CFV solar test laboratory

TESTING — CERTIFICATION — INNOVATION

Improvements in CFV's Outdoor IAM Measurement Method

Last Update: 2018-04-29

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PV Systems Symposium, May 2018

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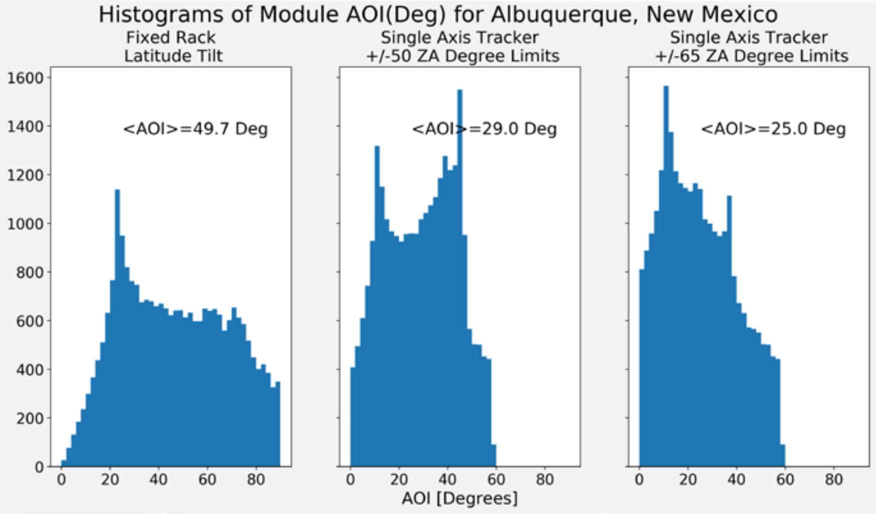
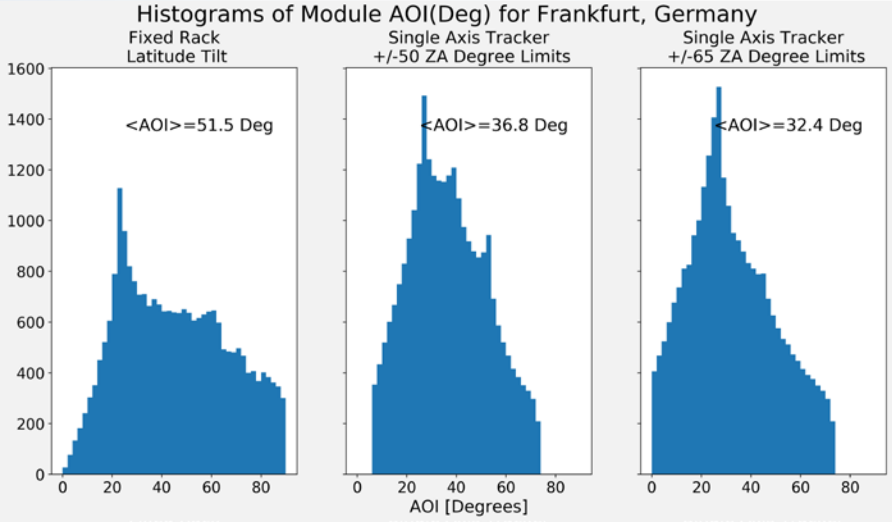
Table of Contents

What is IAM and Why Do We Need It?

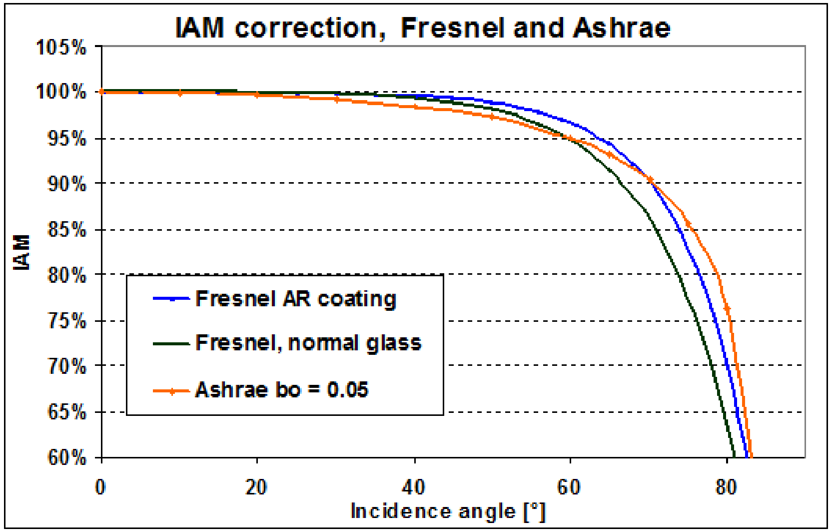
- The incidence angle modifier (IAM) is defined as the fraction of beam irradiance absorbed from a flat-plate module's front surface as a function of angle of incidence (AOI).
- Modules are oriented at non-zero AOI during most of the year, with high latitude sites most influenced.
- IAM impact can be reduced through use of single axis trackers, but not eliminated, and thus should be well understood.





Sandia Model, IEC 61853-2, PVsyst

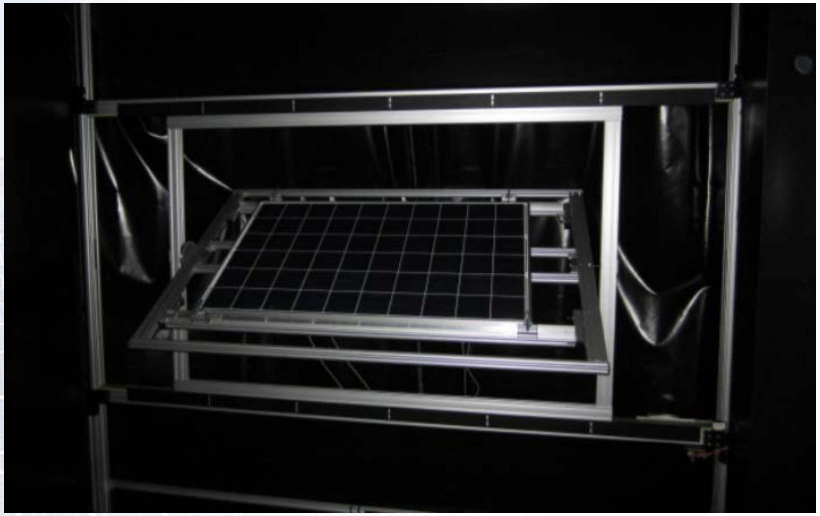
- Sandia Model incorporated the incident angle modifier in 2004 (SAND2004-3535), described by a 5th order polynomial fit to measured data, $f_2(\theta)$.
- IEC 61853-2:2016 describes methods to measure spectral responsivity and incidence angle effects (relative transmission). Both indoor and outdoor methods are described.
- PVsyst 6 allows user to define custom IAM profile for a module type.
- The aim is to calculate the effective irradiance injected into a module.



PVsyst

Indoor IAM Measurement

- **Defined in IEC 61853-2:2016 §7.2**
  - **Measure $I_{SC}(\theta)$ over a range of incident angles from 0° to 80° in steps of 5-10 °.**
  - **Generally requires special samples, e.g. mini module with minimum of one active cell (cSi), modified full size modules, or small coupon samples for thin-film modules.**
  - **Requires well collimated light source and stray light mitigation.**
- **Equipment Requirements:**
  - **Class B(uniformity)/C(temporal stability) solar simulator**
  - **Recommended >95% of irradiance from within 10° FOV**
  - **Module mounting fixture allowing position accuracy within +/- 1 deg**



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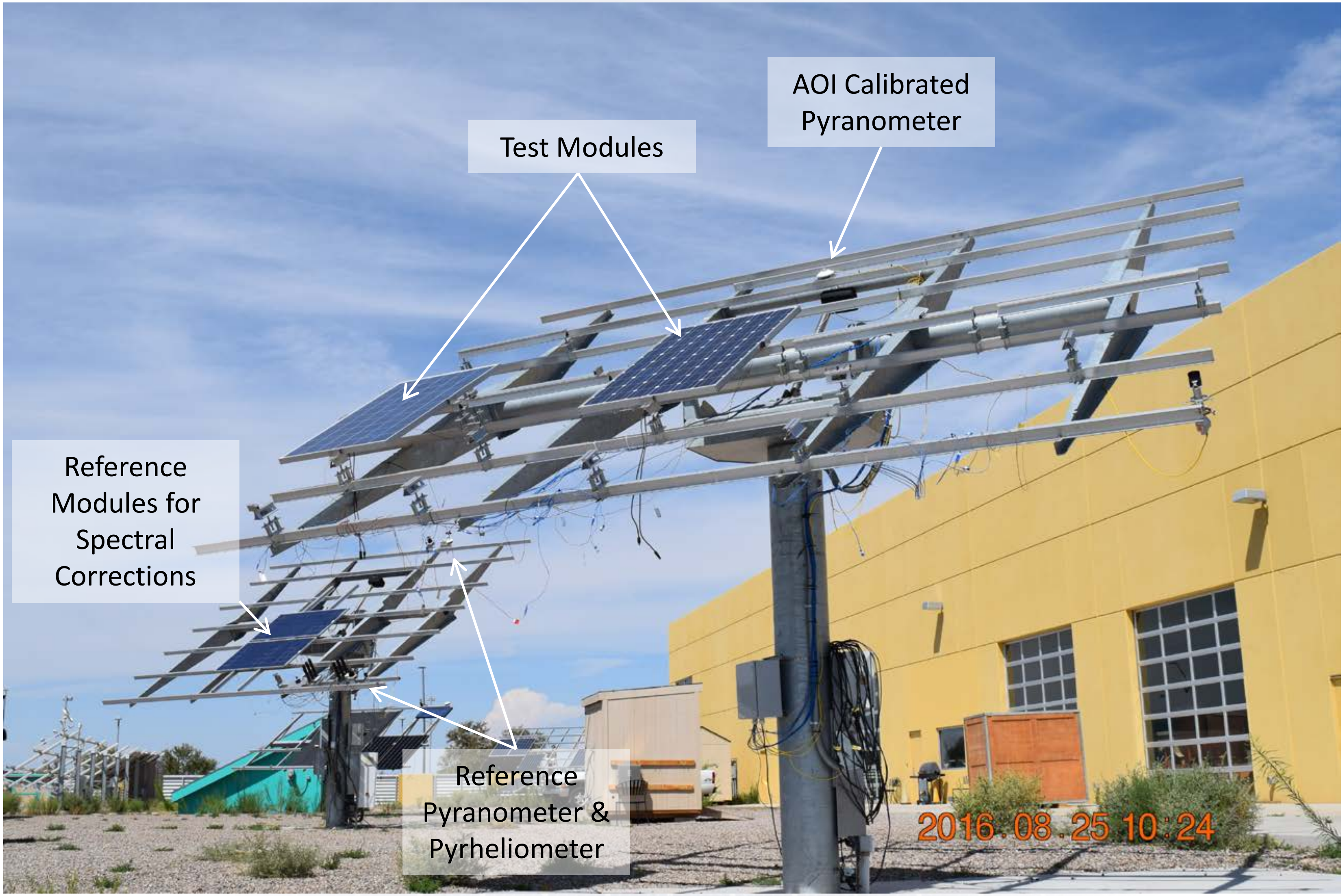
Outdoor IAM Measurements at CFV

- **Relevant procedure defined in IEC 61853-2:2016 §7.3. CFV method is similar, jointly developed with Sandia.**
  - SAND2016-5284
  - Install pyrheliometer (DNI) and pyranometer (POA) on a reference two-axis tracker. Reference tracker to follow the Sun during the entire test.
  - Install and align test modules on a second two-axis tracker. Install AOI calibrated pyranometer along with test modules for measurement of AOI dependent diffuse irradiance.
  - Allow module temperatures and irradiance sensors to stabilize.
  - Move the AOI test tracker to increasing AOI with 3 minute dwells at each AOI step to ensure module $I_{SC}(\theta)$ and irradiance sensors have stabilized.
  - Analyze the data according to Eq. (4) of IEC 61853-2:

$$\tau(\theta) = \frac{I_{SC}(\theta)G_{POA,0} - I_{SC,0}G_{Diff}(\theta)}{I_{SC,0}G_{DNI}\cos(\theta)}$$

Outdoor IAM Measurements at CFV

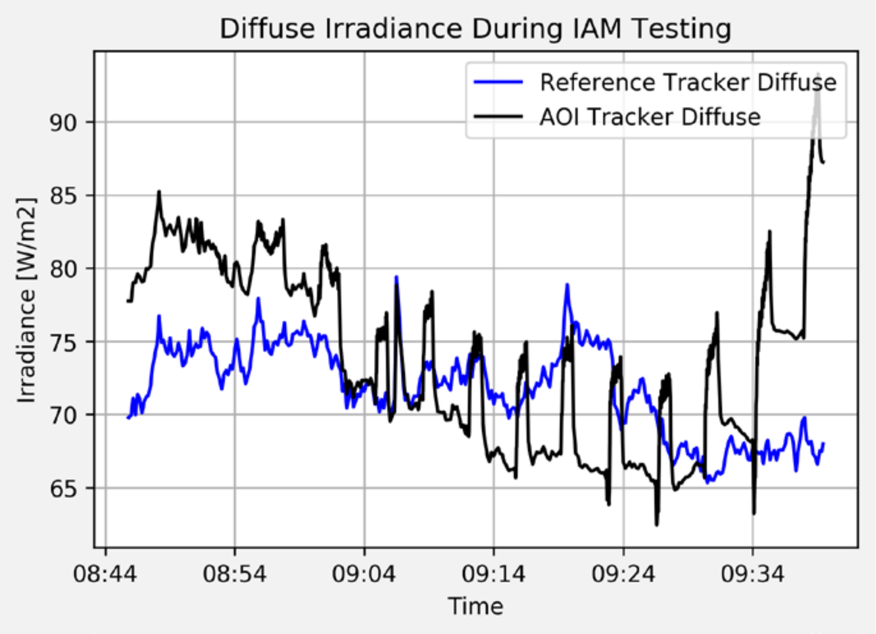


Pros and Cons of Indoor and Outdoor

- **Advantages/Disadvantages of Indoor Method**
  - Not weather-dependent
  - Diffuse irradiance can be minimized
  - No temperature correction necessary (except for steady state simulators)
  - Restricted to mini modules or single cell measurements. (Coupons are not always possible and accurate, especially for monolithic TF modules)
  - Volume uniformity of solar simulators is not ideal for IAM measurements.
- **Advantages/Disadvantages of Outdoor Method**
  - Compatible with all module designs and non-destructive
    Light source is the sun, with the correct spectrum and shape (disk source, not point).
  - Strongly weather dependent.
  - AOI calibrated pyranometers and/or specialized trackers are required.

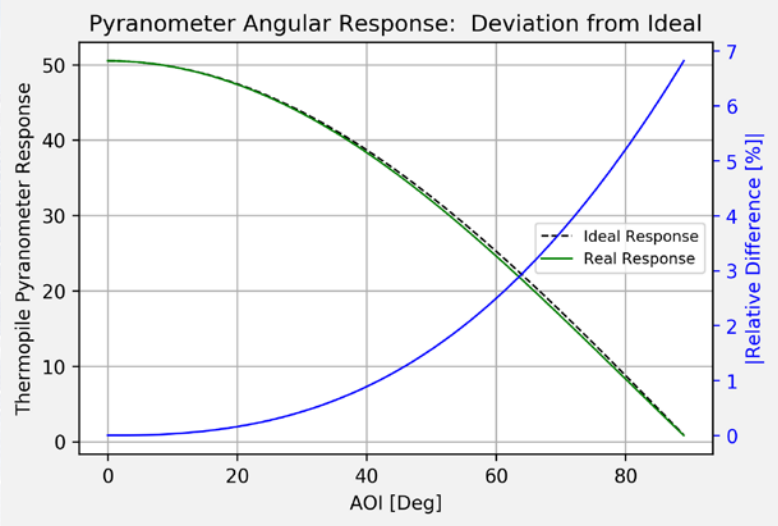
Non-uniform Diffuse Irradiance

- AOI testing with the tracker pointed too close to the horizon can lead to errors due to non-uniform diffuse mitigation.
- Due to mechanical limitations of most commercial 2-axis trackers, IAM testing CANNOT be performed in elevation only while tracking the Sun in azimuth enabling direct measurement of diffuse with a shaded pyranometer.
- CFV uses a 'El+7°' method, keeping the tracker pointed above the Sun, reducing the variability of the diffuse component (But it MUST be measured!).



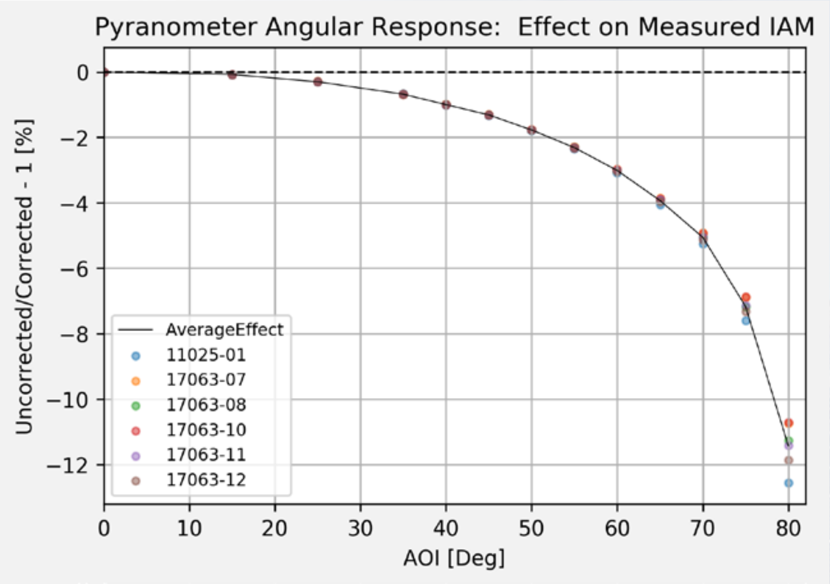
Pyranometer Characteristics

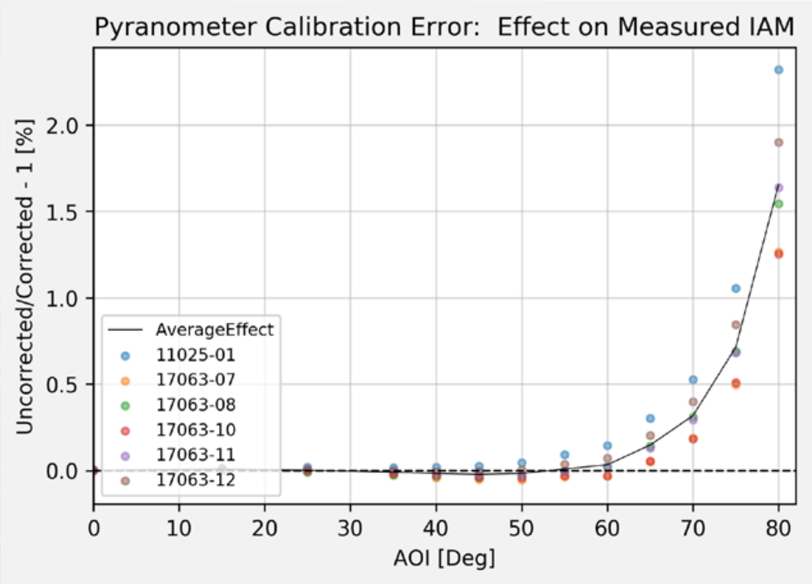
- Pyranometers have non-negligible response times. Tracker movement during the test must include dwells in order to allow pyranometer response to stabilize. Response times can vary from ~15 to 60 seconds.
- Contrary to the common belief, pyranometers are actually not perfect cosine receivers. AOI calibrated pyranometers can be used for measuring diffuse irradiance in the test module plane.



Pyranometer Characteristics

- **Analysis of IAM test data without correction for angular response of the pyranometer leads to relative errors in the measured IAM of ~12% at 80° AOI.**





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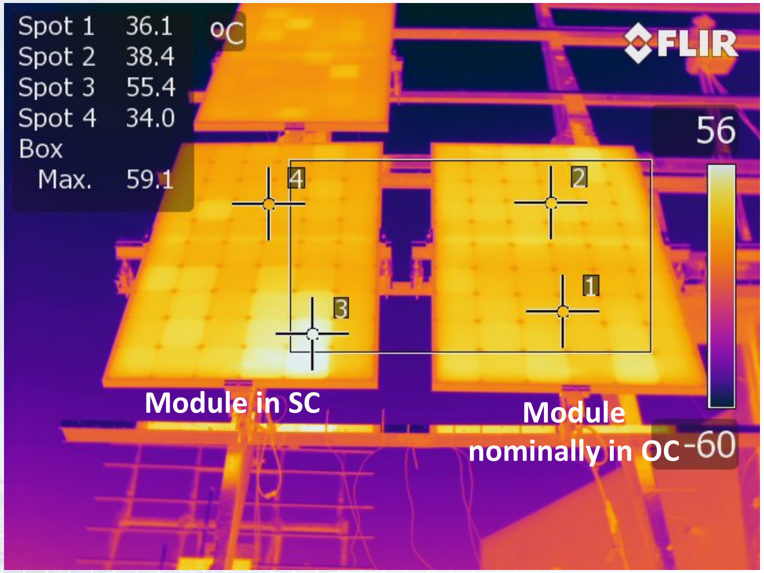
Module Temperature Uniformity

- Module $I_{SC}(\theta)$ is temperature corrected using module temperatures measured with calibrated thermocouples.
- Module is in open circuit except when measuring (as specified in IEC), which improves module temperature uniformity.
- Spatial variation of module temperatures are minimized, ensuring accurate temperature corrections.



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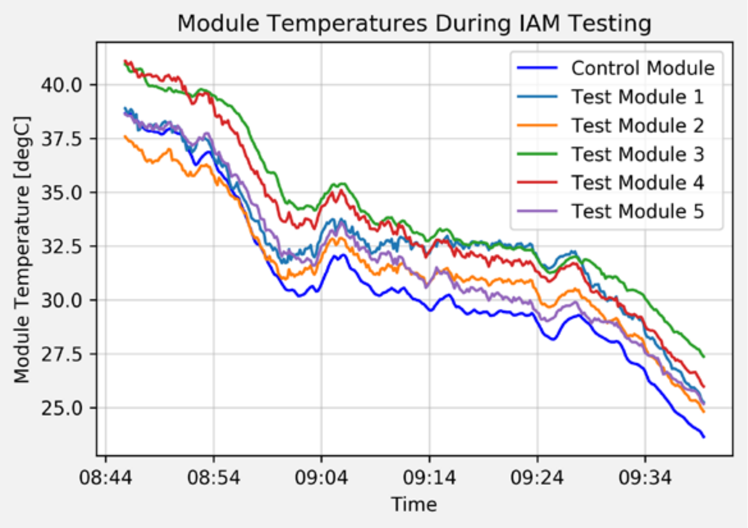
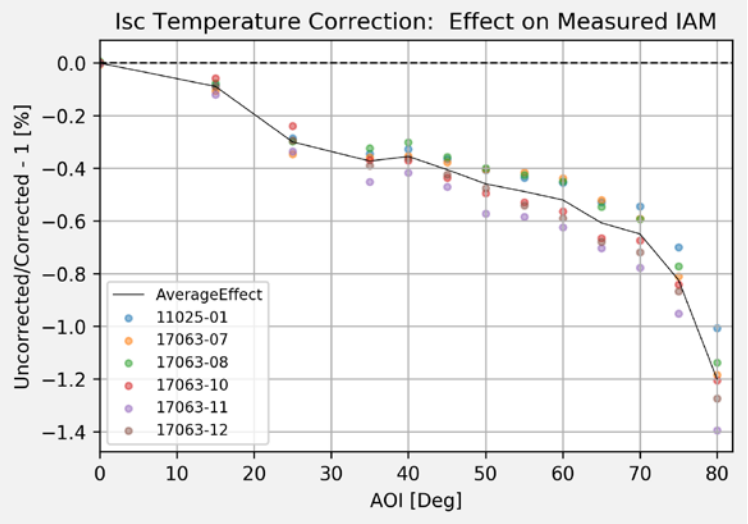
Module Temperature Correction

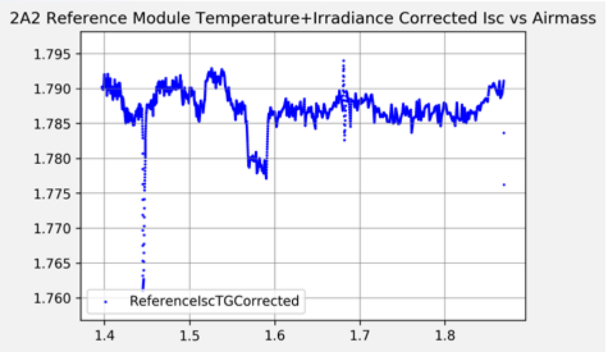
- **Module temperatures can vary by as much as 15-30 °C during a test (0.6-1.2% assuming $\alpha_{Isc} = 0.04\ \%/°C$).**
- **In the absence of measured α_{Isc} coefficients datasheet values are adopted.**
- **Errors in the IAM due to errors in the adopted temperature coefficients are small, since the α_{Isc} is small.**

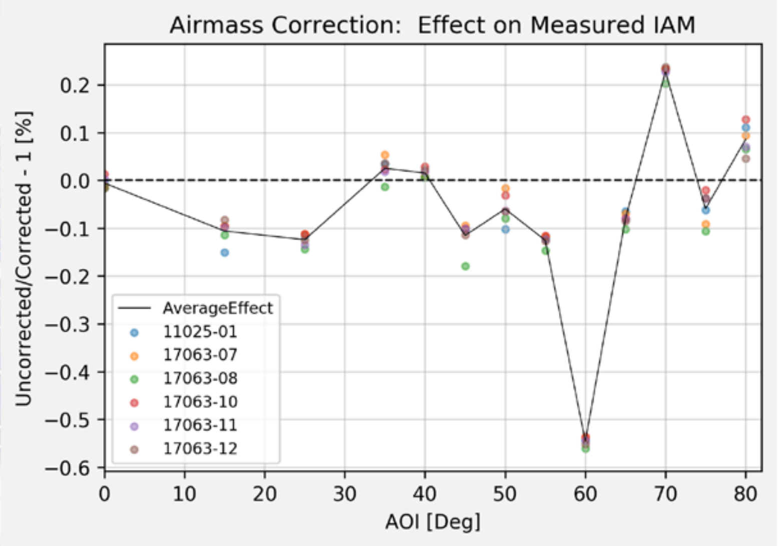




Spectrum Change During Test

- Due to tracker axis limits, testing is NOT conducted at solar noon, but rather at larger Solar zenith angles in either the morning or afternoon.
- To account for spectrally induced changes in module $I_{SC}(\theta)$ due to airmass, spectrally identical reference modules are installed on the reference tracker used for measuring DNI.
- Spectral corrections are derived using temperature and irradiance corrected reference module.
- Relative errors of ~1% can be corrected for.





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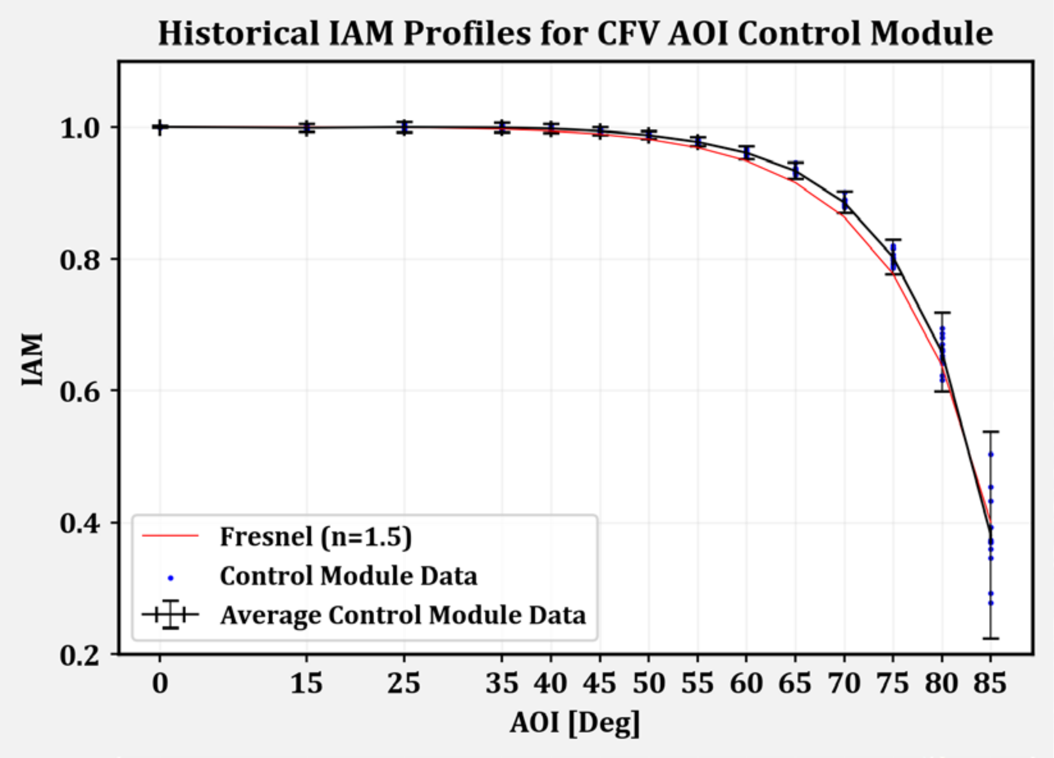
2 Years of Control Module Measurements

- **During each IAM test a non-ARC control module is measured and serves as a benchmark for validating each test.**
- **12 AM/PM pairs of IAM measurements since mid-2016 are represented.**



Summary

- IAM measurements are important for yield calculations, especially for higher latitude sites.
- Outdoor IAM testing is a viable method with important advantages over the indoor method.
- CFV continually strives to improve IAM test methodology through hardware, procedure and analysis improvements.