Recent Advancements in Outdoor Measurement Techniques for Angle of Incidence Effects

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Abstract

Reflection losses from a PV module become increasingly pronounced at solar incident angles >60°. However, accurate measurement in this region can be problematic due to tracker articulation limits and irradiance reference device calibration. We present the results of a measurement method enabling modules to be tested over the full range of 0-90° by articulating the tracker in elevation only. This facilitates the use of a shaded pyranometer to make a direct measurement of the diffuse component, reducing measurement uncertainty. We further present the results of a real-time intercomparison performed by two independent test facilities ~10 km apart

Test Objectives

- Compare the consistency between trackers when performing three different types of tracker articulation
- Demonstrate the use of elevation only/measured diffuse for performing an AOI characterization
- Perform a real-time intercomparison between Sandia and CFV under nominally identical sky conditions (~10km apart)
- Perform an assessment of seasonal variations in AOI measurements.

Equipment

- Three Azimuth-Elevation solar trackers capable of AOI range between 0° and 90°, designated SNL1, SNL2 and CFV.
- AOI-corrected pyranometers measuring global POA irradiance (E_{POA}), mounted in the module test plane
- Pyranometer measuring the diffuse POA irradiance (E_{diff}), mounted in the module test plane (SNL2 only)
- Pyrheliometers measuring DNI (E_{DNI}), mounted on separate weather trackers
- Short circuit current and module temperature measurement
- Four nominally identical PV modules (SunTech STP085S-12Bb-1)

Tracking Methods

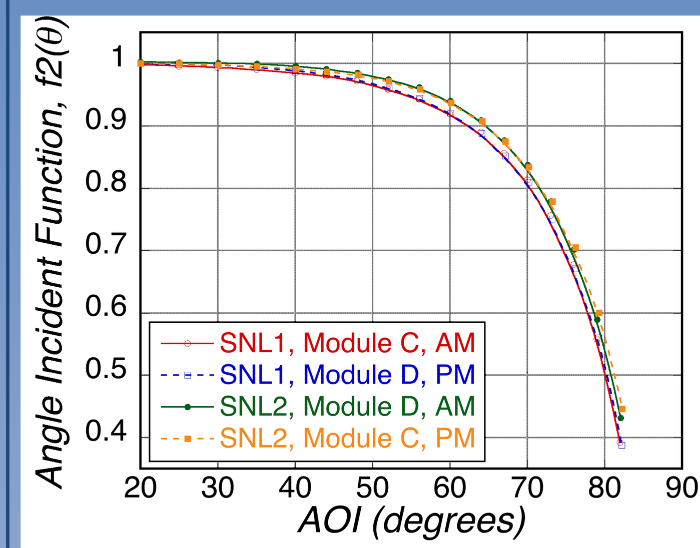
- ***Tracker Elevation = 10°:*** the elevation axis is rotated down to an elevation of 10° above the horizon while the azimuthal axis continues to track the Sun. This elevation is then held constant while the azimuthal axis is rotated to achieve the desired AOI.
- ***Sun Elevation + 7°:*** the elevation axis is rotated up to point 7° above the current sun elevation while the azimuthal axis continues to track the Sun. The relative offset above the Sun is then maintained while the Azimuthal axis is rotated to achieve the desired AOI.
- ***Elevation Only:*** the elevation axis is rotated over the full range of 0°-90° relative to the Sun while the Azimuthal axis continues to track the Sun.

Plane of Array Diffuse Irradiance Measurement

- Elevation only tracking method enables use of a shaded pyranometer to measure POA diffuse directly during measurement of AOI function
- Eliminates need for AOI corrected pyranometer
- Eliminates uncertainty associated with calculating POA diffuse

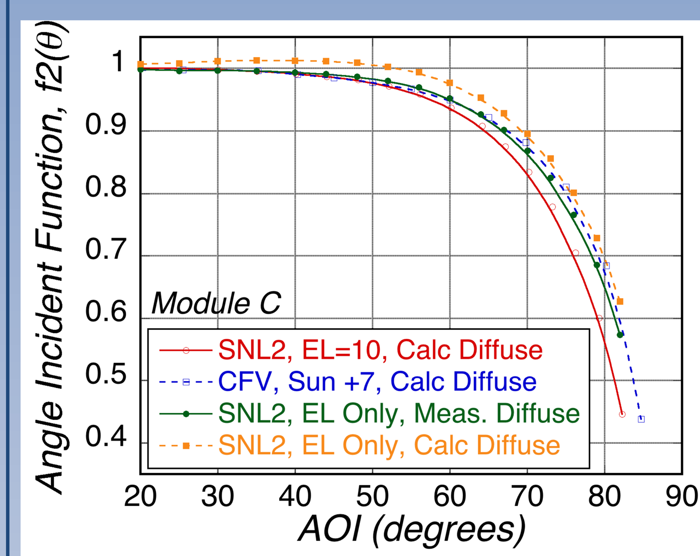
Results and Discussion

Differences Between Modules on Different Trackers



- Modules C and D were tested simultaneously on SNL1 and SNL2 trackers using EL=10 method
- AOI functions determined using the SNL1 tracker were consistently lower than SNL2 tracker
- We believe the difference is due to uncertainty in the AOI calibration of the Global POA pyranometers

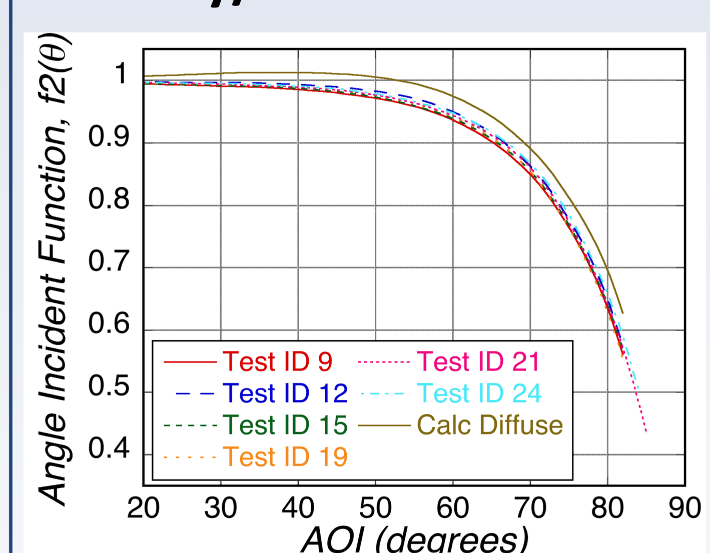
Differences Between Tracker Articulation Methods



- A single module was tested using all three methods.
- Sun+7 and EL Only (measured diffuse) appear to be comparable
- EL=10 was consistently lower than the other two methods
- EL Only (calculated diffuse) rose above unity at intermediate AOI, likely due to calibration uncertainty

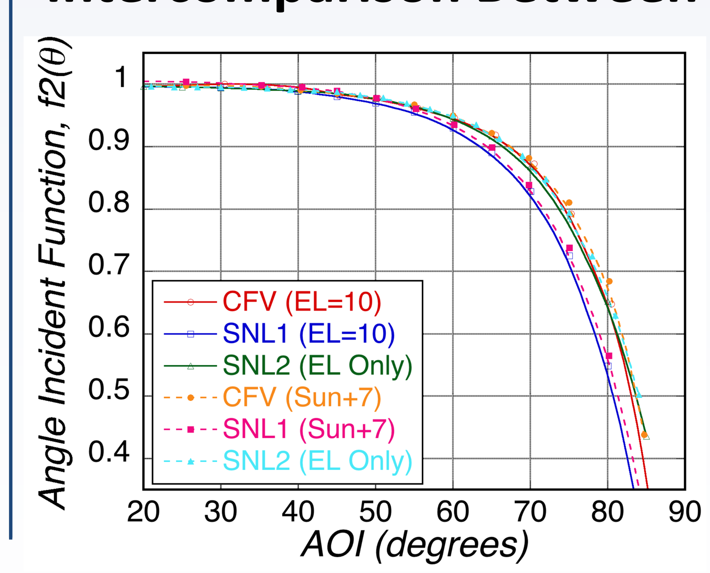
Method	Pros	Cons
Elevation=10	• Can achieve large range of AOI at Solar Noon • Can be performed with most commercial trackers	• High sensitivity to ground reflections • Requires accurate AOI correction for global POA pyranometer
Sun+7	• Low Sensitivity to ground reflections • Can be performed with most commercial trackers	• May require testing when solar conditions are changing rapidly • Requires accurate AOI correction for global POA pyranometer
Elevation Only	• Can achieve large range of AOI at Solar Noon • Eliminates need for AOI corrected pyranometer • Simplified tracker motion profile	• Mild Sensitivity to ground reflections (appears to be mitigated by measured diffuse) • Cannot be performed with most commercial trackers

EL Only/Measured Diffuse POA Irradiance



- Six individual tests across multiple days and modules are compared
- Maximum deviation between tests was approximately 1%
- Use of Measured Diffuse instead of Calculated Diffuse mitigates rise above unity
- This method in general produced the most consistent AOI functions

Intercomparison Between Sandia and CFV



- Two sets of tests were conducted simultaneously with all three trackers under identical sky conditions
- SNL2 (EL Only) and CFV trackers produced nearly identical AOI functions
- Functions generated on SNL1 were consistently lower than functions produced by the other two trackers

Angle of Incidence Function, $f_2(\theta)$

E_e	Effective solar irradiance that reaches the cells (dimensionless)
E_o	Reference irradiance (1000 W/m²)
E_b	Beam component of irradiance (W/m²)
E_{DNI}	Direct normal irradiance (W/m²)
E_{diff}	Global diffuse irradiance (W/m²)
E_{POA}	Global irradiance on the plane of the module (W/m²)
$f_1(AM)$	Empirical function relating air mass to I_{sc} as a proxy for solar spectral influence (dimensionless)
$f_2(\theta)$	Empirical function relating reflection losses due to solar incidence angle to I_{sc} (dimensionless)
I_{sc}	Short circuit current (A)
I_{sco}	Short circuit current at STC (A)
I_{scr}	Reference short circuit current measured at 0° incidence angle during determination of f(q)(A)
T_c	Cell temperature inside module (°C)
T_m	Module back sheet temperature (°C)
T_0	Reference temperature (25°C)
ΔT	Reference temperature difference between module back sheet and cell (3°C)
f_d	Fraction of diffuse irradiance used by the module (dimensionless)
α_{Isc}	Short circuit current temperature coefficient (1/°C)
θ	Incident angle between the direct beam and the normal to the module surface (°)

General Form

$$I_{scr} = \frac{I_{sc}E_0}{f_1(AM)\left[E_b + f_d E_{diff}\right]\left[1+\alpha_{Isc}[T_c - T_0]\right]}$$

$$f_2(\theta) = \frac{\left[\frac{I_{sc}}{I_{scr}}\right]\left[\frac{E_0}{f_1(AM)\left[1+\alpha_{Isc}[T_c - T_0]\right]}\right] - f_d E_{diff}}{E_b}$$

$$E_{POA} = E_b + E_{diff}$$

$$E_b = E_{DNI}\cos\theta$$

$$T_c = T_m + \frac{E_{POA}}{E_0}\Delta T$$

Measured Global POA and DNI (Standard Method)

$$I_{scr} = \frac{I_{sc}E_0}{E_{POA}\left[1+\alpha_{Isc}[T_c - T_0]\right]}$$

$$f_2(\theta) = \frac{\left[\frac{I_{sc}}{I_{scr}}\right]\left[\frac{E_0}{1+\alpha_{Isc}[T_c - T_0]}\right] - E_{POA} + E_{DNI}\cos\theta}{E_{DNI}\cos\theta}$$

Measured Diffuse POA and DNI (New Method)

$$I_{scr} = \frac{I_{sc}E_0}{\left[E_{DNI} + E_{diff}\right]\left[1+\alpha_{Isc}[T_c - T_0]\right]}$$

$$f_2(\theta) = \frac{\left[\frac{I_{sc}}{I_{scr}}\right]\left[\frac{E_0}{1+\alpha_{Isc}[T_c - T_0]}\right] - E_{diff}}{E_{DNI}\cos\theta}$$

Summary

- Articulation of the tracker over the full range of 0-90° in elevation only allows accurate positioning and measurement to be made near solar noon when sky conditions are changing the least.
- This articulation method enables the use of a shaded pyranometer to directly measure the diffuse component, eliminating uncertainty.
- Equivalency between different test methods employed at two independent labs was demonstrated by a real-time intercomparison.
- Incident angle loss factors were not seen to display a seasonal variation between results obtained at the winter solstice and vernal equinox.

SunShot U.S. Department of Energy · U.S. DEPARTMENT OF ENERGY · NNSA National Nuclear Security Administration

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