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

Using an equivalent slope error to quantify beam errors of heliostats

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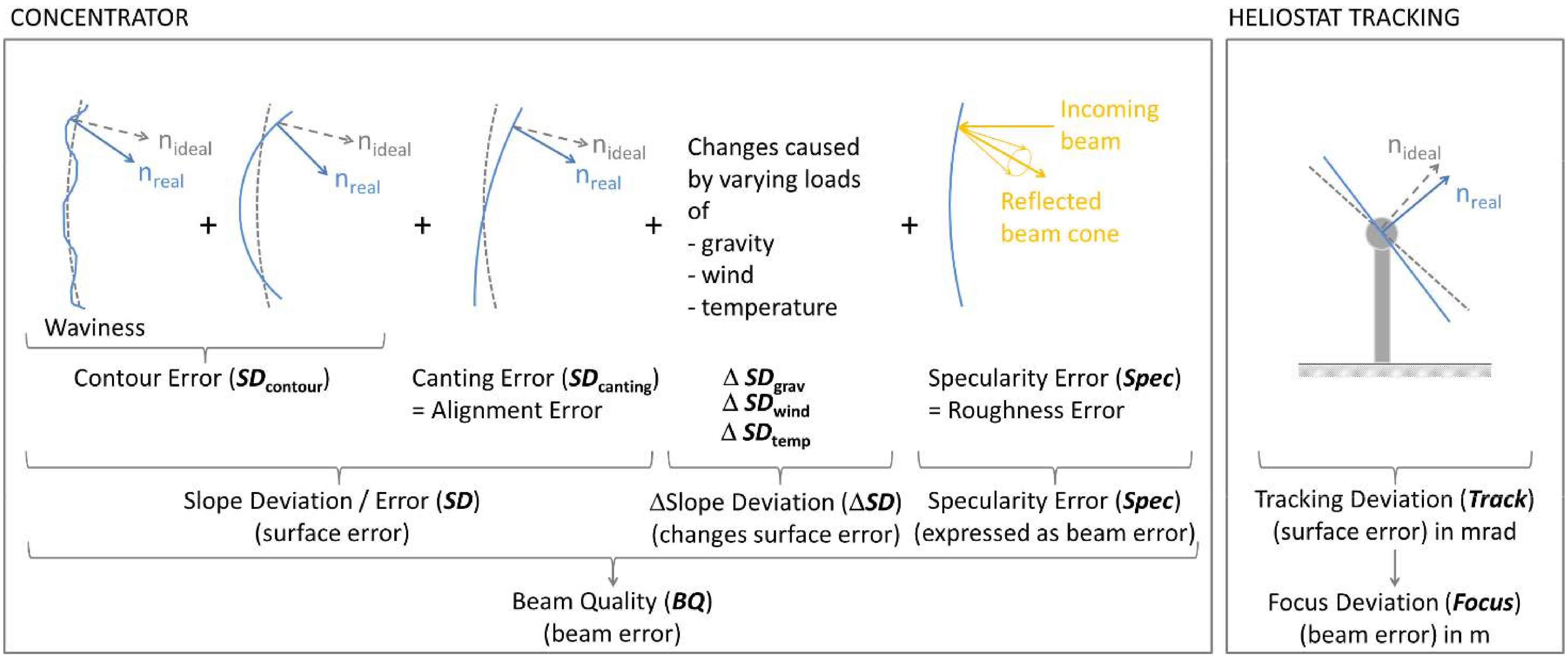
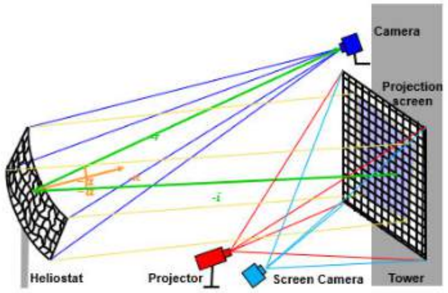
Types of beam errors

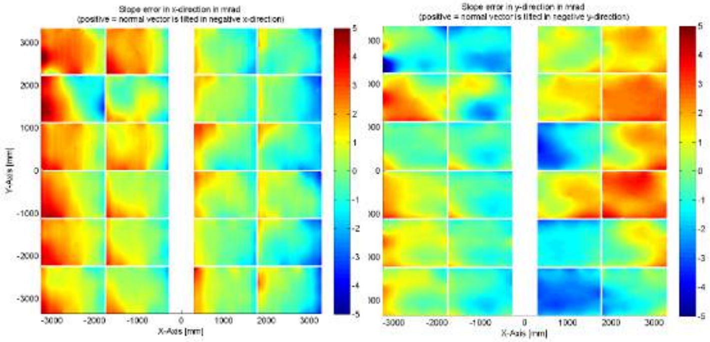


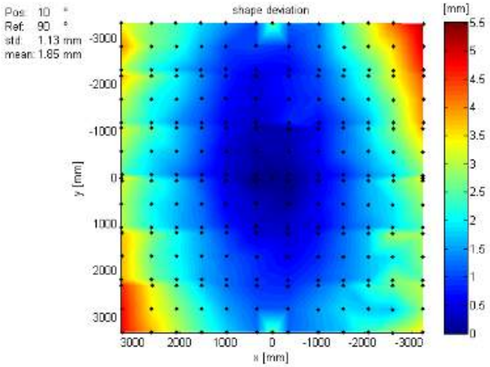
Roger et al, 2023. SolarPACES Guidline for Heliostat Performance Testing

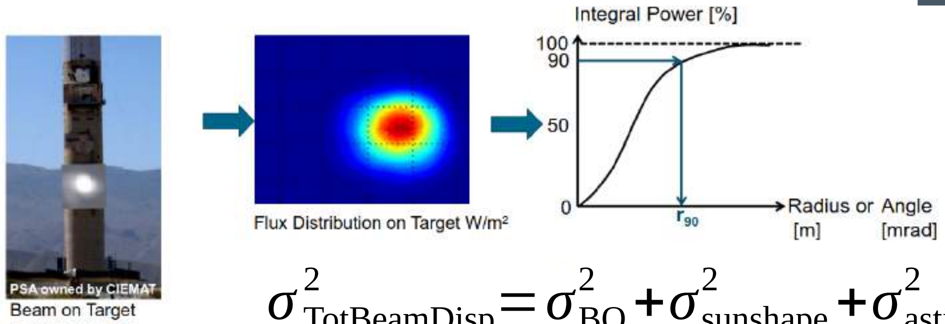
Measurement Method

- Indirect method: flux mapping by a beam characterisation system (BCS)
- Direct method: deflectometry, photogrammetry, laser radar
  → slope deviation matrices in relation to ideal shape

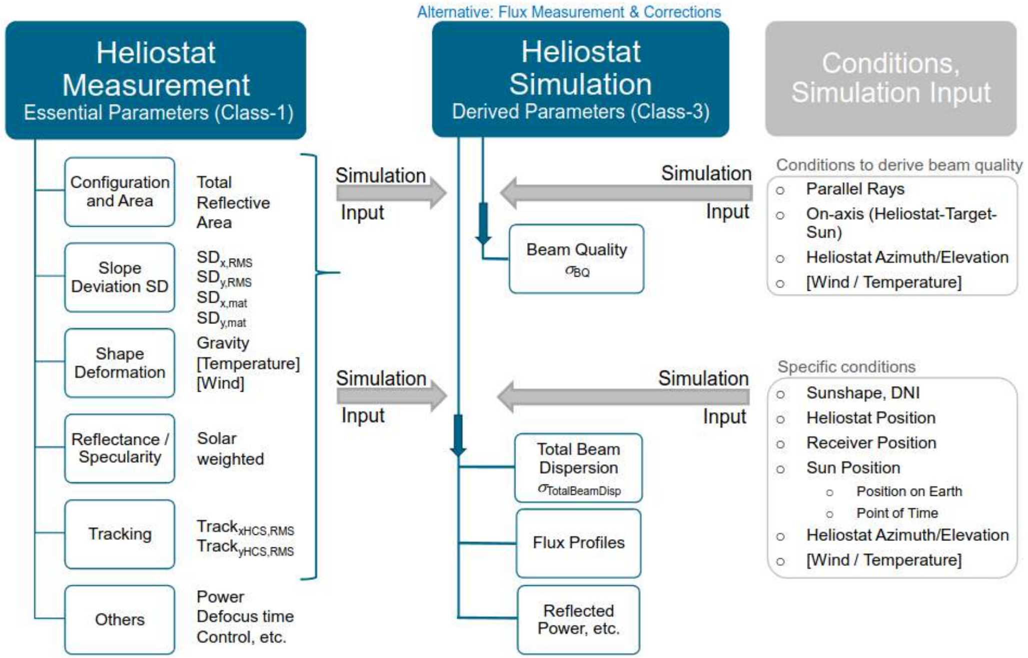






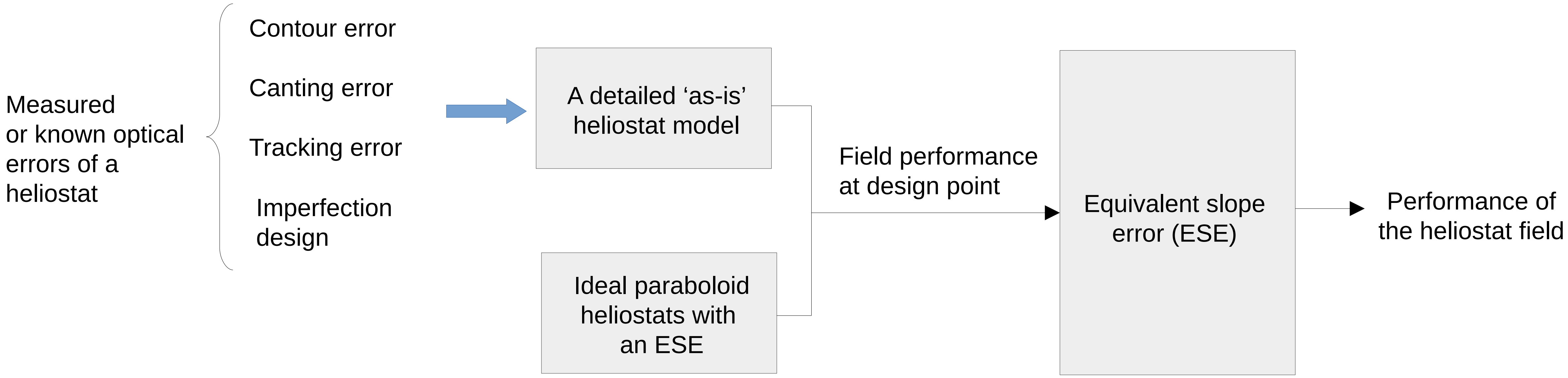


$$\sigma^2_{TotBeamDisp} = \sigma^2_{BQ} + \sigma^2_{sunshape} + \sigma^2_{astigm}$$



Objectives

- Establish the interface between measured data and optical simulations
- Convert measured optical errors into an equivalent model for whole field and annual performance analysis

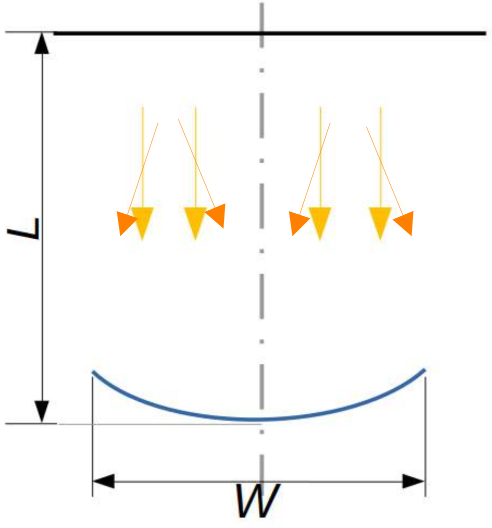


Benefits of using an equivalent slope error:

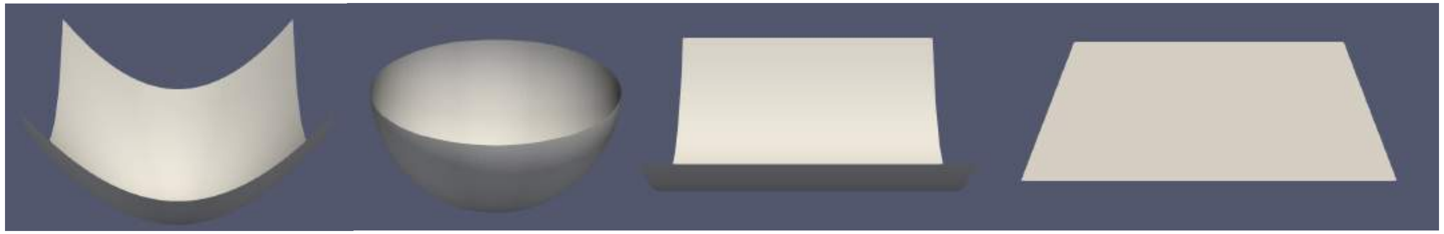
- A straightforward way to quantify beam quality
- A consistent way to compare the magnitude of different types of beam errors.
- Applicable using flux mapping or BCS data
- Easy to implement in ray-tracing simulations to perform heliostat field design, O&M planning, and annual performance analysis.

Method

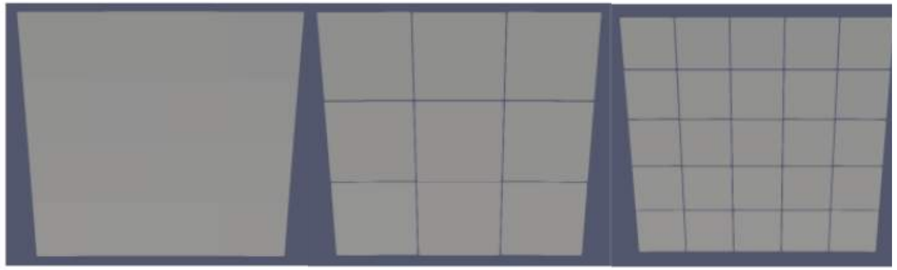
- On-axis arrangement: no astigmatism error
- Perfect surface features: 0 slope error, 100% reflectivity
- Irradiation source
  - Collimated rays
  - Buie sunshape 2%



- Four reflector shapes
  - Paraboloid
  - Sphere
  - Parabolic-cylinder
  - Flat



- Different heliostat design
  - Single facet
  - 3×3
  - 5×5



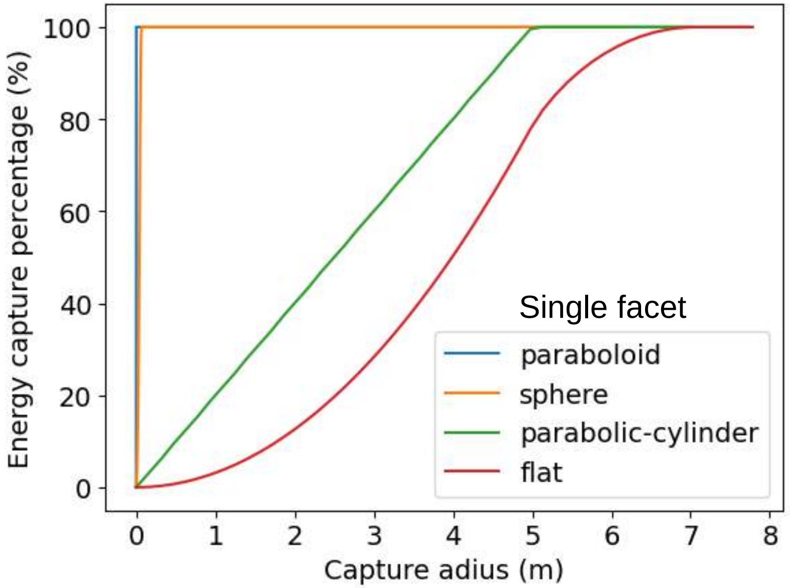
- Energy capture percentage

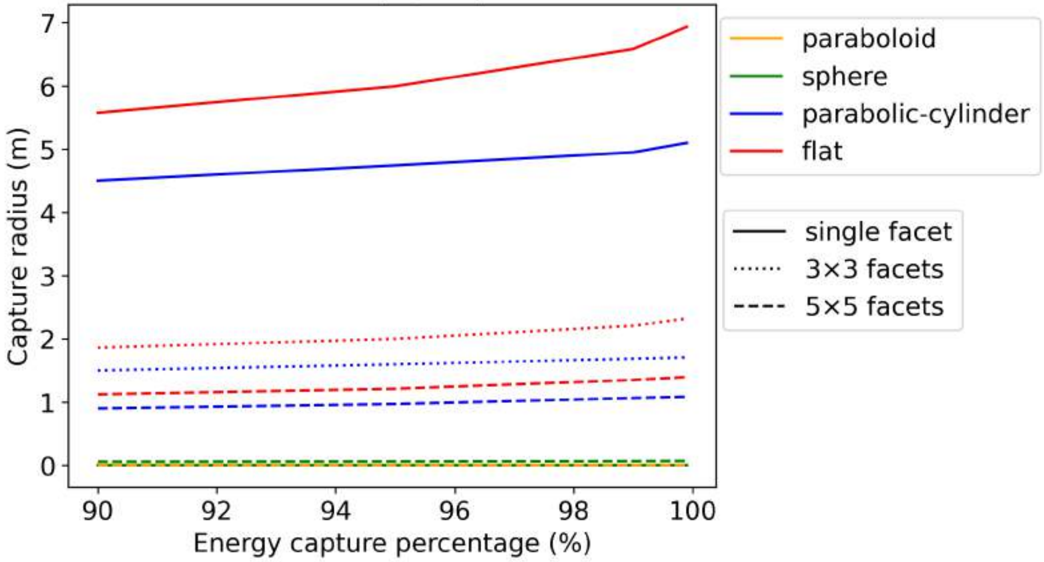
$$\psi = \frac{\sum q_{i,\text{abs}} A_i}{Q_{\text{abs}} + Q_{\text{spillage}}}$$

- Different slant range distances: 100, 500, 1000m

Collimated rays, ideal case

Reflectors in 12 configurations, 0 surface, 0 slope error, on-axis arrangement, ideally focused



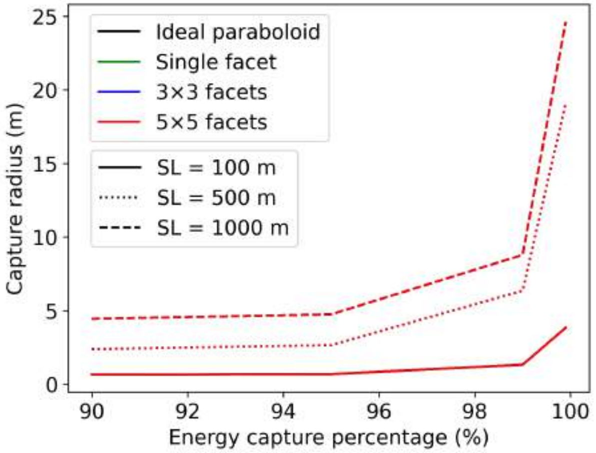


- Without sunshape and surface slope errors, the beam shape remains unchanged across different slant (SL) ranges.
- A spherical reflector with a radius of curvature (ROC) twice the SL range provides the same concentration ratio as an ideal paraboloid reflector.
- A single-facet parabolic-cylindrical reflector offers a line focus feature and performs better than a flat single-facet reflector.
- Using multiple ideally canted facets by the slant range significantly increases the concentration ratio for both flat and parabolic-cylindrical facets.
- More canted facets result in better concentration because the overall shape of the collector more closely resembles a paraboloid.
- Ideally canted 5x5 flat facets can reduce the capture radius from 5–6m to around 1m, comparable to parabolic-cylindrical facets.

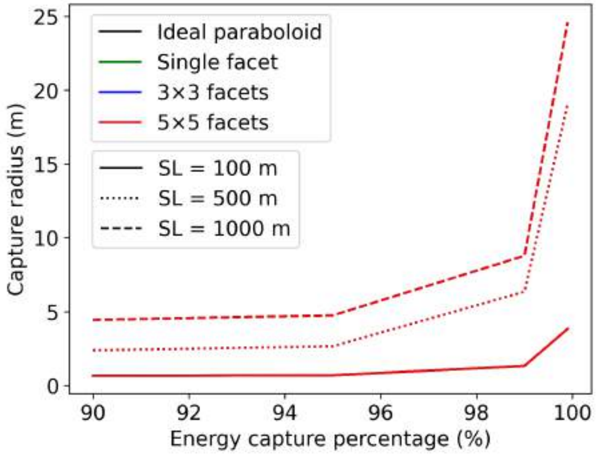
Buie sunshape

Reflectors in 12 configurations, 0 surface slope error, on-axis arrangement, ideally focused

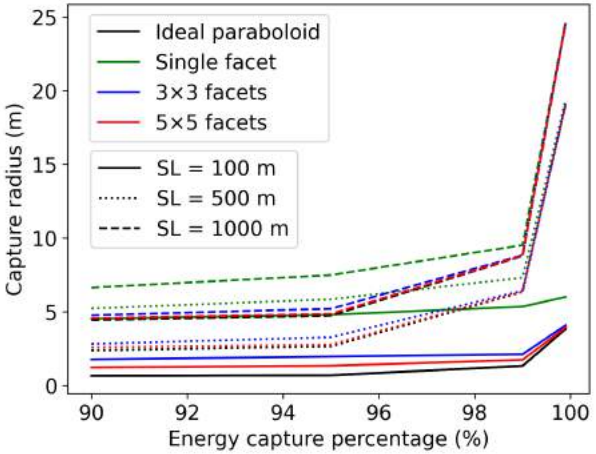
Paraboloid



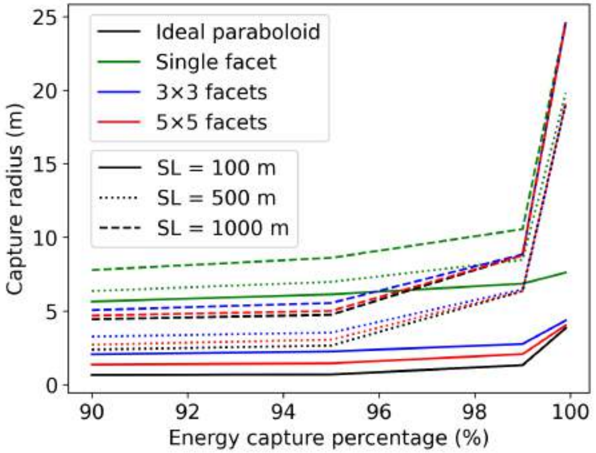
Sphere



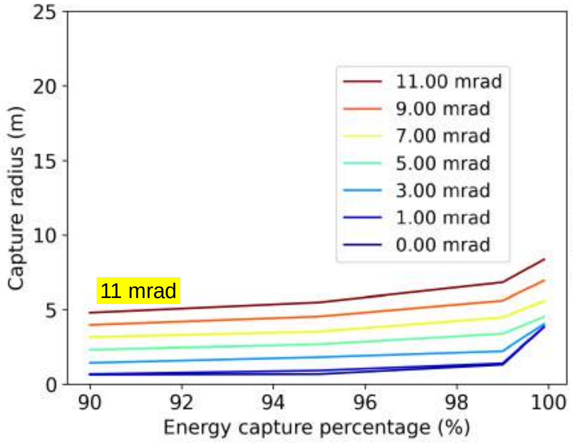
Parabolic-cylinder



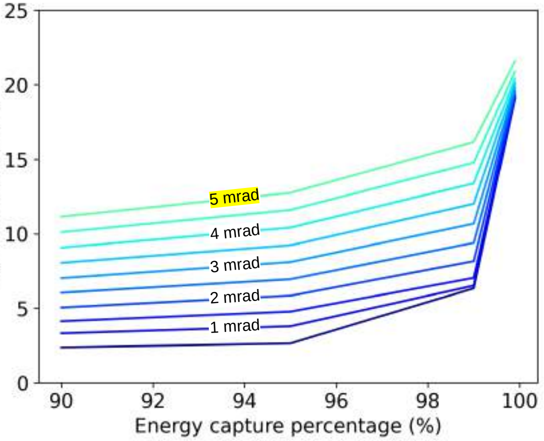
Flat



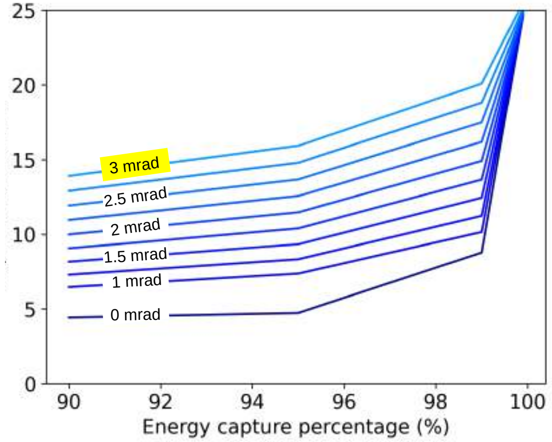
An ideal paraboloid reflector with slope errors (focal length = slant (SL) range)



SL = 100m



SL = 500m



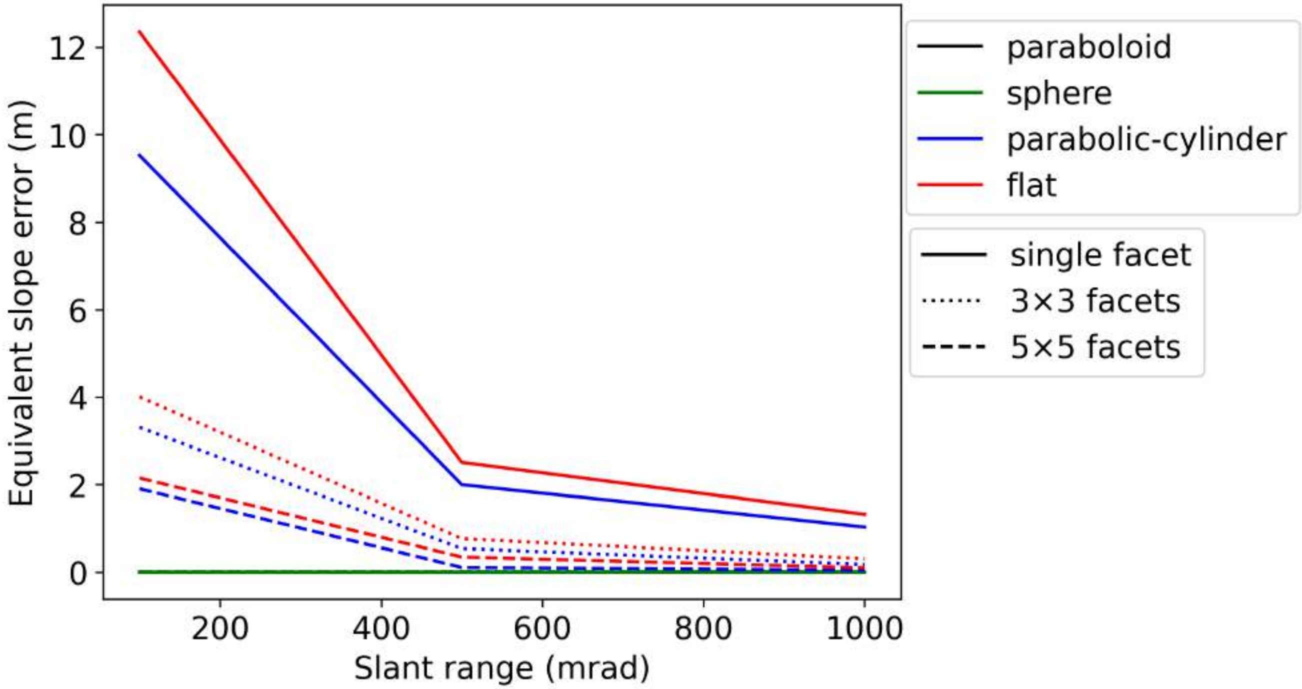
SL = 1000m

- When sunshape is included, beam shapes spread more as the SL range increases.
- There is no performance difference between an ideal paraboloid concentrator and a flat reflector when they are far from the target. For a heliostat 1 km from the target, the beam tail can extend to 25 m.
- Equivalent slope error (ESE) is the slope error on an ideal paraboloid that matches the capture radius of an "as-is" heliostat configuration.

Equivalent slope error (ESE)

Reflectors in 12 configurations, 0 surface slope error, on-axis arrangement, ideally focused

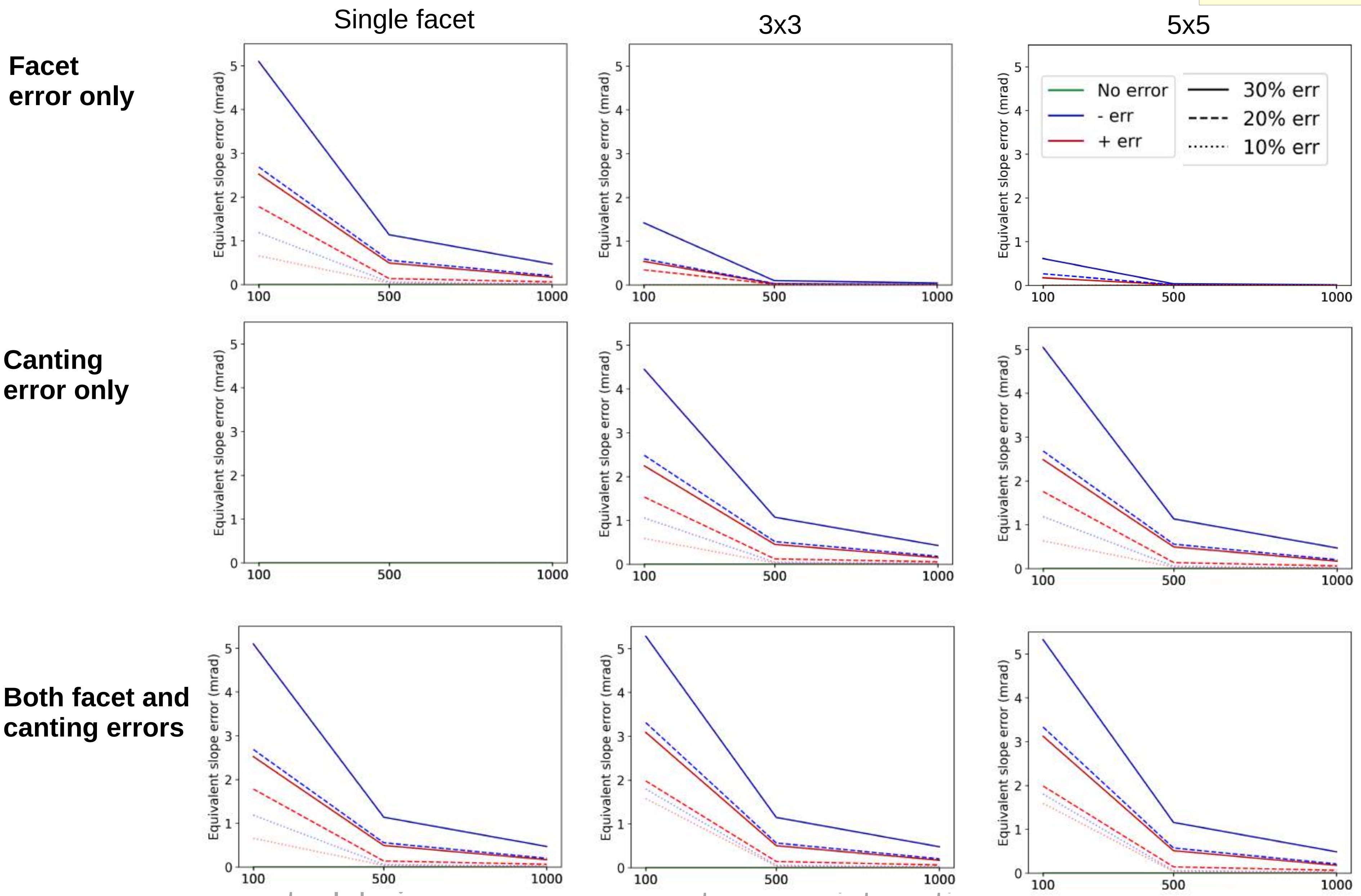
ESE (mrad)	Single	3×3	5×5	Single	3×3	5×5	Single	3×3	5×5
	SL = 100 m			SL = 500 m			SL = 1000 m		
Paraboloid	0	0	0	0	0	0	0	0	0
Sphere	0	0	0	0	0	0	0	0	0
Parab-cylinder	9.5	3.3	1.9	2.0	0.5	0.1	1.0	0.2	0
Flat	12.3	4.0	2.2	2.5	0.8	0.3	1.3	0.3	0.1



- Spherical facets perform as well as a paraboloid.
- Non-ideal shape heliostats perform better and is comparable with ideal shape heliostats at greater distances due to sunshape spreading the beam.
- A single flat facet is equivalent to 12.3 mrad at 100 m from the target, but reduces to 1.3 mrad at greater distances.
- A 5x5 flat-facet heliostat is equivalent to 2.2 mrad at 100 m and performs almost as well as an ideal paraboloid with 0.1 mrad ESE.

ESE of facet focus and canting errors

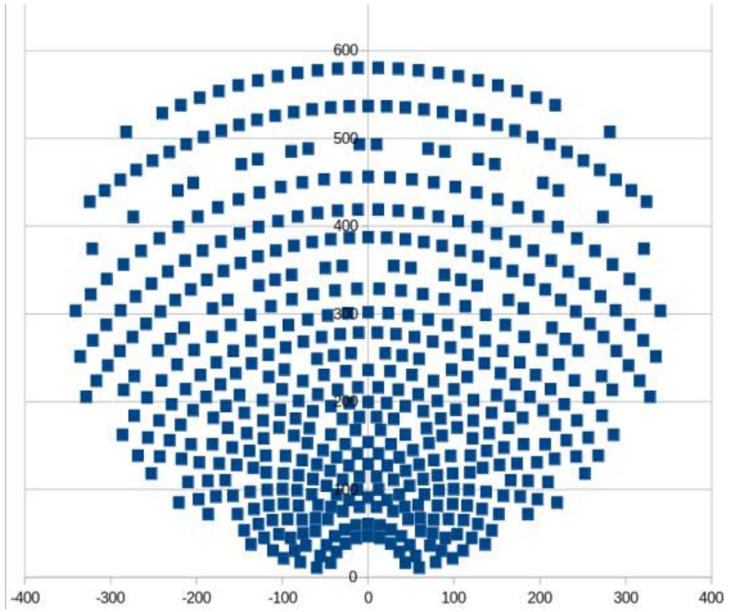
- **Paraboloid facets**
- **Radius of 95% energy capture**



- A negative error indicates a shorter focal length than the ideal focus, while a positive error indicates a longer focal length.
- A negative error means the reflector is more curved.
- A positive error means the reflector is flatter.
- A more curved reflector generally performs worse than a flatter one.
- More facets allow for greater tolerance of facet-level errors.
- A 5x5 flat-facet heliostat has only 2.2 mrad at 100 m

Full field case

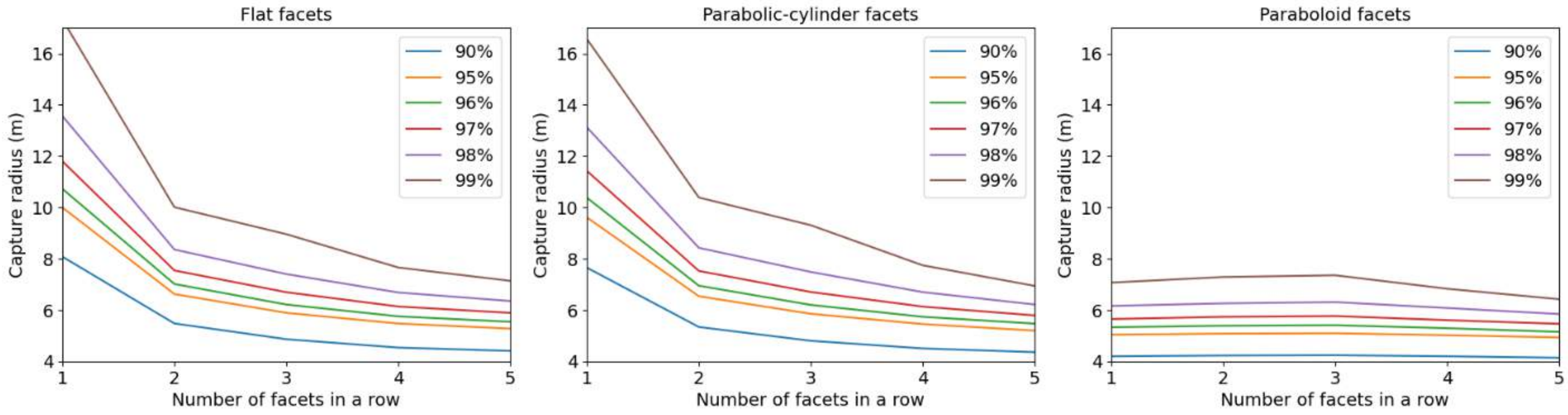
- Design point: summer solstice, solar noon
  azi=180, ele=78
- Heliostat layout: 524 heliostats
- Aiming point (0, 0, 62)
- 20 million rays using Solstice ray tracing program



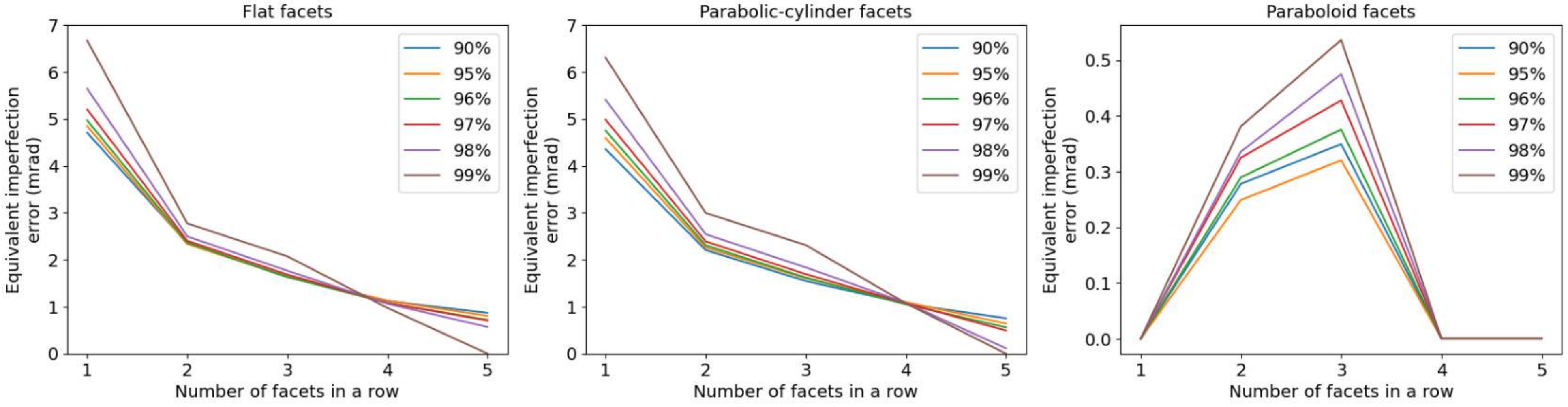
Sun	
site location:	Barstow, CA (N34º53′, W116º56′)
sun shape	Buie
CSR:	0.02
DNI W/m2	1000
Atmospheric Attenuation	0
Heliostat	
shape	Paraboloid
mirror width and height (m)	10
focal length (m)	slant range
mirror reflectivity:	0.95
Normal slope error	2 mrad
Tracking	azi-ele
Receiver	
shape:	Flat square, billboard
width and height (m)	20
absorptivity	1
location:	(0,0,62)
rotation	0 (vertical)

Results – full field, design point

Ideal focus and canting for facets in different shapes



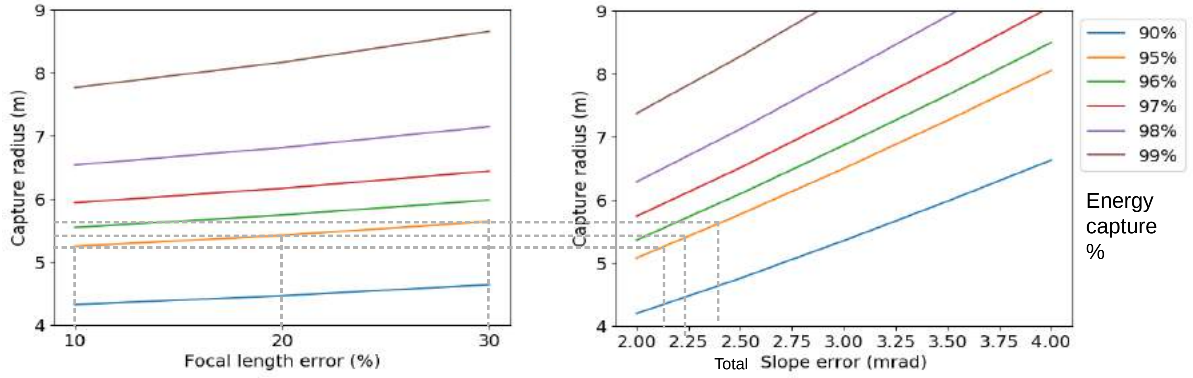
Equivalent slope errors

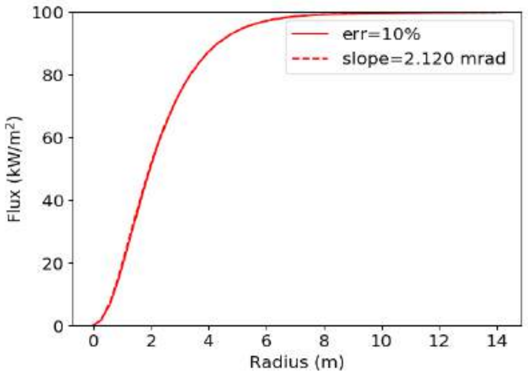


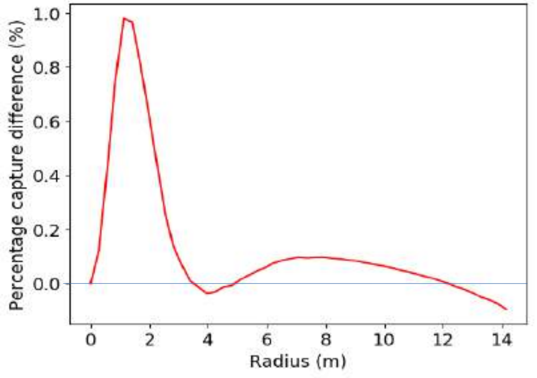
Results – full field, annual performance

Matching capture radius of 95%

- It is hard to use an equivalent slope error to fit the whole flux distribution
- but it is ok to use an ESE to predict the energy capture

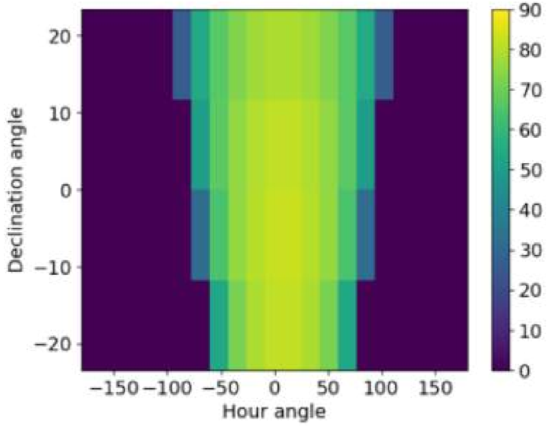




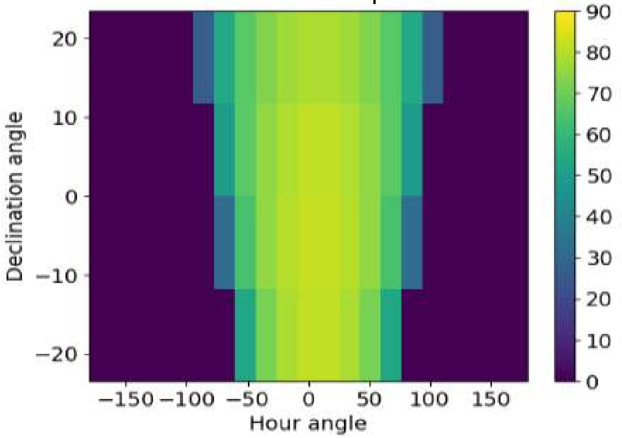


Verification: annual optical efficiency for the 10% focal length error

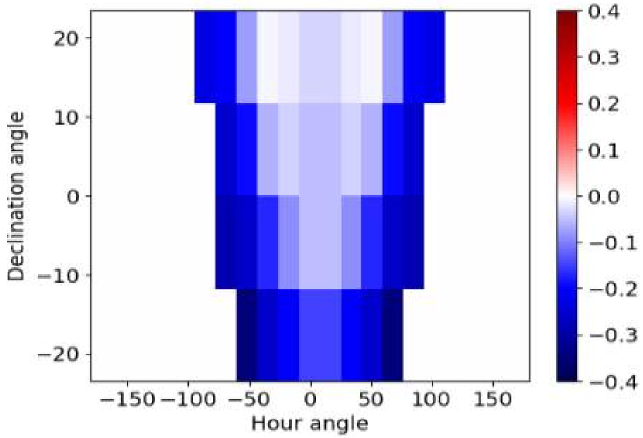
10% focal length error



2.12mrad total slope error



Difference in efficiency %



Conclusions and future work

- ESE is obtained by matching the radius of energy capture between an ‘as-is’ flux map and an ideal paraboloid heliostat with a slope error.
- It is validated that the ESE obtained at the design point for the full field can be applied to annual performance analysis.
- ESE offers a straightforward way to compare the magnitude of different types of beam errors.
- When sunshape is included, beam shapes spread more as the SL range increases. There is no performance difference between an ideal paraboloid concentrator and a flat reflector when they are far from the target.
- Non-ideal shape heliostats perform better and are comparable with ideal shape heliostats at greater distances due to sunshape spreading the beam.
- A single flat facet is equivalent to 12.3 mrad at 100 m from the target but reduces to 1.3 mrad at greater distances.
- A 5x5 flat-facet heliostat is equivalent to 2.2 mrad at 100 m and performs almost as well as an ideal paraboloid with 0.1 mrad ESE.
- More facets allow for greater tolerance of facet-level errors.
- A more curved reflector generally performs worse than a flatter one.

Future Work:

- How to use the ESE of a single heliostat to obtain the ESE of the whole field.
- Investigate more types of optical errors.

Questions?

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