U.S. Department of Energy
HelioCon
Heliostat Consortium for Concentrating Solar-Thermal Power

Intern Projects in Heliostat Technologies at NREL and SNL

The HelioCon Intern Team
Host: Dr. Rebecca Mitchell

NREL Transforming ENERGY

Sandia National Laboratories

August 28, 2024

conceptual design • components • integration • mass production • heliostat field

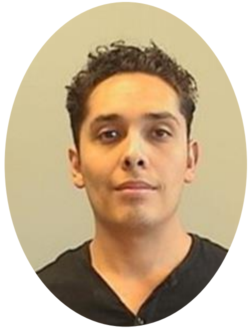
HelioCon Intern Presenters

Milo Davis, NREL
Mentor: Devon Kesseli

Kyle Sperber, NREL
Mentor: Dr. Rebecca Mitchell

Justin Kilb, NREL
Mentor: Dr. Alex Zolan

Yu Zhou, NREL
Mentors: Dr. Rebecca Mitchell, Guangdong Zhu, Paul Ndione



Javier Martell, SNL
Mentor: Dr. Ken Armijo

Taylor Johnson, SNL
Mentor: Dr. Randy Brost

Nicholas Phelps, SNL
Mentor: Dr. Randy Brost

Madeline Hwang, SNL
Mentor: Dr. Randy Brost

Kristina Ji, SNL
Mentor: Jeremy Sment

Seminar Guidelines

- The seminar will be recorded and shared afterwards
- Please stay on mute with cameras off during the presentations
- Feel free to put questions in the chat during the presentations; make sure to indicate who your question is for
- During the Q/A, you may unmute and turn your camera on to ask your questions

Intern Projects at the National Renewable Energy Laboratory (NREL)

NREL
Transforming ENERGY

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HelioCon: NIO Software Refactoring

Milo Davis, Kyle Sperber

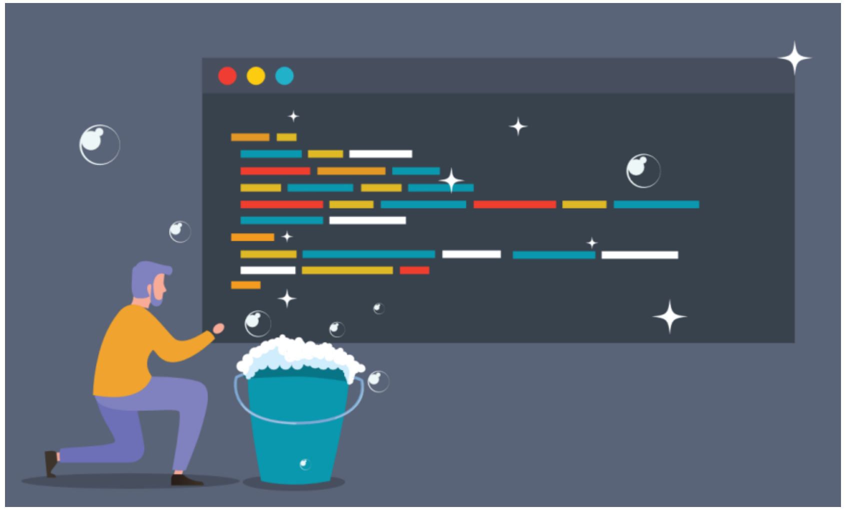
NIO needed refactoring for easier use and integration of new features.

Organization and Maintenance:

- NIO GitHub branches were pruned and cleaned
- A new workflow established with GitHub with standards for creating, rebasing, and merging new branches.
- A weekly meeting was established to keep the GitHub repository maintained.

A Cleaner NIO Pipeline:

- Connected data-parsing and post-processing, previously had to be run separately
- Standardization of snake-case naming
- Generalization of NIO to different CSP fields (complete removal of hard-coded values)



HelioCon: Corner Detection Issues

Milo Davis, Kyle Sperber

Issues arose with data from Cerro Dominador

Heliostat Corners are Important:

- Corners are used to transform the images for post-processing
- Corners are used to determine the camera position

Issues:

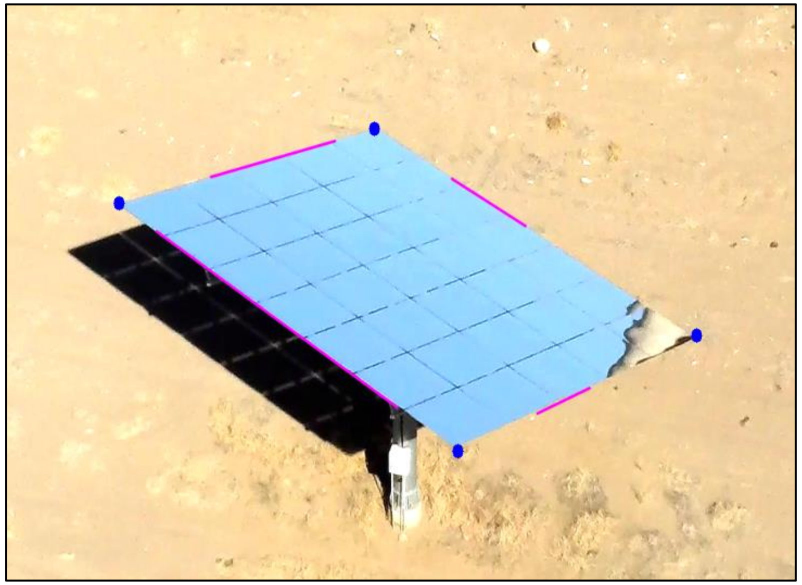
Using NIO on data from the Cerro Dominador plant revealed some issues in Corner Detection.

K-means Color Clustering Issues:

- Color clustering blending heliostat with ground
- Color clustering blending tower with ground

Other Issue:

- Requires special perspective of heliostat as rhombus shape



Corner Detection on a Crescent Dunes heliostat

HelioCon: Template Flow

Milo Davis, Kyle Sperber

Template Matching:

Identifies specific shape in an image by mapping a sub-image onto it

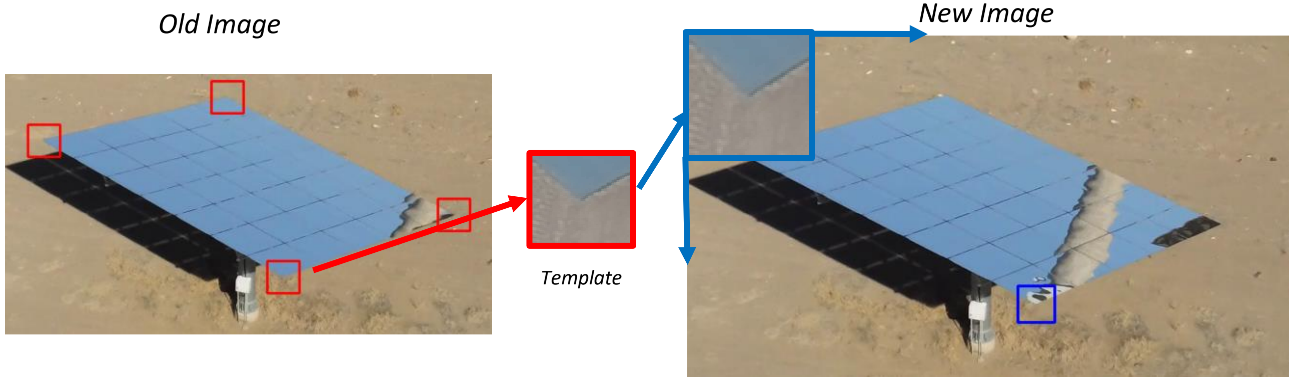
Lucas-Kanade Optical Flow:

Tracks displacement of pixels between frames, allowing tracking and prediction of pixel movement

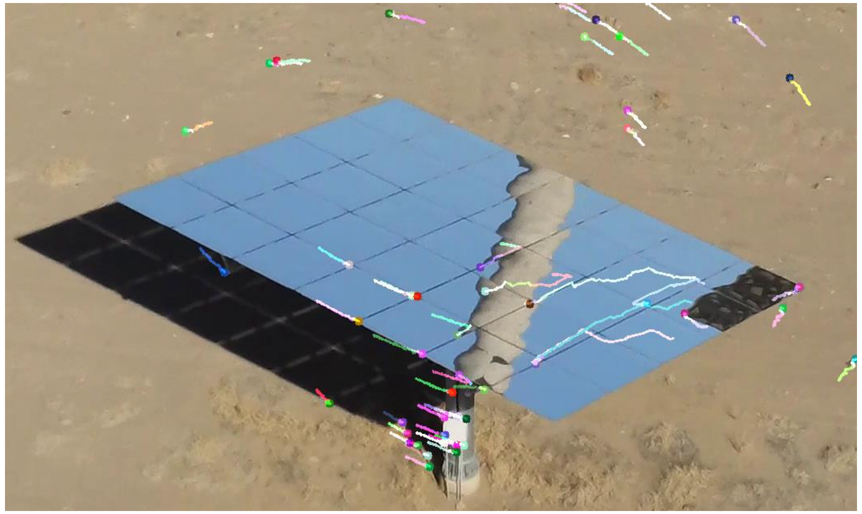
New Corner Detection – Template Flow:

1. Manually select initial corners
2. Create template images of a chosen size from the corner point
3. Determine corner candidates by template matching as well as the optical flow prediction
4. Calculate distance between the corner candidates and the previous corner
5. If corner candidate is below a pixel distance threshold, select as new corner and generate template
6. Repeat

A Template Match on a corner from a previous frame



Optical Flow on sixty images

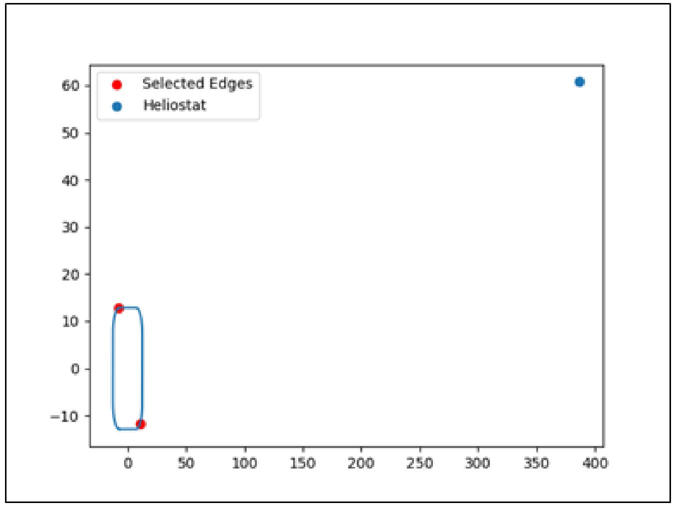


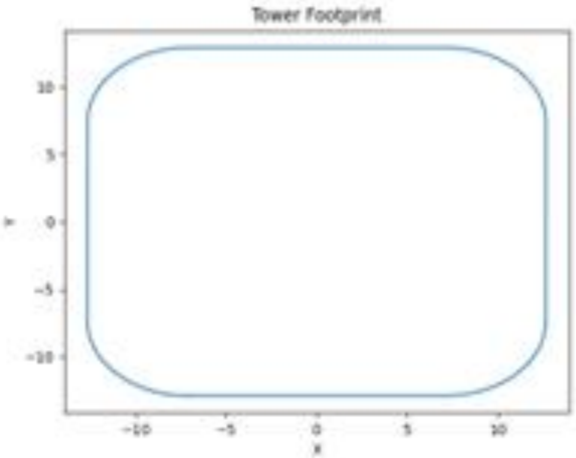
HelioCon: Tower Footprint

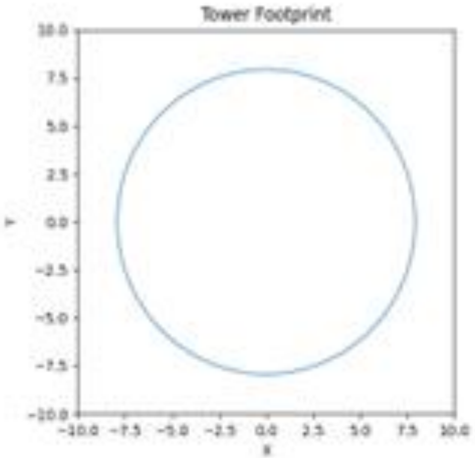
Milo Davis, Kyle Sperber

Complex Tower Geometry – Footprints:

- Towers come in different shapes and sizes
- Footprints are generated by tower schematics
- These footprints identify what part of the tower the heliostat sees
- Knowing what is seen by the heliostat helps compute accurate errors





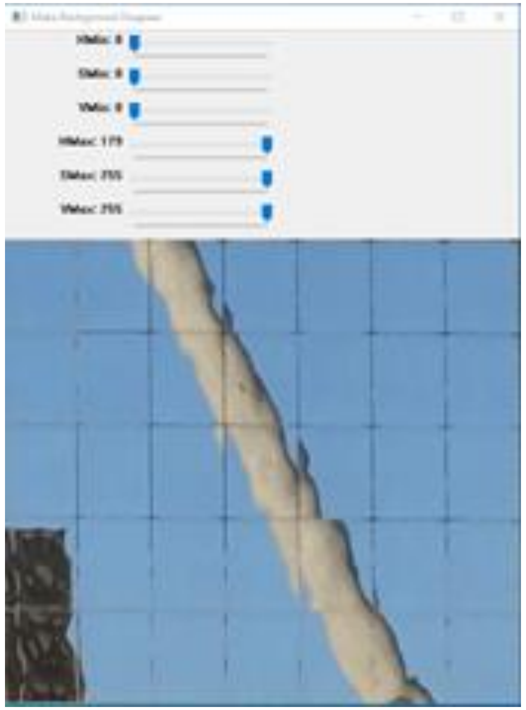


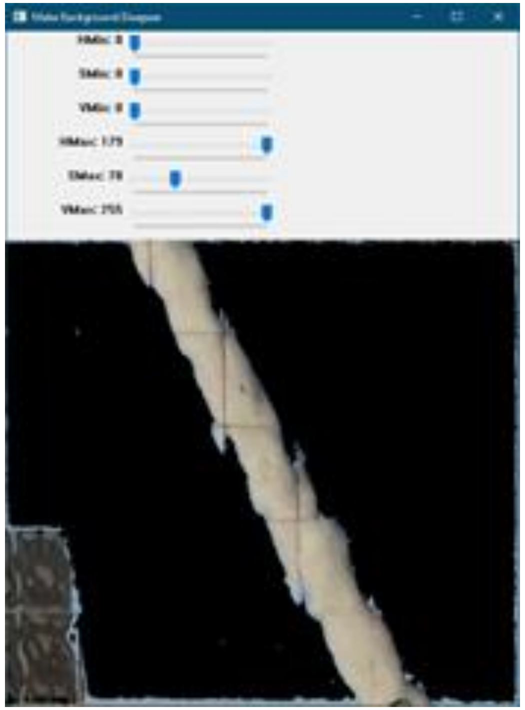
HelioCon: Tower Color

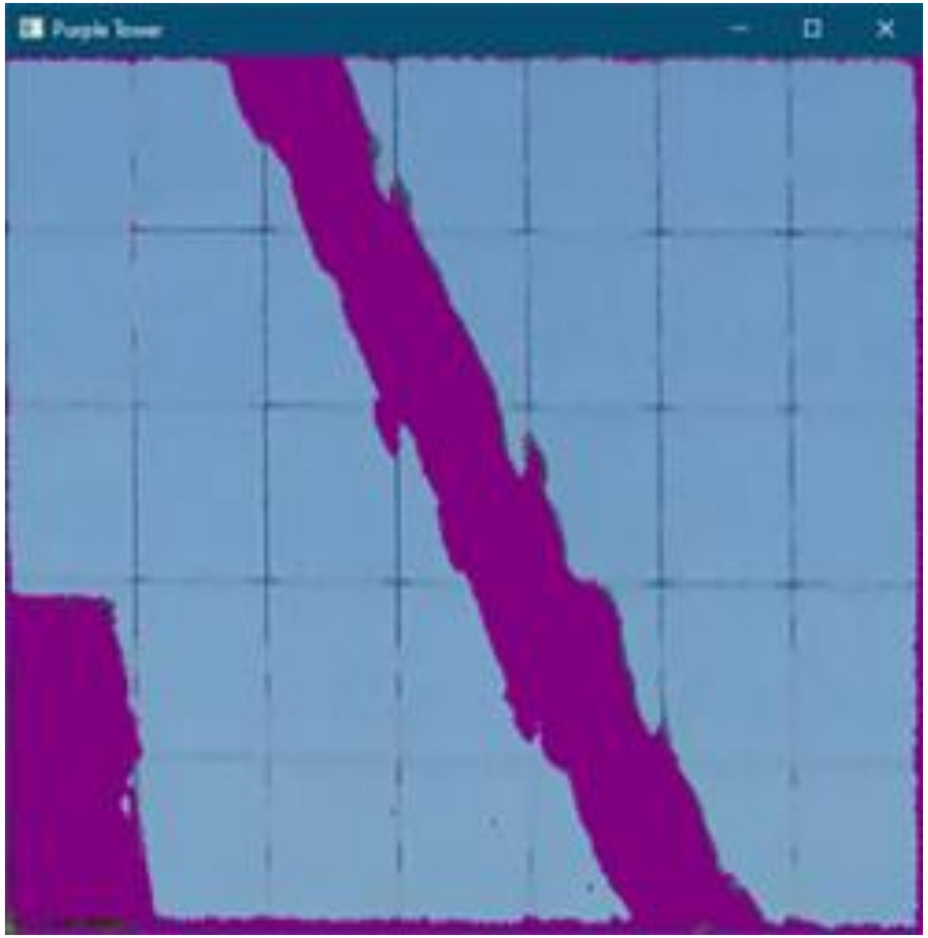
Milo Davis, Kyle Sperber

New Color Calibration – HSV Limiting:

- NIO uses color calibration to help reliably detect the tower
- The first image is calibrated to remove the background
- Sets the HSV limits to find the tower
- Turns the tower purple for easy edge detection







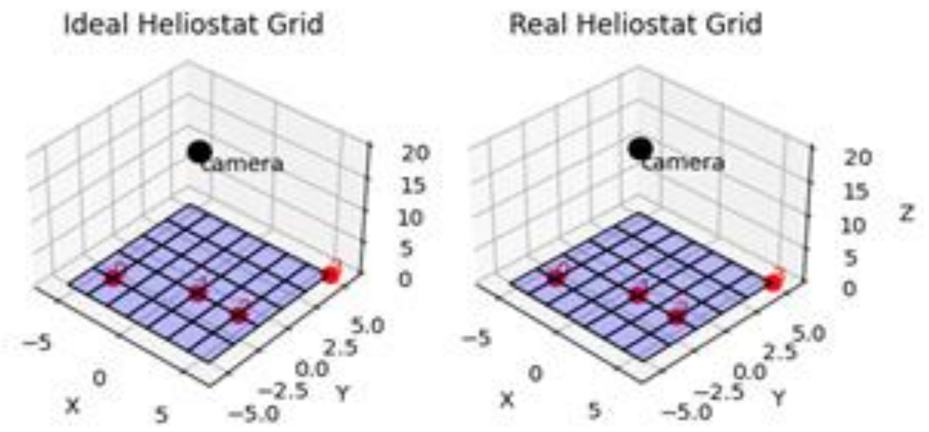
HelioCon: Camera Sensitivity

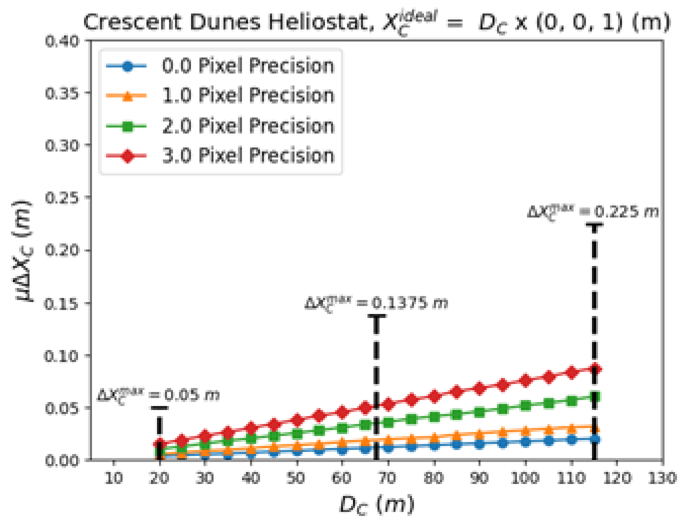
Milo Davis, Kyle Sperber

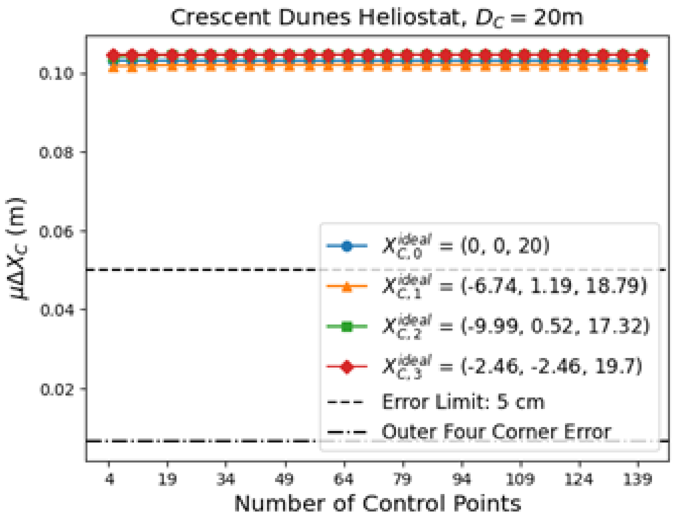
Camera Sensitivity Study – Verifying NIO:

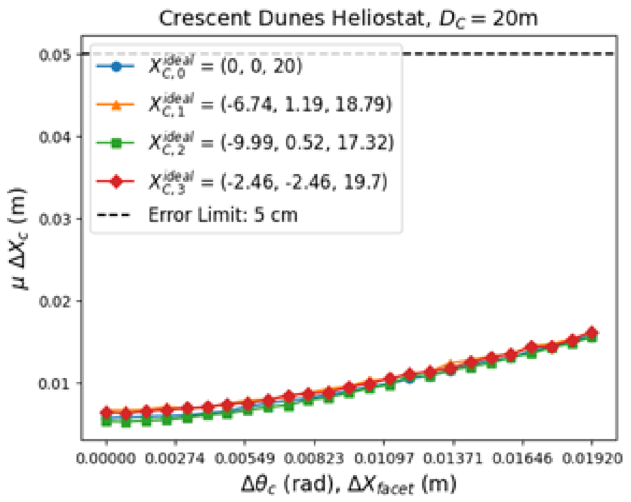
Verifying NIOs Methodology for reliable error calculation

- Number of Reference Points
- Distance from Heliostat
- Limits of Pixel Uncertainty
- Limits of Physical Heliostat Canting Error









Monte Carlo Simulation to Assess Quality of Heliostat Washing Policies Obtained via Optimization Methods for Concentrating Solar Power Plants

Justin Kilb
Alex Zolan

Photo from iStock-627281636

Project Summary

- This work supports the Technoeconomic Analysis (TEA) task within HelioCon
- We seek to address a TEA gap relating to CSP solar field O&M modeling validation
  - CSP O&M cost is highly sensitive to mirror soiling rates (fig 1)

- Some existing methods
  - **Soiling**
    - Sarver et al. (2013): Arid and windy environments can experience efficiency losses up to 10% per day for a horizontal surface
  - **Improving Operations**
    - Wolferstetter et al. (2018): Cleaning methodologies for PV and parabolic troughs
    - Alon et al. (2014): Wash rate is maximized by optimizing routing
    - Zolan and Mehos (2022): Determine economics of extra vehicles on call for dust storms
    - Cholette et al. (2023): Determine staffing levels using stochastic soiling model

Annual O&M per soiling rate and heliostat cost

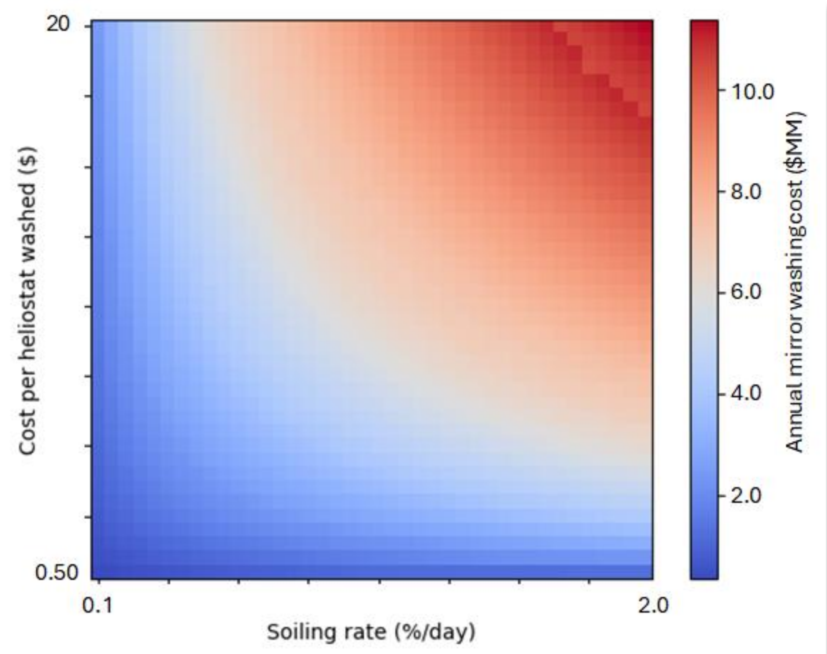
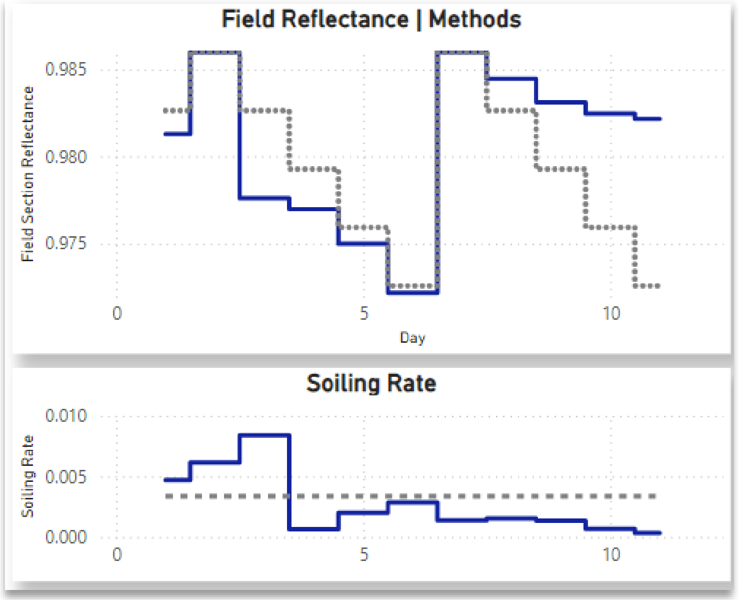


Fig 1: Alexander Zolan and Michael Cholette

We aim to simulate a mirror washing operation with stochastic weather events and soiling

Simulating with stochastic soiling and infrequent events

Variable soiling rates



- **Stochastic simulation scenario**
- **Deterministic simulation scenario**

Numerical approach

Analytical (and existing) **approach**

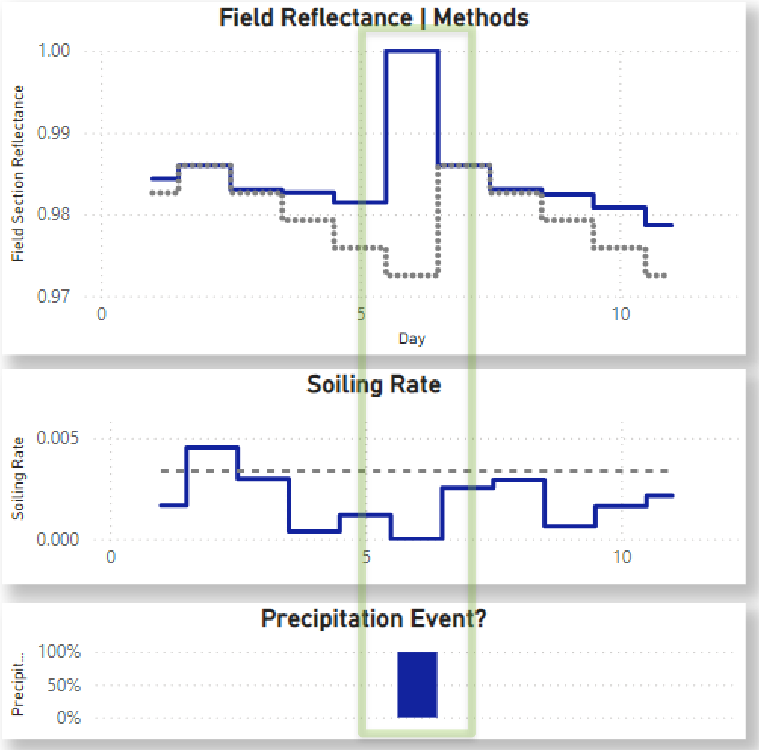
$$(s_{vt} + \bar{s}_{ft} E_{vt})$$

$$\min_{P,W,X,E} \sum_{t \in \mathcal{T}} \left(r_t \cdot \sum_{f \in \mathcal{F}} \left(d_{ft} \sum_{v \in \hat{\mathcal{V}}_f} (s_{vt} + \bar{s}_{ft} E_{vt}) X_{vft} \right) + \sum_{v \in \mathcal{V}} c^W_{vt} W_{vt} \right) + \sum_{v \in \mathcal{V}} c^P_v P_v$$

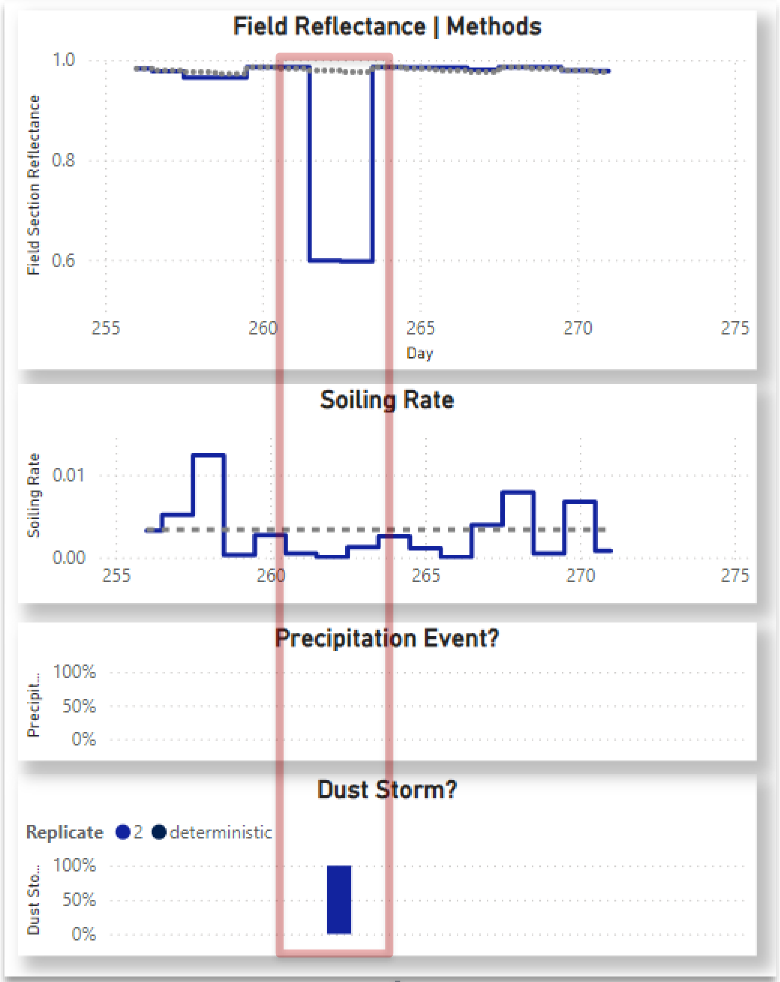
Mixed-integer nonlinear program objective

Wales et al. (2021)

Precipitation events



Dust storm events

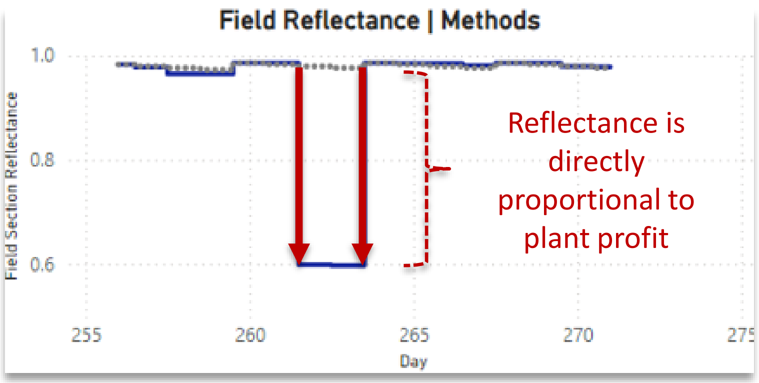


Monte Carlo

Summary and next steps

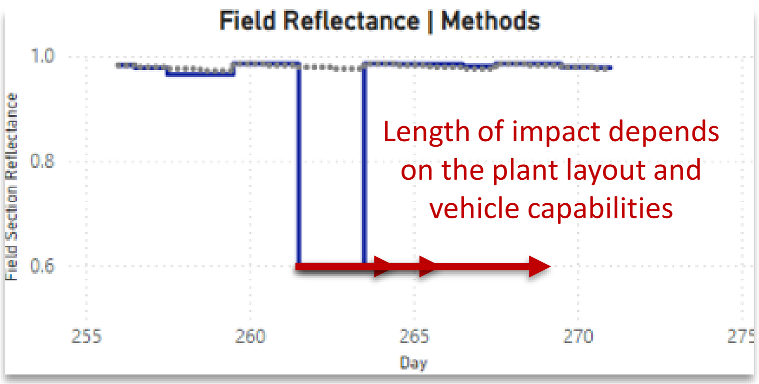
Currently in progress

- Operational scheduling with policy-based decisions
  - Incorporating weather or reflectance thresholds for vehicle purchase and operational decisions
    - Reserve vehicles
    - Conditional vehicle scheduling
- Value of information
  - Considering uncertainty in soiling measurement frequency and accuracy



Project impact

- What is the value of reserve vehicles?
- What is the value of adaptive scheduling?
  - Cross training work force
  - Seasonal hires
- At what cost is automation economical?



HelioCon Database

Yu Zhou

HelioCon
https://heliocon.org/

↓

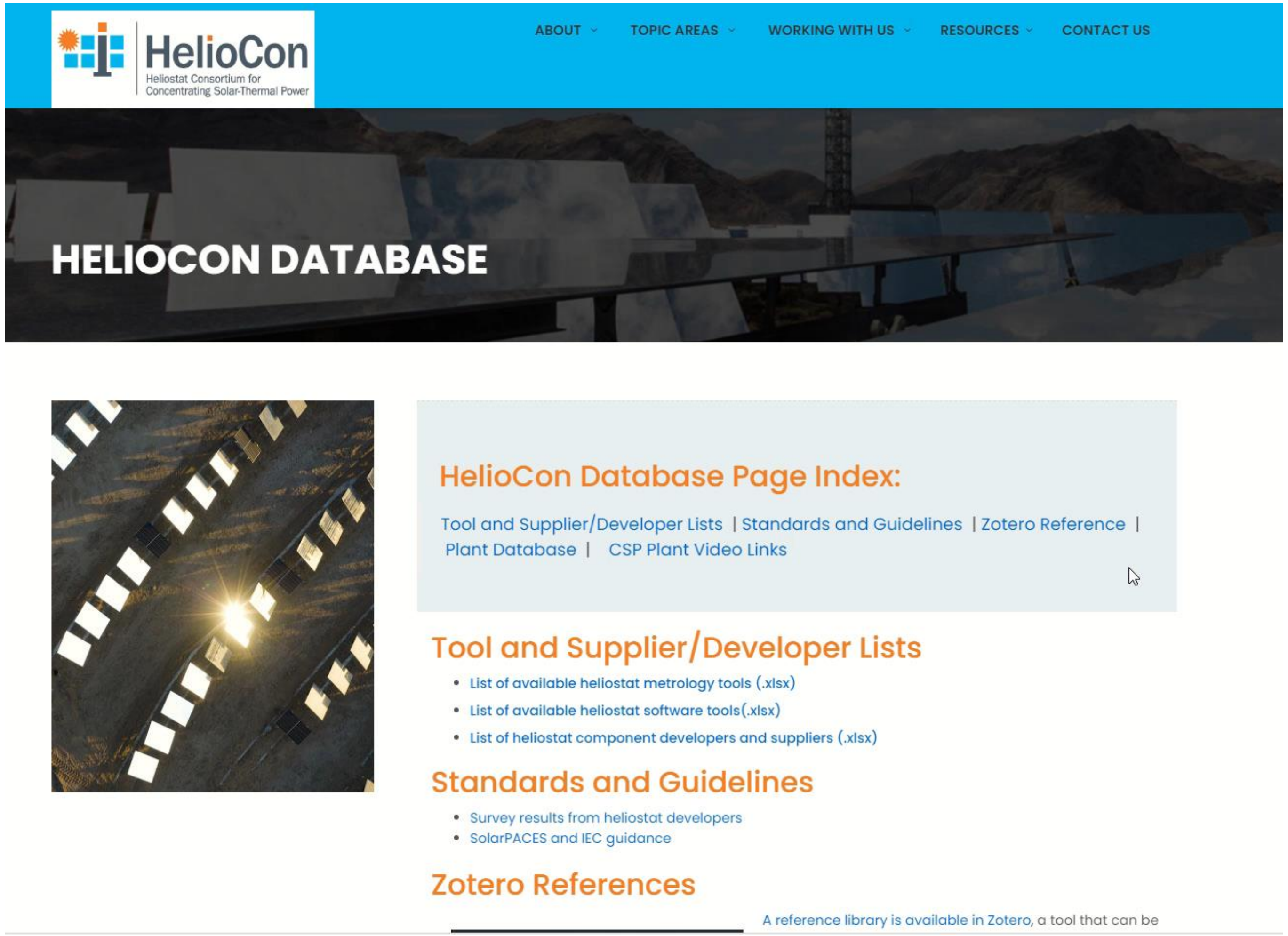
Resources
https://heliocon.org/resources/resources-1.html

↓

HelioCon Database
https://heliocon.org/plant_information_overview.html

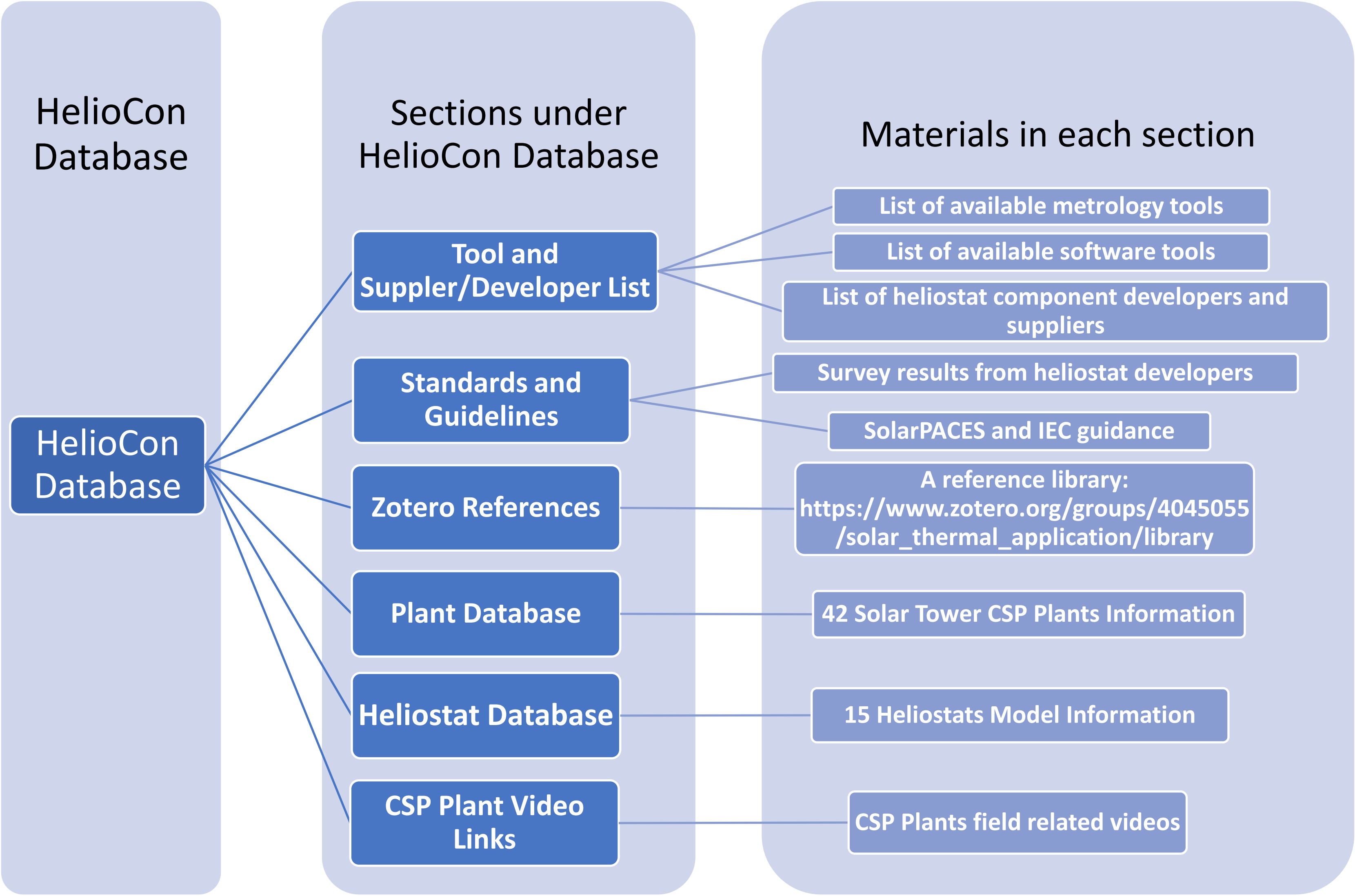
↓

Tool and Supplier/Developer List
Standard and Guidelines
Zotero Reference
Plant Database
Heliostat Database
CSP Plant Video Links



HelioCon Database

Yu Zhou

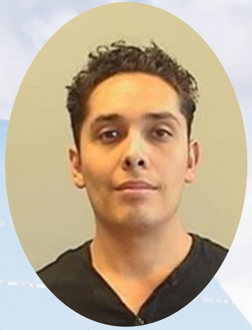


Audience

- CSP/heliostat technology developers
- Researchers
- Other stakeholders for heliostat research and development.
- Newcomers who are interested in CSP technology.

Intern Projects at Sandia National Laboratories (SNL)

Sandia National Laboratories



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Mentor: Jeremy Sment

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HelioCon
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Development of a Digital Wind Tunnel for Heliostat Wind Load Analysis

Javier A. Martell
Mentor: Dr. Kenneth Armijo

August 28, 2024

Research Goals

Javier Martell

Study the effects of wind loads on heliostats under different materials and configurations.

- Develop digital wind tunnel model to capture static pressure on heliostat at different wind speeds and directions.
- Develop modal analysis of heliostat structure to extract and identify normal modes.
- Develop harmonic analysis by using modal analysis and pressure data to study structure response to wind loading.

CFD Analysis

- 4 m/s wind speeds normal to the heliostat.

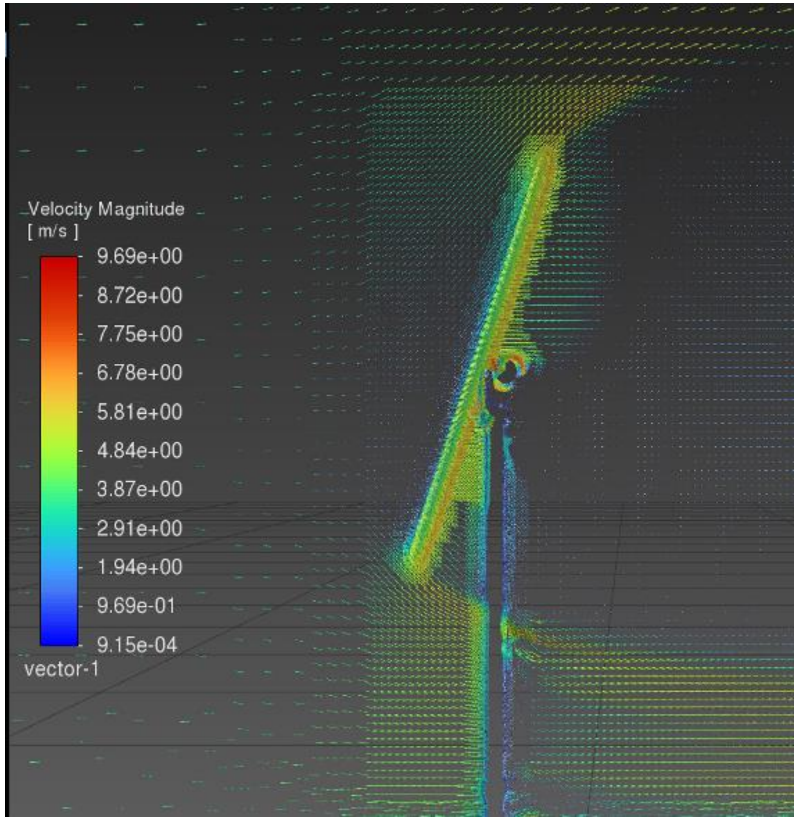


Figure 1: Velocity vectors cross-section view.

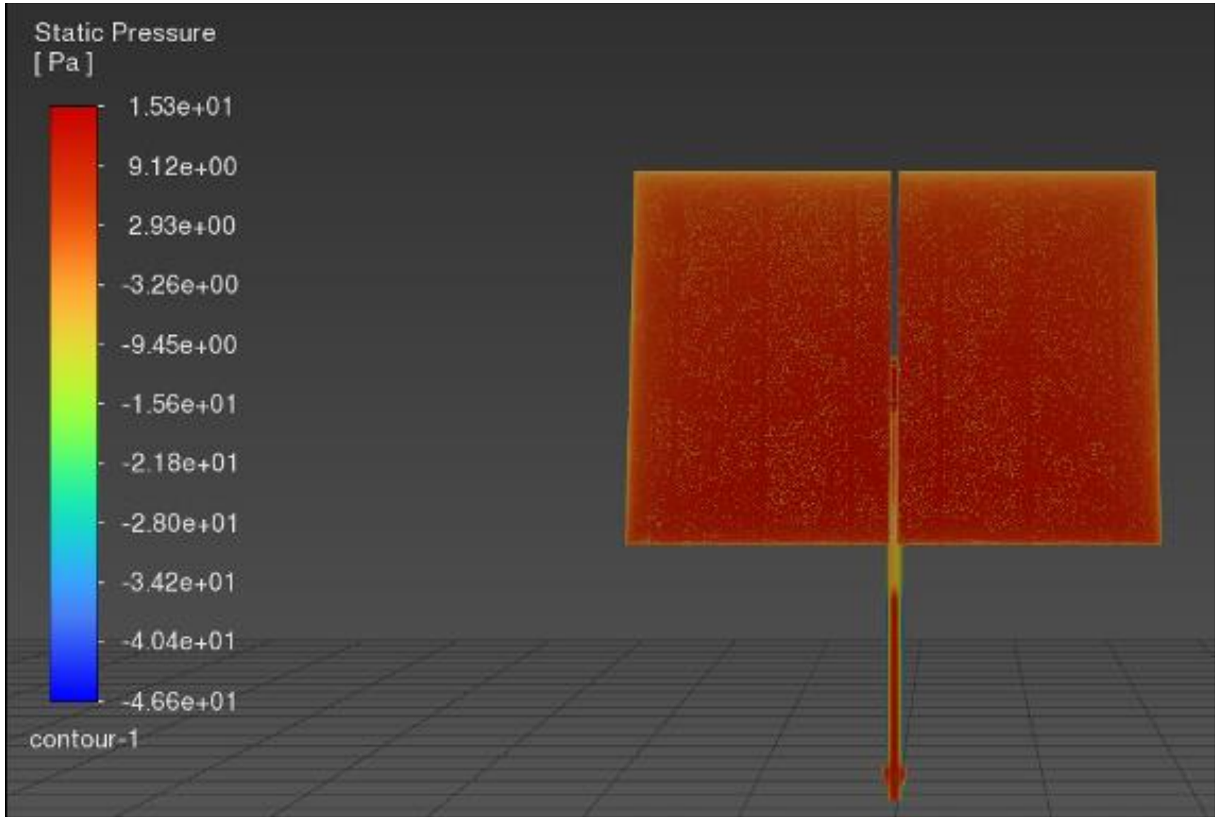


Figure 2: Heliostat contour of static pressure.

Modal Analysis

- Modal analysis provides engineers with information regarding how the design will respond to different types of dynamic loading and can be used, for example, to avoid resonant vibrations that can be harmful to the structure.
- First natural frequencies occurred at 1.4449, 1.612, 2.3164, and 5.3976 Hz.

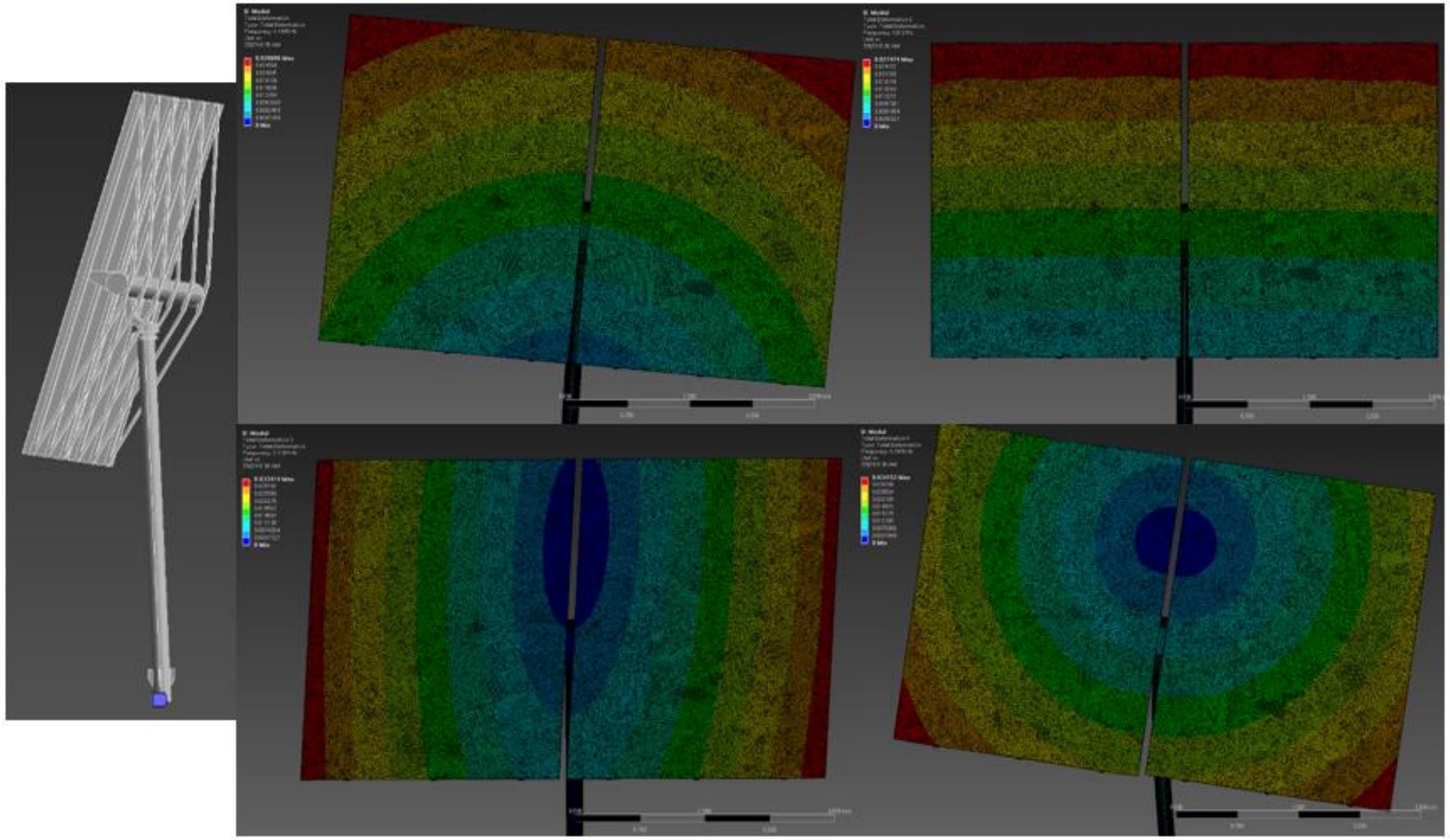


Figure 3: Heliostat fixed constrain (left) and normal modes (right).

Harmonic Response Analysis

- The harmonic response analysis determines the steady-state response of a structure that is subjected to loads that vary sinusoidally over time.

- This analysis enables us to verify whether the designs will successfully handle resonance, fatigue and other harmful effects of forced vibrations.

- Maximum frequency response: 1.6 Hz.

- Maximumm normal stress: 8,106.8 Pa.

- Maximum directional deformation: 1.372e-02 m.

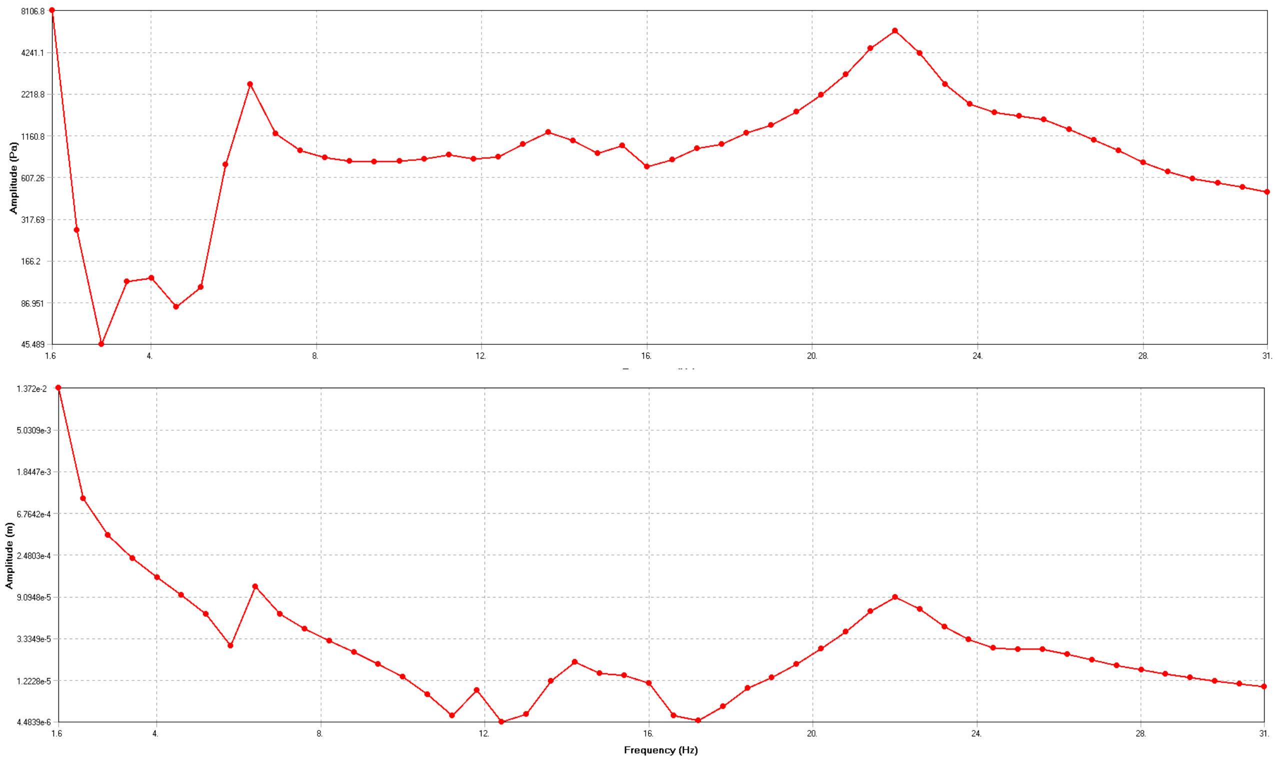
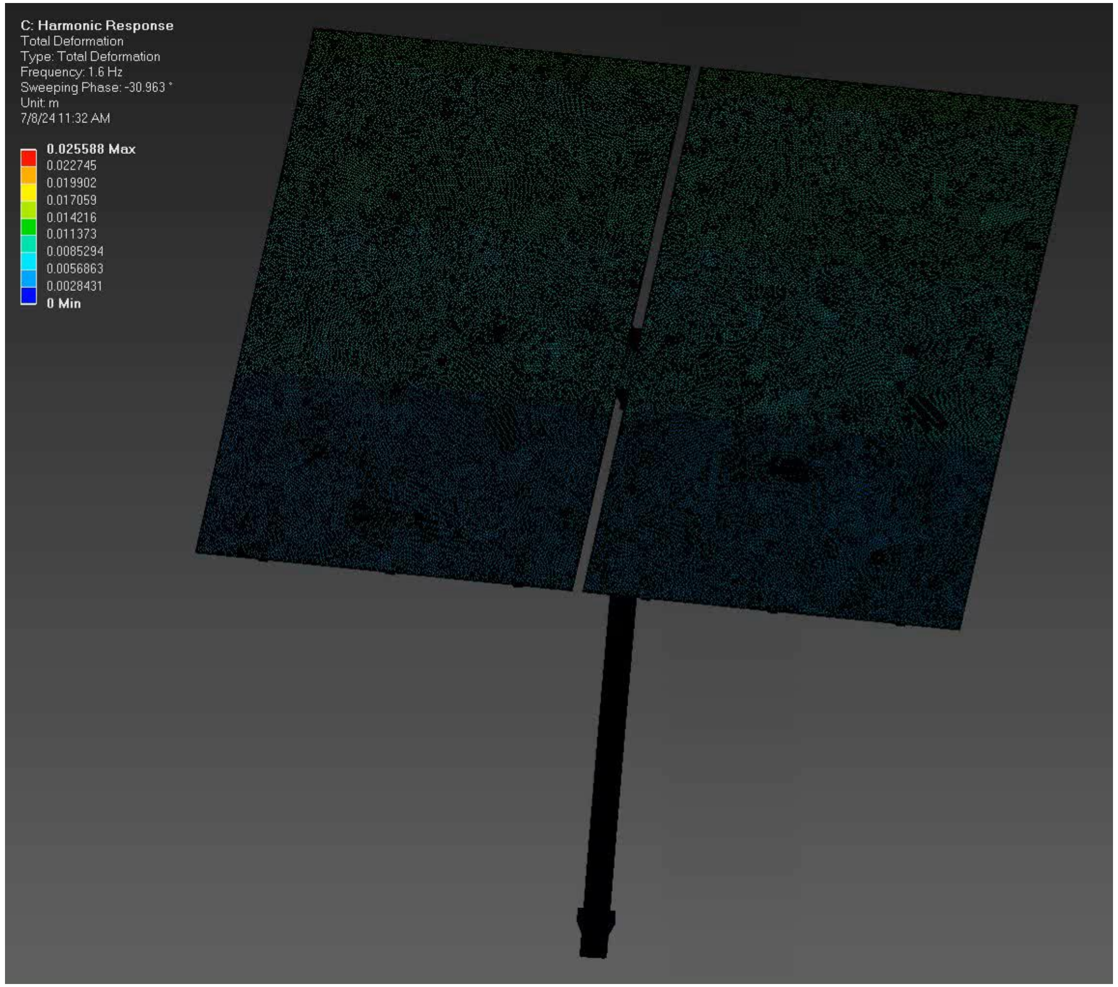


Figure 4: Normal stress (up) and directional deformation (down) response in x-axis.

Harmonic Response Analysis



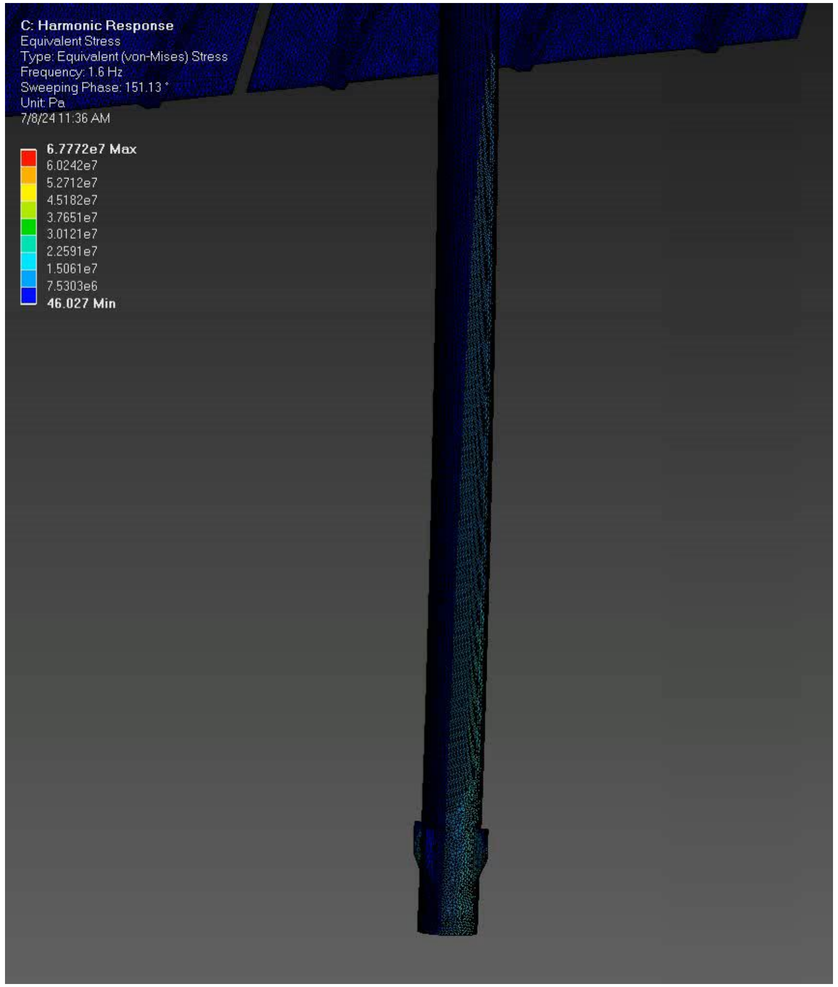


Figure 4: Normal stress (up) and directional deformation (down) response in x-axis.

Technoeconomic analysis of a hybridized PV-CSP plant integrated with particle thermal energy storage

HelioCon
Heliostat Consortium for Concentrating Solar-Thermal Power

Sandia National Laboratories

Photon Vault

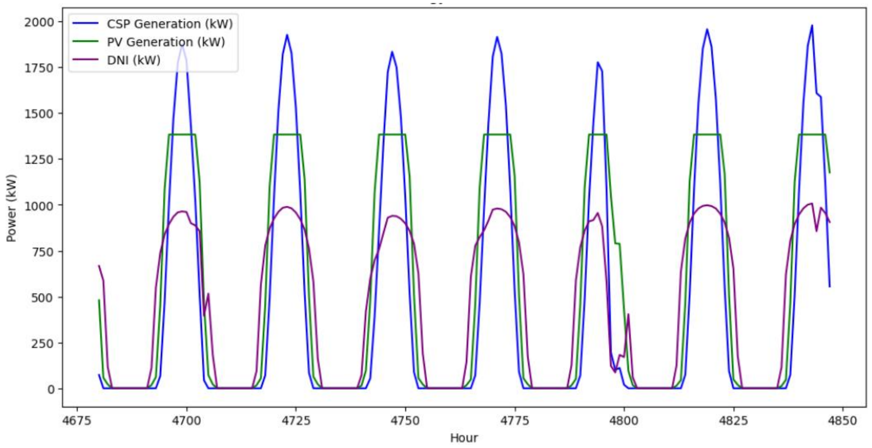
Taylor Johnson, Luke McLaughlin
Sandia National Laboratories

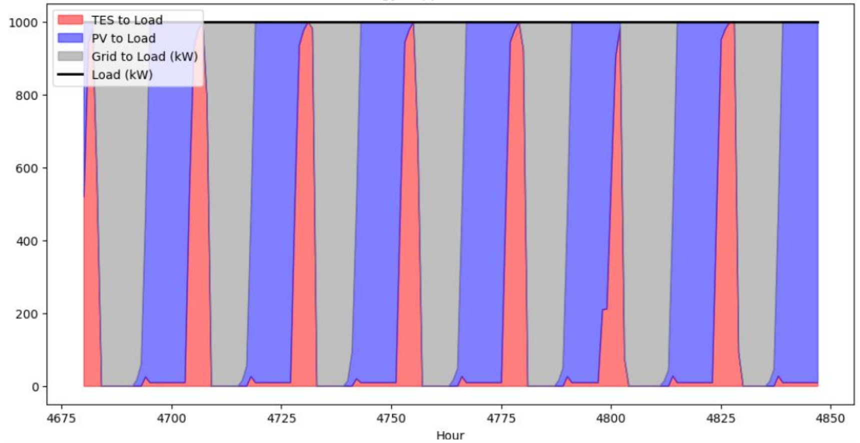
Page, AZ Case Study Results for Photon Vault System

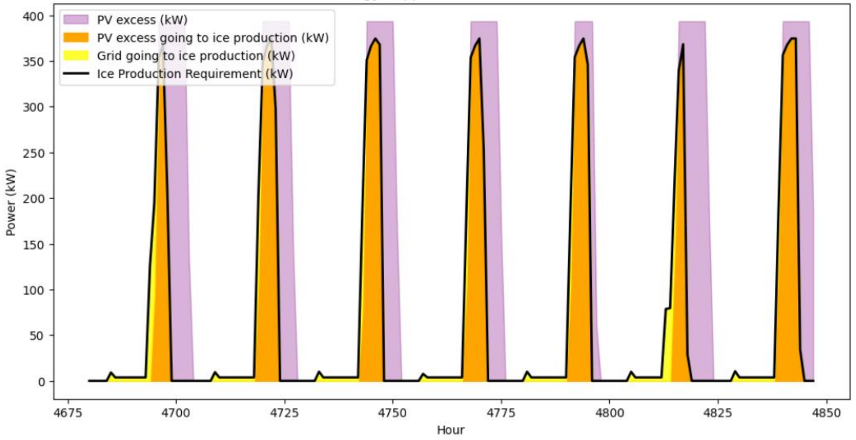
- Photon Vault introduces a hybrid photovoltaic and concentrated solar power system integrated with a novel particle thermal energy storage media

- Technoeconomic analysis of Photon Vault's system for a 1 MW case study in Page, AZ reveals minimum cost occurs at 11.8 cents/kWh, with PV and CSP sources integrated with TES providing 91.1% of the annual energy demand

- The study suggests allocating excess electricity from the photovoltaic array to the thermal storage, rather than the production of ice for the heat sink, results in a lower LCOE and higher proportion of the load met by RES







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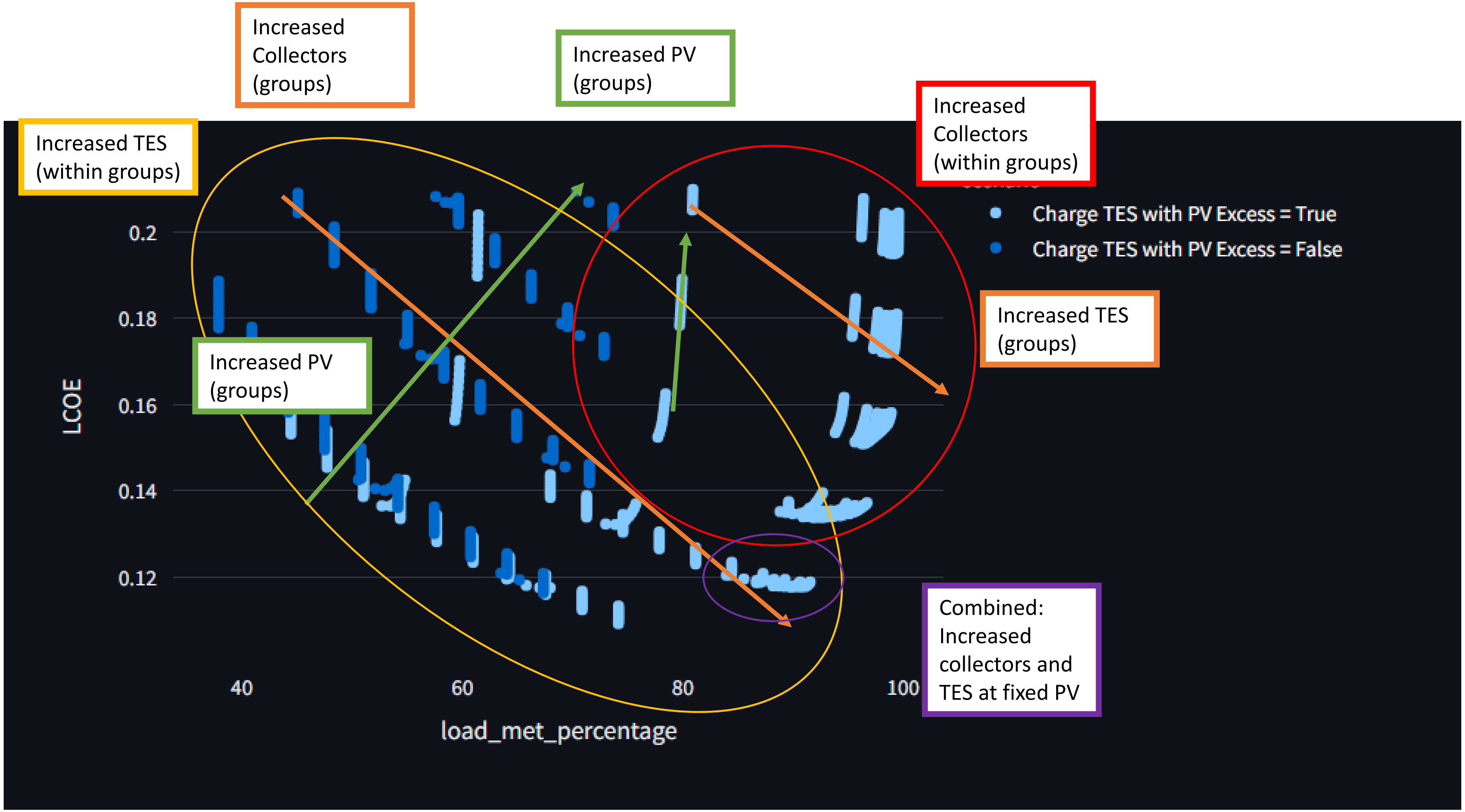

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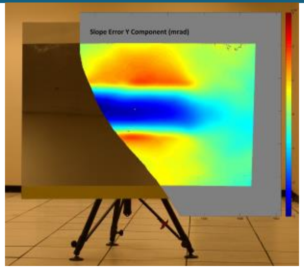
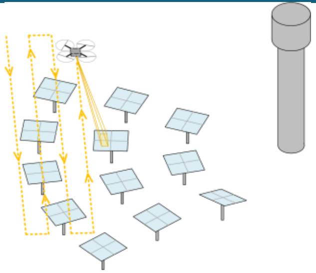
Characterizing a Precise Ground Truth Mirror for CSP Optical Metrology





Nicholas Phelps

with direction, help, and support from
Randy Brost, Braden Smith, and Gino Perez

August 28, 2024

Presented at the *HelioCon Student Seminar,*
Virtual, August 28, 2024.

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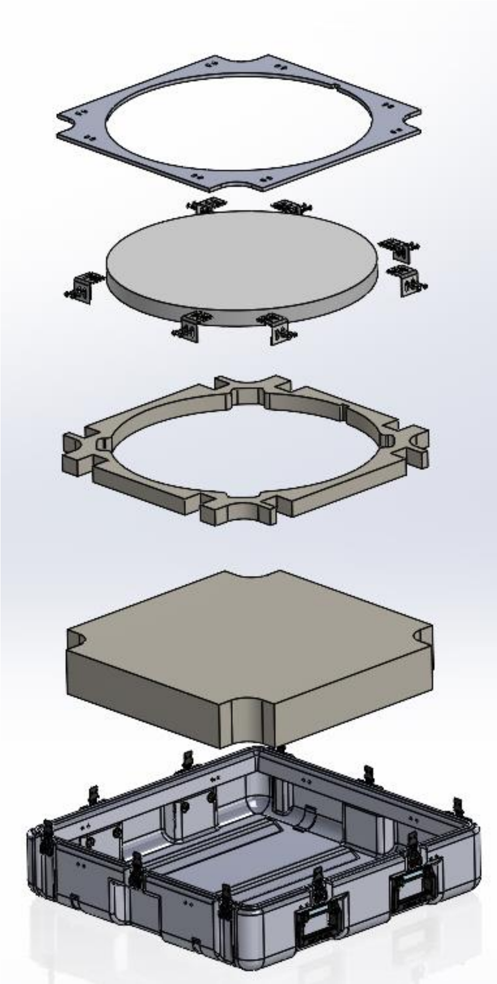
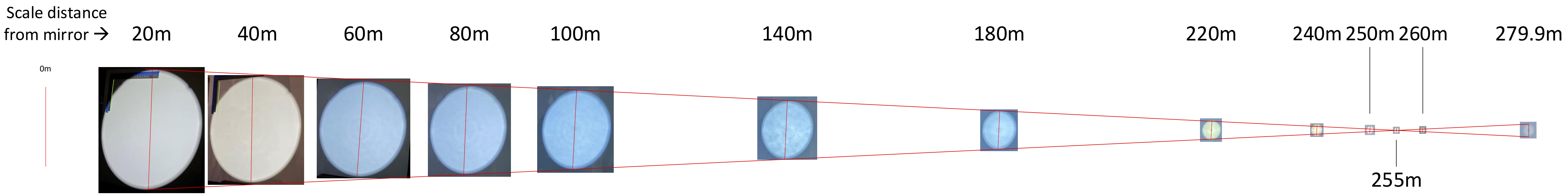
SAND2024-10871C

Ground Truth Methods & Standards

- Ground truth methods provide simple, physical confirmation for rapid characterization methods
- Need baseline provided by well-understood optical objects
- Ground truth mirror needs:
  - Very high optical accuracy
  - High dimensional stability—no sag, or change in shape with tilt angle
  - Smooth surface—no tool marks
  - Focal length of F = 100m implies radius of curvature R = 200m

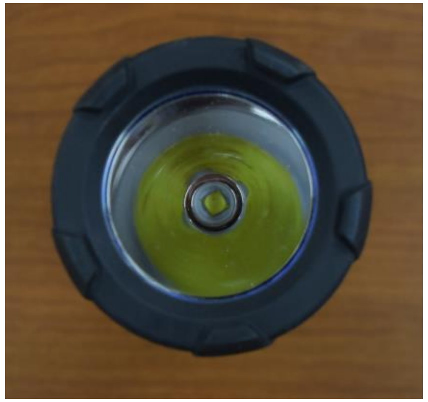


Return-Spot Test & Results

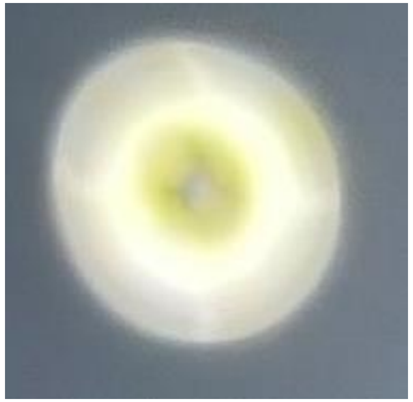


- Indicates center of curvature is near 255m, not the 200m specification given to the manufacturer
- Reflected spots are crisp and keep shape of light source: very high quality optical surface
- **Smallest reflected spot is roughly 11mm wider than flashlight aperture over the 510m total optical path length — very low error**

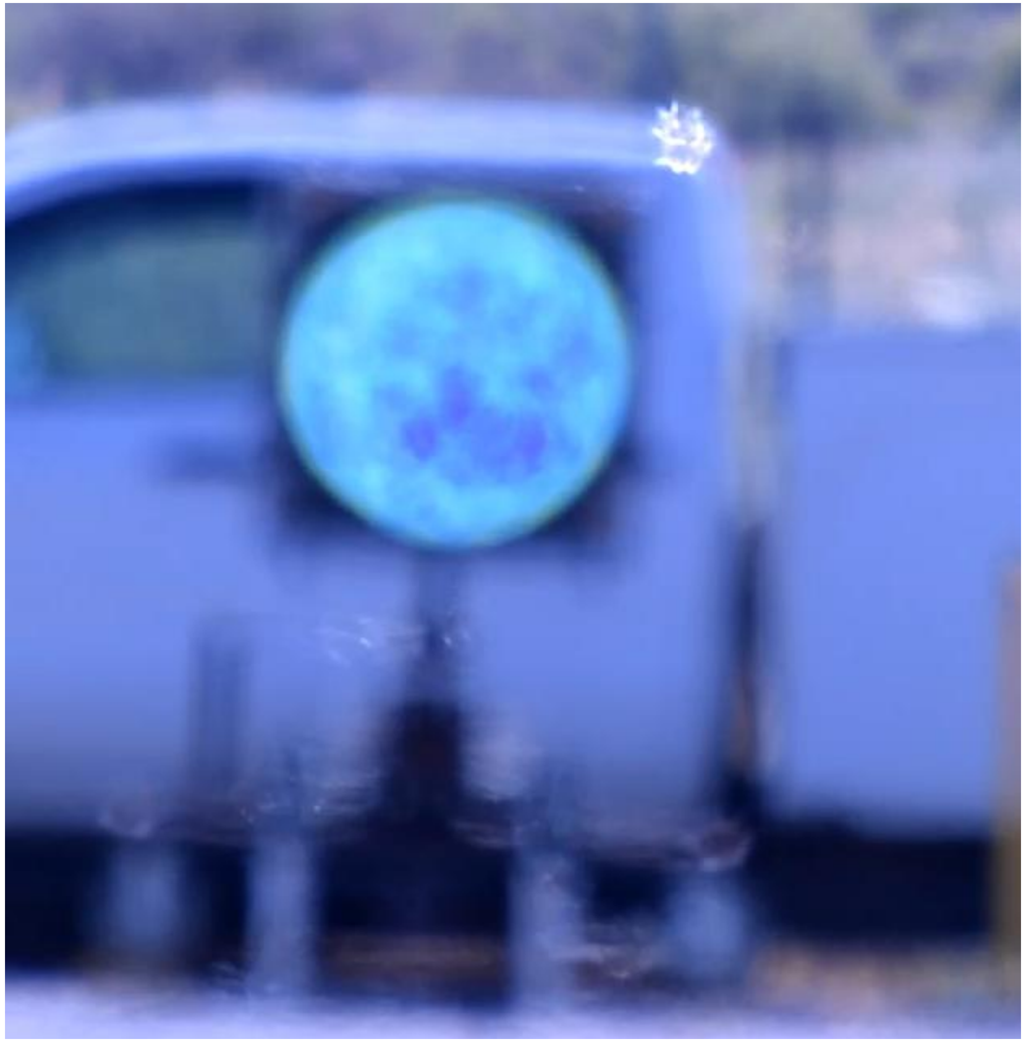
Flashlight used for test

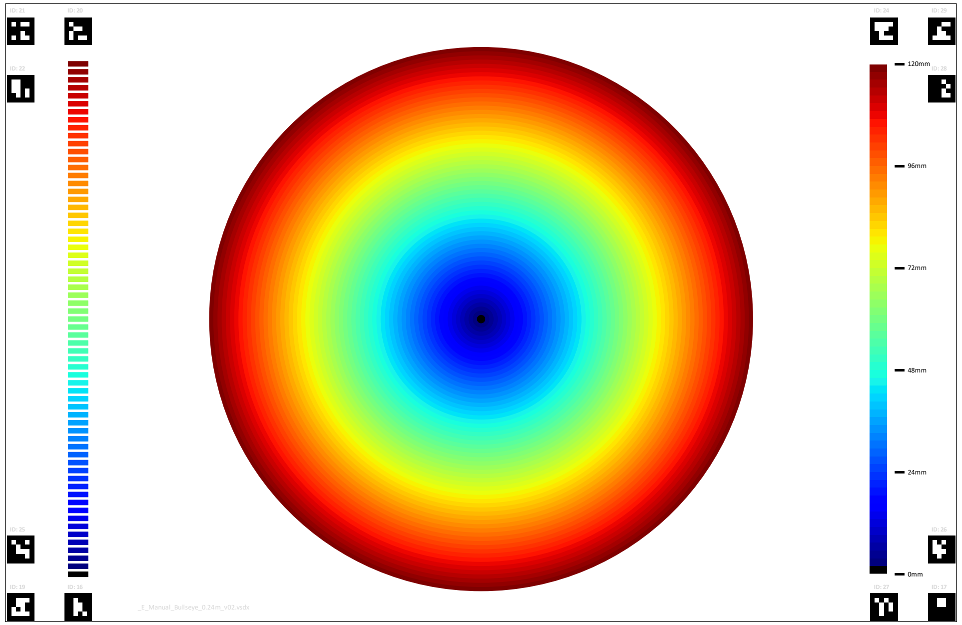


Returned Spot at 255m



Color Bullseye Test & Results





- Target has 0.24m diameter & is positioned 255m from mirror
- Darker blue indicates lower slope error
- Result indicates very low levels of error

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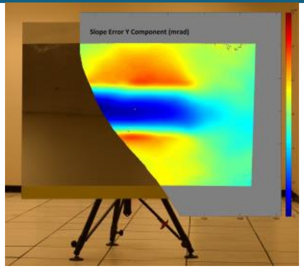
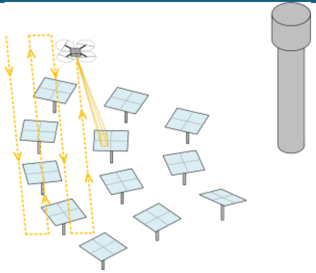
Calculating Off-Axis Canting Angles





Madeline Hwang

Supported by Randy Brost, Ben Bean, Braden Smith, Evan Harvey, Tristan Larkin, and other members of NSTTF.

August 28, 2024

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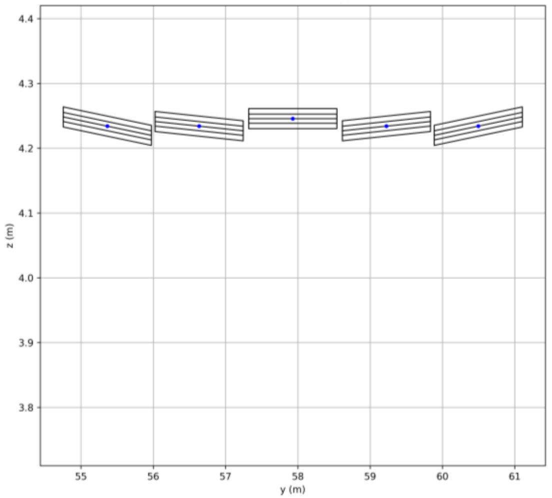
Off-Axis Canting

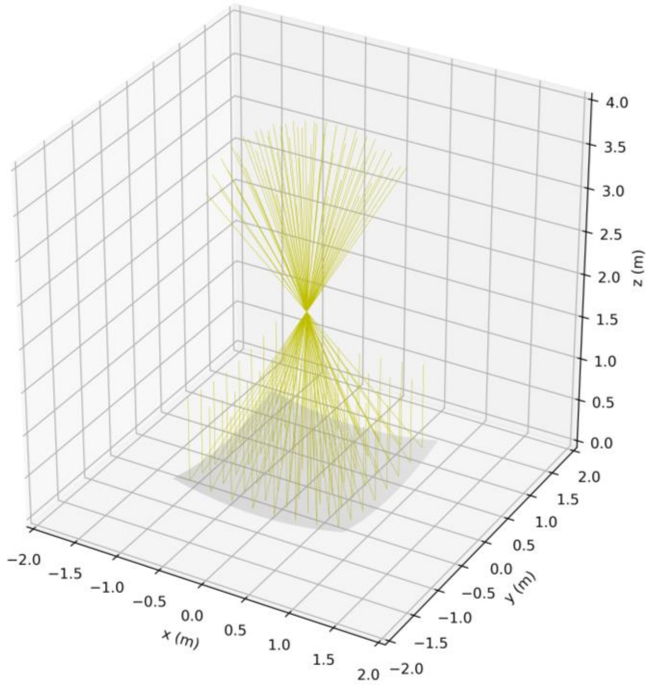
What is Canting?

- Focusing vs Canting
- On-Axis vs Off-Axis Canting
- Our NSTTF Heliostats are Canted Off-Axis

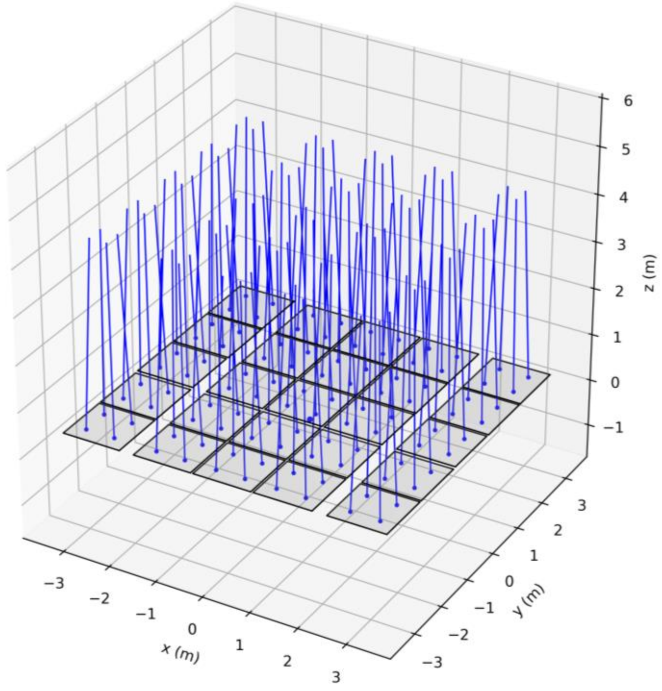
NSTTF Heliostat Canting Exaggerated



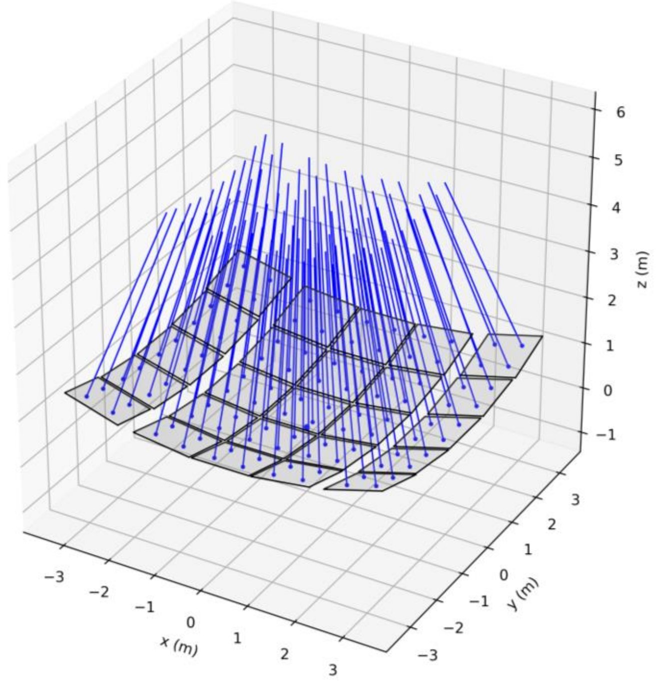
Focused Mirror



NSTTF Heliostat without Canting



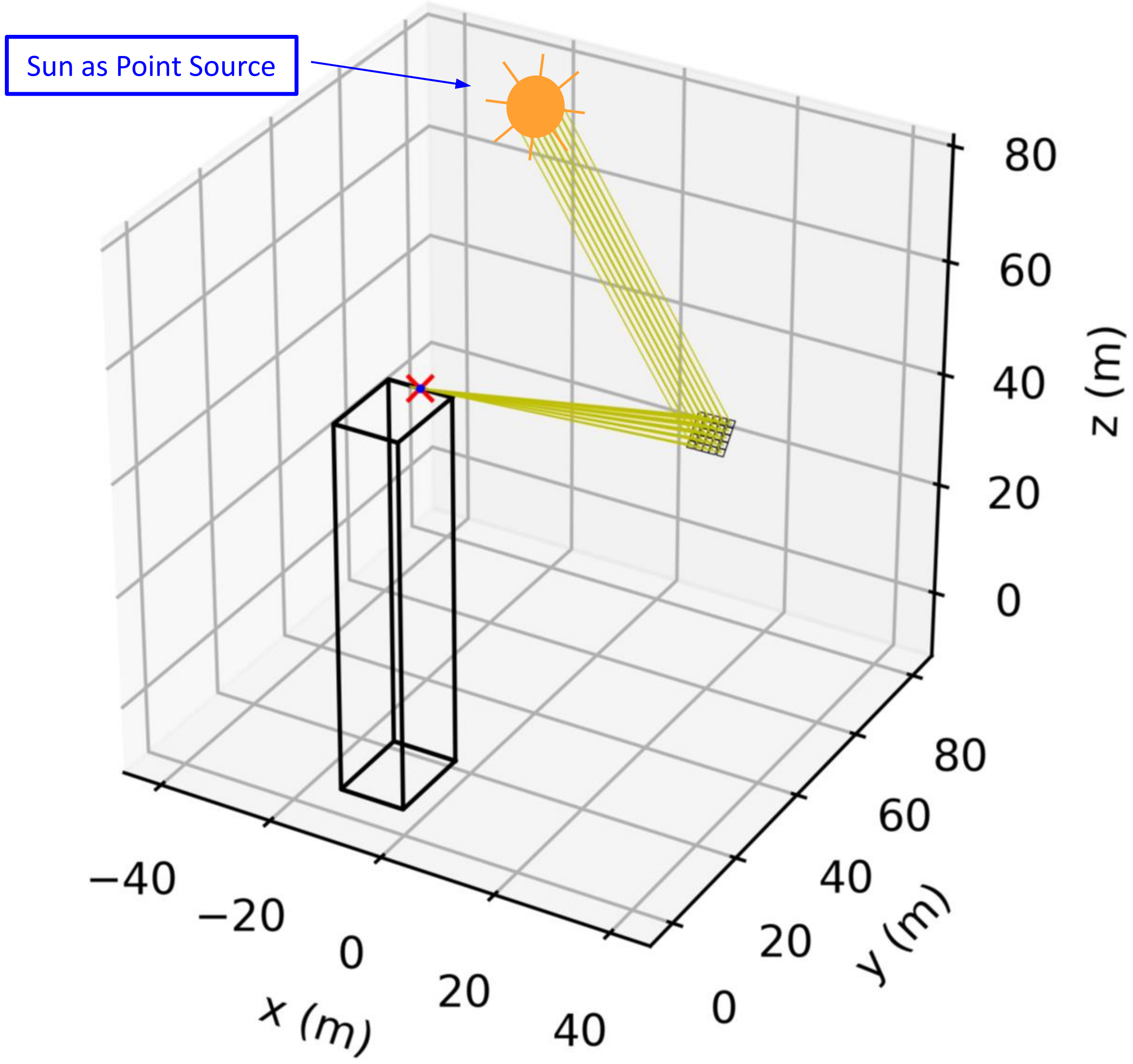
NSTTF Heliostat with Canting Exaggerated



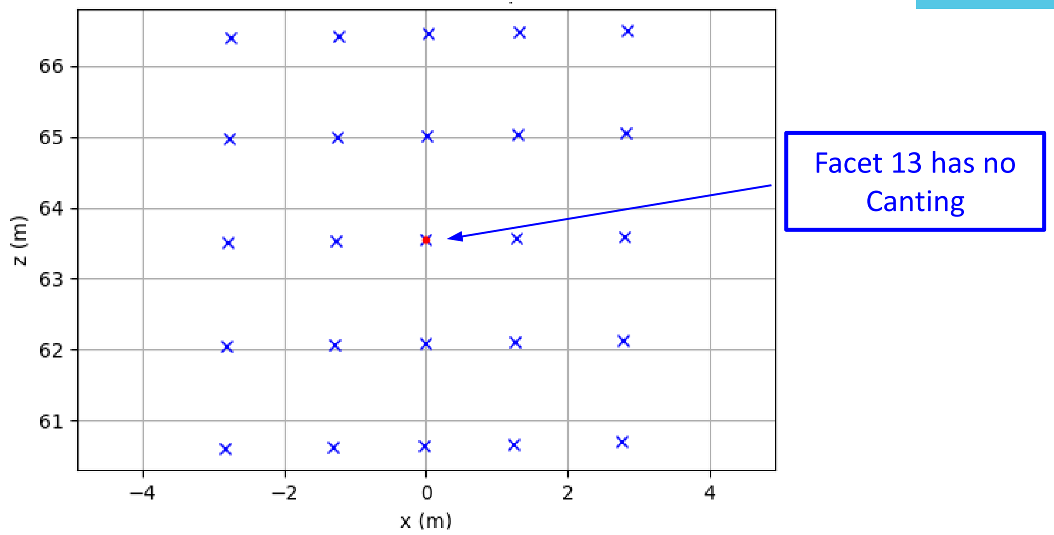
Images in Example Suite of OpenCSP

Computation of Canting Angles

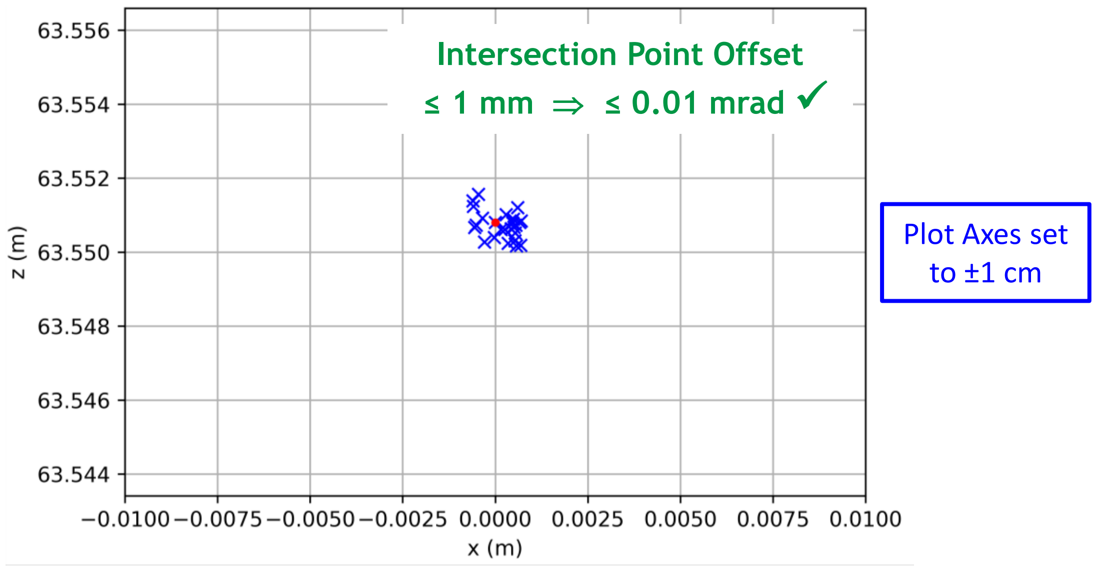
Off-Axis Canted NSTTF Heliostat*



Intersection at Aimpoint without Canting



Intersection at Aimpoint with Canting



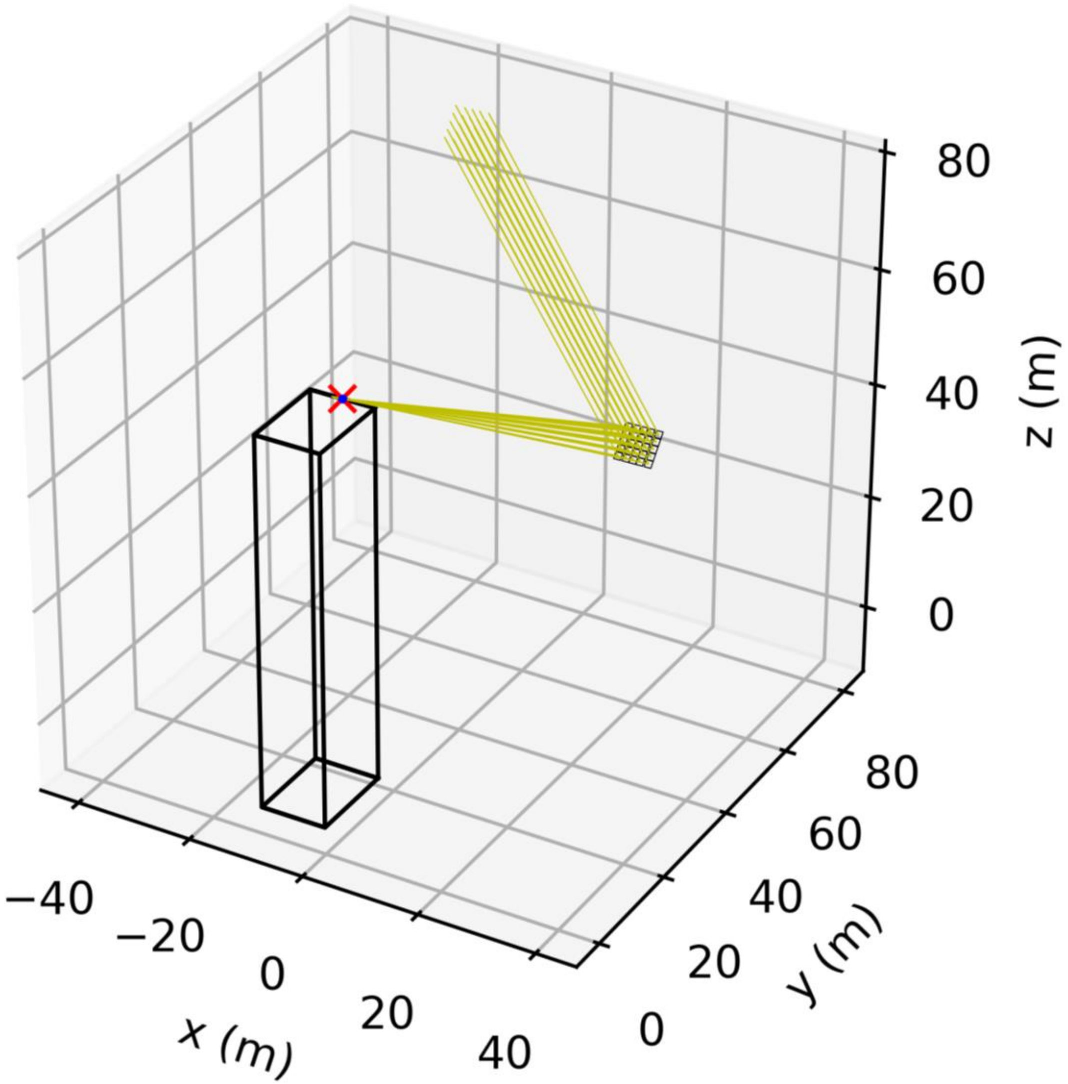
Variability due to Utilizing Binary Search Algorithm

* Spring Equinox at Solar Noon (March 21st, 13:13:5 MT)

Conclusion and Path Forward

- Off-axis canted heliostats produce higher flux at the target time than on-axis canted heliostats.
- We will compute ideal canting angles for all 214 NSTTF heliostats and then compare against direct measurements.
- This is part of a larger ground truth effort to determine canting angles.
- Will be published as a part of OpenCSP.

<u>Off-Axis Canted NSTTF Heliostat</u>



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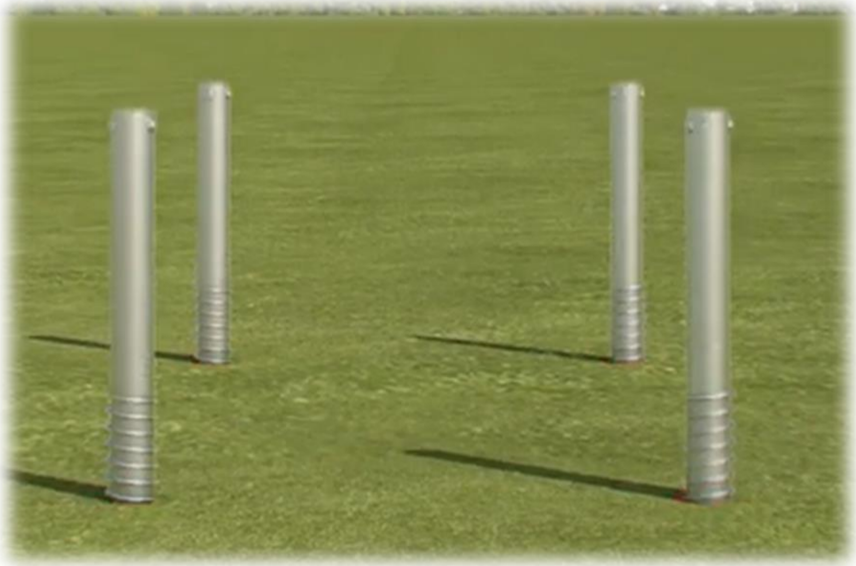
Analysis of Ground Screws for Low-Cost Heliostat Installations

- The project investigates optimizing anchoring methods and foundation costs for small-mirror heliostat installations, aiming to address the high cost, complexity, and environmental harm associated with current practices.
- Ground screws are tested as a foundation method for their low cost, ease of installation, and minimal environmental impact compared to traditional concrete foundations.
- The study involves testing various ground screw lengths across different soil types to determine the optimal configuration based on maximum axial and lateral loading, heliostat area, maximum wind speed, and soil composition.



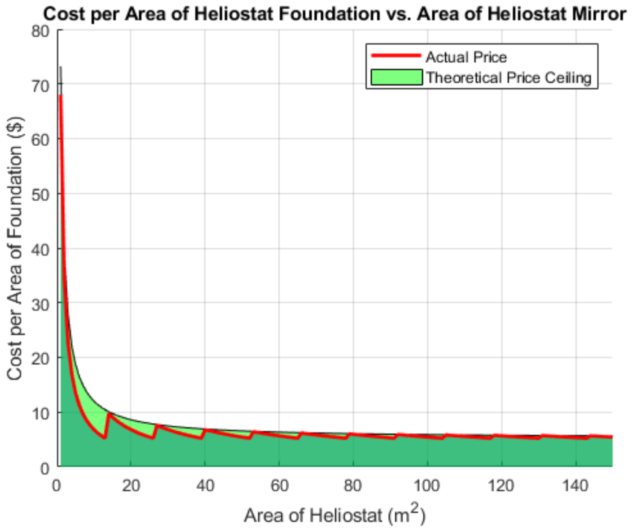
American Ground Screw

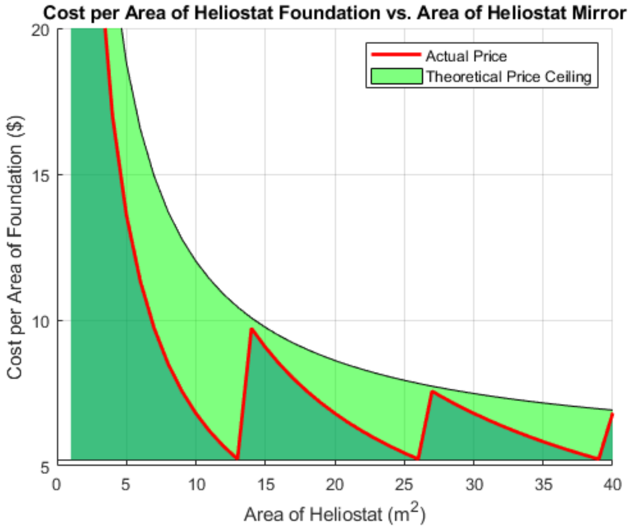
American Ground Screw

Kristina Ji

Analysis of Ground Screws for Low-Cost Heliostat Installations

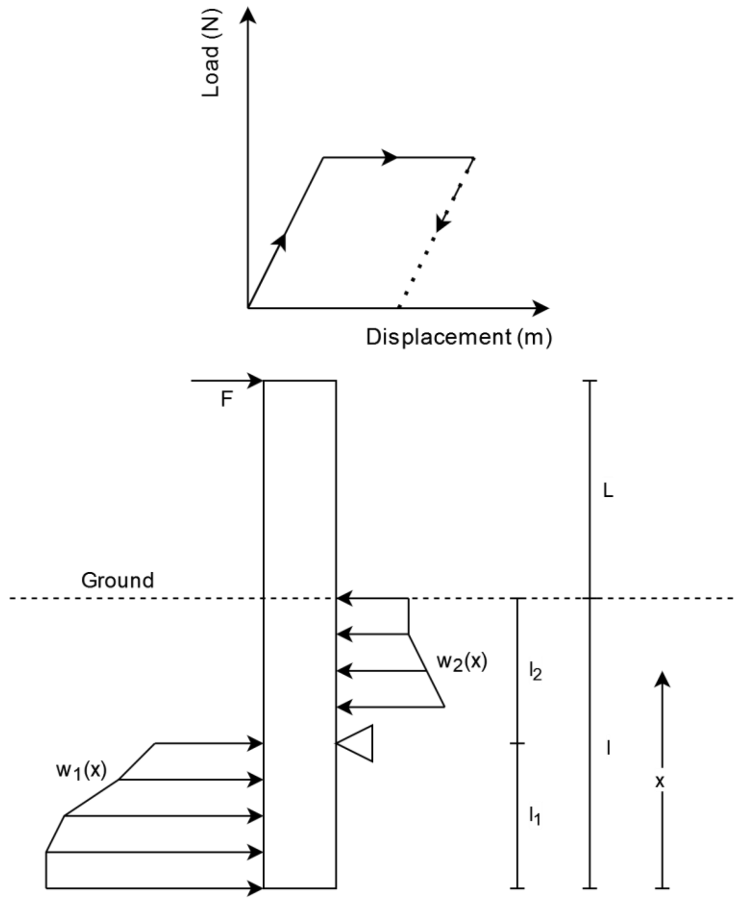
- Initial findings indicate a price floor of approximately \$5 per m^2 for mounting large heliostats using ground screws, with costs peaking for smaller heliostats. The project's goal is to lower the mounting costs for small heliostats to this price floor.
- Further experimentation and analysis should be done for a wide range of ground screw sizes and configurations to search for a method of price reduction for the mounting solution of small heliostats.





Analysis of Ground Screws for Low-Cost Heliostat Installations

- For testing, the ground screws will be loaded until failure of the soil to determine the maximum wind load for each type of screw.
- The data points can then be interpolated to provide a continuous function of allowable wind load vs. soil type and ground screw size.
- From this, a matrix can be generated for cost of heliostat mounting solution, mounting parameters, and installation location.



$$F = \int_{l_1}^{l_1+l_2} w_2(x)dx - \int_0^{l_1} w_1(x)dx$$

$$F \cdot (L + l_2) = \int_0^{l_1} w_1(x) \cdot (l_1 - x)dx + \int_{l_1}^{l_1+l_2} w_2(x) \cdot (x - l_1)dx$$

Thank You Mentors!

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Paul Ndione, NREL

Dr. Ken Armijo, NREL

Dr. Randy Brost, NREL

Jeremy Sment, SNL

Future Opportunities with HelioCon for Students

- Science Undergraduate Laboratory Internships (SULI) at NREL and SNL
  - How to apply: https://science.osti.gov/wdts/suli/How-to-Apply
  - Applications for Spring due **Oct 2**, applications for summer due **Jan 8**
- Internships with HelioCon:
  - https://heliocon.org/hiring_opportunity.html
- Internships at NREL
  - https://www.nrel.gov/careers/internships.html
- Fellowships at SNL
  - https://www.sandia.gov/careers/career-possibilities/students-and-postdocs/fellowships/
  - https://www.sandia.gov/working-with-sandia/academic-partnerships/postdoctoral-research-and-fellowship-programs/
- Internships at DOE
  - SETO: https://www.energy.gov/eere/solar/fellowships-and-research-opportunities
  - EERE: https://www.energy.gov/eere/education/internships-fellowships-graduate-and-postdoctoral-opportunities

More From HelioCon

- Past seminar presentations available on the HelioCon seminar webpage: https://heliocon.org/resources/heliocon_esev.html
- More resources can be found on the HelioCon resources webpage: https://heliocon.org/resources/resources-1.html
- Subscribe to the seminar series or get in touch: heliostat.consortium@nrel.gov

Next Seminar on September 18th!

HelioCon Seminar Series: Wind driven loads on solar collectors: Perspectives from Two Field Campaigns
Speaker: Dr. Shashank Yellapantula, NREL
When: 1-2pm MT, Wed Sept 18

New HelioCon Seminar Host

Dr. Brooke Stanislawski will host the HelioCon Seminar series starting in September