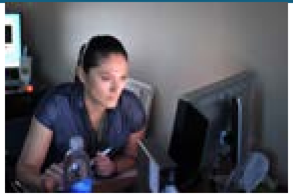
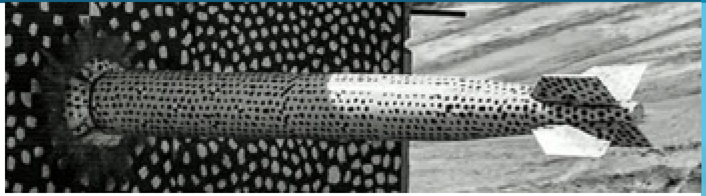
Sandia National Laboratories

Differential Analysis of the Incident Angle Response of Utility-Grade PV Modules





PRESENTED BY

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U.S. Department Of Energy

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Sravanthi Boppana, Kendra Passow, Jim Sorensen, Bruce H. King and Charles Robinson, "Impact of Uncertainty in IAM measurement on Energy Prediction," *7th World Conference on Photovoltaic Energy Conversion (WCPEC-7)*, Waikoloa, HI, 2018.

Bruce H. King and Charles D. Robinson, "Comparative Angle of Incidence Characterization of Utility Grade Photovoltaic Modules," SAND 2018-12462, Sandia national Laboratories, Albuquerque, NM 2018

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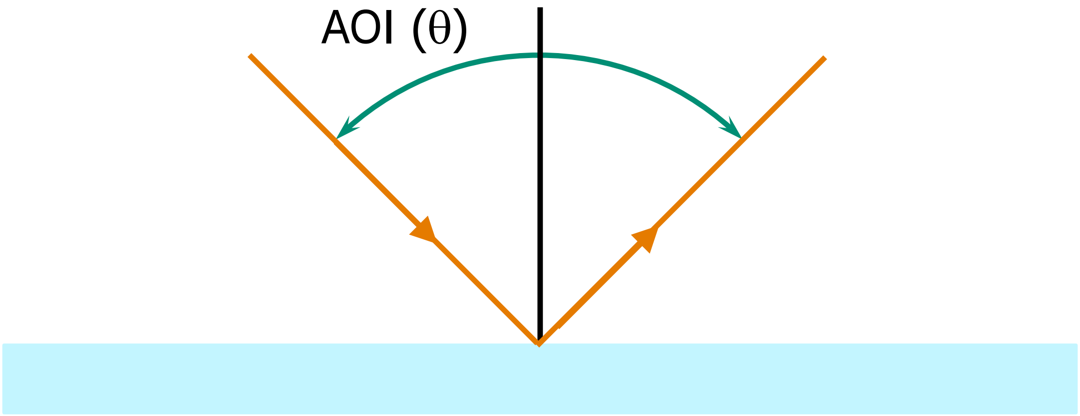
Introduction

Introduction

- Angle of Incidence (AOI) response describes REFLECTION losses from the front surface of a PV module
  - It does not tell us anything about direct transmission through the glass
- Accounted for in performance models by a unitless AOI function or Incident Angle Modifier

$$E_{net} = E_{DNI}\cos(\theta) f_2(\theta) + E_{diff}$$

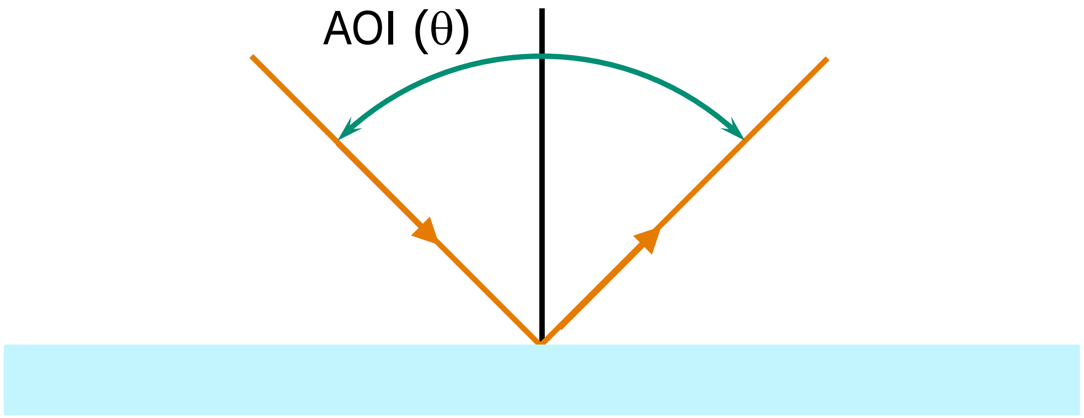
- Anti-reflective coating (ARC) products may ENHANCE direct transmission while also affecting reflection losses (for better or worse)
- Differences in the reflective properties between modules can be difficult to discern; day-to-day and site-to-site variability increase uncertainty in these differences



Introduction

- In this presentation, we explore a differential method for visualizing and quantifying the differences in the reflective (AOI) properties of several modules and the potential impact on system power
- Several commercial utility grade modules and a module with an experimental ARC are used to demonstrate the method
- A key point, all testing was performed simultaneously, making direct comparisons possible

MFG	Model	PSEL ID
First Solar	FS4 (No ARC)	3262
First Solar	FS4 (non-prod ARC 1)	3261
JA Solar	JAM6(k)-72-4BB 345W	3268
Yingli	YL330P-35b	3267



Test Method

Outdoor Angle of Incidence Characterization Method

Equipment:

- **Azimuth-Elevation solar tracker** capable of rotating the test plane to solar incident angles between 0° and 90°
- **Global Pyranometer** in the test plane measuring diffuse POA irradiance (E_{diff})
- **Pyrheliometer** on a separate weather tracker measuring Direct Normal Irradiance (E_{DNI})
- **Current-Voltage** (IV) sweep system
- **Module temperature** measurement system

Environmental Conditions:

- High Irradiance, low diffuse
- Low variation in Irradiance during test
- Low wind speed/changes in ambient temperature during test

0°	5°	10°	15°	20°	25°	30°	35°
40°	44°	48°	52°	56°	60°	64°	67°
70°	73°	76°	79°	82°	85°	87°	89°

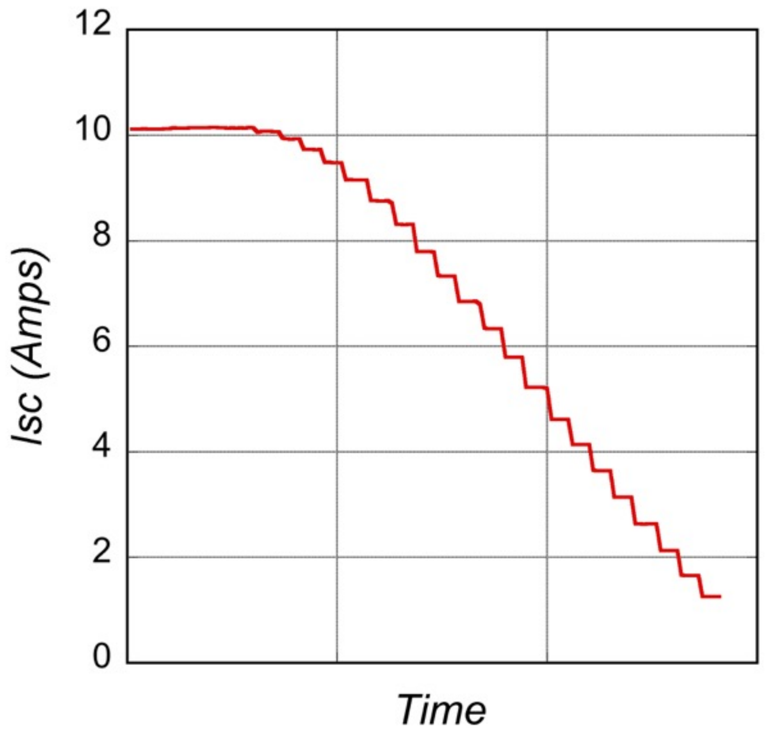
Typical Incident Angles

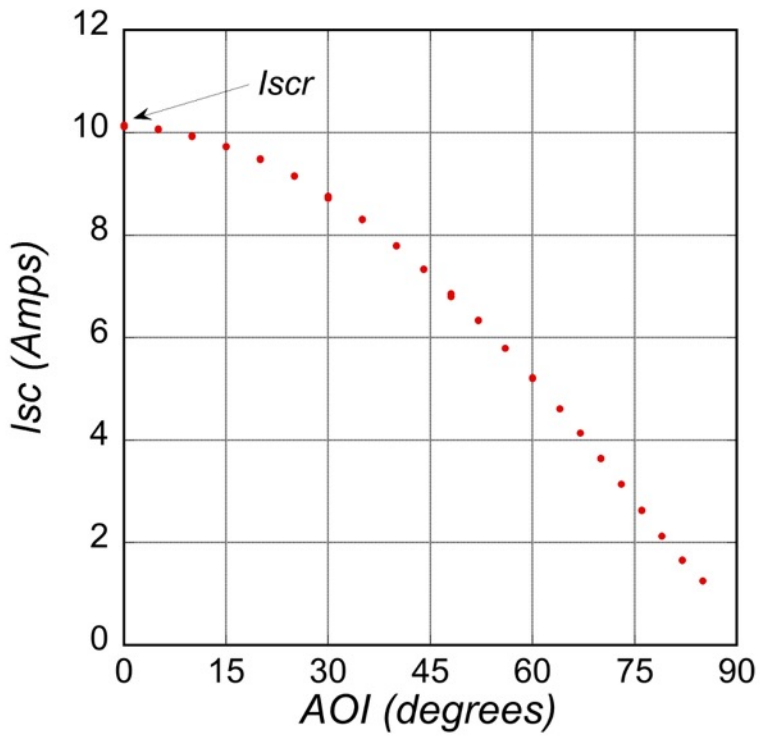
Bruce H. King, Clifford W. Hansen, Dan Riley, Charles D. Robinson, Larry Pratt, "Procedure to Determine Coefficients for the Sandia Array Performance Model (SAPM)," SAND2016-5284, Sandia National Laboratories, Albuquerque, NM, 2016.

Outdoor Angle of Incidence Characterization Method

Procedure:

- Initiate IV scans, 2 scans/minute typical
- Hold module normal to the Sun for a minimum of 10 minutes. Ensure Short Circuit Current (I_{sc}) is stable
- Index tracker off sun
- Dwell for several minutes at each AOI, collect 4-5 IV curves per condition.





Analysis

- Correct measured Isc for temperature and spectrum

$$I_{sc,Tr,AM1.5} = \frac{I_{sc}}{f_1(AM)[1 + \hat{\alpha}_{Isc}[T_c - T_0]]}$$

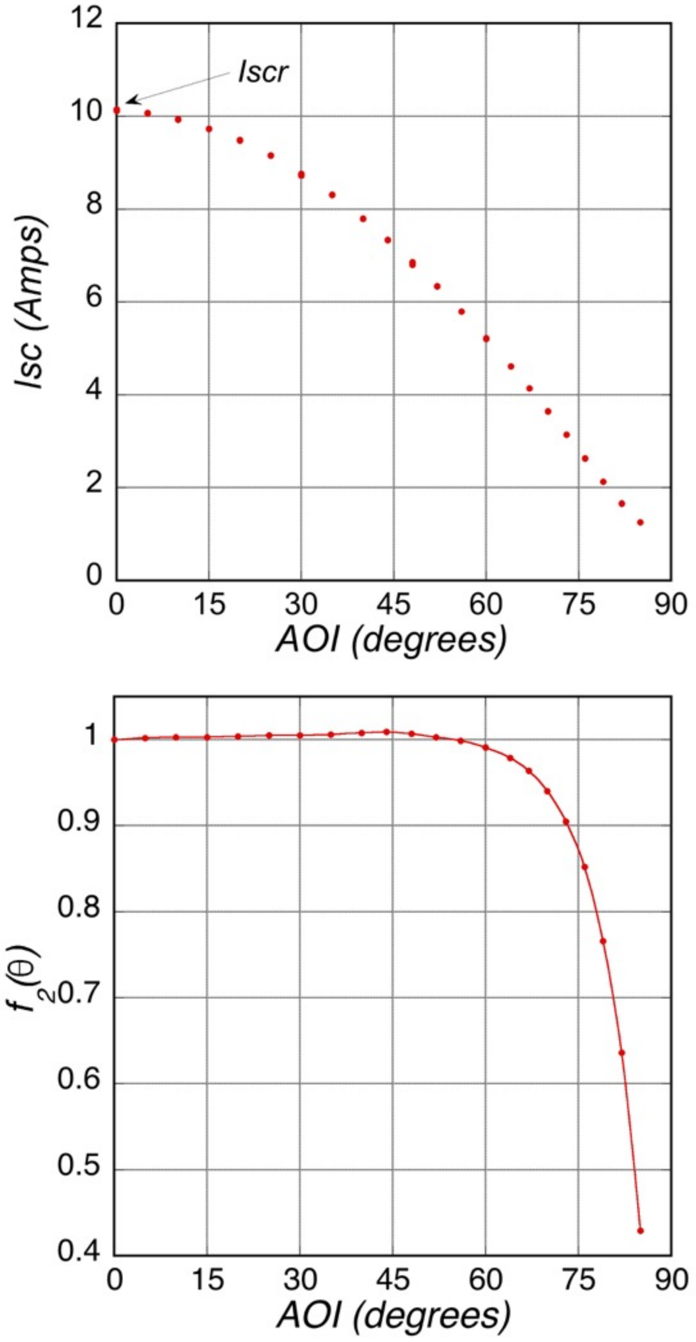
- Find reference I_{scr} at AOI = 0°

$$I_{scr} = \frac{1}{n}\sum\left(I_{sc,Tr,AM1.5}\left(\frac{E_0}{E_{DNI} + E_{diff}}\right)\right)_n \quad @\ AOI = 0°$$

- Find normalized I_{sc} (Nisc)

$$Nisc = \left(\frac{G_0}{G_{DNI}\cos\theta}\right)\left(\frac{I_{sc,Tr,AM1.5}}{I_{scr}} - \left(\frac{G_{diff}}{G_0}\right)\right)$$

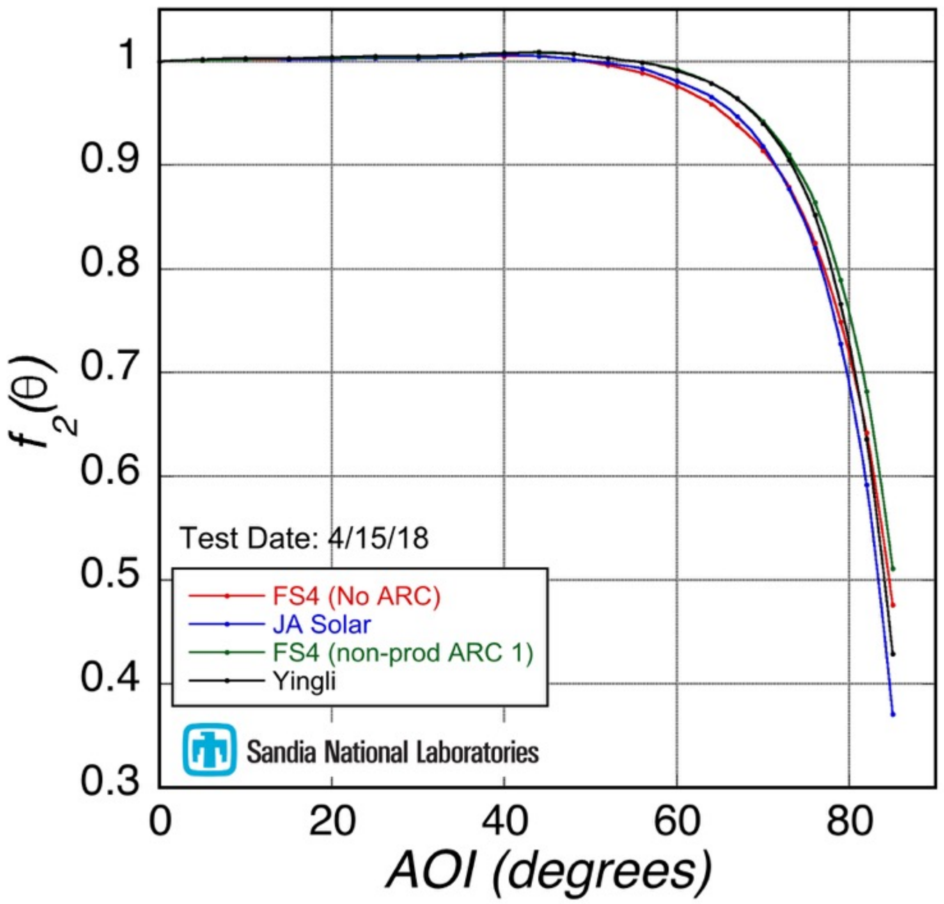
- Plot Nisc vs AOI to visualize function, $f_2(\theta)$



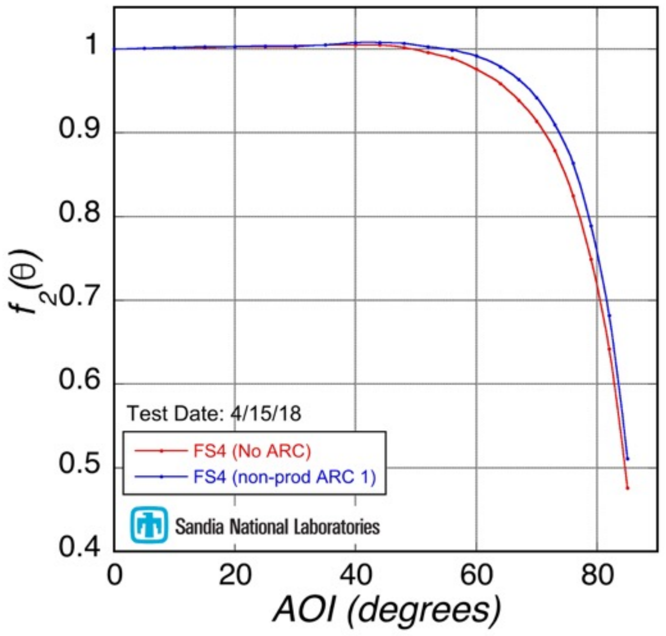
Test Results and Differential Analysis

Results – Standard Reporting

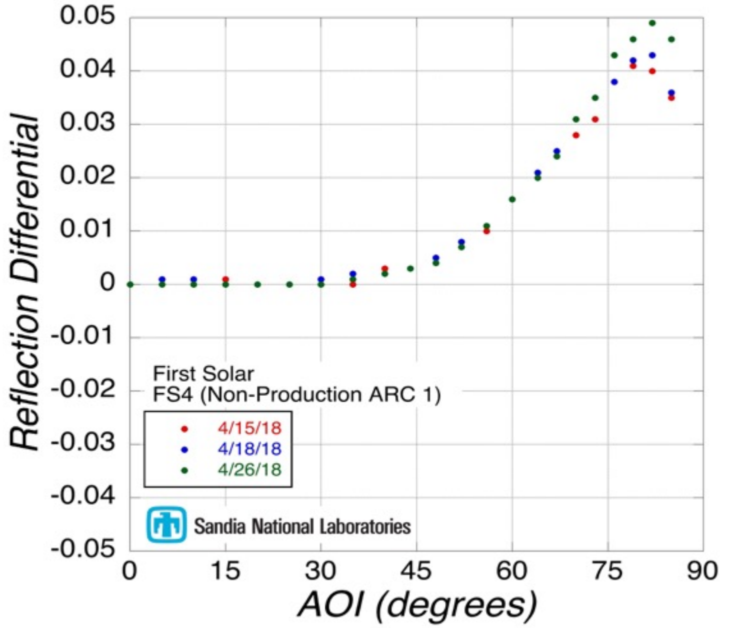
- All modules relatively flat (pure cosine response) out to ~ 55°
- Minor apparent differences beyond 55°
- Yingli and First Solar ARC1 appear to be similar and consistently outperform all other modules commercial modules
- Performance assessment is typically visual and subjective ("better" or "worse")



New Approach to Quantifying Performance – Differential Analysis



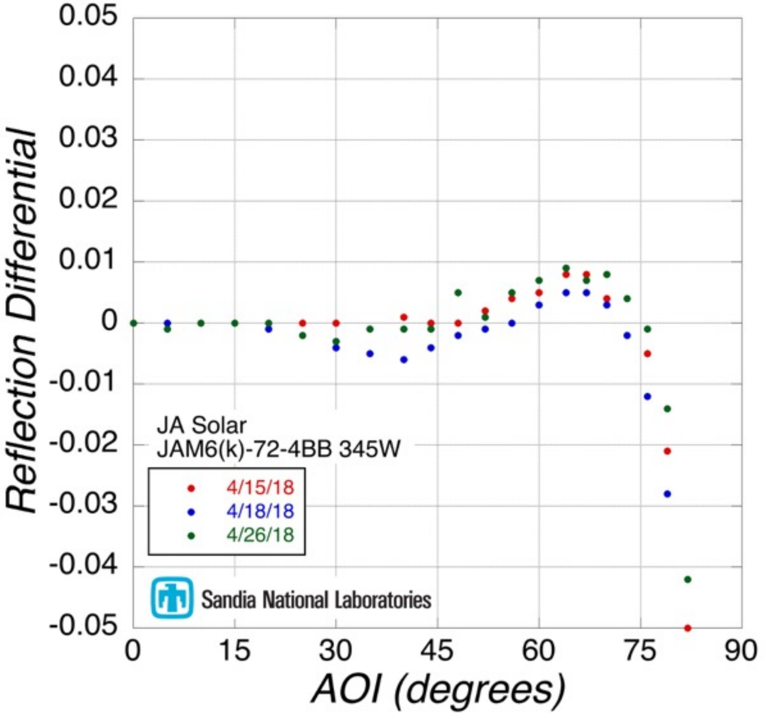
$$Nisc = \left(\frac{G_0}{G_{DNI}\cos\theta}\right)\left(\frac{I_{sc,Tr,AM1.5}}{I_{scr}} - \left(\frac{G_{diff}}{G_0}\right)\right)$$

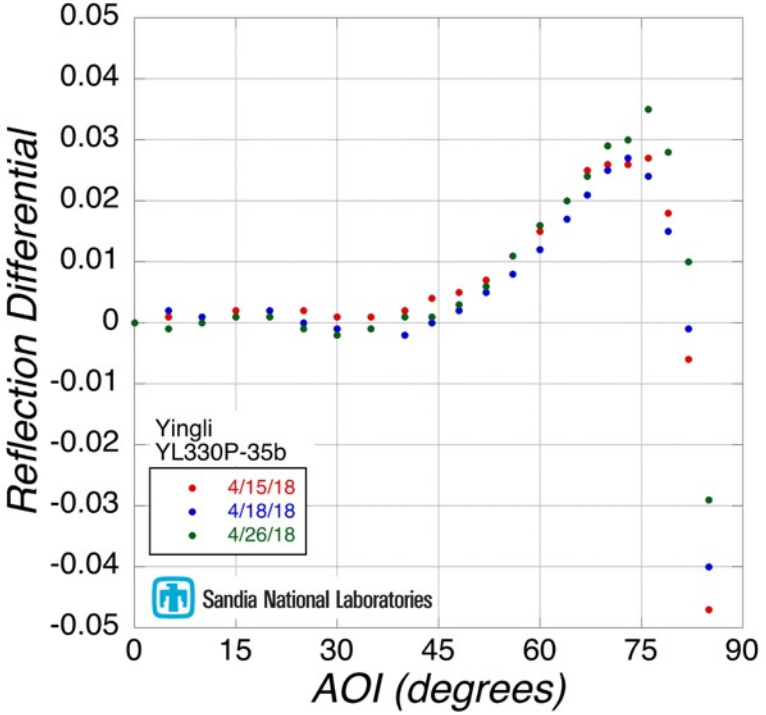


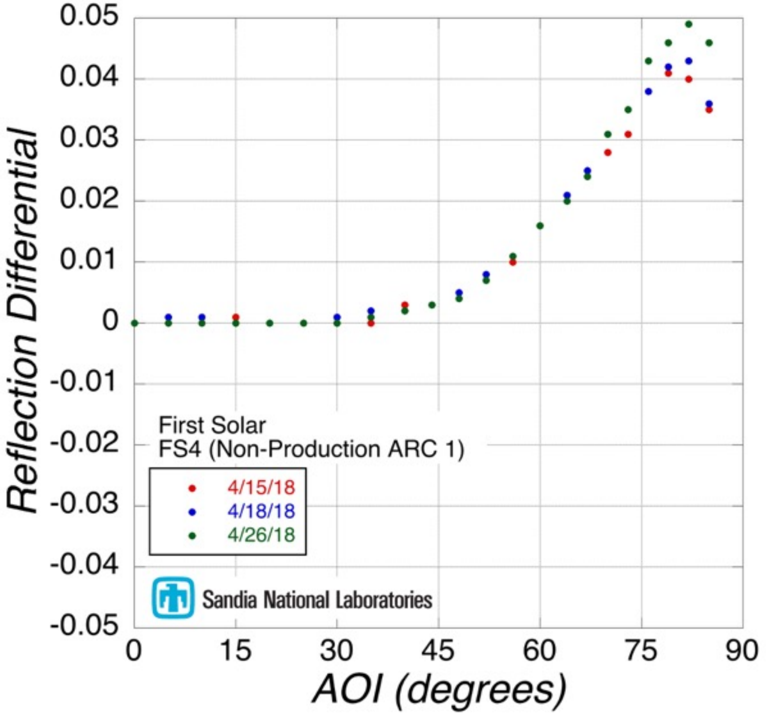
$$\Delta f_2(\theta) = \left(\frac{G_0}{G_{DNI}\cos\theta}\right)\left(\left(\frac{I_{sc,Tr,AM1.5}}{I_{scr}}\right)_2 - \left(\frac{I_{sc,Tr,AM1.5}}{I_{scr}}\right)_1\right)$$

- Determine simple differential between test device and a reference
- For this example, we use a plain glass module with no ARC
- Reference and test device must be measured simultaneously to eliminate differing environmental conditions between tests
- Resulting differential is independent of diffuse light and only dependent on DNI

Differential Analysis - Examples







- Examples for two commercial modules and a First Solar module with experimental ARC
- Divergence from plain glass behavior can be seen as low as 30°
- All modules showed a boost at higher AOI. Degree of boost appears to be correlated with peak θ.
- Differential for commercial modules went negative at high AOI.
- Differential for one module showed a dip at intermediate AOI, ~35°.

Application to PV System Performance

Application to PV System Performance

Goals:

- Demonstrate applicability of differential analysis to simulate differences in system performance
- Apply for multiple modules, multiple system configurations

Systems

- Fixed Tilt 35°, Fixed Tilt 10°, single axis tracker (SAT)
- Modules: JA Solar, Yingli, First Solar Non-Production ARC1

Inputs

- 2017 weather from on-site weather station at Sandia (Albuquerque, NM)
- High temporal resolution, 1 minute samples
- $f_2(\theta)$, $\Delta f_2(\theta)$ for each module from simultaneous outdoor testing

Modeling Steps

- Determine AOI (θ) for each time step, each system orientation
  pvl_getaoi.m, pvl_singleaxis.m

- Calculate diffuse irradiance for each AOI (only used for % gain calculations)
  pvl_haydavies1980.m, pvl_extraradiation.m

- Determine $\Delta f_2(\theta)$ for each time step, each system orientation
  lookup table with spline interpolation

- Calculate Net Irradiance difference, Net Irradiance for plain glass module

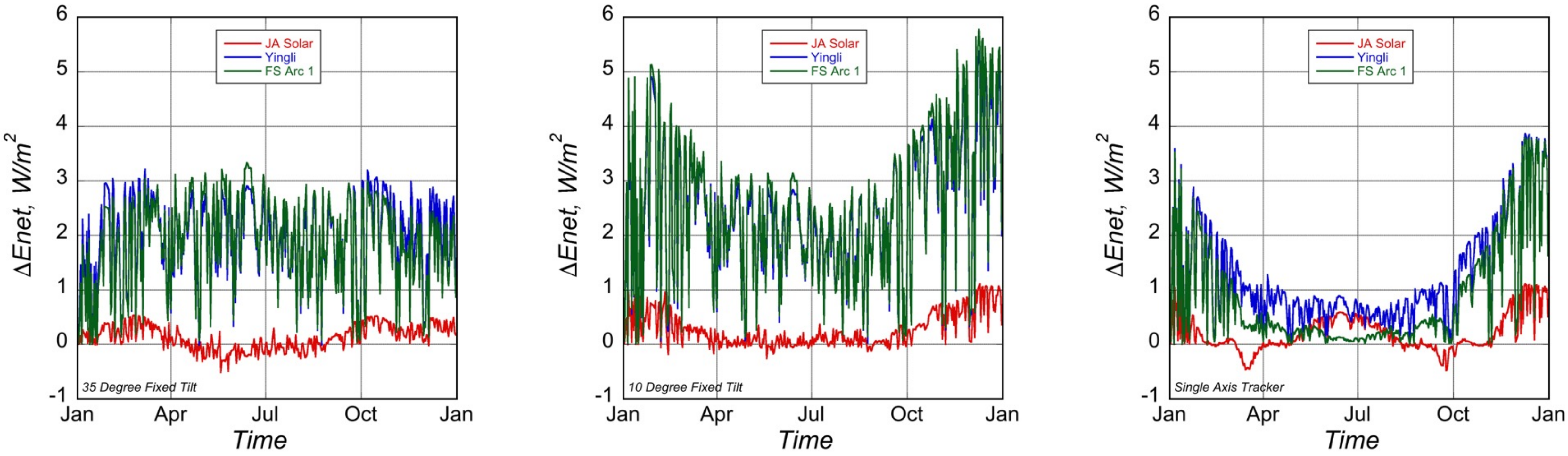
$$\Delta E_{net} = E_{DNI} \cos(\theta)[\Delta f_2(\theta)] \qquad E_{net} = E_{DNI} \cos(\theta) f_2(\theta) + E_{diff}$$

- Determine Daily Average Difference in Net Irradiance

- Determine Daily % Difference in Irradiance, compared to plain glass (directly comparable to % power gain or loss)

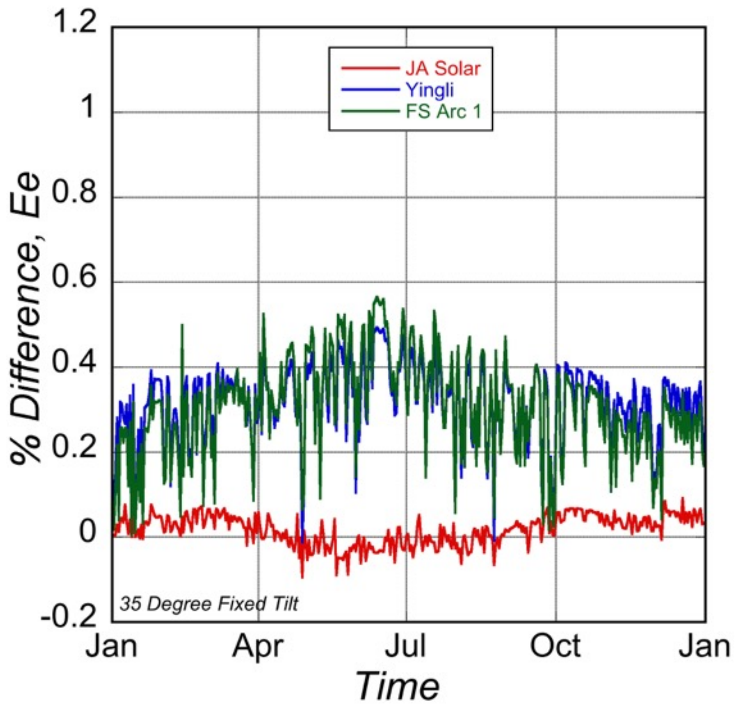
$$\%\Delta E_{net} = \frac{E_{DNI} \cos(\theta)[\Delta f_2(\theta)]}{E_{DNI} \cos(\theta) f_2(\theta)_1 + E_{diff}}$$

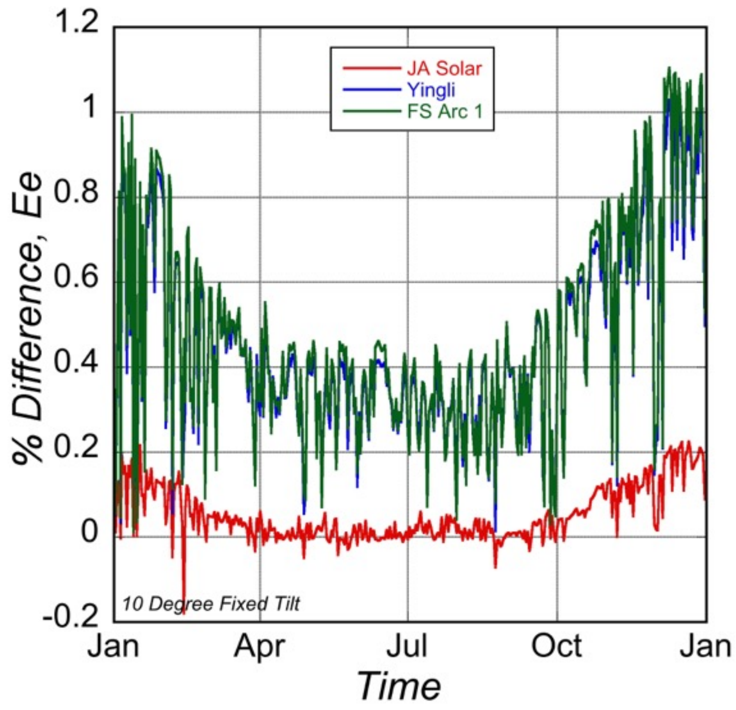
Difference in Net Irradiance

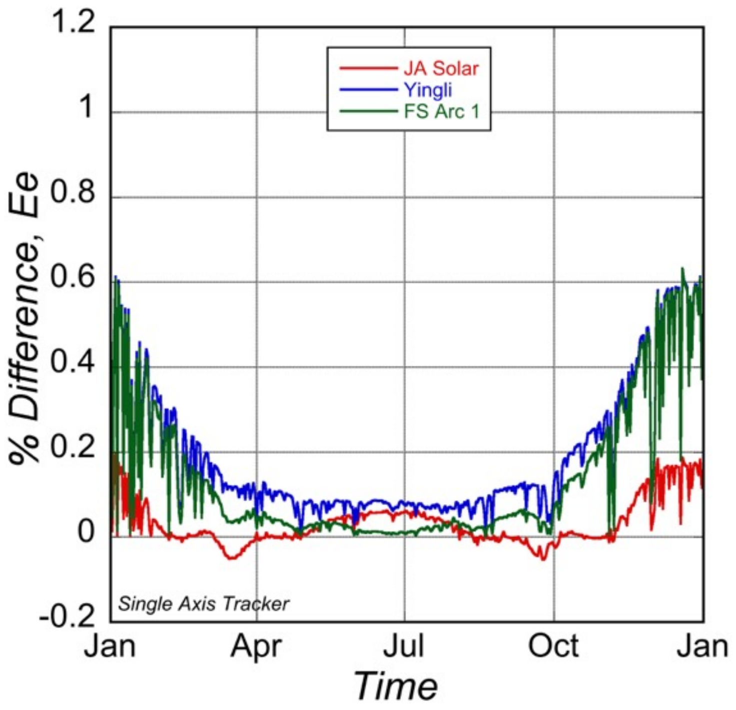


- Results are normalized for length of day – reveal seasonal differences that are dependent on AOI only
- Performance differences can clearly be seen, both between modules and systems
- For 35° Tilt, gains for the two modules with the most pronounced differential are seasonally flat
- For both 10° Tilt and Single Axis Tracker, gains for these same two modules show strong seasonality (better relative performance in Winter)

% Difference, Relative to Plain Glass

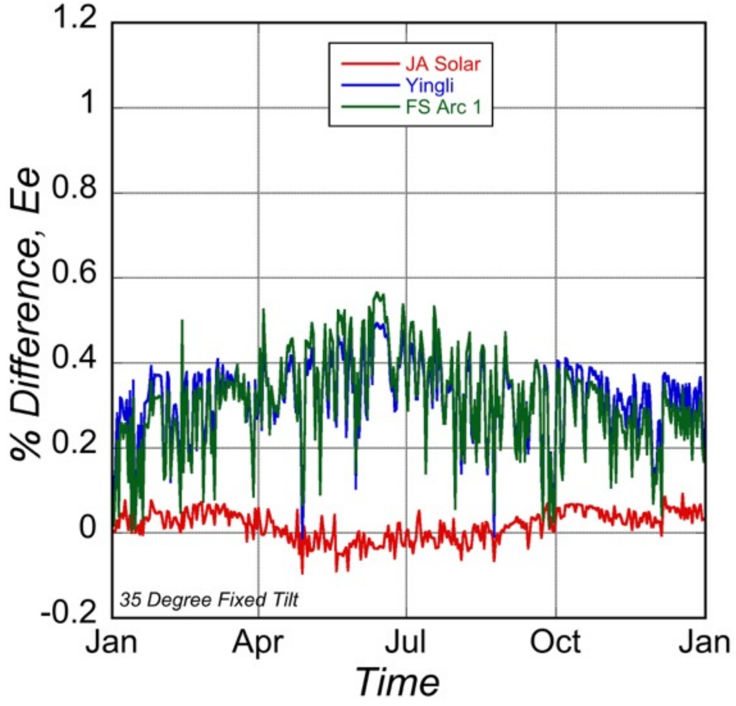


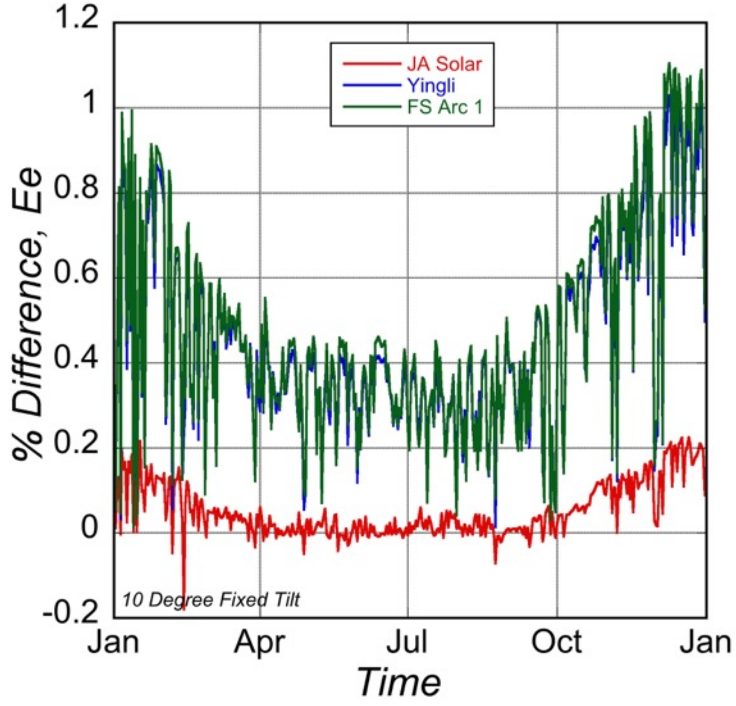


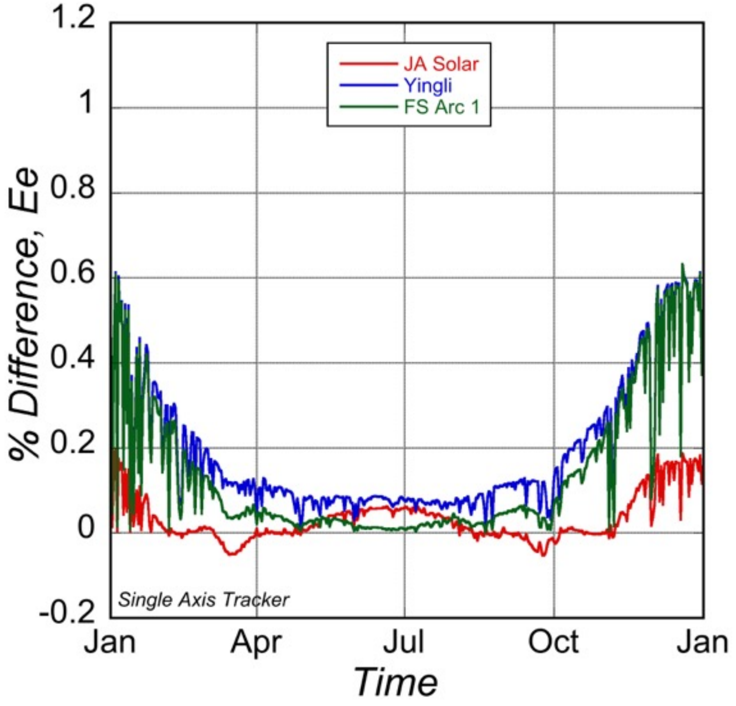


- Results are totaled for each day, includes seasonal differences due to length of day
- Performance differences relative to the reference module (plain glass) can be quantified
- For 35° Tilt, modules with seasonally flat gains in differential provide a higher % gain in summer due to longer day
- For both 10° Tilt and Single Axis Tracker, seasonal gains are more pronounced.
- For 10° Tilt, Winter gains up to 1% are observed.

Annual Gain







Annual % Gain in Effective Irradiance

Module	Orientation		
	35° Tilt	10° Tilt	SAT
JA Solar	0.02	0.04	0.03
Yingli	0.33	0.44	0.16
First Solar ARC1	0.33	0.46	0.10

- Annual gains (approaching 0.5%) were highest for 10° Tilt orientation
- Annual gains were modest for Single Axis Tracker
- Module with lowest differential response showed negligible annual gains in any orientation

Summary

- Differential Analysis is an effective approach to visualize and quantify the effectiveness of ARCs at non-normal incidence angles
- “Better” performing modules show minimal differential response at low incidence angles and strong peaks at higher angles
- “Weaker” modules may show dips in response at lower angles. This may negate gains seen at higher angles.
- Differential Analysis can be extended to demonstrate effectiveness of different ARCs in different deployment scenarios
- Of the scenarios investigated, 10° Fixed Tilt benefitted the most from good ARCs and Single Axis Trackers benefitted the least.

Reminder: Gains or losses in Incident Angle response due to an ARC are IN ADDITION TO gains in normal transmission

Thank You!

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