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

High-Speed Assessment of Heliostat Fields without Disrupting Operations

Randy Brost, Dan Small, David Novick, Benjamin Bean
Sandia National Laboratories

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Sandia Concentrating Solar Optics Laboratory (CSOL)

Mission:

Promote construction of high-performance heliostat fields, by delivering high performance, easy-to-access solutions.

Key products in the works:

- SOFAST – High-resolution mirror slope measurement.
- UFACET – High-speed drone-based field inspection. Today's focus
- Ground truth – Simple methods or objects with known accuracy.
- OpenCSP – Foundation classes, applications, and data for community development.

Thanks

We thank the DOE Solar Technologies Office and the Sandia LDRD program for their support.

TEAM

- Randy Brost
- Braden Smith

Manager:

- Margaret Gordon

Students:

- Ben Bean
- Felicia Brimigion
- Madeline Hwang
- Tristan Larkin
- Estevan Rodrigues

Staff:

- Lam Banh
- Roger Buck
- Robert Crandell
- Anthony Evans
- Luis Garcia Maldonado
- Kevin Good
- Dimitri Madden
- Dave Novick
- Daniel Ray
- Dan Small
- Benson Tso

What Problems are We Trying to Solve?

Advance* Calibration

During construction: What corrections will be needed for accurate beam pointing?

Accelerated Calibration

During plant startup: What corrections are needed for accurate beam pointing?

In-Field Heliostat Assessment

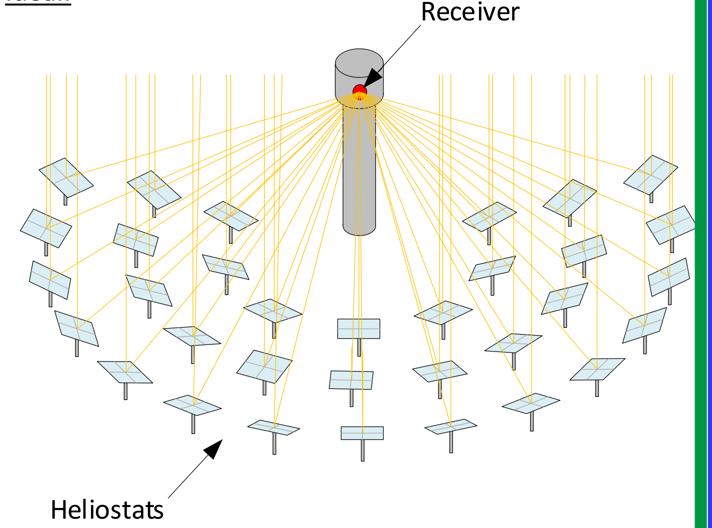
During operation:

- Have any heliostats changed?
- Which ones?
- By how much?

* Here “Advance” means “ahead of field operation,” similar to “advance notice before an event.”

Heliostat Optical Metrology Problems

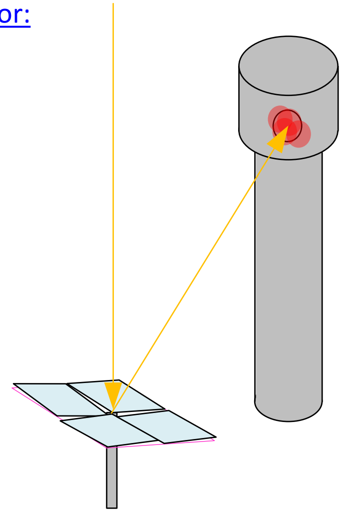
Ideal:



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

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

Slope Error:

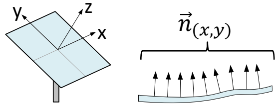


Slope error causes irregular, defocused beam.
Power is not focused in expected location.

Measure:

- Optical slope:

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

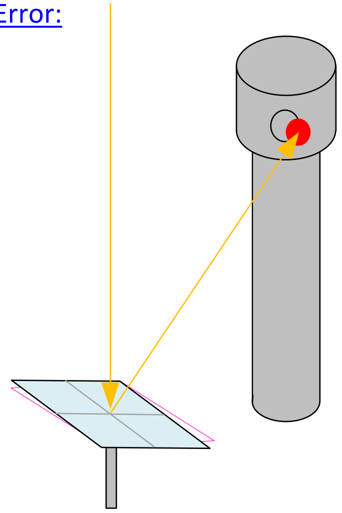


- **Varies with configuration, temperature.**

Corrective actions:

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

Pointing Error:

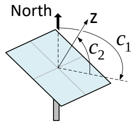


Pointing error causes beam to miss target.
Power is not in expected location.

Measure:

- Correction function:

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

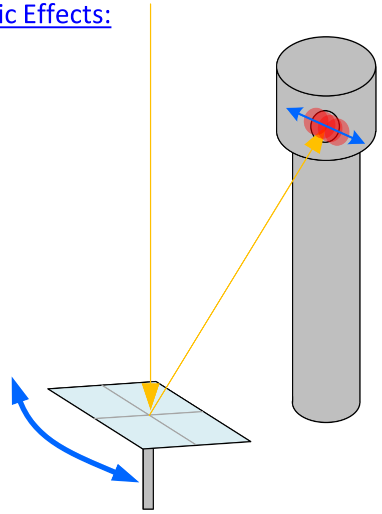


- **For all sun positions in solar year.**
- Two flavors:
  - Offline calibration.
  - Real-time, during operation.

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.

This Presentation

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.

Requirements:

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

Other Drone-Based Heliostat Metrology Efforts

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

Most closely related

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

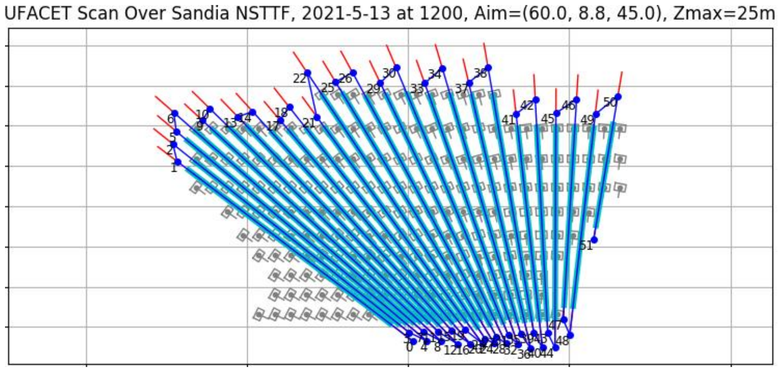
Precursor

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

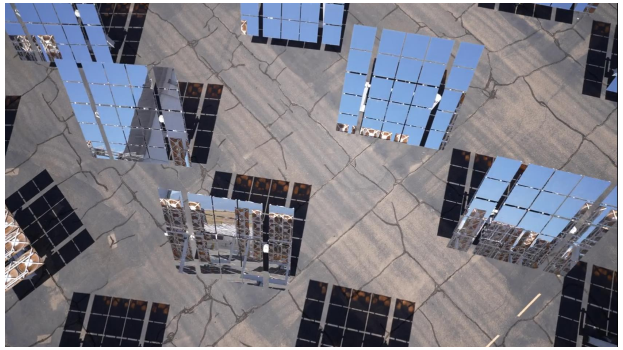
Quick Overview of Approach

1. Flight Plan

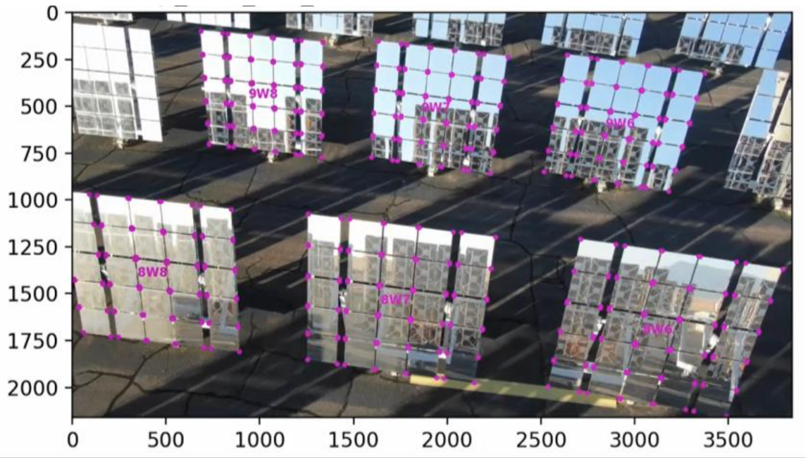


2. Fly Drone

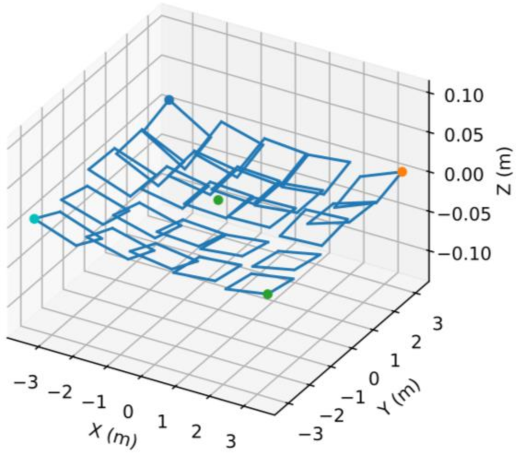
3. Capture Video



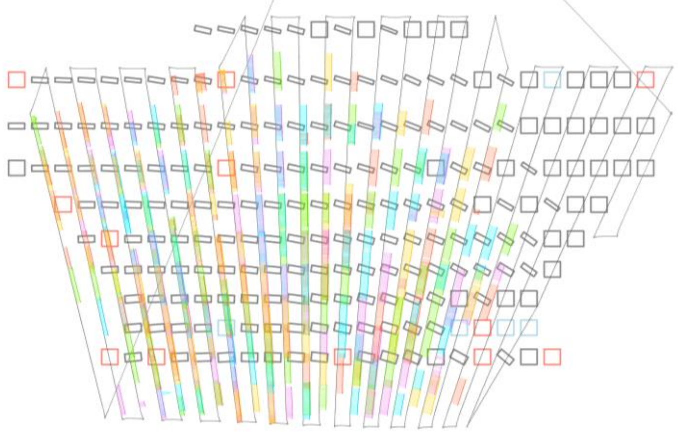
4. Analyze Video



5. Heliostat Analysis



6. Trajectory Analysis



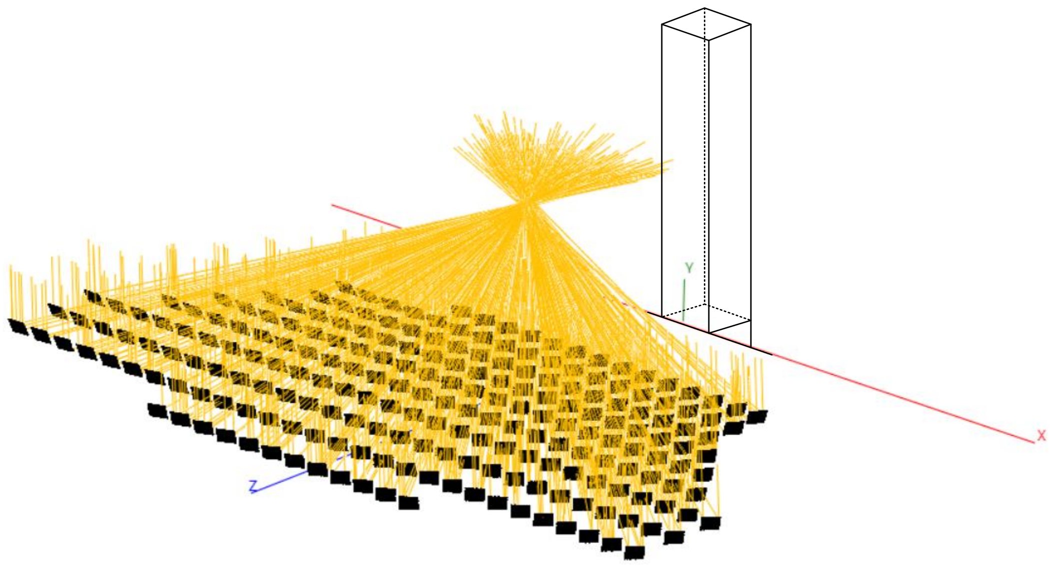
This system is not finished.

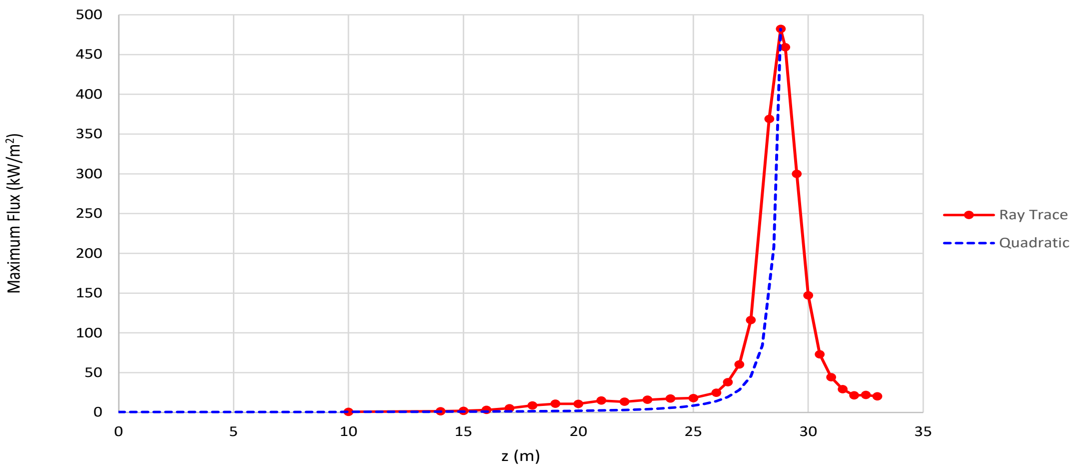
Why This is Hard

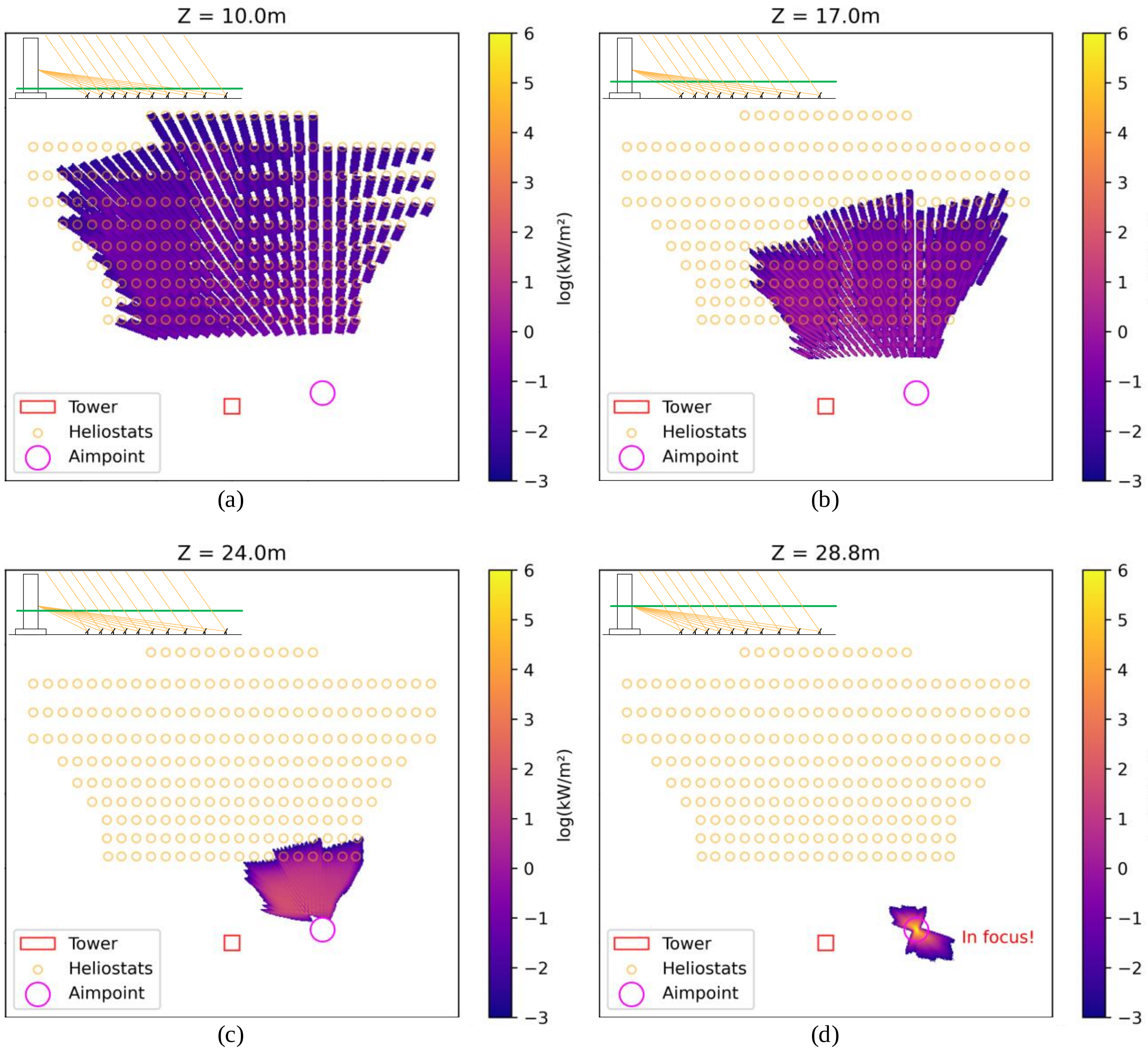
- Safety
- Scale
- Speed
- Non-intrusive
- High Accuracy
- Vary with configuration
- Lack of data
- Lack of ground truth
- Varying light, sky
- Varying design
- Heliostat motion
- Optical effects
- UAS position uncertainty

Flight Safety #1: Where Is the Flux?

Flux over an active heliostat field:







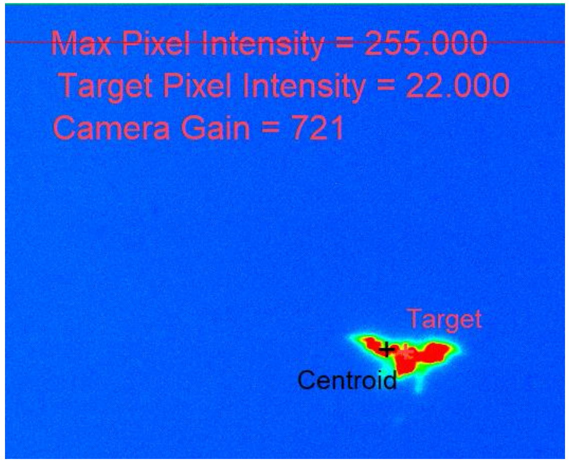
Flight Safety #2: What Is the Flux Limit?

<u>Intentionally subjecting a drone to high flux:</u>

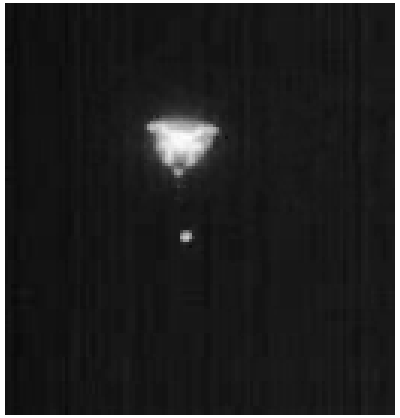
- DJI Phantom 4 equipped with various temperature sensors, plus thermographic imaging.
- We set 1, 2, 4, and 5 heliostats on a standby aim point, and manually flew the UAS into the focus.
- Under four heliostats (< 80 kW/m^2), we observed the UAS ejecting a piece of hot debris, and then the UAS departed 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.

Before

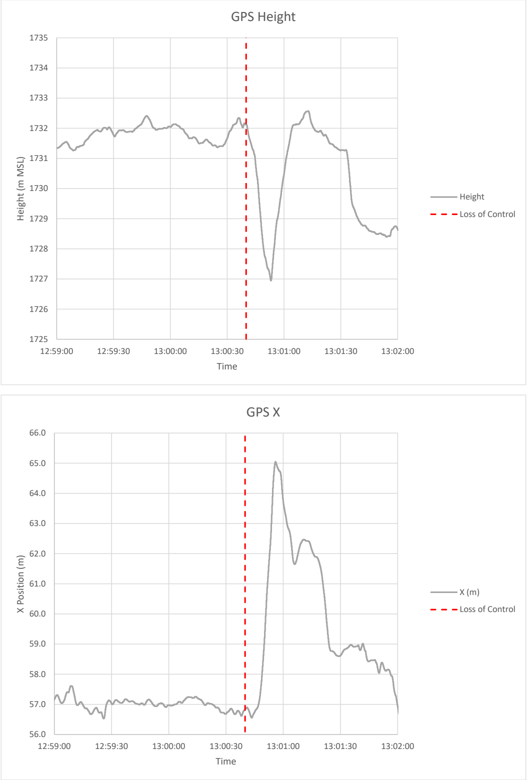
After



BCS image of UAS under high flux



Thermographic image of hot debris ejection



Trajectory logs during loss of control

See video “Rec-000009.wmv” cue 00:10 – 00:25

Why This is Hard

Safety – Solar flux, flight operations

Scale
Wide area – For example, Crescent Dunes is ~6 km^2.
Large number points – Calibrating 10,000 heliostats ⇒ 350 million points!*

Speed – Calibrating 10,000 heliostats in a month ⇒ under 9 sec/heliostat, ~3,400 heliostat/day.*

Non-intrusive
Construction – Tower might be varying, no light on the tower.
Operation – Don't interrupt production, don't complicate operation.

High Accuracy – ±0.65 mrad heliostat performance,[1] tighter tolerance for metrology.

Vary with configuration – Both optical shape and pointing corrections vary with heliostat configuration.

Lack of data – Log synchronization difficult. Survey data may be unavailable, unclear, obsolete, or even the question of interest.

Lack of ground truth – How do we verify measurement results are correct?

Varying light, sky – Image processing must be robust in the face of a wide variety of conditions.

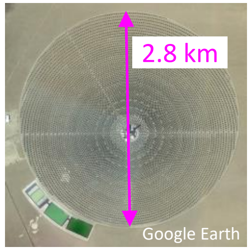
Varying design – Tower structure, height, heliostat design, size, and row spacing all vary widely between fields.

Heliostat motion
Due to tracking – Motion may occur at unpredictable intervals, may lag variably from log times.
Due to wind – Heliostat flutter in the wind may cause large changes in reflected images, even for light winds.

Optical effects
Distortion – Reflected image distortion increases with camera-to-mirror and mirror-to-target distance, and may become extreme.
Far-field issues – Occlusion of tower features lower than the receiver, atmospheric aberration due to thermal effects.

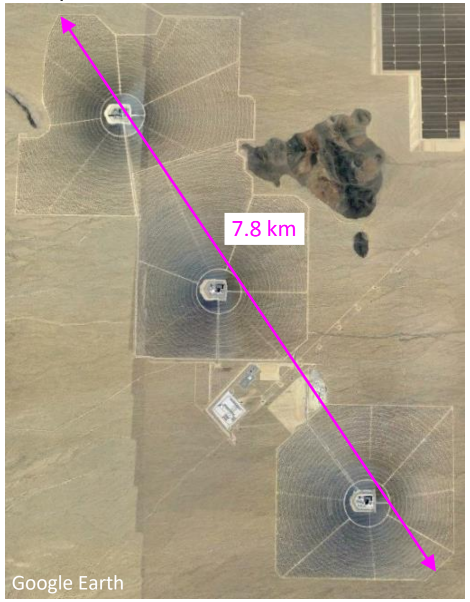
UAS position uncertainty – Even with RTK GPS, uncertainty in drone absolute position is substantial (e.g., ±7 cm xy, ±10 cm z).

Crescent Dunes:



>10,300 heliostats
> 360,000 facets

Ivanpah:



>173,000 heliostats
> 340,000 facets

* See backup slide notes.
[1] Ye Wang, et al, forthcoming.

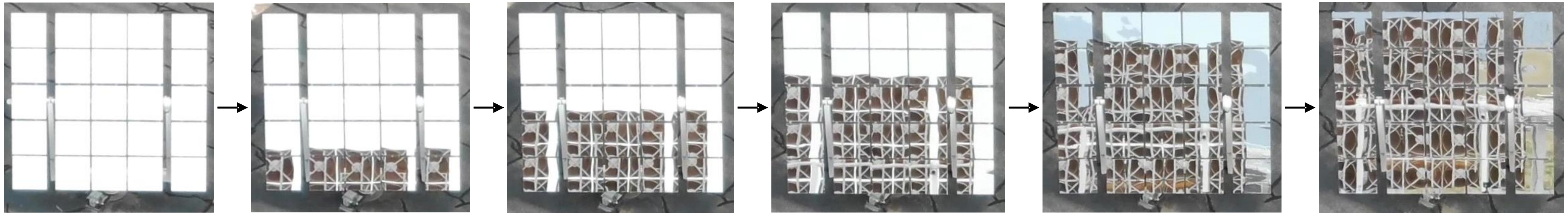
Our goal is to build a system that works successfully in the face of all of these real-world issues.

Our Approach

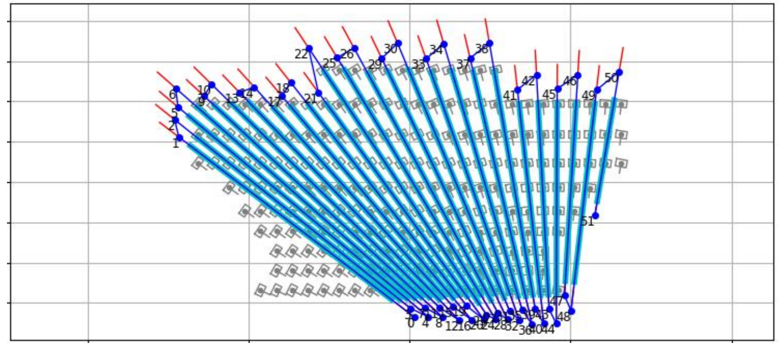
Safety	→ Identify flux safety constraints, plan flights to avoid flux, rigorous flight procedures.
Scale	
Wide area	→ Use high-speed UAS, design for long endurance.
Large number points	→ Rich set of optical targets, video image data.
Speed	→ Efficient heliostat tour, long smooth passes with little acceleration, design flight path for high-speed data capture.
Non-intrusive	
Construction	→ Design for heliostats at non-tracking positions (e.g., different time), use non-tower optical references.
Operation	→ Operate in situ, with no change to field operations.
High Accuracy	→ Aim for ±0.1 mrad absolute accuracy. High image resolution, view distances to maximize precision, highly redundant data.
Vary with configuration	→ Simultaneous (u_x,u_y) slope measurement. Design to measure across full heliostat working envelope.
Lack of data	→ Don't assume reliable input data. Measure everything (except facet size).
Lack of ground truth	→ Ground truth strategy and campaign.
Varying light, sky	→ Diverse data set: multi-location, multi-day, multi-flight-mode, multi-heliostat-conditions. Design robust algorithms.
Varying design	→ Don't rely on particular heliostat or tower features. They may be absent, or unrecognizable.
Heliostat motion	
Due to tracking	→ Capture redundant data on multiple passes, expecting motion; discard data where there is evidence of heliostat motion.
Due to wind	→ ?
Optical effects	
Distortion	→ Reduce camera-mirror-target distances.
Far-field issues	→ Reduce use of far-field optical targets.
UAS position uncertainty	→ Photogrammetry using existing heliostat field features.

Flight Planning

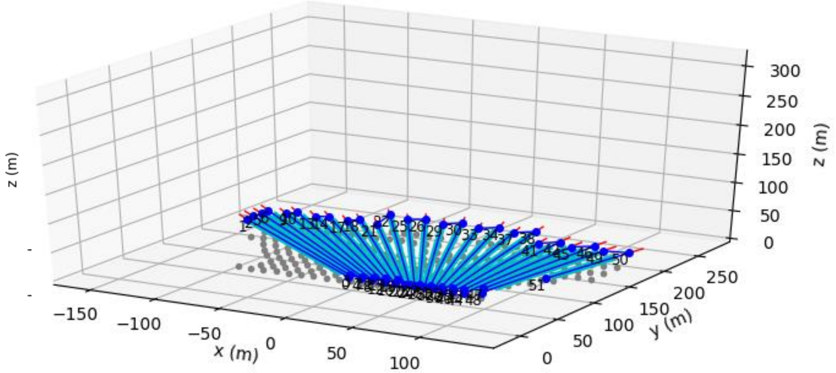
Goal: Scan reflection of adjacent heliostats



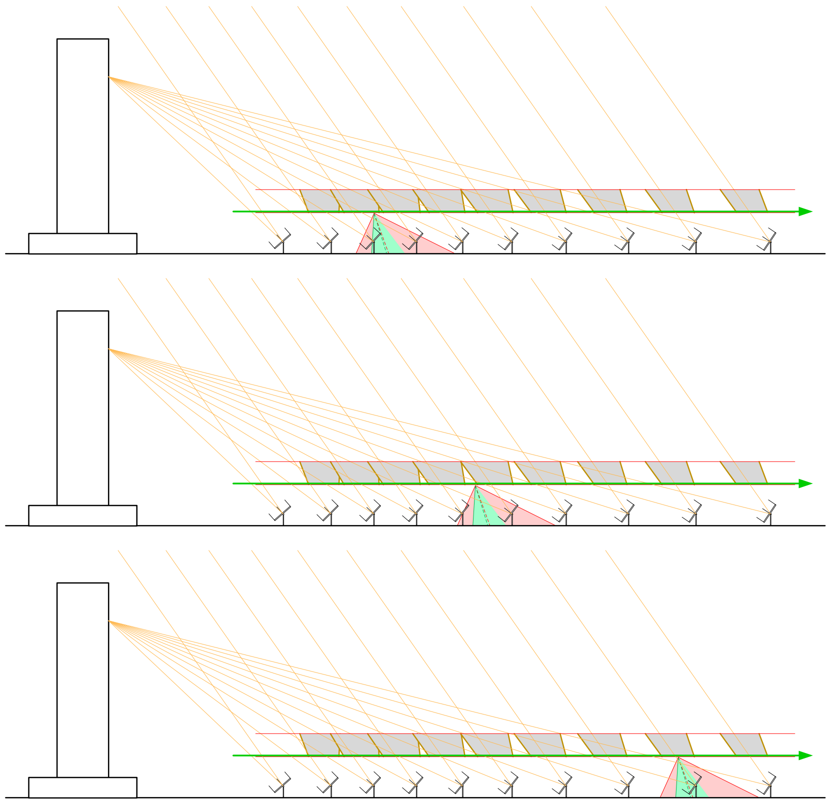
XY Analysis:



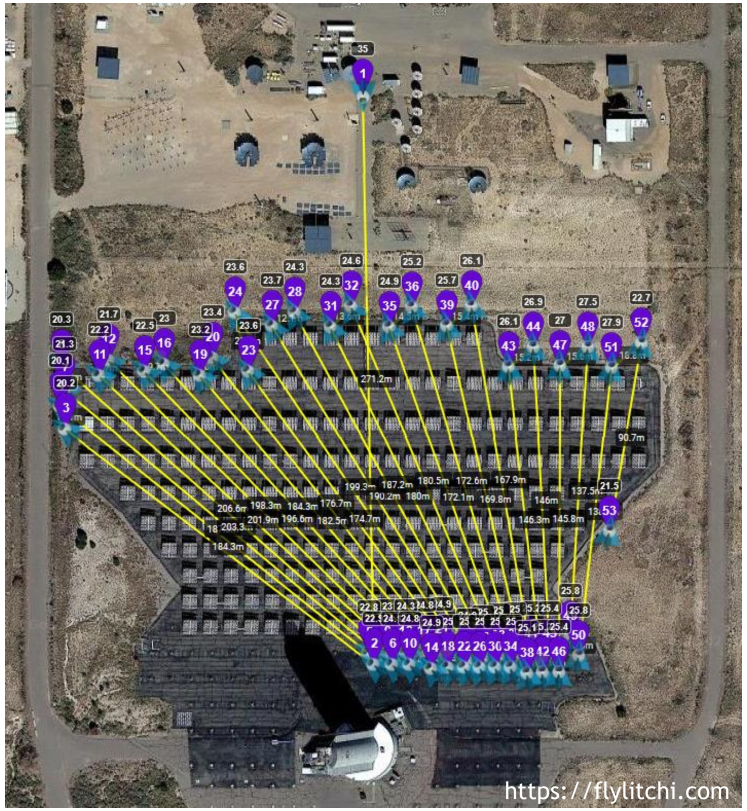
3-d Plan:



Altitude/Gaze Analysis:



Flight-Ready:



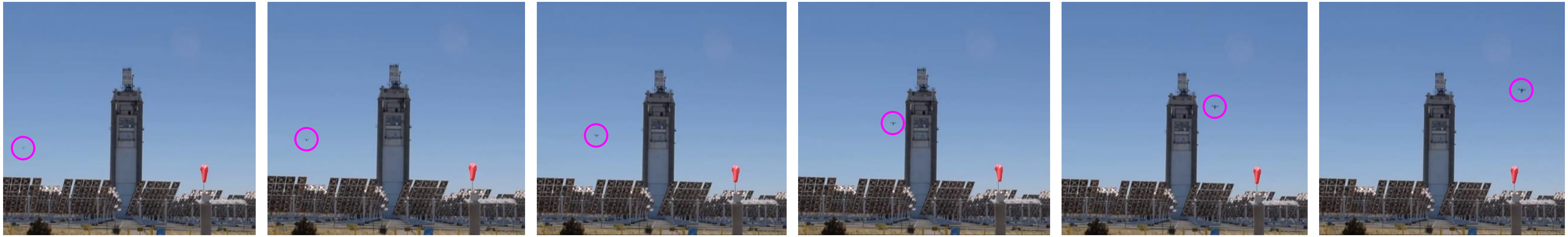
Flight Execution

Unmanned Aircraft System (UAS):

Operation issues:

- Checklists:
  - ❑ Weather
  - ❑ UAS flight systems
  - ❑ Imaging devices
  - ❑ GPS RTK
  - ❑ Communications
  - ❑ Air space
- Energy management – all systems.
- Image collection capacity.
- Post-flight temperature.
- Log data.

May 13, 2021:

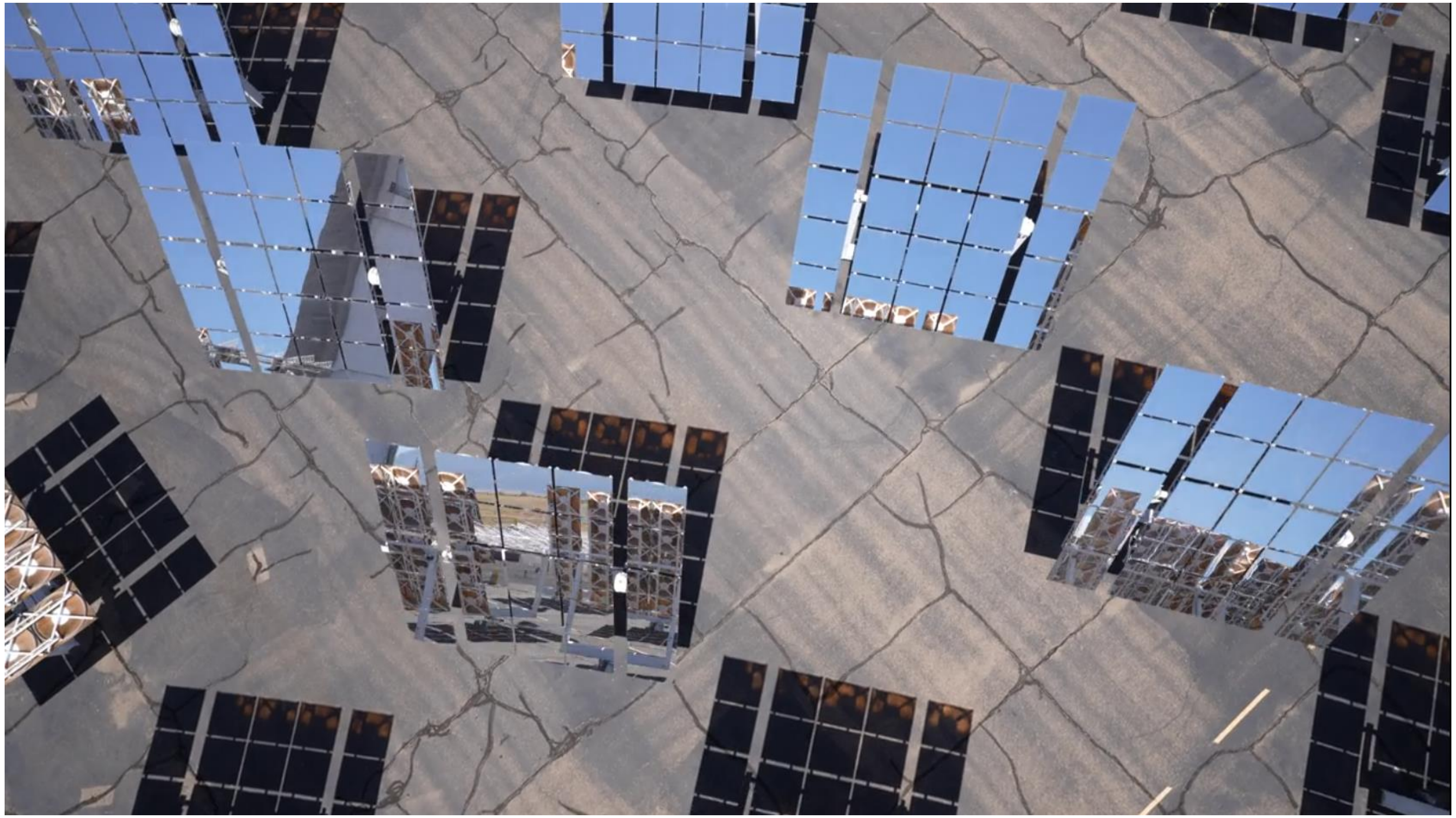


The entire Sandia NSTTF field is tracking on-sun to a standby aim position.

At scan speed of 25 km/h, typical flight time to scan Sandia NSTTF field is 16-21 minutes.

Post-flight temperatures ranged from 25 °C to 47 °C.

View from the Air



Flight May 13, 2021

Video: “210513-1210_NSza45_U_sony_C0039_s3m15_d825_HD.MP4” Suggested cue range: 5:40 → 7:00.

Data Processing

Algorithm synopsis:

1. Synchronize video with flight GPS log (Δt, Δx, Δy, Δz, $\Delta \alpha$, $\Delta \gamma$, $\Delta \tau$).
2. Use field model to predict heliostat image locations.
3. Identify key frames suitable for image search.

Manual, for now

4. Search key frames for heliostat corners.
5. Track corners over time, exploiting temporal locality.
6. Identify 3-d locations of individual heliostat facets.
7. Compute *rough* canting angle estimates from facet locations.
8. Identify camera trajectory relative to each heliostat.
9. Align camera trajectories to estimate global drone trajectory.
10. Calculate heliostat angles seen at time of drone passage.

Automatic*

11. Analyze reflections to estimate slope, pointing.
12. Error, state-of-health analysis.

Not yet

* Automated codes are still under development. Some include "magic numbers," and have not been generalized across many examples.

Output:

- Sequence of heliostat appearances in video, with defining corners.
- As-measured model of heliostat facet positions.
- Photogrammetry-based rough canting angles.
- Heliostat (az,el) estimates, at times of drone passage.
- Computation quality test metrics.

Synchronization and Key Frame Identification

Algorithm synopsis:

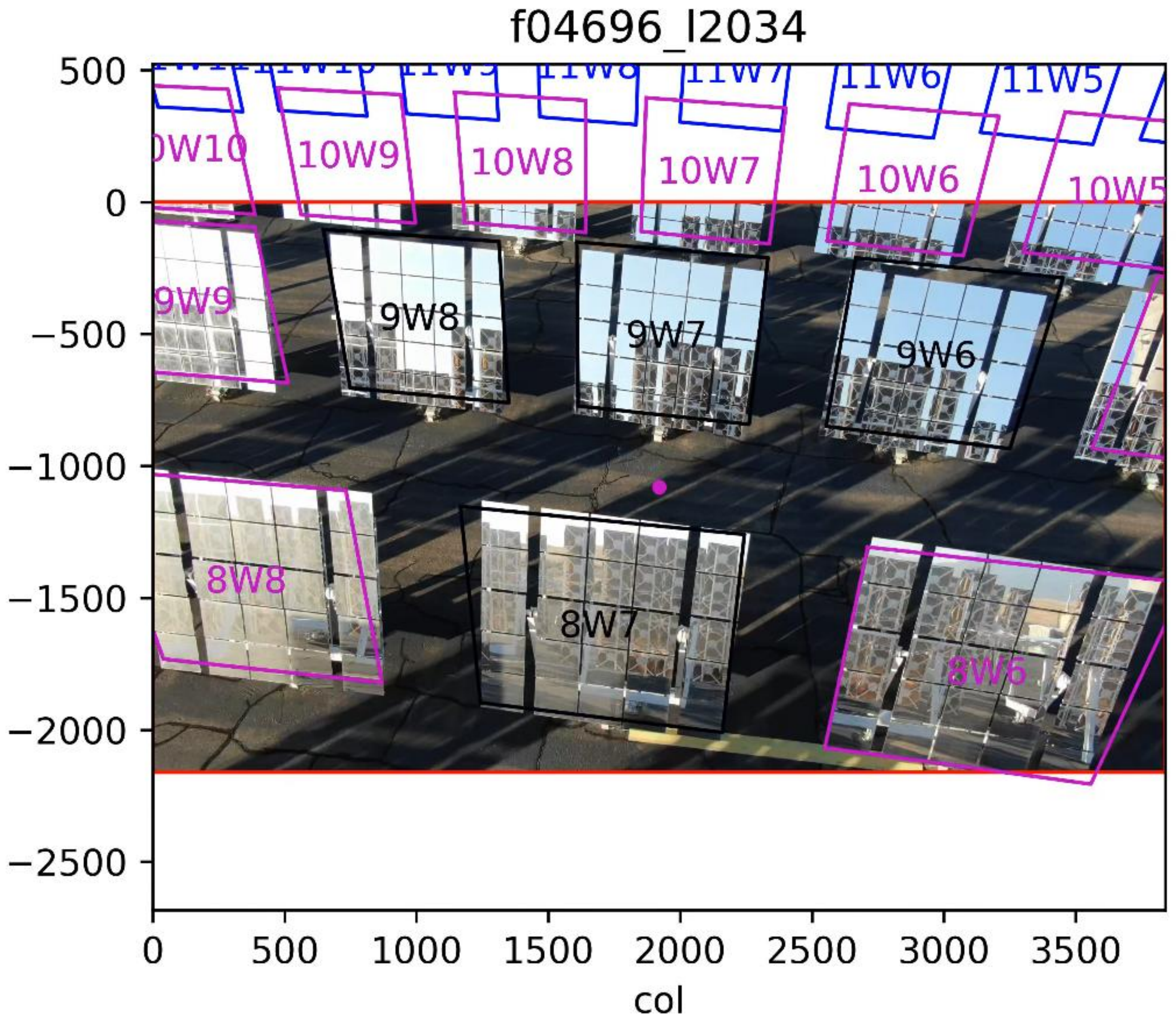
1. Synchronize video with flight GPS log (Δt, Δx, Δy, Δz, $\Delta \alpha$, $\Delta \gamma$, $\Delta \tau$).
2. Use field model to predict heliostat image locations.
3. Identify key frames suitable for image search.
4. Search key frames for heliostat corners.
5. Track corners over time, exploiting temporal locality.
6. Identify 3-d locations of individual heliostat facets.
7. Compute *rough* canting angle estimates from facet locations.
8. Identify camera trajectory relative to each heliostat.
9. Align camera trajectories to estimate global drone trajectory.
10. Calculate heliostat angles seen at time of drone passage.
11. Analyze reflections to estimate slope, pointing.
12. Error, state-of-health analysis.

Manual

Output:

- Sequence of heliostat appearances in video, with defining corners.
- As-measured model of heliostat facet positions.
- Photogrammetry-based rough canting angles.
- Heliostat (az,el) estimates, at times of drone passage.
- Computation quality test metrics.

Synchronization Video



Flight December 3, 2020

Video: "201203_expected_frames_locations_overlay.mp4" Suggested cue range: 2:21 → 3:18.

Heliostat Tracking and Analysis

Algorithm synopsis:

1. Synchronize video with flight GPS log (Δt, Δx, Δy, Δz, $\Delta\alpha$, $\Delta\gamma$, $\Delta\tau$).
2. Use field model to predict heliostat image locations.
3. Identify key frames suitable for image search.

Automatic*

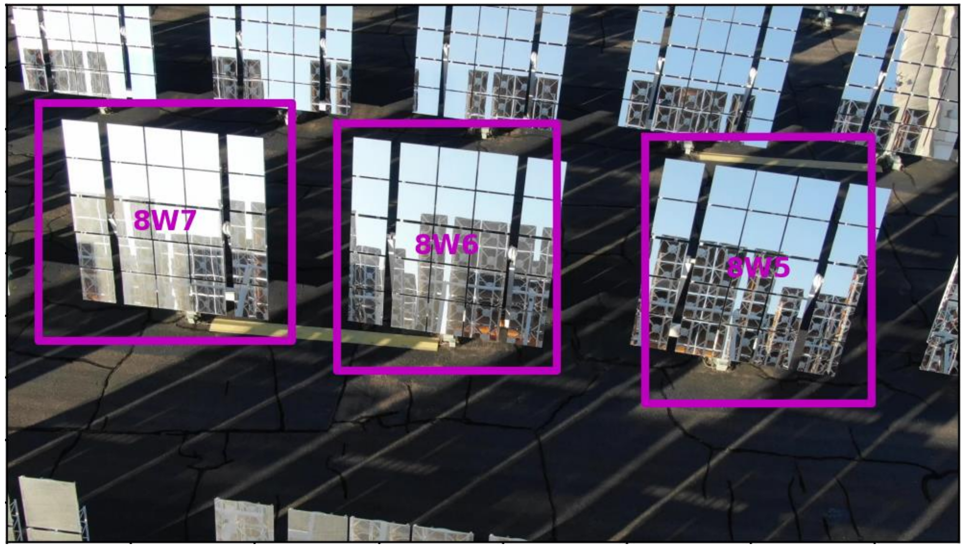
4. Search key frames for heliostat corners.
5. Track corners over time, exploiting temporal locality.
6. Identify 3-d locations of individual heliostat facets.
7. Compute *rough* canting angle estimates from facet locations.
8. Identify camera trajectory relative to each heliostat.
9. Align camera trajectories to estimate global drone trajectory.
10. Calculate heliostat angles seen at time of drone passage.
11. Analyze reflections to estimate slope, pointing.
12. Error, state-of-health analysis.

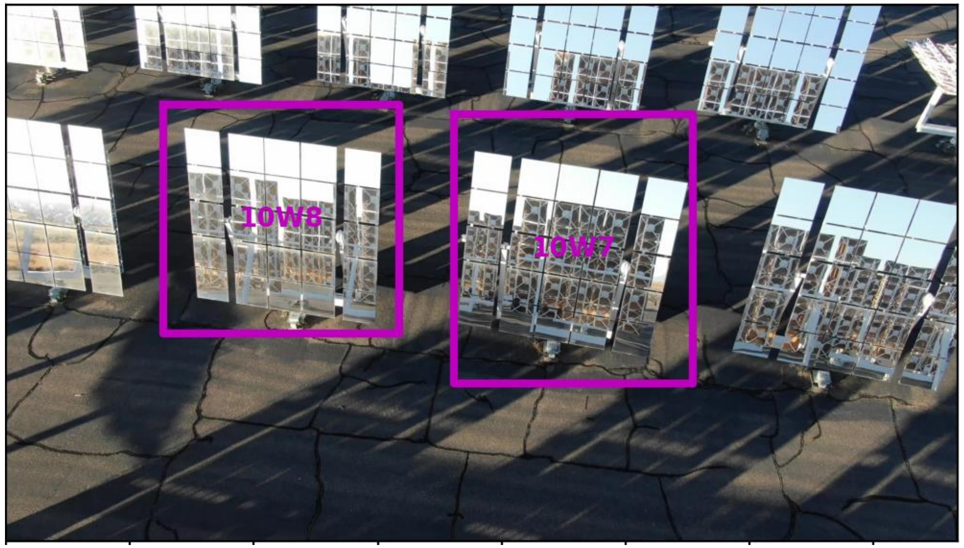
Output:

- Sequence of heliostat appearances in video, with defining corners.
- As-measured model of heliostat facet positions.
- Photogrammetry-based rough canting angles.
- Heliostat (az,el) estimates, at times of drone passage.
- Computation quality test metrics.

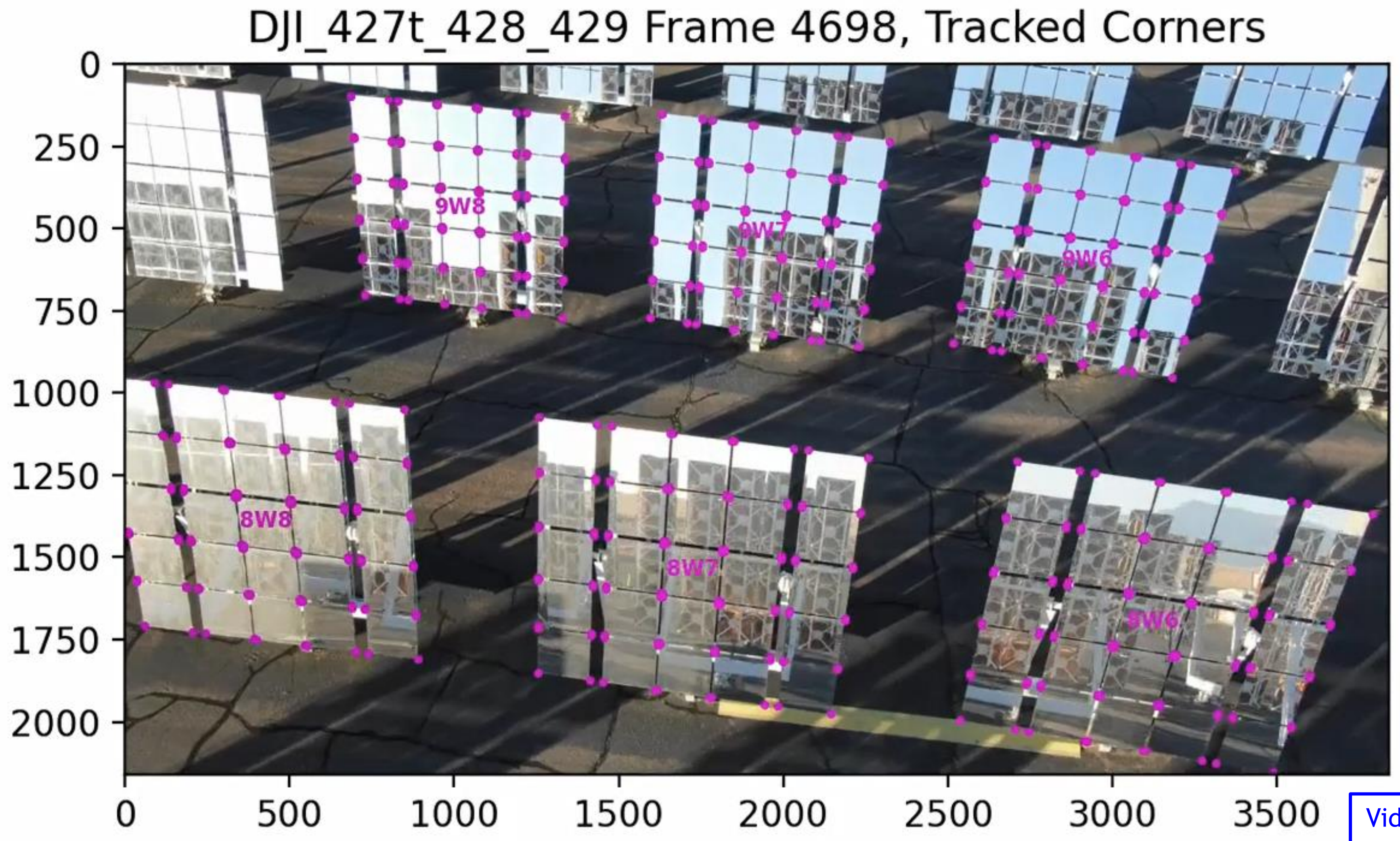
* Automated codes are still under development.

Example manually selected key frames:





Tracking Video



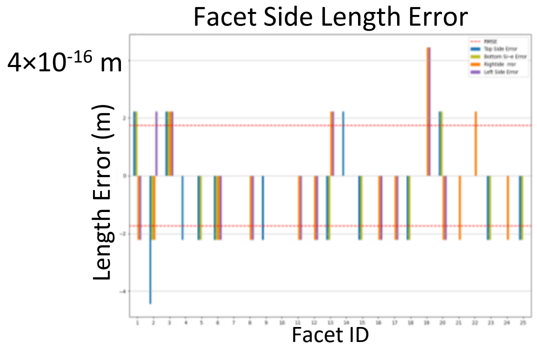
Flight December 3, 2020

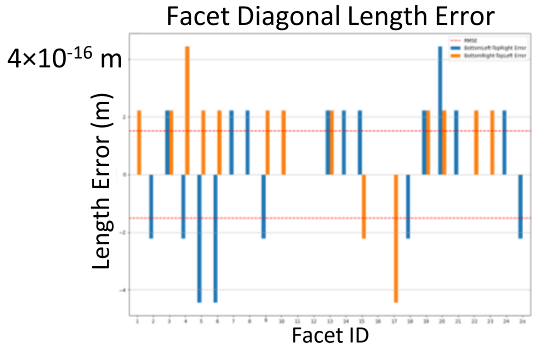
Video: ""DJI_427t_428_429_video_tracks_Trim_1.22-3.20.mp4" Suggested cue range: 1:05 → 2:02.

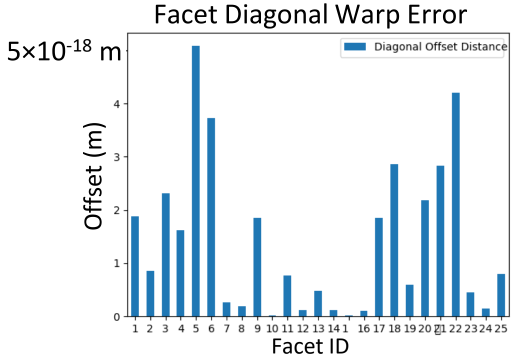
Video length:	12 min, 22 sec
Frames in video:	18,570
Manual key frames:	188
Frames tracked:	12,939
Points tracked:	2,702,019
Heliostats tracked:	168

Heliostat 3-d Analysis

Numerical Quality Checks

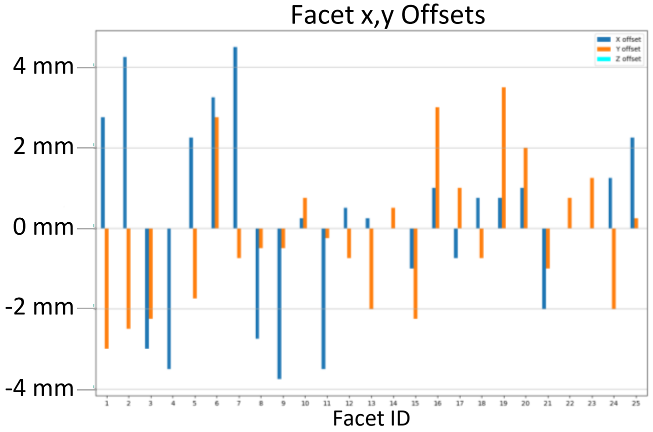


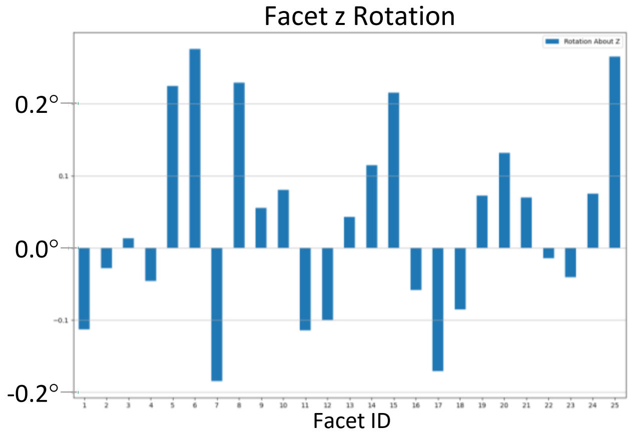




Error values ≈ 0 ✓

Facet Position Offsets

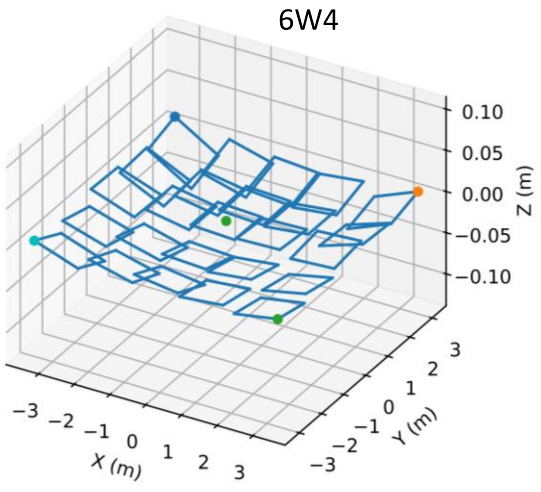




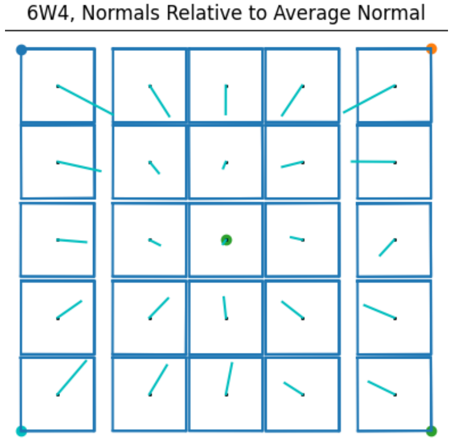
Facet deviations consistent with observation. ✓

(Not measured yet.)

3-d Rendering



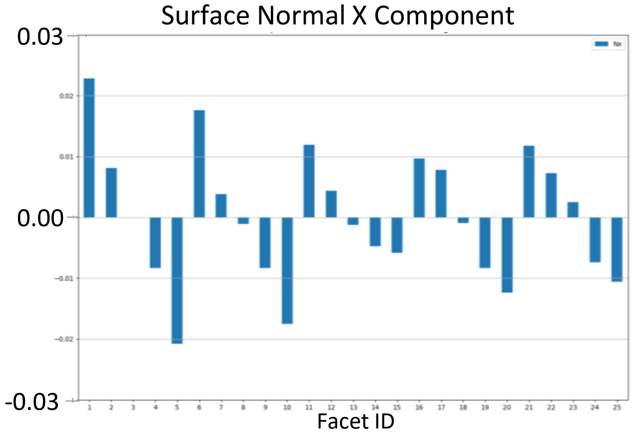
(z axis exaggerated)

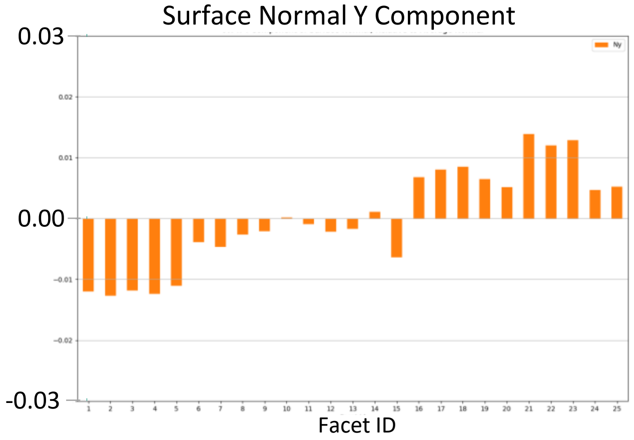


Canting angles concave. ✓

Canting angles progress. ✓

Canting Angles (from Photogrammetry)





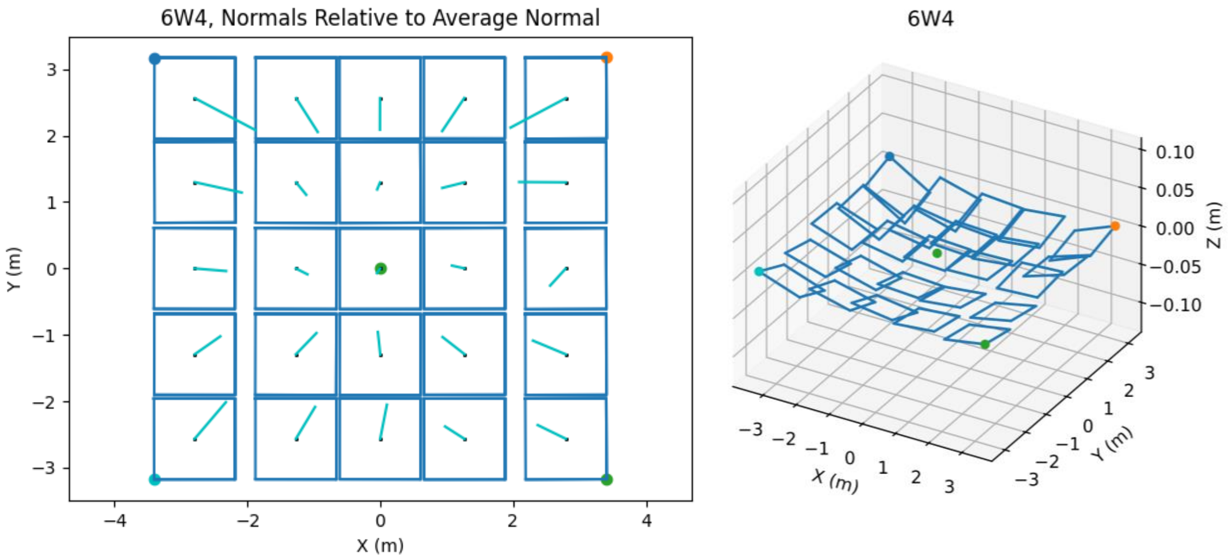
Surface normal pattern matches expected. ✓

X vs. Y surface normal magnitudes consistent with off-axis canting. ✓

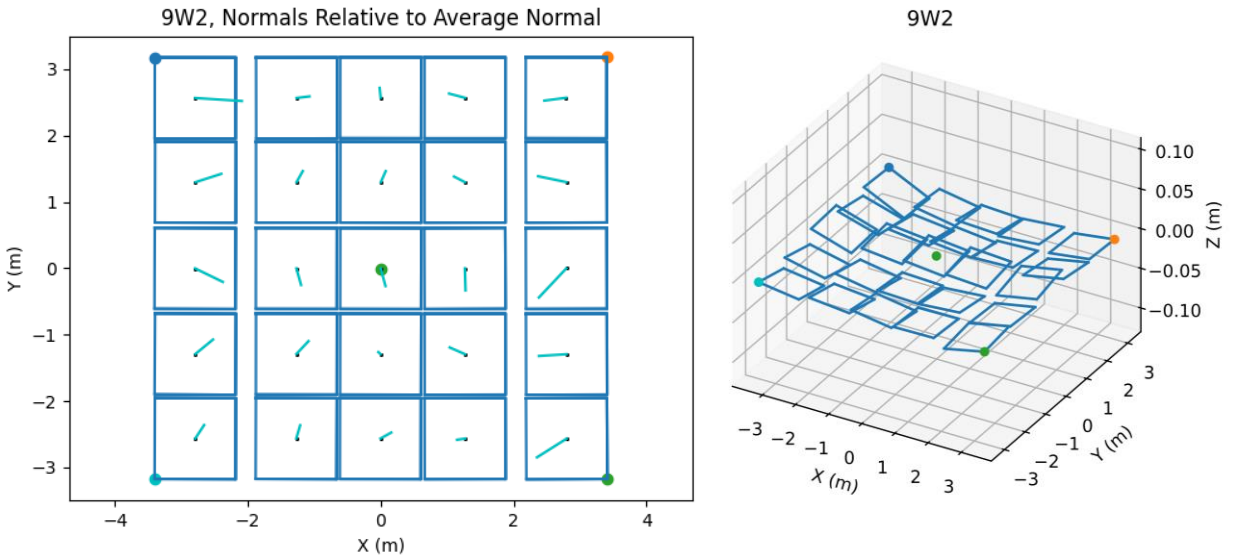
Similar results automatically computed for all 168 heliostats found.

Not All Results Are So Good

Good example:



Not-so-good example:

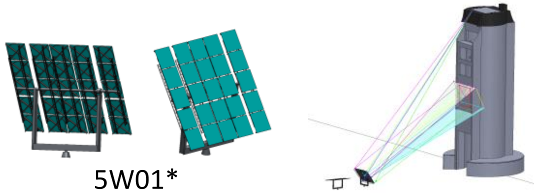


Are these measurements correct?

If not, off by how much?

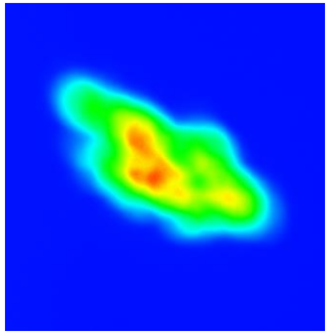
These results motivated our pursuit full-heliostat ground truth.

Ground Truth Check: NSTTF Heliostat 5W01

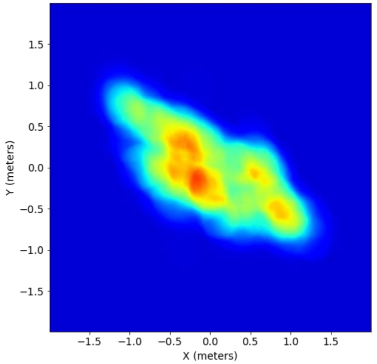


BCS

BCS Image



SOFAST Ray Trace

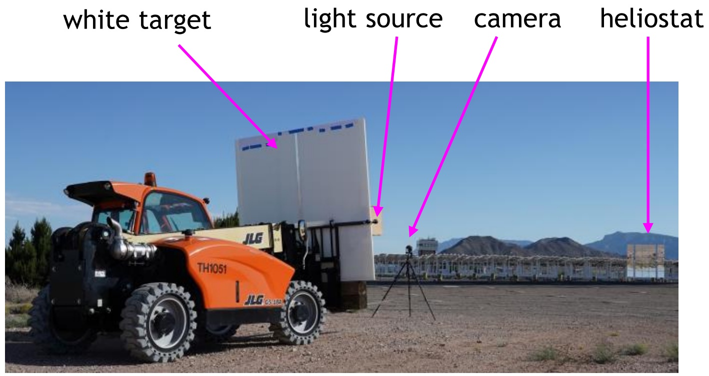


Images are similar scale.

Image capture and ray trace both June 30, 2022 at 2:06 PM.

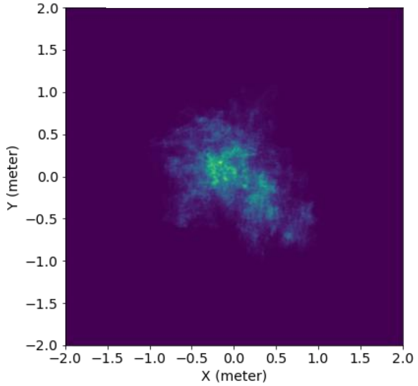
Achieving this match required manual adjustment of SOFAST calibration parameters.

2f Returned Spot



2f Returned Spot Image

SOFAST Ray Trace

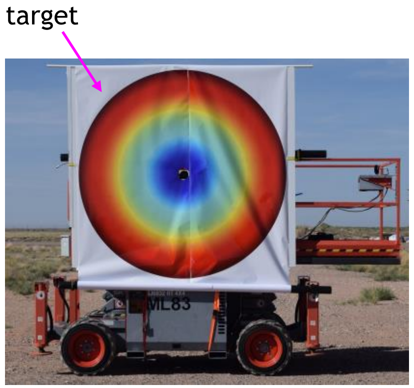


d = 131.6 m, one among a sequence

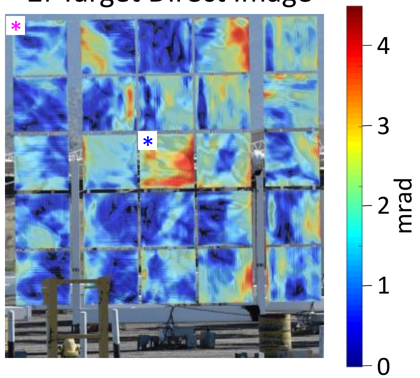
Images are same scale.

* Heliostat focal length, astigmatism unknown.

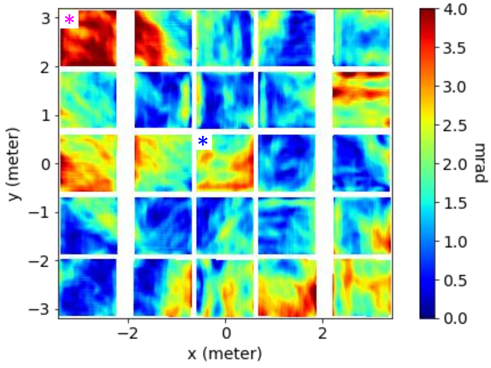
2f Color Target



2f Target Direct Image



SOFAST Slope Error Magnitude



distance = 166.7 m

Note similarities (*) and discrepancies (*).
Work in progress.

Full Field Trajectory Analysis

Steps:

For each heliostat:

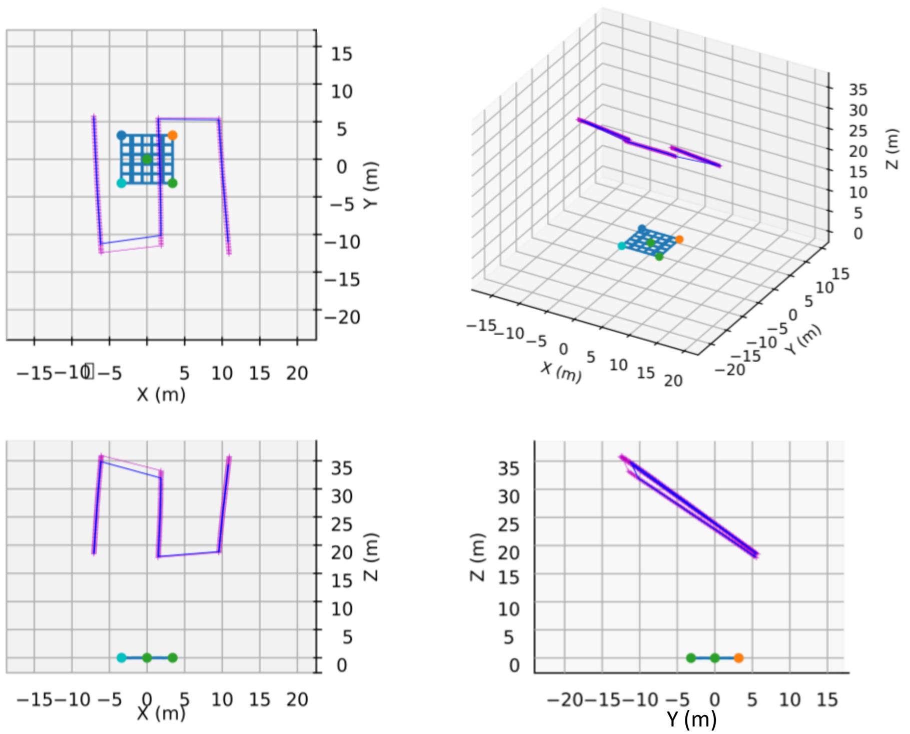
- For each frame in which heliostat fully appears:
  - Compute camera position relative to heliostat, using photogrammetry.
- Assemble results to form trajectory segments relative to the heliostat.

Rotate all heliostat (az,el) angles to align per-heliostat segments.

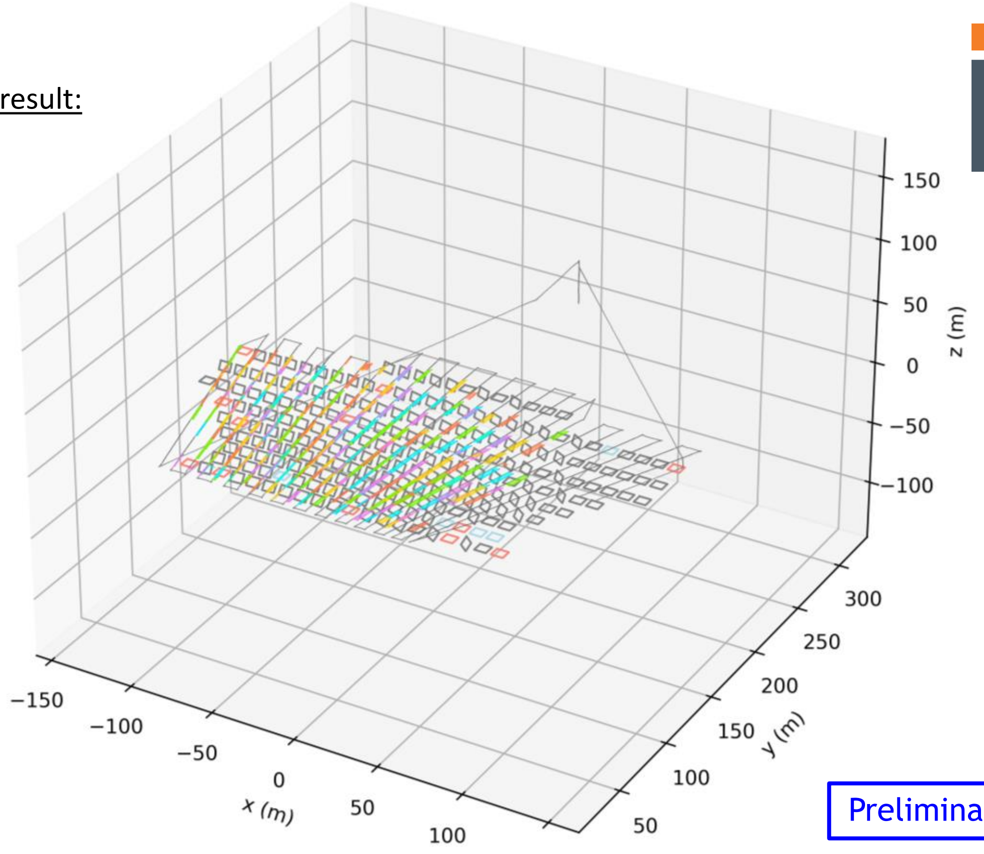
Register per-heliostat path segments to construct a vision-based full field trajectory.

Note heliostat orientations at each drone passage time.

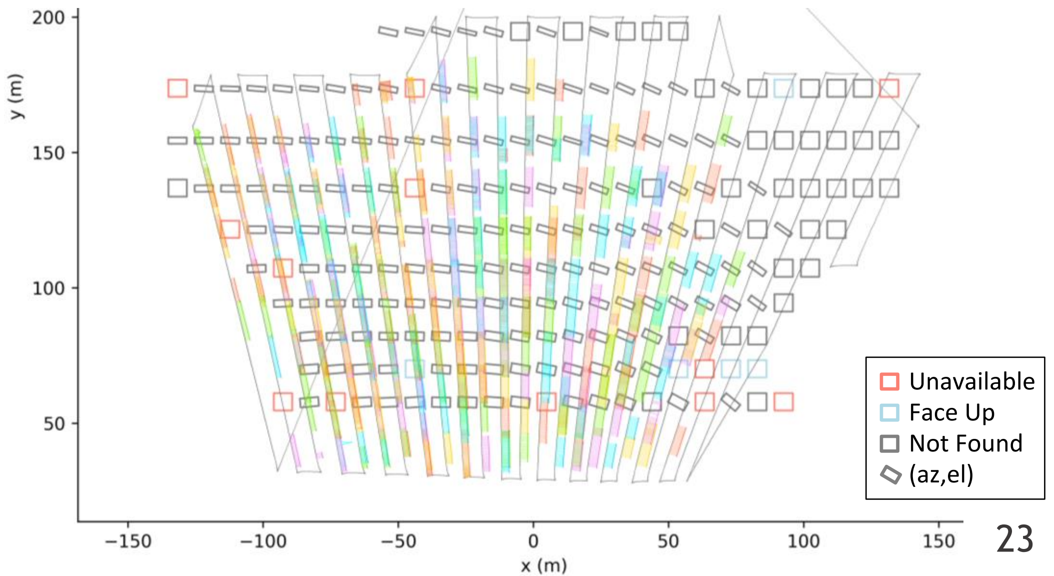
6W4



Full-field result:



Preliminary



Assessment

Challenge	Our Approach	Assessment
Safety	→ Plan flights to avoid flux, rigorous procedures.	→ Success.
Scale		
Wide area	→ High-speed UAS, design for long endurance.	→ Success, long endurance not demonstrated. Large data volume.
Large number points	→ Rich set of optical targets, video image data.	→ Density low compared to deflectometry.
Speed	→ Efficient low-acceleration flight trajectory.	→ Success. 4 sec/heliostat, 1,750 heliostat/day. Endurance needed.
Non-intrusive		
Construction	→ Exploit non-tracking heliostat positions.	→ Success.
Operation	→ Scan with no change to field operations.	→ Success.
High Accuracy	→ Aim for ±0.1 mrad absolute accuracy.	→ **Accuracy analysis pending.** Small heliostats may degrade accuracy.
Vary with configuration	→ Simultaneous (u_x,u_y) slope measurement.	→ Design success, but **slope measurement not implemented.**
Lack of data	→ Measure everything (except facet size).	→ Success, but **not complete.** Pointing *error* requires log synchronization.
Lack of ground truth	→ Ground truth strategy and campaign.	→ Success, but not complete.
Varying light, sky	→ Diverse data set, design robust algorithms.	→ 168 heliostats tracked, manual key frames, only one flight. **Incomplete.**
Varying design	→ Don't rely on heliostat or tower features.	→ Avoids detailed design features, but may degrade for smaller heliostats.
Heliostat motion		
Due to tracking	→ Design for allowing heliostats to move.	→ Success, but not complete.
Due to wind	→ ?	→ Current methods are vulnerable to heliostat flutter.
Optical effects		
Distortion	→ Reduce camera-mirror-target distances.	→ Distortion reduced, but reflected points not complete. Still vulnerable.
Far-field issues	→ Reduce use of far-field optical targets.	→ Avoided long distances, but indirect chain to estimate pointing direction.
UAS position uncertainty	→ Photogrammetry using existing features.	→ Success, but not complete and UAS position accuracy not yet understood.

Conclusion

Drones are attractive for in-field heliostat assessment, because they can cover wide areas quickly. Productivity depends on flight data capture efficiency, endurance, and turnaround time.

Our approach is designed to overcome key challenges in drone-based heliostat metrology.

We have achieved:

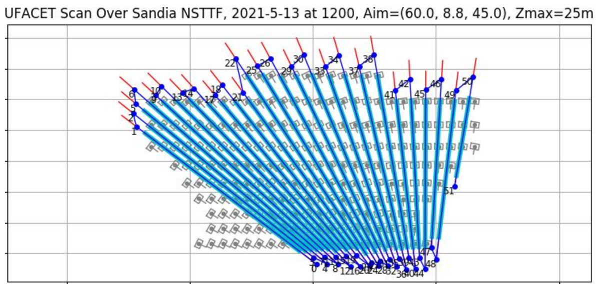
- Initial understanding of solar flux flight safety hazards.
- Automated flight planner.
- Efficient flight operations, gathering data for 45 flights at multiple locations.
- For one data flight:
  - Given manual key frames, automatic tracking of 168 heliostats (81%).
  - Photogrammetry estimates of intra-heliostat facet locations and *rough* canting angles.
  - Progress toward ground truth to cross-check heliostat metrology systems.
  - Estimates of drone trajectories relative to each heliostat.
  - Global drone trajectory estimate.
  - Estimate of heliostat orientations at the time of drone passage.

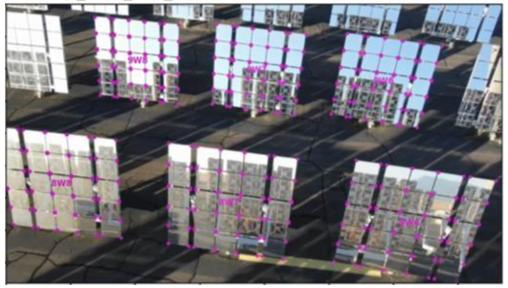
We pursuing fully automated video processing, for all flights in the data set.

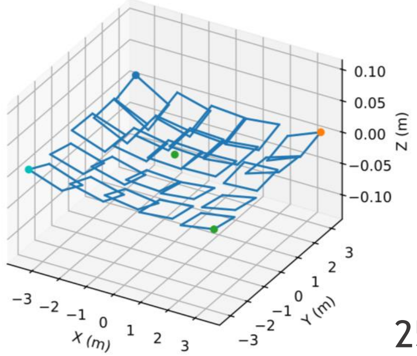
More work is required. Key questions:

- Reliability of fully automated high-volume video processing?
- Drone position estimation accuracy?
- Slope measurement density and accuracy?
- Pointing measurement accuracy?

Our aim is to produce a robust solution that scales.







BACKUP SLIDES

Scale and Speed Notes

Number of points required to calibrate 10,000 heliostats:

10,000 heliostats, each has 35 facets, 100 points/facet, 10 measurements/heliostat ⇒ 350 million points.

And yet 100 points per facet is fairly coarse.

For comparison, SOFAST Tower measured over 170,000 points per facet when measuring a full NSTTF heliostat.

Speed required to calibrate 10,000 heliostats in a month:

10,000 heliostats, 10 measurements/heliostat ⇒ 100,000 measurements.

One month has 30 days ⇒ 3,333 measurements/day ⇒ ~3,400 heliostat/day.

Assume 8 measurement hours per day ⇒ 28,800 sec/day

(28,200 sec/day) / (3,333 heliostat/day) = 8.64 sec/heliostat ⇒ ~9 sec/heliostat.

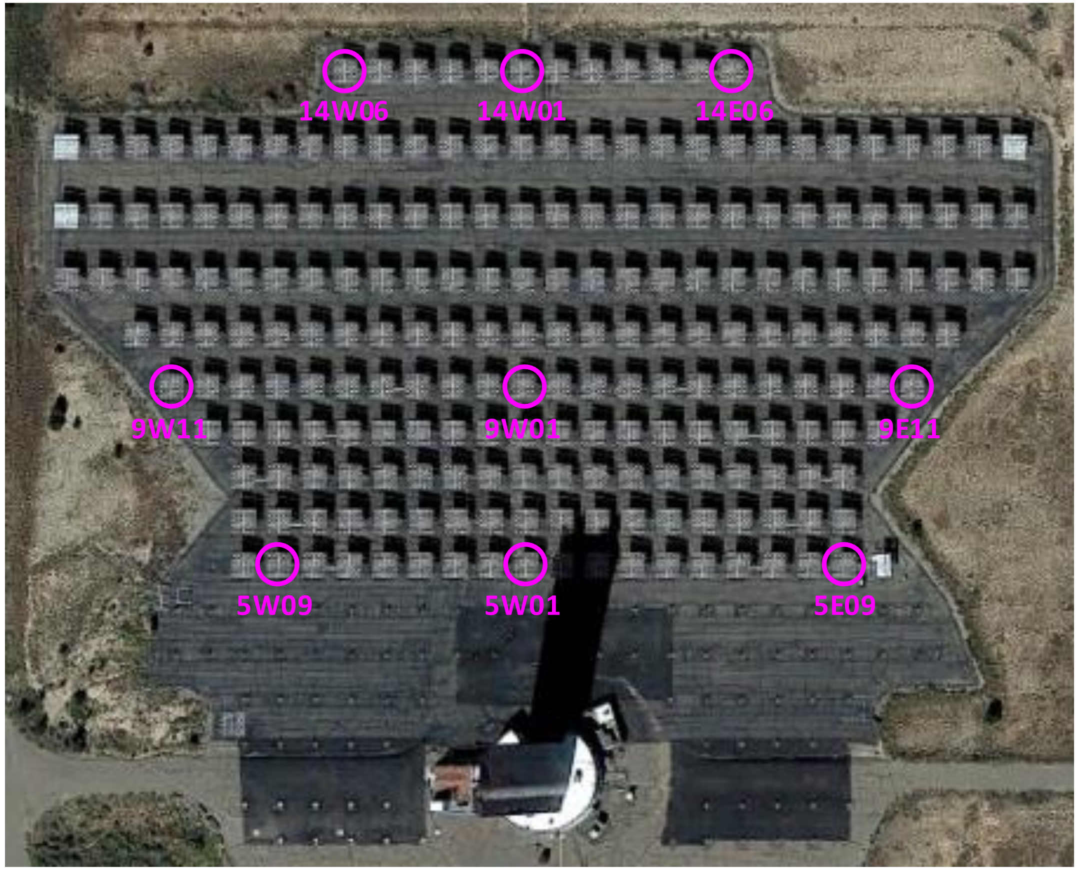
⇒ under 9 sec/heliostat, ~3,400 heliostat/day.

This estimate is optimistic, because it assumes 8 measurement hours per day.

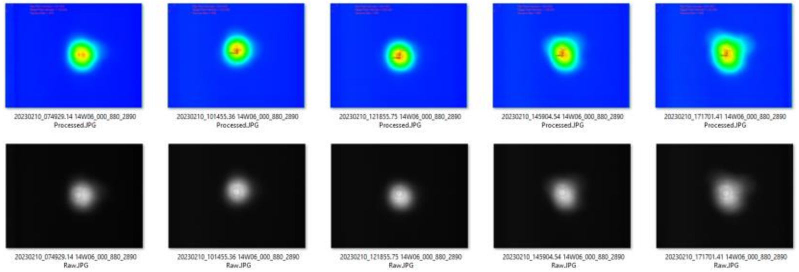
Weather and other factors are likely to reduce this up time; therefore faster measurement speed is required to calibrate 10,000 heliostats in a month.

Heliostats Studied

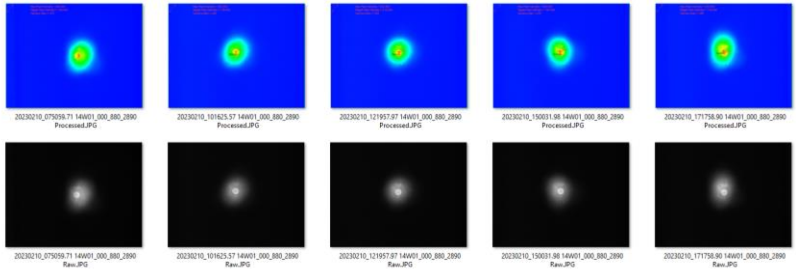
Heliostats for pictures:



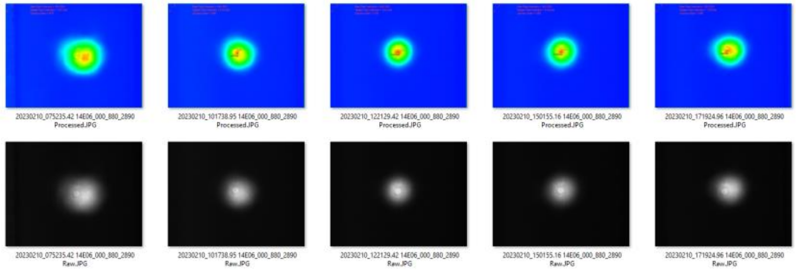
14W06



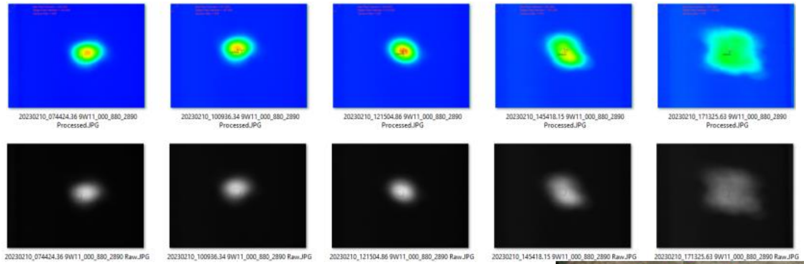
14W01



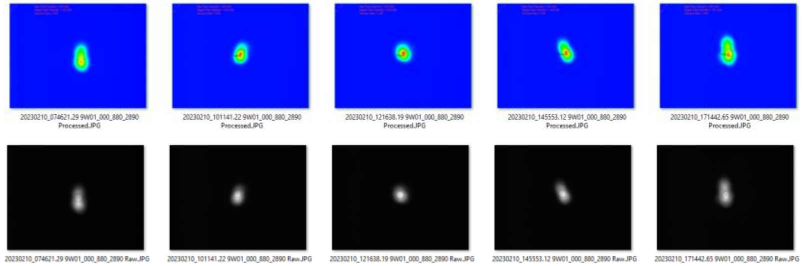
14E06



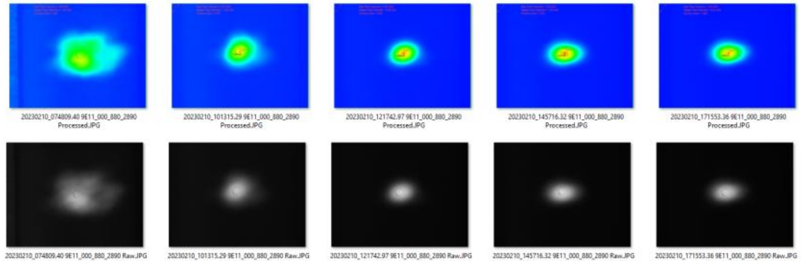
9W11

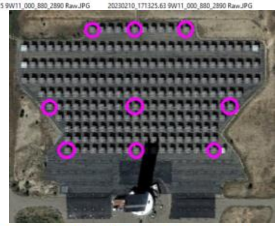


9W01

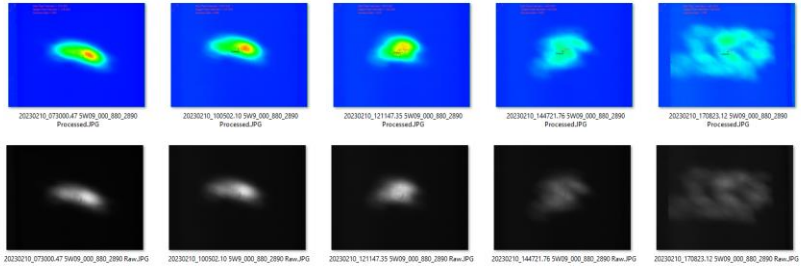


9E11

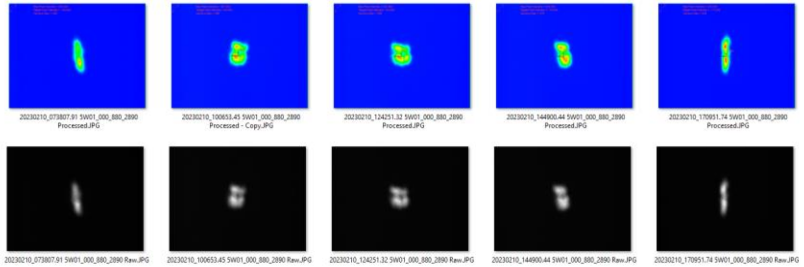




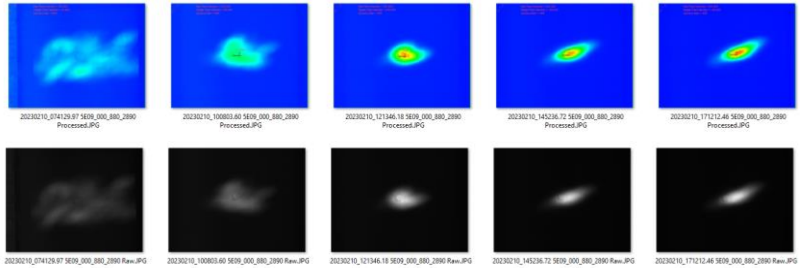
5W09



5W01

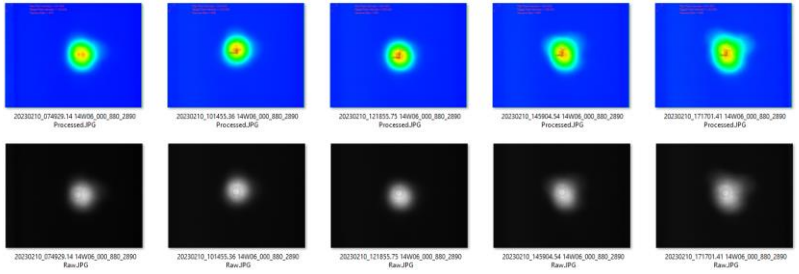


5E09

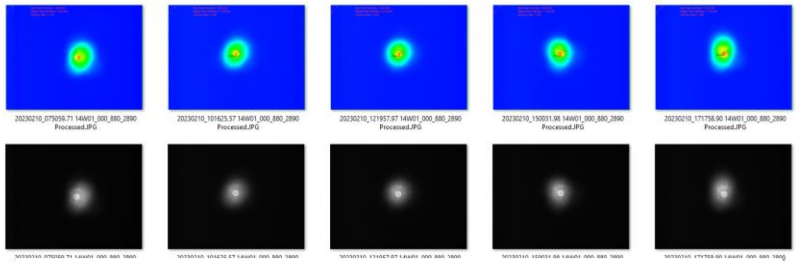


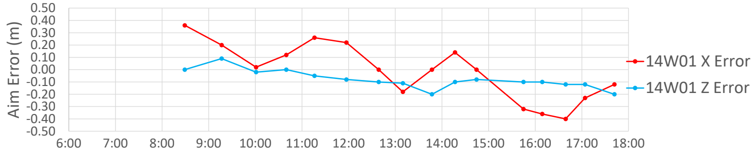
2/10/2023

14W06

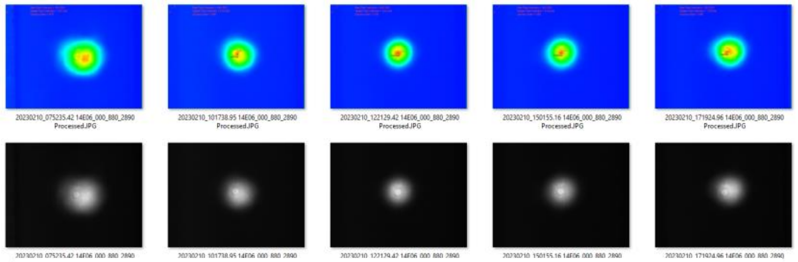


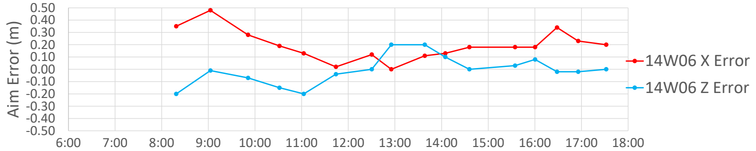
14W01



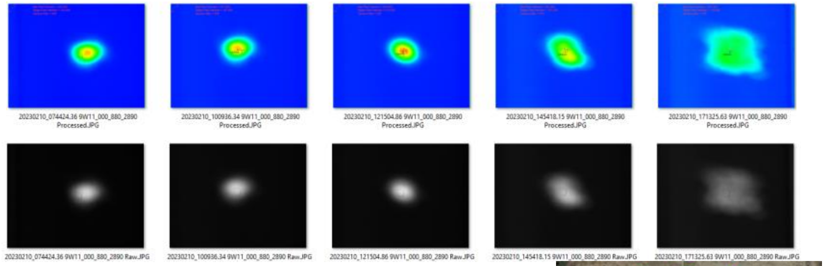


14E06

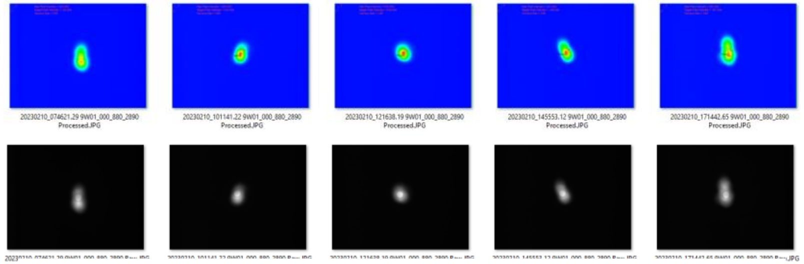


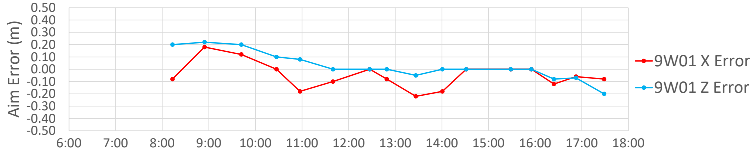


9W11

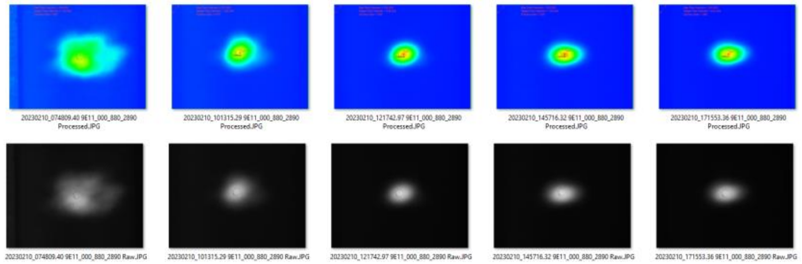


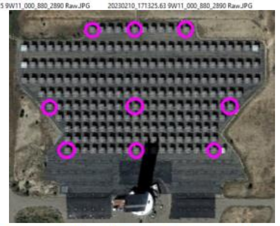
9W01



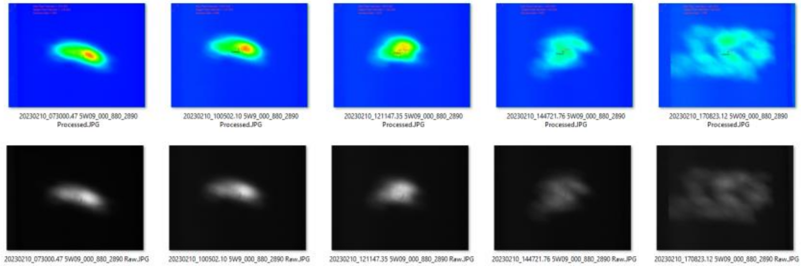


9E11

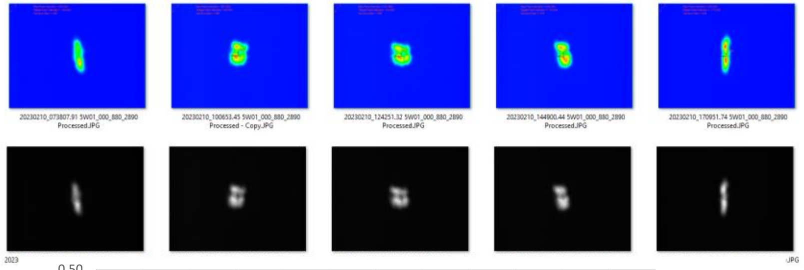


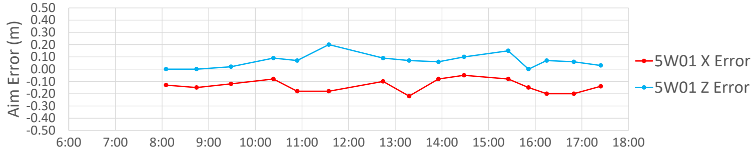


5W09

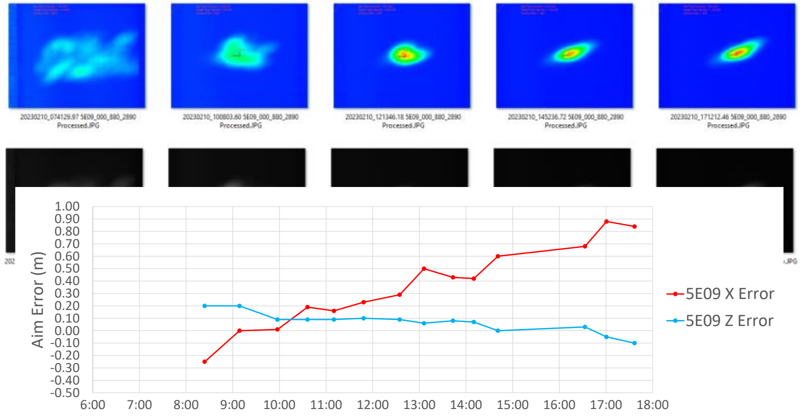


5W01





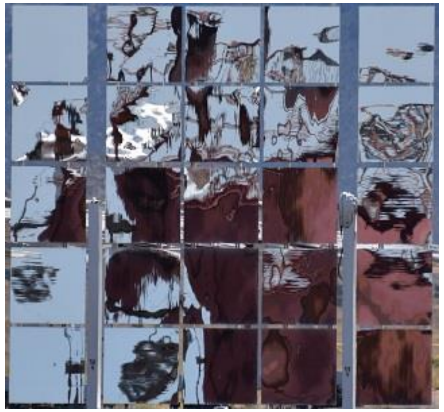
5E09



Distortion

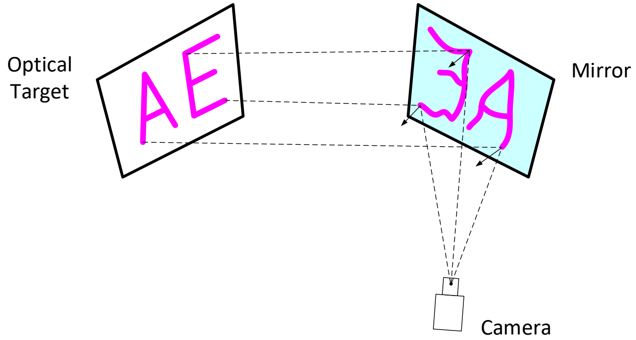
- CSP mirrors can exhibit highly distorted reflections.
- Feature-based correspondence methods are vulnerable to confusion in mapping, given a distorted image.
- In contrast, SOFAST uses a pixel-based correspondence mapping scheme which is fundamentally immune to distortion.

Distortion Example



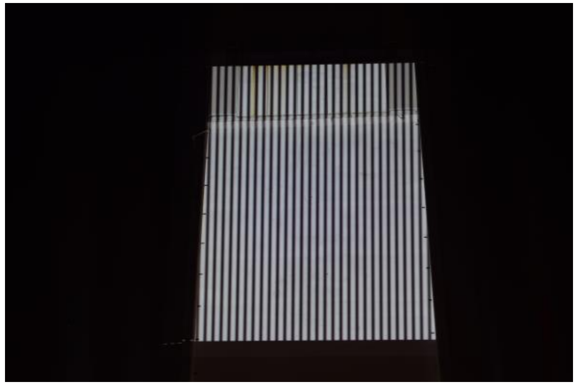
Reflected distortion depends on conditions.

Feature-Based Correspondence



Excessive distortion can cause feature recognition to fail.

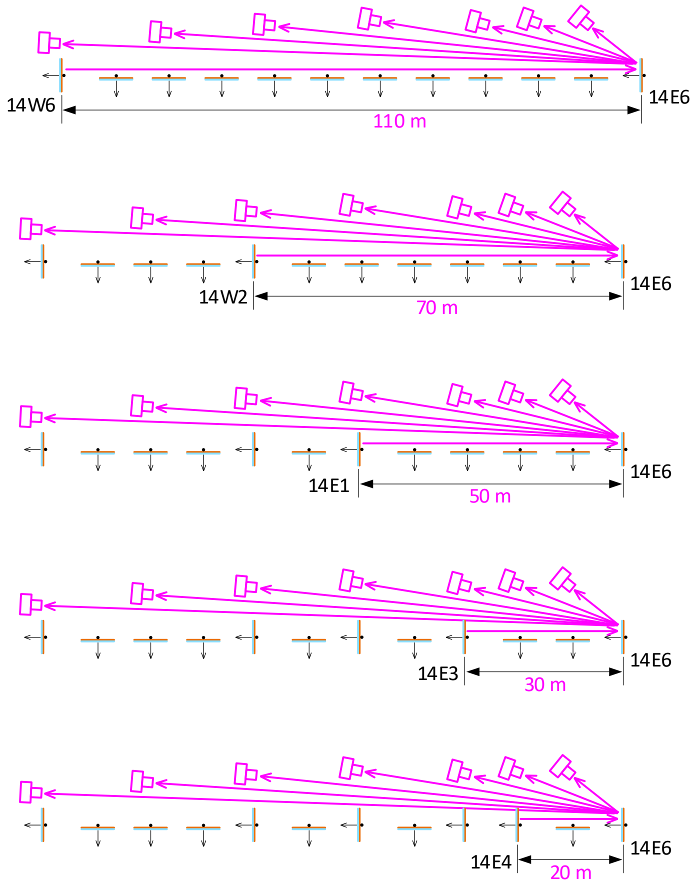
SOFAST Fringes and Distorted Reflection



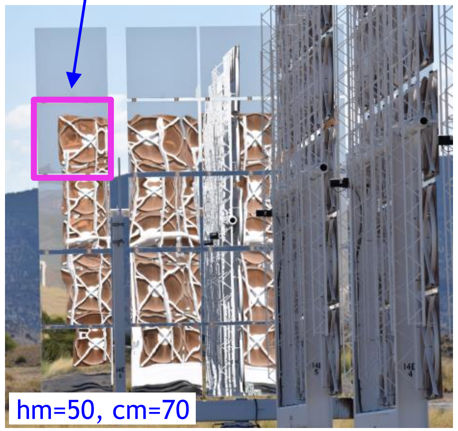
Not a problem for SOFAST.

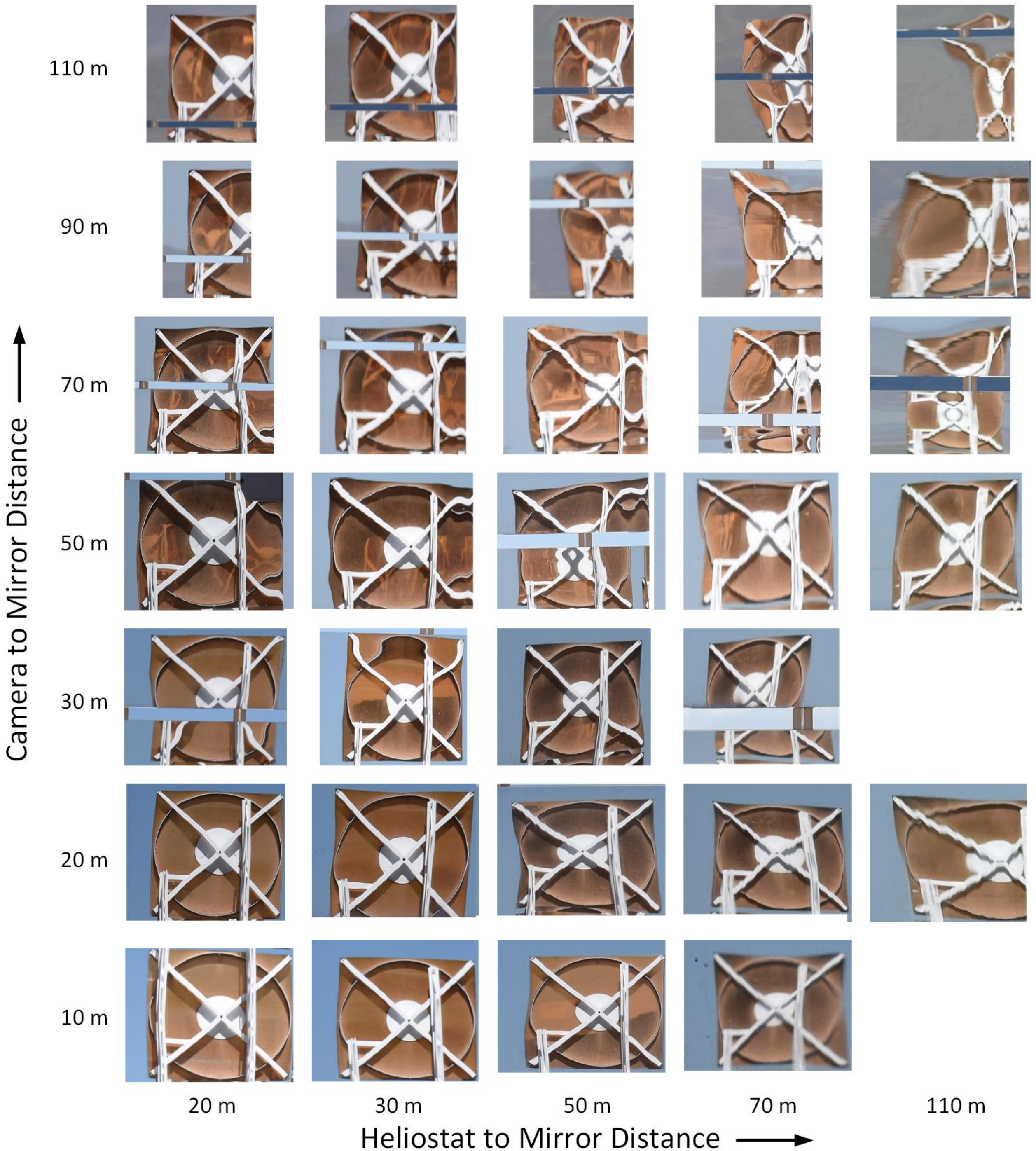
CSP Mirror Distortion Effects

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



Photograph, then crop

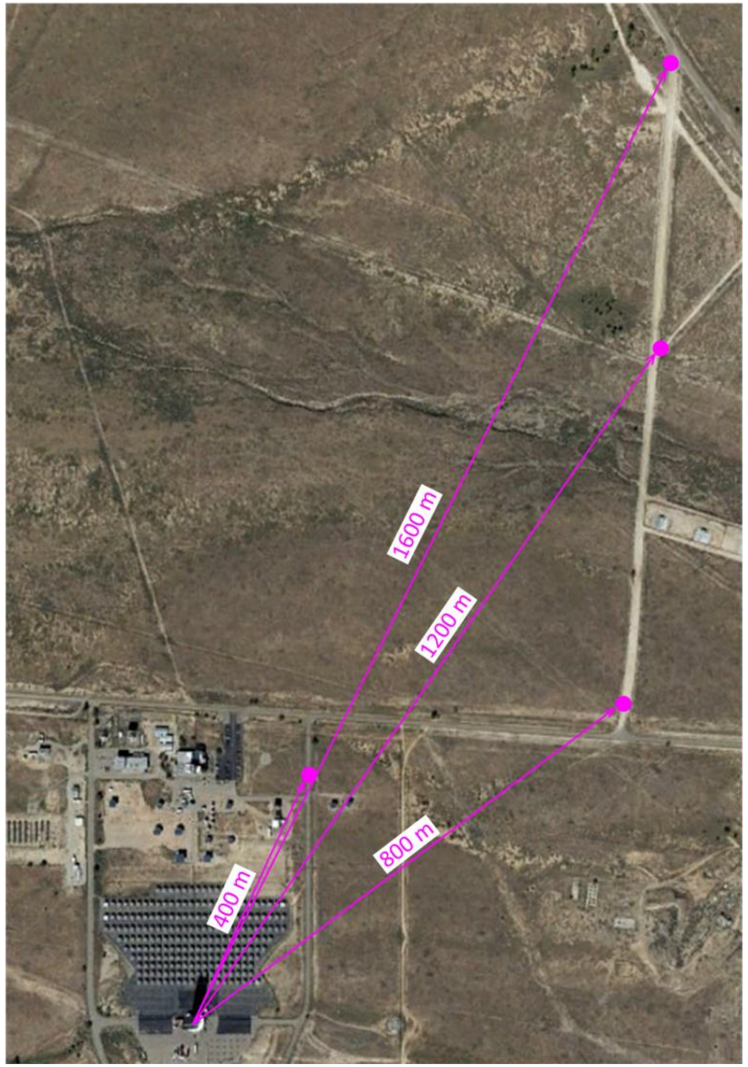




Conclusion:
Distortion increases with heliostat-to-mirror distance, and also with camera-to-mirror distance.

Tower-to-Mirror Distortion

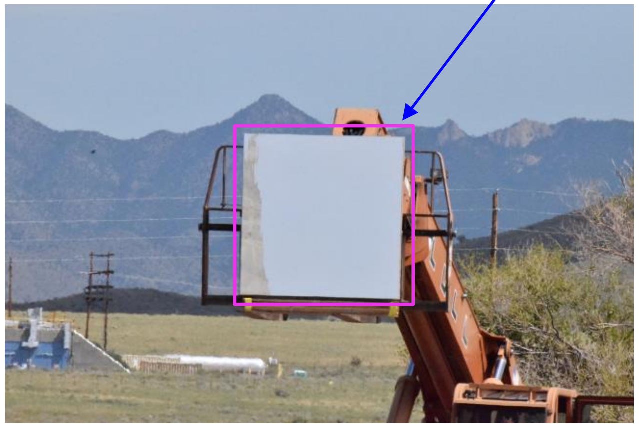
Single facet method:



Images captured at 25, 50, 100, and 150 m from the mirror.
Lateral moves at each point, to simulate UAS scan.

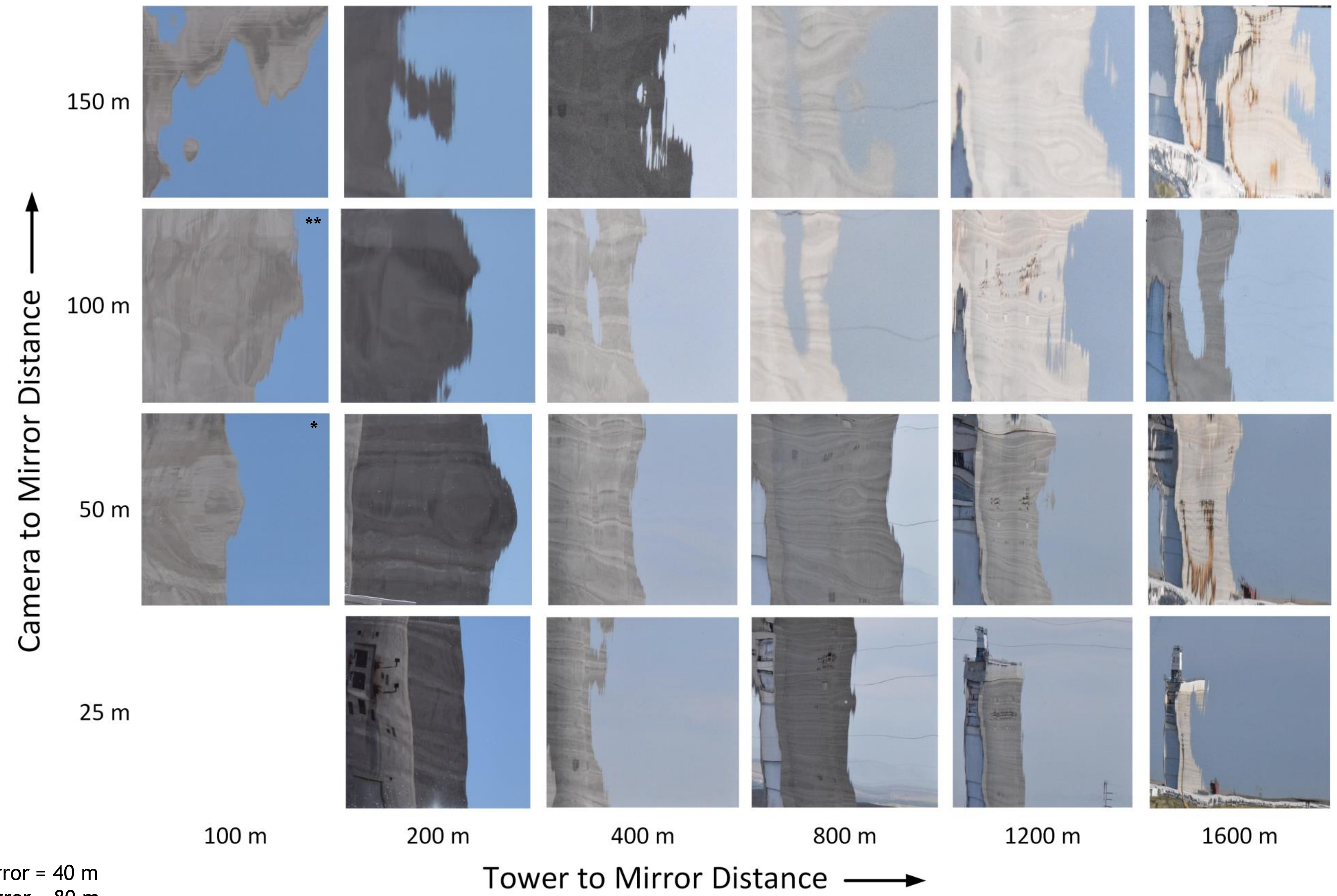
Flat mirror

Photograph, then crop to facet



A flat mirror was used, so that:
(a) Non-imaging optic distortion would not occur, and
(b) Focal length mismatch would not be an issue.

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



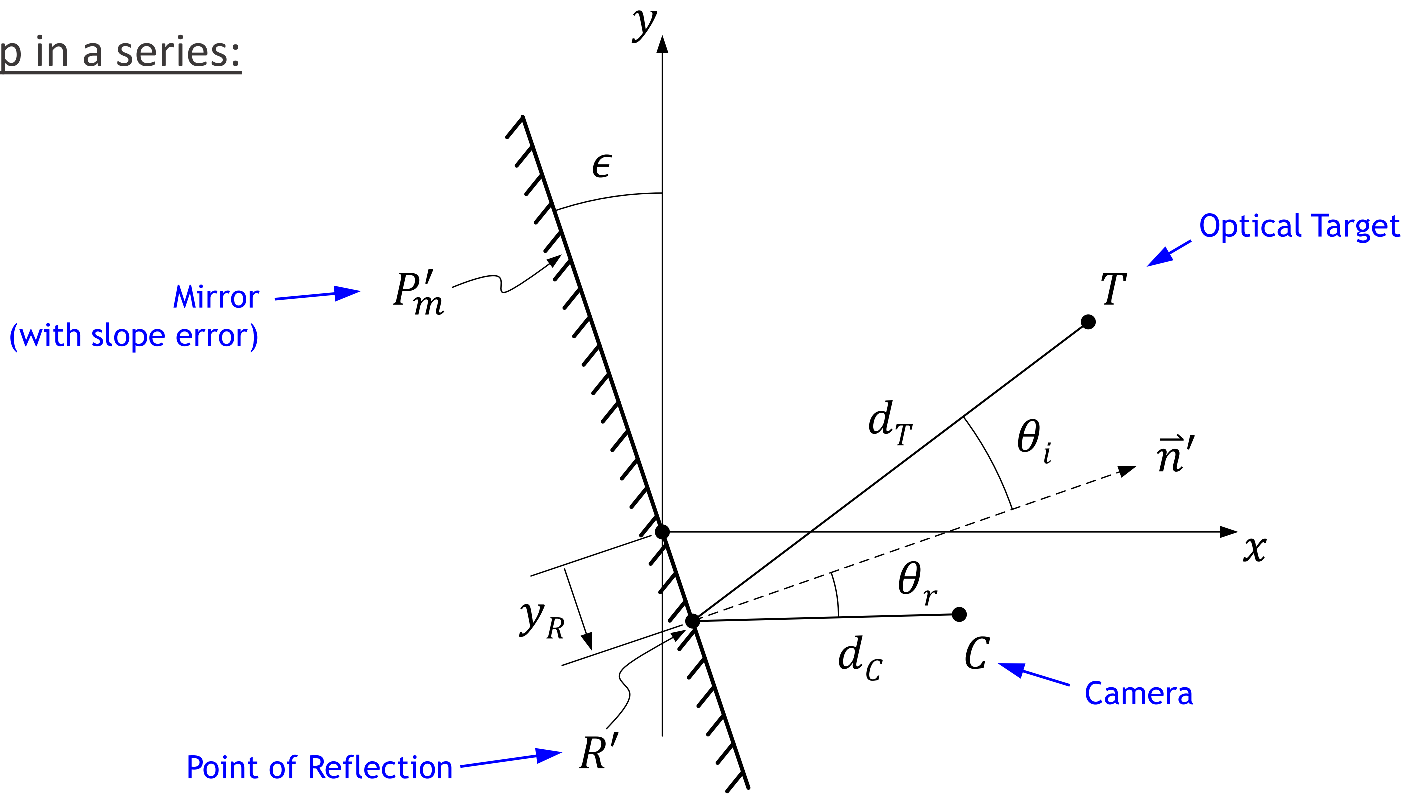
<u>Conclusion:</u>
We see distortion increase with camera-to-mirror distance, but we do not see a clear increase with tower-to-mirror distance.

Why?

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

Modeling Mirror Distortion

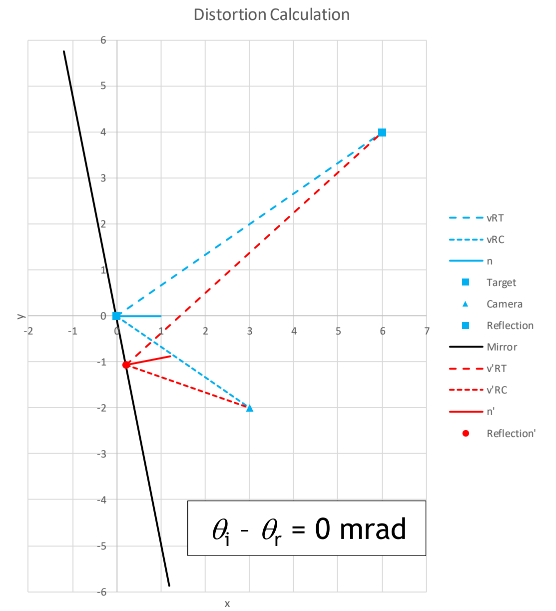
One step in a series:

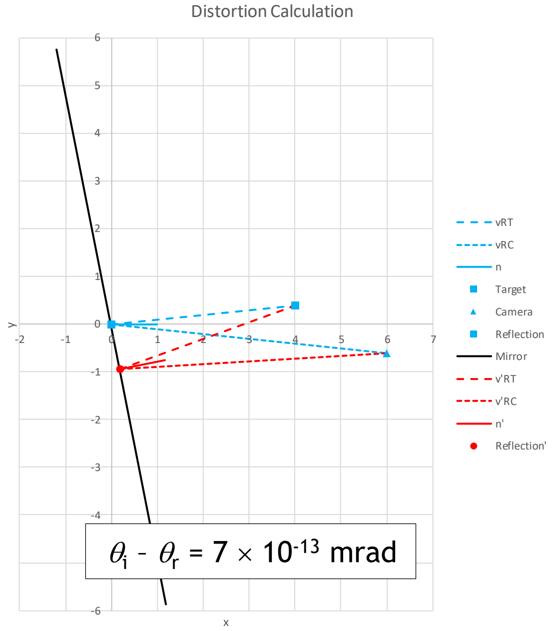


After several derivation steps:

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

Computer verification:





Modeling Mirror Distortion

If slope errors are small:

Main result

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

1. Sign of the error is correct for our example.
2. Distortion grows linearly with slope error ϵ. (Within small angle assumption)
3. As the incidence angle θ_i becomes very high, distortion grows rapidly.
4. Distortion grows with both target-to-mirror and camera-to-mirror distance.
5. Distortion grows rapidly (with the square) of the total optical path length.
6. Both target-to-mirror and camera-to-mirror distance have a symmetric effect on distortion, if both are similar magnitude.

If d_T >> d_C:

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

7. Matches long-distance tower-to-mirror observations.

This explains our observations:

1. For heliostat-to-heliostat reflections, distortion grows with both target-to-mirror and camera-to-mirror distance.
2. For tower-to-mirror reflections, distortion grows primarily with camera-to-mirror distance.

Computer verification: Approximation error for ϵ = 10 mrad: 0.004%, 0.0002% for two cases studied. (Percentages calculated with respect to smaller of d_T, d_C.)

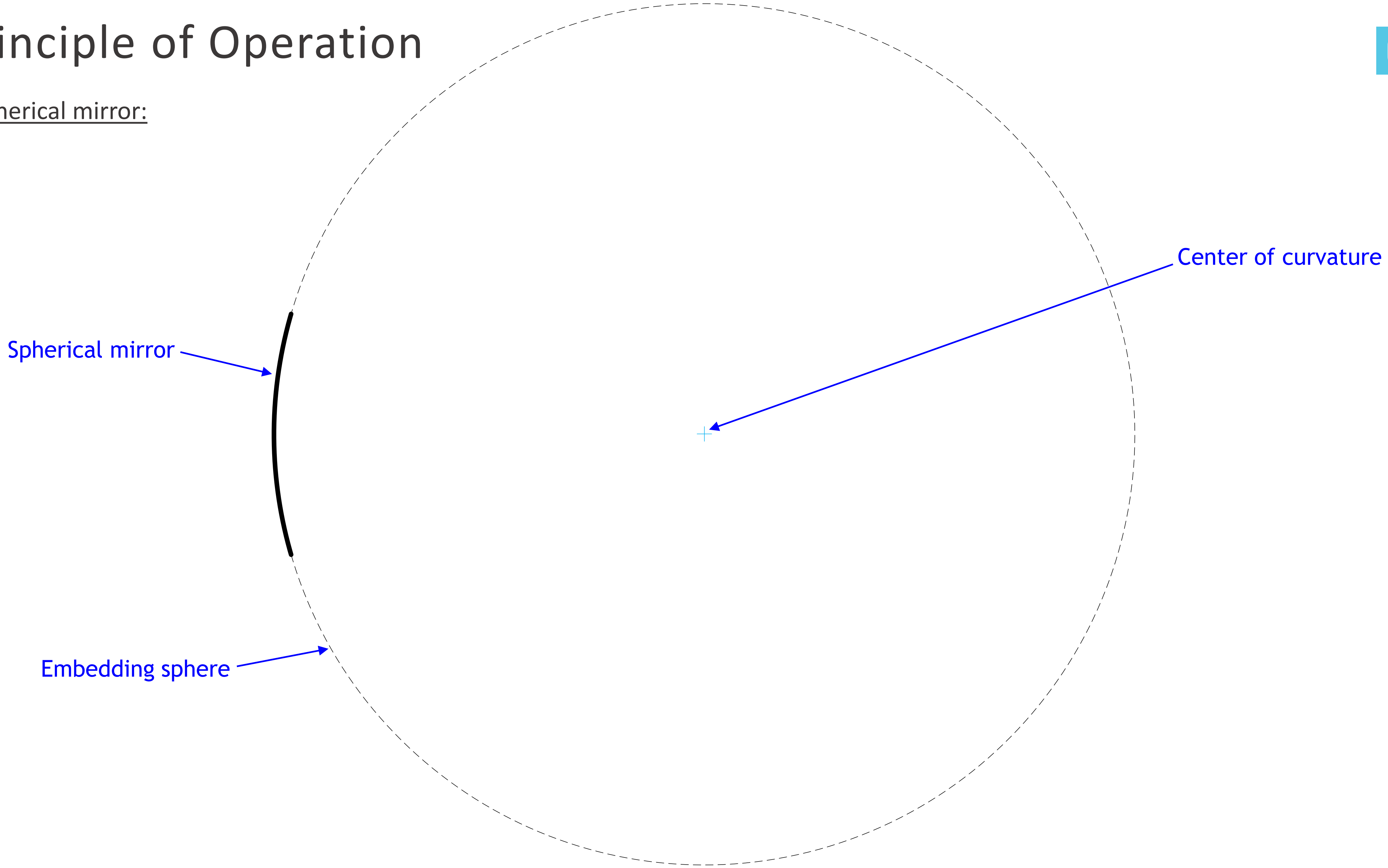
Ground Truth

We are pursuing two types of ground truth:

- *Ground truth methods.* Simple and inherently accurate. Okay to be slow, inconvenient, or have limited scope.
- *Ground truth physical standards.* Physical objects with known metric properties. Ideally inexpensive and can be replicated anywhere.

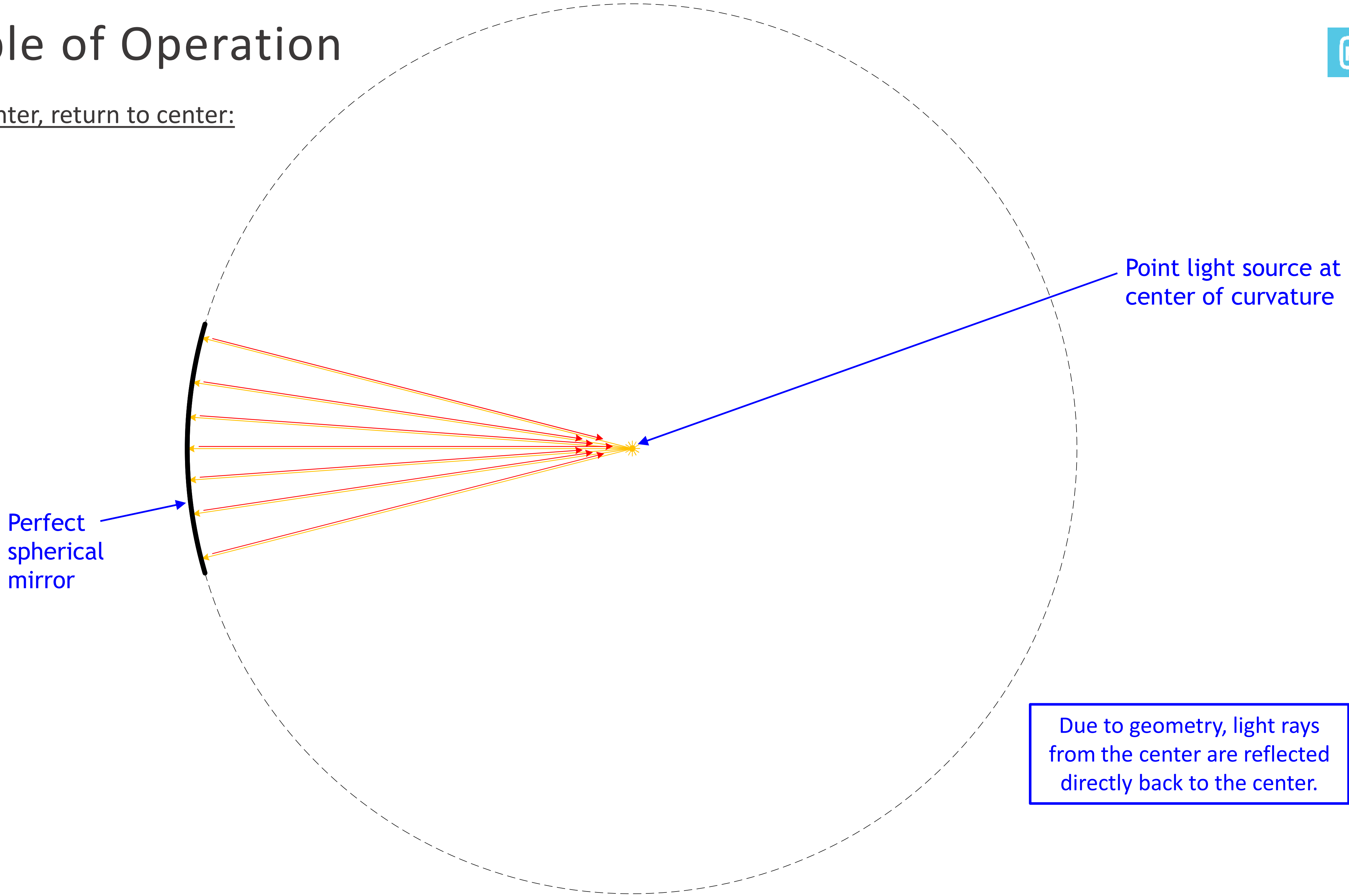
Principle of Operation

A spherical mirror:



Principle of Operation

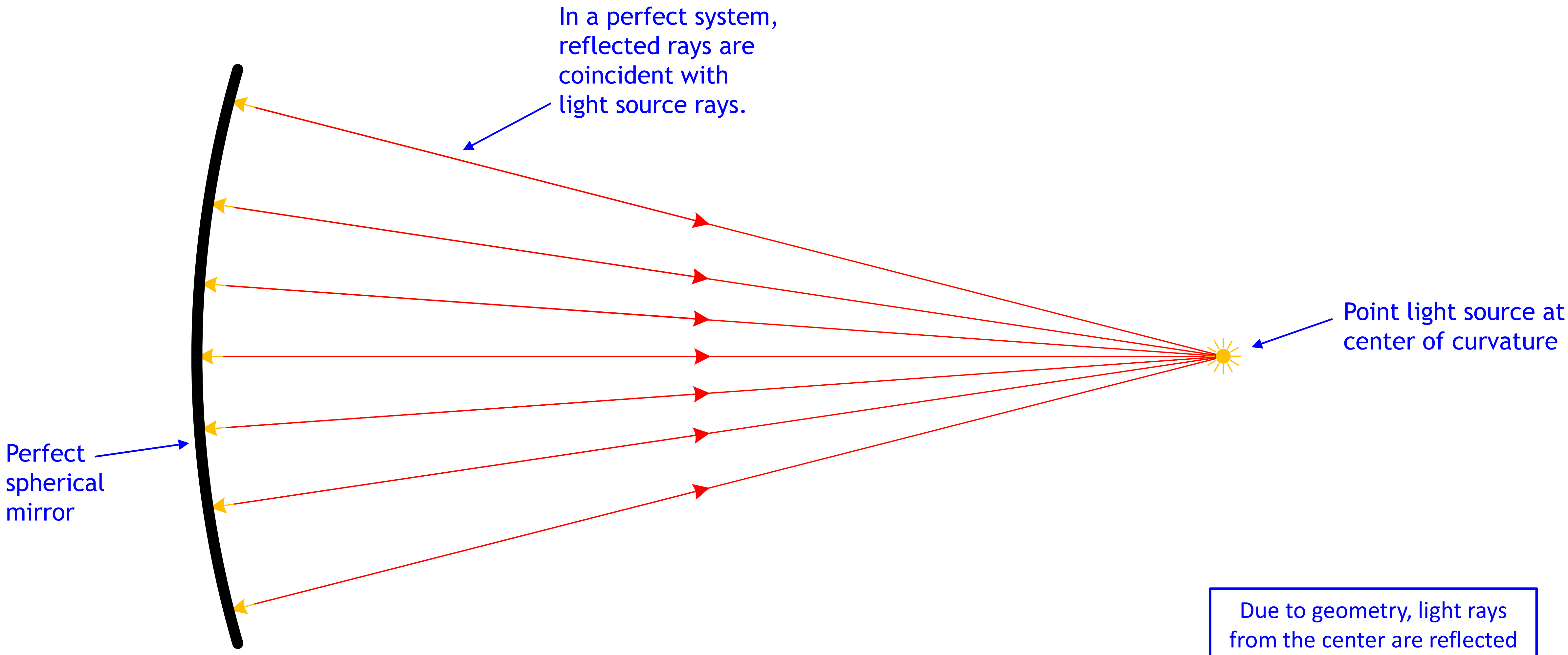
Rays from center, return to center:



Due to geometry, light rays from the center are reflected directly back to the center.

Principle of Operation

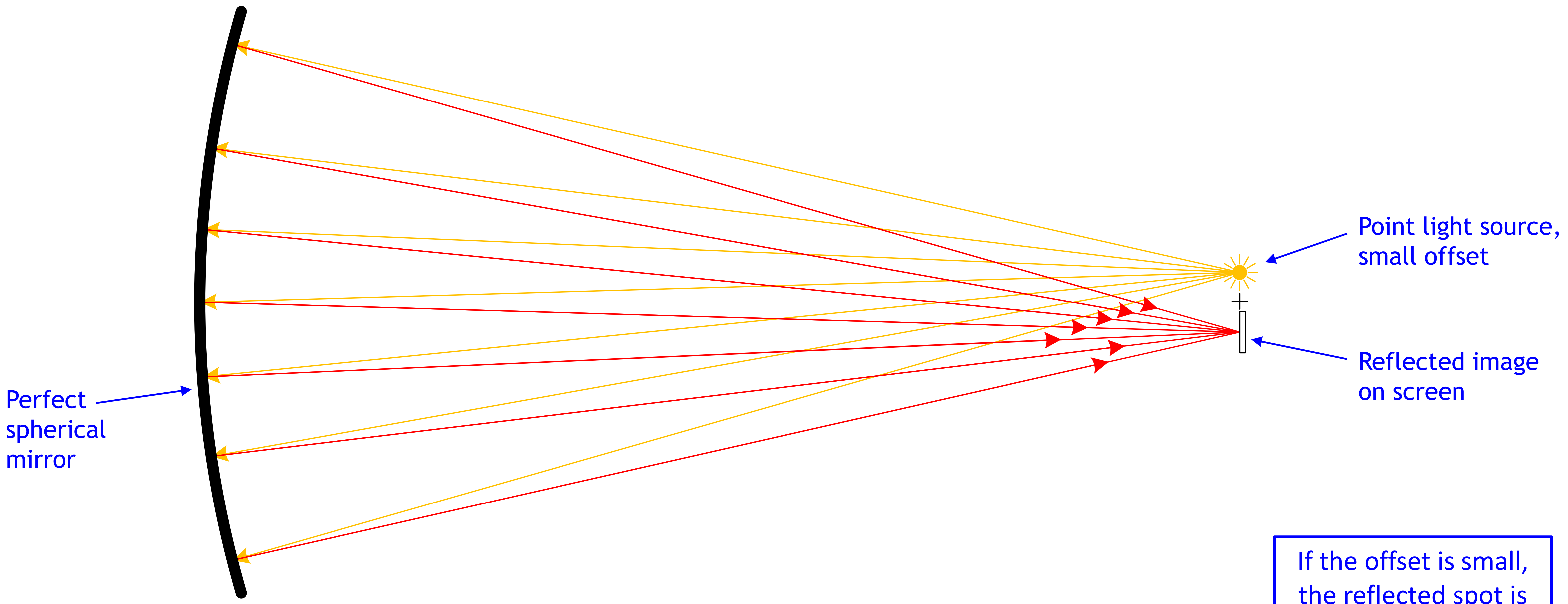
Zooming in:



Due to geometry, light rays from the center are reflected directly back to the center.

Principle of Operation

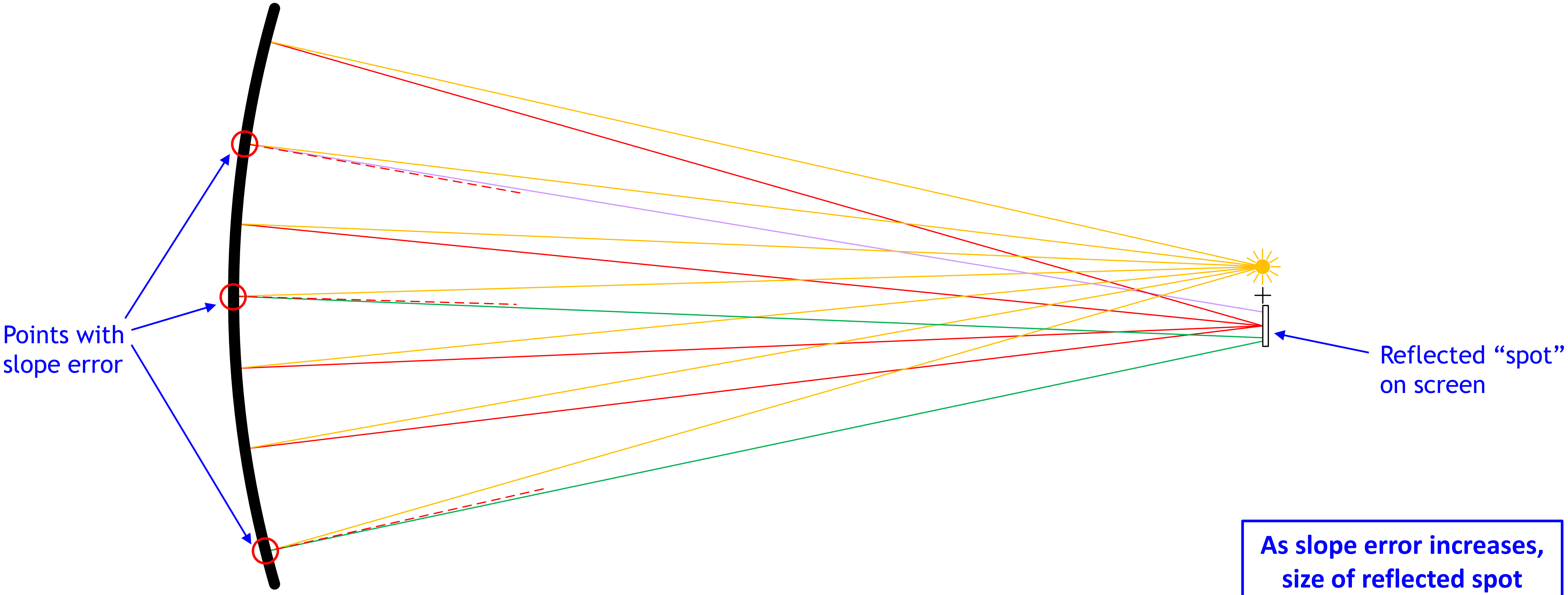
A slight offset:



If the offset is small, the reflected spot is nearly identical.

Principle of Operation

The effect of errors:



As slope error increases, size of reflected spot increases.

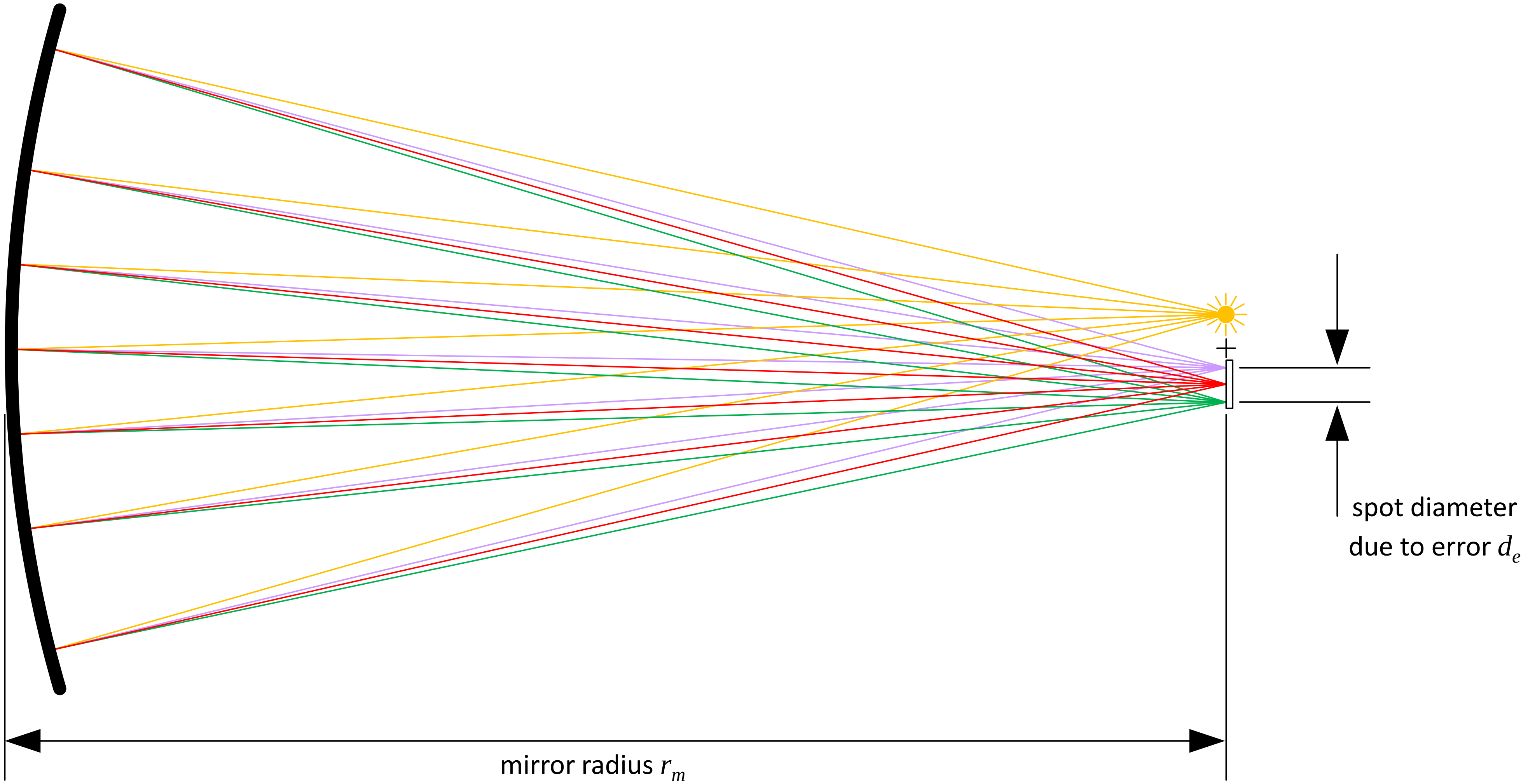
Principle of Operation

Slope error ϵ:

Spot diameter indicates overall error:

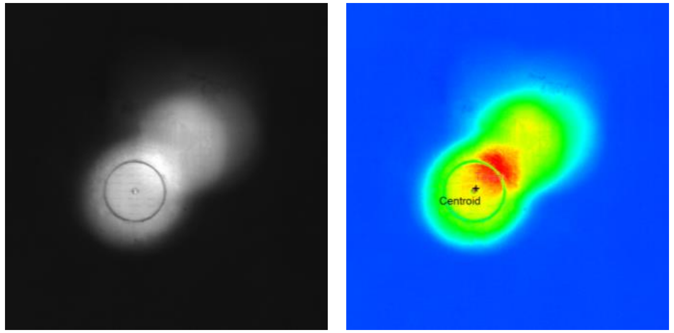
$$\epsilon = \frac{d_e}{4r_m}$$

Requires small angle assumption, which is valid if $r_m \gg d_e$.



Ground Truth Methods

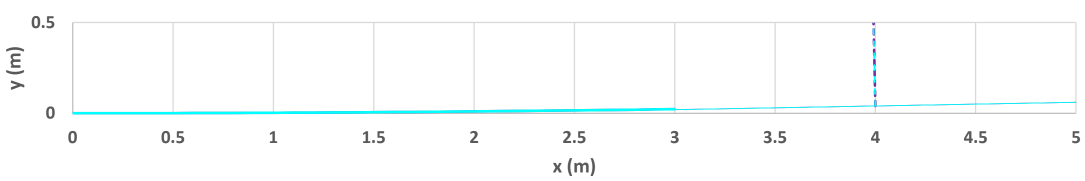
BCS



Direct measure of desired function.

Strachan's Observation[1]

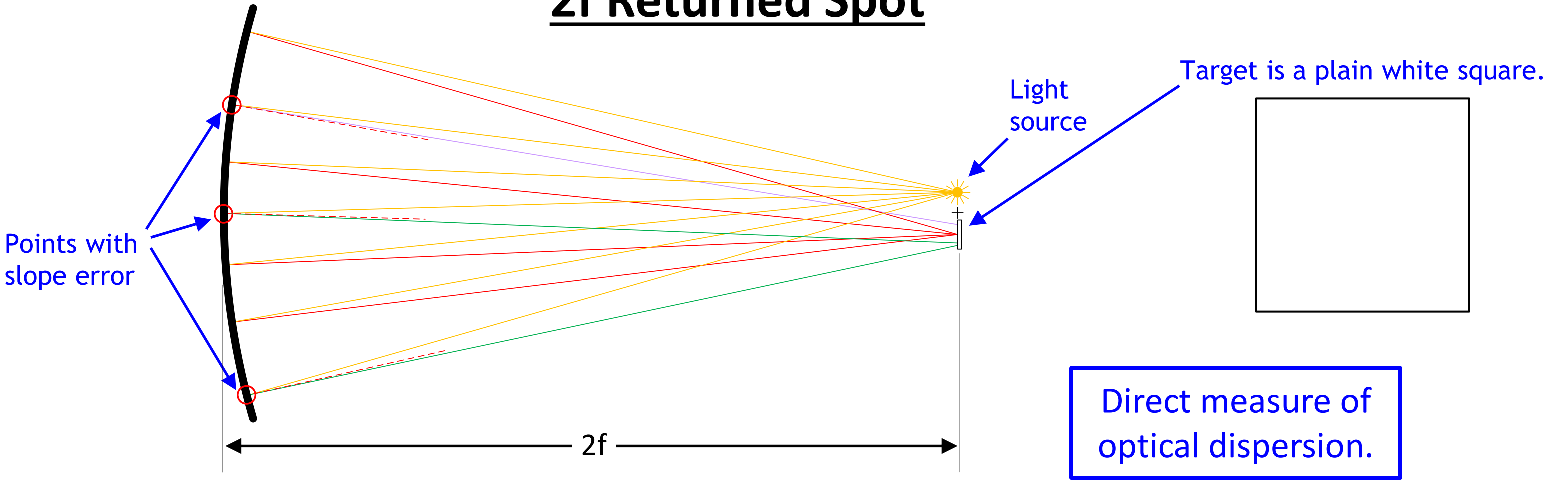
For 100m focal length:



At 4 m aperture radius:

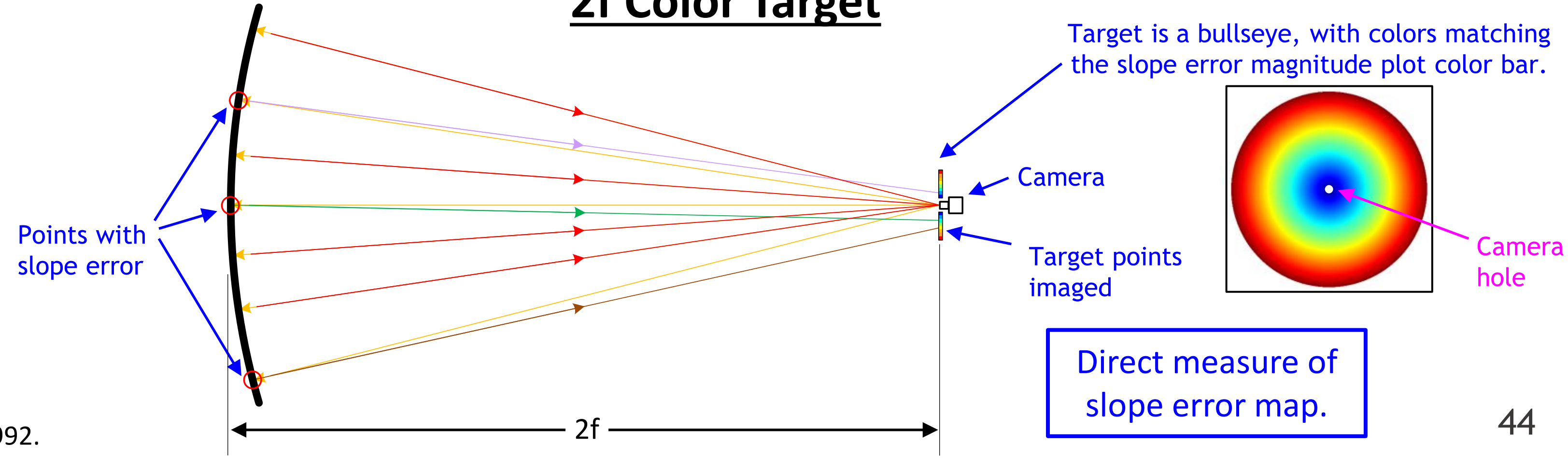
Focal Length (m)	Δ Slope (mrad)
100	0.00400
200	0.00050

2f Returned Spot



Direct measure of optical dispersion.

2f Color Target



Direct measure of slope error map.

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

Comparing Ground Truth Methods

BCS

Strengths:

- Simple.
- Directly measures the function of interest.

Limitations:

- Information-losing: Slope details lost.
- Reduced specificity, due to sun shape.
- Reduced signal strength with large heliostat-to-target distance.
- Day, clear sky required.

2f Returned Spot

Strengths:

- Very simple. No calibration calculations.
- Very low cost.
- For high-quality optics, sub-milliradian specificity.
- Robust to misalignment.
- Can assess astigmatism.

Limitations:

- Information-losing: Slope details lost.
- Requires large target (white).
- Requires long distance clear line of sight.
- Night only.
- Error magnitude only.

2f Method Target Diameter

Function of mirror focal length and mirror error:

$$d = 8f\epsilon$$

where

d is target diameter (m)

f is focal length (m)

ϵ is maximum slope error (rad)

Note independent of mirror size!

2f Color Target

Strengths:

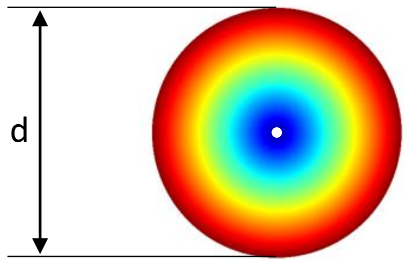
- Very simple. No calibration calculations.
- Low cost.
- Day or night.
- Map of error across mirror surface.
- Sub-milliradian specificity.

Limitations:

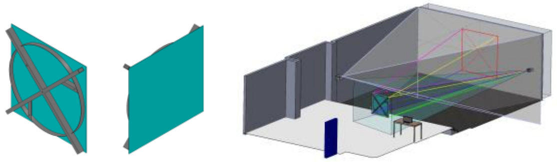
- Requires large target.
- Requires long distance clear line of sight.
- Magnitude only; not X or Y components.

Work in Progress:

- How respond to misalignment?
- How best handle astigmatism?



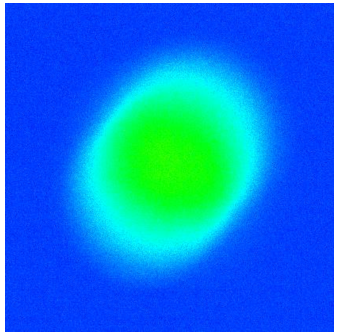
Ground Truth Check: NSTTF Facet



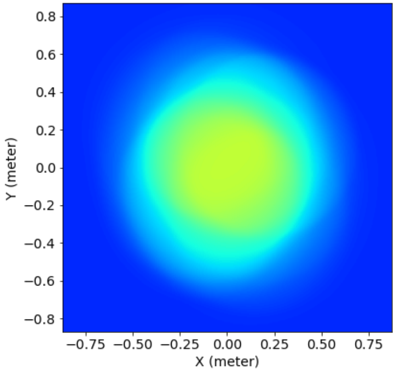
f = 100 m*

BCS

BCS Image



SOFAST Ray Trace

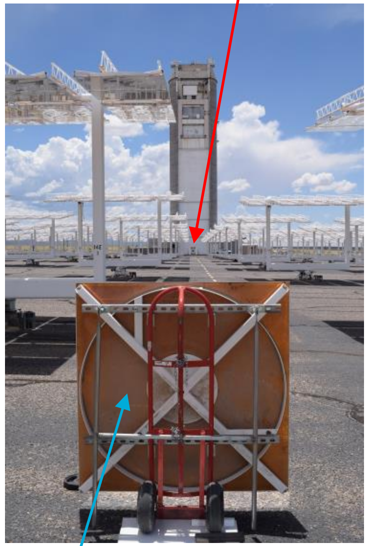


Images are same scale.

Image capture and ray trace both June 30, 2022 at 2:40 PM.

2f Returned Spot

White Screen/Flashlight

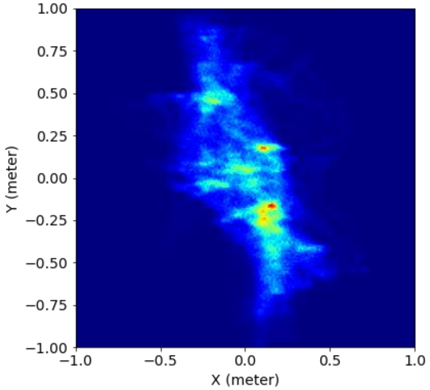


distance ≈ 200 m

Mirror (Back Side)

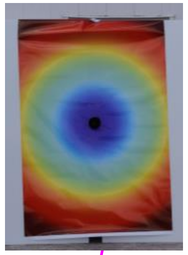
2f Returned Spot Image

SOFAST Ray Trace



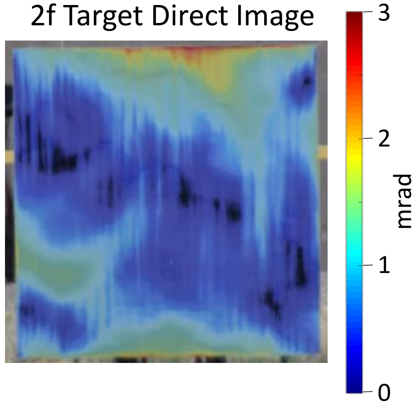
Images are same scale.

2f Color Target

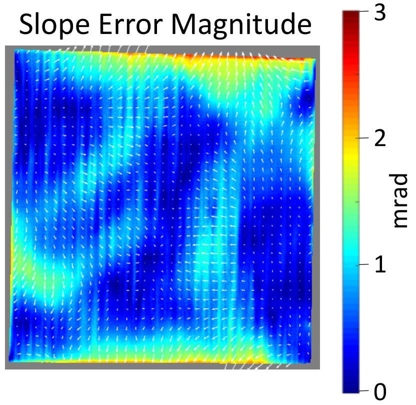


distance ≈ 200 m

2f Target Direct Image



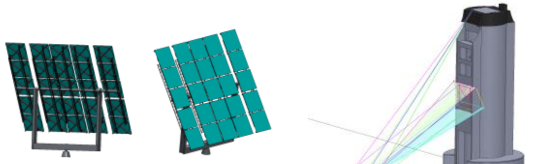
SOFAST Slope Error Magnitude



Quantitative comparison is work in progress.

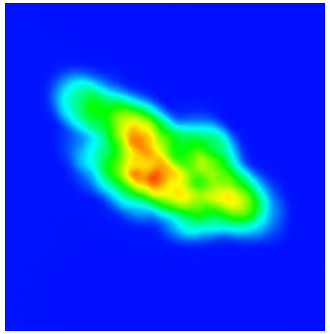
* NSTTF facets are adjustable. SOFAST was used to set focal length to 100 m, as measured by SOFAST.

Ground Truth Check: NSTTF Heliostat 5W01

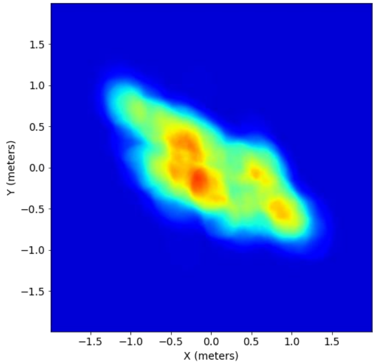


BCS

BCS Image



SOFAST Ray Trace



Images are similar scale.

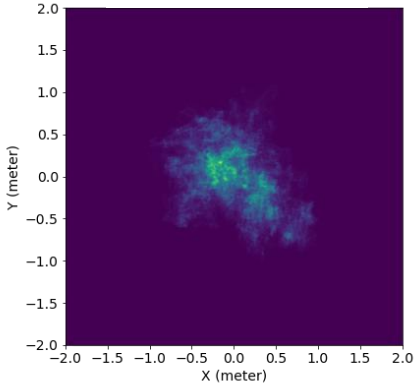
Image capture and ray trace both June 30, 2022 at 2:06 PM.

Achieving this match required manual adjustment of SOFAST calibration parameters.

2f Returned Spot

2f Returned Spot Image

SOFAST Ray Trace

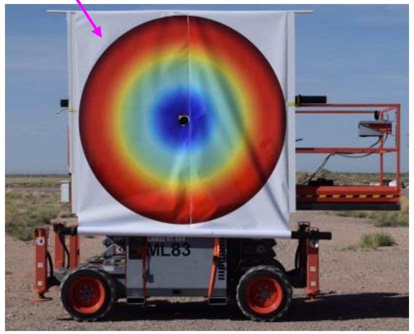


d = 131.6 m, one among a sequence

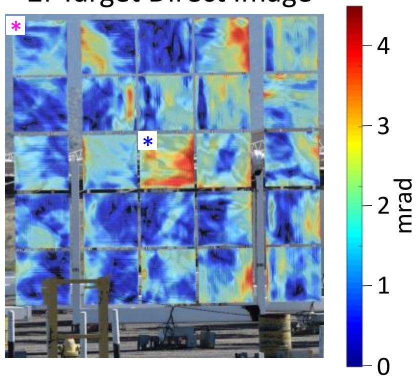
Images are same scale.

* Heliostat focal length, astigmatism unknown.

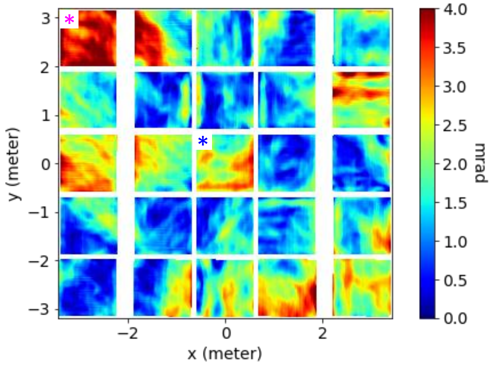
2f Color Target



2f Target Direct Image



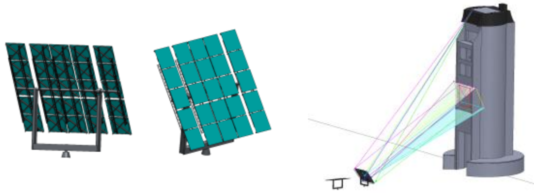
SOFAST Slope Error Magnitude



distance = 166.7 m

Note similarities (*) and discrepancies (*).
Work in progress.

Output Summary: NSTTF Heliostat 5W01

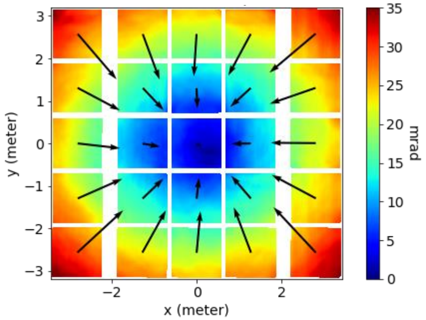


Absolute

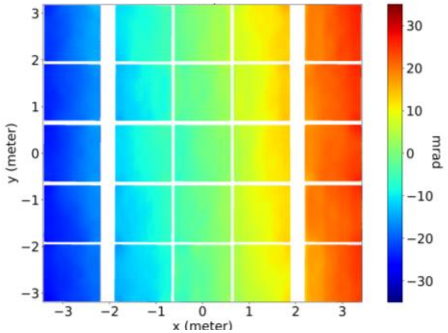
Input: Measurement

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

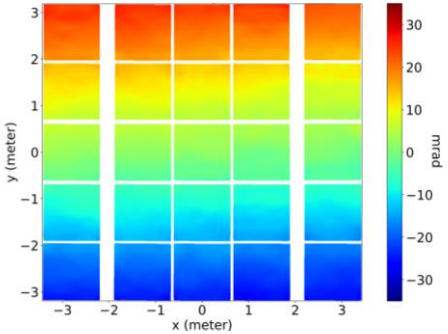
Slope Magnitude



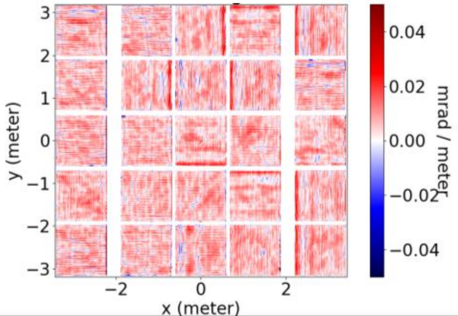
X Slope



Y Slope



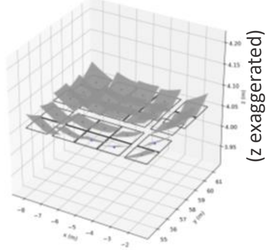
Curvature



Error

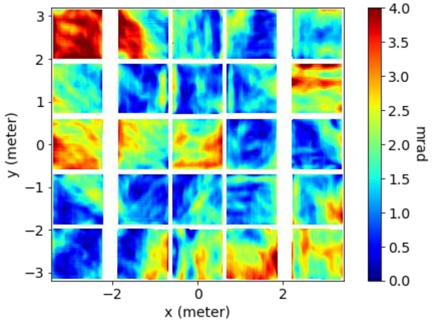
Add: Design Reference

Ideal Design

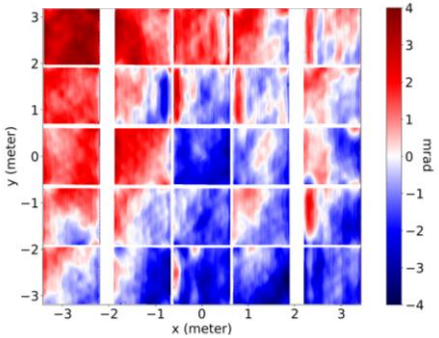


On-axis canting.
Slant distance 57.2 m.

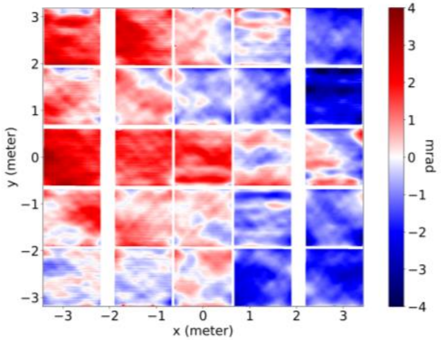
Slope Error Magnitude



X Slope Error



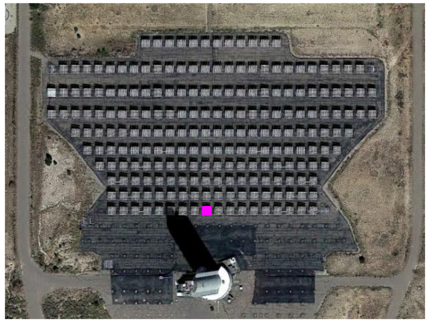
Y Slope Error



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	
RMS canting error Y:	1.2 mrad	
Range canting error X:	[-3.2, +2.0] mrad	
Range canting error Y:	[-2.5, +2.3] mrad	

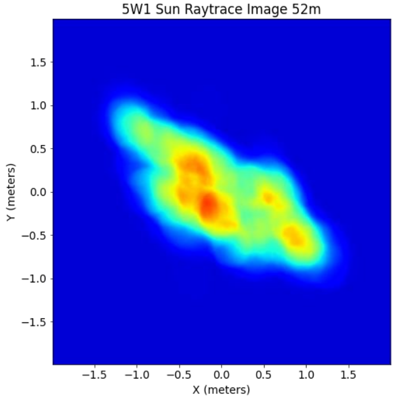
Ray Trace

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)

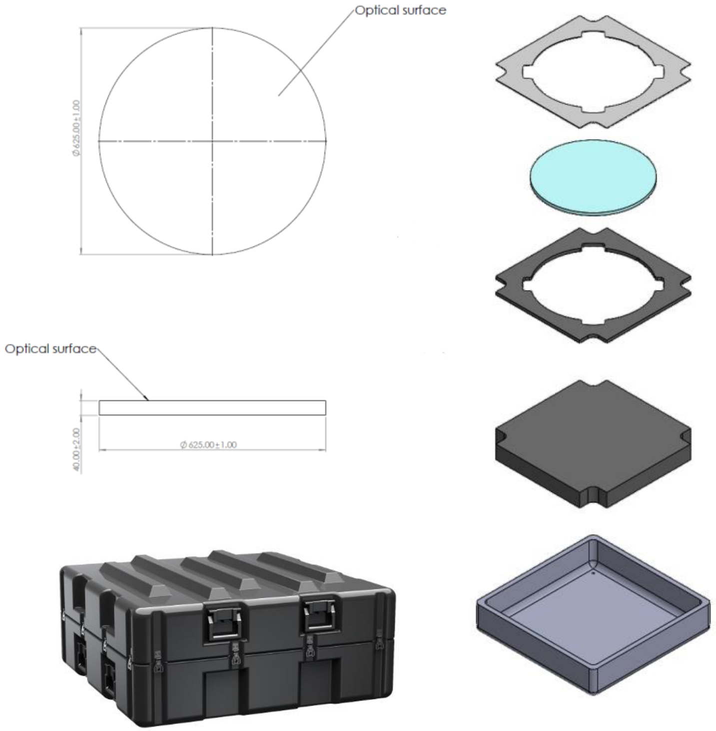
Ground Truth Physical Standards

- Ground truth physical standards are objects where you know what the measurement result should be. If you use an instrument to take a measurement and the answer is not what's expected, you know the problem is with the instrument.
- The best physical ground truth standards are low cost and easy to replicate anywhere – a Dewar with ice water for calibrating temperature is a familiar example.
- Other ground truth physical standards are standard references that are prepared by laboratories with certified equipment. These need to be checked periodically to ensure that they have not degraded.
- We are pursuing ground truth standards of both kinds.
  1. A **plano water pool** is easy to replicate and reliable if vibrations are not present. This appears well-known in CSP (e.g., T. März, et al. 2011). It has two disadvantages:
     - It only works face-up, and cannot be used to calibrate instruments that measure mirrors in other orientations.
     - It has virtually zero curvature, and thus cannot be used to assess an instrument's ability to measure curvature – an important aspect for CSP metrology.
  2. We are purchasing a **high-quality concave mirror** produced by a manufacturer of optics made to imaging tolerances. It is a monolithic glass disk 625 mm in diameter and 40 mm thick, with a concave spherical optical surface with a curvature radius R = 200 m, corresponding to a 100 m focal length. We have placed a contract with Cosmo Optics, and delivery is expected sometime this summer.

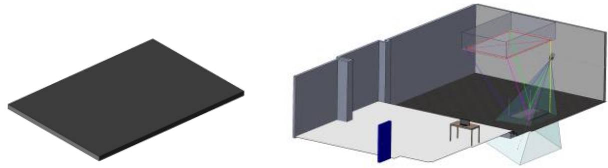
     The returned spot test will be a simple, effective method for checking the mirror.

Plano Water Pool

f = 100 m Calibration Mirror Design



Plano Water Pool Test



Water pool ground truth measurement done on March 8, 2023.

Improvements:

- Better water setup.
- A photogrammetric screen calibration was done the same day.
- No occlusions in field of view of water pool.

Notes:

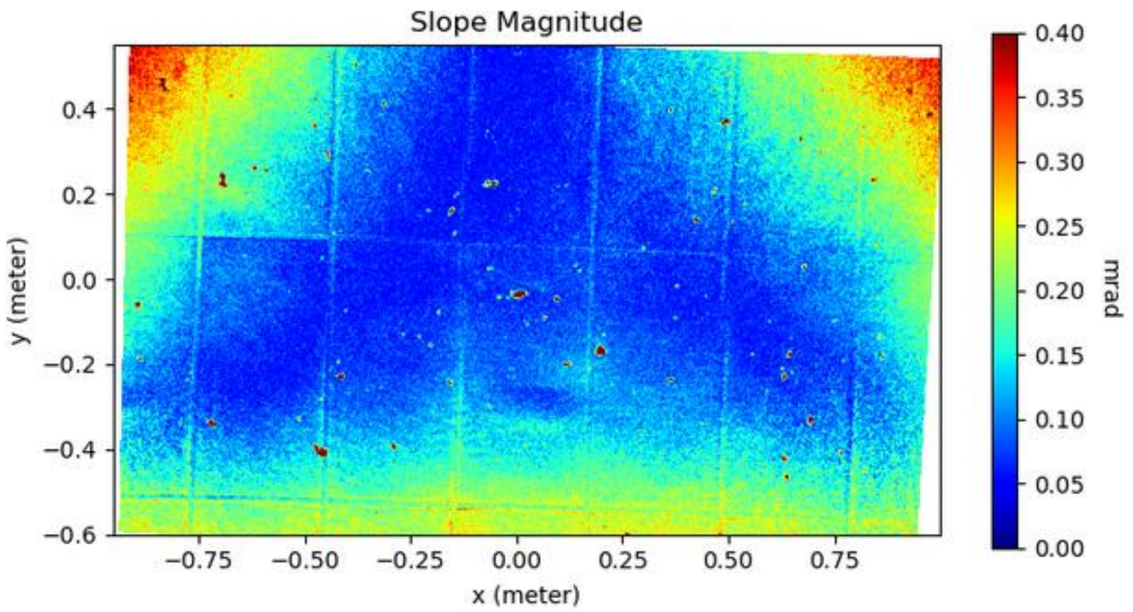
- Calibration parameters were optimized via gradient descent algorithm.
- Fitting equation was constrained to plano surface.

X RMS: 0.131496 mrad

Y RMS: 0.113820 mrad

Magnitude RMS: 0.173914 mrad

Optimized Slope Map



Corner errors of 0.4 mrad are high. Work in progress.

Legal Notice