SOLAR ENERGY
TECHNOLOGIES OFFICE
U.S. Department Of Energy

Assessing the optical performance impact of tracking error in an operational concentrated solar power plant using Monte Carlo ray-tracing simulation

B. J. Stanislawski, M. Wagner, U. Egerer, S. Dana, A. Sharma, and S. Yellapantula

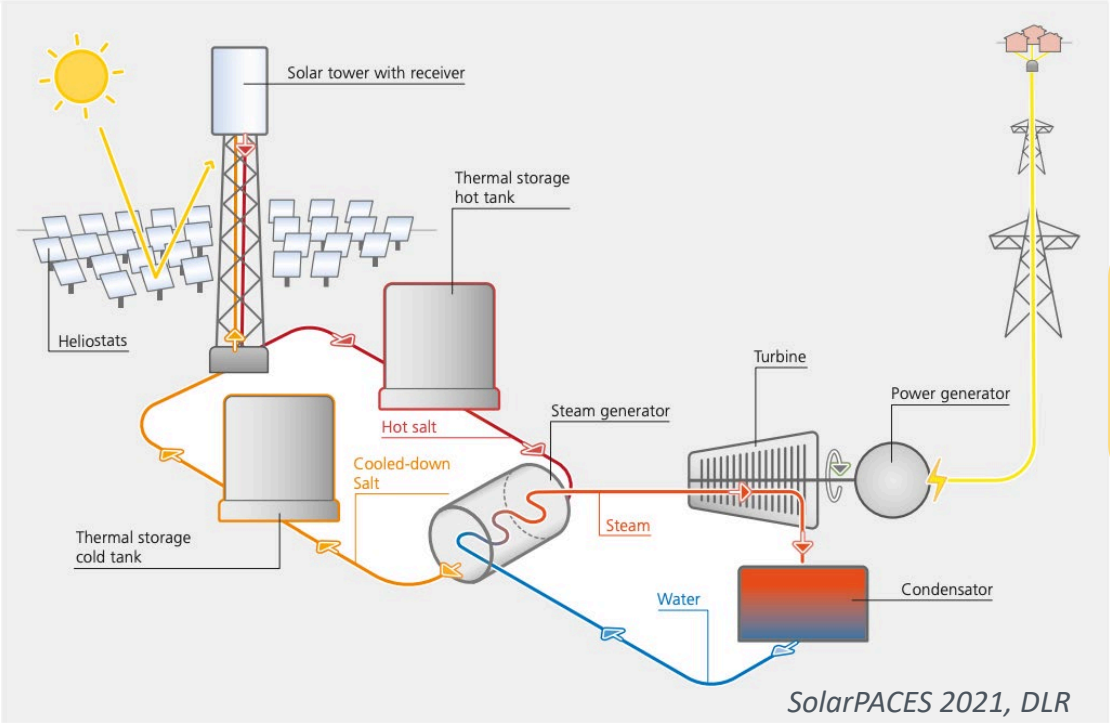
ASME Energy Sustainability 2023
July 10-12, 2023 | Washington, D.C.

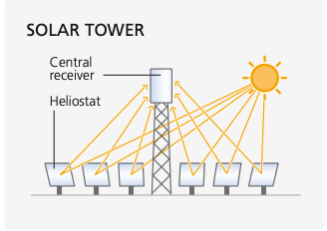
NREL

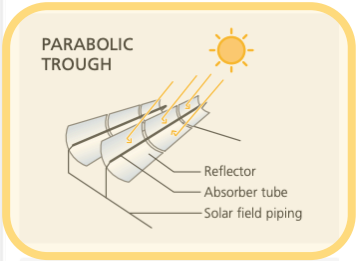

Concentrating Solar Power (CSP)

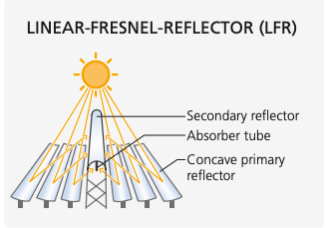
Funded by:
SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

Why CSP?





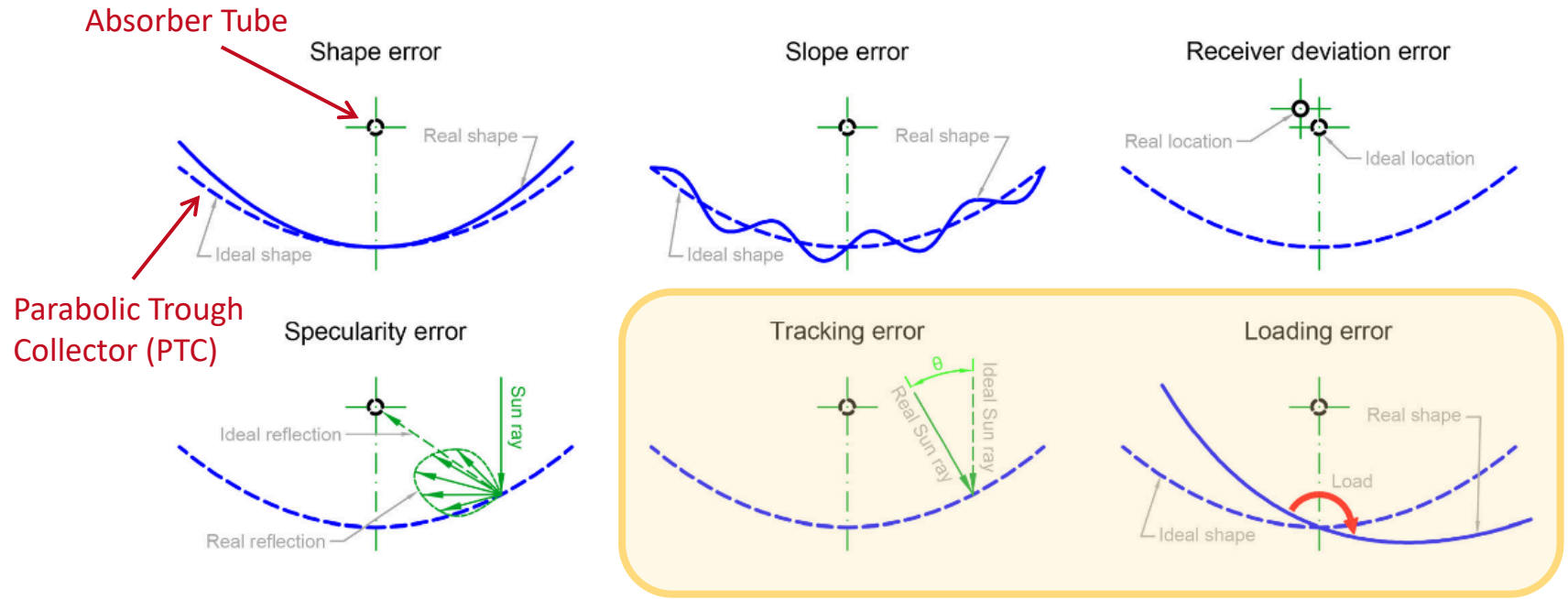




Unlike solar photovoltaic technologies, CSP has an **inherent capacity to store heat energy** for later conversion to electricity.

Funded by:
SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

Geometric Error Reduces CSP Plant Performance



(Tagle-Salazar et al. 2020)

Funded by:
SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

Tracking Error Reduces Optical Performance

Tracking error: the angular offset of a collector away from the sun position along the transversal plane.

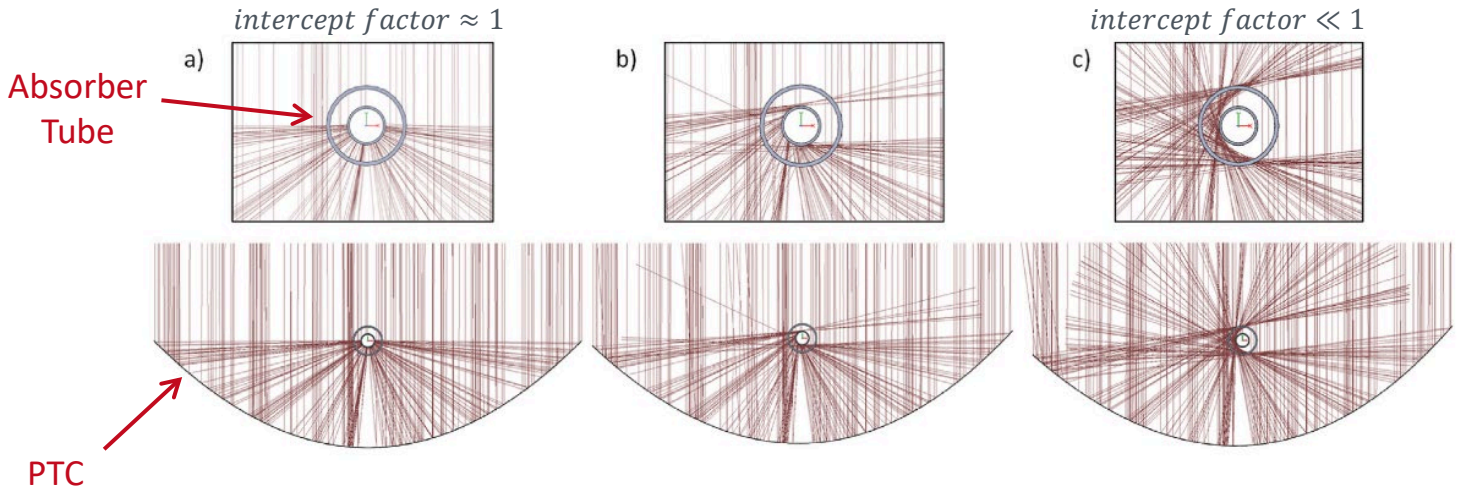


Fig. 7. Solar radiation path for selected tracker error presented in the cross-section: a) $\theta_x = 0°$, b) $\theta_x = 2°$, c) $\theta_x = 4°$.

Stanek et al. 2022

$$intercept\ factor\ (\gamma) = \frac{number\ of\ rays\ that\ hit\ the\ absorber}{number\ of\ rays\ that\ hit\ the\ collector}$$

Research Questions

1. What extent of tracking error is observed at three rows of an operational CSP plant?
2. What are the sources of the tracking error?
3. How does this tracking error impact optical performance?

Funded by:
SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

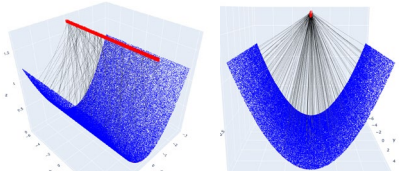
Modeling Performance Impact of Tilt Error

Inputs

- Field data from the Nevada Solar One (NSO):
  - Site location
  - Optical properties
  - Measured trough angle.

PySolTrace

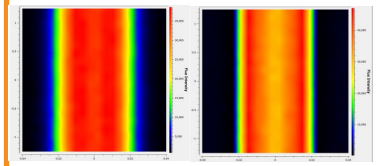
- SolTrace API performs Monte-Carlo based ray-tracing simulation *(Stanislawski et al. 2023)*.



- Additional development for quantifying optical and plant performance.

Outputs

- Comparisons of:
  - Flux distribution



  - Optical efficiency for exterior vs interior rows.
- For ideal vs deflected solar collectors.

Nevada Solar One CSP Plant

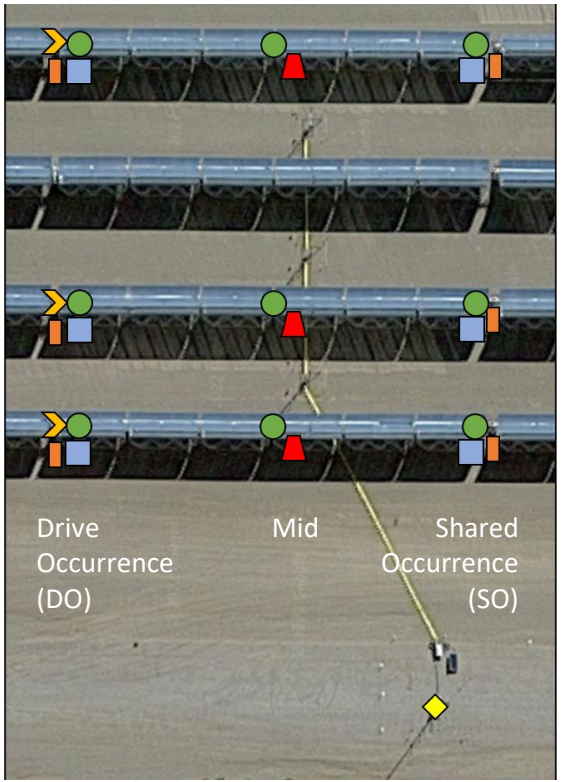
72-megawatt (MW) capacity, 0.5 hours of full-load storage

Boulder City, Nevada

Funded by:
SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

Load Measurement Campaign – Signal Overview

Measuring Tilt Angle

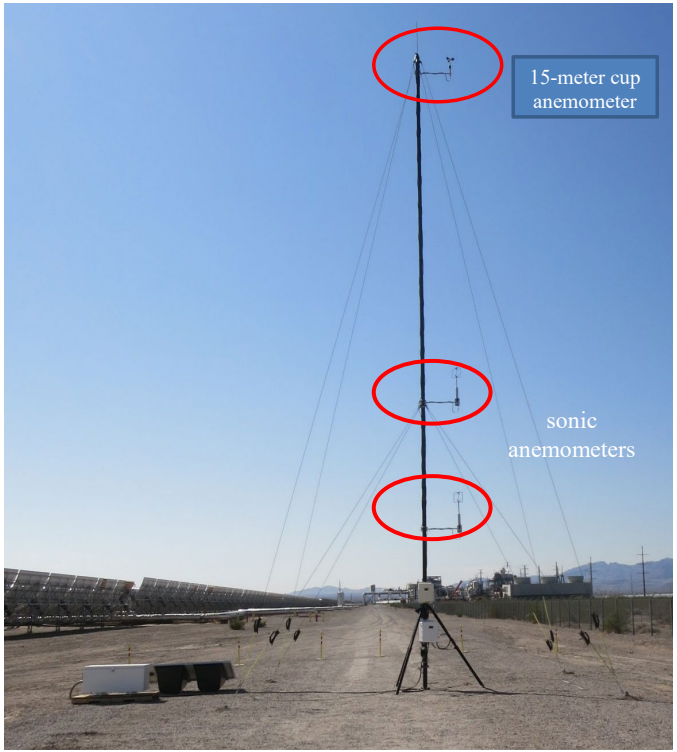


Key:

- Drive Torque
- Pylon Bending
- Dynamic Tilt
- Accelerations
- Mirror Vibration
- Wind Speed

Dana et al. 2022

Measuring Inflow Wind

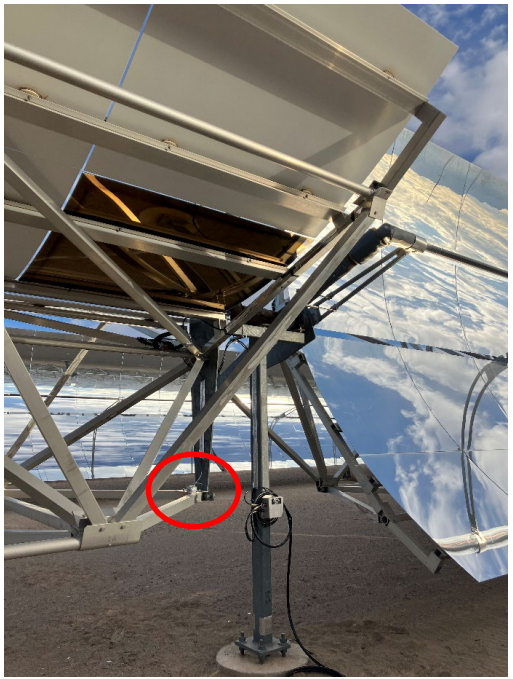


Dana et al. 2022

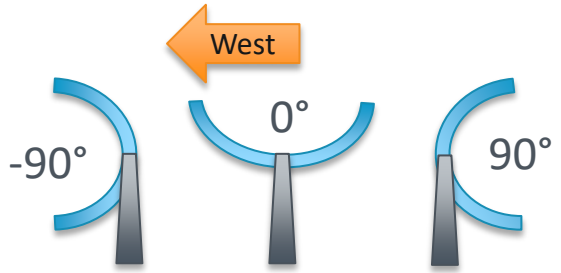
Funded by:
SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

Load Measurement Campaign – Dynamic Tilt

Dynamic tilt measured at three locations along the collector (DO, Mid, SO)



Dana et al. 2022

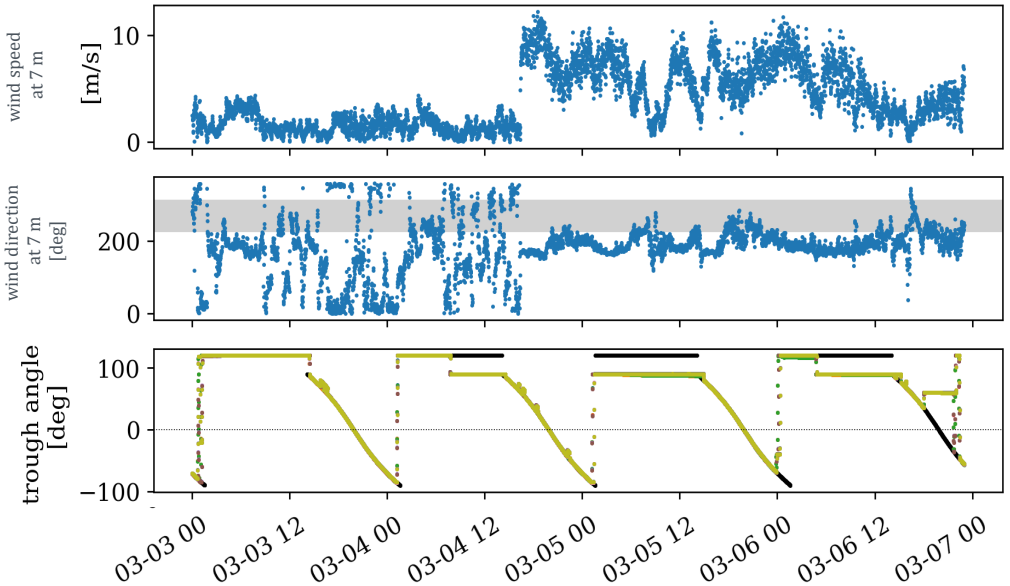


- Measurements from November 2022 – June 2023.
- Collected at 20 hertz with 10-second statistical windows.

Funded by:
SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

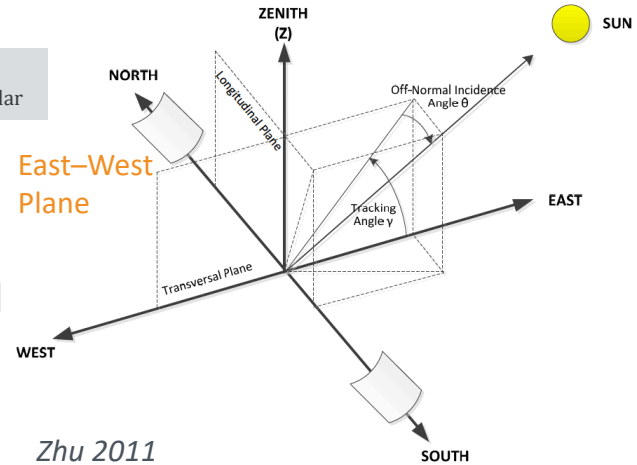
NSO Measurement Data

First-of-its-kind, long term data collection at an operational plant



Stanislawski et al. 2023

Calculating the sun position:

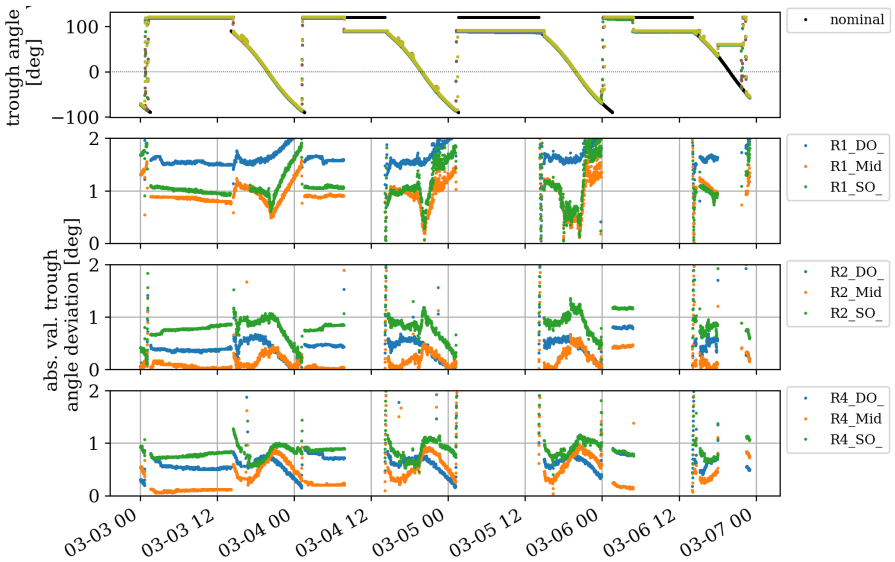


Zhu 2011

Funded by:
SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

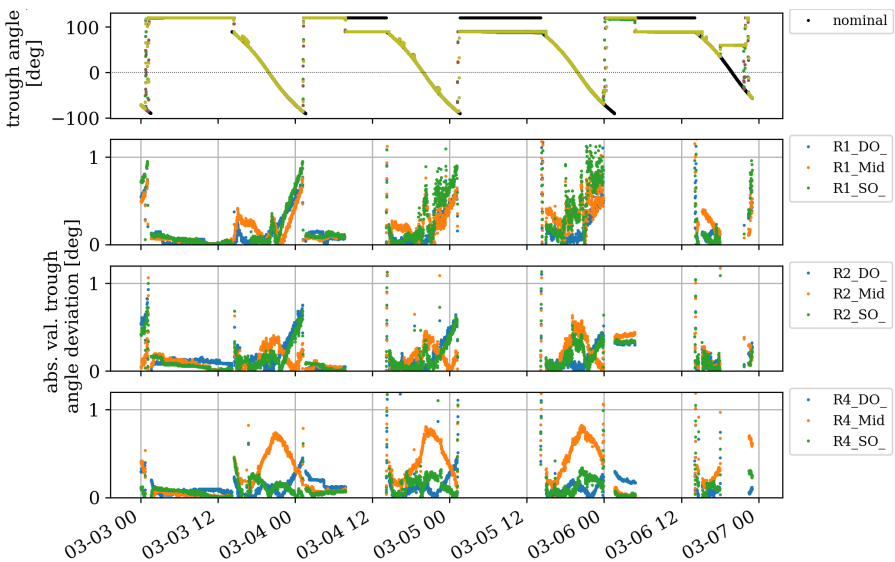
Calculating tracking error

No night-time offset adjustment



Stanislawski et al. 2023

Subtracting night-time offset



Stanislawski et al. 2023

Trough angle deviation represents tracking error (including all error sources).

Funded by:
SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

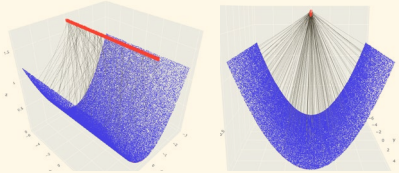
Modeling Performance Impact of Tilt Error

Inputs

- Field data from NSO:
  - Site location
  - Optical properties
  - Measured trough angle.

PySolTrace

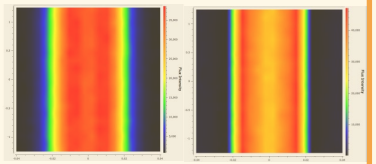
- SolTrace API performs Monte-Carlo based ray-tracing simulation (*Stanislawski et al. 2023).*



- Additional development for quantifying optical and plant performance.

Outputs

- Comparisons of:
  - Flux distribution



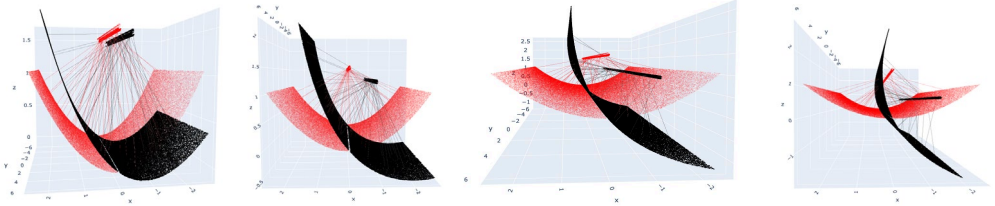
  - Optical efficiency for exterior vs interior rows
- For ideal vs deflected solar collectors.

Funded by:
SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

PySolTrace Evaluates Optical Performance

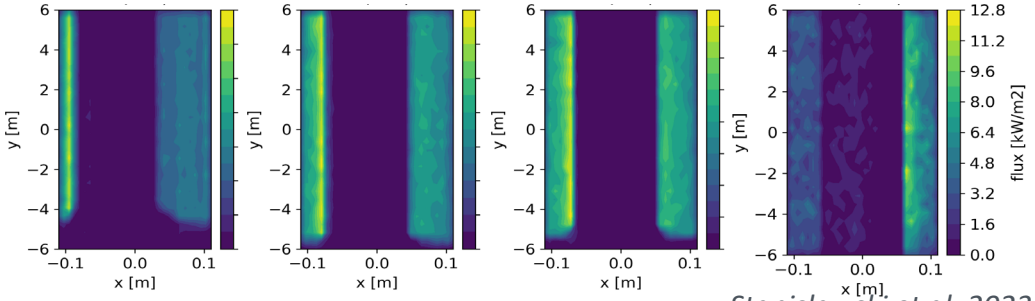
Built on top of the existing SolTrace Python API, this **open-source tool** feeds in a field measurement data of tilt angle and sun positions from SPA and generates:

- **Ray-tracing results to compute optical performance at each tilt angle.**



Stanislawski et al. 2023

- **Flux maps at each tilt angle.**

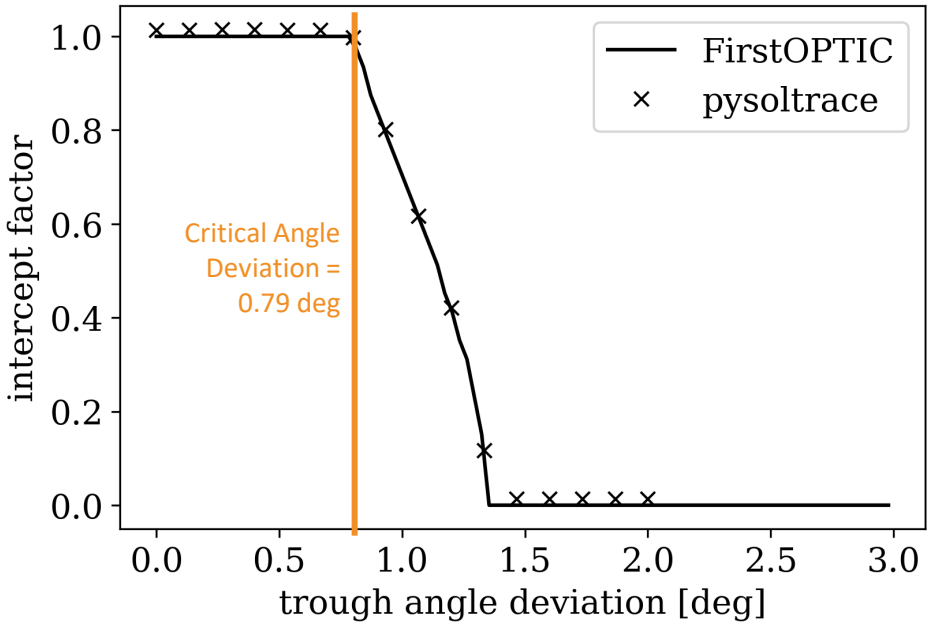


Stanislawski et al. 2023

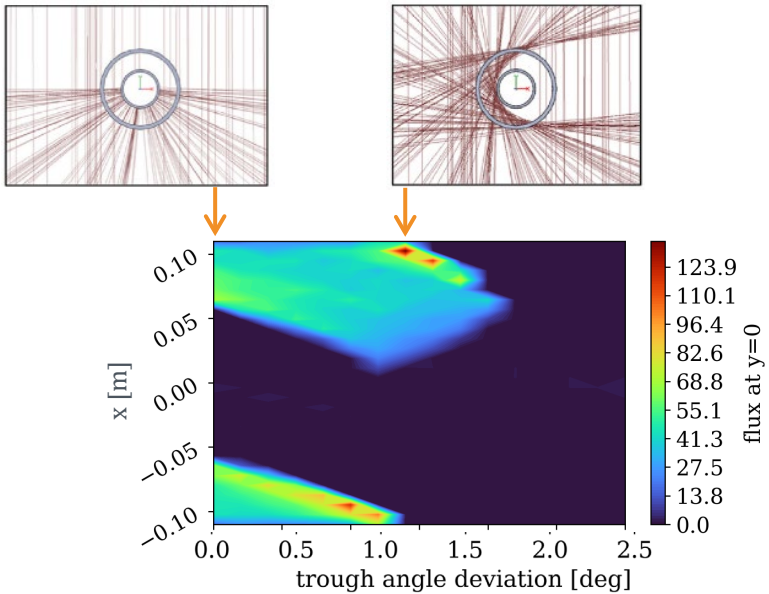
Funded by:
SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

Validating PySolTrace: LS-2 PTC

$$intercept\ factor\ (\gamma) = \frac{number\ of\ rays\ that\ hit\ the\ absorber}{number\ of\ rays\ that\ hit\ the\ collector}$$



Stanislawski & Yellapantula 2023



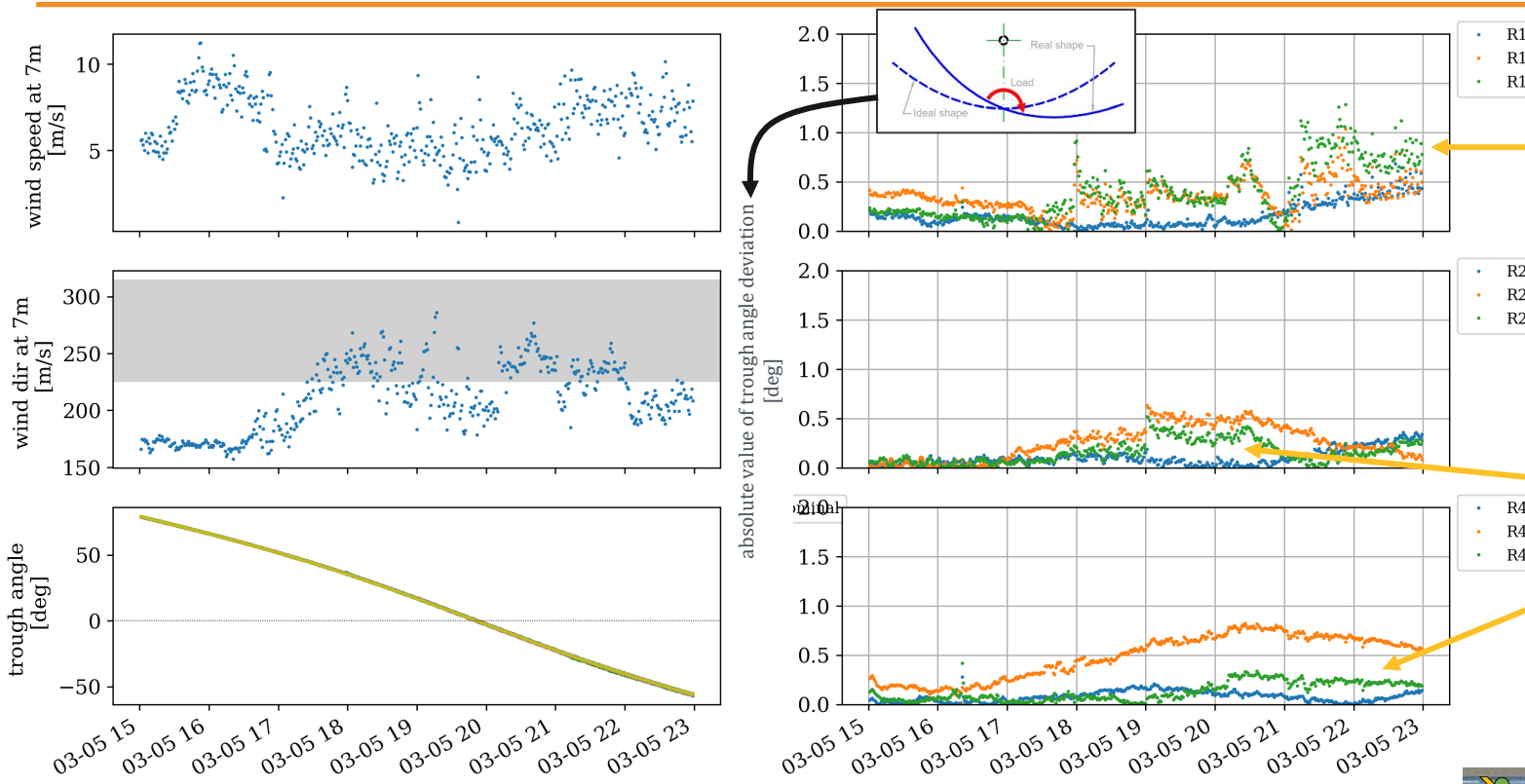
PySolTrace results show strong agreement with FirstOPTIC *(Zhu & Lewandowski 2012)* results.

Research Questions

1. What extent of tracking error is observed at three rows of an operational CSP plant?
2. What are the sources of the tracking error?
3. How does this tracking error impact optical performance?

Funded by:
SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

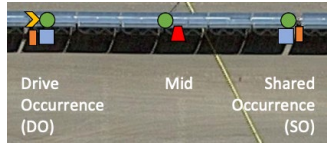
Trough Tilt Angle on March 5, 2023



Row 1 shows greater dynamic variation than other sheltered rows.

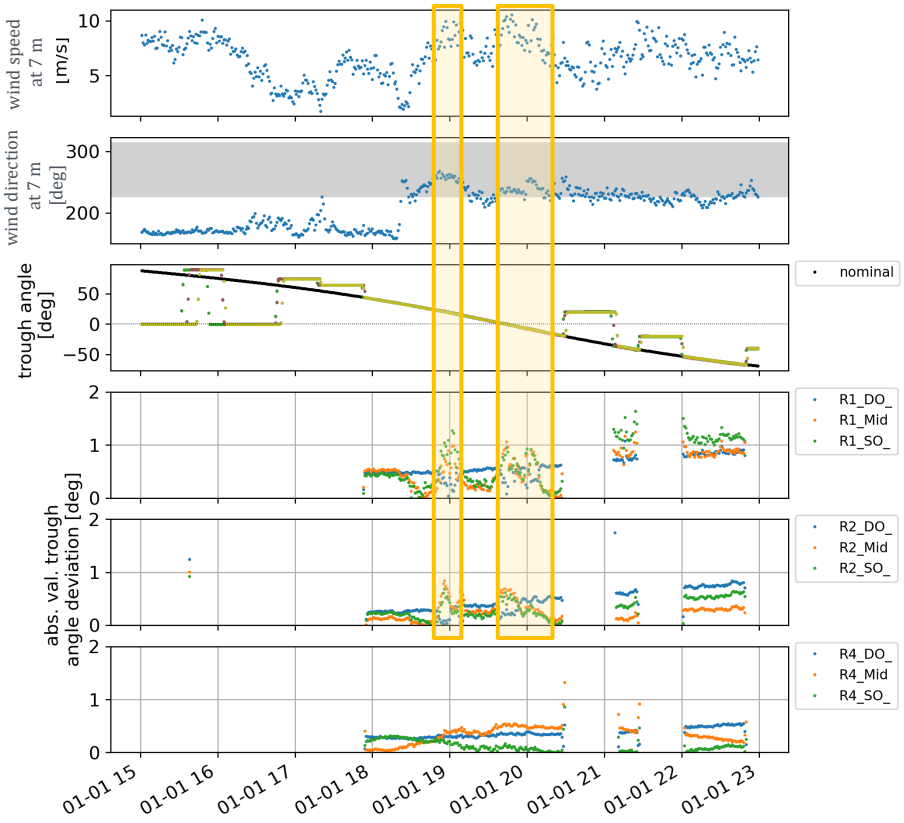
All rows reveal torsional movement

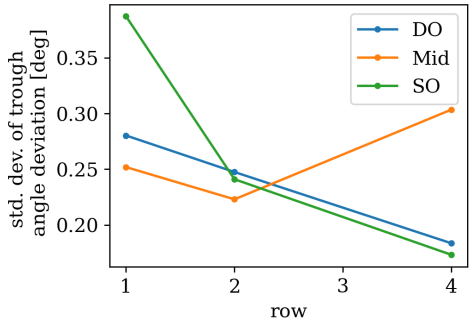
Stanislawski et al. 2023



Funded by:
SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

Tracking Error Sources: Wind Loading



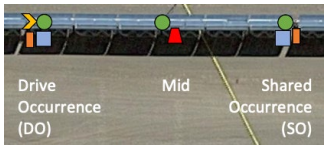


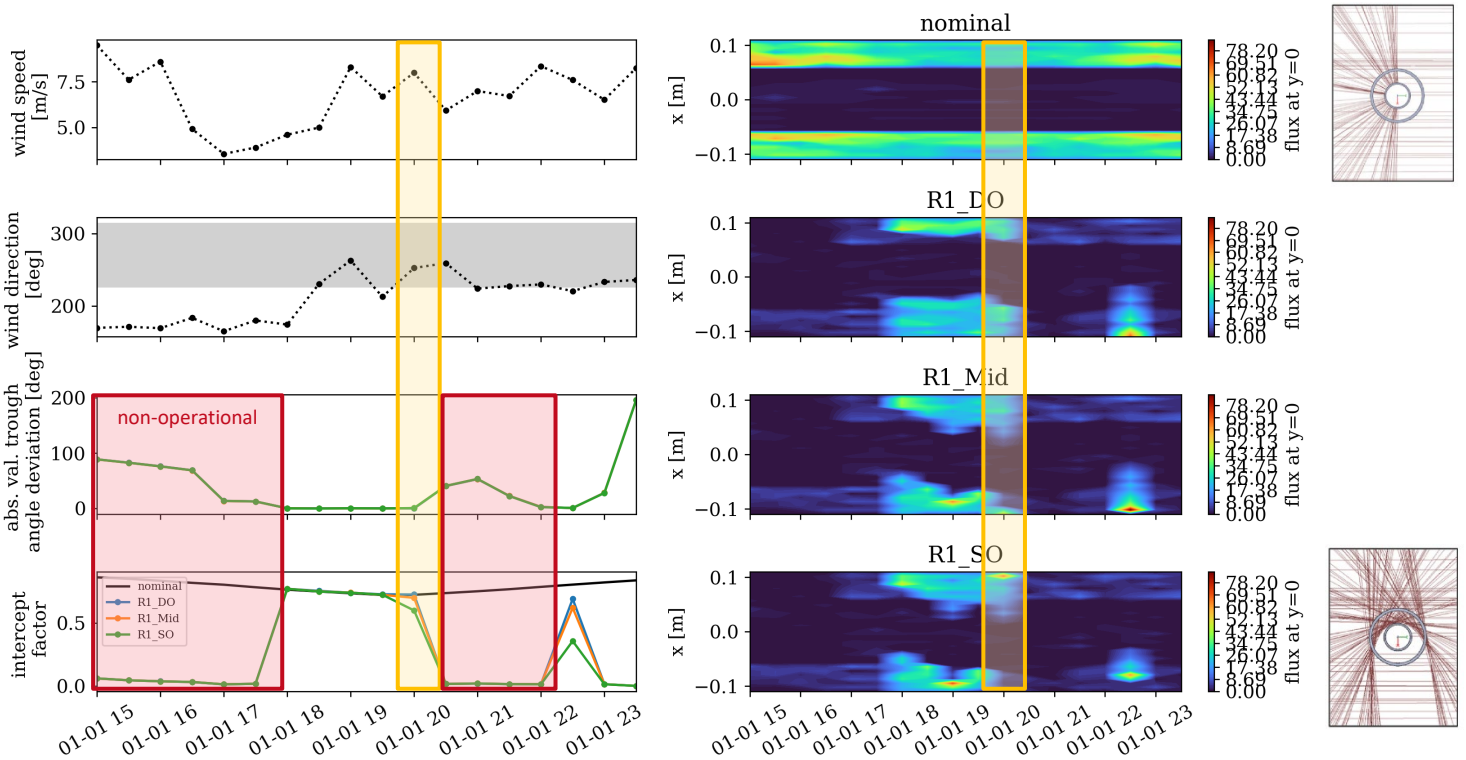
Variation of tilt angle is the highest at Row 1 and decreases deeper into the array, indicating wind loading.

Stanislawski et al. 2023

Funded by:
SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

Optical Performance During Strong Winds



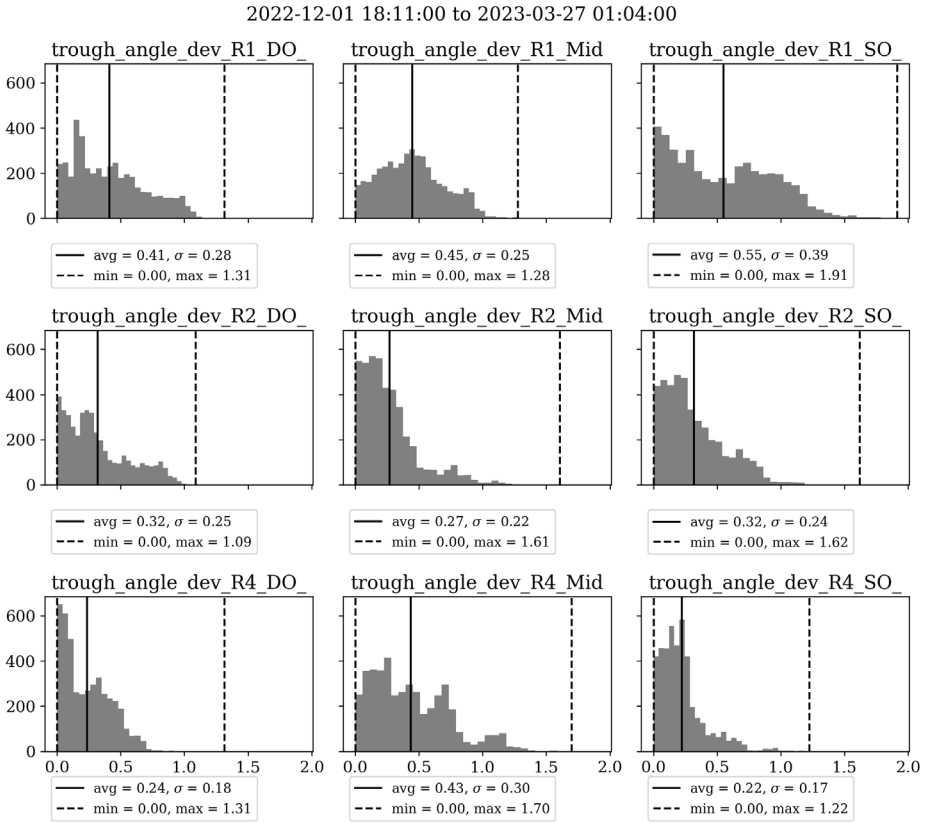


During strong winds that are perpendicular to the troughs, optical performance drops. The SO (shared occurrence) is most sensitive to wind loading.

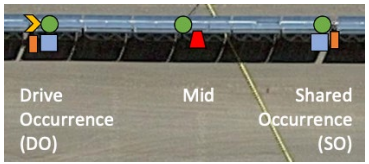
Stanislawski et al. 2023

Funded by:
SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

Characterizing Long-Term Tracking Error

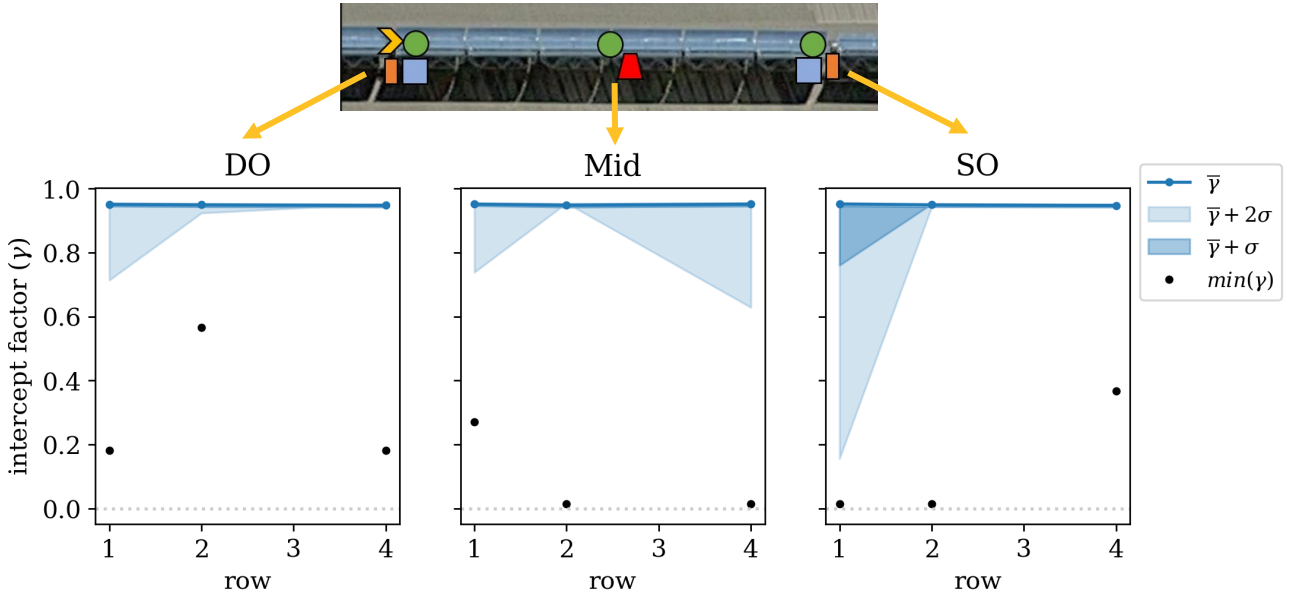


Stanislawski et al. 2023



Funded by:
SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

Characterizing Long-Term Optical Performance



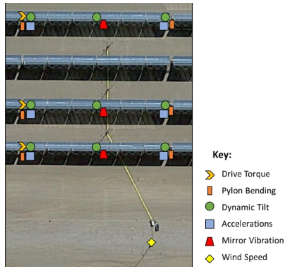
Stanislawski et al. 2023

On average, the observed rows exhibit high optical performance; however, at peak tracking error, optical performance can drop to zero.

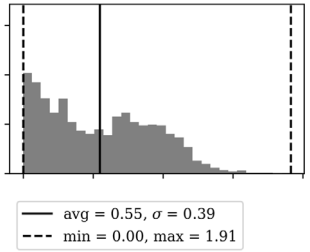
Contributions of this Work

SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

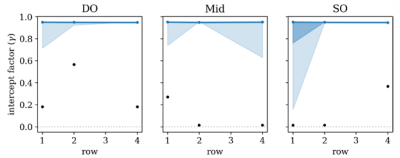
Created first-of-its-kind long-term field measurement dataset of operational CSP plant



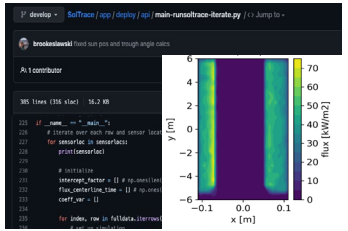
Characterized tracking error at an operational CSP plant



Quantified the impact of tracking error on optical performance



Adapted open-source optical performance tool to use field measurements



Thank You

Brooke Stanislawski (NREL)
brooke.stanislawski@nrel.gov

NREL/PR-5000-86850

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Solar Energy Technologies Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

Back up

Funded by:
SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

Load Measurement Campaign - Instrumentation

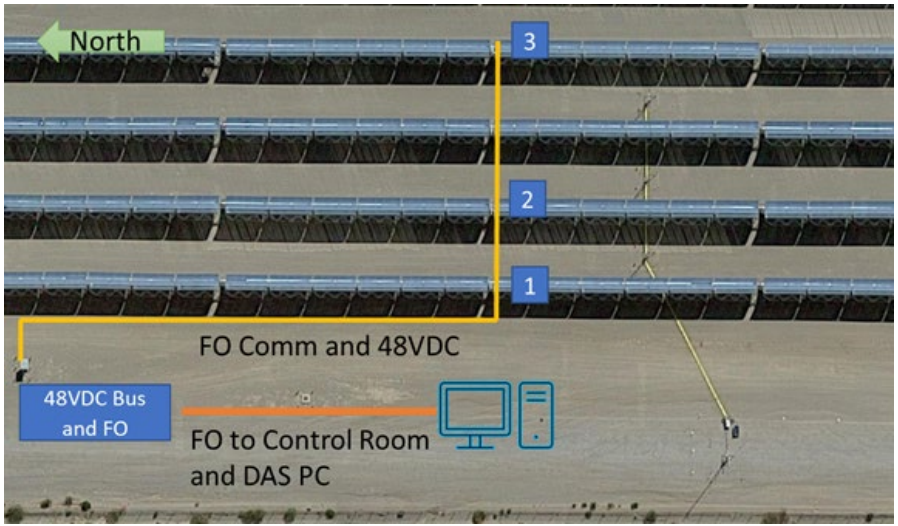
Component	Instrument	Model (common)	Quantity Measured
Dynamic Tilt	Inclinometer	2gig BH-1800-000-2M, 0.05° accuracy	Position, deg

Loads Data Acquisition system (DAS)

1. EtherCAT based
2. Highly configurable and scalable
3. Validated through years of experiments and remote deployments
4. GPS timestamped data

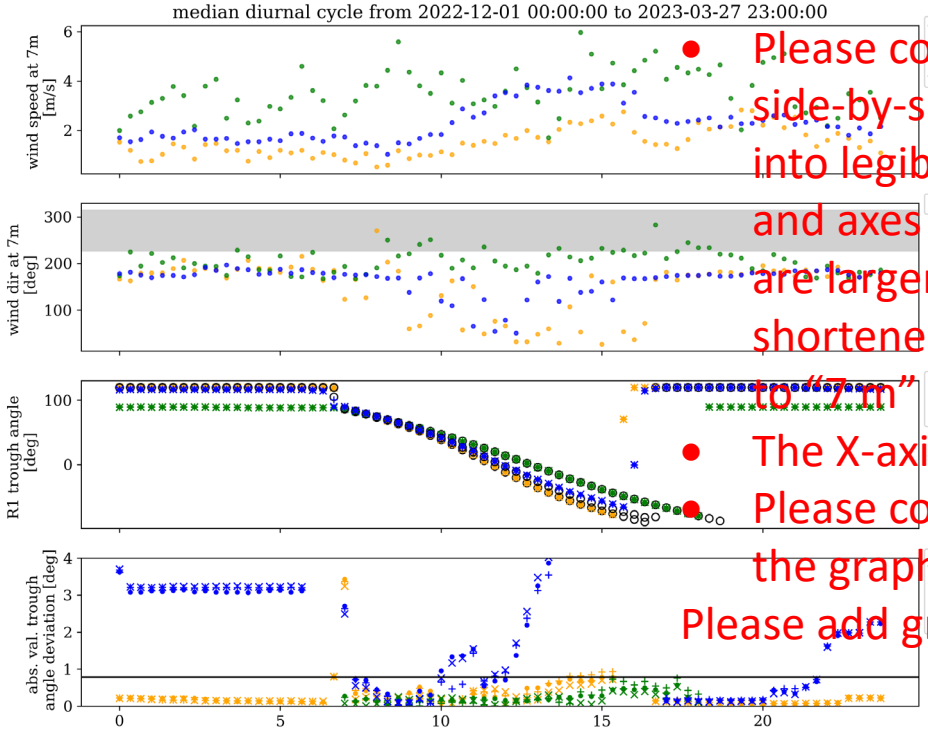
Three CSP structures in three rows are targeted

1. Three chassis/boxes deployed



Funded by:
SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

Tracking Error on a Characteristic Day



Stanislawski et al. 2023

- Please consider making the graphs int side-by-side so that you can enlarge th into legibility. If not, could you replace and axes labels with text box overlays are larger? And, if possible, write out shortened words (abs. var.) and add a to “7m” where it appears.
- The X-axis is missing a label.
- Please consider capitalizing the first w the graph caption (“Median”)

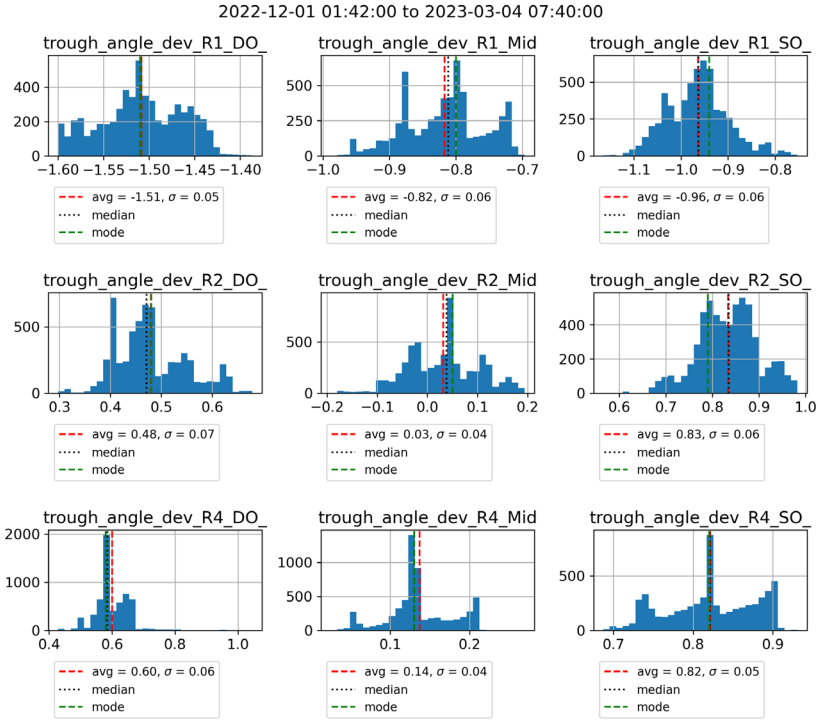
Please add graphic credit/source.

Row 1’s optical performance drops to 50% on the median day in the afternoon in the winter.

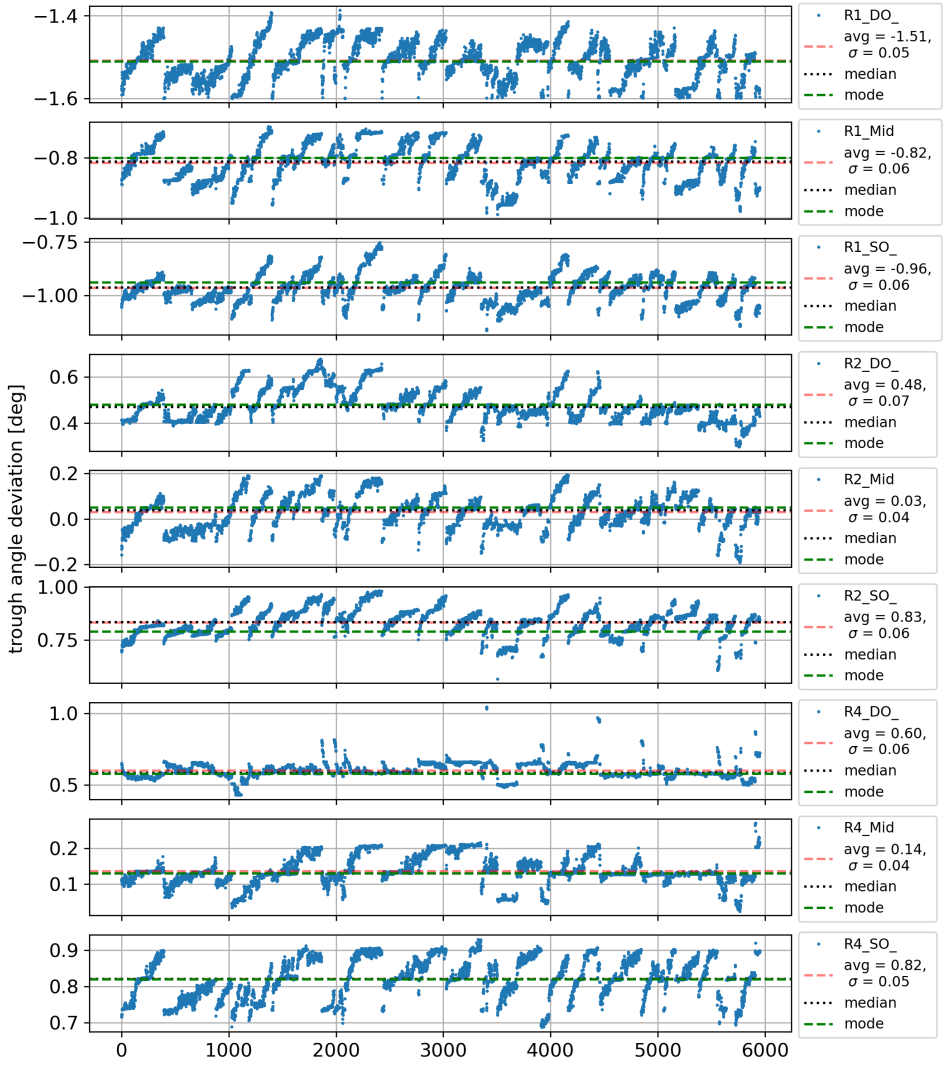
In the fall, optical performance dips in the evening.

characterizing offset

low winds (< 1 m/s) and stow (120 deg +/- 1 deg)

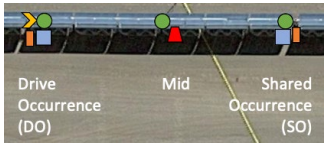


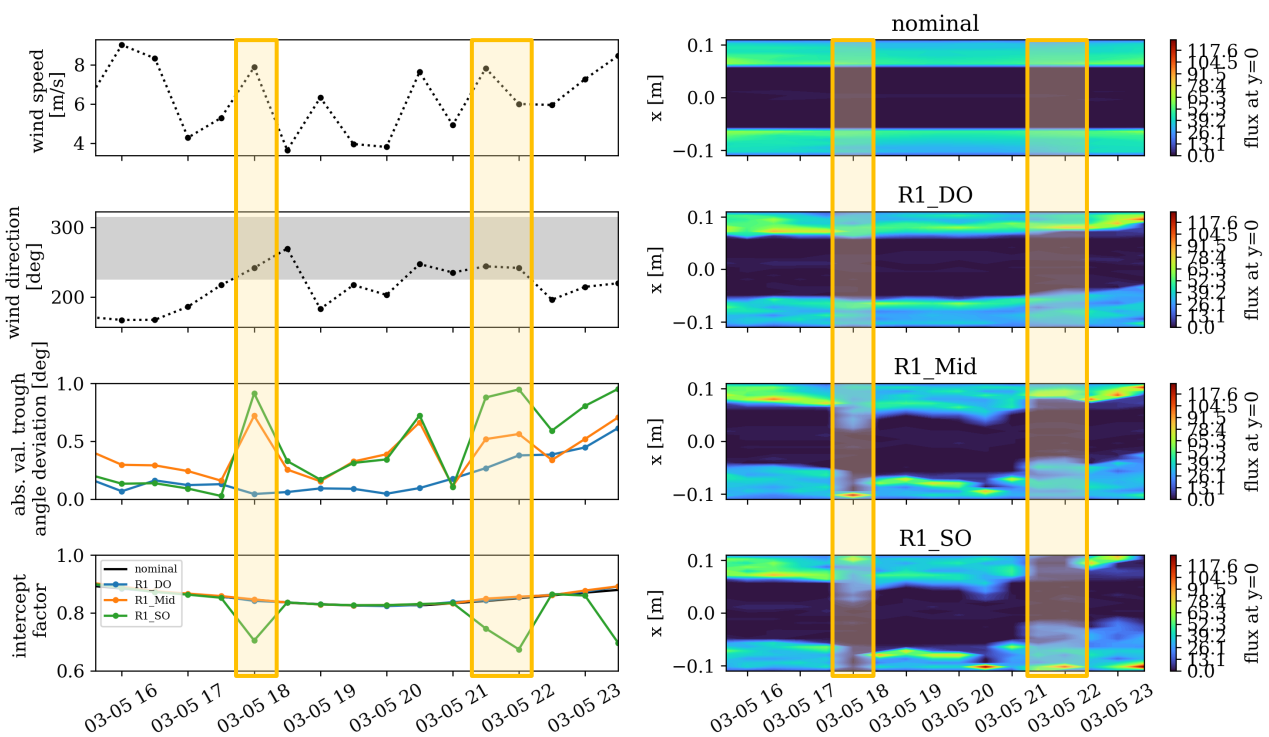
offset = mean -> uncertainty of +/- 2σ captures 95% of data



Funded by:
SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

Optical performance during strong winds





During strong winds that are perpendicular to the troughs, optical performance drops. The SO (shared occurrence) is most sensitive to wind loading.

Funded by:
SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

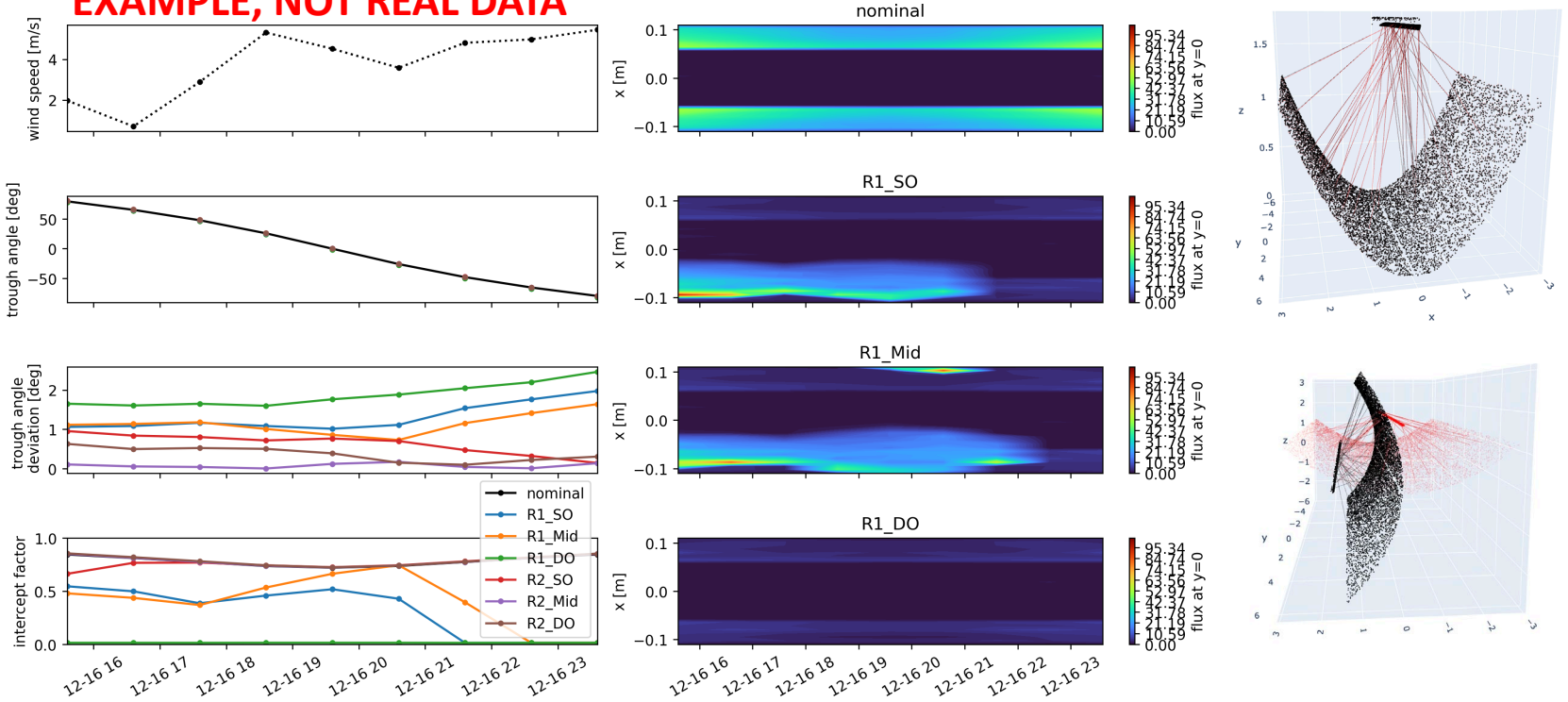
NSO mirrors have suffered from wind damage

Damaged mirrors at the northern edge of the trough field after a high northerly wind event on Sept 28th-30th, 2022.

Funded by:
SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

Example of tilt angle impact on performance

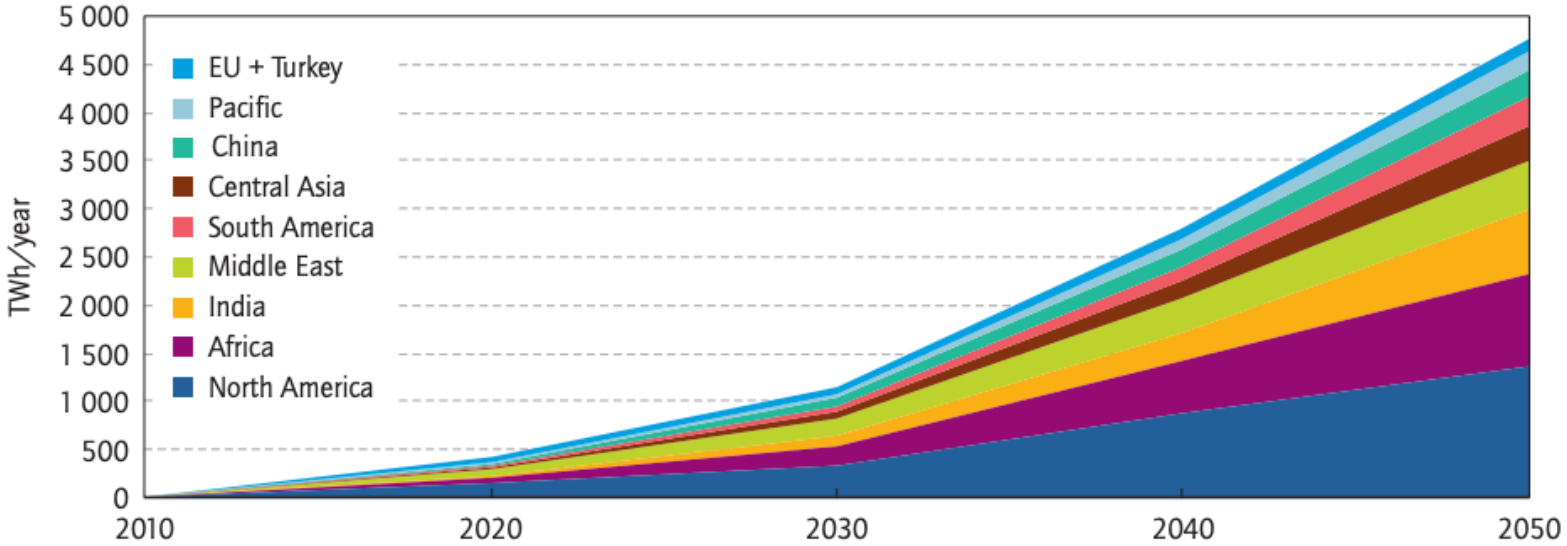
EXAMPLE, NOT REAL DATA



Preliminary results generated by Monte Carlo ray-tracing functionality in pysoltrace (currently uses constant DNI, which will be changed)

Funded by:
SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

Forecasted Growth of CSP Worldwide



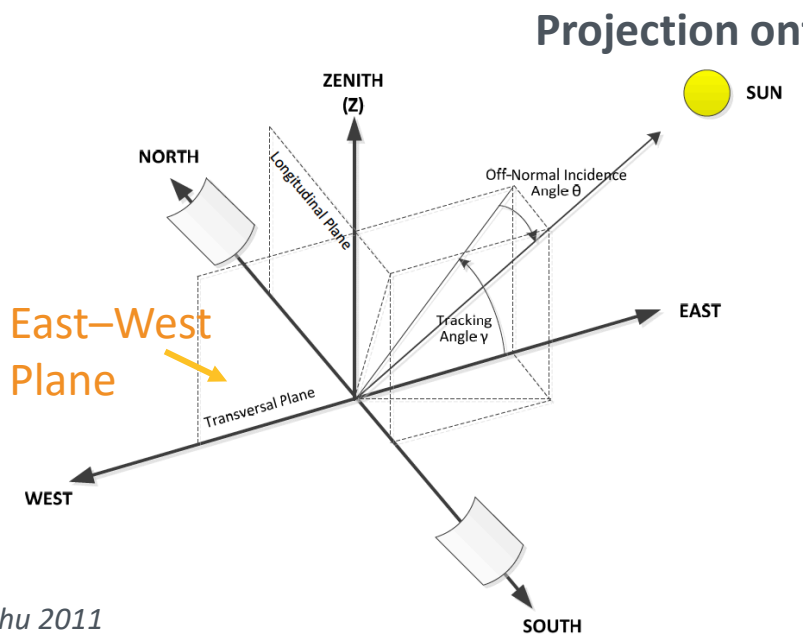
International Energy Agency CSP Technology Roadmap, 2010

By 2050, CSP is expected to generate 10% of the electricity in the US *(DOE Solar Futures Study 2021)*.

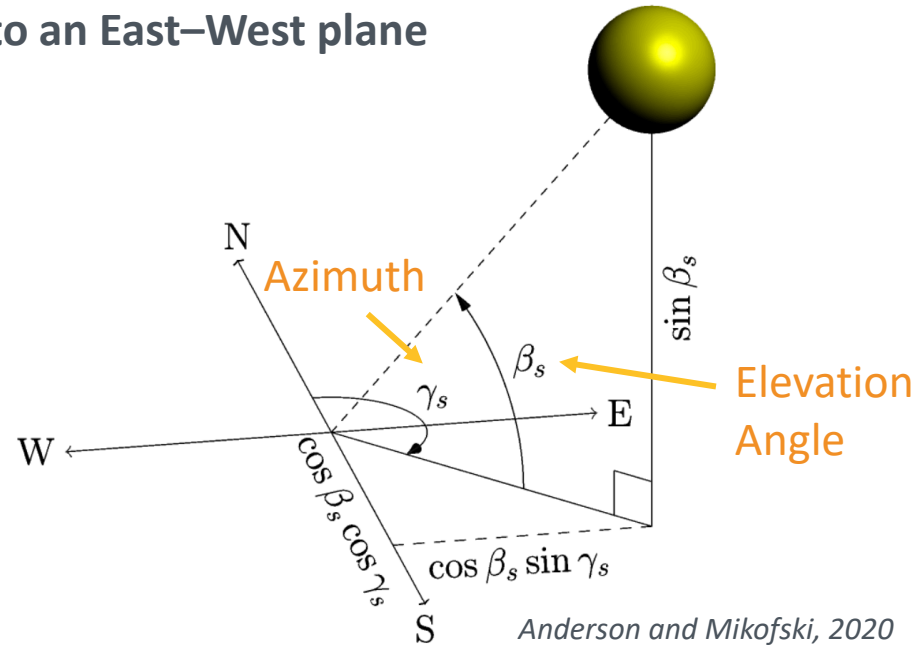
Funded by:
SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

Calculating the Nominal Tilt Angle

We use a Python library for the National Renewable Energy Laboratory's Solar Position Algorithm (SPA) to find the sun azimuth and elevation angles in time.



Zhu 2011



Anderson and Mikofski, 2020

Funded by:
SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

Load Measurement Campaign – Background

- Statistics Processing data from the DAS
- Sampled at 1kHz
- Stored at two rates:
  - 20Hz, 1-min file length
  - 1-Hz, 24-hour file length
- 10-second statistics processed and saved natively
  - Resolve high frequency dynamics
- Date range: 11/18/2022 to 6/02/2023
- Data filtered for mean wind speeds greater than 3 m/s from the 15m cup anemometer on the inflow tower.
- Collector position filtering using the Row 1 Drive inclinometer signal
- No wind direction reference in the loads DAS, must be time synchronized with the met data

Funded by:
SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

Why tracking error?

- like this but for tracker error, slope error, etc and for PTCs

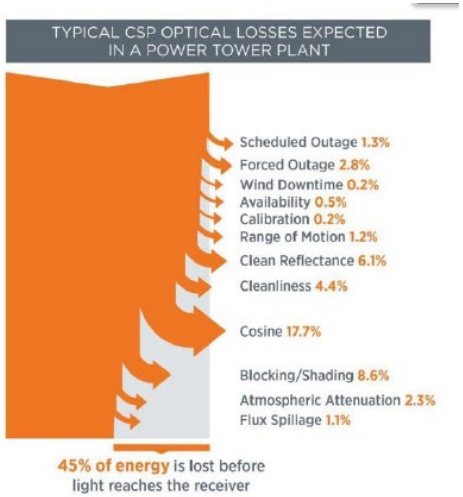


Figure 6. Losses between the collector and the receiver in a CSP system account for 45% of incoming energy.

Funded by:
SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

Impact on Optical Performance

- What does this mean for the overall plant performance?

how does this affect annual, plant-level performance? – assume row 1 data represents entire row 1 and same for rows 2,4 -> can say that _% of the time, intercept factor drops to __, which equates to an annual performance loss of _% - does SAM do this (using input of tracker error)