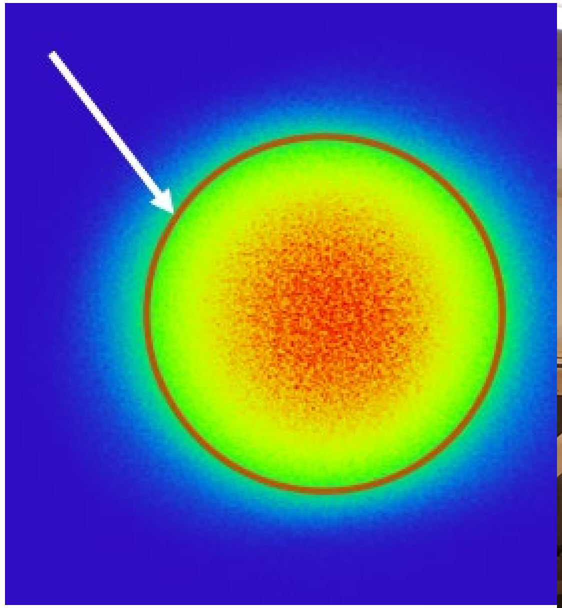
Design and Performance of a Heliostat with a Twisting Mechanism to Maintain Focus Through the Day

THE UNIVERSITY OF ARIZONA

Presentation for SolarPACES 2023



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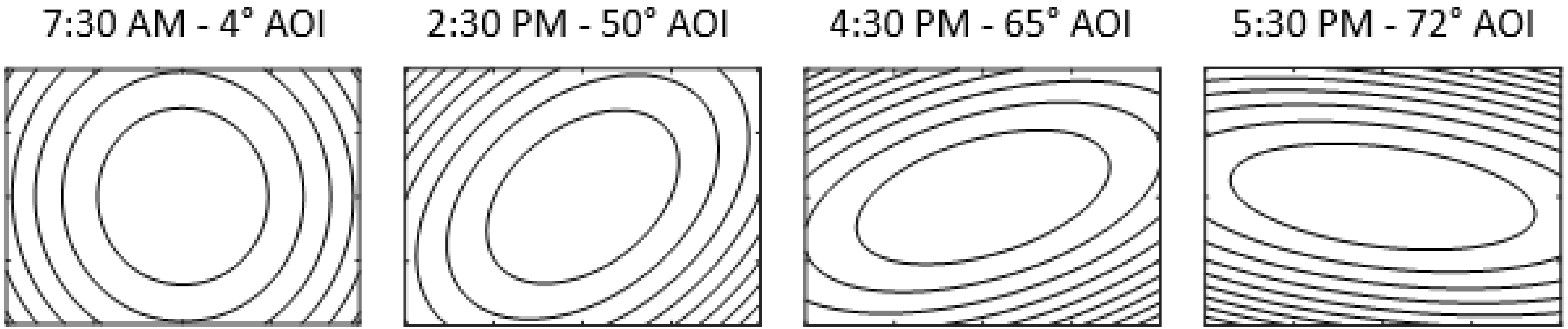
Why focusing heliostats?

- Goal: Store energy at higher temperatures
  - Higher Carnot efficiency
  - Solar industrial process heat (SIPH)
- Need higher concentration at receiver
- Current CSP recipe:
  - Flat heliostats, small compared to receiver
  - Contribution from each one is small
  - Takes ~ 50,000 heliostats to get 500x concentration on the receiver

- Focusing heliostats concentrate sunlight 10-30x depending on focal length
  - Can achieve high concentration/temperature with far fewer
- Can focusing be made simply such that the added cost is low enough to make economic sense?

Maintaining focus throughout the day

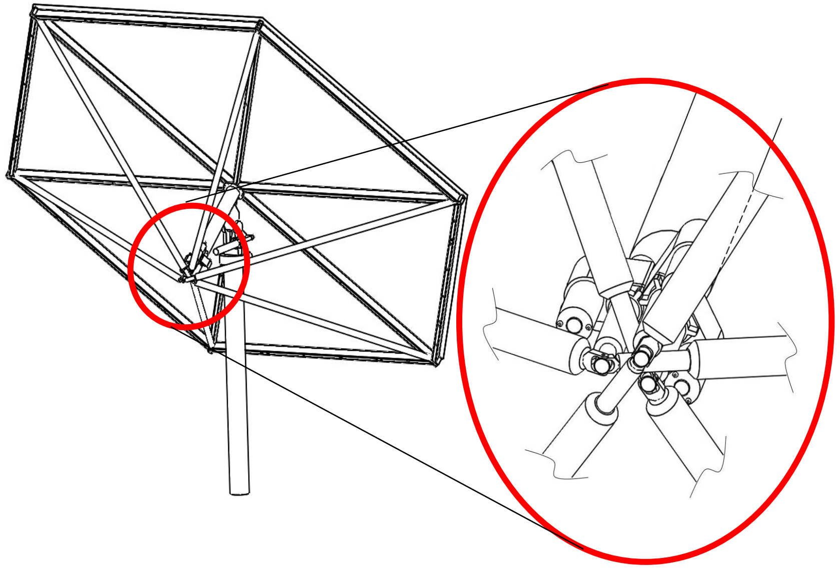
- A fixed concave shape loses focus as the sun moves
- Active shape changing is needed to maintain a focus throughout the course of a day
- Contours below from ray-trace modeling show the different biconic reflector shapes needed from early morning to late afternoon for a representative heliostat

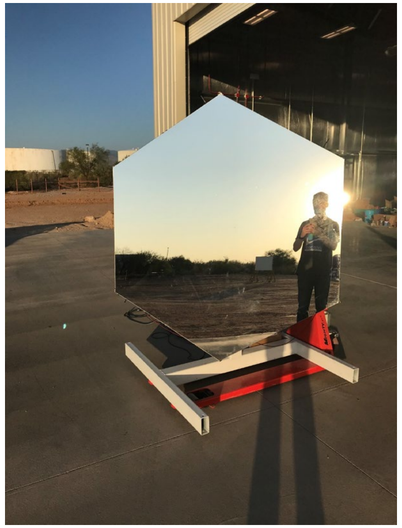


- For heliostat due W of a receiver at 20° elevation, equinox, 33° lat.
- Ellipse axis rotates through the day

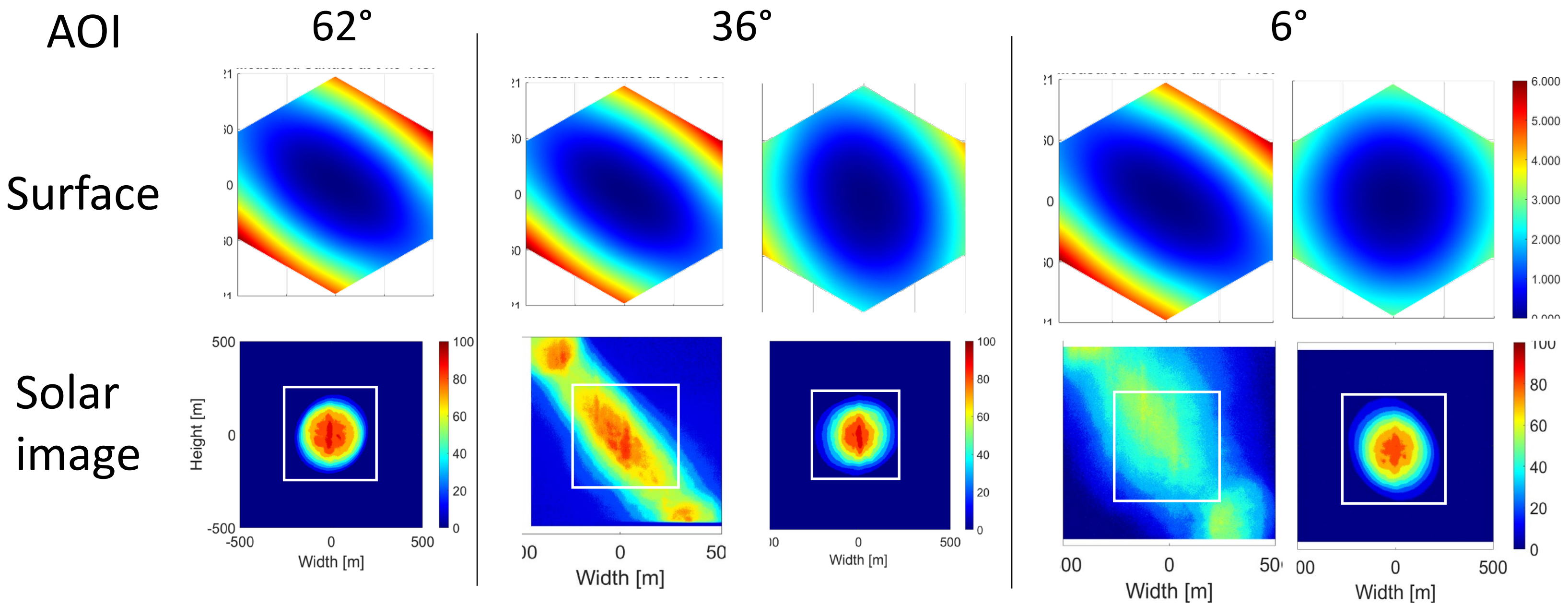
2020 field test with hexagonal heliostat

- Attach reflector panel to frame, set initial shape with support pads
- Connect back struts from corners to central nodes
- 3 computer- controlled actuators to set shape



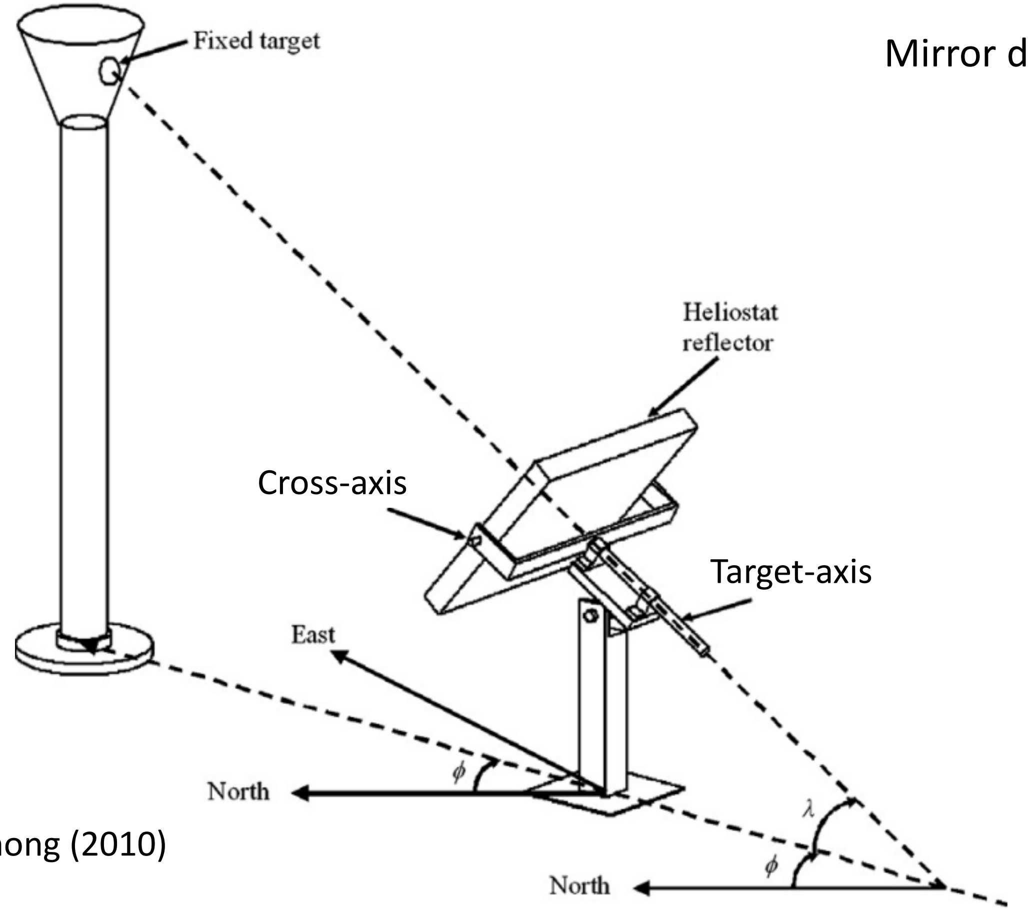


Solar disc image obtained at 2:30 pm, screen 40 m to the East, 62° AOI



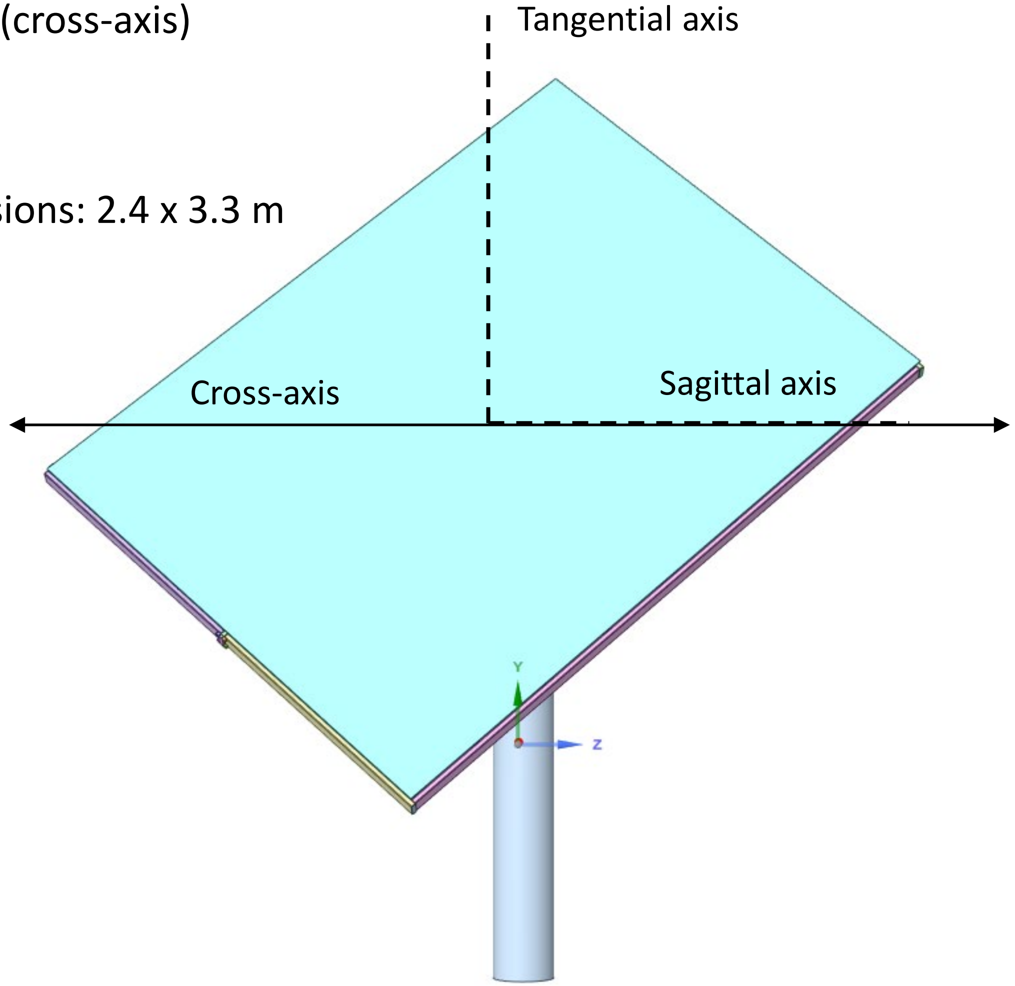
New approach – Target-axis mount

- One axis points to receiver (target-axis), the other runs perpendicular (cross-axis)
- Target axis and solar vector form the plane of incidence
- Mirror is rotated 45 degrees relative to cross-axis

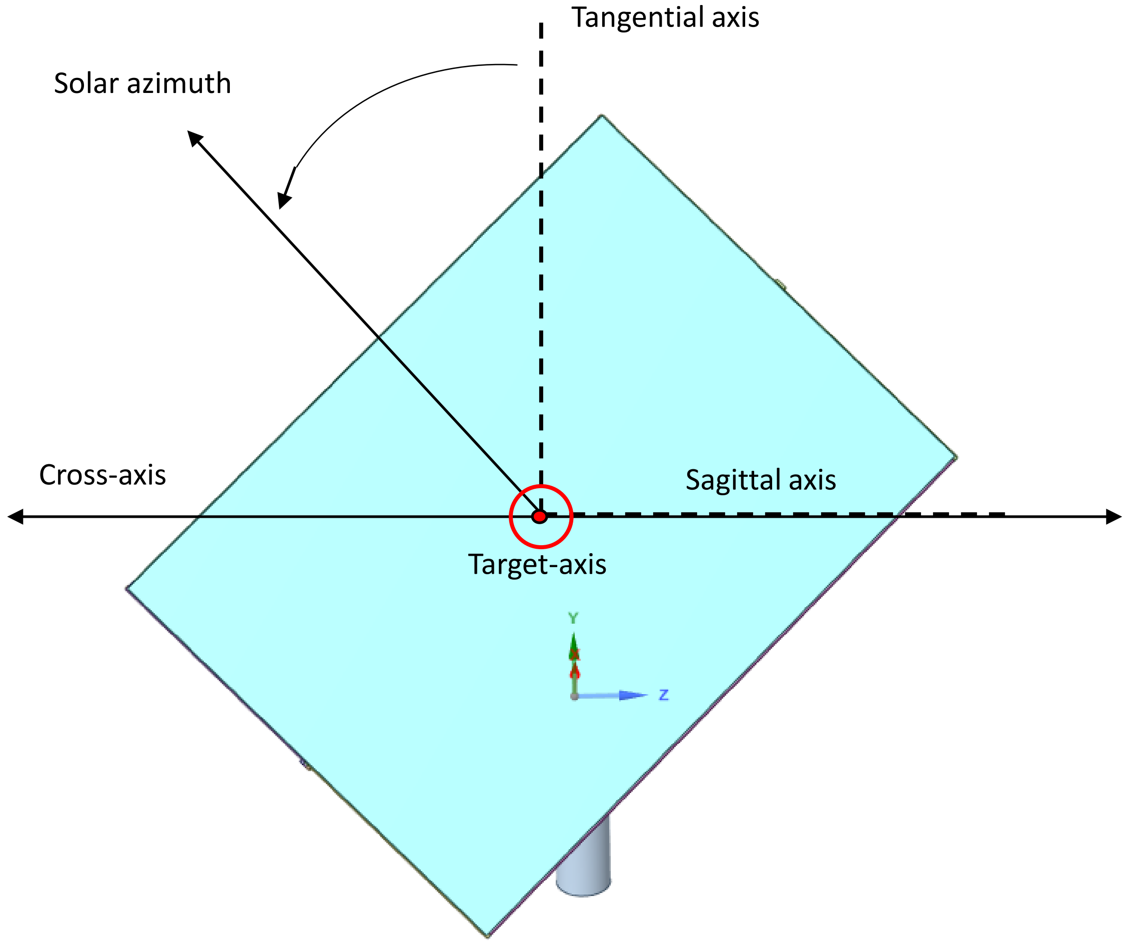


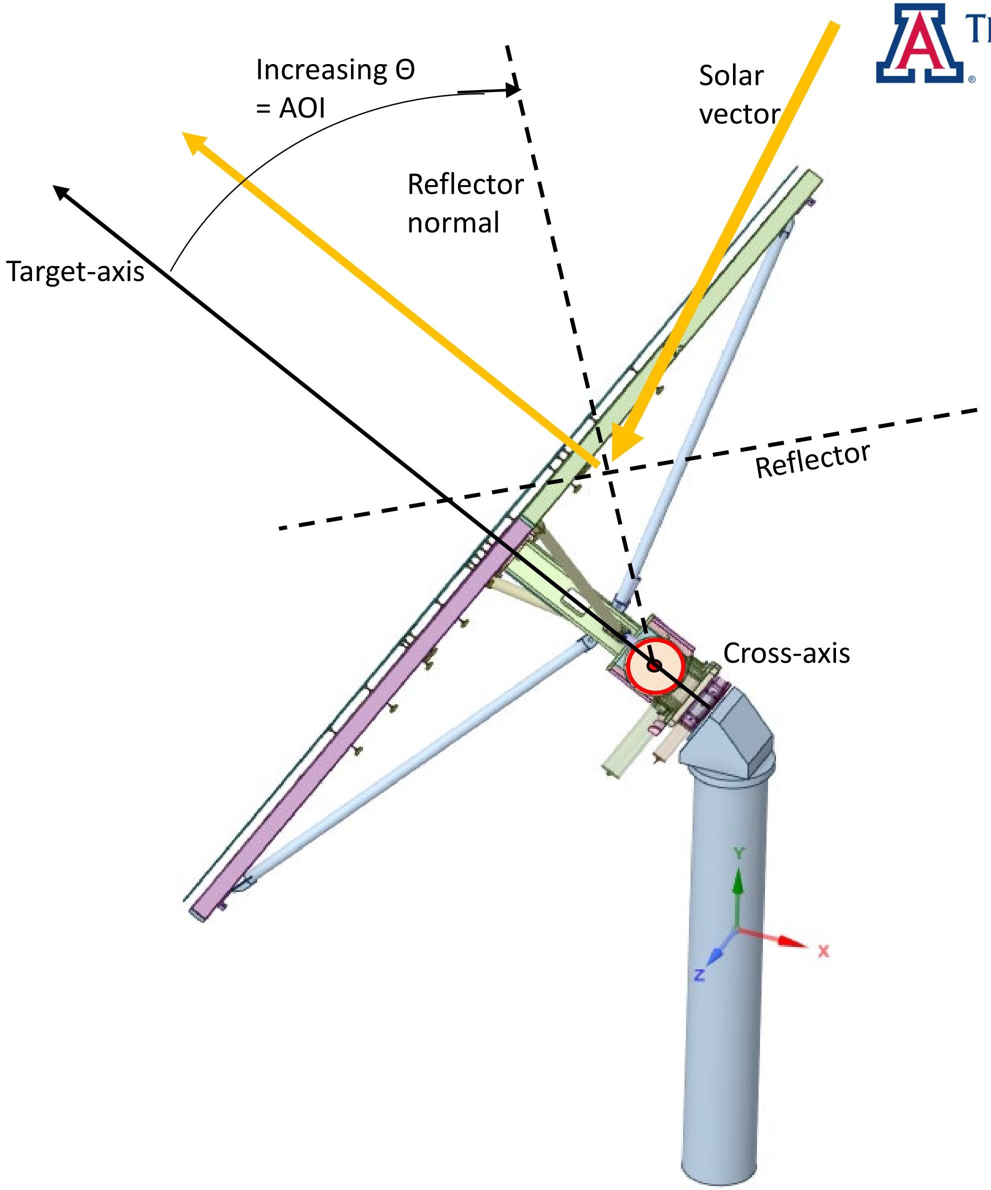
K. K. Chong (2010)

Mirror dimensions: 2.4 x 3.3 m



Pointing

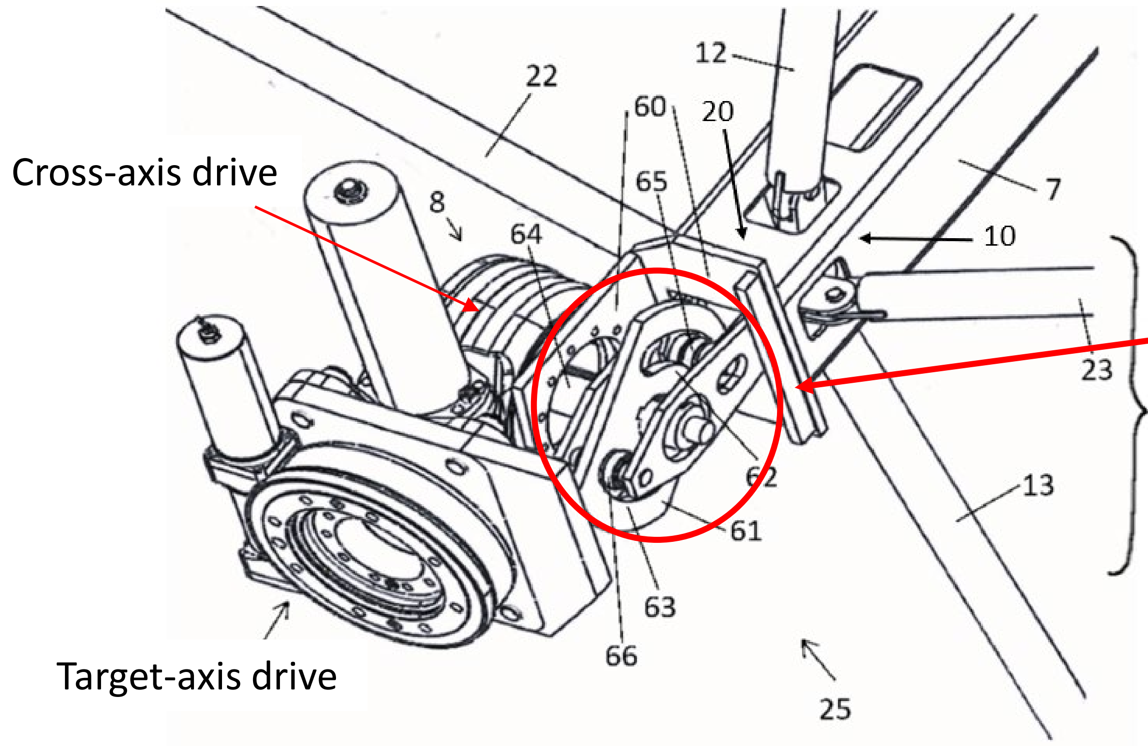




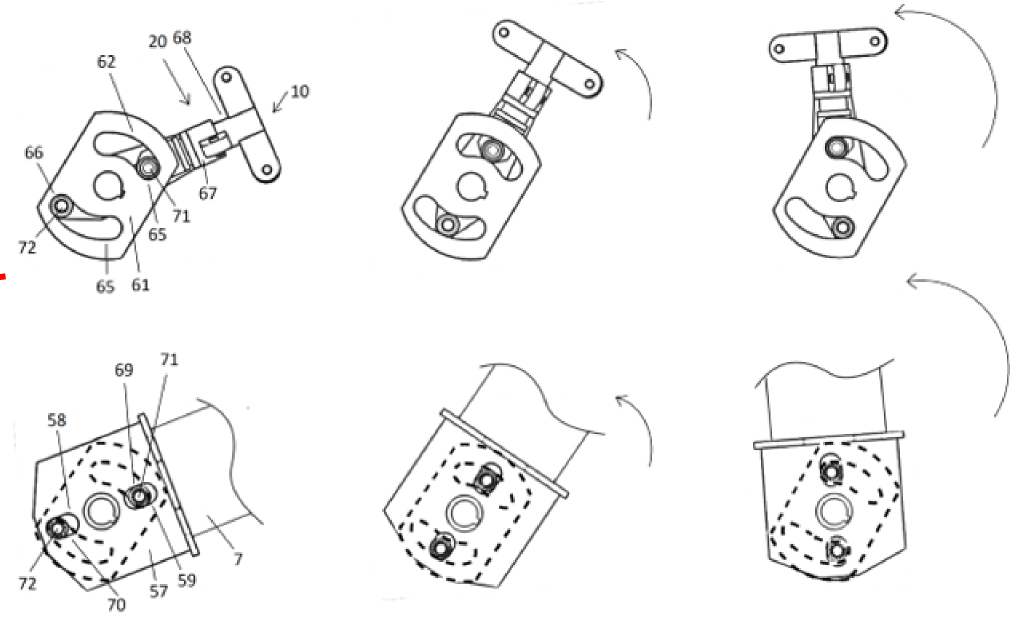
Tangential axis is aligned to plane of incidence

Cross-axis angle = angle of incidence

Passive shape changing – no actuators required



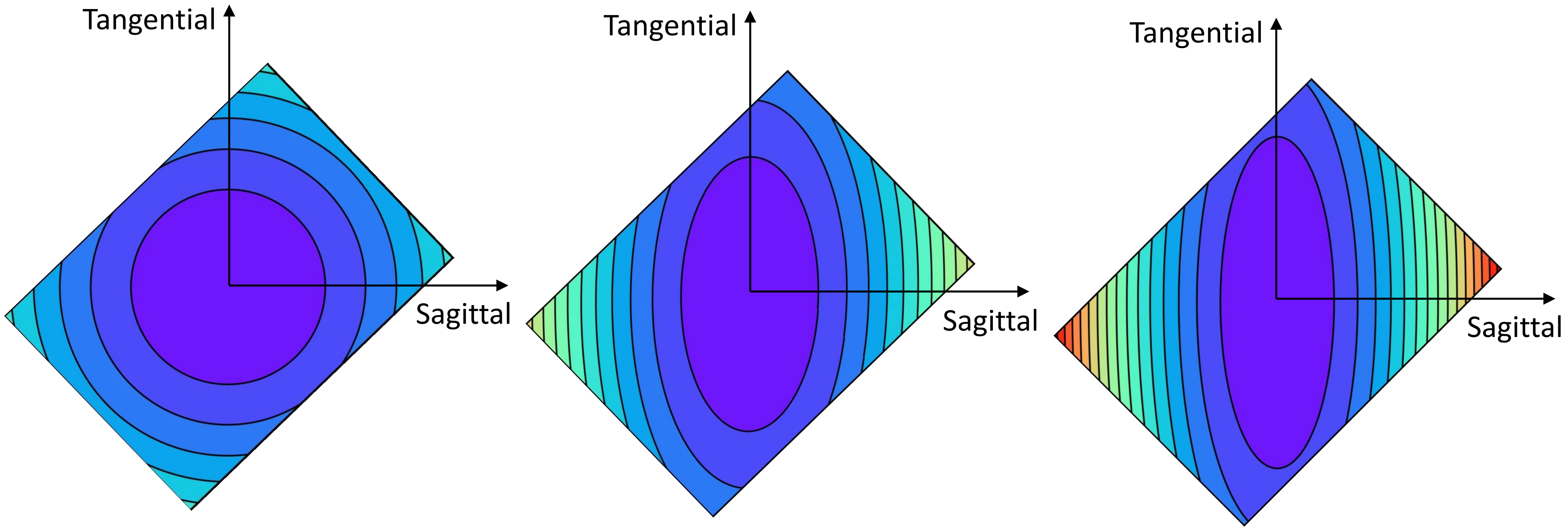
Cam and wheel linkage between cross-axis drive and back struts



Interface plates

Ideal biconic shapes for 113 m focal length

- Biconics are in a fixed orientation on the mirror for target-oriented mount



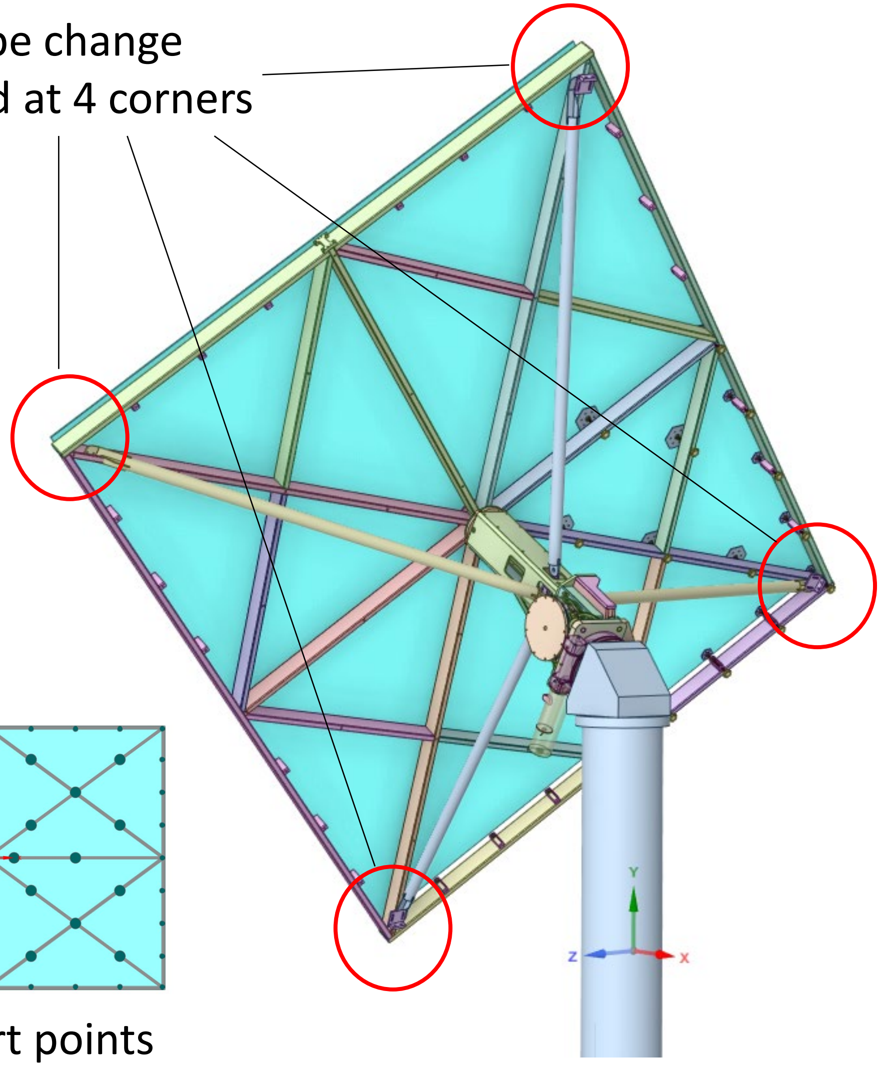
0 degrees AOI

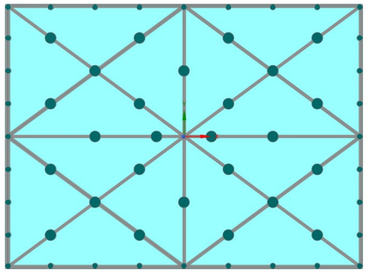
60 degrees AOI

70 degrees AOI

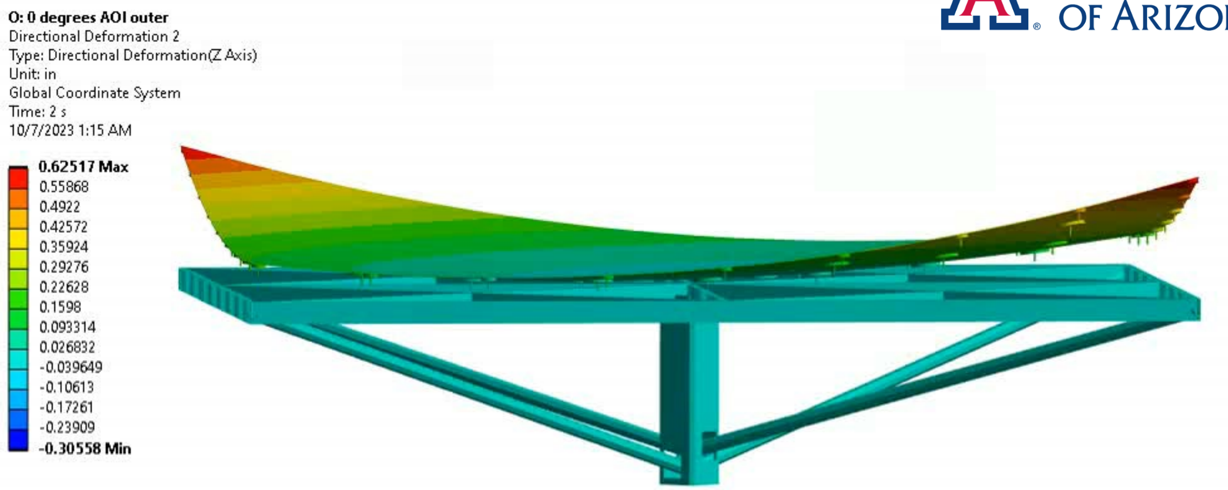
“Twisting” heliostat

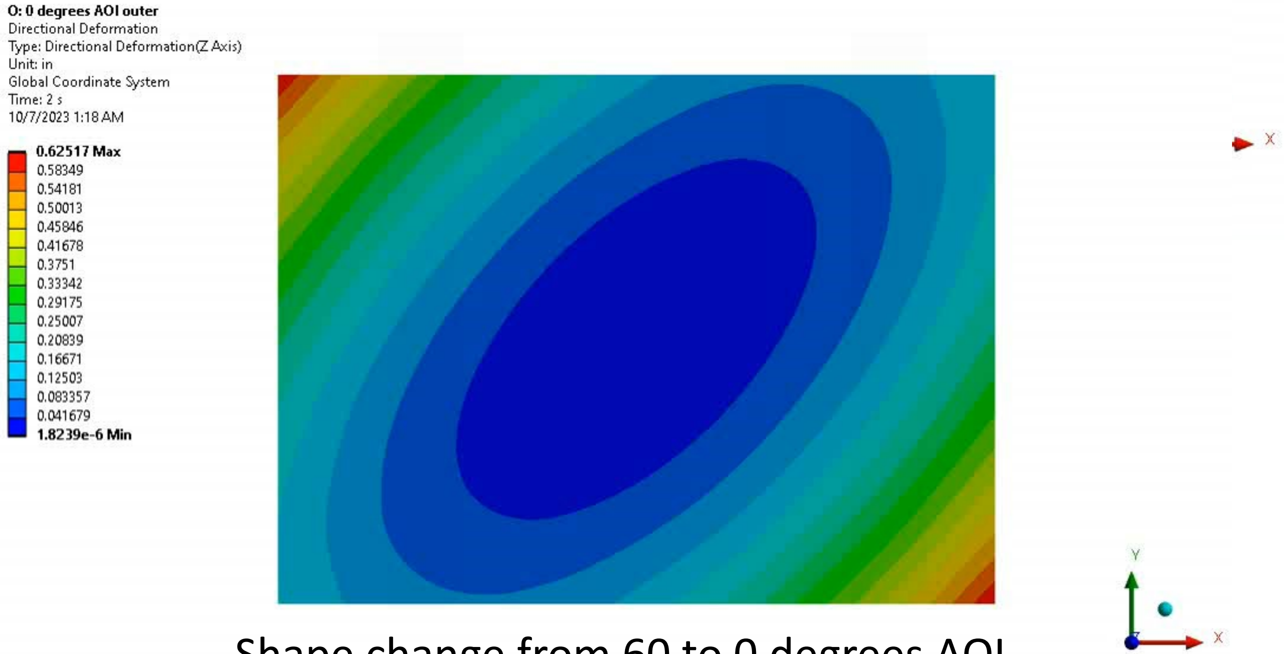
All shape change induced at 4 corners





58 support points



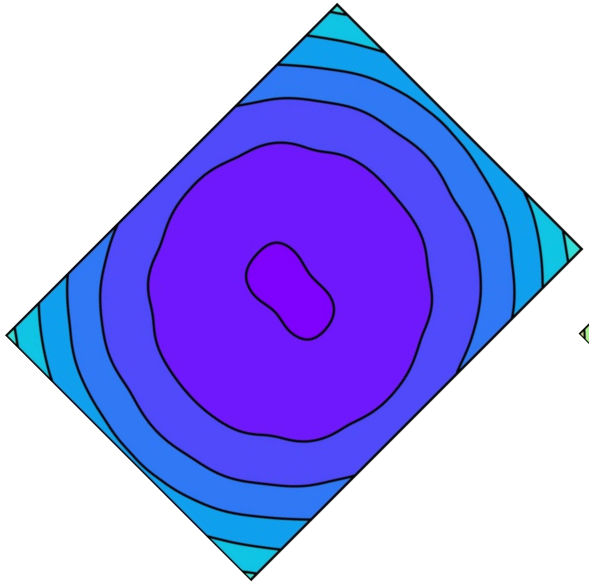


Shape change from 60 to 0 degrees AOI

Modeled performance

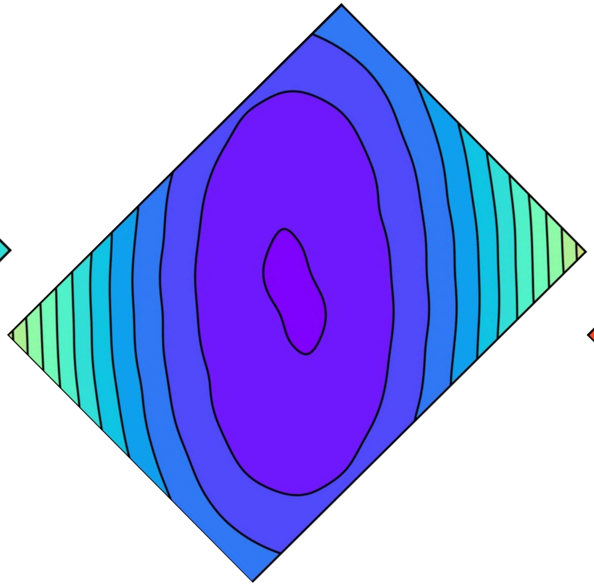
- Twisting, gravity + 11 mph headwind at 30-degree impingement (Peterka 1992, GEC 2003)
- RMS slope error < 0.7 mrad
- Encircled energy in 1 m diameter: 89%

RMS: 0.66 mrad



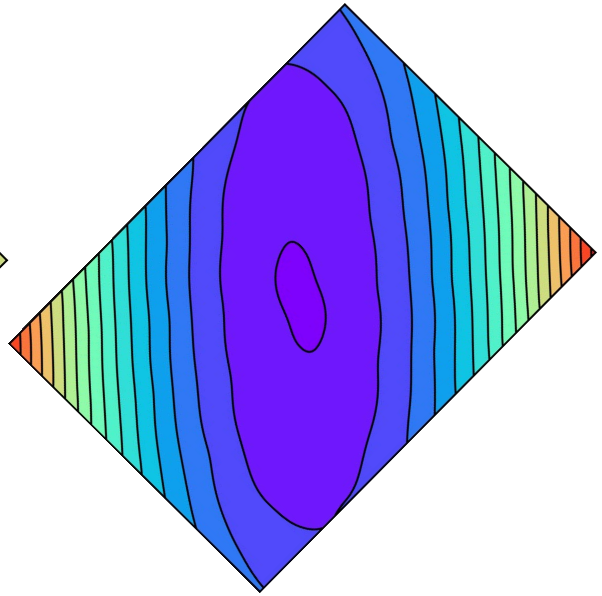
0 deg AOI

RMS: 0.53 mrad



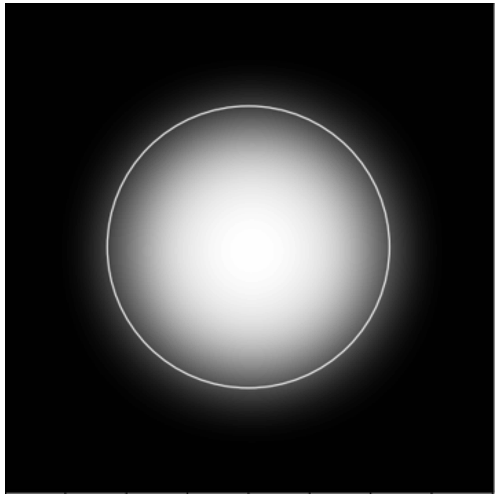
60 deg AOI

RMS: 0.63 mrad



70 deg AOI

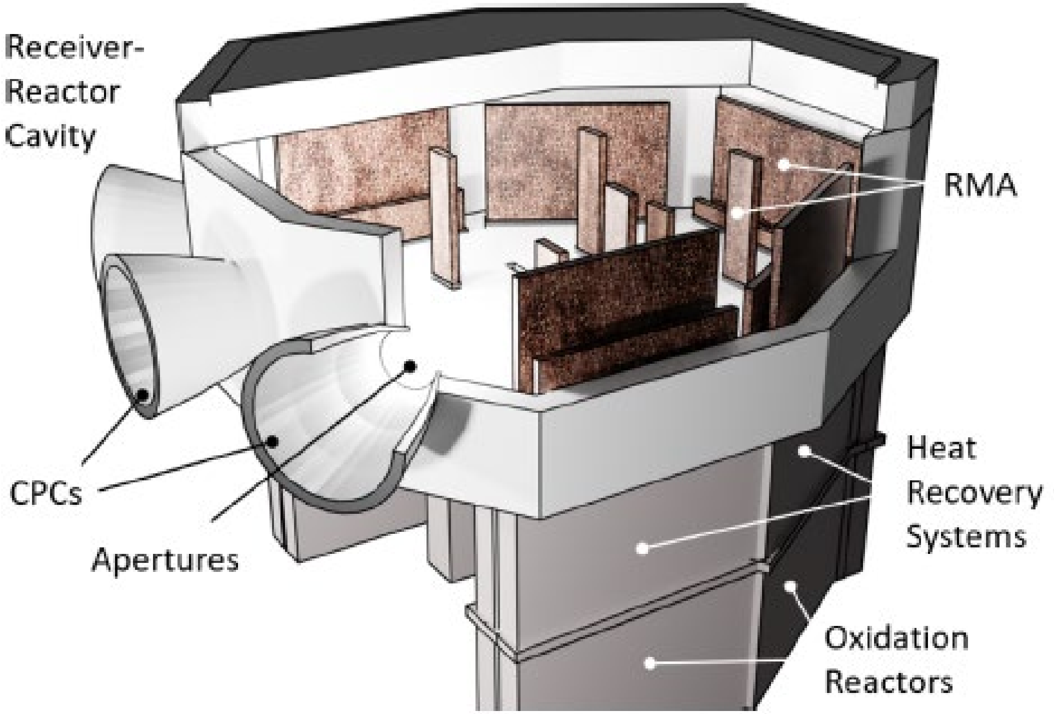
Encircled Energy: 89%



Energy in 1 m diameter circle

Applications

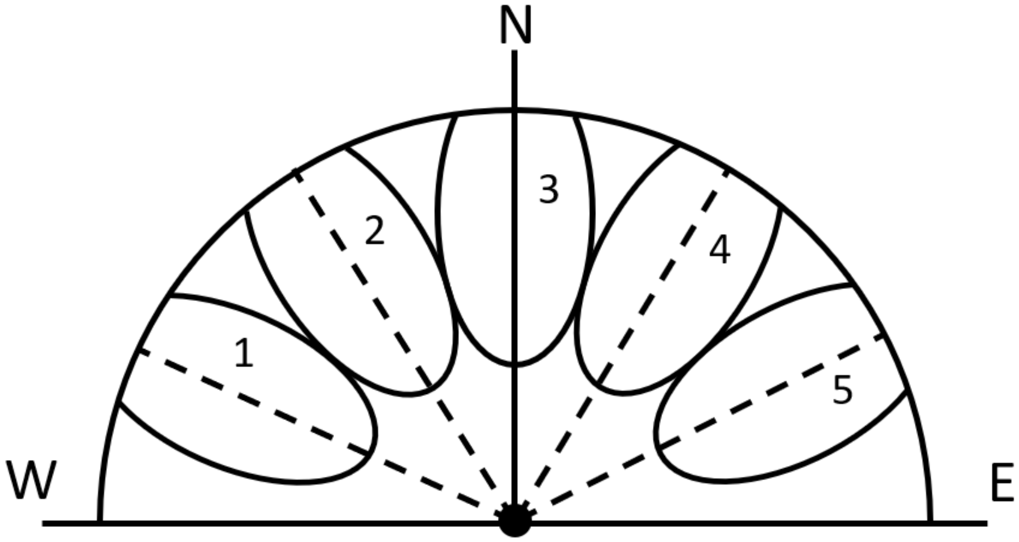
- Traditional surround field
  - 2000 twisting heliostats, 1.2 x 1.2 m receiver, 1700x concentration, 11 MW (R. Angel 2022)
- Solar industrial process heat (SIPH) requiring T > 1000°C
- Examples: Making cement from lime and thermochemical water splitting
- Temperatures of ~ 1500 C require concentrations ~3000x
- Can be reached through the day by a field of twisting heliostats feeding CPCs (Compound parabolic concentrators)



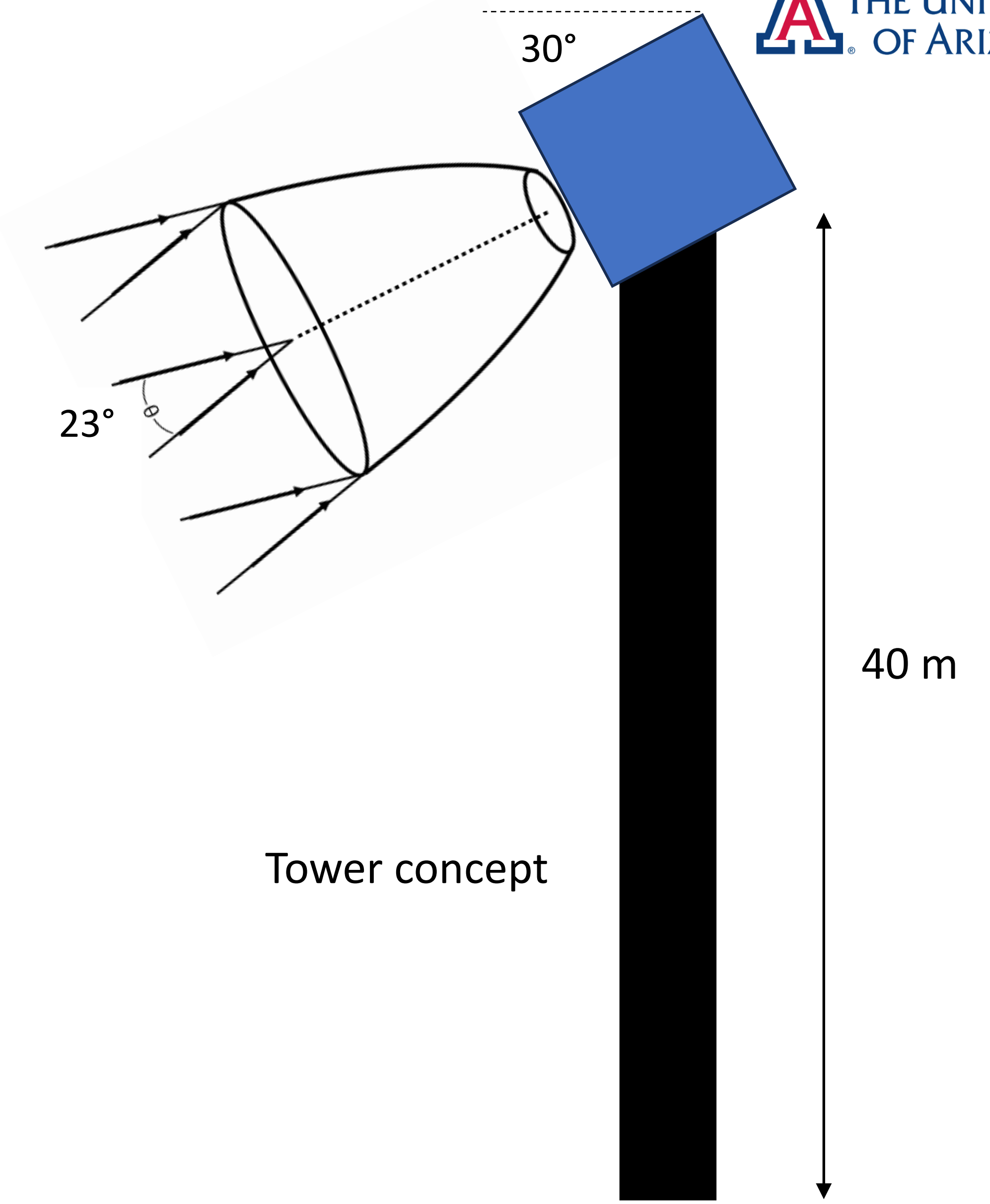
Brendelberger et al. (2022)

CPC tower/field concept

- CPC entrance pupil: 1 m
- CPC concentration: 10x
- 5 CPCs accepting light from 5 groups of heliostats



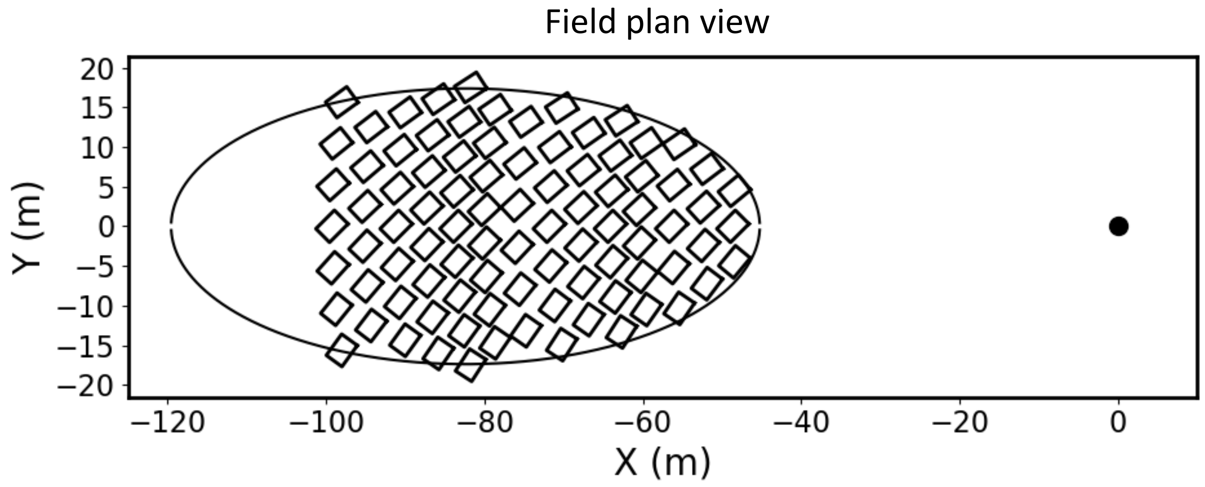
Field concept

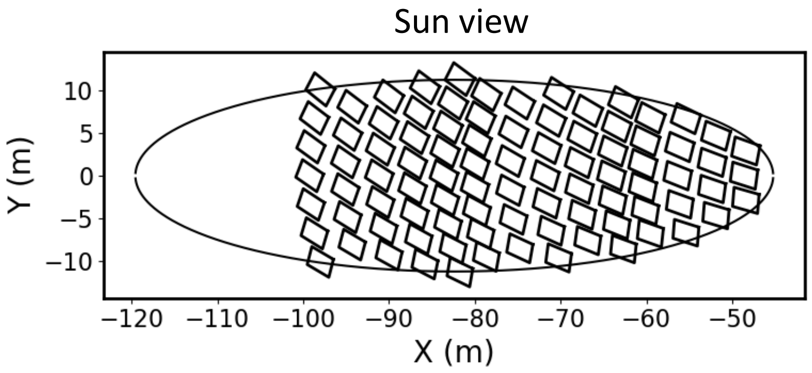


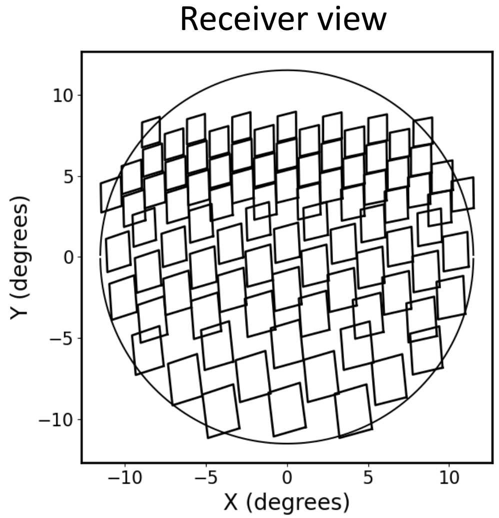
Tower concept

Heliostat layout and field throughput

- 90 heliostats
- Total ground area: 1600 m^2
- Total heliostat area: 720 m^2
- Spaced 45 – 100 m from tower
- Focal lengths: 70 – 110 m
- Avg cosine factor: 0.8
- Avg shadowing/blocking: 9%
- **Geometric throughput: 73%**







Total optical throughput and concentration

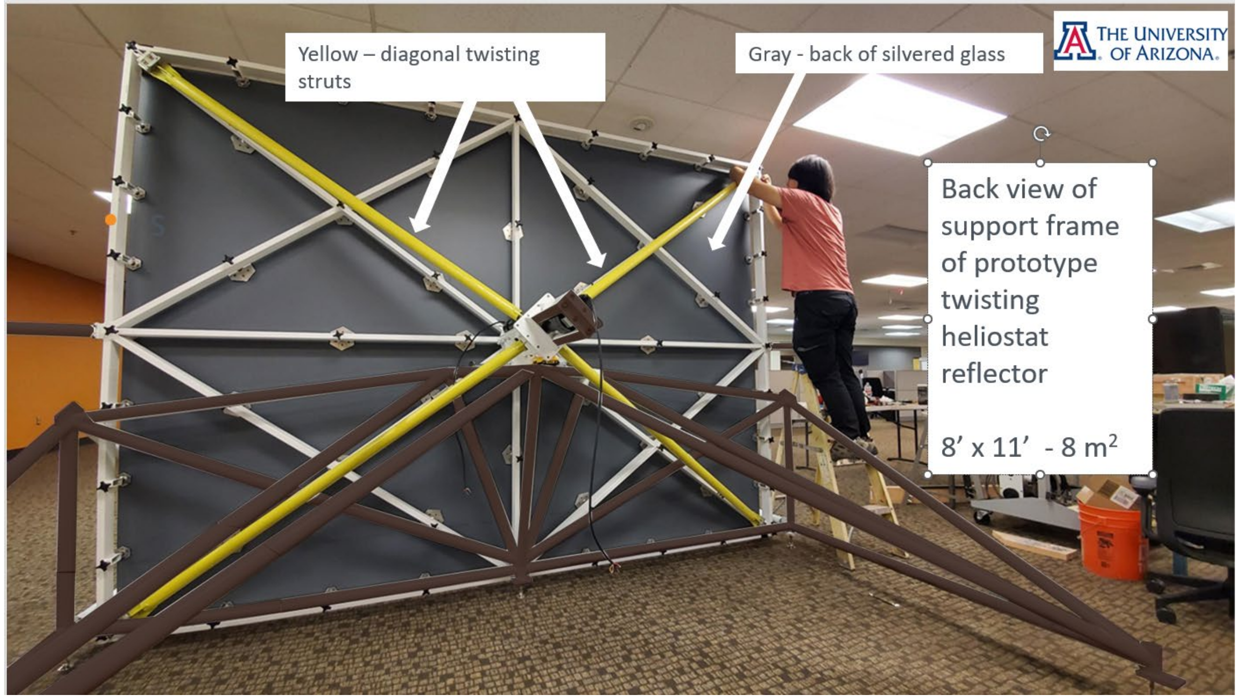
Throughput source	Fraction
Spillage	0.89
Geometric throughput	0.73
Heliostat reflectivity	0.9
CPC reflectivity	0.9
CPC window transmission	0.9
Solar concentration calculation	
Total throughput (fraction of heliostat area)	0.47
Total heliostat area	720 m^2
Effective area of sunlight	341 m^2
CPC entrance pupil area	0.79 m^2
CPC concentration	10x
Total solar concentration	**4316x**

Design/analysis summary

- Individual twisting heliostat
  - Shape changing is passive – no actuators required
  - Finite element analysis shows an individual heliostat can be shaped to <0.7 mrad RMS slope accuracy in the field
- Field design with CPCs
  - 450 heliostats, 3600 m^2 total mirror area
  - 1.6 MW into receiver
  - Twisting heliostat field and CPC can deliver solar concentrations > 4000x with CPC

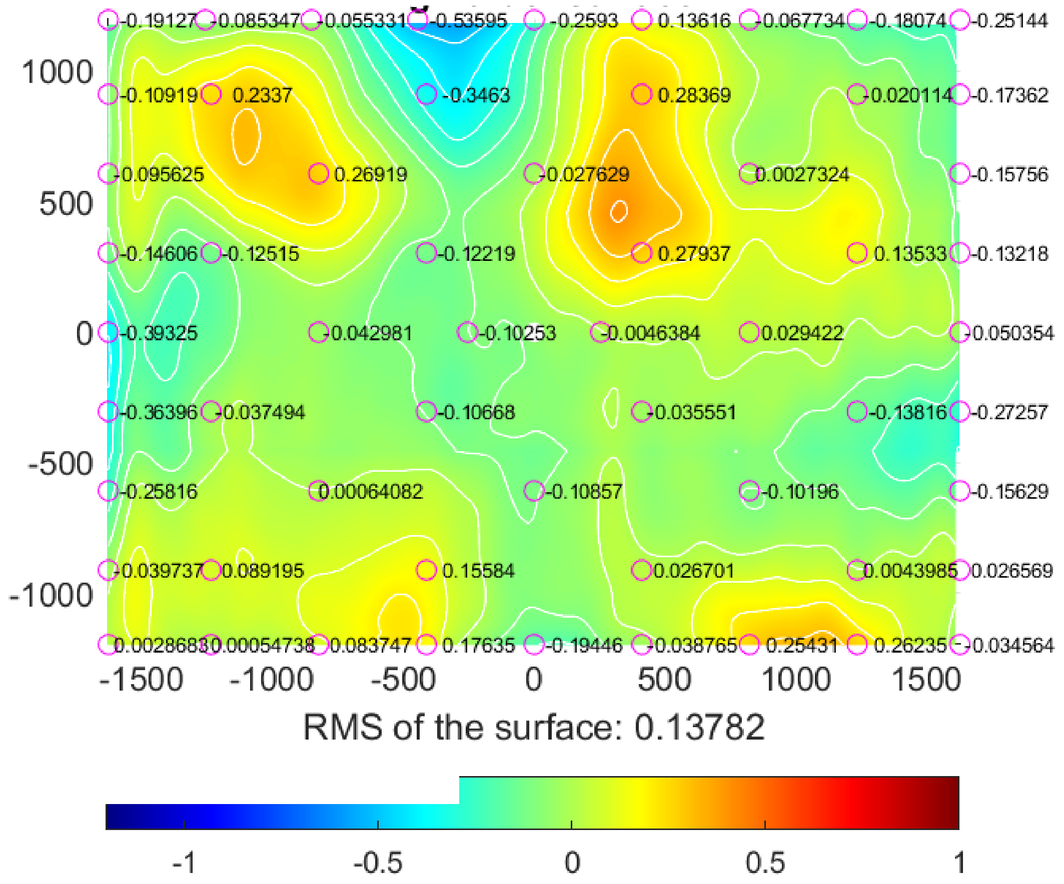
Prototype construction and metrology

- current status



Measured surface shape of 3.3 x 2.4 m reflector

- Surface set by adjusting 58 points for
  - 113 m focal length
  - Biconic needed for 60° AOI
- Contour map, measured by reflectometry with 1 in. spatial resolution, shows departure from ideal biconic shape
- Surface error is 140 μm rms
- Same surface error when twisted to 0° AOI

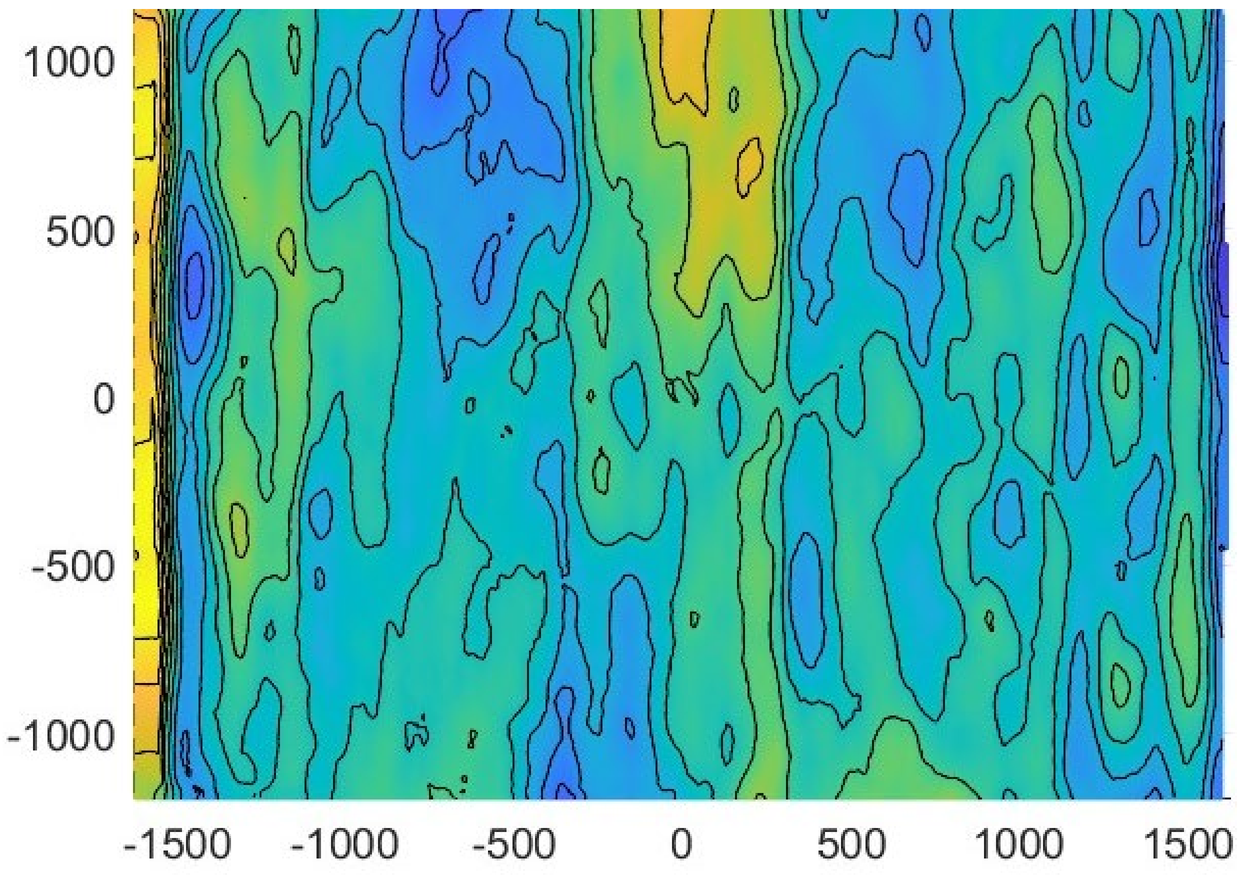


Slope errors of the same reflector

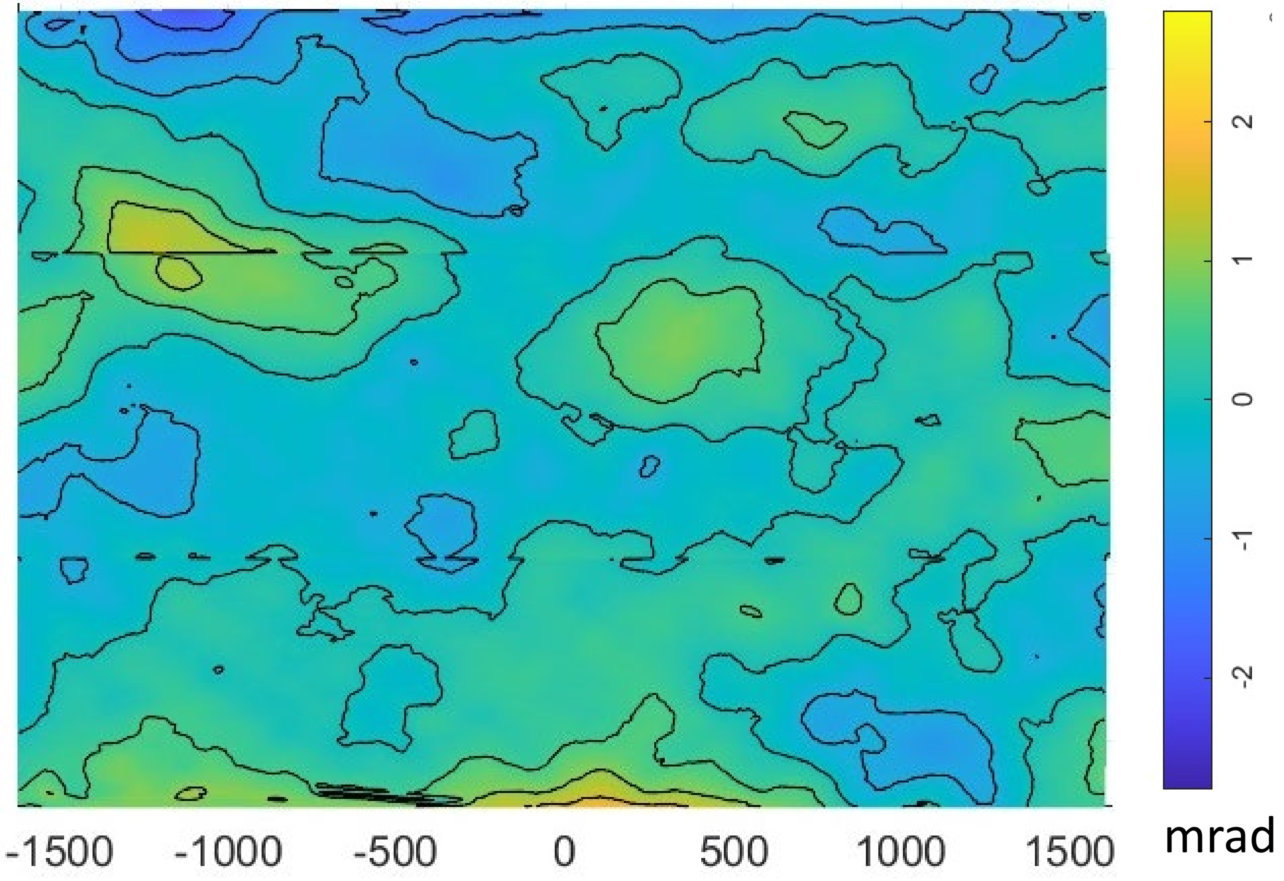
– departure from fitted biconic surface

y slope accuracy limited by adjustment accuracy to 0.41 mrad rms

x slope shows added vertical ripples of 0.52 mrad rms from float glass manufacture

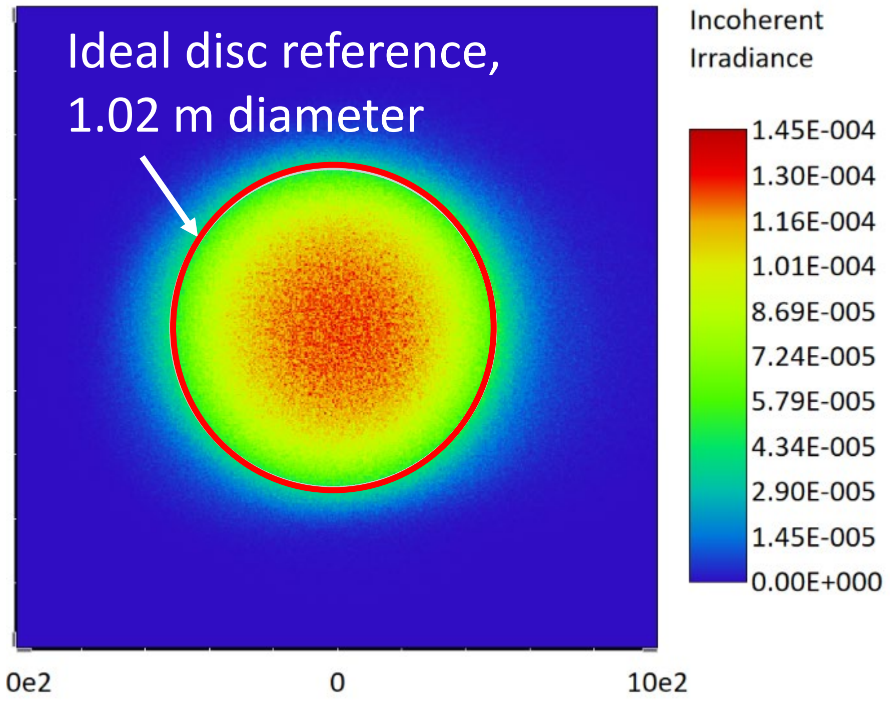


x slope 0.66 mrad rms

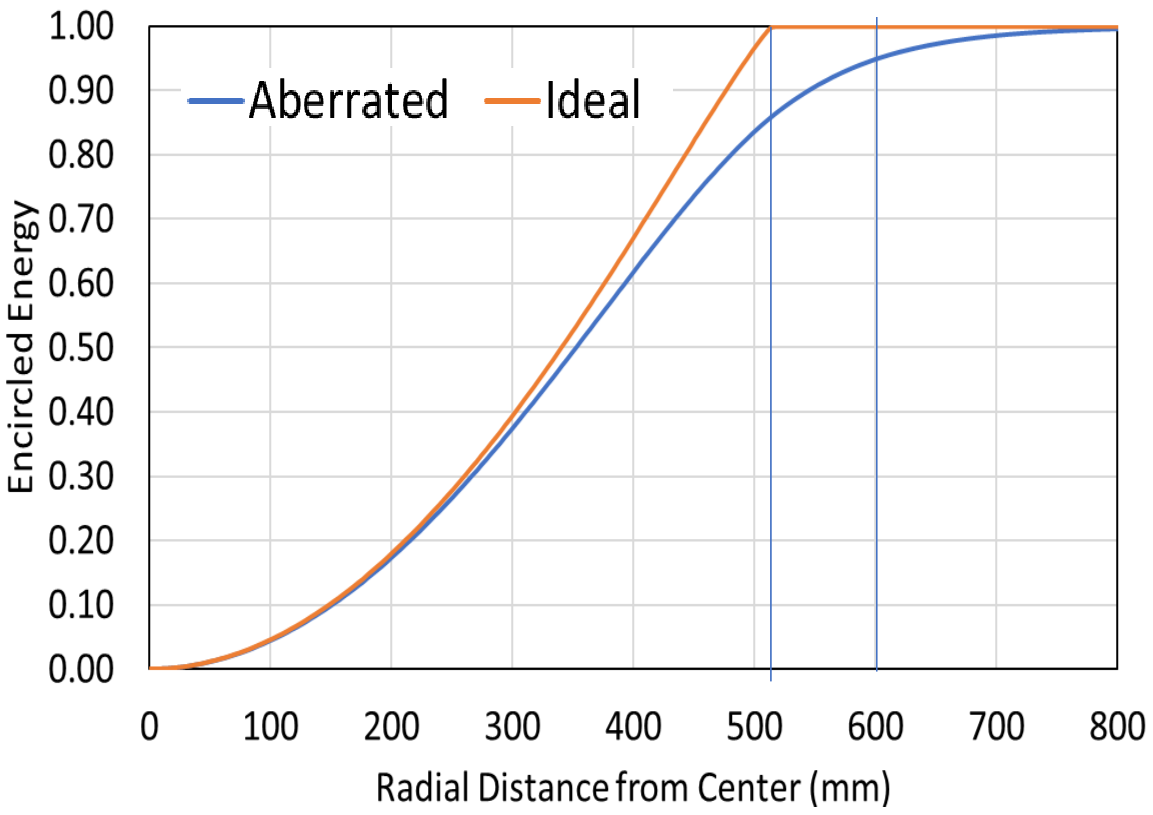


y slope 0.41 mrad rms

Disc image calculated for measured surface



- Image at 113 m focal distance



- Encircled energy
  - 86% in ideal 1.02 m dia.
  - 95% in 1.2 m diameter

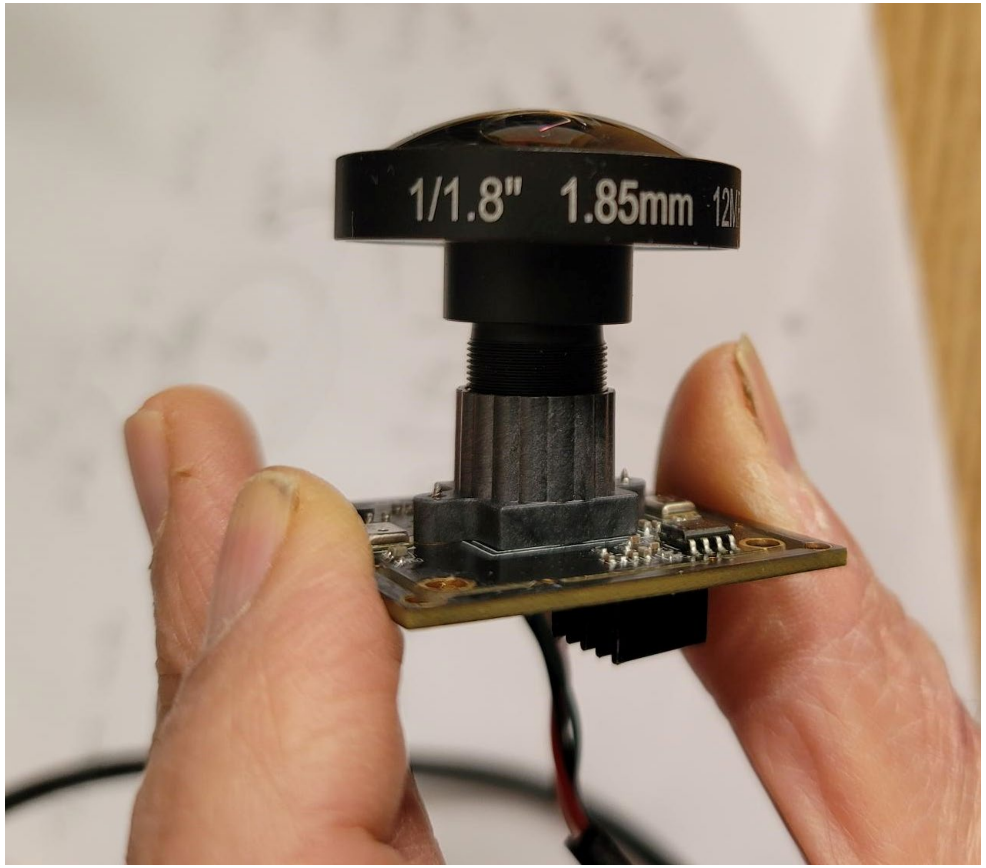
Next steps/Acknowledgements

- Next steps
  - Complete tracker assembly, and mechanical coupling mechanism
  - On sun testing at University of Arizona Tech Park
  - Test prototype at Sandia National Labs NSTTF with Co-I Randy Brost
- US Department of Energy
  - Small Innovative Projects in Solar (SIPS)
  - HelioCon

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

Closed-loop tracking

- Wide angle camera mounted behind glass with center section of silvering removed
- Camera to be rigidly attached in fixed position relative to mirror normal and tangential axis
- Views simultaneously the sun and a distant LED source at fixed location
- Control loop uses observed positions of the LED source and sun



Fatigue life analysis

- Based on published Weibull statistics for float glass (Pisano 2015) and subcritical crack growth mechanics
- Annual wind speed distribution from Lee Ranch, NM, USA (GEC 2003)
- Wind loads calculated by Peterka 1992
- Computed mirrors stresses vs wind speed for worst case load configuration
  - 30-degree impingement up to 50 mph, stow position up to 90 mph
  - Inner row heliostat at 70-degree AOI bending

Survival probability ~ 90% after 30 years