



Clé de Sol



Genetic Algorithms and Heliostats Control: High Flexibility High Accuracy Flux Control for Odeillo's Big Solar Furnace

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Summary

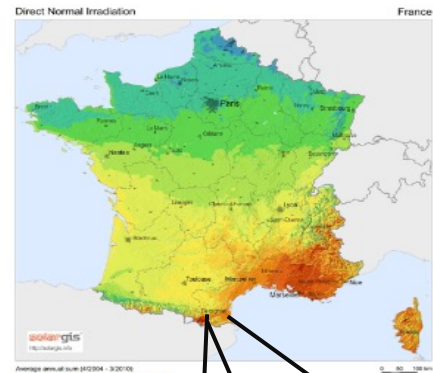
- Laboratory and supporting project
- The problem
- One solution: GA optimization
- Application & results

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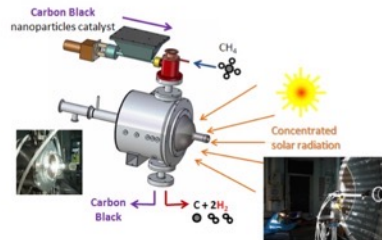
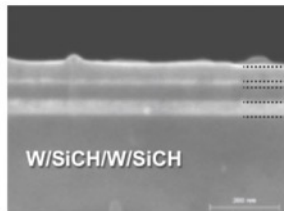
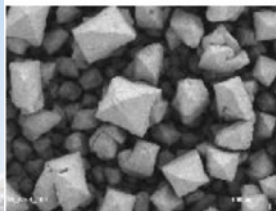
PROMES-CNRS laboratory

PROcesses , Materials  and Solar Energy  Laboratory,
from CNRS 

- About 150 persons  , scientists, students and support staff
- 3 research axis, some since 1947!
 - **Next gen CSP**
 - **Materials for Energy and for Aerospace**
 - **Solar chemistry and thermodynamics processes**
- 3 locations
 - Perpignan (close to university)
 - Odeillo: with the solar furnaces & cie, from 1 to 1000 kWth
 - Thémis: 4500 kWth solar tower



PROMES-CNRS from nano to industrial pilot scale — TRL 2 to 6


 10^{-9} m

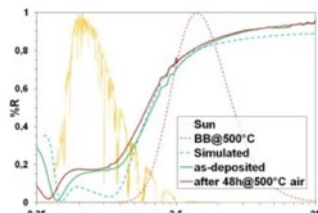
 10^{-6} m

 10^{-3} m

0,1 m

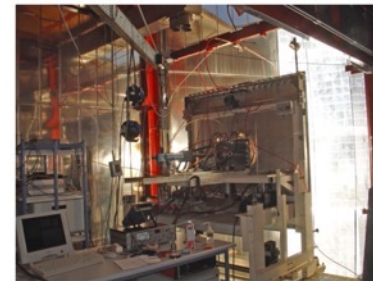
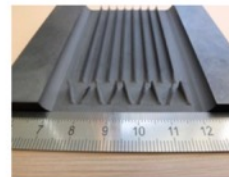
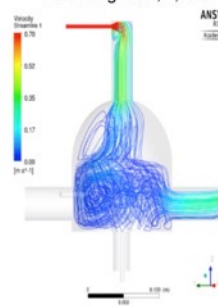
1 m

100 m



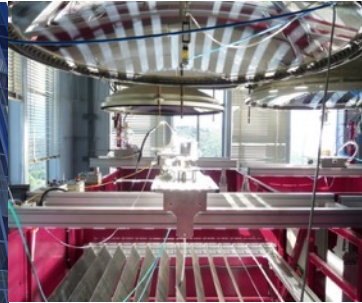
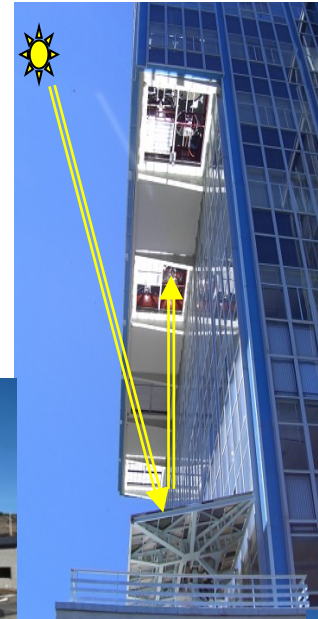
Thermo-optical selectivity
(design, fabrication, stability)

Modelling: flow, T, CO



vortex flow $V \sim 0.2$ m/s, $T_{\text{dome}} = 450-750$ K, $T_{\text{sample}} = 2000$ K, P/Ar flux, recirculation

PROMES-CNRS solar facilities *small to large scale, low to high flux* *Recognized as European Research Infrastructure (SFERA & EU-SOLARIS)*

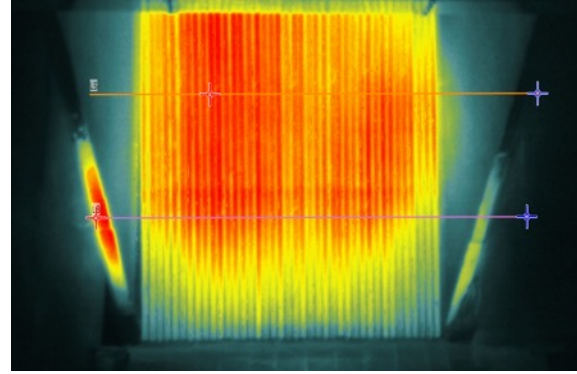
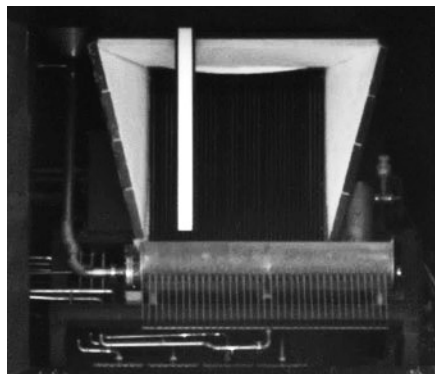


- 12 solar furnace 1, 2, 6 et 1000 kW concentration from 5 000 to 16 000 suns, up to 4000°C
- 1 complete solar loop with 200kW parabolic trough and termocline(MicroSol'R)
- 1 solar tower, 5000 kW (Thémis)
- 1 dish (Stirling), 50 kW (EuroDish)



CLÉ-DE-SOL project

- European Regional Development Funds (ERDF), managed by Occitanie (FR)
- 1 M€, 2021-2022, PROMES-CNRS
- 4 axis to **improve hosting and testing** on our large facilities: focus on Thémis and 1000kW
 - Improve knowledge of the facilities → *flux measurements (poster+oral here @SP22)*
 - Improve control of the heliostats fields → *aiming strategy (other oral here @SP22)*
 - Improve reliability and accuracy of Thémis heliostats field → *SCADA & cie*
 - Improve knowledge of temperature distribution at focal point → *IR solarblind camera*

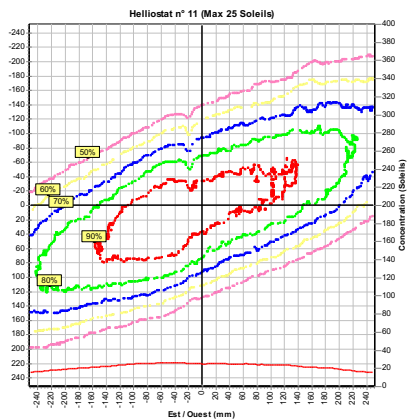


The problem: flux distribution

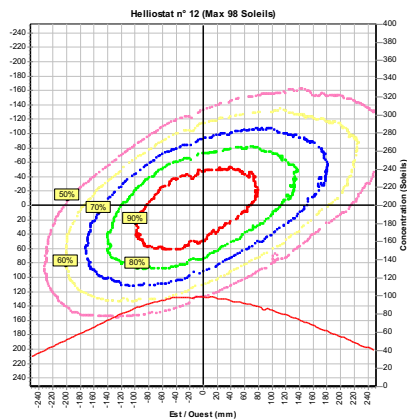
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Heliostat aiming strategy 1/3

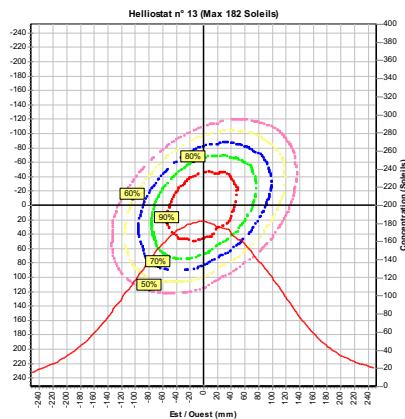
- Objective: **control** delivered power on solar receiver (1) > flux distribution (2) > temperature distribution (3)
- Means of action: **heliostat choice**, and **heliostat aiming locations**
- Each heliostat has different contribution on receiver: **± same power**, but **different power density**: 10 to 400 suns (our solar furnace) ; and **different shapes** at focal point



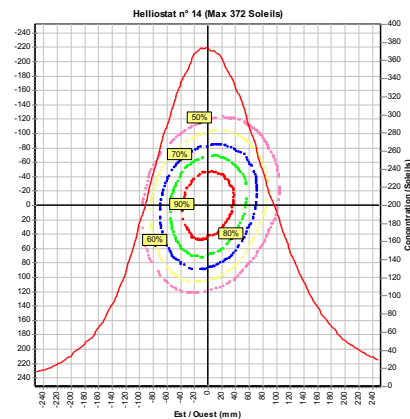
25 suns



98 suns



182 suns

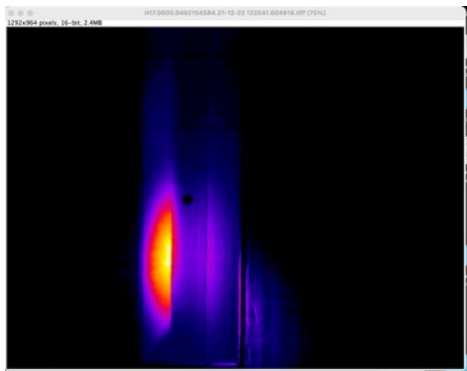


372 suns

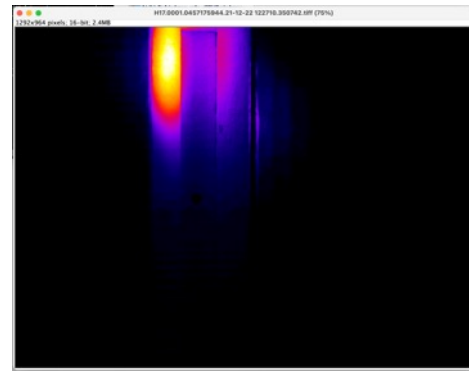
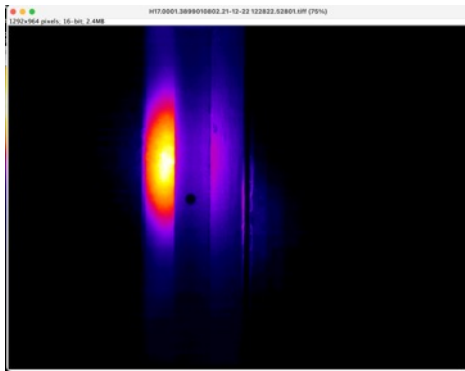
Heliostat aiming strategy 2/3

- Objective: control delivered power > flux distribution > temperature distribution
- Means of action: heliostat choice and aiming locations
- Each heliostat has different contribution: \pm same power, but **different power density**: 10 to 400 suns and **different shapes?**
- At one instant: for a solar tower: beam **translates**. For a solar furnace: beam **changes of shape** quickly.

+10 cm higher



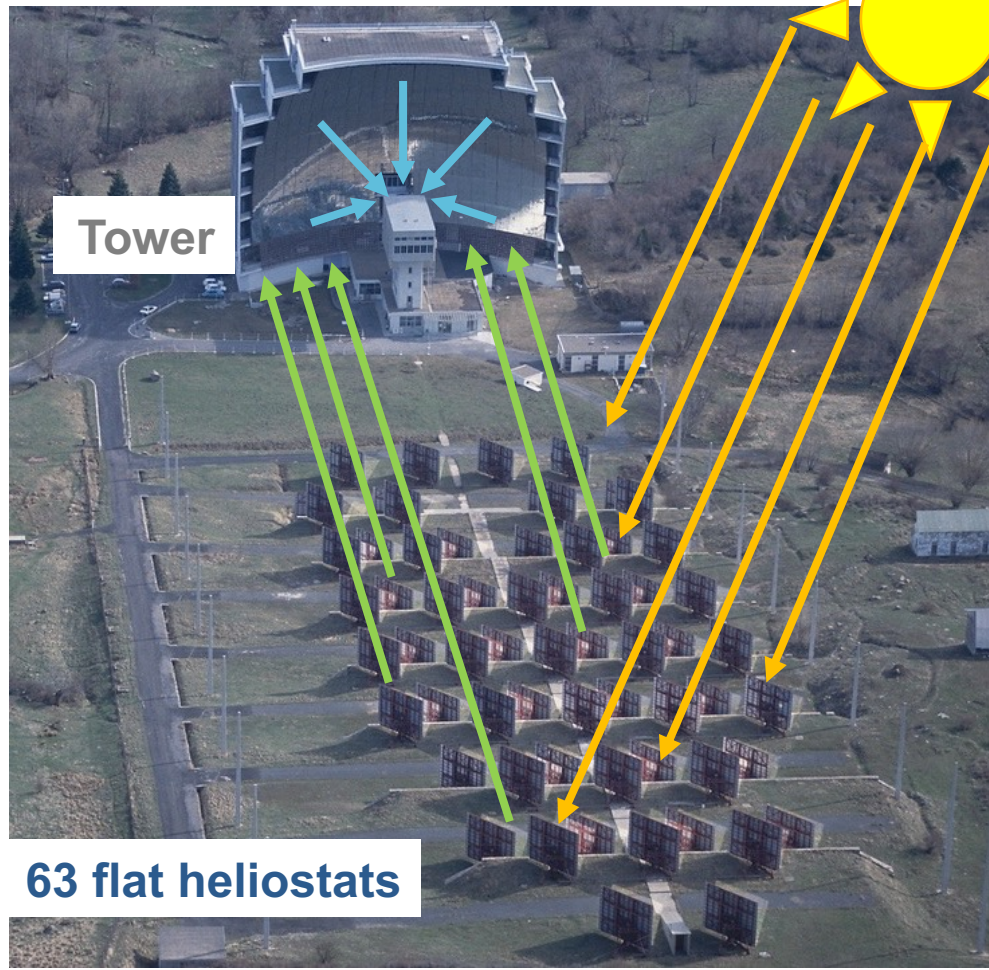
+10 cm higher



Odeillo's Big Solar furnace

- First operation in 1969
- 63 flat heliostats (2835 m²)
- 18m focal parabola (1800 m²)
- Spot size: 100 cm diameter
- **1000 kWth** usable
- Range: 10 to **10000 suns**
- Up to **3500°C**
- **NON LINEARITIES**: shadows from solar tower and from shutter doors

Parabola

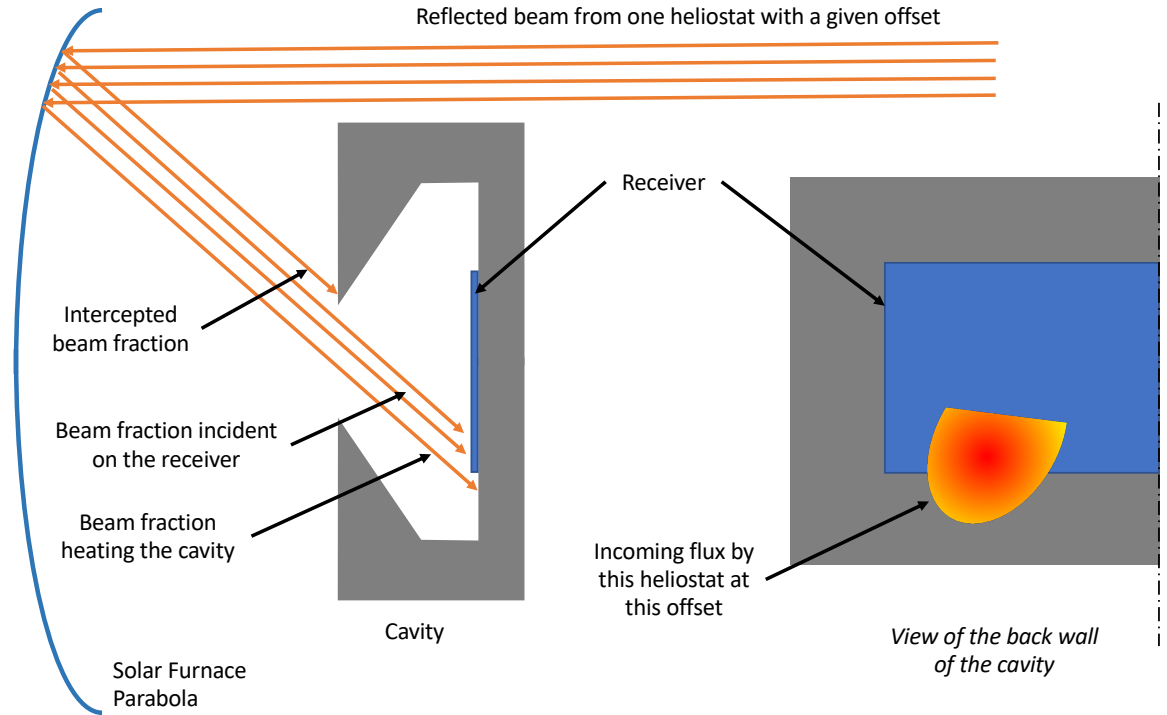


Heliostat aiming strategy 3/3

also for solar towers: receiver in cavity

- Cavity receivers have higher efficiency
- But control of flux is harder as the cavity acts as a diaphragm

hence non linear!



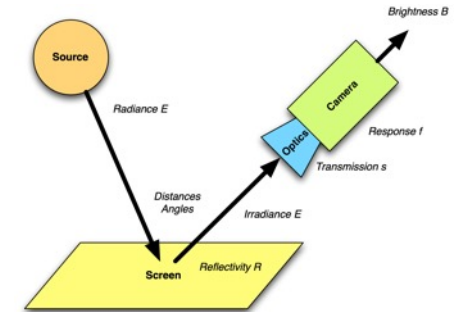
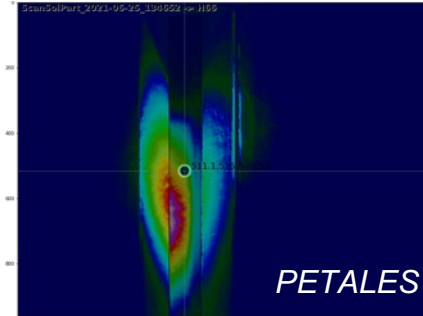
5 dimensions problem??

- $D = 1$: heliostat choice
- $D = 2 \text{ \& } 3$: flux distribution at focal plane, point of interest

$$x_1 \in [1..63]$$



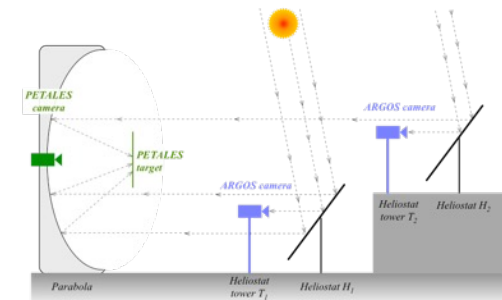
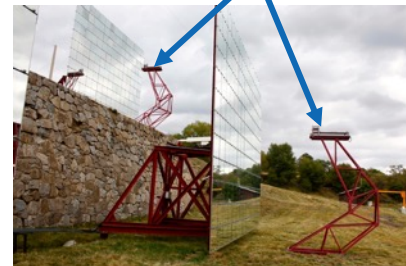
$$x_{2,3} \in [0..1000] \times [0..1000] \text{ mm}$$



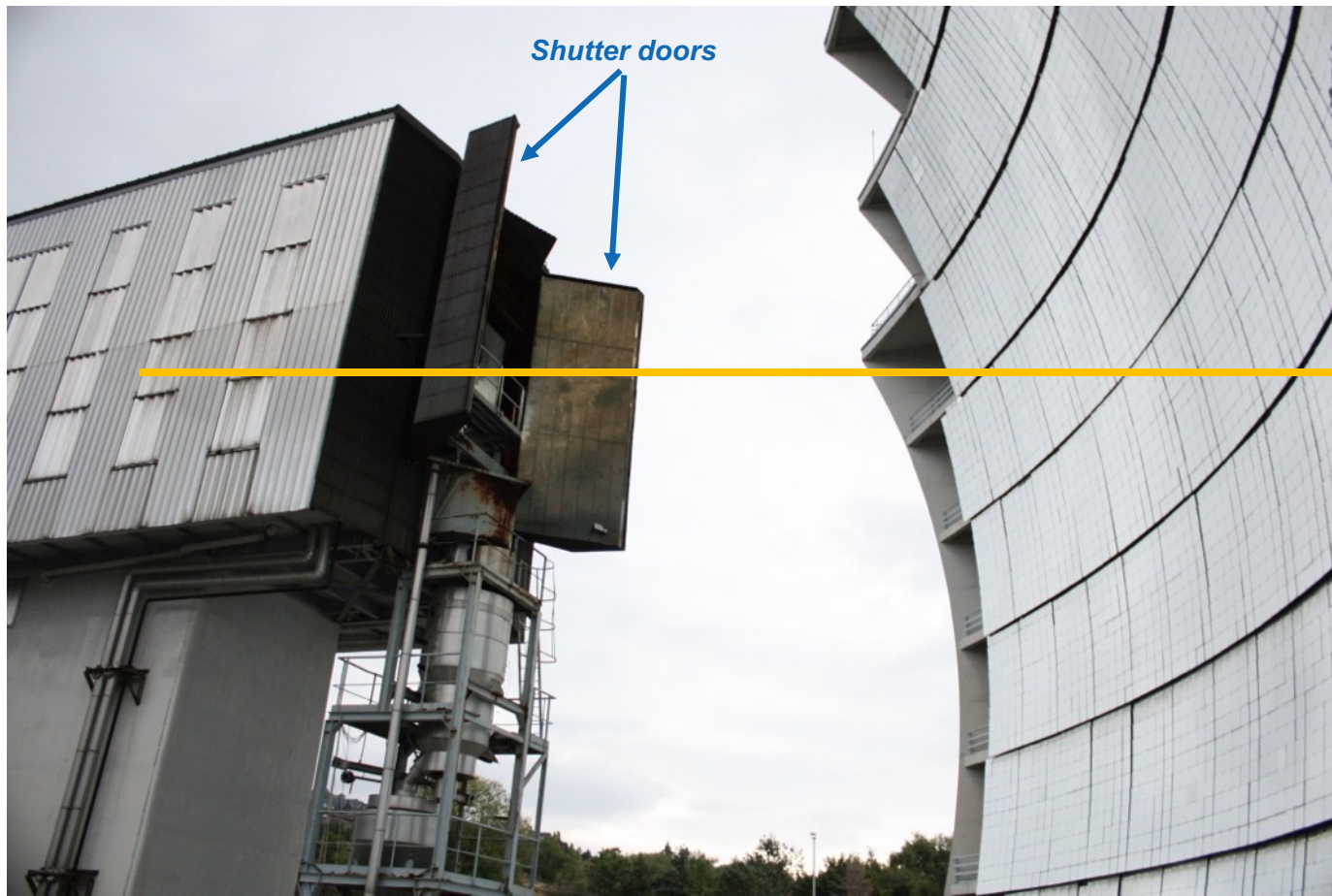
- $D = 4 \text{ \& } 5$: aiming direction of the heliostat (with ARGOS cameras for close loop sun-tracking)

$$x_{4,5} \in [0..1292] \times [0..964]$$

ARGOS cameras



5 dimensions?? and more possible! Z axis position, beam angle, shutter opening...



Size of the space to explore (test case)

25 heliostats (1D)

Scanned each on 1 square meter aiming point area

Every 5 cm position: 20 x 20 aiming points (2D)

So 400 flux maps (2D) per heliostat

That's **400²⁵ possible configurations**

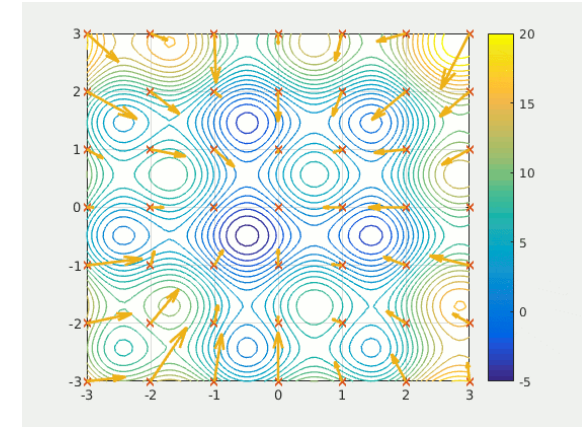
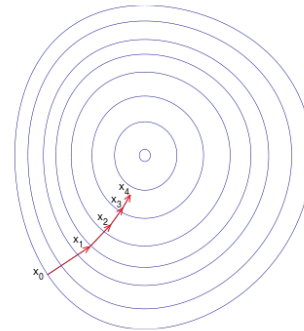
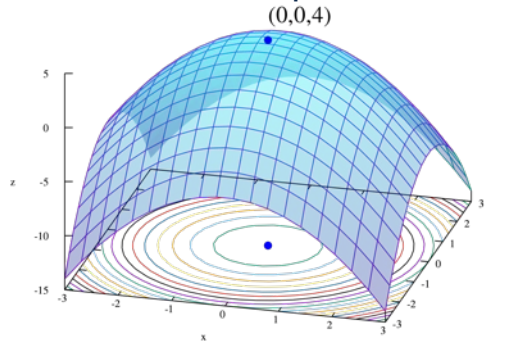
That's $1.12 \cdot 10^{65}$, which is one billion times less than there is of atoms in the observable universe...

Genetic algorithm for heliostats aiming strategy

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(some) Optimization techniques

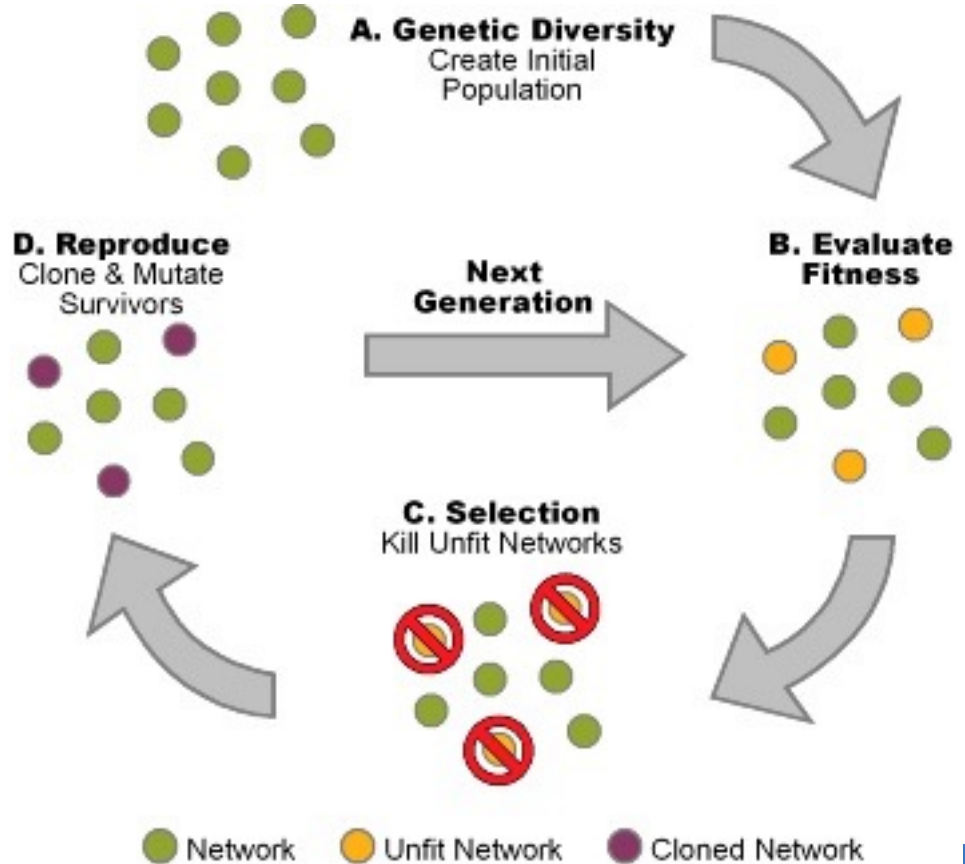
- Solar towers without cavity => **continuous optimization**: lots of algorithm available
 - Gradient descent...
 - Swarm based: particles swarm (PSO), bees, ants, fishes...



- Solar furnace or solar receiver with cavity => **non continuous** : less algorithms available
 - Brute force
 - Genetic algorithms...

Genetic algorithm

- Evolutionary algorithm
- Coded characteristics in genome:
 - For each heliostat: aiming point
- Fitting evaluation:
 - flux distribution
- Python MP + numpy (vector)
- ~1 minute per simulated universe
- (Hours) days to get solutions on high end desktop PC



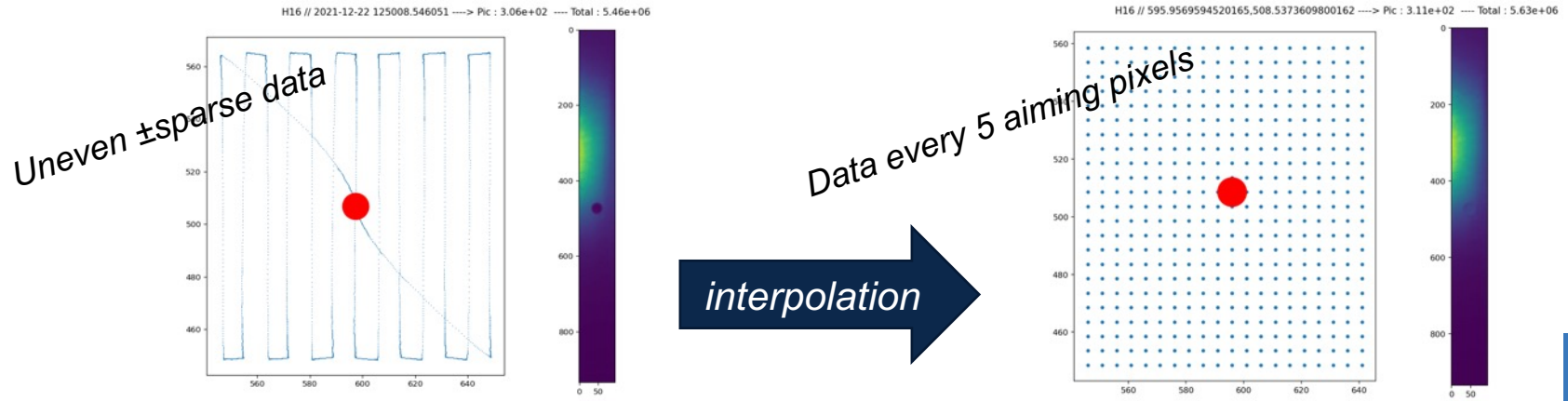
Application & results

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5D experimental flux database *dedicated oral (was earlier...)*

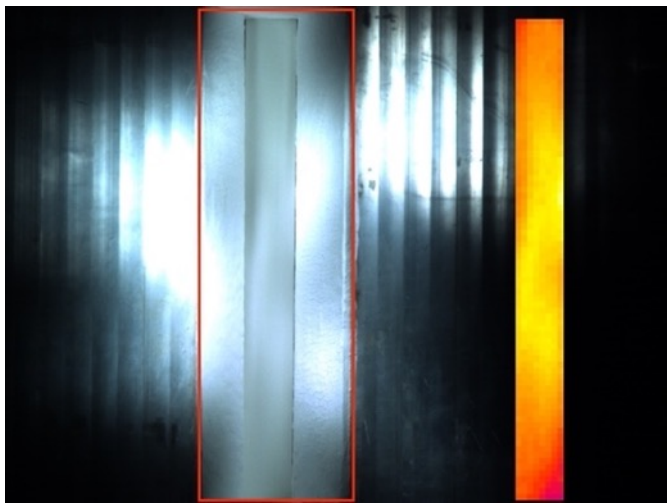
- Technique: experimental flux data (camera+radiometer) + interpolation
- Automatic ballet of heliostats with S trajectories at focal point
- 40 GB raw data in 1h20 for 25 heliostats, transformed in 8 GB evenly spaced 5D dataset



Running the GA and applying it

- Calculating 10,000's solutions to cover wide mean flux range
- Selecting best configurations
- HTML UI to apply heliostats aiming points

➤ *Works great in simulation and early tests*



Manips SolPart 2022 : 43 configurations

```
[785917] 47.5 soleils - 31 → 57 -  $\sigma$ =±4.4 - 11 hélios
[8d654a] 48.7 soleils - 36 → 59 -  $\sigma$ =±4.5 - 13 hélios
[742300] 49.5 soleils - 32 → 60 -  $\sigma$ =±4.8 - 13 hélios

[aa7f6c] 99.9 soleils - 76 → 113 -  $\sigma$ =±4.9 - 15 hélios
[872881] 100 soleils - 81 → 115 -  $\sigma$ =±5 - 16 hélios
[a76a17] 98.7 soleils - 83 → 118 -  $\sigma$ =±5.1 - 14 hélios

[78ff93] 149.8 soleils - 121 → 168 -  $\sigma$ =±5.6 - 15 hélios
[cdc0d2] 145.2 soleils - 116 → 159 -  $\sigma$ =±5.7 - 16 hélios
[2cc0f1] 149.1 soleils - 124 → 166 -  $\sigma$ =±5.8 - 17 hélios

[a60467] 196.9 soleils - 162 → 214 -  $\sigma$ =±6.7 - 18 hélios
[c3b3f4] 200 soleils - 177 → 223 -  $\sigma$ =±6.7 - 19 hélios
[ef3d60] 199.9 soleils - 176 → 220 -  $\sigma$ =±6.7 - 20 hélios

[472bb2] 240 soleils - 211 → 257 -  $\sigma$ =±7.1 - 21 hélios
[35a738] 248.3 soleils - 223 → 264 -  $\sigma$ =±7.1 - 20 hélios
[74ed8c] 238.4 soleils - 211 → 254 -  $\sigma$ =±7.2 - 21 hélios

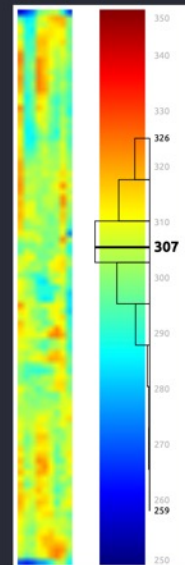
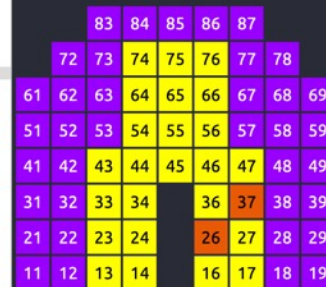
[c7970e] 311.6 soleils - 274 → 330 -  $\sigma$ =±8.8 - 19 hélios
[d19d7a] 309.8 soleils - 258 → 327 -  $\sigma$ =±8.9 - 19 hélios
[f572fe] 306.6 soleils - 259 → 326 -  $\sigma$ =±9.2 - 24 hélios

[e27e2a] 352.2 soleils - 306 → 369 -  $\sigma$ =±9.1 - 20 hélios
[d7fe9a] 341.2 soleils - 301 → 359 -  $\sigma$ =±9.4 - 20 hélios
[e910bd] 360.3 soleils - 316 → 382 -  $\sigma$ =±9.4 - 18 hélios

[f1faf3] 395.5 soleils - 334 → 416 -  $\sigma$ =±9.8 - 22 hélios
[0ab1ee] 385.8 soleils - 335 → 407 -  $\sigma$ =±9.9 - 22 hélios
[8feecf] 392.7 soleils - 345 → 413 -  $\sigma$ =±10 - 21 hélios

[cf8ea6] 430 soleils - 373 → 456 -  $\sigma$ =±10.8 - 18 hélios
[ca0df9] 444.6 soleils - 391 → 465 -  $\sigma$ =±10.9 - 23 hélios
[332061] 431.5 soleils - 351 → 451 -  $\sigma$ =±10.9 - 23 hélios

[6bb9c8] 479.4 soleils - 412 → 501 -  $\sigma$ =±11.8 - 24 hélios
[957c52] 492.3 soleils - 414 → 522 -  $\sigma$ =±11.9 - 24 hélios
[fc84c2] 506.5 soleils - 429 → 528 -  $\sigma$ =±11.9 - 20 hélios
```



Sélectionner la configuration: Historique de tir:

Flux moyen de **306.6** soleils, de 259 à 326 soleils, en utilisant 24 héliostats.

Attente

Mettre en tir

Palette de couleurs: Page d'affichage: de à soleils. Automatique

Configurations de tir exportées le 2022-03-22 16:58:34.123116 UTC

L'EUROPE S'ENGAGE
L'OCCITANIE AGIT



But non usable actual results

- 5D flux database flawed:
 - Radiometer was not properly working
 - Datasets (1 to 10 Hz acquisition rate): time synchronization to improve
 - Adjust heliostat speed to increase recorded points and help sync?
 - Change interpolation techniques??
- **No major issues on the GA side**
 - *Option: add resilience aiming quality to the fitting process evaluation*





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