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

Intern Projects in Heliostat Technologies at NREL, SNL, and DOE

The HelioCon Intern Team
Host: Dr. Rebecca Mitchell

August 1, 2022

HelioCon Intern Team

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Mentor: Dr. Alex Zolan

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Mentor: Dr. Randy Brost

Mackenzie Dennis, NREL
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Natalie Gayoso, SNL
Mentor: Dr. Ken Armijo

Kyle Heinzman, NREL
Mentor: Tucker Farrell

Maggie Kautz, NREL
Mentors: Dr Guangdong Zhu, Dr. Rebecca Mitchell

Mojolaoluwa Keshiro, NREL
Mentor: Devon Kesseli

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Mentor: Dr. Ken Armijo

Dylan Mayes, NREL
Mentor: Tucker Farrell

Nicole Piatko, DOE
Mentor: Andru Prescod

Katelyn Spadavecchia, NREL
Mentors: Mackenzie Dennis and Devon Kesseli

Gabriel Shuster, NREL
Mentor: Dr. Rebecca Mitchell

Daniel Tsvankin, NREL
Mentor: Dr. Matt Muller

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

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

Raven Barnes, NREL
Mentor: Dr. Alex Zolan

Mackenzie Dennis, NREL
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Heliostat performance testing and validation

Mackenzie Dennis

Beam Characterization System (BCS) Overview

Kyle Heinzman

BCS Hardware & Data Collection

Katelyn Spadavecchia

BCS Software Development

Daniel Tsvankin

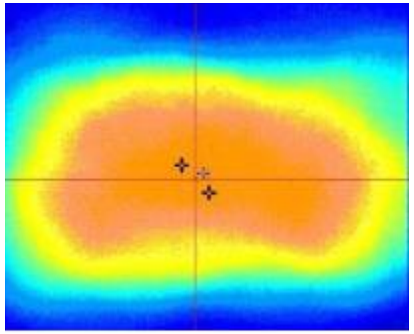
BCS support and heliostat standard qualification and validation

HelioCon: BCS Overview

Mackenzie Dennis

Beam Characterization Systems:
Automated image processing to detect and correct for heliostat pointing error

Setup and process:
- A heliostat in the field is diverted from the receiver onto target
- Camera takes photo of beam on target
- Image processing algorithm finds:
  - Beam shape and flux map
  - Beam placement on target
  - Pointing/ tracking error of heliostat



Flux map (Sandia)

BCS target on receiver tower

- "Sandia Capabilities for the Measurement, Characterization, and Analysis of Heliostats for CSP.," July 1, 2013. https://doi.org/10.2172/1090214.
- *The Performance of Concentrated Solar Power (CSP) Systems*, 2017

HelioCon: BCS Hardware/Data Collection

Kyle Heinzman

Objective:

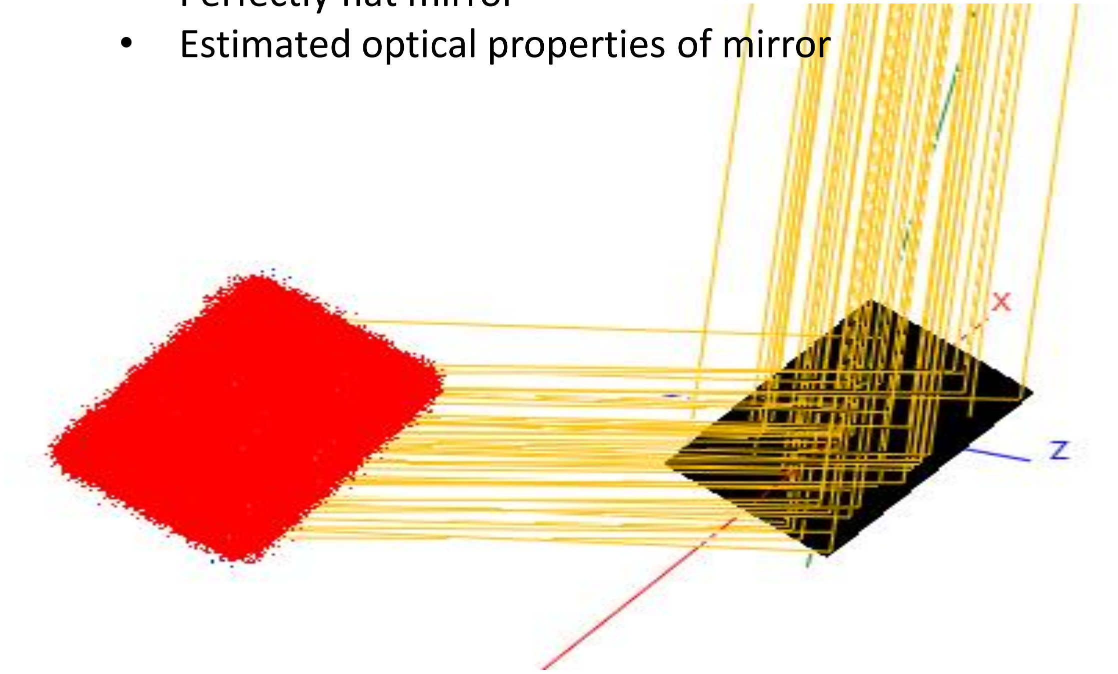
- To design and develop the necessary hardware to train a BCS image processing algorithm.

Experimental Modeling:

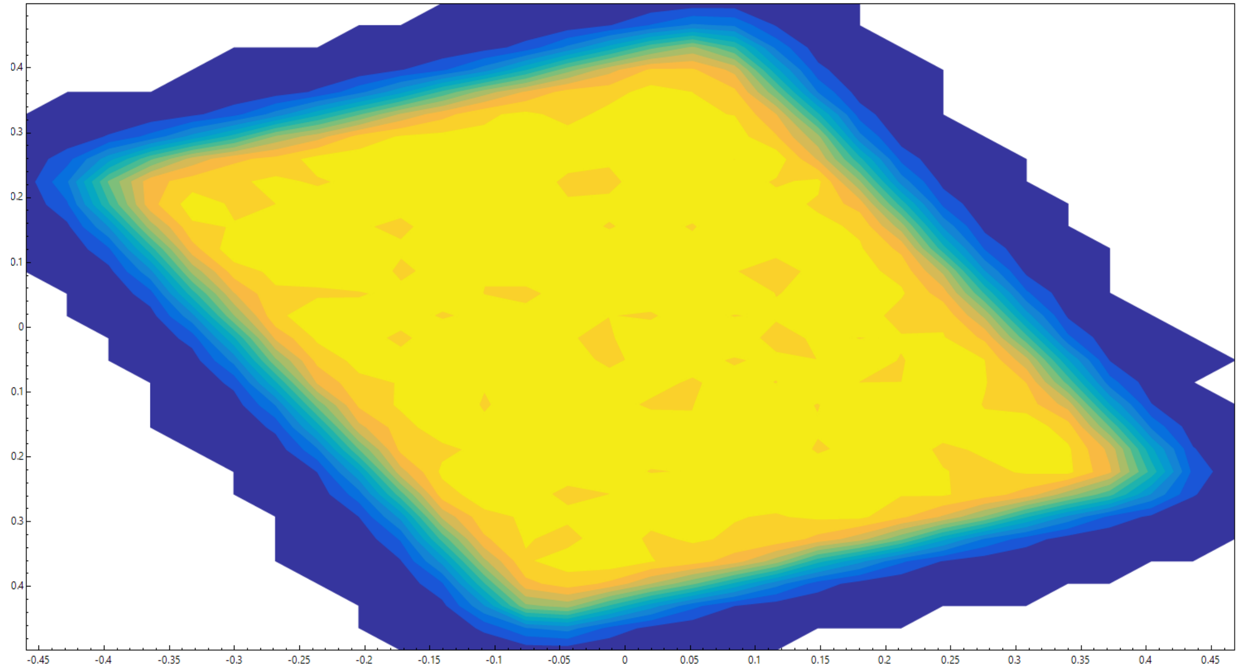
SolTrace used to model experimental setup & determine maximum target size.

Assumptions:

- Perfectly flat mirror
- Estimated optical properties of mirror



SolTrace ray modeling



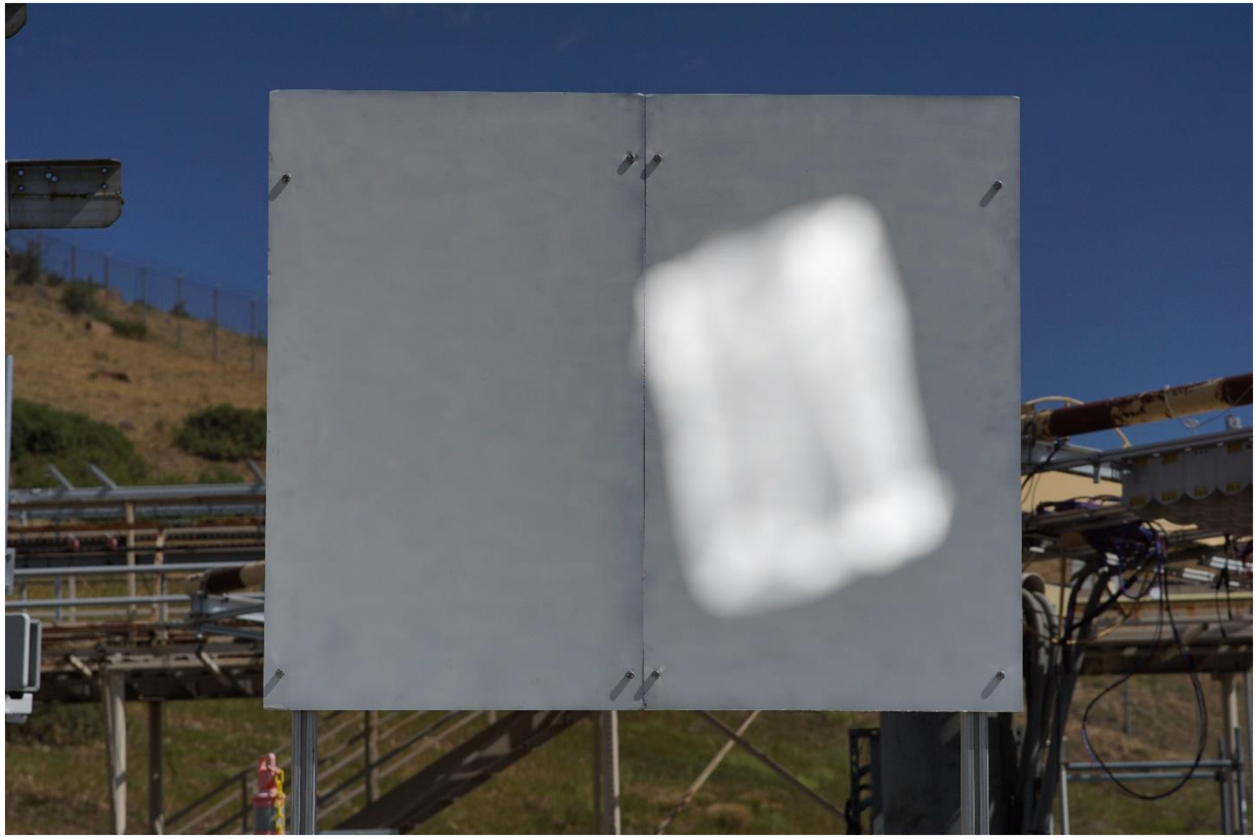
Corresponding flux map

HelioCon: BCS Hardware/Data Collection

Kyle Heinzman, Mackenzie Dennis, Daniel Tsvankin

Heliostat Frame

Target Frame



Beam image collected at the Outdoor Testing Facility (OTF)

Design Constraints:

- Mirror to Target Size
  - Mirror Size = 21” by 31”
  - Target Size = 4ft by 3.2ft
- Forces due to Wind Loading
- Target Material & Coating

HelioCon: BCS Hardware/Data Collection

Kyle Heinzman, Mackenzie Dennis, Daniel Tsvankin

Experimental Testing:

- Repeatability
- Compatibility of Images with Algorithm
  - Camera Specs / Settings
  - Camera Position / Orientation

Data Measurements for Repeatability	Camera Settings Manipulated
Distances	Aperture
Compass Orientation (Aimpoints)	Shutter Speed
Inclination angles	ISO sensitivity

OTF BCS experimental setup

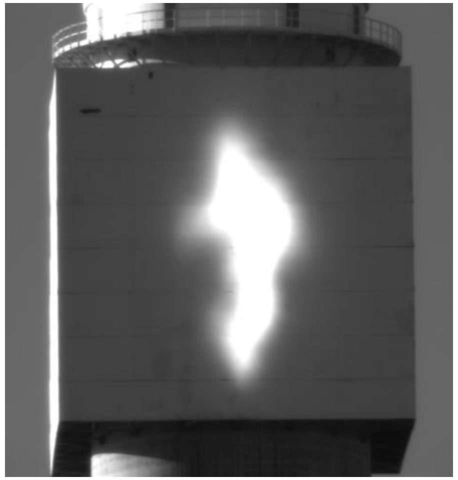
Future of Project:

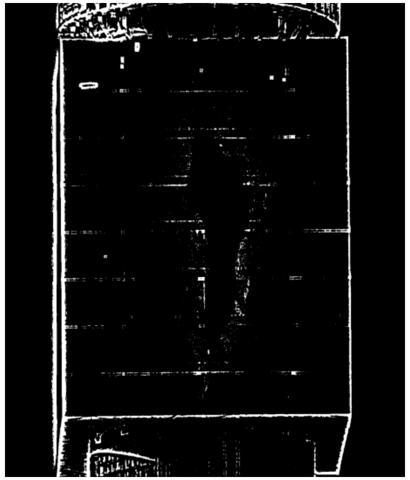
- ➢ Upscale model for OTF roof testing using an automated heliostat with solar tracking.
- ➢ Rectangular target design used with BCS image processing software can characterize site specific CSP Power Towers plants.

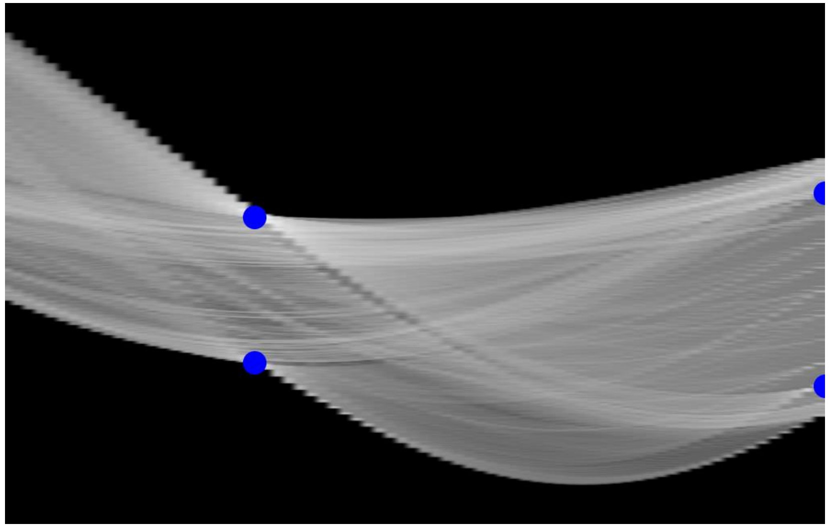
HelioCon: BCS Software Development

Katelyn Spadavecchia, Devon Kesseli, Mackenzie Dennis,

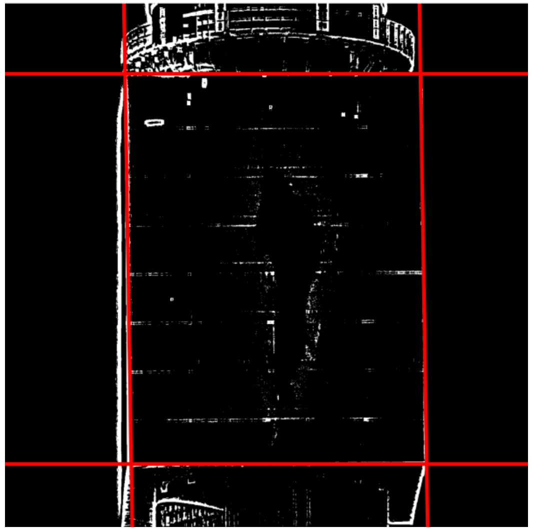
1. Import Images (Crescent Dunes)
2. Create Binary Image using filters
3. Apply Hough Transformation
4. Extract Hough Lines
5. Segment and intersect lines
6. Test each image

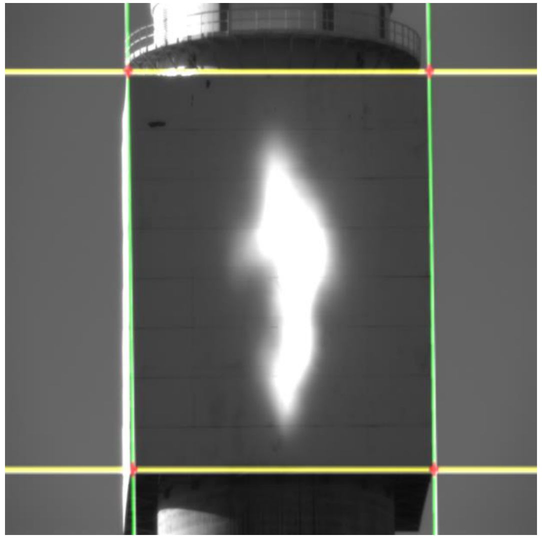






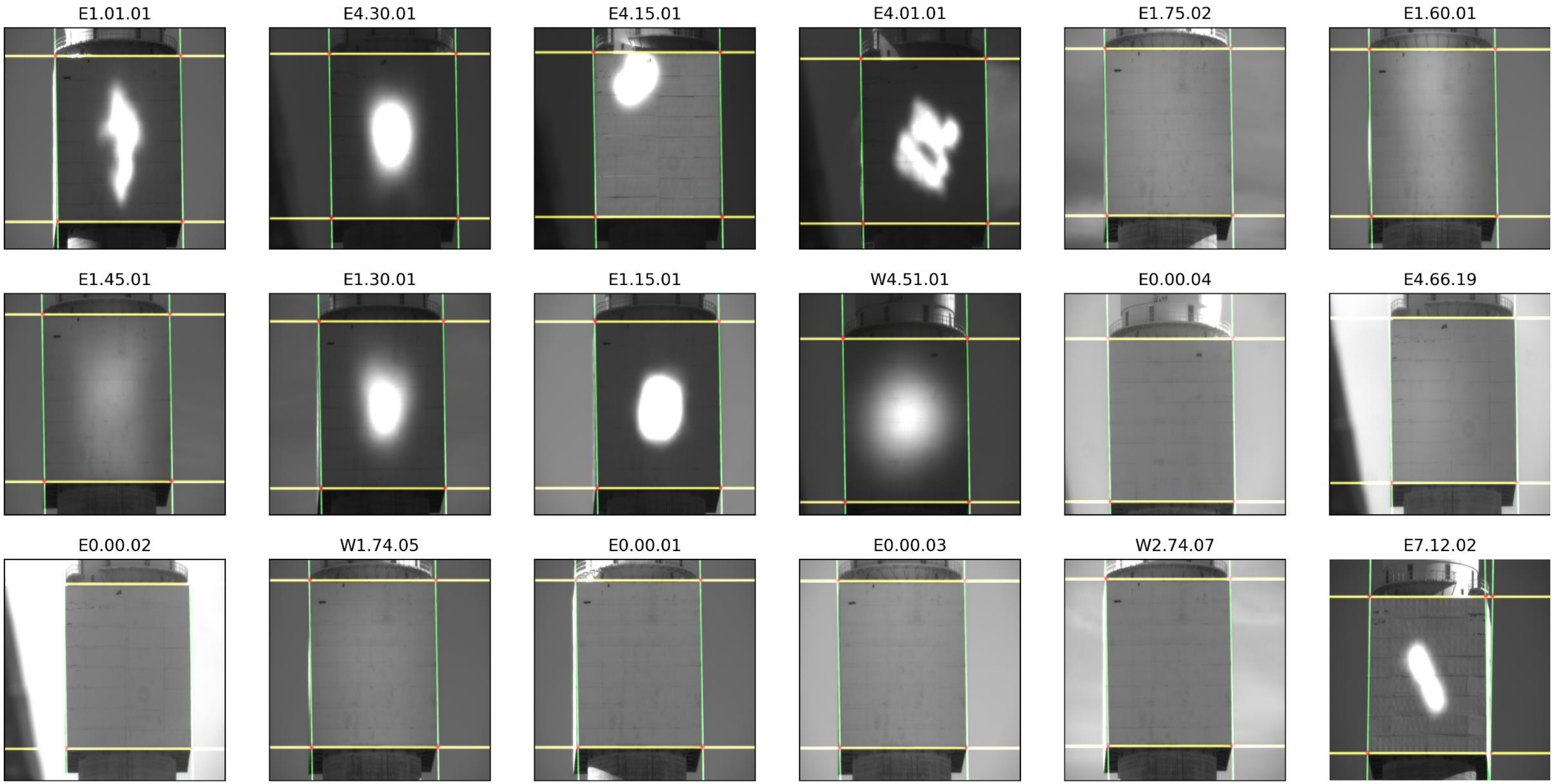
Detected Lines





HelioCon: BCS Software Development

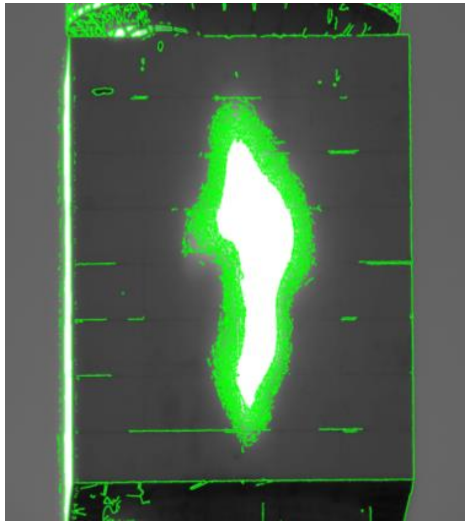
Katelyn Spadavecchia, Devon Kesseli, Mackenzie Dennis



HelioCon: BCS Software Development

Katelyn Spadavecchia, Mackenzie Dennis

- Images were taken at OTF with varying target aspect ratios and camera ISO settings
- Larger target ratios are better for detecting edges
- No clear ISO preference



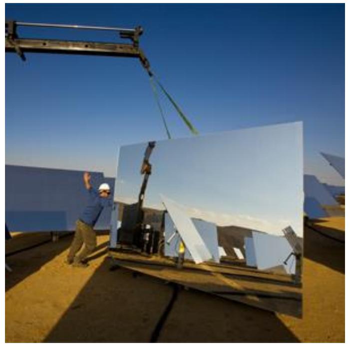
Future of Project

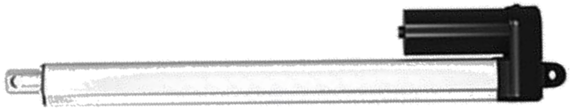
With accurate target edges, features of the beam such as centroid and diameter can be identified more meaningfully.

HelioCon: Standards Development

Daniel Tsvankin

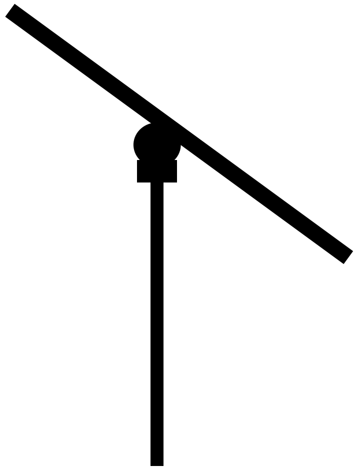
Component testing





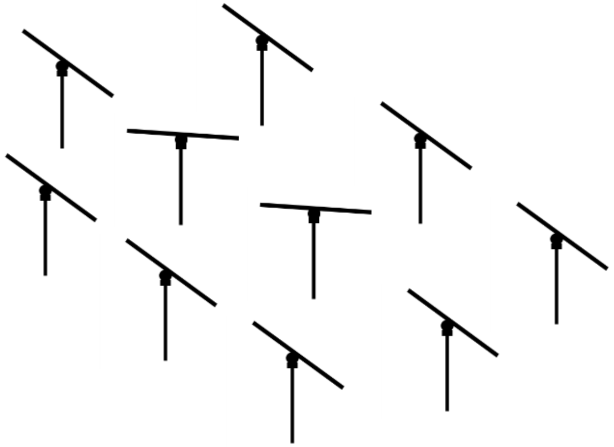
Hemispherical reflectance (reflector)
Specular reflectance (reflector)
Abrasion resistance (all)
Ingress resistance (all)
MTBF and lifespan (all)
Backlash and hysteresis (drives)

Heliostat testing



Beam error after HALT
Pointing accuracy after HALT
System reliability
System serviceability

Field performance testing

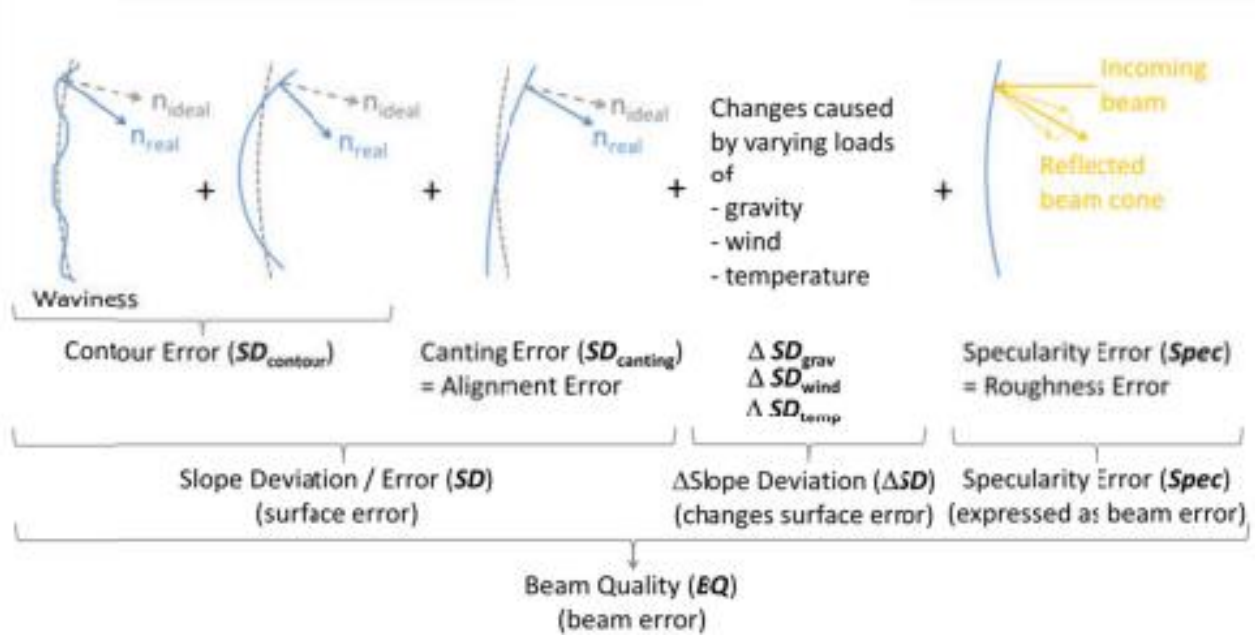


Flux control and capacity
Field safety and operability
Soiling
Site acceptance

HelioCon: Standards Development

Daniel Tsvankin

- Mechanical longevity tests adapted from IEC 62817
- Beam quality tests adapted from SP
  - Simulation
  - Physical test
- Tracking error tests adapted from SP and IEC
- Publicly-available software for processing test images



Heliostat performance parameters from SolarPACES Guideline for heliostat performance testing

- SolarPACES Guideline
- IEC 62817
- IEC 62108

Gap **identification**
IEC language **translation**
Procedure **modification**
Test **verification**
Tool **development**

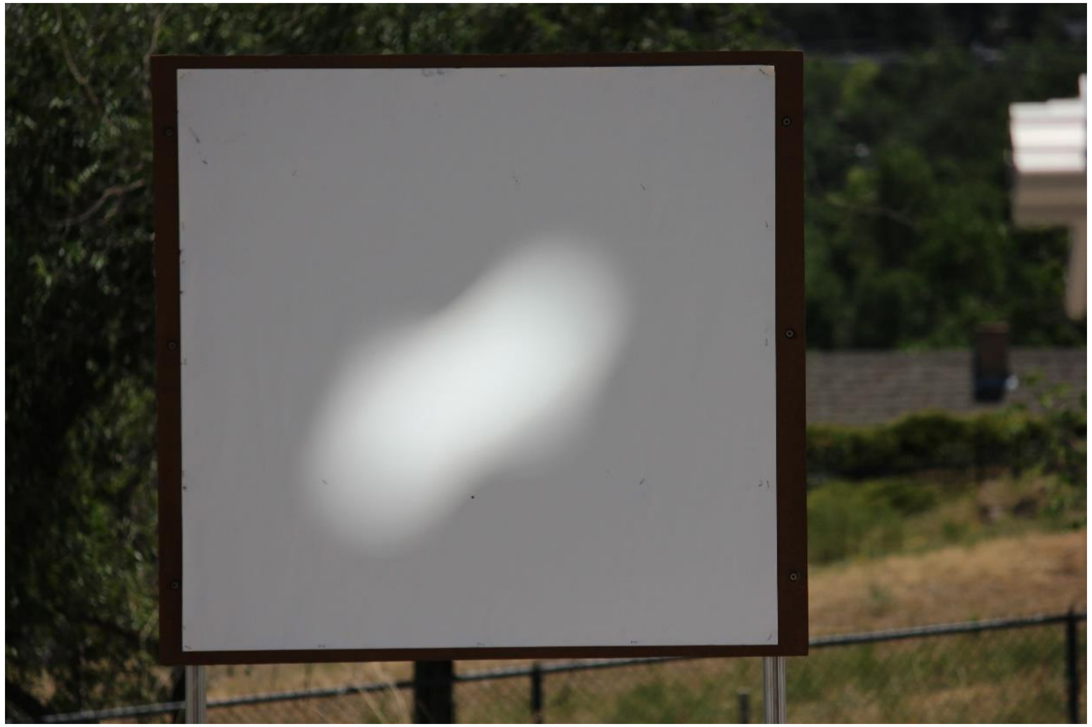
IEC 62842-4-X

HelioCon: Standards Validation

Daniel Tsvankin, Kyle Heinzman, Mackenzie Dennis

Configurable solar tracker at the NREL Outdoor Test Facility

- Static (on ground) and dynamic (tracker-mounted) mirror setups
- Feedback loop between running tests, updating standards language, and developing accompanying tools

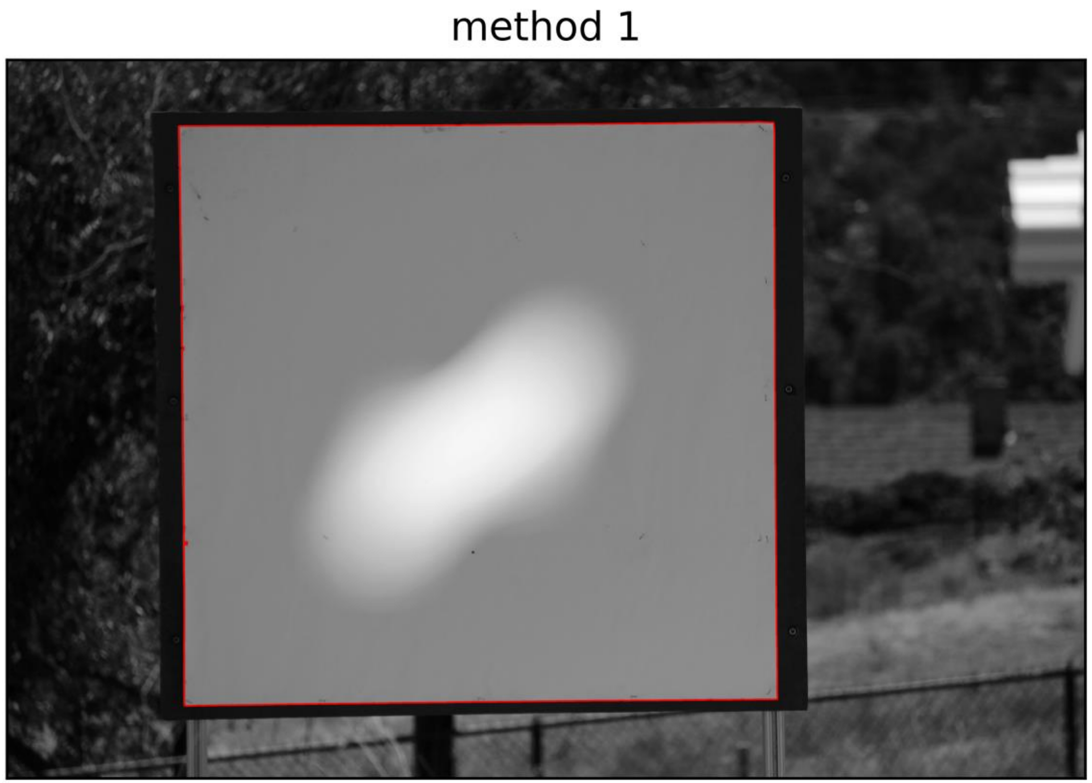


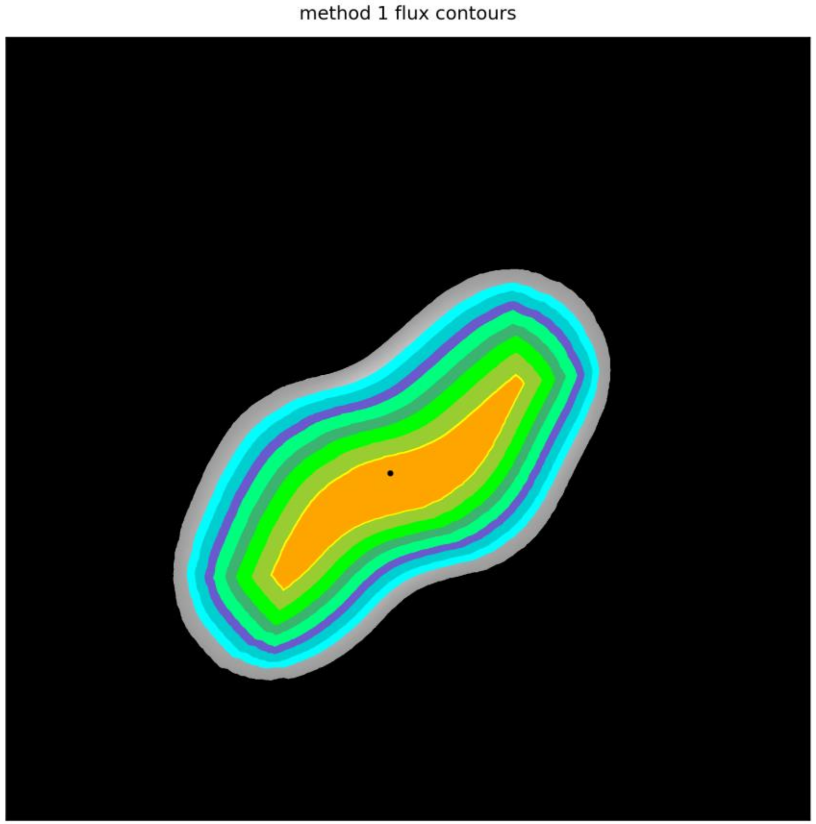
Sample beam image from 1' x 1' flat mirror tile mounted to tracker

HelioCon: Standard Tools

Daniel Tsvankin, Katelyn Spadavecchia

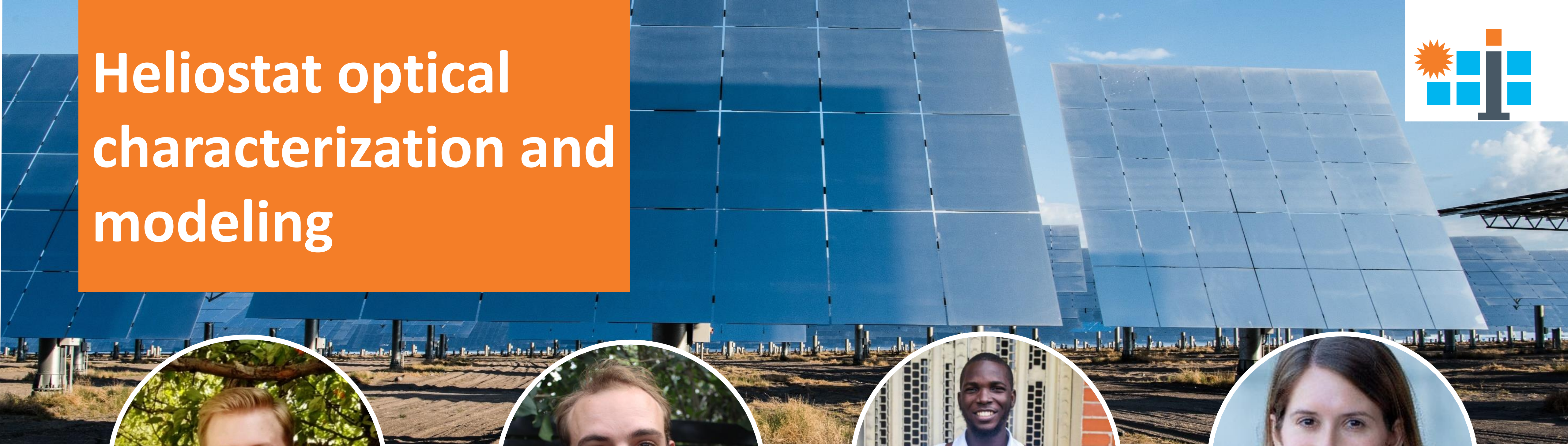
- Goal: publicly-available software for processing beam-on-target methodologies
  - Collection of feedback from partner institutions
- Image-based approximation of SolarPACES beam quality and tracking accuracy values





Sample program output. Dot is beam centroid. Each color represents 10% of the overall flux. Removing the gray region yields the 90% flux region, which is used for further analysis under SolarPACES Guidelines and the draft IEC standard.

Heliostat optical characterization and modeling



Dylan Mayes

Non-Intrusive Optical (NIO) tool Automation

Gabriel Shuster

NIO slope error sensitivity analysis

Mojolaoluwa Keshiro

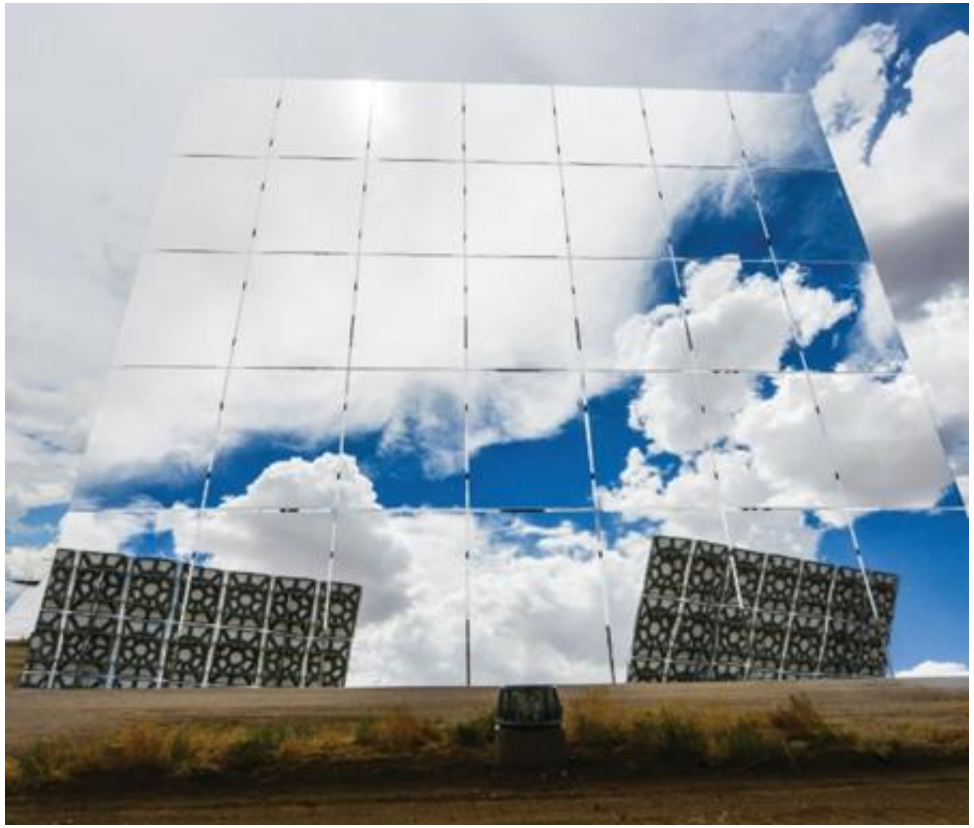
Lab NIO development

Maggie Kautz

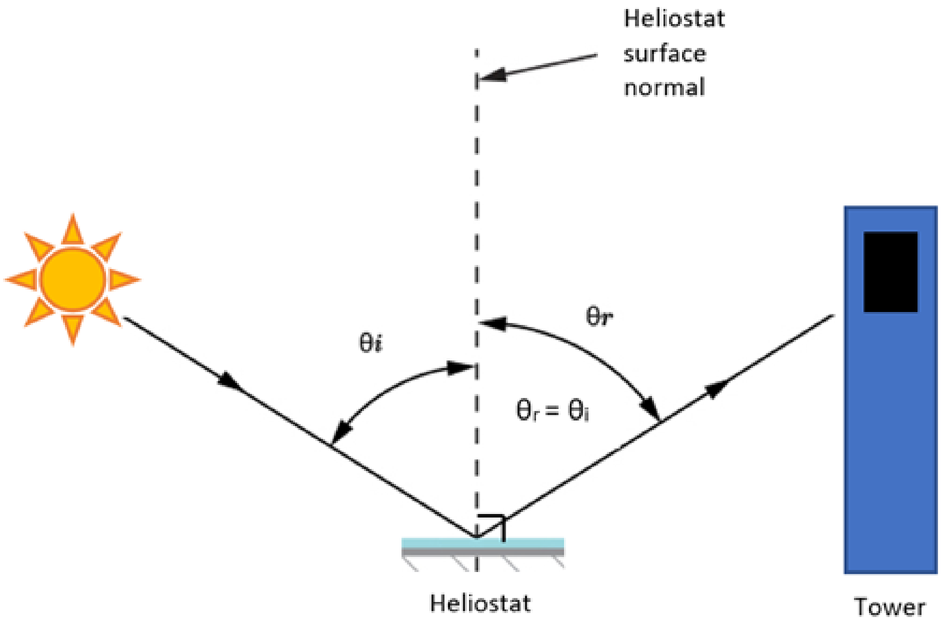
Optimizing heliostat shape through ray trace modeling

Heliostats & the Non-Intrusive Opitcal Method (NIO)

Mojolaoluwa Keshiro



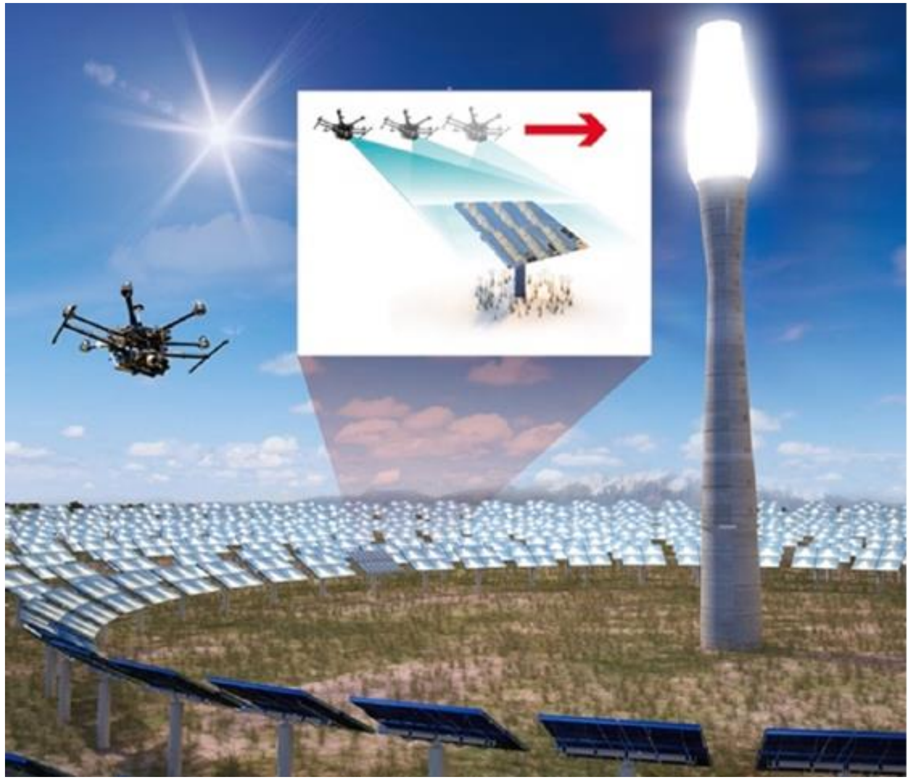
A Heliostat



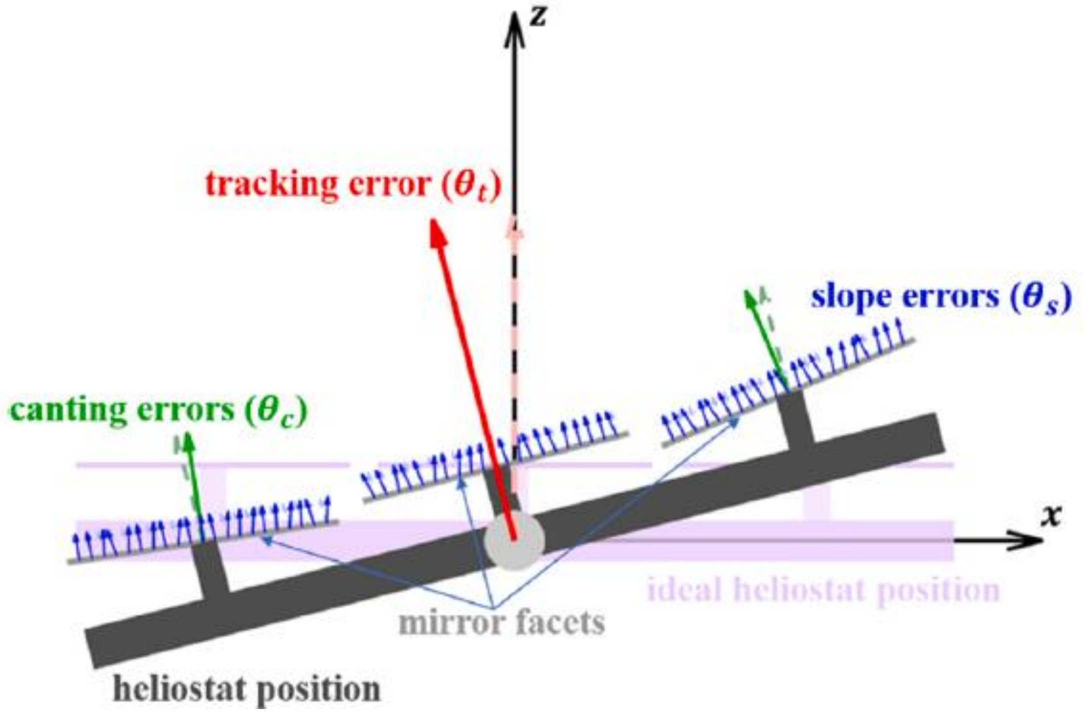
The law of reflection

HelioCon: NIO Algorithm Overview

Mojolaoluwa Keshiro, Dylan Mayes, Gabriel Shuster



UAS image data collection for the NIO method (Mitchell and Zhu, 2020)



Optical error types measured by the NIO method (Mitchell and Zhu, 2020)

Dylan

HelioCon: NIO Algorithm Overview

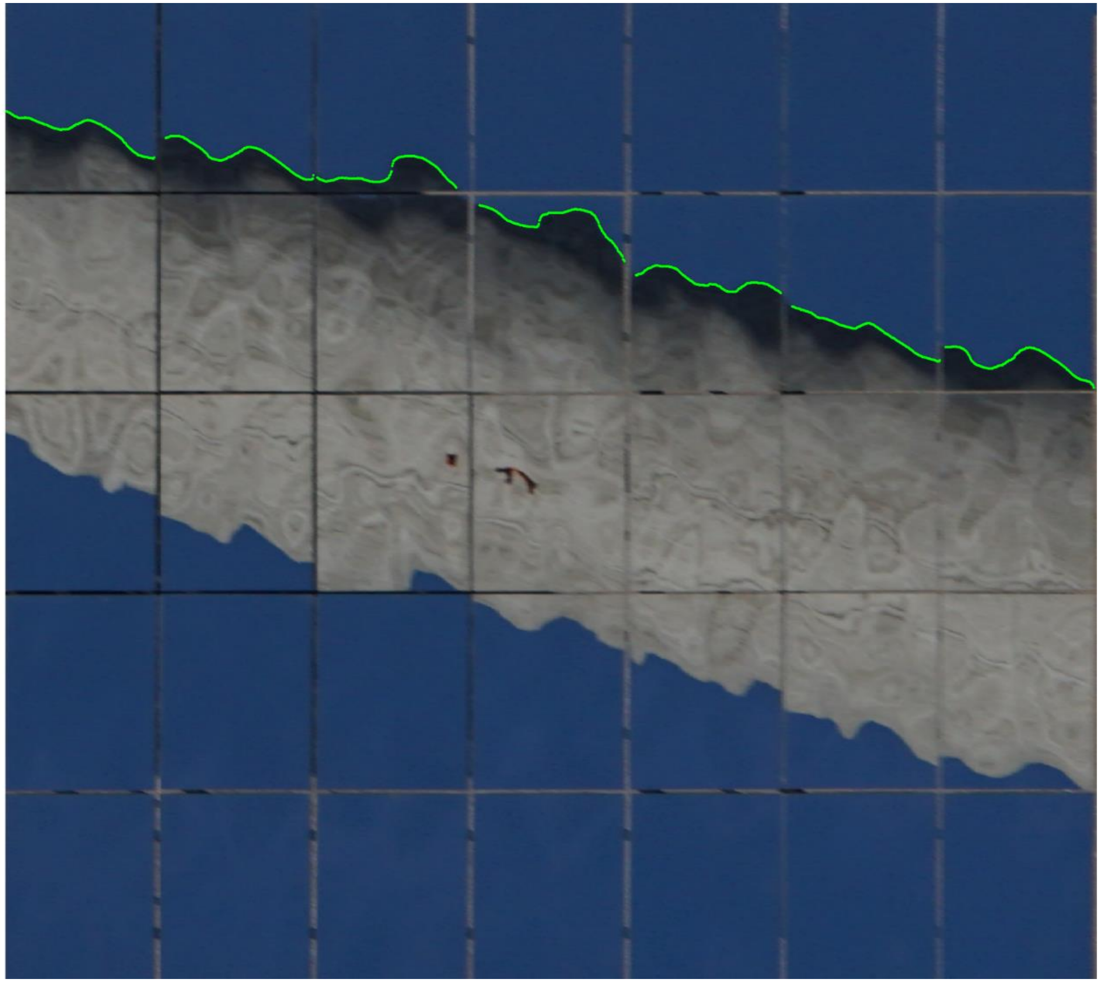
Dylan Mayes, Gabriel Shuster

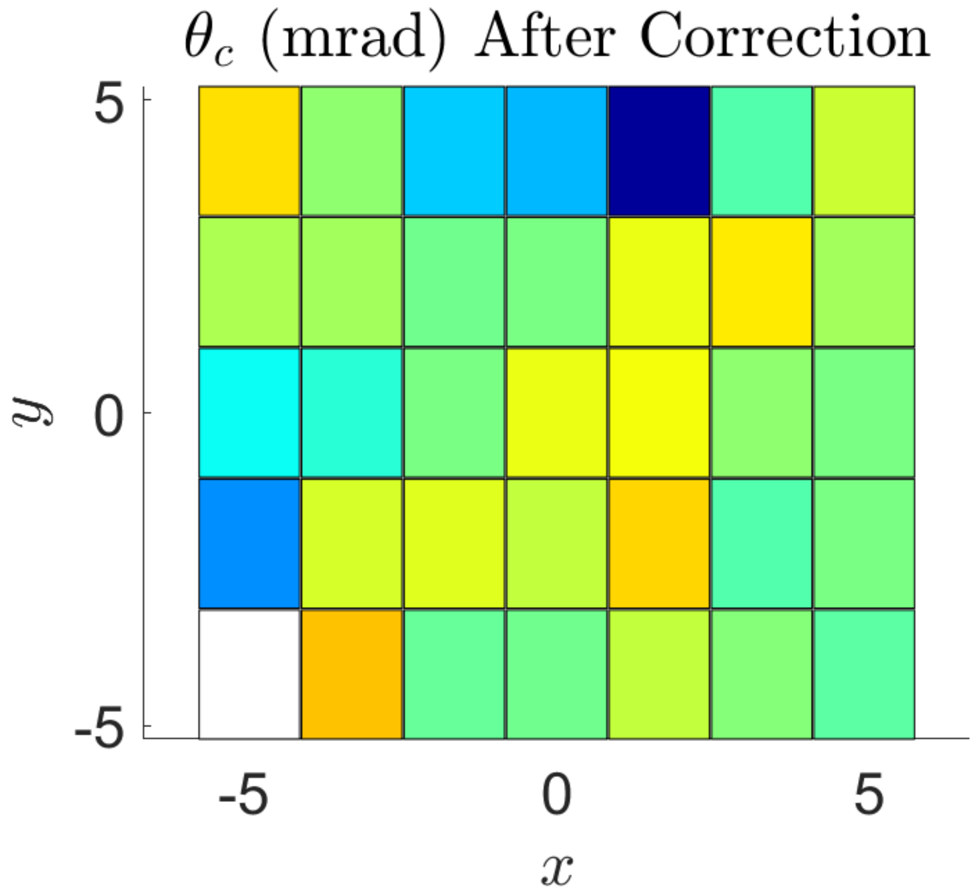
- Processes image datasets collected from field acquisition stage using UAS
- Outputs image dataset as input to MATLAB post-processing error analysis

- Original algorithm development and testing
- Serves as the backbone for NIO approach theory and calculations
  - Slope error uncertainty
  - Canting error, heliostat tracking error

HelioCon: NIO Algorithm Overview

Dylan Mayes, Gabriel Shuster


Edge detection plot for the tower reflection (top side in this case)



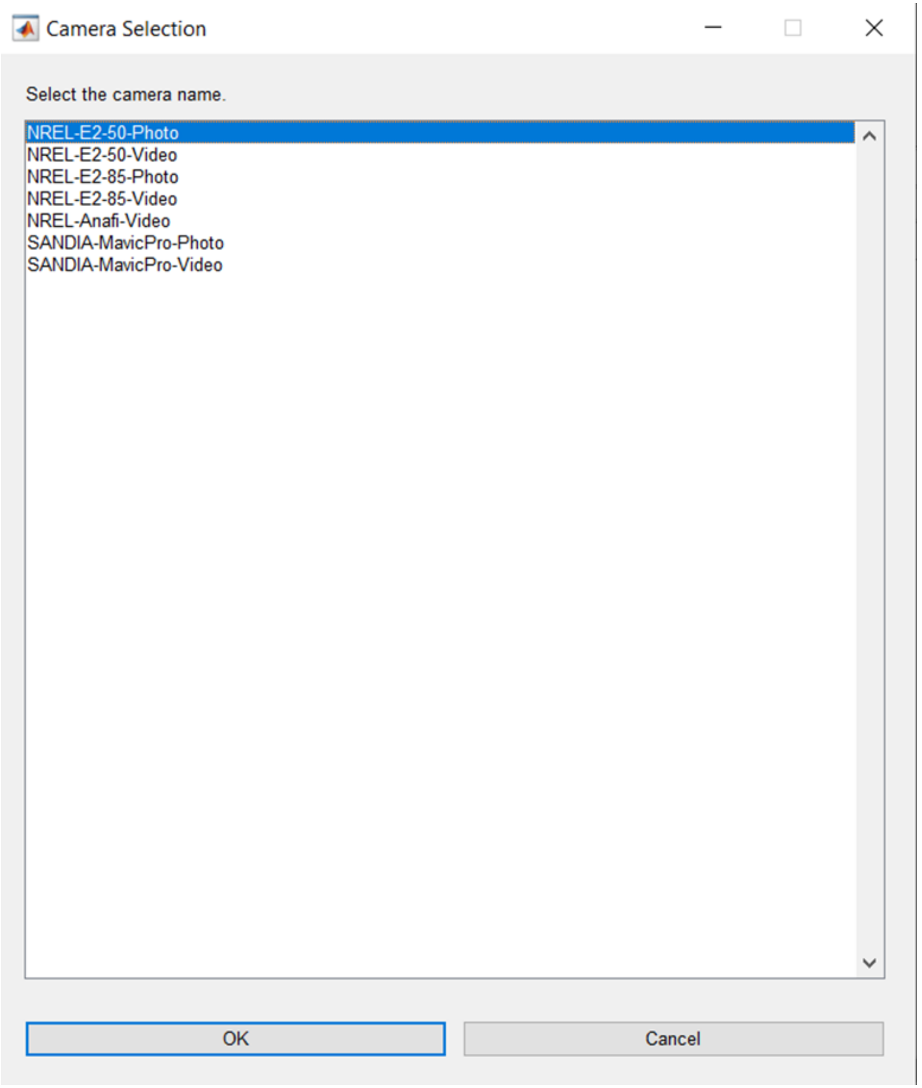
Canting error plot per facet generated from optical error calculations

Dylan

HelioCon: NIO Automation

Dylan Mayes

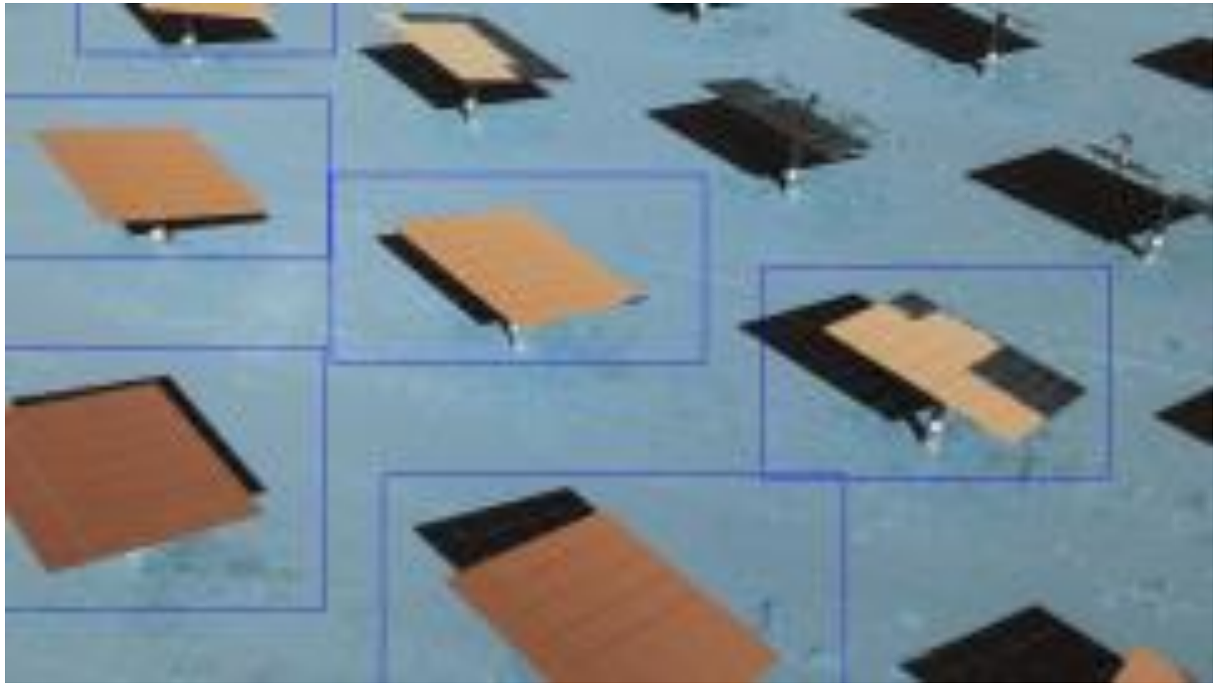
- Remove user inputs
- Develop functionality, loops, and calculations
- Decrease labor time to run and process code
- Create GUI to assist the user
- Remove user interaction with blocks of code



HelioCon: NIO Automation

Dylan Mayes

- Automatic feature detection
  - Corners, tower edges, and ID of heliostat
- Compilation and merging of original and automated NIO algorithms using GitHub
- Automation removes hours of labor needed to run the algorithm



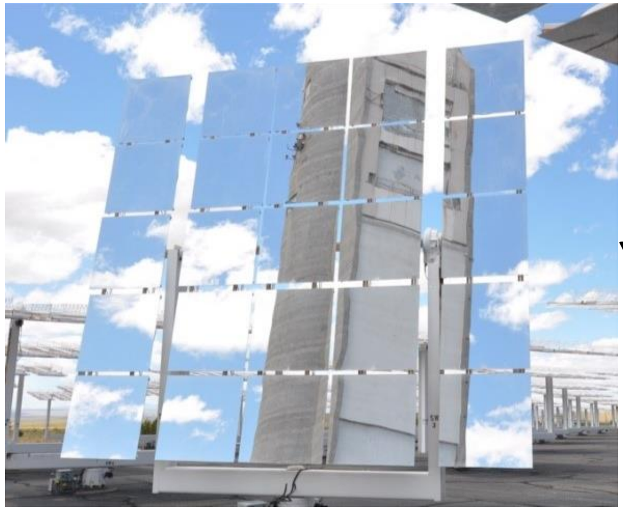
Automatic heliostat detection from images

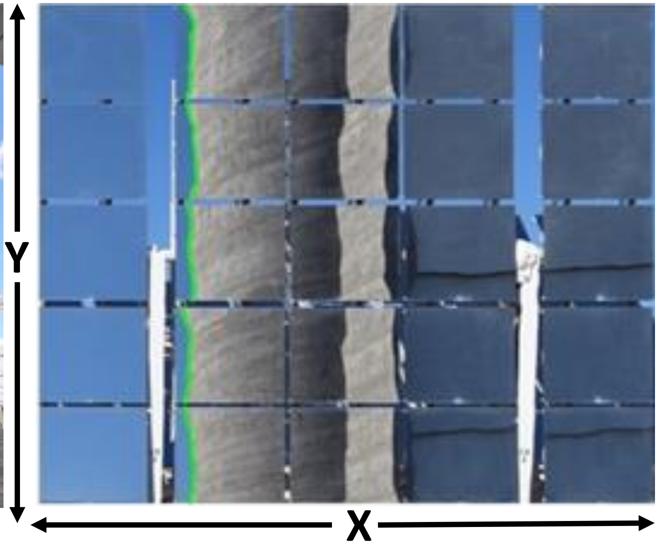
NIO Slope Error Sensitivity Analysis

Gabriel Shuster

NIO method uses drone captured images of heliostats to calculate slope error

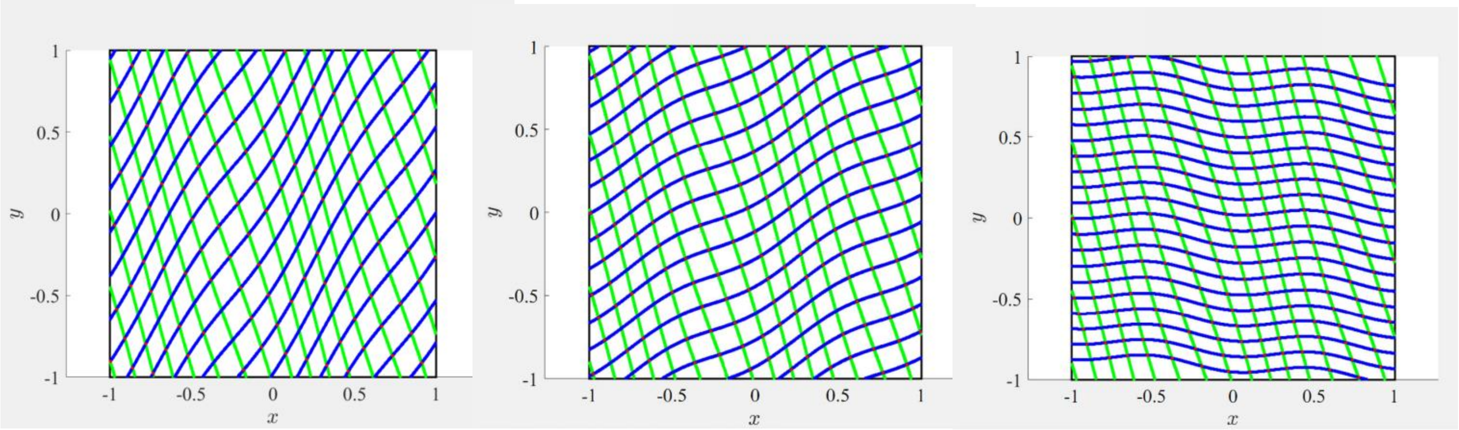
- Reflected tower edge shows warping of mirror surface
  - One reflection line -> one dimension of information





Two reflection lines needed to fully characterize mirror surface

- Error in calculation will be too great if difference between heliostat position is too small
- Used simulated reflection lines to find useful range of positions

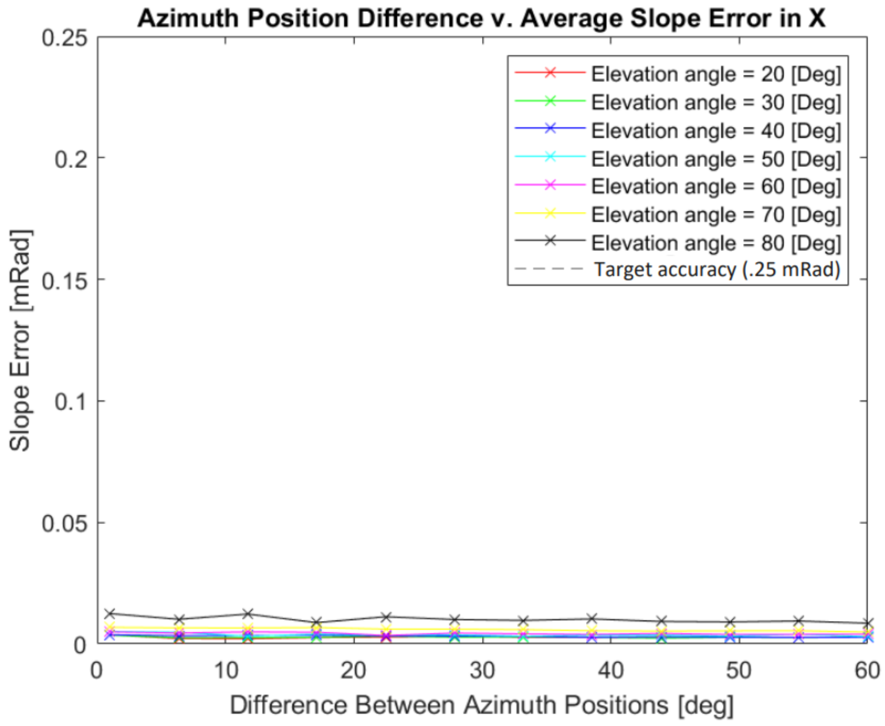


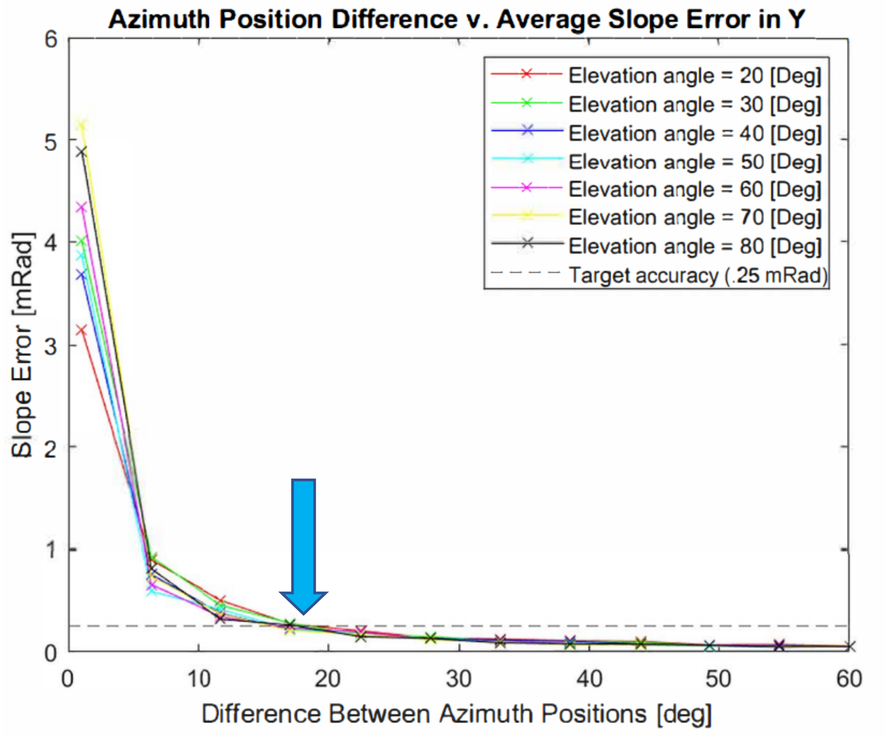
NIO Slope Error Sensitivity Analysis

Gabriel Shuster

Reflected lines are mostly vertical -> more information is known in the x-dimension

- Smaller error values in x-dimension
- Larger error values in y-dimension





As difference between azimuth angle increases the error in Y becomes smaller

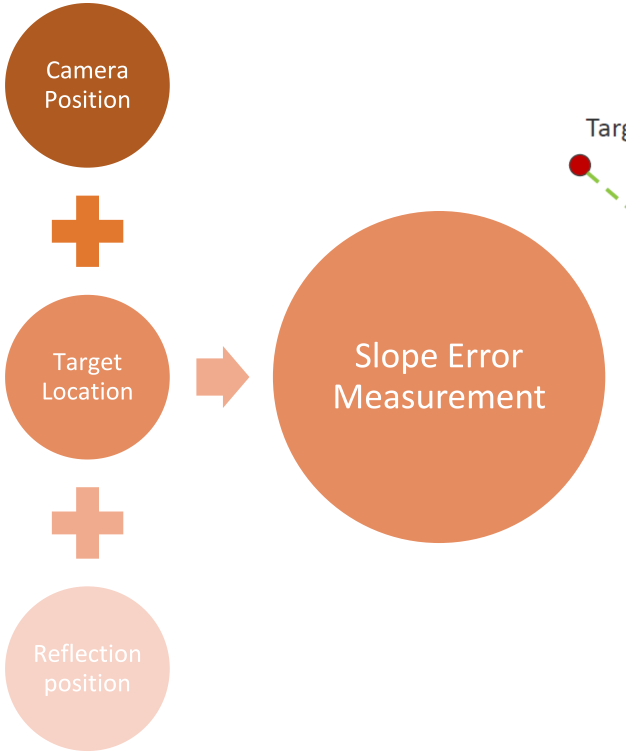
- The minimum difference between azimuth angles is 19 degrees
- Elevation angle has little effect on slope error

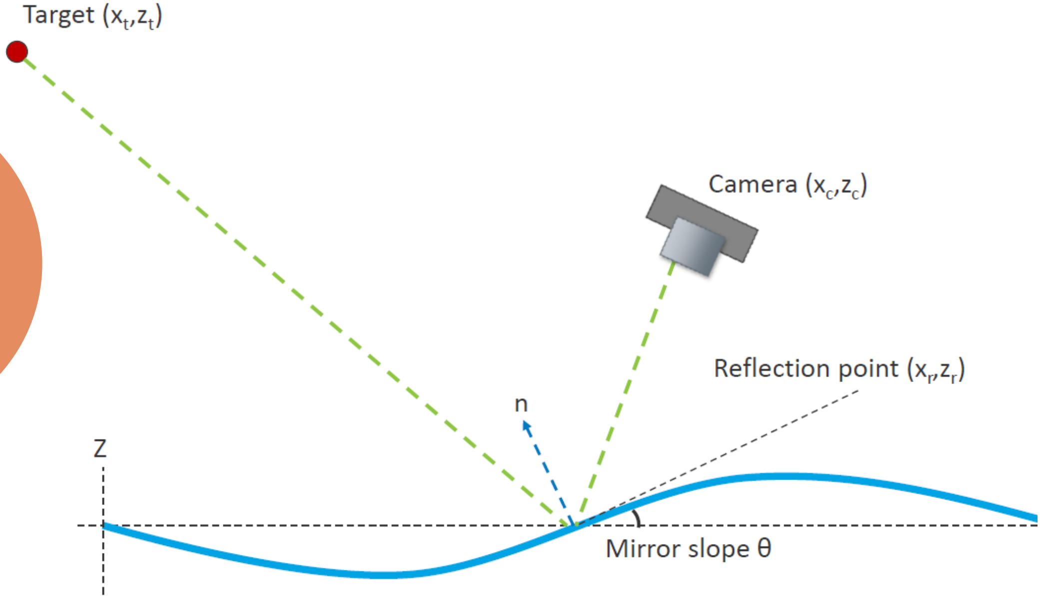
Laboratory Non-Intrusive Optical(NIO) Technology Development

Mojolaoluwa Keshiro

- Joined at the post-software development stage

- Moving to python
- More Image tests
- Sensitivity Studies

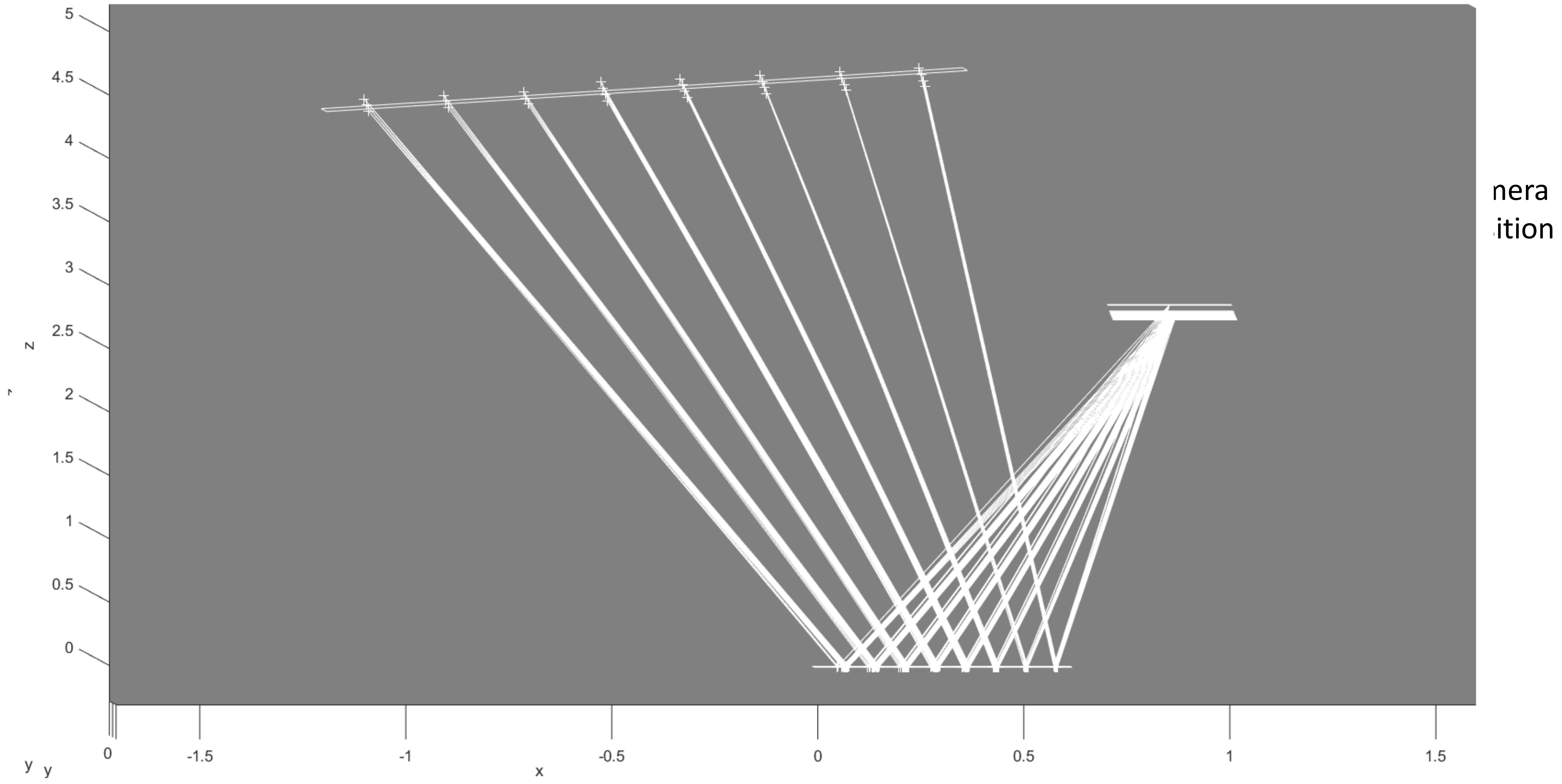




More parameters depend on these too

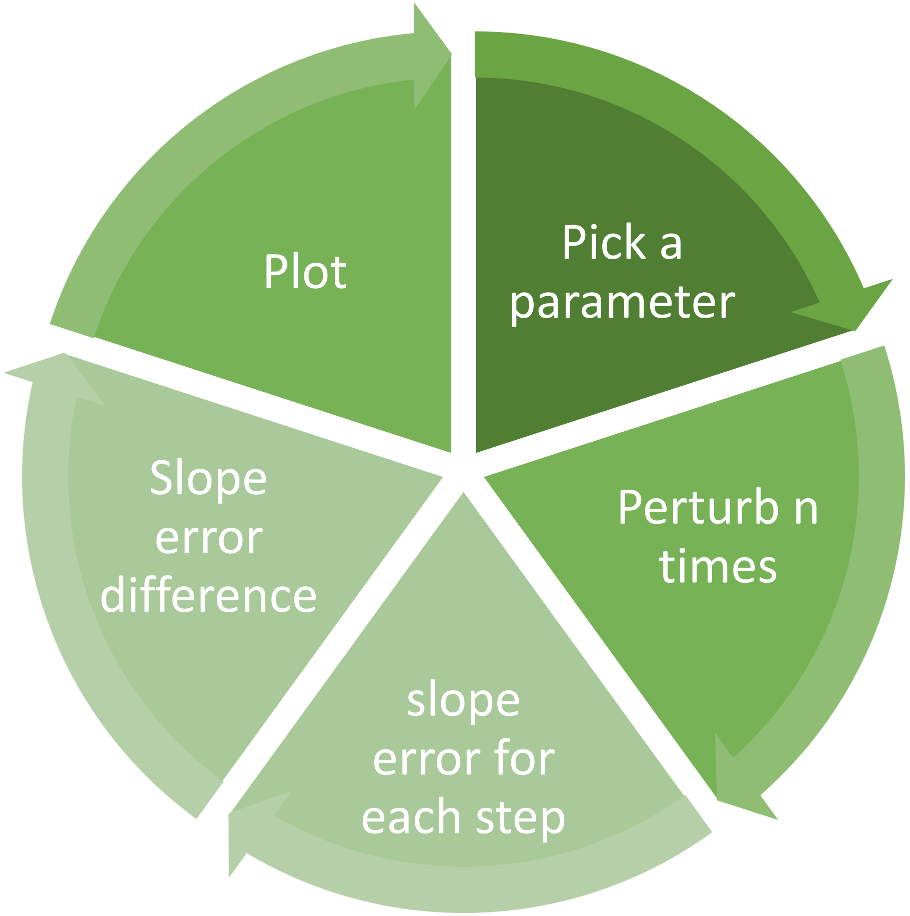
Mojolaoluwa Keshiro

Setup Visualization



Sensitivity Analysis

Mojolaoluwa Keshiro



Major Results

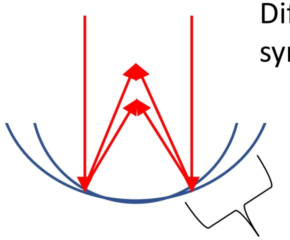
Maximum Uncertainty Values to reduce errors to 0.25 mrad maximum

Perturbed Parameter	Allowable Uncertainty	Usual Uncertainty
Heliostat corner	0.005m	0.003
Camera position	0.006m	0.15 *using initial method
Target points position	0.006	0.00039
Reflected points	3.2 pixels	<1

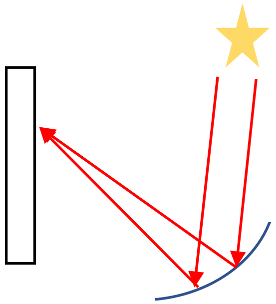
Fixed Shape Optimization of Heliostat Mirror

Maggie Kautz

- **Power tower plant**: a field of mirrors, heliostats, **concentrate sunlight** onto a central tower that has water or sand running through it as the medium for driving a heat engine.
- Efficiency needs to be increased.
- The goal of this project is to determine the **optimal fixed shape** of a heliostat mirror that will yield the highest **intercept factor** on the power tower throughout a given day and ultimately throughout a year.

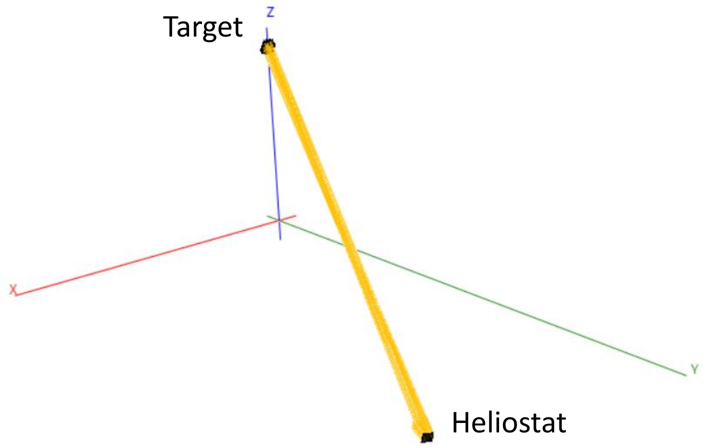


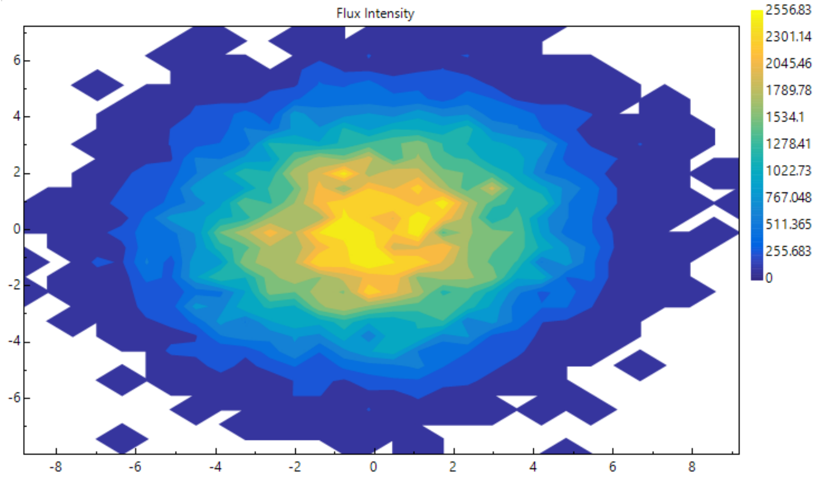
Different focal length symmetric parabolas



Off-axis parabolas for off-axis light

$$IF = \frac{Power\ intercepted\ by\ target}{Power\ incident\ on\ heliostat}$$





HelioCon Resource, Training, and Education (RTE) Group

Mackenzie Dennis

Heliostat Education and Reference Library

Gabriel Shuster

Website Structure, DEI, and Available Resources

Raven Barnes

Standards and O&M Best Practices

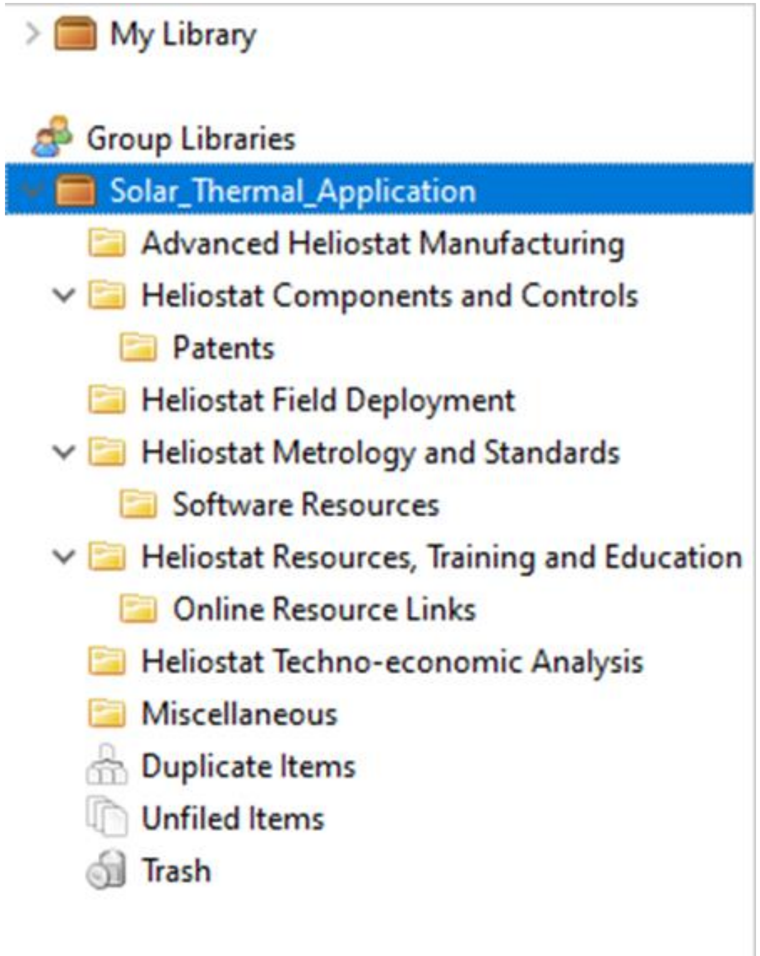
Mojolaoluwa Keshiro

Social Media

HelioCon: RTE Database Development

Mackenzie Dennis

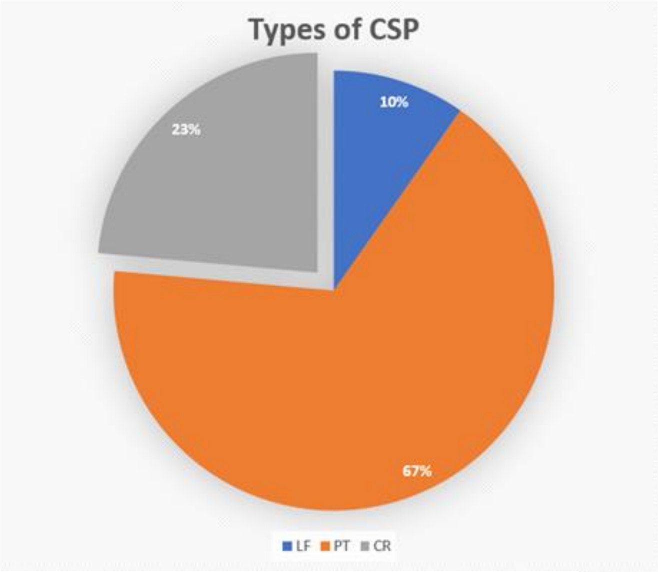
- Central database: currently in Zotero
  - Over 1000 resources
  - Searching, sorting, topic areas
    - Easy citations
  - Tutorial
  - HelioCon website: Resources content (Gabe)
- Other resources
  - Intro videos
  - Useful images
  - Online resources

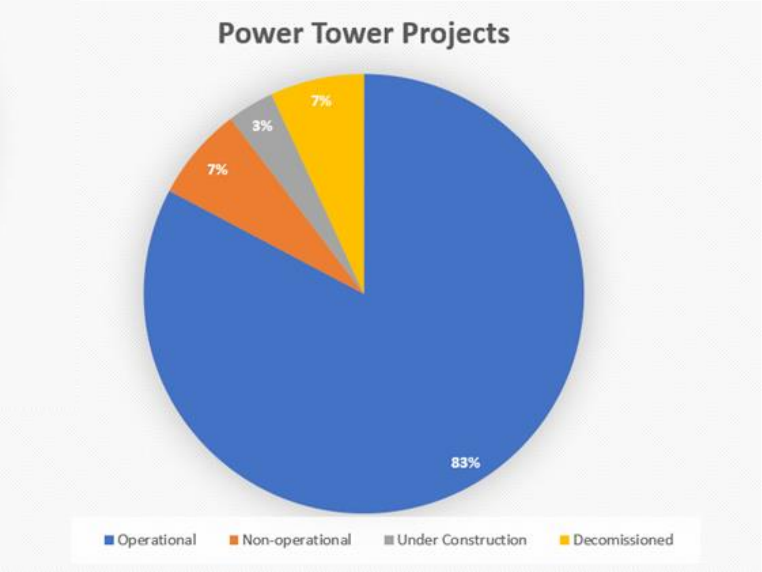


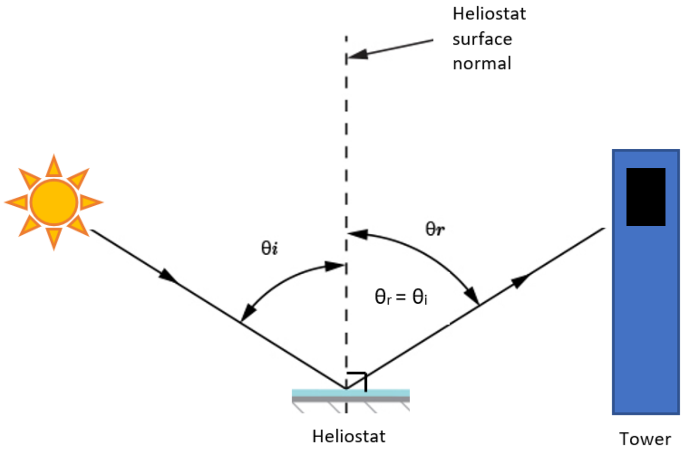
HelioCon: RTE Materials

Mackenzie Dennis

- Literature review and paper
- "An Overview of Heliostats and Concentrating Solar Power Tower Plants"
  - March 2022
- Basics and overview of advanced topics
- Condensed resources for each topic



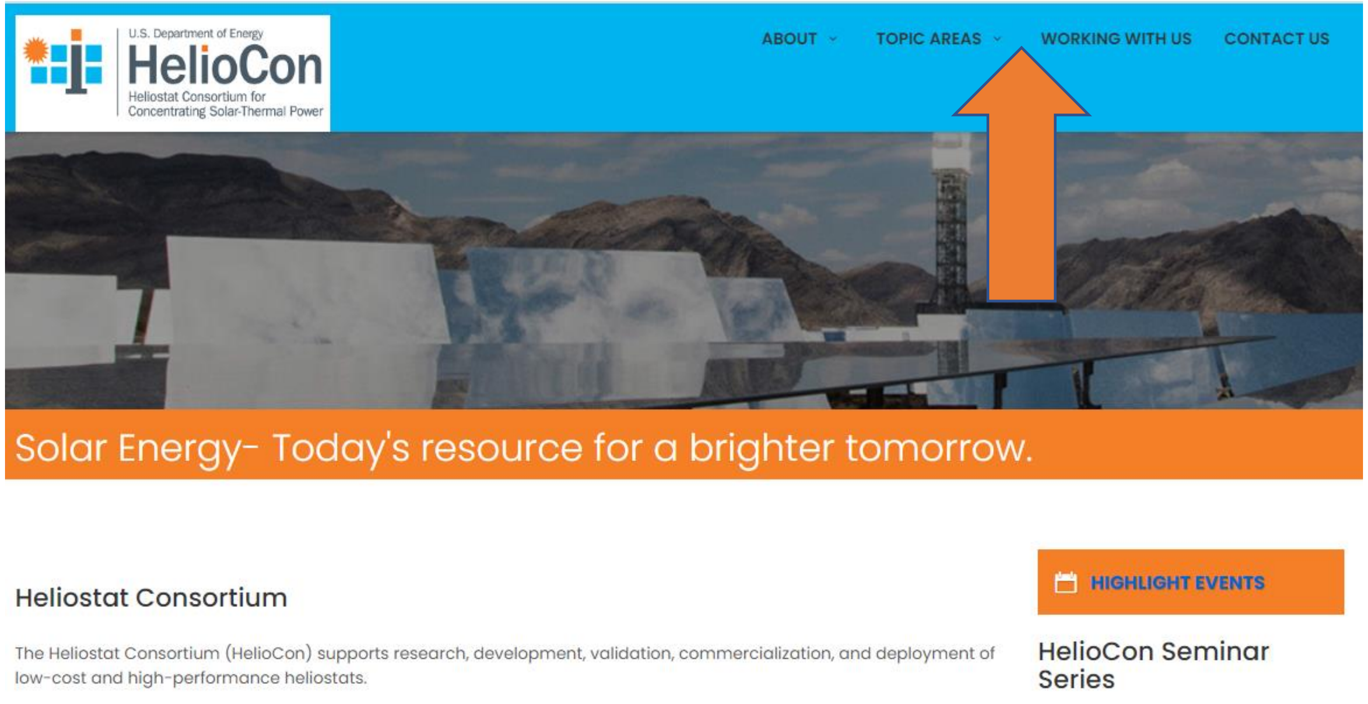




Public Resources for CSP Understanding

Gabriel Shuster

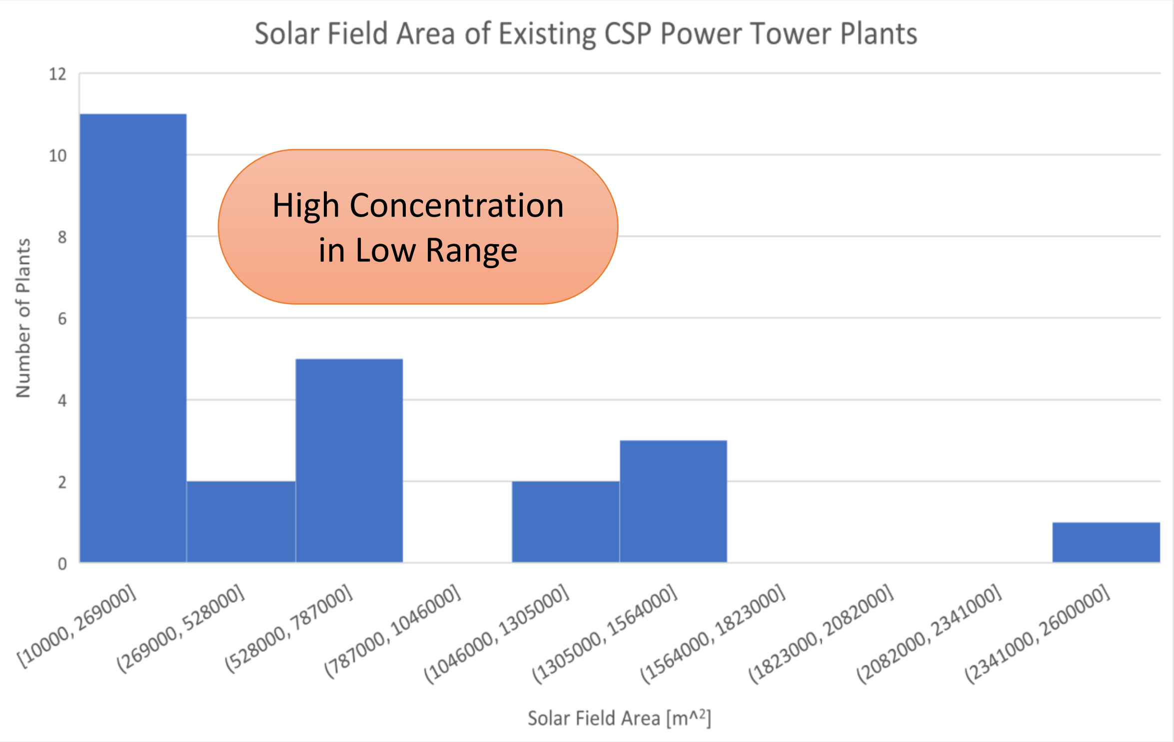
- Created structure for the Resource section of the HelioCon Website
  - Place for people to learn about CSP and heliostats
  - More knowledgeable workforce
  - Lower costs associated with training staff
- Publicly available resources
  - Overview paper
  - Available Software: DelSol, SolTrace, SAM, NIO, etc.
  - Zotero library



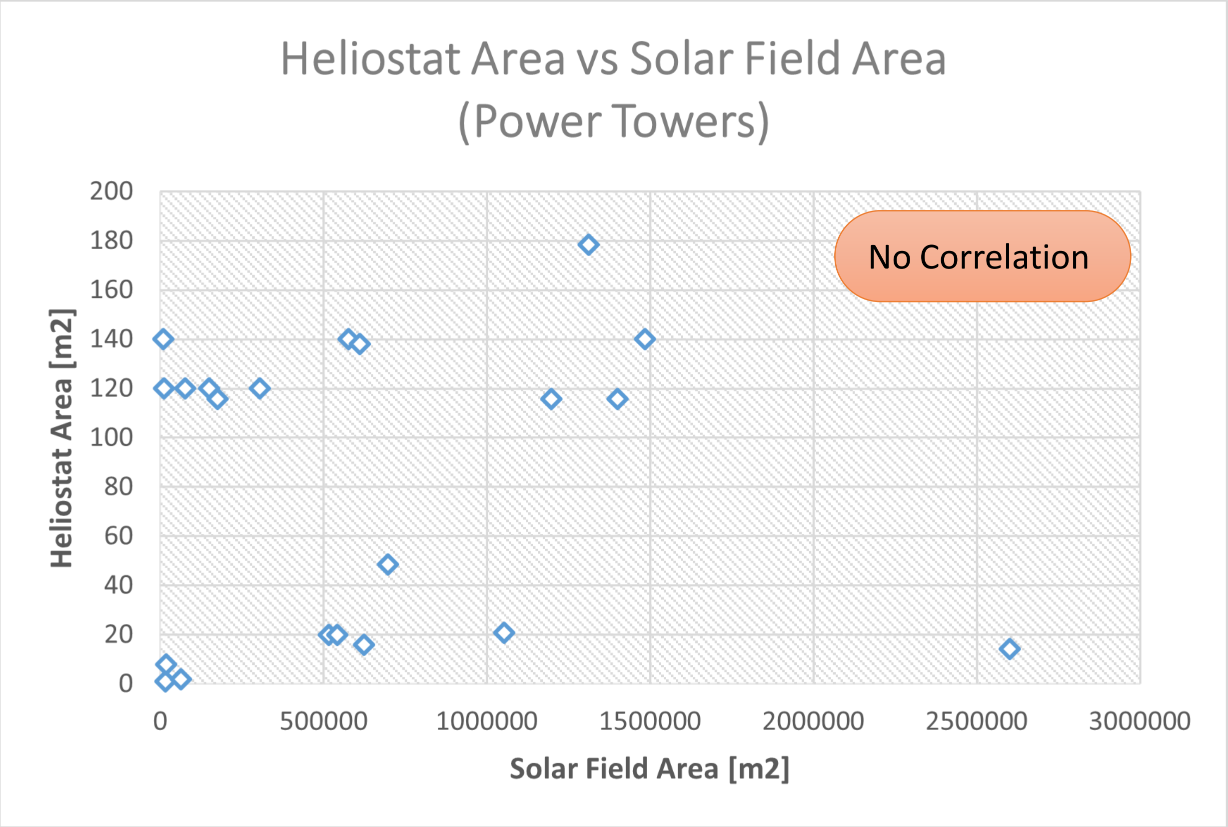
- Diversity, Equity and Inclusion
  - Comprehensive plan in RTE section
  - Incorporate in every aspect of HelioCon
- Industry standards and O&M
  - List of current standards
  - Best practices of current CSP plants

Resource Database Information Compilation

Gabriel Shuster & Raven Barnes



- Database of general information on CSP tower plants
  - Developed with SolarPaces and literature review
  - Zoterro Resources



- Compilation of general/best practices related to the O&M of CSP tower plants
  - Best Practices report by NREL
  - Roadmap report by HelioCon
  - Interviews with industry professionals in CSP tower plants

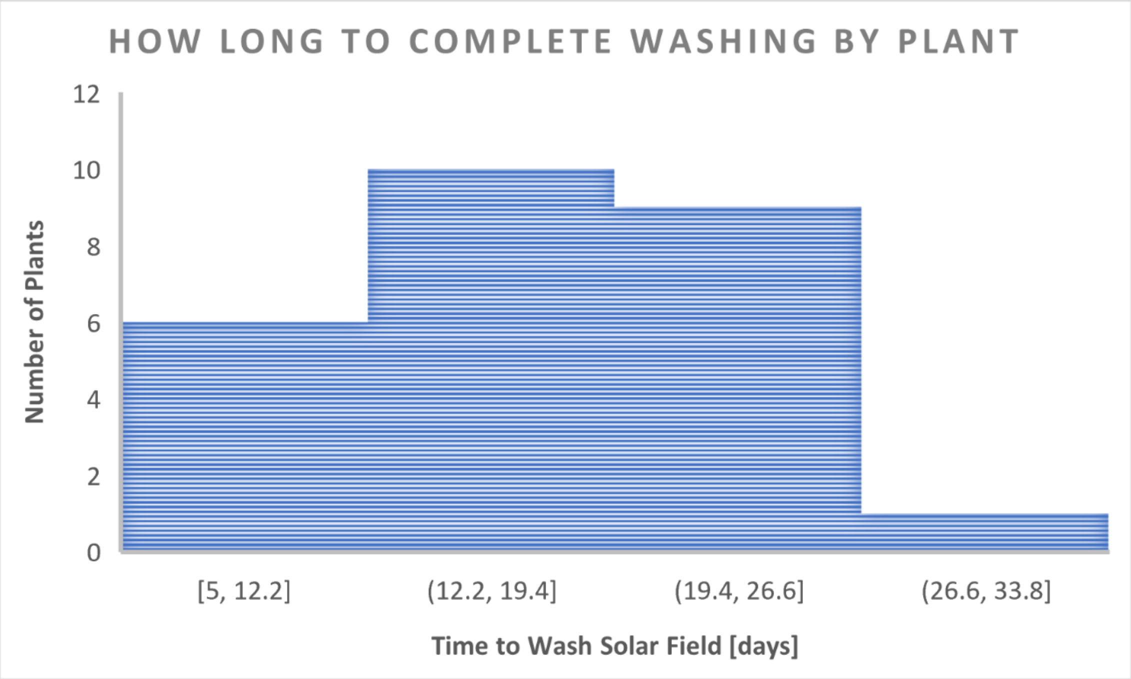
Survey of Industry Professionals

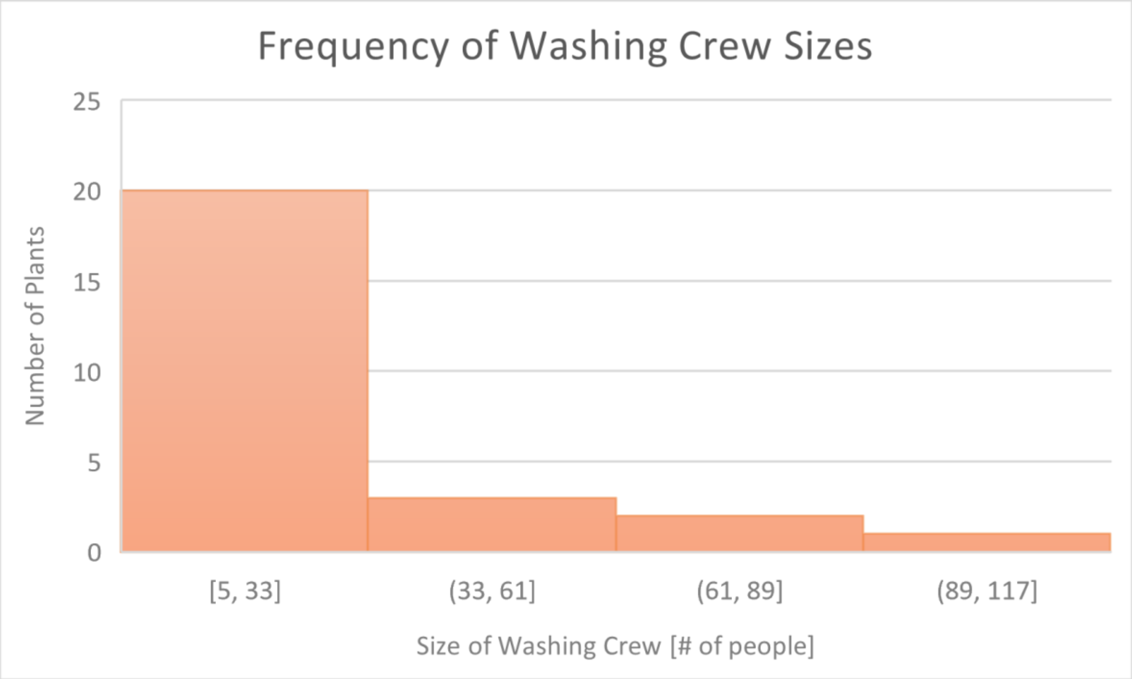
Raven Barnes

Survey developed using O&M database

- Staffing
- Washing
- Calibration
- Vegetation Control
- Equipment Malfunction
- Soiling
- Extreme Weather
- Wind Speeds

Survey is currently being broadened to include questions by other HelioCon task groups of the roadmap report





HelioCon Social Media CSP Education

Moj

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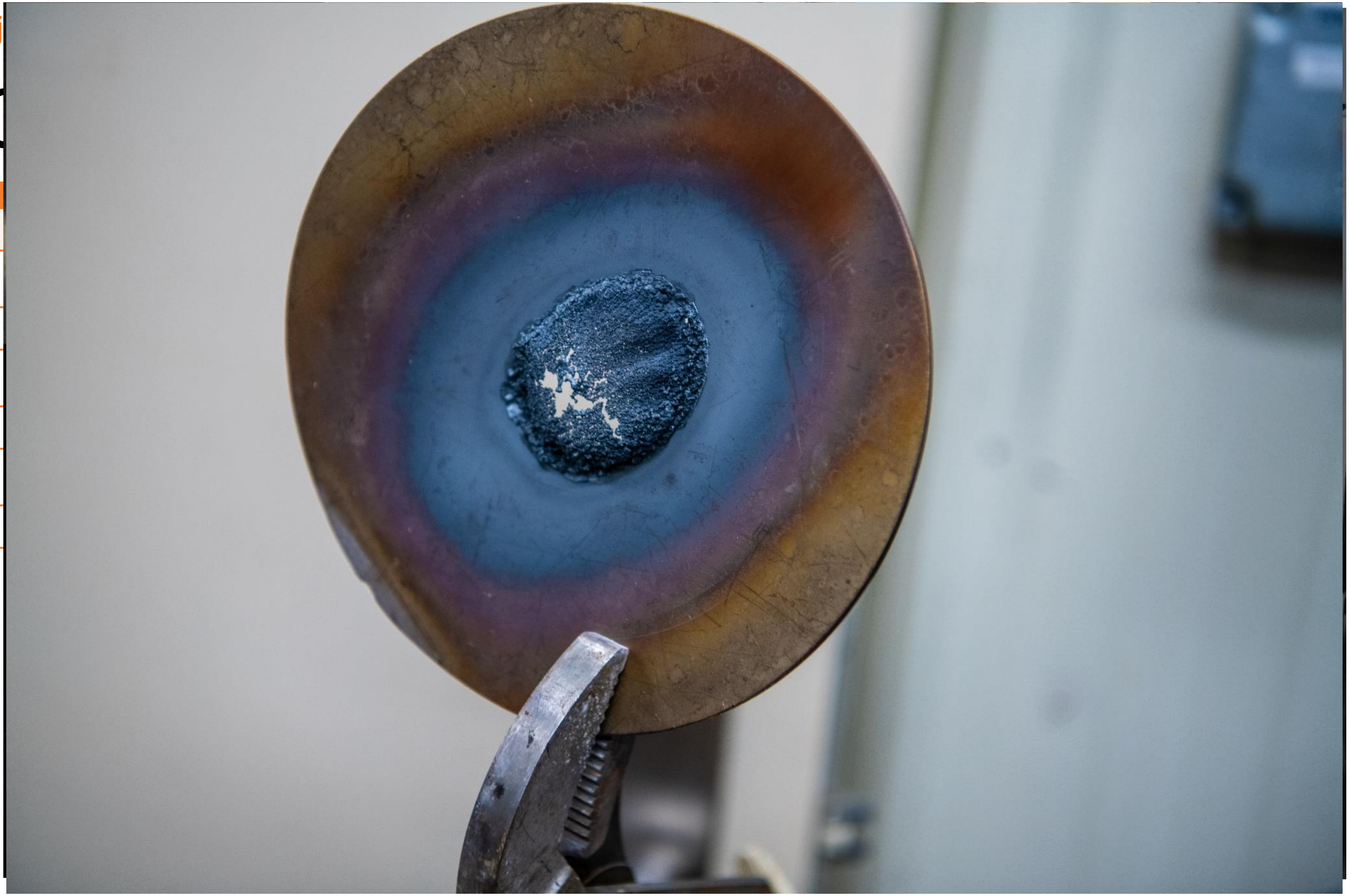


conceptual design • components • integration • mass production • heliostat field

Intern Projects at Sandia National Laboratories (SNL)

Sandia National Laboratories

Felicia Brimigion, SNL
Mentor: Dr. Randy Brost

Natalie Gayoso, SNL
Mentor: Dr. Ken Armijo

Dimitri Madden, SNL
Mentor: Dr. Ken Armijo

SOFAST Interactive CAD Tool

Felicia Brimigion

Sandia National Laboratories

SOFAST is a Sandia tool for precise CSP mirror measurements.

We have created a SOLIDWORKS interactive SOFAST tool to aid in the visualization of the SOFAST testing setup and environment.

This tool allows the user to not only visualize their setup in their space, but to also assess what equipment and their sizes can or cannot be used in their desired space.

- Ex: screen size, type of projector and lenses, camera lens, and their positions necessary to execute the test accurately
- Ex: what mirror sizes are possible

The tool allows the user to adjust the model to visualize the correct positioning required of projector, mirror, and camera in order to work effectively in their space/environment.

The model is built to automatically update the mirror's reflection accurately according to Snell's law when adjusting either the mirror's or camera's angles and positions.

This allows the user to solve for three distinct cases:

1. known mirror, unknown environment
2. known environment, known mirror, unknown mirror placement
3. general purpose instrument optimal design (see figs 3 and 4)

The interactive SOFAST tool has been used to design 8 test setups to date.

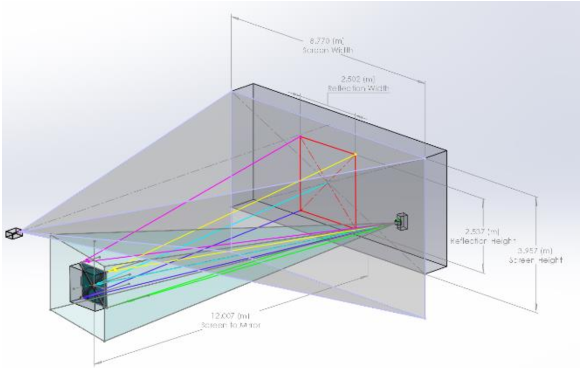


Figure 1 – Generic SOFAST interactive tool

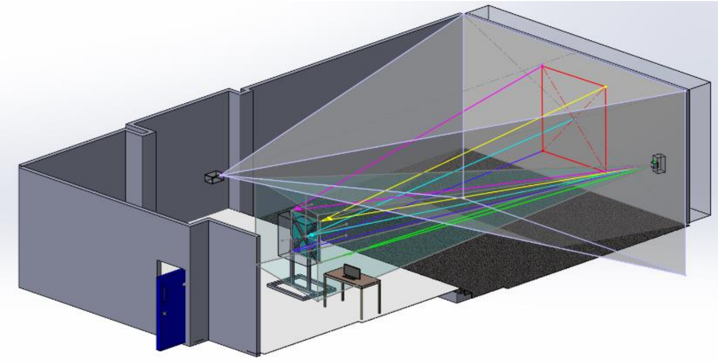


Figure 2 – SOFAST 1 setup in Optics Lab

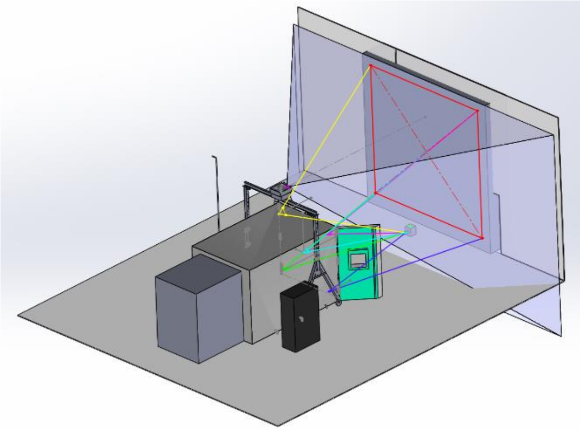


Figure 3 – Temperature Chamber testing environment

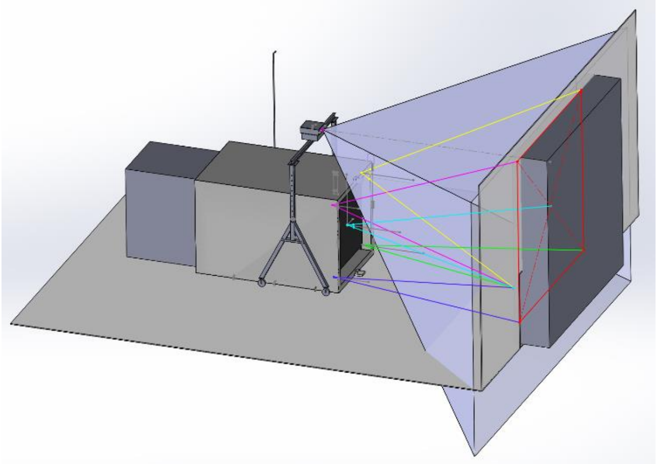


Figure 4 – Front view of temperature chamber, mirror can be seen in the opening of the chamber

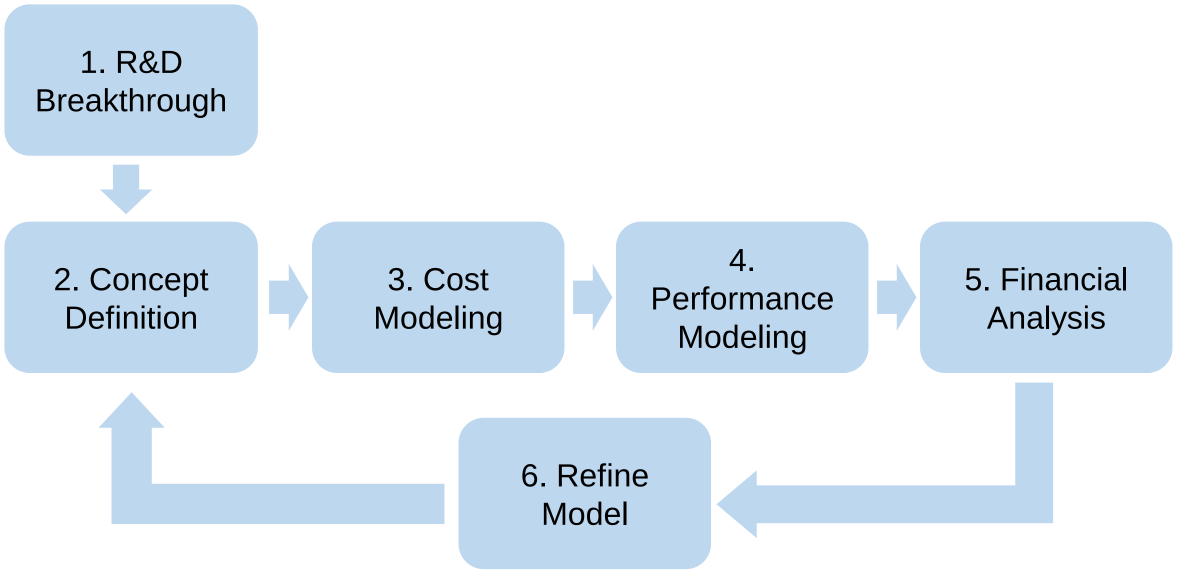
HelioCon: CSP Techno-Economic Analysis Modeling

Sandia National Laboratories: Natalie Gayoso

Objective: Compare and contrast methodologies and data sources for modeling heliostat fields. Use results to develop preferred methods, improve data sources, and attempt to answer fundamental questions about CSP heliostat field design and performance

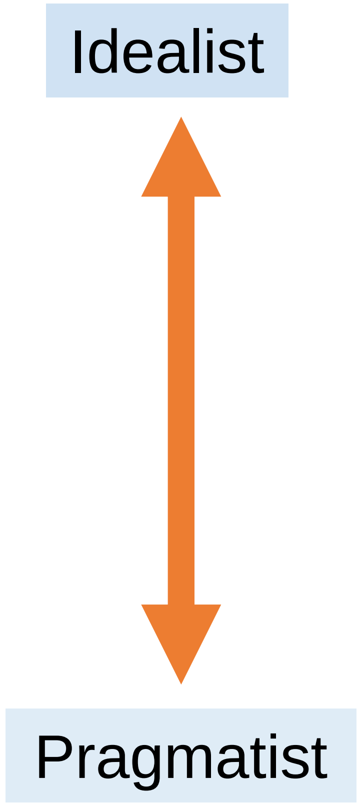
What is Techno-Economic Analysis (TEA)?

Identifies economic feasibility and sustainability of a new technology by analyzing costs, benefits, and uncertainties in scaling up a system.



Why do we do TEA?

Sandia National Laboratories: Natalie Gayoso



- Maximize the impact of your research by identifying important cost/benefit drivers
- Establish a common language between industry and researchers
- Differentiate yourself by demonstrating the knowledge and desire to commercialize
- A customer or reviewer asks for a "TEA"

Initial Literature Review Results

Sandia National Laboratories: Natalie Gayoso

	150 m² SM [1] ($/m²)	148 m² ATS [1] ($/m²)	48.5 m² Commercial [2] ($/m²)	27 m² Advanced [2] ($/m²)
Mirror Module	42.99	23.06	17.00	15.88
Support Structure	19.08	21.21	19.96	11.12
Drive	26.67	27.11	16.08	16.36
Drive electrical	1.76	1.78	7.98	6.00
Controls	1.87	1.94	14.43	6.74
Pedestal	16.73	16.96	6.79	8.11
Total Direct Cost	109.11	92.06	82.24	64.21
Overhead/Profit (20%)	21.82	18.41		
Total Fabricated Price	130.93	110.47	82.24	64.21
Field wiring	7.30	7.40	9.01	9.46
Foundation	2.30	2.28	5.15	6.01
Field alignment	2.41	6.34		
Rotation Assembly			12.19	7.08
Site labor			16.39	7.79
Transportation			2.29	1.37
Total Installed Price	**142.90**	**126.50**	**127.27**	**95.92**

Table 1. Heliostat cost breakdown of four heliostat scenarios: Stretch Membrane (SM), Advanced Thermal System (ATS), Stelio Commercial, and SunRing Advanced heliostats, respectively

Key Takeaways:

- There is potential to reduce cost by downsizing the heliostat aperture area
- There are a number of drivers favoring smaller heliostats that can be identified using TEA and can guide design direction throughout the entire development cycle of CSP

References:
[1] Kolb et al. (2007). Heliostat Cost Reduction Study.
[2] Kurup et al. (2022). Cost Update: Commercial and Advanced Heliostat Collectors.

Important Challenges

Sandia National Laboratories: Natalie Gayoso

Analyze cost parameters further, such as:

- Levelized Cost of Energy
- Levelized Cost of Heat
- Levelized Cost of Optics
- Levelized Cost of Coatings

Explore open-source TEA tools to model CSP tower plants

- System Advisory Model (SAM)
- SolarPILOT
- SolTrace
- SolarTherm

Objective: Develop heliostat field, tower, and receiver model for industrial process heat application

Heliocon: Components and Controls

Dimitri Madden

National Solar Thermal Test Facility (NSTTF)

NSTTF of Sandia National Laboratories is the only CSP test facility of its kind

- The NSTTF has been at the forefront of CSP for 40+ years
- Combined with our collective experience, we performed an extensive review of historical, existing, and cutting edge heliostat technology
- We have identified standards, heliostat components, and control systems that could all be improved to reduce heliostat cost and improve efficiency

Intern Projects at the Department of Energy's (DOE) Solar Energy Technologies Office (SETO)

Nicole Piatko, DOE
Mentor: Andru Prescod

Heliostat Drives and Opportunities for Cost Reduction: Objectives

Nicole Piatko

- Define the characteristics necessary for a heliostat drive
- Review the state of the art for heliostat drives
- Describe the obstacles in drive development
- Explore cost reduction opportunities for drives

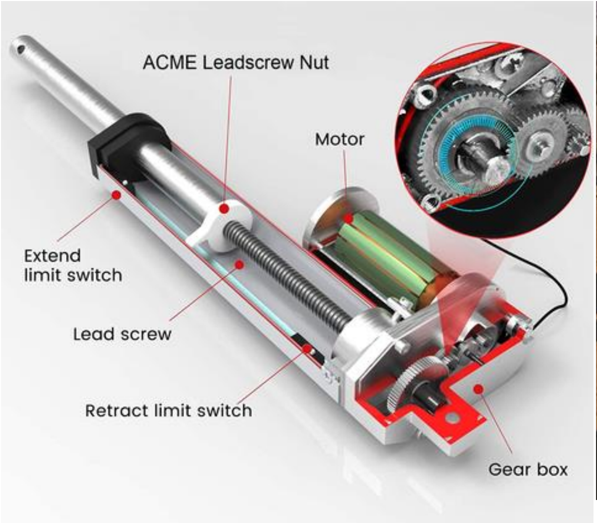
Drive Requirements

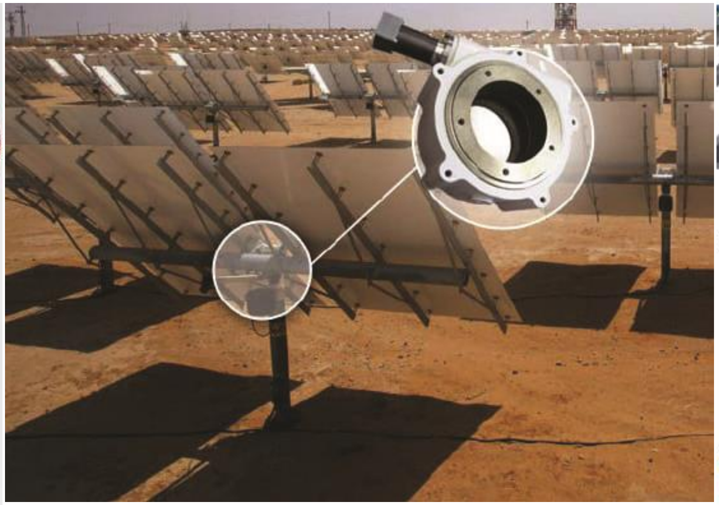
Nicole Piatko

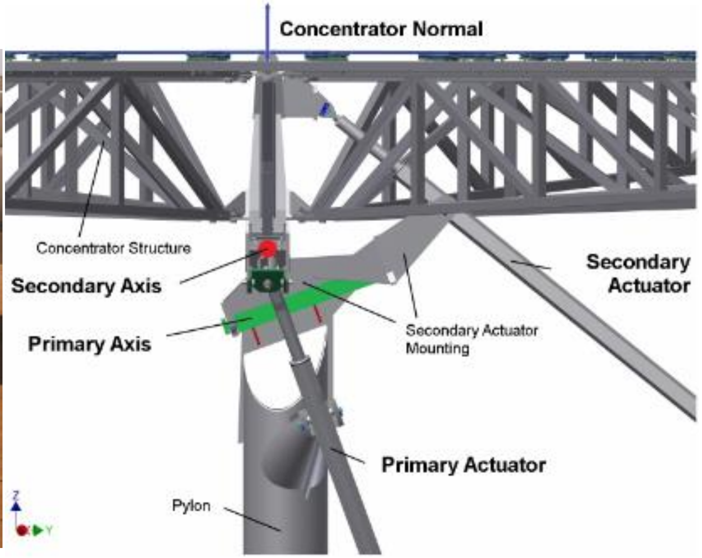
- High reduction ratio
- No back driving, self locking
- Static and dynamic torque
- Low backlash of less than 0.5 mrad
- High pointing accuracy
- Lifetime of 30 years with low maintenance

The State of the Art

- Azimuth-elevation
  - Worm gear for azimuth
  - Linear actuator for elevation
- Linear drive system
  - Two linear actuators







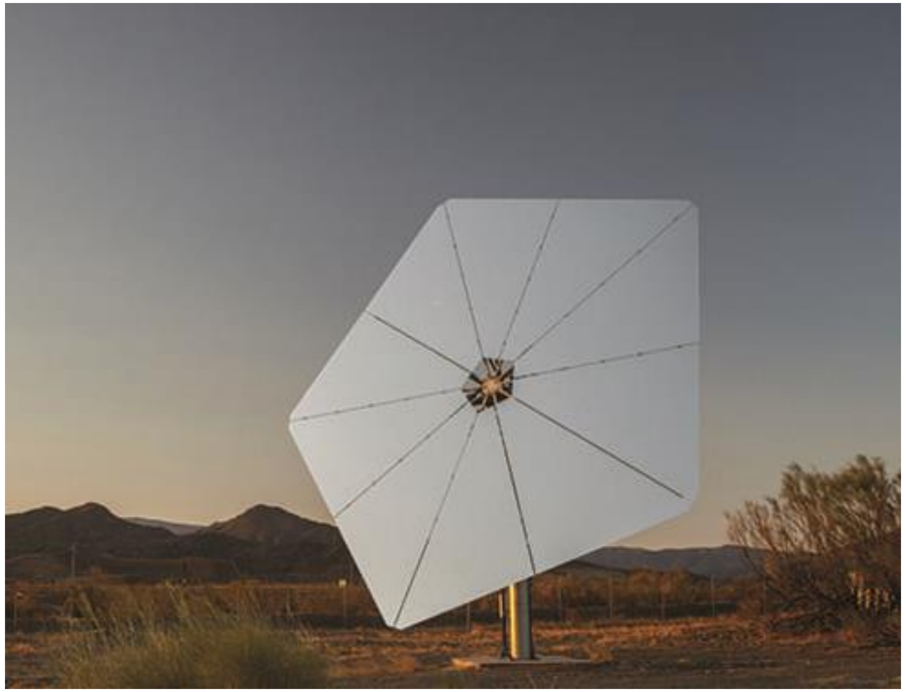
ASTRI Heliostat Cost Down Scoping Study – Final Report (ASTRI 2014)
Double Enveloping Worm Gear | Worm Drive Gear | Cone Drive
Linear Actuators 101 - How does an Actuator work | FIRGELLI (firgelliauto.com)

Worm Gear Technology Helps CSP Plant Stay Locked on Target (powermag.com 2019)
Heliostat field cost reduction by ‘slope drive’ optimization (Arbes 2016)

The obstacles

Nicole Piatko

- High cost of material, parts, and manufacturing
- Lack of standard methods or specifications for testing



Opportunities for cost reduction

- Heliostat developers choosing linear drive systems
- Decreasing the cost of manufacturing by creating a supporting heliostat industry
- Funding research into drive testing and drive development

Recommendation

- Research and development into a specific heliostat mirror area size range to create focus on standardization and development of heliostats in industry

Thank You Mentors!

Dr. Ken Armijo, SNL

Dr. Randy Brost, SNL

Mackenzie Dennis, NREL

Tucker Farrell, NREL

Devon Kesseli, NREL

Dr. Rebecca Mitchell, NREL

Dr. Matt Muller, NREL

Andru Prescod, DOE

Dr. Gaungdong Zhu, NREL

Dr. Alex Zolan, NREL

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 5**, applications for summer due **Jan 10**
- 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 now available on the NREL YouTube learning channel: https://www.youtube.com/playlist?list=PLmIn8Hncs7bGAK-hIf4qxuAbHUHK-xgZK
- Slides and flyers available here: https://drive.google.com/drive/folders/1162LN82ImgurpCODnJDLKsERCWo-698R
- Subscribe to the seminar series or get in touch: heliostat.consortium@nrel.gov

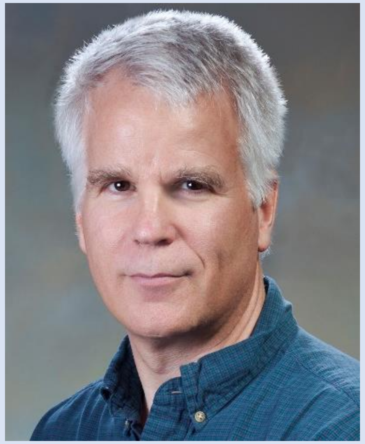
Next Seminar August 11th!

HelioCon Seminar Series: Advanced Manufacturing for Heliostats - What We Can Learn from Automotive Joining Technologies, Materials, and Automation

Speakers: Wagon Wills, Gonzalez Group | Dr. Randy Brost, SNL

When: 3-4 pm MDT Thursday August 11th

Zoom:https://nrel.zoomgov.com/j/1608929076?pwd=RStHcURySCtpRnVyYkgrKzBOTS81UT09



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- Subscribe to the seminar series or get in touch: heliostat.consortium@nrel.gov