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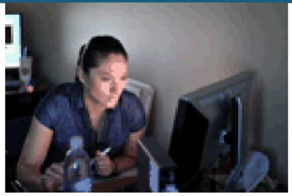
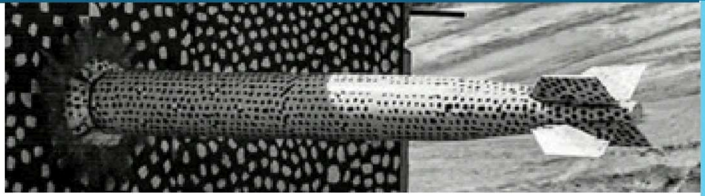
Differential Analysis of the Incident Angle Response of Utility-Grade PV Modules





PRESENTED BY

Bruce King and Charles Robinson

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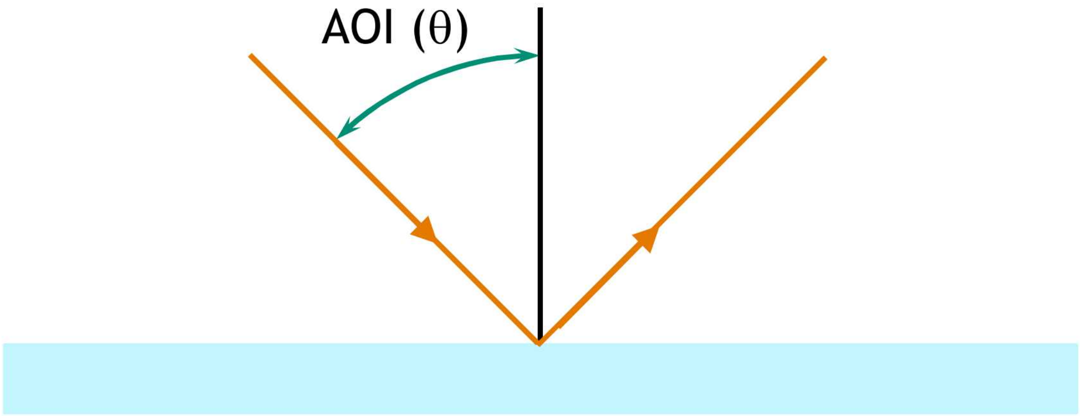
Introduction

Introduction

- Angle of Incidence (AOI) response describes combined off-axis losses from a PV module due to both front surface and internal reflections
  - 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

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

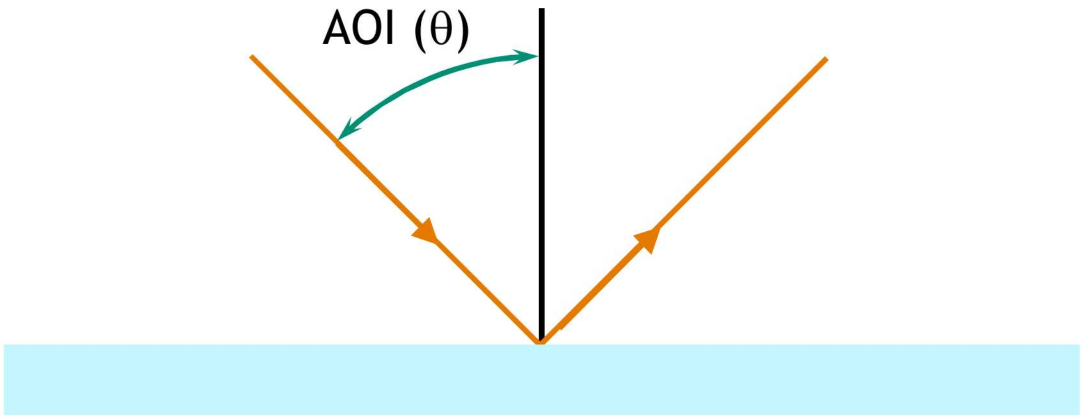
- Anti-reflective coating (ARC) products may ENHANCE direct transmission while also affecting AOI losses (for better or worse)
- Differences in the reflective properties between modules can be difficult to discern; day-to-day and site-to-site variability increase uncertainty in these differences



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

ID	Model	SNL ID
Mod1	Commercial, no ARC	3262
Mod2	Commercial, unknown ARC	3268
Mod3	Commercial, unknown ARC	3267
ARC1	Commercial, experimental ARC	3261



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°

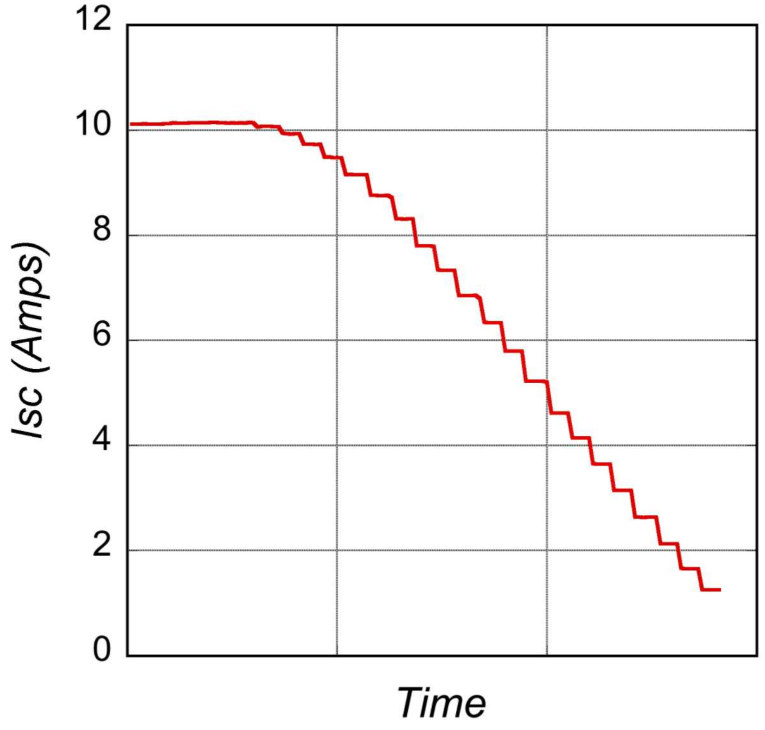
Typical Incident Angles

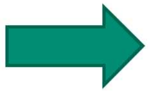
Bruce H. King, Clifford W. Hansen, Dan Riley, Charles D. Robinson, Larry Pratt, "Procedure to Determine Coefficients for the Sandia Array Performance Model (SAPM)," SAND2016-5284, Sandia National Laboratories, Albuquerque, NM, 2016.

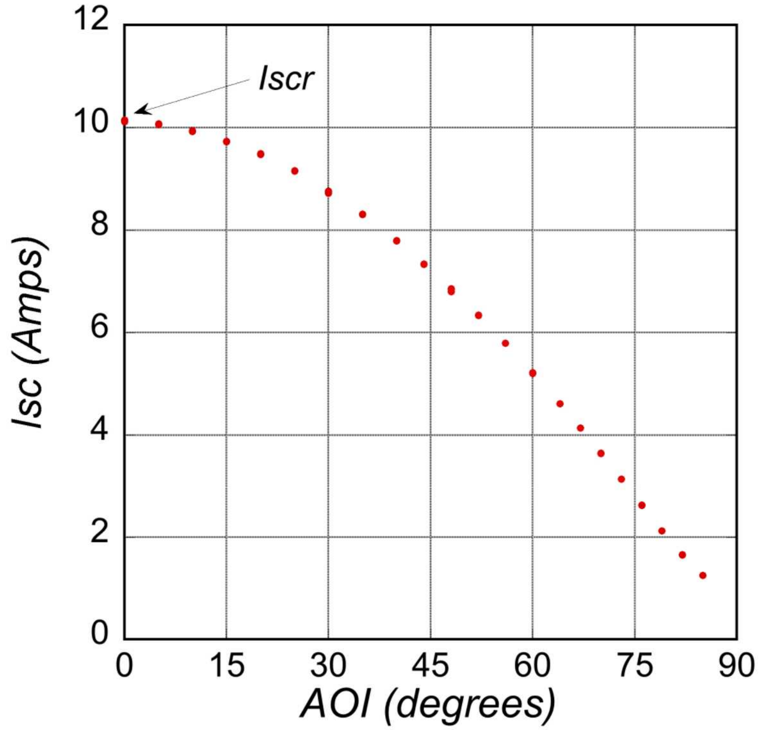
Outdoor Angle of Incidence Characterization Method

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

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

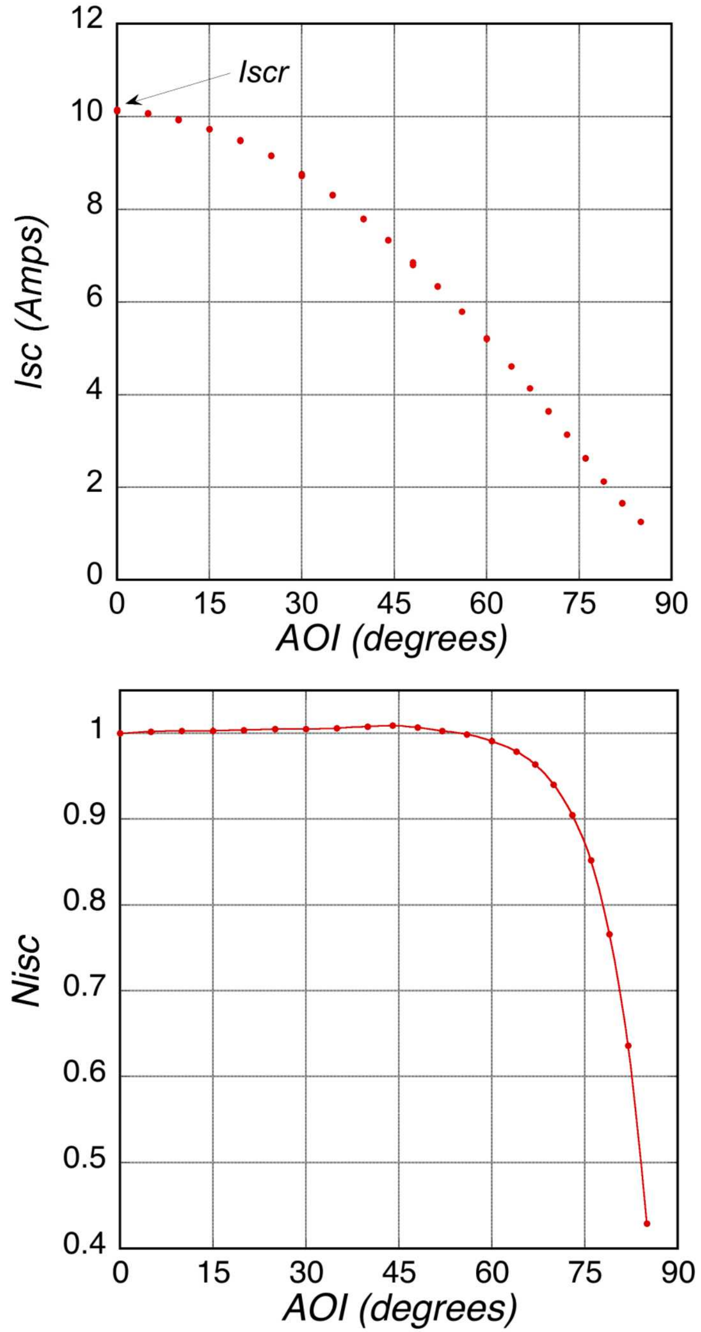
- Find reference I_{scr} at AOI = 0°

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

- Find normalized I_{sc} (Nisc)

$$Nisc = \left[\frac{E_0}{E_{DNI}\cos\theta}\right]\left[\frac{I_{sc,Tr,AM1.5}}{I_{scr}} - \left[\frac{E_{diff}}{E_0}\right]\right]$$

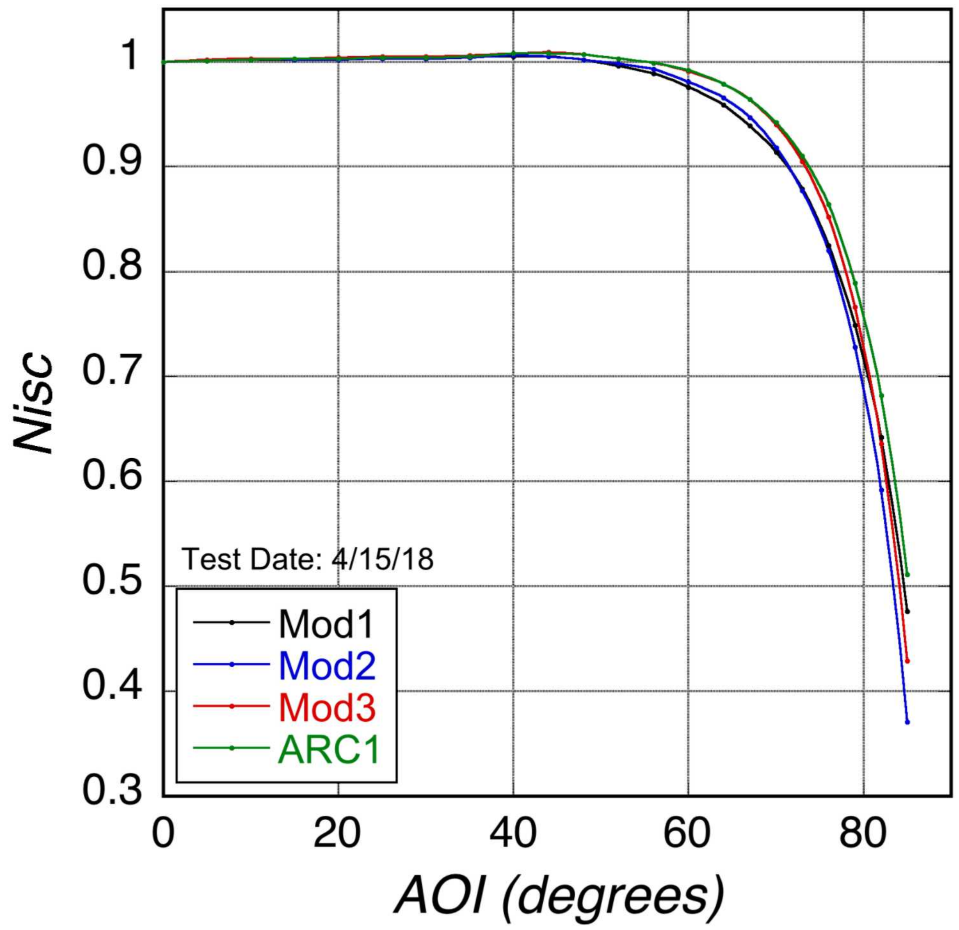
- Plot Nisc vs AOI to visualize function, $f_2(\theta)$



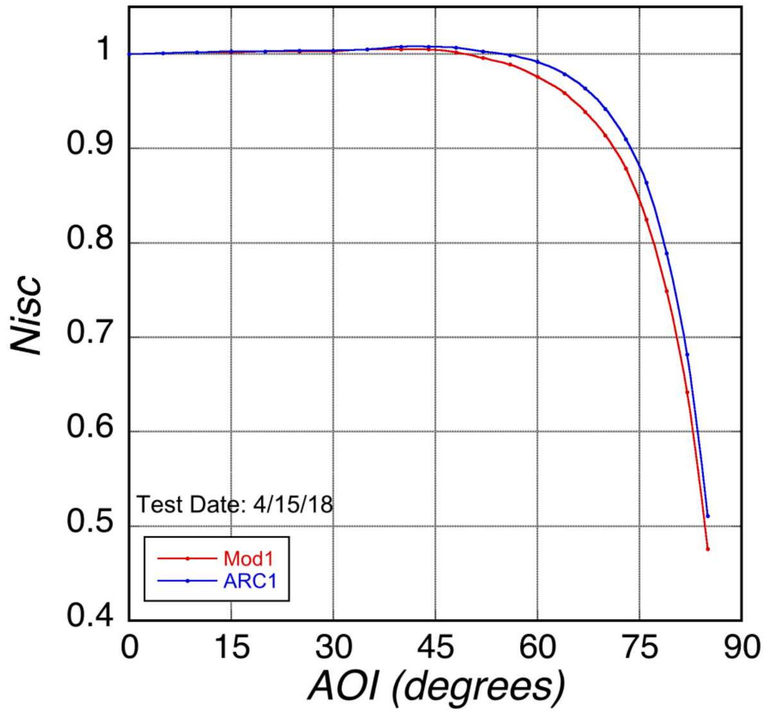
Test Results and Differential Analysis

Results – Standard Reporting

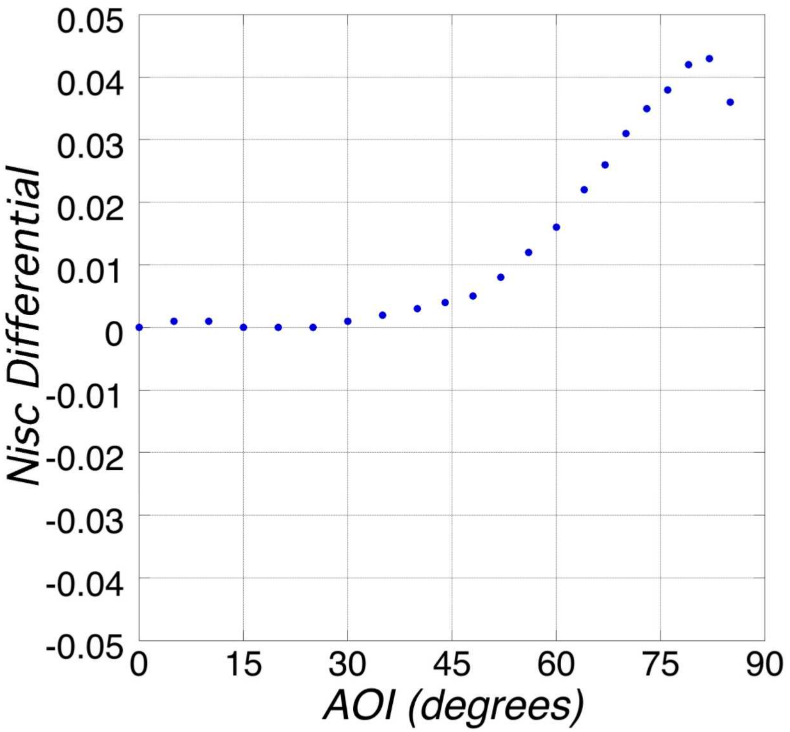
- All modules relatively flat (pure cosine response) out to ~ 55°
- Minor apparent differences beyond 55°
- Mod3 and ARC1 appear to be similar and consistently outperform all other modules commercial modules
- Performance assessment is typically visual and subjective (“better” or “worse”)



New Approach to Quantifying Performance – Differential Analysis



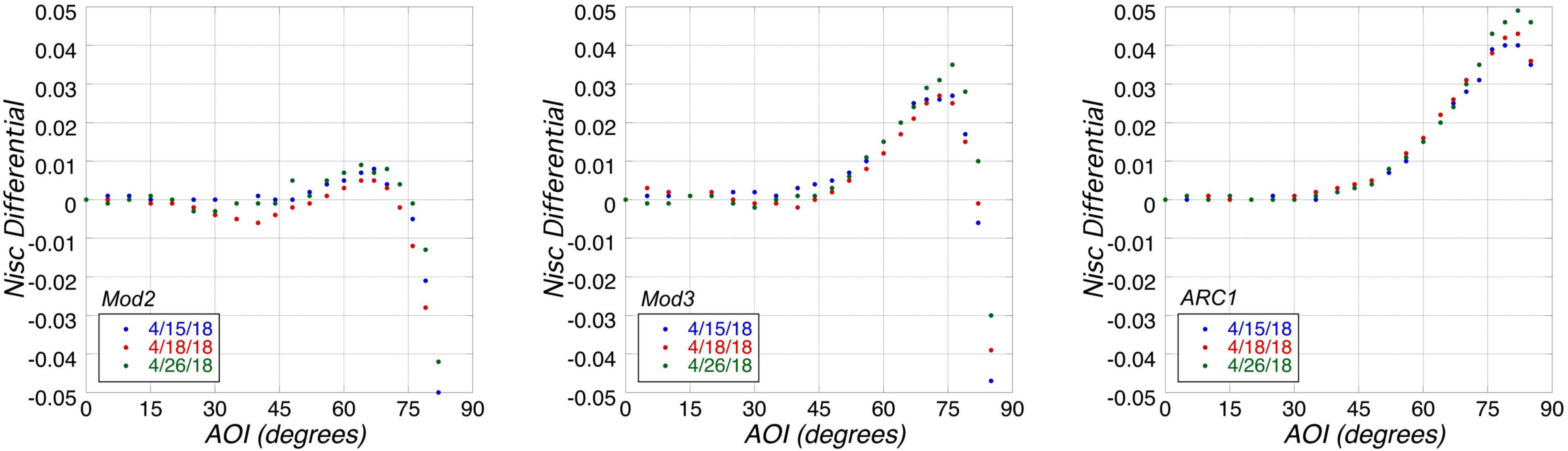
$$Nisc = \left[\frac{E_0}{E_{DNI}\cos\theta}\right]\left[\frac{I_{sc,Tr,AM1.5}}{I_{scr}} - \left[\frac{E_{diff}}{E_0}\right]\right]$$



$$\Delta Nisc = \left[\frac{E_0}{E_{DNI}\cos\theta}\right]\left[\left[\frac{I_{sc,Tr,AM1.5}}{I_{scr}}\right]_2 - \left[\frac{I_{sc,Tr,AM1.5}}{I_{scr}}\right]_1\right]$$

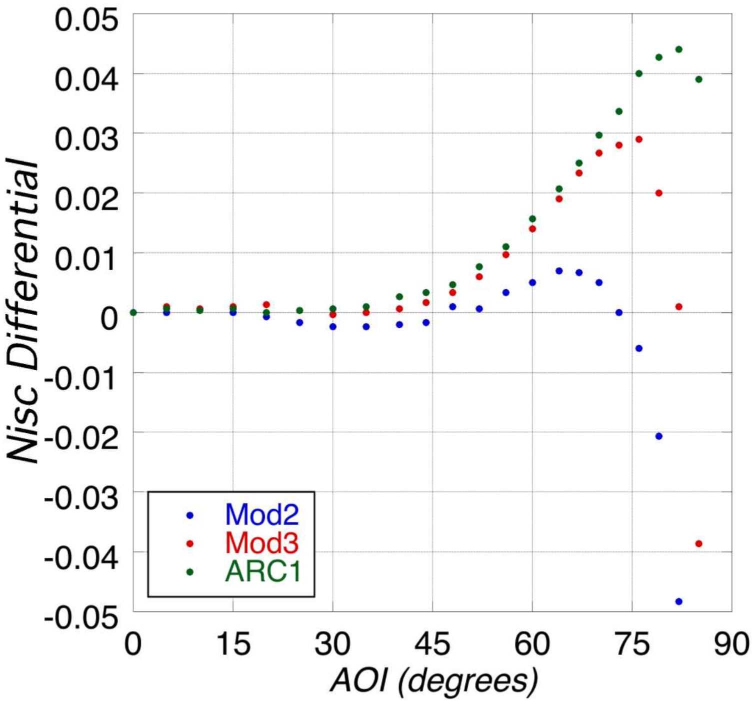
- Determine simple differential between test device and a reference
- For this example, we use a plain glass module with no ARC
- Reference and test device must be measured simultaneously to eliminate differing environmental conditions between tests
- Resulting differential is independent of diffuse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

Differential Analysis – Three Modules, Three Days



- Differential was determined for three modules tested on three separate days
- General shape of the curve is consistent for each module on different days
- Differential clearly highlights improvement at high AOI
- Mod2, with least benefit, visibly displays the greatest spread between days
- ARC1 displays tight spread between days
  - *Most closely matches construction of the plain glass reference – future investigation*

Differential Analysis – Average of 3 Days



- Results averaged across three days of testing
- Differences can clearly be seen between not only the plain glass module but each other
- 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 Mod2 dips at intermediate AOI, ~35°
- Peak as high as 4.5% can be seen, but at steep angle where power is low

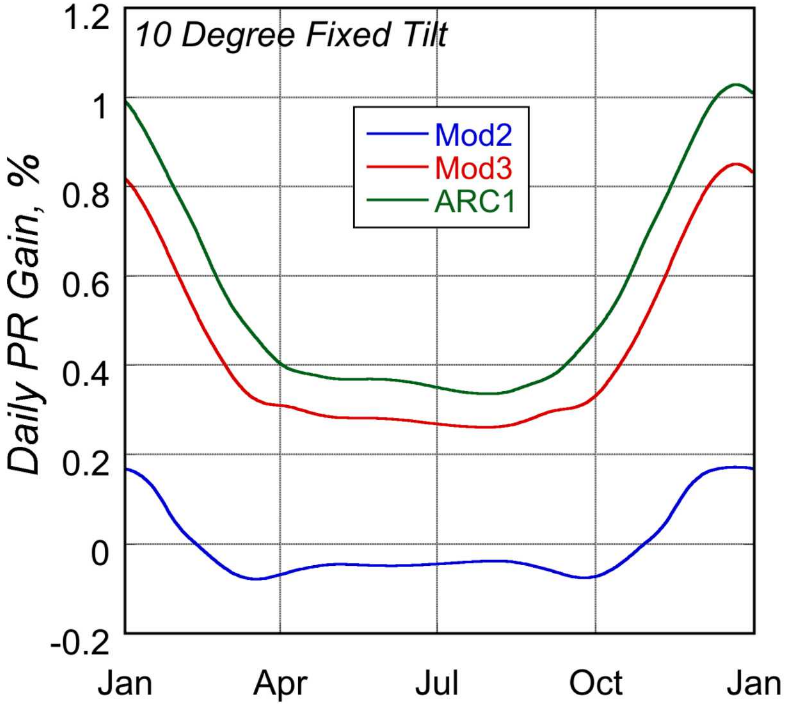
Predicted Annual Gain in PV System Performance

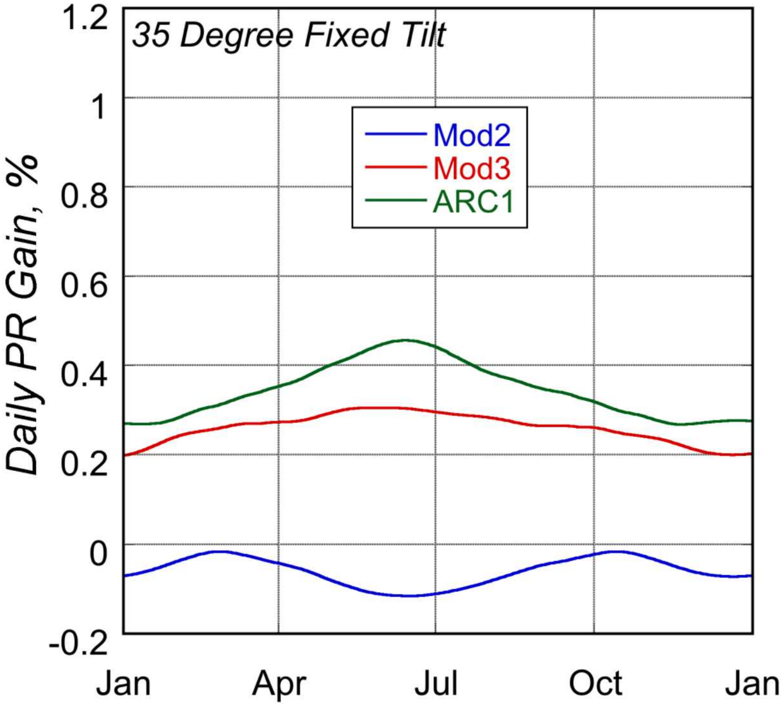
Application to PV System Performance

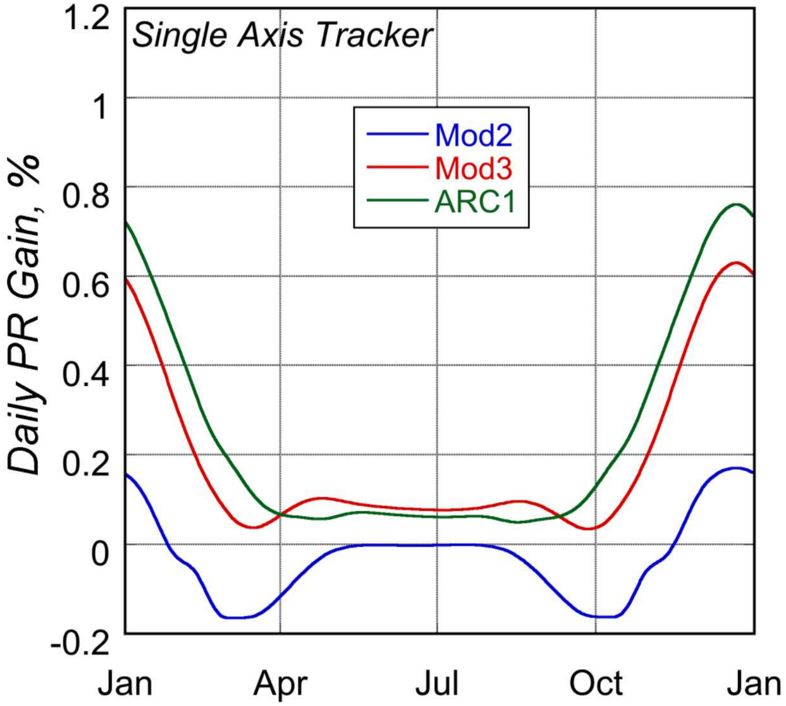
- Apply differential to system performance predictions to understand potential absolute gains
  - Focus on reflective properties only: factors such as cell temperature and spectrum were not considered
  - Differences in system power directly proportional to differences in net effective irradiance
- Differential response for each module was applied a range of fixed tilt orientations from 0° to 60°, and a Single Axis Tracker (SAT)
- One year synthetic clear-sky data set generated for Albuquerque, NM
  - Clear sky functions from PV_LIB were used to generate E_{DNI} and E_{GPOA} for each timestep and orientation
  - Set upper bound on potential gains
- $\Delta f_2(\theta)$ for each module found from a lookup table of averaged values using spline interpolation
- Simplified version of a Performance Ratio was used to normalize calculated values and determine potential absolute gains

$$PR\ Gain = \frac{\sum_k \left[E_{DNI} \cos(\theta)[\Delta f_2(\theta)]\right]_k [time]_k}{\sum_k [E_{GPOA}]_k\ [time]_k}$$

Daily PR Gain

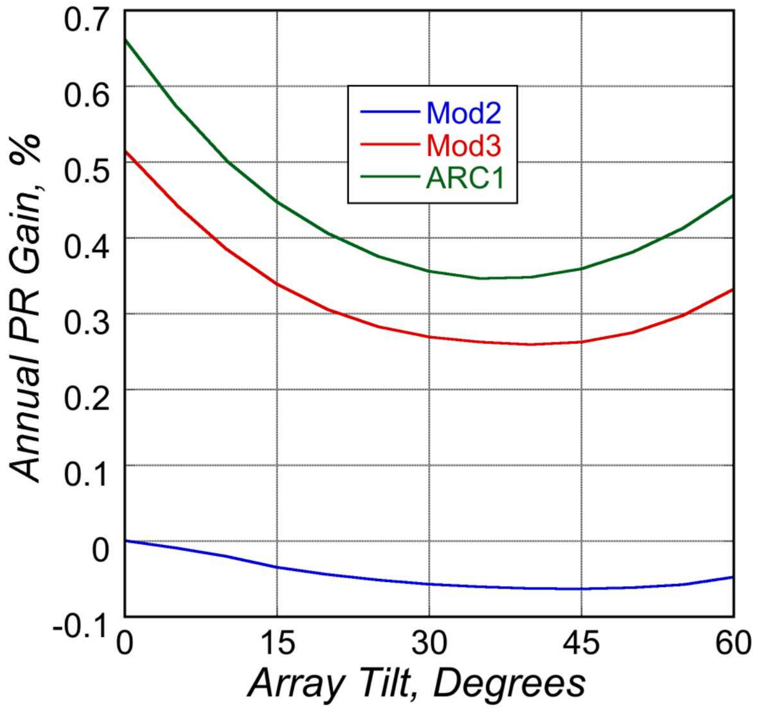






- Performance differences can clearly be seen, both between modules and systems
- Seasonal gains as high as 1% can be seen
- Seasonality most pronounced for 10 Degree Fixed and Single Axis Tracker
- For 35 Degree Fixed Tilt, gains are more seasonally flat, but upwards of 0.5%
- Gains for SAT largely vanish during the summer months, regardless of differential response

Annual PR Gain, 0° - 60° Fixed Tilt and SAT



Annual PR Gain, %

Module	Orientation		
	10° Tilt	35° Tilt	SAT
Mod2	-0.02	-0.06	-0.04
Mod3	0.39	0.26	0.15
ARC1	0.50	0.35	0.18

- Experimental ARC1 shows potential gains of 0.5% or greater at shallow array tilt angle
- ARC1 consistently show 0.1% greater gain than Mod3 at all fixed tilt orientations.
- Minimum gains were realized at close to the optimal orientation of 35°for Albuquerque
- Annual gains were modest for Single Axis Tracker
- Mod2 showed negligible annual gains or even losses for all scenarios

Summary

- Differential Response provides an effective way of visualizing improvements in performance of advanced coatings at non-normal incidence angles
- Mathematically, Differential response is independent of diffuse irradiance
- "Better" performing modules show minimal differential response at low incidence angles and strong peaks at higher angles
- Differential response can be applied to system performance predictions to understand potential absolute gains
- Seasonal gains as high as 1% were predicted for sub optimal (shallow tilt) installations whereas annual gains of 0.5% or better were predicted for these same configurations
- Single-axis trackers were consistently seen to benefit the least from advanced coatings

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

Thank You!

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