STERG

SOLAR THERMAL ENERGY RESEARCH GROUP

Optical characterization of radial-staggered heliostat fields: Model validation with SolarPILOT

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Contents

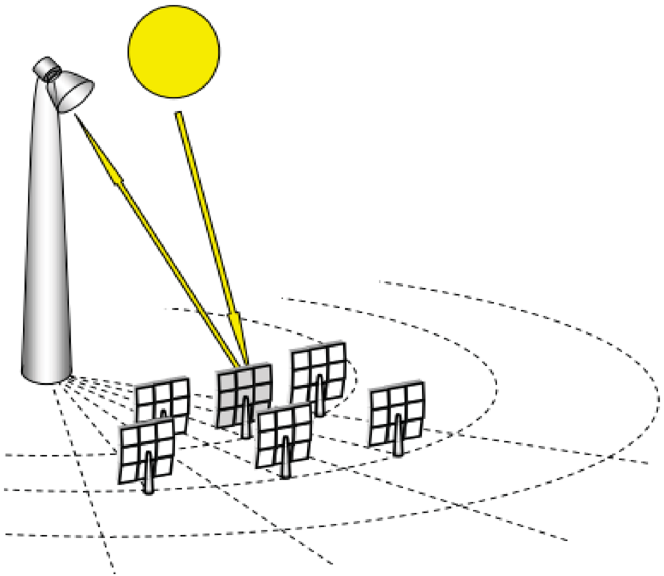
1. Introduction

Heliostats in a power tower plant

Heliostats must be placed in such a way that there is minimum optical and mechanical interference from one another.

Several variables must be optimized:

- Heliostat position in the field
- Outer land boundary
- Receiver type and dimensions
- Height of the tower



Source: https://sam.nrel.gov/

1. Introduction

Power tower plant design

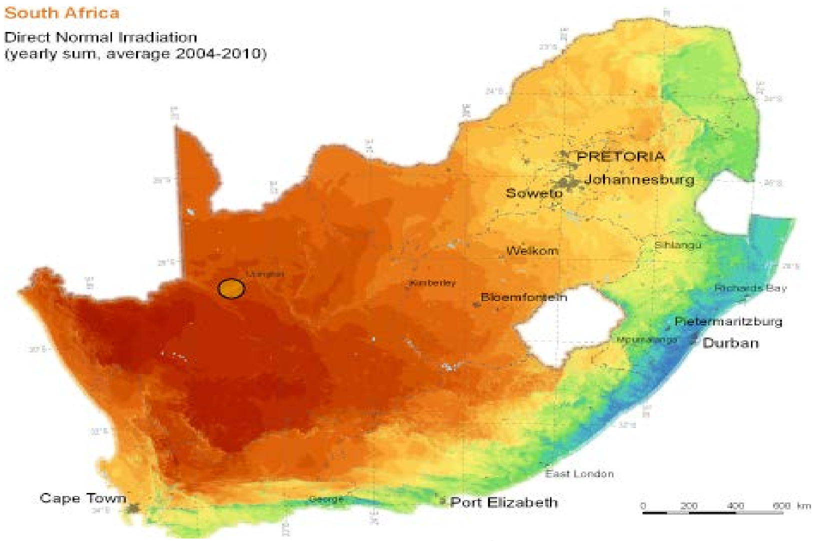
Location: Upington, South Africa

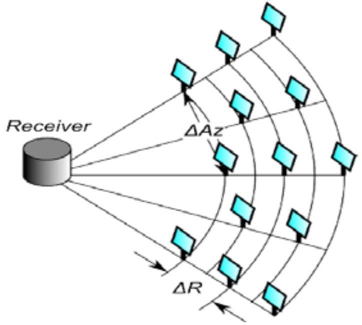
Plant net capacity: 100 MW_e

Thermal Energy Storage (TES): 8 hours

Solar Multiple (SM): 1.8

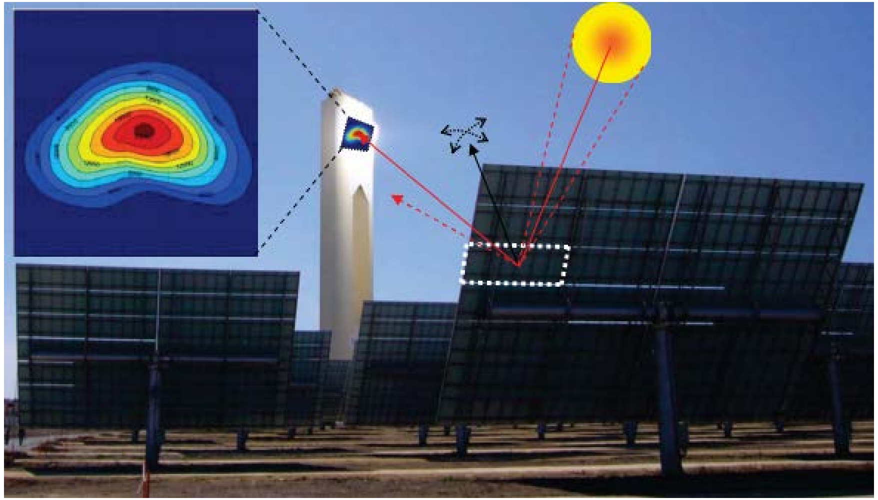
Heliostat field layout: Radial Staggered pattern





2. Optical characterization of power towers plants

Calculation of the reflected beam image in the target plane



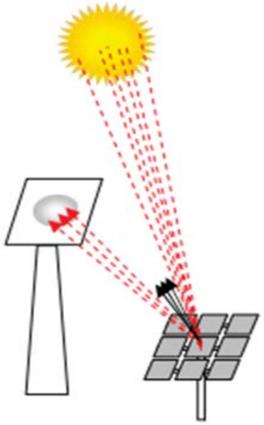
Deviation due to:

- Sunshape error
- Tracking errors
- Slope errors
- Canting errors
- Structural deflection errors
- Temperature dependent errors

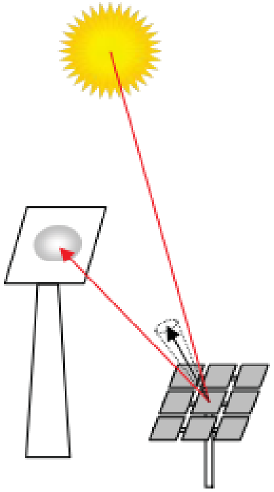
2. Optical characterization of power towers plants

Two methods

Statistical approach (Monte-Carlo Ray-Tracing (MCRT))



Analytical approach (Convolution method)



$$I(x,y) = \frac{e^{-(x^2+y^2)/2}}{2\pi} \sum_{i=0}^{\infty} \sum_{j=0}^{\infty} \frac{C_{ij}}{i!\,j!} \cdot H_i(x) \cdot H_j(y)$$

Source: Pitz-paal, Robert Heliostat field design for solar thermochemical processes

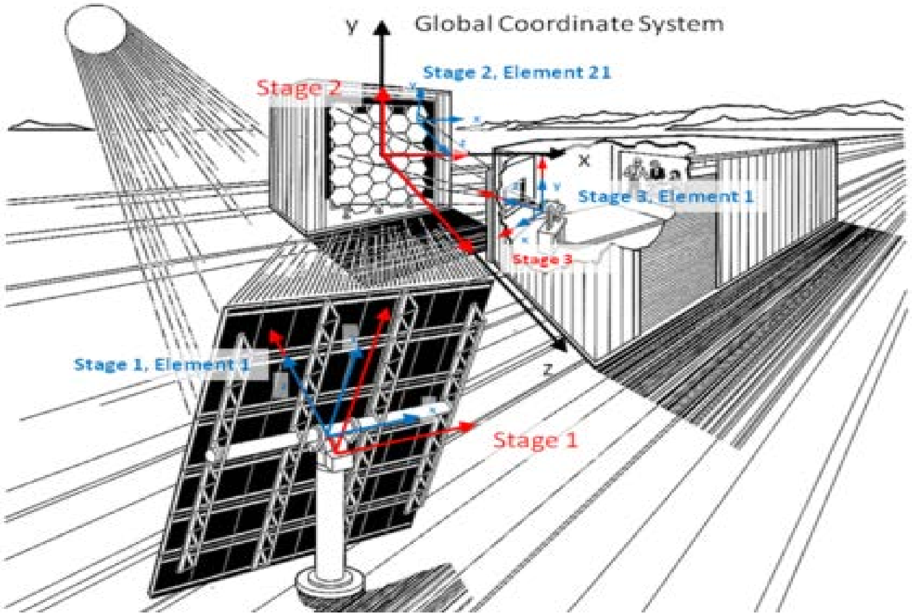
2. Optical characterization of power towers plants

Statistical approach (MCRT)

Randomly chosen bundle of rays from one surface to another, with the surface irradiance proportional to the number of rays causing impact.

Replicates real photon interactions providing accurate results.

Longer processing time.



Source: Wendelin, Tim. SolTRACE: A New Optical Modeling Tool for Concentrating Solar Optics

2. Optical characterization of power towers plants

Analytical approach (Convolution method)

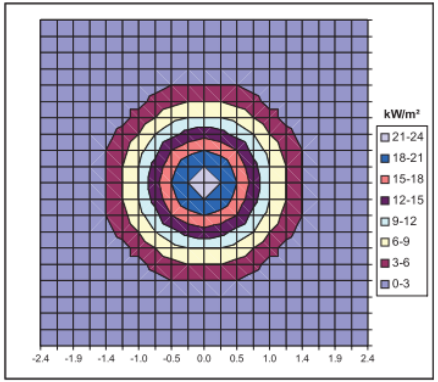
Reflected image of a heliostat can be described by a circular normal distribution (Gaussian).

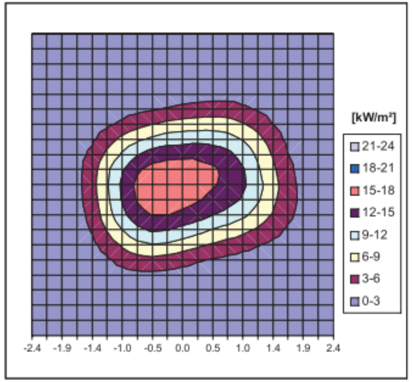
$$F(r) = \frac{1}{2\pi\sigma^2} e^{-\frac{r^2}{2\sigma^2}}$$

$$\sigma^2 = \sigma_{sun}^2 + \sigma_{beam\ quality}^2 + \sigma_{astigm}^2 + (2 \cdot \sigma_{track})^2$$

Lower computation time.

Only a few limited shapes of the reflected image can be modelled.





single mirror, incident angle 37.6° (left: HFLCAL, right: ray tracing)

Source: Wendelin, Tim. SolTRACE: A New Optical Modeling Tool for Concentrating Solar Optics

2. Optical characterization of power towers plants

Examples of codes using these methods

Statistical approach (MCRT)

- SolTrace
- MIRVAL
- HELIOS
- STRAL
- Tonatiuh

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Analytical approach (Convolution method)

- UHC -RCELL Suite
- DELSOL3*

*truncated Hermite function expansion to describe the shape of the reflected image in two dimensions.

- HFLCAL

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A new approach to integrate both MCRT and the analytical methods where heliostat layouts can be generated quickly while using ray-tracing techniques is highly desirable.

3. Modeling with SolarPILOT

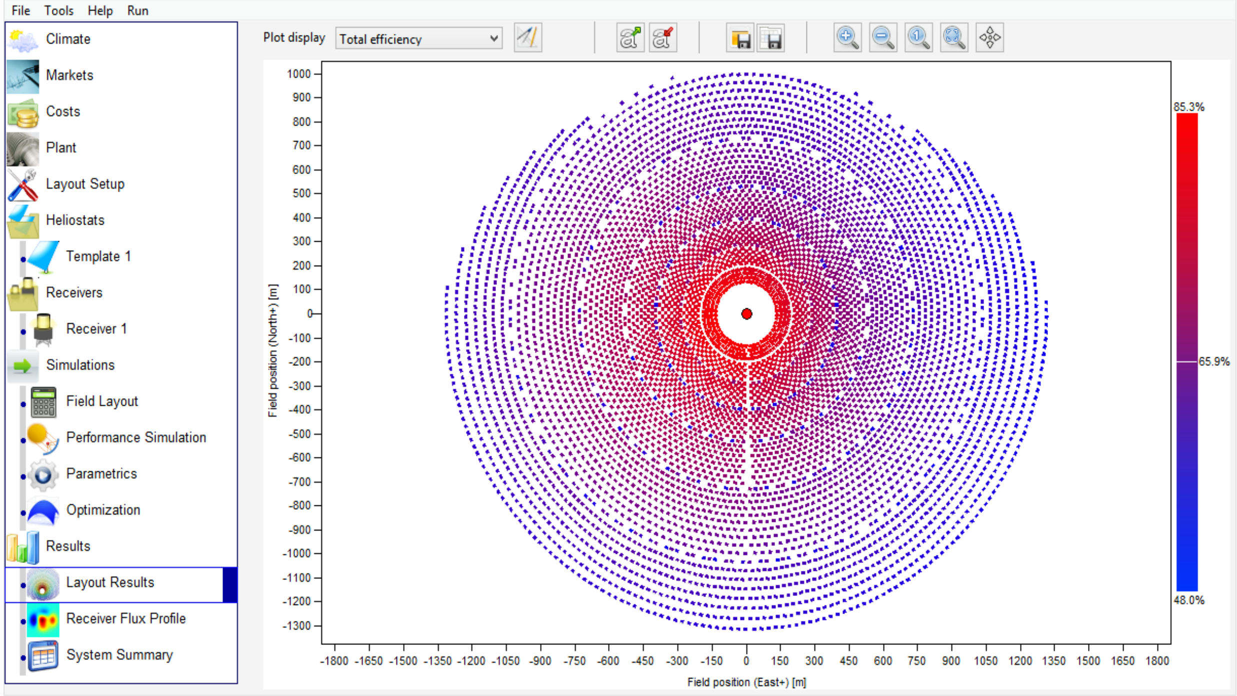
Solar Power tower Integrated Layout and Optimization Tool (SolarPILOT)

Integrates analytical and MCRT approach.

Generate and optimize heliostat field layouts.

Conducting a parametric study with different heliostat templates.

A user friendly graphical user interface (GUI).



Source: Wagner and Wendelin, SolarPILOT: A Tool for Solar Power Tower Layout and Optimization

3. Modeling with SolarPILOT

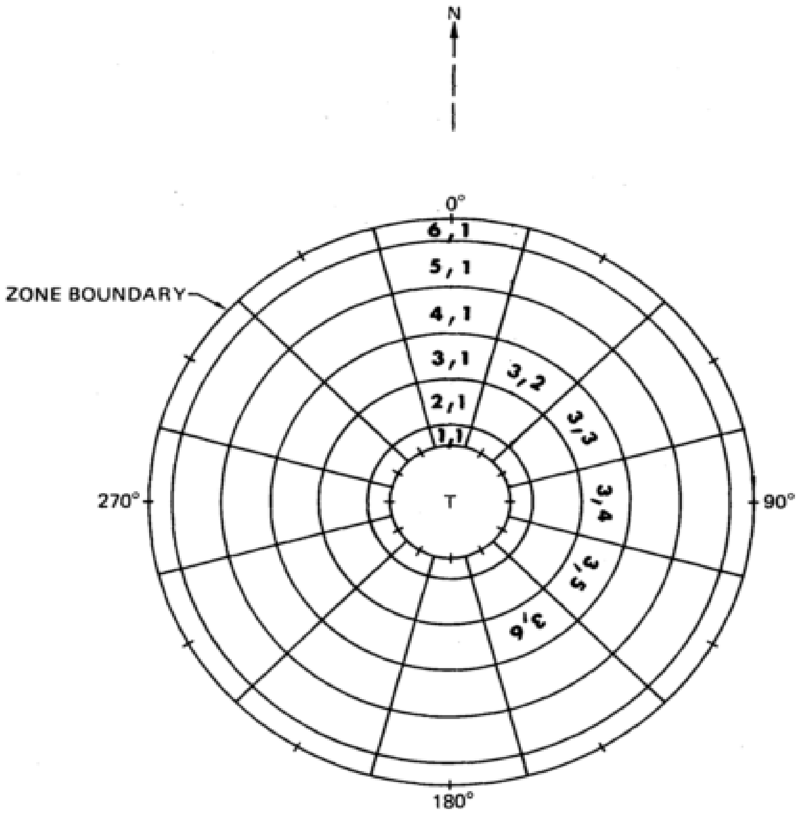
SolarPILOT model description - Background

Hermite function is applied to individual heliostats.

Different from the conventional approach of DELSOL3.

DELSOL3 calculates the performance at a set of field points.

Assumption: Each field point represents the average performance in a surrounding zone of heliostats.



Source: B. Kistler, A user's manual for DELSOL3: A computer code for calculating the optical performance and optimal system design for solar thermal central receiver plants

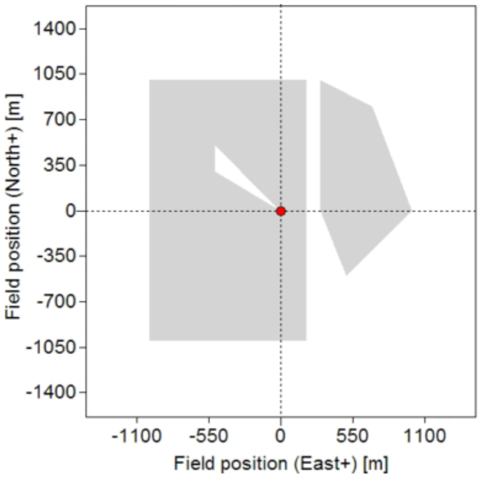
3. Modeling with SolarPILOT

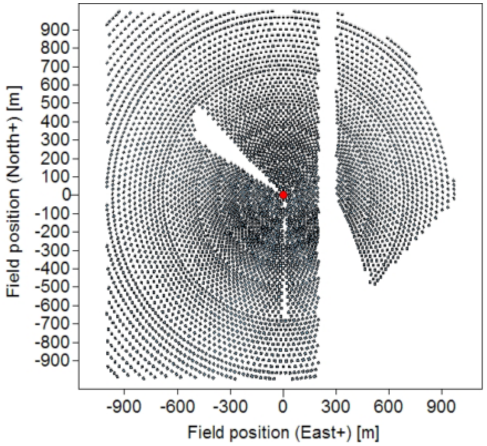
SolarPILOT model description - Modification

New method - dynamic heliostat grouping to calculate the computationally expensive interception efficiency.

Approximating the annual yield of a power tower using a subset of time steps over a year (instead of an annual simulation).

Land areas can be specified to be included or excluded from the layout





Source: Wagner and Wendelin, SolarPILOT: A Tool for Solar Power Tower Layout and Optimization

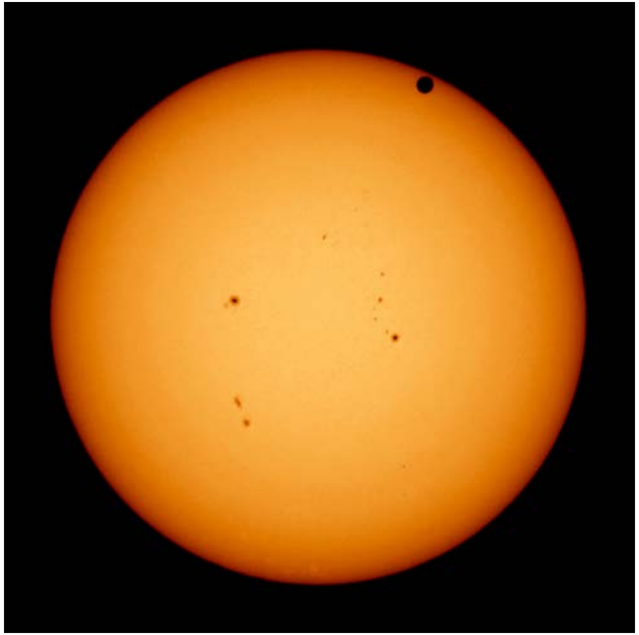
Location, Sunshape, Insolation and Atmospheric attenuation

Latitude (°N) : -28.433

Sunshape: Limb darkened Sun - Assumption

Insolation model: Weather data

Atmospheric attenuation model: DELSOL3 Clear day
Visibility 5 km - Assumption



Limb: *Limbus* in Latin- meaning edge

Source: Brocken Inaglory - Own work, CC BY 2.5, https://commons.wikimedia.org/w/index.php?curid=19842075

4. Plant location and atmospheric conditions

System Design:

Variable	Value/Description	Variable	Value/ Description
Heliostat total surface area (m^2)	115.56	Design point DNI (W/m^2)	950
Total surface slope error (mrad)	2.6	Layout method (-)	Radial Staggered
Total tracking/pointing error (mrad)	0.63	Radial spacing method (-)	Blocking eliminated
Receiver type (-)	External	Number of days simulated (-)	12
Receiver thermal power (MWt)	502	Simulation hour frequency (-)	1
Allowable peak flux (kW/m^2)	1100	Sun location at design point (-)	Spring equinox
Receiver absorber area (m^2)	869.84	Heliostat cost per Unit area ($/m^2$)	177

5. Heliostat field layout and optimization

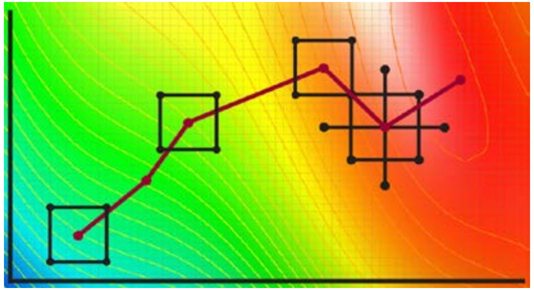
Response Surface Optimization algorithm calculates the Solar field design power:

$$\dot{q}_{sf,des} = \dot{q}_{inc} \cdot \alpha - \dot{q}''_{hl} \cdot A_{rec} - \dot{q}_{pipe}$$

Thermal power incident on the receiver

Convective and radiative heat losses

Piping heat losses



RSGS optimization algorithm

Initial step size: 0.02

Maximum iterations: 200

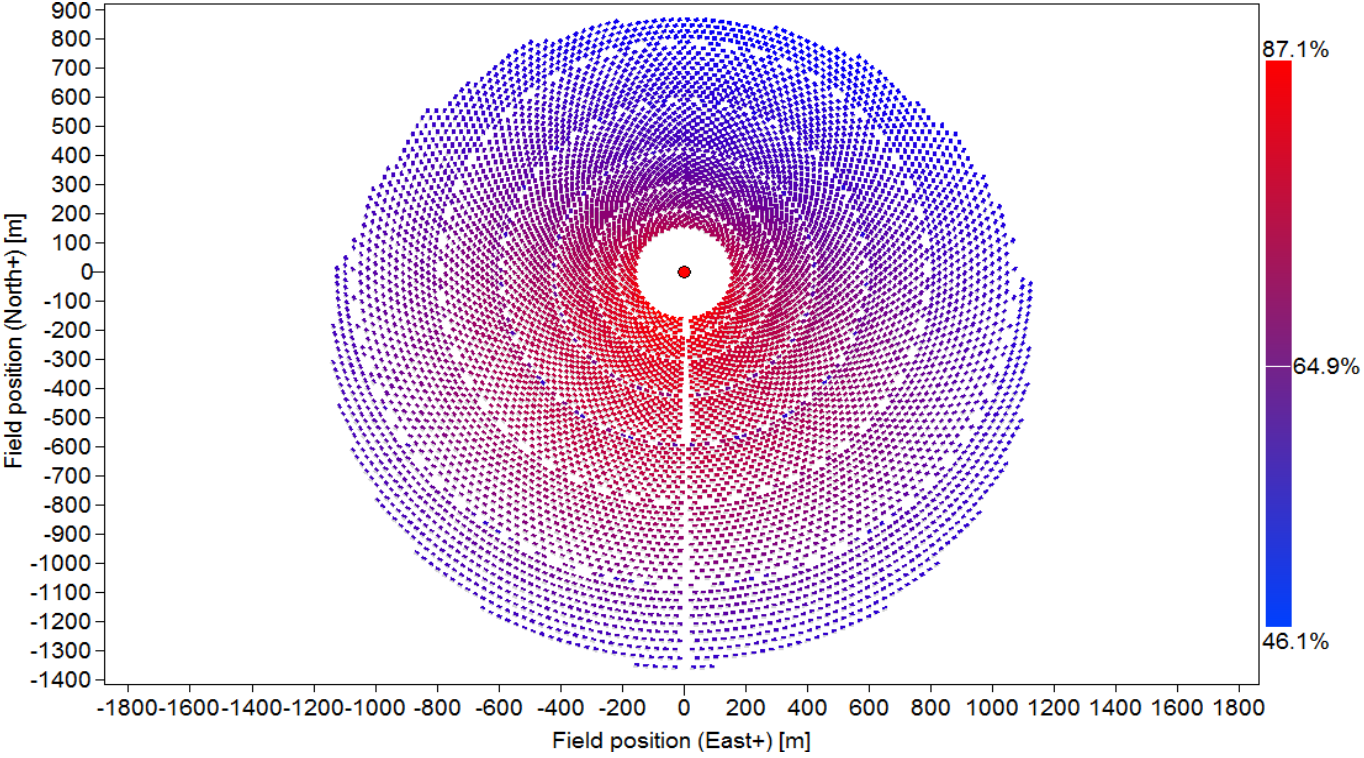
Convergence tolerance: 0.001

Objective: Lowest LCOE values

Different values for the height of the tower, the receiver dimensions and heliostat positions around the receiver explored.

5. Heliostat field layout and optimization

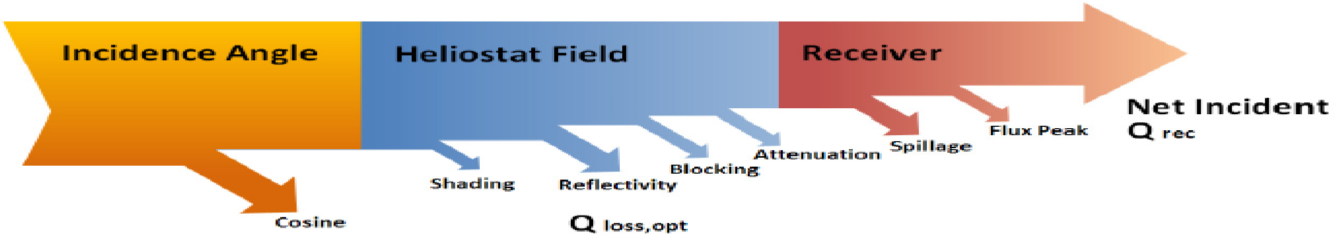
Sun position: Solar Noon, Spring Equinox



7965 heliostats
115.56 m² heliostat
927 113 m² reflective area
212.9 m receiver optical height

6. Performance simulation and optimization

Results – Model and SolarPILOT

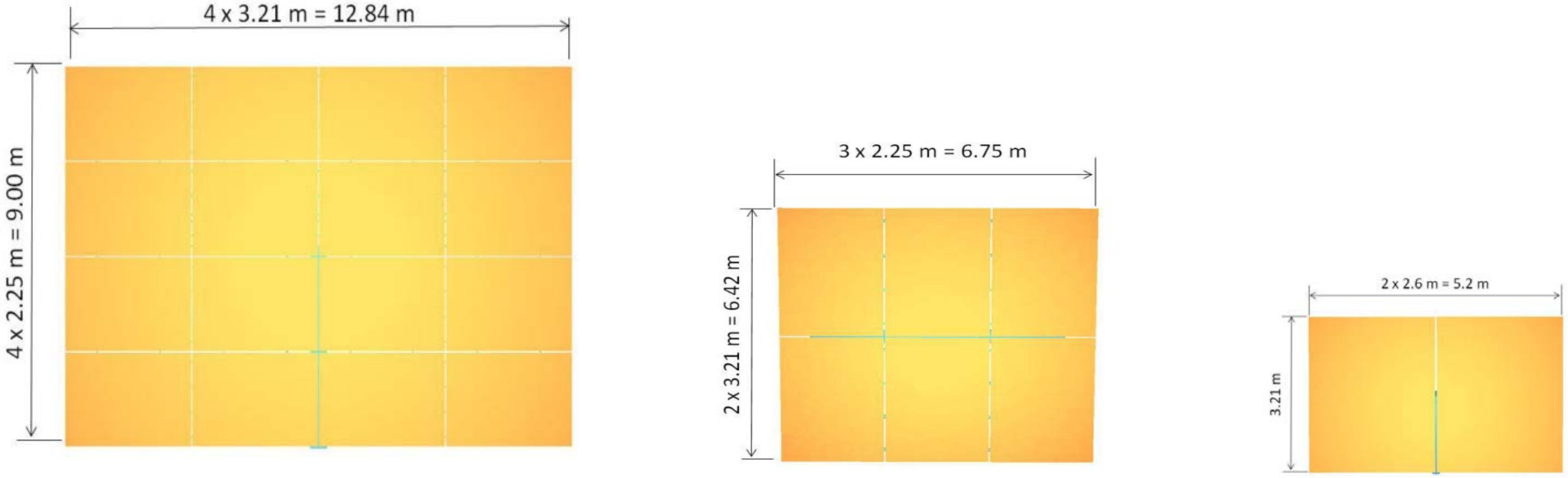


Result (Solar Noon, Spring Equinox)	Model	SolarPILOT
Cosine efficiency	79.47 %	79.90 %
Blocking efficiency	99.07 %	99.40 %
Atmospheric attenuation efficiency	91.93 %	91.90 %
Heliostat reflection	90.25 %	90.25 %
Interception efficiency	97.53 %	96.10 %
Solar field efficiency	63.702 %	63.302 %

7. Conclusion and Outlook

Importance of Optical characterization

- Important role in Heliostat cost reduction
- Optical performance with three heliostats
- Heliostat cost-scaling, optical performance and annual O&M costs
- LCOE model, not $/ m^2



Thank you !

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CRSES

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