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

Improvements in **Re**flected **T**arget **N**on-intrusive **A**ssessment (ReTNA)

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ASME ES 2023

July 10^{th}-12^{th}, 2023

conceptional design • components • integration • mass production • heliostat field

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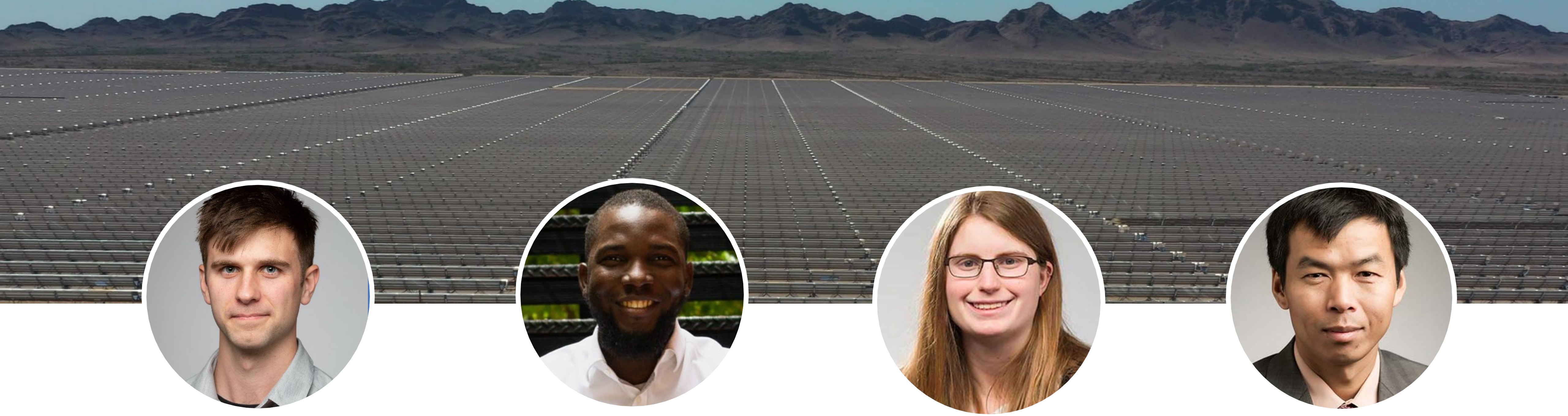
Project Team



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Objective

Reflected **T**arget **N**on-intrusive **A**ssessment (**ReTNA**) - a tool for:

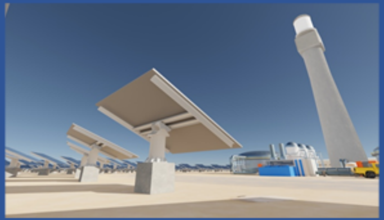
- Assembly line QA/QC, particularly at small installations.
- Adaptability to measurement at a variety of heliostat sizes and orientations.

NIO (NREL's tool for field analysis)

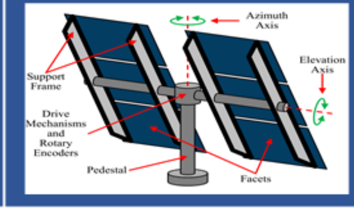
ReTNA

Heliostat Development Cycle

Conceptual Design:



Heliostats Components:



An Integrated Heliostat:

Mass Production of Heliostats:

A Heliostat Field:

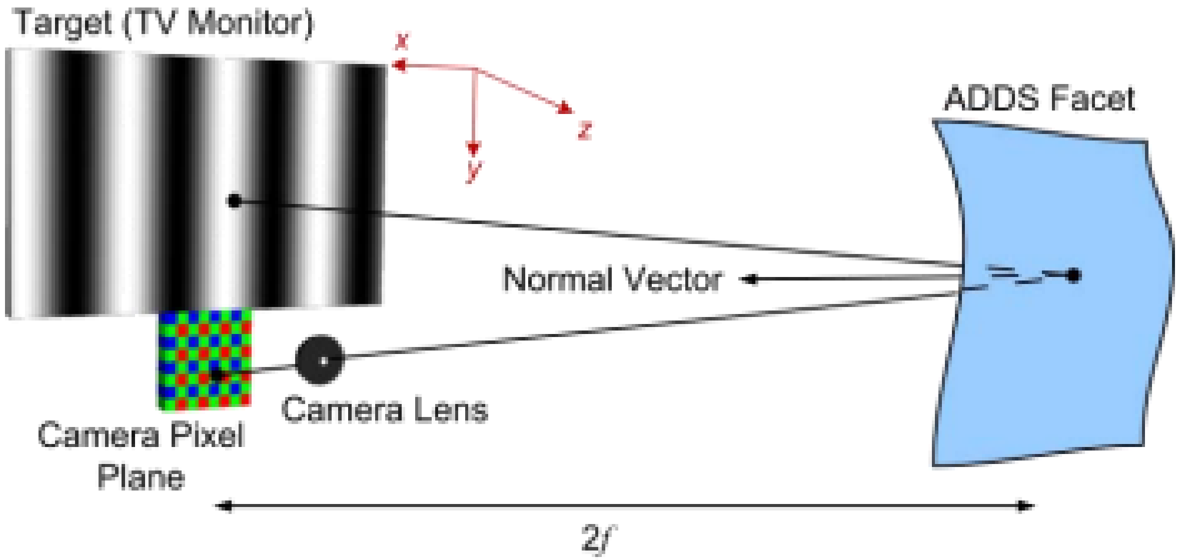
Component testing – measurement after wind load simulation and repeated stress testing.

An Integrated Heliostat: full scale heliostat testing, facet canting measurement.

Mass Production of Heliostats: Assembly line quality assurance and control.

State-of-the-Art

- **Some tools already exist!**
  - Fringe Deflectometry – powerful, high resolution, complicated setup (QDec, SOFAST, Fraunhofer ISE)
  - Photogrammetry – well established, but requires targets attached to mirror surface
  - Reflected Target (ReTNA, VIS-PT)



[Finch and Andraka, 2012 https://doi.org/10.1115/ES2011-54455](https://doi.org/10.1115/ES2011-54455)

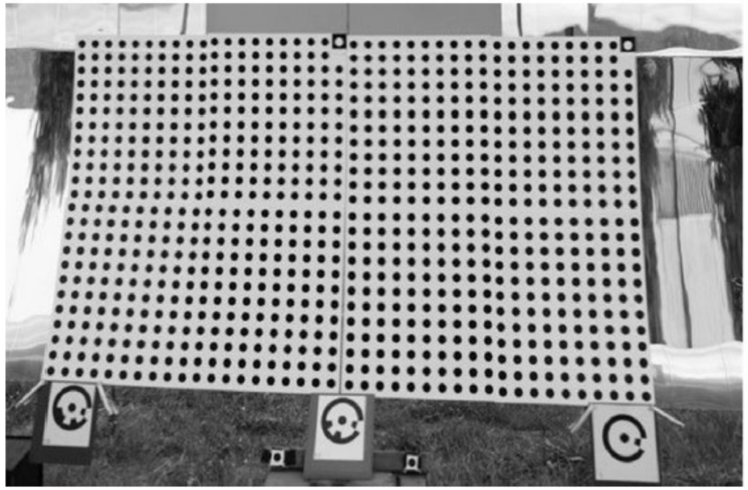


Fig. 6. Photogrammetry measurements carried out at ENEA's PTC facility by CENER's technicians.

C. A. Arancibia-Bulnes, M. I. Peña-Cruz, A. Mutuberría, R. Díaz-Uribe, and M. Sánchez-González, “A survey of methods for the evaluation of reflective solar concentrator optics,” *Renewable and Sustainable Energy Reviews*, vol. 69, pp. 673–684, Mar. 2017, doi: 10.1016/j.rser.2016.11.048.

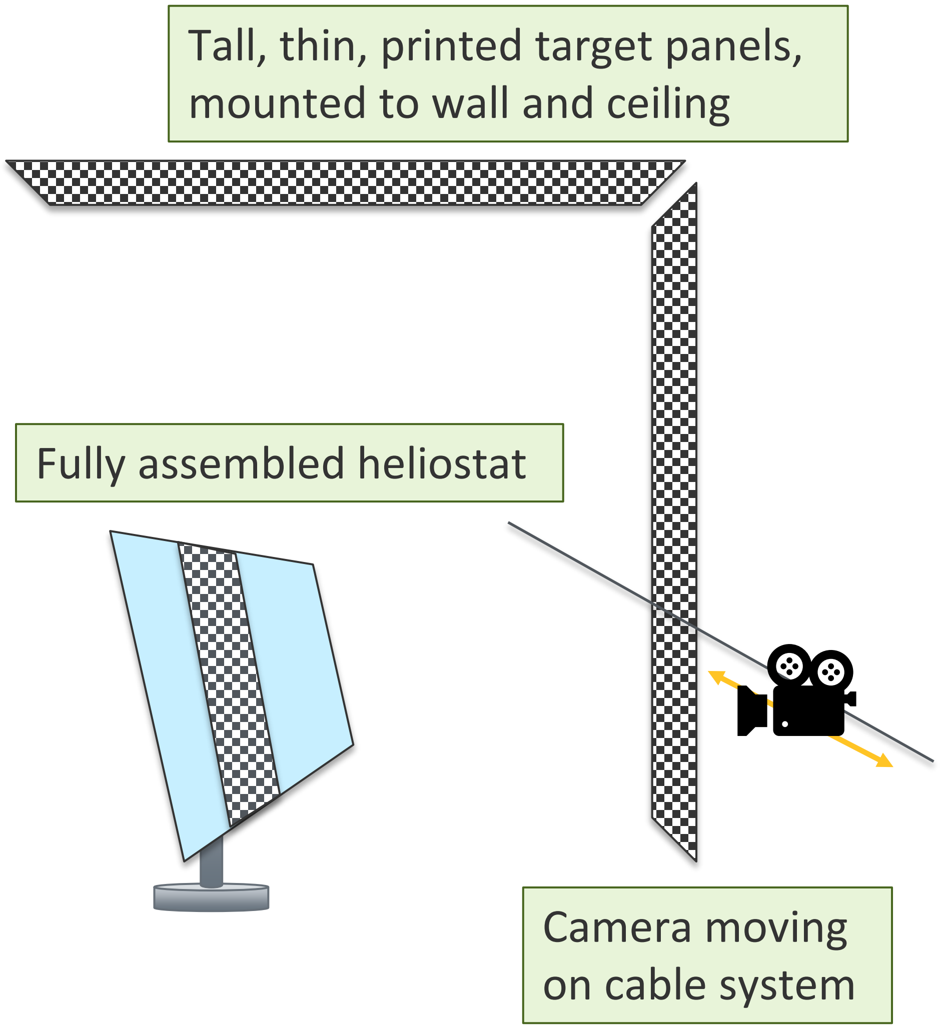
ReTNA Motivation

Powerful fringe deflectometry methods already exist. Printed target methods have some advantages:

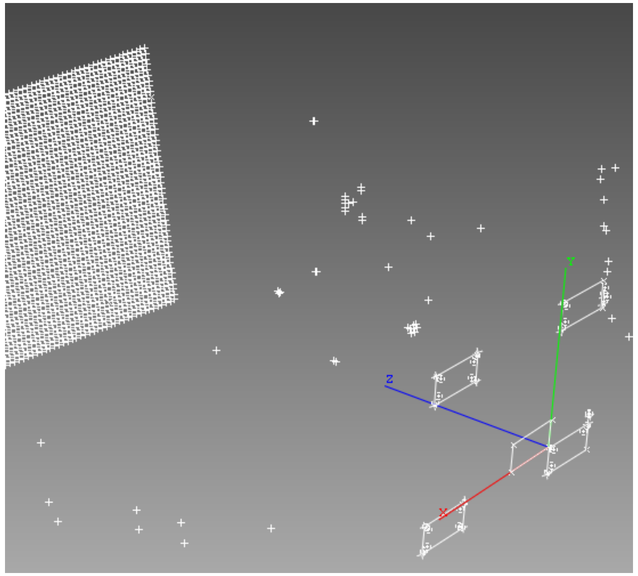
- **Low cost, easy setup** vs. large screen target needed for fringe deflectometry – easy to install for any size/orientation heliostat.
- Can leverage recent advances in CV, open-source tools.
- **Easy to debug**, direct measurement of target points with PG removes setup precision requirements.
- **Ambient lighting**, for warehouse or assembly line.
- **2D slope measurement** with a single image.

Disadvantages:

- Lower **resolution** compared to fringe methods



ReTNA Features



Reflected **T**arget **N**on-intrusive **A**ssessment (**ReTNA**)

1. Photogrammetry locates mirror and all target points in space.
2. Camera collects images of reflected targets.
3. Camera position is solved directly from image.
4. Reflected target points automatically identified
5. Measure mirror **surface slope** and facet **canting**.

ReTNA Workflow

Series of Images

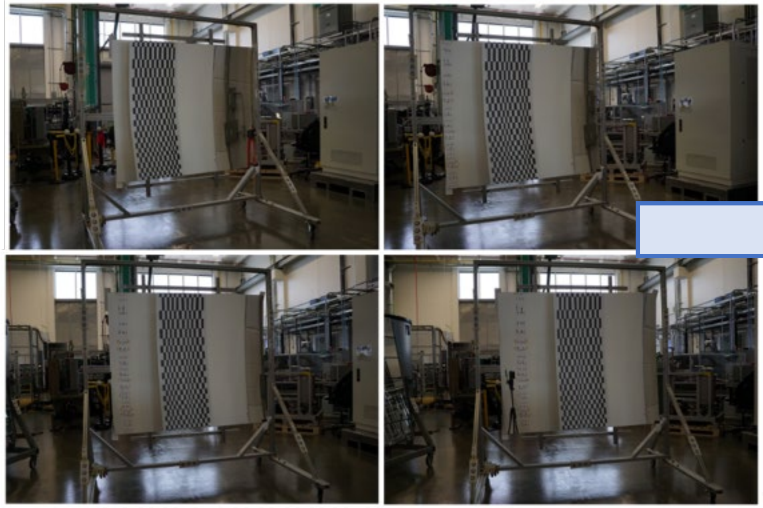
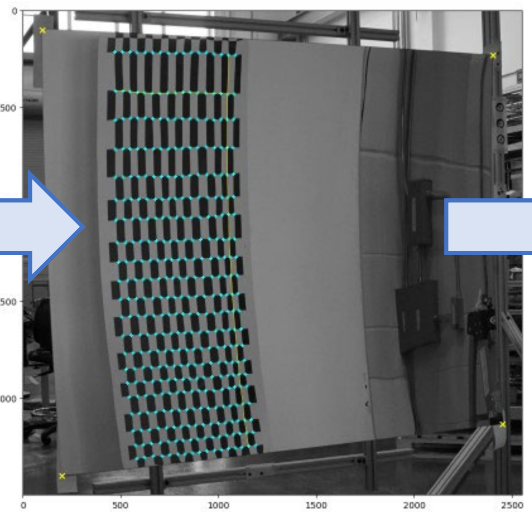
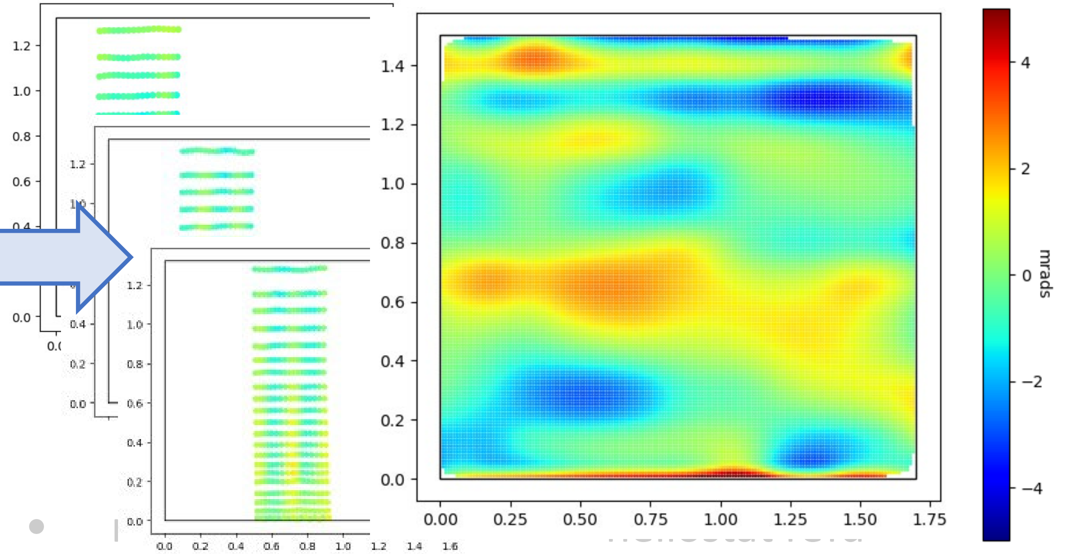


Image Processing



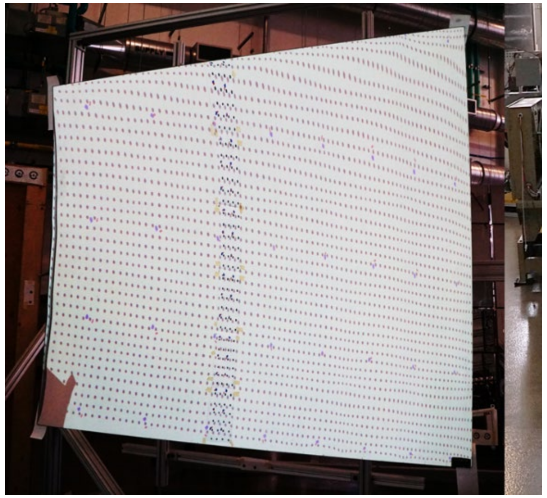
Full Facet or Heliostat Surface Analysis

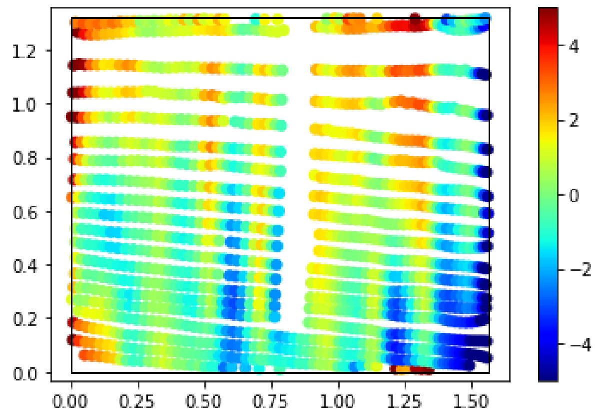


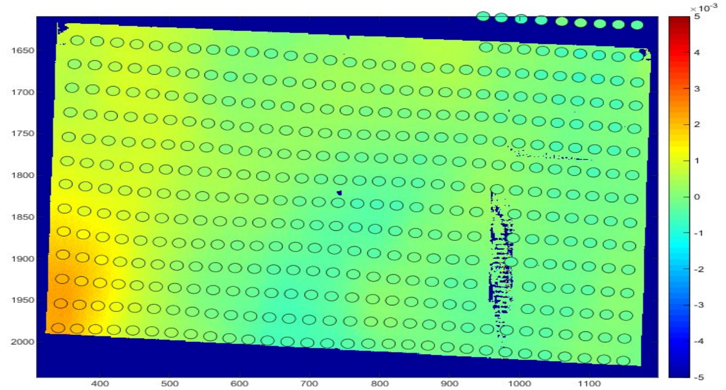
Previously...

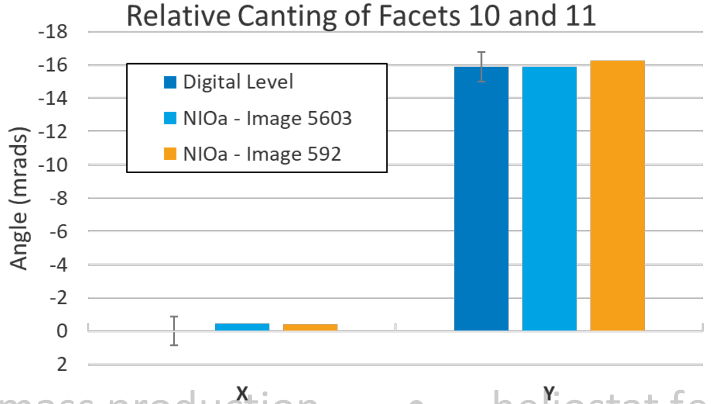
Large target, single image analysis

- Repeated measurement, heliostat and parabolic trough facet.
- Qualitative comparison to SOFAST
- Canting measurement validation with inclinometer.









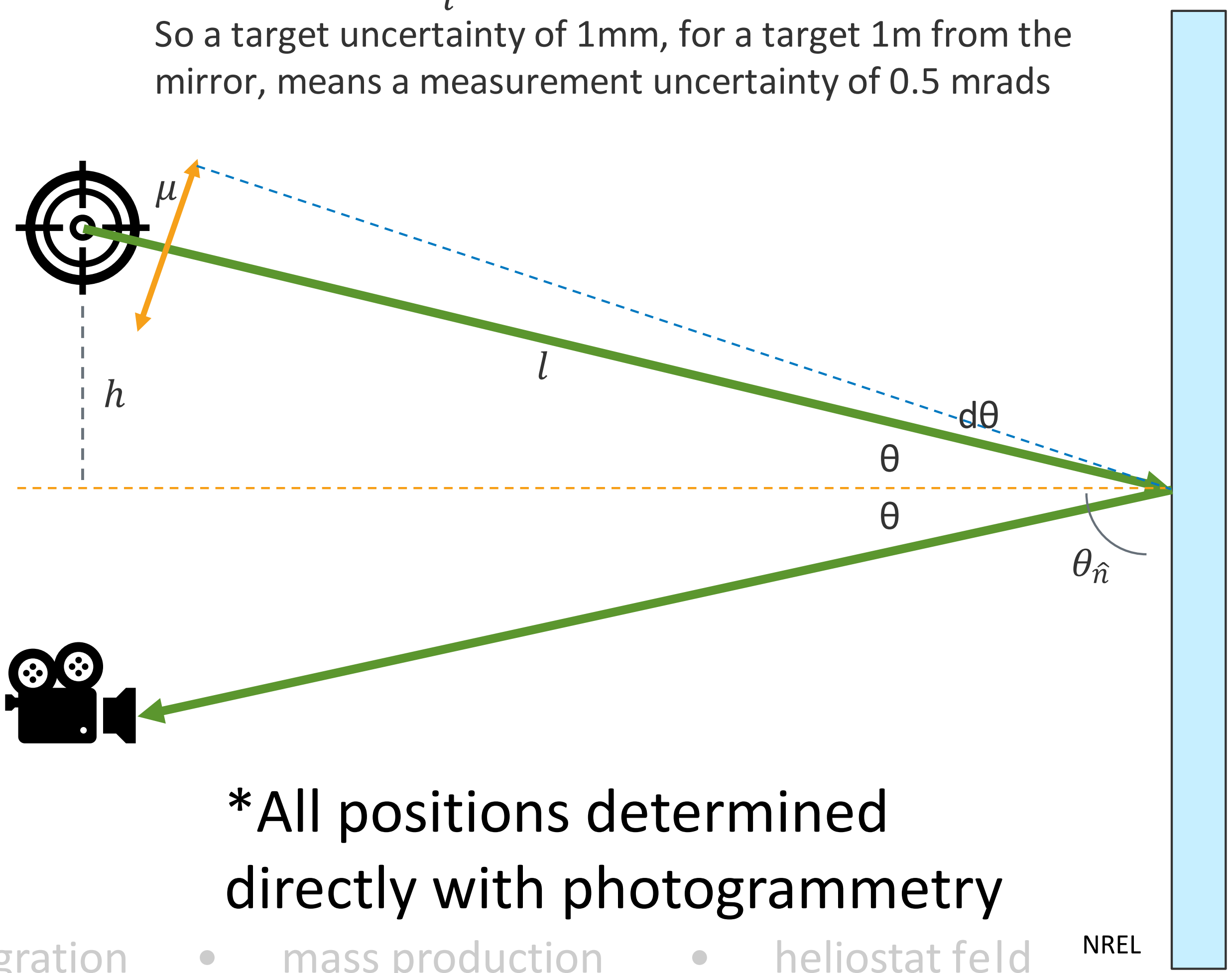
Approach Accuracy

- Errors in camera, target, and reflection position lead to errors in the resulting measurement.
- First order estimate by small angle approx. More detailed studies completed.
- Balancing act:
  - Smaller distances = higher precision required.
  - Larger distances = unrecognizable targets.
- Greatly superior to slope measurement with direct PG

Small angle approx.:

$$\frac{\mu}{l} = Sin(d\theta) \approx d\theta = 2\theta_{\hat{n}}$$

So a target uncertainty of 1mm, for a target 1m from the mirror, means a measurement uncertainty of 0.5 mrads



*All positions determined directly with photogrammetry

NREL

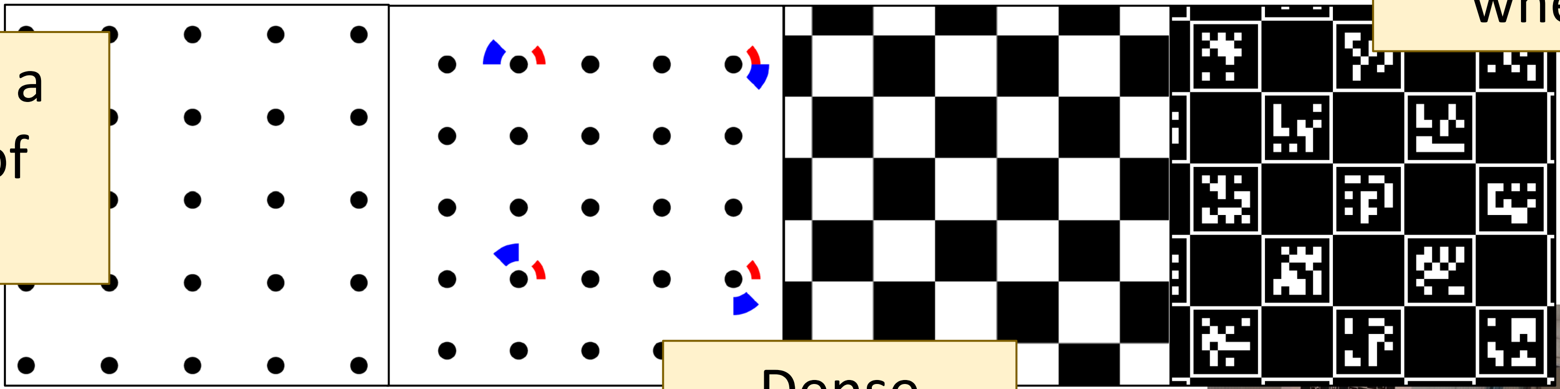
Leveraging Advancements in Computer Vision

For fast, automatic analysis, targets must be:

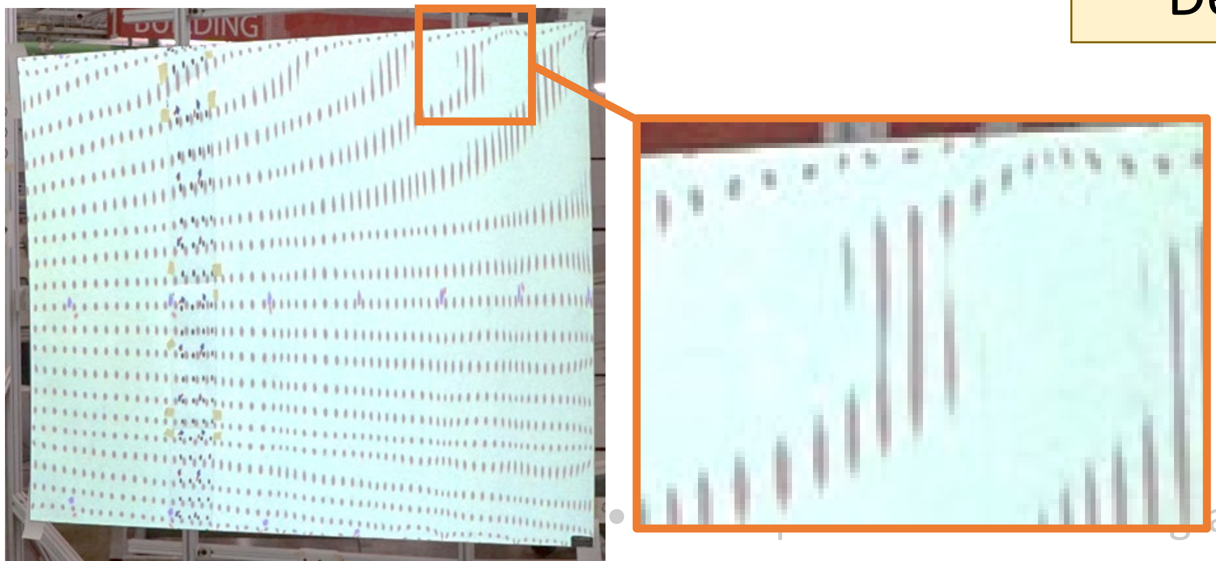
Distinguishable

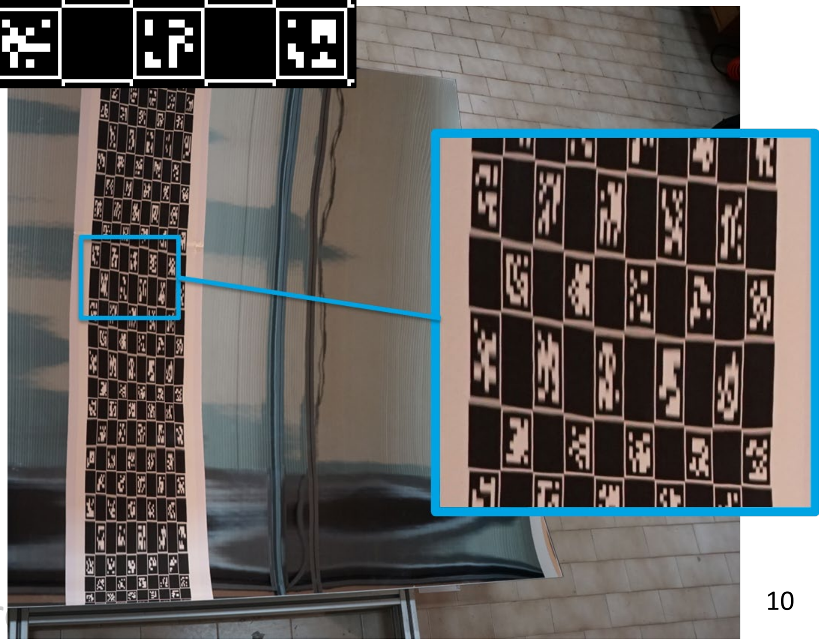
Robust (distinguishable even when distorted)

Identifiable to a high degree of accuracy.



Dense

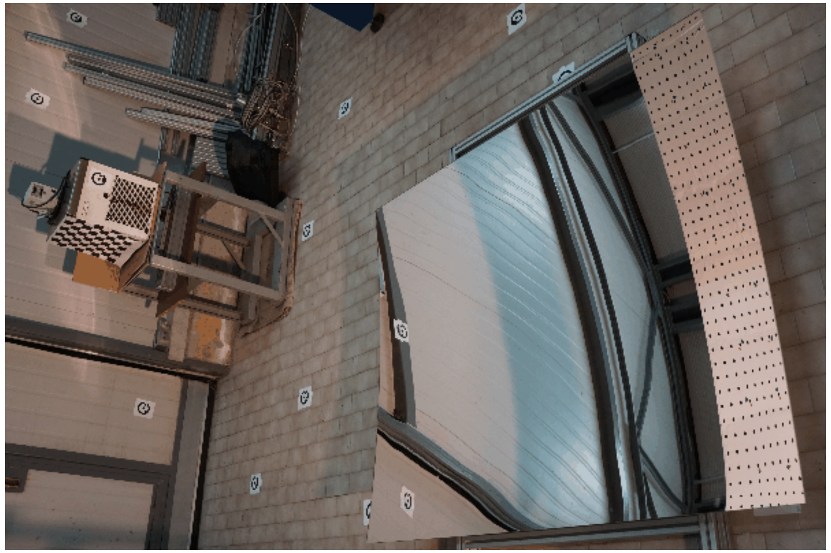


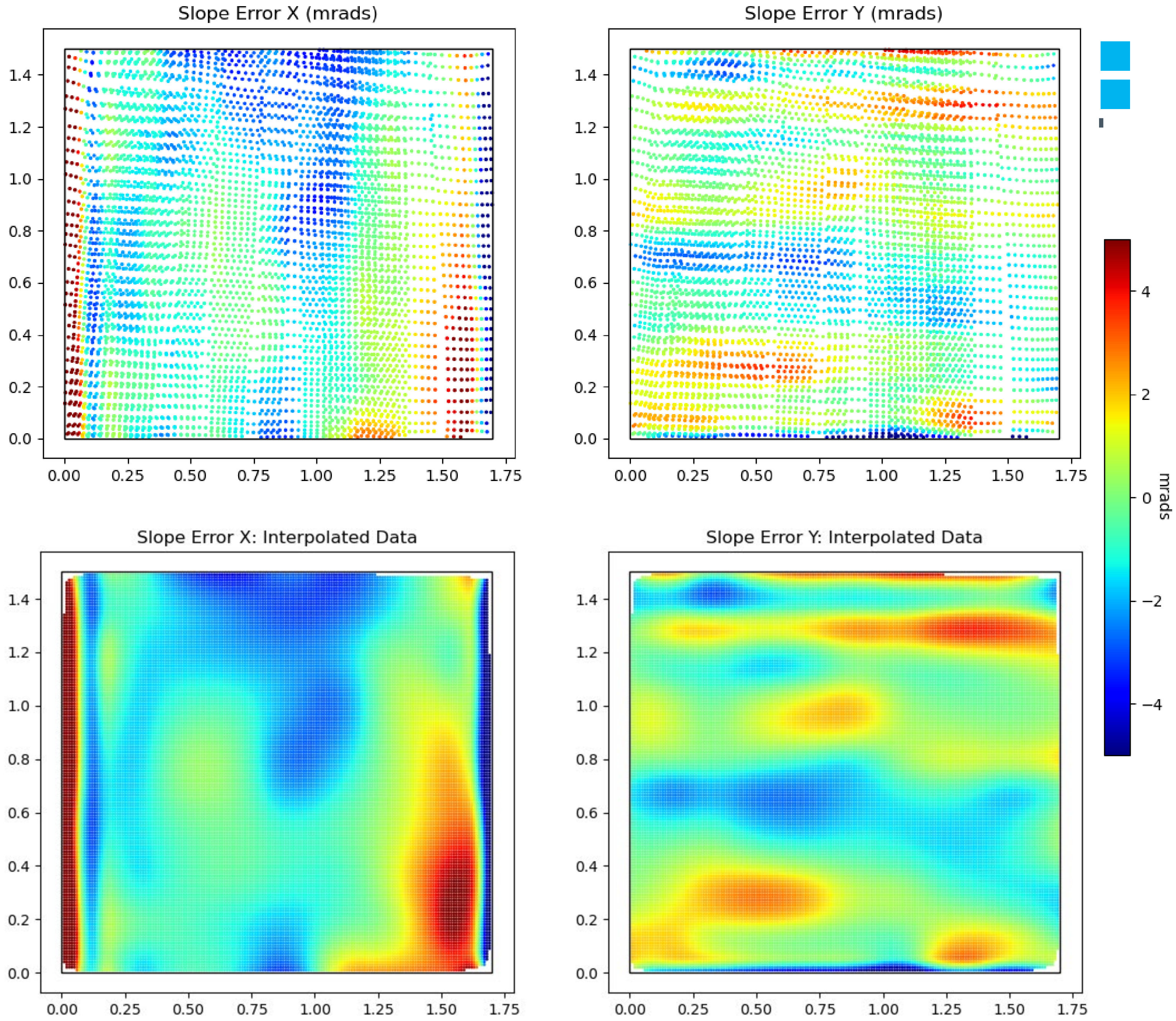


Results

In the last 6 months, we tested:

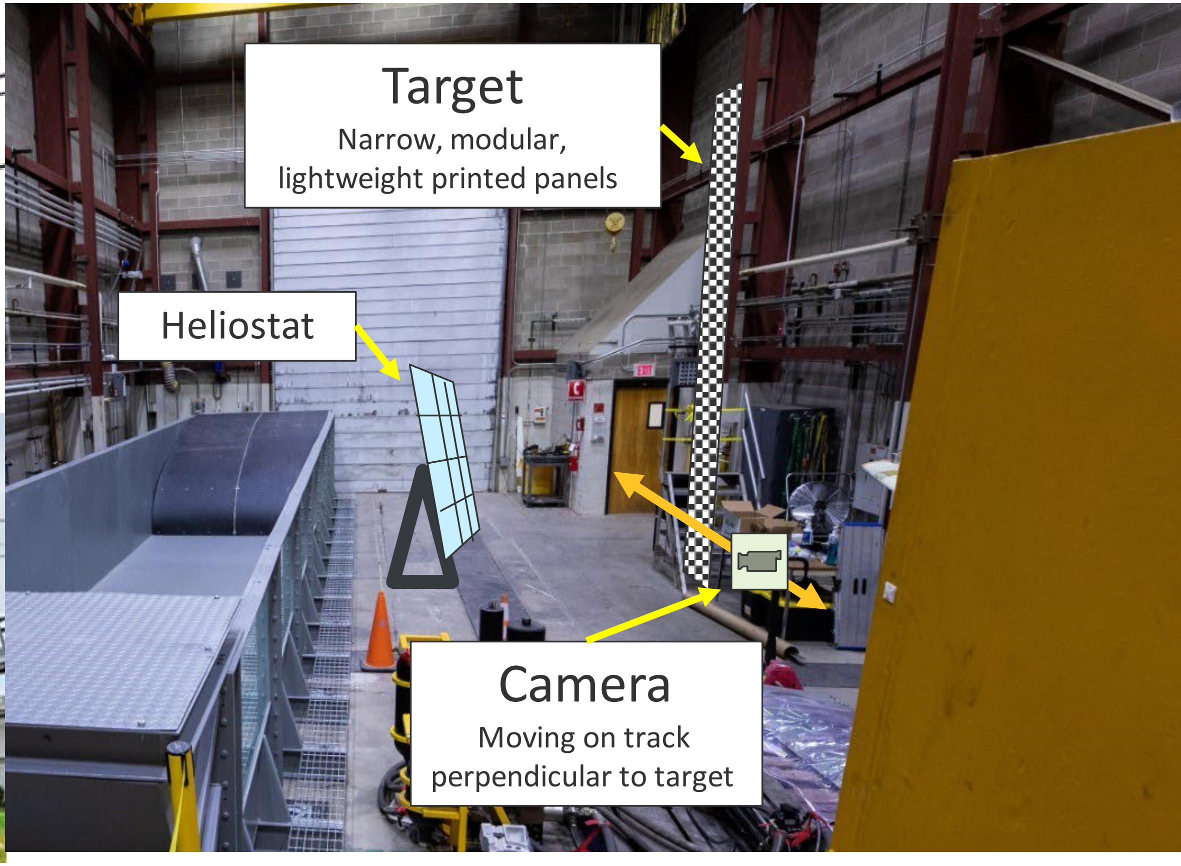
- **Combining data from multiple images**
- **Interpolating results.**
- **PG improvements**





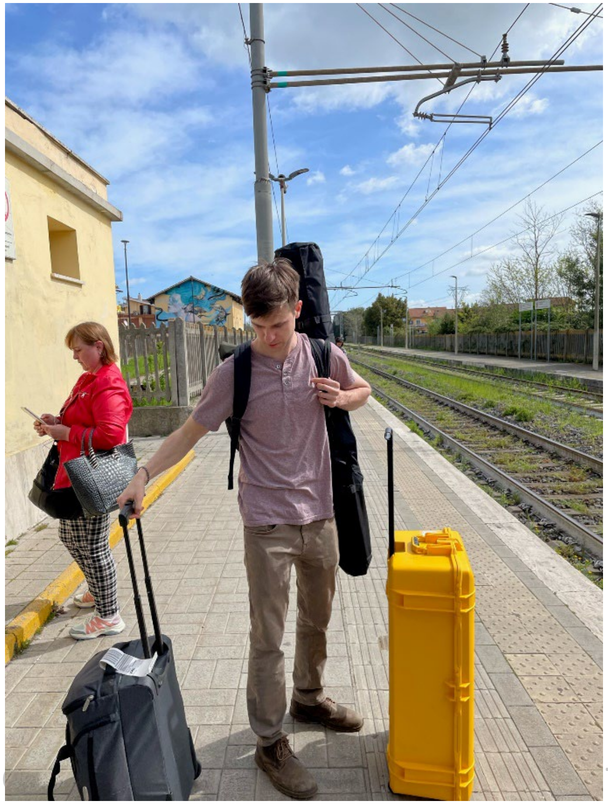
Automated System Development

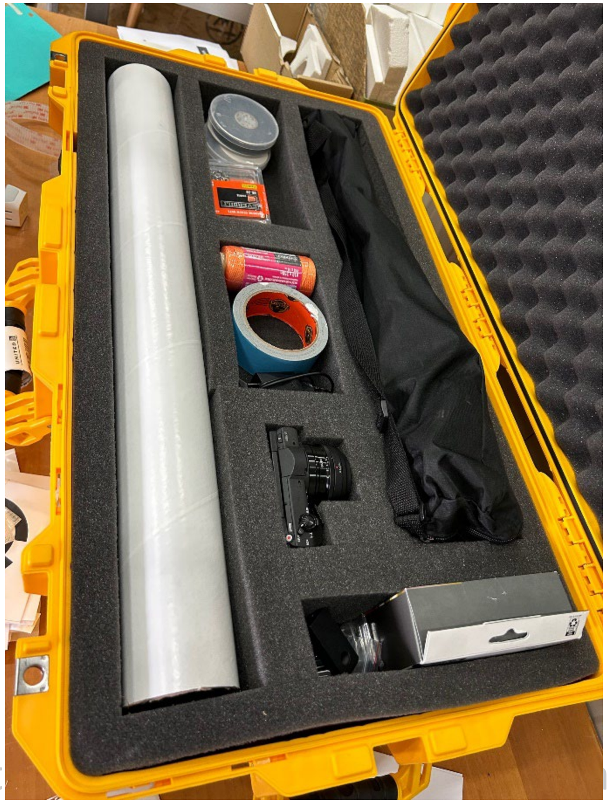
Lightweight automated data collection system under development.

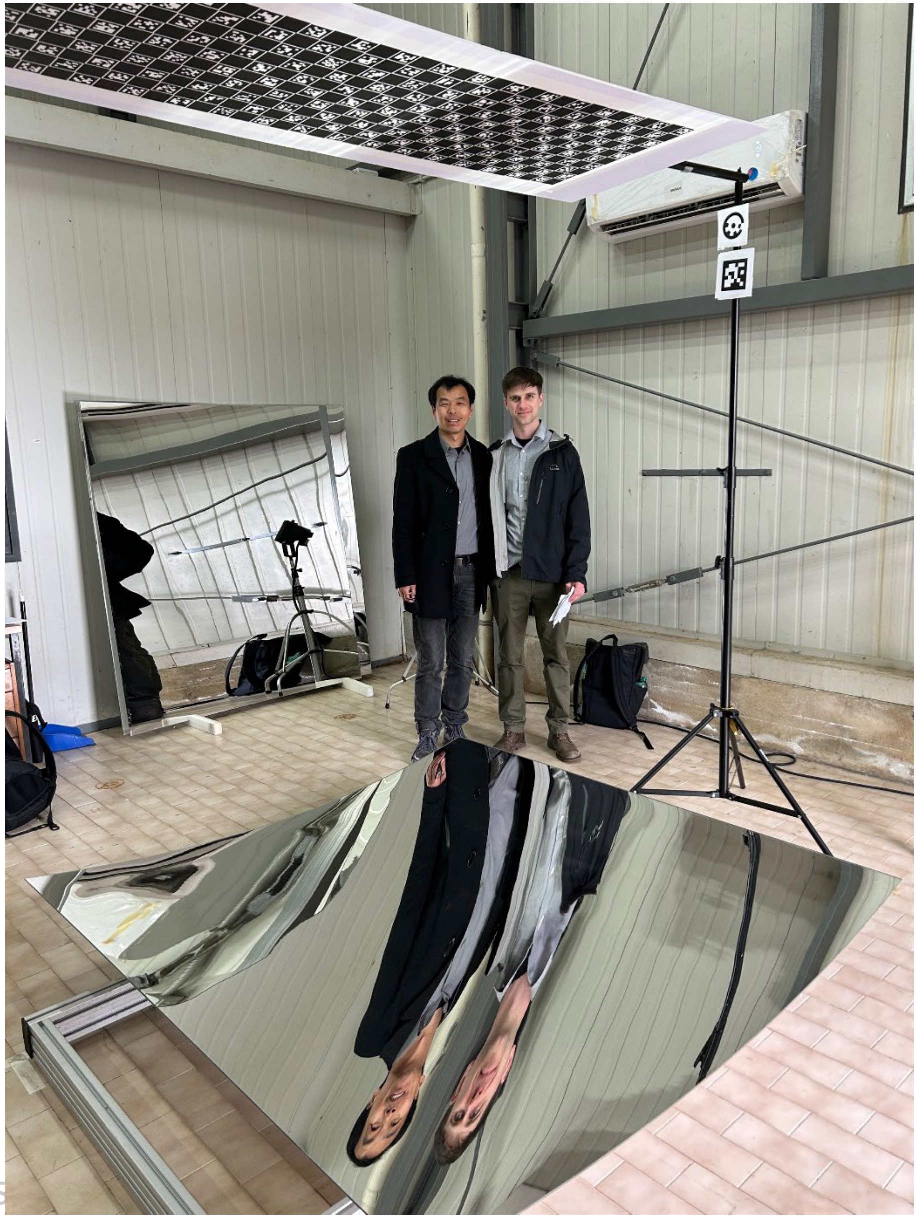


Portable System Development

Portable version for measurement at ENEA – the lightest possible automated optical measurement system?







concepti

Questions or Comments?

Thank You!

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NREL/PR-5700-86027

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 U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Solar Energy Technologies Office. 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.

NREL Transforming ENERGY

Additional Slides

HelioCon Milestones and Information

HelioCon Milestones

Milestone 2.5.2: NREL will expand and validate the warehouse optical metrology tool (NIO-a) developed in FY22. A new test apparatus will be built in NREL's new Heliostat Opto-mechanical Performance Assessment Laboratory (Helio-OPAL), and NIO-a measurements will be compared with other surface metrology systems. The tool's ability to collect and assess slope and canting measurement within a target uncertainty will be demonstrated. The data collection and analysis procedures will be streamlined for fast commercial data collection using computer vision and photogrammetry methods. Instructions for data collection and analysis will be captured in a formal operations manual. Collect data in Helio-OPAL lab space.

Milestone	Title	Metrics	Success Values	Assessment Tool
2.5.2	Refinement, validation, and streamlining of indoor optical quality assessment tool (NIO-a), and Helio-OPAL lab development.	1) Measurement uncertainty of slope error measurement. 2) Improved software setup and operation time. 3) NIO-a documentation. 4) Completion of prototype system installation at Helio-OPAL facility and test campaign.	1) 0.25 mrads, 95% confidence level. 2) <8 hours for new system setup and calibration, <20 minutes for measurement and analysis. 3) Instruction manual document. 4) Yes.	Slope error measurement uncertainty can be done by 1) a direct comparison with SOFAST by using a mobile mini heliostat at NREL; 2) multiple measurements on the same heliostat and then calculate its uncertainty using student t method by specifying a confidence level of 95%. Test procedures and data collection times will be documented.

HelioCon Milestones

Metrics	Success Values	Assessment Tool
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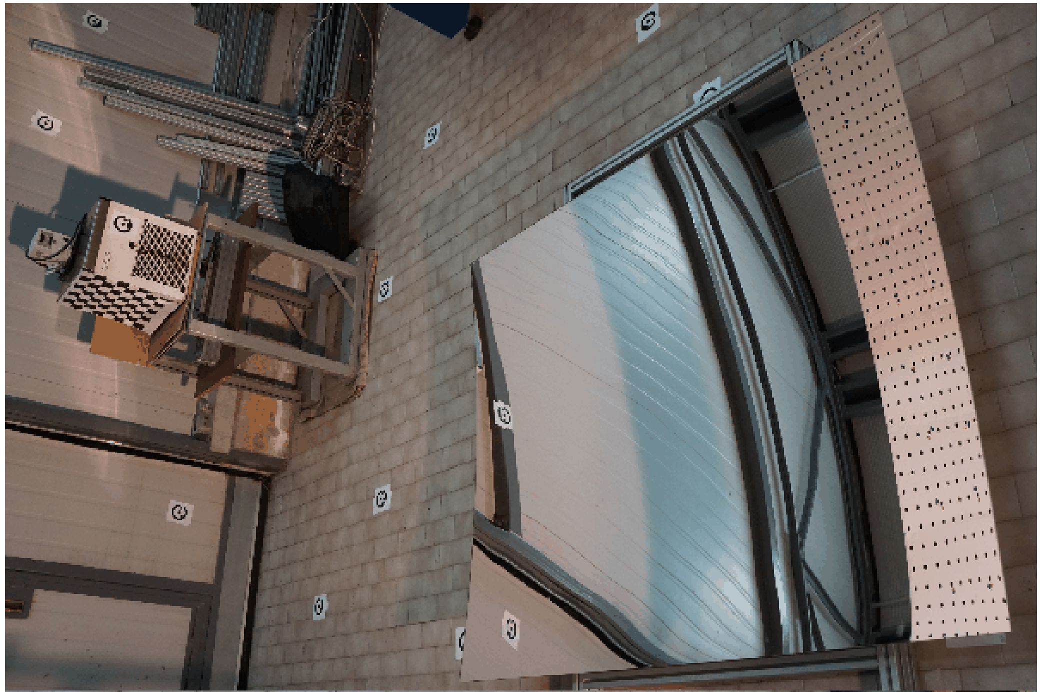
1. Round robin with EU labs will meet this with a much higher confidence level. Original plan for direct comparison with SOFAST at NREL not possible at this time. Repeatability tests ongoing, on track.
2. This was the major development focus this year and will be met easily. Still low hanging fruit to reduce setup and analysis time.
   a) Set up from nothing: <4 hrs.
   b) Set up new mirror on existing setup: <1 hr*.
   c) Analysis of setup system <10 minutes.
3. Draft instructions for lab and portable data collection complete. Instructions for running software in progress.
4. On track. Initial build complete 7/14. Target setup and demo by 7/28. Analysis complete 8/18.

Additional Slides

Extra info

Results

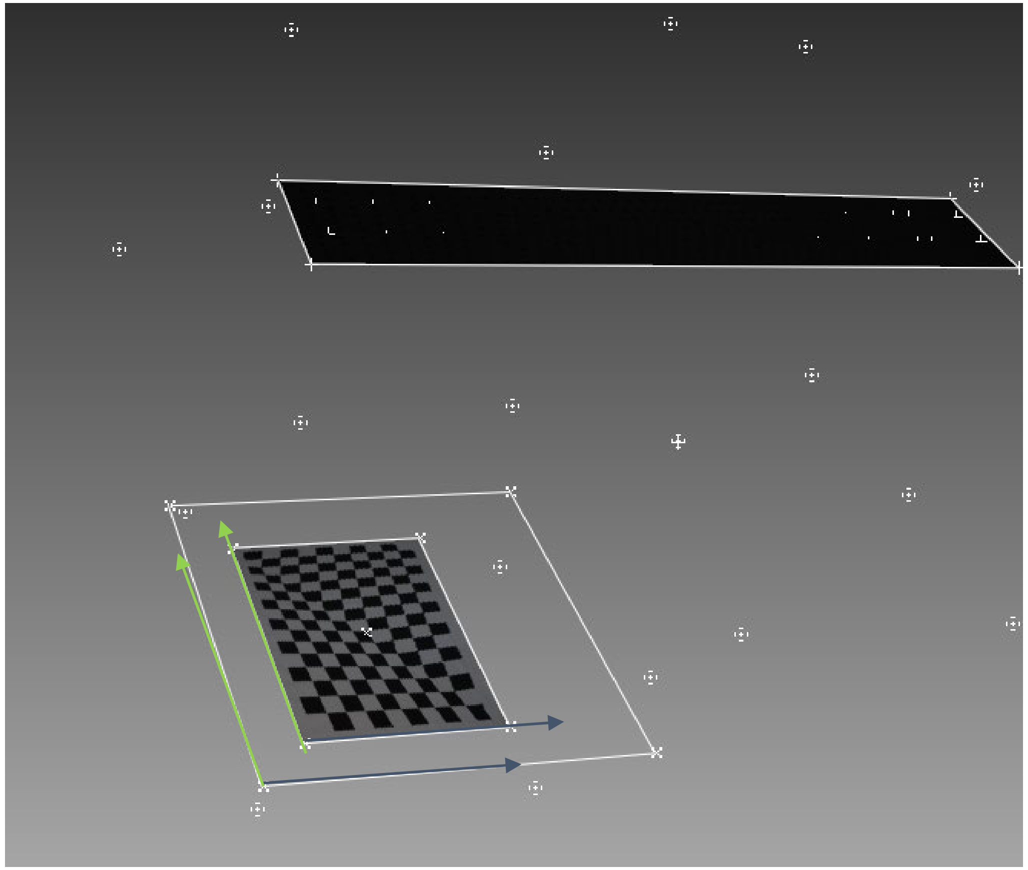
Interpolated results

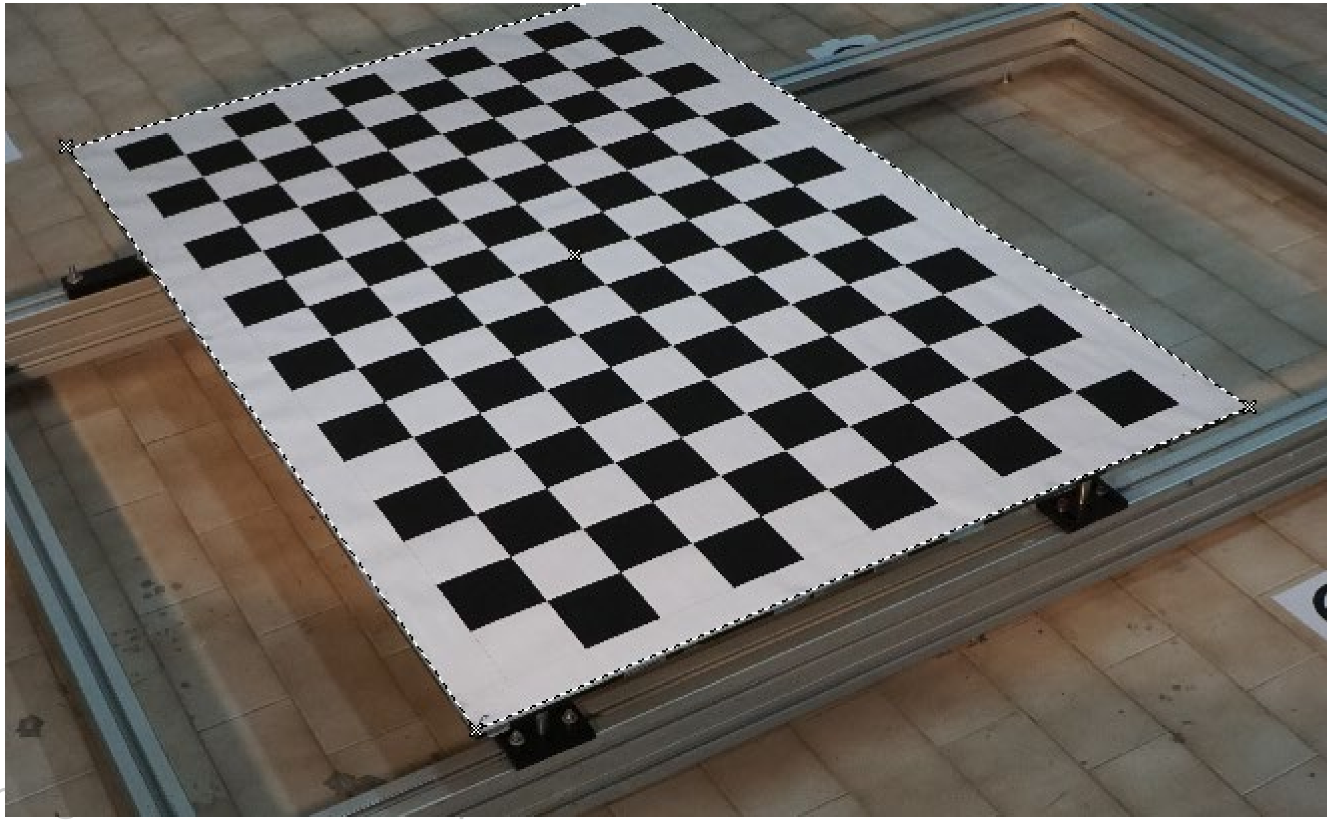


Reference Frames

Translation, rotation…

Thanks for all the help with this Marco!

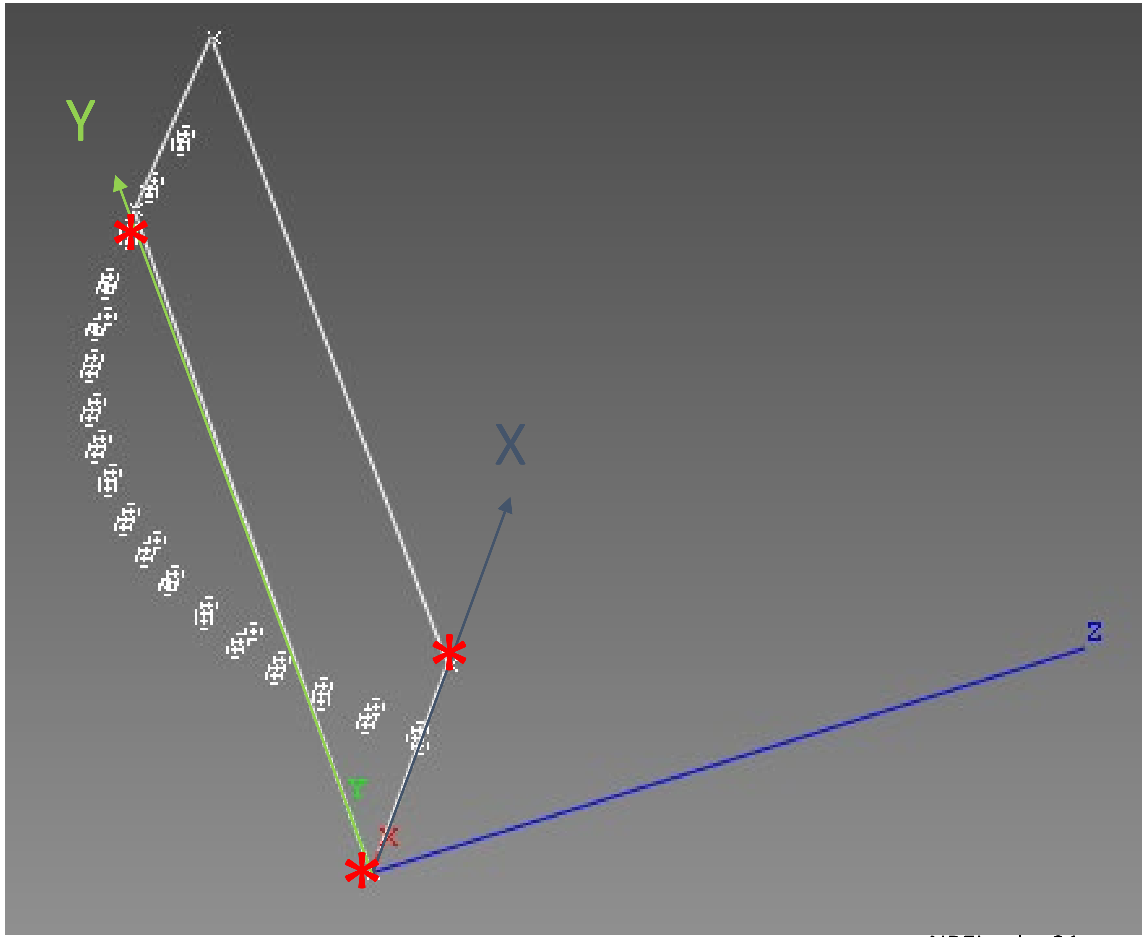




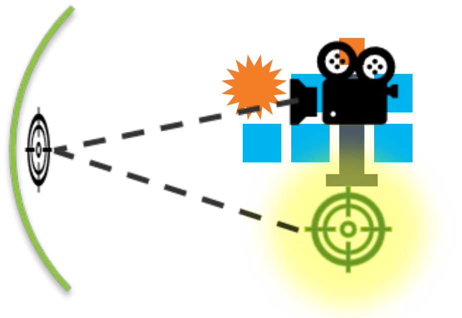
Reference Frames

All points found in common reference frame:

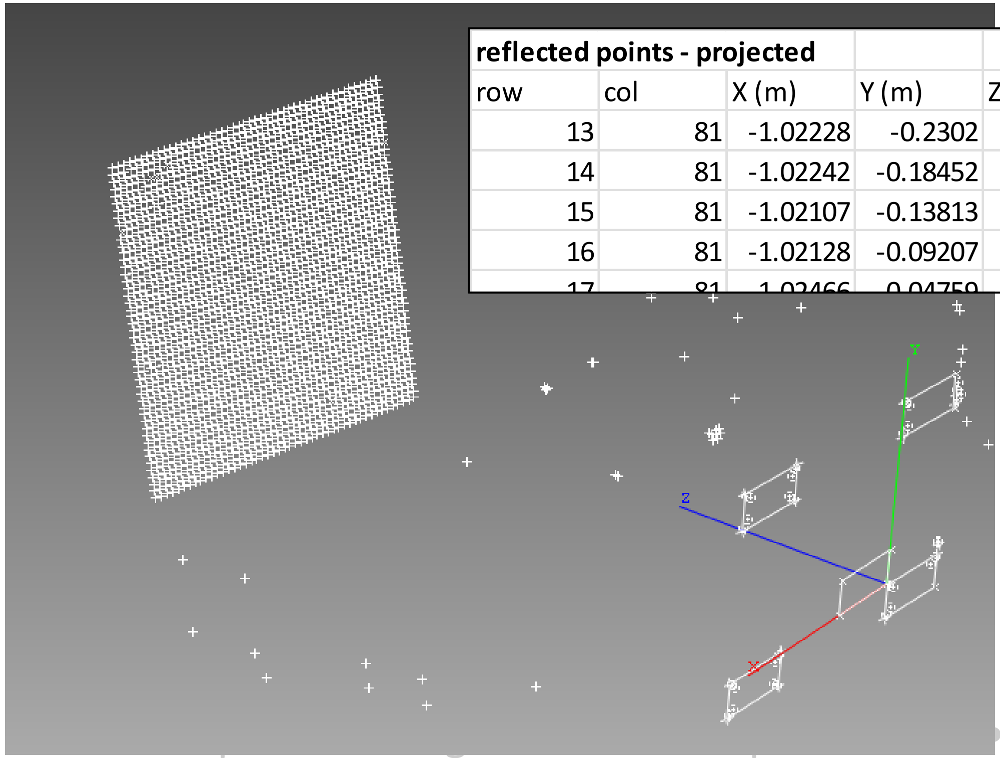
- **3 corners, determined by photogrammetry from multiple images**
- **Currently these are manually marked in images.**
- **No fixed frame in our lab, or visible mounting points on the mini-heliostat**



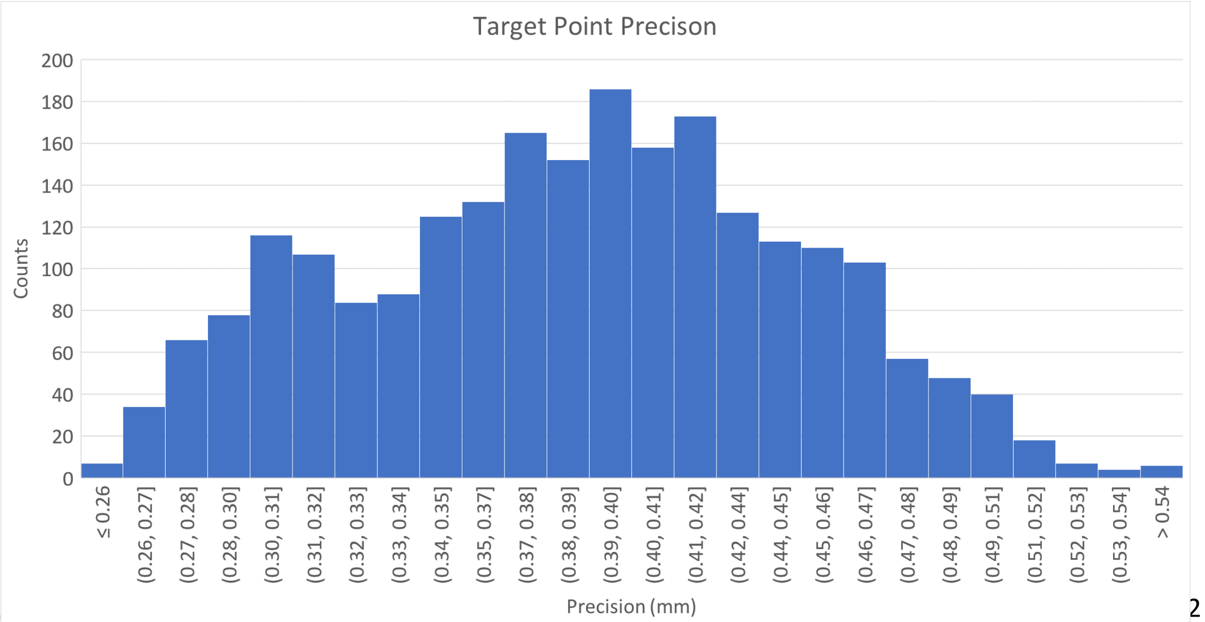
3D Scene Construction



- Photogrammetry used to create 3D scene (find target points in mirror reference frame).
- From this, we can create a target point dictionary and measure point precision.
- Once per setup.
- We are working to move from commercial photogrammetry software to custom tools.
- Since target points are found in 3D directly, we can ignore projector distortion and target bending.

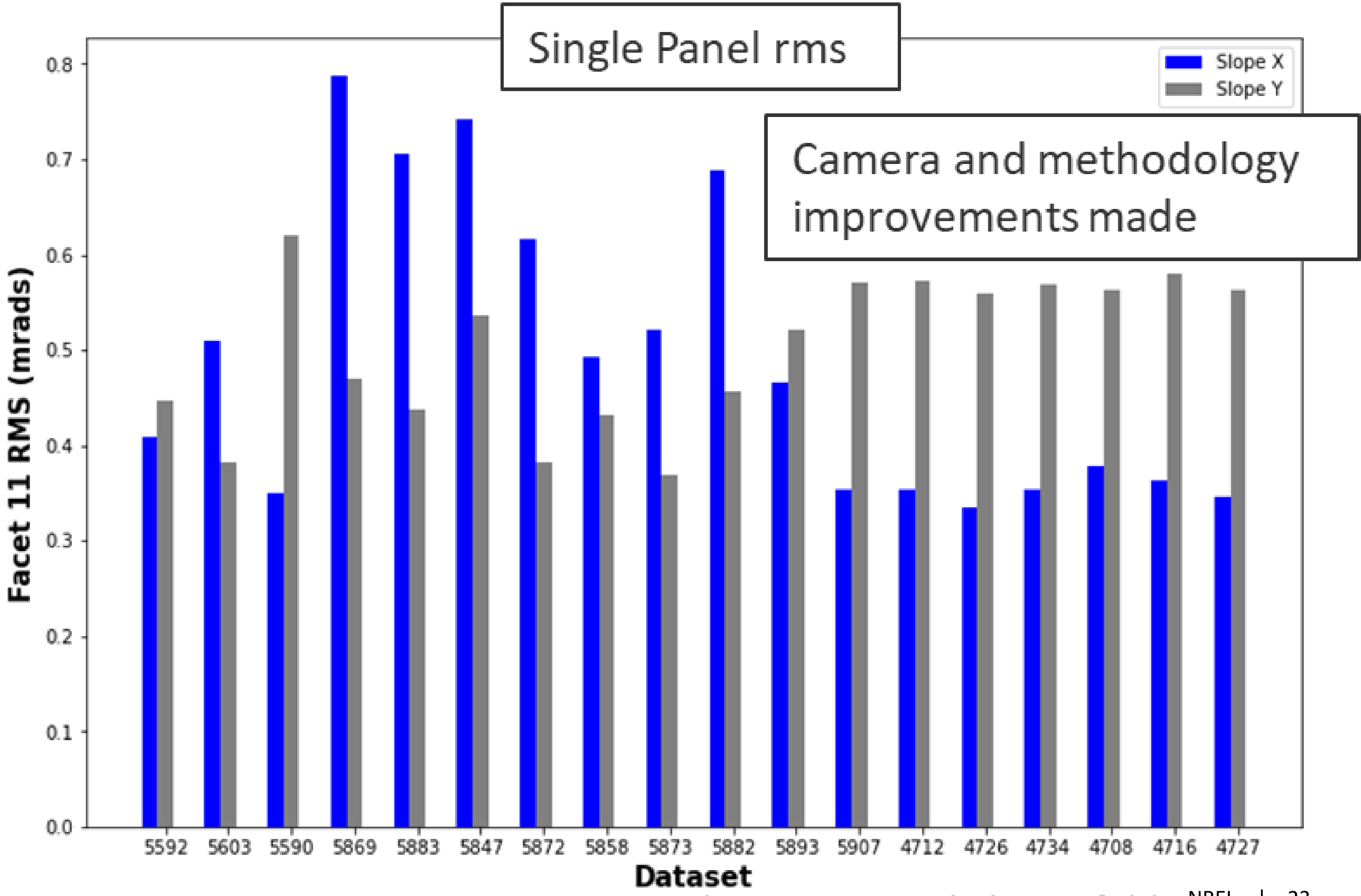


reflected points - projected				
row	col	X (m)	Y (m)	Z (m)
13	81	-1.02228	-0.2302	3.998268
14	81	-1.02242	-0.18452	4.008303
15	81	-1.02107	-0.13813	4.017723
16	81	-1.02128	-0.09207	4.026391
17	81	-1.02466	-0.04759	4.04001



Repeated Measurement: Panel rms

Repeated measurement on a single (flat) mirror panel.



Repeated Measurement: Point Comparison

- **ReTNA data sampling is not consistent between datasets.**
- **For each dataset, we can interpolate onto a regular grid**
- **We can compare the value at each grid point, and look at the standard deviation.**
- **Warnings: only 8 datasets so far, all using the same target model, different images/camera position.**

Standard Deviation of Grid Point Measurements