SFERA-III

Solar Facilities for the European Research Area

1st Summer School “Thermal energy storage systems, solar fields and new cycles for future CSP plants”
WP1 Capacity building and training activities
Odeillo, France, September 9th-11th 2019

Solar Facilities for the European Research Area

“New concepts of line focus and point focus concentrators”

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NETWORKING

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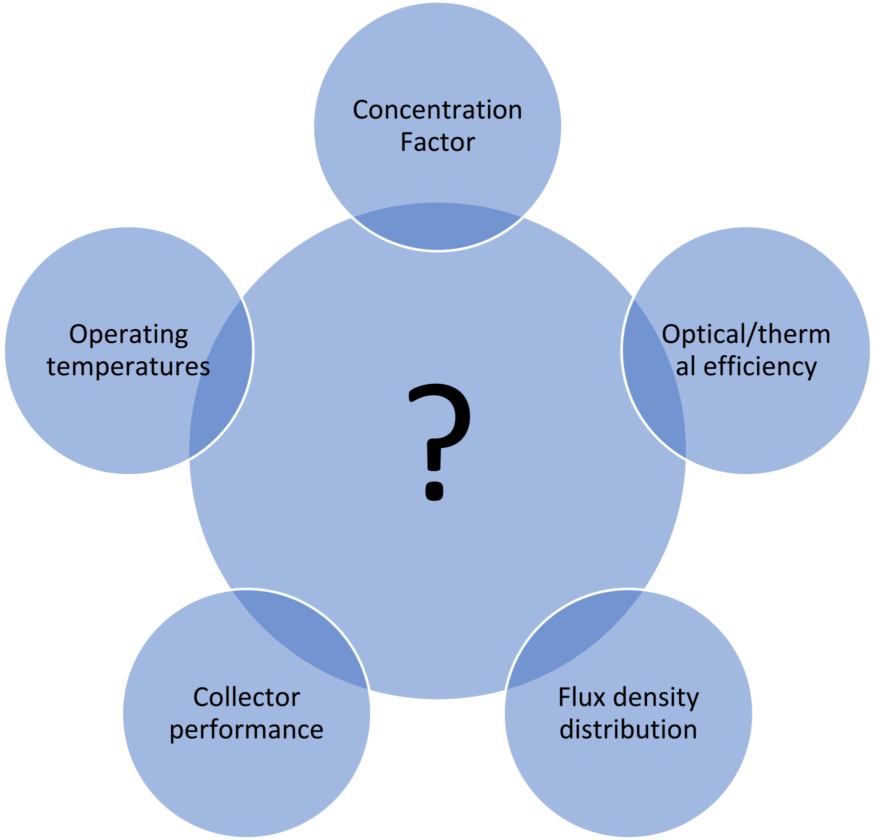
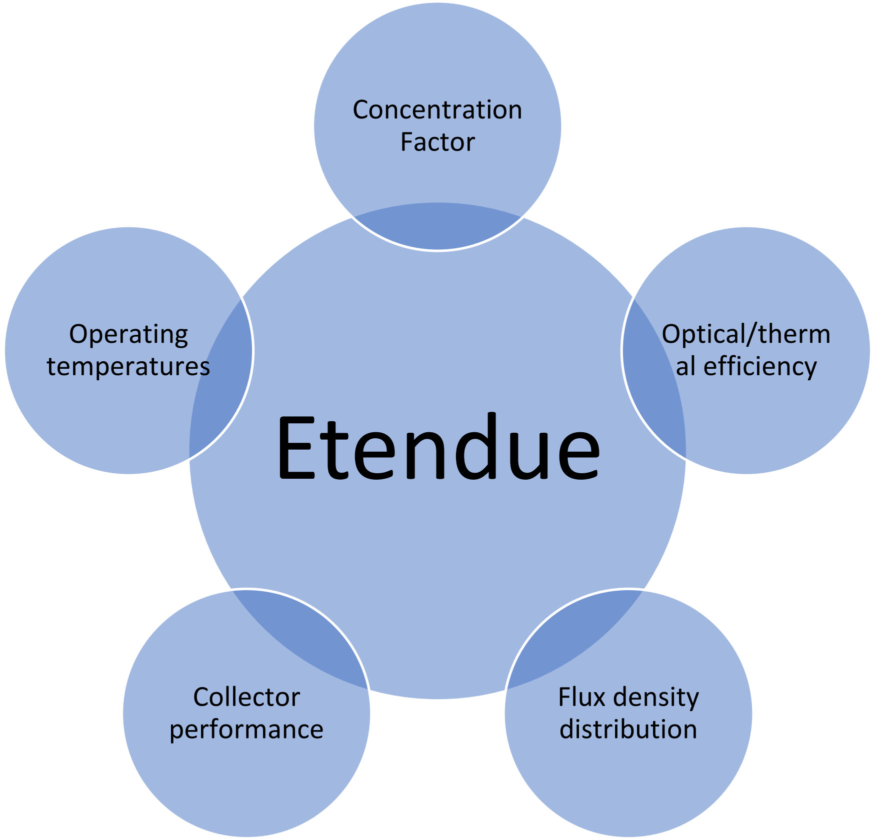
Outline

- The main guiding idea of solar concentration
- The limits of concentration and non-imaging optics
- Line focusing concentrators
  - Parabolic trough concentrators
  - Linear Fresnel concentrators
- Point focusing concentrators
  - Parabolic dish concentrators
  - Central Tower concentrators
- Future developments and trends
- Conclusions
- References

What is the main guiding idea of solar concentration?



The main guiding idea of solar concentration



Etendue

Concentration Factor

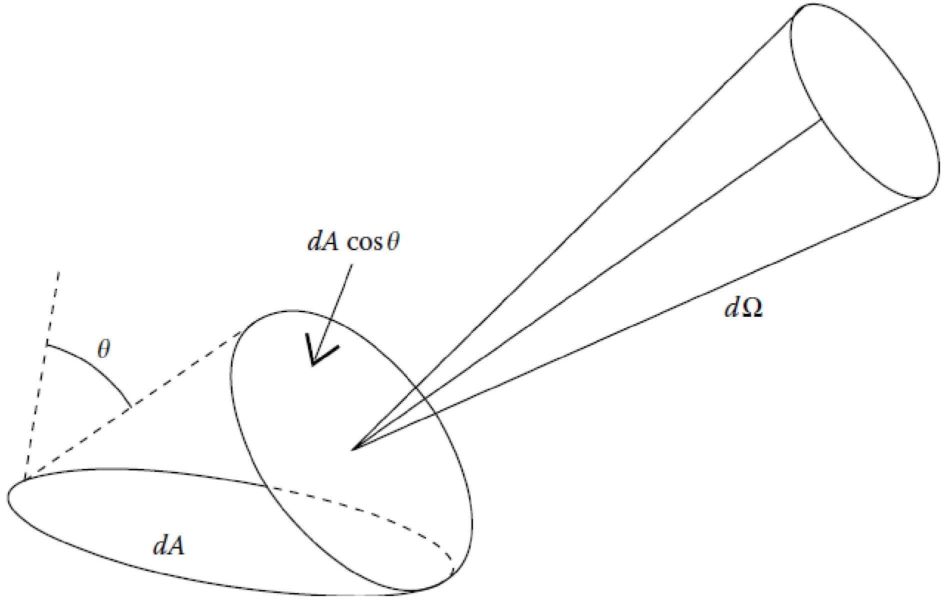
Optical/thermal efficiency

Flux density distribution

Collector performance

Operating temperatures

The concept of Etendue

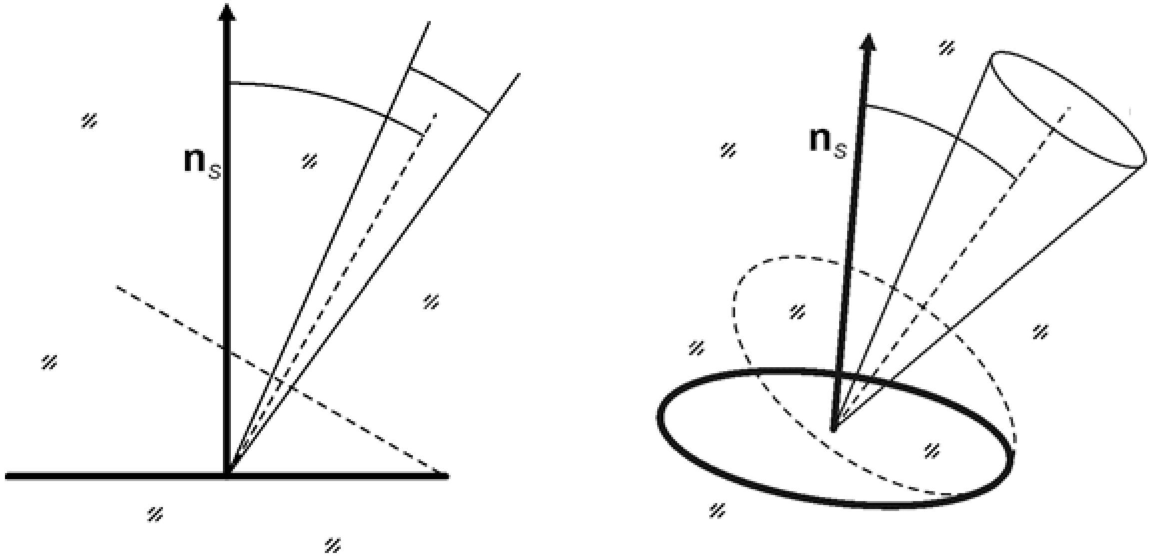


- **Spatial room** (light crosses dA in direction θ): dA cosθ
- **Angular room** (from within the solid angle): dΩ

$$dU = n dA \cos\theta \, d\Omega$$

Etendue is a geometrical quantity that measures the **amount of "room" available for light to pass through**

The concept of Etendue



Etendue for a differential surface element in 2D (left) and 3D (right)

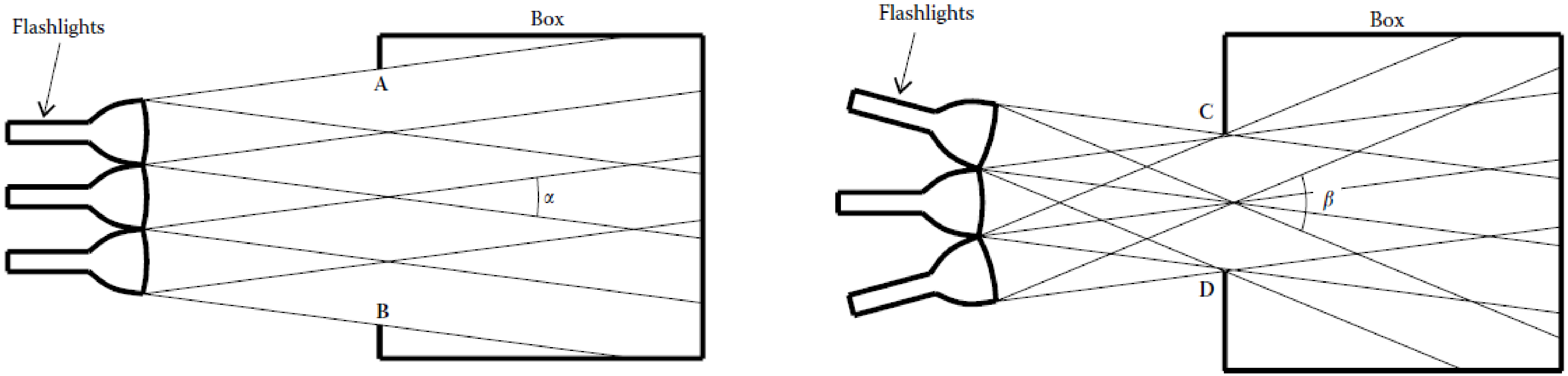
- **In 2D-systems:**

$$dU = ndA\cos\theta\, d\Omega$$

$$U = nA\int_{-\theta}^{+\theta}\cos\theta\, d\theta = 2nA\sin\theta$$

Which corresponds to the etendue of the light crossing a length *A* within a solid angle ±θ

The concept of Etendue

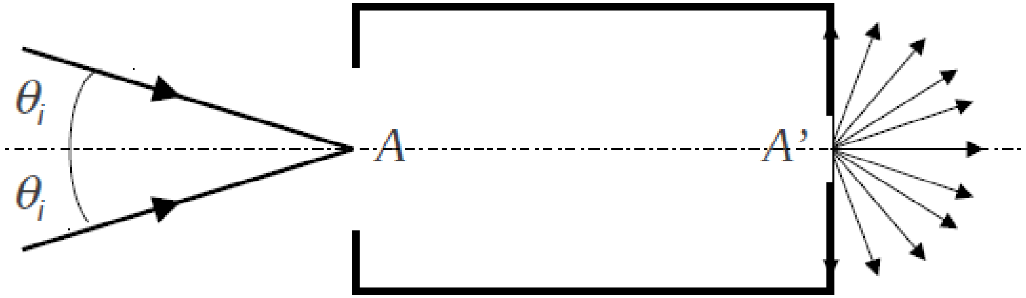


$$U_1 = 2n[\mathbf{A},\mathbf{B}]\sin\alpha$$

$$U_2 = 2n[\mathbf{C},\mathbf{D}]\sin\beta$$

From the conservation of the étendue ($U_1 = U_2$) → $\beta > \alpha$

Conservation of etendue and maximum concentration



Etendue incident on a aperture *A* within a solid angle ±θi and exiting though a surface *A'*. What is the maximum concentration C = A/A' possible?

- The etendue at entrance *A*, U_A, is given by:

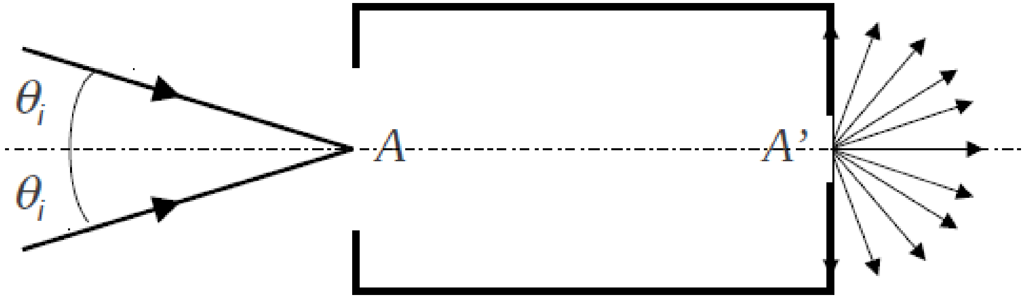
$$U_A = 2nA\sin\theta_i$$

- The etendue at exit *A'*, $U_{A'}$, is given by:

$$U_{A'} = 2nA'\sin\theta_e$$

- Conservation of etendue implies $U_A = U_A'$

Conservation of etendue and maximum concentration



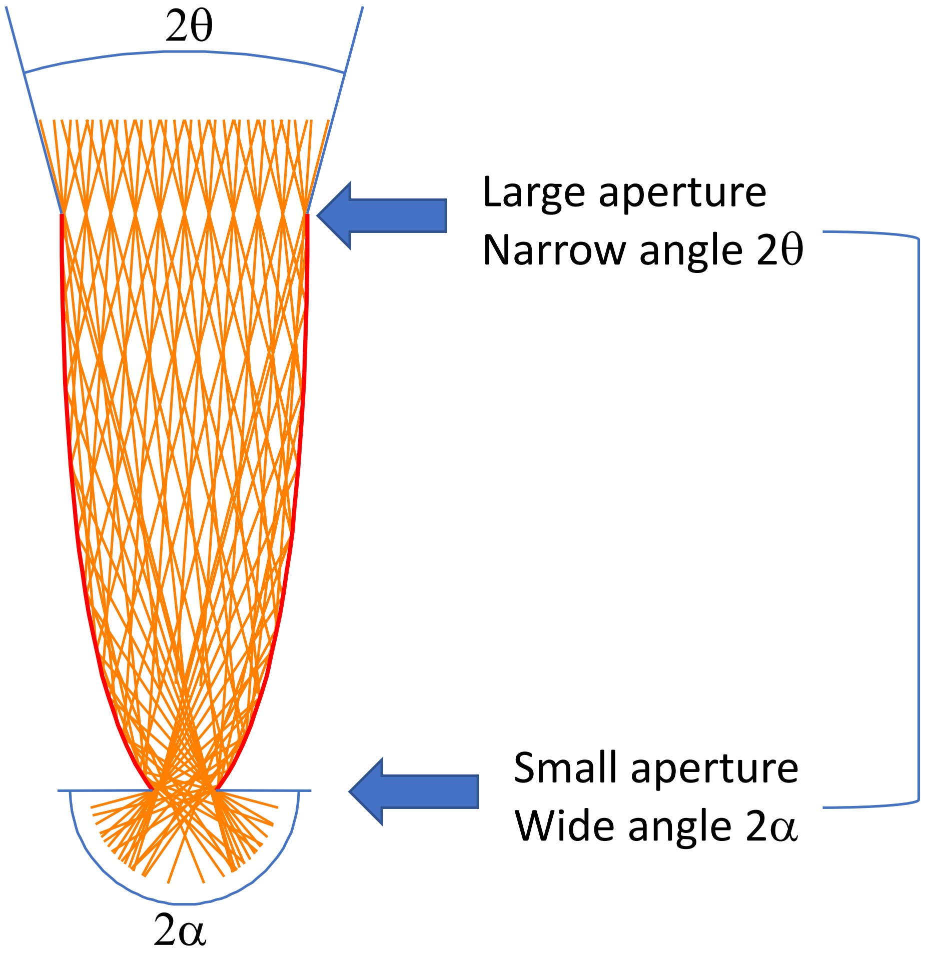
Etendue incident on a aperture *A* within a solid angle ±θi and exiting though a surface *A'*. What is the maximum concentration C = A/A' possible?

- We want the maximum etendue (maximum concentration) at the exit. Therefore, $\theta_e = \pi/2$ and for a uniform medium *n*=1:

$$2A\sin\theta_i = 2A'$$

$$\boxed{\frac{A}{A'} = C = \frac{1}{\sin\theta_i}}$$

Maximum concentration for 2D-systems

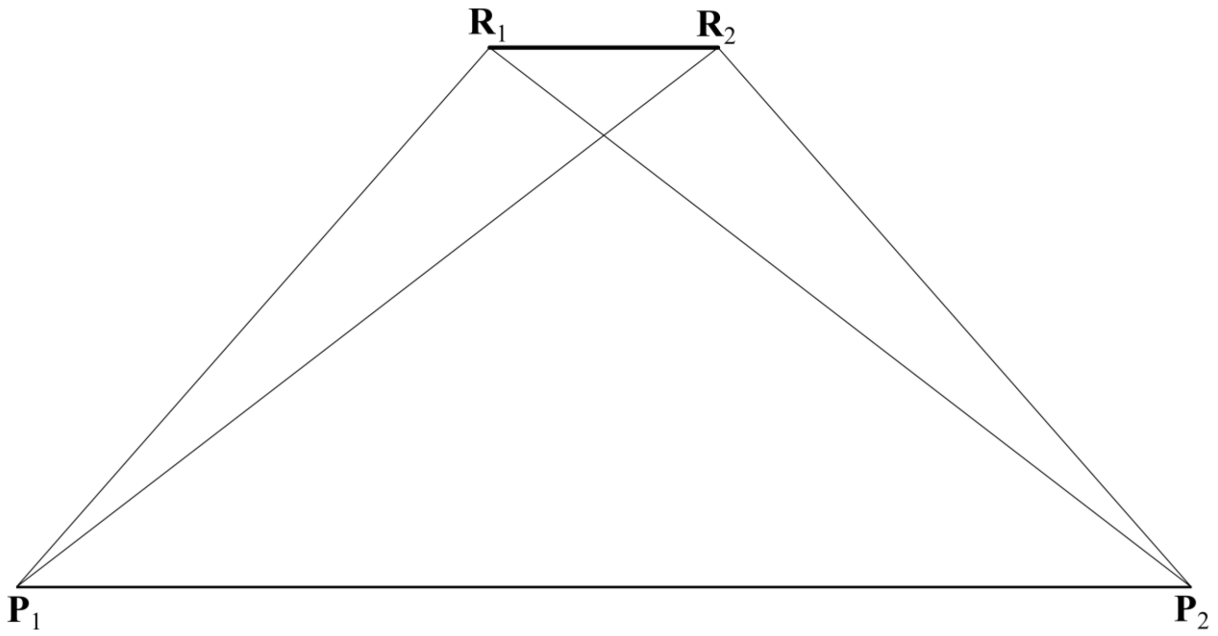


Large aperture
Narrow angle 2θ

Small aperture
Wide angle 2α

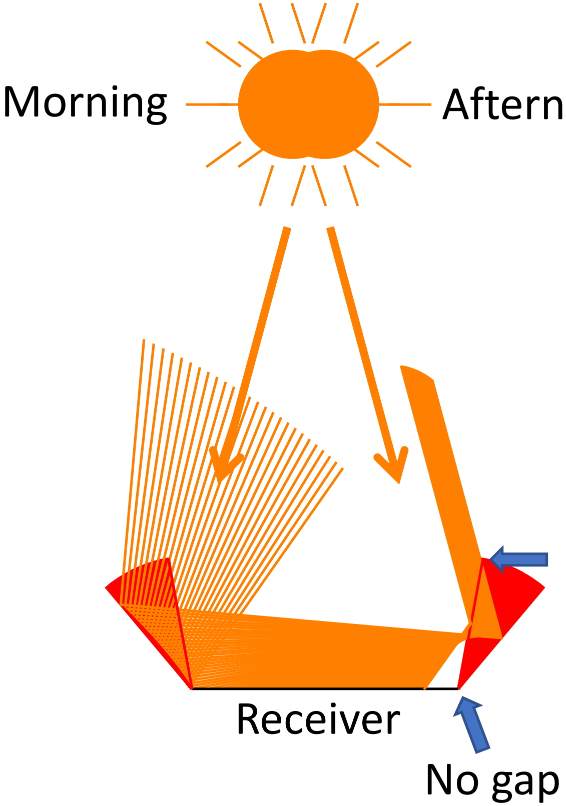
Conservation of etendue

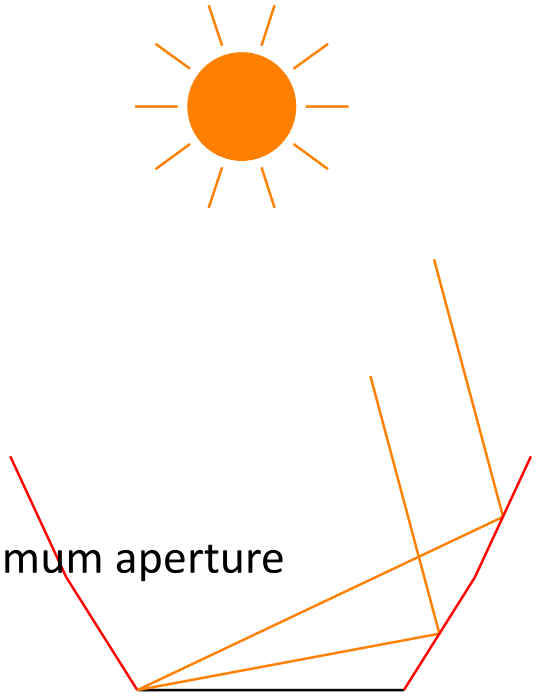
A trade-off: **The Hottel's string method.** The etendue exchanged between two surfaces can be given by the difference of the optical path length.

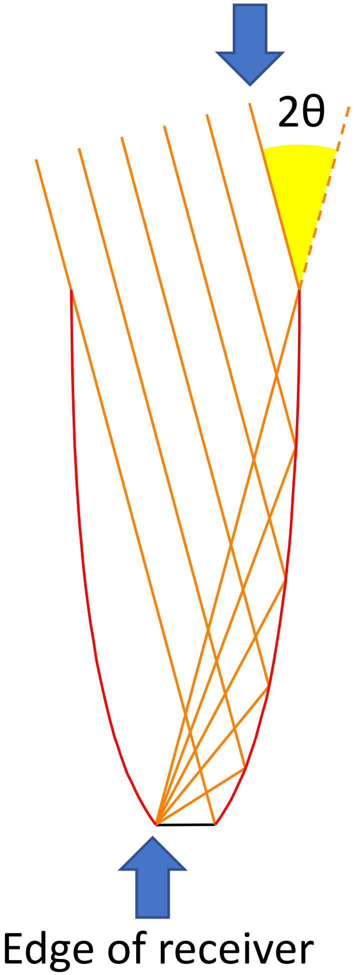


$$U_{\mathrm{P1P2-R1R2}} = [\mathbf{P}_1, \mathbf{R}_2] + [\mathbf{P}_2, \mathbf{R}_1] - [\mathbf{R}_1, \mathbf{P}_1] - [\mathbf{R}_2, \mathbf{P}_2]$$

The limits of concentration and non-imaging optics



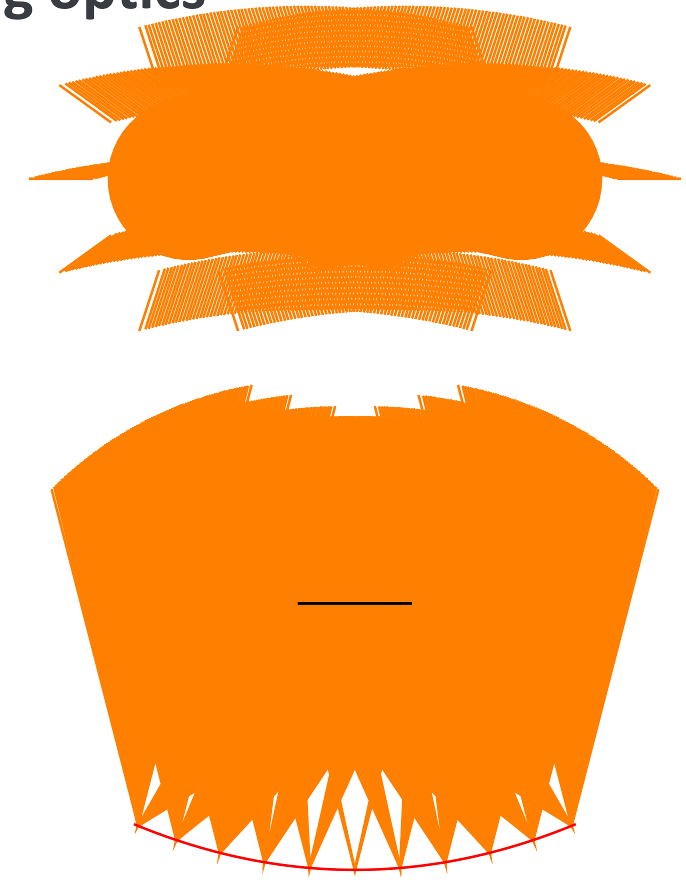




Edge-Ray Principle: Edge rays of the incoming radiation are redirected to the edges of the receiver.

The limits of concentration and non-imaging optics

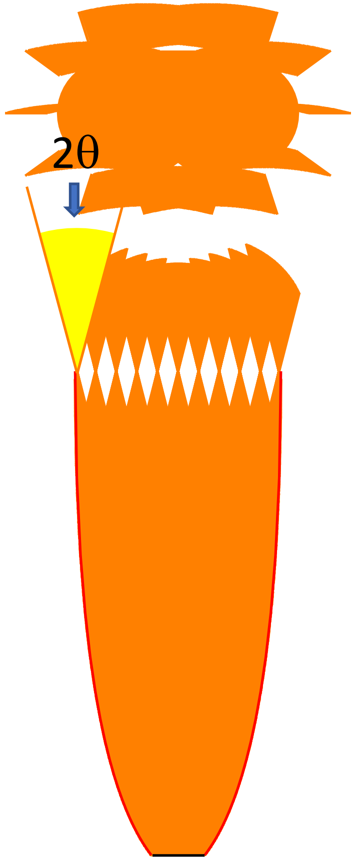
Imaging optics such parabolas, lens, etc., tend to violate the Edge-Ray Principle. They form image(s) somewhere between ±θ but not at the maximum acceptance angle.



Small acceptance angle!

The limits of concentration and non-imaging optics

Non-Imaging optics such as CPC, Trumpet, etc., respect the Edge-Ray Principle. They form image(s) at maximum acceptance but not in between ±θ.

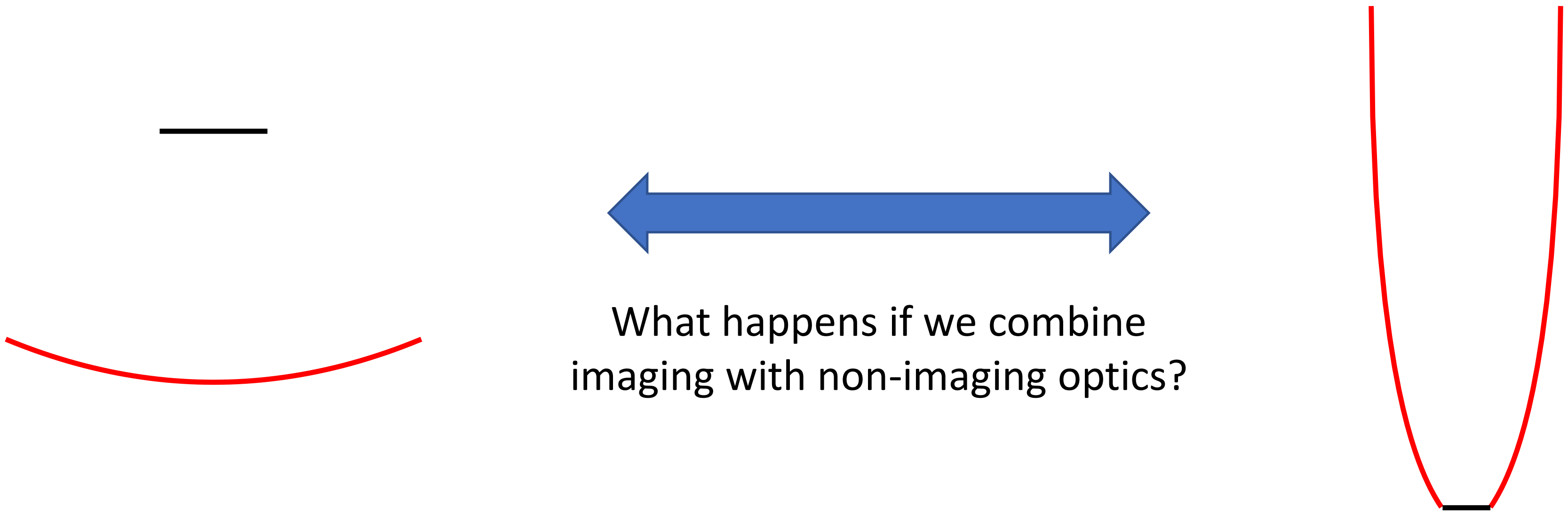


Maximum acceptance angle!

The limits of concentration and non-imaging optics

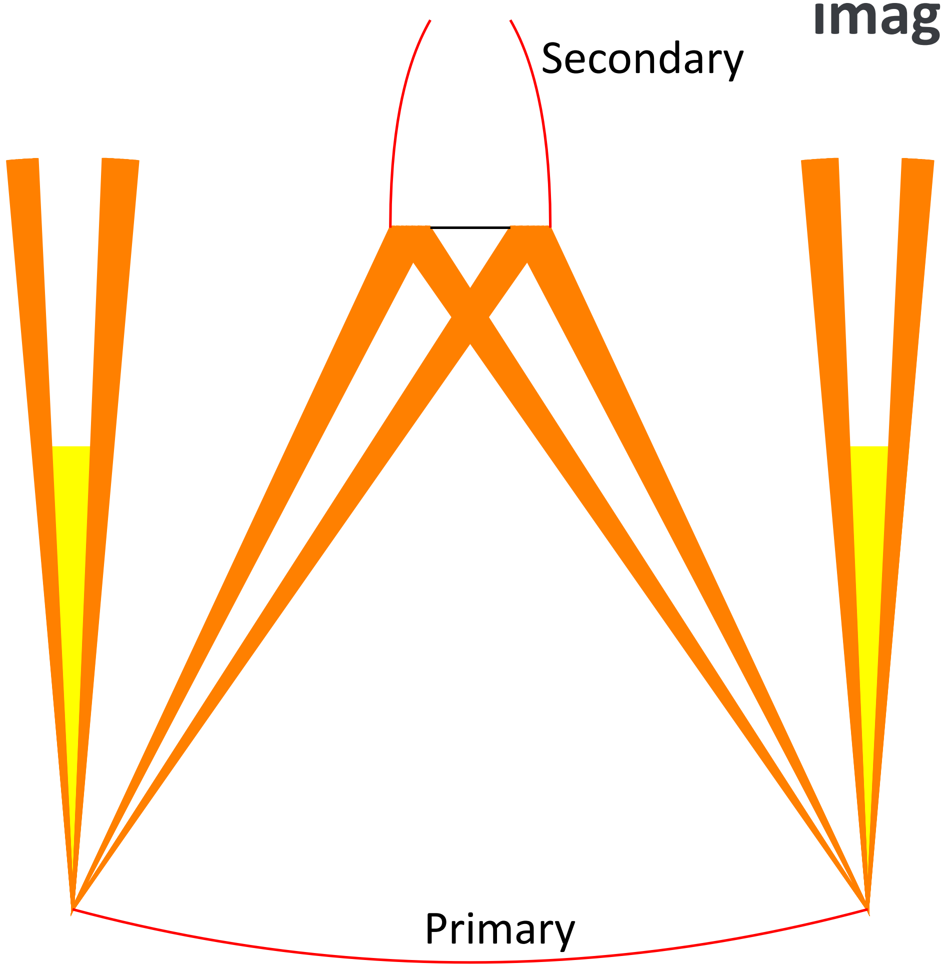
Imaging optics usually fall short from the theoretical limits (small acceptance-angle for a given concentration factor). However, they are compact (low f-number)

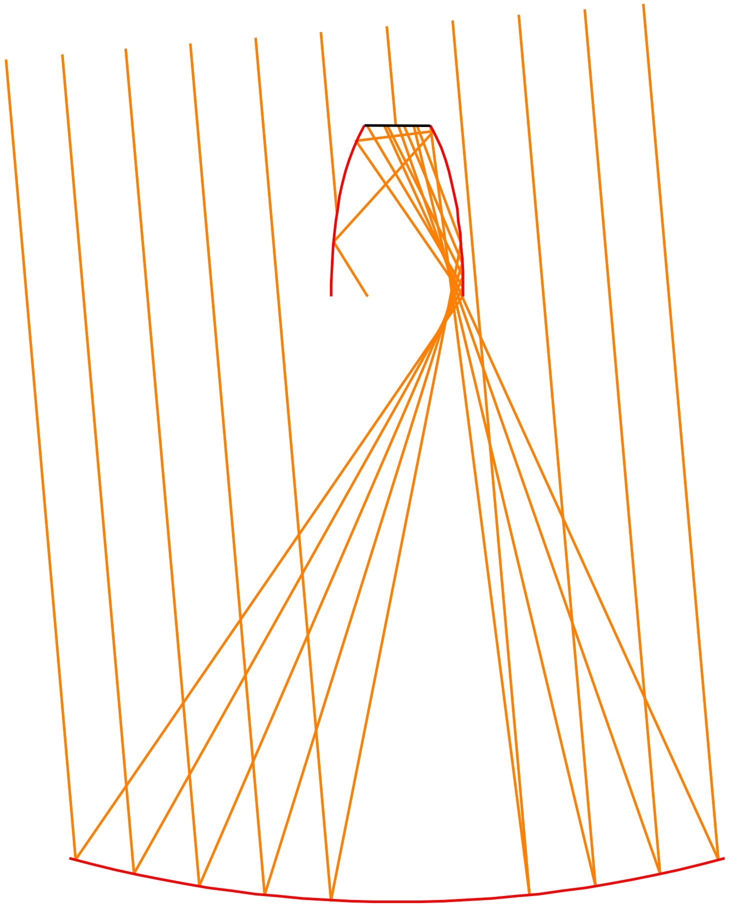
Non-Imaging optics usually reach the theoretical limits (maximum acceptance-angle for a given concentration factor). However, they are not compact (high f-number)



What happens if we combine imaging with non-imaging optics?

The limits of concentration and non-imaging optics

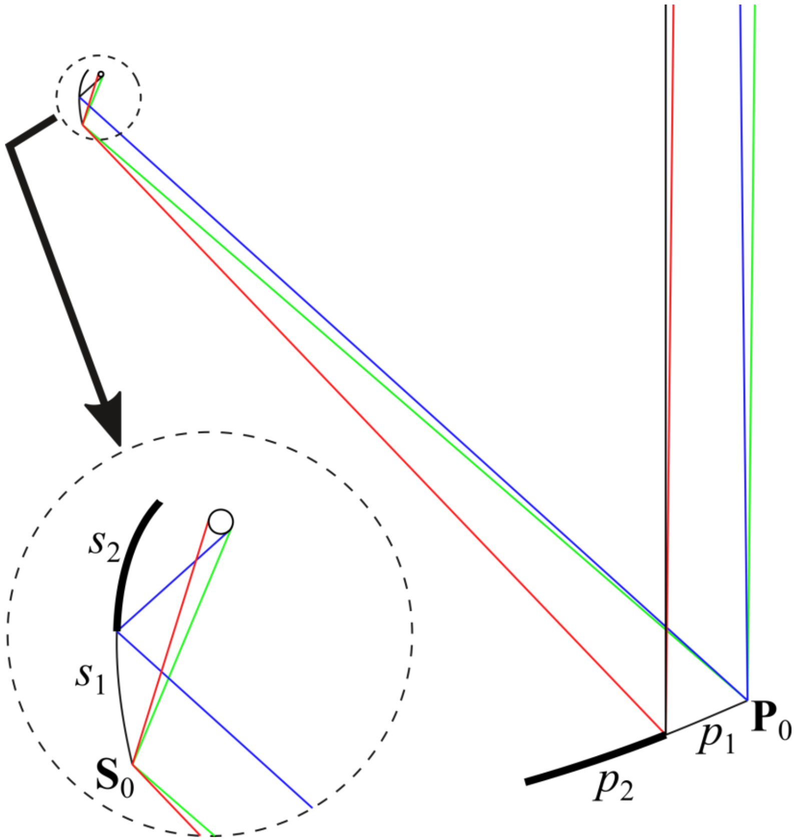


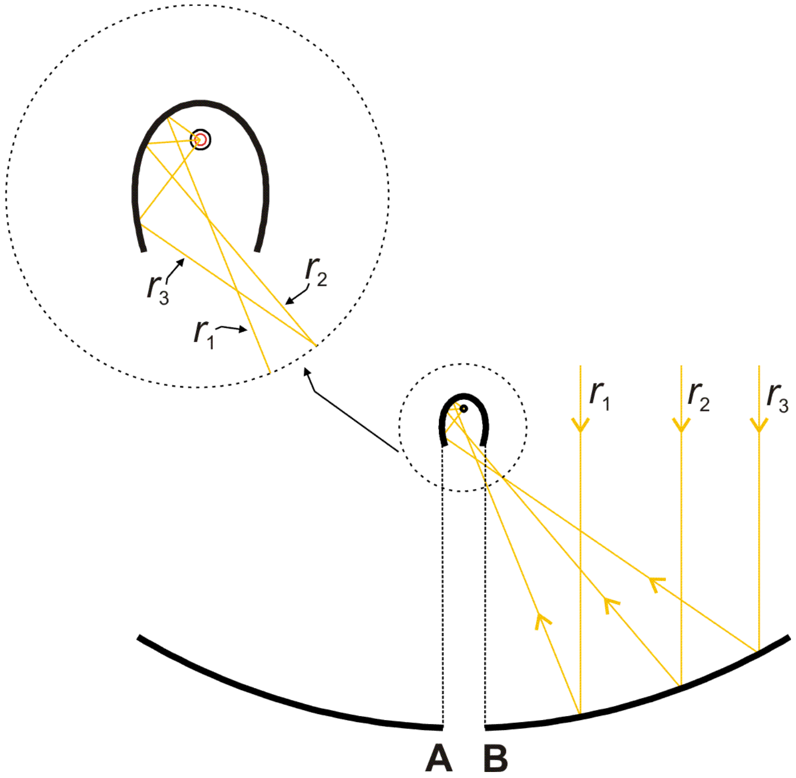


Compared to CPC:
Trades some acceptance for compactness

Compared to the parabola:
Trades some compactness for acceptance

Line Focusing Concentrators – Parabolic Trough concentrators





- Simultaneous Multiple Surface method with double reflective mirrors (XX SMS)

- Designed for maximum concentration (etendue conservation and edge-ray principle)

- Light enters perpendicularly to the receiver to reduce Fresnel losses.

Line Focusing Concentrators – Parabolic Trough concentrators

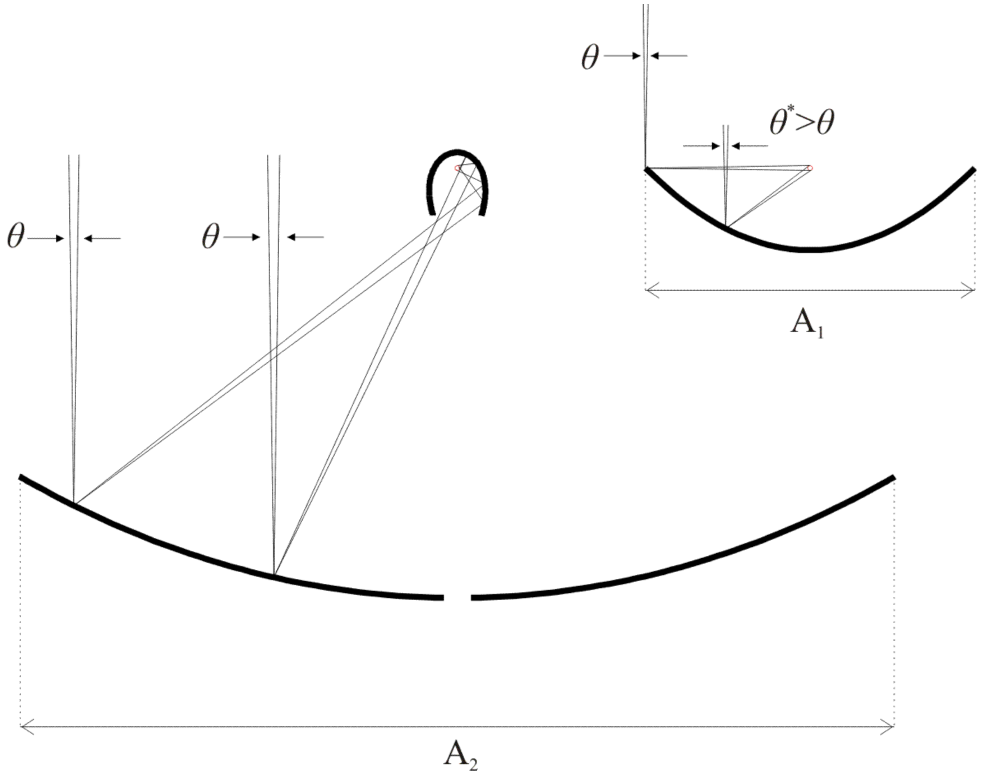
A comparison with PT concentrators

	Aperture size (m)	Receiver radius (m)	Aspect ratio (Height/Width)	φ (deg)	Cg (X)	θ (deg)	CAP	η_{opt0}
PT	5,77	0,035	0,30	80,3	26,24	0,694	0,32	0,81
XX SMS	11,08	0,035	0,51	55	50,38	0,694	0,61	0,72

Optic	DNI Faro, Portugal (kWh/m2)	Collected Energy per aperture area (kWh/m^2)	Total amount of collected energy (kWh)*
PT	2234	1304	7524
XX SMS		1150	12742

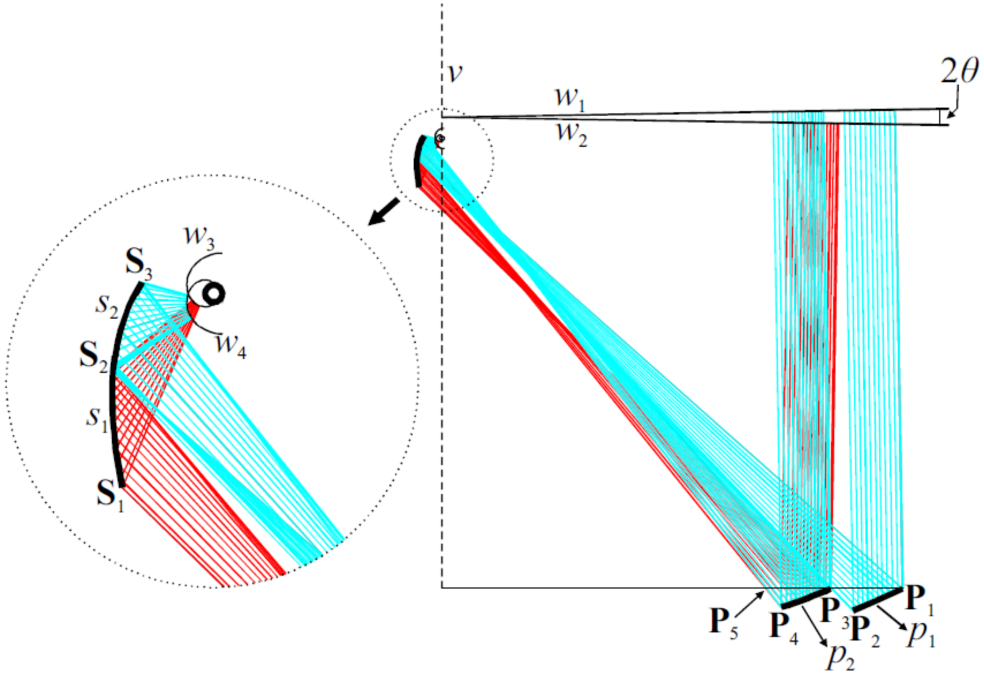
* - For a length of 1m. Calculations done using a raytracing technique.

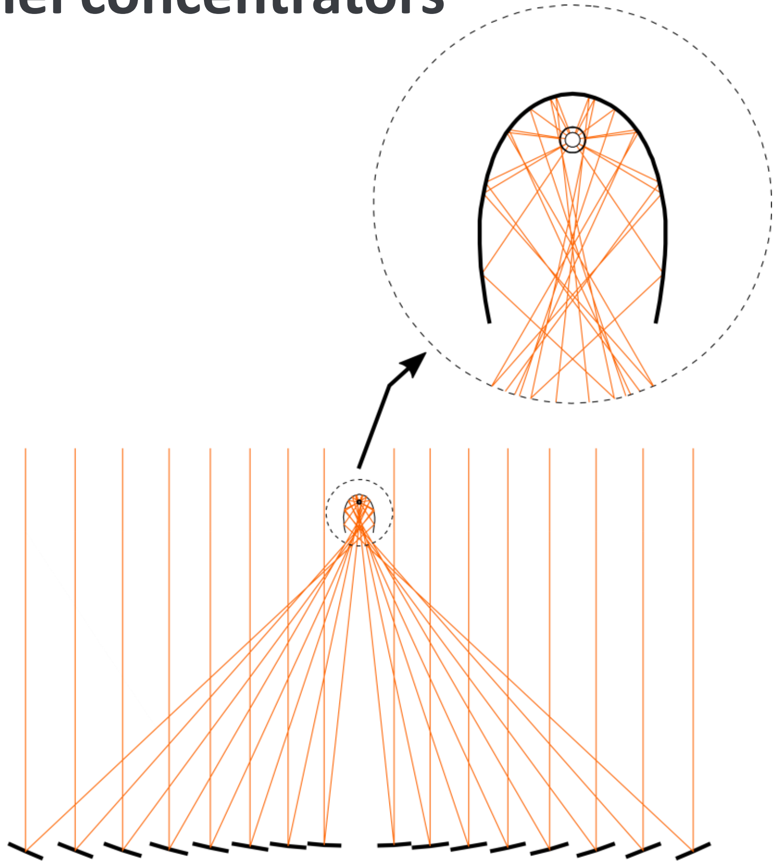
Line Focusing Concentrators – Parabolic Trough concentrators



A2 >> A1! The XX SMS has a much **LARGER** aperture width for the same acceptance-angle of the PT concentrator.

Line Focusing Concentrators – Linear Fresnel concentrators





- Linear Fresnel XX SMS (similar to the previous XX SMS)
- Maximum concentration
- Maximum compactness of heliostats

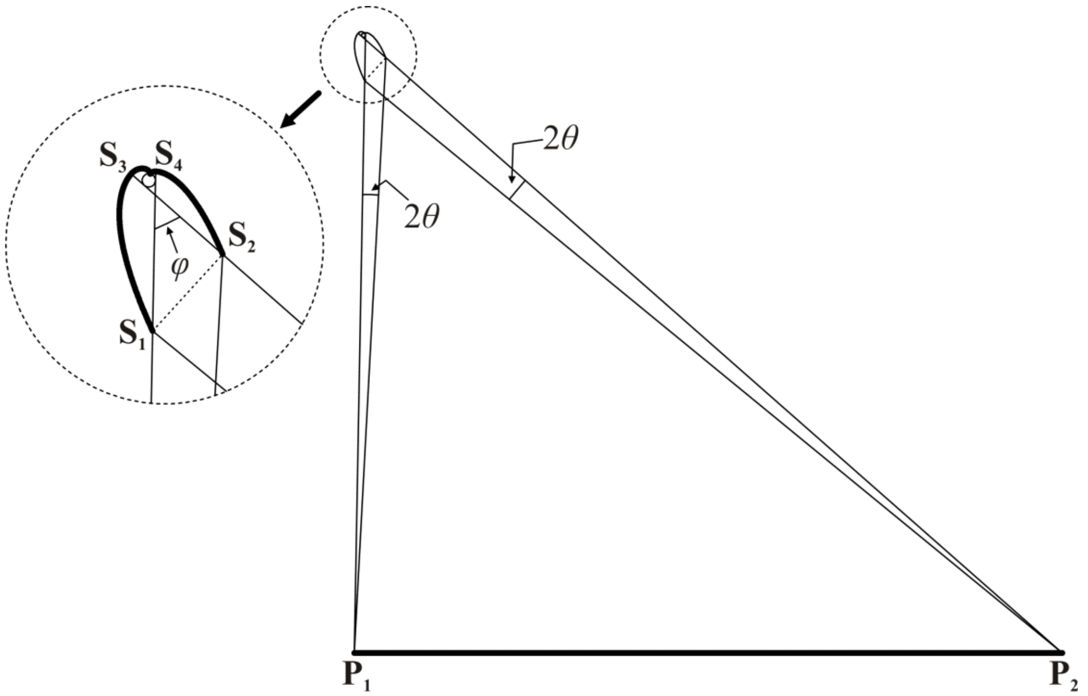
Line Focusing Concentrators – Linear Fresnel concentrators

A comparison with PT concentrators and Fresnel with CPC concentrators

Optic	DNI Faro, Portugal (kWh/m2)	Cg (X)	θ (°)	CAP	η_{opt0}	Collected Energy (kWh)*
Fresnel CPC	2234	48.21	0.44	0.38	0.68	11361
Fresnel XX SMS #1		73.71	0.44	0.57	0.68	15122
PT		26.24	0.69	0.32	0.81	7527
Fresnel XX SMS #2		52.95	0.69	0.64	0.66	10622

* - For a length of 1m. Calculations done using a raytracing technique.

Line Focusing Concentrators – Linear Fresnel concentrators



The etendue, *U*, exchanged between $\mathbf{P}_1$ and $\mathbf{P}_2$ is given by:

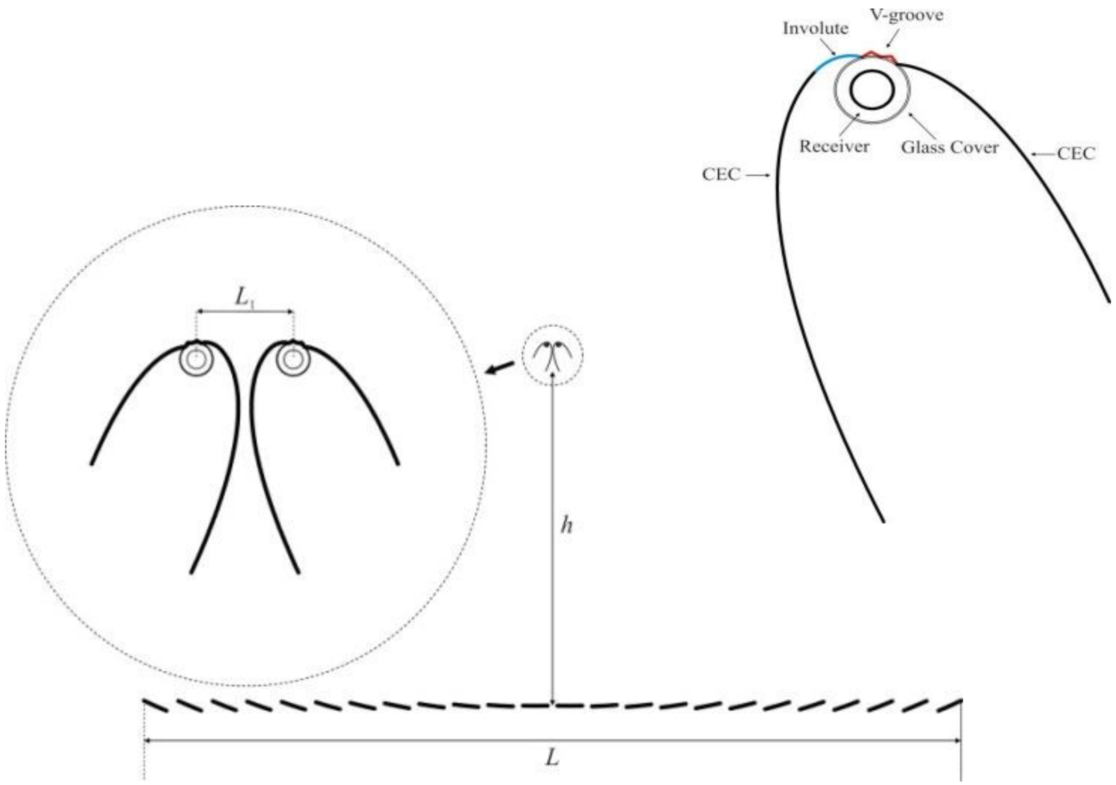
$$U = [\mathbf{P}_1, \mathbf{S}_2] + [\mathbf{P}_2, \mathbf{S}_1] - [\mathbf{P}_1, \mathbf{S}_1] - [\mathbf{P}_2 - \mathbf{S}_2]$$

The maximum etendue capture by the receiver, U_R, is given by *(r* is the radius)*:*

$$U_R = 4\pi r$$

$$\Rightarrow \boxed{r = \frac{U}{4\pi}}$$

Line Focusing Concentrators – Linear Fresnel concentrators



- Compact system with two receivers placed at the same tower with a low distance ($L_1 < 0.5$m) between them.
- Asymmetric set of primary/secondary stage CEC combinations
- It uses a very large primary (L> 20m) contributing for the reduction of rows in the total field;
- The two evacuated tubular receivers can be fed by a single pipe and merge in a single exit pipe.

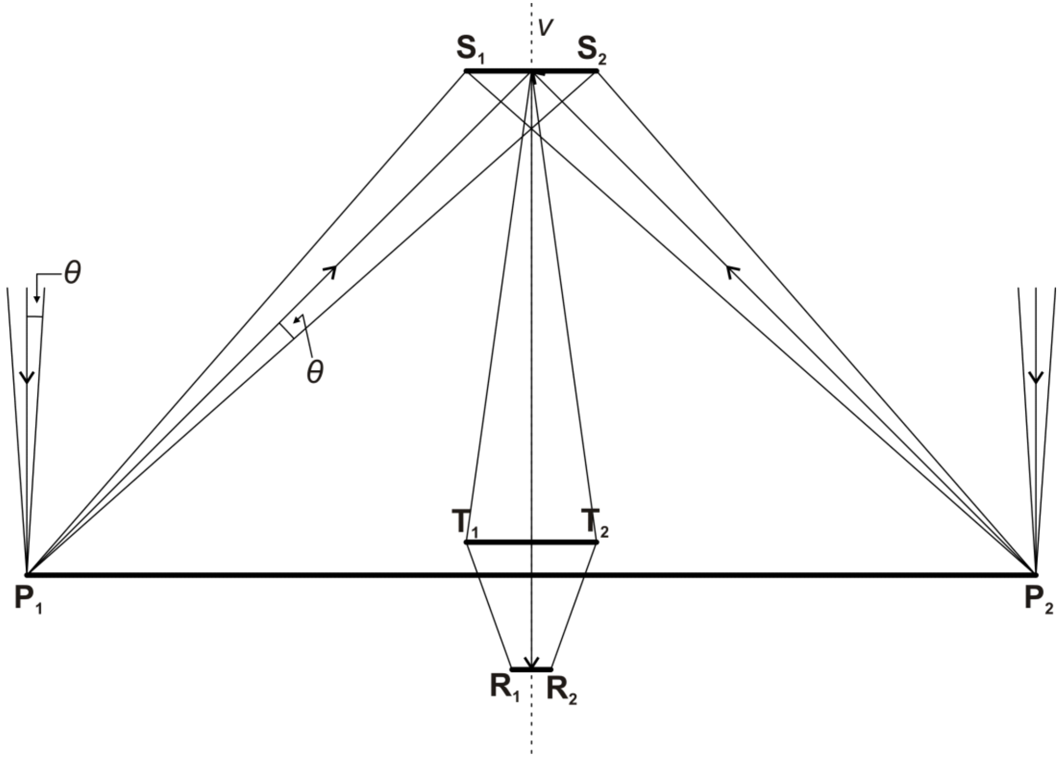
Line Focusing Concentrators – Linear Fresnel concentrators

Geometric data and performance estimation

Optic	Aperture width (m)	Total mirror aperture width (m)	Receiver radius (m)	Receiver height (m)	Number of mirrors	Mirror width (m)	Cg (X)	φ (°)
Dual Asymmetric CEC LFR Concentrator	26	22	0.035	10.8	22	1	45	49.73

Location	Thermal Energy delivered (kWh)	Electricity produced (kWh)	Total average yearly efficiency (kWh)
Faro, Portugal	2.11 x 10^8	8.38 x 10^7	0.14
Hurgahda, Egypt	3.02 x 10^8	1.22 x 10^8	0.16

Point Focusing Concentrators – Parabolic dish concentrators



The etendue reaching the primary **P_1P_2**, U_{P1P2}, is given by:

$$U_{\mathrm{P1P2}} = 2[\mathbf{P_1}, \mathbf{P_2}] \sin\theta$$

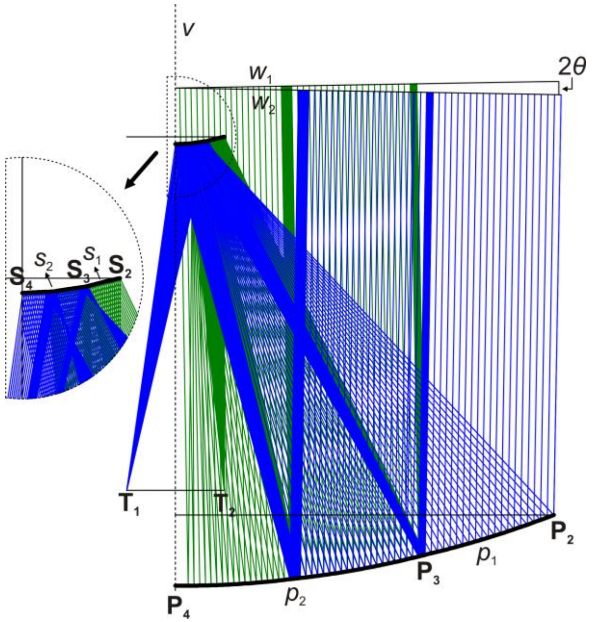
$$U_{\mathrm{P1P2-S1S2}} = [\mathbf{P}_1, \mathbf{S}_2] + [\mathbf{P}_2, \mathbf{S}_1] - [\mathbf{S}_1, \mathbf{P}_1] - [\mathbf{S}_2, \mathbf{P}_2]$$

$$U_{\mathrm{S1S2-T1T2}} = [\mathbf{S}_1, \mathbf{T}_2] + [\mathbf{S}_2, \mathbf{T}_1] - [\mathbf{S}_1, \mathbf{T}_1] - [\mathbf{S}_2, \mathbf{T}_2]$$

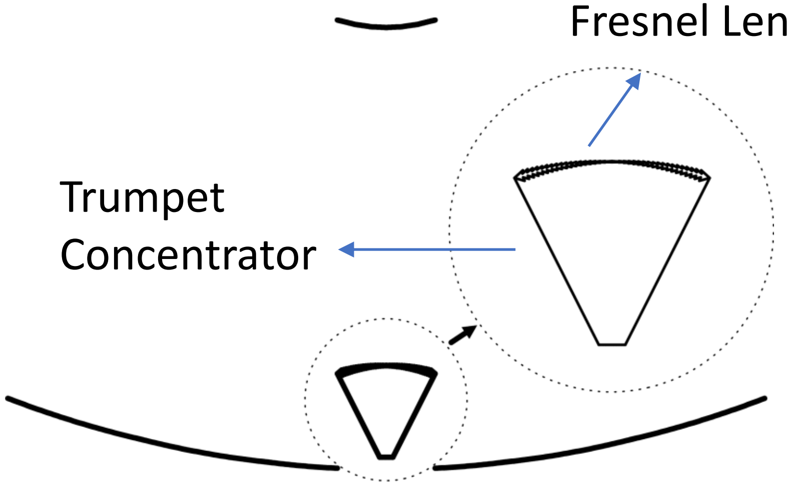
$$U_{\mathrm{T1T2-R1R2}} = [\mathbf{T}_1, \mathbf{R}_2] + [\mathbf{T}_2, \mathbf{R}_1] - [\mathbf{T}_1, \mathbf{R}_1] - [\mathbf{T}_2, \mathbf{R}_2]$$

The conservation of the etendue implies that $U_{P1P2}= U_{S1S2-T1T2}$ and the same between **T_1T_2** and **R_1R_2**.

Point Focusing Concentrators – Parabolic dish concentrators



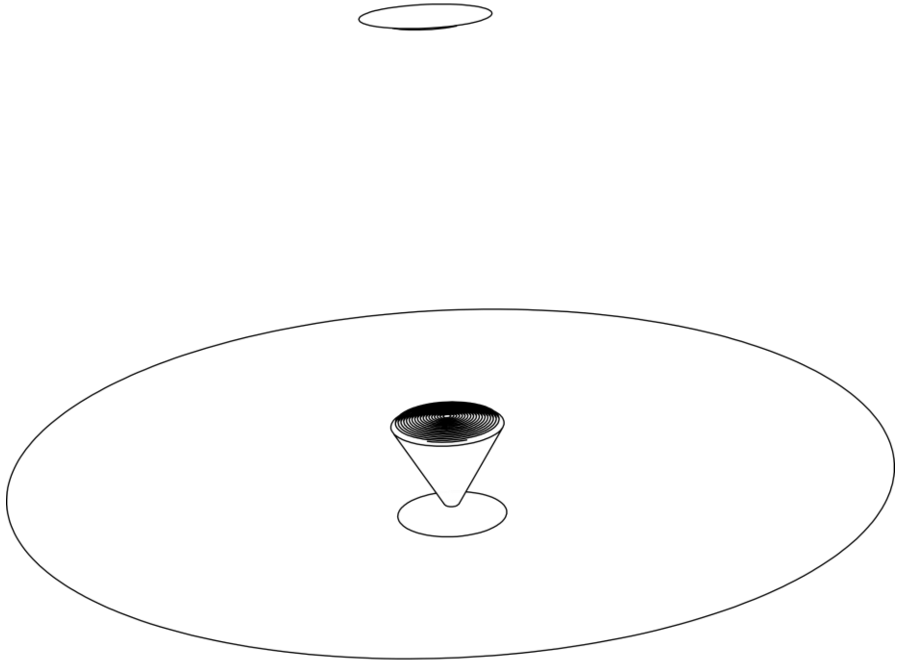
Design



Fresnel Lens

Trumpet
Concentrator

2D-version



3D-version

Point Focusing Concentrators – Parabolic dish concentrators

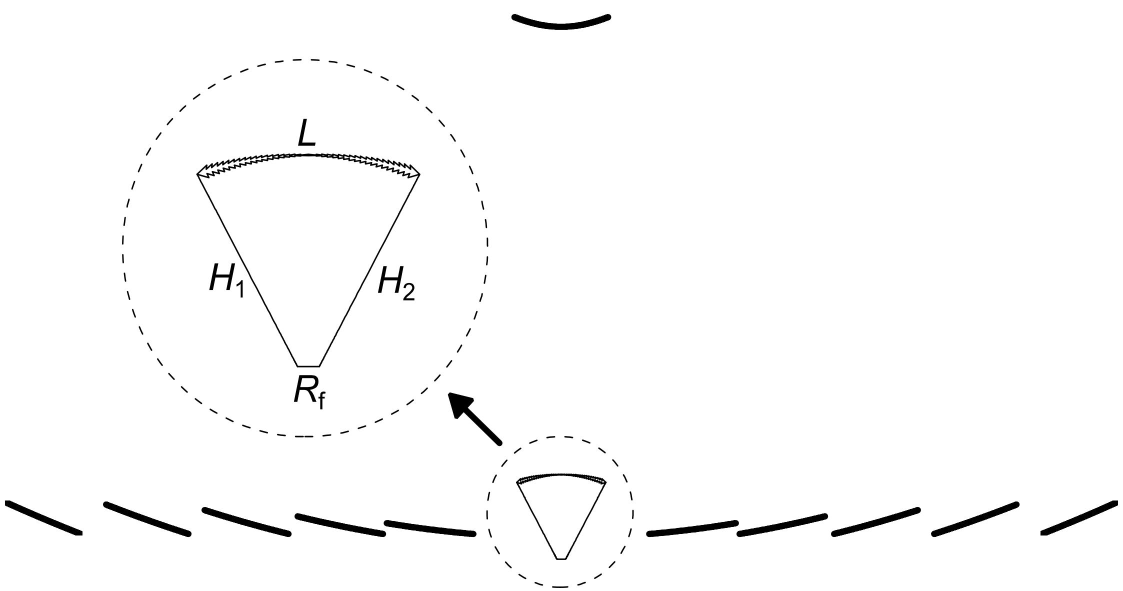
Geometric data and expected performance (using a raytracing method). Materials used: 92% of reflectivity, 90% of absorptivity, 90% of transmissivity and 1.48 of refractive index (lens).

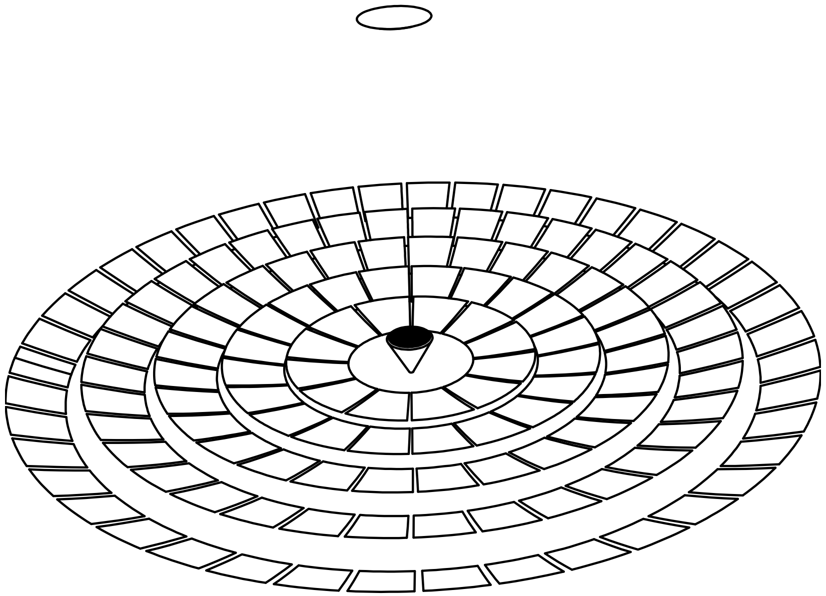
Aperture width (m)	Receiver Height (m)	Fresnel Lens width (m)	Receiver width (m)	η_{opt}	C_g (X)	θ (deg)	CAP	Peak Power @ DNI 1000W/m^2
7	4.1	0.91	0.12	0.5	2339	0.58	0.49	20kW

- Advantages: Practical configuration with a interesting CAP value;
- Drawbacks: The terceary touches the receiver + multiple reflections inside of the trumpet leading to lower optical efficiencies.

Point Focusing Concentrators – Central Tower concentrators

The same ideas can be applied to Central Tower Concentrators





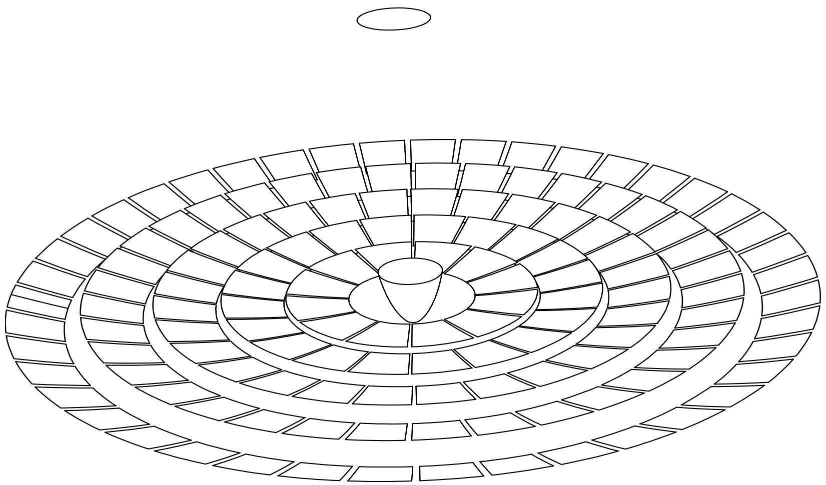
Point Focusing Concentrators – Central Tower concentrators

Geometric data and expected performance (using a raytracing method). Materials used: 92% of reflectivity, 90% of absorptivity, 90% of transmissivity and 1.48 of refractive index (lens).

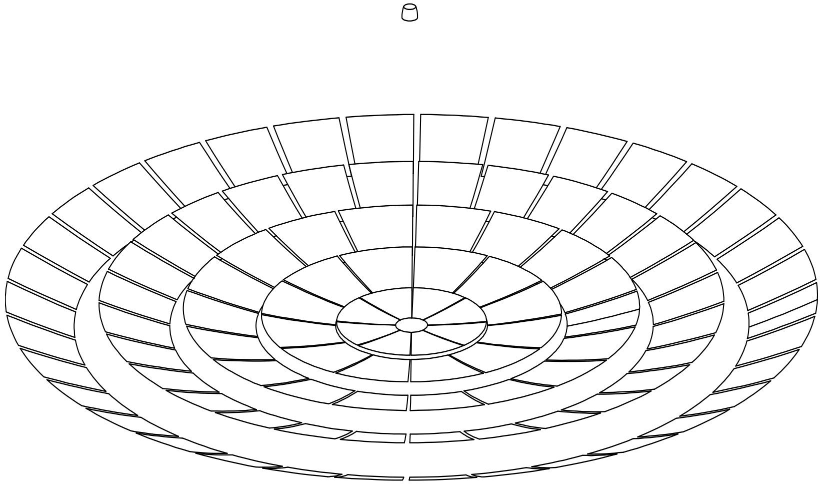
Optic	Total reflective Area (m^2)	Number of heliostats	Receiver height (m)	Secondary mirror area (m^2)	Terceary cavity volume (m^3)	Receiver area (m^2)	C_g (X)	θ (deg)	η_{opt0}	CAP_{3D}	Peak Power @ DNI 1000W/m^2
ST Beam Down with Trumpet+ Fresnel lens terceary concentrator	3407	112	95	57	38	1.01	2300	0.55	0.5	0.46	1.7 MW

Point Focusing Concentrators – Central Tower concentrators

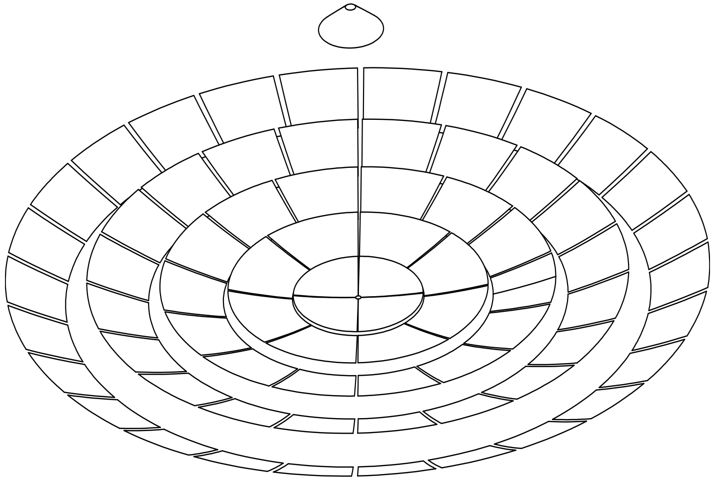
Other configurations are possible…



CT beam-down with CEC-type terceary



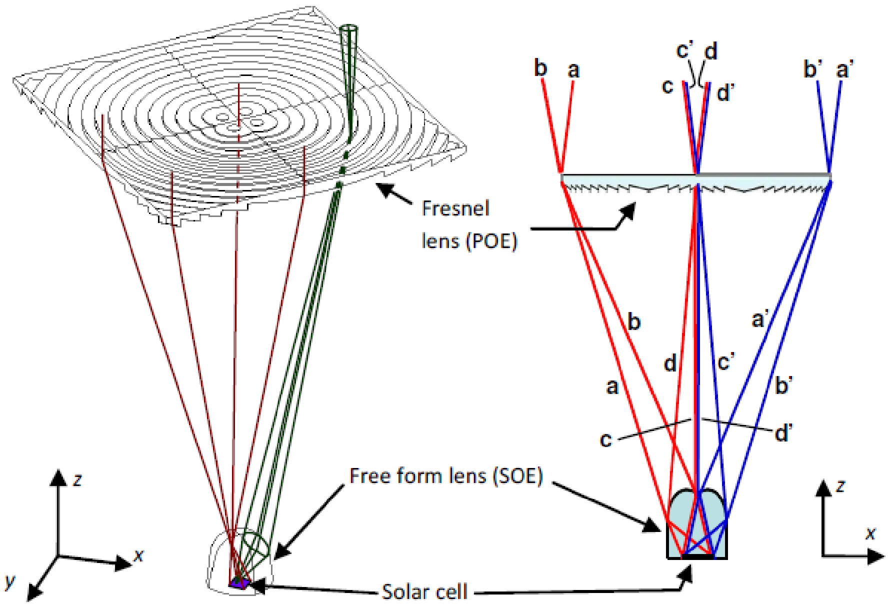
CT with CEC-type secondary



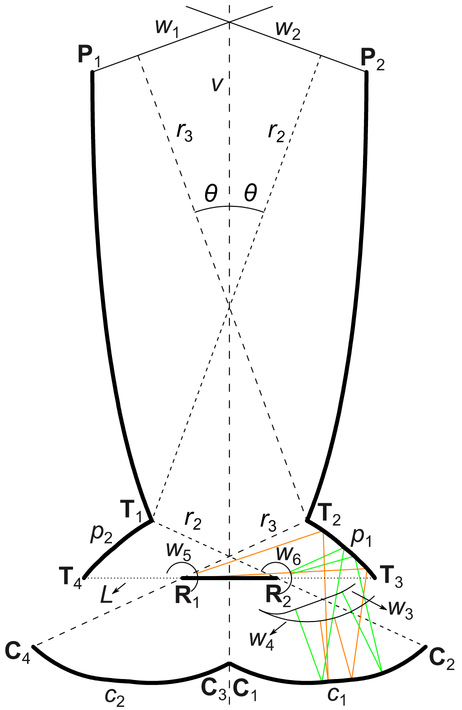
CT with TERC secondary

Future developments and trends

These configurations have two main problems: The non-uniform distribution of the light over the receiver and the thermal short-circuits due to the no gap between the mirrors and the receiver.



Fresnel Kohler lens for better uniformization of the light



Ideal concentrators with gaps

Conclusions

- Etendue-coupling is the main guiding idea of solar concentration
- Imaging optics fall short from the theoretical limits but they can be improved using non-imaging optics
- Multiple configurations for line-focus and point-focus are possible but the principles are the same: etendue-conservation and edge-ray principle.
- These optics achieve higher CAP values, hence improving of the overall performance of these systems
- There is still room from improvements, especially regarding the light distribution over the receiver and gap-losses control.

References

- Chaves, J., Introduction to nonimaging optics, CRC Press, Taylor and Francis Group
- Winston, R., Miñano, J.C., Benítez, P., (contributions by Shatz, N., Bortz, J.,C.), Nonimaging Optics, Elsevier Academic Press, Amsterdam, 2005.
- Canavarro, D. et al, "New second-stage concentrators (XX SMS) for parabolic primaries; Comparison with conventional parabolic trough concentrators", Solar Energy Volume 92, June 2013, Pages 98-105, https://doi.org/10.1016/j.solener.2013.02.011
- Canavarro, D., et al, "Simultaneous Multiple Surface method for Linear Fresnel concentrators with tubular receiver", Solar Energy Volume 110, December 2014, Pages 105-116, https://doi.org/10.1016/j.solener.2014.09.002
- Canavarro, D. et al, "New dual asymmetric CEC linear Fresnel concentrator for evacuated tubular receivers", AIP Conference Proceedings 1850, 040001 (2017); https://doi.org/10.1063/1.4984397
- Canavarro, D., et al., "Simultaneous multiple surface method for the design of new parabolic dish-type concentrator using a Cassegranian approach", AIP Conference Proceedings 2126, 050001 (2019); https://doi.org/10.1063/1.5117584

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ANY QUESTIONS?

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