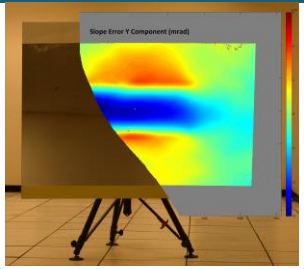
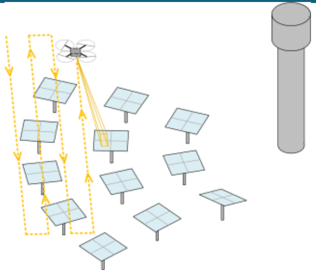
Sandia National Laboratories

Challenges and Solutions in Heliostat Optical Metrology





Randy C. Brost

September 27, 2023

U.S. DEPARTMENT OF ENERGY NNSA

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Overview

- Key Metrology Problems
- Complicating Factors
- State of the Art
- Metrology Gaps
- Emerging Solutions

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We thank:

SOLAR ENERGY TECHNOLOGIES OFFICE U.S. Department Of Energy

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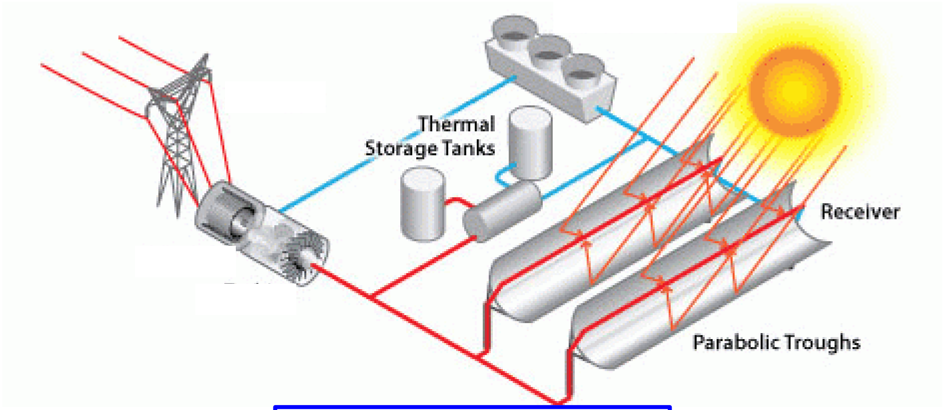
Sandia National Laboratories

LDRD LABORATORY DIRECTED RESEARCH & DEVELOPMENT

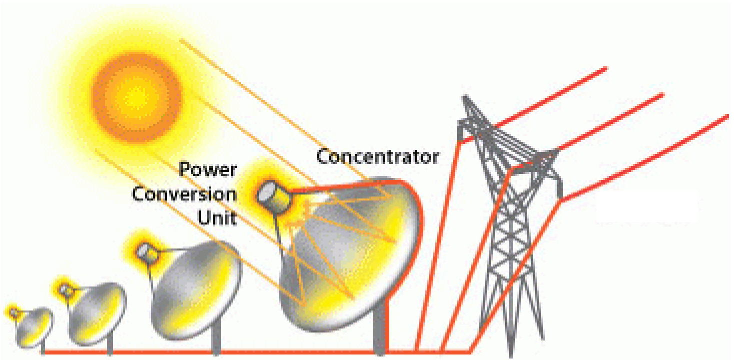
Why Heliostats?

Parabolic Trough[1]



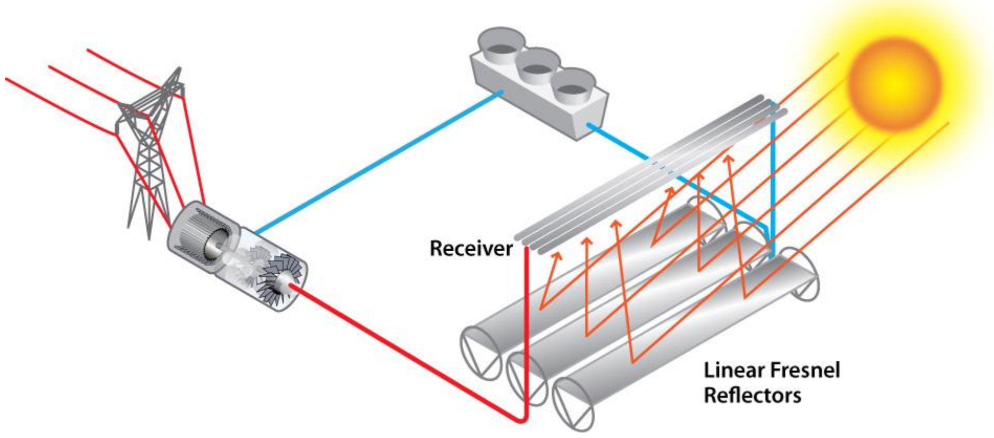
Medium Concentration

Parabolic Dish[2]



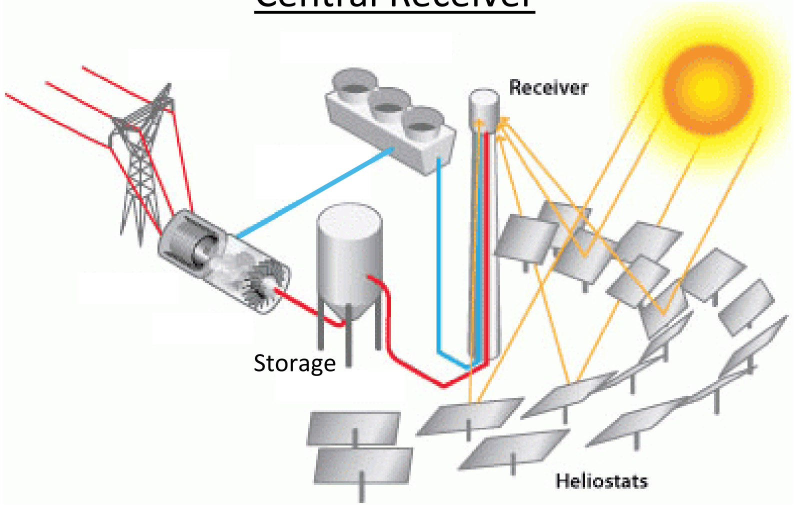
High Concentration, Limited Power

Linear Fresnel[3]



Medium Concentration

Central Receiver[4]

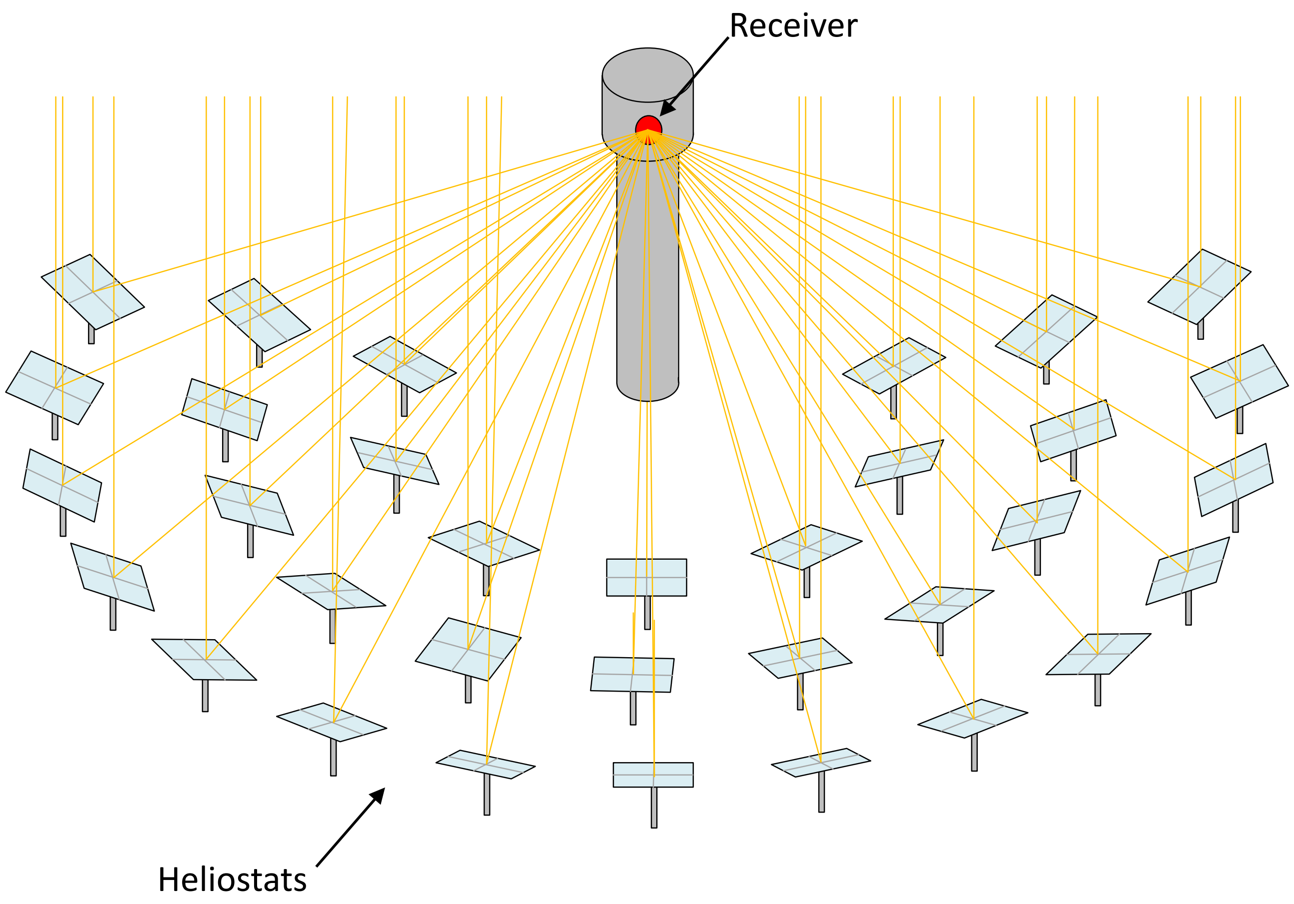


High Concentration, High Power

Only heliostats combine high concentration and high power.

[1] https://www.energy.gov/eere/solar/linear-concentrator-system-concentrating-solar-thermal-power-basics
[2] https://www.energy.gov/eere/solar/dishengine-system-concentrating-solar-thermal-power-basics
[3] https://www.energy.gov/eere/solar/articles/linear-fresnel-power-plant-illustration
[4] https://www.energy.gov/eere/solar/power-tower-system-concentrating-solar-thermal-power-basics

An Ideal Heliostat Field



No Error
Heliostats produce tight beams.
All focus on desired target.

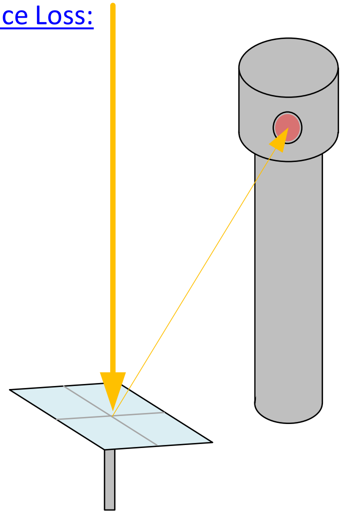
⇒ High Temperature (T > 1000 °C)
High Power ($P > 100\ MW_{th}$)

Consequences of optical error:

- Directly reduce temperature and power.
- Spillage can cause damage.
- Unpredictable hot spots, leading to either (a) damage or (b) conservative operation.

Errors Reducing Heliostat Performance

Reflectance Loss:

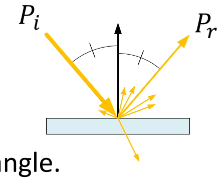


Soiling or degradation causes loss of reflectance.
Power is reduced.

Measure:

- Specular reflectance:

$$\rho = \frac{P_r}{P_i}$$

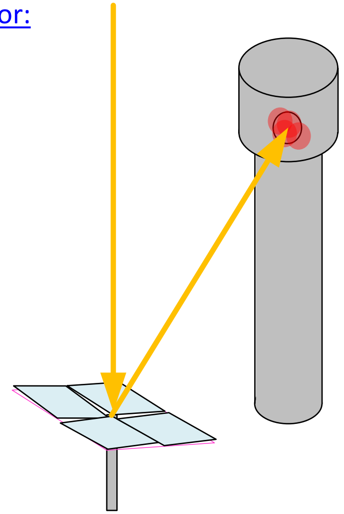


- Varies with incidence angle.
- Varies with wavelength.
- **Varies with time, plant location.**

Corrective actions:

- Wash mirrors – when?
- Replace degraded mirrors.

Slope Error:

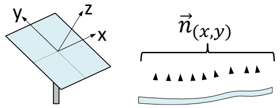


Slope error causes irregular, defocused beam.
Power is not focused in expected location.

Measure:

- Optical slope:

$$f(x,y) \rightarrow \vec{n}_{(x,y)}$$

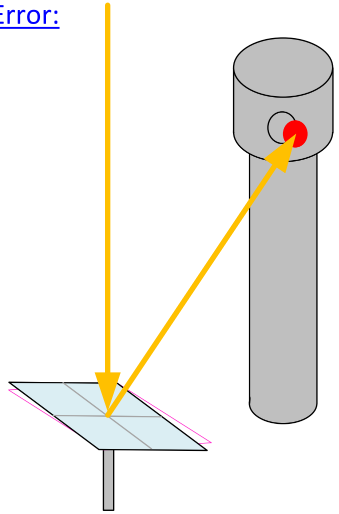


- **Varies with configuration, temperature.**

Corrective actions:

- Design refinement.
- Manufacturing control.
- In-field maintenance (rare).

Pointing Error:

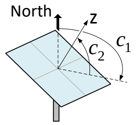


Pointing error causes beam to miss target.
Power is not in expected location.

Measure:

- Correction function:

$$f(c_1, c_2) \rightarrow [\Delta c_1, \Delta c_2]$$

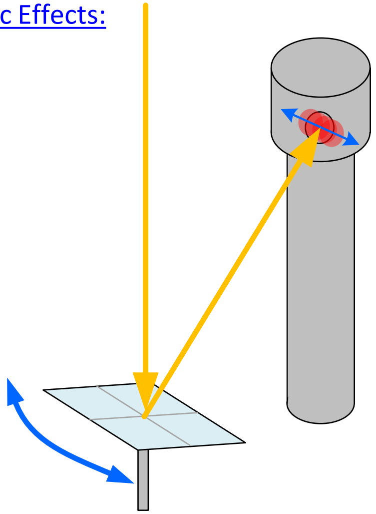


- **For all sun positions in solar year.**
- Two flavors:
  - Offline calibration.
  - Real-time, during operation.

Corrective actions:

- Apply correction function via software control.

Dynamic Effects:



Beam oscillations due to wind or control.
Power location varies over time.

Measure:

- Shape variation with time.
- Pointing variation with time.
- Wind-induced: Flutter response.
- Self-induced: Control dynamics.

Corrective actions:

- Design refinement.
- Operation strategy.

Requirements:

- Measurement accuracy must be < 0.01° (< 0.15 mrad).
- Measurements must be in situ, daylight, high speed.

Key Questions

Material Design

Mirror optical properties?

Mirror durability?

Product Design

Prototype optical shape?

Prototype pointing accuracy?

Variation with conditions (range of motion, temperature,…)?

Process Design

Does product meet specified tolerances?

Process parameters to control?

Manufacturing

Does product meet optical tolerances?

Is the process starting to drift?

Field Installation and Commissioning

Optical change between manufacture and installation?

What corrections enable accurate pointing?

Operation

What is soil level? Does it vary across the plant?

Do any heliostats require adjustment or maintenance?

For a repaired heliostat, what adjustments are required?

All

Can we trust each measurement? How do we know they are accurate?

Requirements vary with development phase:

- **Product design:**
  High resolution
  All conditions (tilt, temp, wind)
  Low cost
  Available
- **Process design:**
  High resolution
  Support process optimization
  Available
- **Manufacturing:**
  High speed
  High reliability
  Factory-friendly
- **Installation:**
  Outdoors
  Both shape and pointing
  Accelerate calibration.
- **Operation:**
  Outdoors
  Non-intrusive
  Low cost

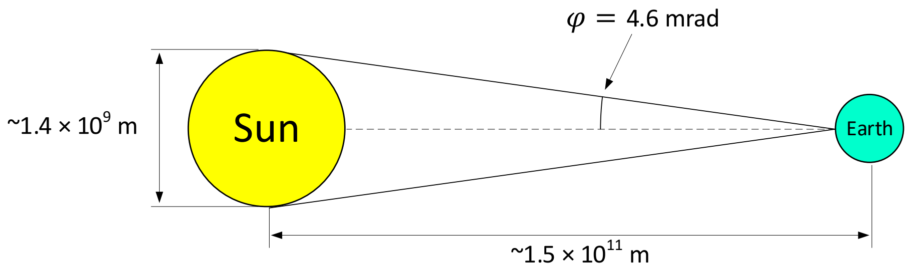
Related indirect question:

What do results imply for economic performance?

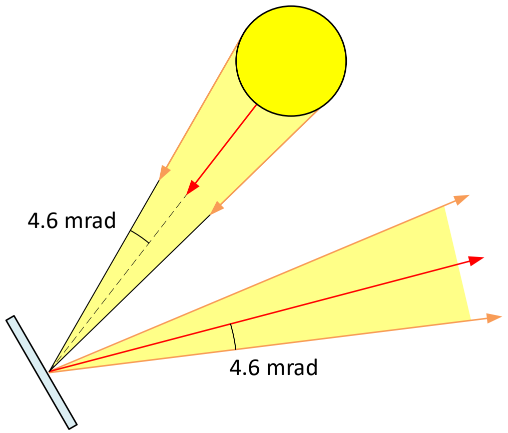
Complicating Factors

Sun Diameter

Sun is not a point source:*



Beam reflected from a point expands:

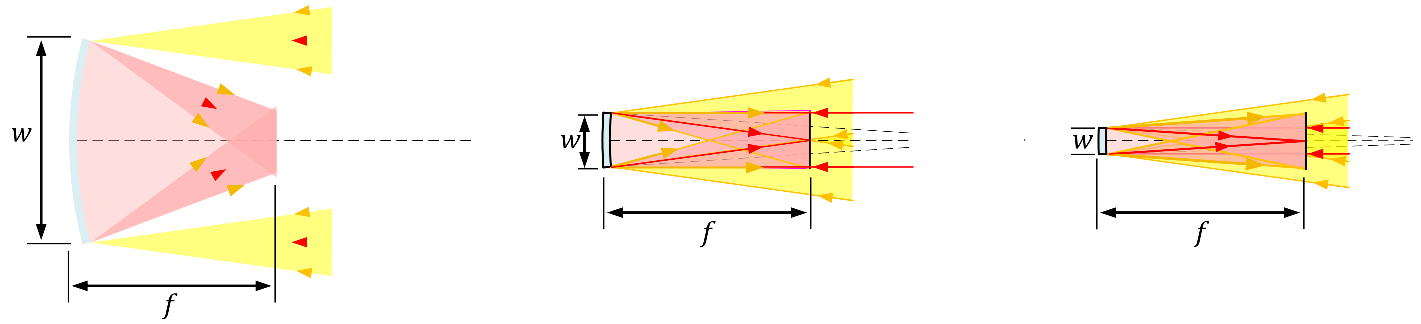


* Drawings exaggerate sun angle φ.

Beam from a heliostat expands or contracts based on w/f ratio:

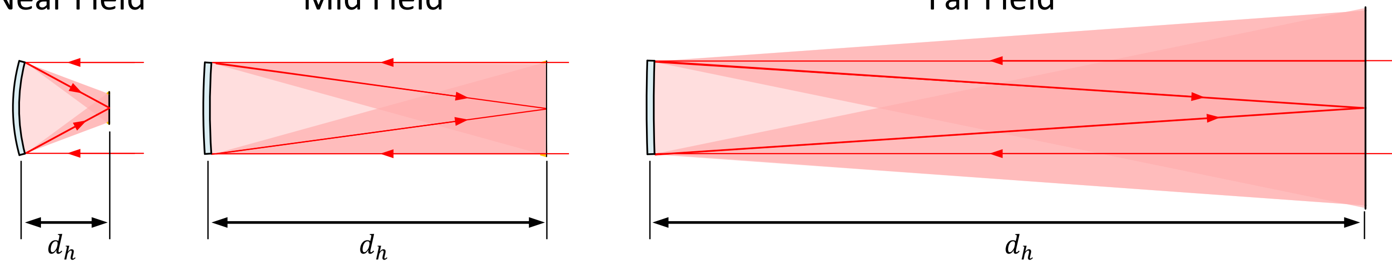
$\varphi = 4.6$ mrad

$$\frac{w}{f} > 4\tan(\varphi/2) \qquad \frac{w}{f} = 4\tan(\varphi/2) \qquad \frac{w}{f} < 4\tan(\varphi/2)$$



Contract | Break Even | Expand

BCS signal strength (BSS) decreases with square of distance to tower:



$$BSS = \frac{I_b}{I_s} = \frac{P_b/A_b}{I_s} = \frac{\frac{I_s A_h}{[d_h \tan(4.6\text{ mrad})]^2}}{I_s}$$

$$BSS \propto \frac{A_h}{{d_h}^2}$$

⇒ If BCS is used for calibration (see below), drives large heliostats for large plants. This in turn drives large row-to-row spacing, and increased wind load moments.

Notes

Regarding the beam expand/contract break-even threshold:

Beam shape expand/contract break-even analysis is an approximation that assumes sun, mirror vertex, and receiver are all on a common optical axis. This is almost never the case for real heliostats, which makes the expand/contract crossover analysis more complex. But the general principle still holds.

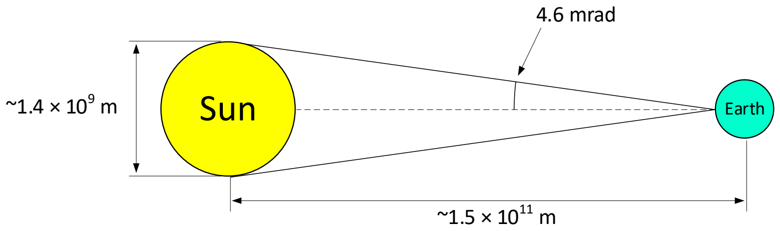
For simplicity, this analysis also assumes that the heliostat shape is well approximated by a sphere. This is a very good approximation for heliostats with high f/w ratios and no astigmatism. High f/w is typical for most heliostats, but some include astigmatism. Nonetheless, the general trend holds.

Regarding BCS signal strength:

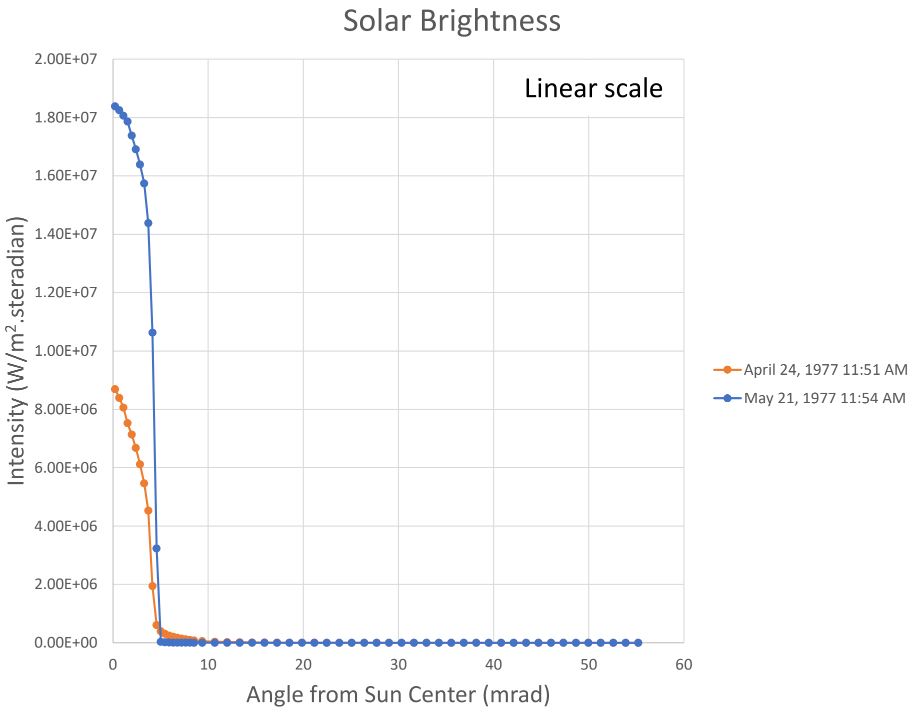
BSS	BCS Signal Strength: Beam irradiance on target compared to ambient irradiance
A_h	Heliostat aperture area
d_h	Distance from heliostat to tower
I_s	Solar irradiance intensity
P_b	Power of reflected beam, at the tower
I_b	Intensity of reflected beam, at the tower
A_b	Cross-section area of reflected beam, at the tower

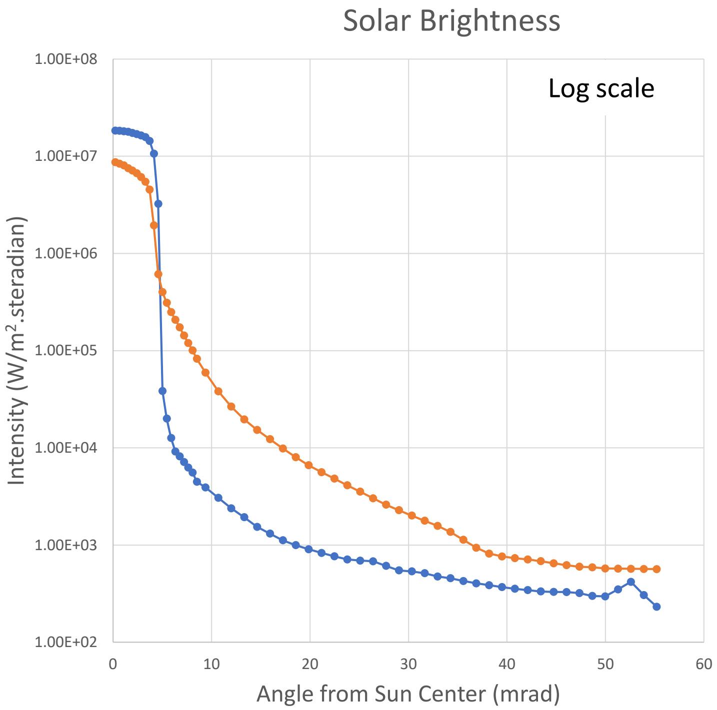
This simple derivation assumes a perfectly focused heliostat. If the heliostat is not perfectly focused, due to either error or sun incidence angle (see below), then the BCS signal strength gets worse.

Solar Brightness Profile



Sun edge is not sharp:





Location: Sandia NSTTF
Data collected by the Lawrence Berkeley Laboratory (LBL)
Available: https://www.nrel.gov/grid/solar-resource/circumsolar.html

From Noring, et al 1991:
"Circumsolar radiation is caused by forward scattering of light through small angles by particles (aerosols) in the earth's atmosphere with dimensions on the order of or greater than the wavelength of light. The aerosol particles may be composed of ice crystals or water droplets in thin clouds. They may be dust or sea salt particles, smoke or fumes, photochemical pollutants, sulfuric acid droplets, solid particles with a water mantle, flocks formed of a loose aggregate of smaller particles, or any of a large variety of solid, liquid or heterogeneous materials that are small enough to be airborne. The amount and character of circumsolar radiation vary widely with geographic location, climate, season, time of day, and observing wavelength."

From Noring, et al 1991:
"Pyrheliometers, the instruments normally used to measure the direct solar radiation, typically have a field of view of 5° to 6°. The pyrheliometer measurement includes a large portion of the circumsolar radiation and thus overestimates the amount of direct sunlight that would be collected by a concentrating system."

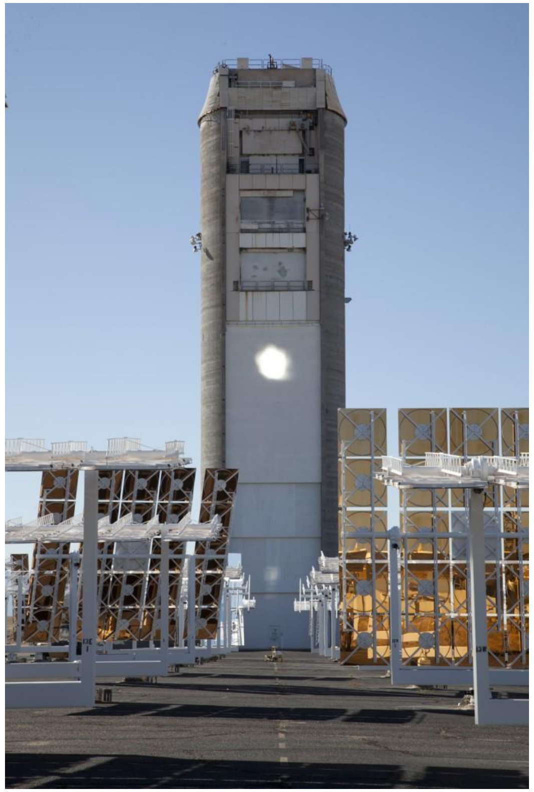
⇒ Weather station DNI measurements may overestimate solar resource unless pyrheliometer FOV is reduced.

Literature sources:

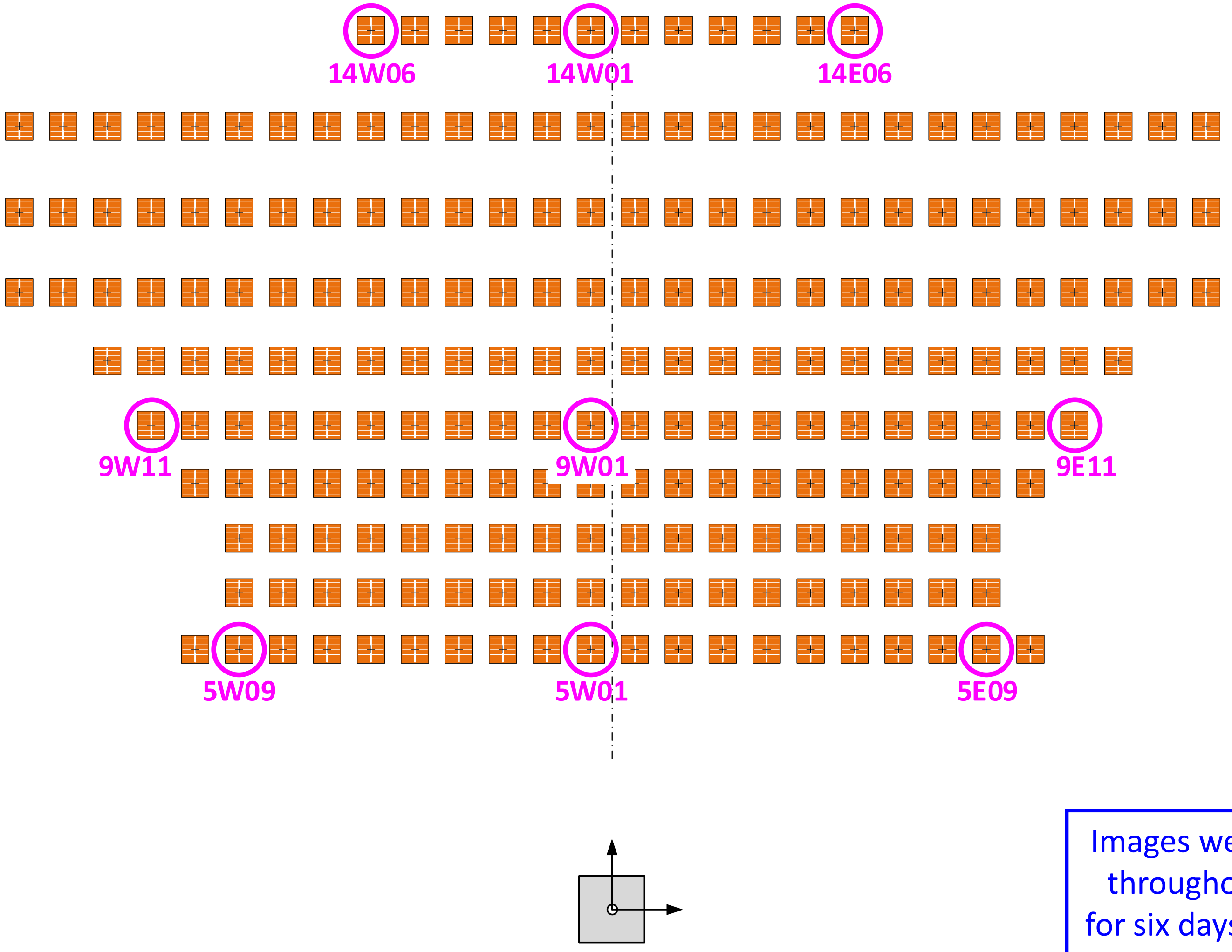
- W. Stine and R. Harrigan. *Solar Energy Fundamentals and Design,* John Wiley & Sons, 1985.
- J. Noring, D. Grether, and A. Hunt, Circumsolar Radiation Data: The Lawrence Berkeley Laboratory Reduced Database. NREL Technical Report NREL/TP—262-4429, December 1991.
- A. Neumann, et al, Representative Terrestrial Solar Brightness Profiles, *Transactions of the ASME* **124**, pp. 198-204, May 2002.
- D. Buie, A. Monger, and C. Dey, Sunshape distributions for terrestrial solar simulations. *Solar Energy* **74**, pp. 113-122, 2003.

Heliostats Studied for Beam Shape

BCS spot:

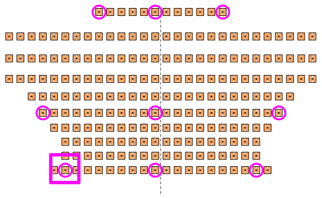


Heliostats studied:



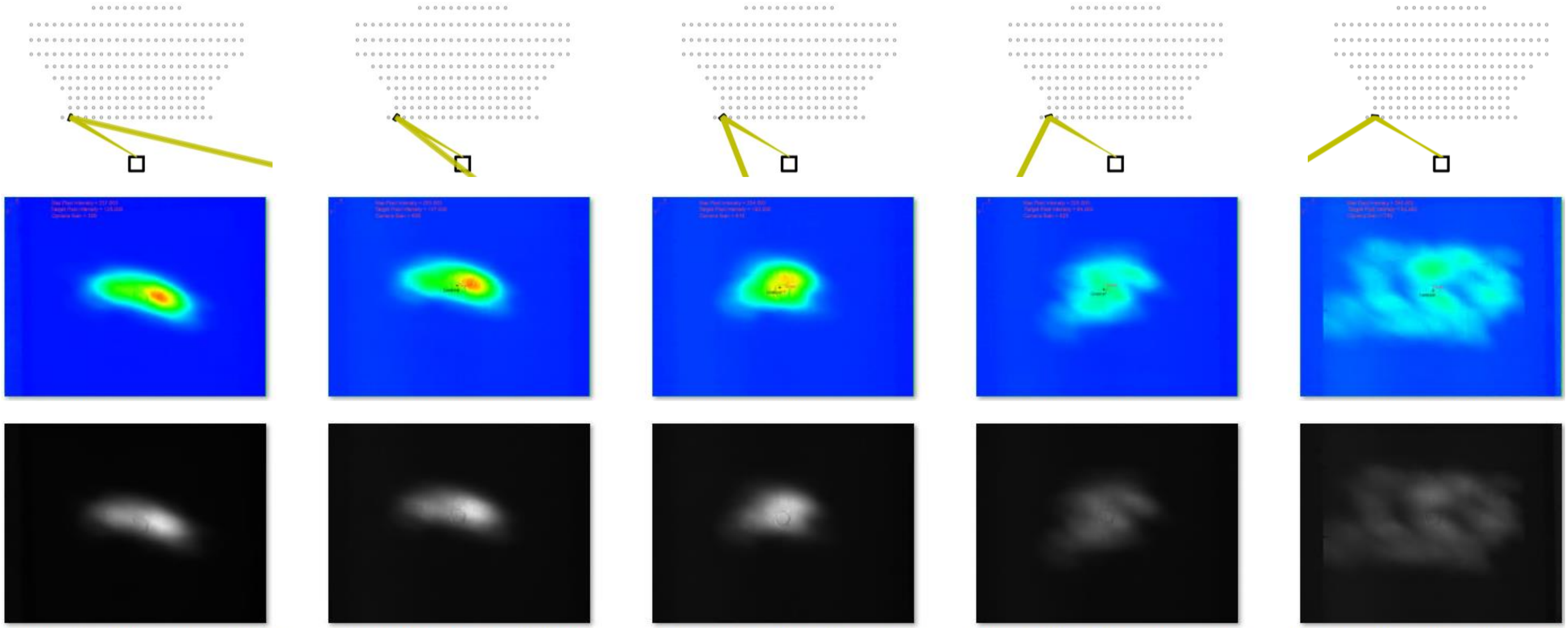
Images were collected throughout the day, for six days throughout the year.

Images collected February 10, 2023.



BCS Spot Variation Example

5W09

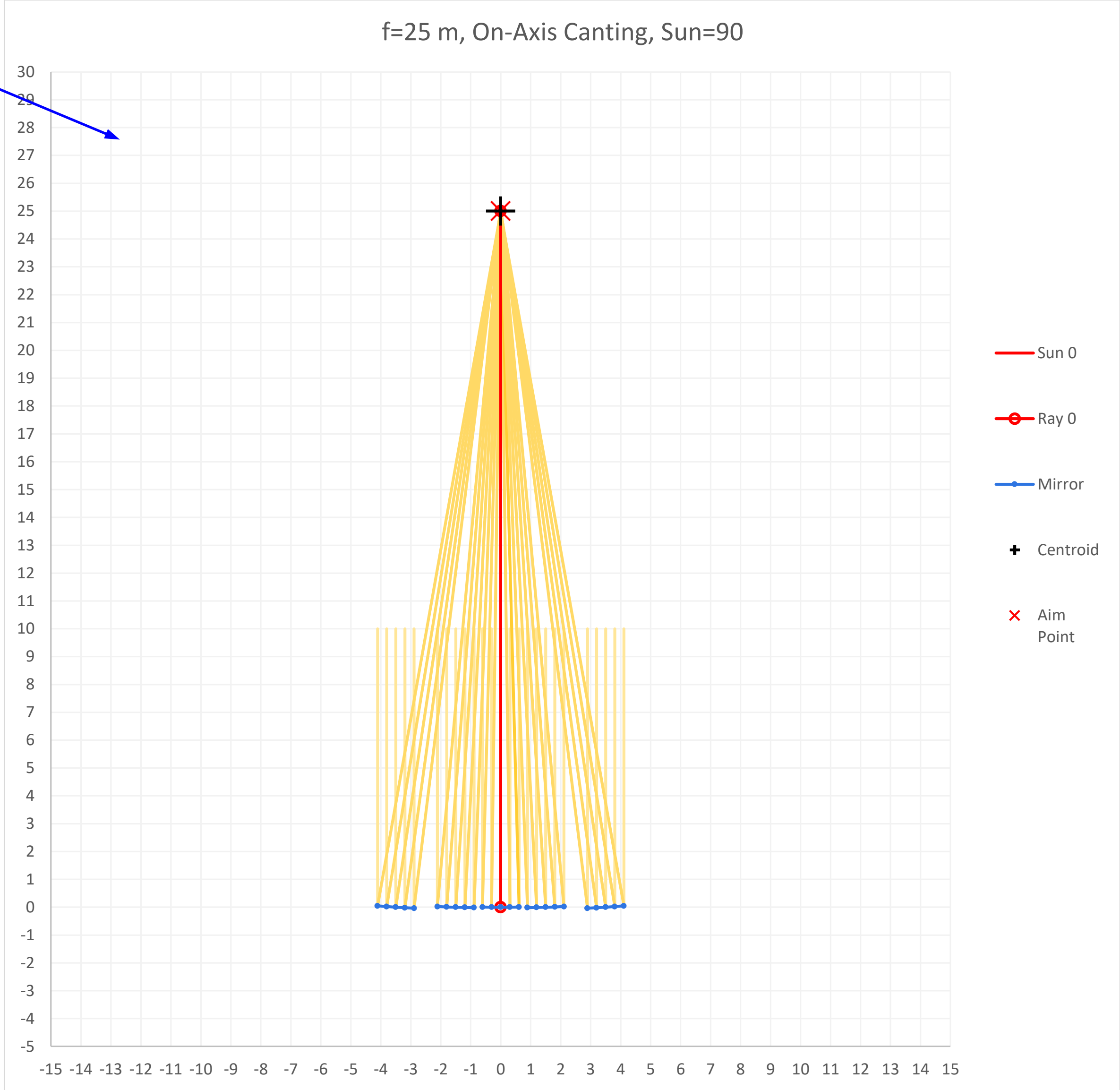


Early Solar Noon Late

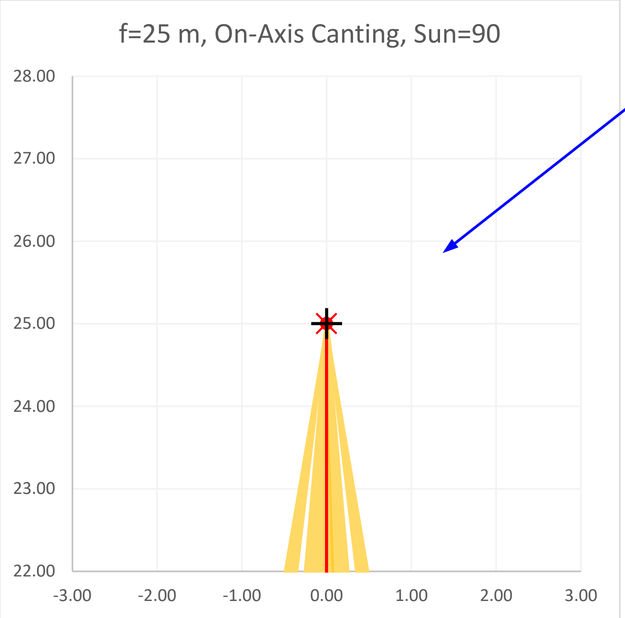
Heliostat Reflection Under Increasing Incidence Angle

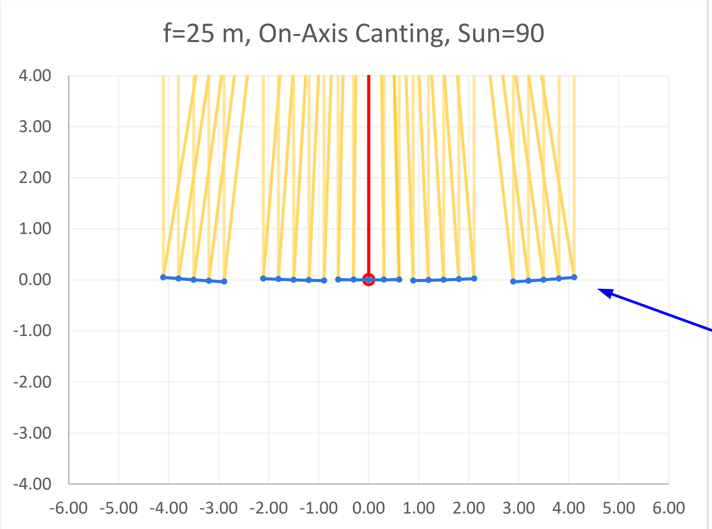
On-axis canting, sun incidence 0°:

Overall view



Zoom-in Target





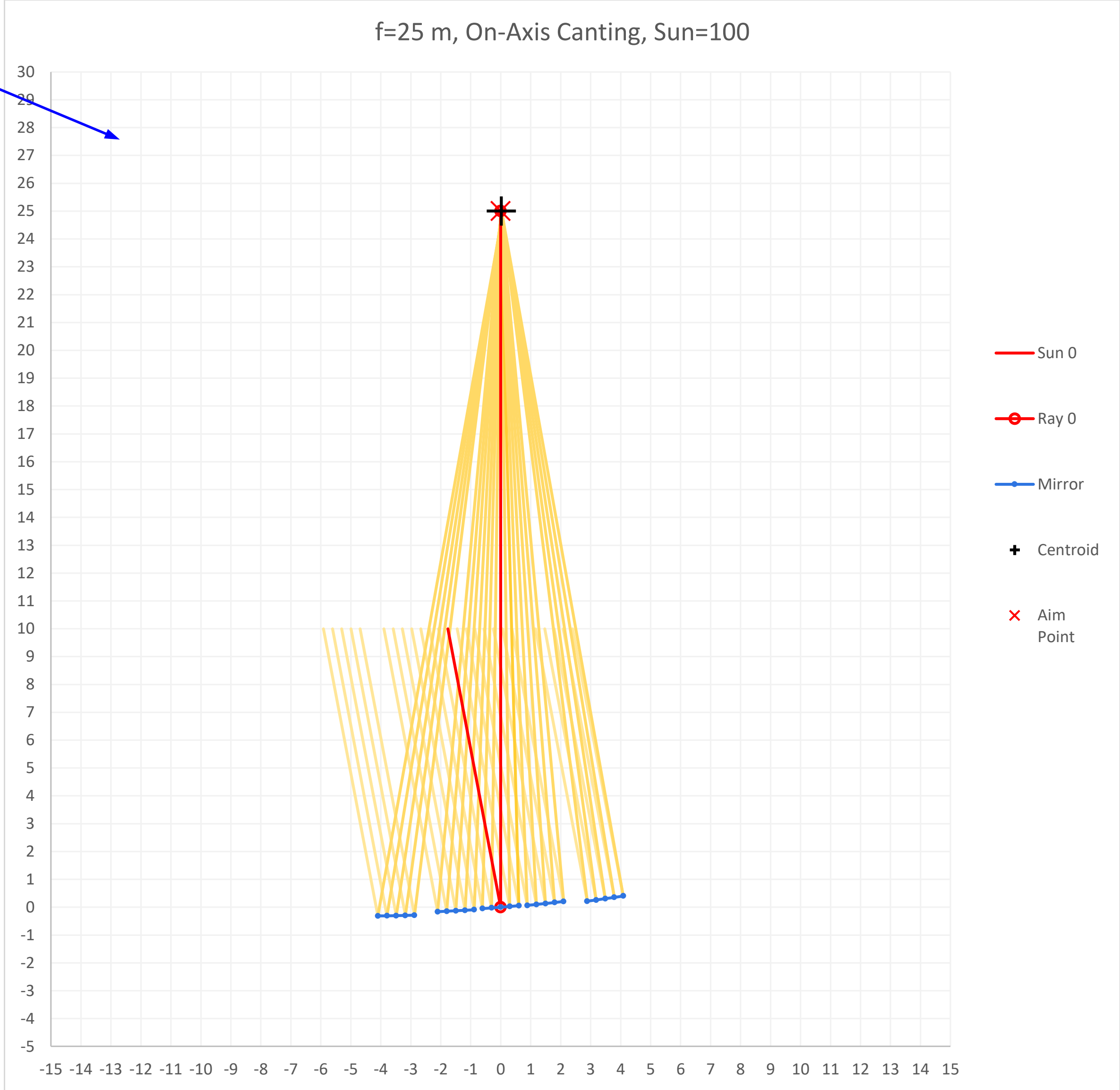
Zoom-in Mirror

Sun is modeled as a point source. Sun shape not included.

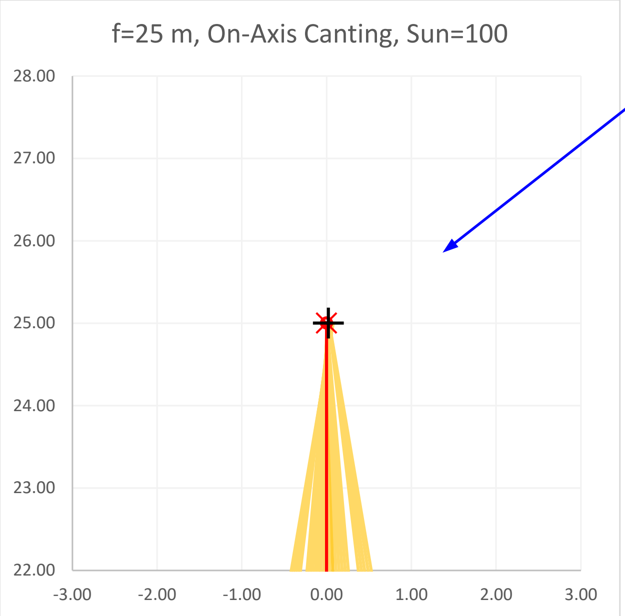
Heliostat Reflection Under Increasing Incidence Angle

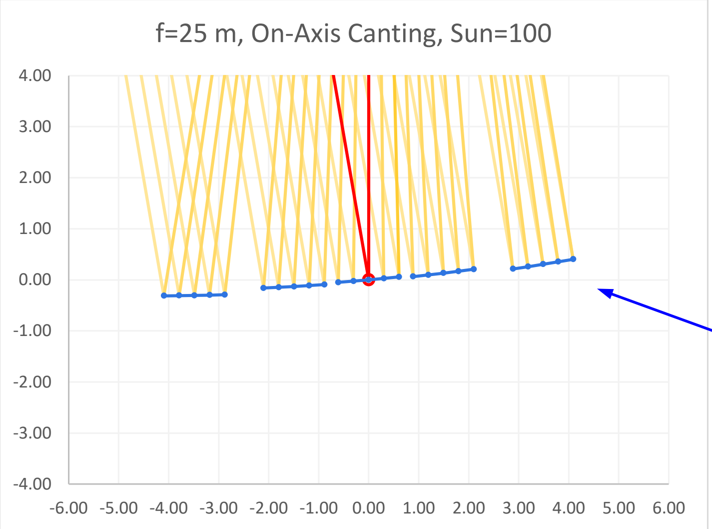
On-axis canting, sun incidence 10°:

Overall view



Zoom-in Target





Zoom-in Mirror

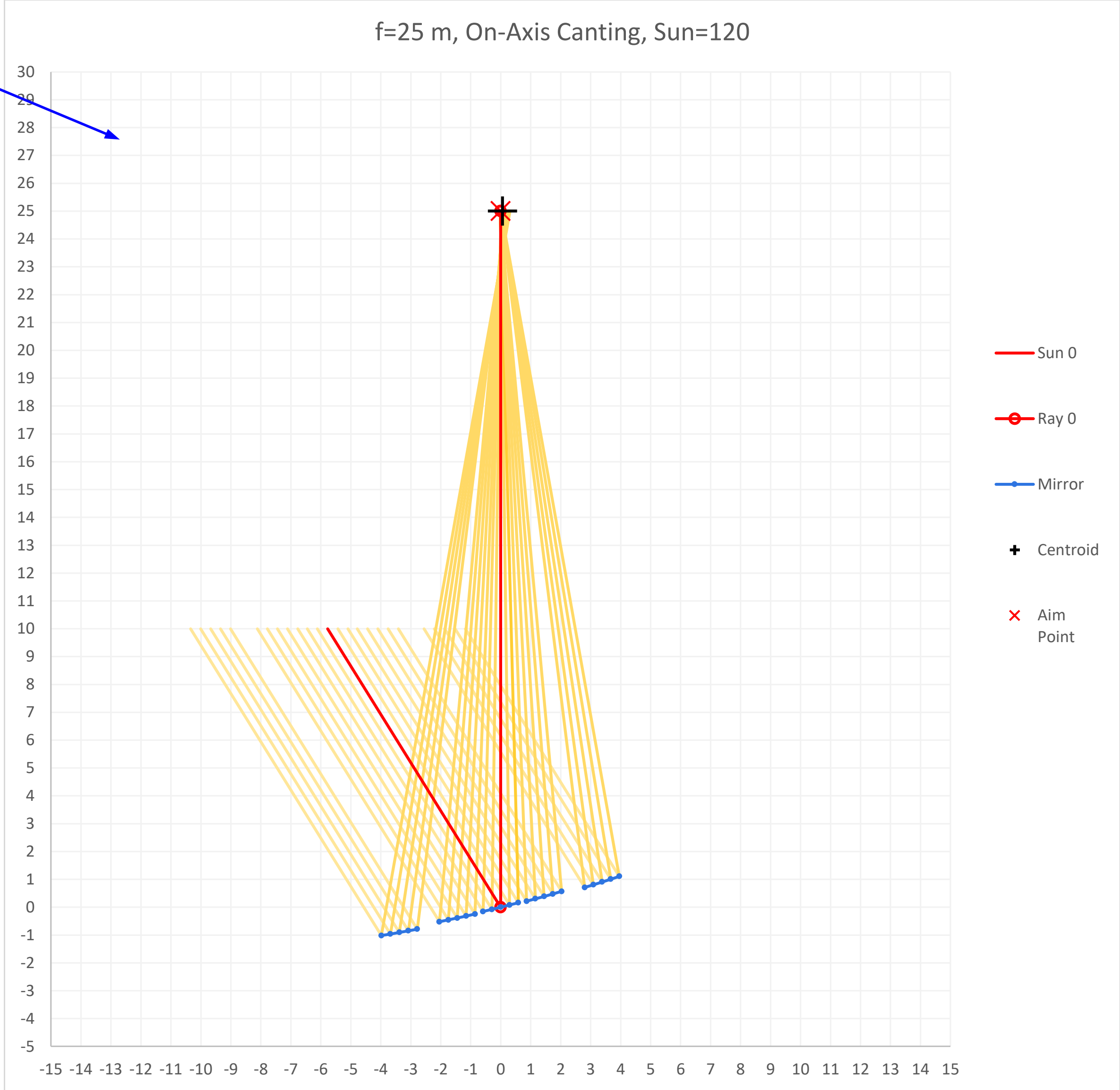
Inquiries: OpenCSP@sandia.gov

Sun is modeled as a point source. Sun shape not included.

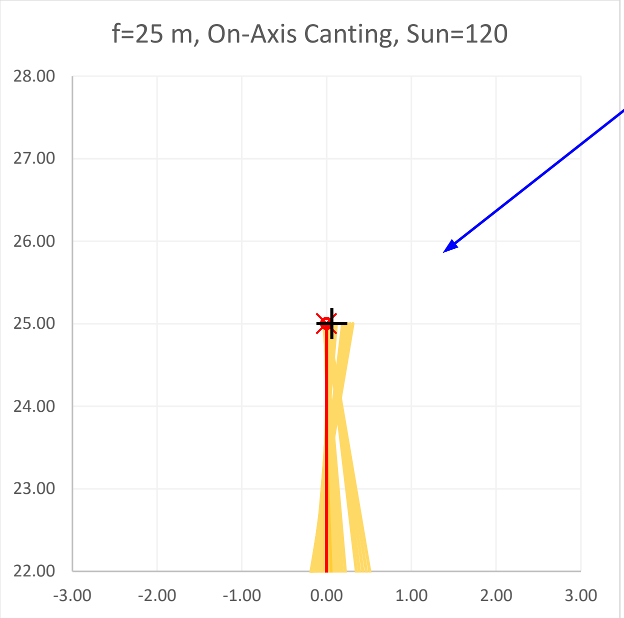
Heliostat Reflection Under Increasing Incidence Angle

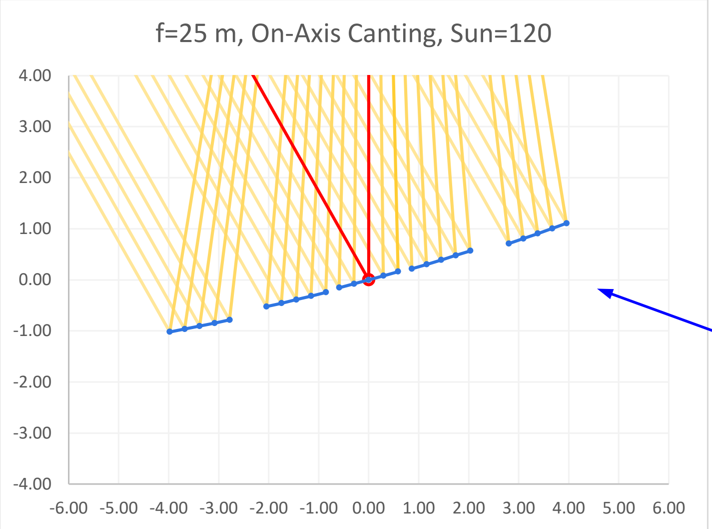
On-axis canting, sun incidence 30°:

Overall view



Zoom-in Target



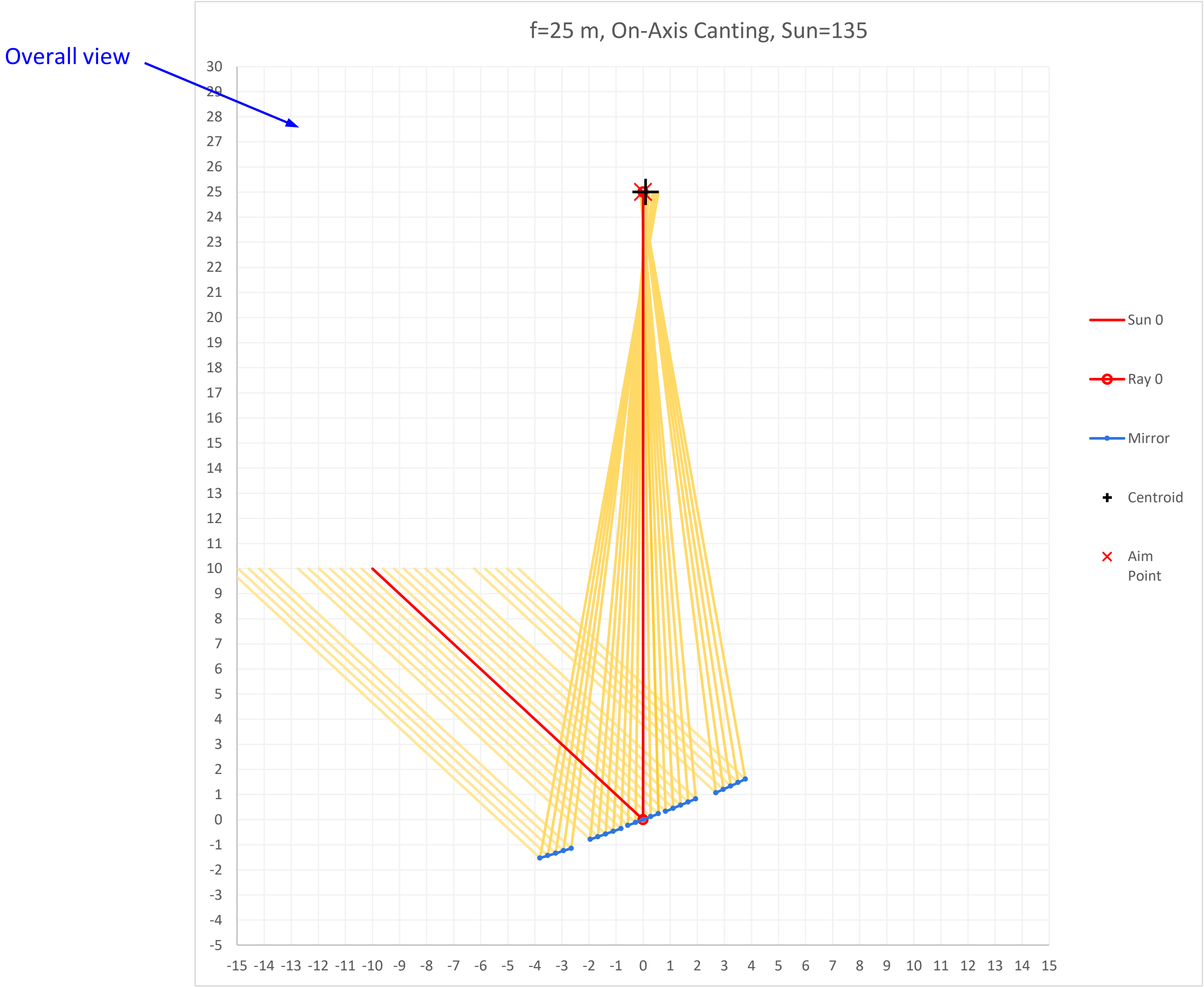


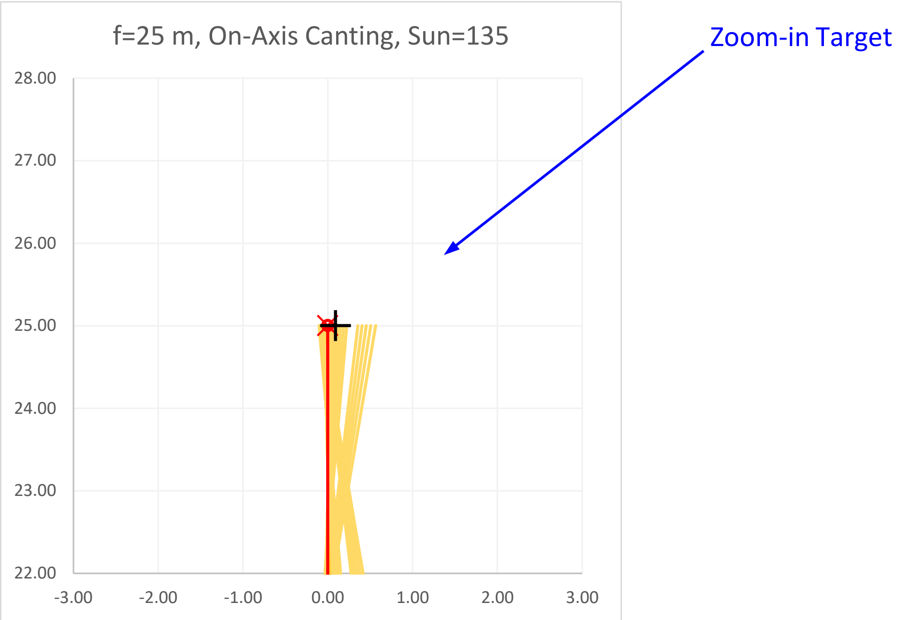
Zoom-in Mirror

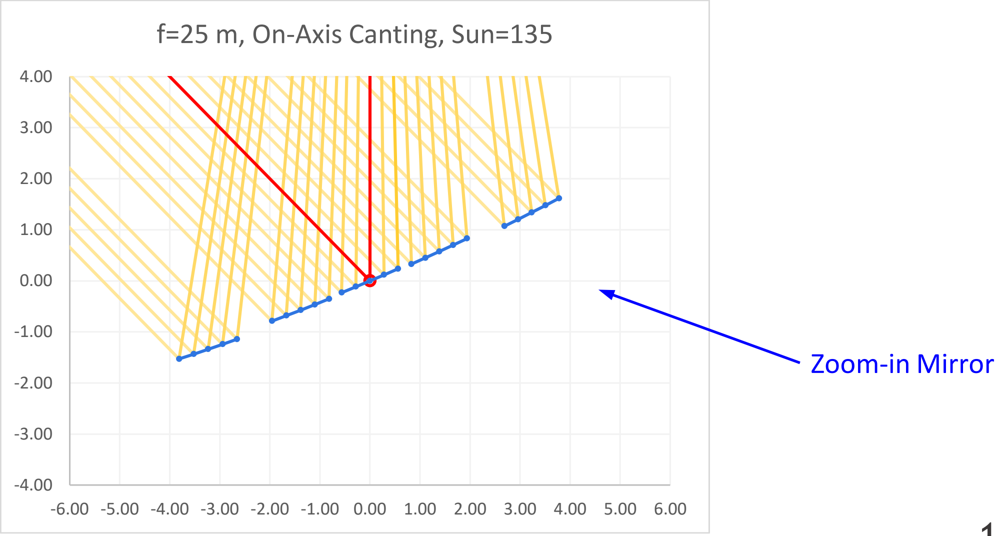
Sun is modeled as a point source. Sun shape not included.

Heliostat Reflection Under Increasing Incidence Angle

On-axis canting, sun incidence 45°:







Inquiries: OpenCSP@sandia.gov

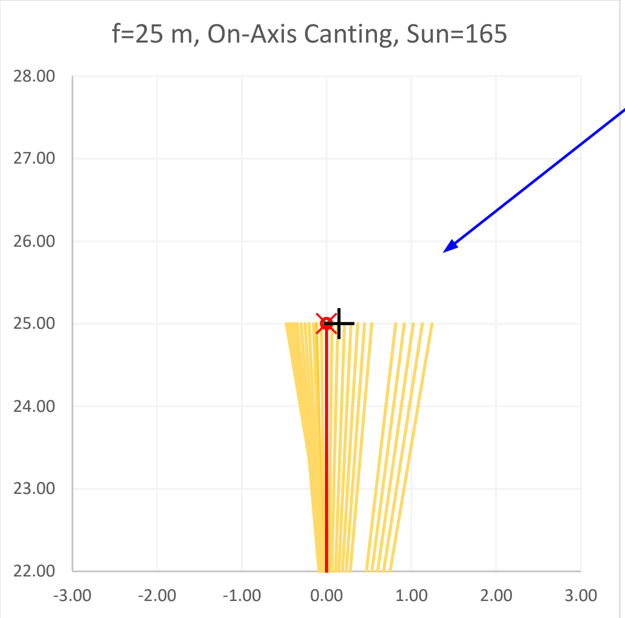
Sun is modeled as a point source. Sun shape not included.

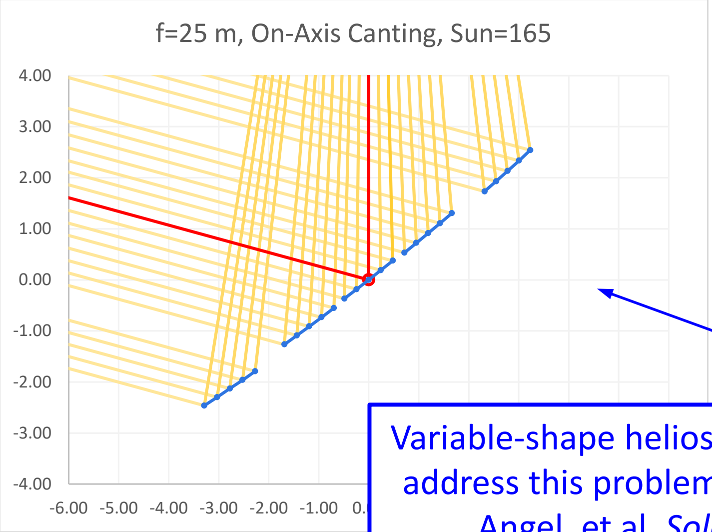
Heliostat Reflection Under Increasing Incidence Angle

On-axis canting, sun incidence 75°:

Overall view

Zoom-in Target





Zoom-in Mirror

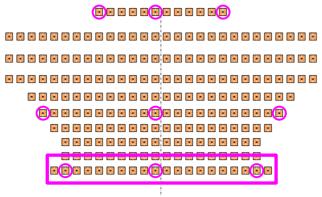
Variable-shape heliostats are designed to address this problem. For example, see Angel, et al. *SolarPACES* 2020.

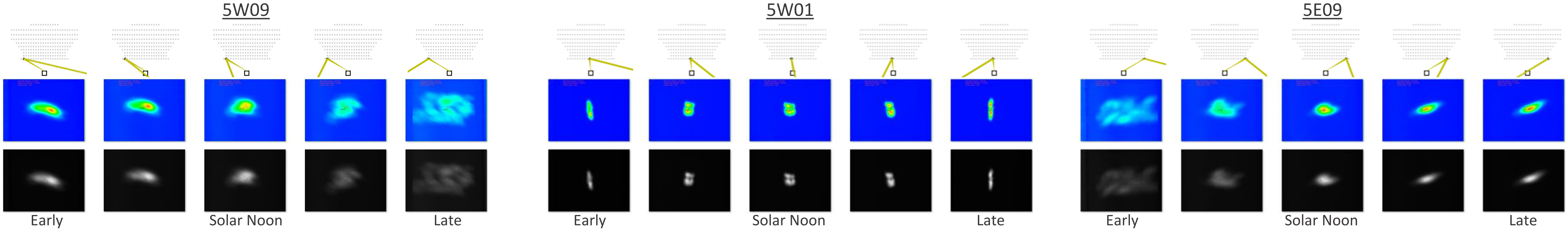
Inquiries: OpenCSP@sandia.gov

Sun is modeled as a point source. Sun shape not included.

One Day: Winter Solstice Mid Spring Equinox

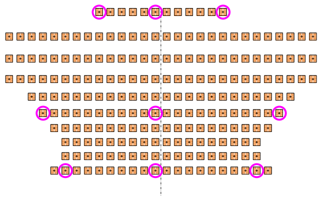
Images collected February 10, 2023.

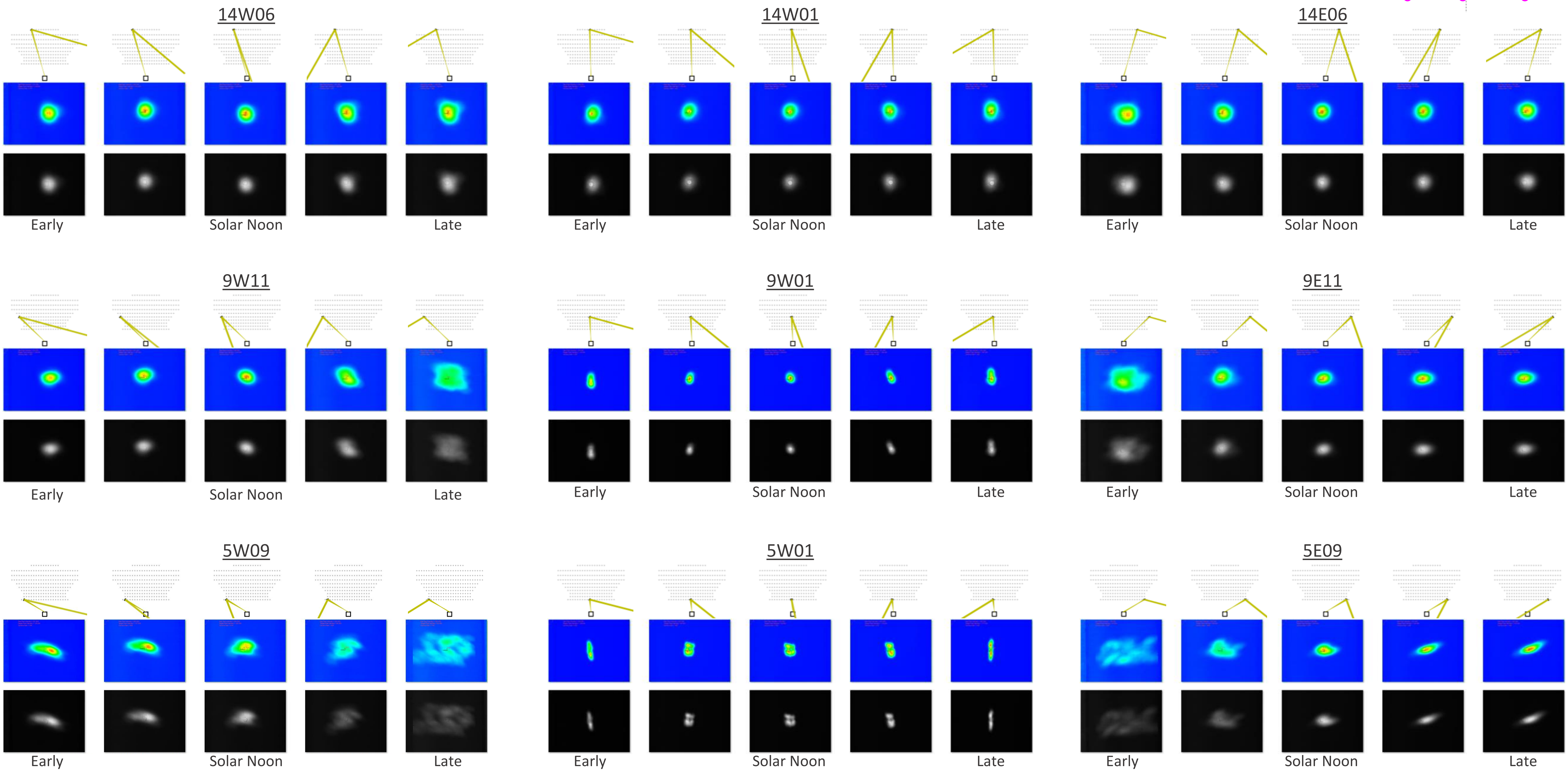




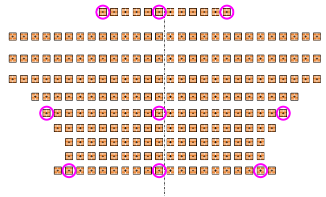
One Day: Winter Solstice Mid Spring Equinox

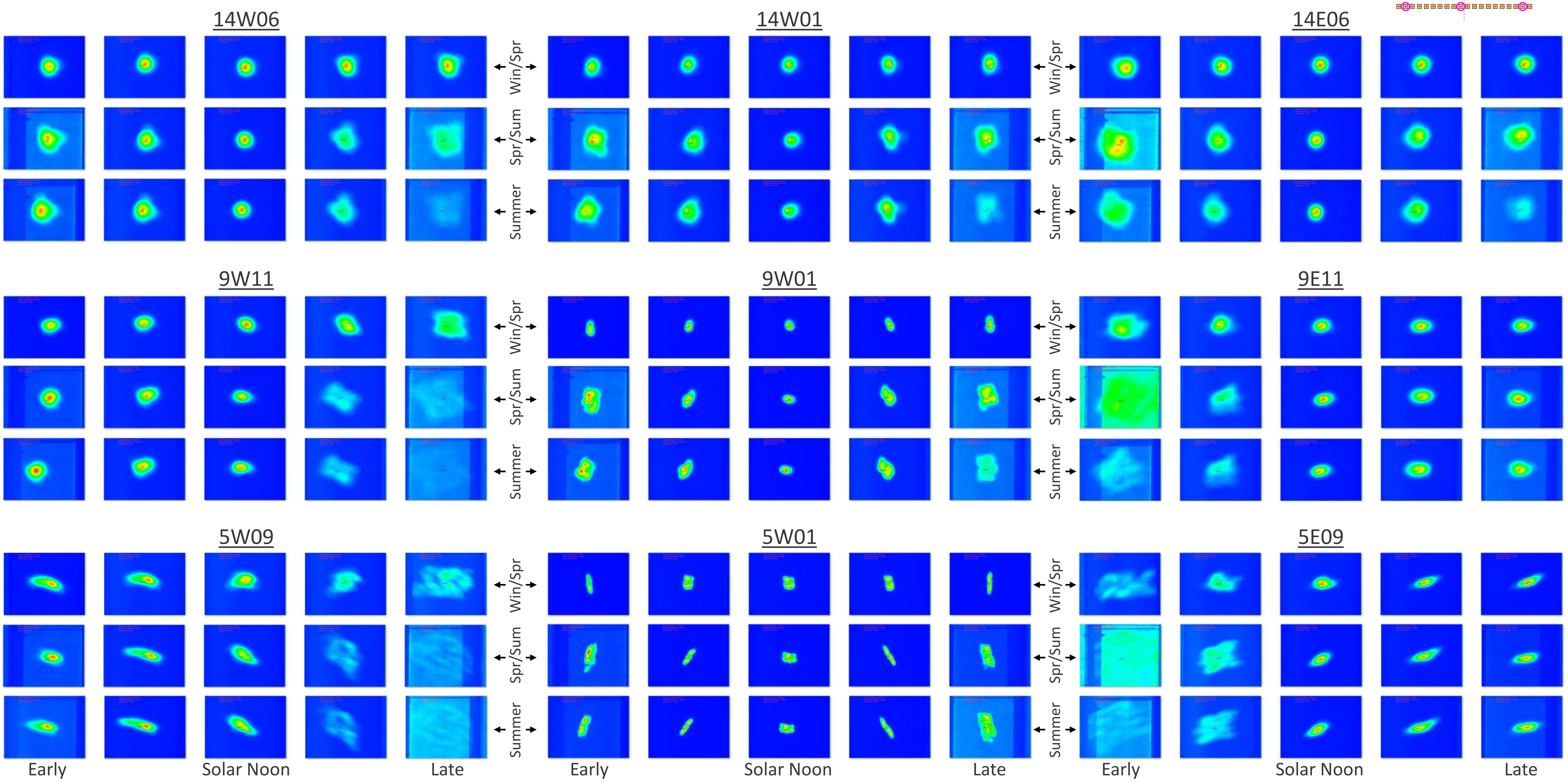
Images collected February 10, 2023.



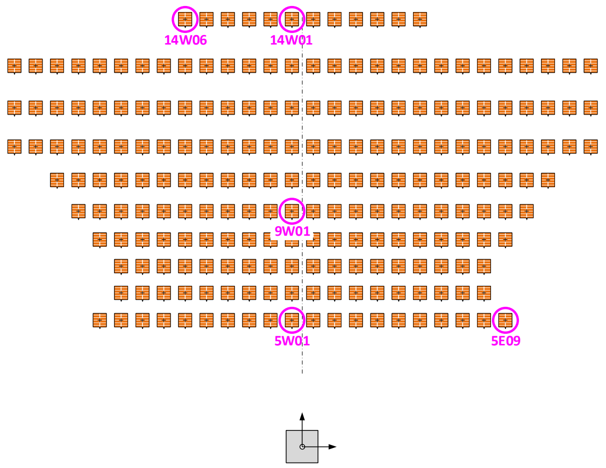


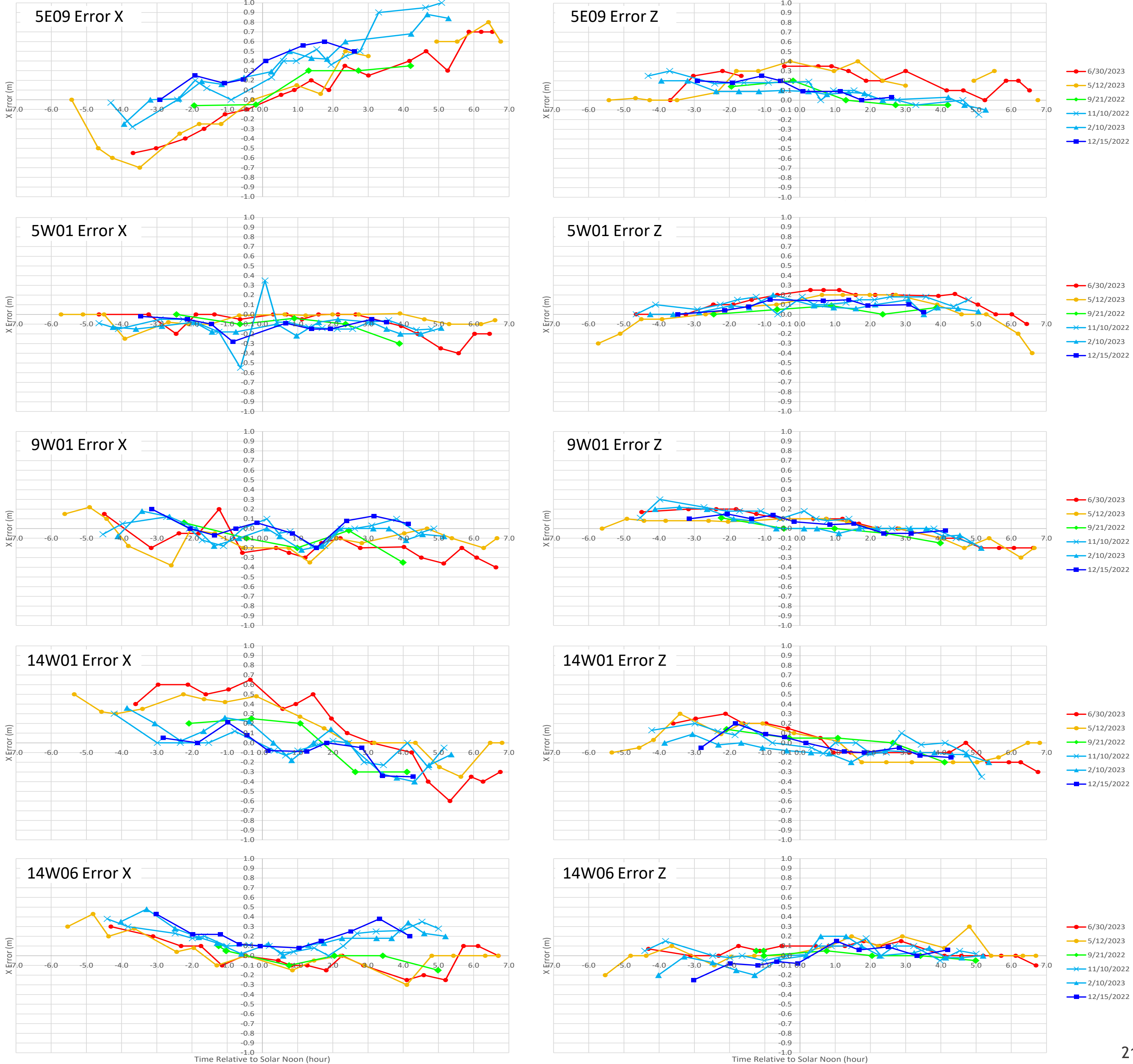
¾ Year: Winter/Spring, Spring/Summer, Summer





Pointing Corrections Vary with Time





Observations:

- Trends are clear within the day and across the year. Consider the winter-to-summer trend in 5E09, 14W01, and 14W06.
- With steep sun incidence (5E09 near sunrise, 5W09 near sunset), uncertainty is higher because the beam is diffuse.
- If we imagine a square receiver of side length d_r and a hypothetical square spot, then an aim error Δx would yield an flux capture fraction of $(d_r - \Delta x)/d_r$. A circular receiver does worse.
- Consider a back-row heliostat that is perfectly aimed and perfectly focused. Assuming sun half-angle 0.45 mrad and slant distance from 14E06 to the BCS target is 196 m, the spot from an ideal 14E06 would have diameter 1.76 m. Assume a 1.6 m receiver diameter.
- Pointing errors exceed 0.4 m in many cases, reducing power >25%.

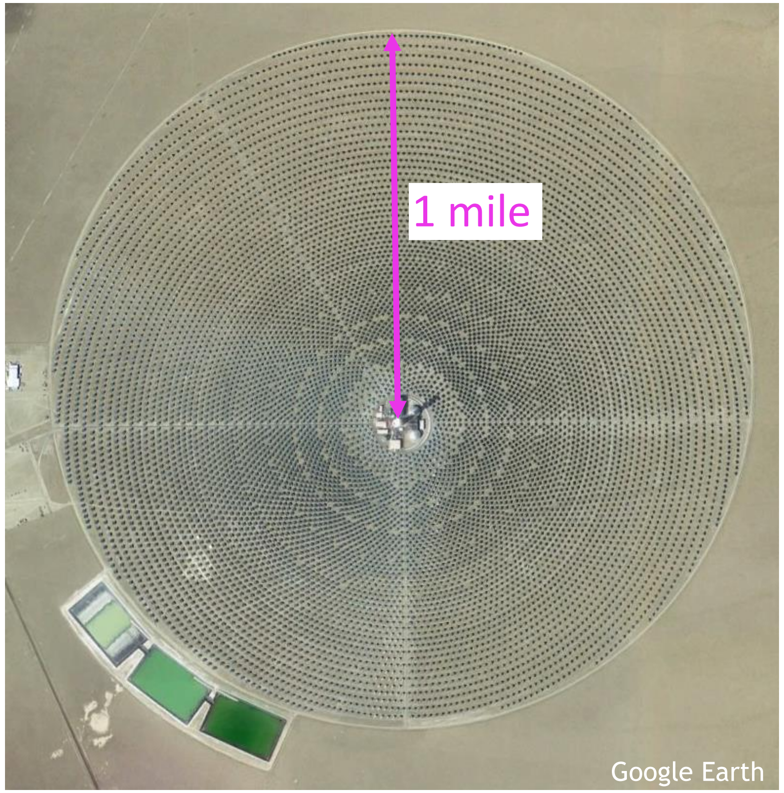
Color legend:

Winter Solstice → Equinox → Summer Solstice

Sheer Size

An example large commercial heliostat field:

Crescent Dunes Solar Power Plant

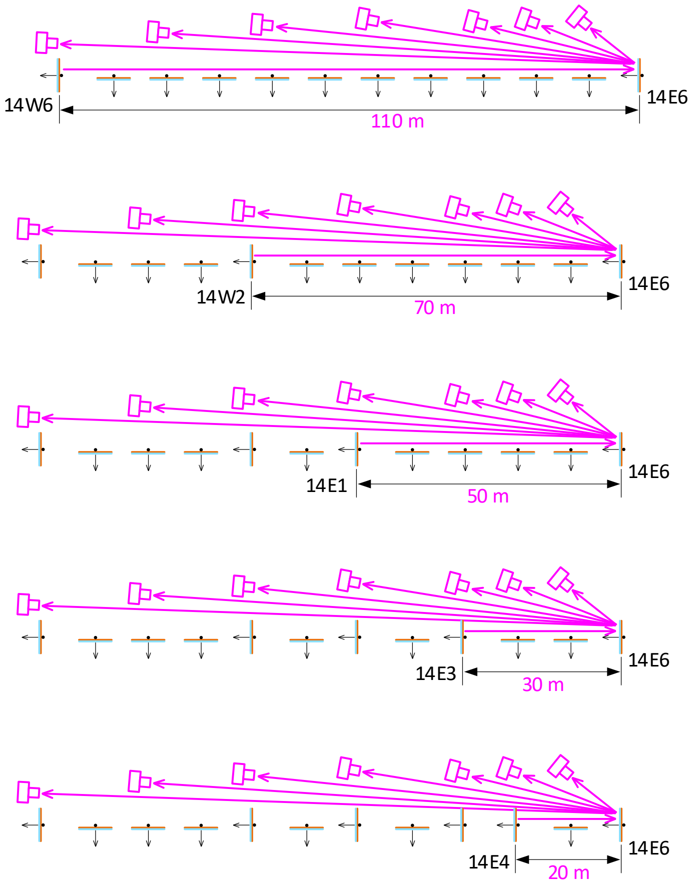


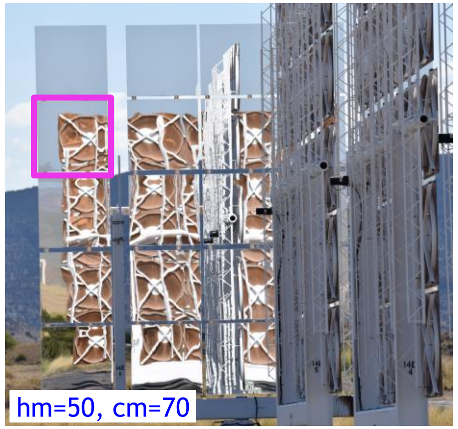
>10,300 heliostats
> 360,000 facets

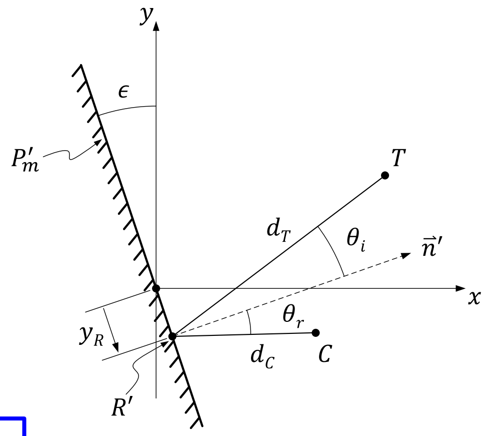
Crescent Dunes Heliostats

Geometric Distortion

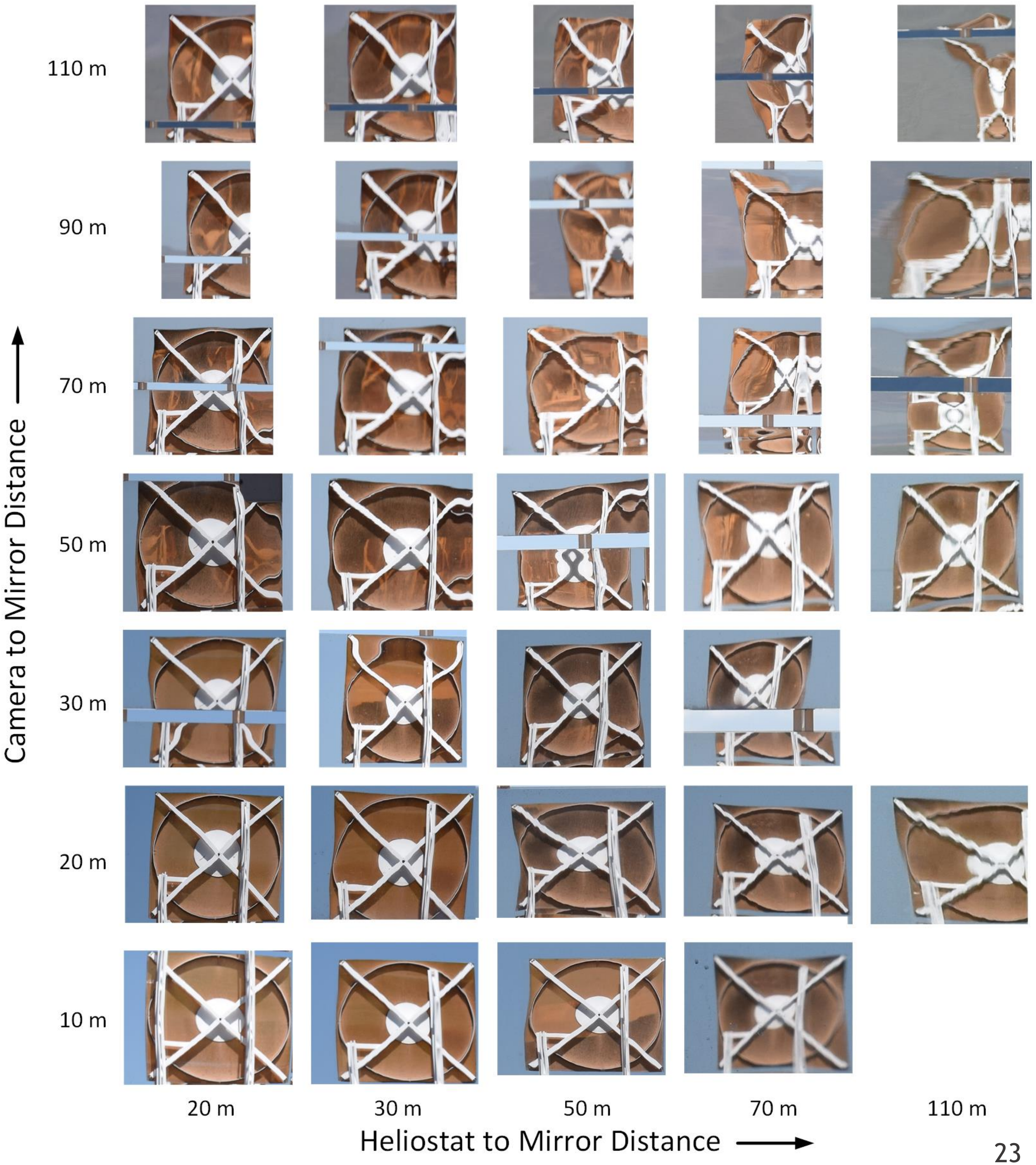
Varying Heliostat-to-mirror and camera-to-mirror distance:





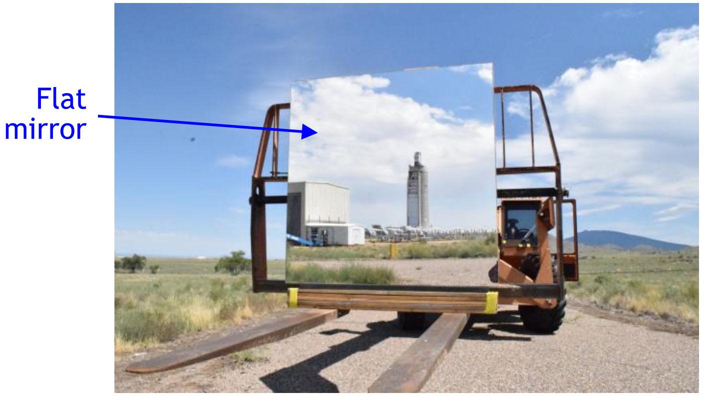


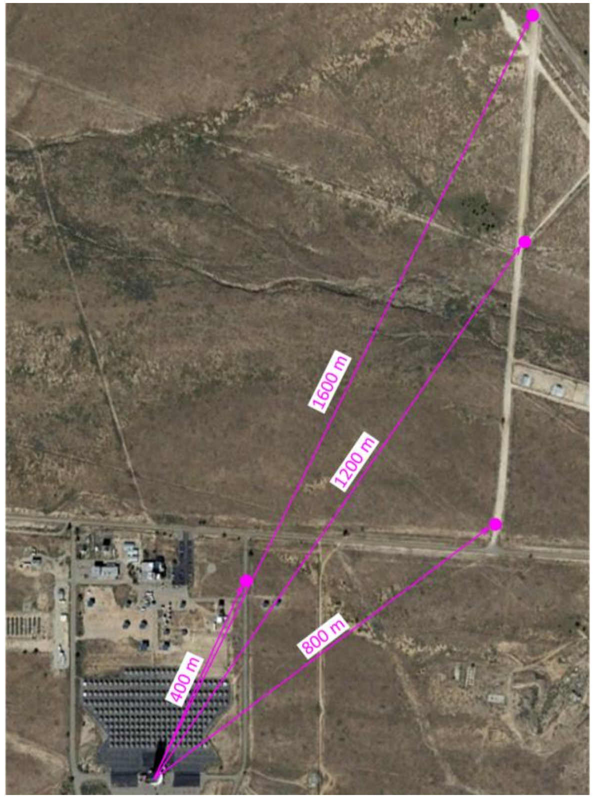
$$y_R = \frac{-2\, d_T d_C\, \epsilon}{cos(\theta_i)[d_T + d_C]}$$

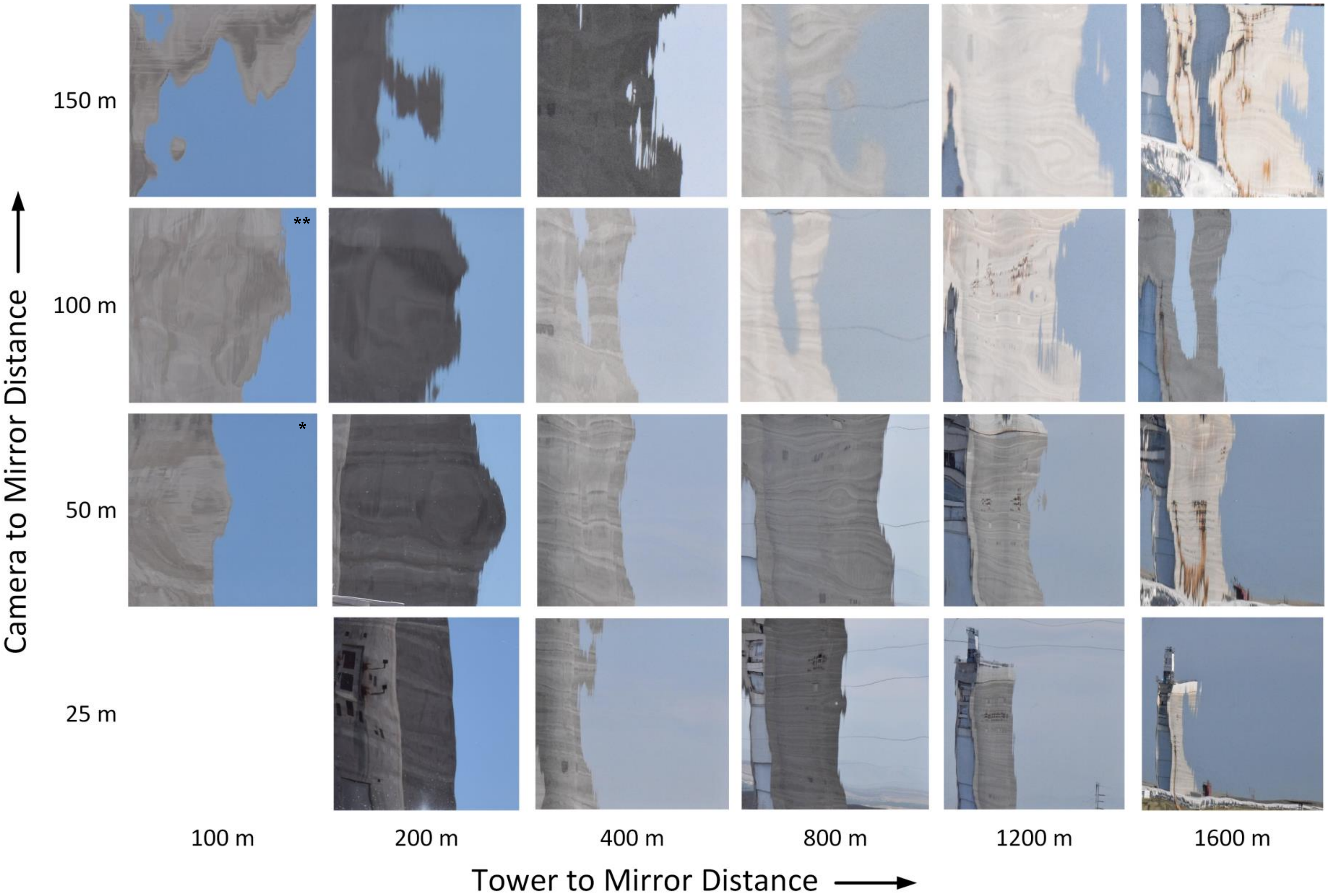


Distortion increases with heliostat-to-mirror distance, and camera-to-mirror distance.

Distortion: Tower-to-Mirror vs. Camera-to-Mirror Distance







Images at 25, 50, 100, and 150 m from the mirror.

* camera-to-mirror = 40 m
** camera-to-mirror = 80 m

Implication: Beware long optical path lengths.

Atmospheric Distortion

A warm afternoon:

Flip between the slides, and watch the cars.

If there is this much variation due to atmospheric effects, how can we do precise metrology over long optical path lengths?

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Flip between the slides, and watch the cars.

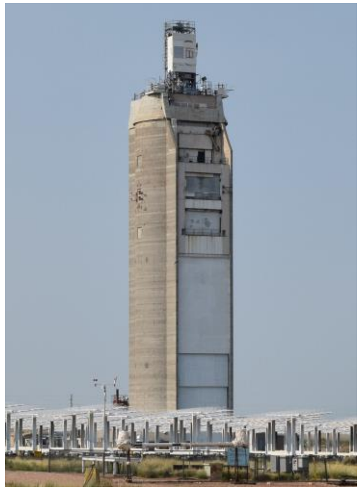
If there is this much variation due to atmospheric effects, how can we do precise metrology over long optical path lengths?

High-Frequency Effects

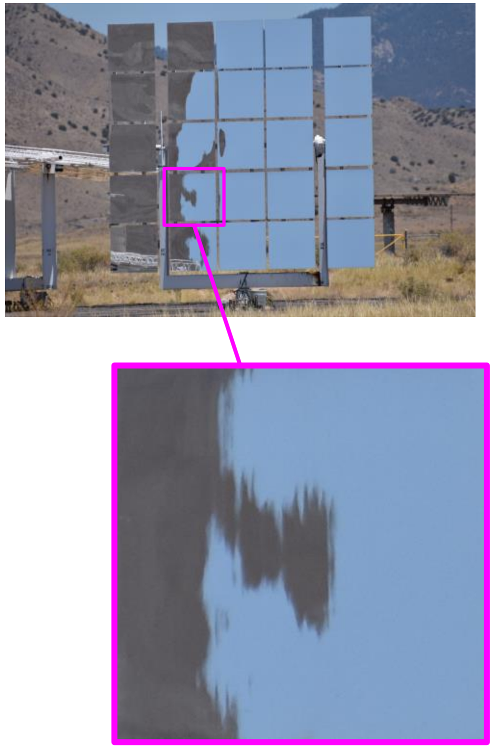
CSP mirrors can exhibit high-frequency aberrations:

- We have observed high-frequency reflection effects in several mirrors from multiple manufacturers.
- These effects can influence reflectivity and energy production.

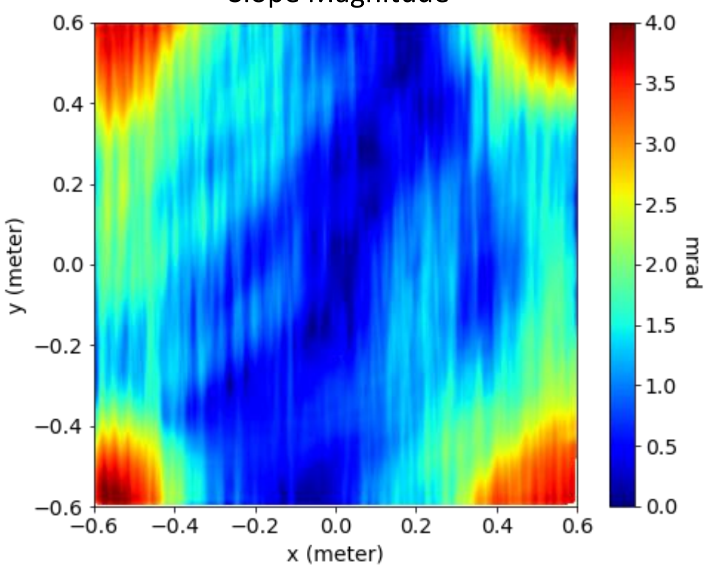
NSTTF Tower

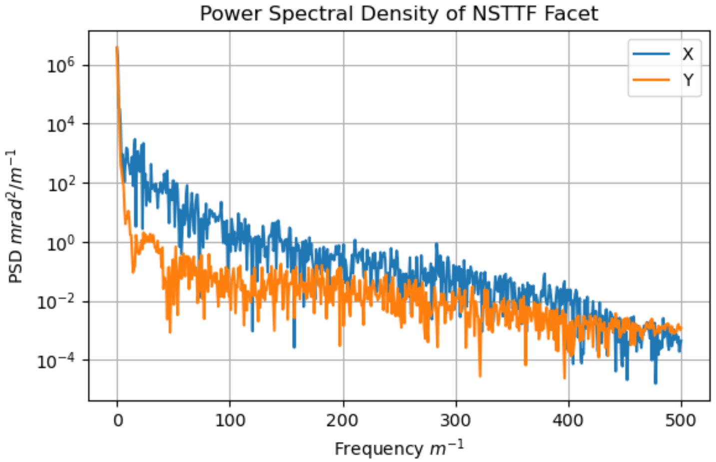


Tower Edge Seen in Reflection



Example SOFAST measurement:



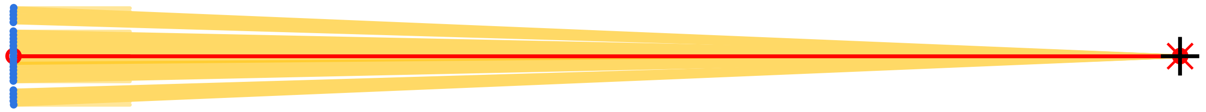


Metrology techniques which employ coarse sampling strategies can incorrectly report smoothness.

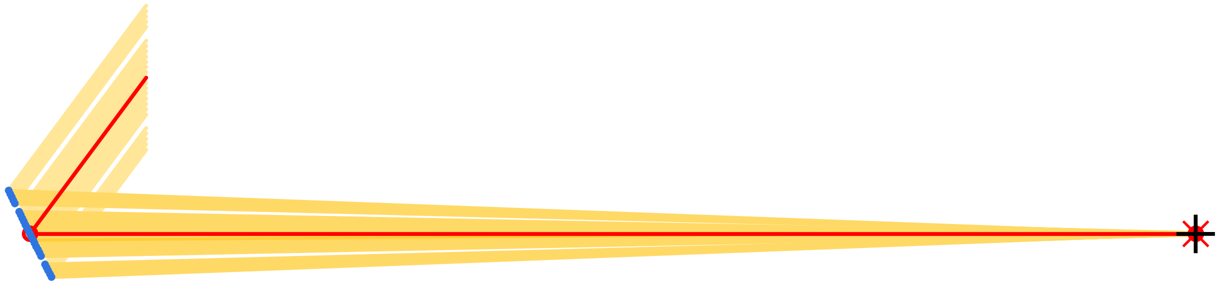
Position-based methods face a dilemma: Low resolution, which misses high-frequency effects, or high resolution, where measurement noise can introduce artificial slope deviation?

Complex Optical Shape

On-axis canting – Intuitive:



Off-axis canting – Maximum performance at solar noon:



Other canting strategies:

- R. Buck and E. Tuefel. Comparison and Optimization of Heliostat Canting Methods. *Journal of Solar Energy Engineering* **131**, February 2009.
- W. Landman and P. Gauche. Influence of canting mechanism and facet profile on heliostat field performance. *Energy Procedia* **49**, pp. 126-135, 2014.

2-d Study

f = 100 m:

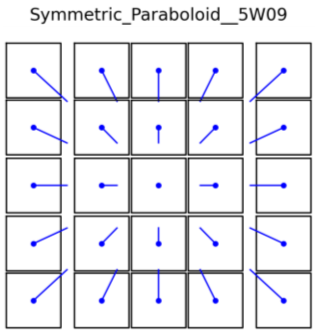
Facet	Canting Angle (mrad)
1	-17.5
2	-7.5
3	0.0
4	7.5
5	17.5

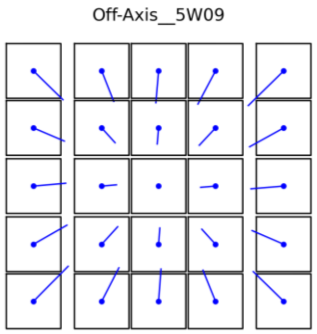
f = 100 m, incidence 53°:

Facet	Canting Angle (mrad)
1	-15.4
2	-6.7
3	0.0
4	6.8
5	15.9

Max change: 2.1 mrad
Asymmetry y: 0.5 mrad

3-d Study*





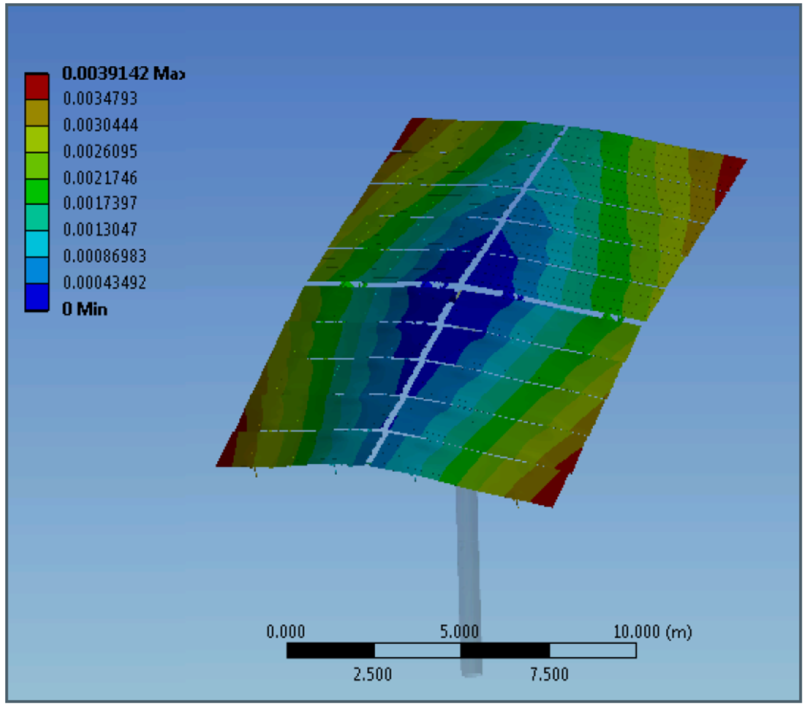
Max change: <pending> mrad
Asymmetry x: <pending> mrad
Asymmetry y: <pending> mrad
Asymmetry xy: <pending> mrad

* Solar noon on Spring Equinox.
5W09: [-82.85m, 57.92m, 2.61m]
aim = [0 m, 8.8 m, 60 m]
d_{slant} = 112.1 m

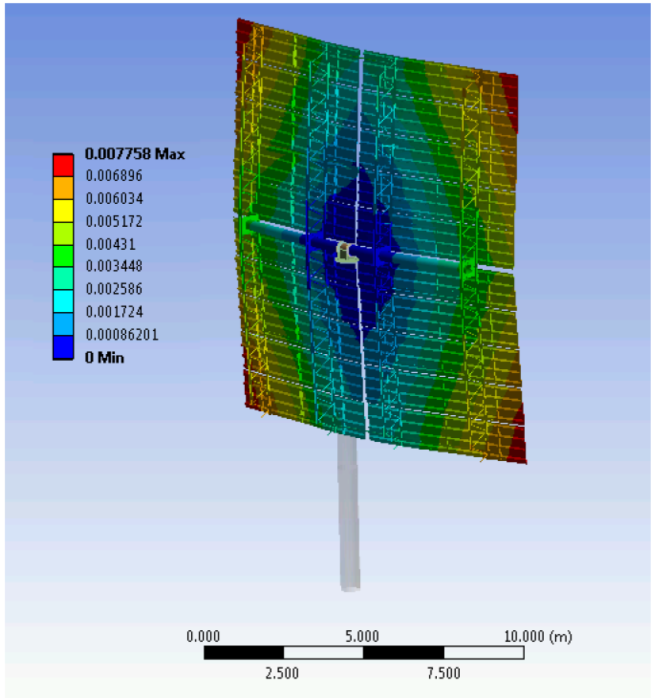
Metrology systems must be able to measure complex heliostat optical shapes.

Heliostat Deflection with Tilt

Model of heliostat deflection with different elevation angles:



Noon, Summer Solstice



Late afternoon, Winter Solstice

https://www.osti.gov/servlets/purl/1106187

Power-weighted elevation angle:

$$\theta_{power\ weighted} = \frac{\sum_{i=1}^{8760} DNI_i * cosine\ factor_i * \theta_{Elevation\,i}}{\sum_{i=1}^{8760} DNI_i * cosine\ factor_i}$$

Key Elevation Angles for ATS Heliostat @ NSTTF Site	Angle
Solar Noon, Equinox	**29.279**
Solar Noon, Summer Solstice	**41.402**
Solar Noon, Winter Solstice	**17.953**
Power-Weighted Elevation Angle	**22.934**

Annual power-weighted intercept factor:

- **Un-deformed: 66.6%**
- **Power Weighted: 62.7%**
- **Equinox Angle: 60.3 %**

Model predicts deformation causes a 6.3% drop in annual intercept. Setting canting angles with heliostat at power-weighted elevation angle reduces predicted loss to only 3.9%

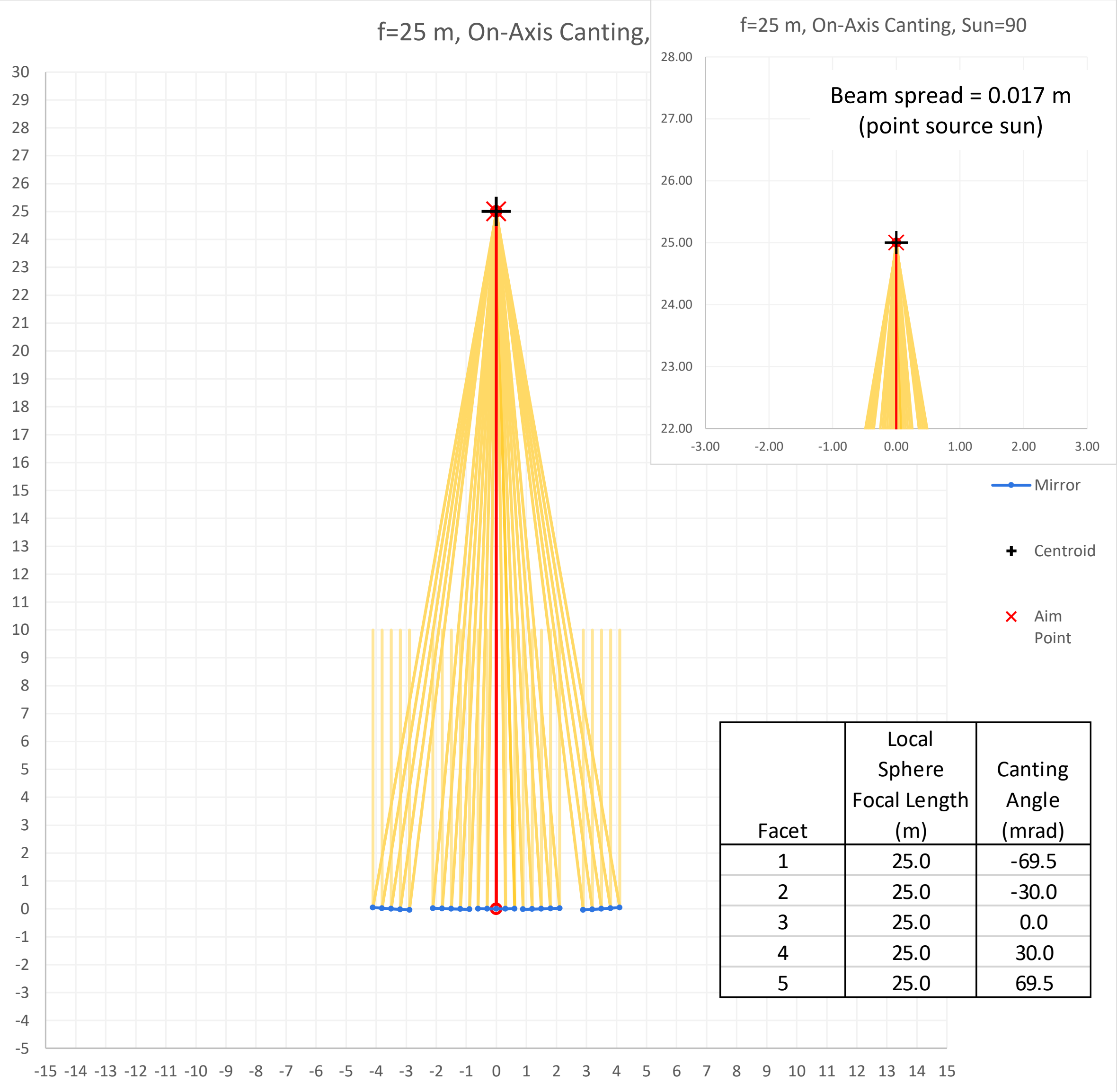
From: **J. Yuan, C. Ho, and J. Christian. Compensation of Gravity Induced Heliostat Deflections for Improved Optical Performance.** *ASME 2013 7th International Conference on Energy Sustainability*, 2013. https://www.osti.gov/servlets/purl/1106187

Also: J. Yuan, J. Christian, and C. Ho. Compensation of Gravity Induced Heliostat Deflections for Improved Optical Performance. *Journal of Solar Energy Engineering*, 2015.

Assessing gravity effects requires measurement at different tilt angles.

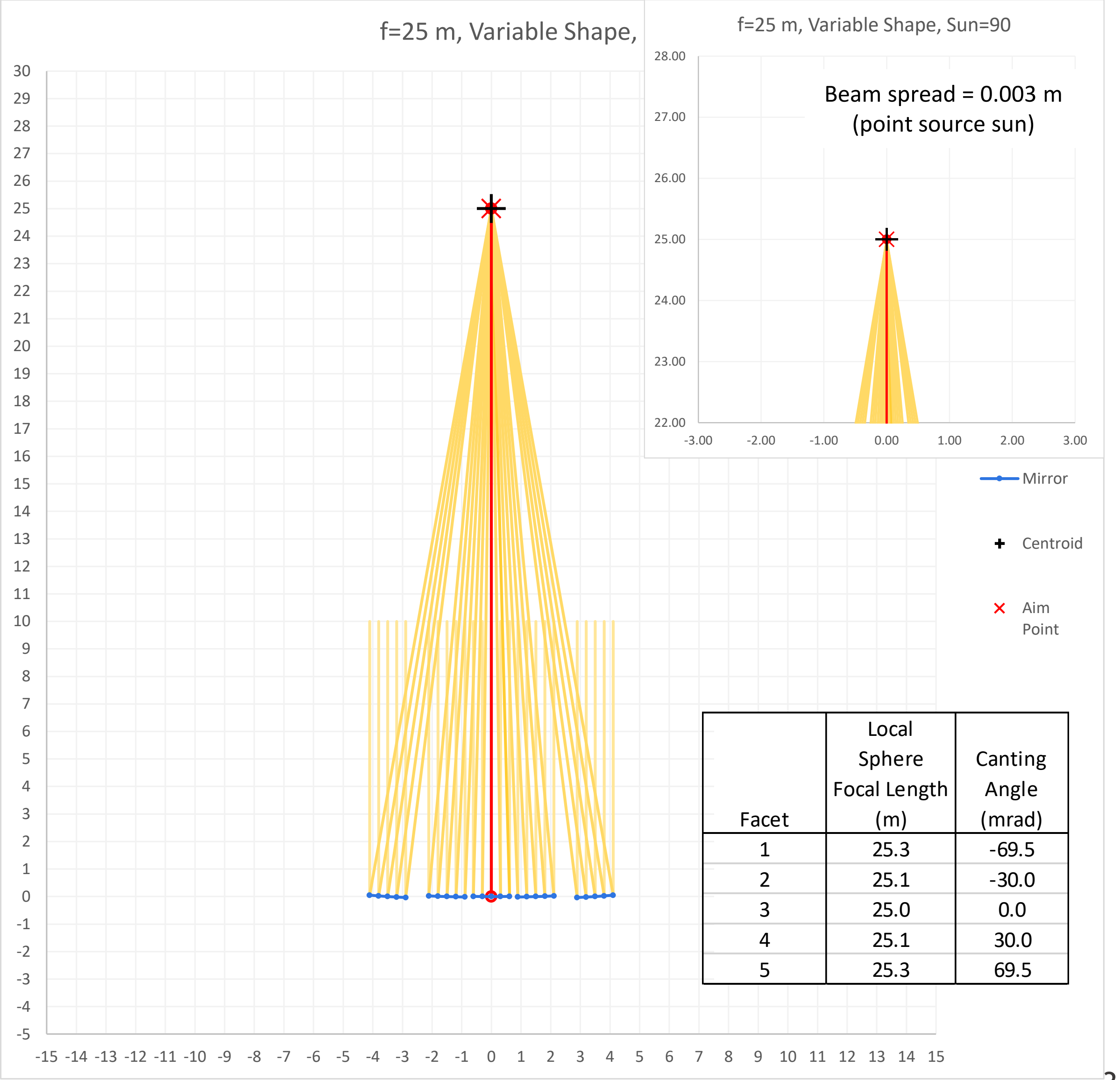
Some Heliostats Intentionally Change Shape

Constant shape:



Facet	Local Sphere Focal Length (m)	Canting Angle (mrad)
1	25.0	-69.5
2	25.0	-30.0
3	25.0	0.0
4	25.0	30.0
5	25.0	69.5

Variable shape:

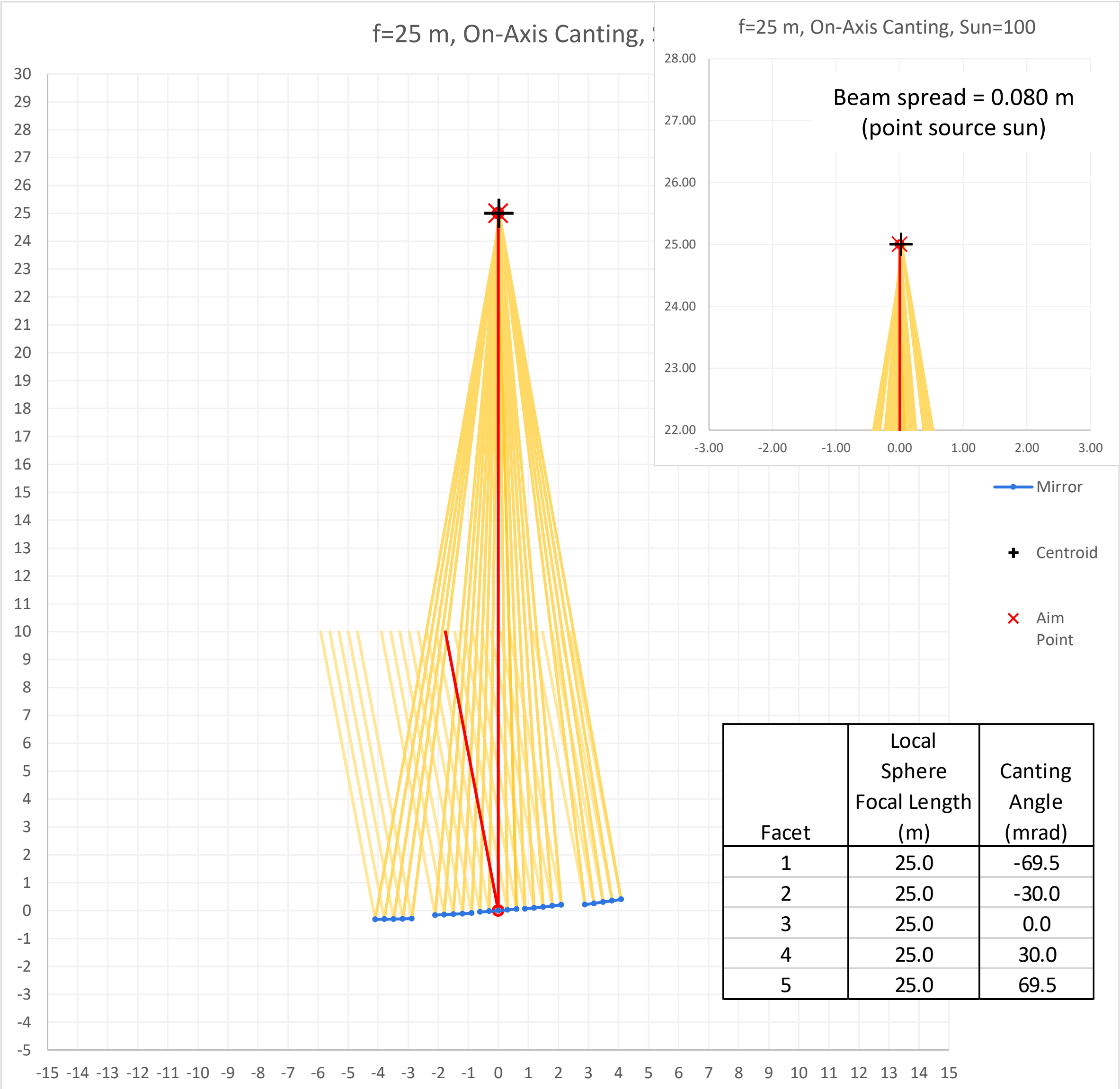


Facet	Local Sphere Focal Length (m)	Canting Angle (mrad)
1	25.3	-69.5
2	25.1	-30.0
3	25.0	0.0
4	25.1	30.0
5	25.3	69.5

Sun is modeled as a point source. Sun shape not included.

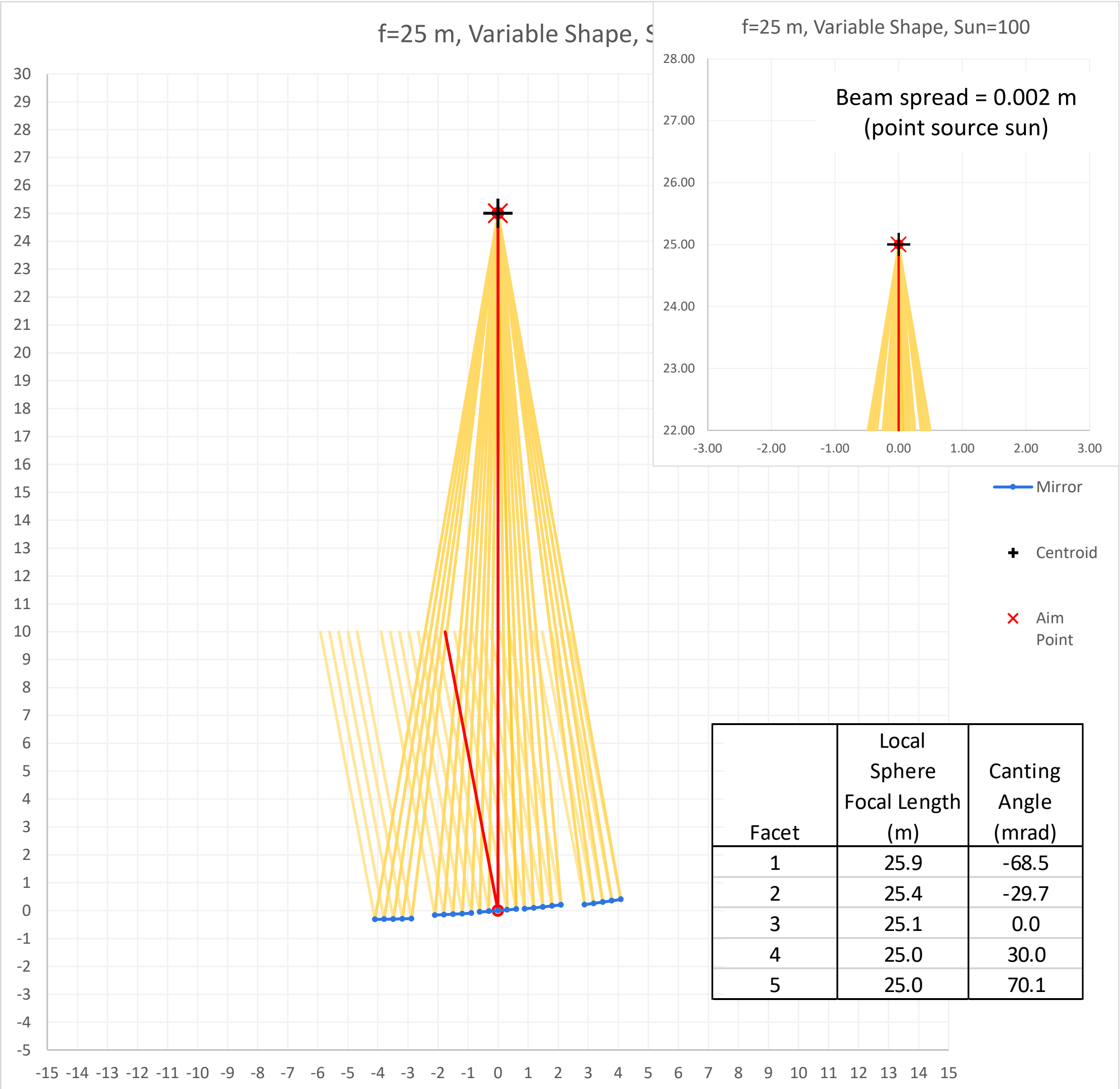
Some Heliostats Intentionally Change Shape

Constant shape:



Facet	Local Sphere Focal Length (m)	Canting Angle (mrad)
1	25.0	-69.5
2	25.0	-30.0
3	25.0	0.0
4	25.0	30.0
5	25.0	69.5

Variable shape:



Facet	Local Sphere Focal Length (m)	Canting Angle (mrad)
1	25.9	-68.5
2	25.4	-29.7
3	25.1	0.0
4	25.0	30.0
5	25.0	70.1

Inquiries: OpenCSP@sandia.gov

Sun is modeled as a point source. Sun shape not included.

Some Heliostats Intentionally Change Shape

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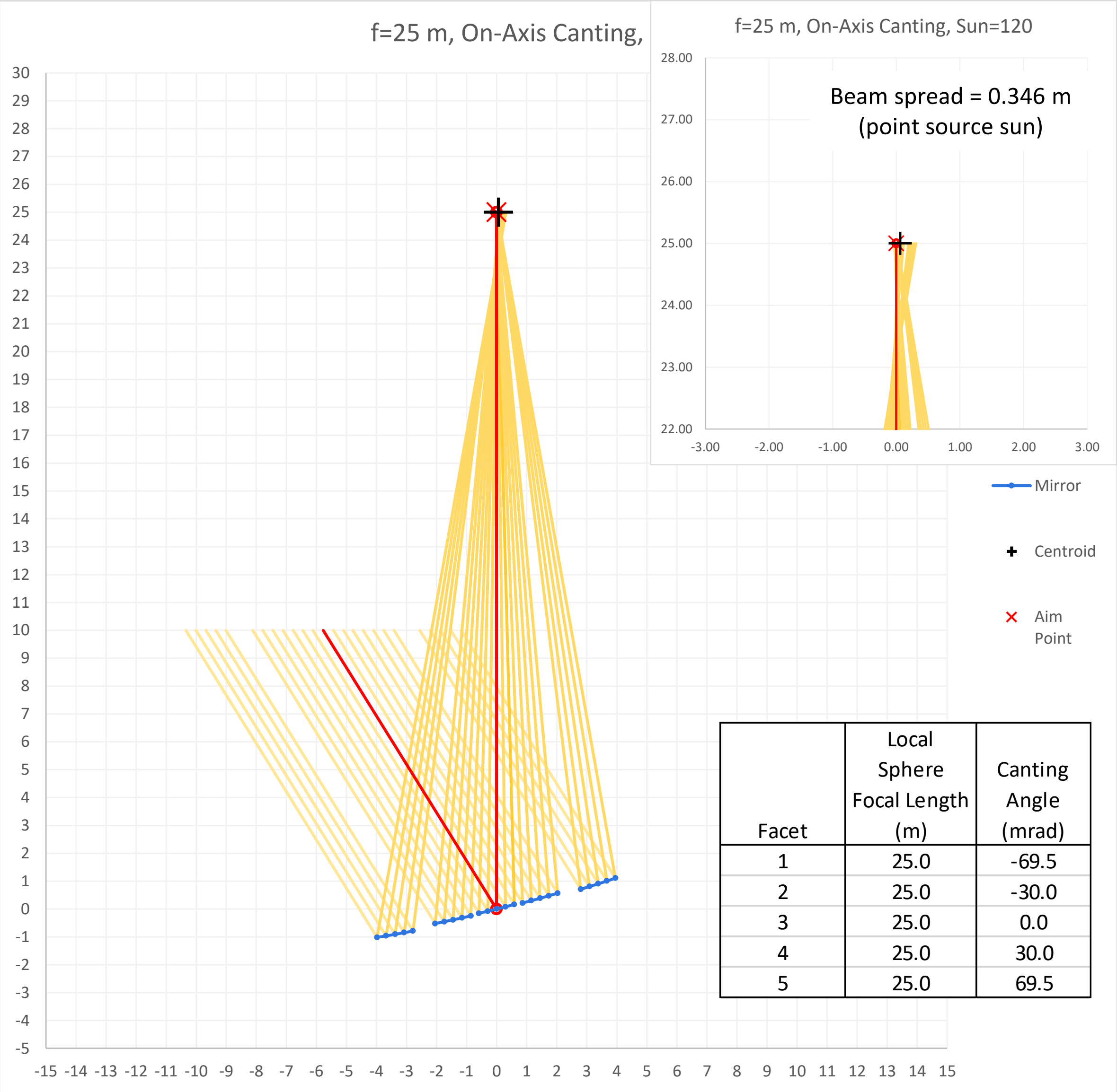
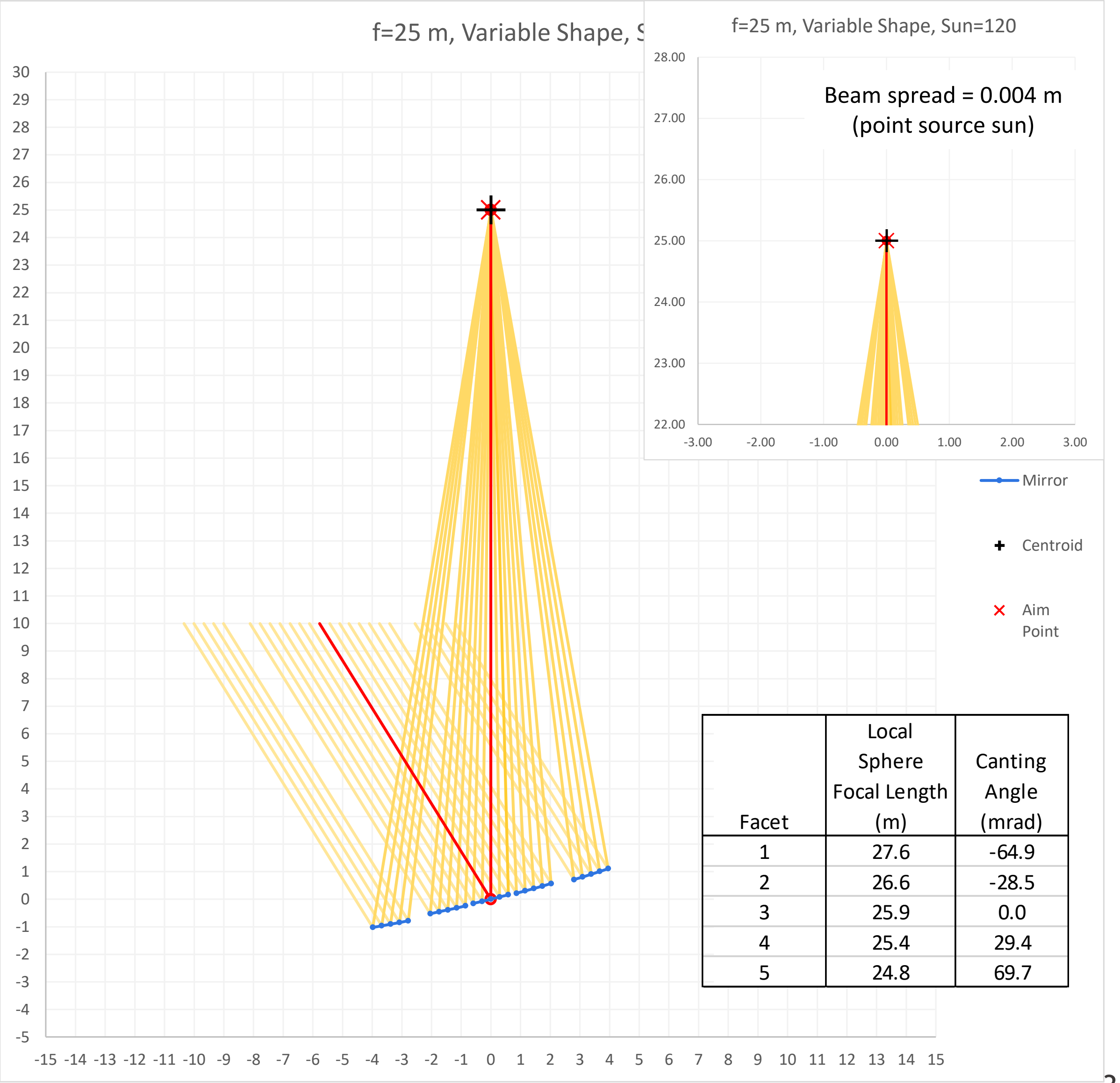


Facet	Local Sphere Focal Length (m)	Canting Angle (mrad)
1	25.0	-69.5
2	25.0	-30.0
3	25.0	0.0
4	25.0	30.0
5	25.0	69.5

Variable shape:

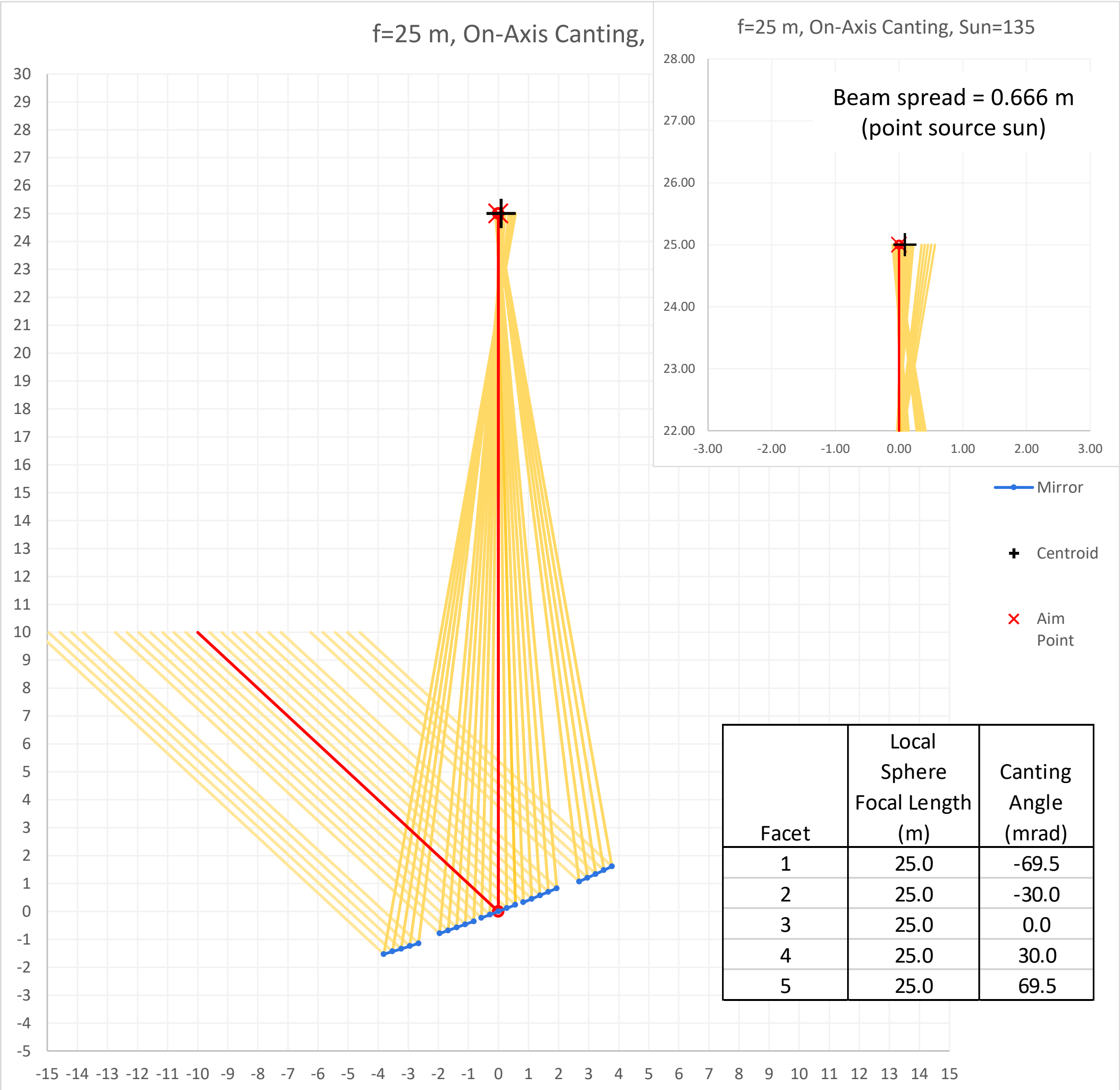


Facet	Local Sphere Focal Length (m)	Canting Angle (mrad)
1	27.6	-64.9
2	26.6	-28.5
3	25.9	0.0
4	25.4	29.4
5	24.8	69.7

Sun is modeled as a point source. Sun shape not included.

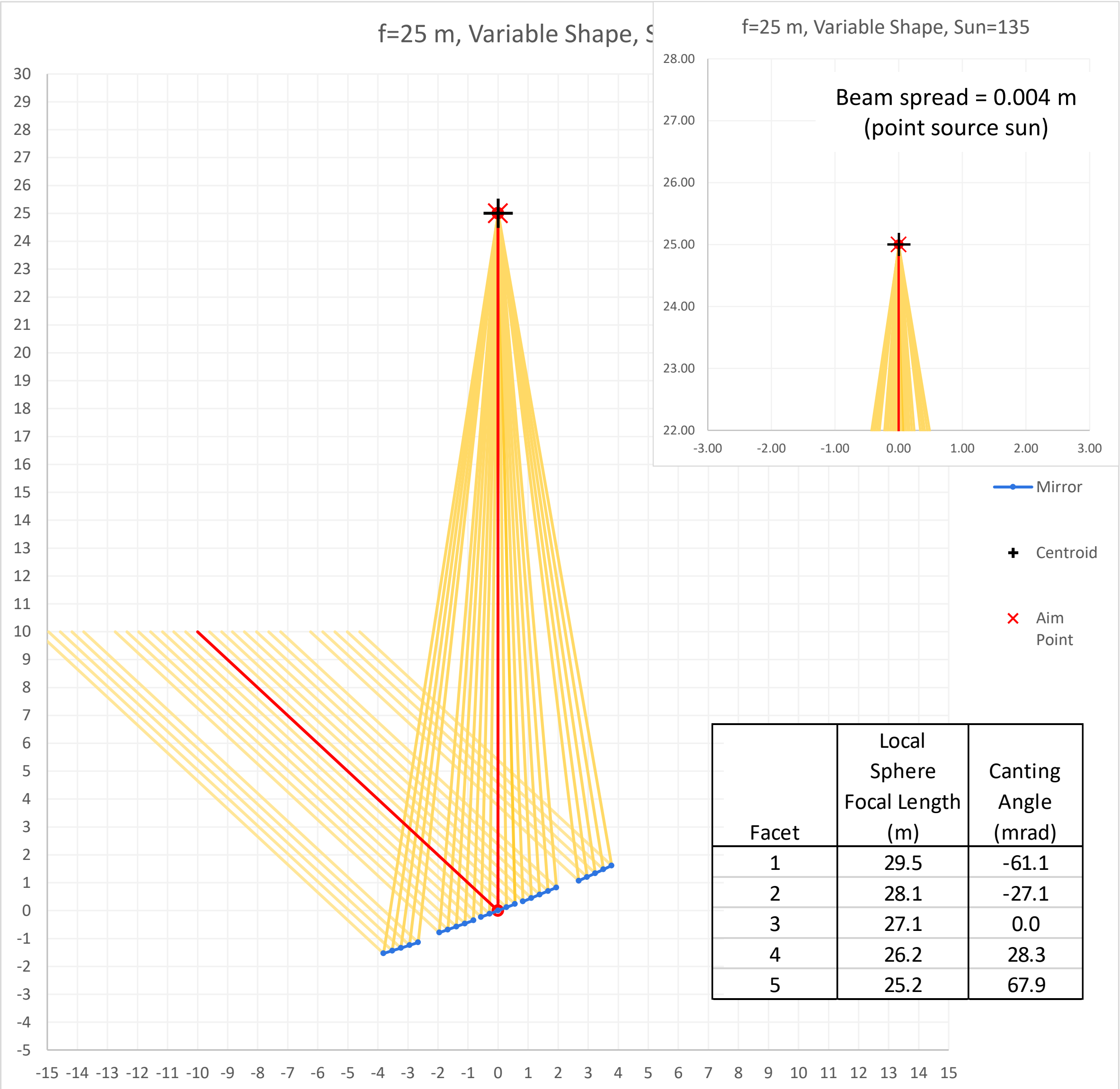
Some Heliostats Intentionally Change Shape

Constant shape:



Facet	Local Sphere Focal Length (m)	Canting Angle (mrad)
1	25.0	-69.5
2	25.0	-30.0
3	25.0	0.0
4	25.0	30.0
5	25.0	69.5

Variable shape:



Facet	Local Sphere Focal Length (m)	Canting Angle (mrad)
1	29.5	-61.1
2	28.1	-27.1
3	27.1	0.0
4	26.2	28.3
5	25.2	67.9

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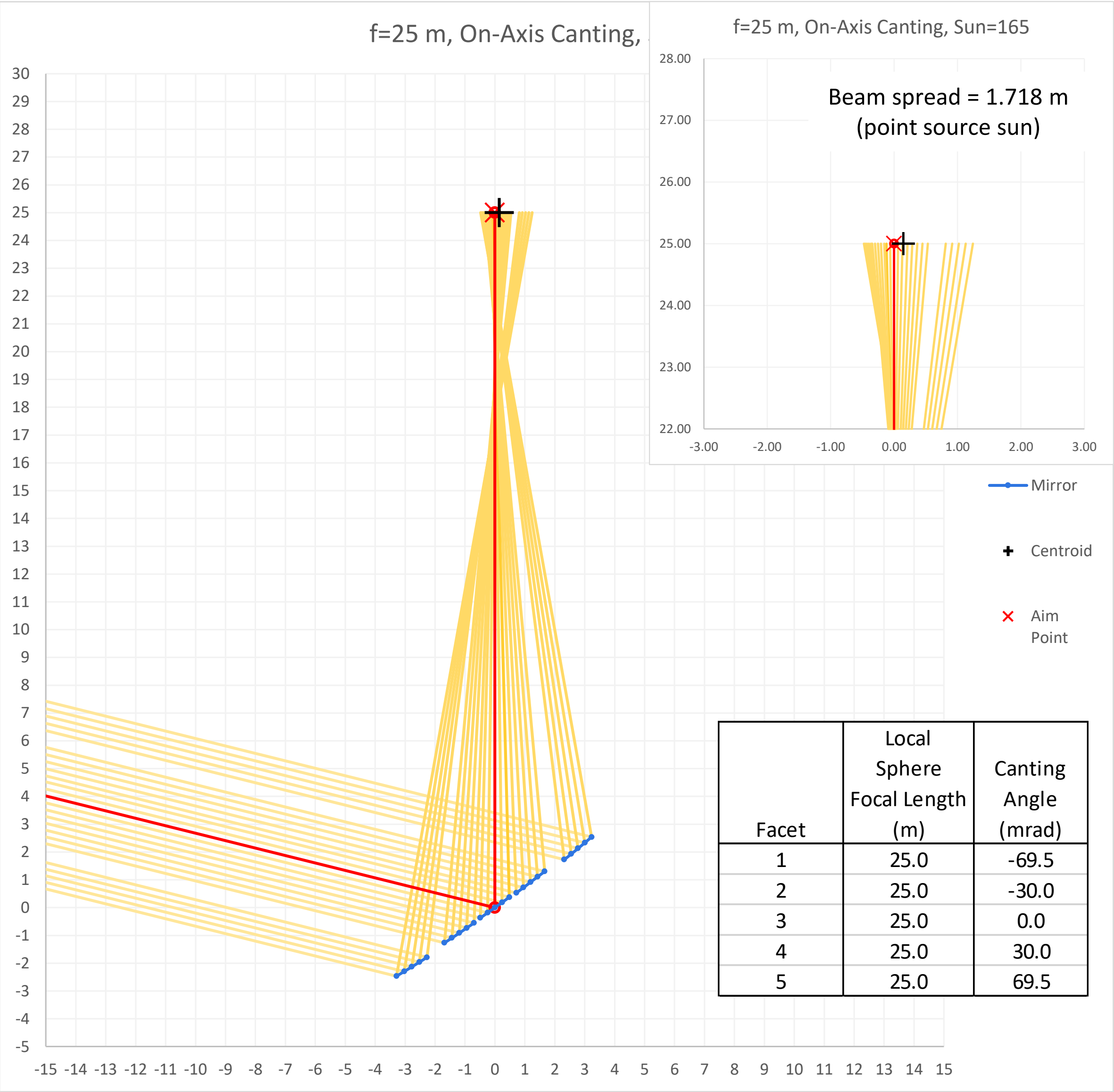
Sun is modeled as a point source. Sun shape not included.

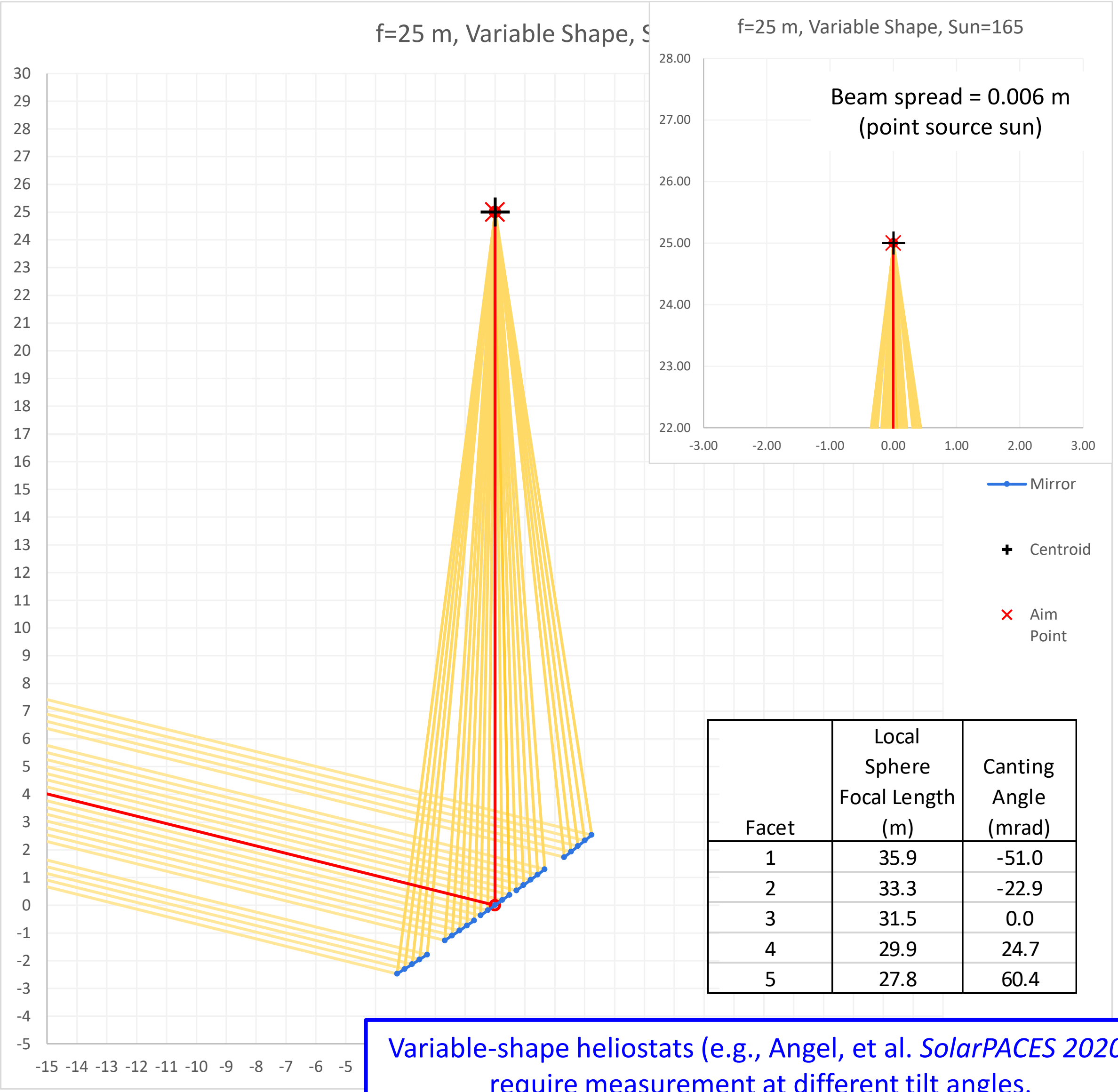
Some Heliostats Intentionally Change Shape

Constant shape:



Facet	Local Sphere Focal Length (m)	Canting Angle (mrad)
1	25.0	-69.5
2	25.0	-30.0
3	25.0	0.0
4	25.0	30.0
5	25.0	69.5

Variable shape:



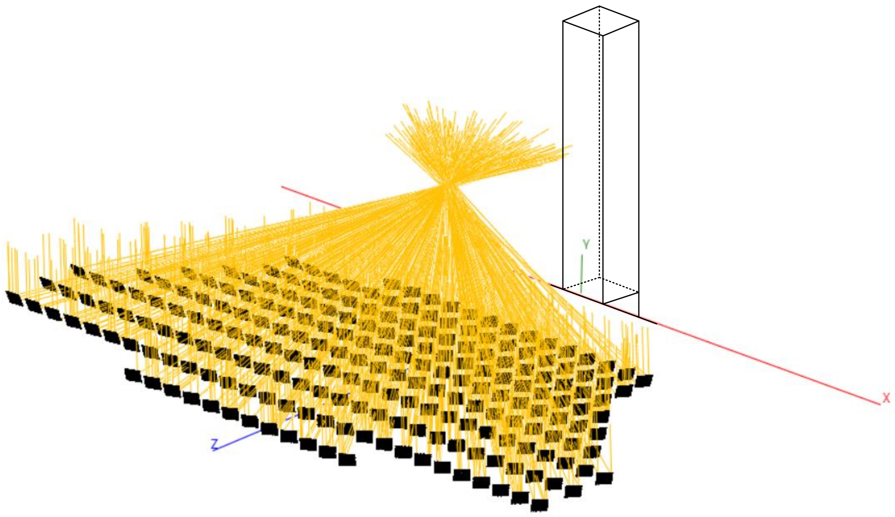
Facet	Local Sphere Focal Length (m)	Canting Angle (mrad)
1	35.9	-51.0
2	33.3	-22.9
3	31.5	0.0
4	29.9	24.7
5	27.8	60.4

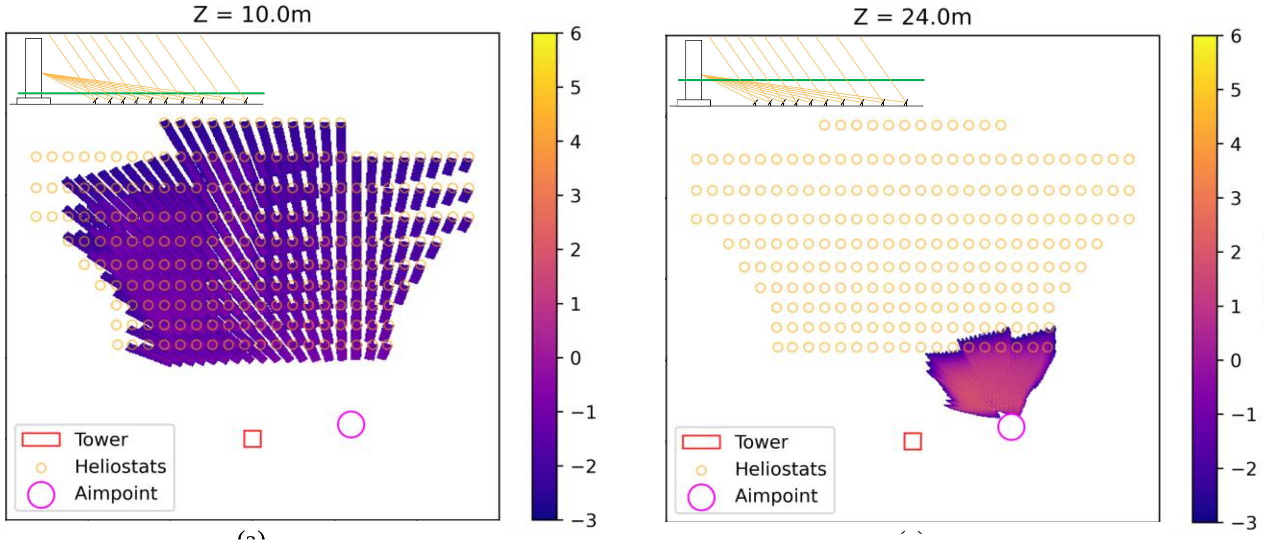
Variable-shape heliostats (e.g., Angel, et al. *SolarPACES 2020*) require measurement at different tilt angles.

Sun is modeled as a point source. Sun shape not included.

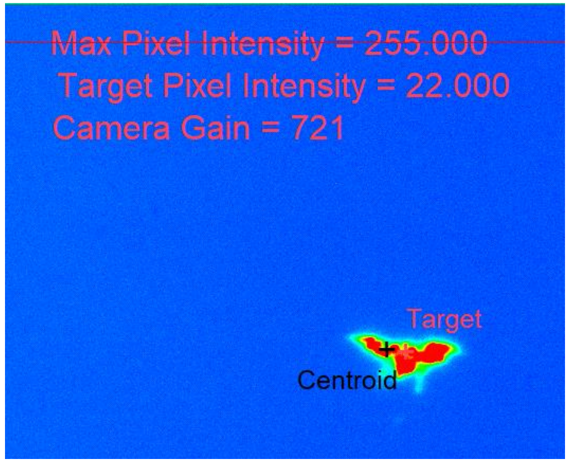
Flight Safety: High Flux Over Active Field

Where is the flux?

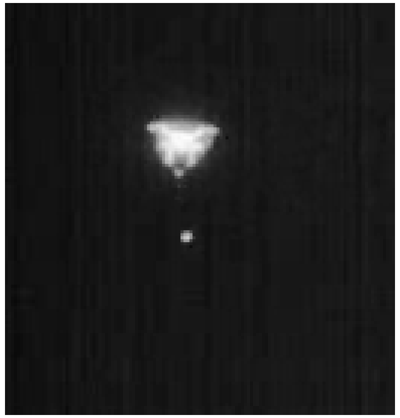




What is the flux limit?



BCS image of UAS under high flux



Thermographic image of hot debris ejection

- Under four heliostats (< 80 kW/m^2), we observed the UAS ejecting a piece of hot debris, and then the UAS departed controlled flight, losing 5 m altitude and deviating 8 m east before recovering.
- Significant damage was observed post flight. Thermographic imaging indicated that UAS skin temperature exceeded 200 °C. Flight logs listed electronic speed controller (ESC) temperatures exceeding 100 °C.

After

Desired Metrology Characteristics

Primary characteristics:

- Accurate (verified against ground truth)
- Precise
- High sampling resolution
- Measure slope
- Distortion tolerant
- Astigmatism tolerant

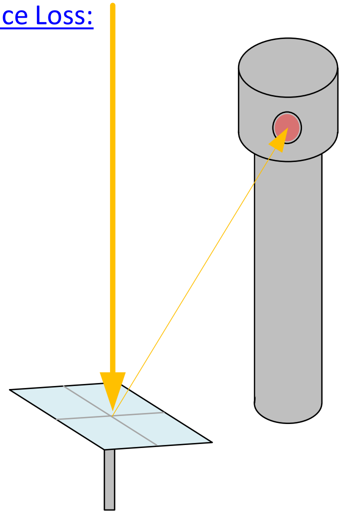
Outdoors:

- Measure optical pointing and slope
- Daytime
- Non-intrusive
- Wind tolerant
- Measure at different tilt angles (deflection, variable shape)
- Measure at different temperatures
- Measure wind effects
- Able to measure very large mirrors
- Avoids long optical path length problems
- Safe despite high flux
- Fast

State of the Art

Reflectance Loss

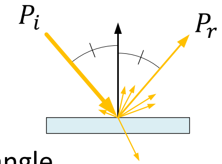
Reflectance Loss:



Soiling or degradation causes loss of reflectance.
Power is reduced.

Measure:
- Specular reflectance:

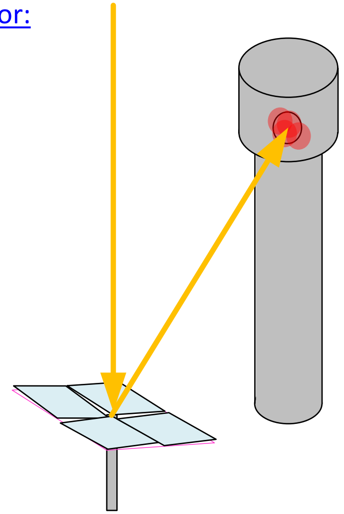
$$\rho = \frac{P_r}{P_i}$$



- Varies with incidence angle.
- Varies with wavelength.
- **Varies with time, plant location.**

Corrective actions:
- Wash mirrors – when?
- Replace degraded mirrors.

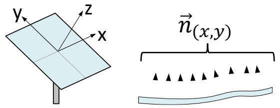
Slope Error:



Slope error causes irregular, defocused beam.
Power is not focused in expected location.

Measure:
- Optical slope:

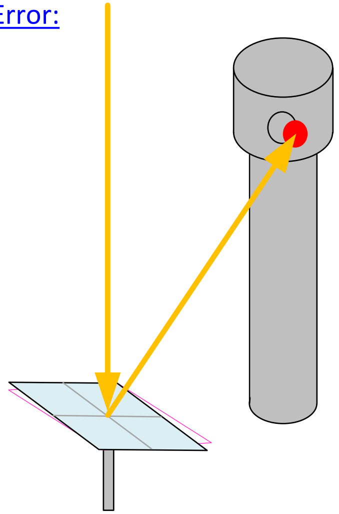
$$f(x, y) \rightarrow \vec{n}_{(x,y)}$$



- **Varies with configuration, temperature.**

Corrective actions:
- Design refinement.
- Manufacturing control.
- In-field maintenance (rare).

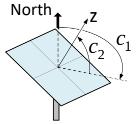
Pointing Error:



Pointing error causes beam to miss target.
Power is not in expected location.

Measure:
- Correction function:

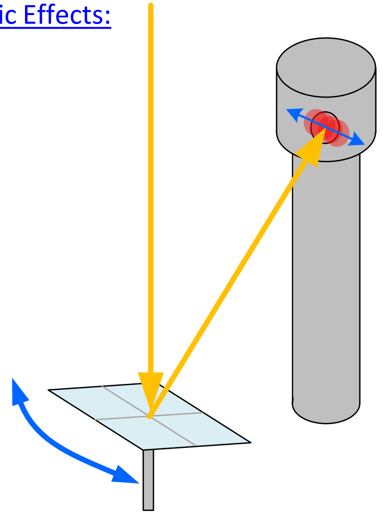
$$f(c_1, c_2) \rightarrow [\Delta c_1, \Delta c_2]$$



- **For all sun positions in solar year.**
- Two flavors:
  - Offline calibration.
  - Real-time, during operation.

Corrective actions:
- Apply correction function via software control.

Dynamic Effects:



Beam oscillations due to wind or control.
Power location varies over time.

Measure:
- Shape variation with time.
- Pointing variation with time.
- Wind-induced: Flutter response.
- Self-induced: Control dynamics.

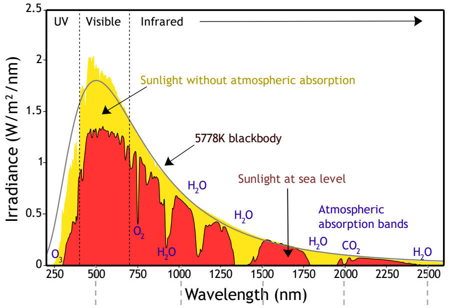
Corrective actions:
- Design refinement.
- Operation strategy.

Requirements:
- Measurement accuracy must be < 0.01°.
- Measurements must be in situ, daylight, high speed.

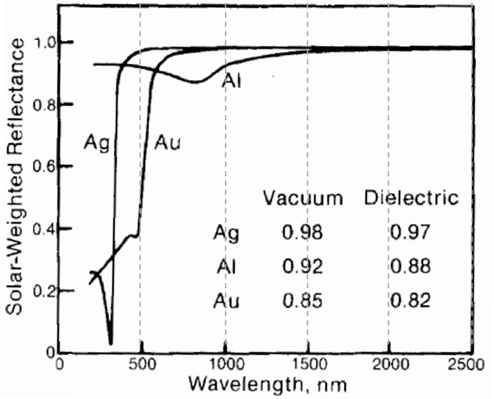
Measuring Reflectance Loss

Material Reflectance Loss

Spectrum of Solar Radiation (Earth)[1]



Spectral Reflectance [2]



(Specular Reflectance Not Shown)

SolarPACES Guideline[3]

Key Parameter:

Solar-Weighted Specular Reflectance

Mature Instruments

Material Degradation

Example outdoor test:

NREL Accelerated Weathering [4]

Example indoor test:

Xenon Arc Lamp Exposure (XALE) [5]

Example commercial testing:

CFV Labs [6]

Key Parameter:

Response to environment

Mature Instruments

Soiling

Example soiling:

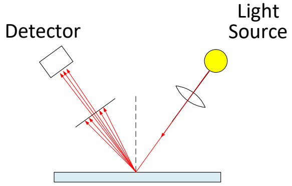
Example BRDF:

[7]

Point measurement:

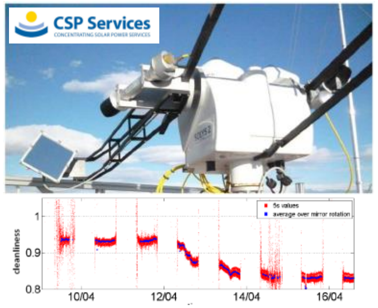
[8]

[9]



See comparison survey.[10]

Measurement stations:



[11]

AVUS Soiling Station [12]

Key Parameter:

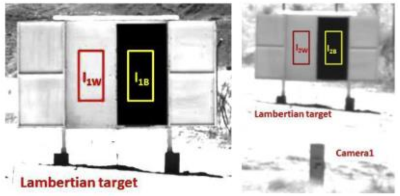
Specular reflectance in the field

BRDF: Mature
Point measure: Mature
Wide area: Ongoing

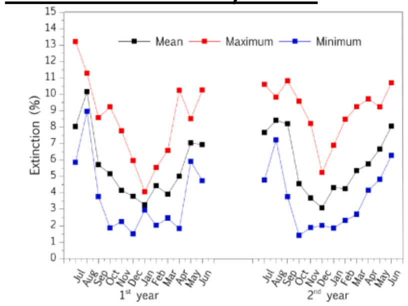
Atmospheric Extinction

Apparatus:

[13]



Data over two years:



[14]

Key Parameter:

Air transmittance loss

Mature Instruments

Citations for Measuring Reflectance Loss

Material Reflectance Loss

1. Solar spectrum: https://commons.wikimedia.org/wiki/File:Solar_Spectrum.png.
2. Reflectance spectra: Silver/Glass Mirrors for Solar Thermal Systems.
   Solar Energy Research Institute (SERI) Report SERI/SP-271-2293, June 1985.
3. A. Fernandez-Garcia, et al. Parameters and Methods to Evaluate the Reflectance Properties of Reflector Materials for Concentrating Solar Power Technology. SolarPACES Official Reflectance Guideline Version 3.0. March 2018.

Material Degradation

4. NREL Outdoor Ultra-Accelerated Weathering System: https://www.nrel.gov/csp/facilities.html.
5. T. Farrell, F. Burkholder, and Guangdong Zhu. Measurement and Reporting Guidelines for Solar Mirror Aging Tests Using Xenon Arc Lamp Exposure (XALE). NREL Technical Report NREL/TP-5700-84330, April 2023.
6. CFV Labs: https://www.cfvlabs.com/.

Soiling

7. Scatter Works: https://thescatterworks.com/wp-content/uploads/Scatterometer-Overview-7.pdf
   John Stover. *Optical Scattering: Measurement and Analysis, 2nd Edition.* SPIE Press 1995.
8. Devices and Services 15R-USB Specular Reflectometer. https://www.devicesandservices.com/prod02.htm.
9. Surface Optics Corporation 410-Solar Visible / NIR Portable Reflectometer.
   https://surfaceoptics.com/products/reflectometers-emissometers/solar-absorptance-measurements-410/
10. Wette, et al. Comparison of Commercial Reflectometers for Solar Mirrors. *SolarPACES 2022.*
11. CSP Services TraCS System: https://www.cspservices.de/wp-content/uploads/CSPS-TraCS-Soiling.pdf
12. AVUS soiling station: G. Bern, et al. AVUS – Automatic Soiling Rate Measurement Supporting O&M and Performance Prediction of Concentrating Solar Thermal Power Plants – Analysis of Soiling Events. *SolarPACES 2022.*

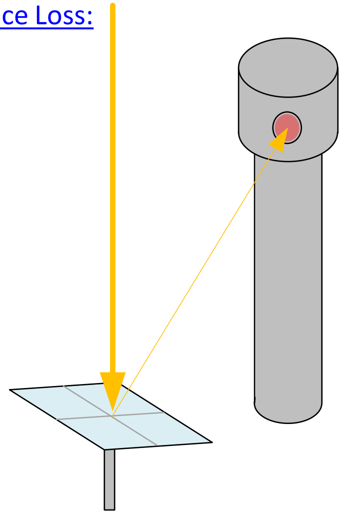
Atmospheric Extinction

13. J. Ballestrín, et al. Solar extinction measurement system based on digital cameras. Application to solar tower plants. *Renewable Energy* **125**, pp.648-654, 2018.
14. Carra, et al. Interannual variation of measured atmospheric solar radiation extinction levels. *Sustainable Energy Technologies and Assessments* **51**, 2022.

There is much more work in these areas; this is just a sample.

Slope Error

Reflectance Loss:

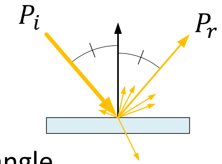


Soiling or degradation causes loss of reflectance.
Power is reduced.

Measure:

- Specular reflectance:

$$\rho = \frac{P_r}{P_i}$$

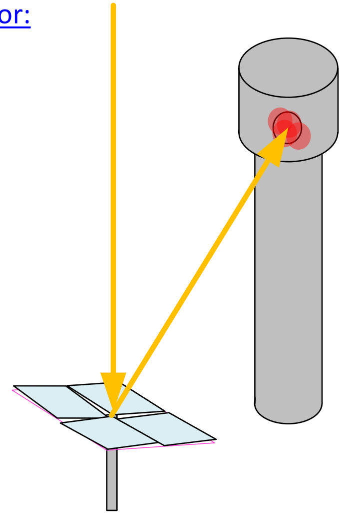


- Varies with incidence angle.
- Varies with wavelength.
- **Varies with time, plant location.**

Corrective actions:

- Wash mirrors – when?
- Replace degraded mirrors.

Slope Error:

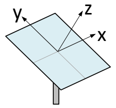


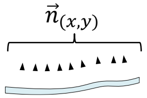
Slope error causes irregular, defocused beam.
Power is not focused in expected location.

Measure:

- Optical slope:

$$f(x, y) \rightarrow \vec{n}_{(x,y)}$$



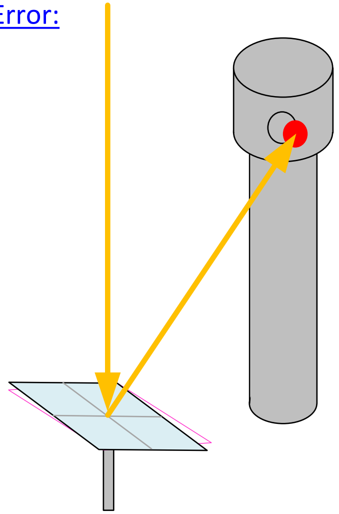


- **Varies with configuration, temperature.**

Corrective actions:

- Design refinement.
- Manufacturing control.
- In-field maintenance (rare).

Pointing Error:

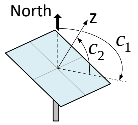


Pointing error causes beam to miss target.
Power is not in expected location.

Measure:

- Correction function:

$$f(c_1, c_2) \rightarrow [\Delta c_1, \Delta c_2]$$

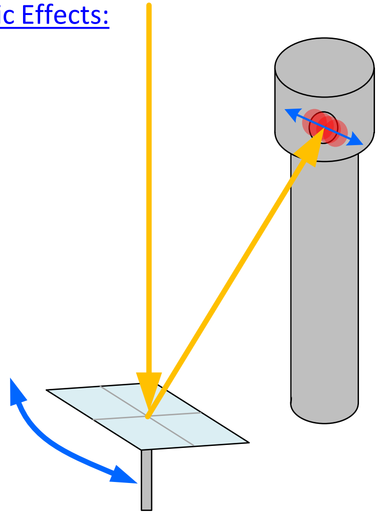


- **For all sun positions in solar year.**
- Two flavors:
  - Offline calibration.
  - Real-time, during operation.

Corrective actions:

- Apply correction function via software control.

Dynamic Effects:



Beam oscillations due to wind or control.
Power location varies over time.

Measure:

- Shape variation with time.
- Pointing variation with time.
- Wind-induced: Flutter response.
- Self-induced: Control dynamics.

Corrective actions:

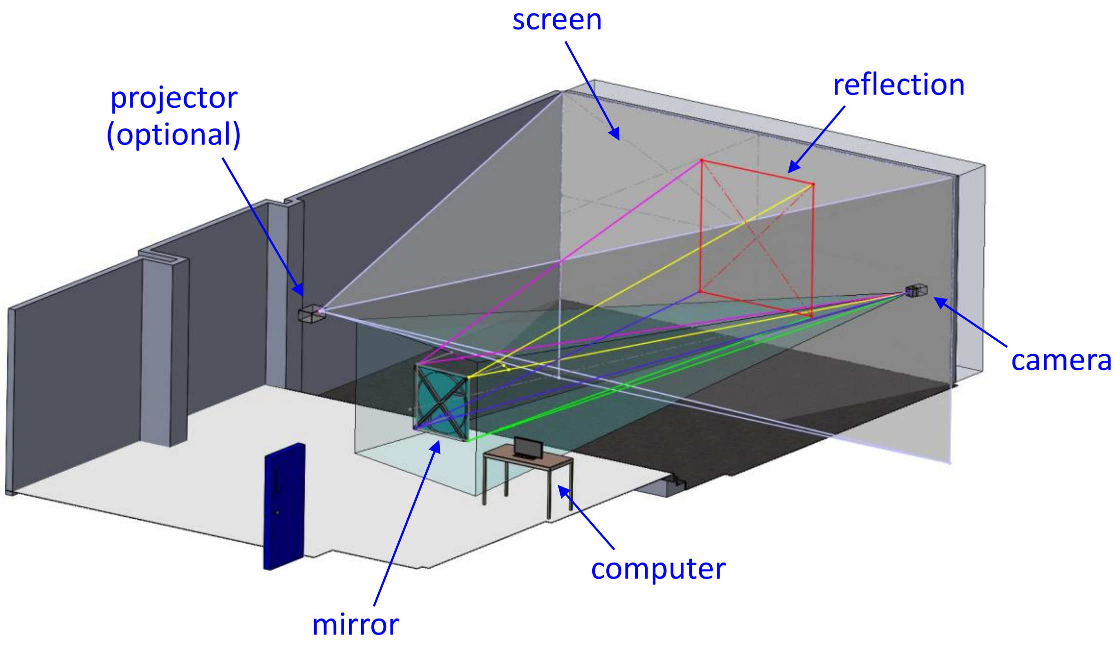
- Design refinement.
- Operation strategy.

Requirements:

- Measurement accuracy must be < 0.01°.
- Measurements must be in situ, daylight, high speed.

SOFAST: High-Resolution Slope Measurement

Basic SOFAST Elements



Prototype Development

- What areas need improvement?
- Any artifacts (ripples, warping,…)?

Process Development

- Bad areas?
- Consistency?

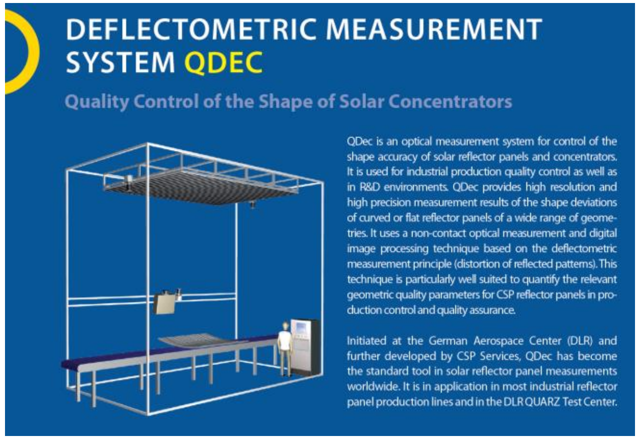
Factory Production

- Meets specs?
- Process control?

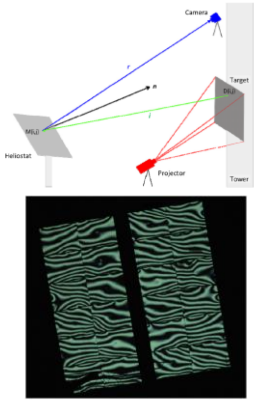
Example related papers (abbreviated):

- T. Wendelin, et al. Video Scanning Hartmann Optical Testing, 2006.
- T. März, et al. Validation of Two Optical Measurement Methods, 2011.
- S. Ulmer, et al. Automated Measurement of Heliostat Slope Errors, 2011.
- C. Andraka, et al. Rapid Reflective Facet Characterization, 2014.
- N. S. Finch, et al. Uncertainty Analysis SOFAST, 2014.
- A.M. Bonanos, et al. Heliostat surface shape characterization, 2019.
- M. Montecchi, et al. VISproPT Commissioning, 2022.
- CSP Services. QDec-M. CSPS-QDec.pdf.
- D. Kesseli, et al. New Reflected Target Optical System, 2023.

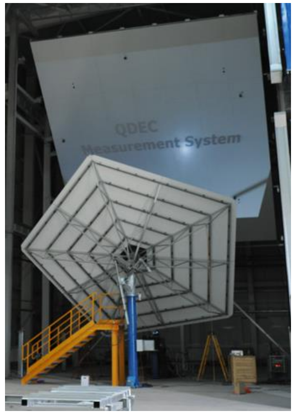
DLR/CSP Services Accomplishments



https://www.cspservices.de/wp-content/uploads/CSPS-QDec.pdf



Ulmer, et al. 2014.

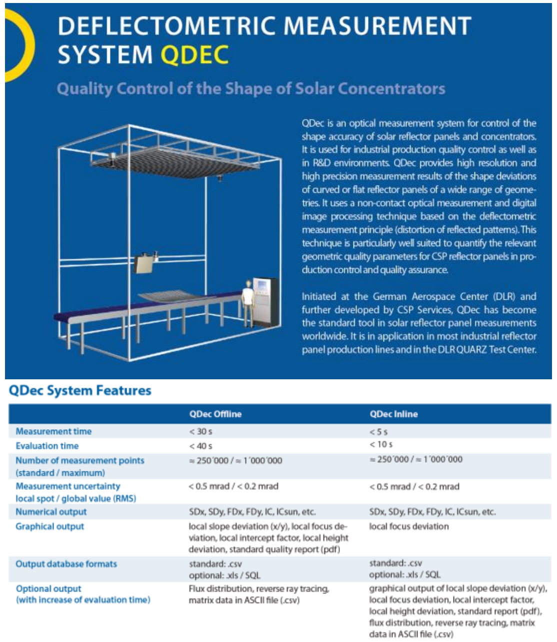


https://www.cspservices.de/quality-control/

Citations for High-Resolution Slope Measurement

- T. Wendelin, et al. Video Scanning Hartmann Optical Testing of State-of-the-Art Parabolic Trough Concentrators. Solar 2006 Conference (ISEC '06), Denver, Colorado, July 2006. Also NREL NREL/CP-550-39590, June 2006.
- T. März, et al. Validation of Two Optical Measurement Methods for the Qualification of the Shape Accuracy of Mirror Panels for Concentrating Solar Systems. *Journal of Solar Energy Engineering* **133**, August 2011.
- S. Ulmer, et al. Automated High Resolution Measurement of Heliostat Slope Errors. *Solar Energy* **85**, pp. 685-687, 2011.
- C. Andraka, et al. Rapid Reflective Facet Characterization Using Fringe Reflection Techniques. *Journal of Solar Energy Engineering* **136**, February 2014.
- N. S. Finch and C. E. Andraka. Uncertainty Analysis and Characterization of the SOFAST Mirror Facet Characterization System. *Journal of Solar Energy Engineering* **136**, February 2014.
- A.M. Bonanos, M. Faka, D. Abate, S. Hermon, and M.J. Blanco. Heliostat surface shape characterization for accurate flux prediction. *Renewable Energy* **142**, pp. 30-40, 2019.
- M. Montecchi, G. Cara, and A. Benedetti. VISproPT commissioning and SFERA-III WP10 Task3 round-robin on 3D shape measurements: recommended procedure and ENEA results. ENEA Report TERIN-STSN/2022/14, November 2022.
- CSP Services. QDec-M. https://www.cspservices.de/wp-content/uploads/CSPS-QDec.pdf.
- D. Kesseli, et al. A New Reflected Target Optical Assessment System - Stage 1 Development Results. *SolarPACES 2022.* Also NREL Report NREL/CP-5700-84142, August 2023.

DLR/CSP Services Accomplishments


DEFLECTOMETRIC MEASUREMENT SYSTEM QDEC

Quality Control of the Shape of Solar Concentrators

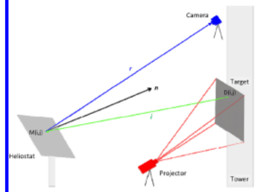
QDec is an optical measurement system for control of the shape accuracy of solar reflector panels and concentrators. It is used for industrial production quality control as well as in R&D environments. QDec provides high resolution and high precision measurement results of the shape deviations of curved or flat reflector panels of a wide range of geometries. It uses a non-contact optical measurement and digital image processing technique based on the deflectometric measurement principle (distortion of reflected patterns). This technique is particularly well suited to quantify the relevant geometric quality parameters for CSP reflector panels in production control and quality assurance.

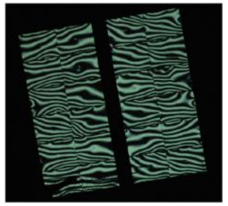
Initiated at the German Aerospace Center (DLR) and further developed by CSP Services, QDec has become the standard tool in solar reflector panel measurements worldwide. It is in application in most industrial reflector panel production lines and in the DLR QUARZ Test Center.

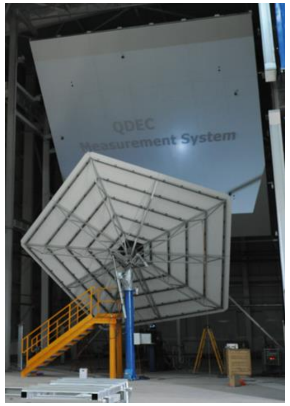
QDec System Features

	QDec Offline	QDec Inline
Measurement time	< 30 s	< 5 s
Evaluation time	< 40 s	< 10 s
Number of measurement points (standard / maximum)	≈ 250'000 / ≈ 1'000'000	≈ 250'000 / ≈ 1'000'000
Measurement uncertainty local spot / global value (RMS)	< 0.5 mrad / < 0.2 mrad	< 0.5 mrad / < 0.2 mrad
Numerical output	SDx, SDy, FDx, FDy, IC, ICsun, etc.	SDx, SDy, FDx, FDy, IC, ICsun, etc.
Graphical output	local slope deviation (x/y), local focus deviation, local intercept factor, local height deviation, standard quality report (pdf)	local focus deviation
Output database formats	standard: .csv optional: .xls / SQL	standard: .csv optional: .xls / SQL
Optional output (with increase of evaluation time)	Flux distribution, reverse ray tracing, matrix data in ASCII file (.csv)	graphical output of local slope deviation (x/y), local focus deviation, local intercept factor, local height deviation, standard report (pdf), flux distribution, reverse ray tracing, matrix data in ASCII file (.csv)

https://www.cspservices.de/wp-content/uploads/CSPS-QDec.pdf



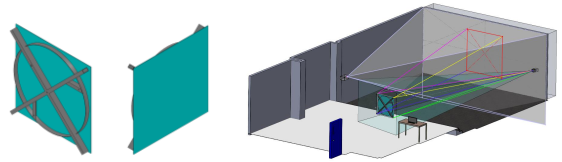




Ulmer, et al. 2014.

https://www.cspservices.de/quality-control/

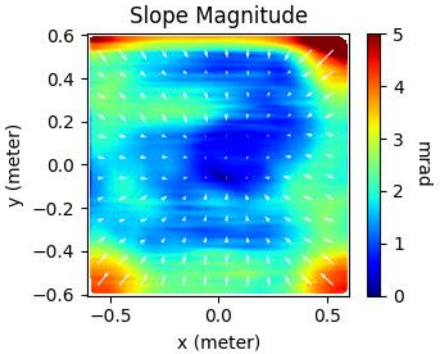
SOFAST Output: NSTTF Facet

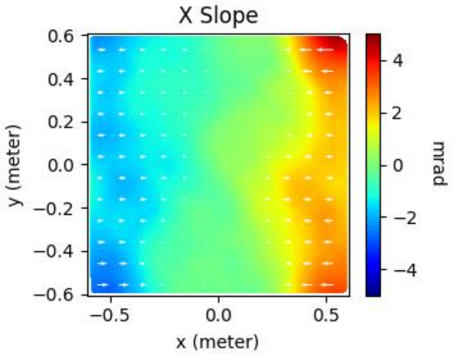


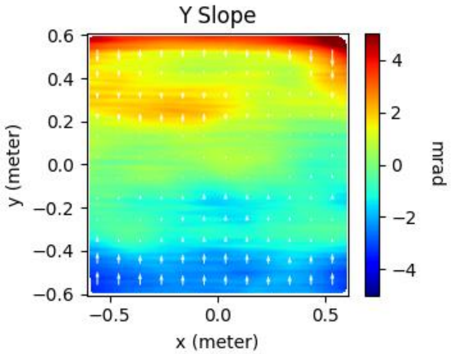
Absolute

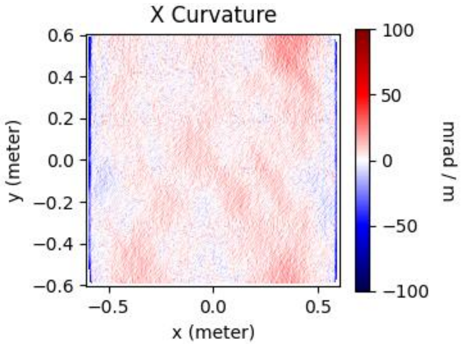
Input: Measurement

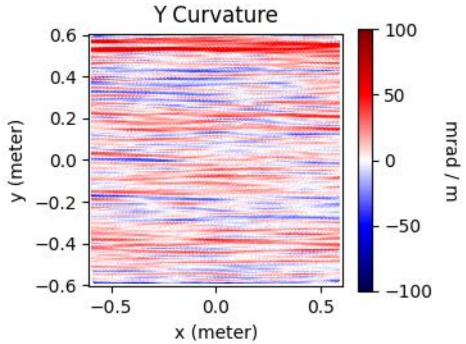
Mirror:	NSTTF Facet N-002
Instrument:	SOFAST Landscape
Date/time:	September 2022
Sample points:	Grid
Number points:	458,523
Resolution X:	1.8 mm/pt
Resolution Y:	1.8 mm/pt
Uncertainty:	±TBD mrad











Error

Add: Design Reference

Ideal Design

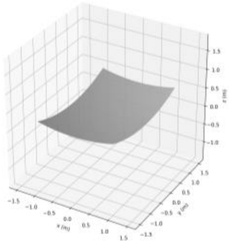
$$z = \frac{x^2}{4f_x} + \frac{y^2}{4f_y}$$

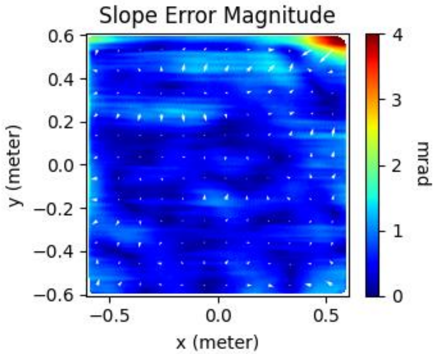
$f_x = 100$ m

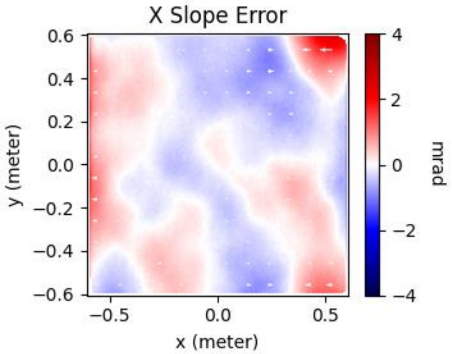
$f_y = 100$ m

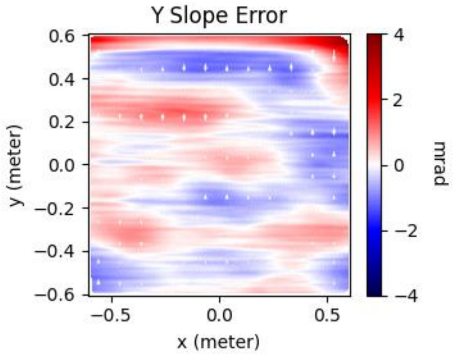
$l_x = 1.22$ m

$l_y = 1.22$ m









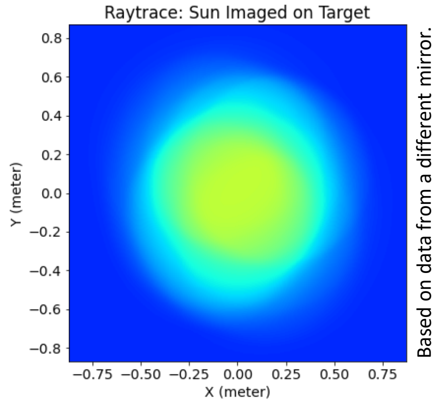
RMS slope error magnitude:	0.74 mrad
RMS slope error X:	0.46 mrad
RMS slope error Y:	0.58 mrad
Range slope error X:	[-1.01, +2.36] mrad
Range slope error Y:	[-1.21, +3.30] mrad
Best-fit focal length X:	125.7 m
Best-fit focal length Y:	114.6 m

Ray Trace

Add: Field Location, Target, Time

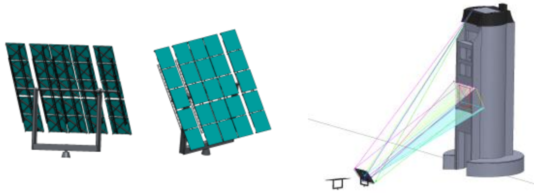
Field location:	[0.0 m, 95.7 m]
Target:	[0.0 m, 8.8 m, 28.9 m] BCS Wall

2022-06-30 14:40:22



SOFAST measures slope directly, samples at high resolution, and is distortion-tolerant.

Output Summary: NSTTF Heliostat 5W01

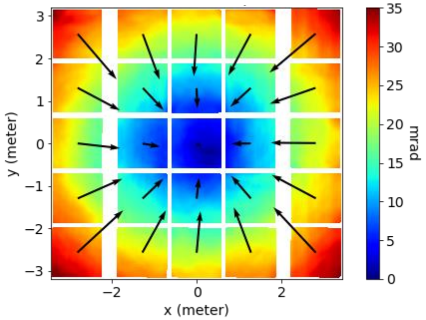


Absolute

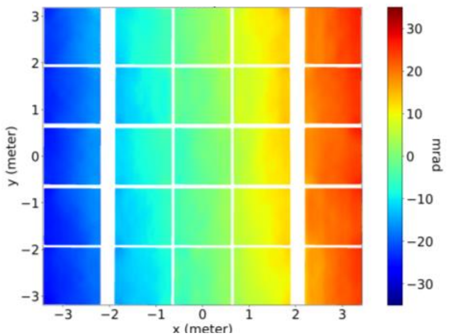
Input: Measurement

Heliostat:	5W01
Instrument:	SOFAST Tower
Date/time:	2022-06-29 23:03
Sample points:	Grid
Number points:	4,446,000/heliostat 178,000/facet
Resolution X:	2.9 mm/pt
Resolution Y:	2.9 mm/pt
Uncertainty:	±TBD mrad

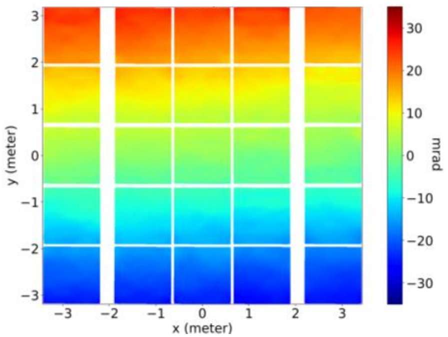
Slope Magnitude



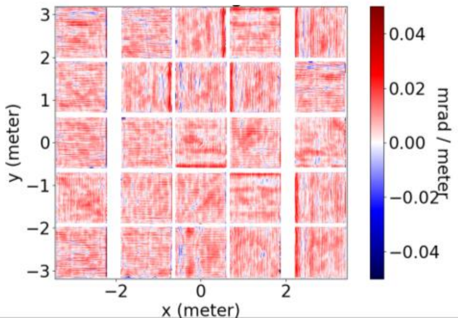
X Slope



Y Slope



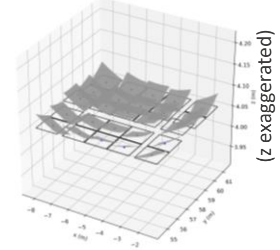
Curvature



Error

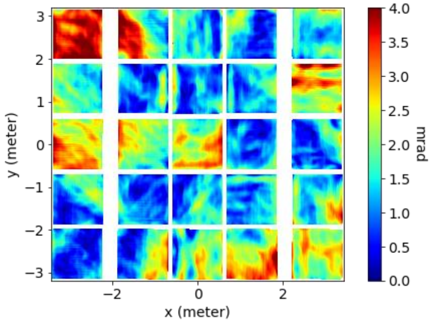
Add: Design Reference

Ideal Design

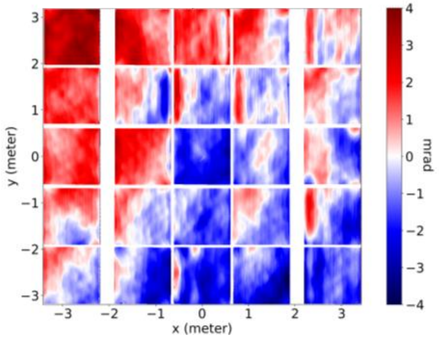


On-axis canting.
Slant distance 57.2 m.

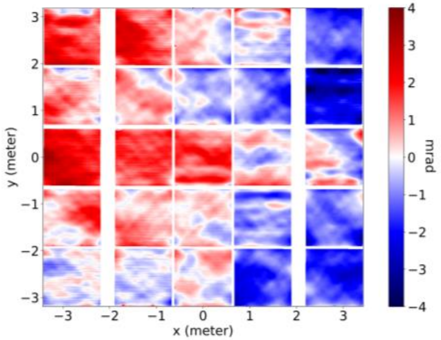
Slope Error Magnitude



X Slope Error



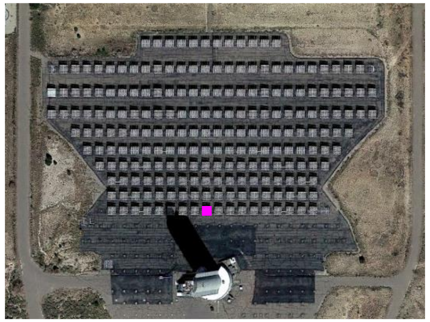
Y Slope Error



RMS slope error magnitude:	2.0 mrad
RMS slope error X:	1.6 mrad
RMS slope error Y:	1.3 mrad
RMS canting error magnitude:	1.7 mrad (n = 25)
RMS canting error X:	1.3 mrad (n = 25)
RMS canting error Y:	1.2 mrad (n = 25)
Range canting error X:	[-3.2, +2.0] mrad
Range canting error Y:	[-2.5, +2.3] mrad

Ray Trace

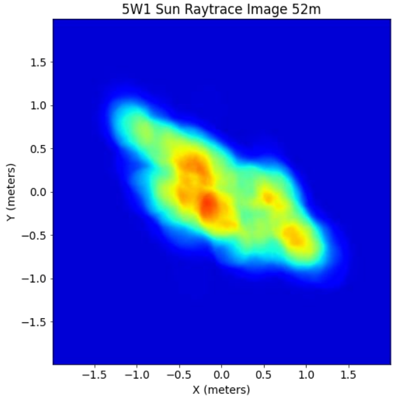
Add: Field Location, Target



Field location: [-4.66 m, 57.9 m]

Target: [0.0 m, 8.8 m, 28.9 m]
BCS Wall

2022-06-30 14:06:09



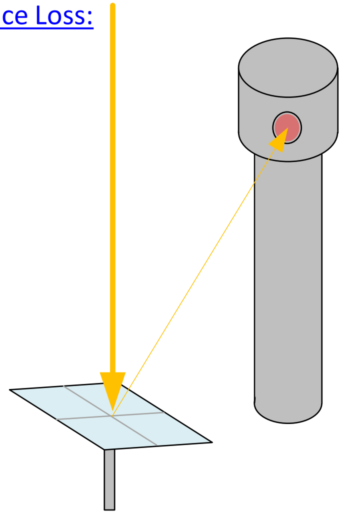
(After adjusting calibration)

Preliminary. Still work in progress.

* Following Ulmer, et al. 2011. They are further along.

Pointing Error

Reflectance Loss:

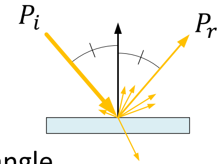


Soiling or degradation causes loss of reflectance.
Power is reduced.

Measure:

- Specular reflectance:

$$\rho = \frac{P_r}{P_i}$$

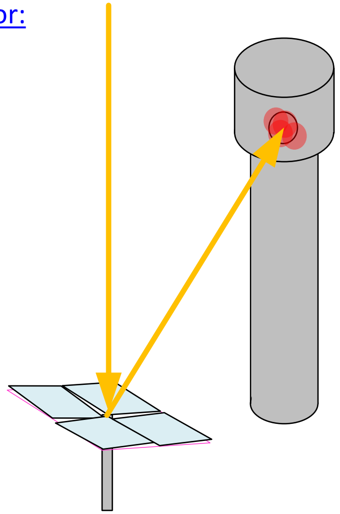


- Varies with incidence angle.
- Varies with wavelength.
- **Varies with time, plant location.**

Corrective actions:

- Wash mirrors – when?
- Replace degraded mirrors.

Slope Error:

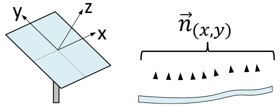


Slope error causes irregular, defocused beam.
Power is not focused in expected location.

Measure:

- Optical slope:

$$f(x, y) \rightarrow \vec{n}_{(x,y)}$$

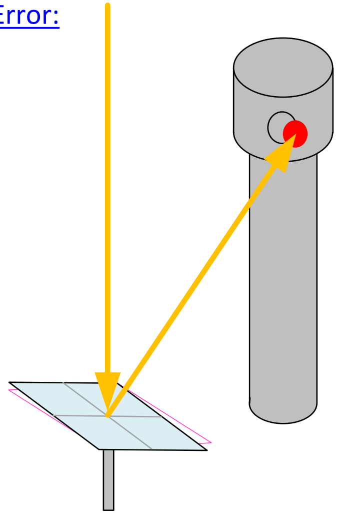


- **Varies with configuration, temperature.**

Corrective actions:

- Design refinement.
- Manufacturing control.
- In-field maintenance (rare).

Pointing Error:

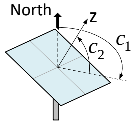


Pointing error causes beam to miss target.
Power is not in expected location.

Measure:

- Correction function:

$$f(c_1, c_2) \rightarrow [\Delta c_1, \Delta c_2]$$

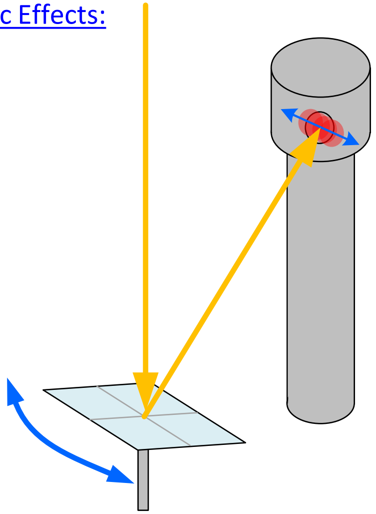


- **For all sun positions in solar year.**
- Two flavors:
  - Offline calibration.
  - Real-time, during operation.

Corrective actions:

- Apply correction function via software control.

Dynamic Effects:



Beam oscillations due to wind or control.
Power location varies over time.

Measure:

- Shape variation with time.
- Pointing variation with time.
- Wind-induced: Flutter response.
- Self-induced: Control dynamics.

Corrective actions:

- Design refinement.
- Operation strategy.

Requirements:

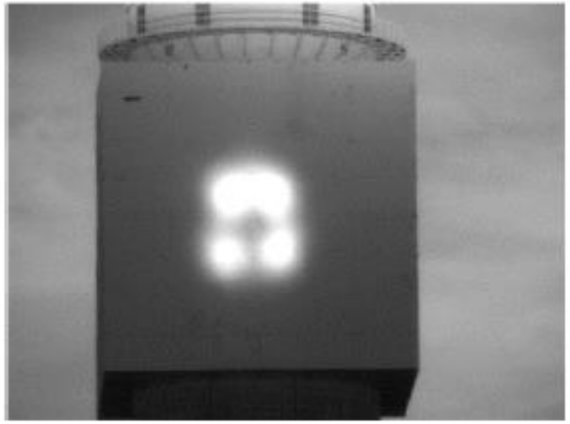
- Measurement accuracy must be < 0.01°.
- Measurements must be in situ, daylight, high speed.

See:

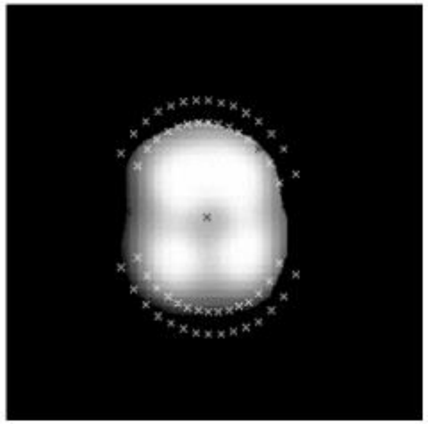
Sattler, et al. Review of heliostat calibration and tracking control methods. *Solar Energy* 207, pp. 110-132, 2020.

Heliostat Calibration

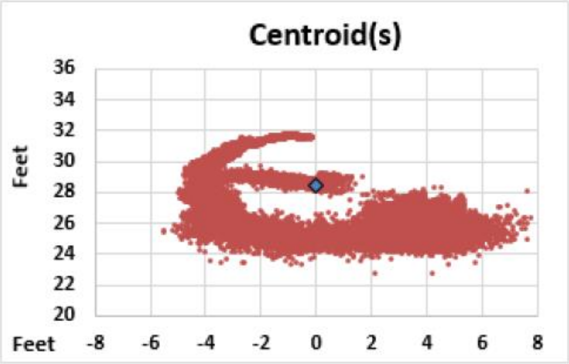
BCS Calibration:*



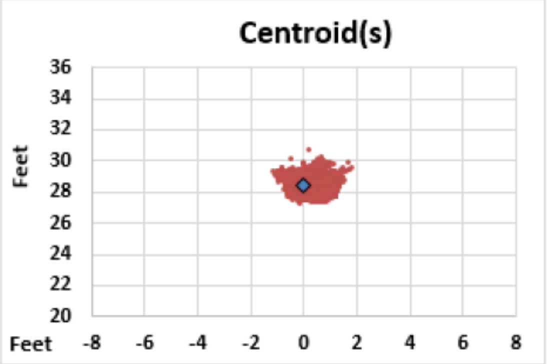
BCS Image



Centroid Analysis

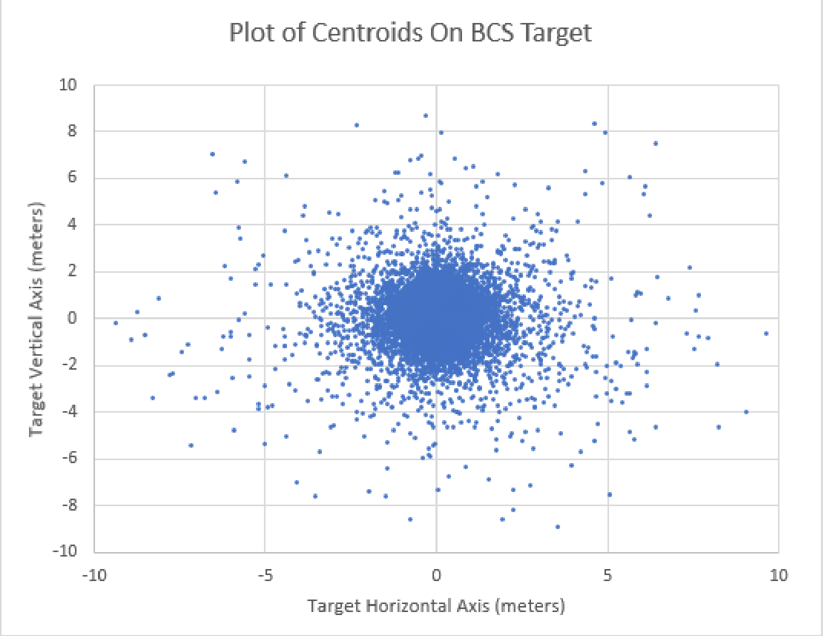


Before (~6,000 heliostats, 2019)



After (~6,000 heliostats, 2019)

Crescent Dunes BCS Analysis			
Number of BCS Images Analyzed: 116886			
Pointing Error Mean Value (mrad)		Pointing Error Standard Deviation (mrad)	
µ (Az)	µ (El)	α (Az)	α (EL)
-0.0725	-0.0217	0.6784	0.6672
Date of Evaluation		Population Size (> 4 BCS)	
03-August-2023 03:00:05 PDT		10175	Heliostats



August 2, 2023 (10,175 heliostats)
Courtesy Mark Ayres, Crescent Dunes

* Ayres, et al. Heliostat Aiming Corrections with Bad Data Detection. *SolarPACES 2019.* Also *AIP Proceedings* **2303** (2020).

See also:

S. Khalsa, C. Ho, and C. Andraka. An Automated Method to Correct Heliostat Tracking Errors. *SolarPACES 2011.*

J. Sattler, et al. Review of heliostat calibration and tracking control methods. *Solar Energy* **207**, pp. 110-132, 2020.

Both the tower and the BCS target set the pace for this calibration method.

Distant heliostats are difficult, due to reduced BCS signal strength (see above).

Heliostat Closed-Loop Control

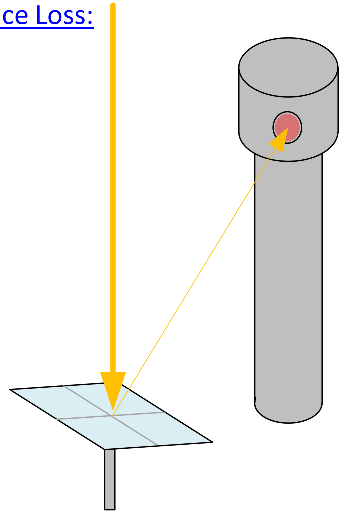
- Heliostat calibration assumes that once individual heliostat "signatures" are identified, they may be used indefinitely for the control of heliostats.
- This has advantages of simplicity, and immunity from short-term perturbations such as wind disturbances.
- However, it requires a lengthy up-front calibration process, and then is oblivious to changes that might occur (such as drift, soil settling, permanent motion due to a wind event, etc).
- *Closed-loop control* offers a way to avoid these limitations.
- However, such systems must function while the heliostat field is operating and producing maximum flux.
- Solutions must be low cost, which challenges approaches that require mounting an active camera on each heliostat, or other special heliostat modifications.
- One current system which accomplishes closed-loop control is the Heliogen SOHOT system.[1]
- See Sattler, et al.[2] for an excellent review of heliostat tracking and control methods.

[1] Sonn, et al. Estimating Orientation of Tracking Heliostats Using Circumsolar Radiance. *SolarPACES 2020.*

[2] J. Sattler, et al. Review of heliostat calibration and tracking control methods. *Solar Energy* **207**, pp. 110-132, 2020.

Dynamic Effects

Reflectance Loss:

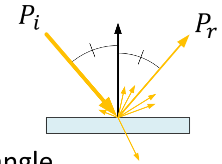


Soiling or degradation causes loss of reflectance.
Power is reduced.

Measure:

- Specular reflectance:

$$\rho = \frac{P_r}{P_i}$$

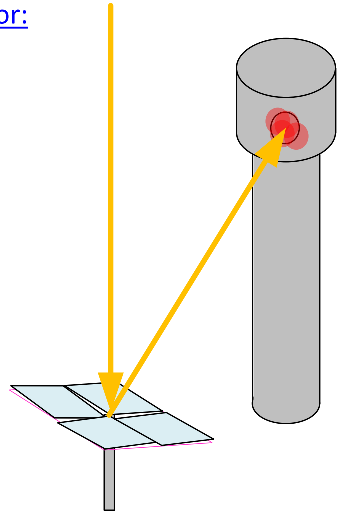


- Varies with incidence angle.
- Varies with wavelength.
- **Varies with time, plant location.**

Corrective actions:

- Wash mirrors – when?
- Replace degraded mirrors.

Slope Error:

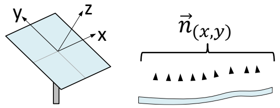


Slope error causes irregular, defocused beam.
Power is not focused in expected location.

Measure:

- Optical slope:

$$f(x, y) \rightarrow \vec{n}_{(x,y)}$$

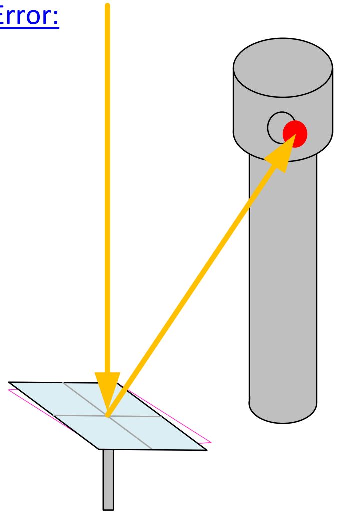


- **Varies with configuration, temperature.**

Corrective actions:

- Design refinement.
- Manufacturing control.
- In-field maintenance (rare).

Pointing Error:

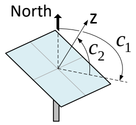


Pointing error causes beam to miss target.
Power is not in expected location.

Measure:

- Correction function:

$$f(c_1, c_2) \rightarrow [\Delta c_1, \Delta c_2]$$



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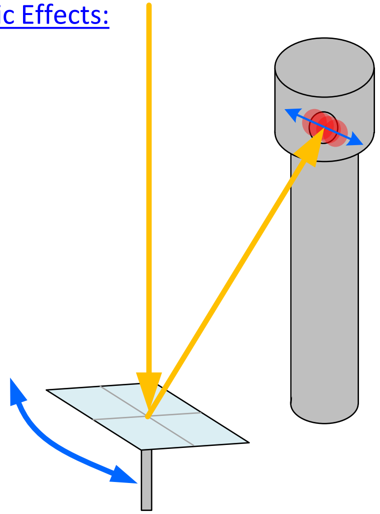


Beam oscillations due to wind or control.
Power location varies over time.

Measure:

- Shape variation with time.
- Pointing variation with time.
- Wind-induced: Flutter response.
- Self-induced: Control dynamics.

Corrective actions:

- Design refinement.
- Operation strategy.

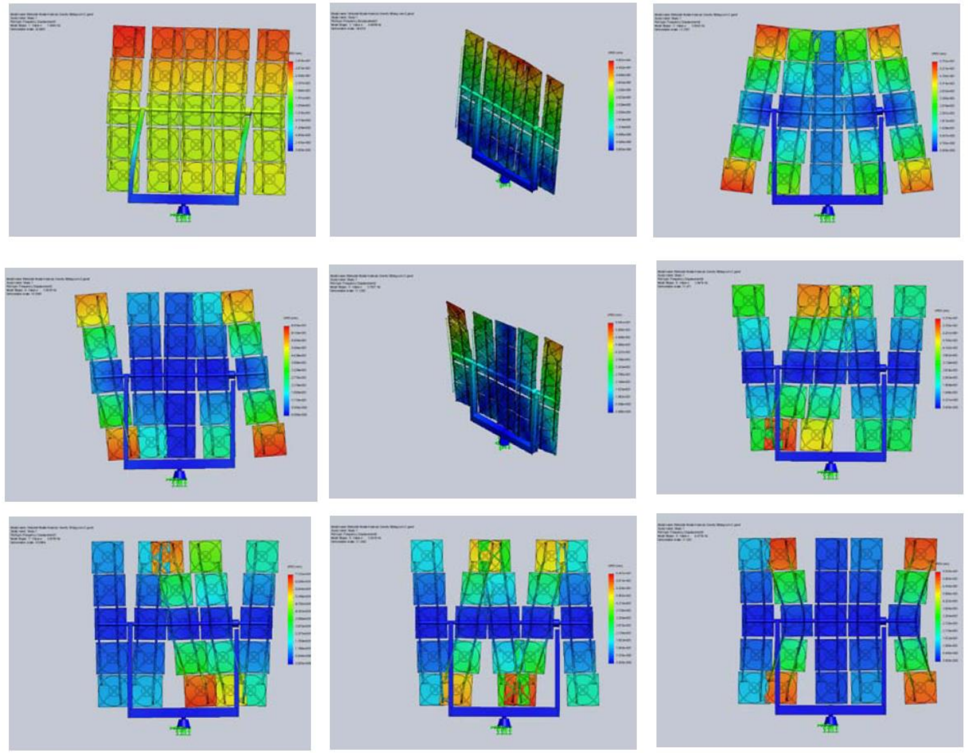
Requirements:

- Measurement accuracy must be < 0.01°.
- Measurements must be in situ, daylight, high speed.

Heliostat Deflection Analysis

Dynamic deformation analysis:

Mode shapes for first 9 predicted modes

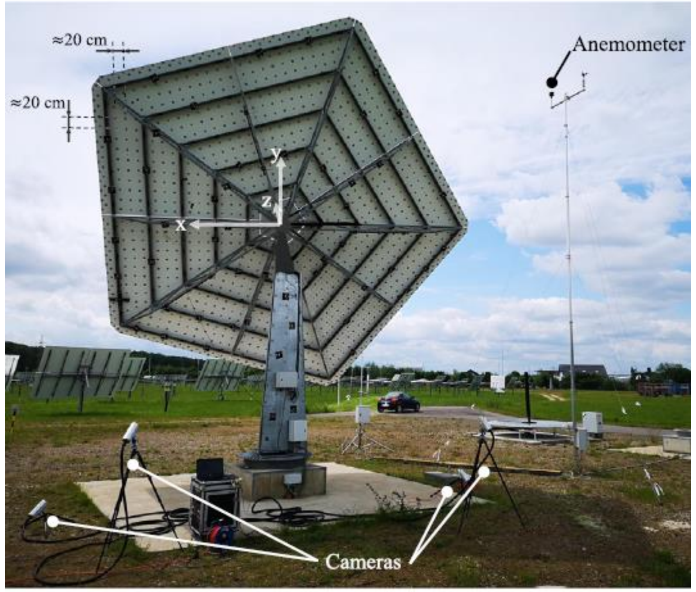


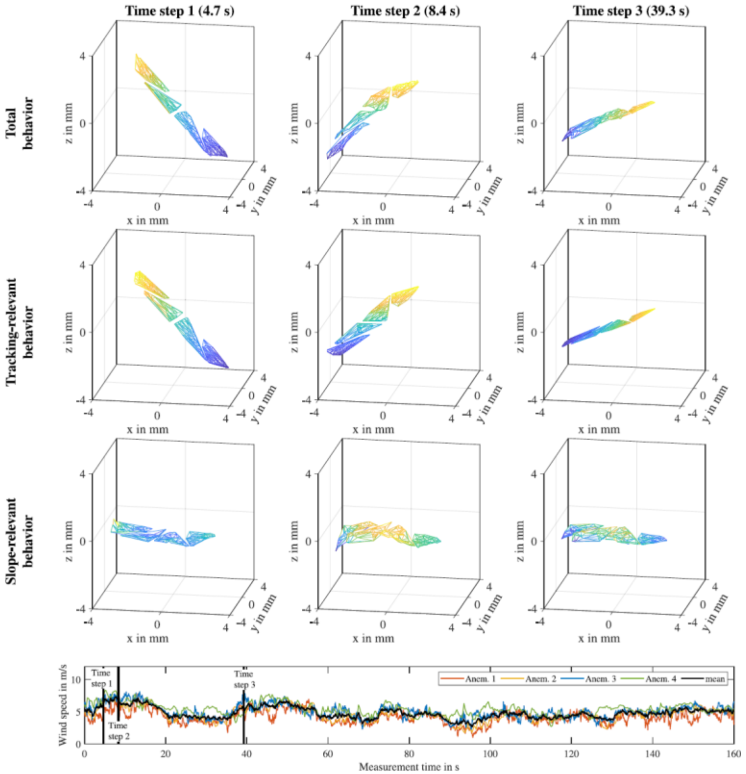
https://www.osti.gov/servlets/purl/1106593

From: D. T. Griffith, et al. Structural Dynamics Testing and Analysis for Design Evaluation and Monitoring of Heliostats. *ASME 2011 Energy Sustainability,* 2011. https://www.osti.gov/servlets/purl/1106593

Also: D. T. Griffith, et al. Structural Dynamics Testing and Analysis for Design Evaluation and Monitoring of Heliostats. *Journal of Solar Energy Engineering,* 2015.

Wind-induced deformation measurement:





From: Kristina Blume, Marc Röger, Tim Schlichting, Ansgar Macke, Robert Pitz-Paal. Dynamic photogrammetry applied to a real scale heliostat: Insights into the wind-induced behavior and effects on the optical performance. *Solar Energy* **212**, pp. 297-308, 2020.

Heliostat Metrology Gaps

Gaps

	Technology	Development Stage	Optical Surface Map	Pointing Accuracy	Surface Change Detection	Pointing Change Detection	Dynamic Motion Analysis	Soiling	Multi-Prescription	Multi-Mass	Multi-Elevation	Multi-Azimuth	Multi-Temperature	Single Facet	Full Heliostat	Full Heliostat Field	Distant Heliostats	Tower Not Required	Non-Intrusive	Full Working Envelope	High Speed	Very High Reliability	Limit Calibration Time	Statistical Process Control	Notes
Optical surface map, fast indoor	CSPS QDec-M	C	✓						✓	✓	✓			✓	✓						✓	✓	✓	✓	All requirements demonstrated. Multi-camera enables screen size similar to mirror.
	Sandia SOFAST	M	✓						✓	✓	✗		✓	✓	¾						✓	✓	✓	¾	Multi-facet measurement implemented. Outdoor full heliostat implementation in progress. Multi-elevation not demonstrated.
Optical surface map, flexible outdoor	Gap		✓	✓	✓				✓	✓	✓	opt	✓	✓	✓		✓	✓		✓					Not all requirements met.
	CSPS QDec-H	C	✓		✓				✓	✓	✗	✗	✓	✓	✓	✓	✗	✗		✗					Limited elevation angles. Requires screen on tower. Difficult in large fields.
	BrightSource Tower Images	M	✓	✓					✓	✓	✓	✓	✓	✓	✓		?	✗		✓					Does this degrade over long range?
Reflected beam direction and size, slow	BCS	M				✓			✓	✓					✓					✓					Widely used. Is standard software available?
Surface map + pointing, fast	Gap		✓	✓										✓	✓	✓	✓	✓	✓	✓	✓				Systems not proven.
	Sandia UFACET	E	✓	?										✓	✓	✓	✓	✓	✓	?	✓				Under development.
	NREL NIO	E	✓	✓										✓	✓	✓	✓	✗	✓	✗	✓				Under development. Initial published results.
	CSPS/DLR HelioPoint-II	E	✓	✓										✓	✓	✓	✓	✓	✓	✓	✓				Under development.
Dynamic wind surface map and pointing	Gap						✓			✓	✓	✓			✓		✓		✓						Optical effects not measured.
	CSPS Dynamic	M					✓			✓	✓	✓			✓		✓		✓						Not optical (dynamic photogrammetry).
Soil assessment across field	CSPS TraCS	C						✓						N/A	N/A	✗	✓		✓						Multiple copies or mobile to give spatial variation.
	ASTRI UAS	E						✓						✓	✓	✓	✓		✓						Initial published results.
Ground truth	Gap		✓	✓			✓							✓	✓			✓				✓			No method for detailed surface map of curved optics
	Water Pool	E	½											✓				✓				½			Horizontal only. No curvature.
	BCS	M			✓	✓			✓	✓				✓	✓			✓				½			Widely used. Not a detailed map of surface error.

Other perspectives:
Some gaps can currently be addressed, at least partially, by composite techniques that combine methods.

CSPS = CSP Services

- C — Commercial product.
- M — Mature research result.
- E — Emerging research.
- (red) — New system needed.

From R. Brost. Question-Based Gap Analysis of Heliostat Optical Metrology Methods. Presented in *SolarPACES 2022.*

Other perspectives:
Many opportunities for improvement.

Emerging Solutions

SOFAST Improvements

Addressing unsolved problems:

- Temperature optical effect?
- Tilt angle optical effect?
- Mobile SOFAST.

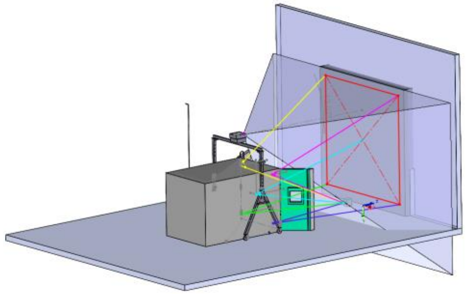
Increasing benefit:

- Ease of use.
- Industrial support.
- Educational version.
- Easy access – **OpenCSP** (OpenCSP@sandia.gov)

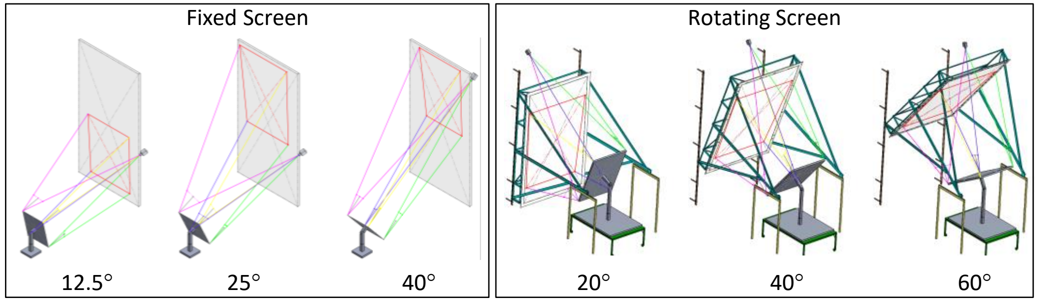
Our goal is to maximize benefit to CSP industry, research, education.

Temperature:[1]

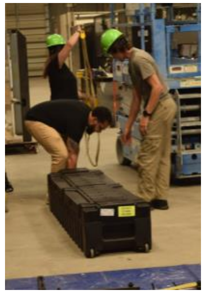
CFV Labs Chamber: -40°C → +85°C


SOFAST Layout with Temperature Chamber

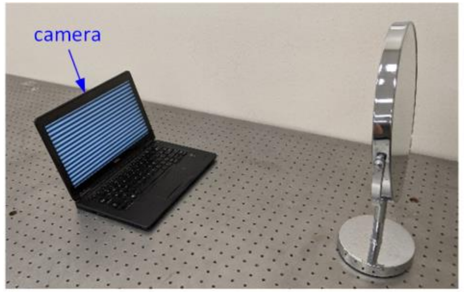
Tilt:

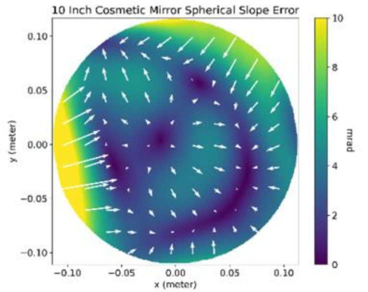


Mobile:



Education:





Related work:

[1] Sartori, et al. Composite Mirror Shape Deviations Due to Temperature Changes. AIP Proceedings **2303**, December 2023.

UFACET: Drone-Based Field Assessment

Accelerated Calibration

During construction.

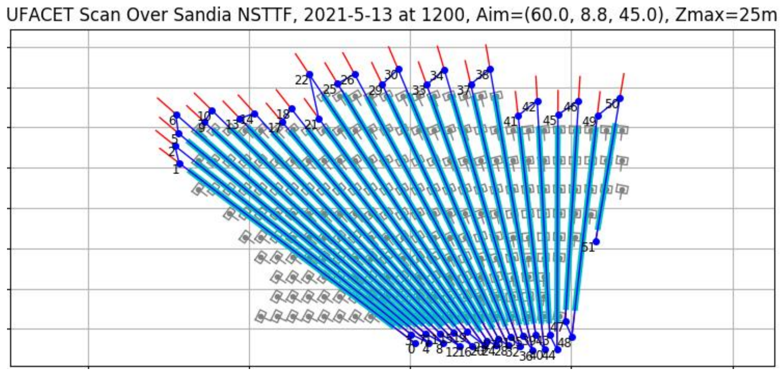
During plant startup.

In-Field Heliostat Assessment

During operation:

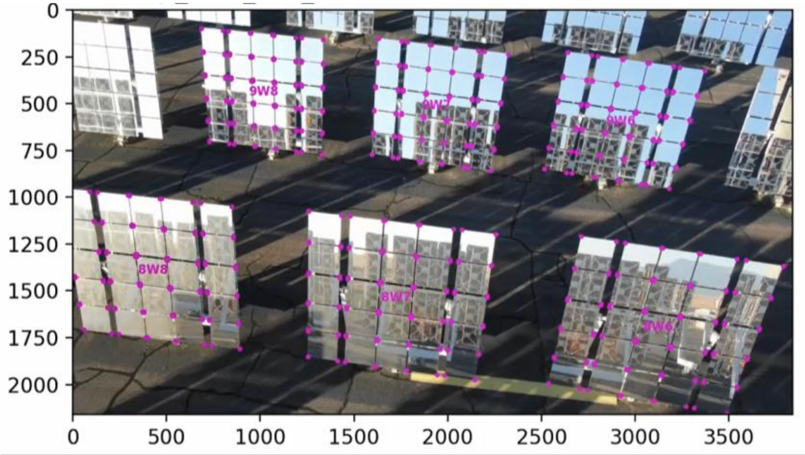
- Have heliostats changed?
- Implications?

Flight Plan

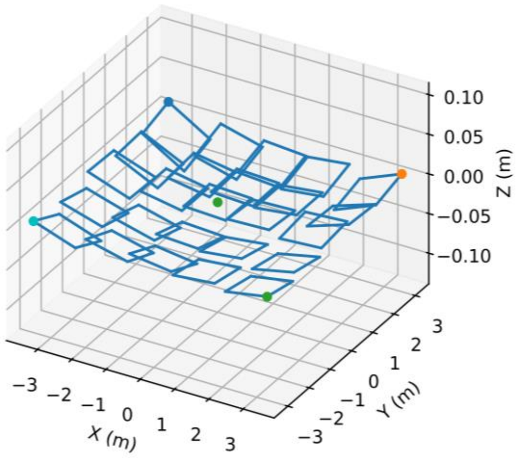


Fly Drone

Analyze Video



Heliostat Analysis



Other drone-based approaches (abbreviated):

Mitchell, et al. NIO Characterize Heliostats, 2020.

Jessen, et al. Two-Stage Offset Method, 2020.
Yellowhair. Aerial Heliostat Canting, 2020.

Wolfertstetter, et al. Airborne Soiling, 2019.
Coventry, et al. Robotic Inspection Soiling, 2019.

Citations for Drone-Based Field Assessment

Other drone-based approaches:

R. A. Mitchell, G. Zhu. A non-intrusive optical (NIO) approach to characterize heliostats in utility-scale power tower plants: Methodology and in-situ validation. *Solar Energy* **209**, pp. 431-445, 2020. https://doi.org/10.1016/j.solener.2020.09.004

W. Jessen, et al. A Two-Stage Method for Measuring the Heliostat Offset. *SolarPACES 2020. AIP Conference Proceedings* **2445**. https://doi.org/10.1063/5.0087036

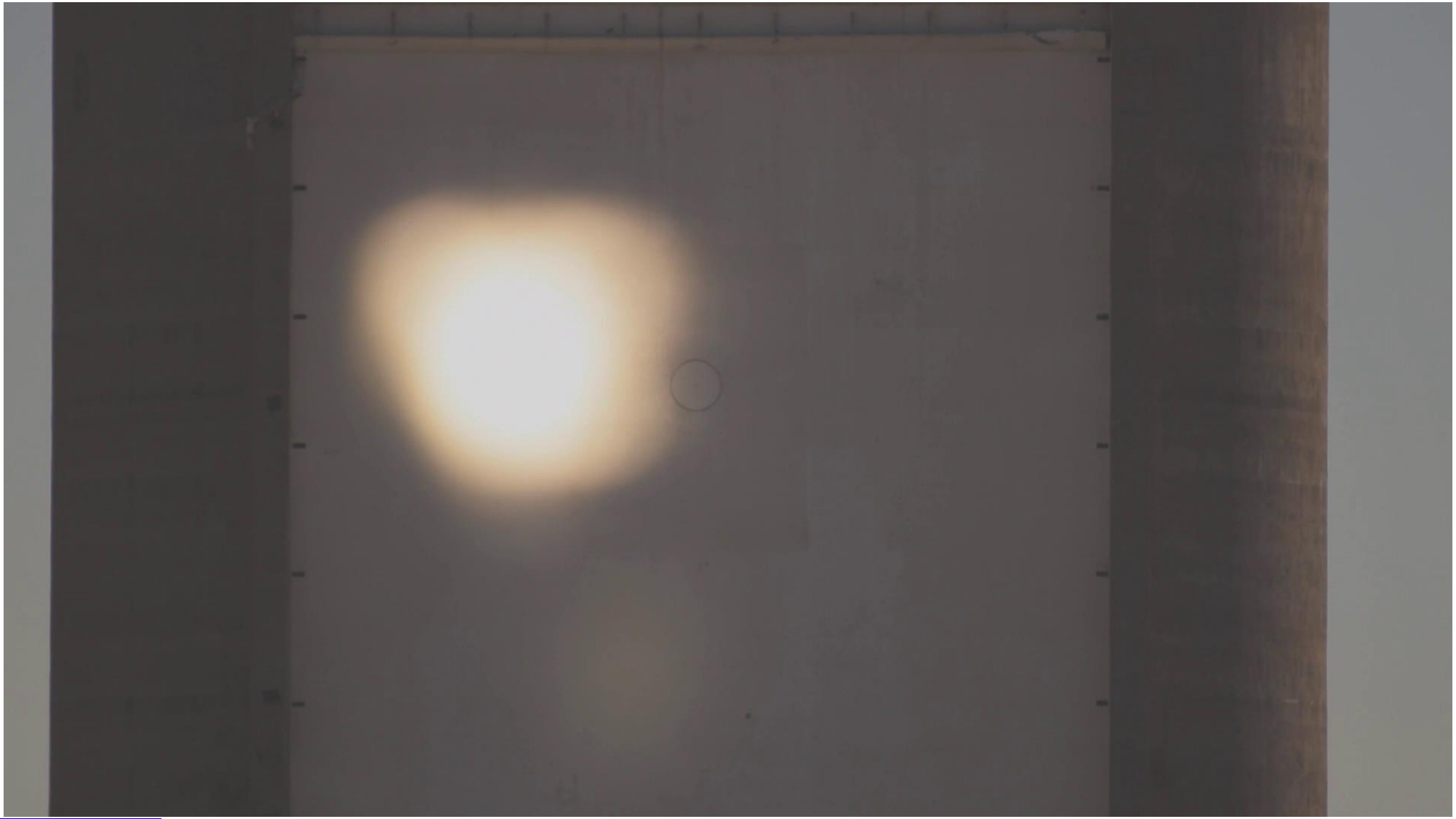
J. Yellowhair. Development of an Aerial Imaging System for Heliostat Canting Assessments. *SolarPACES 2020.*

F. Wolfertstetter, et al. Airborne Soiling Measurements of Entire Solar Fields with Qfly. *SolarPACES 2019. AIP Conference Proceedings* **2303**. https://doi.org/10.1063/5.0028968

J. Coventry, et al. A Robotic Vision System for Inspection of Soiling at CSP Plants. *SolarPACES 2019. AIP Conference Proceedings* **2303**. https://doi.org/10.1063/5.0029493

Dynamic Optical Evaluation

BCS Dynamic Motion:

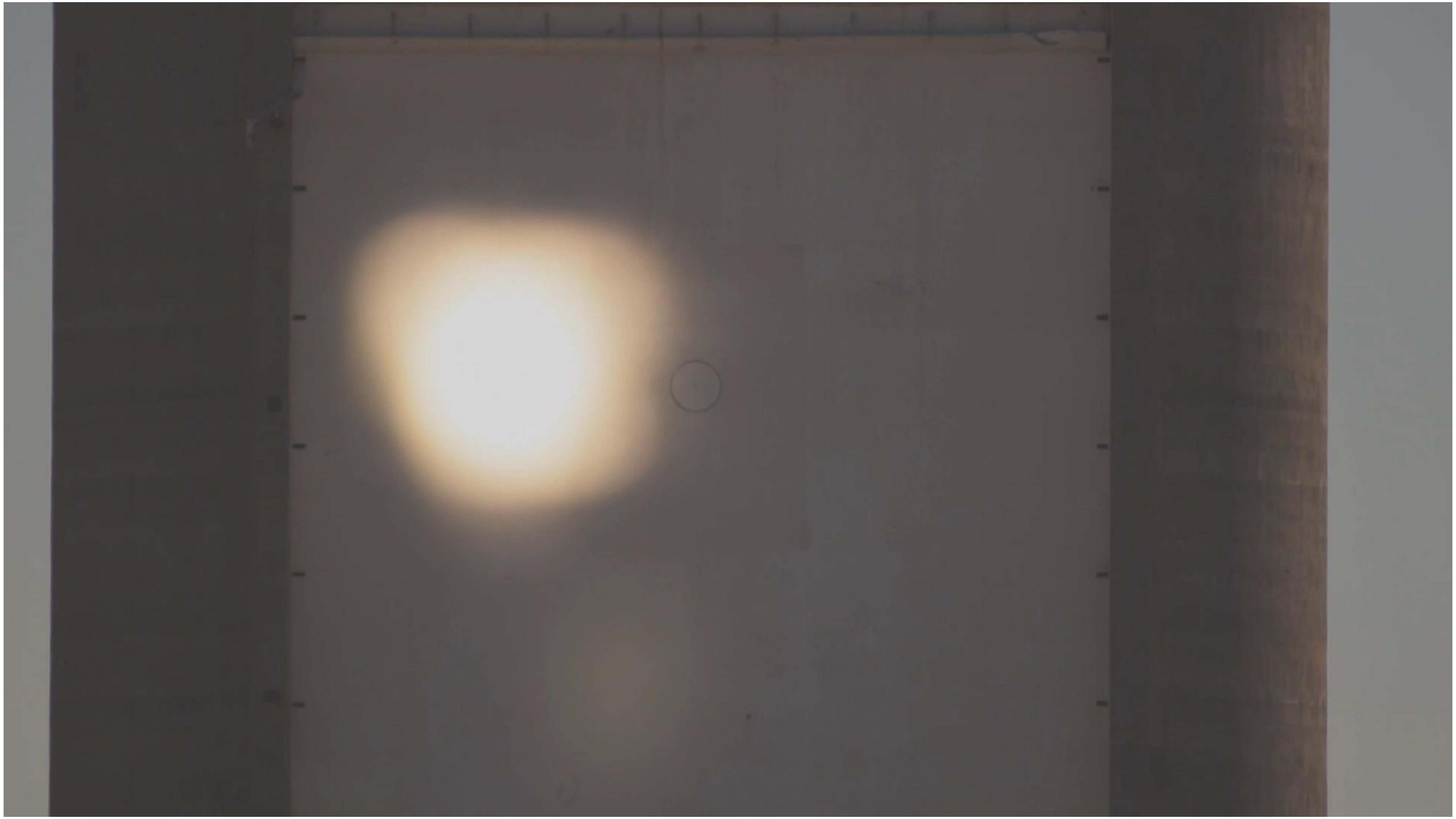


Wind 15 mph, gust up to 30 mph

Flip between the slides.

Dynamic Optical Evaluation

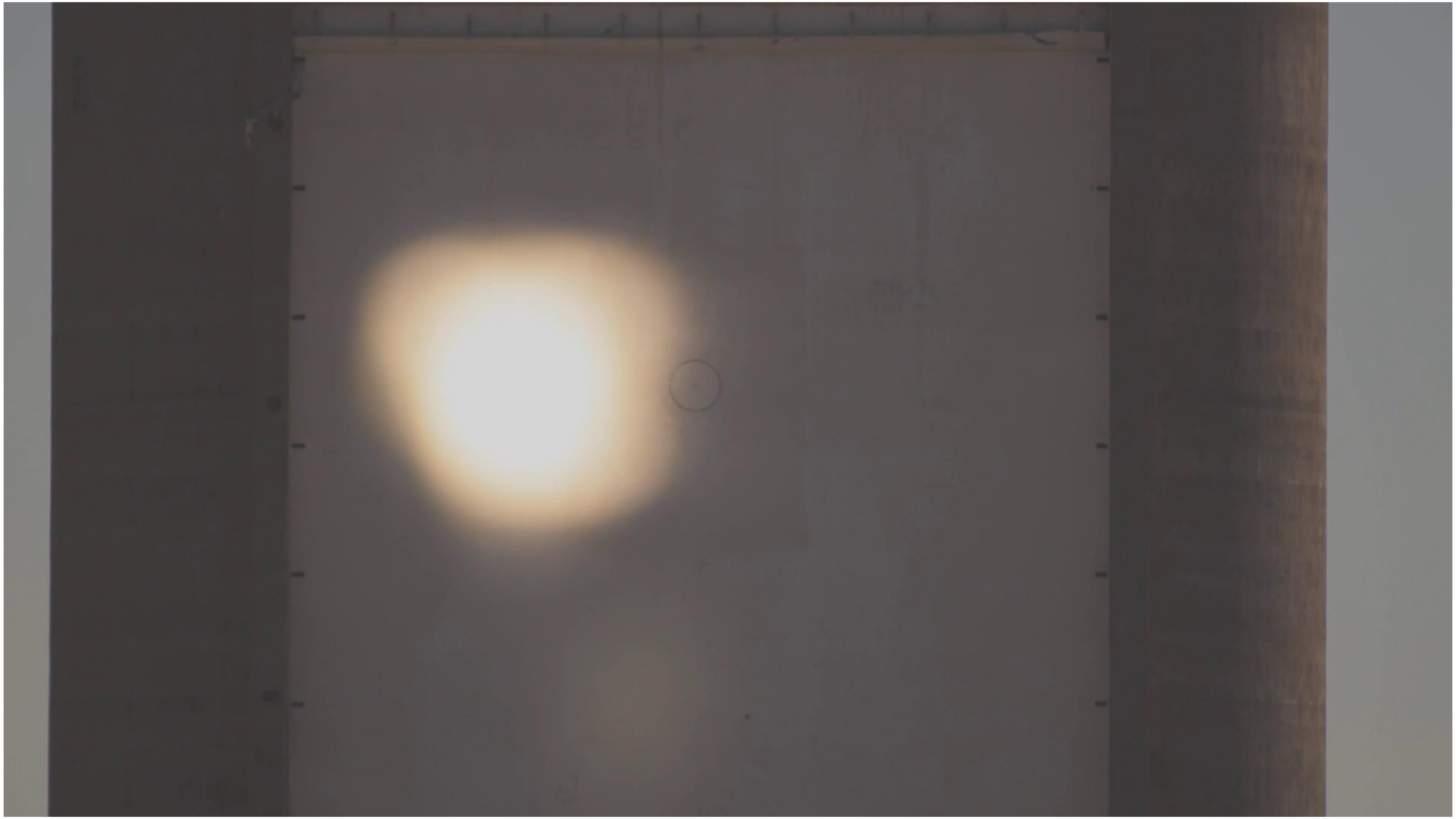
BCS Dynamic Motion:



Wind 15 mph, gust up to 30 mph

Dynamic Optical Evaluation

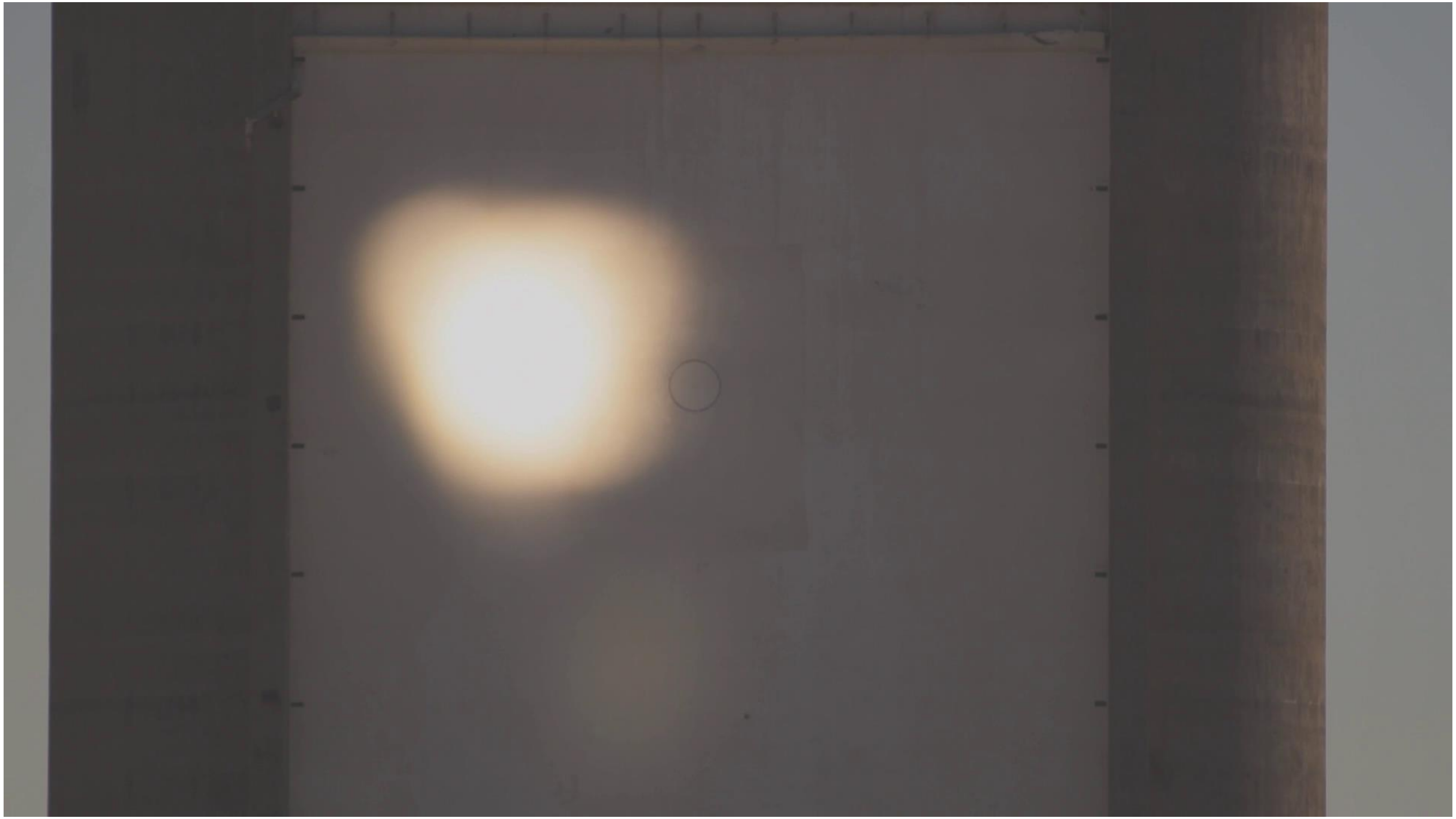
BCS Dynamic Motion:



Wind 15 mph, gust up to 30 mph

Dynamic Optical Evaluation

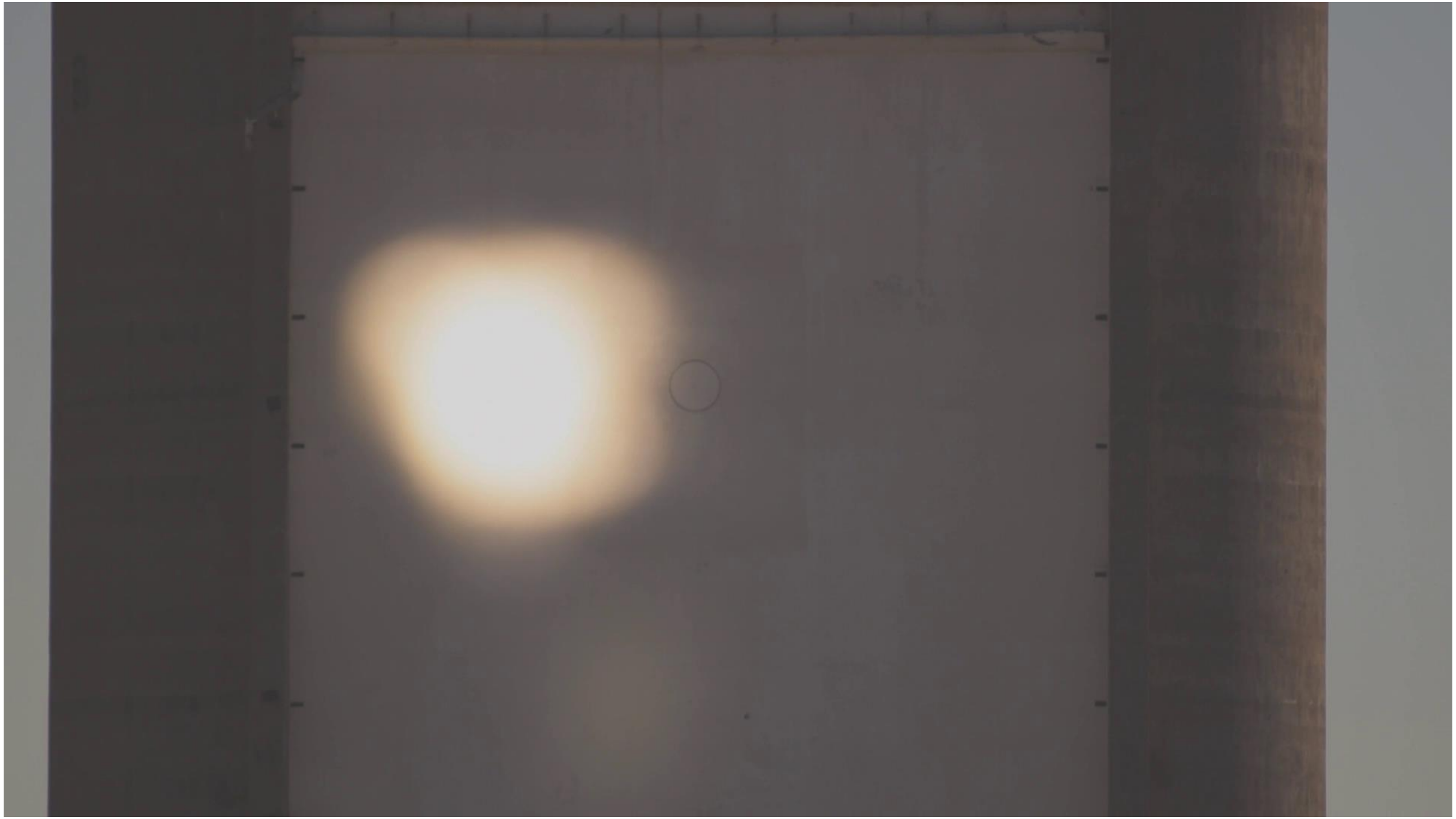
BCS Dynamic Motion:



Wind 15 mph, gust up to 30 mph

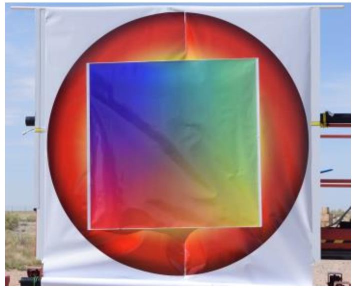
Dynamic Optical Evaluation

BCS Dynamic Motion:

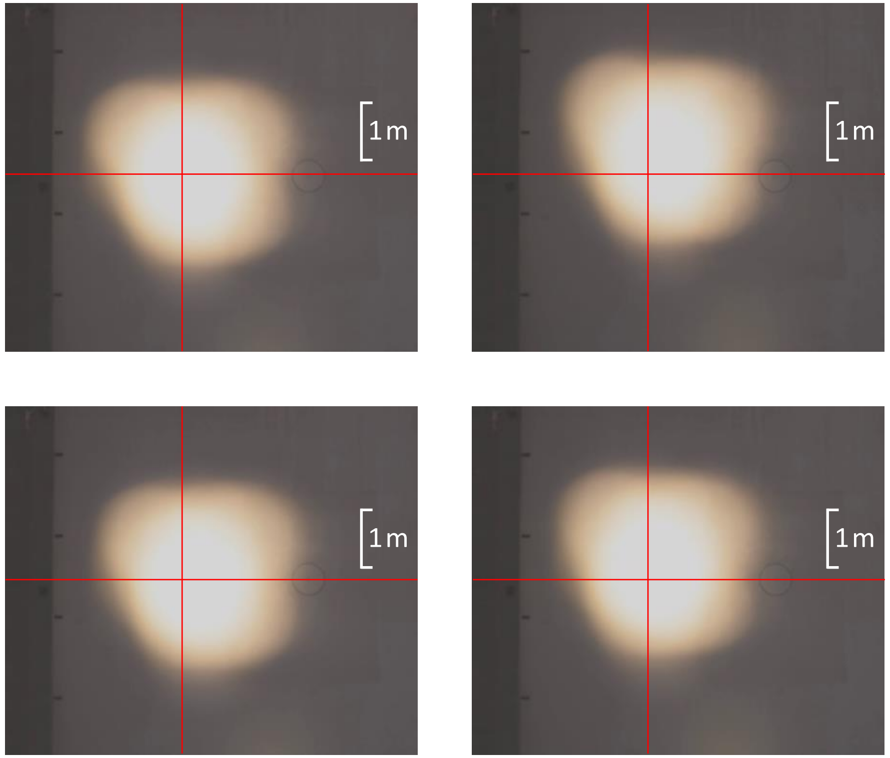


Wind 15 mph, gust up to 30 mph

Dynamic Optical Evaluation



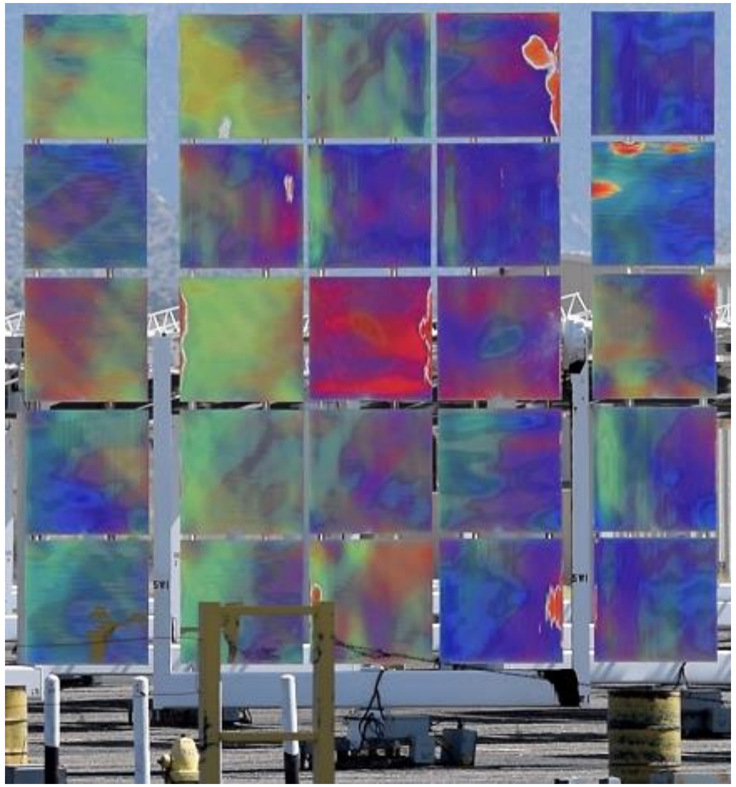
BCS Dynamic Motion



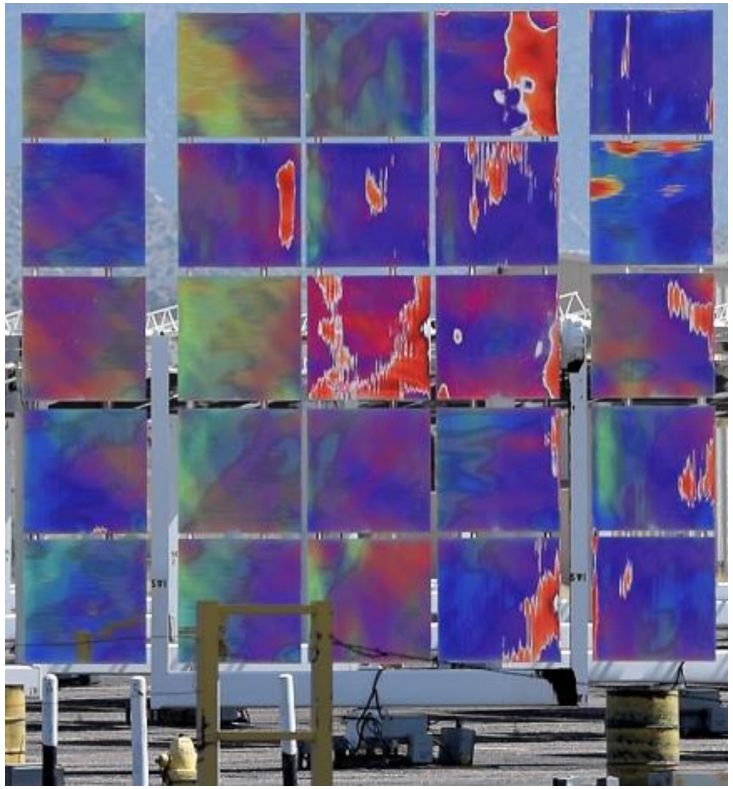
Wind 15 mph
Gust up to 30 mph

Red cross hairs show aim point.
All beam perturbations due to wind.

Change in Optical Intercept Due to Light Wind



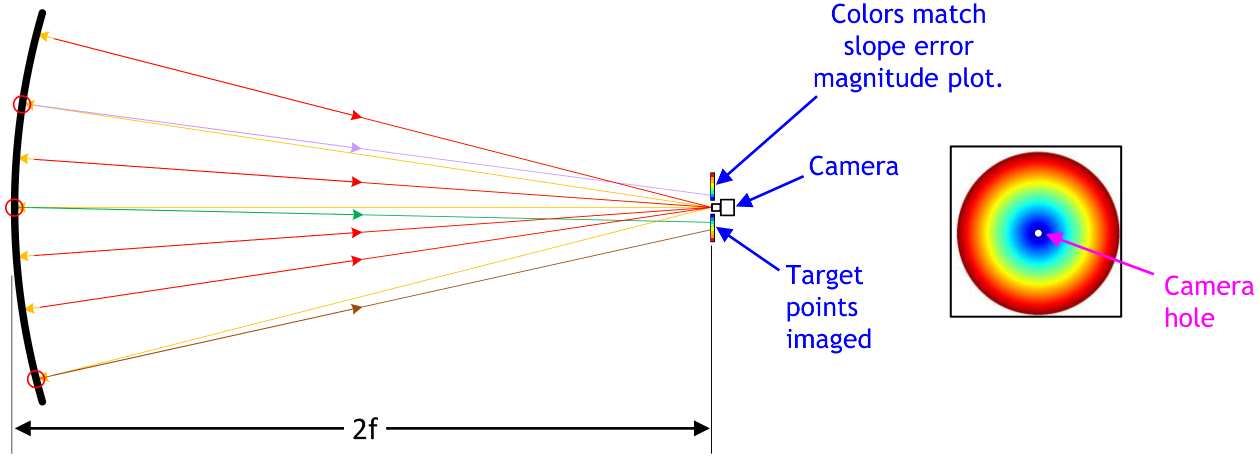
Nominal



9 mph wind gust

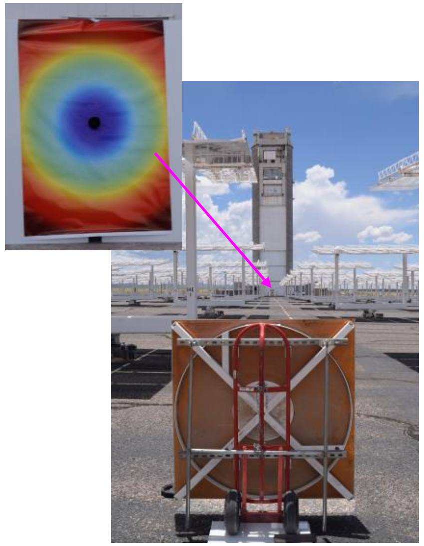
Ground Truth Examples

2f Color Target [1]

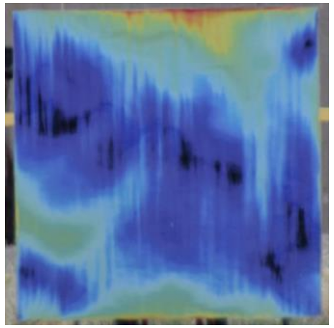


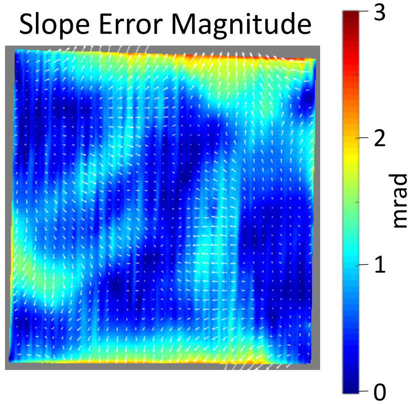
Plano Water Pool [2]

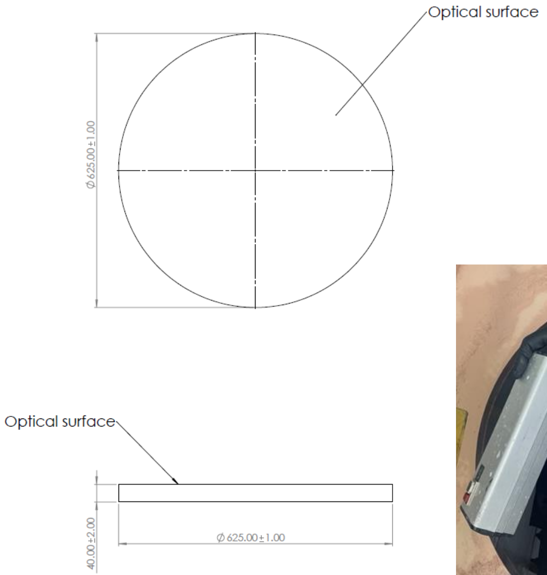
Precision Mirror (f = 100 m)



distance ≈ 200 m







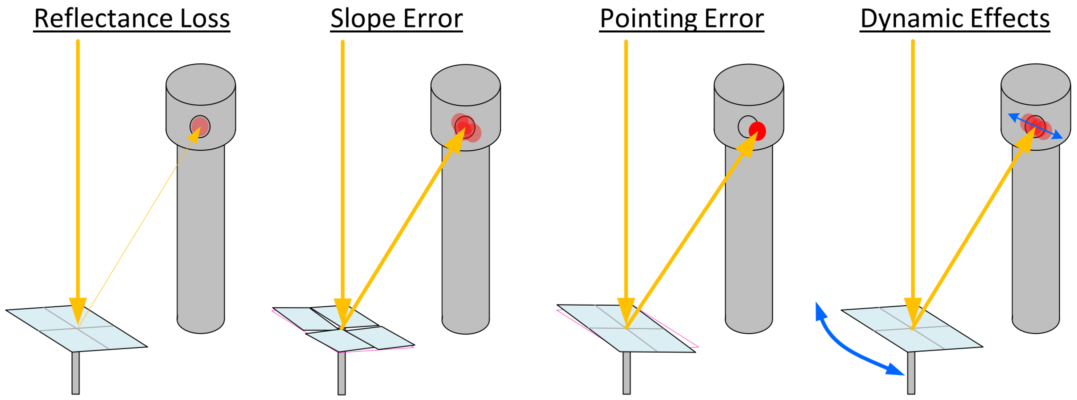
Cosmo Optics
Precision Photonics Artisans

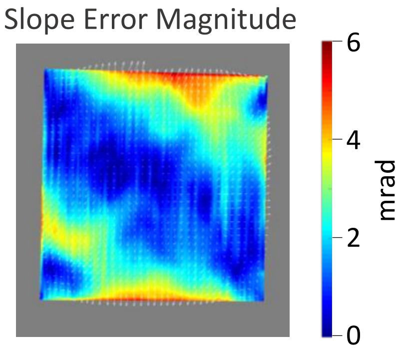
[1] Inspired by J. Strachan. Revisiting the BCS..., Sandia Technical Report SAND92-2789C, 1992.

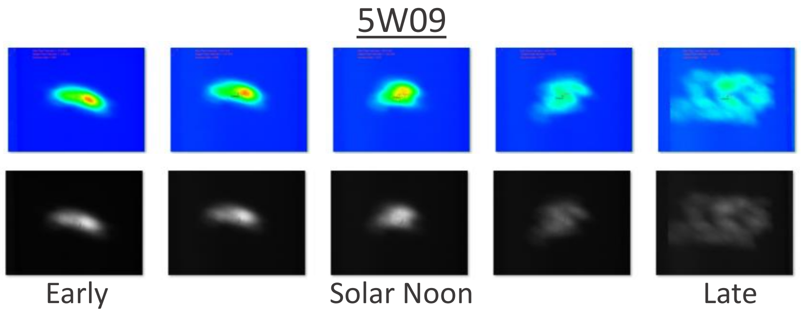
[2] Following T. März, et al. Validation of Two Optical Measurement Methods..., 2011

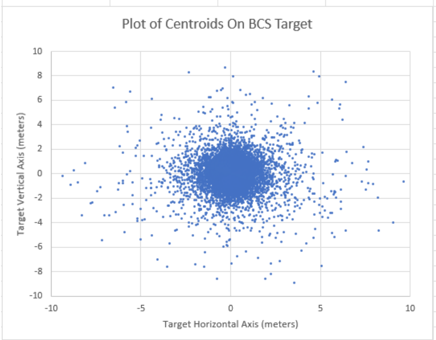
Conclusion

- Heliostat error categories:
  - Reflectance loss
  - Slope error
  - Pointing error
  - Dynamic effects
- Well-established:
  - Material reflectance
  - Indoor high-resolution slope
  - BCS pointing, calibration
- Challenging:
  - Wide-area soiling
  - Optical impact of temperature, tilt, dynamics
  - Distant heliostats
  - Accelerated calibration
  - In-situ optical assessment
  - Ground truth verification
- While seemingly simple, heliostat metrology encounters complex effects and harsh environments.
- Sandia is engaging many of these problems, and seeks to make excellent solutions easily accessible. **OpenCSP@sandia.gov**









Courtesy Crescent Dunes

Note: A lot more great work did not fit!

BACKUP SLIDES

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