SAND2015-4316C

Exceptional service in the national interest

Sandia National Laboratories

Mapping HCPV Module or System Response to Solar Incident Angle

Daniel Riley, Sandia National Laboratories

11th International Conference on Concentrating Photovoltaics

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

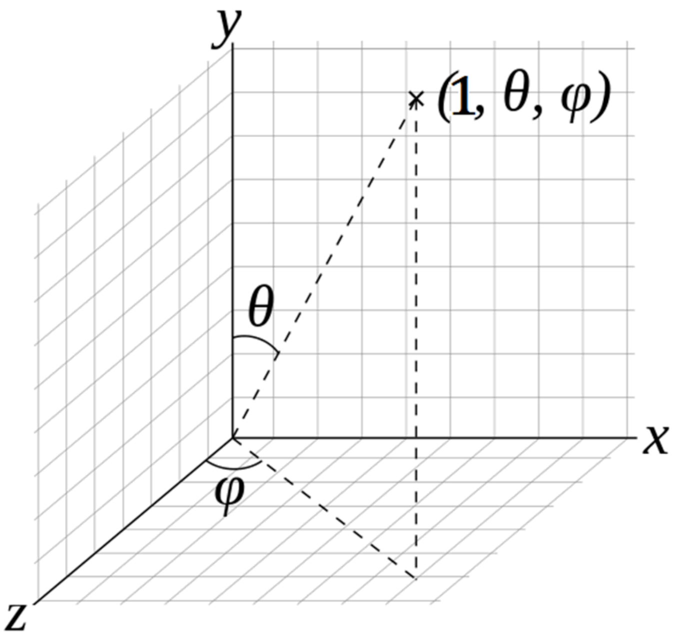
Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. SAND NO. 2011-XXXXP

Overview

- Development of a new description for solar incident angle
- Test and analysis procedures for mapping solar incident angle response
- Results from mapping the incident angle response of an HCPV module
- Benefits of mapping a CPV module or system
- Future work

The Deficiency of AOI

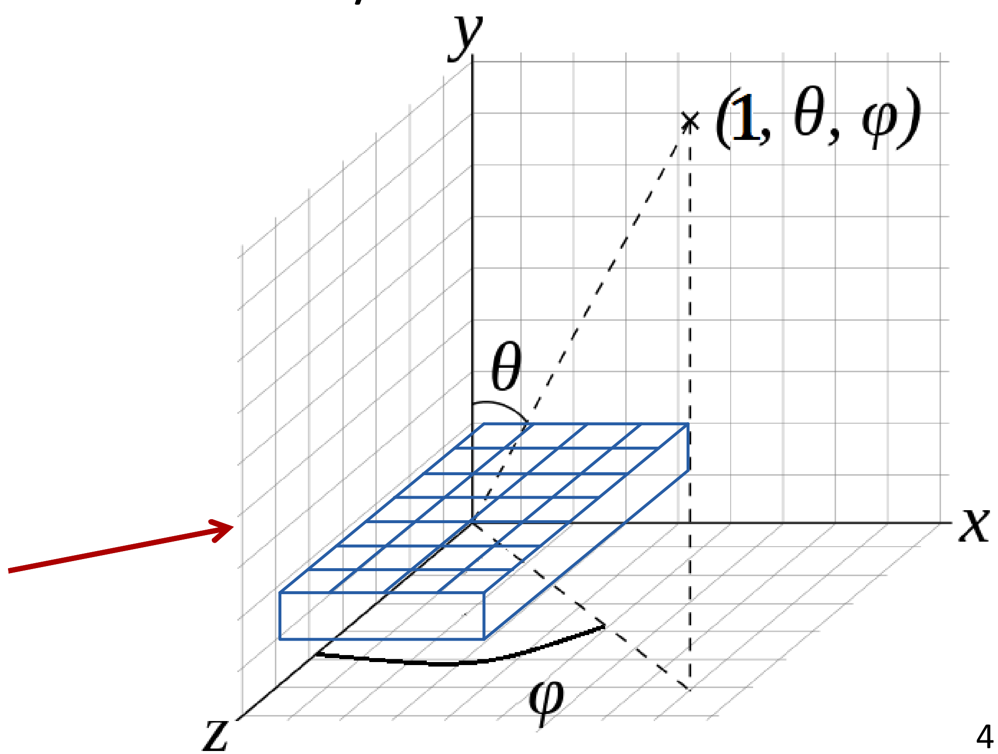
- Angle of incidence (AOI) is the angle between a vector pointing toward the sun and the normal vector of a CPV module or system.
  - It is the "polar angle" of a unit spherical coordinate system (θ)
  - There are an infinite number of sun/module orientations with the same AOI
  - If the response of a module to AOI is rotationally asymmetric, it will respond differently to the same AOI depending on how it is rotated



How to fix the AOI deficiency

- Define the second angle of the unit spherical coordinate system, the “azimuthal angle”, (φ)
  - We call this the “AOI Direction”
- With both angles defined, each module/sun orientation is uniquely identified

In this coordinate system, the module face (or aperture) lies in the x-z plane. The y direction is normal to the module. The vector (1, θ, φ) points from the module to the sun.



Benefits of using AOI Direction with AOI

- 100% compatible with the existing definition of AOI alone
  - The addition of AOI Direction does not require a change in the definition of AOI
  - If you don't need AOI Direction (due to rotationally symmetric response), you don't have to specify it
- Provides general nomenclature acceptable to every module
  - Avoids manufacturer or laboratory specific terms such as:
    - "elevation direction" and "cross-elevation direction" – Sandia
    - "parallel incidence" and "perpendicular incidence" – Solaria
    - "aligned AOI" and "transverse AOI" – Solaria working nomenclature
    - "blah1" and "blah2" – SunPower
    - "AOI" and "Receiver Angle" – Cogenra
- Module-relative, not earth-relative, thus it avoids topocentric terms such as "elevation" and "azimuth"
- Provides *unique* coordinates for each sun position relative to the module
  - This allows for the measurement and visualization of the AOI response surface

Existing methods to measure AOI response

- For modules with rotationally symmetric AOI response, measure the AOI response in one axis
  - How do you know that the AOI response is rotationally symmetric for the entire module or system?
  - Is the test axis representative?
- To address rotationally asymmetric response of a module to AOI, measure the AOI response in two axes
  - Which axes?
  - Why two instead of four (or more)?
  - What’s the response if the module is misaligned in *both* axes?

Mapping AOI response surface (test)

- Mount the device under test (DUT) on a 2-axis tracker
- Move the tracker to orient the module at many AOI/AOI Direction coordinates
  - Measure at many coordinates for a good response curve
  - Keep the test duration short to limit environmental changes
  - Tracker control varies by tracker type (tilt/roll, elevation/azimuth, polar), for elevation/azimuth trackers see D. Riley and C. Hansen, *Sun-Relative Pointing for Dual-Axis Solar Trackers Employing Azimuth and Elevation Rotations*
- Take I-V curve(s) and module temperature(s) at each AOI/AOI Direction coordinate
  - Test during clear-sky conditions with minimal irradiance or spectral changes
  - Simultaneous DNI measurements on a different tracker

Mapping AOI response surface (analysis)

- Adjust the parameter of interest (e.g. I_{MP} or P_{MP}) to a common operating condition, for example, this might be used for HCPV

$$I_{MP,adj} = I_{MP} \times \frac{E_0}{E} \times \left[1 + \alpha_{Imp} \times \left(T_C - T_{C,0}\right)\right]$$

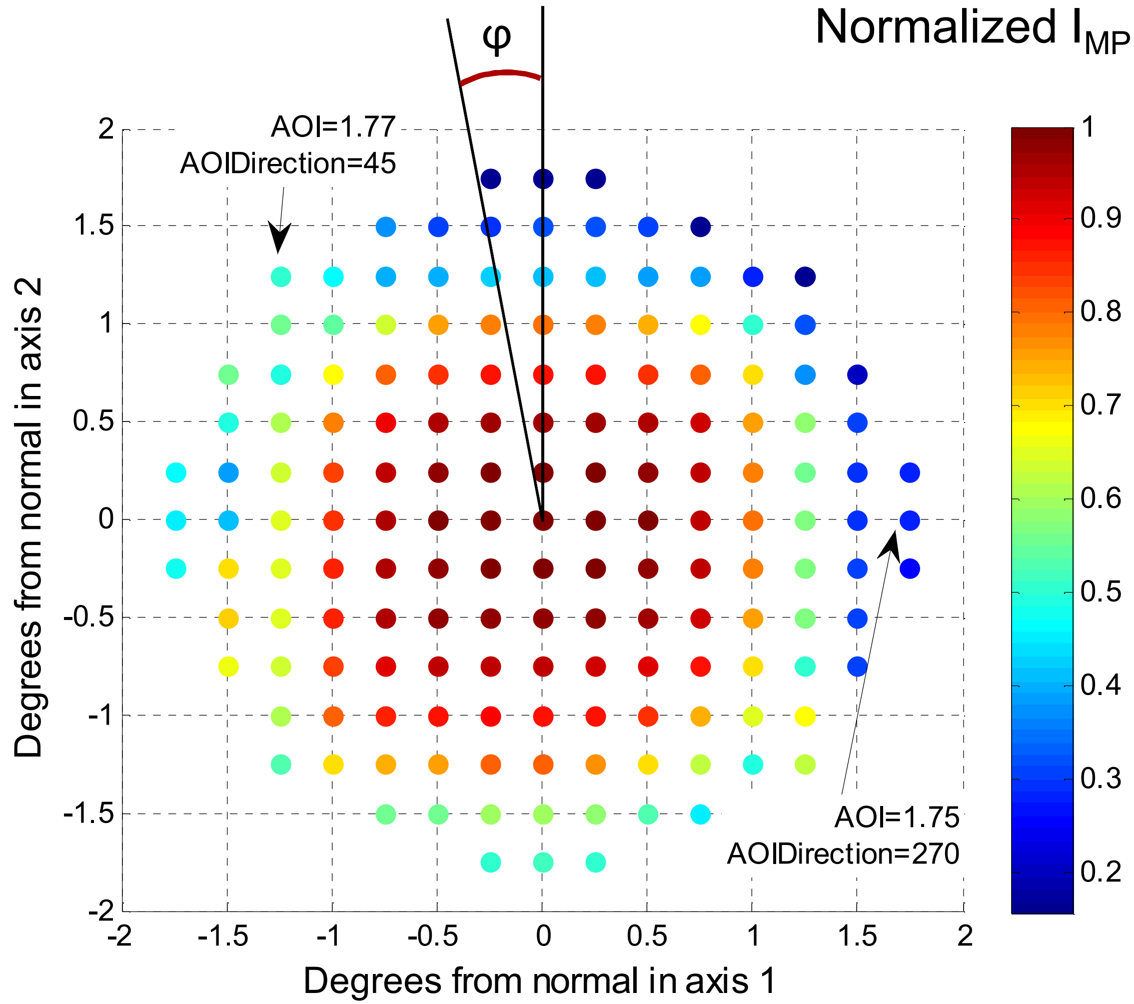
  - The adjustment equation may necessarily change for differing parameters of interest or differing types of CPV modules (LCPV or HCPV)
- Normalize the adjusted parameters by dividing by the maximum observed value

$$I_{MP,norm} = \frac{I_{MP,adj}}{\max\left(I_{MP,adj}\right)}$$

- Plot the normalized parameters as a function of AOI and AOI Direction and visualize the resulting surface

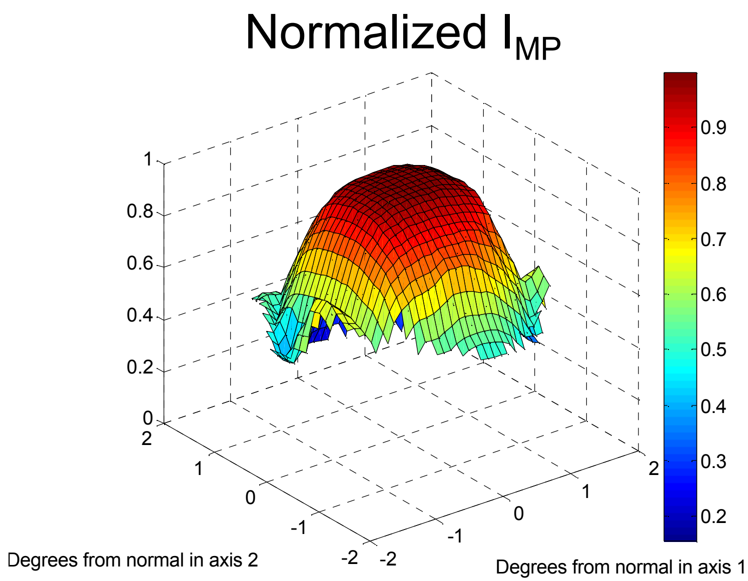
Results: points

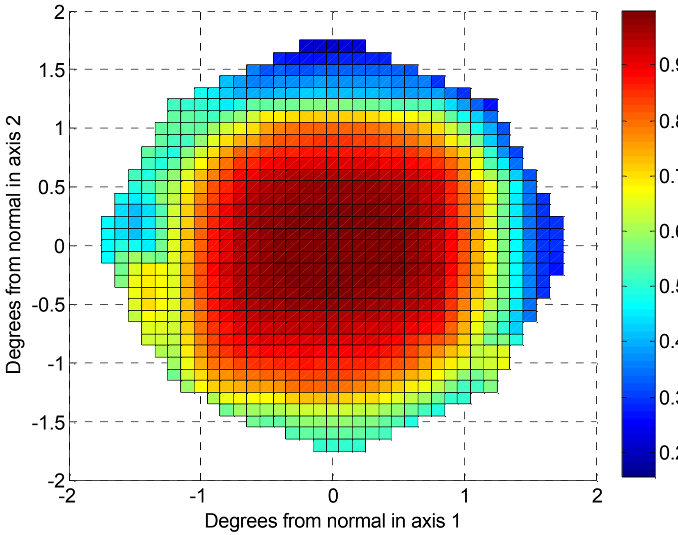
- 161 AOI/AOI Direction coordinates and plotted normalized I_{MP} values
- AOI ranges from 0 to 1.77
- AOI Direction ranges from 0 to 352
- Each normalized I_{MP} is a reference point on the response surface



Results: interpolated surfaces

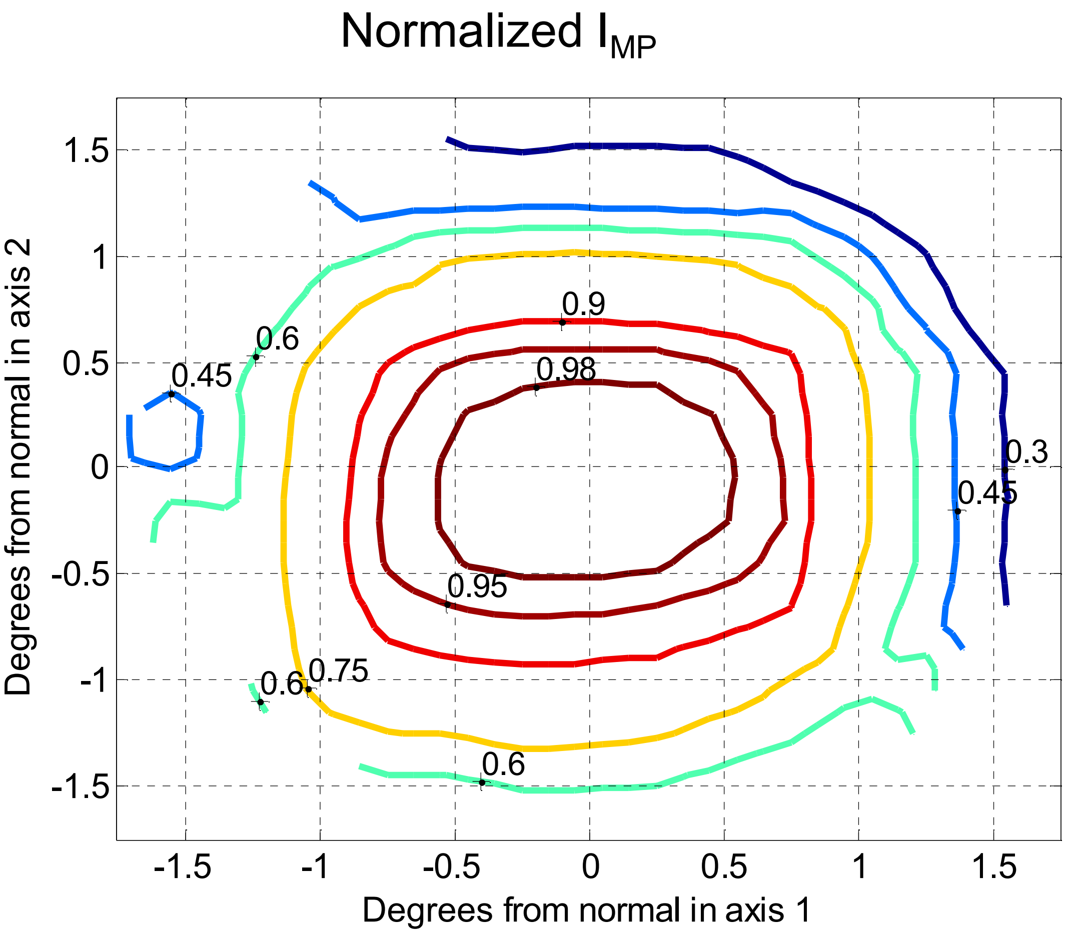
- Interpolate between the points for a complete response surface
  - Linear interpolation seems to work well for most modules, although other interpolations are possible (e.g. cubic)
- The interpolated surface is interesting to look at, but may not be a good tool to extract useful information





Results: contour plot

- A contour plot really brings out the shape of the response surface
- Notice the slightly rectangular shape of the isolines
  - Due to optics?
- Easy to determine:
  - The acceptance angle (10% loss)
    - ±0.9 degrees in AOI Direction 90 and 270
    - ±0.8 degrees in AOI Direction 0 and 180
    - ±1.0 degrees in AOI Direction 135 and 315
  - If the module is well oriented on the tracker



Expanding beyond modules

- Similar testing and analysis could be performed on full systems of HCPV modules on a single tracker

Information provided by AOI response mapping

- Full response surface, not just a “slice” of the surface
  - Get a “slice” in *any* direction
- Acceptance angle in any direction, even if the response is not symmetric
- Diagnostic information
  - Misaligned optics in a module
  - Misaligned modules on a tracker
  - Any optical defects in the lens(es)

Past and future work

- AOI and AOI Direction description and tracker movement algorithm
  - Riley and Hansen, "*Sun-Relative Pointing for Dual-Axis Solar Trackers Employing Azimuth and Elevation Rotations*", DOI: 10.1115/1.4029379
- Adapt the technique to characterize LCPV modules
  - Analysis modification required to remove effects of diffuse radiation utilization in LCPV modules such that only beam response is measured
  - More flexible trackers may be required for larger AOI requirements

Questions?

Daniel Riley

driley@sandia.gov