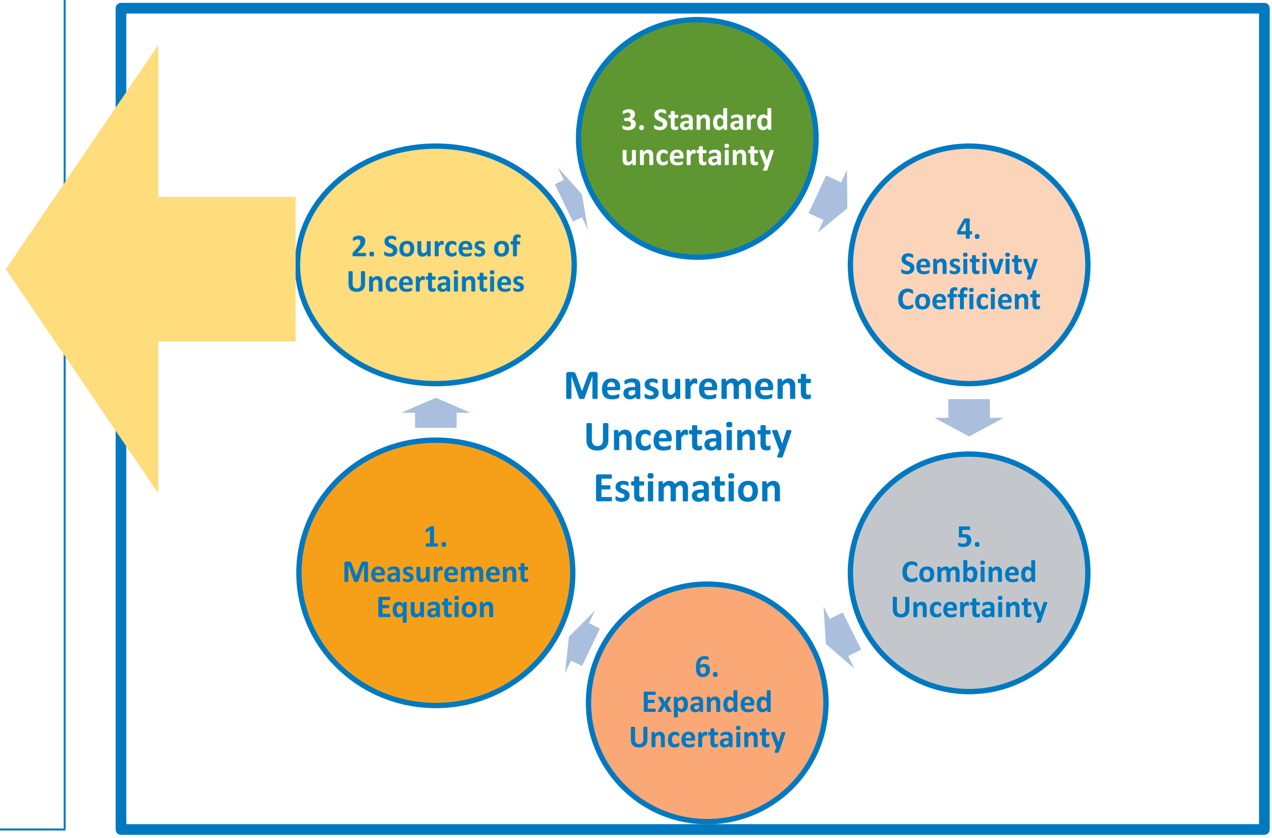
Why Explore Sources of Uncertainty?

- NREL’s Sensing, Measurement, and Forecasting Group collects and disseminates accurate solar resource measurements.
- Best practices for solar resources measurement, calibration, and characterization are followed.
- Advancing best practices benefits solar conversion projects by improving the bankability of the underlying data.
- The accuracy of solar resource measurements depends on:
  - Instrument specifications
  - Calibration procedures
  - Measurement setup
  - Maintenance (cleaning)
  - Location and environmental conditions.

Measurement Uncertainty Estimation

Sources of Measurement Uncertainty

- Calibration
- Spectral response
- Zenith angle response
- Maintenance----Soiling
- Data logger uncertainty
- Temperature dependence
- Nonlinear response
- Thermal offset
- Instrument aging



- Understanding and quantifying each source of uncertainty is essential for the determination of overall uncertainty.

Evaluating Calibration Methods

Overview

- Both indoor and outdoor methods are traceable to the World Radiometric Reference.
- Indoor calibration of radiometers provides:
  - User control of test conditions
  - Calibration results independent of outdoor conditions
  - User convenience.
- Outdoor calibrations are useful for cosine response correction, which ultimately assists in reducing measurement uncertainty.

Calibration Methods

[a] RESPONSIVITY VALUE CASES APPLIED IN THE STUDY. WHEN THERMAL OFFSET CORRECTION IS APPLICABLE (YES), EQUATION (3) IS USED. IF NOT APPLICABLE (NO), EQUATION (4) IS USED.

Cases	Calibration Method	Thermal Offset Correction Applicability		
		Thermopile Pyranometer	Thermopile Pyrheliometer	Silicon Photodiode Pyranometer
Case 1	BORCAL[b] responsivity as a function of solar zenith angle (SZA)	Yes	No	No
Case 2	Manufacturer calibration responsivity at manufacturer-specified SZA in degrees	N/A	N/A	N/A
Case 3	BORCAL responsivity at 45°	Yes	No	No
Case 4	BORCAL responsivity at 45°	No	No	No
Case 5	Manufacturer calibration responsivity at manufacturer-specified SZA in degrees with manufacturer-supplied measurement equation	N/A	N/A	N/A


Progress in PHOTOVOLTAICS

PROGRESS IN PHOTOVOLTAICS: RESEARCH AND APPLICATIONS
Prog. Photovolt: Res. Appl. (2016)
Published online in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/pip.2812

EU PVSEC PAPER

Radiometer calibration methods and resulting irradiance differences

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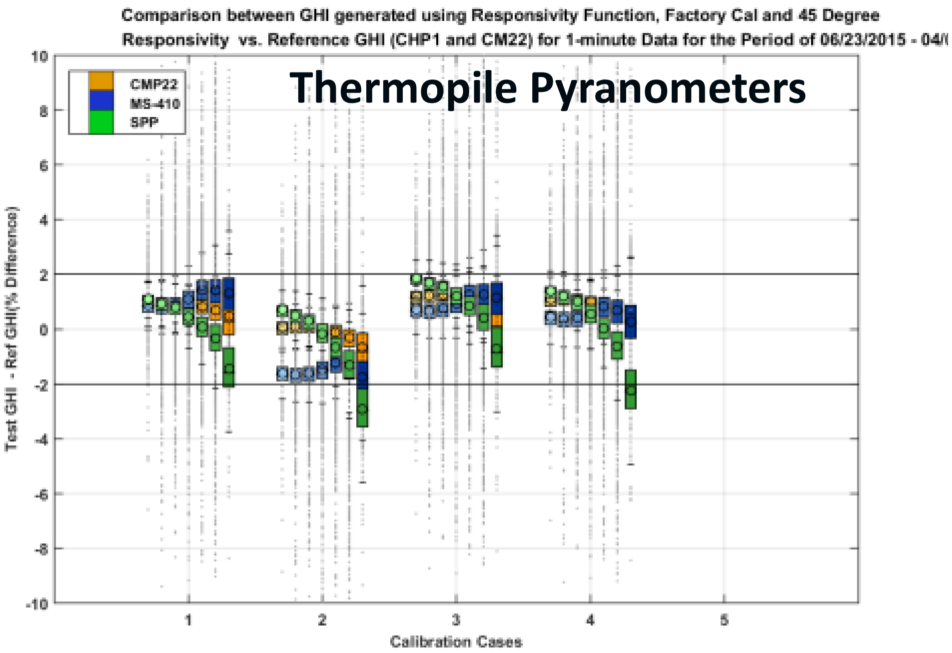
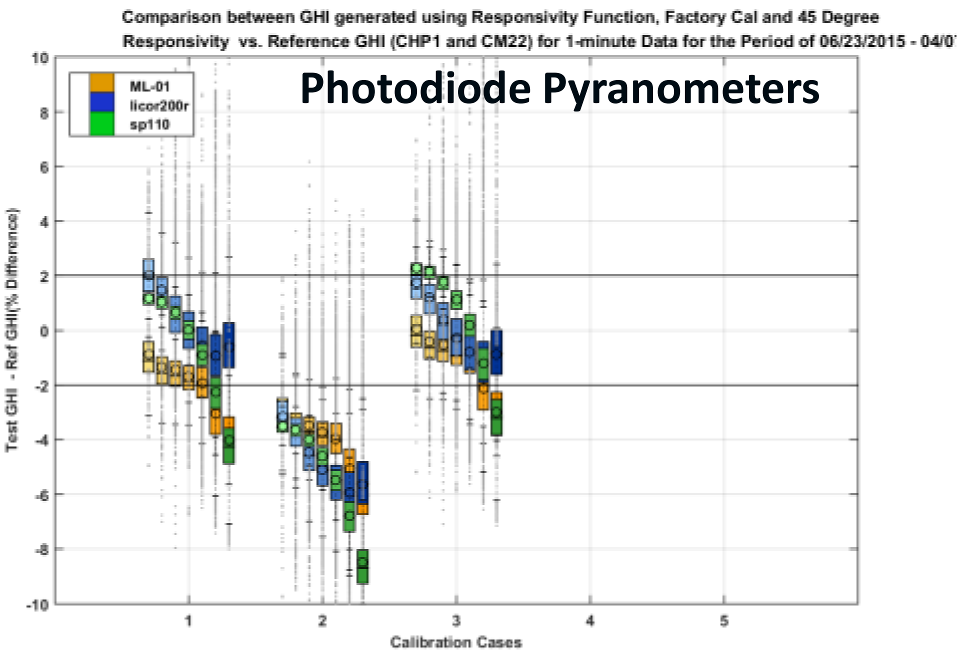
Ten months of 1-minute data for clear-sky conditions (KN>0.6) from 12 radiometers were compared.

[a] The study is published in *Progress in Photovoltaics*: http://onlinelibrary.wiley.com/doi/10.1002/pip.2812/full.

[b] Broadband Outdoor Radiometer Calibrations

GHI: Measurement Differences from Calibration





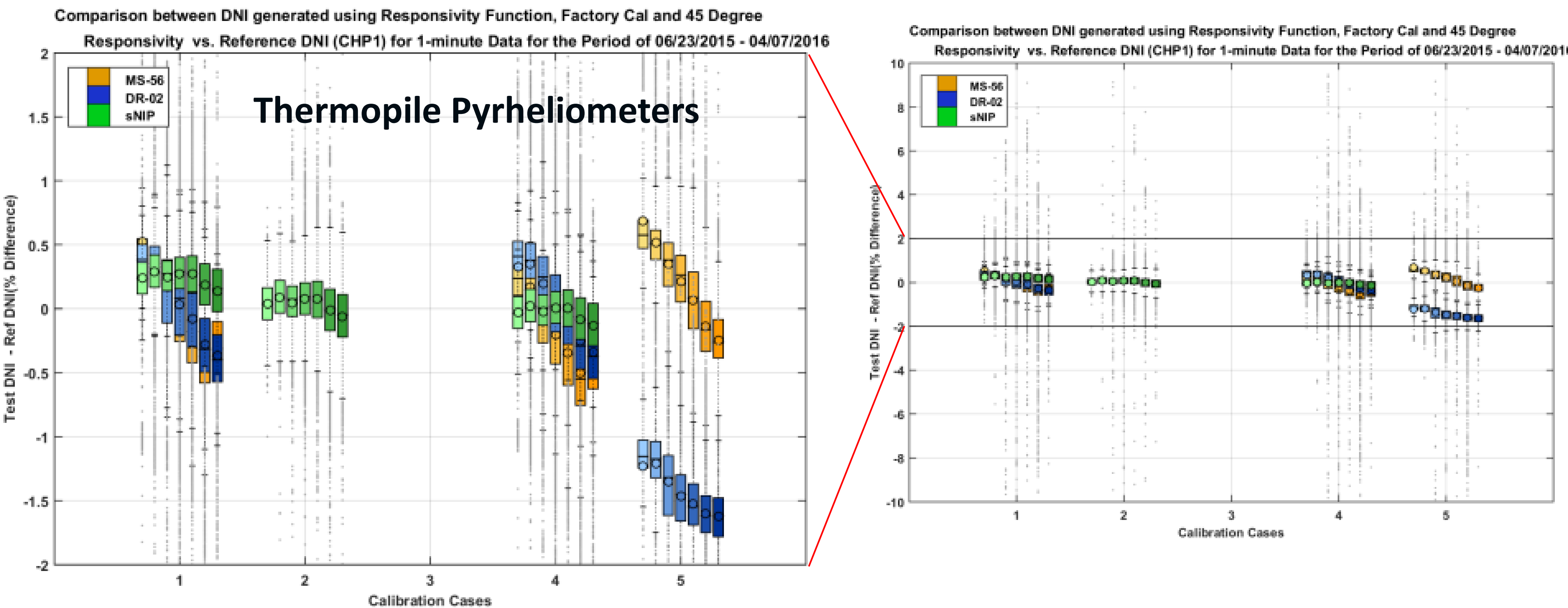
Each colored box shows the interquartile range and represents a 10-degree zenith bin. The circle in each blue box represents the mean, and the black horizontal line represents the median value. Ninety-nine percent of the data lies within the whiskers. Data beyond the whiskers are plotted with dots.

- CMP22 has relatively small difference among all the methods compared to the MS-410 and SPP radiometers.
- For photodiode pyranometers, the manufacturer-supplied responsivities have higher deviation.

(1) BORCAL: Function of SZA, (2) manufacturer-specified SZA in degrees, (3) BORCAL responsivity at 45° with thermal offset correction, (4) BORCAL responsivity at 45° without thermal offset correction, (5) manufacturer-specified SZA in degrees with manufacturer-supplied measurement equation.

DNI: Measurement Differences from Calibration

- The sNIP pyrheliometer data show a better agreement to the reference direct normal irradiance (DNI) (CHP1) data than the DR02 and MS-56 pyrheliometers.
- The NREL responsivity function method provides better results for the DR02 radiometer than the factory responsivity method.



(1) BORCAL: Function of SZA, (2) manufacturer-specified SZA in degrees, (3) BORCAL responsivity at 45° with thermal offset correction, (4) BORCAL responsivity at 45° without thermal offset correction, (5) manufacturer-specified SZA in degrees with manufacturer-supplied measurement equation.

Quantifying Spectral Error

Overview

- In the International Standards Organization (ISO) and World Meteorological Organization (WMO) "spectral selectivity" term is the only specification that does *not* translate directly into a measurement error.
- This is a problem in uncertainty evaluation.

Non-linearity (100 to 1000 W/m^2)	± 0.5 %
Directional response	± 10 W/m^2
Spectral selectivity (350 to 1500 x 10^{-9} m)	± 3 %
Temperature response (interval of 50 K)*	2 %

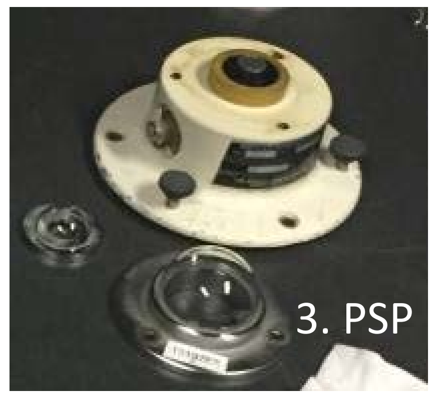
Spectral Mismatch Equation

$$spectral\ mismatch\% = \left[\frac{\int_{350}^{2400} \tau_{dome_{(new,aged)}}(\lambda) \cdot \alpha_{coating_{(new,aged)}}(\lambda) \cdot E_{AM_i}(\lambda)\, d\lambda}{\int_{350}^{2400} E_{AM_i}(\lambda)\, d\lambda} \cdot \frac{\int_{350}^{2400} E_{AM_{1.41}}(\lambda)\, d\lambda}{\int_{350}^{2400} \tau_{dome_{(new,aged)}}(\lambda) \cdot \alpha_{coating_{(new,aged)}}(\lambda) \cdot E_{AM_{1.41}}(\lambda)\, d\lambda} - 1 \right] * 100$$

- τ_{dome}= Dome transmittance
- $\alpha_{(coating)}$= Absorptance of coating
- E_{AM_i}= Spectral irradiance under various air mass (obtained using SMARTS)
- $E_{AM_{1.41}}$= Reference spectral data at AM 1.41 (SZA 45).

Radiometers Included in the Study

Inst#	Model	Type	Comment
1	PSP	Double dome and aged coating	
2	PSP	Double dome and aged coating	
3	PSP	Double dome and aged coating	
4	PSP	Double dome and aged coating	
5	TSP-1	Double dome and aged coating	
6	---	Transmission 2 mm and new coating data (Hukseflux)	Provided by manufacturer
7	---	Transmission 4 mm (Kipp & Zonen)	Provided by manufacturer
8	---	Transmission 4 mm + Fresnel (Kipp & Zonen)	Provided by manufacturer
9	---	SCHOTT-N-WG295	Data sheet

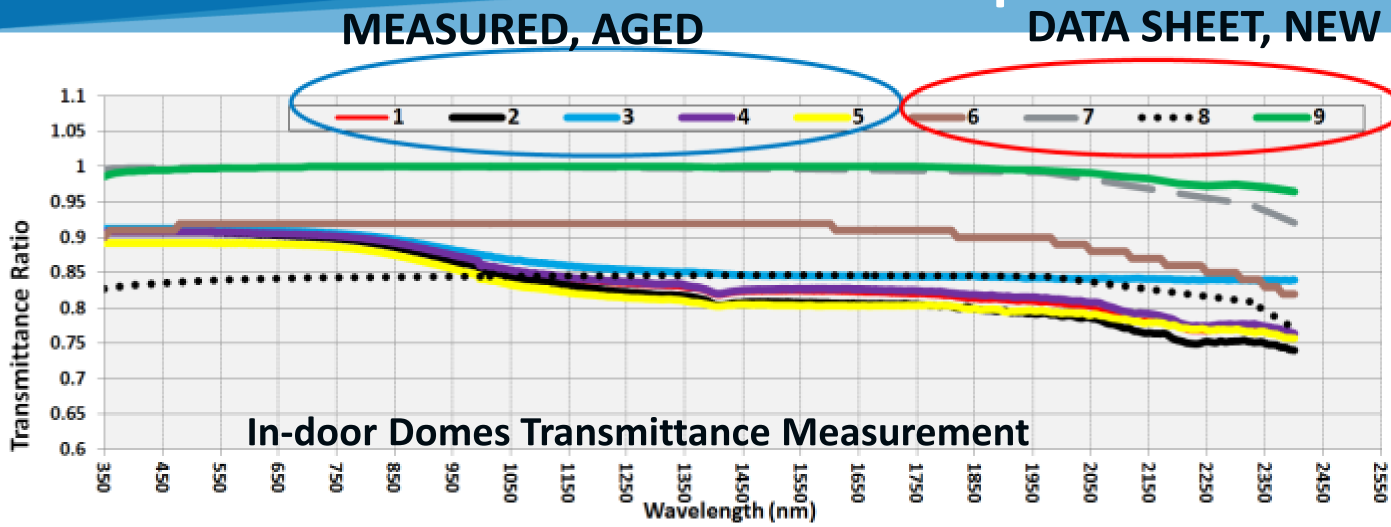


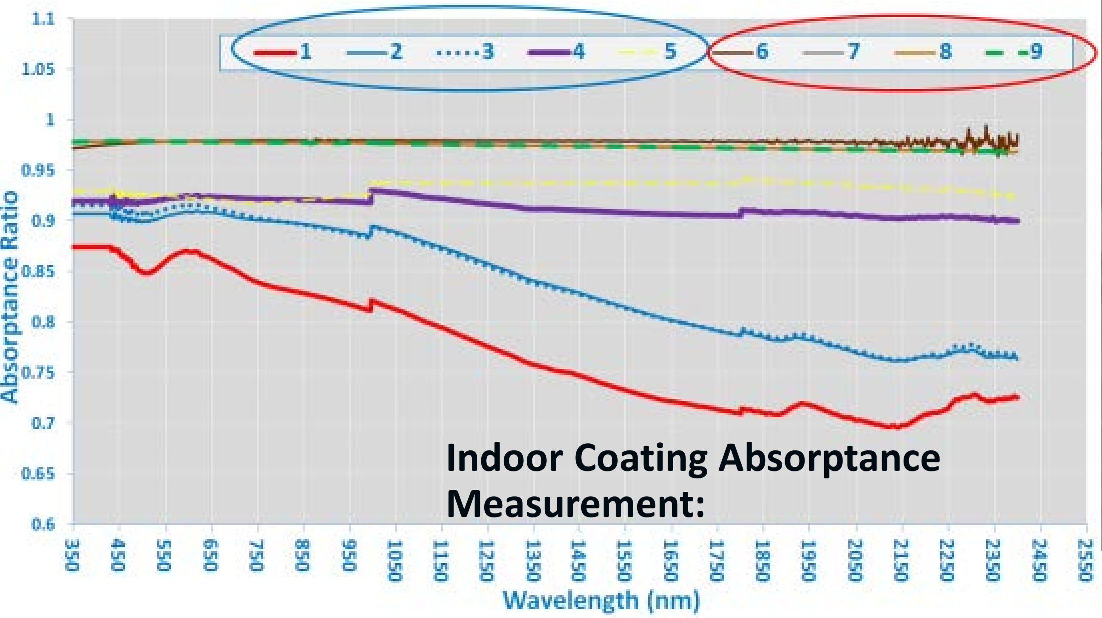
6. Hukseflux
(Data from manufacturer)

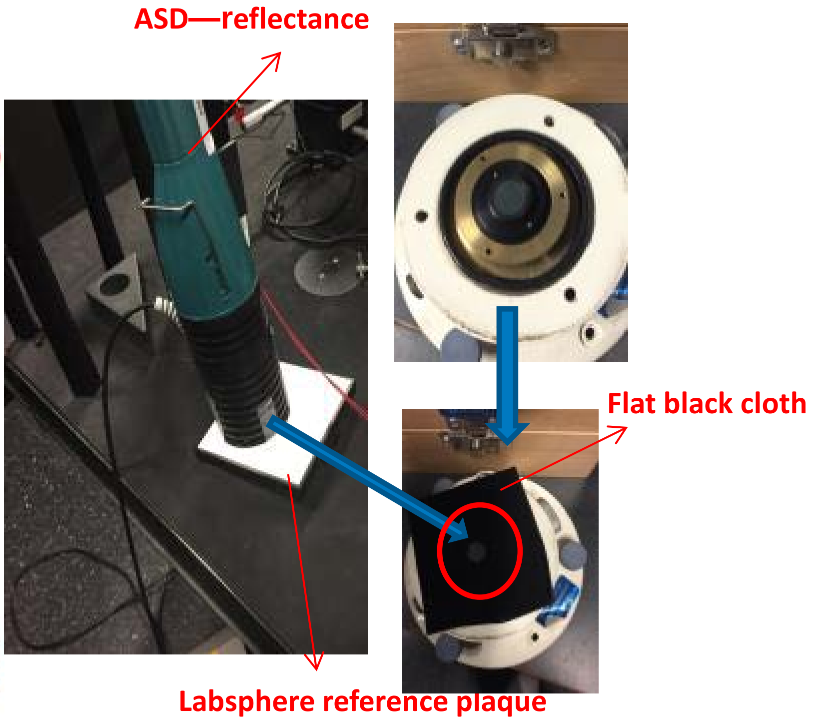
7&8. Kipp & Zonen
(Data from manufacturer)

9. N-WG295

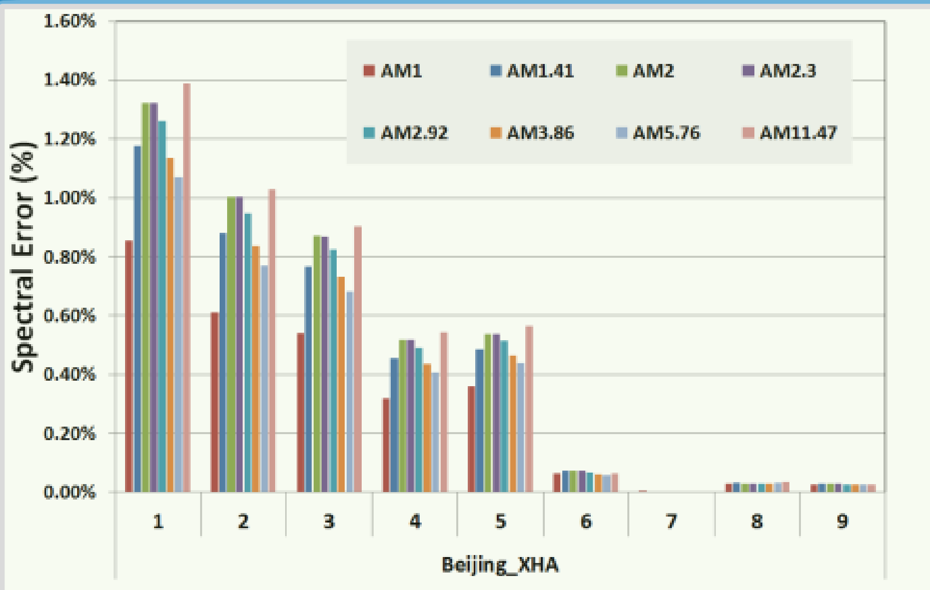
Transmittance and Absorptance Measurement



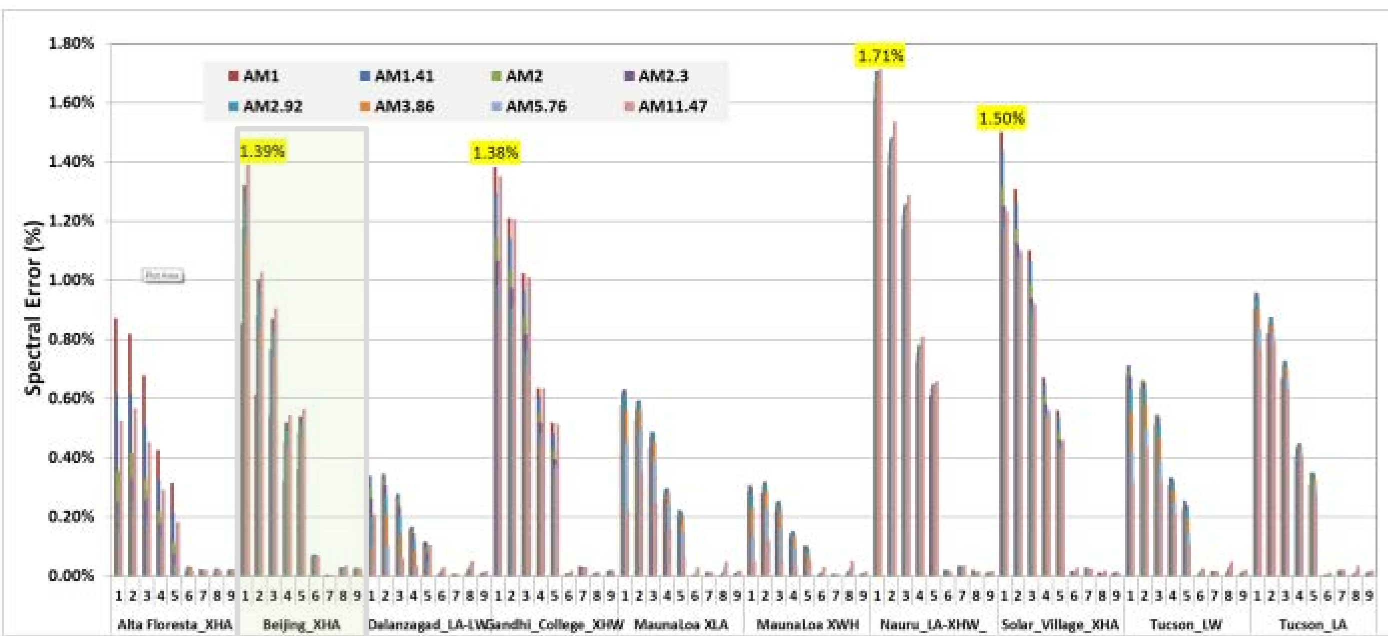


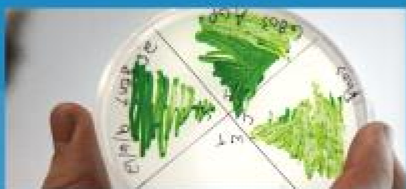


Result Using Indoor Transmittance Measurement (400–2,400 nm)



- Results are based on combined transmittance measurement of the inner and outer dome for Inst# 1–5.
- Numbers 1–9 are instrument numbers and 10 locations under different air mass.
- Numbers 6–9 are new radiometers with new glass transmittance and coating absorptance. —Data obtained from the manufacturers.





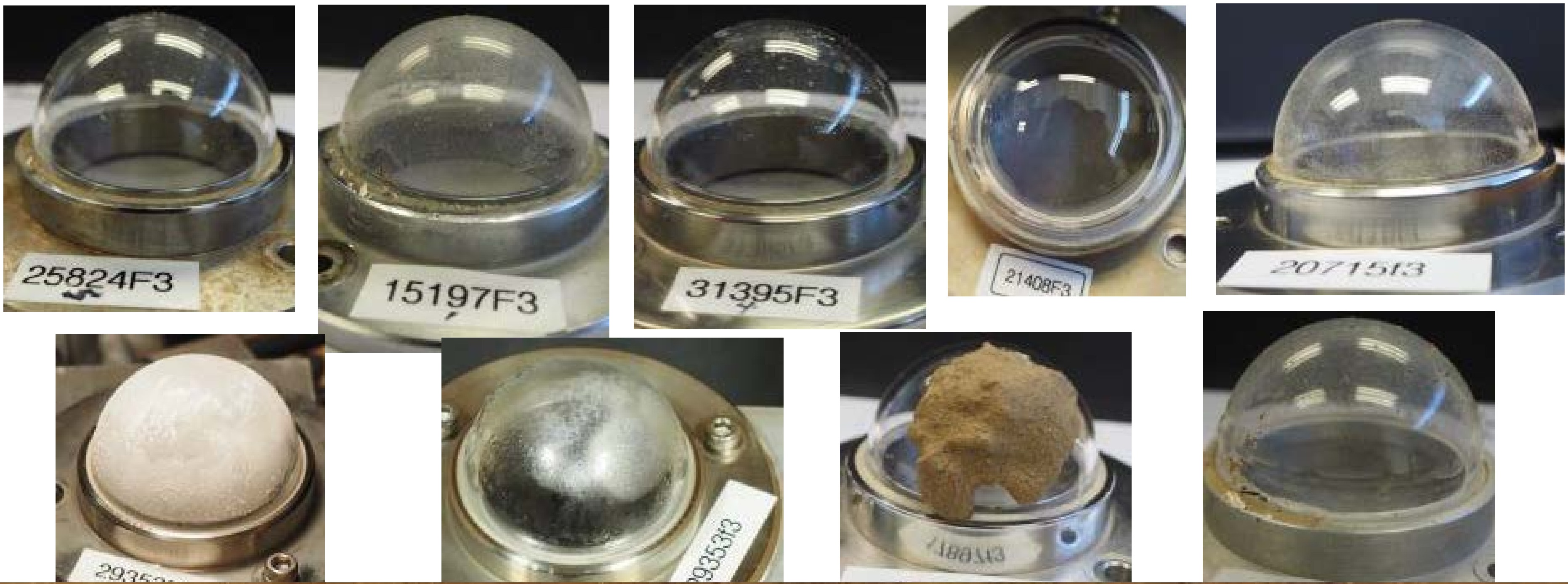


Quantifying Soiling Effects

Overview

- Artificial soiling that simulates various environments complements and/or substitutes natural soiling determination.
- Various degrees of soiling reduce the optical transmittance of the glass dome of the pyranometer, which ultimately reduces the detector output (energy loss).
- The study demonstrates how cleaning radiometers is essential in obtaining accurate radiometric data.
- The study is beneficial for overall measurement uncertainty estimation of radiometric data.
- The study will also assist meteorological station operators in estimating the irradiance reduction due to soiling by comparing the images of the artificial soiling to the field conditions.

Artificial Soiling: Various Types and Levels of Soiling

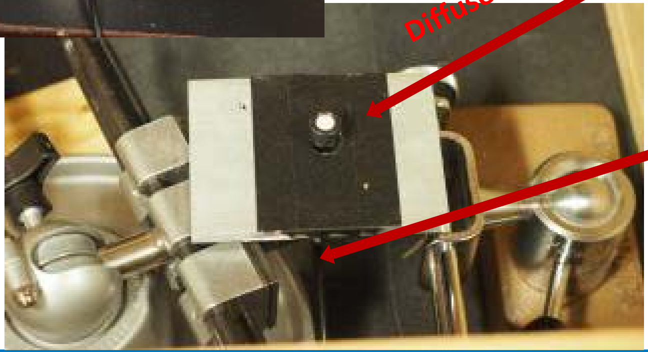


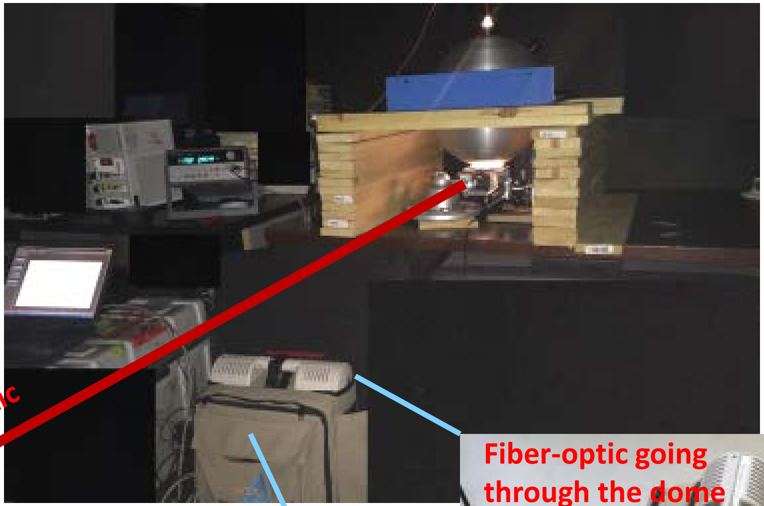
Fourteen artificially soiled pyranometer domes were measured.

Method: Indoor Measurement

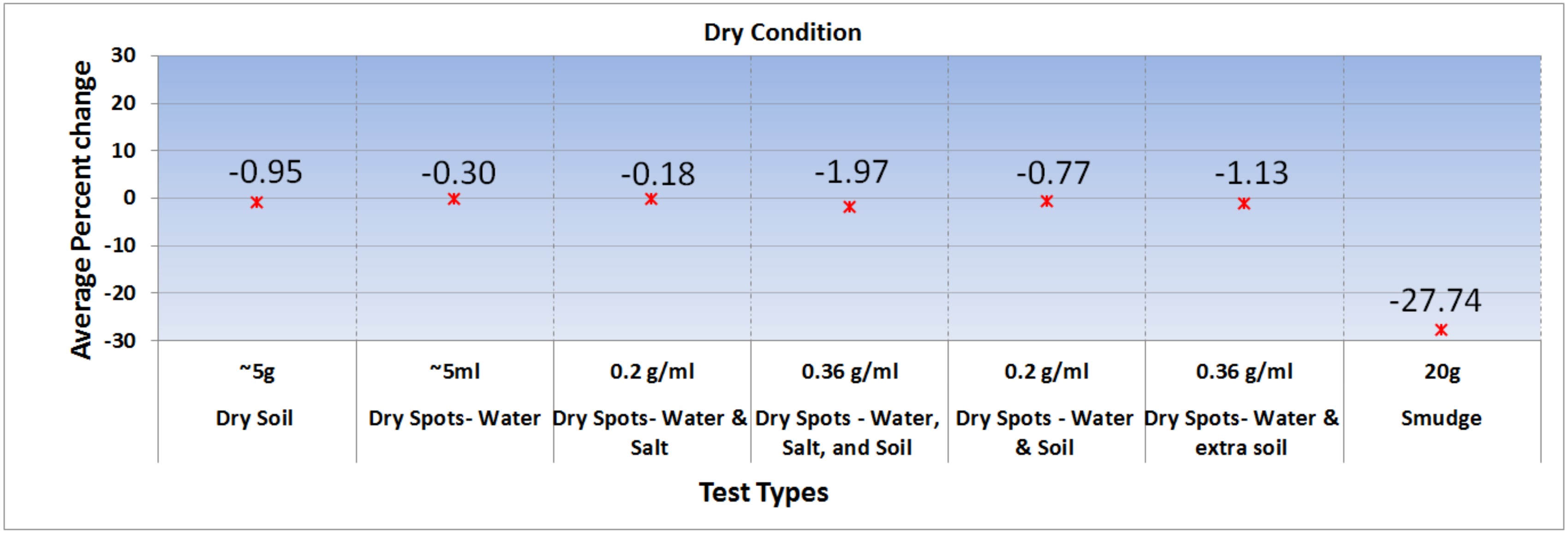
- Working toward the development of a standardized artificial soiling method for thermopile radiometers:
  - ➢ ASD spectroradiometer was used to measure the transmittance (350–2,400 nm).
  - ➢ Stable light source was used to measure the transmittance.
  - ➢ Twelve-inch integrating sphere was used.

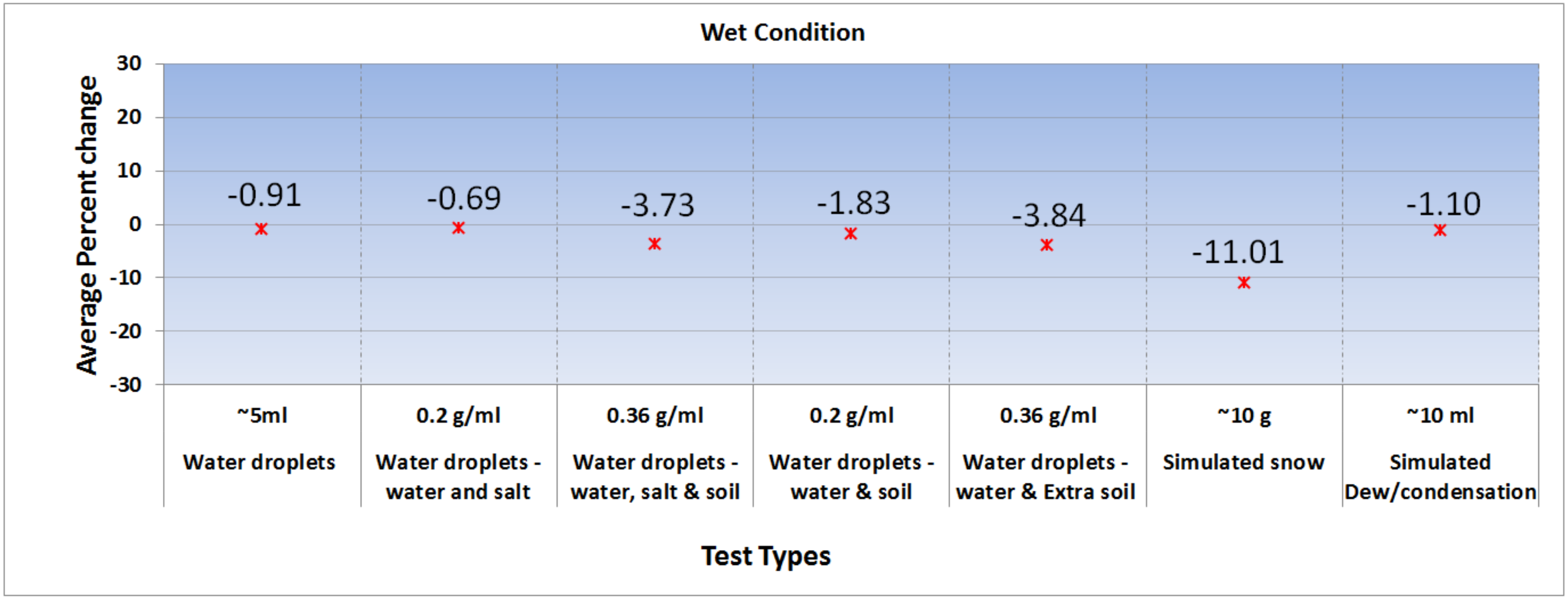
Source: http://www.nrel.gov/docs/fy16osti/66792.pdf





Result


Dry Condition
Average Percent change
30
20
10
0
-10
-20
-30
-0.95
-0.30
-0.18
-1.97
-0.77
-1.13
-27.74
~5g
Dry Soil
~5ml
Dry Spots- Water
0.2 g/ml
Dry Spots- Water & Salt
0.36 g/ml
Dry Spots - Water, Salt, and Soil
0.2 g/ml
Dry Spots - Water & Soil
0.36 g/ml
Dry Spots- Water & extra soil
20g
Smudge
Test Types


Wet Condition
Average Percent change
30
20
10
0
-10
-20
-30
-0.91
-0.69
-3.73
-1.83
-3.84
-11.01
-1.10
~5ml
Water droplets
0.2 g/ml
Water droplets - water and salt
0.36 g/ml
Water droplets - water, salt & soil
0.2 g/ml
Water droplets - water & soil
0.36 g/ml
Water droplets - water & Extra soil
~10 g
Simulated snow
~10 ml
Simulated Dew/condensation
Test Types

Summary

- Solar resource data with known and traceable uncertainty estimates are essential for the site selection of renewable energy technology deployment, system design, system performance, and system operations.
- Developing consensus methodologies of determining solar resource measurement uncertainties is essential in obtaining accurate radiometric data.
- Calibration differences between manufacturers' and outdoor NREL BORCAL provided irradiance differences up to 1%–2% for pyranometers and less than 1% for pyrheliometers.
- Spectral mismatch contributes to spectral error up to 1.6% for indoor transmittance measurement.
- Various degrees of soiling reduce the optical transmittance of the glass dome of the pyranometer, which ultimately reduces the detector output (energy loss). The observed reduction was 0.2%–27%.

Thank you!

Questions?

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