U.S. Department of Energy
HelioCon
Heliostat Consortium for Concentrating Solar-Thermal Power

Non-Intrusive Optics (NIO)

Technology for Characterizing Commercial Heliostat Optical Errors

Tucker Farrell, Dr. Rebecca Mitchell, Dr. Guangdong Zhu, Devon Kesseli

The NREL Optics Team

Dr. Gaungdong Zhu

Dr. Rebecca Mitchell

Tucker Farrell

Devon Kesseli

Miriam Caron

Kyle Sperber

Daniel Tsvankin

NIO Impact

An in-situ heliostat measurement tool to assess slope, canting, and tracking errors on operational heliostats in commercial fields.

- ***Heliostat Consortium Roadmap*** identified the following gaps in heliostat metrology
  - **Opto-mechanical quality calibration after installation**: there is missing metrology for opto-mechanical quality calibration after installation.
  - Opto-mechanical error in-situ monitoring tools: there are missing in-situ monitoring tools for the full spectrum of opto-mechanical error including surface slope error, mirror facet canting error, and heliostat tracking error. **The in-situ tools should be applicable to commercial-scale heliostat fields**
  - Receiver flux quality real-time assurance tools: there are missing validated receiver flux quality real-time assurance tools that can accommodate aiming strategies **based on the knowledge of full field heliostat opto-mechanical performance.**

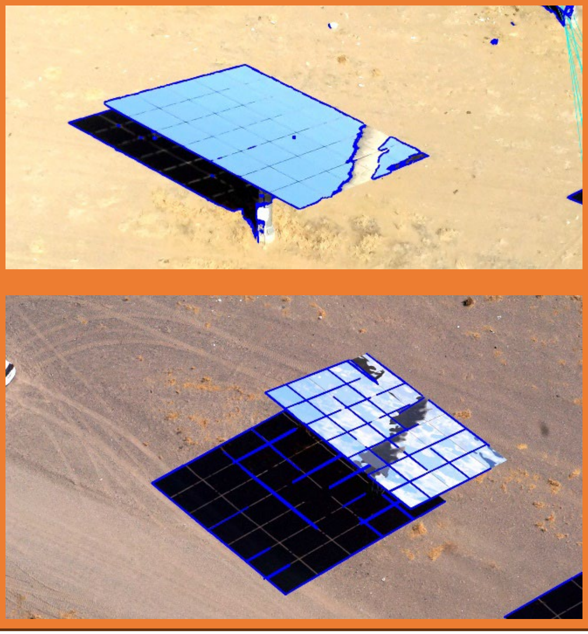
- Stakeholder engagement and feedback
  - Models are used for everything – predicting performance, revenue, availability, aiming strategies
  - The models depend on the input data, you must know your heliostat in its operational condition

NIO Methodology

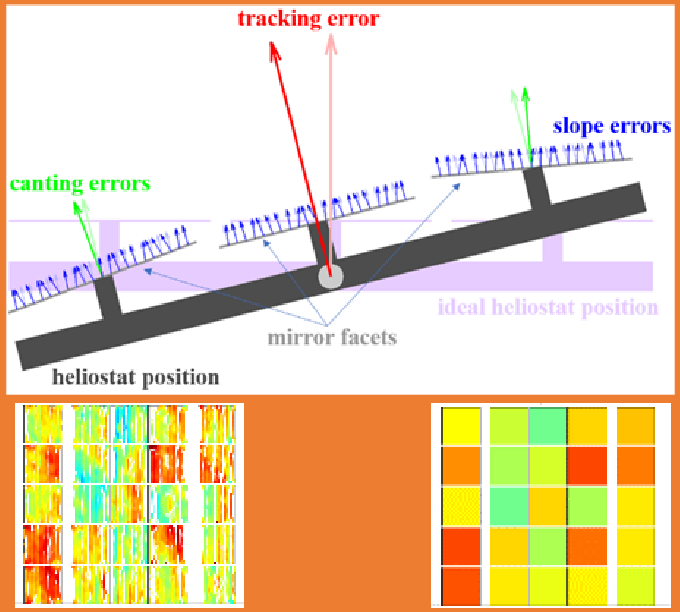
- NIO allows for the efficient optical assessment of a commercial-scale CSP solar field.
- Heliostats are scanned in seconds using Unmanned Aircraft Systems (UAS) imaging.
- The method produces detailed optical characterization data over the full mirror surface for every heliostat (slope, canting, and tracking error).

UAS data collection

Computer vision and ML image processing



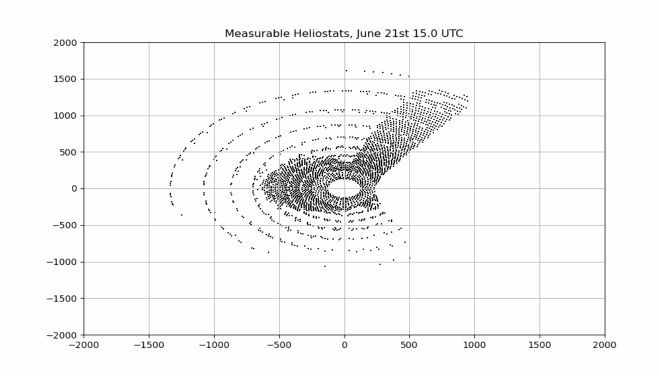
Optical error characterization



NIO Software *Point-wise deviations of the mirror surface normal vector*

1: Field model

- *Define heliostats and tower in space*
- *Assess measurability*

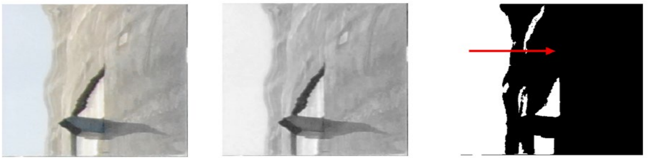


2: Data collection

- *Generate waypoints for a sector of heliostats*
- *Collect video data*

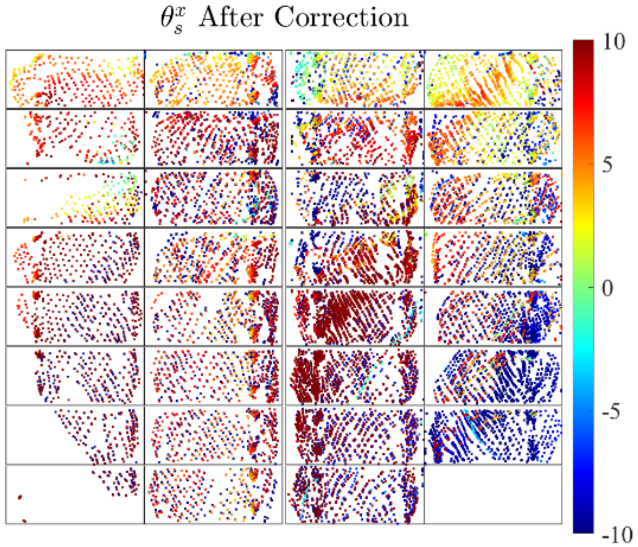
3: Data parsing

- *Define expected orientations*
- *Find heliostats*
- *Find features – heliostat corners and tower edges*
- *Compute a camera position*



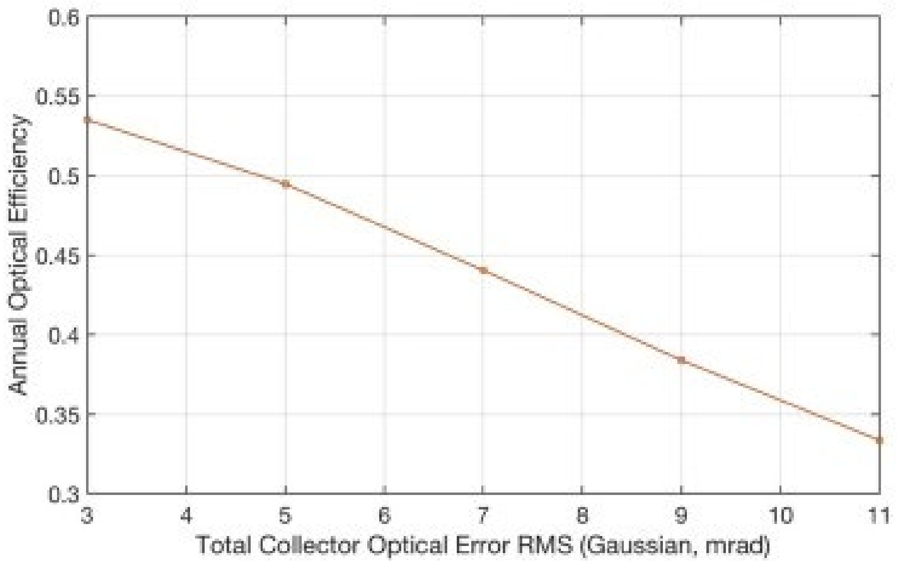
4: Optical errors

- *1D – calculate slope, canting, and tracking normal to reflected tower edge*
- *Apply tracking correction to refine*
- *2D – solve for vector that satisfies reflection conditions for two orientations at single point*



Significance of Slope Error

- *Deviations at the surface of the mirror impact the direction of the incident sunlight and energy reaching the receiver*
- *"An increase of 2 mrad and 4 mrad on the total optical error RMS is equivalent to 1 mrad and 2 mrad on the mirror slope or canting error, respectively" [1]*



[1] A non-intrusive optical (NIO) approach to characterize heliostats in utility-scale power tower plants: Methodology and *in-situ* validation
R. Mitchell, G. Zhu 2020

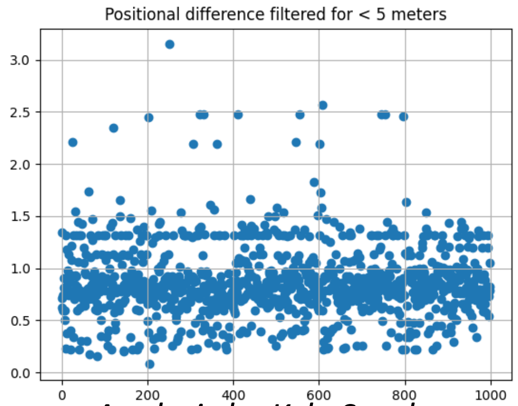
If we can characterize slope error in an operational field:

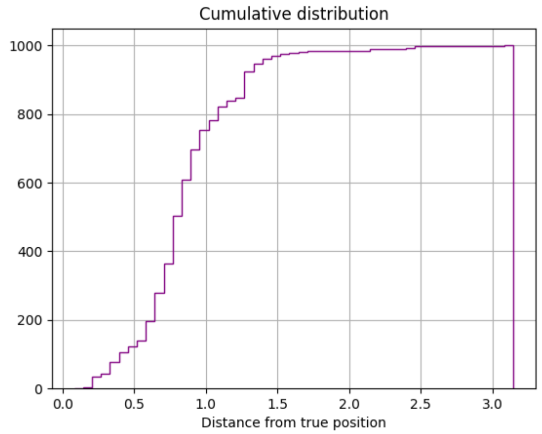
- *Map the flux at the receiver*
- *Build better power models*
- *Itemize solar field error budgets and isolate losses*
- *Optimize aiming strategies and adjust solar field controls to recoup lost power*
- *Monitor reflector degradation*
- *And if absolutely necessary, adjust and replace equipment*

NIO Software Progress

Feature detection sensitivity study
- *Camera position*
- *Lighting*
- *Bounding box variability*
- *Crowded bounding box*

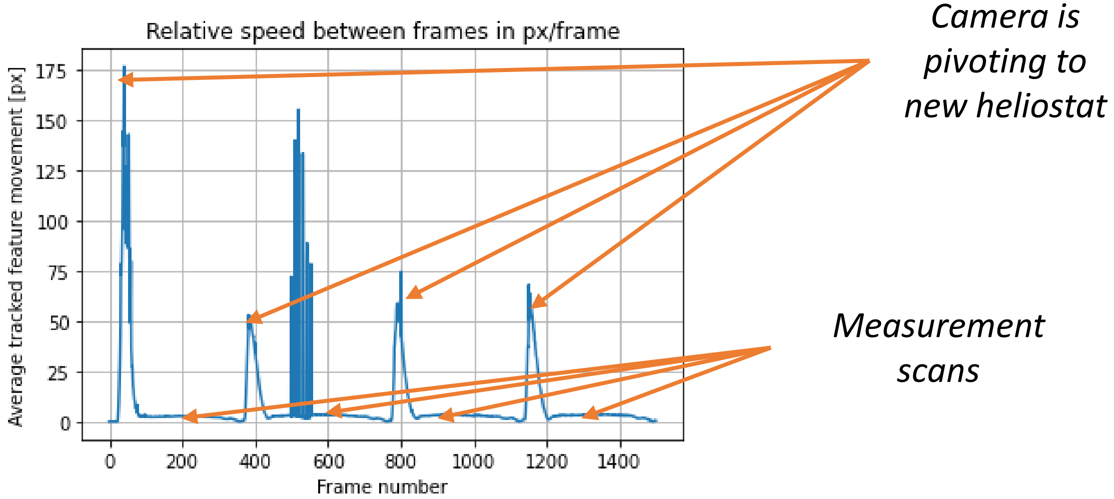
Results
- *Changing camera position create error within 1 meter*
- *Lighting has no impact on the accuracy*
- *Changes in the bounding box size and position produces accuracy within 2.5 meters*
- *Crowding the bounding box causes the biggest effects providing accuracy within 30 meters*





Analysis by Kyle Sperber

Optical flow video segmentation
- *Shi-Tomasi feature detection combined with Lucas-Kanade optical flow*
- *Redetect points every N steps*
- *Compute relative key feature displacements for "speed" between frames*
- *Slow-moving features indicate camera is focused on a heliostat*



NIO Software Progress

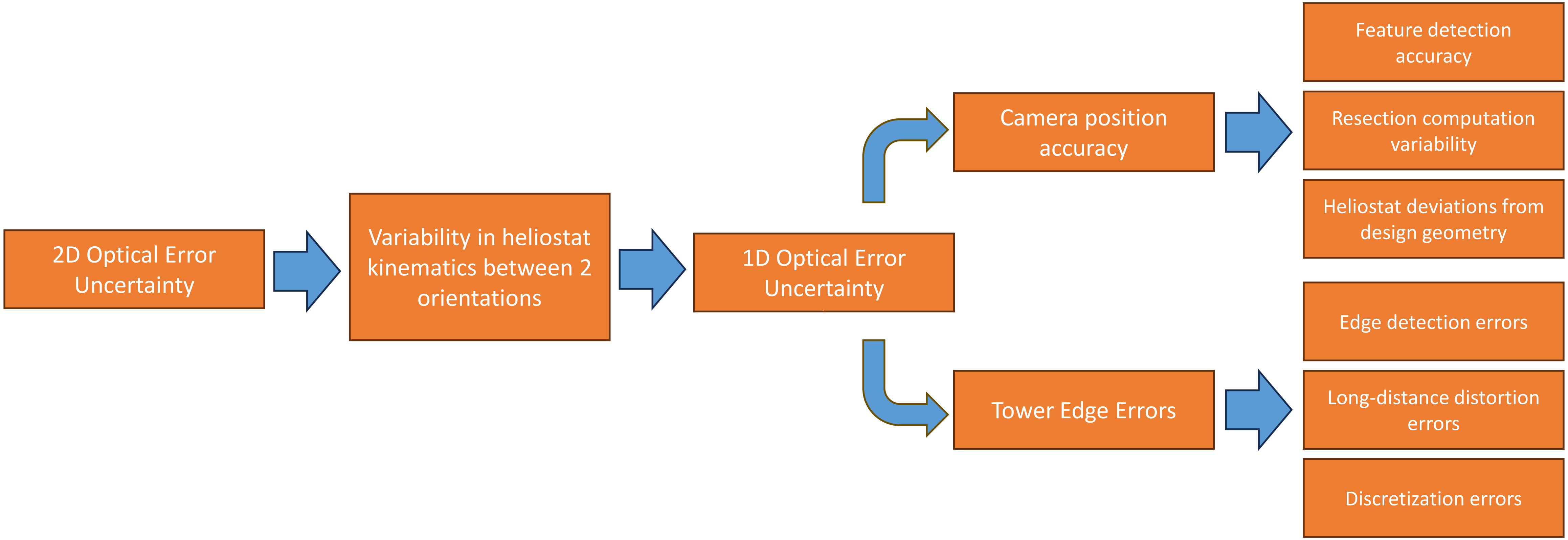
Transcription

- Translated the software from MATLAB to Python
    - Python is free
    - Python is more widely used
    - All of software is in one language
    - Allows software to be changed to object-oriented programing
- Translation is complete and currently flushing out minor bugs to the python version of the software so that it outputs the same results as the MATLAB version

Class architecture (purpose and status)

- Purpose
    - Reduces computer storage
    - Cuts computation time
    - Classes can be reused for other projects
    - Makes future development and bug fixes easier
- Status
    - Initial version is complete flushing out minor bugs to match Matlab version
    - Required computer storage cut by 20%
    - Computation time decreased by 33%

NIO: Characterizing Uncertainty



NIO in the CSP industry

- 75 + stakeholder interviews in the “Lean-Launch” framework
- Slope/shape error on the radar of plant owners, plant managers, heliostat designers…

Planning

- *Heliostat selection*
- *Tech suppliers have internal design tolerances*
- *Issue “performance guarantees” for heliostat*
- *Not verifiable in operation*

Construction

- *Heliostats assembled on site*
- *Measured at construction, then installed*
- *May sit for months/years before plant is operational*

Commissioning

- *Multi-year test/verification of plan*
- *Required to meet power benchmarks*
- *Underperformance can result in liquidated damages for liable parties*

Normal operations

- *Power based on models*
- *Calibration by BCS*
- *Temperature swings, wind, orientation effects, gravity, and environmental factors can degrade mirror surface*

As a commissioning tool

- *Multiple-year, expensive acceptance process*
- *Often a ladder-structure, for example*
  - *Year 1 – 65% design power output*
  - *Year 2 – 75% design power output*
  - *Year 3 – 90% design power output*
- *Liquidated damages can impact underperforming systems*

- *NIO can validate heliostat performance*
  - *As each heliostat is installed*
  - *As the solar field comes online*

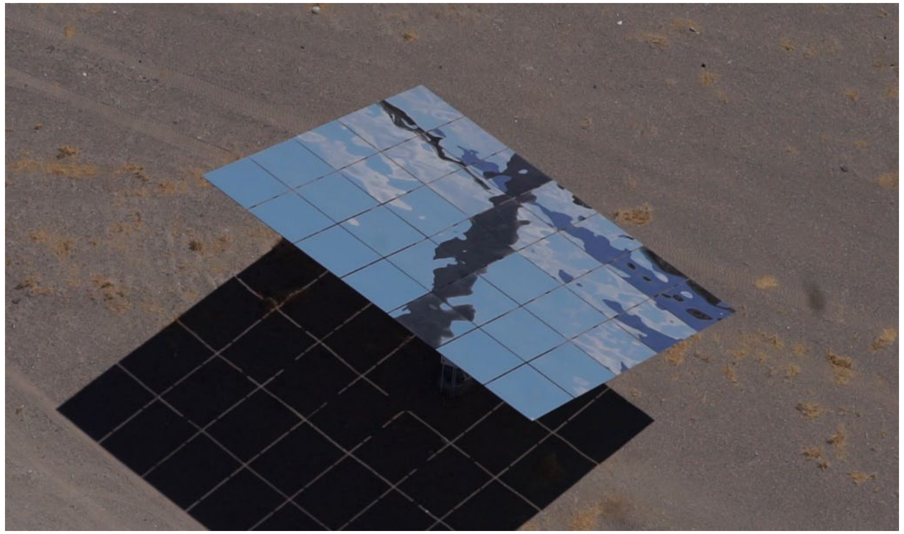
A heliostat is measured with QDec – a system developed at CSPServices

A heliostat is crane-lifted onto a pylon. Typically, no shape validation is done after this is complete.

As a calibration tool

- *The Beam Characterization System (BCS) is commonly used to characterize tracking error*
  - *Some BCS are limited to 1 heliostat per target face, or 4 heliostats at a time*
  - *Distant heliostats can be difficult to calibrate (< 1 km)*
    - *Weaker beam*
    - *Target is saturated from glowing receiver*

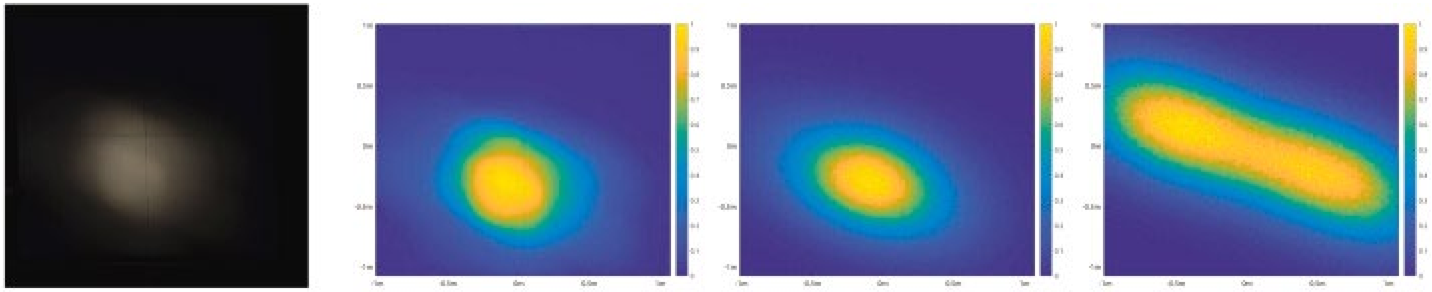
- *Use NIO to supplement existing systems and*
  - *Validate BCS output*
  - *Calibrate distant heliostats*
  - *Add high-resolution beam quality information to calibration*



Sample NIO image taken on heliostat > 1.5 km from the tower

As an optimization tool

- *Optimized aiming strategies require strong models*
- *Strong models require well-characterized heliostats*
- *Current strategies*
    - *Damping with overdesigned fields – more heliostats than needed to cover seasonal changes and optical losses*
    - *Models use assumed or designed errors in heliostat loss budgets*
    - *Heliostats are measured in a single orientation at construction*



(a) Focusing spot photo (b) Measured distribution (c) Identified parameter (d) Designed parameter

Case study found 20% increase in power by optimizing aiming strategy for post-installation optical deviation [2]

[2] Heliostat field aiming strategy optimization with post-installation calibration
R. Zhu et al. Applied Solar Engineering 2022
https://doi.org/10.1016/j.applthermaleng.2021.117720

Thank You

www.nrel.gov

Tucker Farrell
Tucker.Farrell@nrel.gov
National Renewable Energy Laboratory
United States

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the DOE's Solar Energy Technology Office (SETO). The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.