Tracking and shape errors measurement of concentrating heliostats
Outline

1) General Introduction / Context
2) Backward-Gazing Method
3) Numerical Simulations
4) Experiments and Preliminary Results
5) Conclusion and Outlooks
Different types of CSP Plants

- **Tower power Plant** (Gemasolar, Spain)
- **Parabolic Trough** (Shams 1, Abu Dhabi)
- **Dish Stirling** (Eurodish, Odeillo)
- **Linear Fresnel** (NOVATEC BIOSOL)
Why must we characterize the concentrators

Immediate applications
- Decrease the necessary time to adjust thousands of reflective facets
- Identify damaged facets, to be repaired or replaced

More prospective applications
- To evaluate and optimize prototypes
- To predict performance
- To analyze mechanical stress, and the influence of the wind and gravity
- A better control of the heliostat tracking is necessary for the development of pointing strategies
Different types of errors

- Facet alignment error (canting error)
- Heliostat tracking error
- Local surface errors (low or mid-spatial frequency)
Method’s Description

Images of the reflection of the sun on the heliostat are taken from different points of view. By knowing the sun profile, it is possible to reconstruct the optical errors of the mirrors.
Slope Errors Equations

Wavefront reconstruction from the four images

Wavefront to surface slopes transform matrix
Images of the sun reflected by the heliostat WFE slopes and reconstructed from images

WFE slopes corrected from aberrations Heliostat surface slopes

Reference WFE slopes

X slopes

Y slopes

Subtraction

I(P) – Images of the sun reflected by the heliostat

WFE slopes
\( \partial W(P)/\partial x \) and \( \partial W(P)/\partial y \)
reconstructed from images

Reconstructed heliostat surface

WFE slopes to surface slopes matrix

Warp algorithm

Southwell algorithm

Heliosstat surface slopes

Eqs. 4, 9 and 15
Eqs. 16
Warp algorithm

Southwell algorithm

WFE reconstruction
Numerical Simulations
Heliostat and sun models

a) Dimensions of the simulated heliostat in mm

Each facet is misaligned by ±1 mrad around the azimuth and altitude axes

b) Super-Gaussian sun profile with parameter $\xi = 4$

$$B(\varepsilon) = B_0 \exp\left(-\left|\frac{\varepsilon}{\varepsilon_0}\right|^4\right)$$

- Focal length 200 m
- Distance to target 180 m

10% focus mismatch
### Numerical Simulations

#### WFE and slopes Reconstruction Errors

<table>
<thead>
<tr>
<th></th>
<th>Reference values</th>
<th>Measurement errors</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>X slopes (mrad)</strong></td>
<td>5.351</td>
<td>0.039</td>
</tr>
<tr>
<td><strong>PTV</strong></td>
<td><strong>Y slopes (mrad)</strong></td>
<td>5.442</td>
</tr>
<tr>
<td><strong>WFE (mm)</strong></td>
<td>11.164</td>
<td>0.060</td>
</tr>
<tr>
<td><strong>RMS</strong></td>
<td><strong>Required :</strong></td>
<td><strong>Wavefront error &lt; 2 mrad</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Measurement &lt; 0.2 mrad</strong></td>
</tr>
<tr>
<td><strong>Required :</strong></td>
<td>1.794</td>
<td>0.007</td>
</tr>
<tr>
<td></td>
<td>1.953</td>
<td>0.009</td>
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<tr>
<td></td>
<td>3.775</td>
<td>0.009</td>
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</table>

#### Diagram Description:

- The diagrams illustrate the distribution of wavefront error (WFE) and slopes across the X and Y axes.
- The color scale indicates the magnitude of the error, with red and blue representing positive and negative values, respectively.
- The X slopes (mrad) and Y slopes (mrad) are shown in separate plots.
- The WFE (mm) is represented in a third plot.

#### Required Conditions:

- Wavefront error < 2 mrad
- Measurement < 0.2 mrad

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[Image of wavefront error and slope distributions]
Numerical Simulations
Surface Reconstruction Errors

<table>
<thead>
<tr>
<th></th>
<th>Reference values</th>
<th>Measurement errors</th>
</tr>
</thead>
<tbody>
<tr>
<td>X slopes (mrad)</td>
<td>4.243</td>
<td>0.183</td>
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<tr>
<td>Y slopes (mrad)</td>
<td>3.993</td>
<td>0.185</td>
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<tr>
<td>Surface (mm)</td>
<td>7.445</td>
<td>0.468</td>
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<tr>
<td>Required:</td>
<td>1.340</td>
<td>0.046</td>
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<tr>
<td>RMS</td>
<td>1.141</td>
<td>0.053</td>
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<tr>
<td></td>
<td>1.027</td>
<td>0.079</td>
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</tbody>
</table>

- Shape error < 1 mrad
- Measurement < 0.1 mrad
Experiments at THEMIS power plant
Targasonne – France (Pyrenees Mountains)

A 5th camera is used to calibrating the sun profile during images acquisition
Experiments
Acquisitions and Treatments

Raw images

"Rectangularized" images
Experiments - Preliminary Results

Wavefront slopes along X

Wavefront slopes along Y

Simulated slopes
Conclusion and Outlooks

• A four cameras **backward-gazing method** to characterize solar concentrators has been described.

• Numerical simulations have been performed to validate the method, and to demonstrate that its accuracy is compliant with the requirement for concentrating surfaces in solar power plants.

• An experiment has been set-up in THEMIS solar power plant. The method **already works in WFE sensing mode**, but:
  • Image processing has highlighted the difficulty to superimpose the images (“registration”)

• The validation of the method in surface shape sensing mode is in progress.
Possible extension to freeform optics metrology
Other slides

Wavefront and shape errors
Relation with wavefront

Malus’ Theorem
The wavefront is orthogonal to the light rays.
The light rays converge to the focal point O’ for an ideal mirror shape.
Relation with wavefront

Malus’ Theorem
The light rays no longer converge in O’
\[ W(P) \approx 2 \cos(i) \Delta(M) \]
Relation with wavefront

Nijboer’s formulas

\[
\begin{align*}
x' &= D \frac{\partial W(P(x,y))}{\partial x} \\
y' &= D \frac{\partial W(P(x,y))}{\partial y}
\end{align*}
\]