Funding Acknowledgement
Department of Energy
Solar Energy Technologies Office (SETO)
TMs: David Haas & Andru Prescod

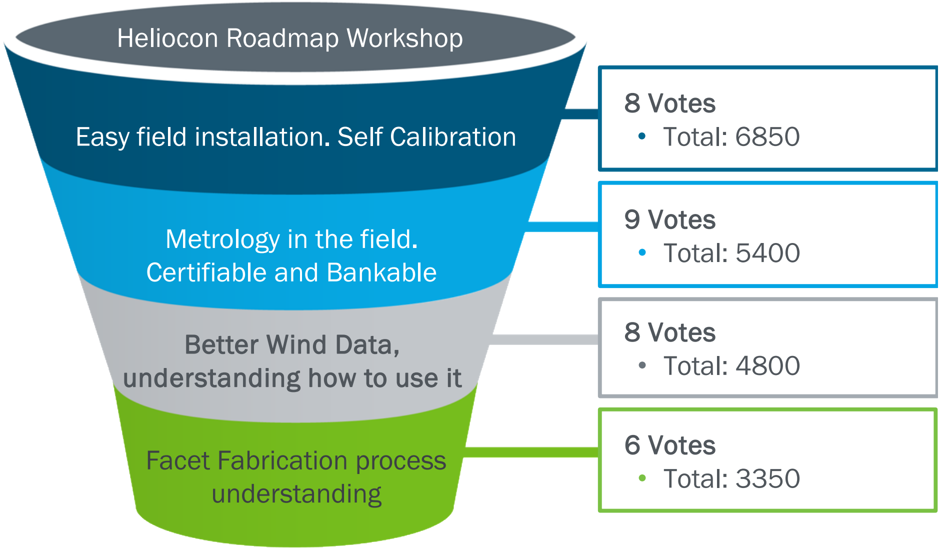
Wind-Driven Loads on Solar Collectors: Observations from the Nevada Solar One and Crescent Dunes Power Plants

Shashank Yellapantula, Ulrike Egerer, Brooke Stanislawski, Geng Xia, Eliot Quon, Ashesh Sharma, David Jager, Scott Dana, Andy Scholbrock, Simon Thao, Brian Manoa, Jerry Hur, Tyler Cary, Mark Iverson & Mark Mehos

National Renewable Energy Laboratory (NREL)

Photo by Dennis Schroeder, NREL 55200

Motivation



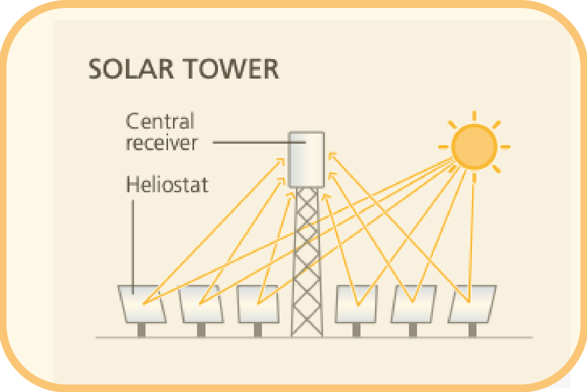
> Accurate solar and wind resource assessment of the site is essential
> – CSP Best Practices Report

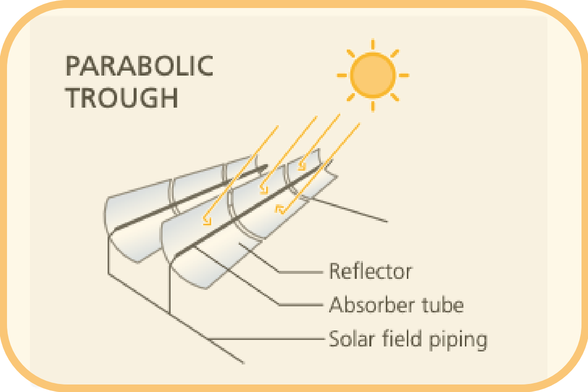
> In addition, no design standards exist for how to take a wind speed and convert it to loads on the collector.
> – CSP Best Practices Report

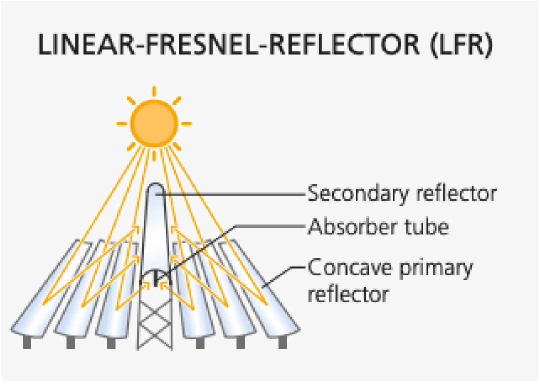
> Care should be taken to make sure the collectors selected are designed appropriately for the wind speeds that will be experienced at the plant site.
> – CSP Best Practices Report

Lack of wind and loads on collectors in an operational field setting

Wind Driven Loads on Solar Collectors



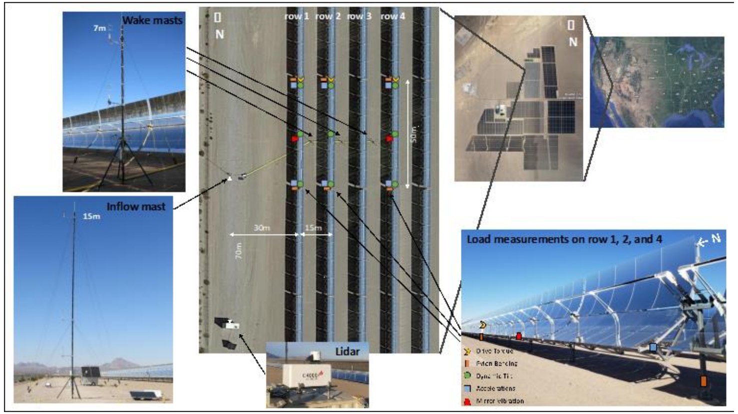




SolarPACES 2021, DLR

1. **Wind driven Loading** impacts both affects life and performance of Solar Collectors
2. Studying impacts of wind loading on CSP solar collectors at **two operational power plants** with troughs and heliostats

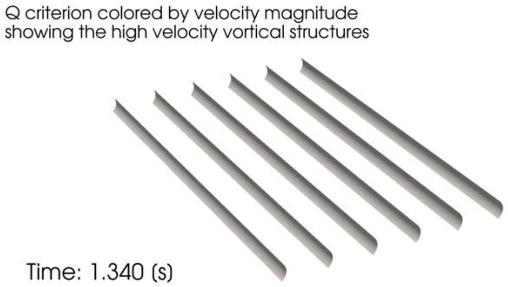
Goals



Collect Wind and Loads data from a parabolic trough power plant, Nevada Solar One (NSO)

Collect Wind and Loads data from a power tower plant, Crescent Dunes

Develop accurate and computationally in-expensive simulation techniques to study deep array effects for troughs and heliostats



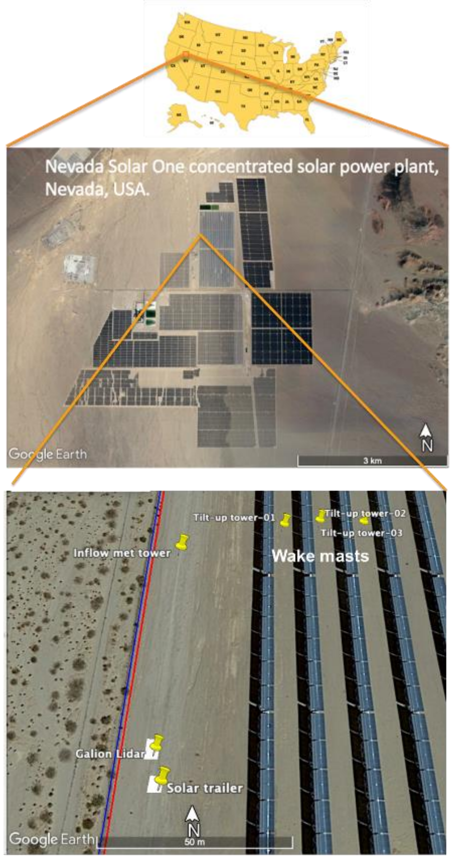
Parabolic Troughs

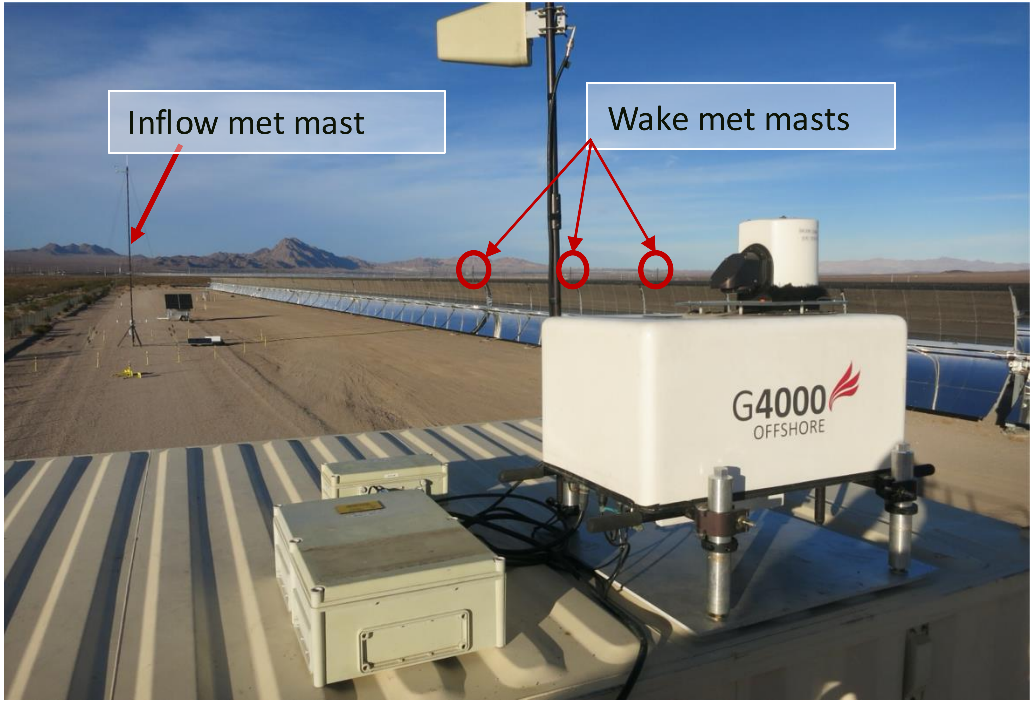
Nevada Solar One CSP Plant

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

Boulder City, Nevada

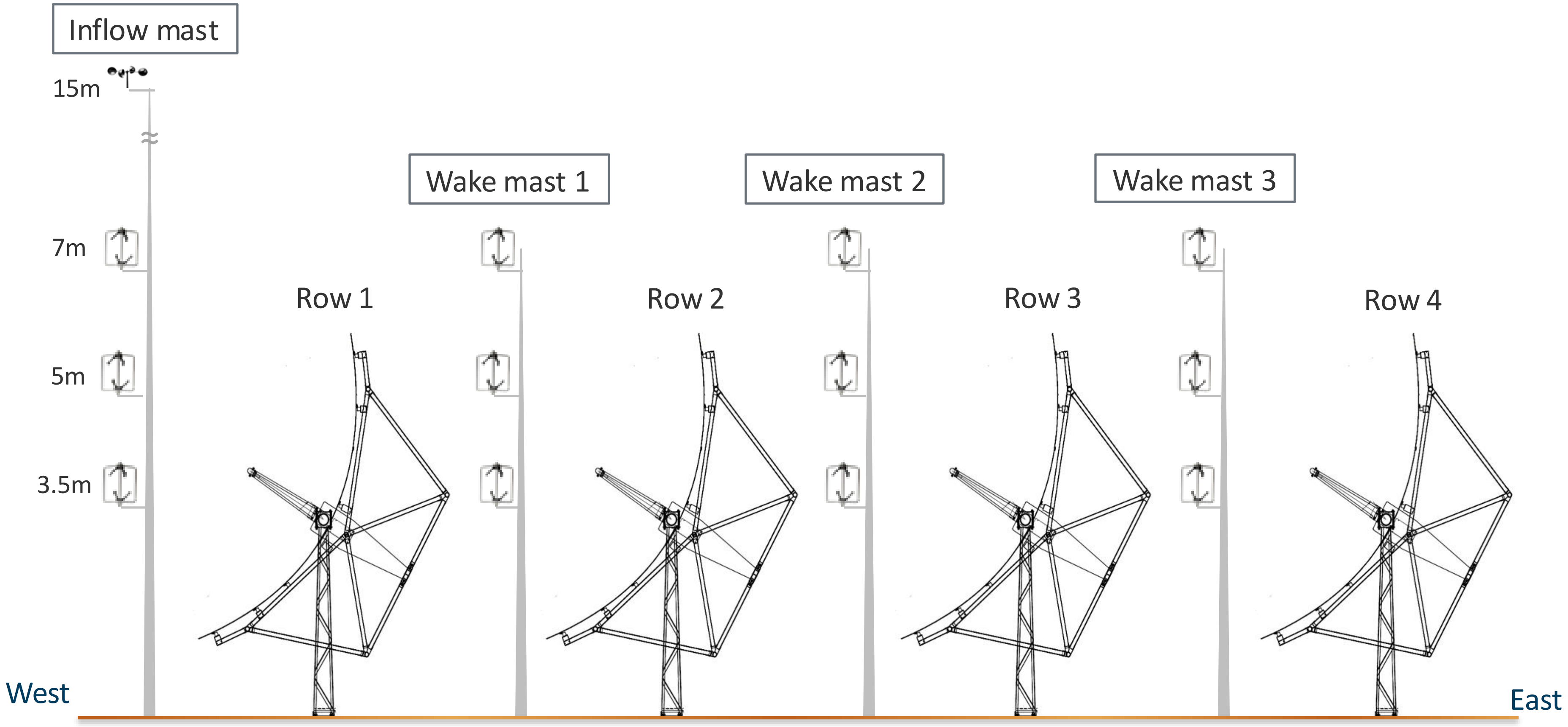
Wind Measurement Set-Up



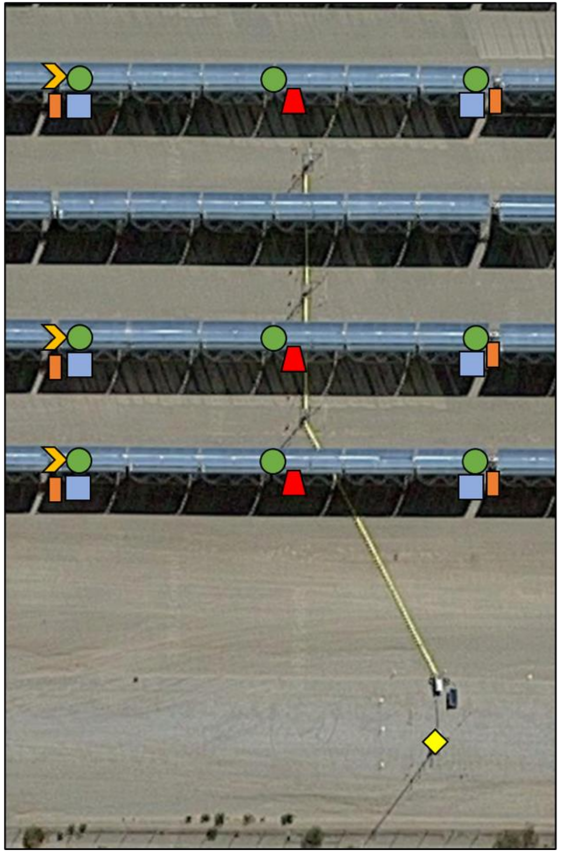


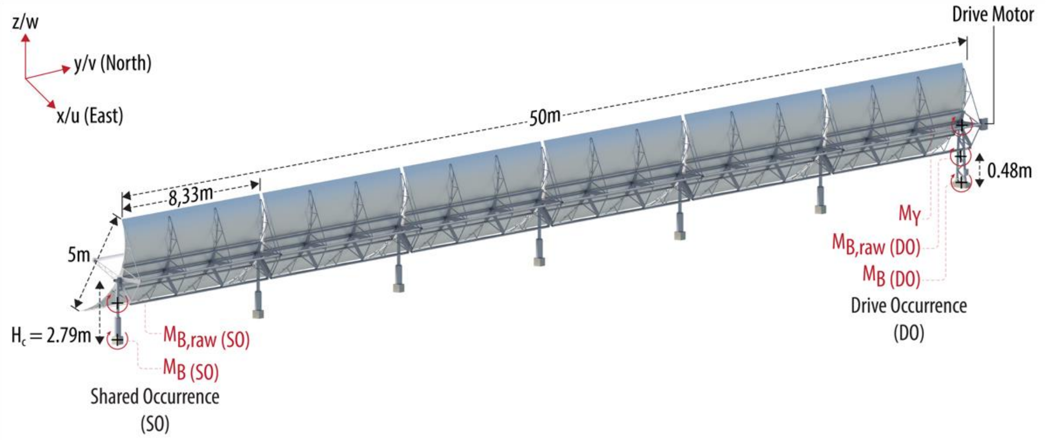
First of a kind measurement campaign in a fully operational power plant

Wind Measurement Set-Up



Load Measurement Campaign – Signal Overview



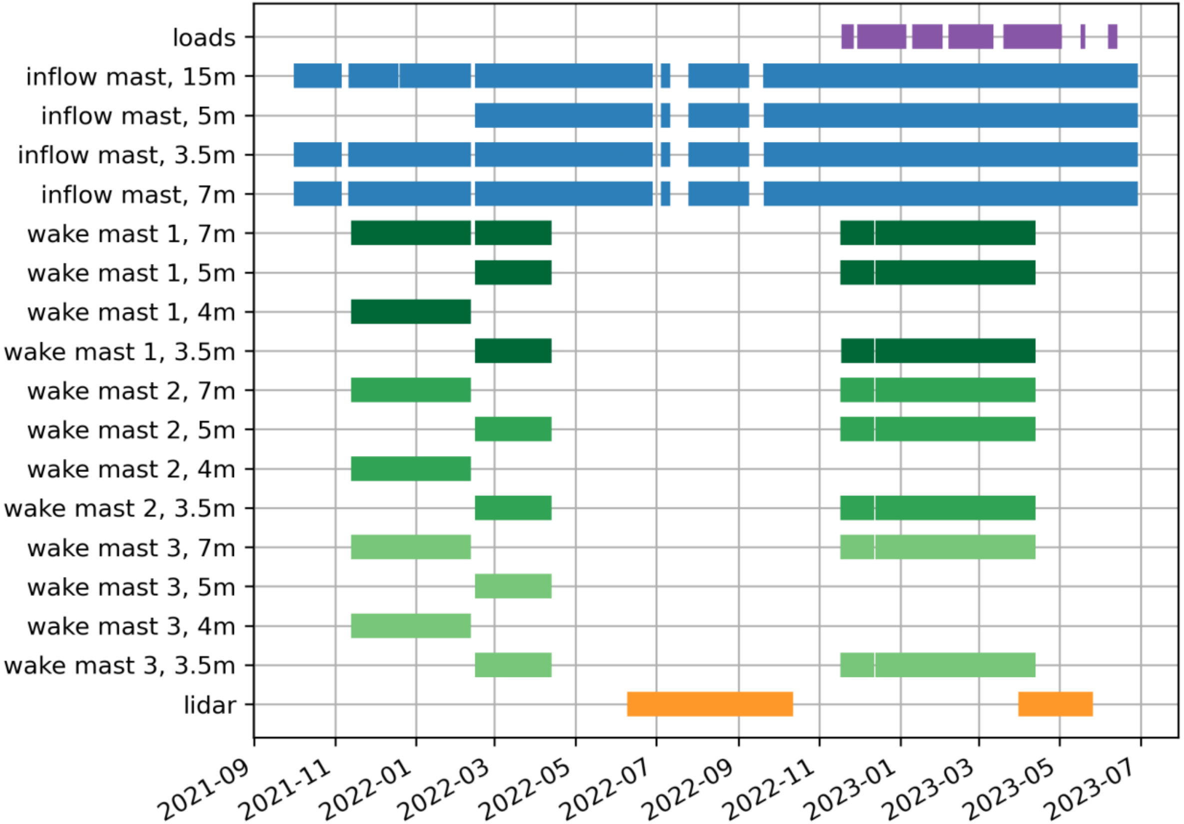


Key:

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

Variable	Symbol	Description	Unit
Loads at row *Z* and location *loc* (*Z*=1,2 or 4; *loc* = DO, SO or Mid)			
RZ_*loc*_Bending	M_B	Bending moment at DO or SO	kNm
RZ_DO_Torque	M_y	Torque moment at DO	kNm
RZ_*loc*_Accel_X	a_x	Acceleration at spaceframe on western edge, perpendicular to mirror plane	g
RZ_*loc*_Accel_Y	a_y	Acceleration at spaceframe on western edge, in mirror plane	g
RZ_Disp_*pos*	d	Mirror displacement at westernmost, mid panel (*pos*=NW, NE, SW, SE or Center), zero-value subtracted	mm
RZ_Disp_*pos*_orig	d_0	Mirror displacement as above, absolute value	mm
RZ_*loc*_Tilt	α	Tilt of spaceframe at DO, Mid or SO	°
Anemometer	U	Wind speed at 15 m height (same as in wind data)	m/s
RZ_*loc*_C_Bending	C_{mb}	Bending moment coefficient at DO or SO	-
RZ_DO_C_Torque	C_{my}	Torque moment coefficient at DO	-
RZ_*loc*_Cfx	C_{fx}	Drag force coefficient at DO or SO	-

Measurement Campaign Overview



First of a kind long-term measurement campaign

1. Wind data continuously collected for 2 years
2. Loads data collected for 6 months

Open Dataset

OpenEI Open Energy Data Initiative (OEDI)

OEDI Data Help About Search

Wind and Structural Loads on Parabolic Trough Solar Collectors at Nevada Solar One

Description

Resources

Citation

Related Datasets

DOI 10.25984/2001061

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Wind loading is a main contributor to structural design costs of Concentrating Solar Power (CSP) collectors, such as heliostats and parabolic troughs. These structures must resist the mechanical forces generated by turbulent wind. At the same time, the reflector surfaces must exhibit the necessary rigidity to maintain their optimal optical performance in windy conditions.

Over two years, NREL conducted comprehensive field measurements of the atmospheric turbulent wind conditions and the resulting structural wind loads on parabolic troughs at the Nevada Solar One (NSO) plant. The measurement set-up included meteorological masts and structural load sensors on four trough rows. Additionally, we commissioned a lidar scanning the horizontal plane over the trough field.

This data set catalogs the high-resolution data set characterizing the complex flow field and resulting structural loads on parabolic trough collectors. By providing this first-of-its-kind data set to the CSP community, we aim to enhance the community's understanding of wind-loading experienced by CSP collector structures. This data set will also help design next-generation solar collectors and photovoltaic trackers.

Organization

National Renewable Energy Laboratory (NREL)

Contact

Shashank Yellapantula

shashank.yellapantula@nrel.gov

303.264.8595

https://data.openei.org/submissions/5938

doi: 10.25984/2001061

https://www.osti.gov/dataexplorer/biblio/dataset/2001061

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Wind and structural loads data measured on parabolic trough solar collectors at an operational power plant

Ulrike Egerer ✉, Scott Dana, David Jager, Geng Xia, Brooke J. Stanislawski & Shashank Yellapantula

Scientific Data **11**, Article number: 98 (2024) | Cite this article

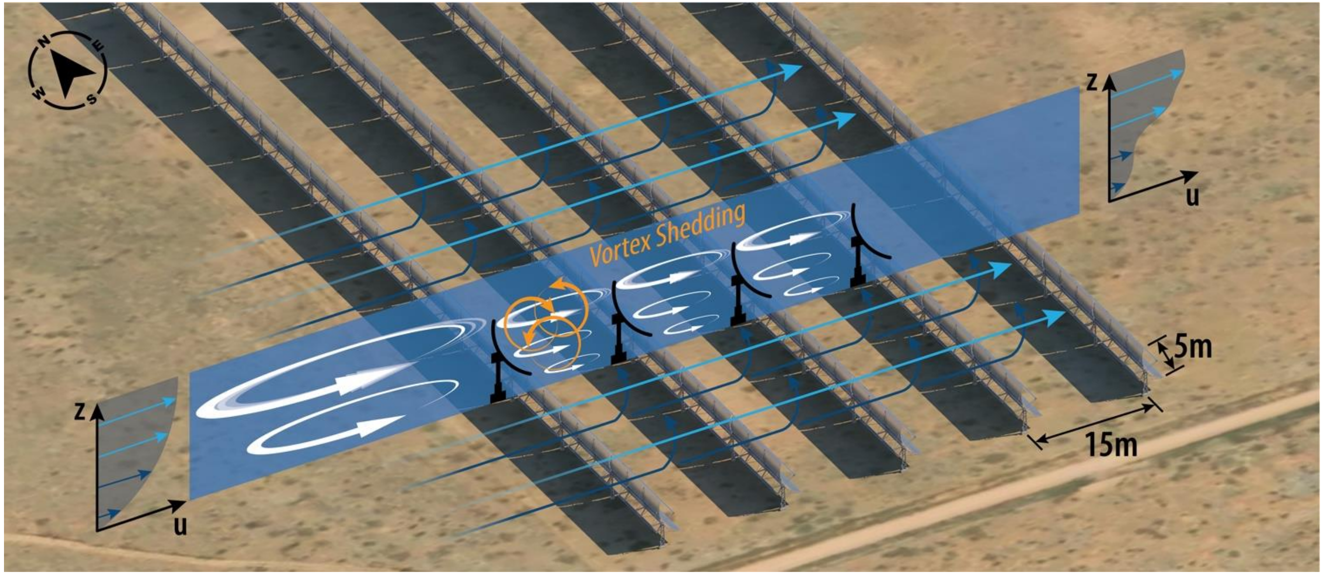
ELSEVIER

Solar Energy
Volume 280, 15 September 2024, 112860

Field measurements reveal insights into the impact of turbulent wind on loads experienced by parabolic trough solar collectors

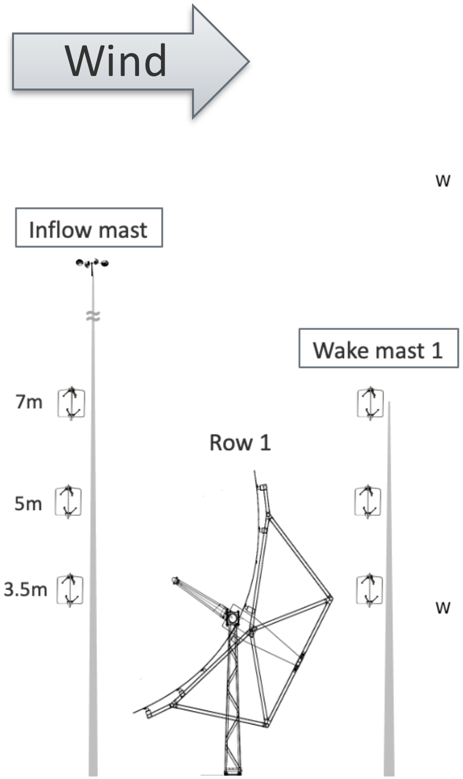
Ulrike Egerer ✉, Scott Dana, David Jager, Brooke J. Stanislawski, Geng Xia, Shashank Yellapantula

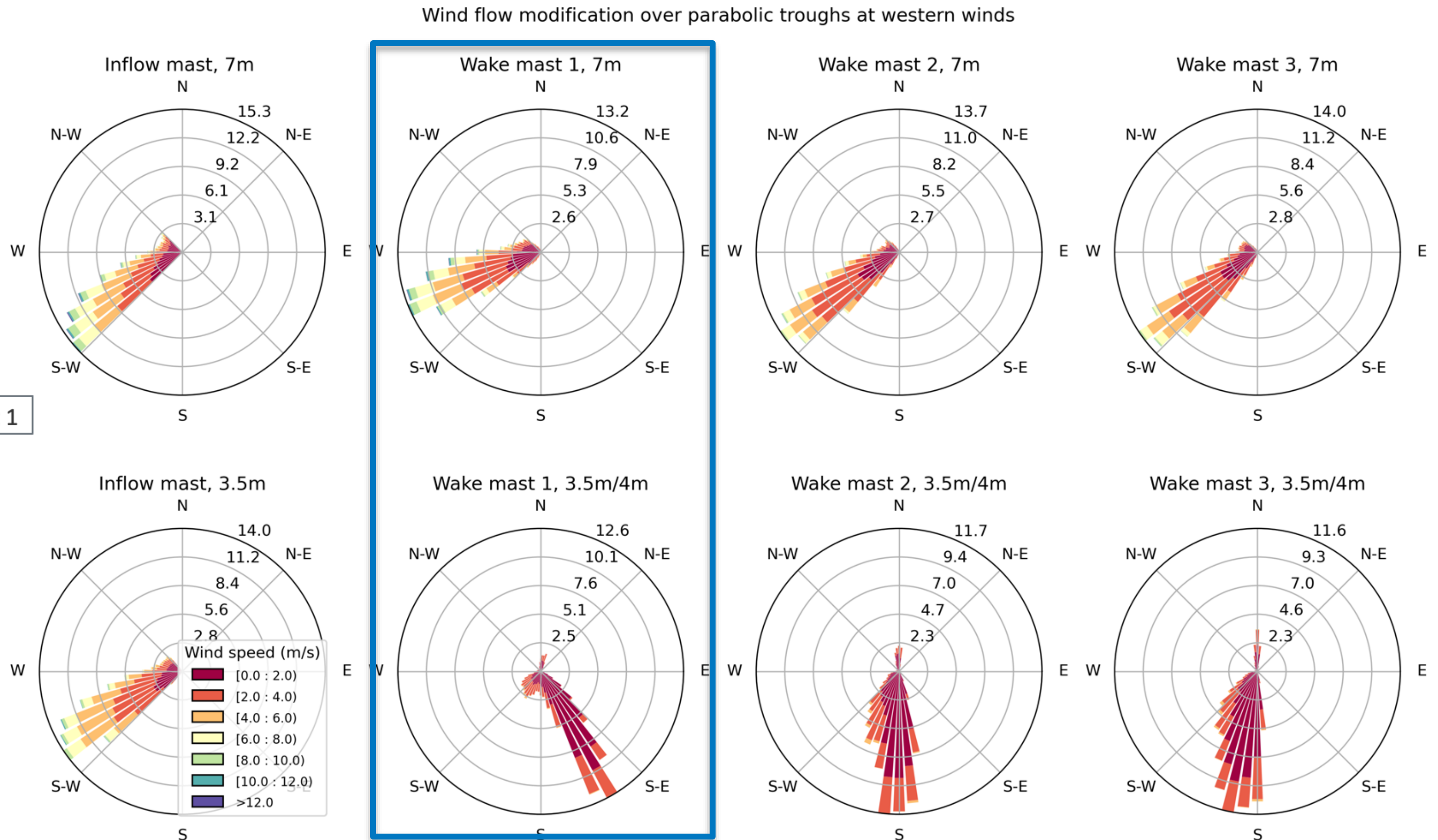
Wind Field Modulation - Troughs



1. Upstream rows blocking the wind
2. Change in wind direction by upstream rows
3. Turbulence modified significantly by trough orientation

Wind Directionality Change - Troughs





Trough rows modify the direction of incoming wind – induce torsional loads on drives & supporting structures

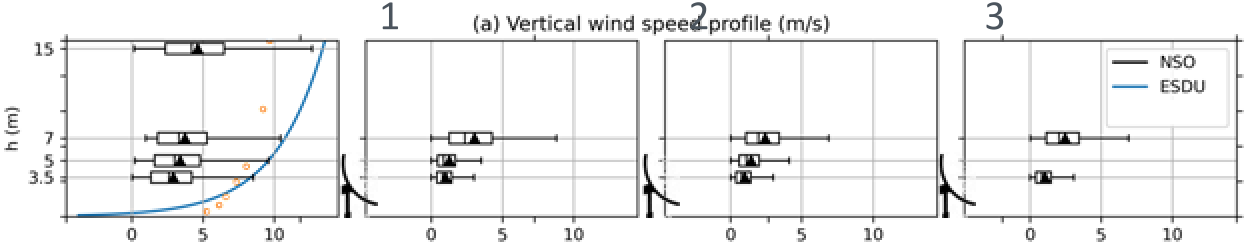
Vertical wind and turbulence profiles

Inflow mast

Wake mast 1

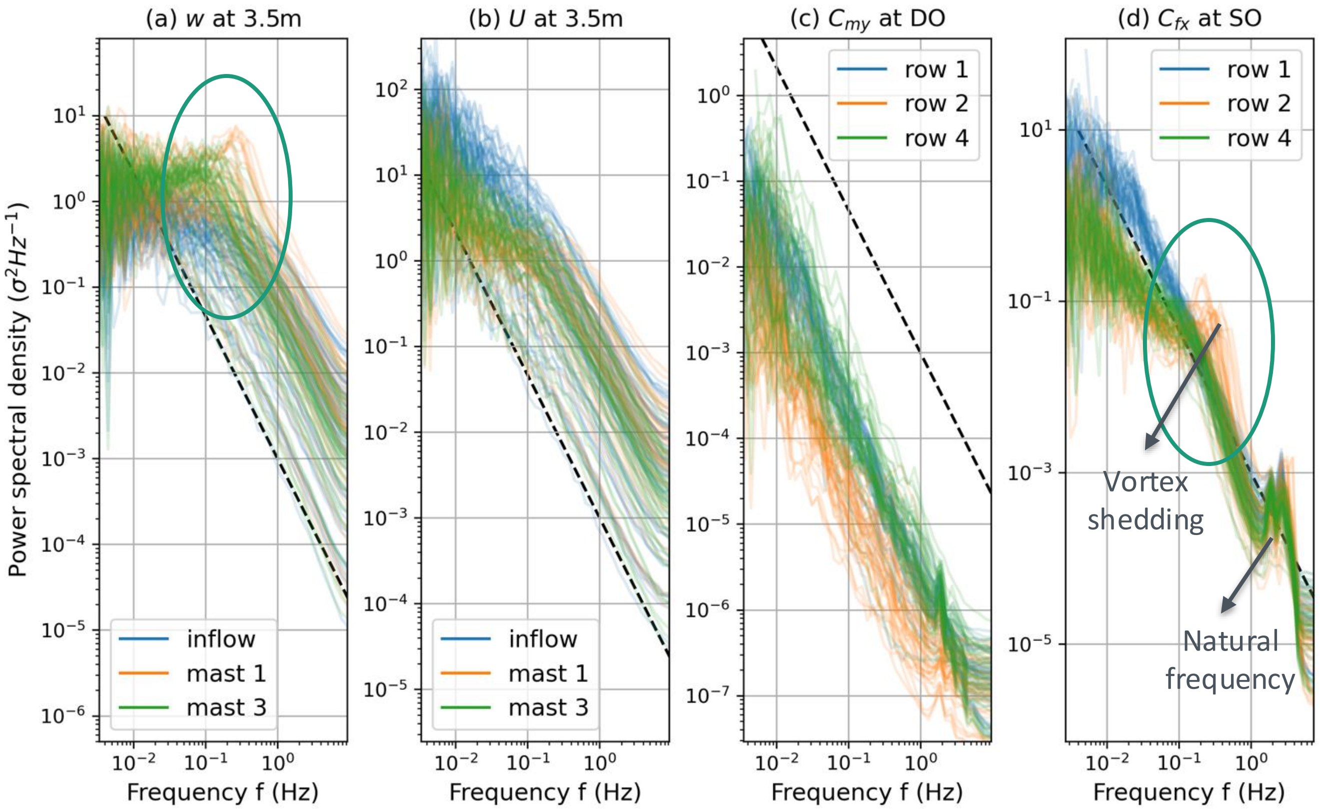
Wake mast 2

Wake mast 3



- Wind speed blocked after row 1.
- At hinge height: less TKE, but increased TI.
- Observed TI is higher than expected from ESDU standard (z_0=0.3).

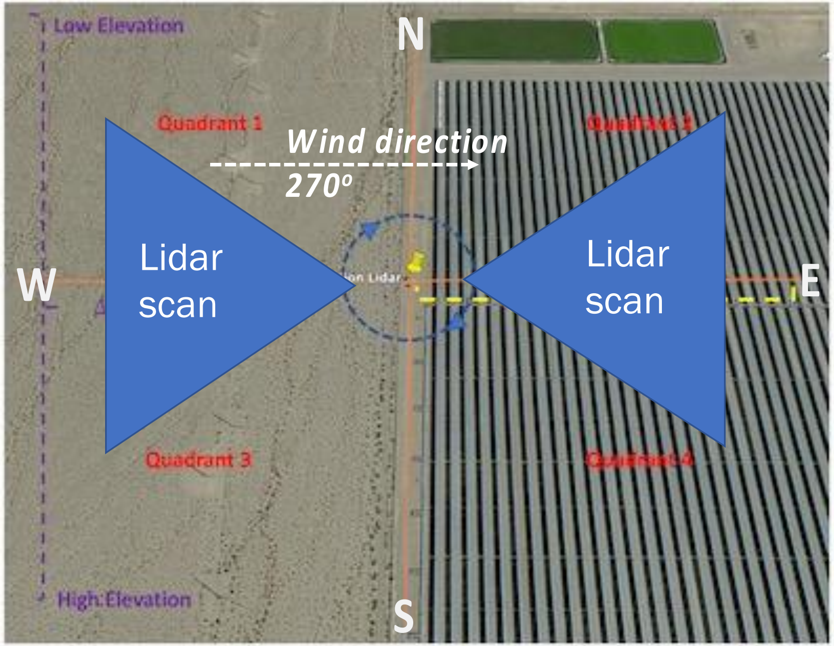
Natural Frequency & Vortex Shedding

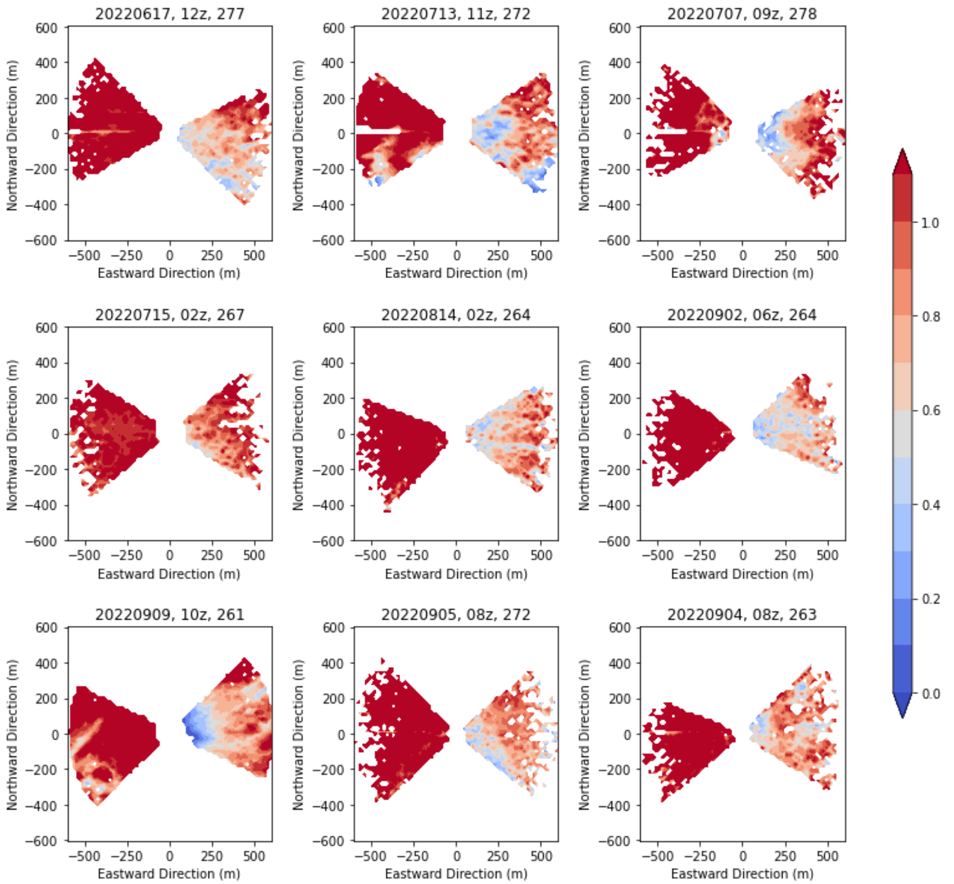


Trough angle 60^{O}

- Spectral peak in *w* after row 1 reflects in drag moment coefficient.
- Vortex shedding dominant phenomenon.
- Length scales coincides with trough dimension.

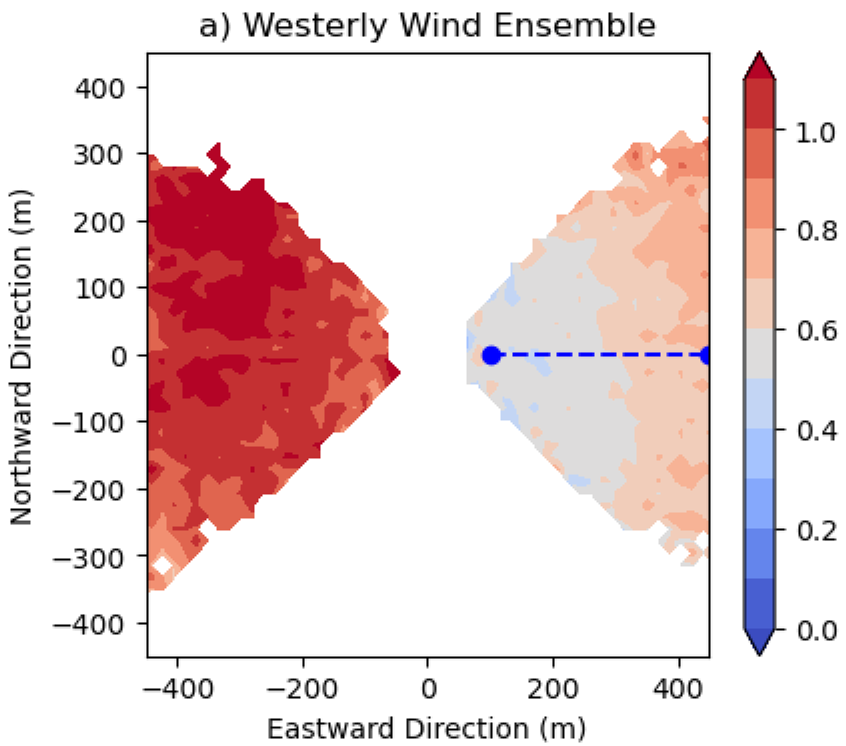
Power Plant Interior – Wind Field

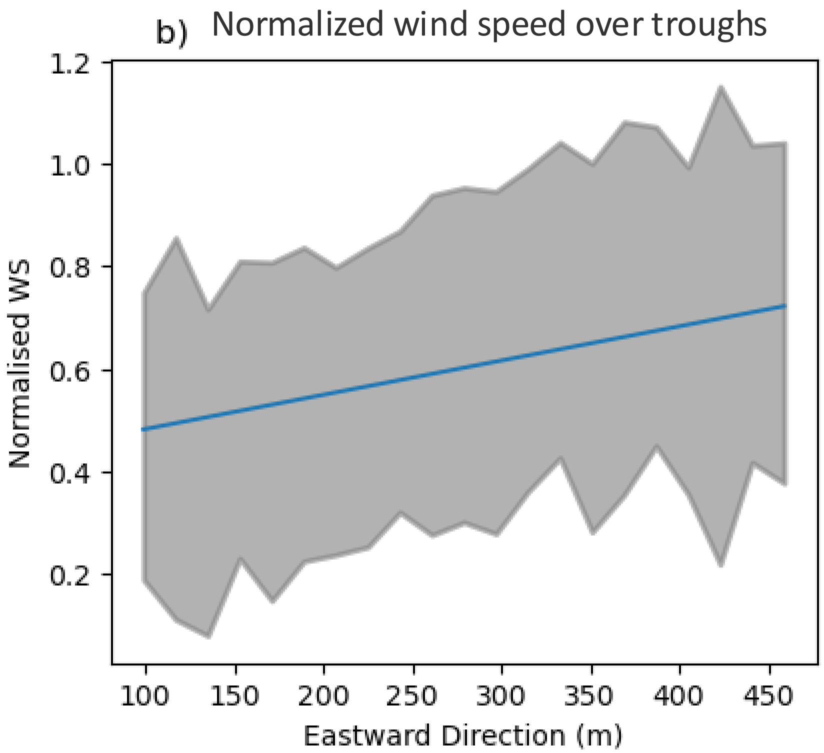




Western winds - perpendicular to the troughs

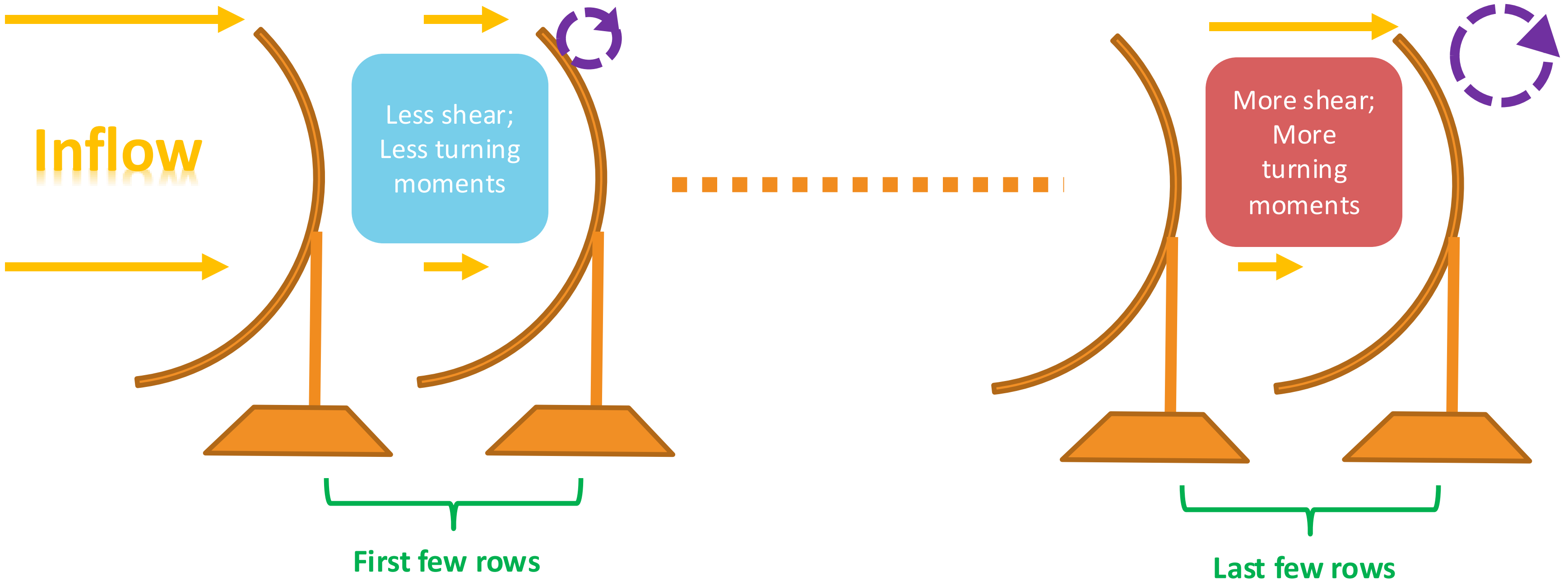
Power Plant Interior – Wind Field





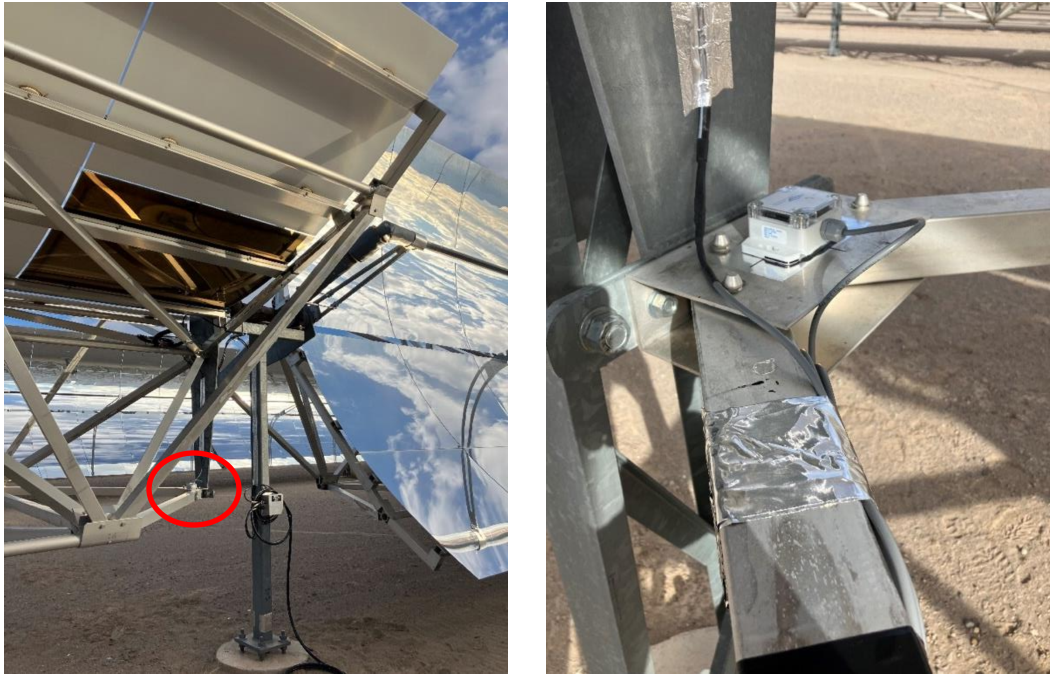
Increased wind shear in the interior of the plant

Power Plant Interior – Wind Field

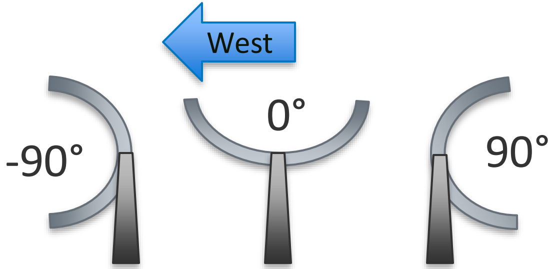


Higher hinge moments on troughs in the interior of the plant

Load Measurement Campaign – Dynamic Tilt

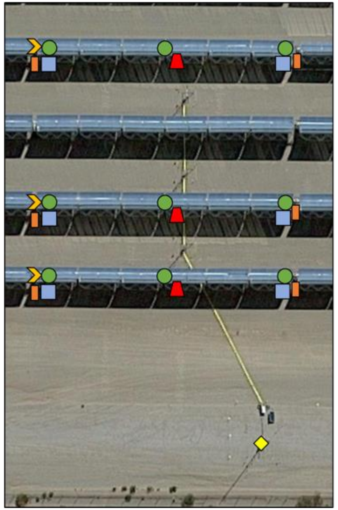


Dana et al. 2022

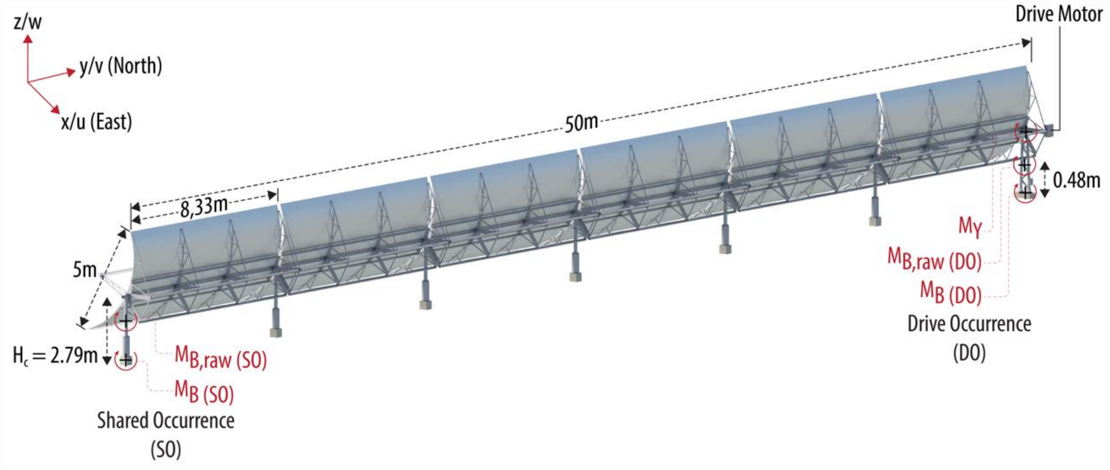


- Inclinometers installed at 3 locations (DO, Mid, SO) on each of the 3 rows
- Measurements from November 2022 – June 2023.
- Collected at 20 Hz frequency with 10-second statistical windows.

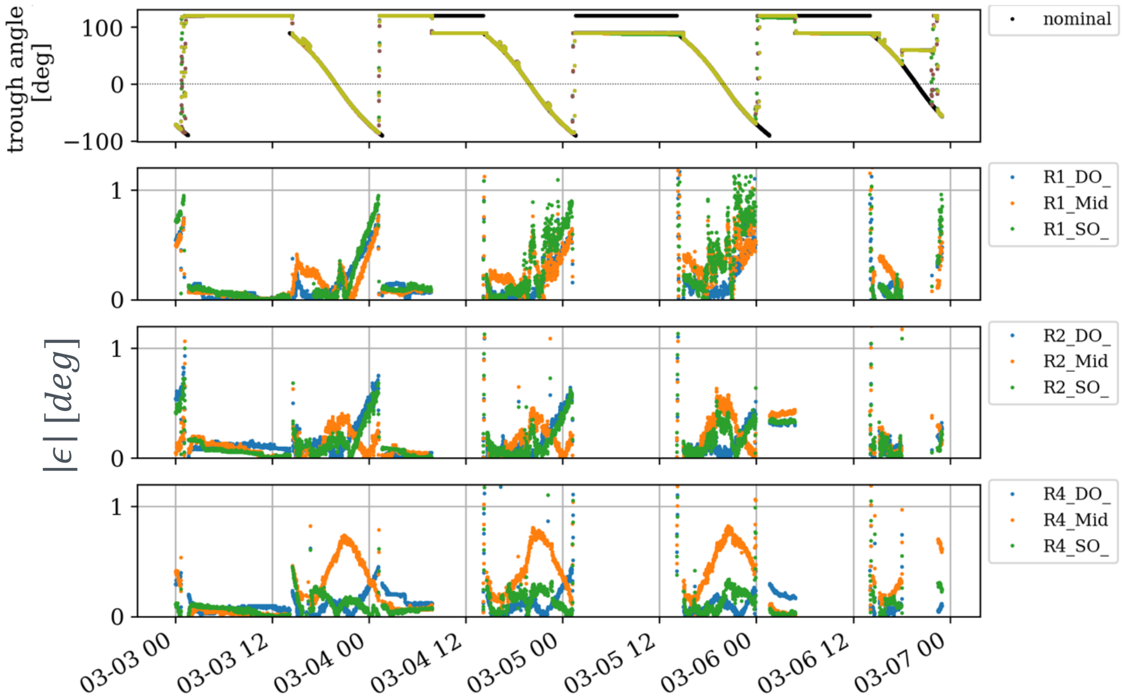
Load Measurement Campaign – Dynamic Tilt



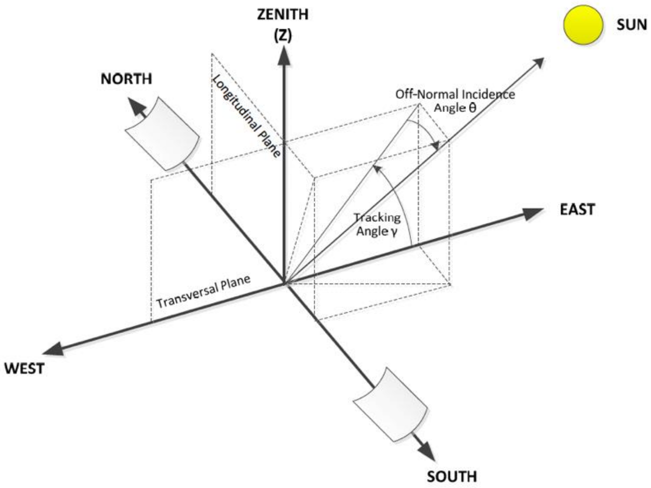
Key:
- Drive Torque
- Pylon Bending
- Dynamic Tilt
- Accelerations
- Mirror Vibration
- Wind Speed



Calculating Tracking Error



Calculating the sun position:

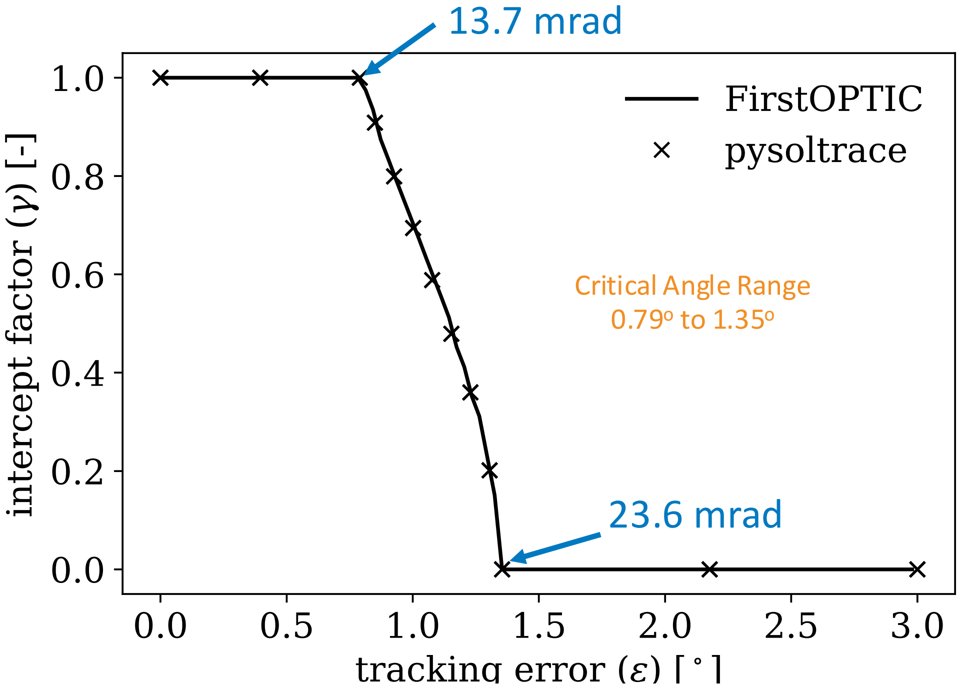


Zhu 2011

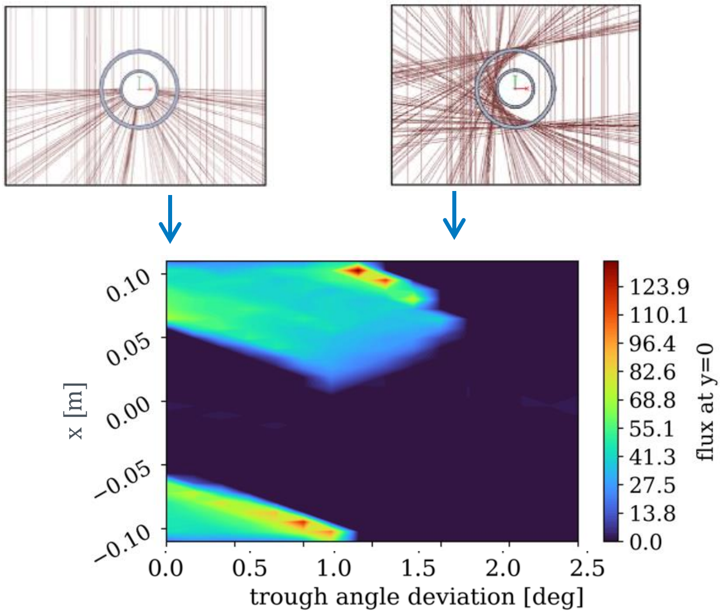
$$\epsilon = \beta - \beta_{nominal} \qquad \epsilon = tracking\ error \qquad \beta = trough\ angle$$

Impact of Tracking Error

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

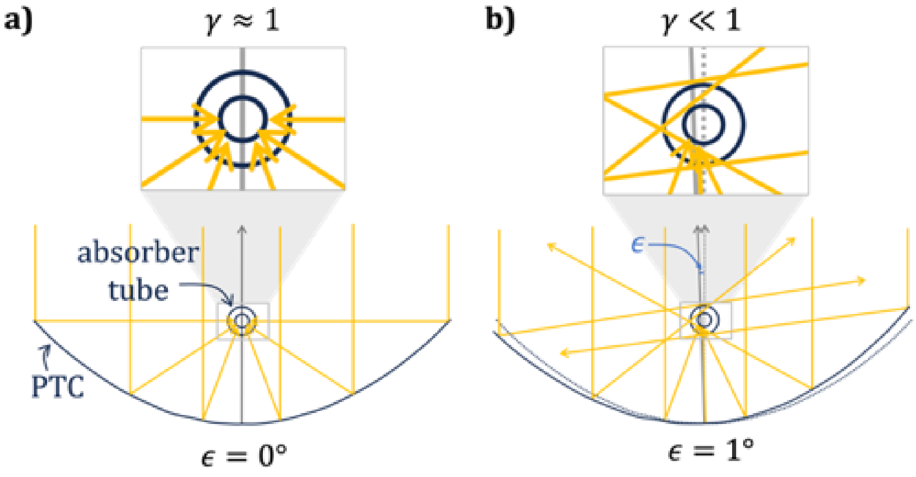


Performed Ray-tracing to compute optical performance at each tilt angle

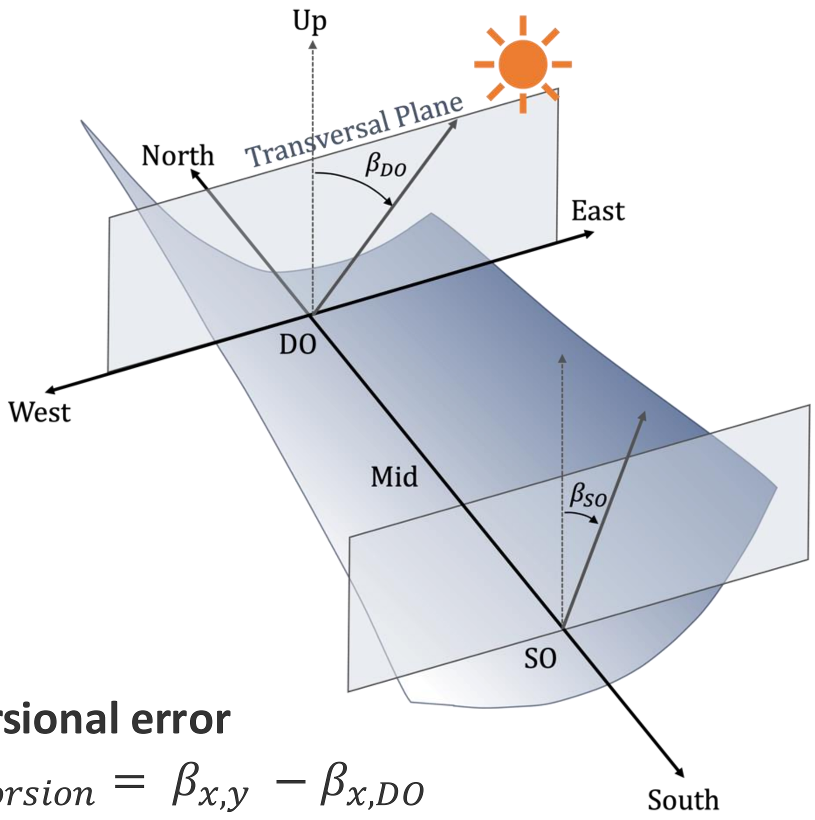


Even at intercept factor ($\gamma \cong 1$) could result in non-uniform heating of receiver tube

Torsion causes angular misalignment



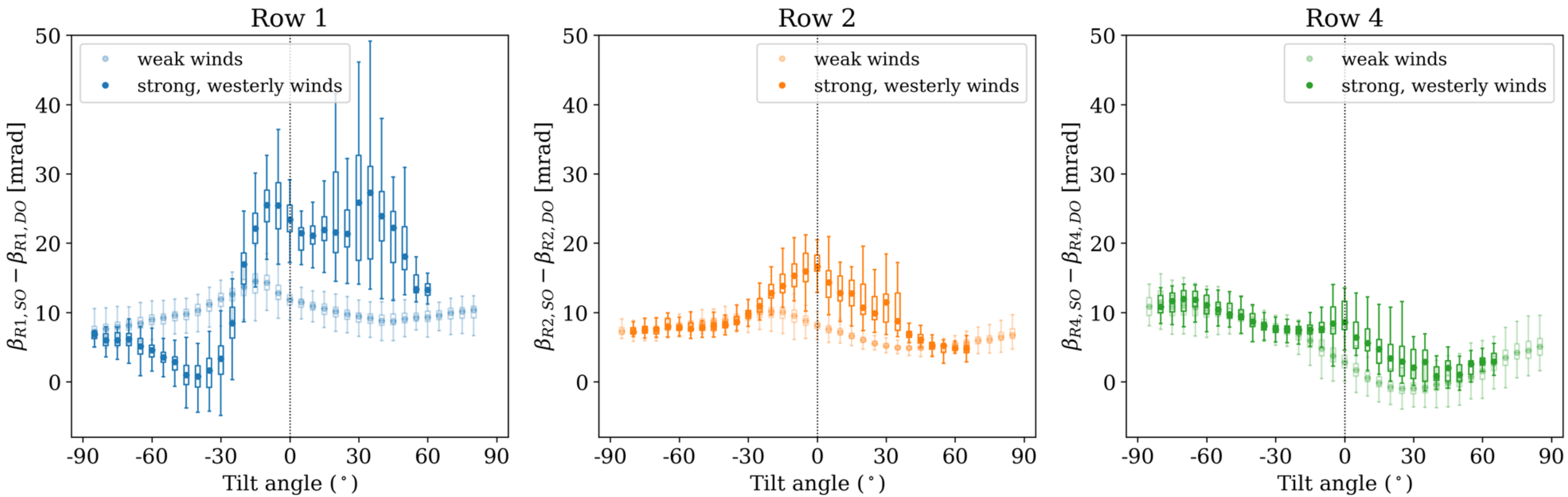
$$intercept\ factor\ (\gamma) = \frac{number\ of\ rays\ that\ hit\ the\ absorber}{number\ of\ rays\ that\ hit\ the\ collector}$$



Torsional error

$$\epsilon_{torsion} = \beta_{x,y} - \beta_{x,DO}$$

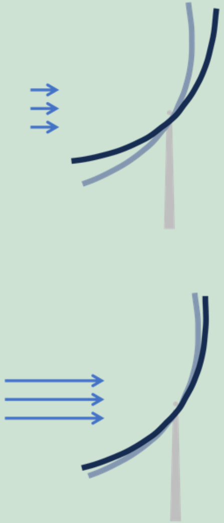
Strong, western winds affect torsional misalignment

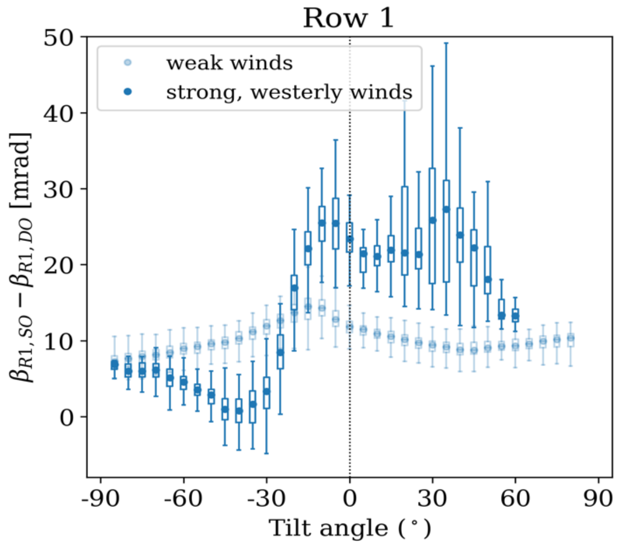


Strong, westerly winds induce greater median torsional error and standard deviation of tilt angle in row 1 than in rows 2 and 4 because **row 1 blocks the incoming wind**

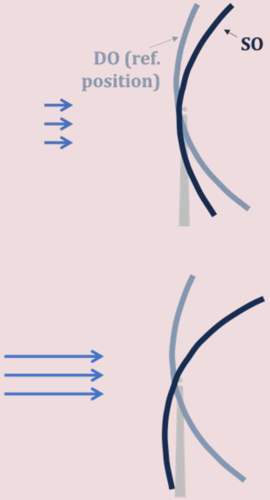
Wind interactions with exterior PTC

$\beta < -20°$





$\beta > -20°$



$\beta = -20°$

Strong westerly winds have
torsional
ce toward
oming

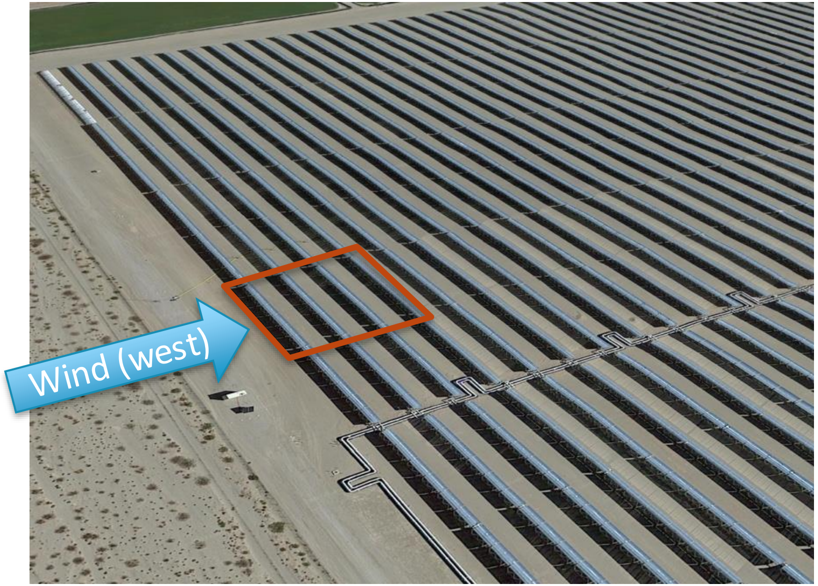
- Higher torsional error during strong winds when facing away from the wind.
- Higher standard deviation during strong winds.

Wind conditions and PTC orientation play an important role in torsion.

Loads: Comparison to Wind Tunnel Tests

Hosoya et al. (2008)

NSO measurements



Hosoya, N, Peterka, J A, Gee, R C, and Kearney, D. 2008. *Wind Tunnel Tests of Parabolic Trough Solar Collectors: March 2001--August 2003*. Golden, CO: National Renewable Energy Laboratory. NREL/SR-550-32282. doi:10.2172/929597.

Loads: Comparison to Wind Tunnel Tests

Hosoya et al. (2008): Comprehensive wind tunnel tests

Torque moment coefficient:

$$C_{my} = \frac{M_y}{\frac{\rho}{2} U^2 \cdot L_{\text{panel}} \cdot W^2}$$

Drag force coefficient:

$$C_{fx} = \frac{F_x}{\frac{\rho}{2} U^2 \cdot L_{\text{segment}} \cdot W}$$

M_y	Torque moment
F_x	Drag force
U	Wind speed
L_{panel}	Length of trough panel
$L_{segment}$	Length of trough segment
W	Aperture width

Hosoya, N, Peterka, J A, Gee, R C, and Kearney, D. 2008. *Wind Tunnel Tests of Parabolic Trough Solar Collectors: March 2001--August 2003*. Golden, CO: National Renewable Energy Laboratory. NREL/SR-550-32282. doi:10.2172/929597.

Loads: Comparison to Wind Tunnel Tests

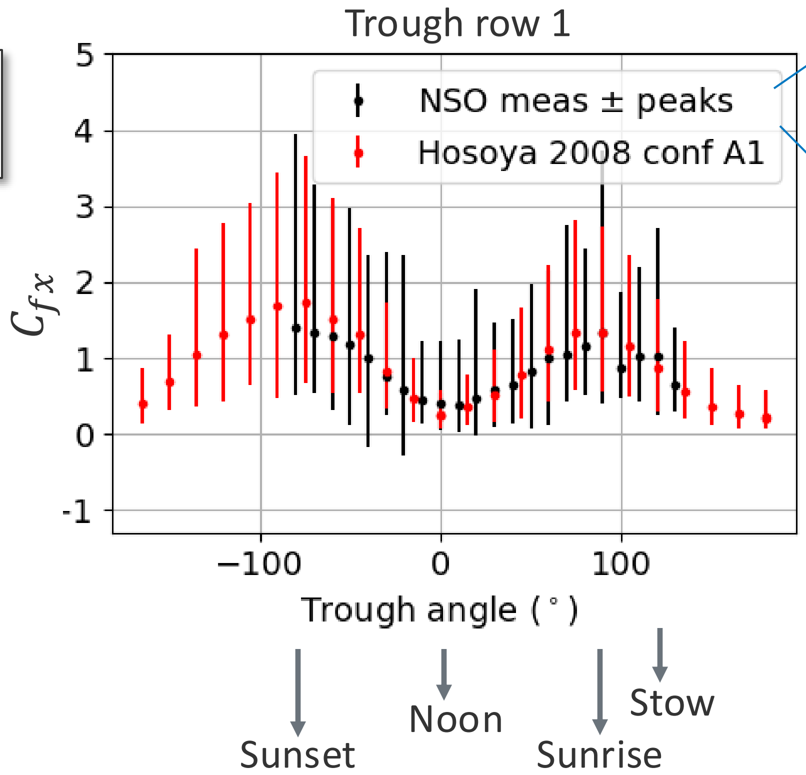
$$C_{fx} = \frac{F_x}{\frac{\rho}{2} U^2 \cdot L_{\text{segment}} \cdot W}$$

$$C_{my} = \frac{M_y}{\frac{\rho}{2} U^2 \cdot L_{\text{panel}} \cdot W^2}$$

Loads: Comparison to Wind Tunnel Tests

Drag force coefficient:

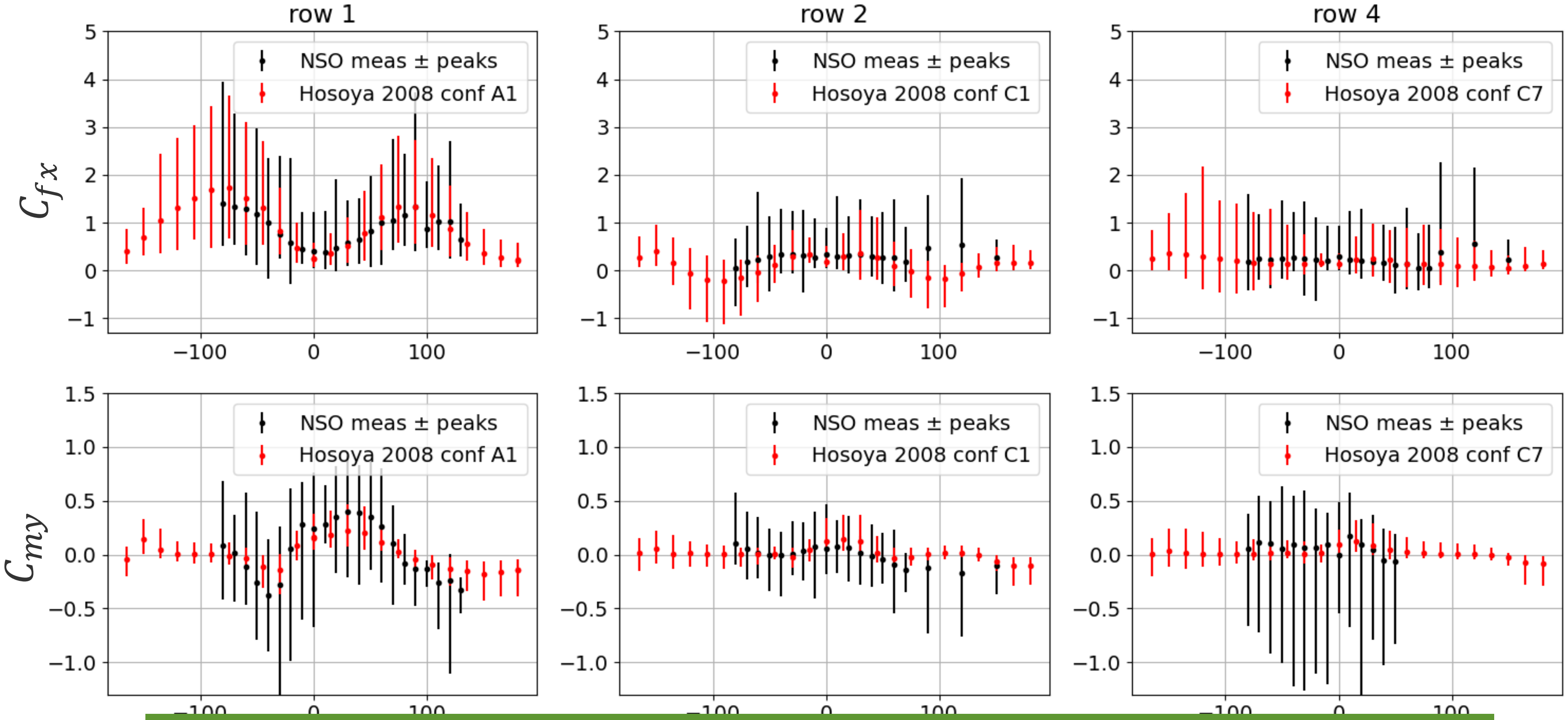
$$C_{fx} = \frac{F_x}{\frac{\rho}{2}U^2 \cdot L_{\text{segment}} \cdot W}$$



NSO: mean ± **peak loads** (wind direction: 260°–280°)

Hosoya et al. (2008): mean ± **peak loads** (0° yaw)

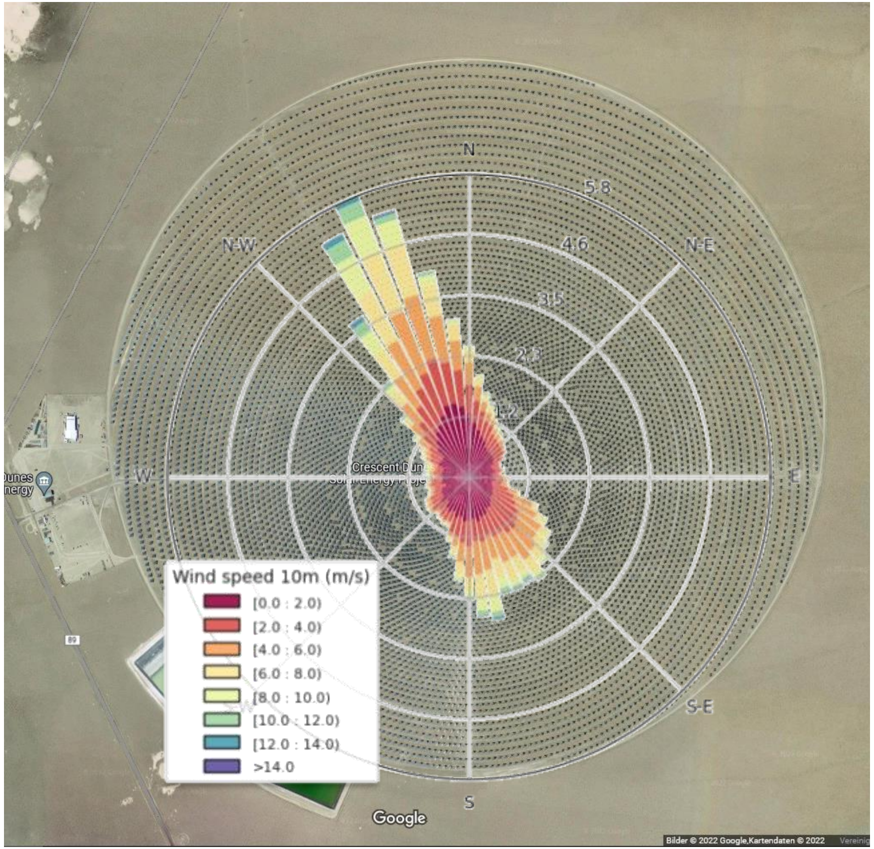
Loads: Comparison to Wind Tunnel Tests



Wind tunnel studies on troughs underpredict dynamic loading on collectors

Heliostats

Crescent Dunes Campaign



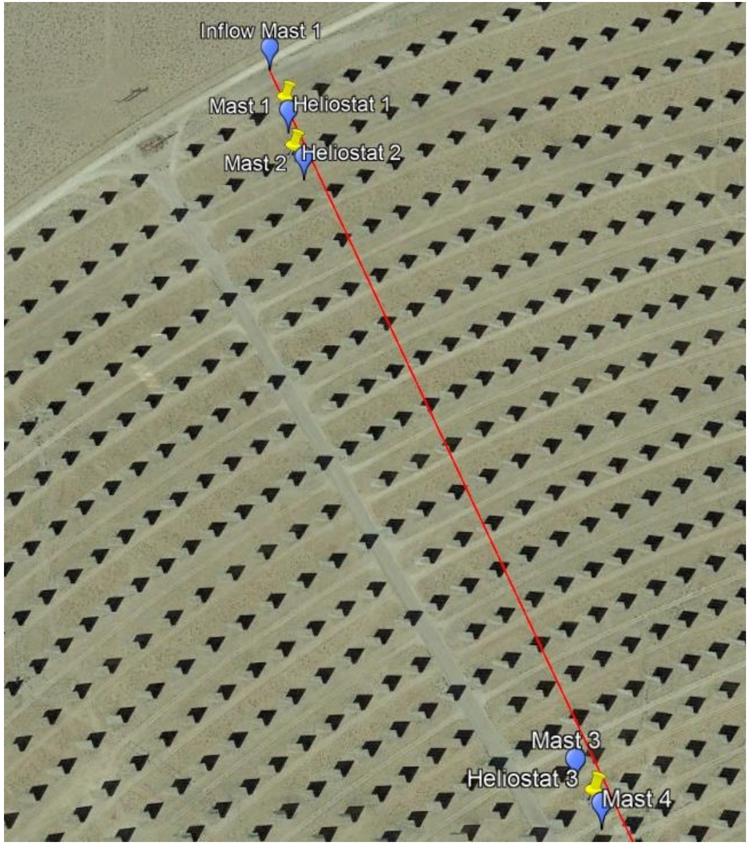
01 A 6-month wind and loads data collection campaign

02 Focus on N-W quadrant of the plant – dominant wind direction

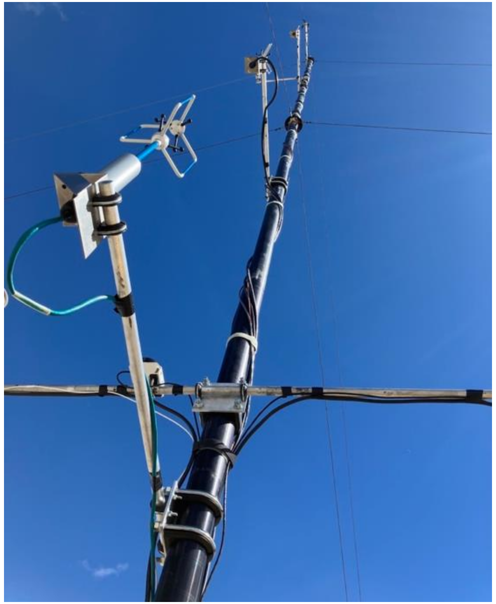
03 Characterize Wind profiles at the edge and in the interior

04 Measure loads on 3 heliostats – Two at the edge and one in the interior

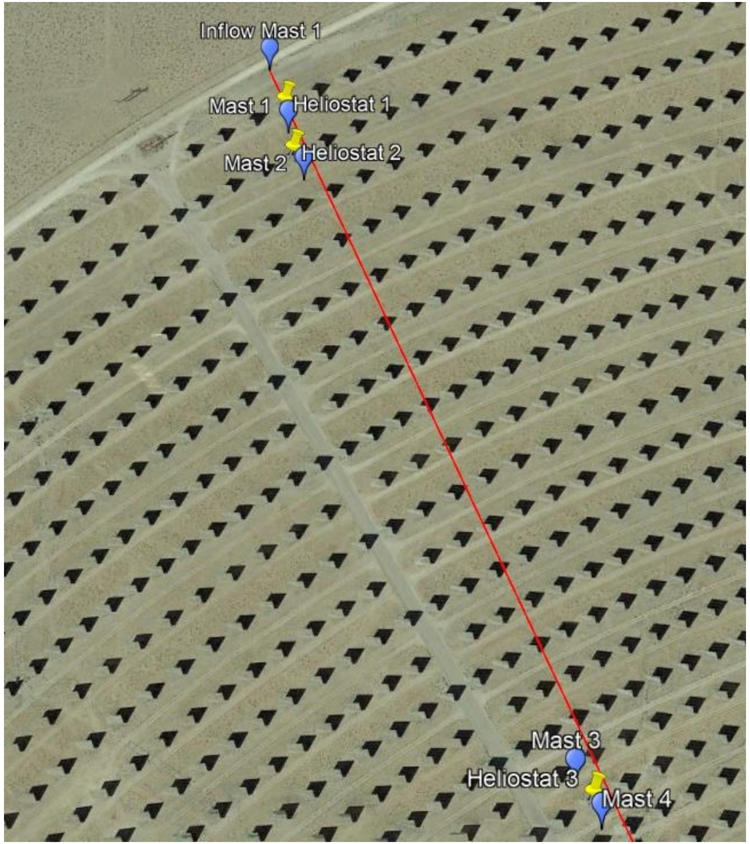
Crescent Dunes Wind Measurement



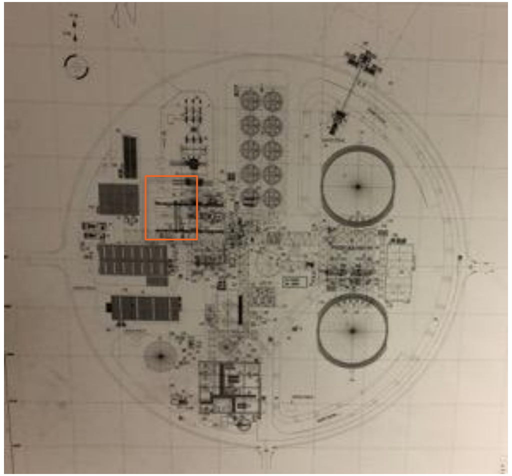
Inflow Mast - 1



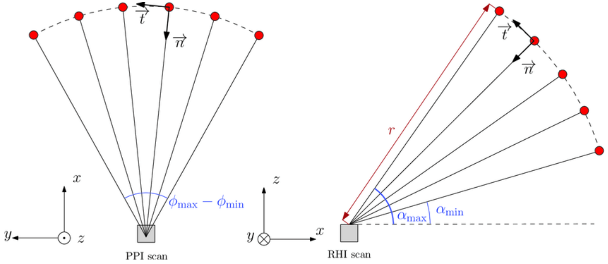
Crescent Dunes Wind Measurement



Crescent Dunes - Lidar

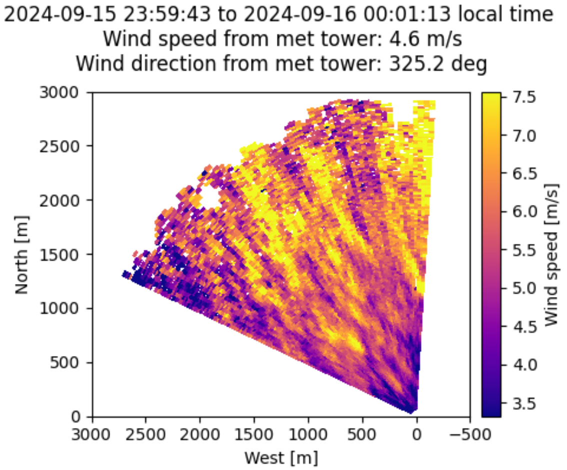


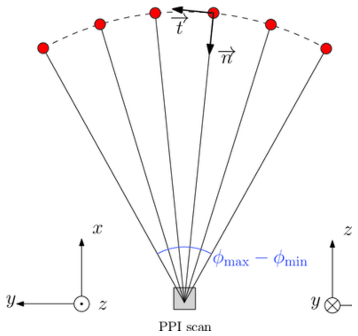
Vertical and Horizontal scans

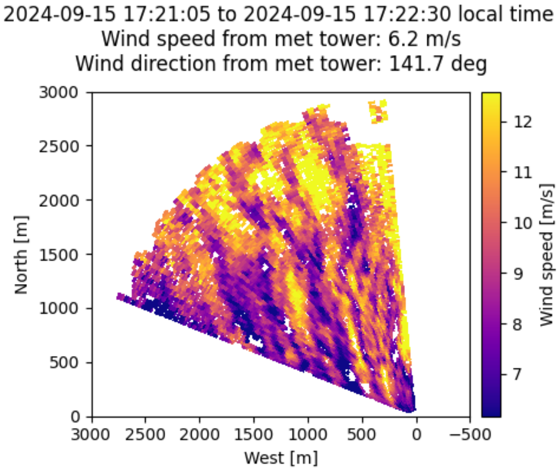


High resolution scanning Lidar installed on the heater bay for full field wind mapping

Crescent Dunes - Lidar

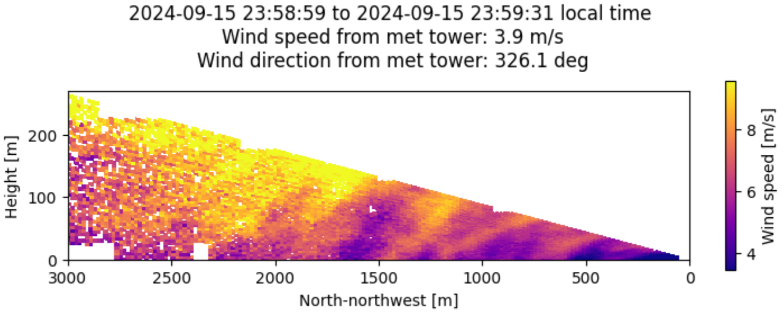


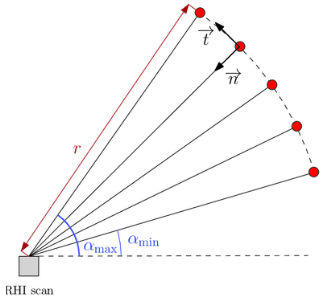


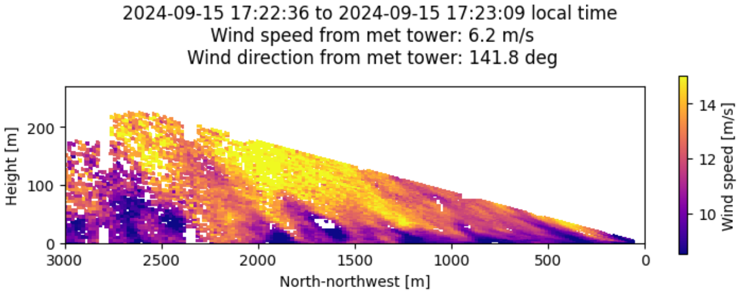


Wind from the North-West

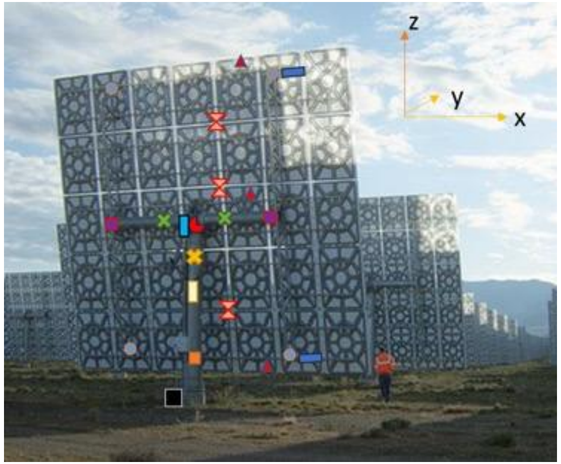
Wind from the South-East







Crescent Dunes Wind and Loads



- Pedestal bending moments (M_x and M_y) to determine foundation loads and validate load distribution on the mirror
- Torque along the torque tube to obtain validation of load distribution along the x-axis and proxy for torque actuator loads
- Torque of the pedestal to assess asymmetrical loading across mirrors and proxy for azimuth drive loads
- Pedestal axial load, to access lift
- Accelerometers across support frame to validate mode shapes, accelerations, spectral content of the facet support structure, and elevation angle
- Mirror displacements to validate cyclic loading response and facet spectral content
- Dynamic tilt to measure elevation angle and torque tube dynamics
- Azimuth position (encoder or altitude sensor)
- Differential pressure for lift/drag/stall measurements

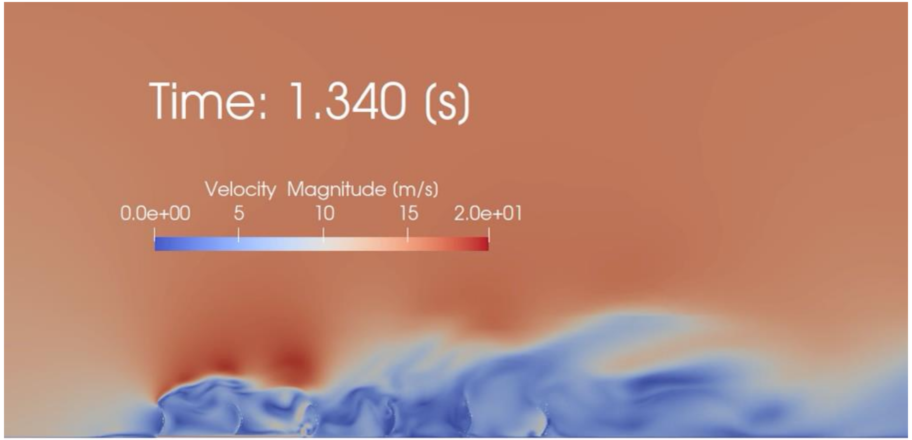
Loads instrumentation installed on 3 Heliostats (2 at the edge of the plant and 1 in the interior)

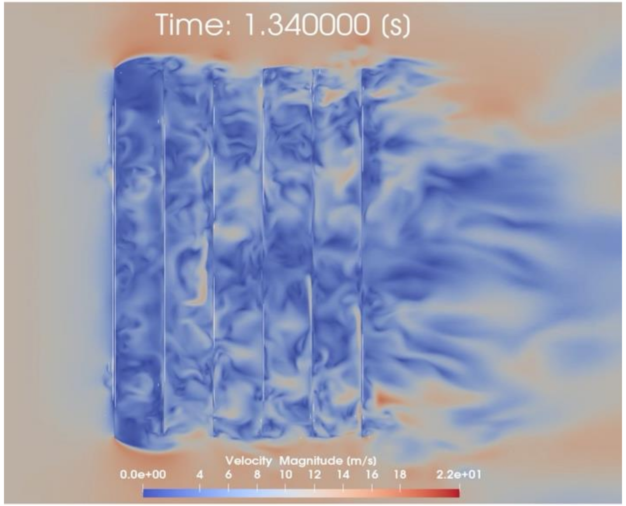
- 3 torque bridges, 2 on torque tube and 1 on the pedestal
- 2 bending bridges on the pedestal near the base
- 1 full axial bridge on the pedestal
- 2 half bending bridges on the support structure of the mirror, top, and bottom end of the mirror
- 2 inclinometers, one on each end of the torque tube
- 1 rotary encoder
- Pressure differential on 3 locations
- 4 Accelerometers on each 4 corners, triaxial accelerations, backside, and in plane

Simulation Model Development

Deep Array Simulation - Troughs

Six-Row Parabolic Trough Large Eddy Simulation (LES)



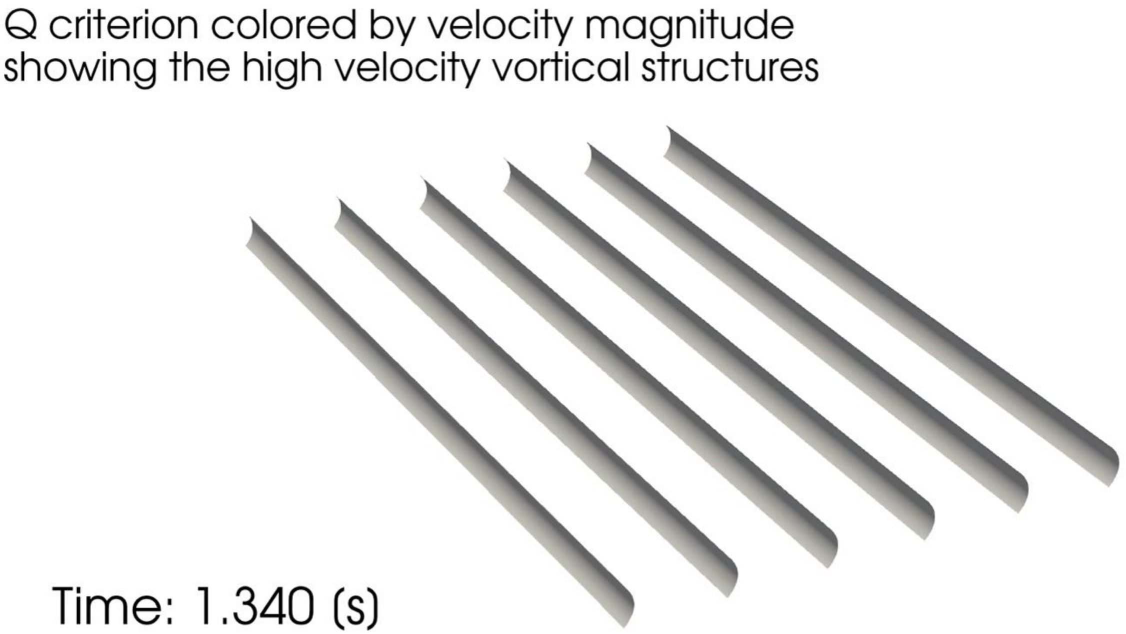


Key design considerations

1. Drag force highest on row 1 and decreases in the downstream rows
2. Moments highest in the downstream rows with higher unsteady variation in rows 5 & 6
3. Edge effects critical

Deep Array Simulation - Troughs

Six-Row Parabolic Trough Large Eddy Simulation (LES)

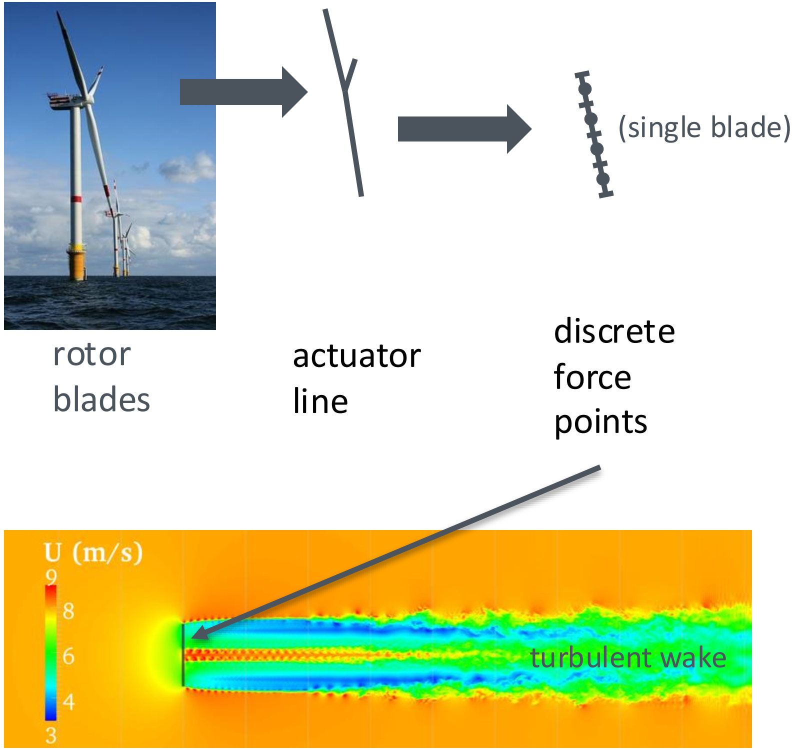


118 million CFD mesh cells

3.2 million CPU-hrs

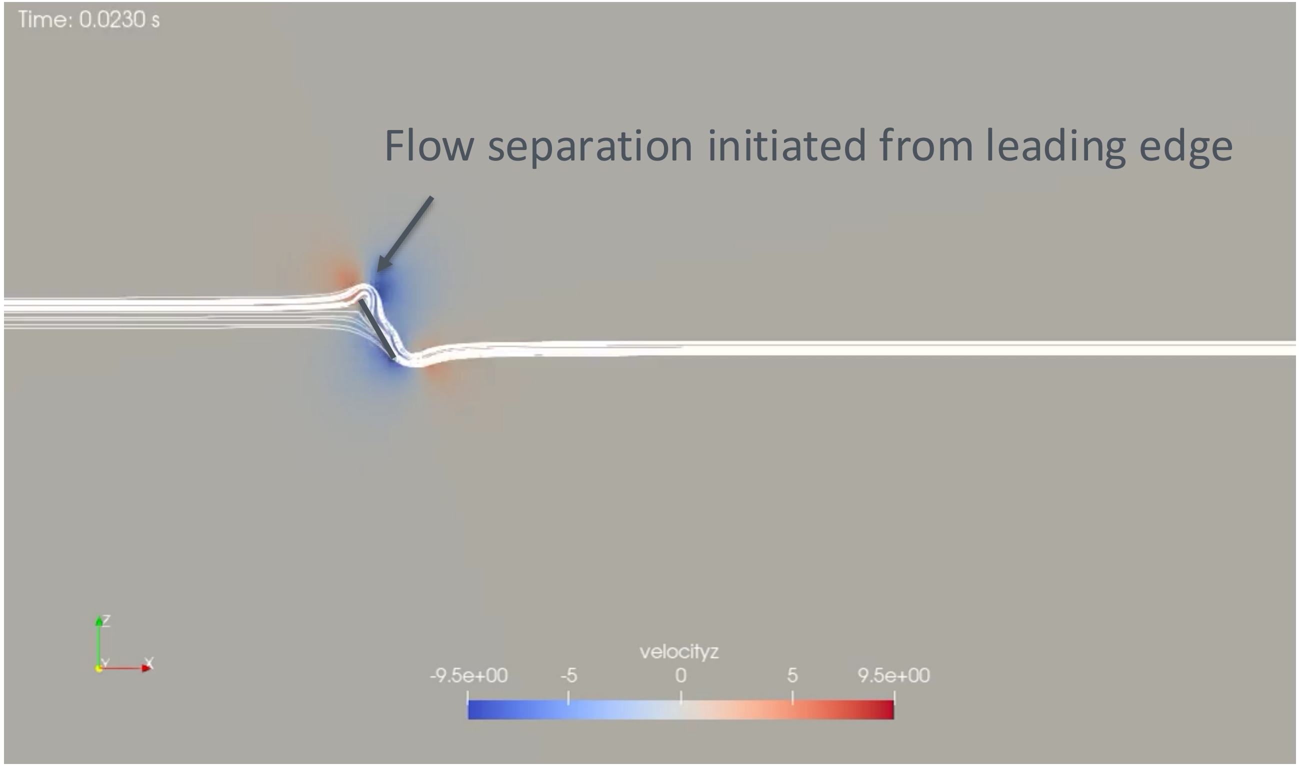
Actuator Force Modeling

1. Validated approach in wind-turbine flow modeling
2. Computationally efficient and generalizable
   - Simulates forces applied *by* a body *on* the fluid
   - Applicable for stationary/moving bodies
3. New challenges for solar collectors
   - Thin body — aerodynamics not known a priori
   - Highly separated flows



Flow past a wind turbine

Actuator Force Modeling in Practice



Simulated conditions

- Isolated collector at 60°
- U=11 m/s

Simulation setup

- Grid spacing
  - Farfield: 0.4 m
  - Around collector: 0.05 m (16 computational cells / length)
- Total grid size: 643k cells

Computational cost

- **10 s** of simulation time in **~22 min** of wall time on **3** compute nodes

A computational speed up of 1100x observed

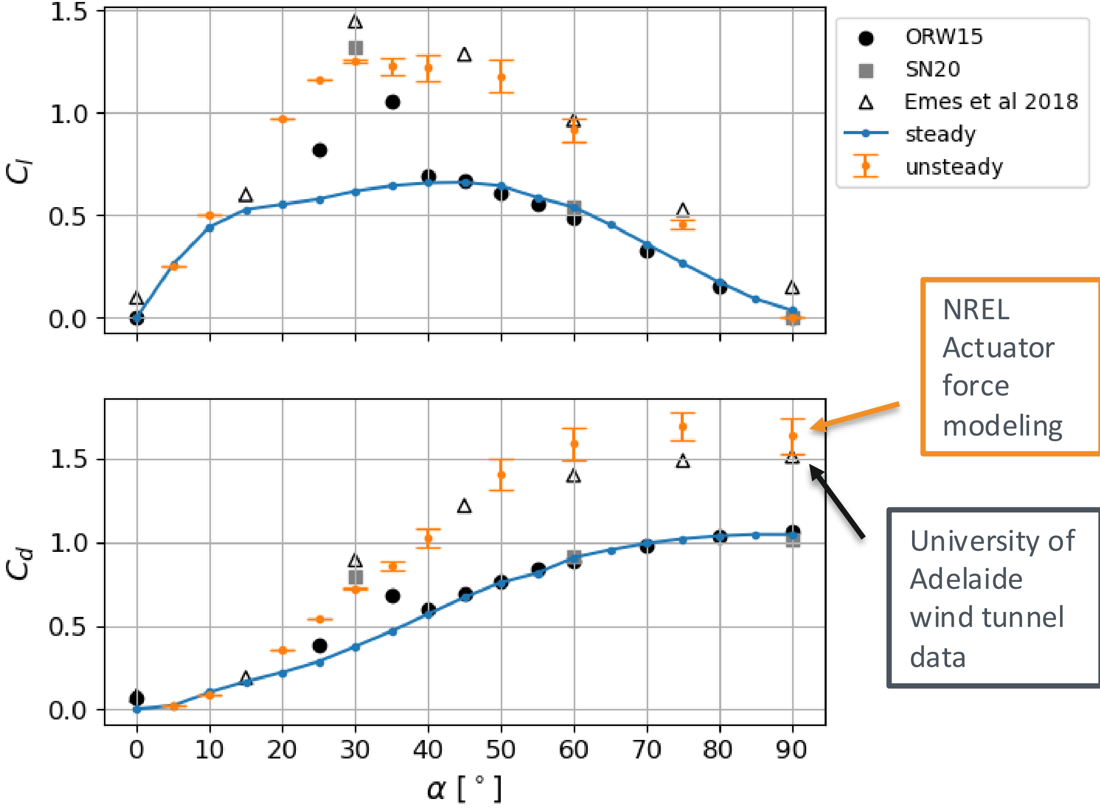
Actuator Force Modeling – Elevation Angle Sweep

1. Unsteady aerodynamics captured at full range of angles

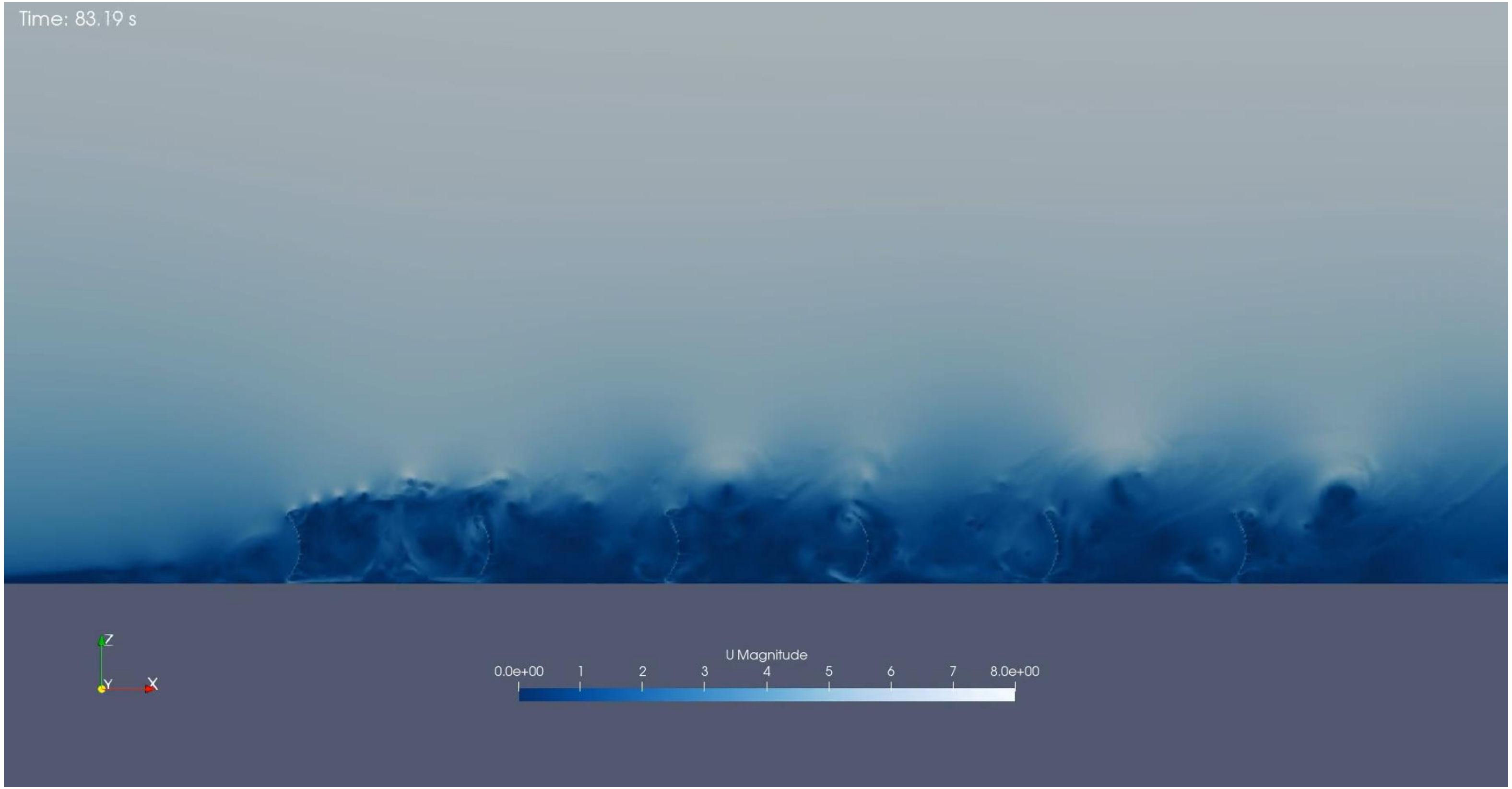
2. Comparisons with University of Adelaide data

3. Each Elevation Angle Simulation Cost: **9 CPU-hrs**

4. A computational speed up of 4900x observed compared against body fitted mesh

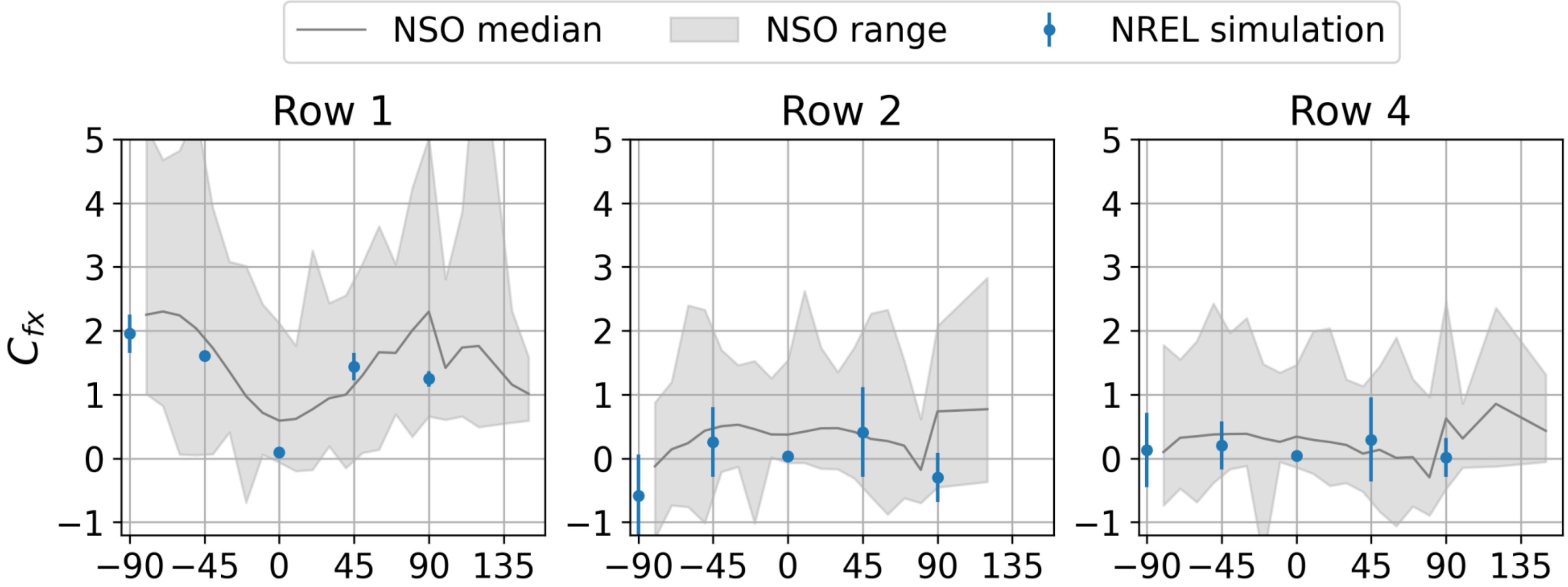


Actuator Force Modeling – Six Row Troughs

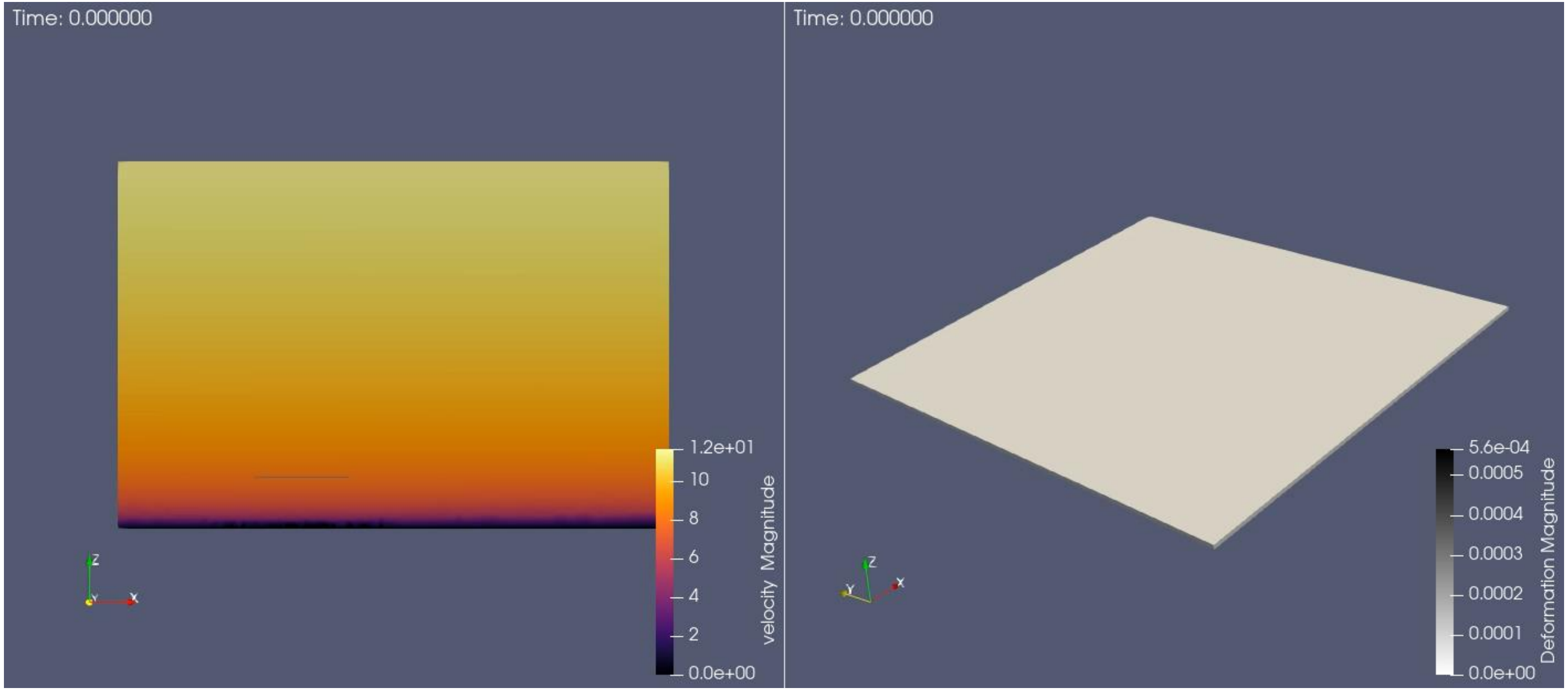


Actuator Force Modeling – Six Row Troughs

Simulations of 6 row trough arrangement compared against field data from NSO

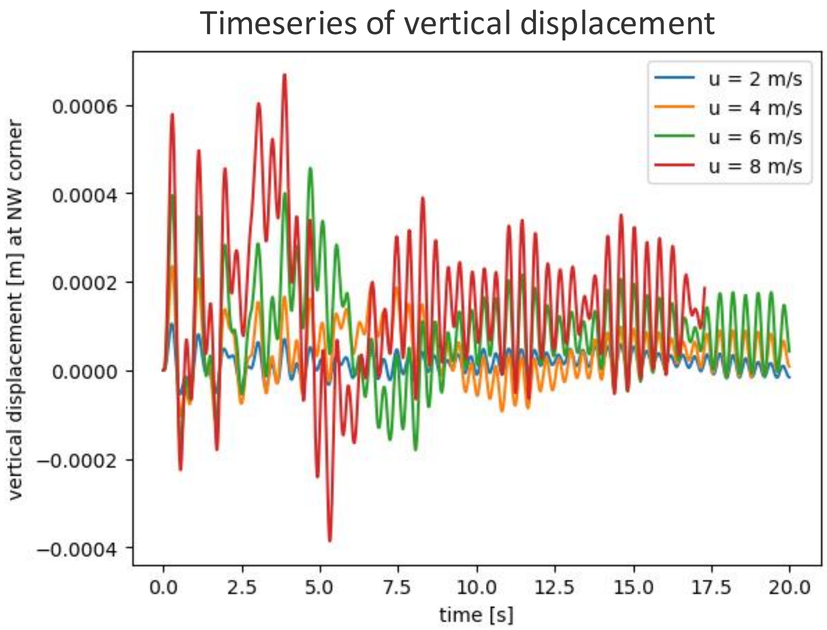


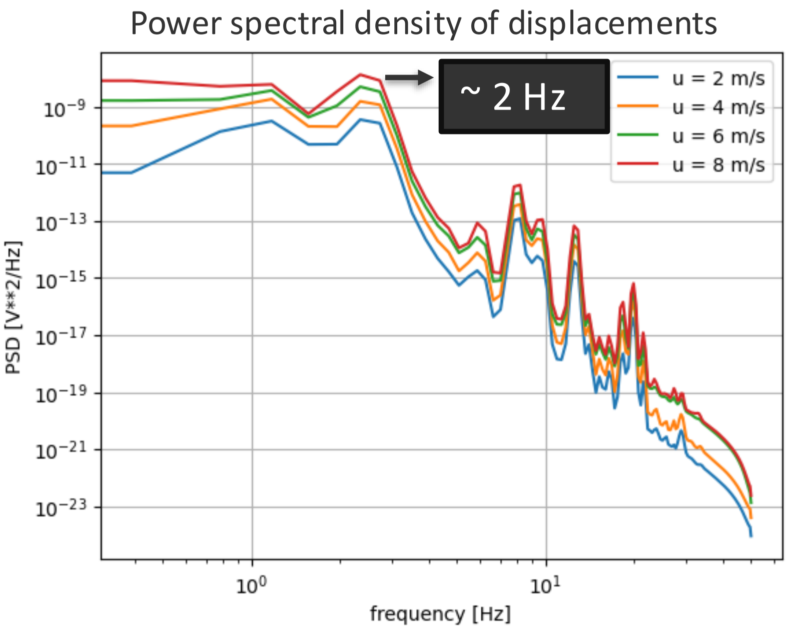
Simulation of Structural Response



Simulation of deforming heliostat under strong wind conditions.

Simulation of Structural Response





- Simulations reproduce 2 Hz tone seen in measurements
- Peak-Peak oscillation of mirror surface ~ 1 mm
- Impact on optical performance will be studied next

Conclusion & Future Work

1. First-of-a-kind long term measurements of wind driven loads & deformations of collector mirror surface were performed at two operational power plants

2. Quantified the impact of wind on loads experienced by parabolic troughs
   - Developed a model for wind modulation by troughs in an operational field
   - Wind tunnel studies found to underestimate dynamic loads
   - High torsional load was observed even on the troughs in the interior rows
   - Poor optical performance of the troughs on the edge row were observed

3. Measurement campaign at Crescent Dunes ongoing to study impact of wind driven loads on Heliostats

4. Plan to test smaller heliostats being installed at the NREL Flatirons campus

Thank You

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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 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.

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