Challenges and Solutions in Heliostat Optical Metrology

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September 27, 2023
Overview

• Key Metrology Problems
• Complicating Factors
• State of the Art
• Metrology Gaps
• Emerging Solutions

We thank:

Concentrating Solar Optics Laboratory (CSOL):
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Why Heliostats?

Only heliostats combine high concentration and high power.

1 https://www.energy.gov/eere/solar/linear-concentrator-system-concentrating-solar-thermal-power-basics
2 https://www.energy.gov/eere/solar/dishengine-system-concentrating-solar-thermal-power-basics
3 https://www.energy.gov/eere/solar/articles/linear-fresnel-power-plant-illustration
4 https://www.energy.gov/eere/solar/power-tower-system-concentrating-solar-thermal-power-basics
Consequences of optical error:

- Directly reduce temperature and power.
- Spillage can cause damage.
- Unpredictable hot spots, leading to either (a) damage or (b) conservative operation.

An Ideal Heliostat Field

No Error

Heliostats produce tight beams. All focus on desired target.

\[ \Rightarrow \text{High Temperature (T > 1000 °C)} \]
\[ \text{High Power (P > 100 MW}_{th}\text{)} \]
Errors Reducing Heliostat Performance

**Reflectance Loss:**
- Soiling or degradation causes loss of reflectance. Power is reduced.

**Measure:**
- Specular reflectance: \( \rho = \frac{P_r}{P_i} \)
- Varies with incidence angle.
- Varies with wavelength.
- Varies with time, plant location.

**Corrective actions:**
- Wash mirrors – when?
- Replace degraded mirrors.

**Slope Error:**
- Slope error causes irregular, defocused beam. Power is not focused in expected location.

**Measure:**
- Optical slope: \( f(x, y) \rightarrow \hat{n}_{(x,y)} \)
  - Varies with configuration, temperature.

**Corrective actions:**
- Design refinement.
- Manufacturing control.
- In-field maintenance (rare).

**Pointing Error:**
- Pointing error causes beam to miss target. Power is not in expected location.

**Measure:**
- Correction function: \( f(c_1, c_2) \rightarrow [\Delta c_1, \Delta c_2] \)
  - For all sun positions in solar year.
  - Two flavors:
    - Offline calibration.
    - Real-time, during operation.

**Corrective actions:**
- Apply correction function via software control.

**Dynamic Effects:**
- Beam oscillations due to wind or control. Power location varies over time.

**Measure:**
- Shape variation with time.
- Pointing variation with time.
- Wind-induced: Flutter response.
- Self-induced: Control dynamics.

**Corrective actions:**
- Design refinement.
- Operation strategy.

**Requirements:**
- Measurement accuracy must be < 0.01° (< 0.15 mrad).
- Measurements must be in situ, daylight, high speed.
Key Questions

Material Design
  Mirror optical properties?
  Mirror durability?

Product Design
  Prototype optical shape?
  Prototype pointing accuracy?
  Variation with conditions (range of motion, temperature, ...)?

Process Design
  Does product meet specified tolerances?
  Process parameters to control?

Manufacturing
  Does product meet optical tolerances?
  Is the process starting to drift?

Field Installation and Commissioning
  Optical change between manufacture and installation?
  What corrections enable accurate pointing?

Operation
  What is soil level? Does it vary across the plant?
  Do any heliostats require adjustment or maintenance?
  For a repaired heliostat, what adjustments are required?

All
  Can we trust each measurement? How do we know they are accurate?

Requirements vary with development phase:

• Product design:
  High resolution
  All conditions (tilt, temp, wind)
  Low cost
  Available

• Process design:
  High resolution
  Support process optimization
  Available

• Manufacturing:
  High speed
  High reliability
  Factory-friendly

• Installation:
  Outdoors
  Both shape and pointing
  Accelerate calibration.

• Operation:
  Outdoors
  Non-intrusive
  Low cost

Related indirect question:
What do results imply for economic performance?
Complicating Factors
**Sun Diameter**

**Sun is not a point source:**

Sun Diameter

\[
\phi = 4.6 \text{ mrad}
\]

\(~1.4 \times 10^9 \text{ m}\)

\(~1.5 \times 10^{11} \text{ m}\)

Beam reflected from a point expands:

\(w > 4 \tan(\phi/2)\)

\(w = 4 \tan(\phi/2)\)

\(w < 4 \tan(\phi/2)\)

Beam from a heliostat expands or contracts based on w/f ratio:

\[\frac{w}{f} > 4 \tan\left(\frac{\phi}{2}\right)\]

\[\frac{w}{f} = 4 \tan\left(\frac{\phi}{2}\right)\]

\[\frac{w}{f} < 4 \tan\left(\frac{\phi}{2}\right)\]

Near Field

Mid Field

Far Field

**BCS signal strength (BSS) decreases with square of distance to tower:**

\[BSS = \frac{I_b}{I_s} = \frac{P_b/A_b}{I_s} = \frac{I_s A_h}{(d_h \tan(4.6 \text{ mrad}))^2} = \frac{I_s A_h}{I_s d_h^2}\]

\[BSS \propto \frac{A_h}{d_h^2}\]

* Drawings exaggerate sun angle \(\phi\).

⇒ If BCS is used for calibration (see below), drives large heliostats for large plants. This in turn drives large row-to-row spacing, and increased wind load moments.
Regarding the beam expand/contract break-even threshold:

Beam shape expand/contract break-even analysis is an approximation that assumes sun, mirror vertex, and receiver are all on a common optical axis. This is almost never the case for real heliostats, which makes the expand/contract crossover analysis more complex. But the general principle still holds.

For simplicity, this analysis also assumes that the heliostat shape is well approximated by a sphere. This is a very good approximation for heliostats with high f/w ratios and no astigmatism. High f/w is typical for most heliostats, but some include astigmatism. Nonetheless, the general trend holds.

Regarding BCS signal strength:

\[ BSS \quad \text{BCS Signal Strength: Beam irradiance on target compared to ambient irradiance} \]
\[ A_h \quad \text{Heliostat aperture area} \]
\[ d_h \quad \text{Distance from heliostat to tower} \]
\[ I_s \quad \text{Solar irradiance intensity} \]
\[ P_b \quad \text{Power of reflected beam, at the tower} \]
\[ I_b \quad \text{Intensity of reflected beam, at the tower} \]
\[ A_b \quad \text{Cross-section area of reflected beam, at the tower} \]

This simple derivation assumes a perfectly focused heliostat. If the heliostat is not perfectly focused, due to either error or sun incidence angle (see below), then the BCS signal strength gets worse.
Solar Brightness Profile

Sun edge is not sharp:

Location: Sandia NSTTF
Data collected by the Lawrence Berkeley Laboratory (LBL)

Literature sources:

From Noring, et al 1991:
“Circumsolar radiation is caused by forward scattering of light through small angles by particles (aerosols) in the earth’s atmosphere with dimensions on the order of or greater than the wavelength of light. The aerosol particles may be composed of ice crystals or water droplets in thin clouds. They may be dust or sea salt particles, smoke or fumes, photochemical pollutants, sulfuric acid droplets, solid particles with a water mantle, flocks formed of a loose aggregate of smaller particles, or any of a large variety of solid, liquid or heterogeneous materials that are small enough to be airborne. The amount and character of circumsolar radiation vary widely with geographic location, climate, season, time of day, and observing wavelength.”

From Noring, et al 1991:
“Pyrheliometers, the instruments normally used to measure the direct solar radiation, typically have a field of view of 5° to 6°. The pyrheliometer measurement includes a large portion of the circumsolar radiation and thus overestimates the amount of direct sunlight that would be collected by a concentrating system.”

⇒ Weather station DNI measurements may overestimate solar resource unless pyrheliometer FOV is reduced.
Heliostats Studied for Beam Shape

BCS spot:

Images were collected throughout the day, for six days throughout the year.
BCS Spot Variation Example

Heliostat Reflection Under Increasing Incidence Angle

On-axis canting, sun incidence 0°:

Inquiries: OpenCSP@sandia.gov

Sun is modeled as a point source. Sun shape not included.
Heliostat Reflection Under Increasing Incidence Angle

On-axis canting, sun incidence 10°:

Sun is modeled as a point source. Sun shape not included.
Heliostat Reflection Under Increasing Incidence Angle

On-axis canting, sun incidence 30°:

Sun is modeled as a point source. Sun shape not included.
Heliostat Reflection Under Increasing Incidence Angle

On-axis canting, sun incidence 45°:

Sun is modeled as a point source. Sun shape not included.
Heliostat Reflection Under Increasing Incidence Angle

On-axis canting, sun incidence 75°:

Variable-shape heliostats are designed to address this problem. For example, see Angel, et al. SolarPACES 2020.
One Day: Winter Solstice Mid Spring Equinox

One Day: Winter Solstice Mid Spring Equinox

¾ Year: Winter/Spring, Spring/Summer, Summer
Pointing Corrections Vary with Time

Observations:

• Trends are clear within the day and across the year. Consider the winter-to-summer trend in 5E09, 14W01, and 14W06.

• With steep sun incidence (5E09 near sunrise, 5W09 near sunset), uncertainty is higher because the beam is diffuse.

• If we imagine a square receiver of side length $d_r$ and a hypothetical square spot, then an aim error $\Delta x$ would yield an flux capture fraction of $(d_r - \Delta x)/d_r$. A circular receiver does worse.

• Consider a back-row heliostat that is perfectly aimed and perfectly focused. Assuming sun half-angle 0.45 mrad and slant distance from 14E06 to the BCS target is 196 m, the spot from an ideal 14E06 would have diameter 1.76 m. Assume a 1.6 m receiver diameter.

• Pointing errors exceed 0.4 m in many cases, reducing power >25%.

Color legend:
Winter Solstice ➔ Equinox ➔ Summer Solstice
Sheer Size

An example large commercial heliostat field:

Crescent Dunes Solar Power Plant

Crescent Dunes Solar Power Plant

Crescent Dunes Heliostats

>10,300 heliostats
>360,000 facets
Geometric Distortion

Varying Heliostat-to-mirror and camera-to-mirror distance:

Distortion increases with heliostat-to-mirror distance, and camera-to-mirror distance.

\[ y_R = \frac{-2 d_T d_c \epsilon}{\cos(\theta_i)(d_T + d_c)} \]
Distortion: Tower-to-Mirror vs. Camera-to-Mirror Distance

Images at 25, 50, 100, and 150 m from the mirror.

* camera-to-mirror = 40 m
** camera-to-mirror = 80 m

Implication: Beware long optical path lengths.
A warm afternoon:

Flip between the slides, and watch the cars.

If there is this much variation due to atmospheric effects, how can we do precise metrology over long optical path lengths?
Atmospheric Distortion

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High-Frequency Effects

CSP mirrors can exhibit high-frequency aberrations:

• We have observed high-frequency reflection effects in several mirrors from multiple manufacturers.
• These effects can influence reflectivity and energy production.

Metrology techniques which employ coarse sampling strategies can incorrectly report smoothness. Position-based methods face a dilemma: Low resolution, which misses high-frequency effects, or high resolution, where measurement noise can introduce artificial slope deviation?
Complex Optical Shape

On-axis canting – Intuitive:

Off-axis canting – Maximum performance at solar noon:

Other canting strategies:

Metrology systems must be able to measure complex heliostat optical shapes.
Heliostat Deflection with Tilt

Model of heliostat deflection with different elevation angles:


Power-weighted elevation angle:

\[
\theta_{\text{power weighted}} = \frac{\sum_{i=1}^{8760} DNI_i \times \cos(factor_i \times \theta_{\text{elevation}})}{\sum_{i=1}^{8760} DNI_i \times \cos(factor_i)}
\]

Key Elevation Angles for ATS Heliostat @ NSTTF Site

<table>
<thead>
<tr>
<th>Elevation Angle</th>
<th>Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar Noon, Equinox</td>
<td>29.279</td>
</tr>
<tr>
<td>Solar Noon, Summer Solstice</td>
<td>41.402</td>
</tr>
<tr>
<td>Solar Noon, Winter Solstice</td>
<td>17.953</td>
</tr>
<tr>
<td>Power-Weighted Elevation Angle</td>
<td>22.934</td>
</tr>
</tbody>
</table>

Annual power-weighted intercept factor:

- Un-deformed: 66.6%
- Power Weighted: 62.7%
- Equinox Angle: 60.3%

Model predicts deformation causes a 6.3% drop in annual intercept. Setting canting angles with heliostat at power-weighted elevation angle reduces predicted loss to only 3.9%.

Assessing gravity effects requires measurement at different tilt angles.
Some Heliostats Intentionally Change Shape

### Constant shape:

- **f=25 m, On-Axis Canting**, Sun=90
- **Beam spread = 0.017 m** (point source sun)

### Variable shape:

- **f=25 m, Variable Shape**, Sun=90
- **Beam spread = 0.003 m** (point source sun)

<table>
<thead>
<tr>
<th>Facet</th>
<th>Local Sphere Focal Length (m)</th>
<th>Canting Angle (mrad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>25.0</td>
<td>-69.5</td>
</tr>
<tr>
<td>2</td>
<td>25.0</td>
<td>-30.0</td>
</tr>
<tr>
<td>3</td>
<td>25.0</td>
<td>0.0</td>
</tr>
<tr>
<td>4</td>
<td>25.0</td>
<td>30.0</td>
</tr>
<tr>
<td>5</td>
<td>25.0</td>
<td>69.5</td>
</tr>
</tbody>
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Sun is modeled as a point source. Sun shape not included.

Inquiries: OpenCSP@sandia.gov
Some Heliostats Intentionally Change Shape

**Constant shape:**

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  - Sun is modeled as a point source. Sun shape not included.

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</tr>
<tr>
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<td>30.0</td>
</tr>
<tr>
<td>5</td>
<td>25.0</td>
<td>69.5</td>
</tr>
</tbody>
</table>

**Variable shape:**

- **f=25 m, Variable Shape:**
  - Beam spread = 0.080 m (point source sun)

- **f=25 m, Variable Shape, Sun=100:**
  - Beam spread = 0.002 m (point source sun)

<table>
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<td>3</td>
<td>25.1</td>
<td>0.0</td>
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<tr>
<td>4</td>
<td>25.0</td>
<td>30.0</td>
</tr>
<tr>
<td>5</td>
<td>25.0</td>
<td>70.1</td>
</tr>
</tbody>
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Inquiries: OpenCSP@sandia.gov
Some Heliostats Intentionally Change Shape

Constant shape:

Variable shape:

Inquiries: OpenCSP@sandia.gov

Sun is modeled as a point source. Sun shape not included.
Some Heliostats Intentionally Change Shape

**Constant shape:**

- Beam spread = 0.666 m (point source sun)

**Variable shape:**

- Beam spread = 0.004 m (point source sun)

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<td>28.1</td>
<td>-27.1</td>
</tr>
<tr>
<td>3</td>
<td>27.1</td>
<td>0.0</td>
</tr>
<tr>
<td>4</td>
<td>26.2</td>
<td>28.3</td>
</tr>
<tr>
<td>5</td>
<td>25.2</td>
<td>67.9</td>
</tr>
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Some Heliostats Intentionally Change Shape

**Constant shape:**

Sun is modeled as a point source. Sun shape not included.

Variable shape:

Variable-shape heliostats (e.g., Angel, et al. SolarPACES 2020) require measurement at different tilt angles.

Inquiries: OpenCSP@sandia.gov
Flight Safety: High Flux Over Active Field

Where is the flux?

What is the flux limit?

- Under four heliostats (< 80 kW/m²), we observed the UAS ejecting a piece of hot debris, and then the UAS departed controlled flight, losing 5 m altitude and deviating 8 m east before recovering.
- Significant damage was observed post flight. Thermographic imaging indicated that UAS skin temperature exceeded 200 °C. Flight logs listed electronic speed controller (ESC) temperatures exceeding 100 °C.
Desired Metrology Characteristics

Primary characteristics:
- Accurate (verified against ground truth)
- Precise
- High sampling resolution
- Measure slope
- Distortion tolerant
- Astigmatism tolerant

Outdoors:
- Measure optical pointing and slope
- Daytime
- Non-intrusive
- Wind tolerant
- Measure at different tilt angles (deflection, variable shape)
- Measure at different temperatures
- Measure wind effects
- Able to measure very large mirrors
- Avoids long optical path length problems
- Safe despite high flux
- Fast
State of the Art
Reflectance Loss

**Requirements:**
- Measurement accuracy must be < 0.01°.
- Measurements must be in situ, daylight, high speed.

**Corrective actions:**
- Design refinement.
- Manufacturing control.
- In-field maintenance (rare).

**Corrective actions:**
- Apply correction function via software control.

**Measure:**
- Specular reflectance: \[ \rho = \frac{P_r}{P_i} \]
  - Varies with incidence angle.
  - Varies with wavelength.
  - Varies with time, plant location.

**Measure:**
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  \[ f(x, y) \rightarrow \eta(x, y) \]
  - Varies with configuration, temperature.

**Measure:**
- Correction function:
  \[ f(c_1, c_2) \rightarrow [\Delta c_1, \Delta c_2] \]
  - For all sun positions in solar year.
  - Two flavors:
    - Offline calibration.
    - Real-time, during operation.

**Dynamic Effects:**
- Beam oscillations due to wind or control.
  - Power location varies over time.

**Corrective actions:**
- Design refinement.
- Operation strategy.
Measuring Reflectance Loss

### Material Reflectance Loss

**Key Parameter:** Solar-Weighted Specular Reflectance

- **Example outdoor test:** NREL Accelerated Weathering
  - [Image of NREL Accelerated Weathering setup]
- **Example indoor test:** Xenon Arc Lamp Exposure (XALE)
  - [Image of Xenon Arc Lamp Exposure setup]
- **Example commercial testing:** CFV Labs
  - [Image of CFV Labs testing setup]

**SolarPACES Guideline**

- **Mature Instruments**

### Material Degradation

**Key Parameter:** Response to environment

- **Example commercial testing:** NREL Accelerated Weathering
  - [Image of NREL Accelerated Weathering setup]
- **Example outdoor test:** Xenon Arc Lamp Exposure (XALE)
  - [Image of Xenon Arc Lamp Exposure setup]

**Examplesoiling:**

- BRDF: Mature
  - [Image of BRDF measurement setup]
- Point measurement: Mature
  - [Image of Point measurement setup]
- Wide area: Ongoing

**Measurement stations: AVUS Soiling Station**

**Example BRDF:**

- [Image of BRDF measurement setup]

**Key Parameter:** Specular reflectance in the field

**Mature Instruments**

### Atmosphere Extinction

**Key Parameter:** Air transmittance loss

**Example outdoor test:** Xenon Arc Lamp Exposure (XALE)

- [Image of Xenon Arc Lamp Exposure setup]

**Data over two years:**

- [Graph showing data over two years]

**Apparatus:**

- [Diagram showing apparatus setup]

**Mature Instruments**
Citations for Measuring Reflectance Loss

**Material Reflectance Loss**


**Material Degradation**

6. CFV Labs: [https://www.cfvlabs.com/](https://www.cfvlabs.com/).

**Soiling**


**Atmospheric Extinction**


There is much more work in these areas; this is just a sample.
Slope Error

Requirements:
• Measurement accuracy must be < 0.01°.
• Measurements must be in situ, daylight, high speed.

Reflectance Loss:
Soiling or degradation causes loss of reflectance. Power is reduced.

Measure:
• Specular reflectance: \( \rho = \frac{P_r}{P_i} \)
  - Varies with incidence angle.
  - Varies with wavelength.
  - Varies with time, plant location.

Corrective actions:
• Wash mirrors—when?
• Replace degraded mirrors.

Slope Error:
Slope error causes irregular, defocused beam. Power is not focused in expected location.

Measure:
• Optical slope: \( f(x, y) \to \tilde{n}_{(x,y)} \)
  - Varies with configuration, temperature.

Corrective actions:
• Design refinement.
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Pointing Error:
Pointing error causes beam to miss target. Power is not in expected location.

Measure:
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  - For all sun positions in solar year.
  - Two flavors:
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Beam oscillations due to wind or control. Power location varies over time.

Measure:
• Shape variation with time.
• Pointing variation with time.
• Wind-induced: Flutter response.
• Self-induced: Control dynamics.

Corrective actions:
• Design refinement.
• Operation strategy.
SOFAST: High-Resolution Slope Measurement

Prototype Development
- What areas need improvement?
- Any artifacts (ripples, warping,...)?

Process Development
- Bad areas?
- Consistency?

Factory Production
- Meets specs?
- Process control?

Example related papers (abbreviated):
- CSP Services. QDec-M. CSPS-QDec.pdf.
Citations for High-Resolution Slope Measurement


• M. Montecchi, G. Cara, and A. Benedetti. VISproPT commissioning and SFERA-III WP10 Task3 round-robin on 3D shape measurements: recommended procedure and ENEA results. ENEA Report TERIN-STS/N/2022/14, November 2022.


SOFAST Output: NSTTF Facet

Absolute
Input: Measurement
Mirror: NSTTF Facet N-002
Instrument: SOFAST Landscape
Date/time: September 2022
Sample points: Grid
Number points: 458,523
Resolution X: 1.8 mm/pt
Resolution Y: 1.8 mm/pt
Uncertainty: ±TBD mrad

Error
Add: Design Reference

Ideal Design
\[ z = \frac{x^2}{4f_x} + \frac{y^2}{4f_y} \]
\begin{align*}
f_x &= 100 \text{ m} \\
f_y &= 100 \text{ m} \\
l_x &= 1.22 \text{ m} \\
l_y &= 1.22 \text{ m}
\end{align*}

Ray Trace
Add: Field Location, Target, Time

Field location: [0.0 m, 95.7 m]
Target: [0.0 m, 8.8 m, 28.9 m]
BCS Wall
2022-06-30 14:40:22

RMS slope error magnitude: 0.74 mrad
RMS slope error X: 0.46 mrad
RMS slope error Y: 0.58 mrad
Range slope error X: [-1.01, +2.36] mrad
Range slope error Y: [-1.21, +3.30] mrad
Best-fit focal length X: 125.7 m
Best-fit focal length Y: 114.6 m

SOFAST measures slope directly, samples at high resolution, and is distortion-tolerant.
Output Summary: NSTTF Heliostat 5W01

**Absolute Input:** Measurement

- **Heliostat:** 5W01
- **Instrument:** SOFAST Tower
- **Date/time:** 2022-06-29 23:03
- **Sample points:** Grid
- **Number points:** 4,446,000/heliostat 178,000/facet
- **Resolution X:** 2.9 mm/pt
- **Resolution Y:** 2.9 mm/pt
- **Uncertainty:** ±TBD mrad

**Error Add:** Design Reference

- **Ideal Design**
- **On-axis canting. Slant distance 57.2 m.**

- **RMS slope error magnitude:** 2.0 mrad
- **RMS slope error X:** 1.6 mrad
- **RMS slope error Y:** 1.3 mrad
- **RMS canting error magnitude:** 1.7 mrad
- **RMS canting error X:** 1.3 mrad
- **RMS canting error Y:** 1.2 mrad
- **Range canting error X:** [-3.2, +2.0] mrad
- **Range canting error Y:** [-2.5, +2.3] mrad

**Ray Trace Add:** Field Location, Target

- **Field location:** [-4.66 m, 57.9 m]
- **Target:** [0.0 m, 8.8 m, 28.9 m]

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 neger

- **Curvature**

**Preliminary. Still in progress.**

* Following Ulmer, et al. 2011. They are further along.*
Pointing Error

Requirements:
• Measurement accuracy must be < 0.01°.
• Measurements must be in situ, daylight, high speed.

Measure:
• Specular reflectance:
  \[ \rho = \frac{P_r}{P_i} \]
  • Varies with incidence angle.
  • Varies with wavelength.
  • Varies with time, plant location.

Corrective actions:
• Wash mirrors – when?
• Replace degraded mirrors.

Reflectance Loss:
Soiling or degradation causes loss of reflectance. Power is reduced.

Slope Error:
Slope error causes irregular, defocused beam. Power is not focused in expected location.

Measure:
• Optical slope:
  \[ f(x, y) \rightarrow \hat{n}(x, y) \]
  • Varies with configuration, temperature.

Corrective actions:
• Design refinement.
• Manufacturing control.
• In-field maintenance (rare).

Pointing Error:
Pointing error causes beam to miss target. Power is not in expected location.

Measure:
• Correction function:
  \[ f(c_1, c_2) \rightarrow [\Delta c_1, \Delta c_2] \]
  • For all sun positions in solar year.
  • Two flavors:
    o Offline calibration.
    o Real-time, during operation.

Corrective actions:
• Apply correction function via software control.

Dynamic Effects:
Beam oscillations due to wind or control. Power location varies over time.

Measure:
• Shape variation with time.
• Pointing variation with time.
• Wind-induced: Flutter response.
• Self-induced: Control dynamics.

Corrective actions:
• Design refinement.
• Operation strategy.

Heliostat Calibration

BCS Calibration:


See also:

Both the tower and the BCS target set the pace for this calibration method.
Distant heliostats are difficult, due to reduced BCS signal strength (see above).
Heliostat Closed-Loop Control

- Heliostat calibration assumes that once individual heliostat “signatures” are identified, they may be used indefinitely for the control of heliostats.
- This has advantages of simplicity, and immunity from short-term perturbations such as wind disturbances.
- However, it requires a lengthy up-front calibration process, and then is oblivious to changes that might occur (such as drift, soil settling, permanent motion due to a wind event, etc).
- Closed-loop control offers a way to avoid these limitations.
- However, such systems must function while the heliostat field is operating and producing maximum flux.
- Solutions must be low cost, which challenges approaches that require mounting an active camera on each heliostat, or other special heliostat modifications.
- One current system which accomplishes closed-loop control is the Heliogen SOHOT system.¹
- See Sattler, et al.² for an excellent review of heliostat tracking and control methods.

Dynamic Effects

**Requirements:**
- Measurement accuracy must be < 0.01°.
- Measurements must be in situ, daylight, high speed.

**Measurements:**
- **Reflectance Loss:**
  - Soiling or degradation causes loss of reflectance. Power is reduced.
  - **Measure:**
    - Specular reflectance: \( \rho = \frac{P_r}{P_i} \)
    - Varies with incidence angle.
    - Varies with wavelength.
    - Varies with time, plant location.
  - **Corrective actions:**
    - Wash mirrors—when?
    - Replace degraded mirrors.

- **Slope Error:**
  - Slope error causes irregular, defocused beam. Power is not focused in expected location.
  - **Measure:**
    - Optical slope:
      \( f(x, y) \rightarrow \Delta r_{(x,y)} \)
    - Varies with configuration, temperature.
  - **Corrective actions:**
    - Design refinement.
    - Manufacturing control.
    - In-field maintenance (rare).

- **Pointing Error:**
  - Pointing error causes beam to miss target. Power is not in expected location.
  - **Measure:**
    - Correction function:
      \( f(c_1, c_2) \rightarrow [\Delta c_1, \Delta c_2] \)
    - For all sun positions in solar year.
    - Two flavors:
      - Offline calibration.
      - Real-time, during operation.
  - **Corrective actions:**
    - Apply correction function via software control.

- **Dynamic Effects:**
  - Beam oscillations due to wind or control. Power location varies over time.
  - **Measure:**
    - Shape variation with time.
    - Pointing variation with time.
    - Wind-induced: Flutter response.
    - Self-induced: Control dynamics.
  - **Corrective actions:**
    - Design refinement.
    - Operation strategy.

**Slope Error Diagram:**
- Slope error causes irregular, defocused beam. Power is not focused in expected location.
- **Measure:**
  - Optical slope:
    \( f(x, y) \rightarrow \Delta r_{(x,y)} \)
  - Varies with configuration, temperature.

**Pointing Error Diagram:**
- Pointing error causes beam to miss target. Power is not in expected location.
- **Measure:**
  - Correction function:
    \( f(c_1, c_2) \rightarrow [\Delta c_1, \Delta c_2] \)
  - For all sun positions in solar year.
  - Two flavors:
    - Offline calibration.
    - Real-time, during operation.

**Reflectance Loss Diagram:**
- Soiling or degradation causes loss of reflectance. Power is reduced.
- **Measure:**
  - Specular reflectance: \( \rho = \frac{P_r}{P_i} \)
  - Varies with incidence angle.
  - Varies with wavelength.
  - Varies with time, plant location.

**Corrective actions:**
- Wash mirrors—when?
- Replace degraded mirrors.
Heliostat Deflection Analysis

Dynamic deformation analysis:

Mode shapes for first 9 predicted modes

Wind-induced deformation measurement:


Heliostat Metrology Gaps
Gaps

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Other perspectives:
Some gaps can currently be addressed, at least partially, by composite techniques that combine methods.

Other perspectives:
Many opportunities for improvement.

Emerging Solutions
SOFAST Improvements

Addressing unsolved problems:

• Temperature optical effect?
• Tilt angle optical effect?
• Mobile SOFAST.

Increasing benefit:

• Ease of use.
• Industrial support.
• Educational version.
• Easy access – OpenCSP
  (OpenCSP@sandia.gov)

Our goal is to maximize benefit to CSP industry, research, education.

Related work:

UFACET: Drone-Based Field Assessment

Accelerated Calibration
During construction.
During plant startup.

In-Field Heliostat Assessment
During operation:
• Have heliostats changed?
• Implications?

Other drone-based approaches (abbreviated):
Citations for Drone-Based Field Assessment

Other drone-based approaches:


Dynamic Optical Evaluation

BCS Dynamic Motion:

Wind 15 mph, gust up to 30 mph
Dynamic Optical Evaluation

BCS Dynamic Motion:

Wind 15 mph, gust up to 30 mph
Dynamic Optical Evaluation

BCS Dynamic Motion:

Wind 15 mph, gust up to 30 mph
Dynamic Optical Evaluation

BCS Dynamic Motion:

Wind 15 mph, gust up to 30 mph
Dynamic Optical Evaluation

BCS Dynamic Motion:

Wind 15 mph, gust up to 30 mph
Dynamic Optical Evaluation

BCS Dynamic Motion

Change in Optical Intercept Due to Light Wind

Wind 15 mph
Gust up to 30 mph

Nominal

9 mph wind gust

Red cross hairs show aim point.
All beam perturbations due to wind.

Colors match slope error magnitude plot.

Target points imaged

Camera hole

Camera

Precision Mirror (f = 100 m)

Plano Water Pool

Following T. März, et al. Validation of Two Optical Measurement Methods..., 2011
Conclusion

• Heliostat error categories:
  o Reflectance loss
  o Slope error
  o Pointing error
  o Dynamic effects

• Well-established:
  o Material reflectance
  o Indoor high-resolution slope
  o BCS pointing, calibration

• Challenging:
  o Wide-area soiling
  o Optical impact of temperature, tilt, dynamics
  o Distant heliostats
  o Accelerated calibration
  o In-situ optical assessment
  o Ground truth verification

• While seemingly simple, heliostat metrology encounters complex effects and harsh environments.

• Sandia is engaging many of these problems, and seeks to make excellent solutions easily accessible. OpenCSP@sandia.gov

Note: A lot more great work did not fit!
BACKUP SLIDES
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