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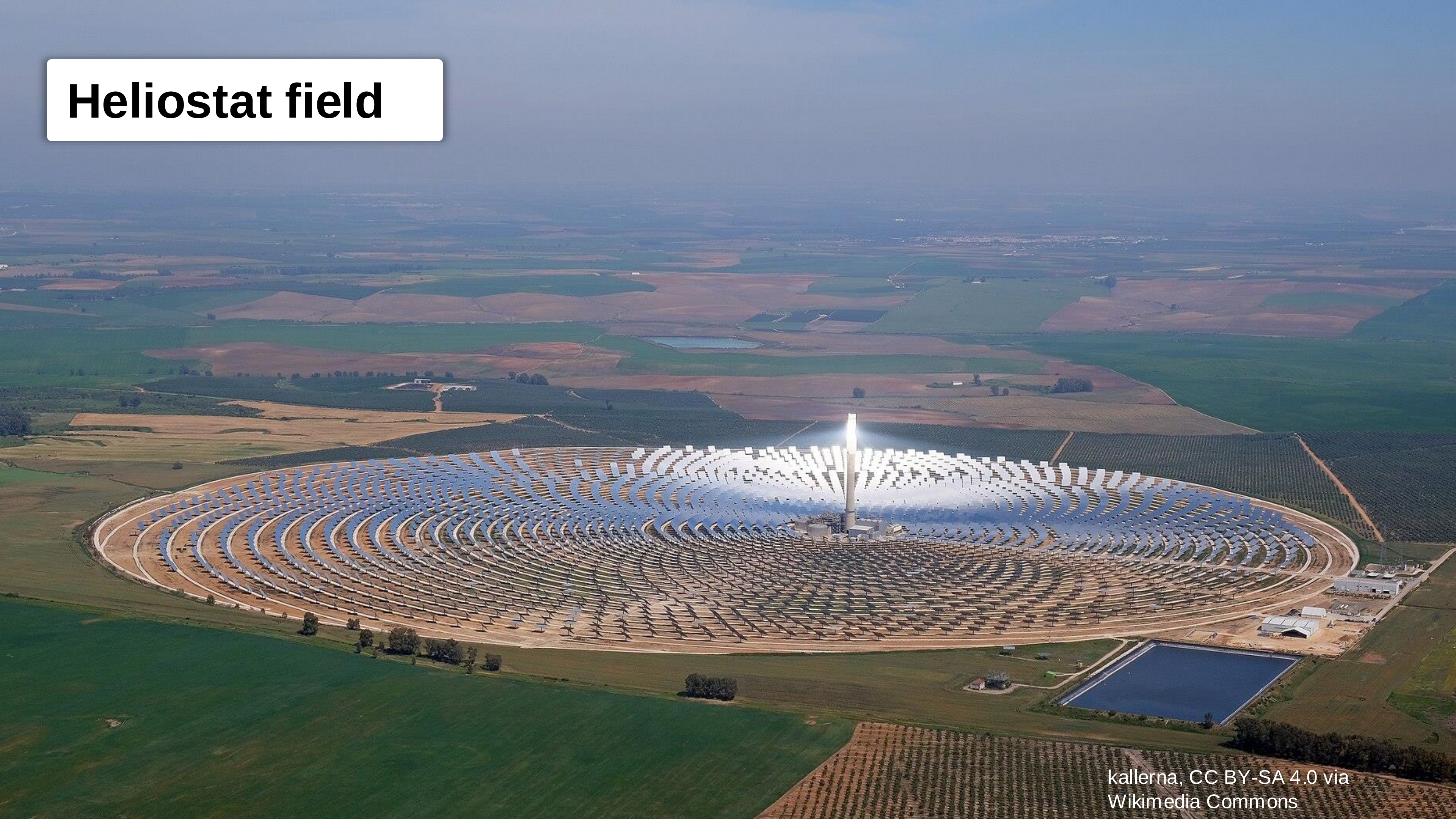
Freeform beam-down secondary concentrators for heliostat fields

Håkon J. D. Johnsen,
Associate Professor,
NTNU Department of Mechanical and Industrial Engineering

Heliostat field



The Very-High Concentration Solar Tower,
IMDEA Energy, Madrid

Photo: IMDEA Energy

Can we make a
solar tower with
furnace-level concentration ratios?

Why?

Electricity production
with thermal energy storage

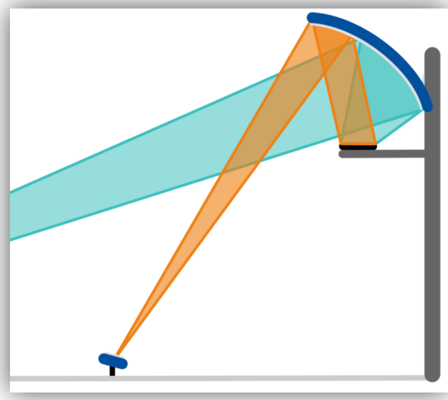
Ultra-high irradiance,
Materials science,
Solar thermochemistry

Outline

$$C_{max} = \left(\frac{1}{\sin(\theta_{max})}\right)^2$$

Concentration limits

Why lower concentration?



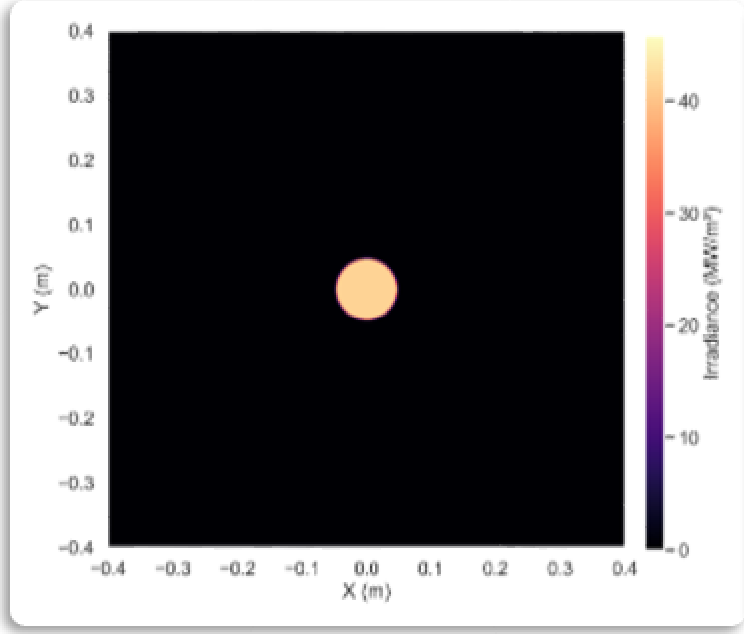
New concept

Thermodynamic limit

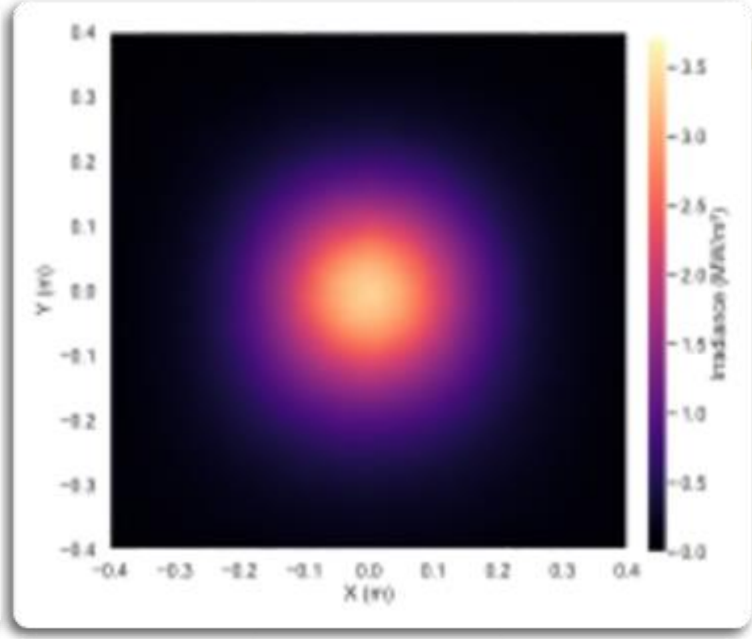
$$C_{max} = \frac{1}{\sin(\theta_{max})^2} \approx 46\,000$$

M. Romero, et. al, “Ultra-modular 500m2 heliostat field for high flux/high temperature solar-driven processes,”, 2017

Irradiance distribution



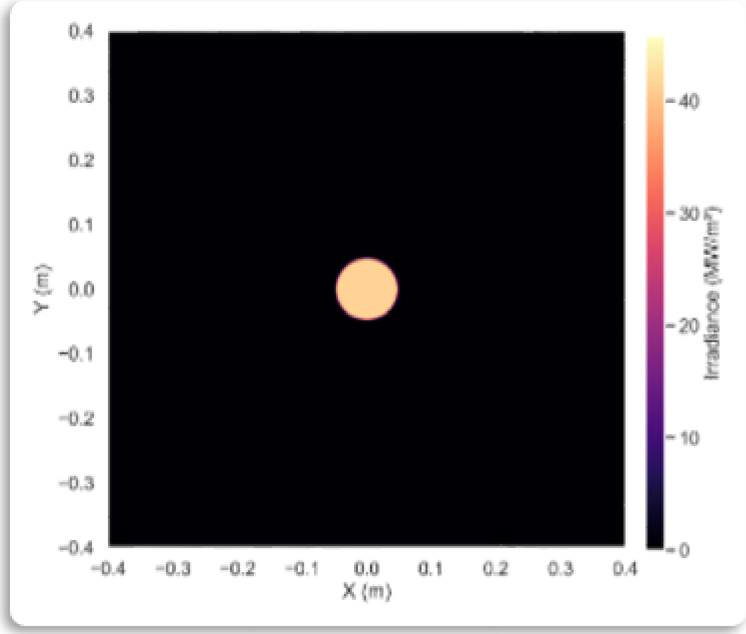
Ideal concentrator



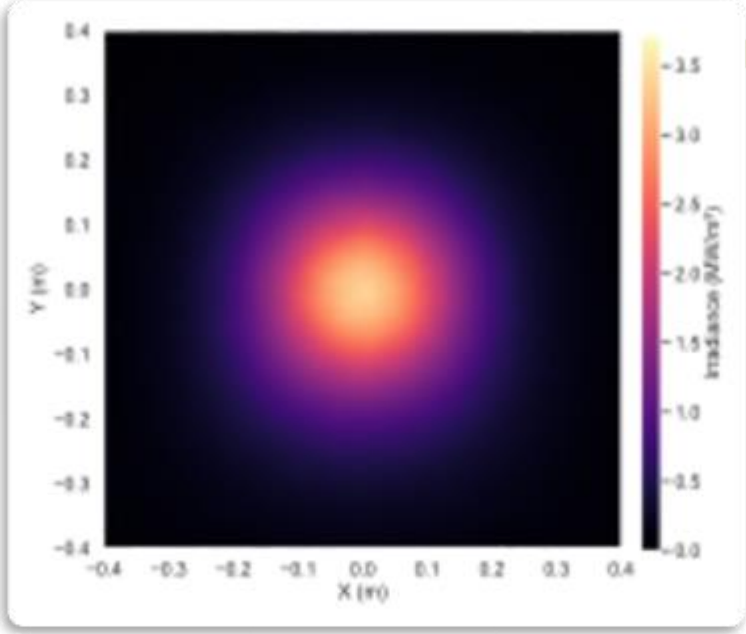
Real heliostat field

Why?

Irradiance distribution

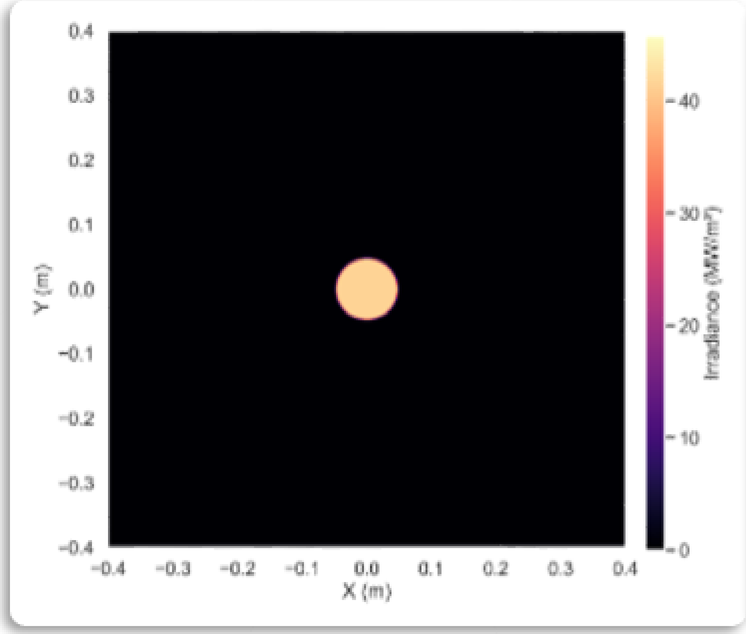


Ideal concentrator

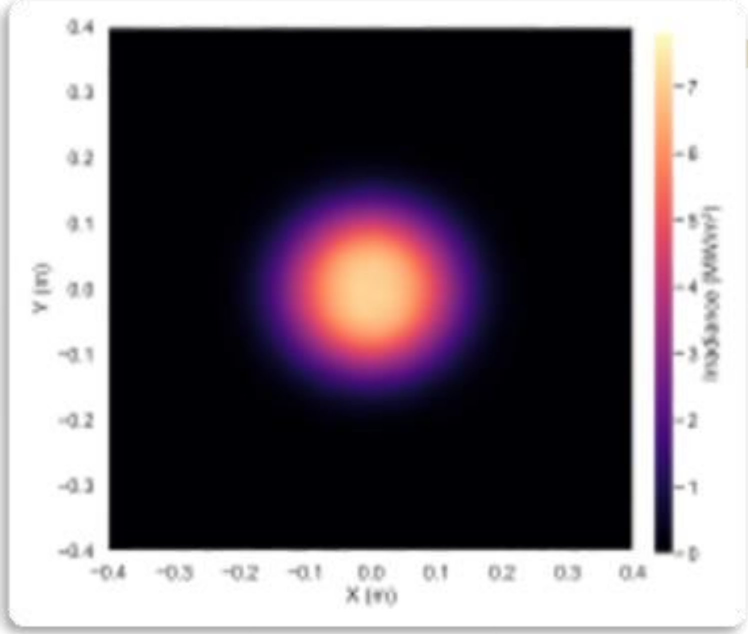


Real heliostat field

Irradiance distribution



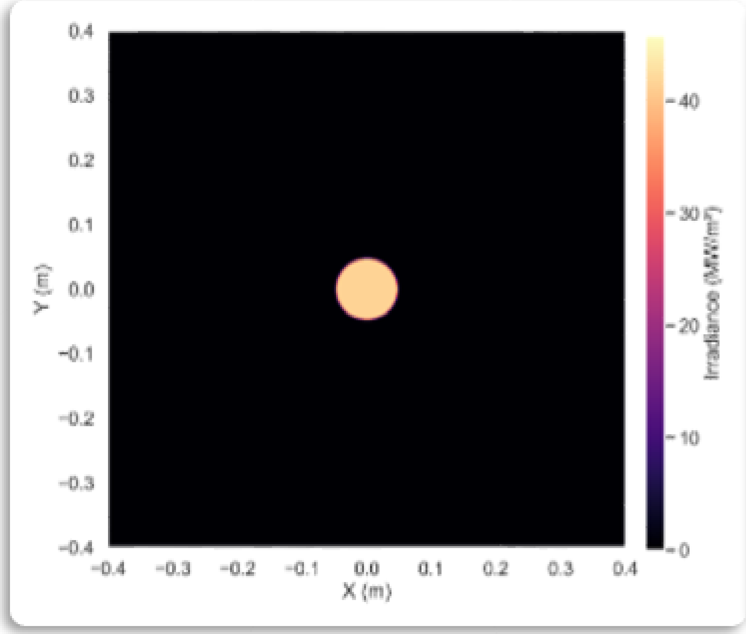
Ideal concentrator



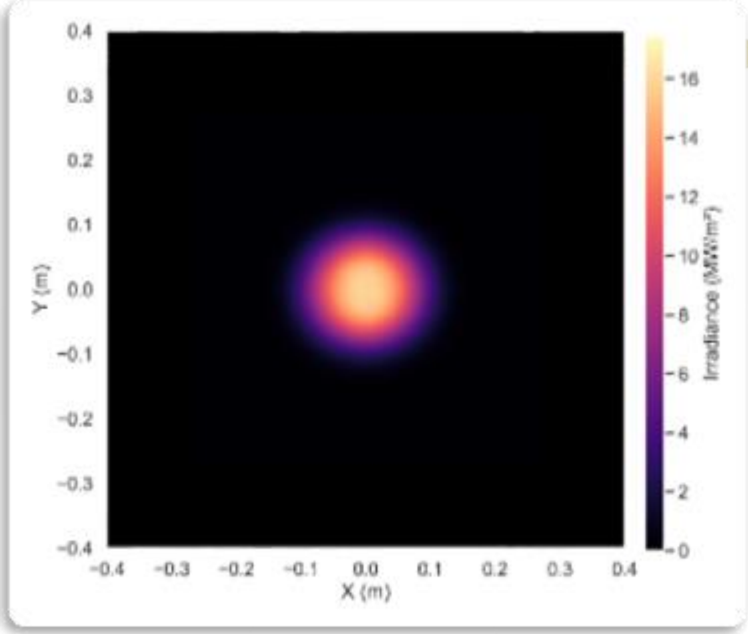
Real heliostat field

+ Perfect heliostats

Irradiance distribution



Ideal concentrator



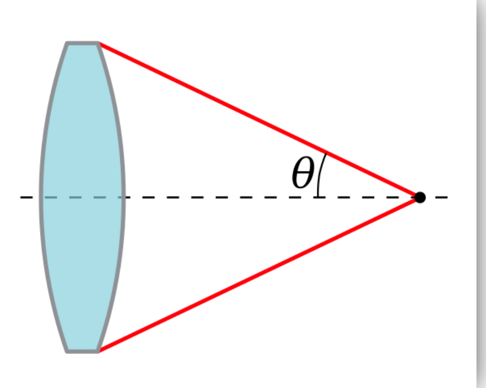
Real heliostat field

+ Perfect heliostats

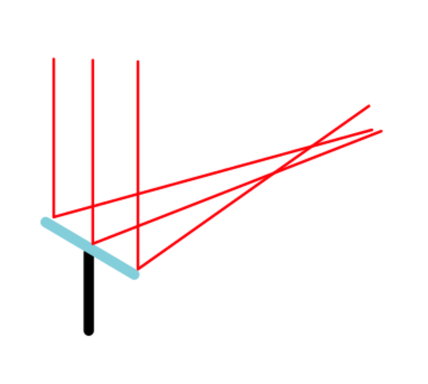
+ Ideal numerical aperture

We are missing something

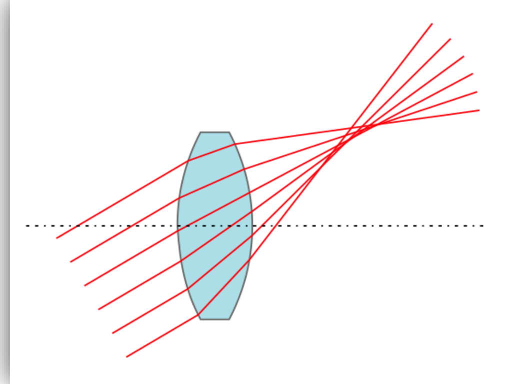
Main causes of reduced concentration



Numerical aperture



Heliostat quality



Coma

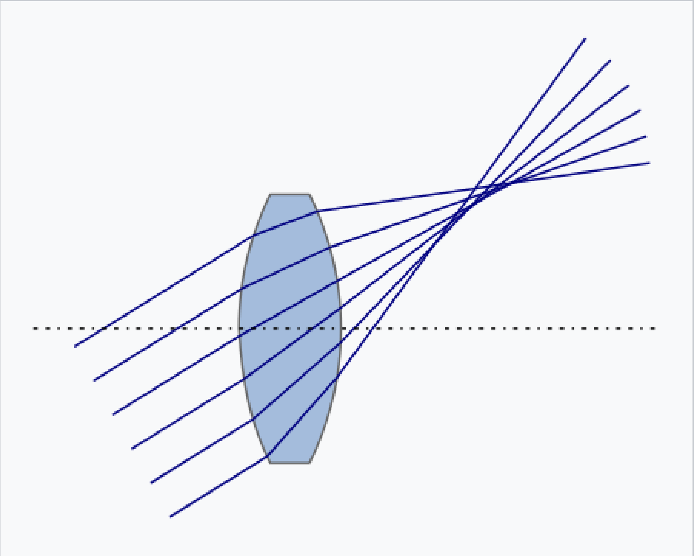
Coma (optics)

29 languages

Article Talk Tools

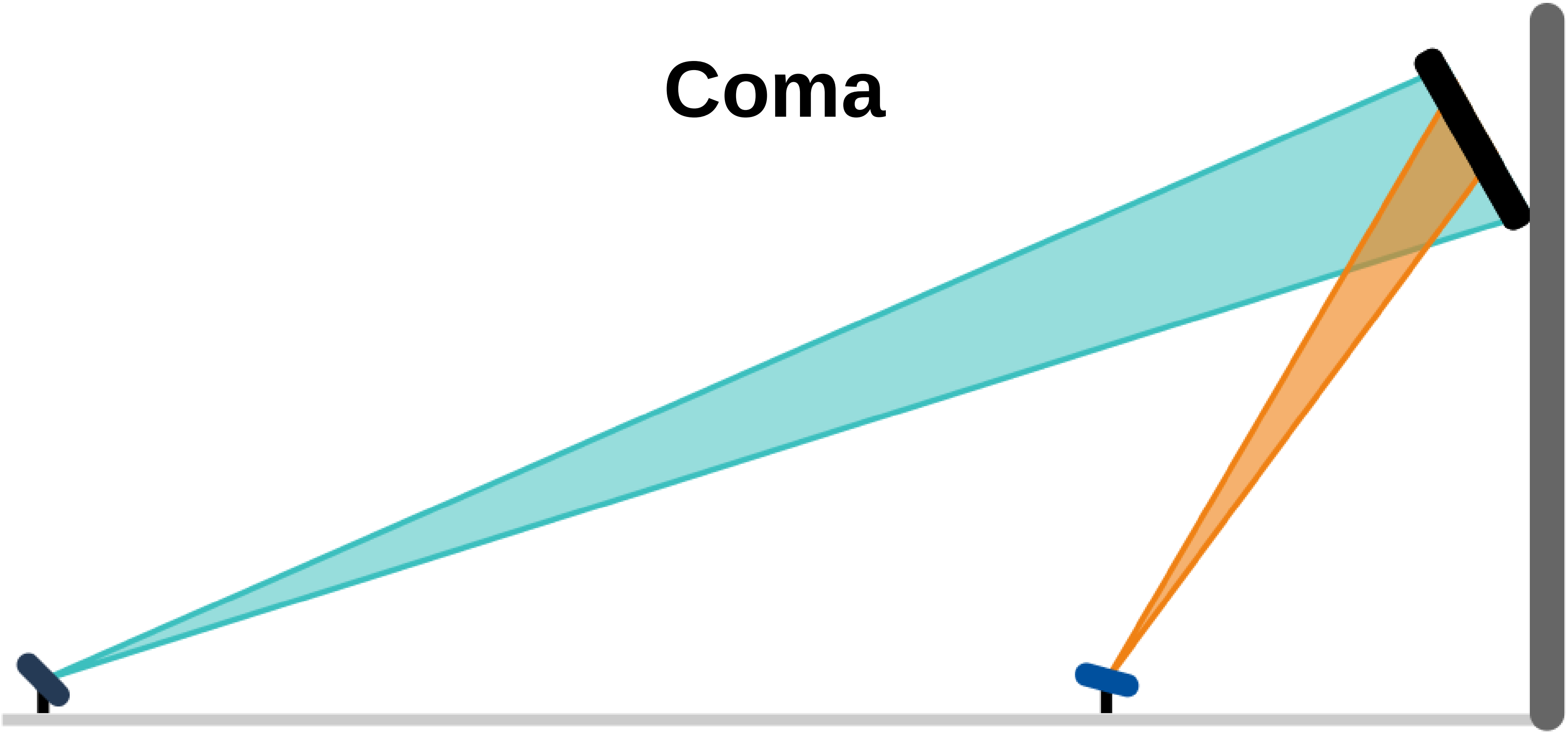
From Wikipedia, the free encyclopedia

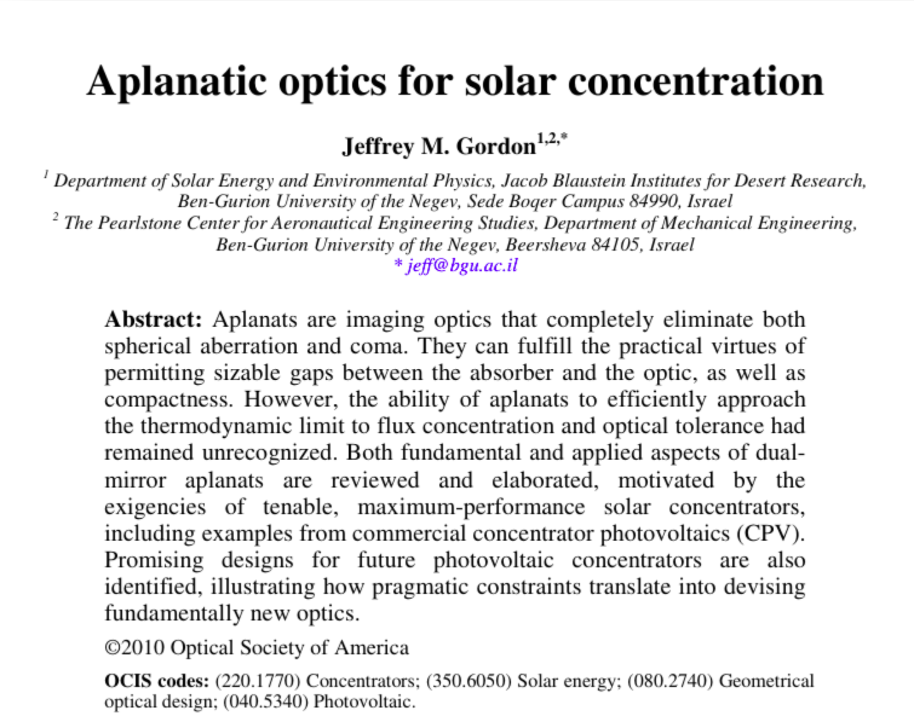
In optics (especially telescopes), the **coma** (/ˈkoʊmə/), or **comatic aberration**, in an optical system refers to aberration inherent to certain optical designs or due to imperfection in the lens or other components that results in off-axis point sources such as stars appearing distorted, appearing to have a tail (coma) like a comet. Specifically, coma is defined as a variation in magnification over the entrance pupil. In refractive or diffractive optical systems, especially those imaging a wide spectral range, coma can be a function of wavelength, in which case it is a form of chromatic aberration.



Coma of a single lens. Each cone of light focuses on different planes along the optical axis.

Coma





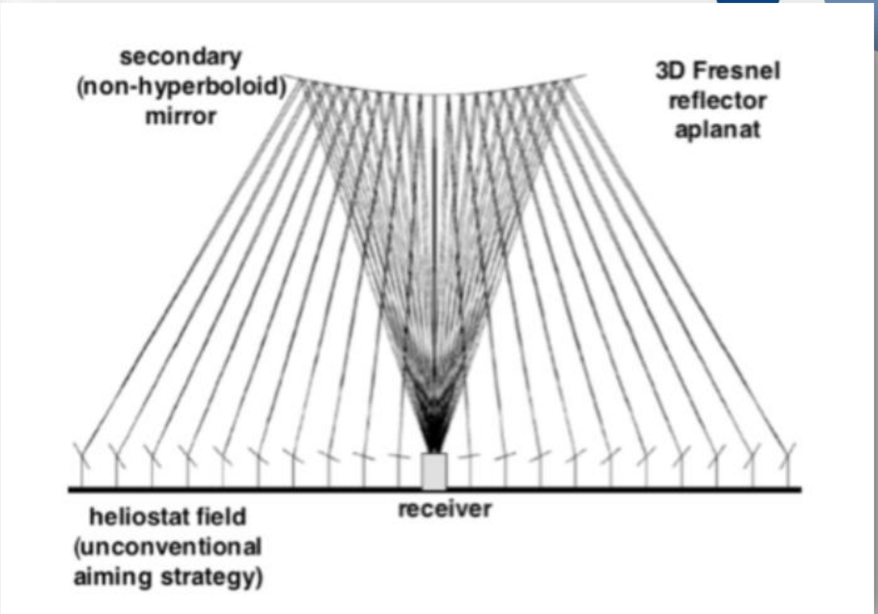
Aplanatic optics for solar concentration

Jeffrey M. Gordon[1,2,*]

[1] *Department of Solar Energy and Environmental Physics, Jacob Blaustein Institutes for Desert Research, Ben-Gurion University of the Negev, Sede Boqer Campus 84990, Israel*
[2] *The Pearlstone Center for Aeronautical Engineering Studies, Department of Mechanical Engineering, Ben-Gurion University of the Negev, Beersheva 84105, Israel*
** jeff@bgu.ac.il*

Abstract: Aplanats are imaging optics that completely eliminate both spherical aberration and coma. They can fulfill the practical virtues of permitting sizable gaps between the absorber and the optic, as well as compactness. However, the ability of aplanats to efficiently approach the thermodynamic limit to flux concentration and optical tolerance had remained unrecognized. Both fundamental and applied aspects of dual-mirror aplanats are reviewed and elaborated, motivated by the exigencies of tenable, maximum-performance solar concentrators, including examples from commercial concentrator photovoltaics (CPV). Promising designs for future photovoltaic concentrators are also identified, illustrating how pragmatic constraints translate into devising fundamentally new optics.

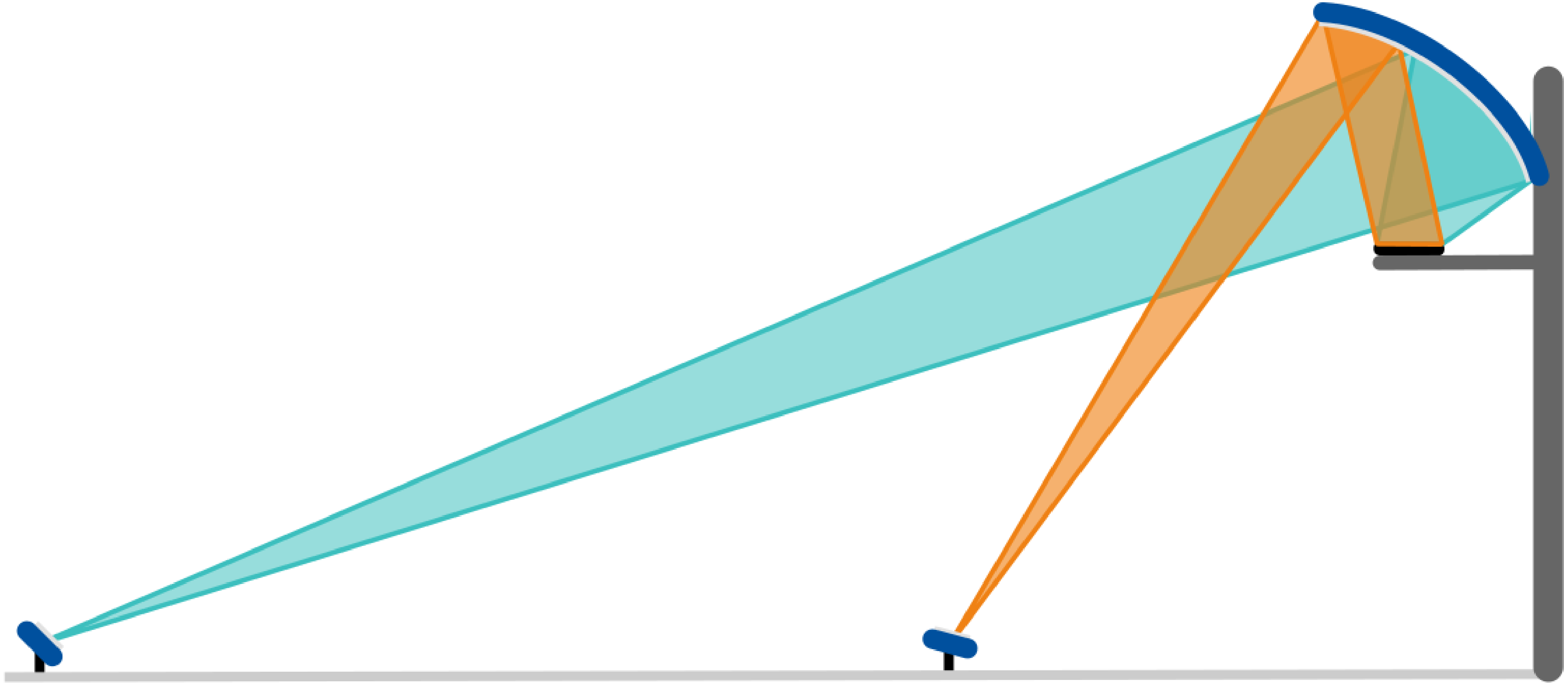
OCIS codes: (220.1770) Concentrators; (350.6050) Solar energy; (080.2740) Geometrical optical design; (040.5340) Photovoltaic.



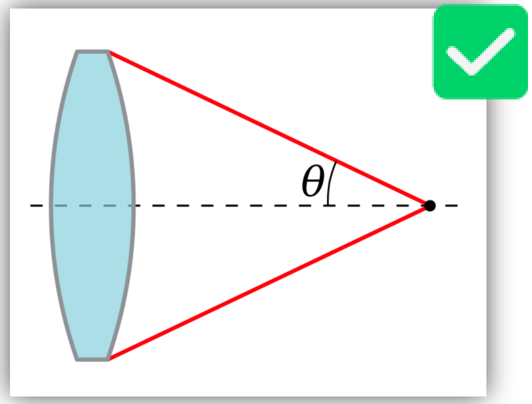
Jeffrey M. Gordon, "Aplanatic optics for solar concentration," Opt. Express 18, A41-A52 (2010)

Jeffrey M. Gordon, Daniel Feuermann, "Aplanatic beam-down solar towers," Proc. SPIE 11120, Nonimaging Optics: Efficient Design for Illumination and Solar Concentration XVI, 111200E (9 September 2019);

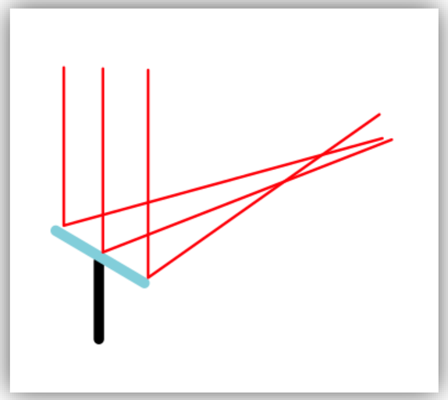
Don't beam down to the ground



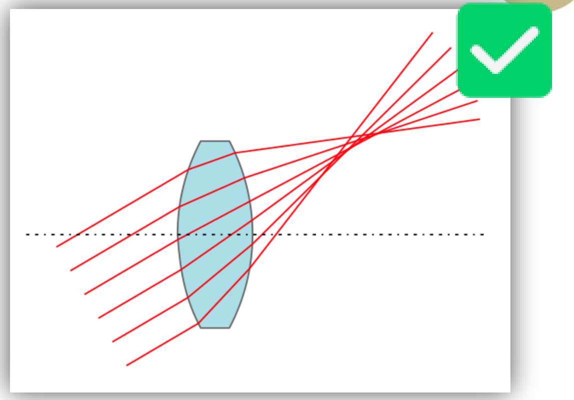
Fix both coma and NA



Numerical aperture



Heliostat quality



Coma

Not quite


Research Article

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Optics EXPRESS

Three surface freeform aplanatic systems

BHARATHWAJ NARASIMHAN,[1,2,*] PABLO BENITEZ,[1,2] JUAN C. MIÑANO,[1,2] MILENA NIKOLIC,[1] AND DEJAN GRABOVICKIC[2]

[1]Universidad Politécnica de Madrid, Cedint, Campus Montegancedo, Pozuelo, 28223 Madrid, Spain
[2]Limbak 4π, 28029 Madrid, Spain
[*]anbharathwaj@cedint.upm.es

Abstract: We address, in detail, the system of differential equations determining a freeform aplanatic system with illustrative examples. We also demonstrate how two optical surfaces, in general, are insufficient in achieving freeform aplanatism through the use of integrability condition for a given reflective freeform aplanatic configuration. This result also alludes to the fact that a freeform aplanatic system fulfills a broader set of conditions than its rotationally symmetric counterpart. We also elaborate on the above results with two illustrative examples (1) A semi aplanatic system which satisfies the generalized sine condition in only one direction and (2) A fully freeform aplanatic reflective system.

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OCIS codes: (080.2720) Mathematical methods (general); (080.2740) Geometric optical design; (080.3620) Lens system design; (080.4225) Nonspherical lens design; (110.0110) Imaging systems; (080.4298) Nonimaging optics.

Test case

Field parameters

- 169 heliostats, each 3m2
- 250 kWth
- Tower height: 15 m
- Focal length: 20m & 30m

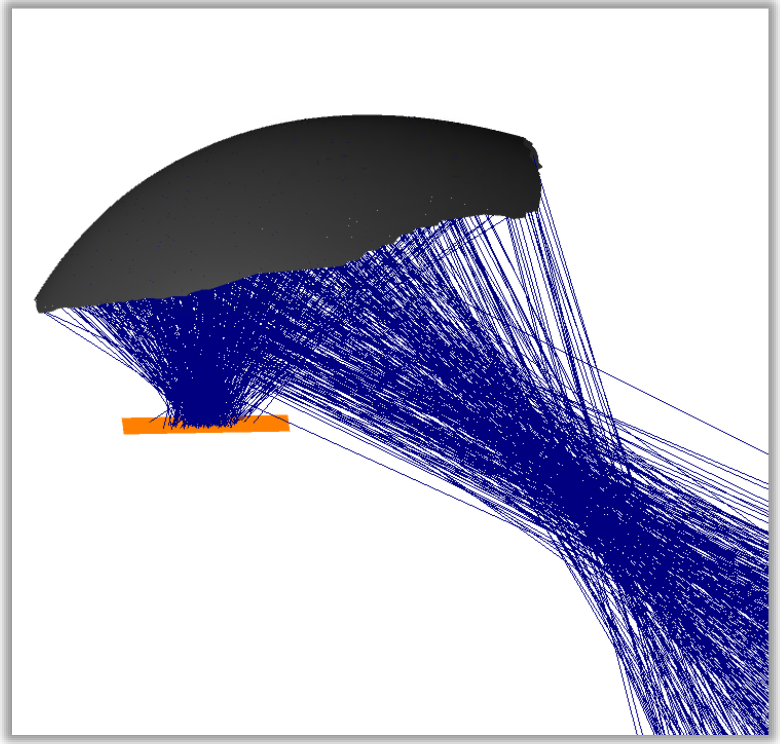
Simulation

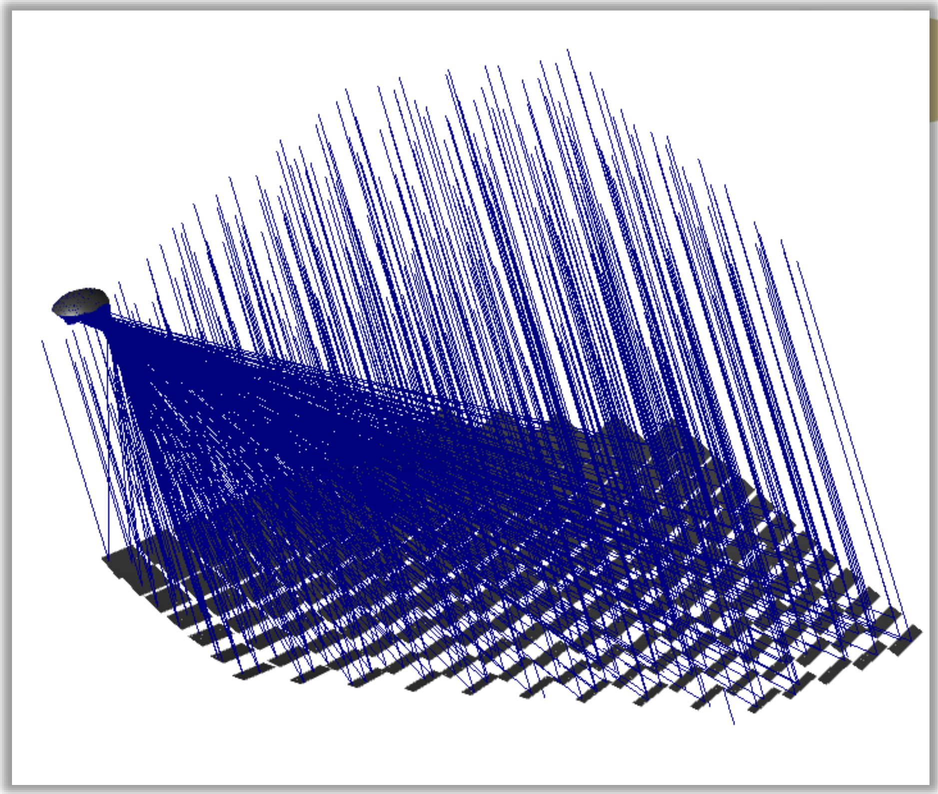
- Slope + tracking error: 1.25mrad RMS
- Solar size: Top-hat, 4.65 mrad half-angle
- Mirror reflectivity: 90%
- Irradiance: 900 W/m2
- Analysis in Zemax OpticStudio

Design method

- Numerical optimization
- Secondary: Freeform 12th order Legendre polynomial
- Aim point: Freeform 12th order Legendre polynomial
- Secondary size: 2.5m x 2.5m
- Simulation for optimization: Differentiable ray-tracer built on Jax

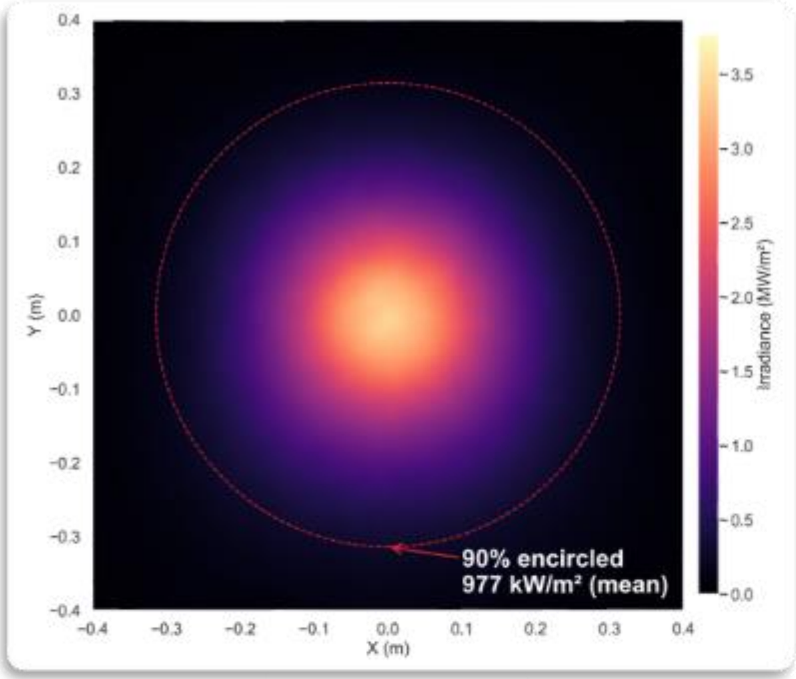
Optimized reflector





Irradiance distribution

Solar noon, summer solstice



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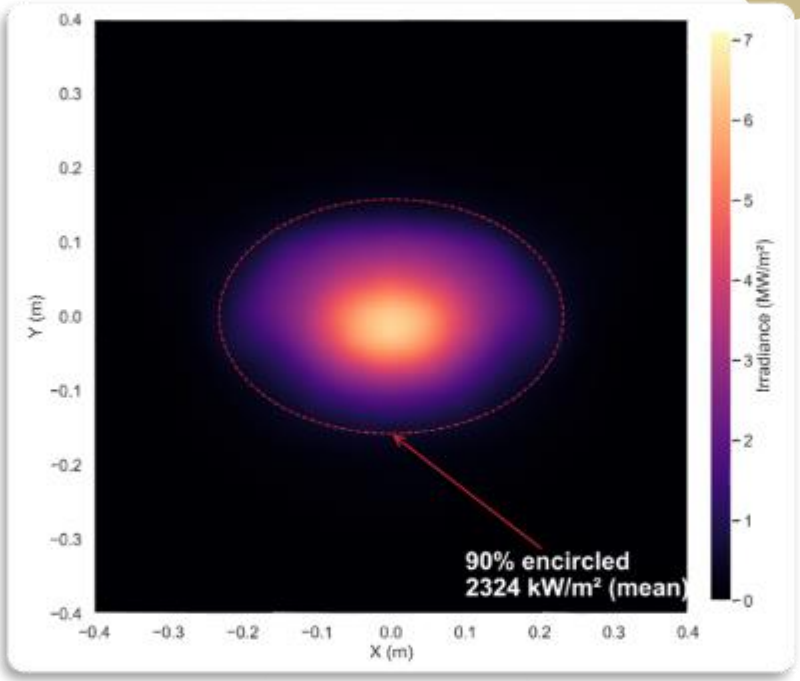
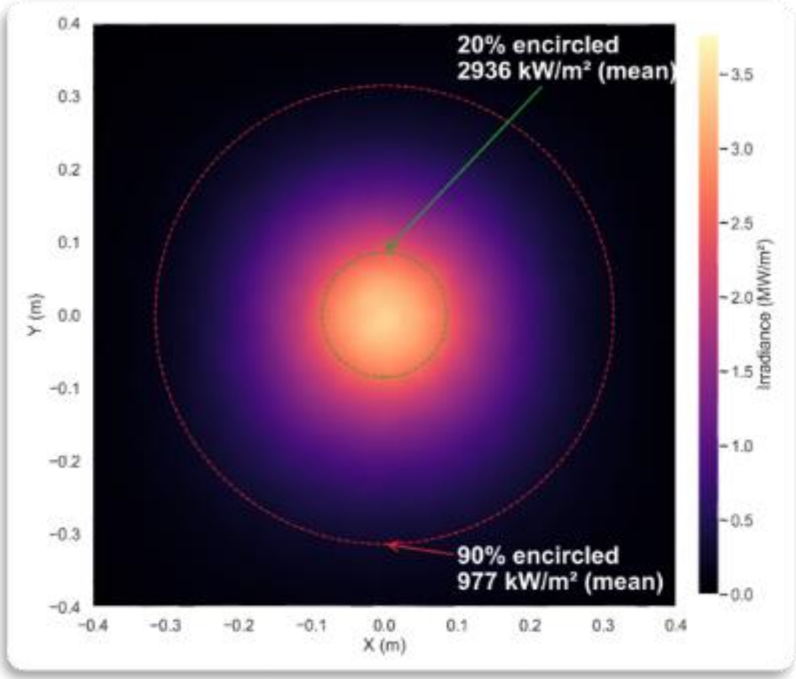


With secondary

Irradiance distribution

Solar noon, summer solstice



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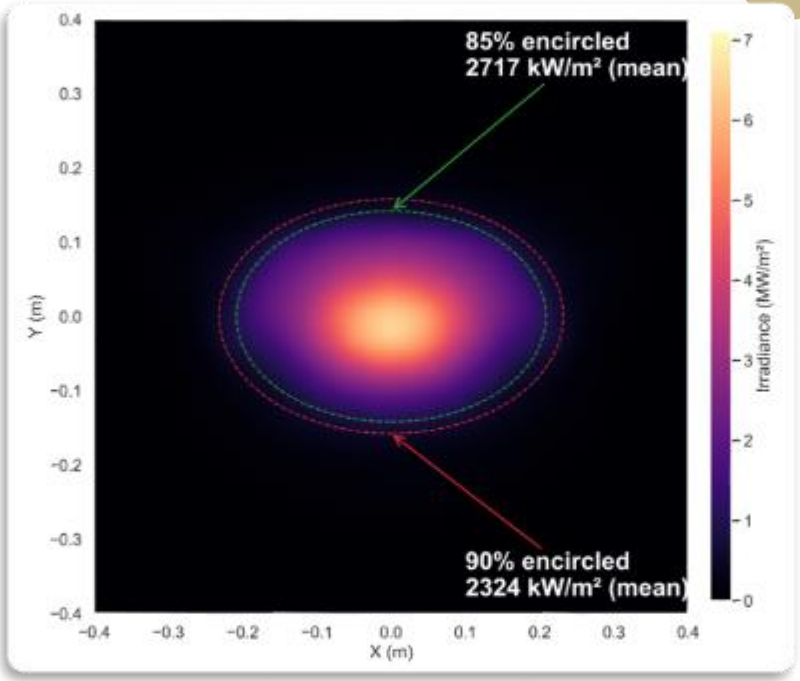
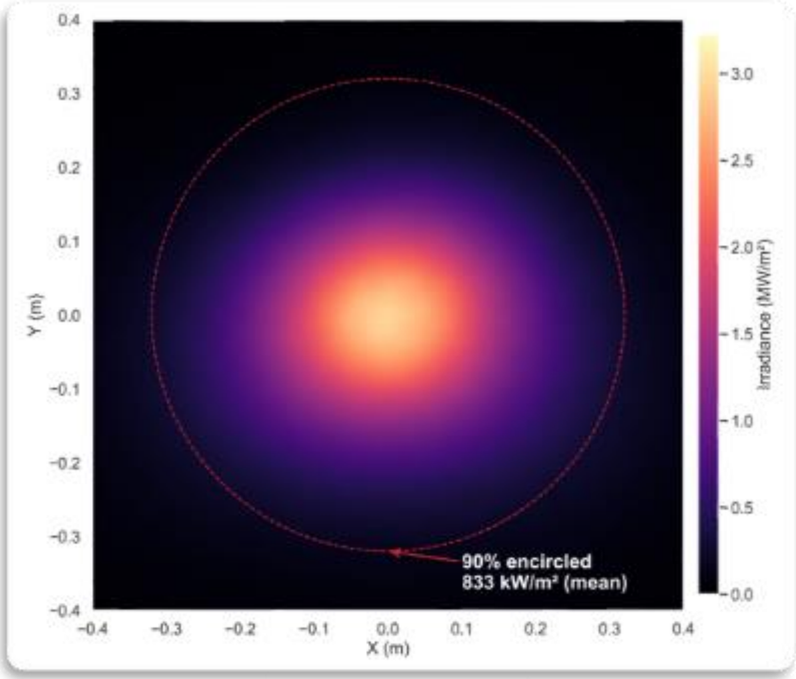


With secondary

Irradiance distribution

Jan 15th 2023, 12:56



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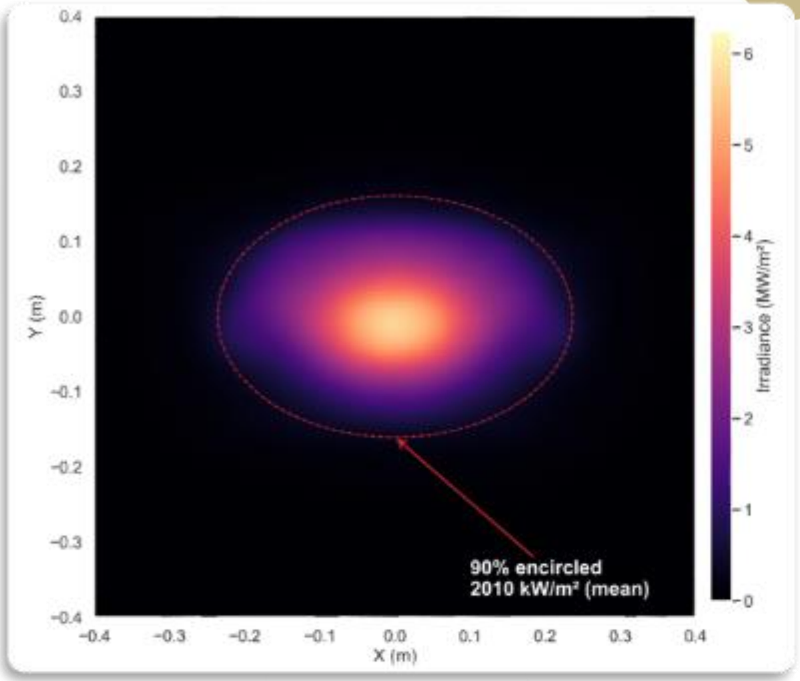
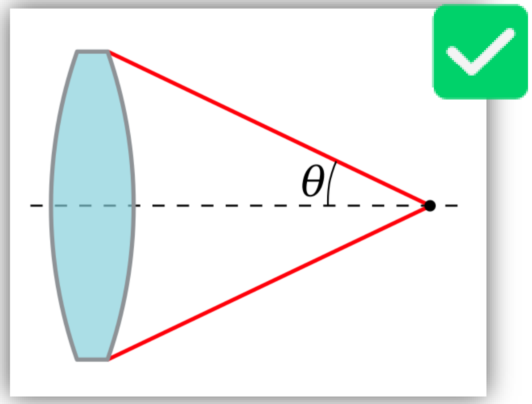
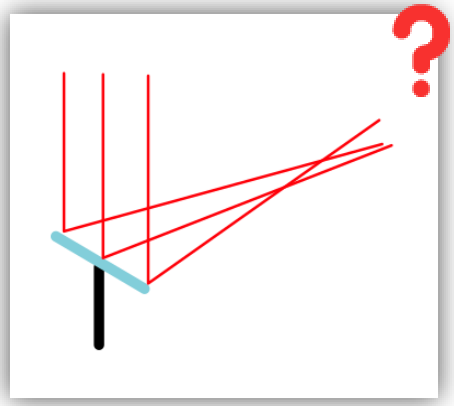


With secondary

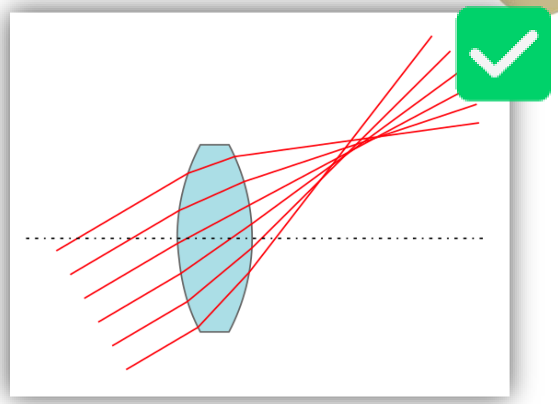
Fix both coma and NA



Numerical aperture



Heliostat quality



Coma

Better heliostats?

Shape-adjustable heliostats – designs for individuals and fields for > 3000 concentration

N. Didato*[a], R. Angel[a], M. Rademacher[a]
[a]Department of Astronomy and Steward Observatory, University of Arizona, 933 N. Cherry Ave., Tucson, AZ, USA 85721

ABSTRACT

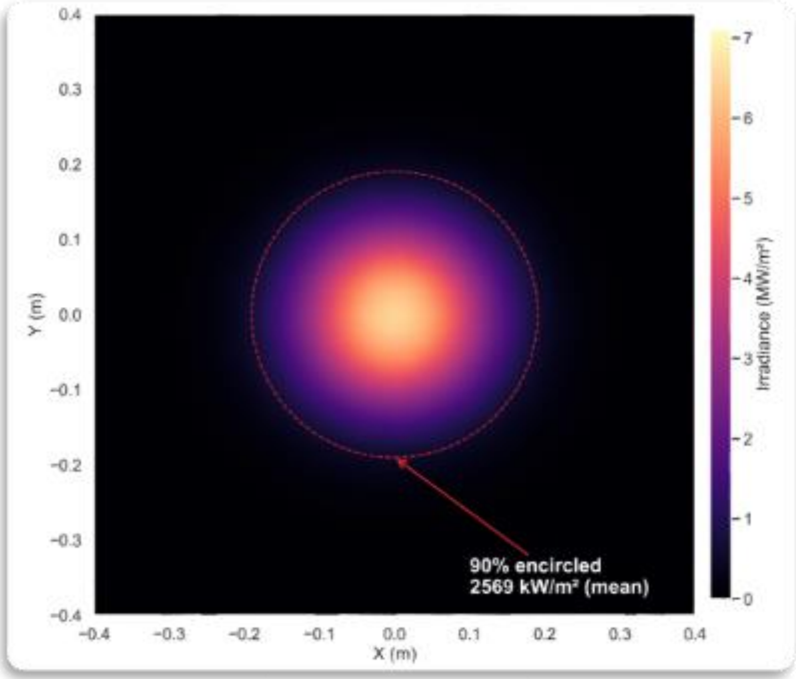
Shape-adjustable heliostats can maintain a focused image of the solar disc on a receiver target throughout the day, as the angle of incidence (AOI) changes on the reflector. This requires the heliostat reflector to be deformed into a unique biconic concave shape dependent on AOI. The reflector comprises a single rectangular sheet of silvered float glass mounted to a steel frame. Its shape is set initially, by adjusting the height of mounting points, to the biconic shape required for imaging at 60 degrees AOI. Shapes for other AOIs are obtained by twisting the frame from its four corners and center. A finite element model was made of a heliostat designed to form a disc image on a 130 m distant receiver using a single sheet glass reflector, 1/8" thick x 130" x 96", supported by 58 points on a rectangular tube frame structure weighing 120 kg. Analysis shows an overall RMS slope error <1 mrad for all AOI from 0 to 70 degrees. Without twisting, the RMS slope error would be ~3.5 mrad at 0° and 70° AOI. Preliminary results from analysis of slope error maps generated from the FE model indicate encircled energies within the ideal solar disc radius of >85% are achievable. Models of fields of closely packed heliostats of this type, on target axis mounts, demonstrate a geometrical throughput into the receiver of >73% of the total mirror area, after accounting for blocking, shadowing, and cosine loss. In one model, with 450 heliostats powering five compound parabolic concentrators at a receiver, a concentration of > 3,000 was obtained at powers > 1 MW, through much of the day.

Keywords: Heliostat, Adjustable, Twisting, Angle of incidence, Focus, Encircled energy, Slope error

J. Roger P. Angel et. al., "Adjustable shape heliostats in fields for concentration > 3,000 at power > 1 MW," Proc. SPIE, 2023

Deformable heliostats

0.86mrad RMS slope & tracking errors, no off-axis aberrations



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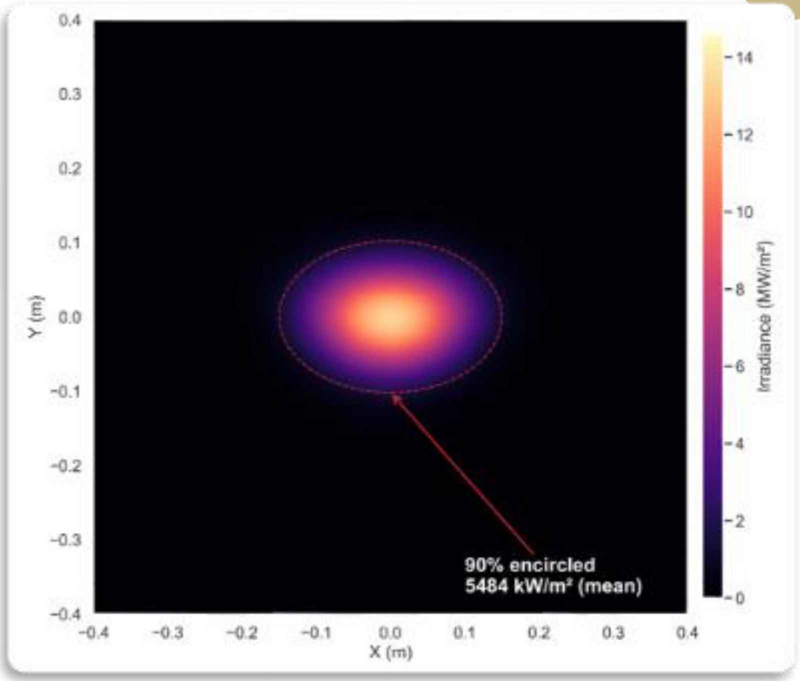


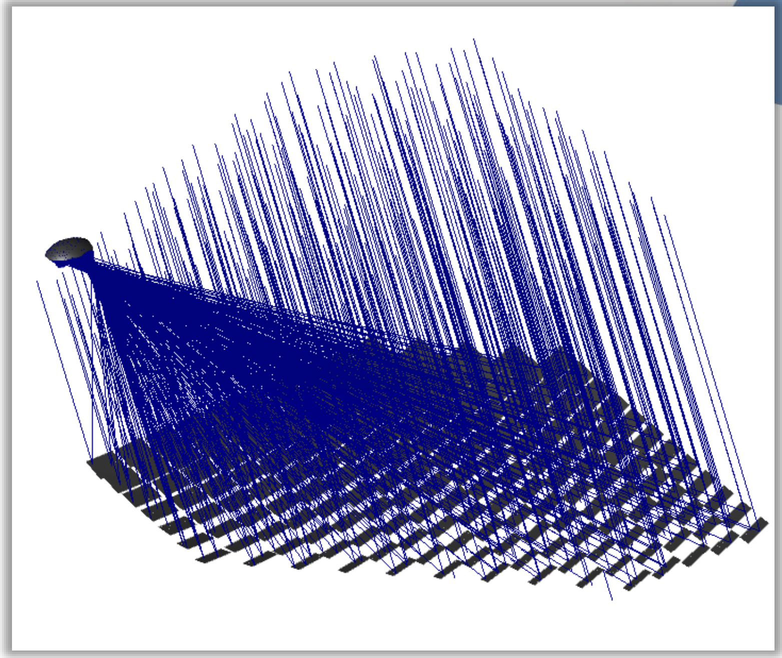
With secondary

Too high concentration?

- Combine with aim point strategy
- Combine with cavity receiver
- New ultra-high temperature applications
  - Solar thermophotovoltaics?

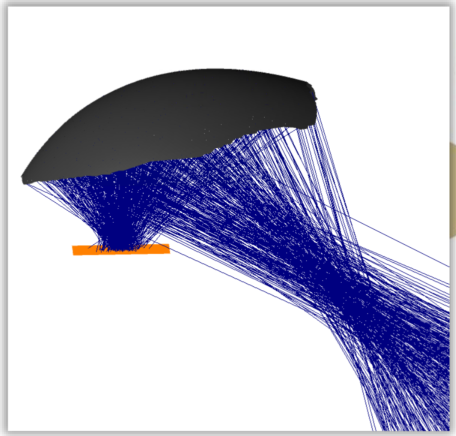
Further work

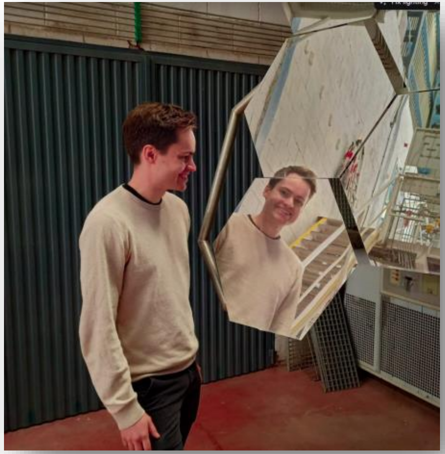
- Explore design landscape
- Secondary mirror size
- Secondary tolerancing & cooling
- Other field sizes and geometries
    - Surround fields, much larger fields
- Physical demonstration



Conclusions

- New approach for secondary concentrator
  - No contact between mirror and receiver
- Furnace-level concentration with the scalability of heliostat fields





Acknowledgements

- Thorsten Denk, Ciemat-PSA
- Jose Gonzalez-Aguilar, IMDEA Energy
- Alex Lehmann, UNSW