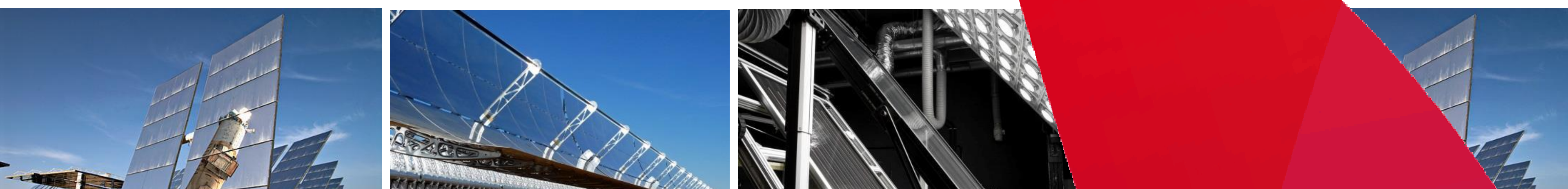

Scalable HeliOstat calibRation sysTem (SHORT)

How to calibrate your whole heliostat field in a single night

April, 2018

Marcelino Sanchez and Cristobal Villasante

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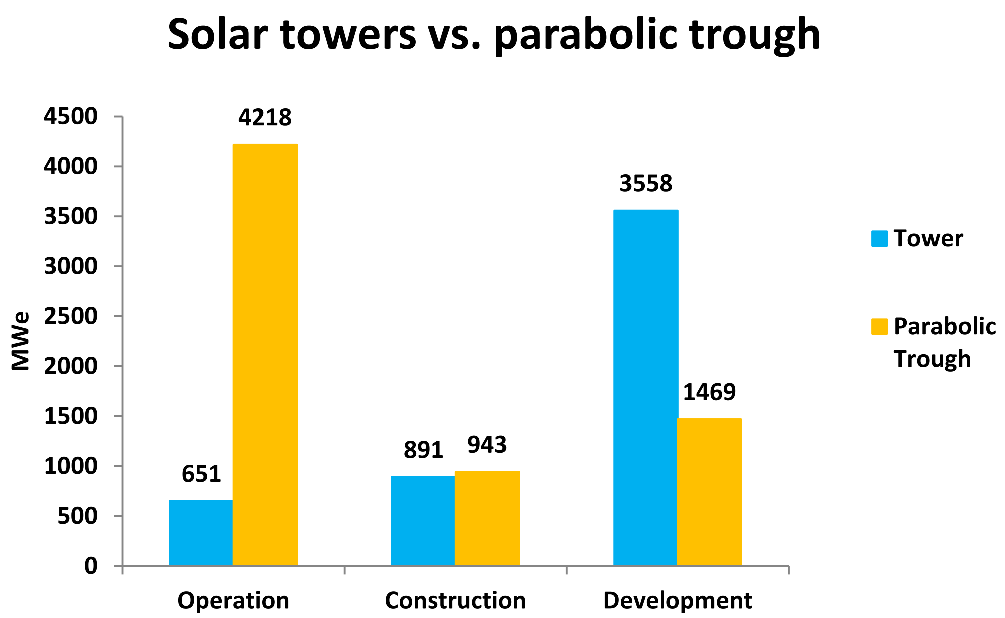
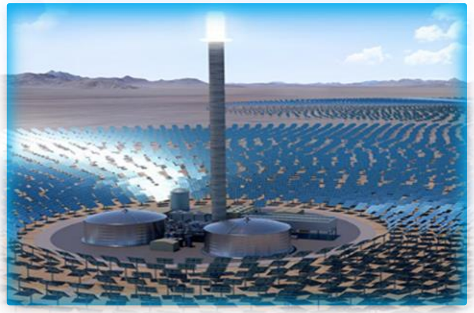
1. Introduction & Context

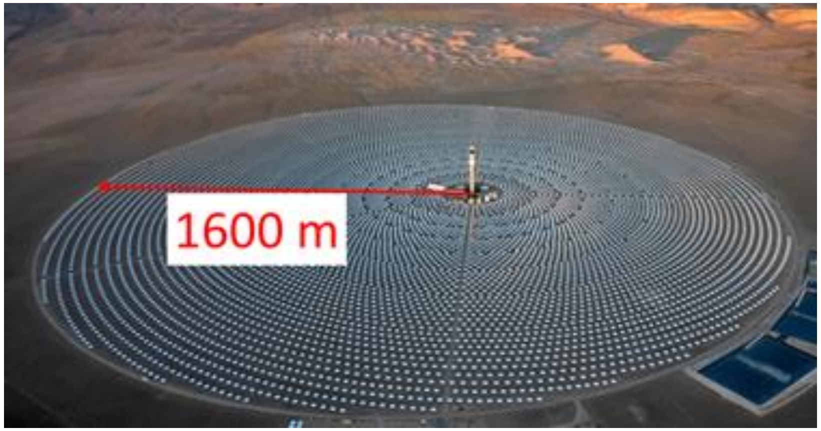
CSP technology trend

- Data from the *CSP Today Global Tracker* shows that solar towers account for nearly half of total capacity under construction and 70% of projects under development.





Solar heliostat fields trend



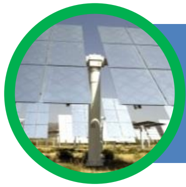
Gemasolar (2011)
Heliostats: 2,650 @ 120 m^2
Aperture: 304,750 m^2
Power: 20 MW
Storage: 15 h

Crescent Dunes (2015)
Heliostats: 10,347 @ 115.7 m2
Aperture: 1,197,148 m2
Power: 110 MW
Storage: 10 h

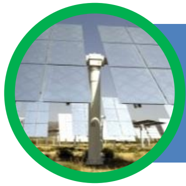
Sept 2017. **DEWA awards AED14.2 billion largest CSP project in the world with a record bid of USD 7.3 cents per kW/h to generate 700MW.** The project will have the world's tallest solar tower, measuring 260 metres.

Introduction & context

Heliostats designs trend



ATS H100
Area: 95 m^2
@ Cesa - 1



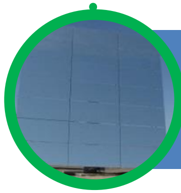
ASINEL
Area: 65 m^2
@ CESA-1

CASA
Area: 40 m^2
@ CESA-1

1980's

ATS-H150
Area: 150 m^2
@ SANDIA

GM-100
Area: 105 m^2
@ PSA



Sanlucar 90
Area: 90 m^2
@ PSA

1990's

Sanlucar 120
Area: 121 m^2
@ PS10-PS20

SENER
Area: 115 m^2
@ Gemasolar

CSIRO
Area: 4,5 m^2
@ CSIRO

2000's

BrightSource
Area: 14,4 m^2
@ Ivanpah

E-Solar
Area: 5 m^2
@ Sierra Sun T.

2010's

EASY CENER & Tekniker
Area: <10m^2
Automatic calibration system
Low cost Cable drive
Lean manufacturing
Partially funded FP7

SENER
Area: 178 m2
@ Noor-Ouarzazate III

2017

?

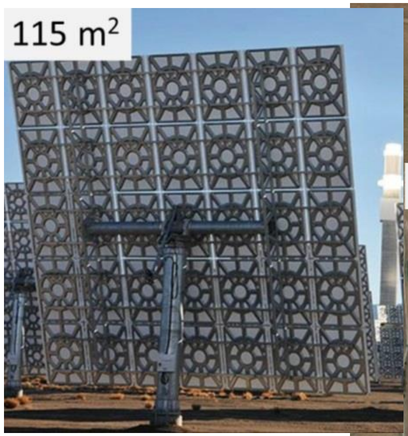
Timeline not to scale

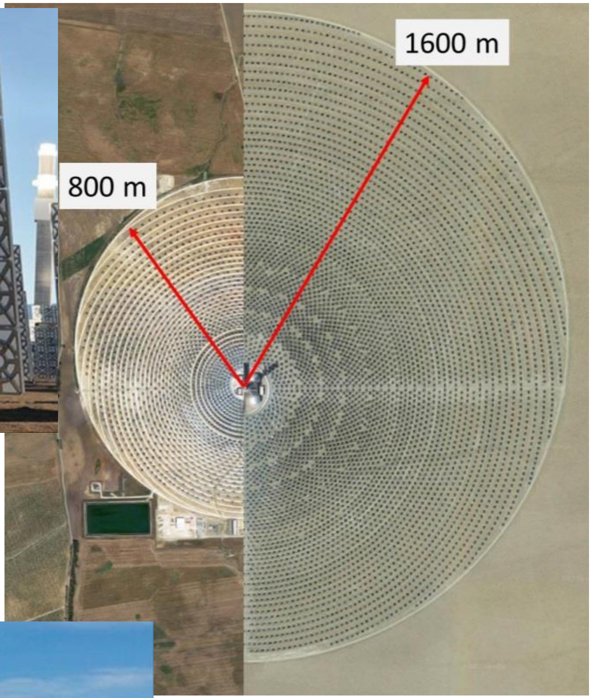
Size increases to reduce cost *(40 m^2 to > 120 m^2)*

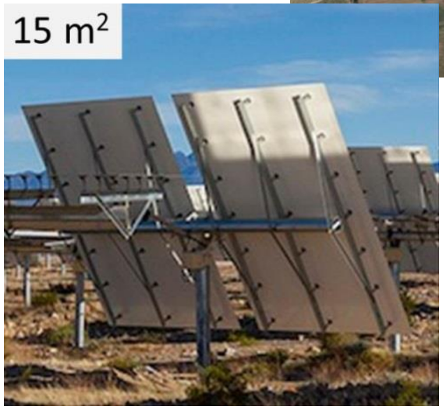
Size decreases to reduce cost

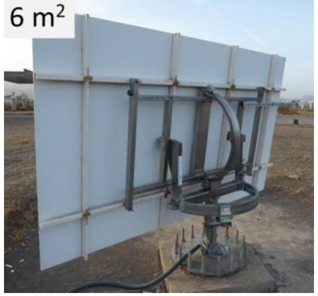
1. Introduction & Context

- Large number of heliostats
  - ✓ Bigger plants
  - ✓ Smaller heliostats
- Pressure to reduce costs
  - ✓ Relax requirements
  - ✓ Reduce the need of long term stability
  - ✓ Simplify installation
- Need for
  - ✓ Quick heliostat installation
  - ✓ Methodologies to guarantee final accuracy on field
  - ✓ and applicable also for large distances between heliostat and tower









Current State

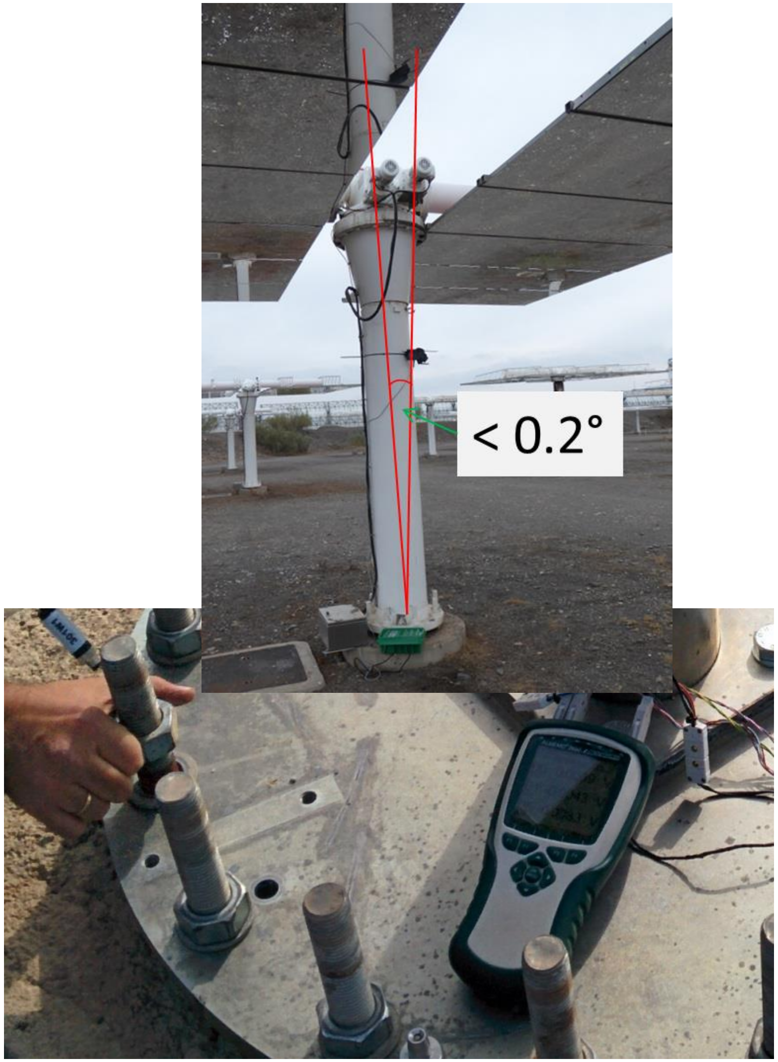
Combination of (one-time) manual adjustment with flux verification

During construction:

- ✓ Make sure heliostat axis are properly aligned
- ✓ Measure inclinations
- ✓ Adjust orientations (screws)

Drawbacks:

- ✓ Very difficult to repeat later on
- ✓ Labor intensive
- ✓ Difficulties to guarantee final accuracy

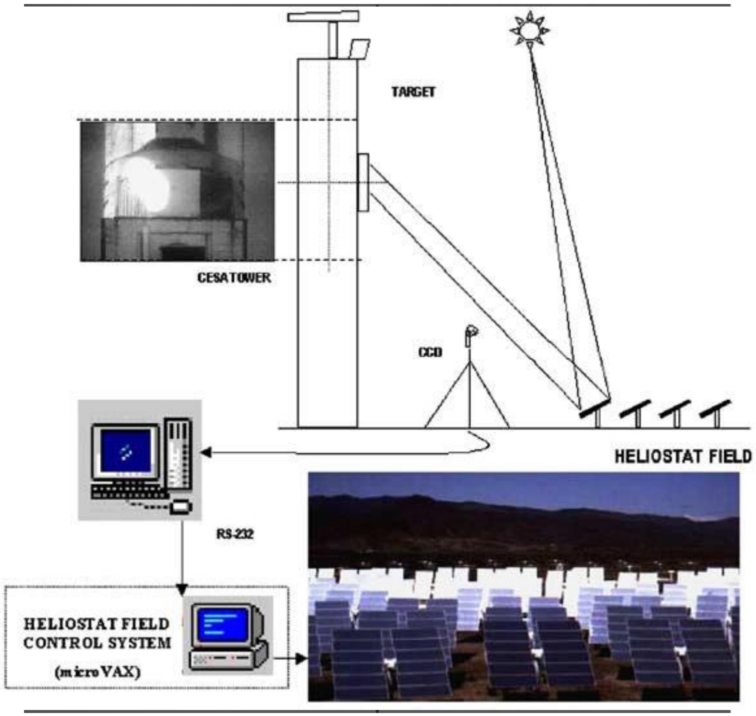


1. Introduction & Context

Current State

During operation:

- ✓ Reflect sun onto target
- ✓ Use camera to detect flux center
- ✓ Measure deviations
- ✓ Calculate angular offset and introduce as offset correction



Berenguel et al. 2004

Drawbacks:

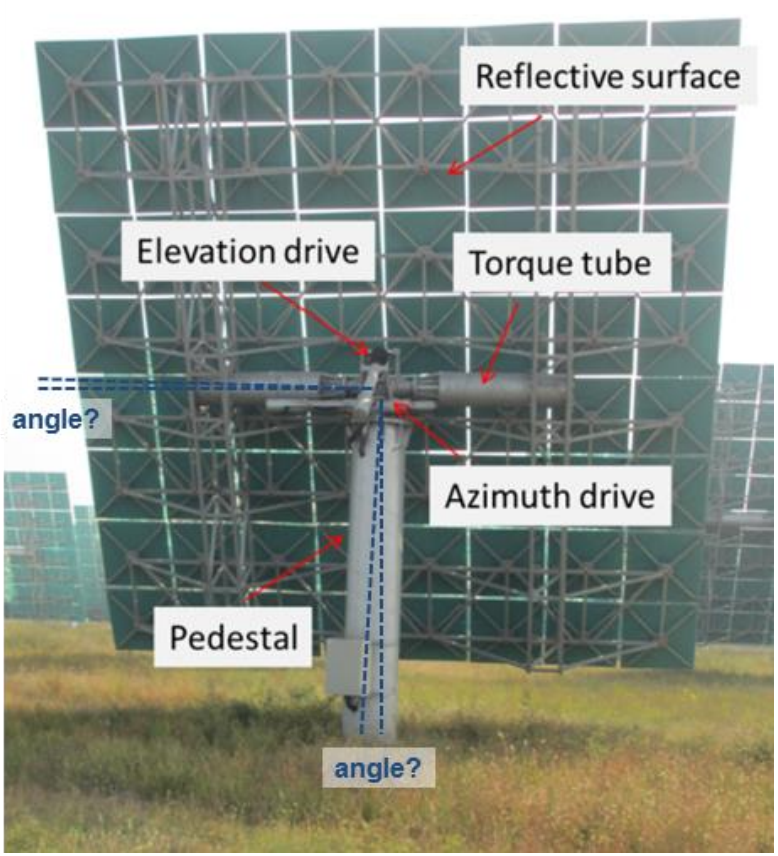
- ✓ One heliostat at a time
- ✓ Takes a very long time for large fields
- ✓ Not fully applicable to **long distance heliostats** where:
- ✓ Reflected image has very low power density
- ✓ Size of reflected image could be bigger than the white target
- ❖ **Impossible to accurately determine actual aiming point**
- ✓ Final accuracy of this methodology depends on heliostat features such us (facet quality, heliostat size and position)

2. SHORT Approach

2. SHORT Approach

Goals:

- ❑ New calibration methodology to identify heliostat actual configuration
  - ✓ Axes orientations (elevation & azimuth)
  - ✓ Angular offsets (elevation & azimuth)
- ❑ Automatic
- ❑ Accurate
- ❑ Fast
- ❑ Highly parallel



2. SHORT Approach

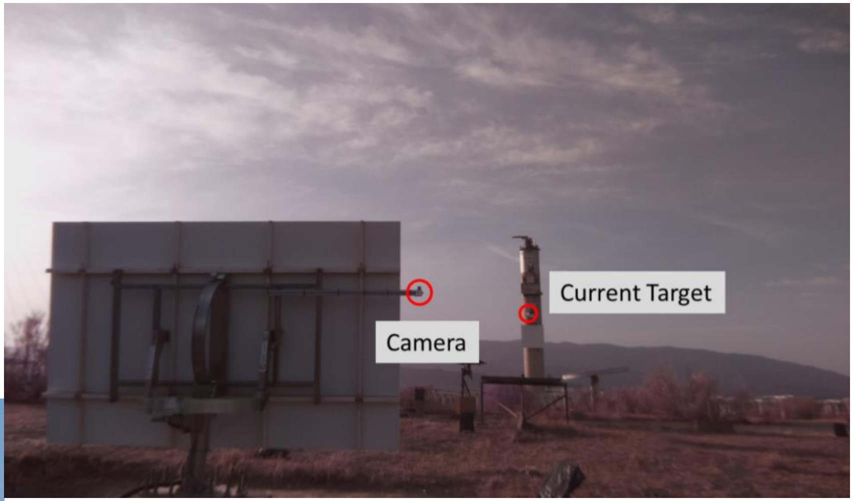
1. Attach a camera to each heliostat

- ❑ Rigid connection to facet structure
  - ✓ No specific position or viewing direction required
  - ✓ Possibly looking sideways or backwards
- ❑ Low-cost camera (mobile devices)

2. SHORT Approach

2. Define targets (anything identifiable) with known locations and covering tracking range

- ✓ Artificial lights
- ✓ Natural lights: sun, moon
- ✓ Objects in the field



Moon

2. SHORT Approach (artificial vision system)

3. Observation of targets in images

- ❑ Storage known positions of each target (x_t, y_t, z_t)
- ❑ Heliostat moves to find each target
- ❑ For each target and position of the heliostat
  - ✓ Automatically detect target in image
  - ✓ Store target ID $\begin{pmatrix} u_{it} \\ v_{it} \end{pmatrix}$
  - ✓ Store encoder values, azimuth, elevation (α_i, β_i)
- ❑ Repeat for several targets and heliostat orientations

4. Model the kinematic behaviour of the heliostat

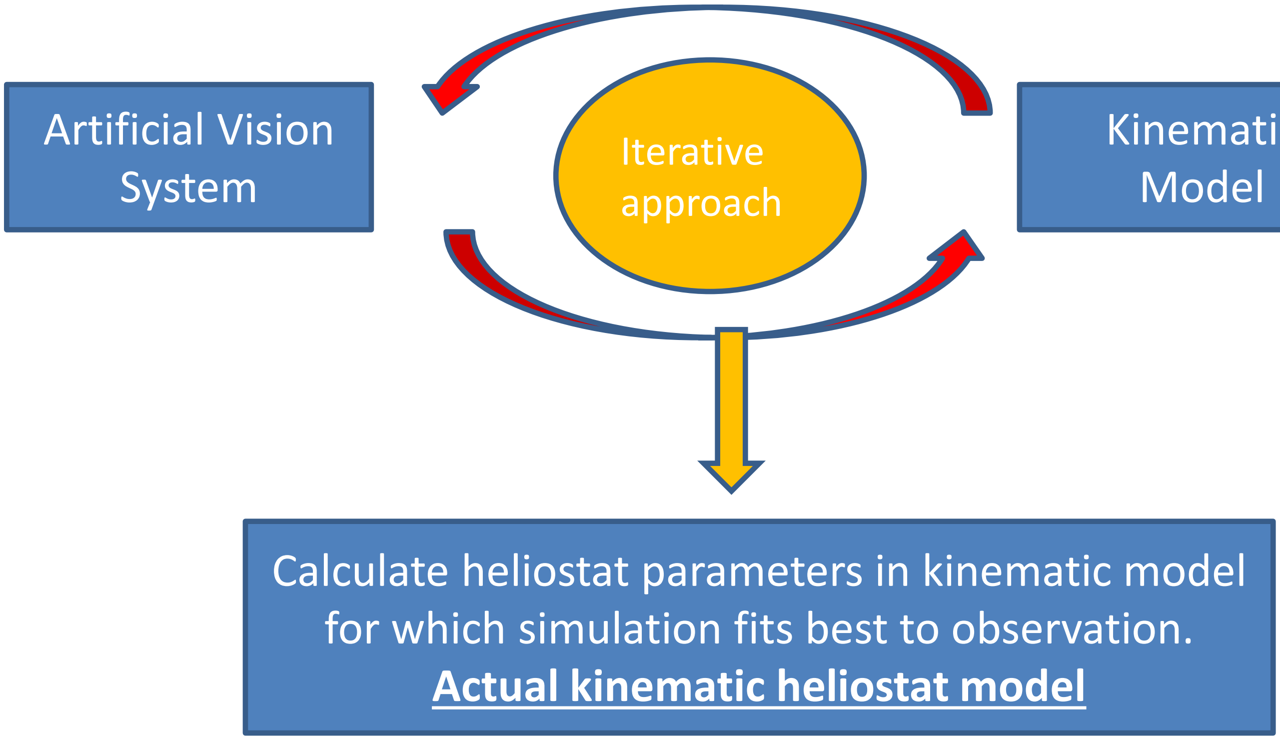
- Iterative process
- Model predicts the image position of a target

$$\begin{pmatrix} u_{it} \\ v_{it} \end{pmatrix} = f\left(\alpha_i, \beta_i; x_t, y_t, z_t; Model_{gen}\right)$$

- **The Kinematic model “evolves”** from a generic heliostat model **to the actual model of the heliostat under calibration, including** accurate real values of heliostat parameters such us **axes position**

$$Axes(position) = Model_{act}(\alpha, \beta)$$

2. SHORT Approach (Calibration system)



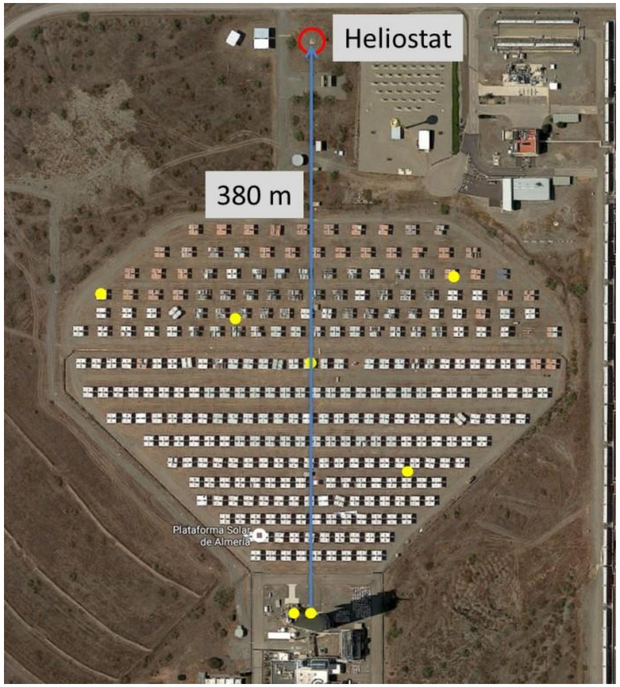
Actual kinematic heliostat model is:

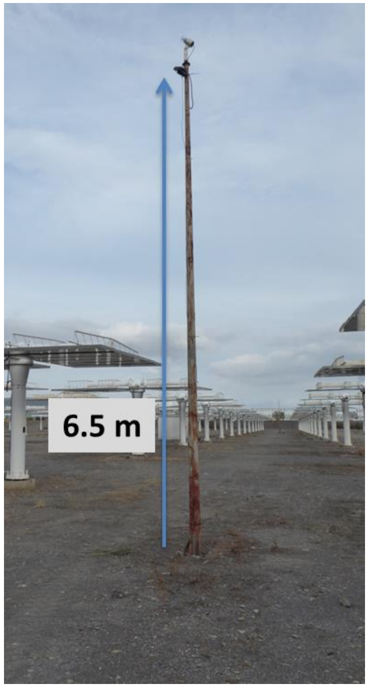
- ✓ Required for heliostat control
- ✓ Based in real accurate measurements
- ✓ Robust to installation "errors"

3. *Experimental Results*

3. Experimental Results

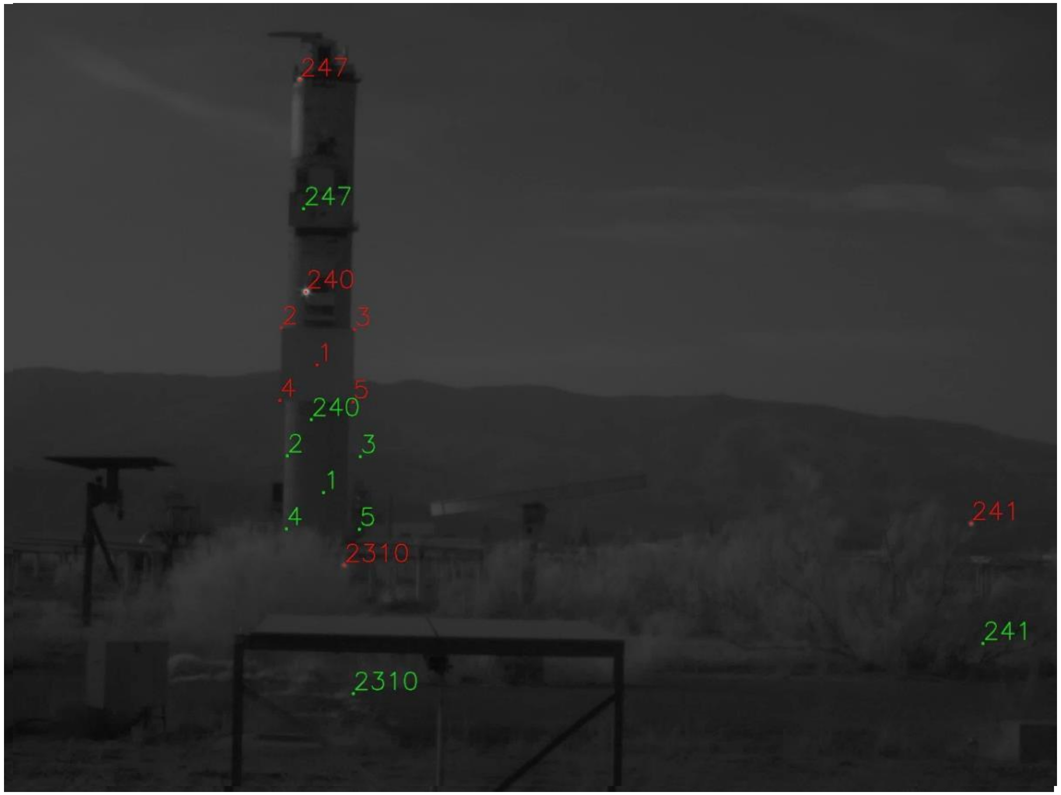
- Tested at PSA in October 2016
- 7 IR targets throughout the solar field
- 53 observations for calibration (additional for evaluations)
- Multiple observations of the same target under different orientations





3. Experimental Results (Calibration)

$$\begin{pmatrix} u_{it} \\ v_{it} \end{pmatrix} = f(\alpha_i, \beta_i; x_t, y_t, z_t; Model)$$



Intermediate kinematic model
Initial kinematic model
Final kinematic model
(heliostat parameters iterative adjustment)
(Actual heliostat parameters)

Calibrated model

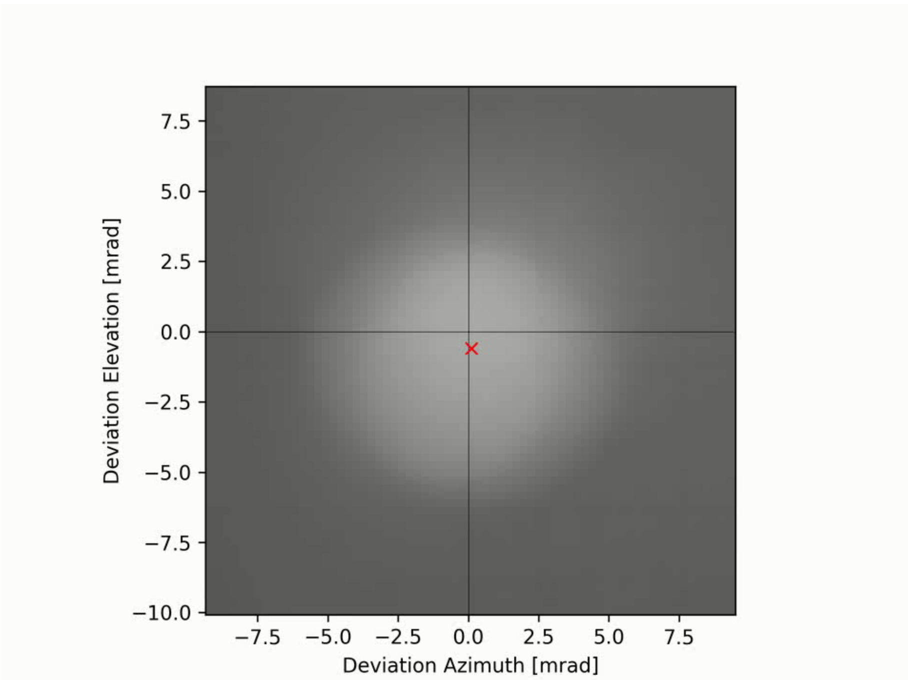
Red: Correct position
Green: Model estimation

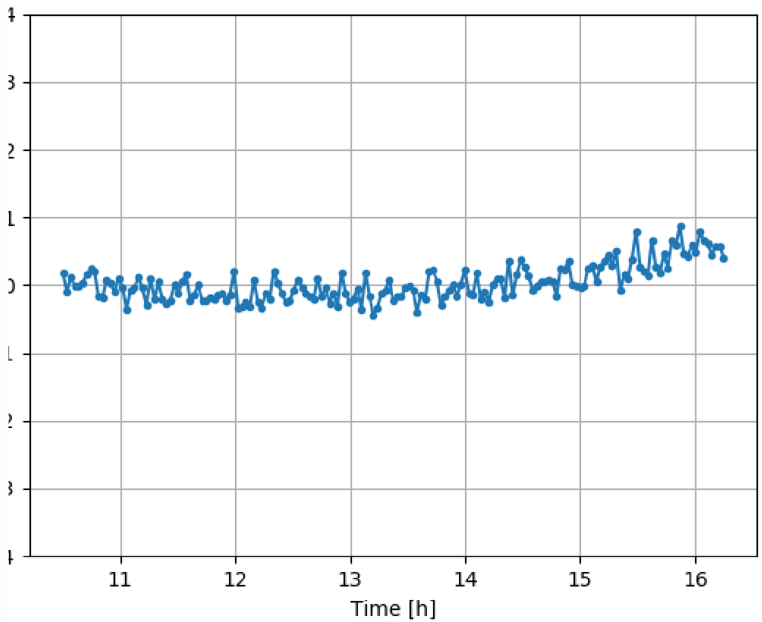
- Precise knowledge how the heliostat is moving
- RMS error of 0.22 mrad in movement prediction

3. Experimental Results (Tracking)

$$Axes(position) = Model(\alpha, \beta)$$

- ➢ Once the actual kinematic model of the heliostat is calculated by SHORT, Heliostat can be moved into desired orientation





<u>Results on a real heliostat tested at PSA (heliostat tracking evaluation all day long)</u>

- ✓ Evaluation of tracking accuracy (sun tracking)
- ✓ 0.6 mrad tracking error (RMS) for the tested heliostat

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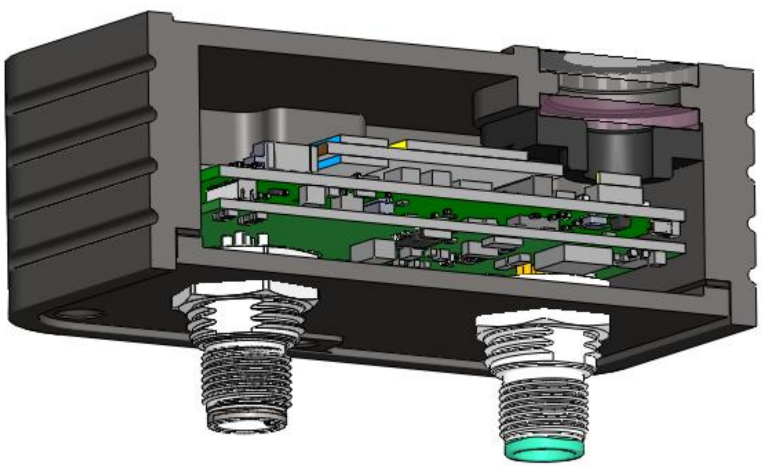
3. Experimental Results (N. Custom hardware development)

- Functionality: Calibration and (optionally) motion control of heliostat
- Highly flexible software architecture
- Traceability of operations supported by a database
- Specs:
  - A7 processor for running high level algorithms on Linux
  - M4 processor for real time motion control
  - Integrated calibration camera and IR filter
  - Integrated motor drivers (azimuth & elevation actuators)
  - Communication buses (RS485, ETH) for plant management and integration with large heliostats



4. Conclusions

4. Conclusions

Scalable HeliOstat calibRation sysTem (SHORT) has been presented:

- SHORT is based on an **automatic parallel calibration** using a **camera attached** to each heliostat
- SHORT has been **validated on field** making test at PSA facilities
- SHORT **calibrates** not only heliostat axes orientation but **the actual kinematic model of each heliostat**
- The **accuracy** of SHORT is i**ndependent of heliostat features and position on field**
- **Experimental** results show **SHORT errors below 0.3 mrad (rms)**
- Calibrate a heliostat takes less than an hour **(heliostat field calibration takes few hours)**
- SHORT **can be applied at night** avoiding any interference with ordinary plant operation
- **SHORT is fast, easy, robust and accurate and can be applied to any heliostat field**

4. Conclusions

Acknowledgements

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Thank you for your attention!!

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