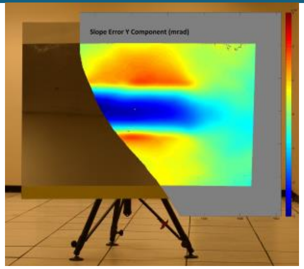
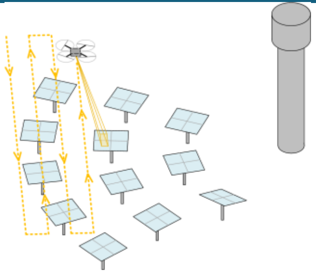
# Variation in Reflected Beam Shape and Pointing Accuracy Over Time and Heliostat Field Position





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Luis Garcia Maldonado, Tristan Larkin

October 9, 2023

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SAND2023-10016C

# Motivation

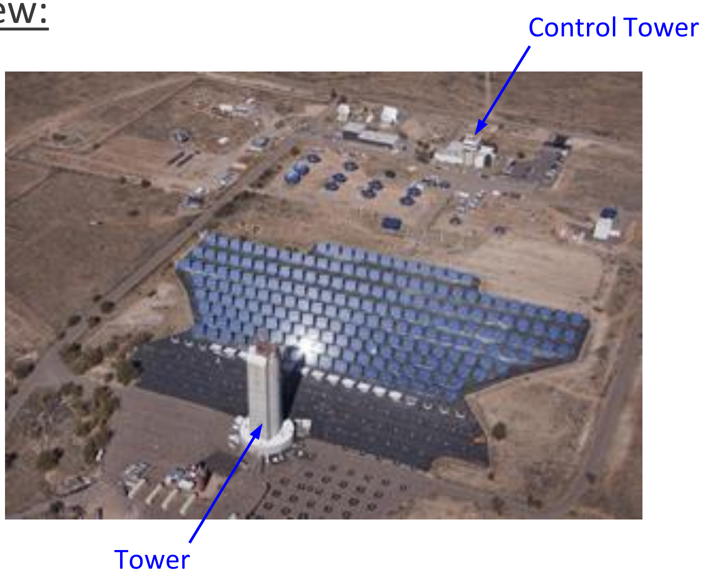
- Heliostat fields can simultaneously achieve high temperature (> 1400 °C) and high power (> 5 $MW_{th}$).
- But this is only possible when the heliostats are in focus, and accurately aimed.
- We know that heliostat beam shape changes with incidence angle. When? How much?
- Heliostats also have pointing error. Do required corrections change through the day/year? How much?
- The paper reports an experiment to directly observe these effects over a full solar year.
- Our results are documented in a data set containing over 120,000 files.
  These data will be publicly released under OpenCSP.*
- Below we report three primary measurements:
  - Variation in **Beam Shape** over time.
  - Variation in **Pointing Correction** over time.
  - **Wind Effects** on pointing.

Our goal is to gain insight into these phenomena by direct observation of nature.

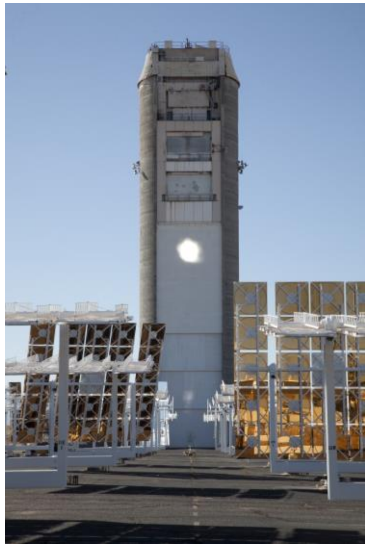
* Inquiries: OpenCSP@sandia.gov

# Sandia National Solar Thermal Test Facility (NSTTF)

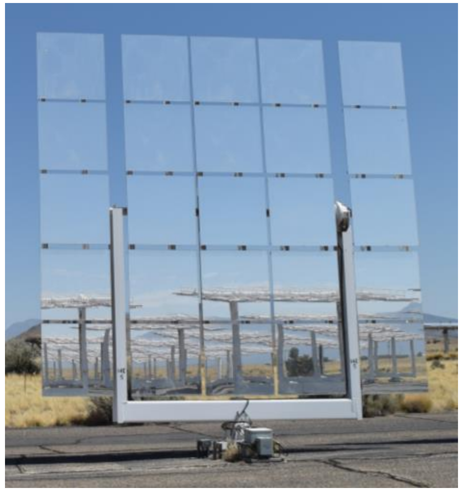
## Overview:

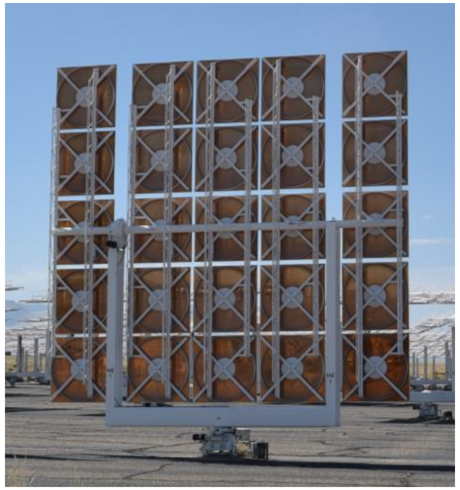



## BCS system:



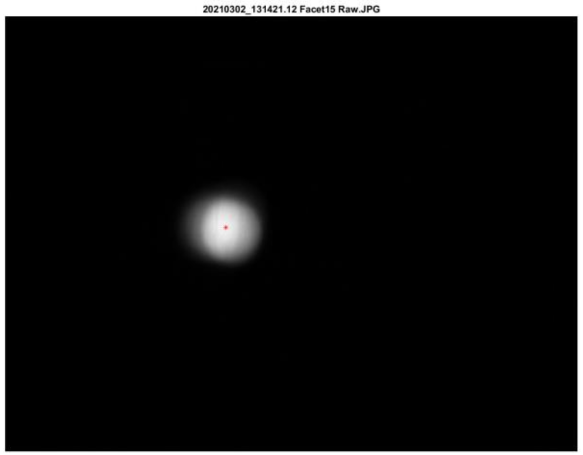
## Heliostat:

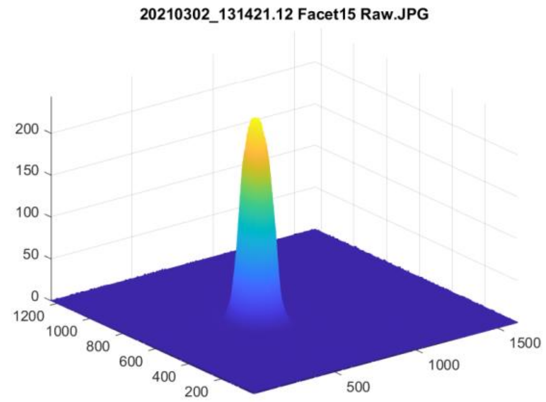




25 Facets

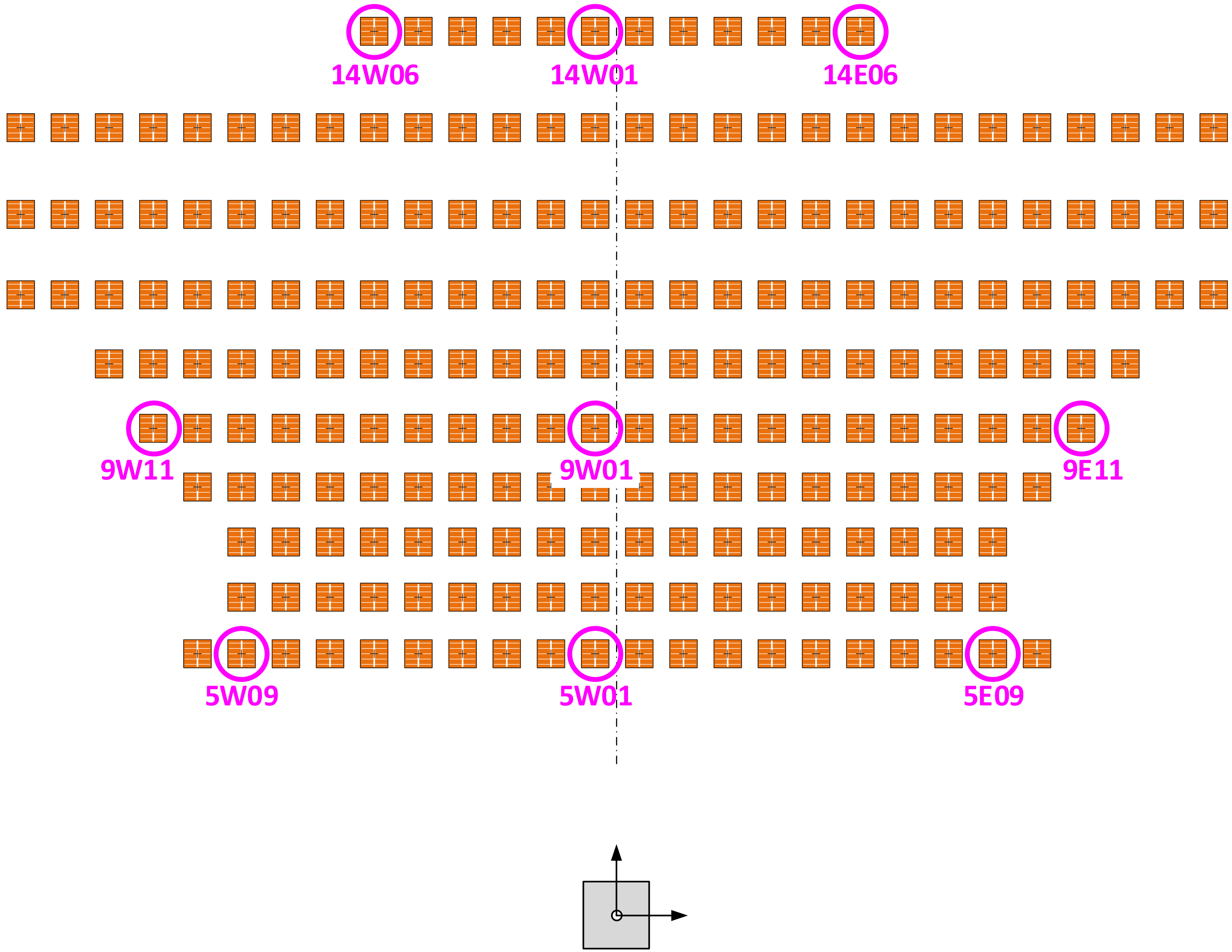
## Example BCS data:



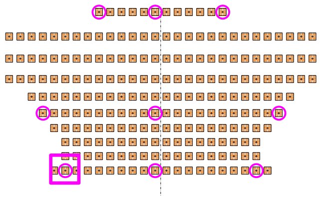



# Beam Shape

# Heliostats Studied for Beam Shape

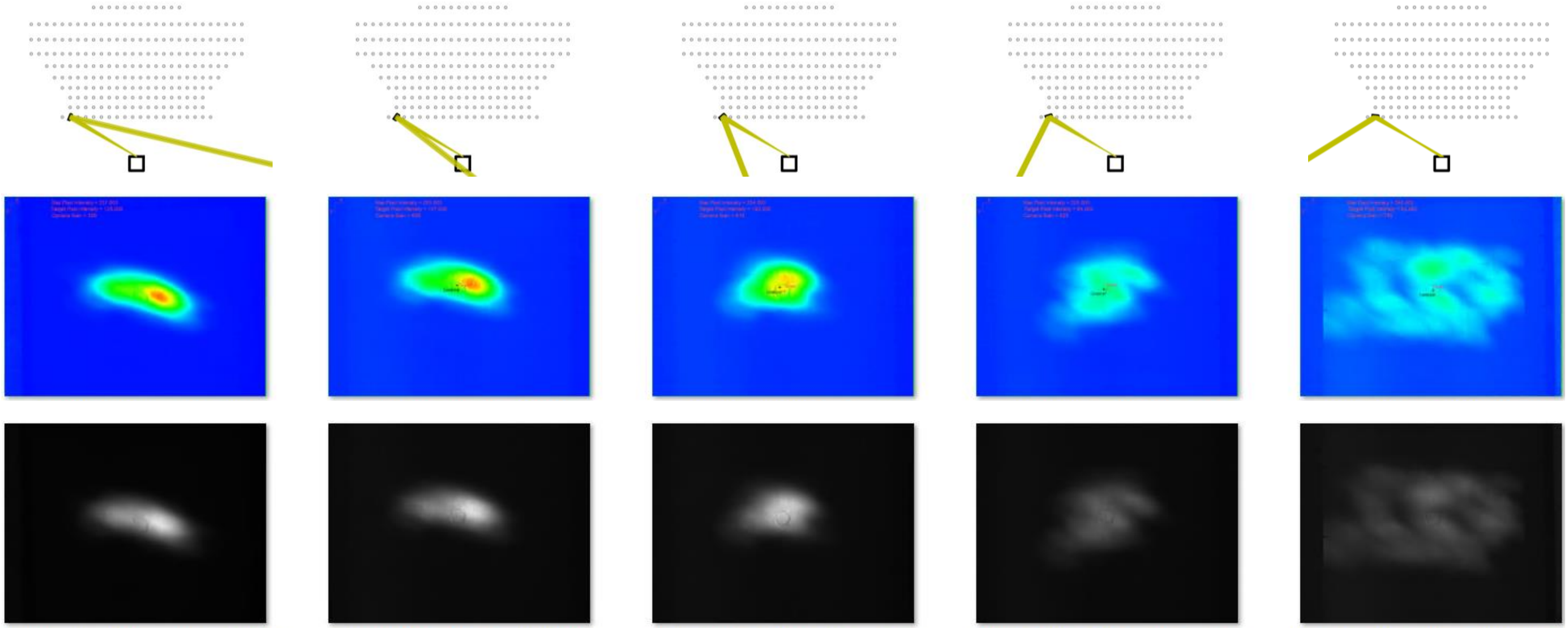


Images collected February 10, 2023.



# One Day: Winter Solstice Mid Spring Equinox

## 5W09



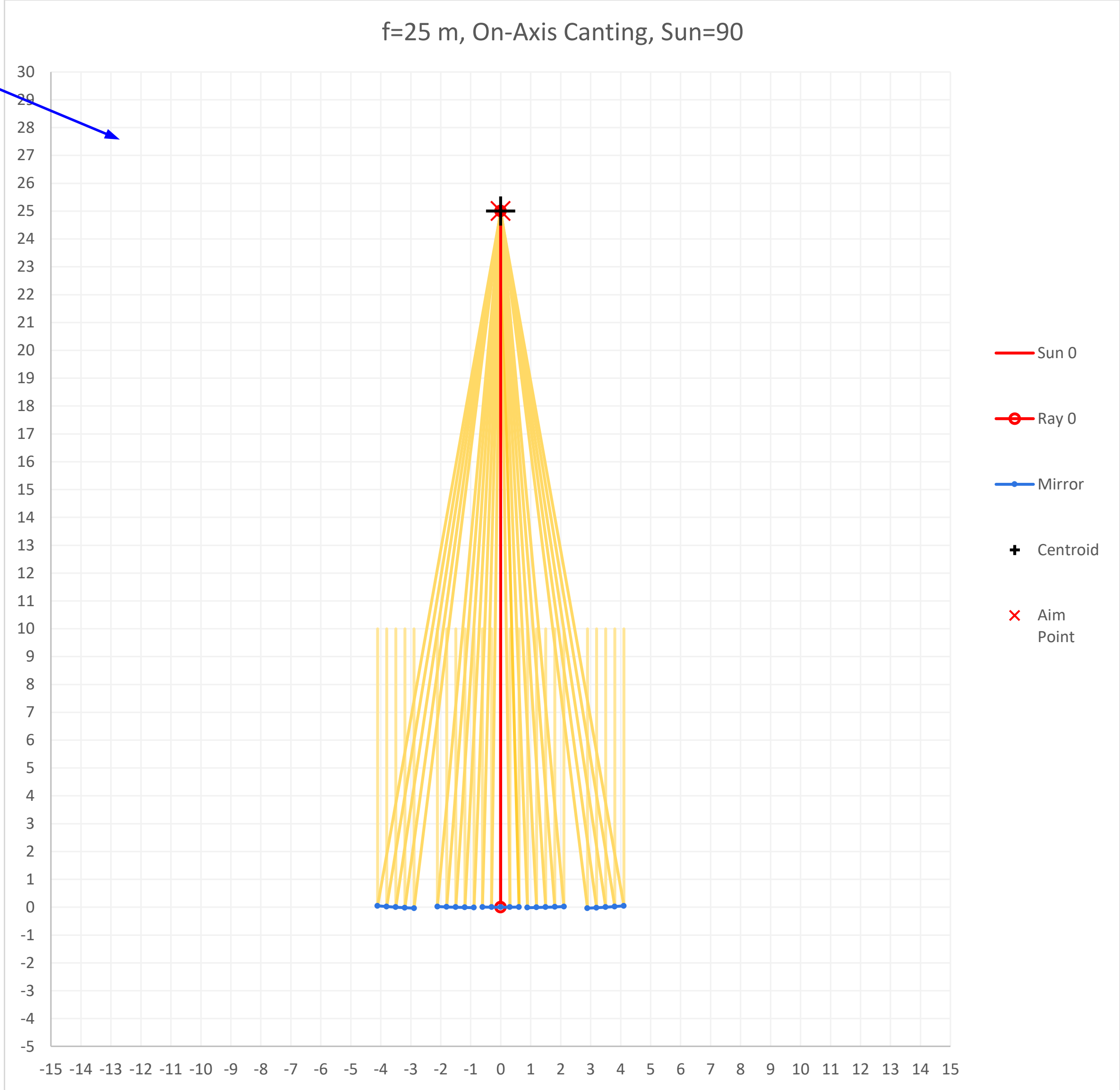
Early | Solar Noon | Late

Beam shape degrades as sun incidence angle increases.

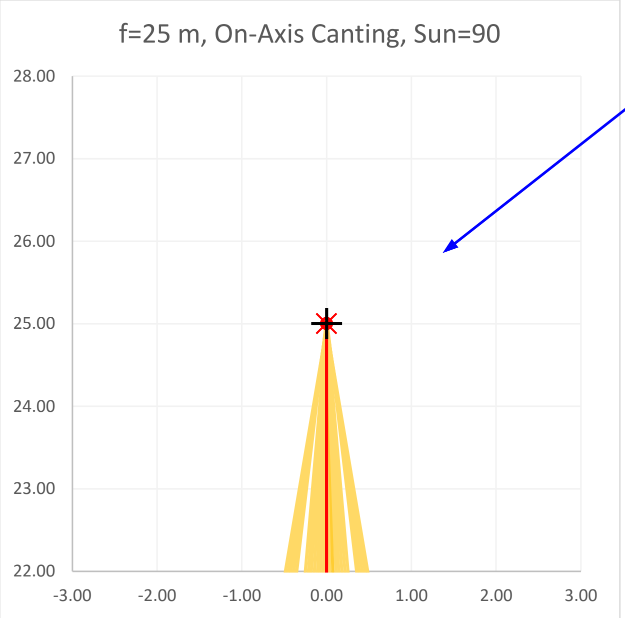
# Heliostat Reflection Under Increasing Incidence Angle

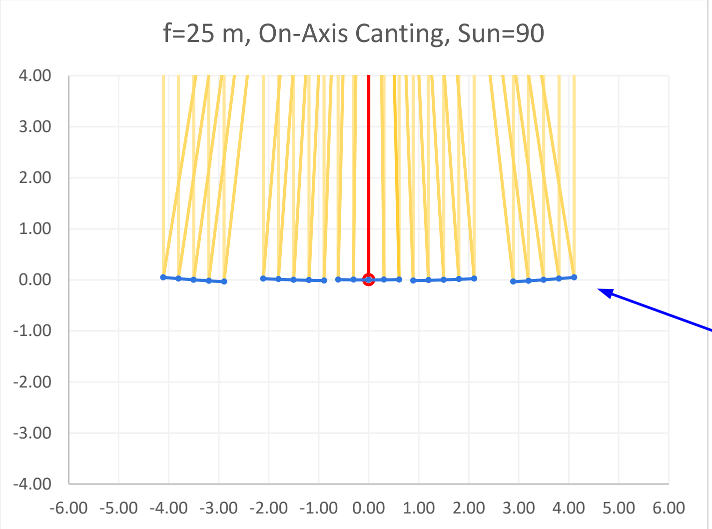
On-axis canting, sun incidence 0°:

Overall view




Zoom-in Target




Zoom-in Mirror

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

# Heliostat Reflection Under Increasing Incidence Angle

On-axis canting, sun incidence 10°:

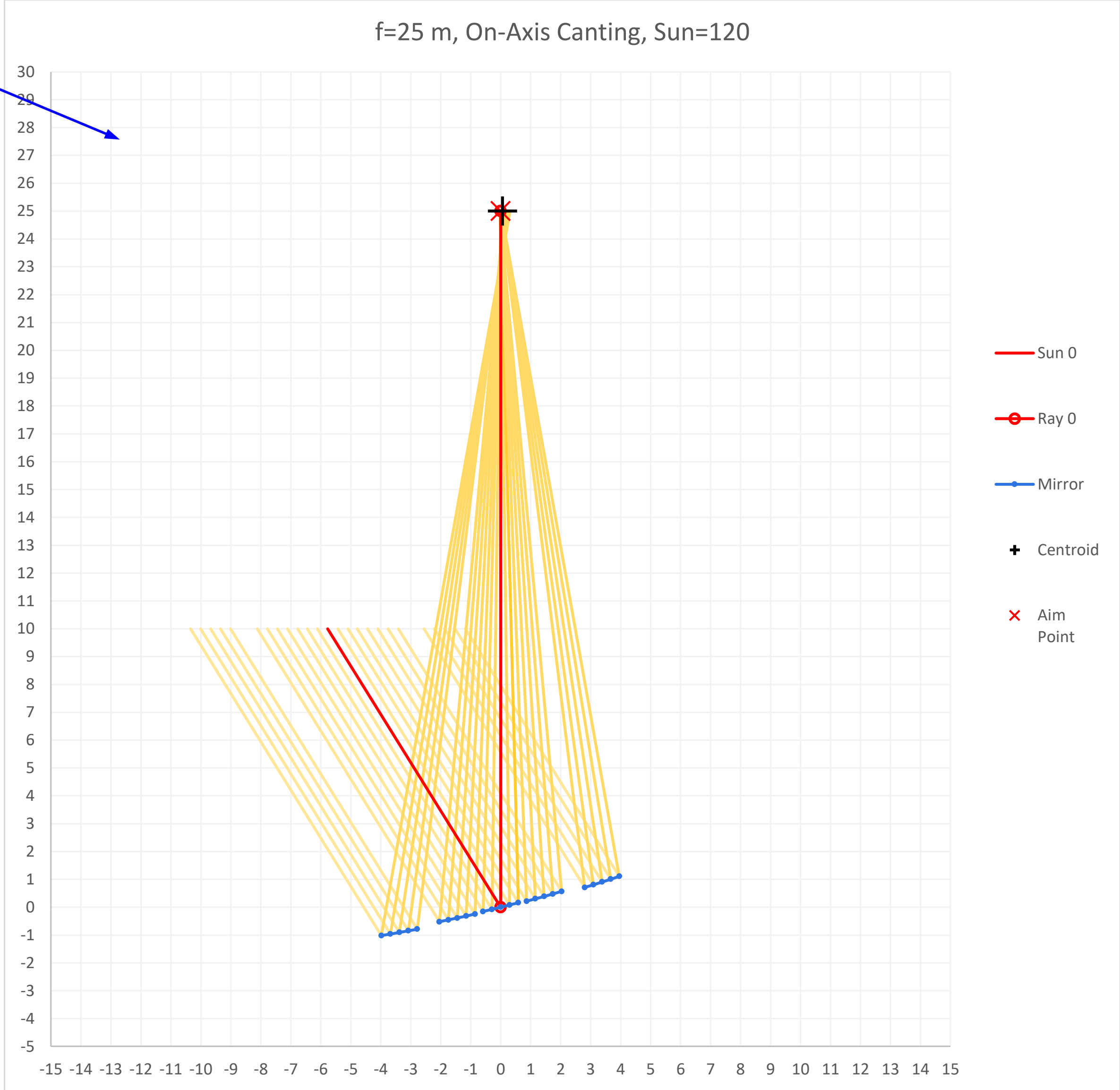



Sun is modeled as a point source. Sun shape not included.

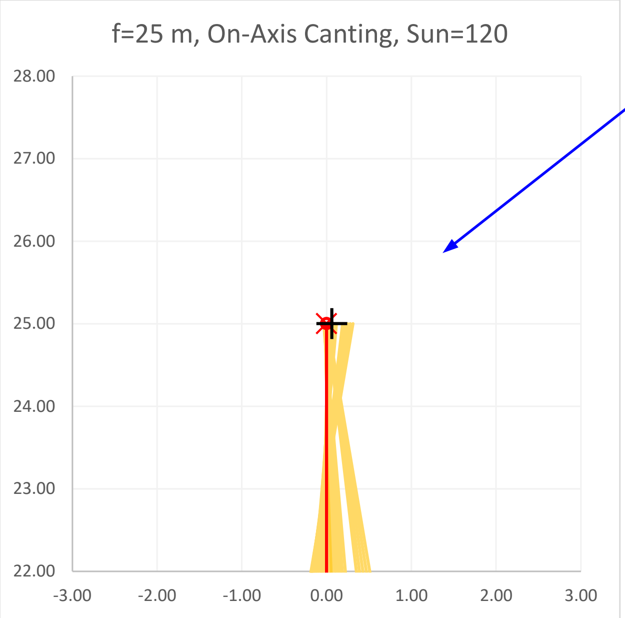
# Heliostat Reflection Under Increasing Incidence Angle

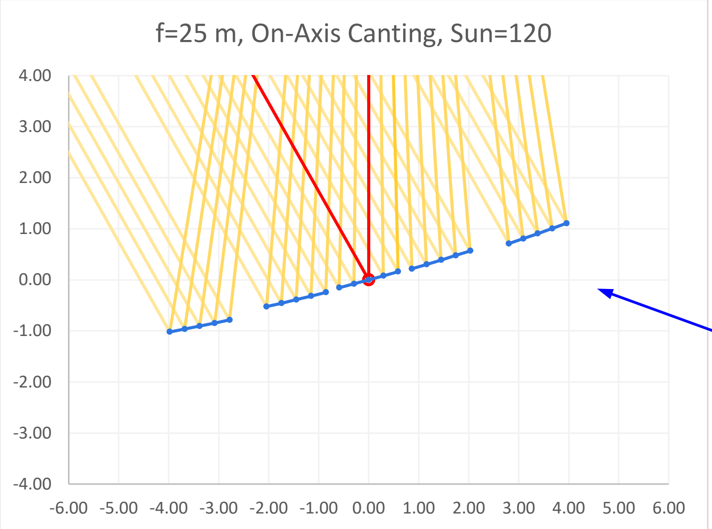
On-axis canting, sun incidence 30°:

Overall view




Zoom-in Target




Zoom-in Mirror

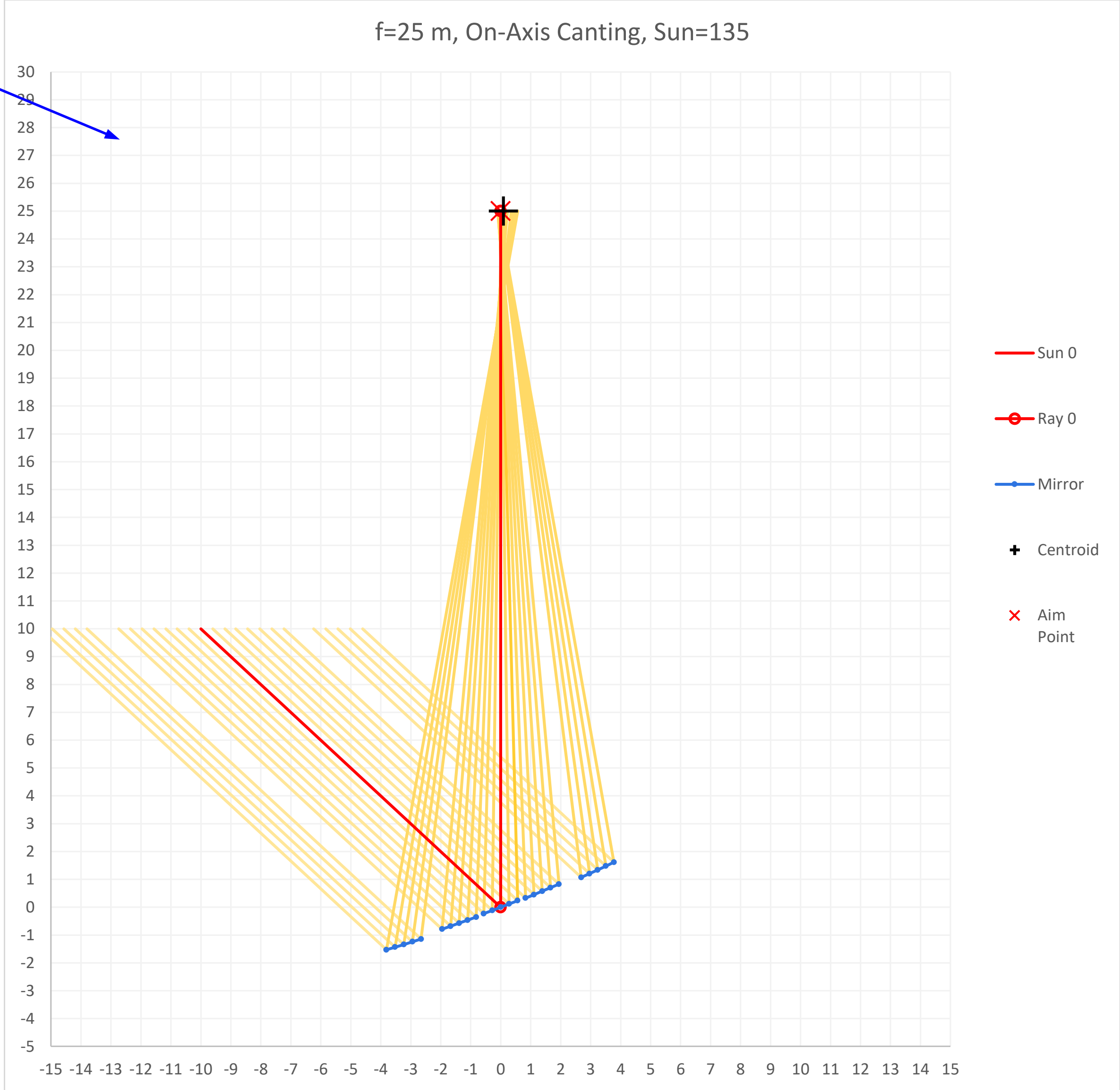


Sun is modeled as a point source. Sun shape not included.

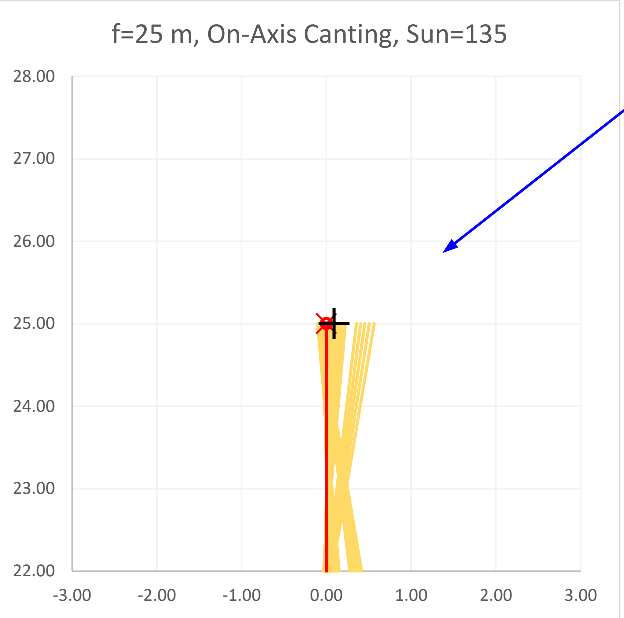
# Heliostat Reflection Under Increasing Incidence Angle

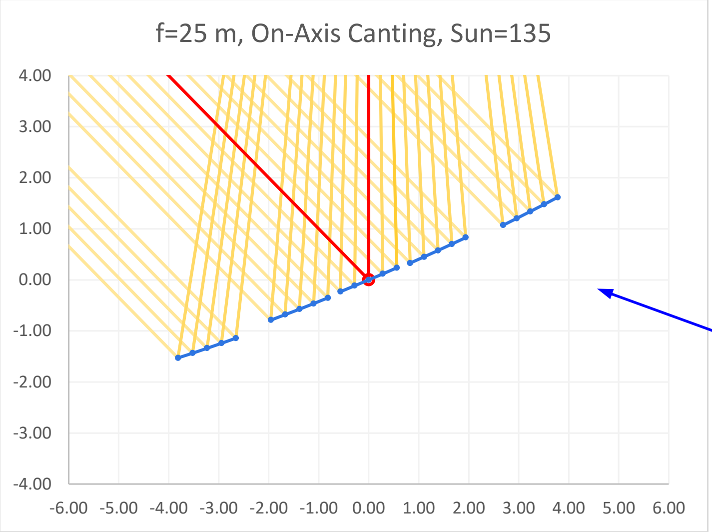
On-axis canting, sun incidence 45°:

Overall view




Zoom-in Target




Zoom-in Mirror

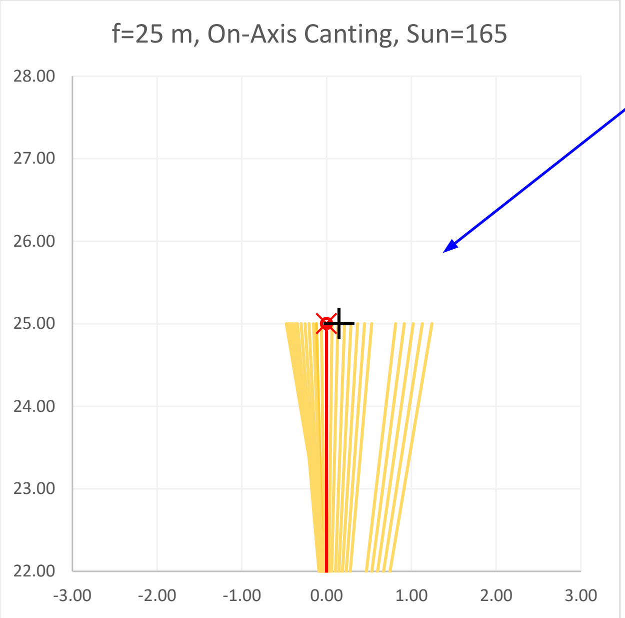
Sun is modeled as a point source. Sun shape not included.

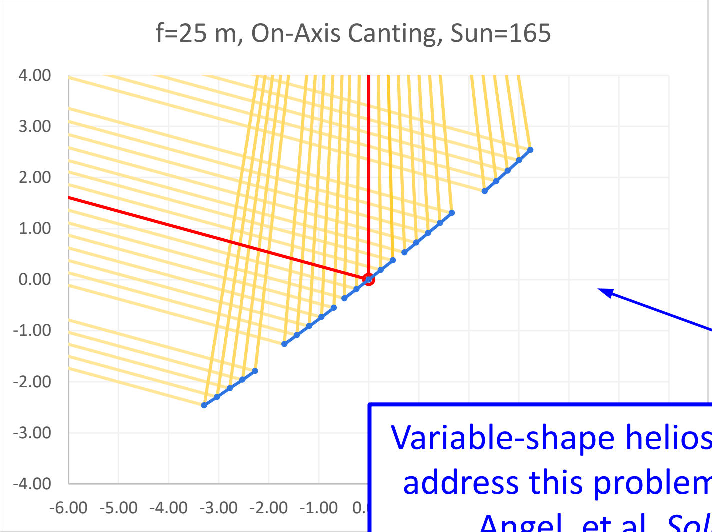
# Heliostat Reflection Under Increasing Incidence Angle

On-axis canting, sun incidence 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.

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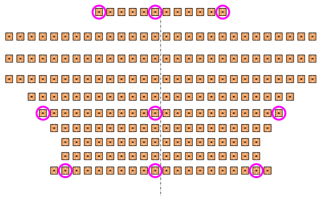
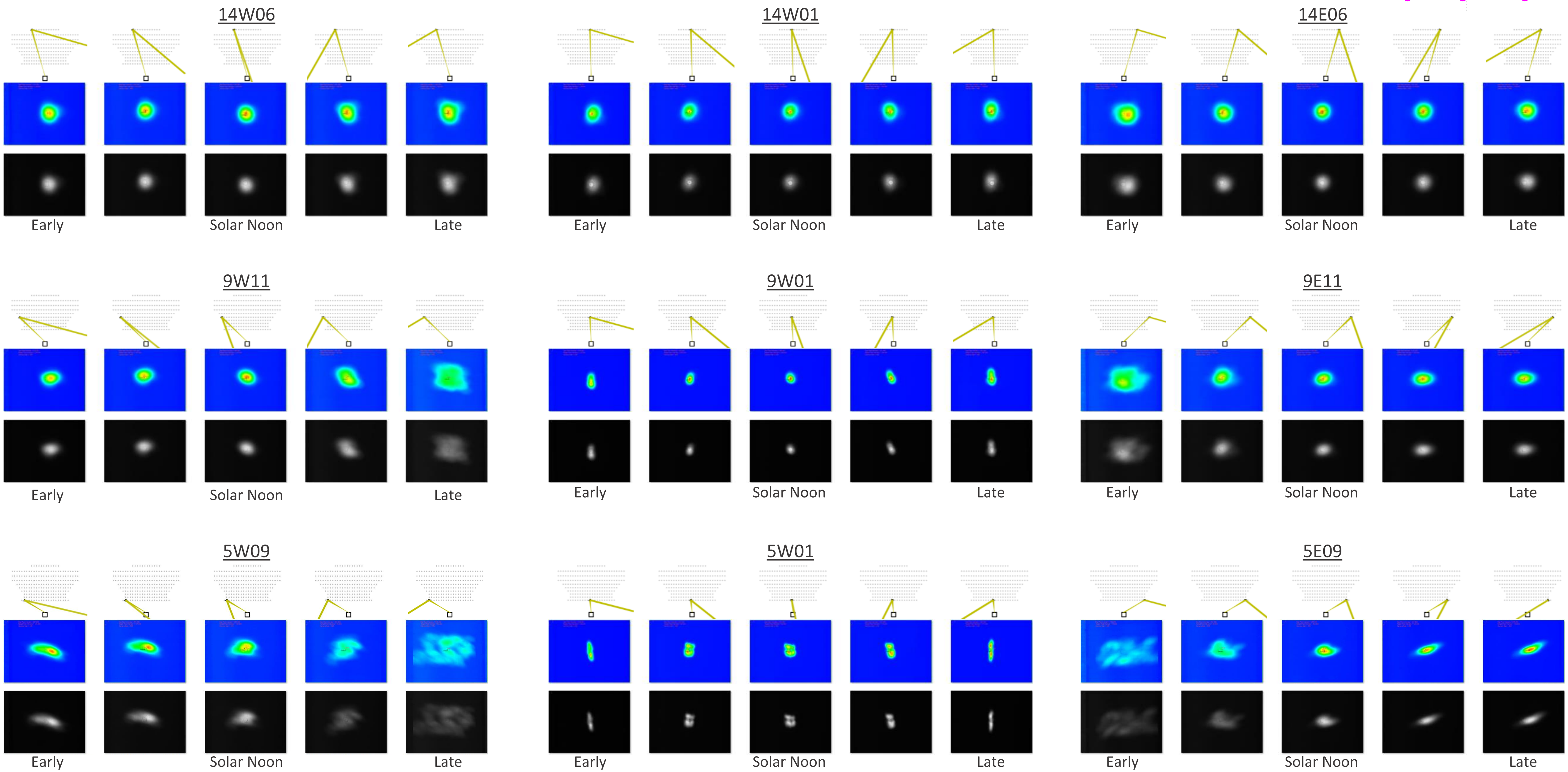
Sun is modeled as a point source. Sun shape not included.

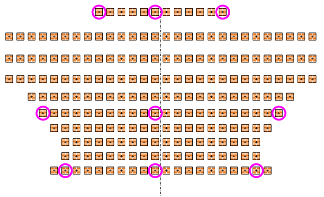
Images collected February 10, 2023.

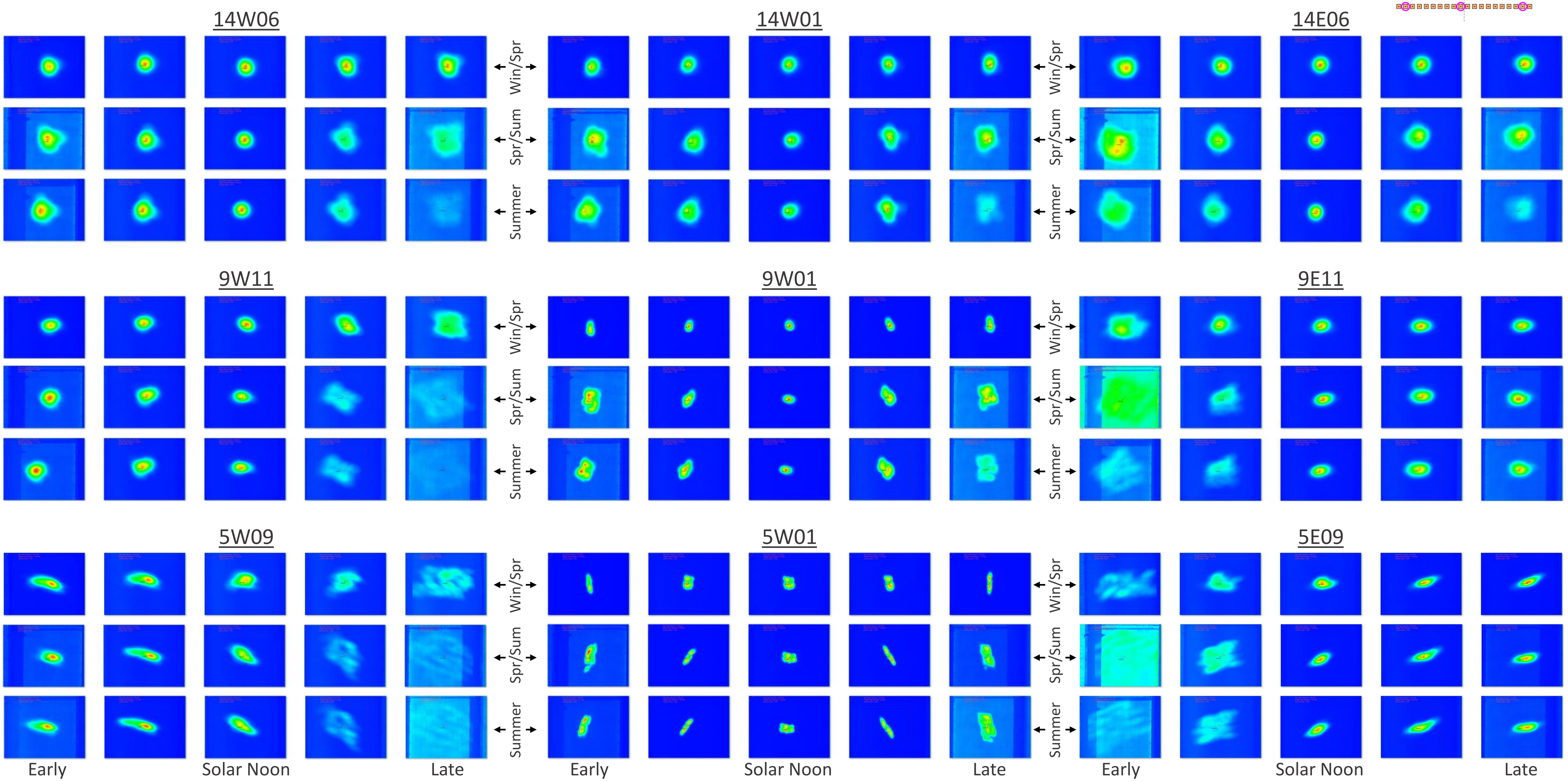


# One Day: Winter Solstice Mid Spring Equinox



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





# Beam Shape Observations

Spots are smallest for heliostats near the tower, and grow for heliostats further from the tower.

Heliostat 5W01 has a larger spot because it is poorly canted. The “bulbs” in the 5W01 multi-facet spot are smaller than rows 9 and 14, indicating that if 5W01 was properly canted, it would have the smallest spot.

Spot growth is minimal at solar noon for all heliostats, because the heliostats are canted for this condition. This remains consistent throughout the year.

For times away from solar noon, spot growth is observed for all heliostats.

Spot growth is worst for heliostats on either side of the field, and maximum spot growth occurs in the morning or afternoon, depending on whether the heliostat is east or west of the tower, respectively.

As heliostat positions deviate further from true north, off-noon spot growth increases.

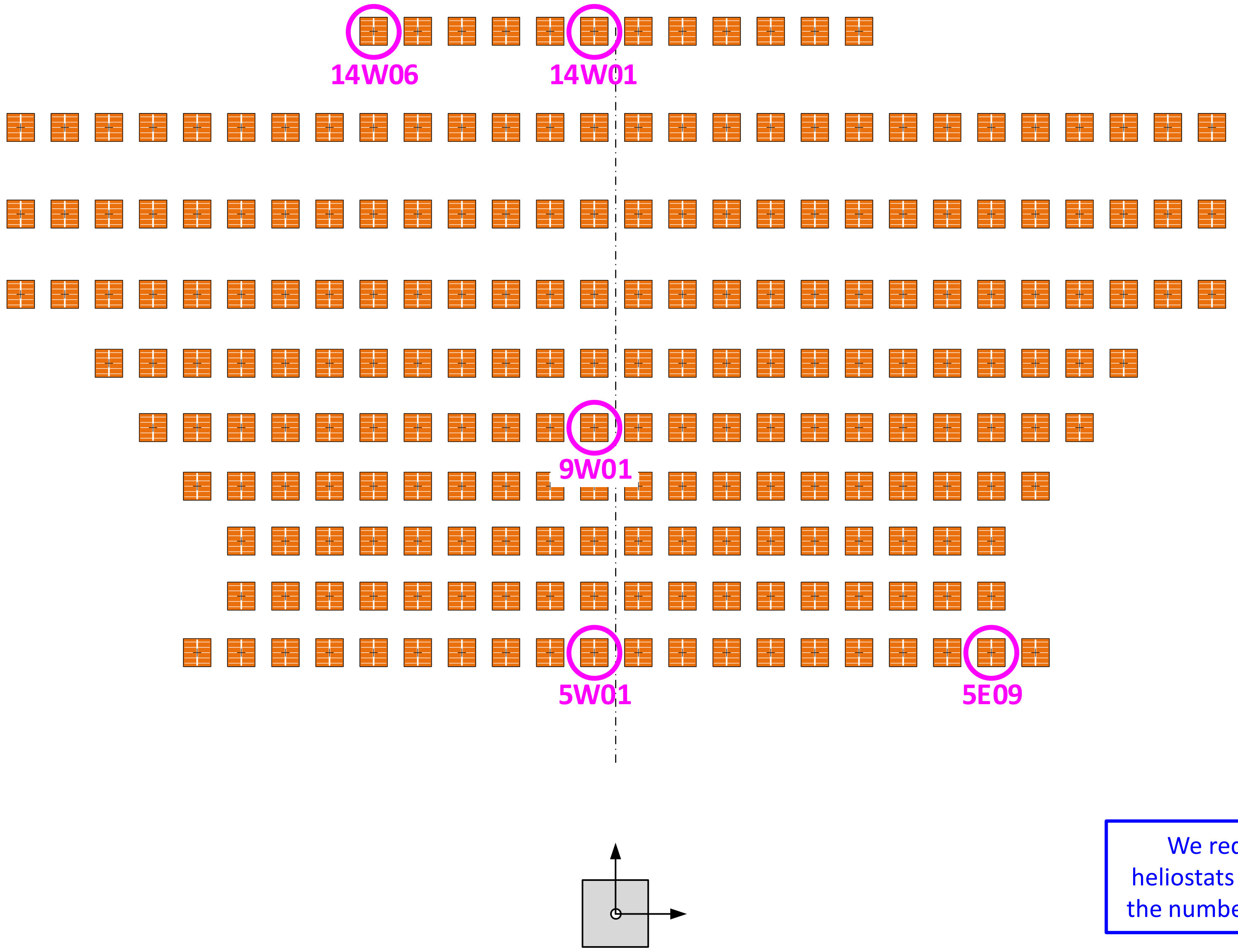
Off-noon spot growth increases in summer, since the higher sun elevation increases incidence angle.

**These observations suggest polar field layouts may yield more consistent performance across the day.**

**These observations suggest variable-focus heliostats may yield more productivity per day.**

# Pointing Correction

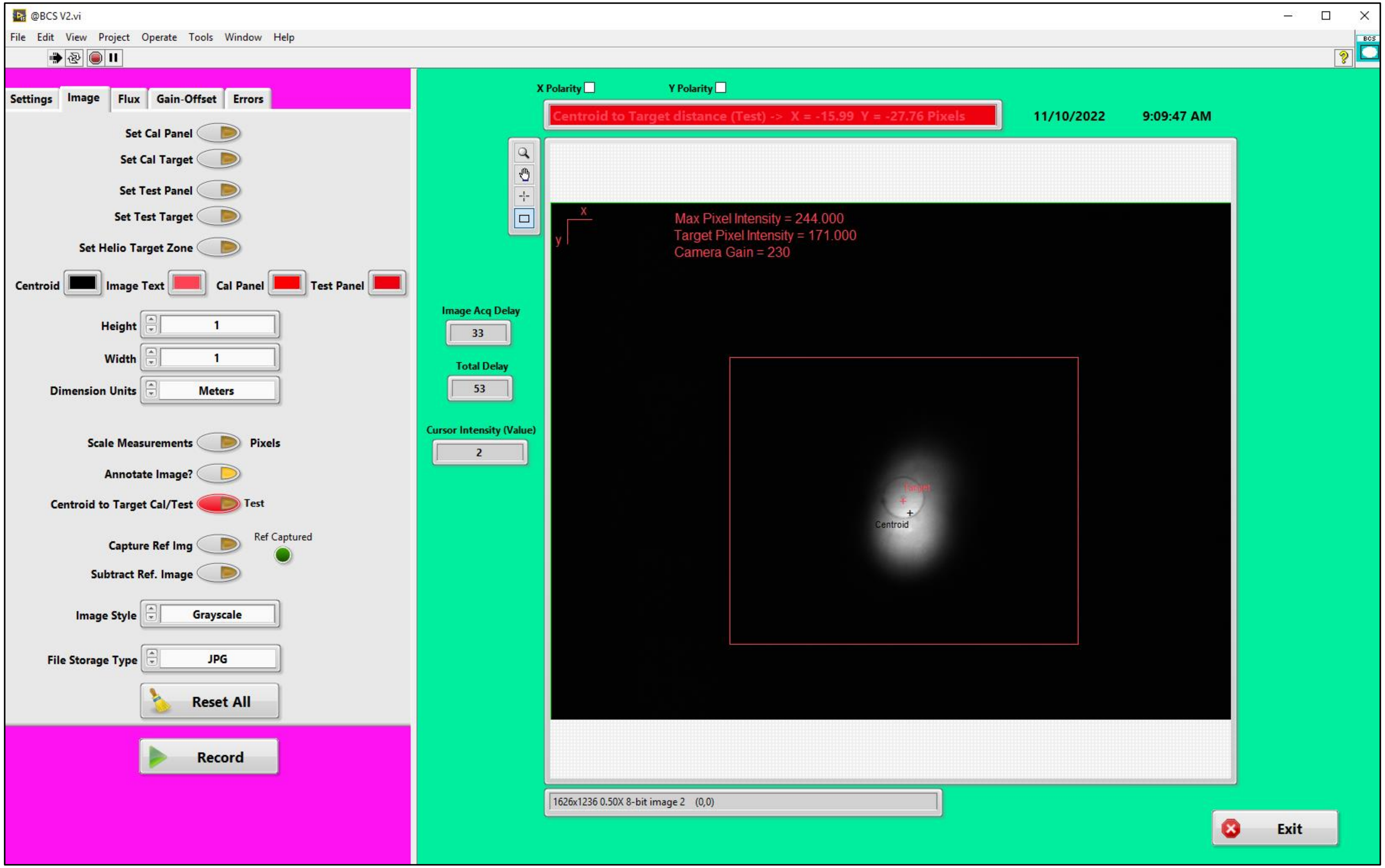
# Heliostats Studied for Pointing Correction




We reduced the number of heliostats to measure, to increase the number of data points per day.

# Measuring Required Pointing Correction

BCS interface:



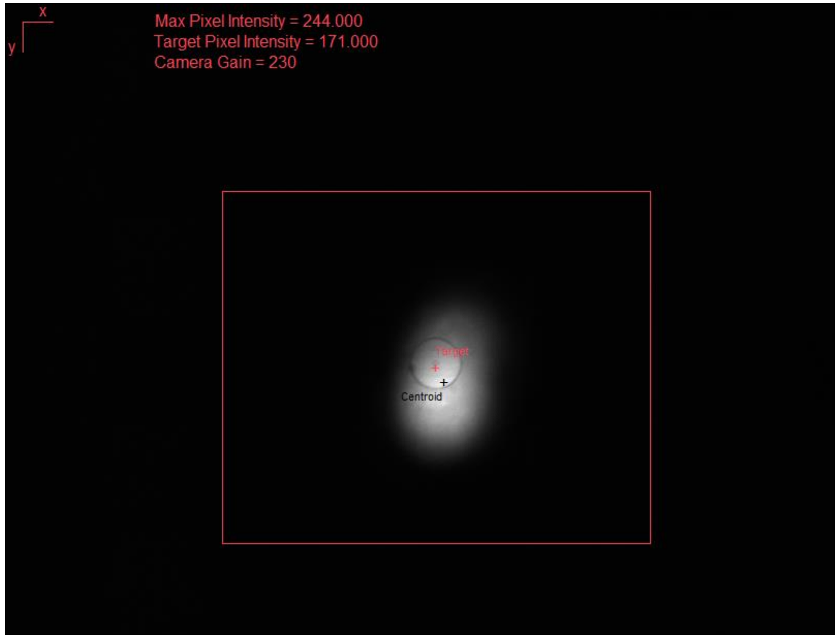
# Example: 9W01

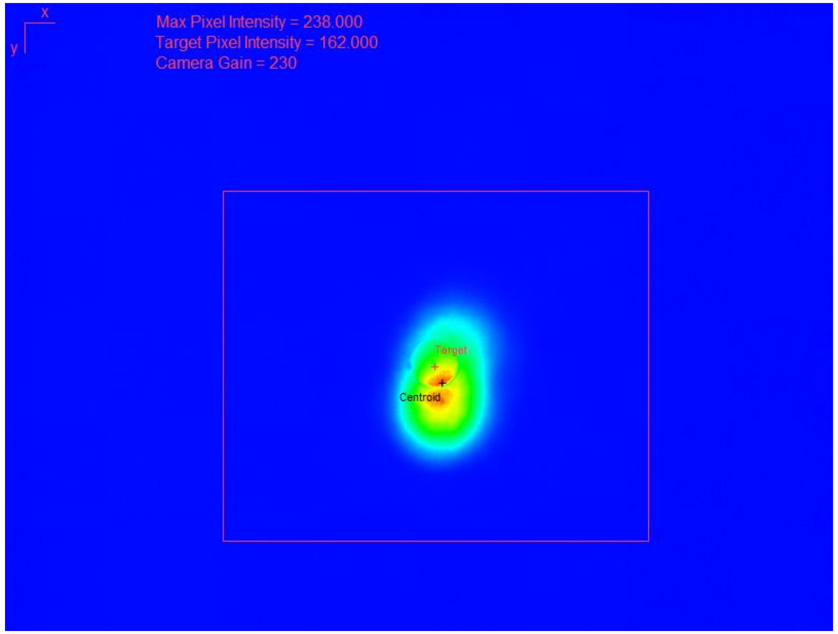
BCS screen shots:

Procedure:

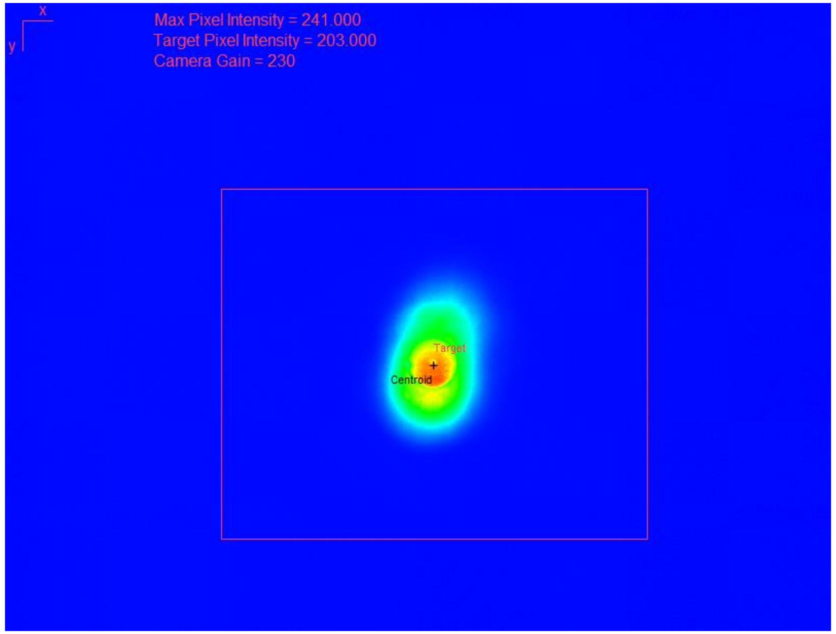
- Red “+” is red rectangle center.
- Red rectangle is set manually, to place “+” on BCS circle center.
- Max pixel intensity is updated frequently in real time.
- Gain is set to avoid pixel saturation (max < 255).
- Black “+” is computed spot centroid.
- Centroid considers entire area within red rectangle, including background.
- Heliostat aim point is manually modified until red and black “+” marks coincide.

## Nominal
[0.00m, 8.80m, 28.90m]



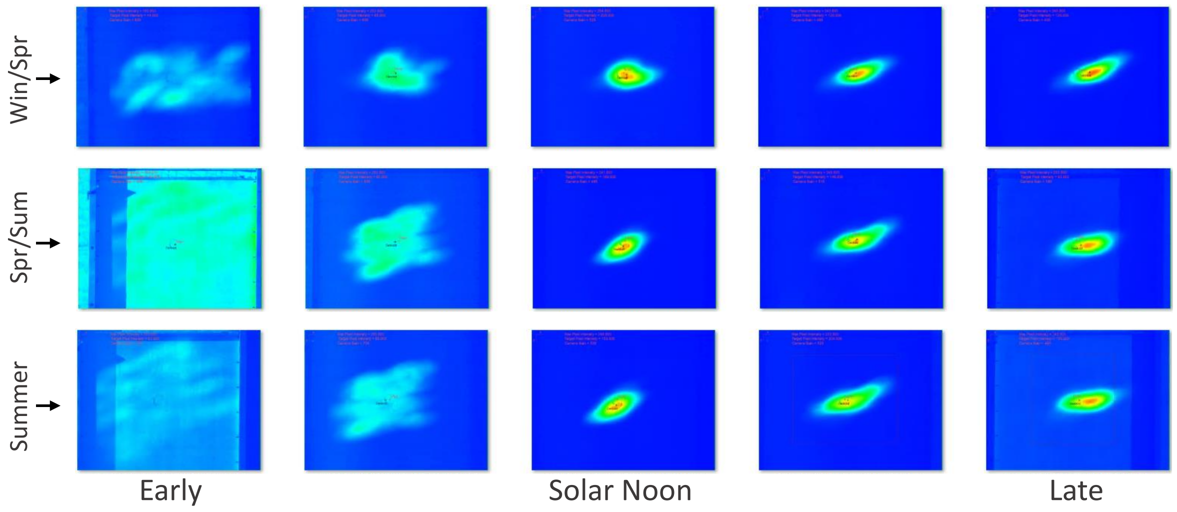



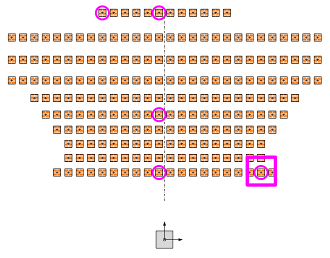

## After Adjustment
[0.12m, 8.80m, 29.12m]

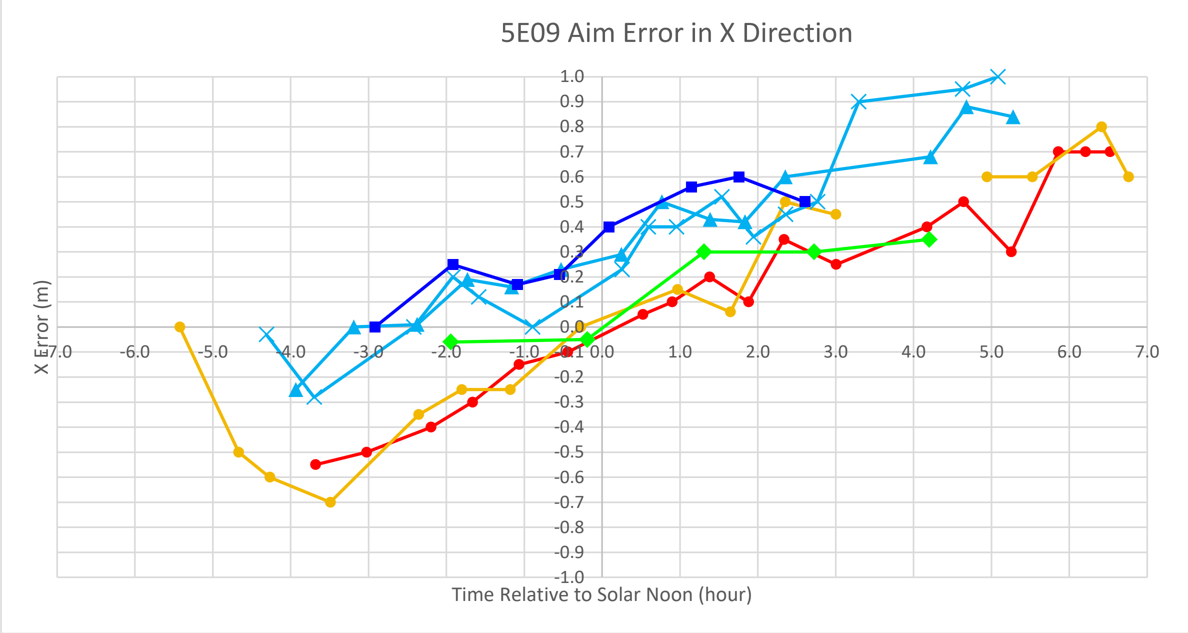



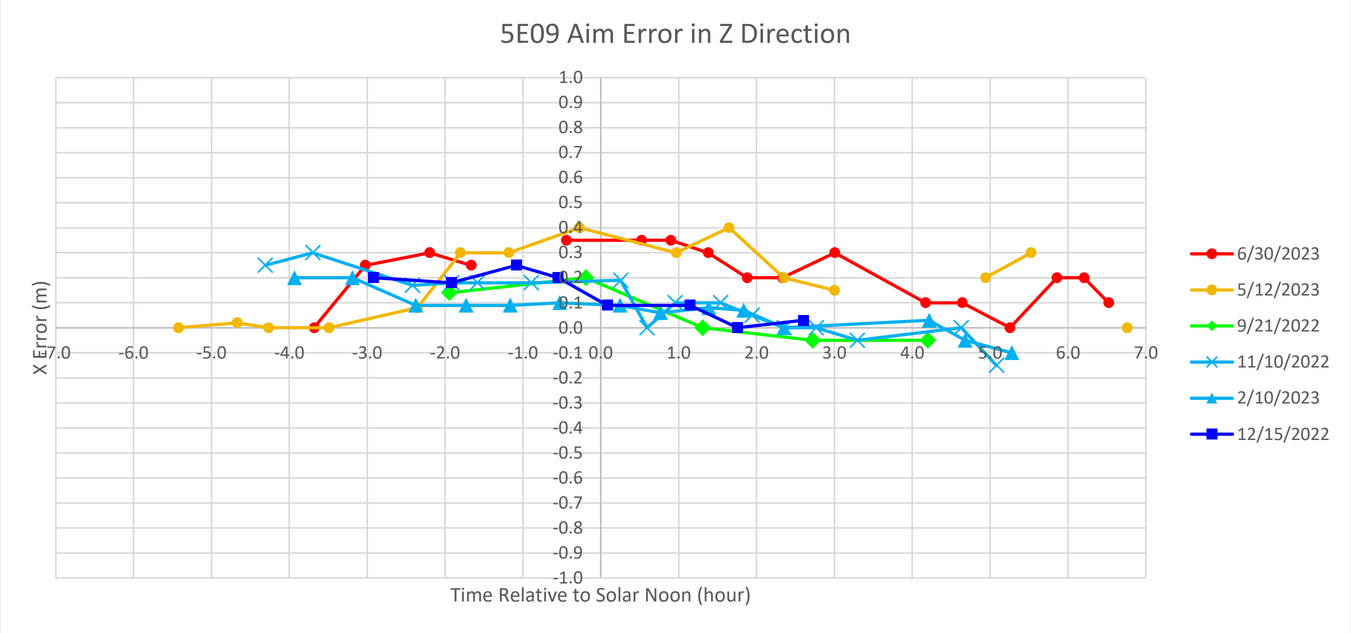
# 5E09

5E09






Color legend:

Winter Solstice → Equinox → Summer Solstice

Systematic variation is observed both across the day and across the year.

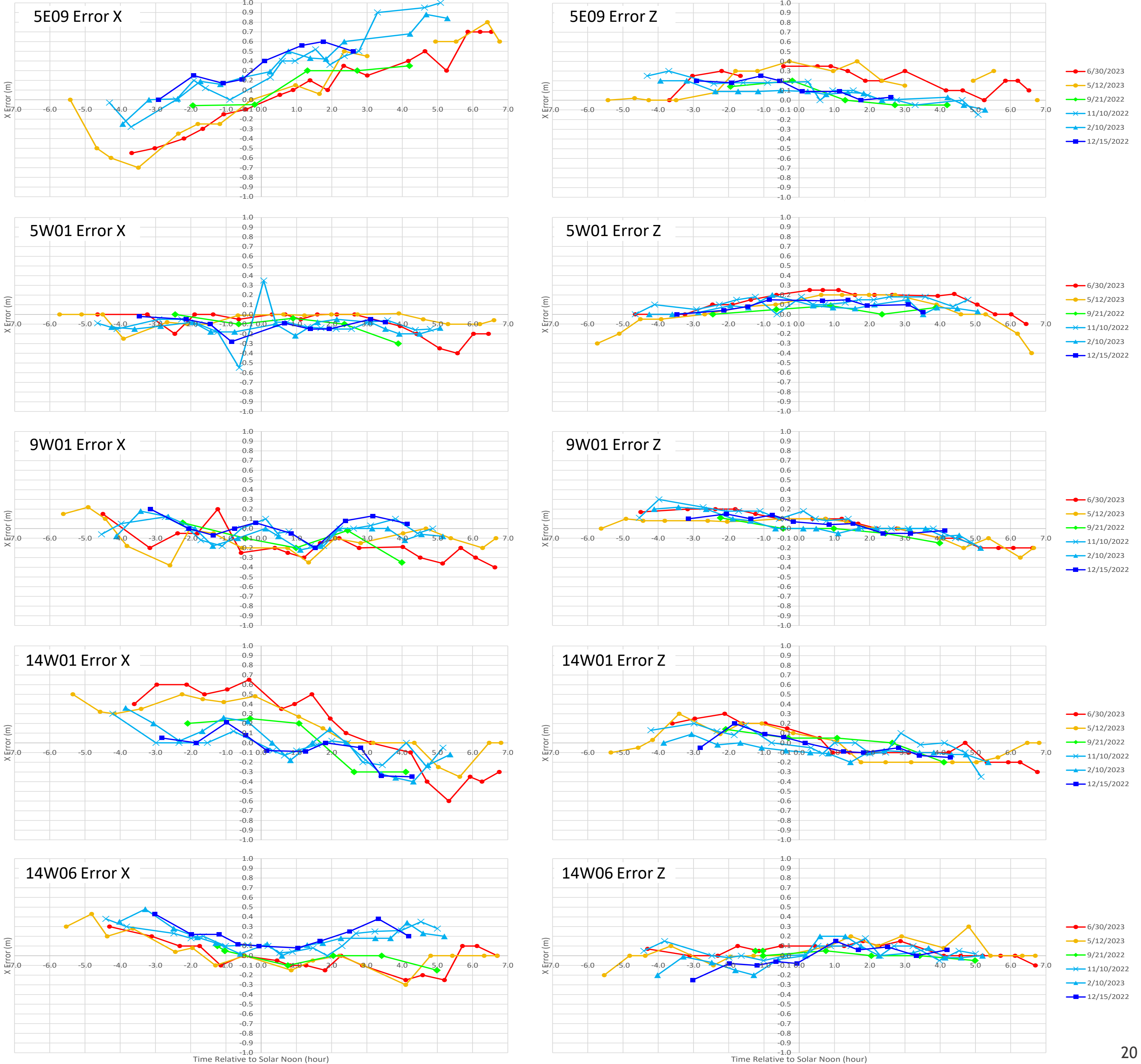
# Pointing Error

Observations:

- Trends in the data are clear, suggesting that noise and uncertainty in our measurement technique is smaller than the underlying signal.
- Trends are clear both within the day, and across the year. For example, consider the winter-to-summer trend in 5E09, 14W01, and 14W06.
- Note that for cases with steep sun incidence angle (e.g, 5E09 near sunrise, 5W09 near sunset), pointing error measurements have more uncertainty 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 $\Delta x$ would yield a 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 4.5 mrad and the slant distance from 14E06 to the BCS target [0m, 8.8 m, 28.9m] is 195.7 m, the spot from an ideal heliostat 14E06 would have diameter 1.76 m. Thus assume a 1.6 m receiver diameter.
- Pointing errors exceed 0.4 m in many cases, reducing power >25%.
- **These observations indicate that identifying heliostat corrections will require multiple measurements spanning the heliostat's useful working envelope.**

Color legend:

Winter Solstice → Equinox → Summer Solstice



# Wind Effects

# BCS Wind Analysis

Early wind flutter analysis (1992):[1]

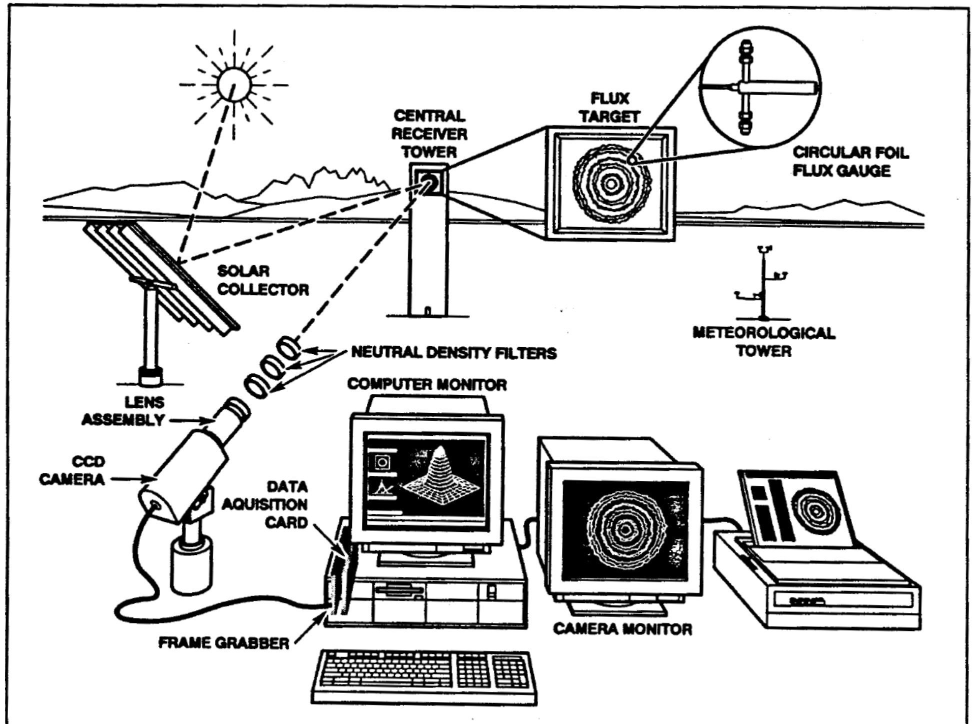



Figure 1: The Beam Characterization System for Heliostat Evaluation

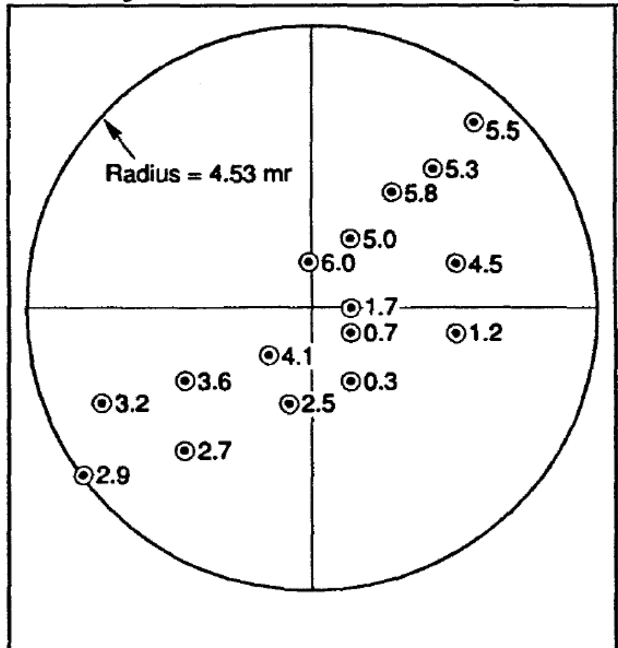
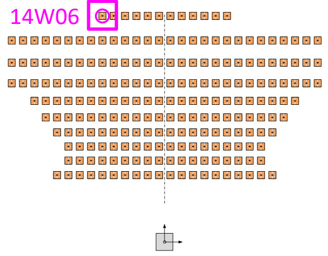



Figure 5: Polar Plot of the Beam Centroid Movement of a Large-Area Heliostat

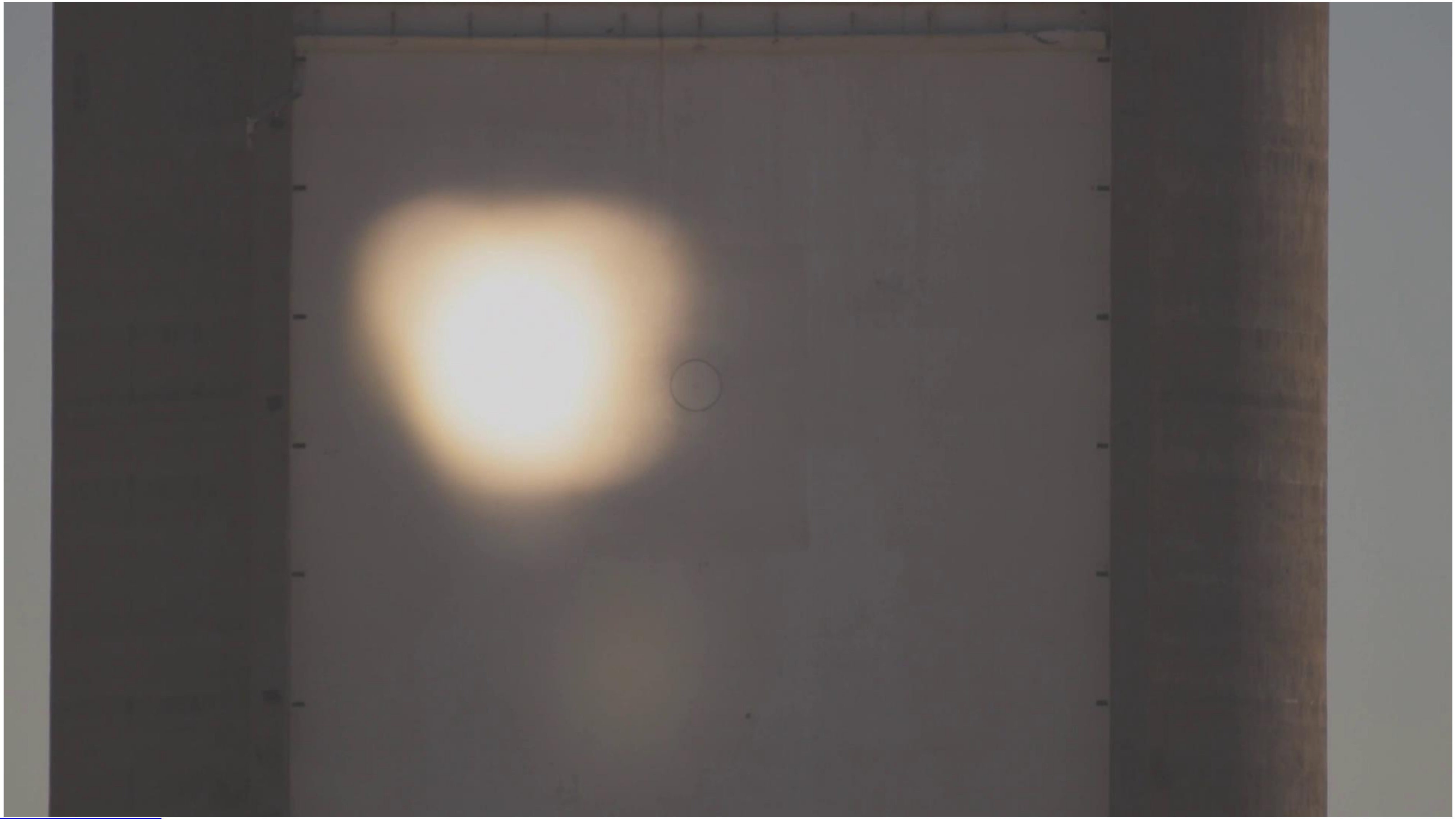
*Heliostat beam movement during an 18 mph wind. Each bull's eye marks the successive location of the beam centroid during a 6 second sequence; each point is labeled with its corresponding time in seconds. The diameter of the circle is 4.65 mr. The circle's center is the average beam centroid position during the test sequence.*

[1]John W. Strachan. Revisiting the BCS, a Measurement System for Characterizing the Optics of Solar Collectors. Sandia Technical Report SAND92-2789C, 1992.

# Dynamic Optical Evaluation




BCS Dynamic Motion:

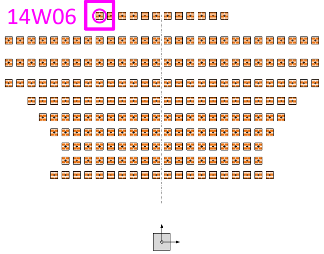


Flip between the slides.

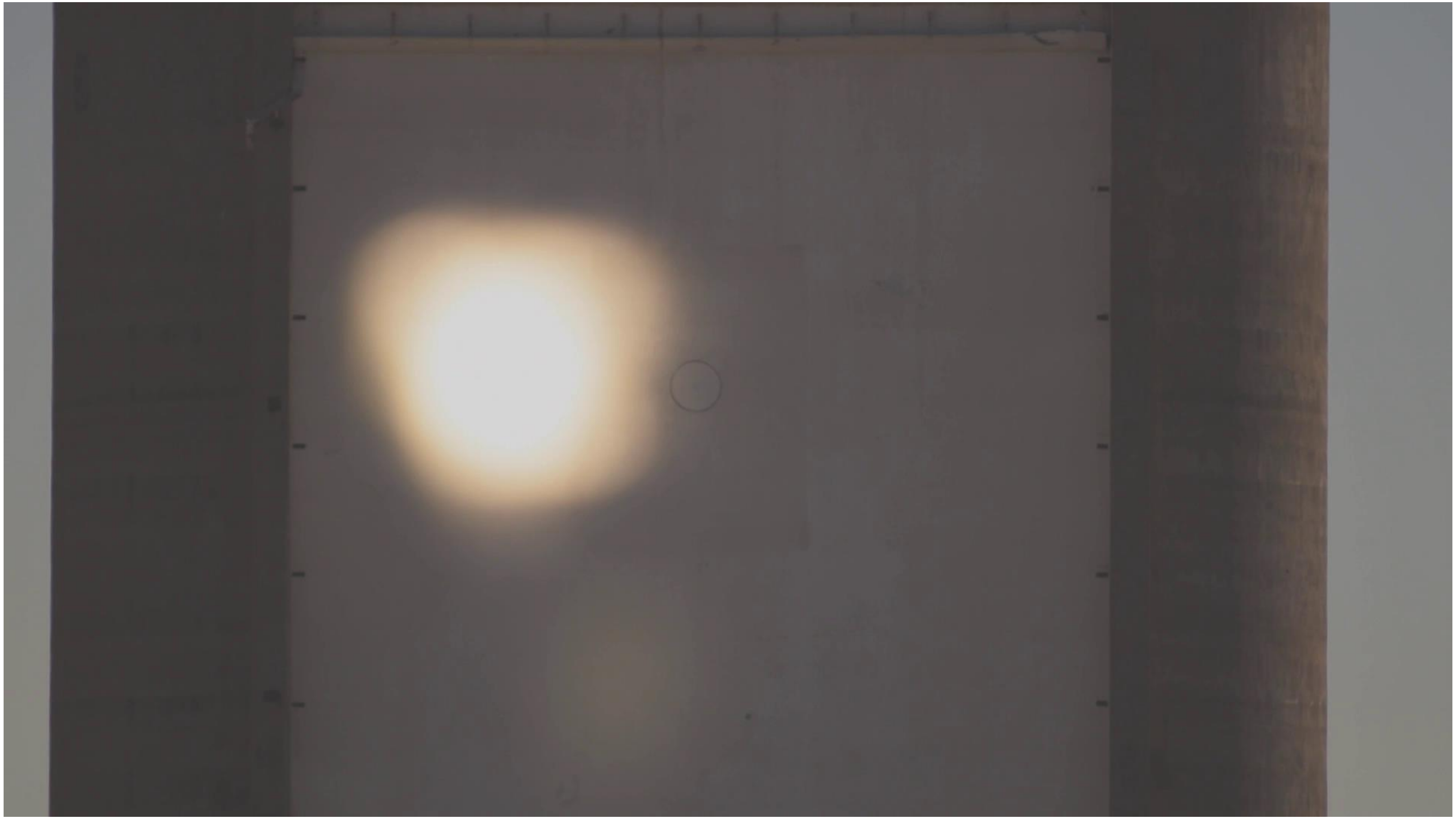
Wind 15 mph, gust up to 30 mph

See DSC_0353_14W06_x=2.25m_trim_2.MOV

# Dynamic Optical Evaluation




BCS Dynamic Motion:



Wind 15 mph, gust up to 30 mph

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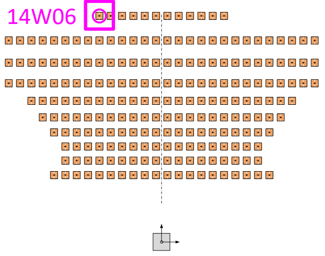
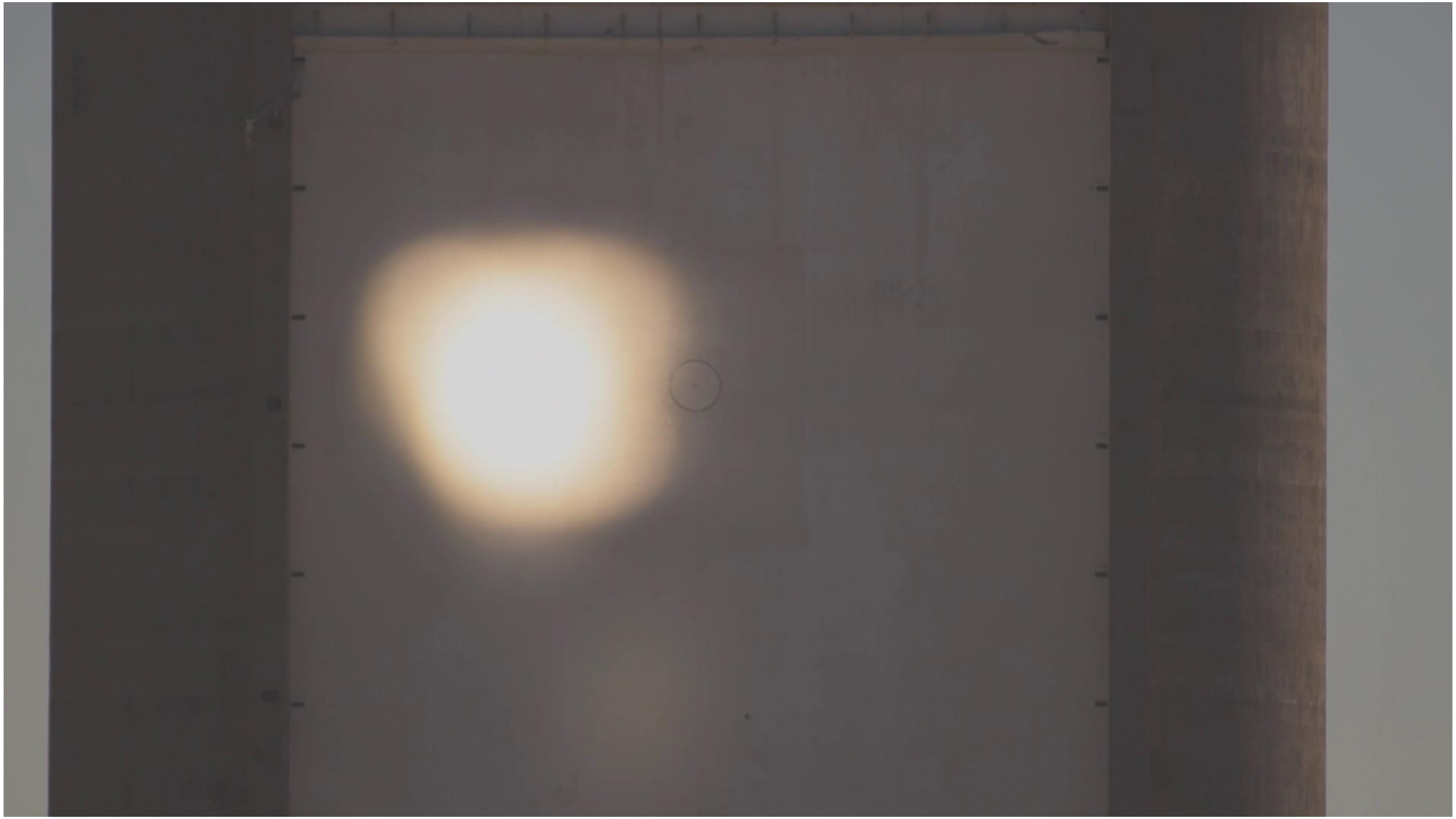
# Dynamic Optical Evaluation




BCS Dynamic Motion:



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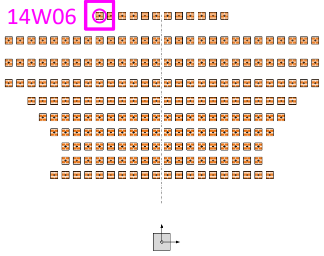
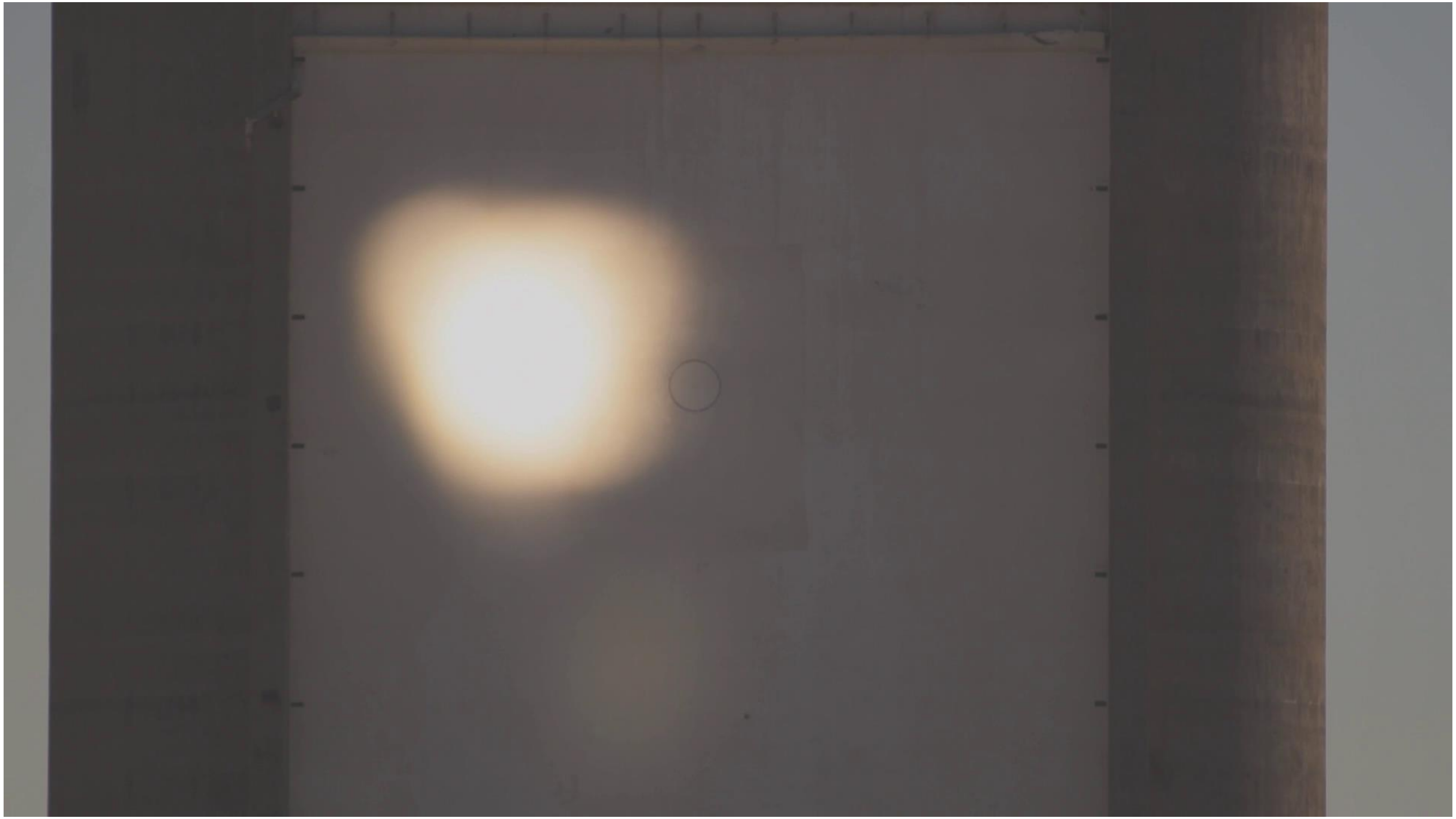



# Dynamic Optical Evaluation

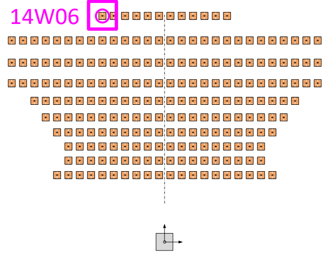
BCS Dynamic Motion:



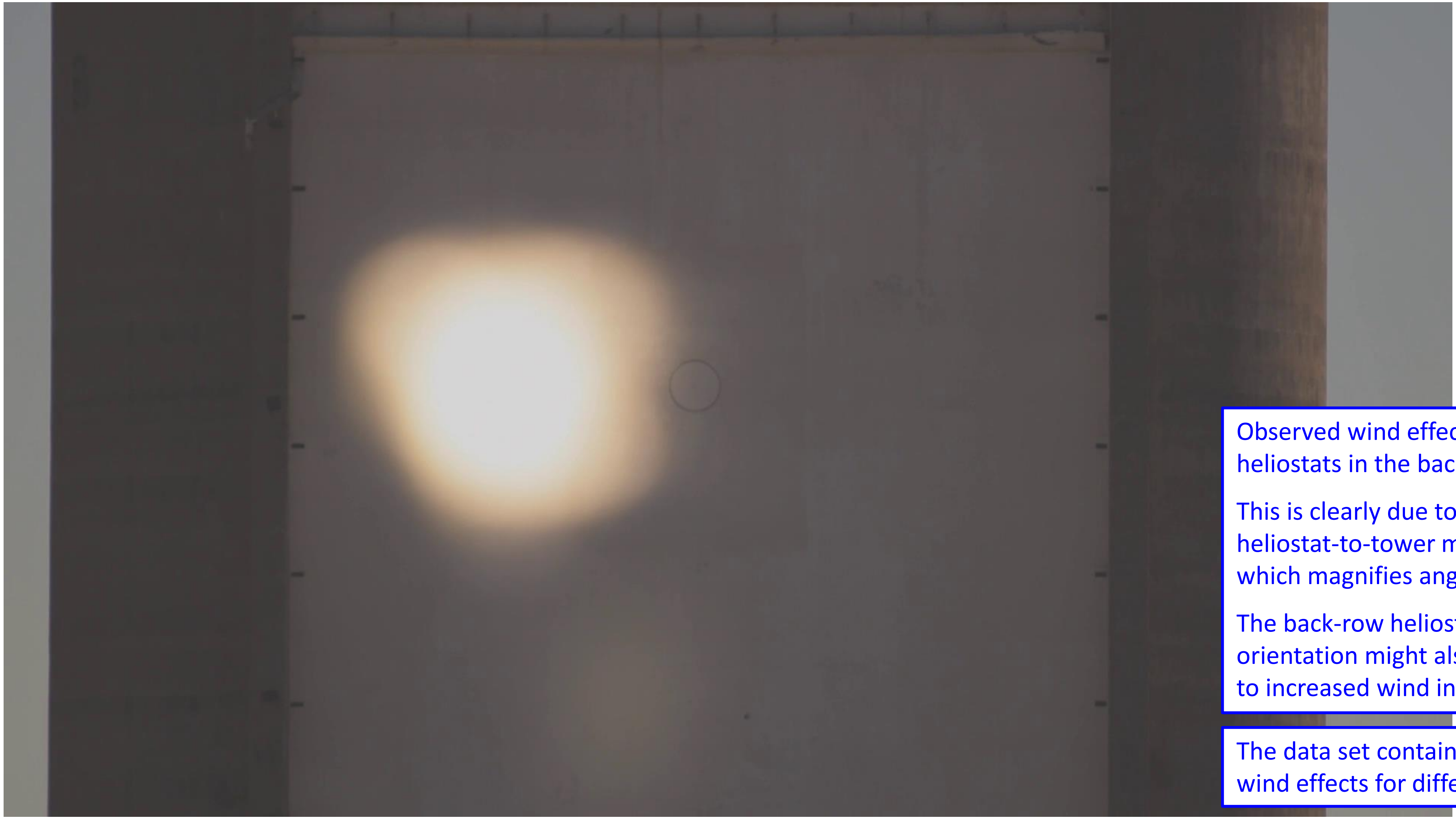
Wind 15 mph, gust up to 30 mph

See DSC_0353_14W06_x=2.25m_trim_2.MOV

# Dynamic Optical Evaluation




BCS Dynamic Motion:



Wind 15 mph, gust up to 30 mph

Observed wind effects were largest for heliostats in the back row.

This is clearly due to the increased heliostat-to-tower moment arm, which magnifies angle perturbations.

The back-row heliostats' more upright orientation might also contribute, due to increased wind interception.

The data set contains observations of wind effects for different heliostats.

See DSC_0353_14W06_x=2.25m_trim_2.MOV

# Discussion

# Summary

- We captured data measuring variation in beam shape, pointing correction, and wind effects.
- Data were collected:
  - ➢ For nine key heliostats spread across the NSTTF field.
  - ➢ Over six days spread throughout the solar year.
  - ➢ Data volume is 290 GB, over 120,000 files.
- Off-noon incidence, pointing error, and dynamic wind flutter were all observed to produce significant degradation in beam focus on target.
- All were observed to vary over time. Off-noon incidence and pointing errors were systematic; wind was intermittent.
- Note that NSTTF routinely operates successfully for its intermittent tests, which occur frequently and are generally performed near solar noon.
- For a continuously running plant, these effects clearly would have an impact on performance and overall economic return.
- This data set could support many additional analysis questions not yet performed.
- The data set will be released as part of the OpenCSP community development environment.
- If you are interested, send email to **OpenCSP@sandia.gov**.

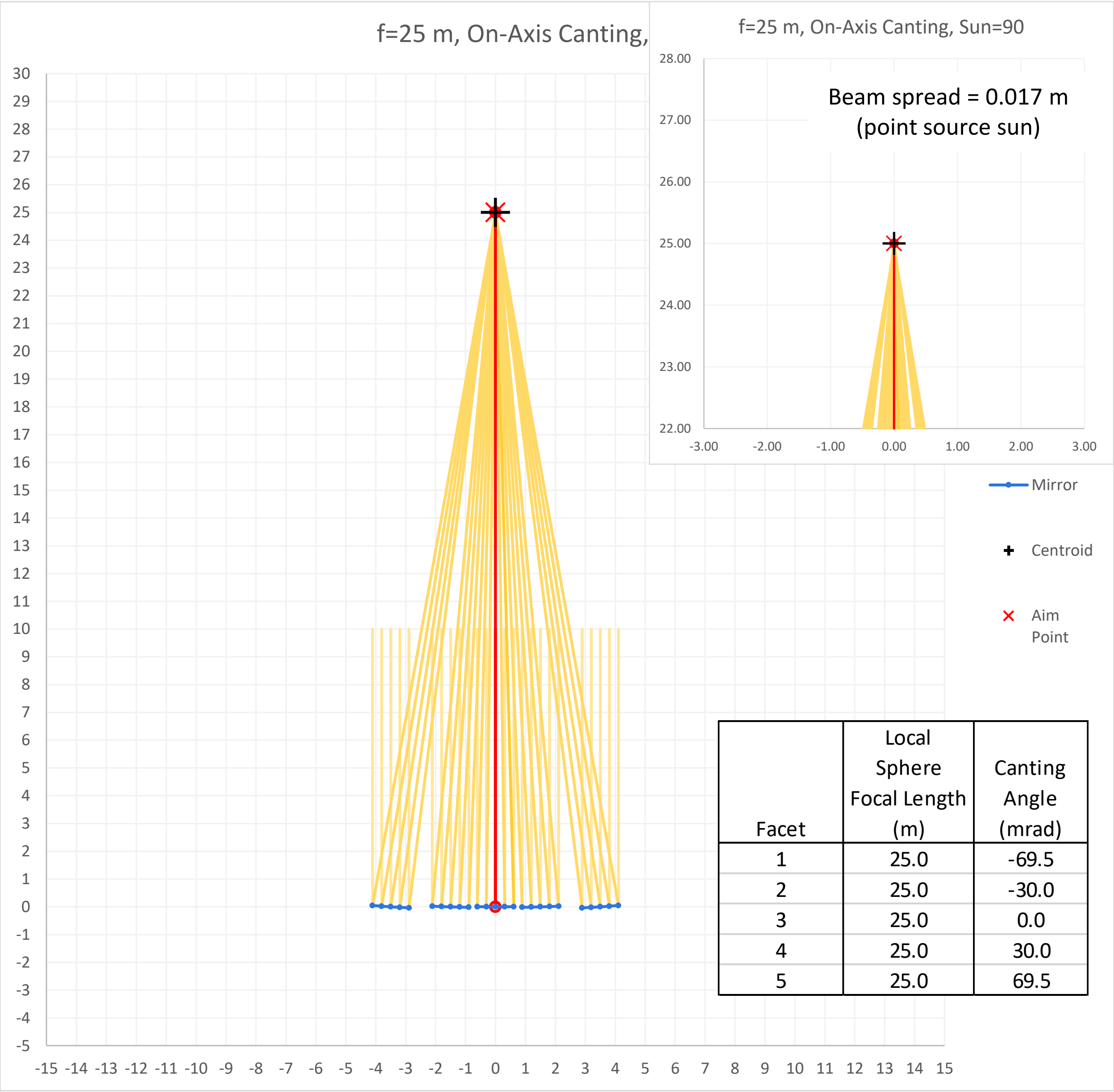
We thank:

SOLAR ENERGY TECHNOLOGIES OFFICE U.S. Department Of Energy

U.S. DEPARTMENT OF ENERGY

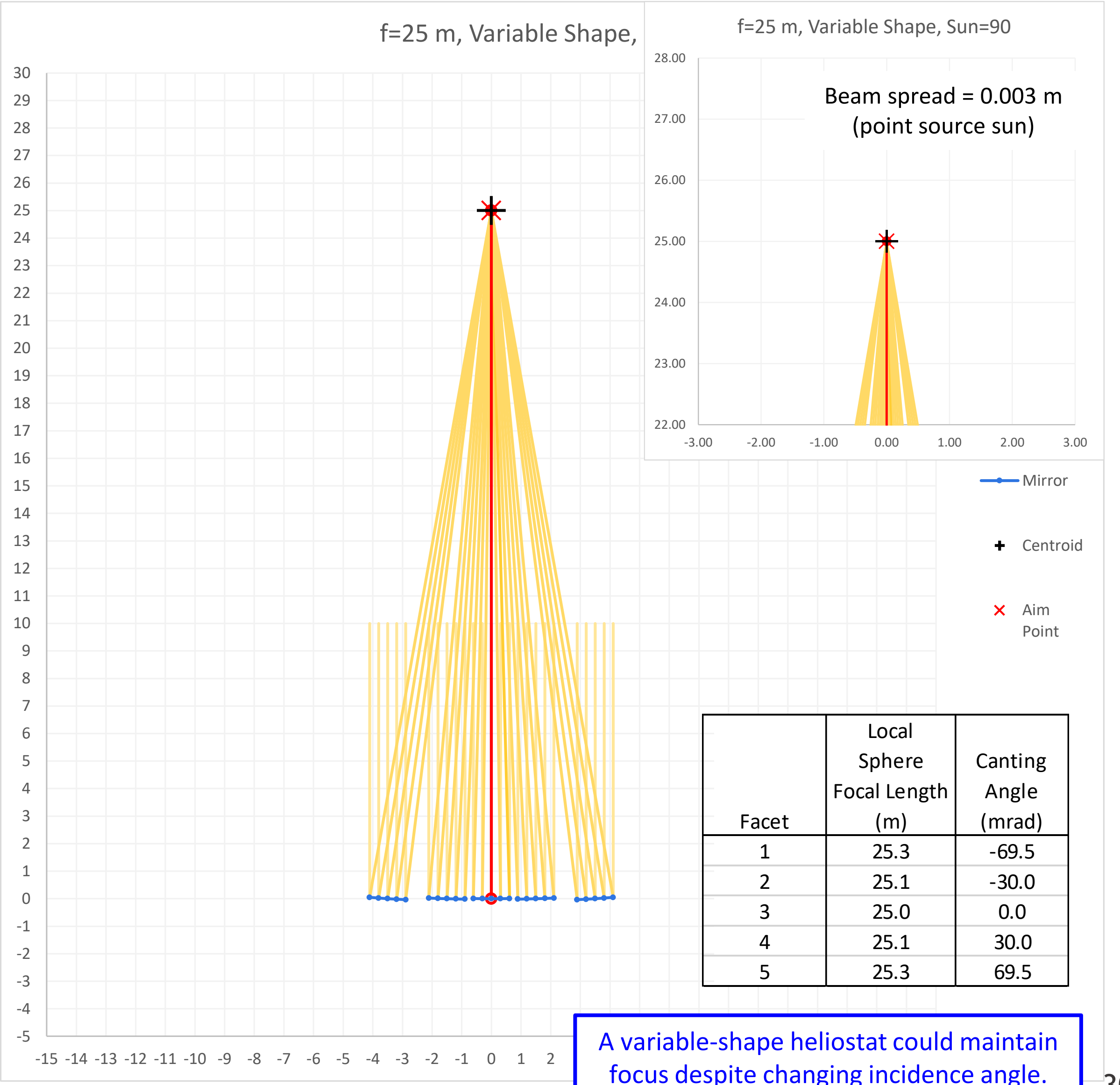
# Some Heliostats Intentionally Change Shape

## 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:



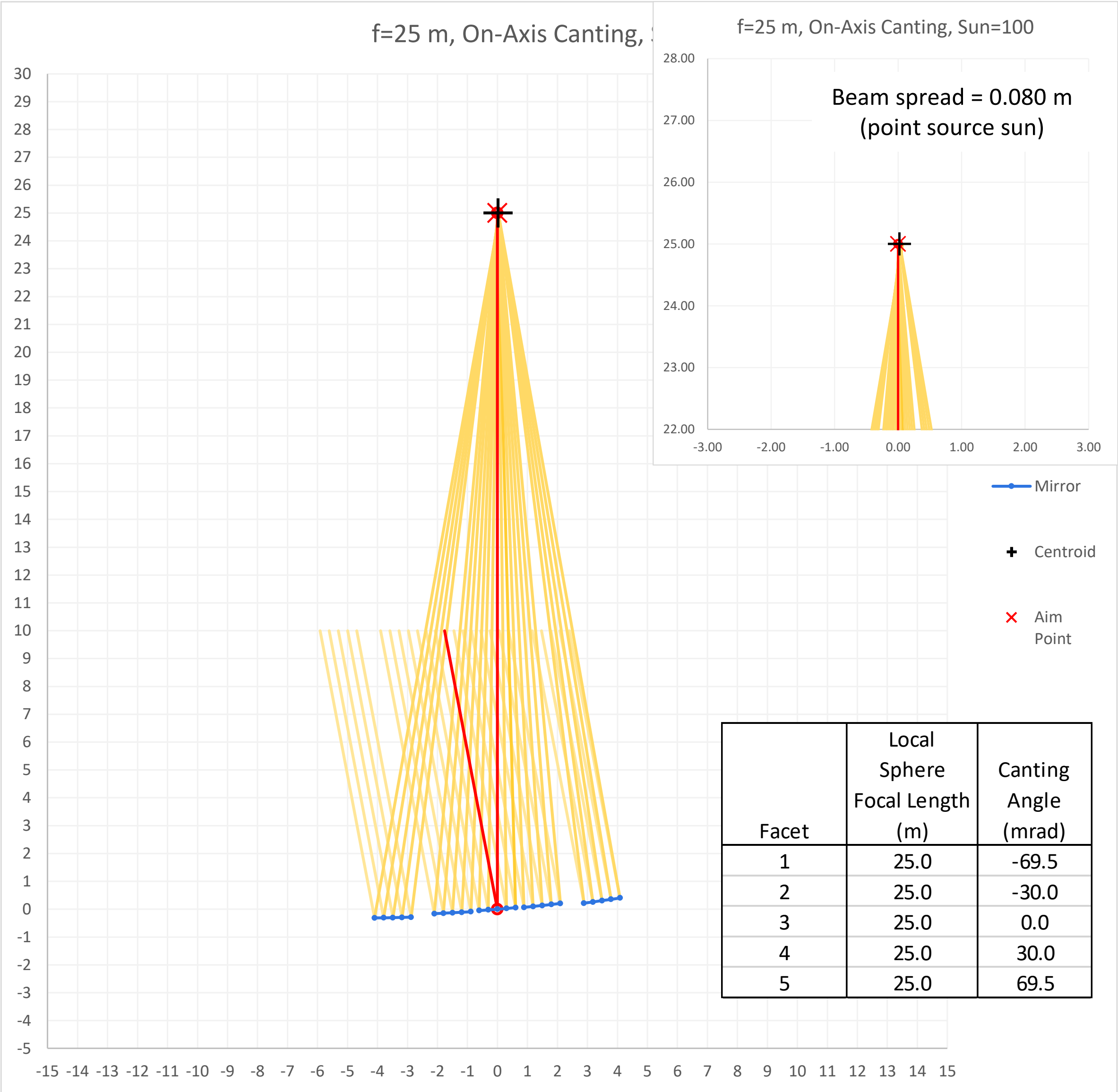

| Facet | Local Sphere Focal Length (m) | Canting Angle (mrad) |
|---|---|---|
| 1 | 25.3 | -69.5 |
| 2 | 25.1 | -30.0 |
| 3 | 25.0 | 0.0 |
| 4 | 25.1 | 30.0 |
| 5 | 25.3 | 69.5 |

A variable-shape heliostat could maintain focus despite changing incidence angle.

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

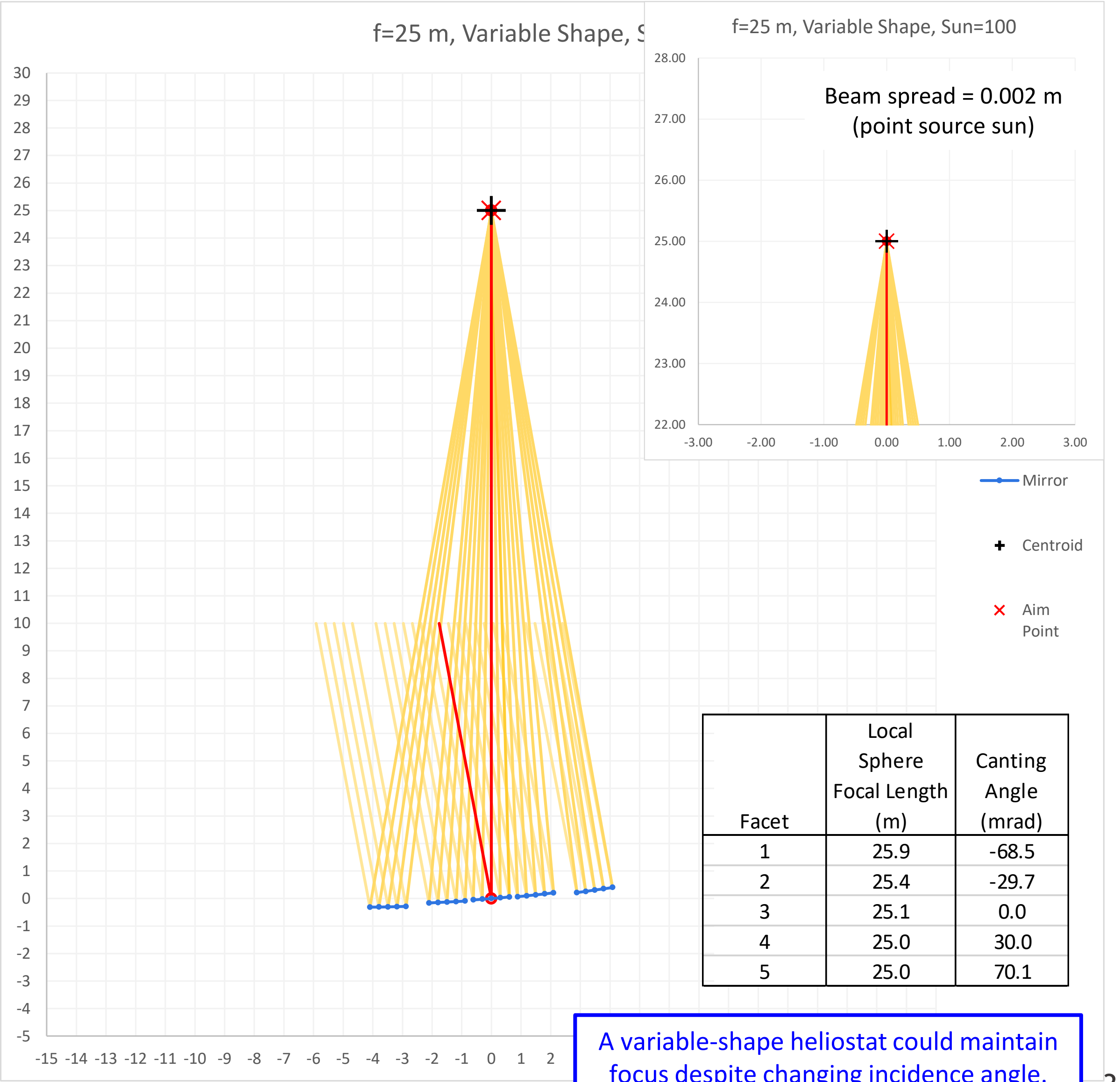
# Some Heliostats Intentionally Change Shape

## 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 |

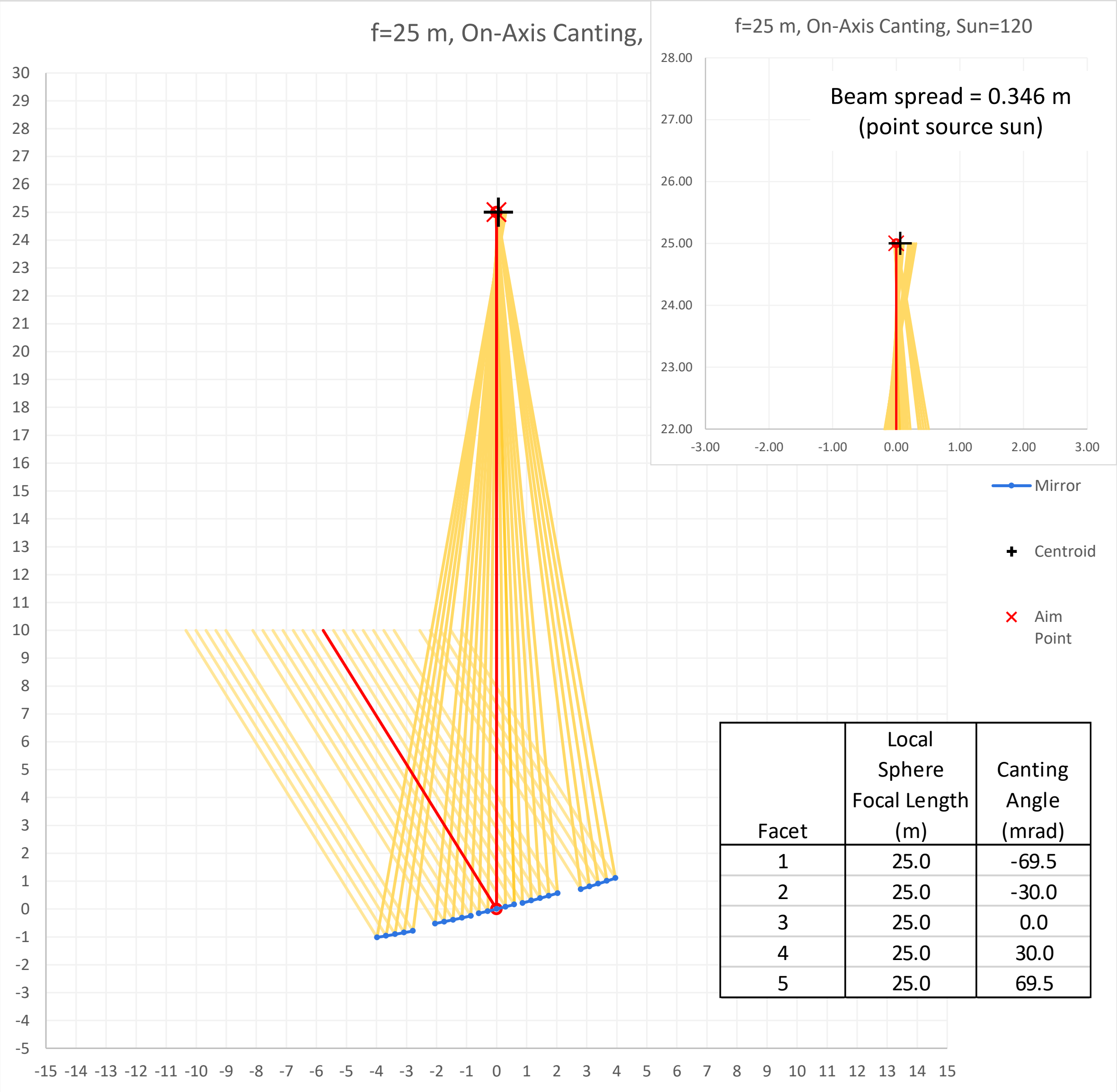
A variable-shape heliostat could maintain focus despite changing incidence angle.

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

Inquiries: OpenCSP@sandia.gov

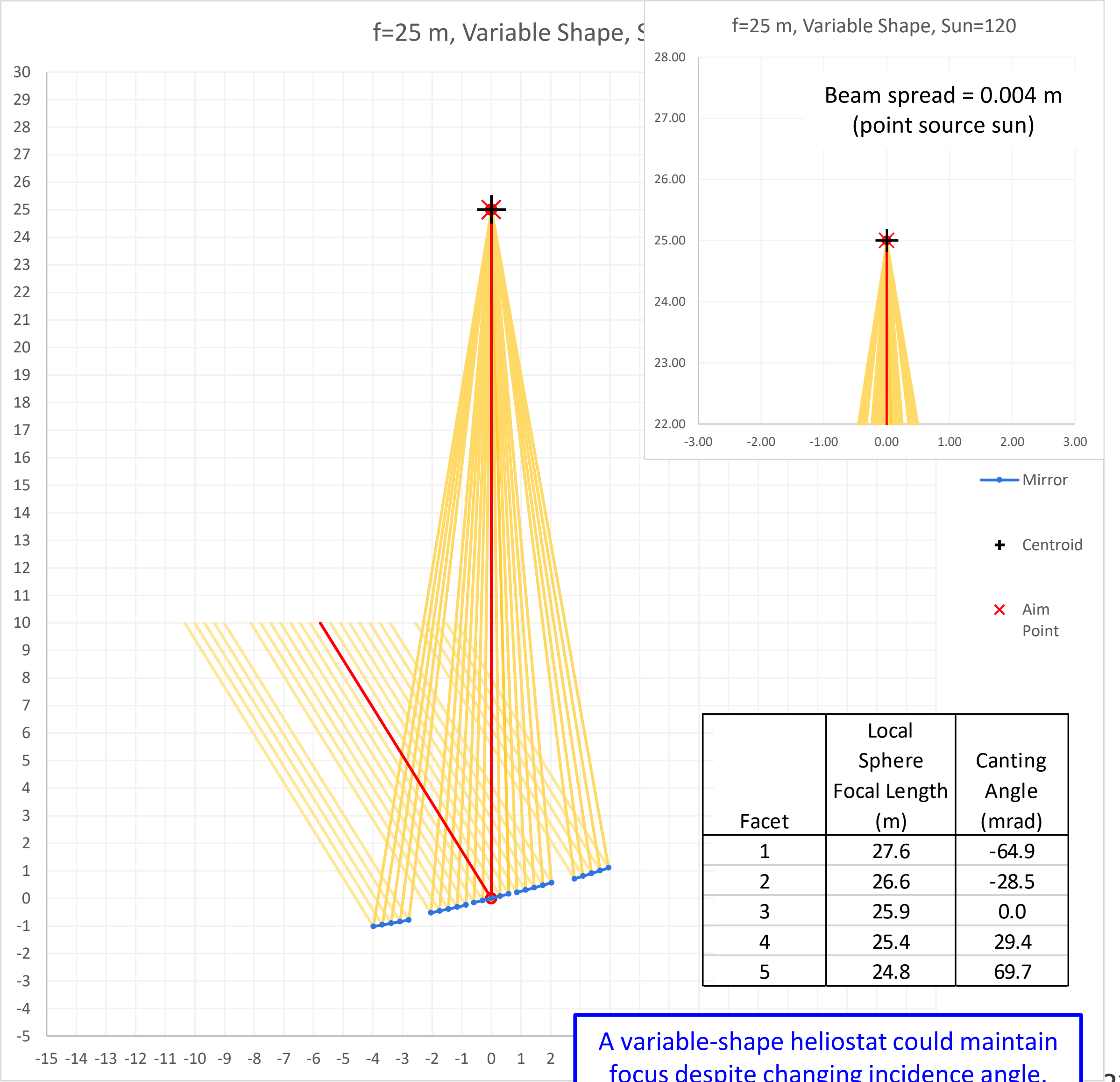
# Some Heliostats Intentionally Change Shape

## 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:



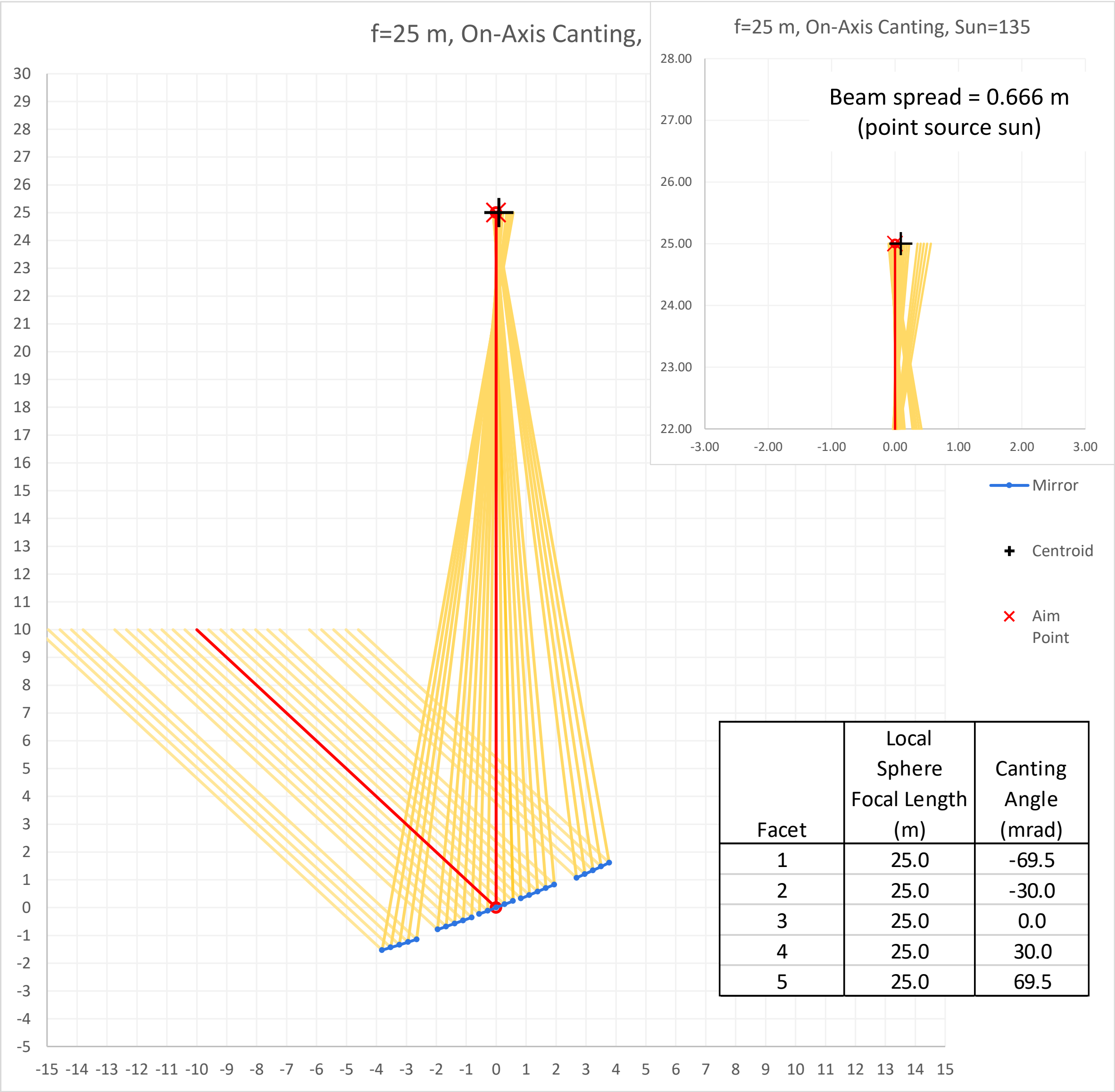

| Facet | Local Sphere Focal Length (m) | Canting Angle (mrad) |
|---|---|---|
| 1 | 27.6 | -64.9 |
| 2 | 26.6 | -28.5 |
| 3 | 25.9 | 0.0 |
| 4 | 25.4 | 29.4 |
| 5 | 24.8 | 69.7 |

A variable-shape heliostat could maintain focus despite changing incidence angle.

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

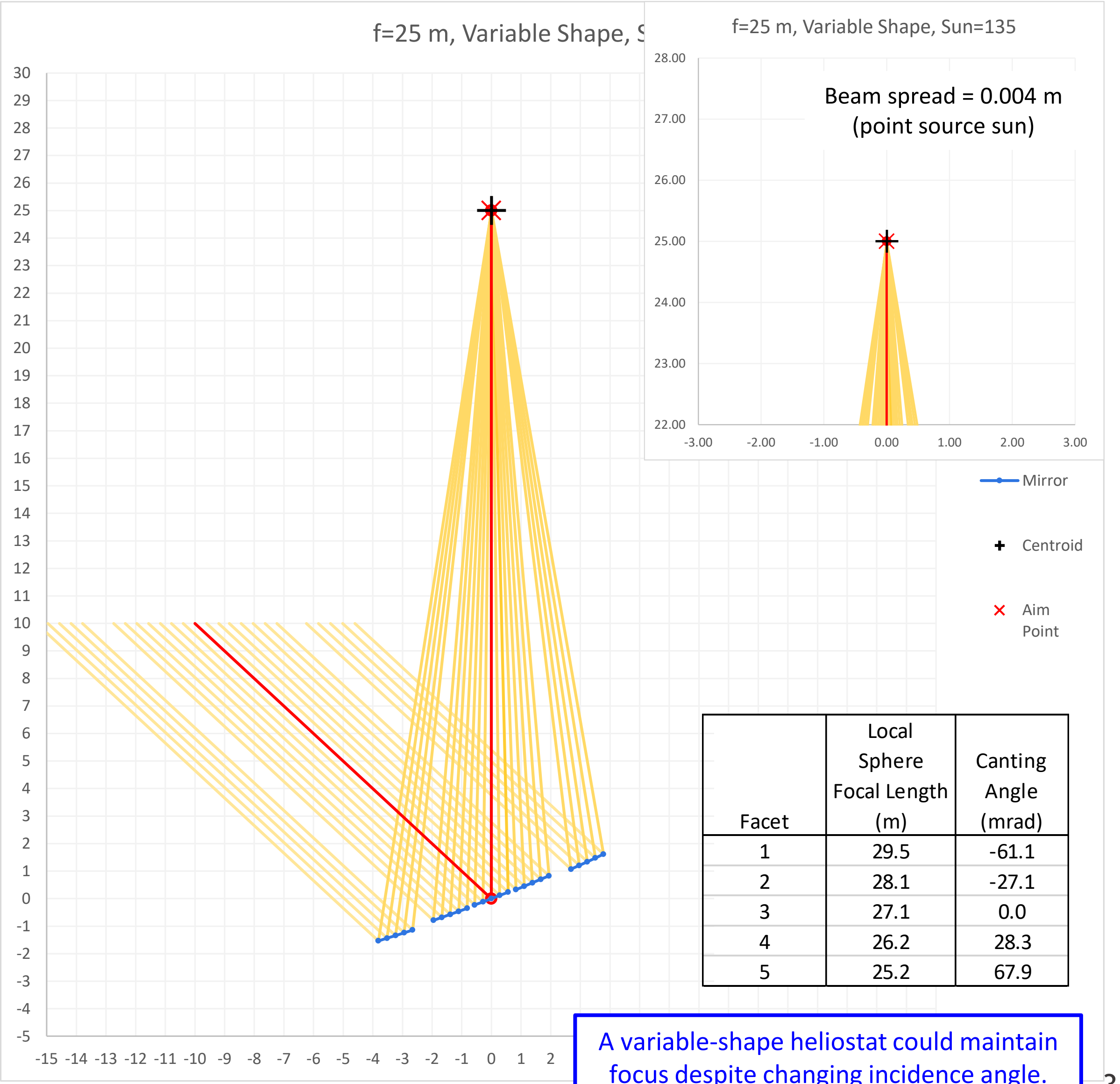
# Some Heliostats Intentionally Change Shape

## 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 |

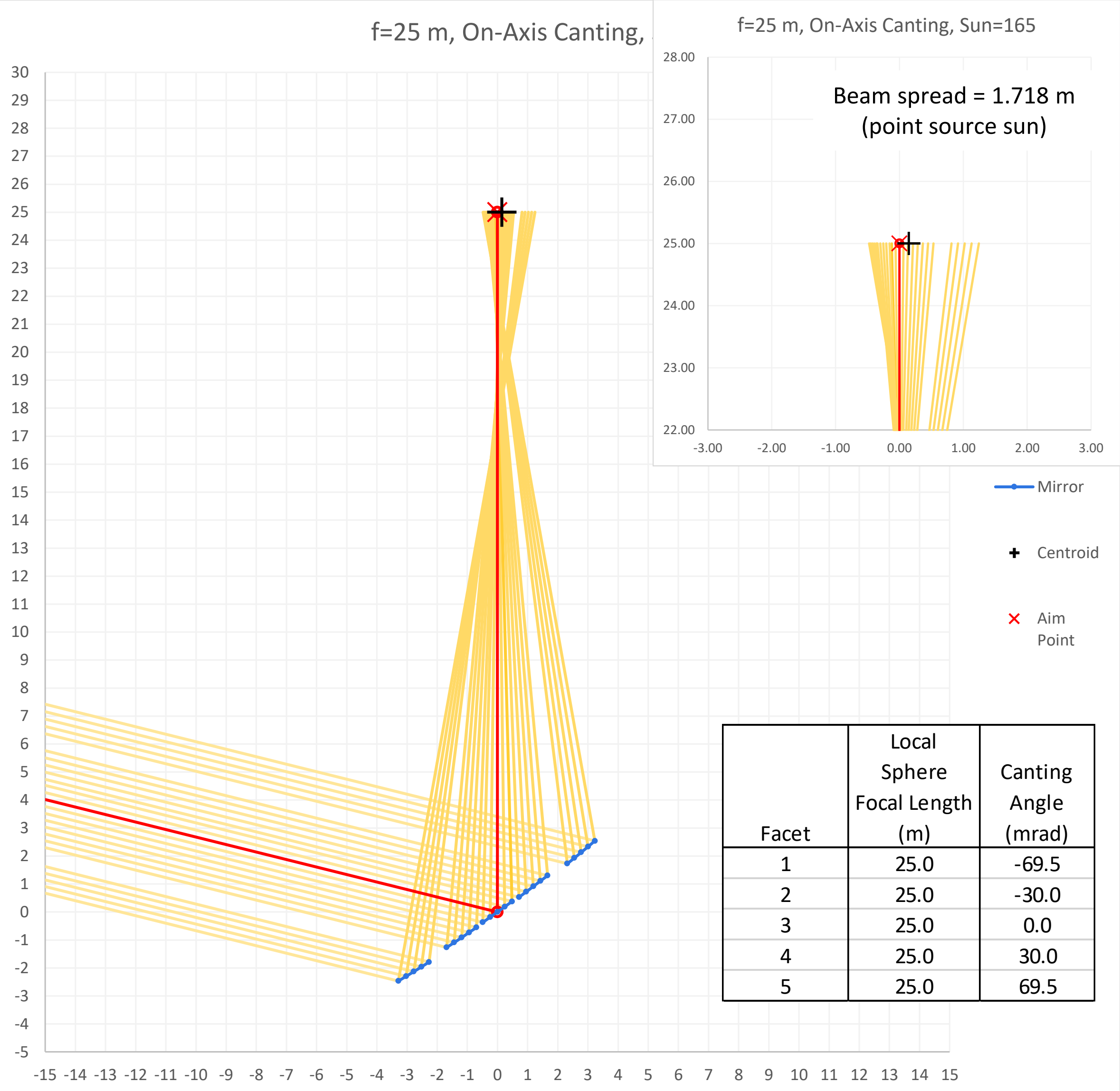
A variable-shape heliostat could maintain focus despite changing incidence angle.



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

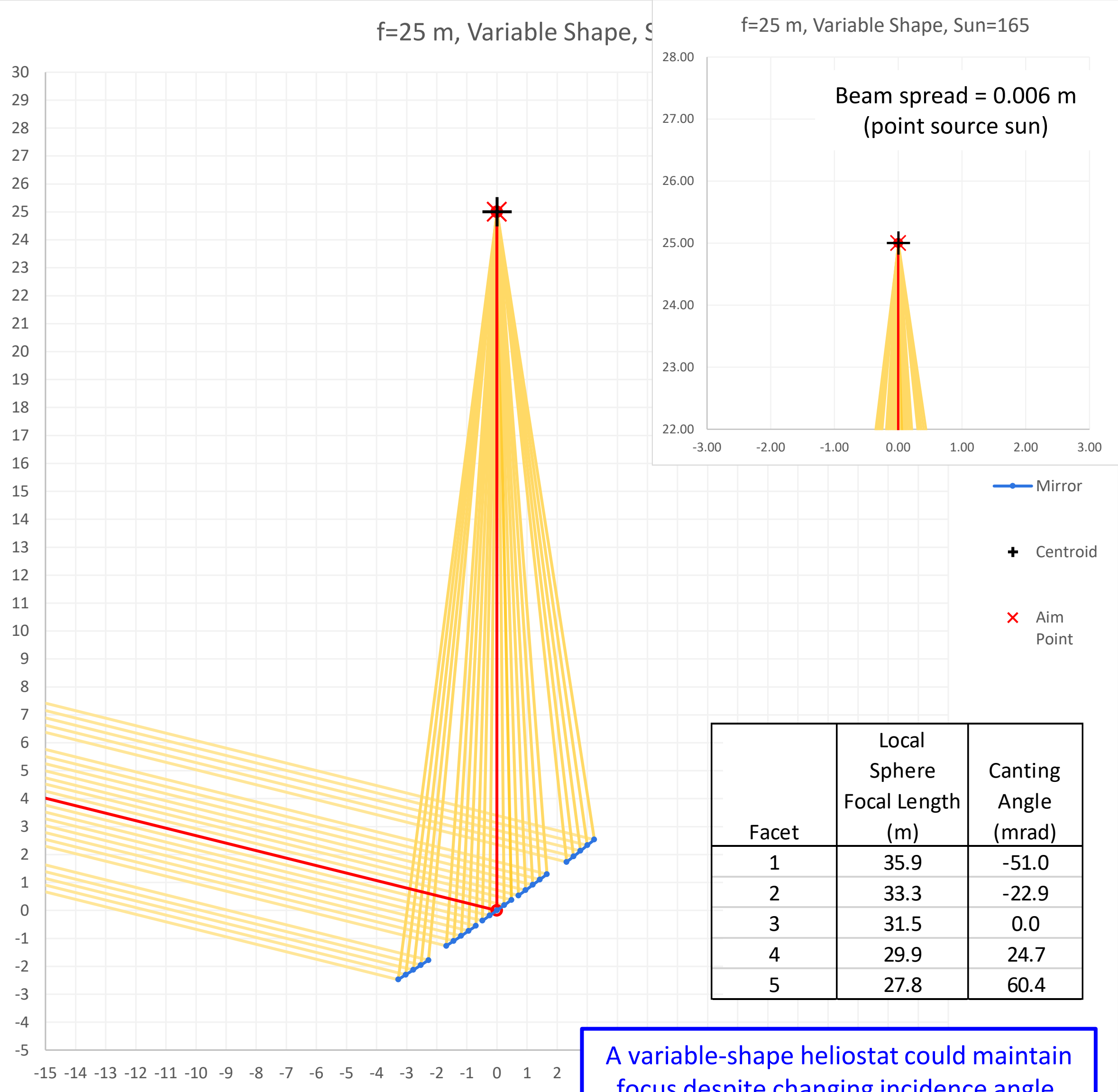
# Some Heliostats Intentionally Change Shape

## 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 |

A variable-shape heliostat could maintain focus despite changing incidence angle.

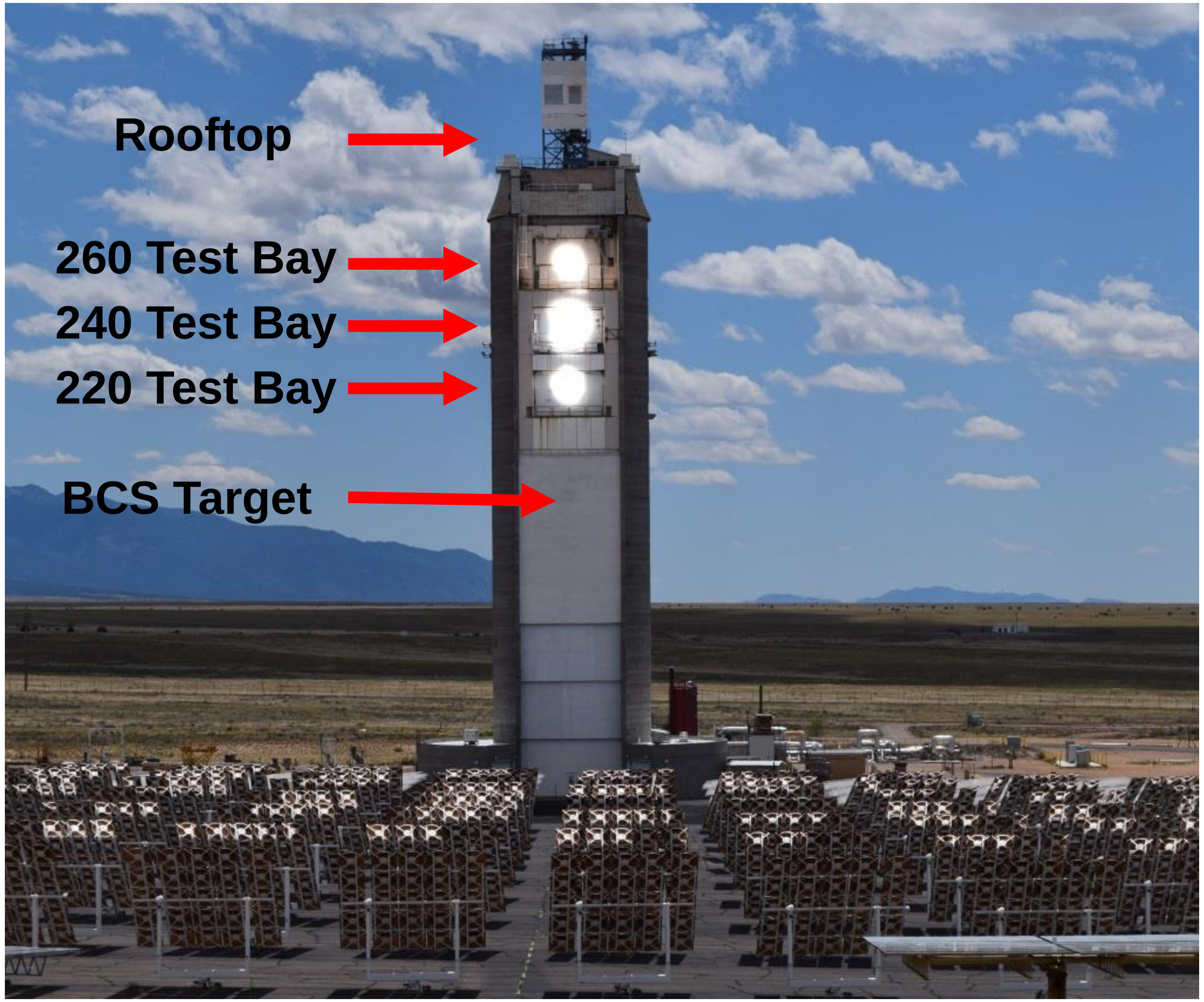
Sun is modeled as a point source. Sun shape not included.

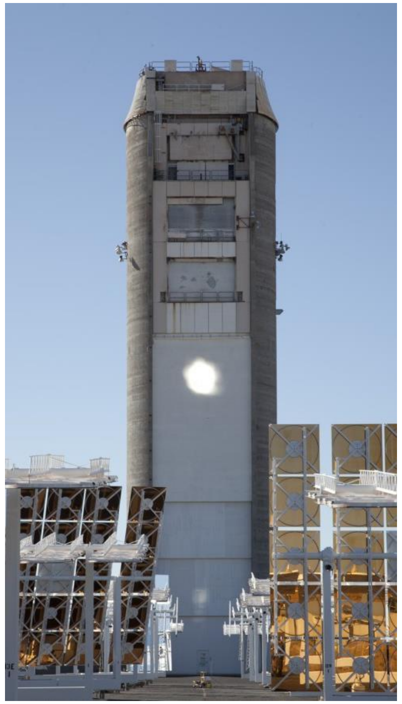
# BACKUP SLIDES

# Legal Notice

# NSTTF Tower

Multiple test bays:



Fiducials

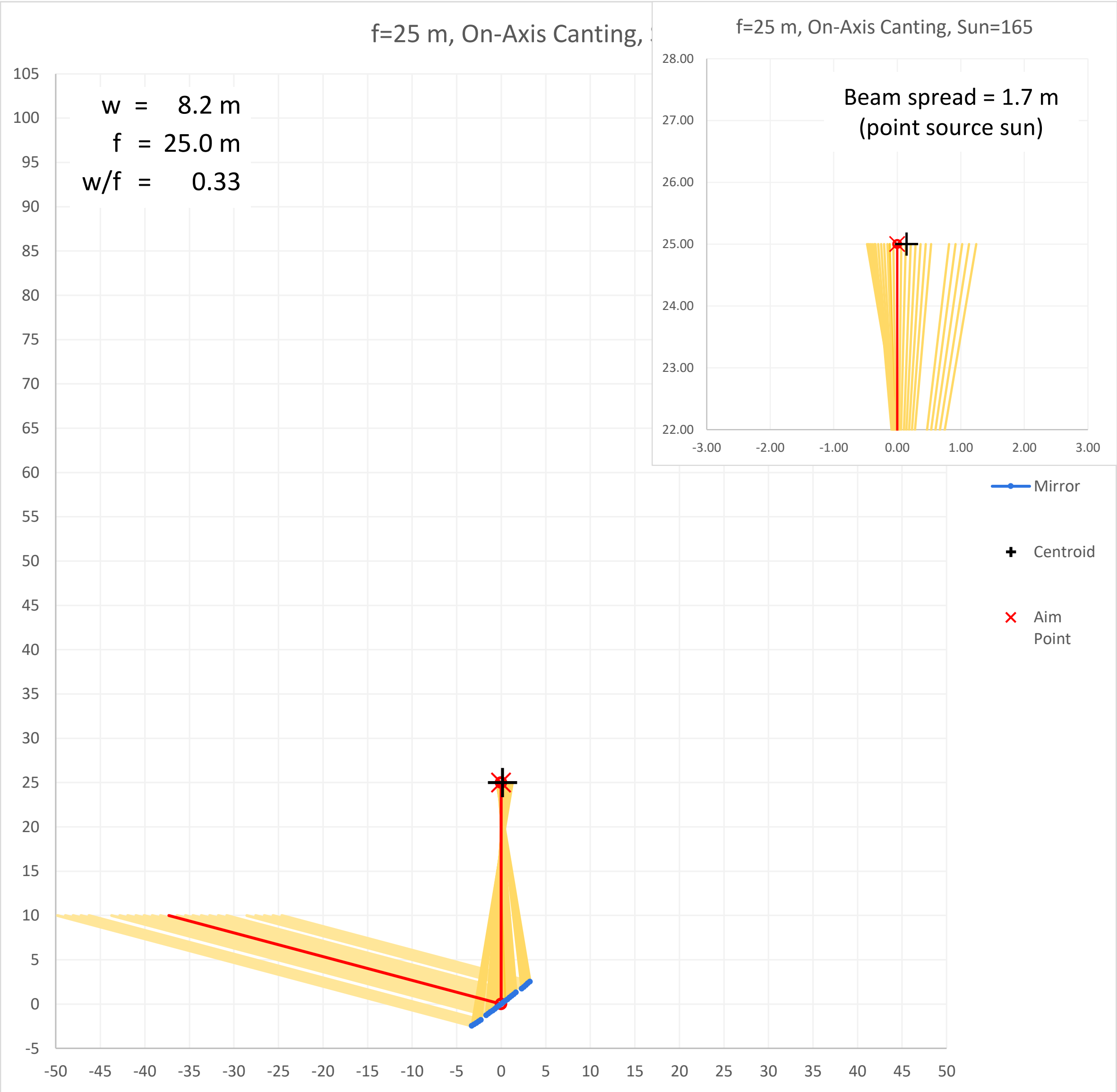
Fiducials

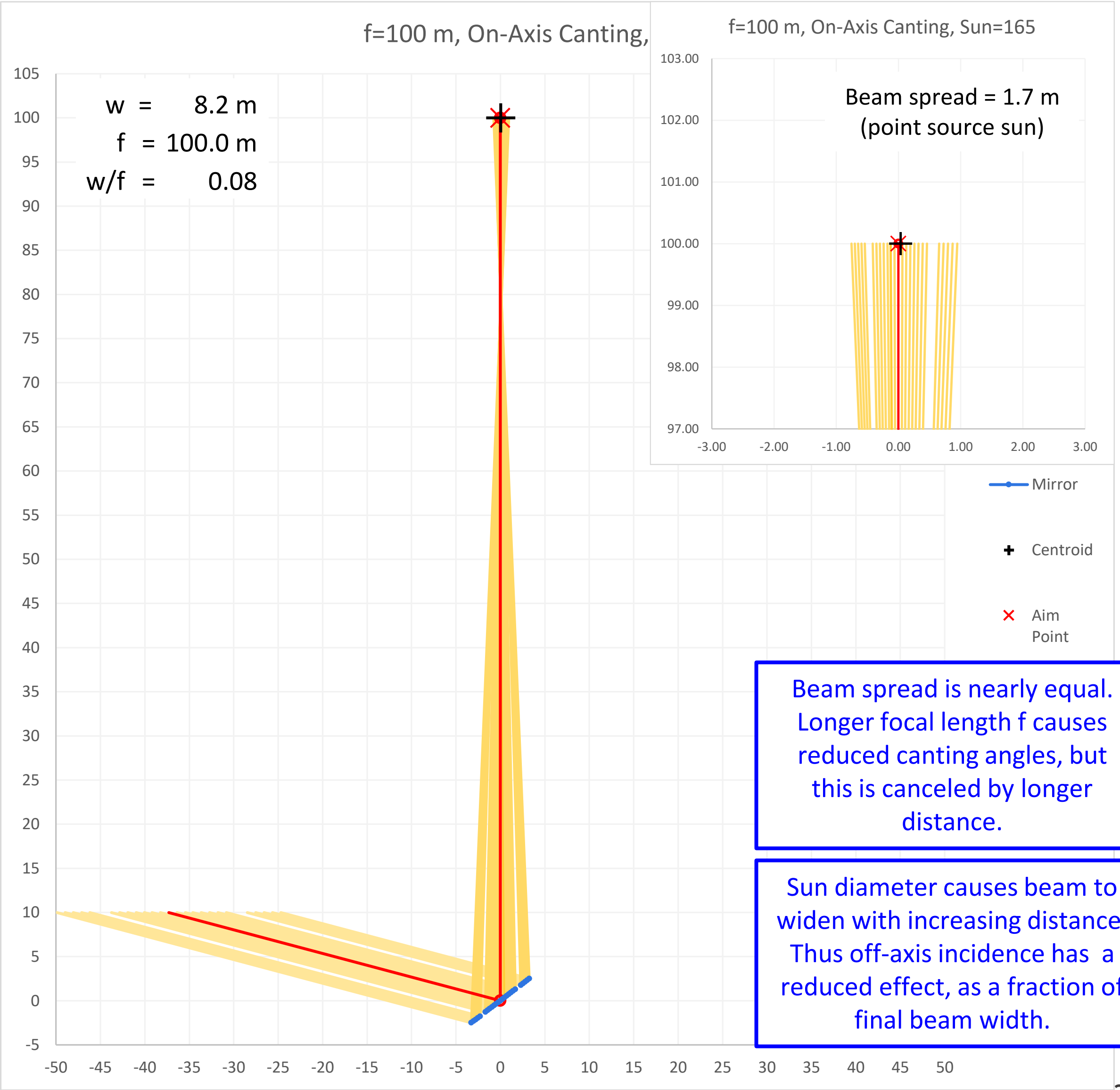
There are multiple standard aim points. The aim point for the small chilled BCS target is [0.0 m, 8.8 m, 28.90 m].

For more detailed NSTTF site information, see OpenCSP Data (URL pending).

# What if Increased Heliostat Distance?

Effect of reducing w/f ratio:




Beam spread is nearly equal. Longer focal length f causes reduced canting angles, but this is canceled by longer distance.

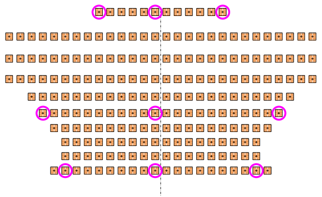
Sun diameter causes beam to widen with increasing distance. Thus off-axis incidence has a reduced effect, as a fraction of final beam width.



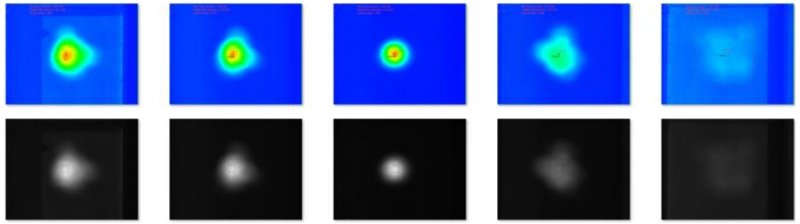
Sun is modeled as a point source. Sun shape not included.

# One Day: Summer Solstice

Images collected June 30, 2023.

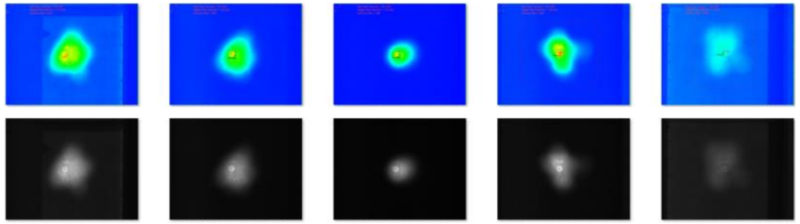


14W06



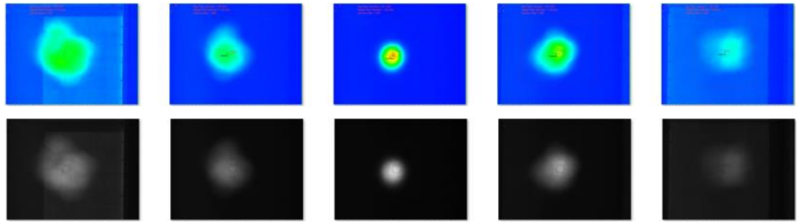
Early Solar Noon Late

14W01



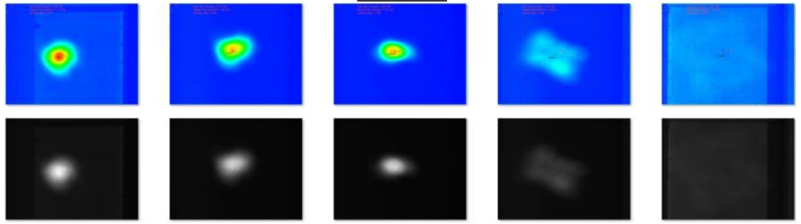
Early Solar Noon Late

14E06



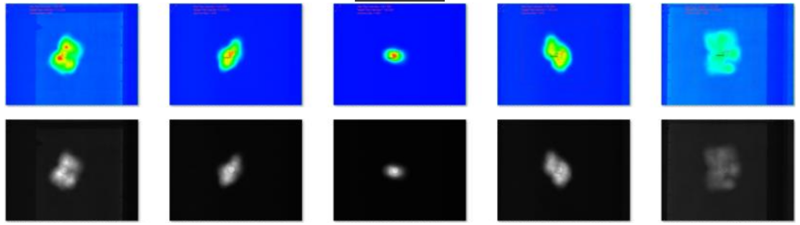
Early Solar Noon Late

9W11



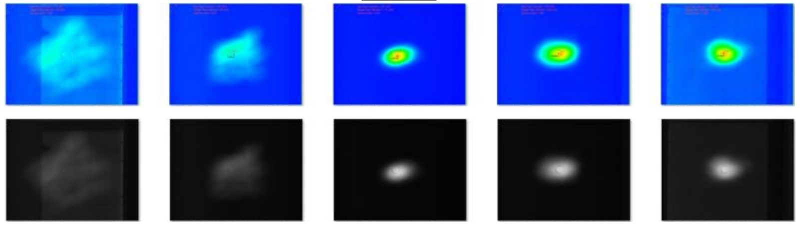
Early Solar Noon Late

9W01



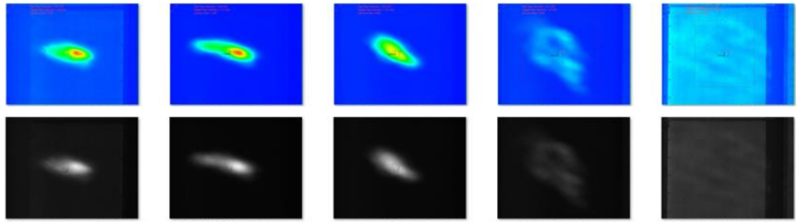
Early Solar Noon Late

9E11



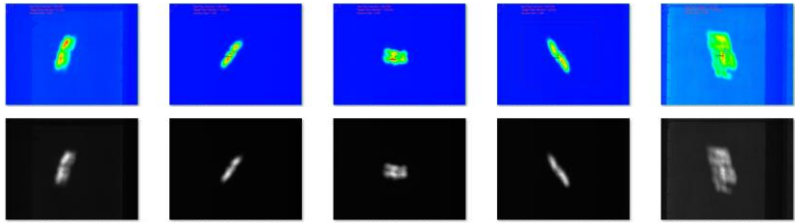
Early Solar Noon Late

5W09



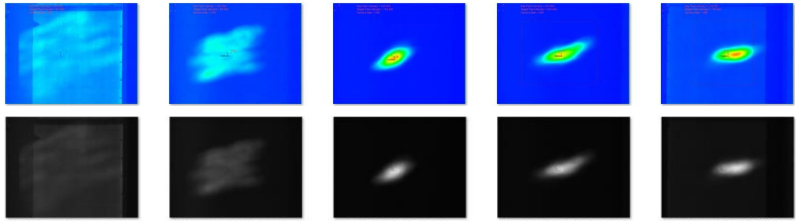
Early Solar Noon Late

5W01



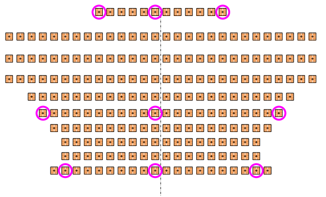
Early Solar Noon Late

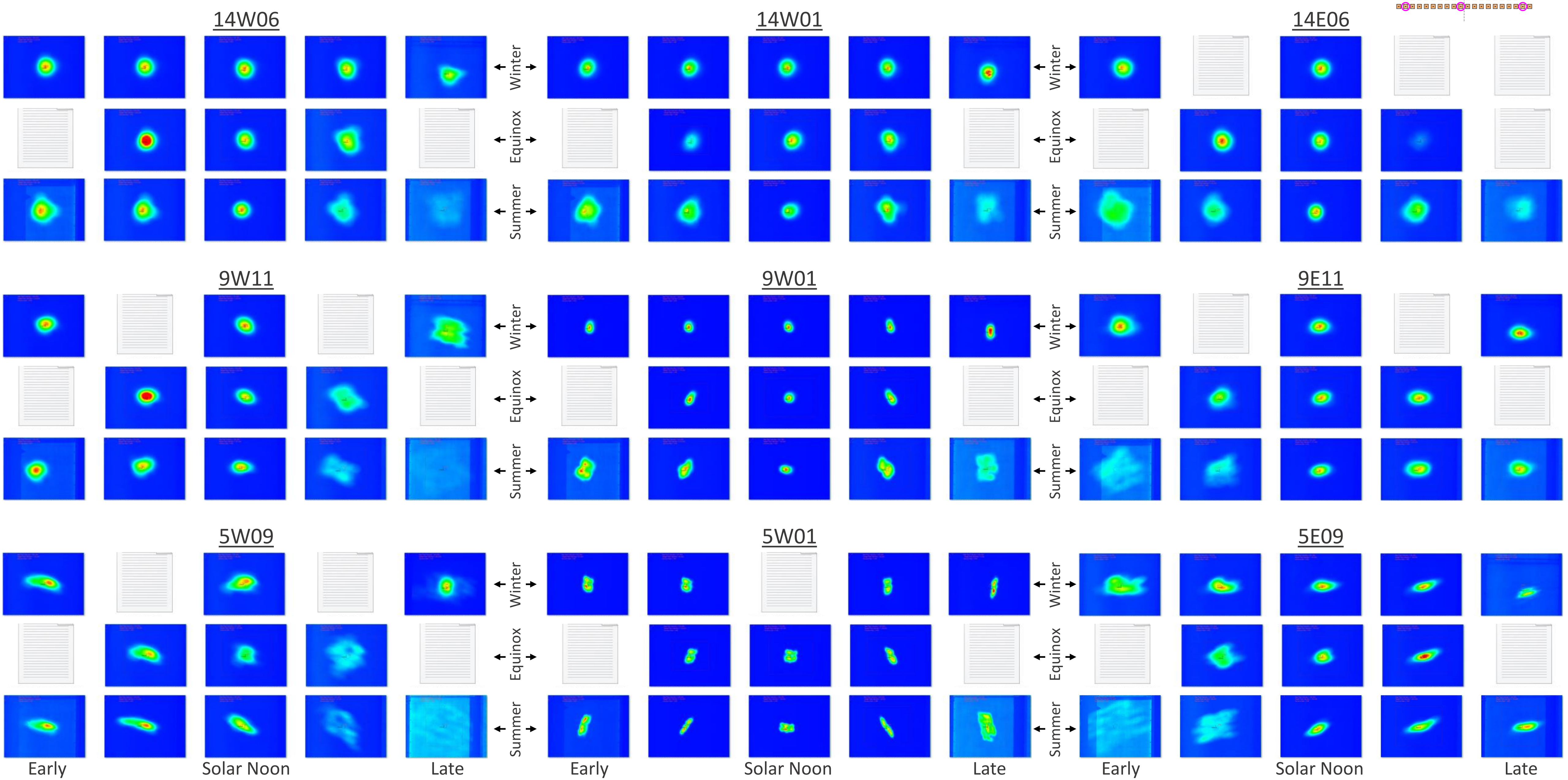
5E09



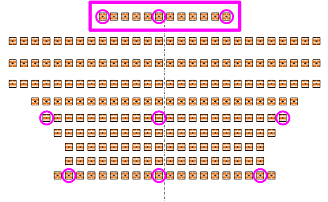
Early Solar Noon Late

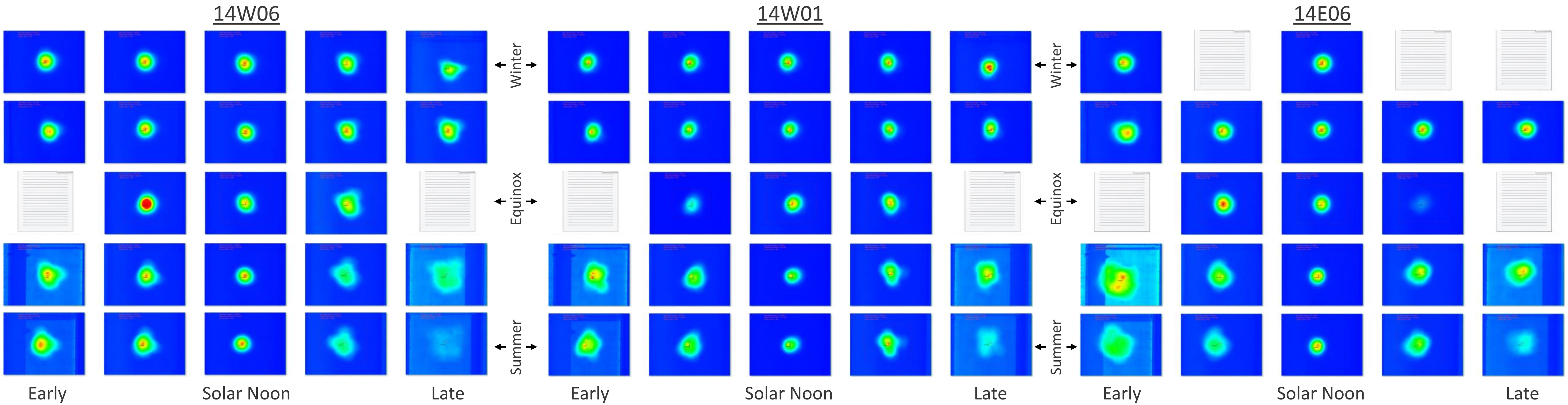
# Full Year – Winter, Equinox, Summer



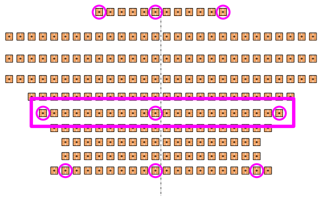


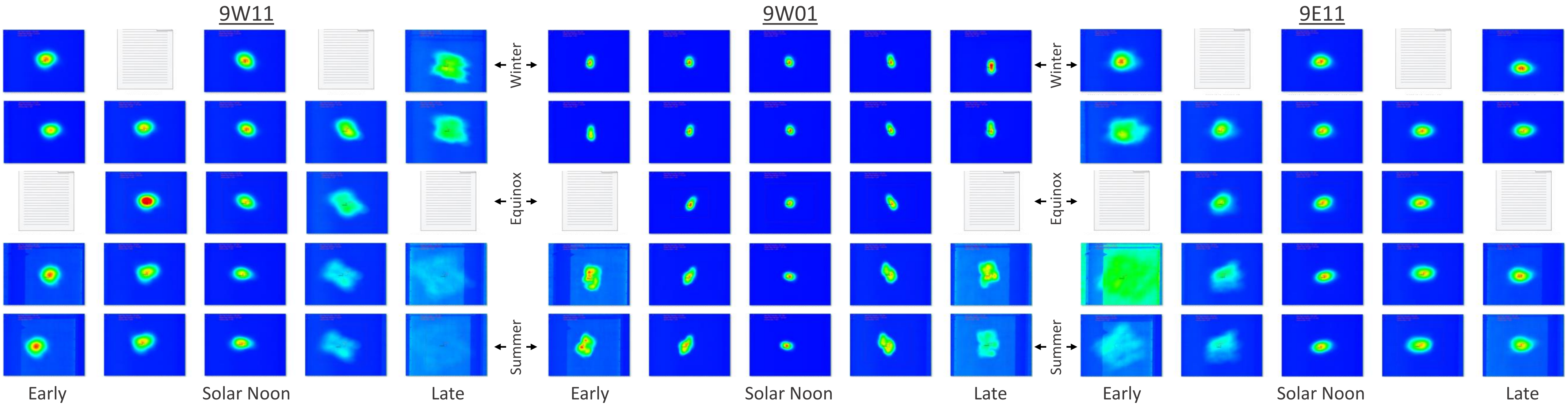
# Full Year – Back Row 14



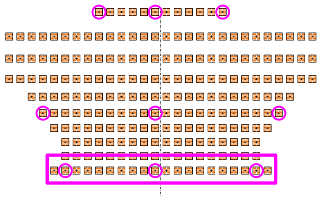


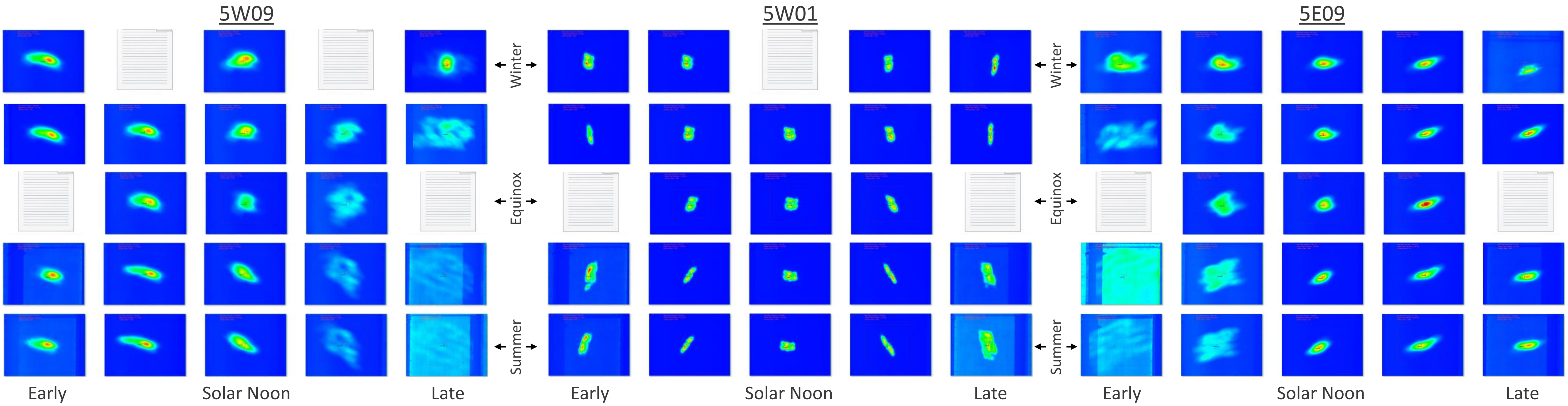
# Full Year – Mid Row 9





# Full Year – Front Row 5





# Full Year – Center Column