Improvements in Optical Surface Measurement Using Reflected Computer Vision Targets

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Contents

Overview

State-of-the-Art Optical Measurement

Interferometry: Ultra high precision, used for telescope mirrors, difficult on larger surfaces and focal lengths.

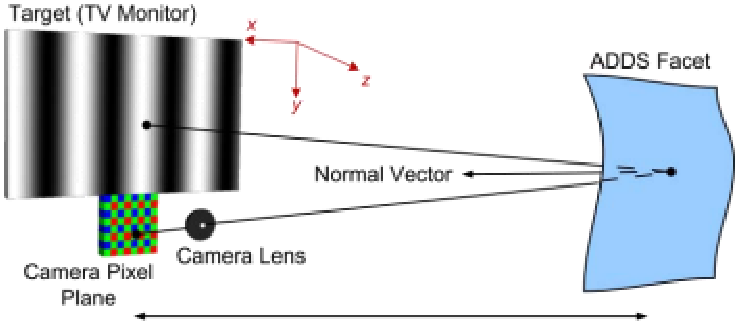
Fringe deflectometry: measurement by reflected fringe pattern. Powerful, high resolution, more complicated setup.

- SOFAST (Sandia)
- Qdec (DLR)
- Fraunhofer ISE

Structured light deflection

- VIS (ENEA).
- ReTNA (NREL)

Photogrammetry: 3D positional measurement: well established, but requires targets attached to mirror surface.



N. S. Finch and C. E. Andraka https://doi.org/10.1115/ES2011-54455

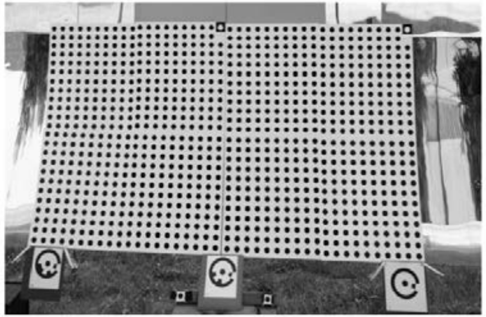


Fig. 6. Photogrammetry measurements carried out at ENEA's PTC facility by CENER's technicians.

Pottler, K., Lupfert, E., Johnston, G. H., & Shortis, M. R. (2005). Photogrammetry: A powerful tool for geometric analysis of solar concentrators and their components. *J. Sol. Energy Eng.*, *127*(1), 94-101. https://doi.org/10.1115/1.1824109

Reflected Target Non-intrusive Assessment (ReTNA)

A complementary technology for the tools available today.

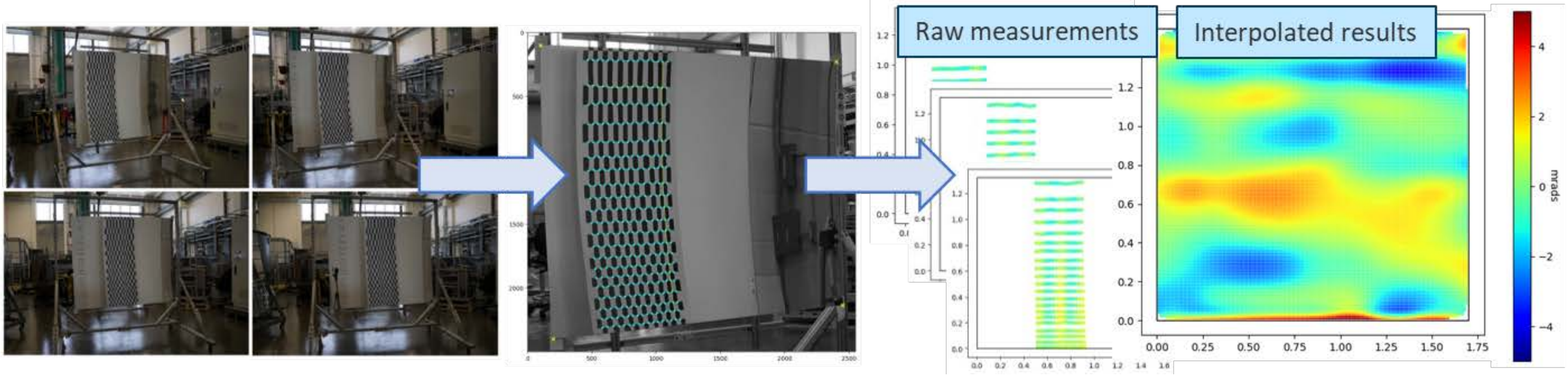
1. Target located in 3D with photogrammetry.
2. Series of images collected of target reflected in mirror surface
3. Deflection yields **surface slope** and **facet canting** measurements

ReTNA Workflow

Series of Images

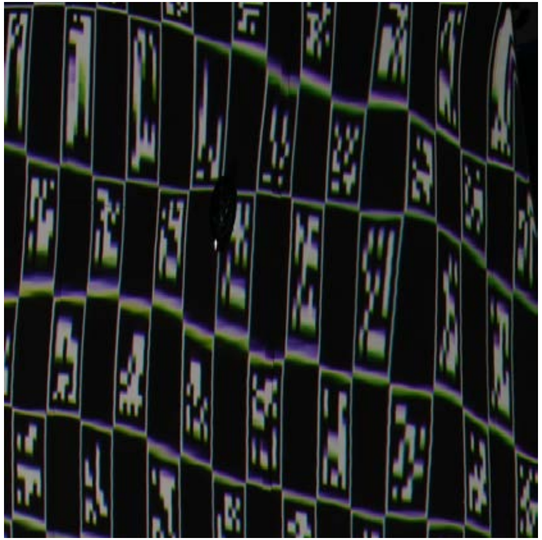
Image Processing

Full Facet or Heliostat Surface Analysis

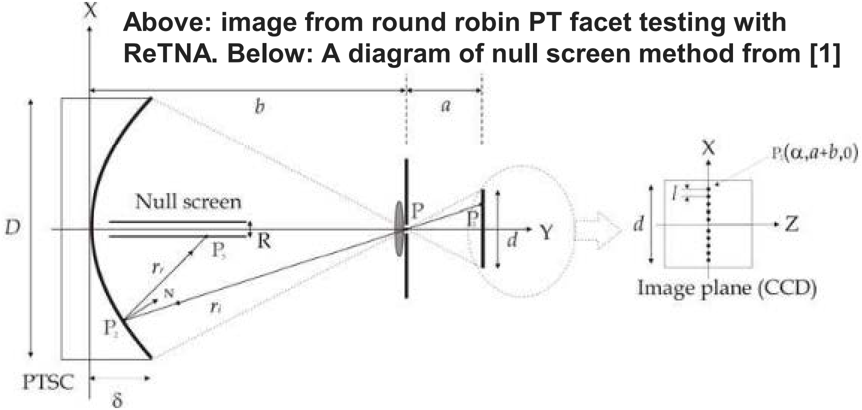


Weaknesses

- Lower resolution than fringe methods.
  - Measurement density determined by target size and camera resolution.
  - We generally target ~1500 measurements/m², potential to improve.
- Difficult to measure mirrors with high curvature (parabolic trough or dish CSP systems)
  - Targets must be recognizable.
  - Some strategies to deal with this:
    - Smaller targets
    - Pre-warped targets (null screen) [1]



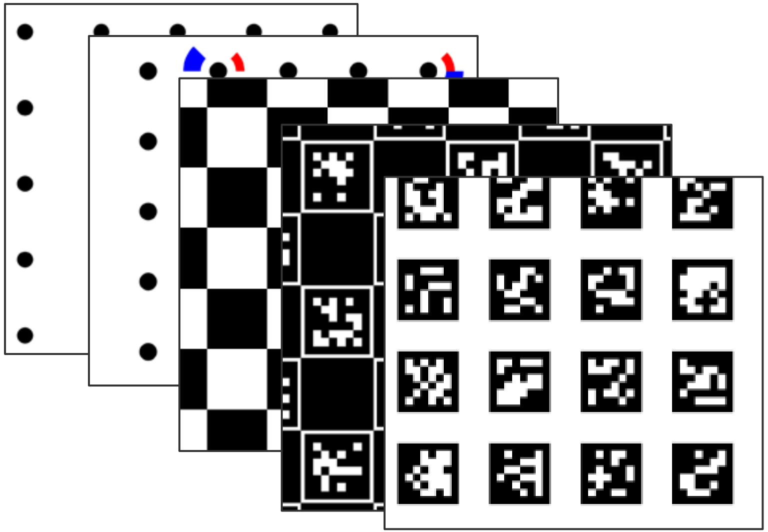
Above: image from round robin PT facet testing with ReTNA. Below: A diagram of null screen method from [1]



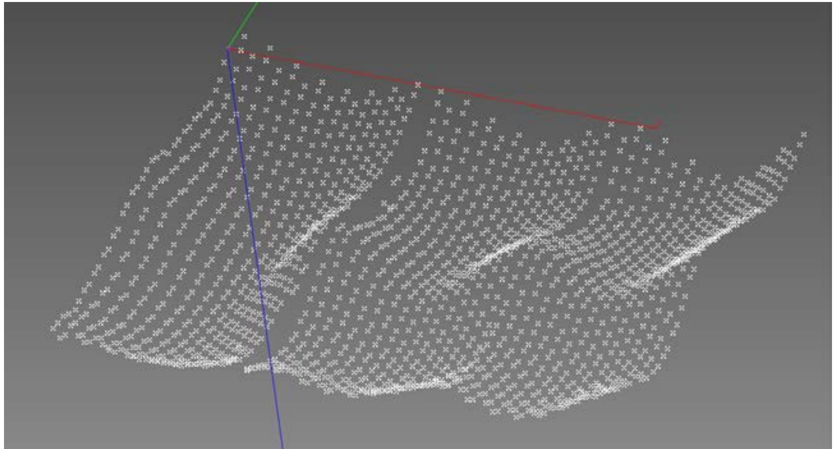
[1] Moreno-Oliva, V. I., Díaz-Uribe, R., & Campos-García, M. (2010). *Shape measurement of solar collectors by null screens* (pp. 169-186). InTech.

Strengths

- 2D Printed target pattern = versatile system
  - Allows for measurement in ambient lighting.
  - Allows for 2D measurement with a single image.
  - Lighter, modular, versatile targets compared to projector screens.
- Target points found in 3D space with photogrammetry
  - No flatness constraints for target, or precision required during setup.
  - Multiple images can be stitched together, to measure larger heliostats.
- Coded Targets yield fast and automatic measurement.



Above: ReTNA target evolution over time. Below: ReTNA target shape, determined with photogrammetry, z-axis exaggerated 10x to show non-flatness, which is acceptable for ReTNA measurement.



Overall

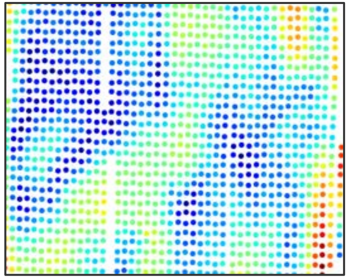
- Lots of opportunity for this type of measurement due to:
  - Consumer camera quality and cost.
  - Computer vision tools
  - Photogrammetry tools
- Very versatile, primary applications are outside of the laboratory:
  - Fast, assembly line, QC measurement
  - Simple qualification checks for R&D

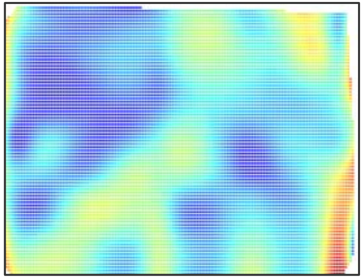
Testing, Validation, and Varied Layouts

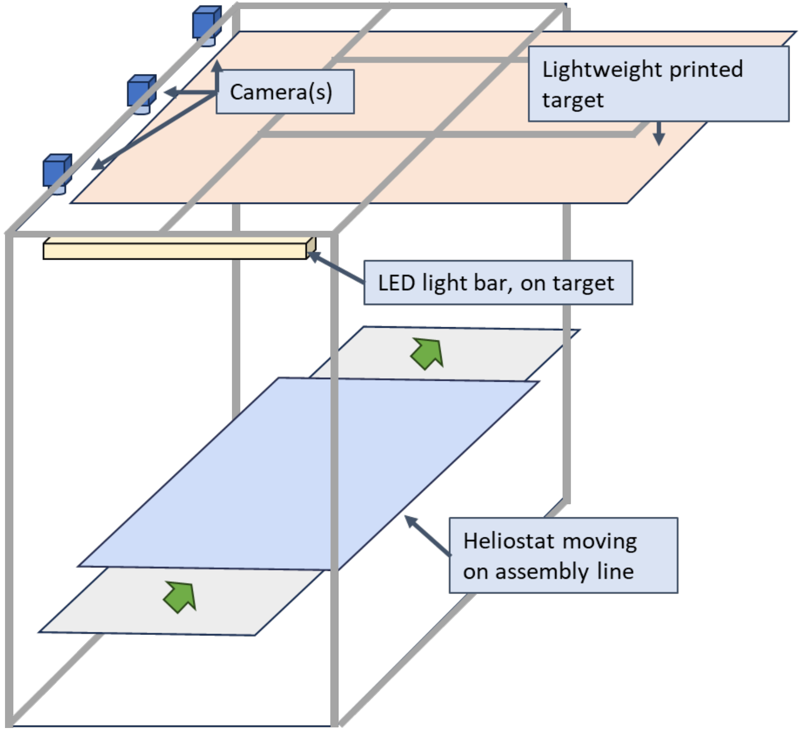
Layout 1 – Assembly Line

Layout: Assembly Line

- Layout changed for integration into a commercial assembly line.
  - No moving parts (except heliostat).
  - Ambient lighting
  - 2D analysis from a single image
  - Initially >700 measurements per m^2. Can likely reach >2000 with single image.
  - Heliostat does not need to be removed from assembly line.

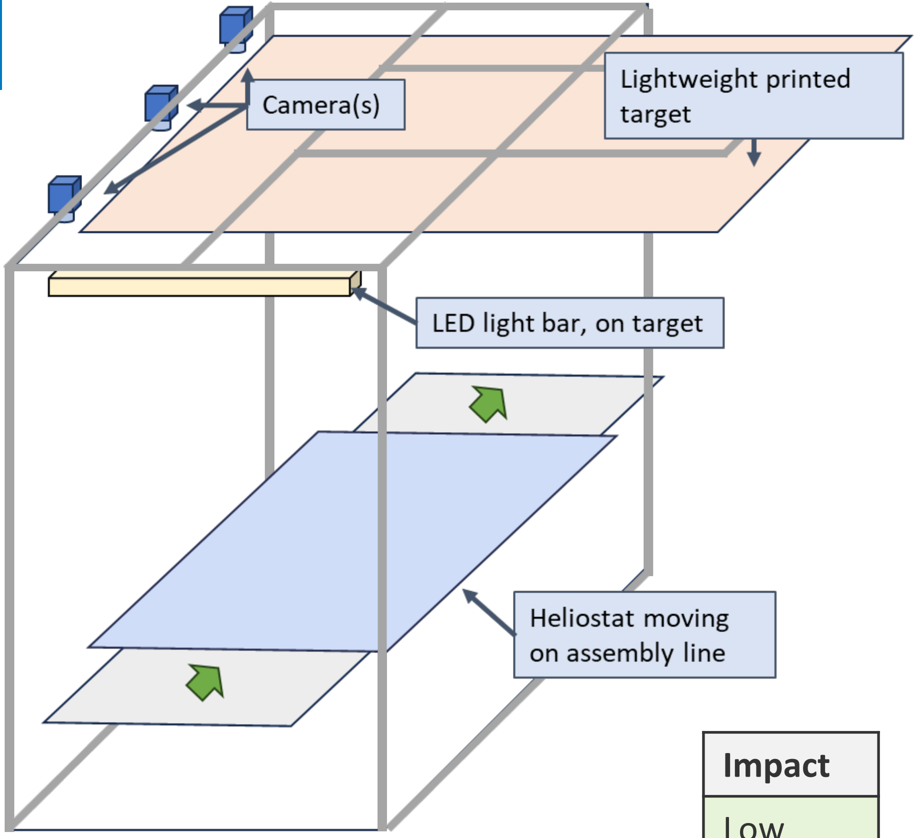






Layout: Assembly Line

- 300+ heliostat measurements
- 10+ full system calibrations
- 2 Target heights, several different camera positions and lenses.



Main sources of error identified

Error Source	Details
Lighting and Exposure	Failure to ID targets, or noisy images
Target Height	Lower target = + angular uncertainty
Camera Lens and Calibration	Lens distortion, focus breathing
System Setup	Target flatness, camera position
PG System Calibration	PG model determines target pt locations

Impact
Low
Medium
High

Assembly Line Layout Results

Versatile measurement demonstrated.
Results consistent (<0.05 mrad) with

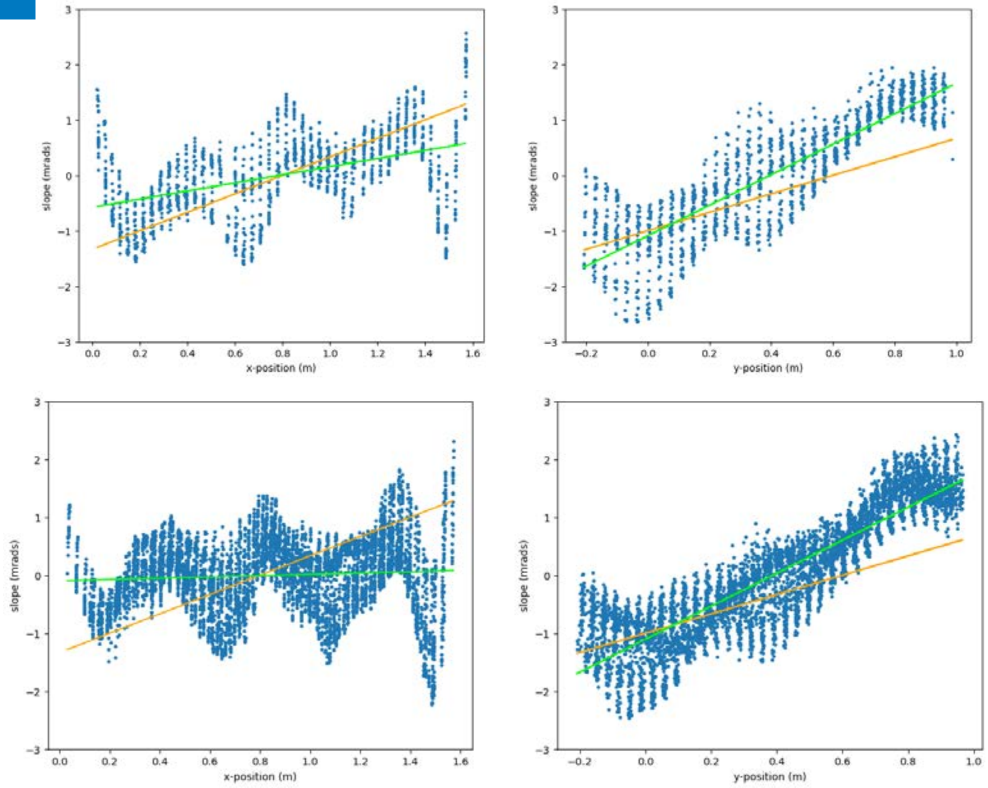
- Soiling/smudging
- Different lighting conditions and camera settings (ISO, shutter)
- Target positions.

Some challenges with camera and lens calibration – this is a primary cause of uncertainty, must be handled carefully.

Single Image vs Scan

- Single image with ~700pts/m^2
- Comparison case stitching together 12 images of a smaller target (~1/3 the size) resulting in 2942/m^2

	Single Image	Scan (% diff)
SE mag rms	-	5% diff
Focal X (m)	>500	>500
Focal Y	-	5% diff

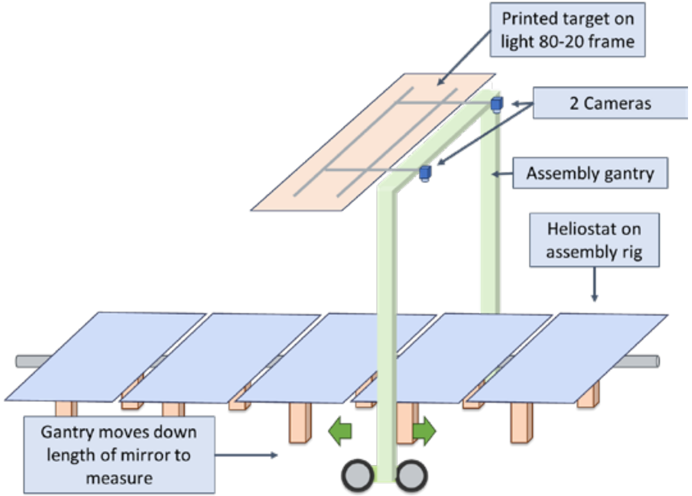


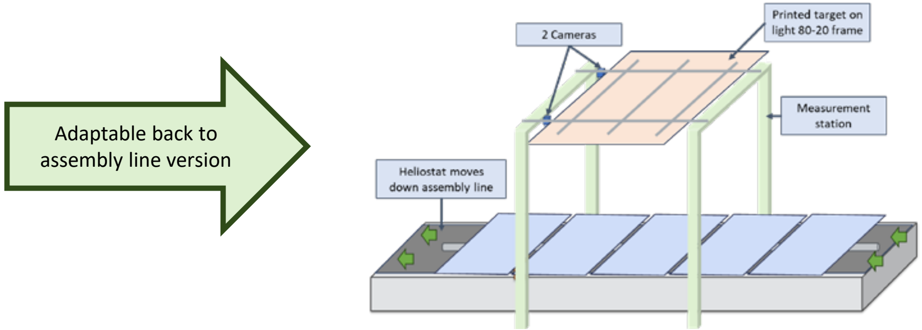
Testing, Validation, and Varied Layouts

Layout 2 – R&D Layout

Layout: Development Environment

- Heliostat developer version for measurement during assembly.
  - Camera(s) and target mounted on rolling gantry crane.
  - Allows for scan of heliostat without removing it from the assembly rig.
  - Can be adapted back to assembly line version for mass production.

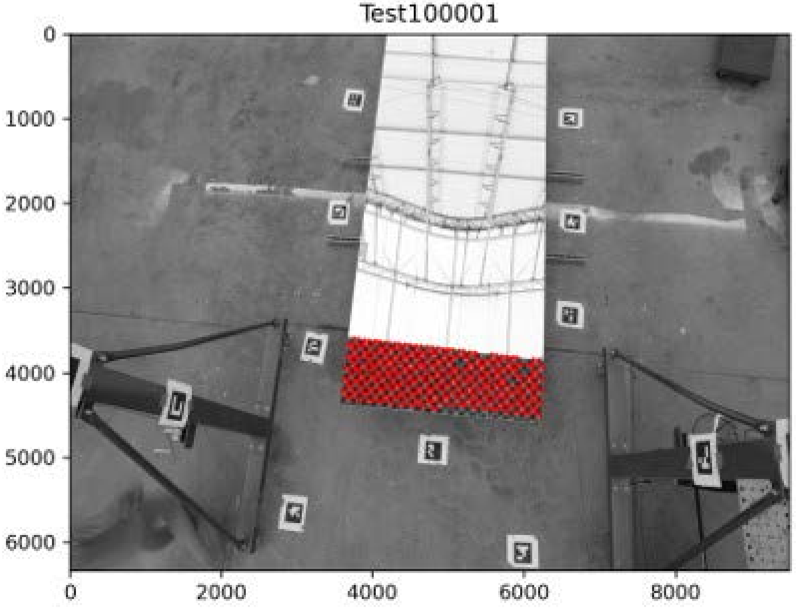




R&D Layout Results

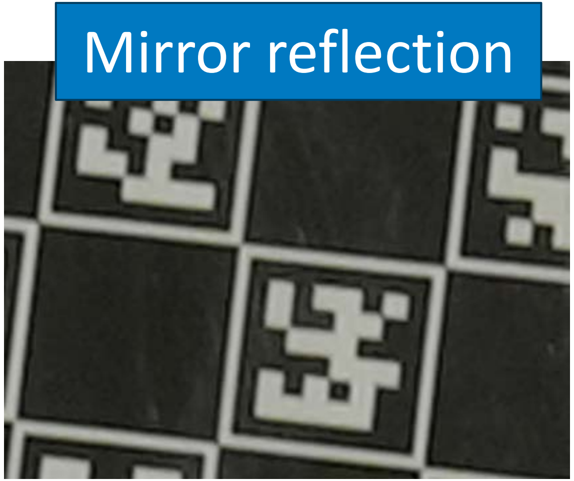
- Preliminary scans on a flat-ish non-commercial mirror to show repeatability.
- Several likely causes of difference:
  - Different sampling points
  - Error in measurement system
- More rigorous measurement with more precise system in progress.

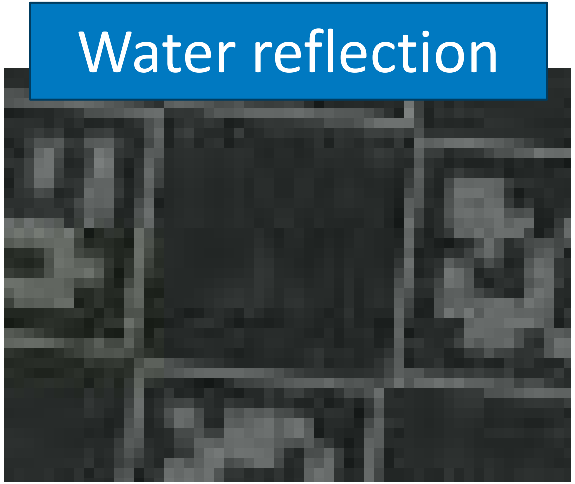
	Difference From Scan 1		
	RMS Error X (mrads)	RMS Error Y (mrads)	RMS Error Mag (mrads)
Scan 1	-	-	-
Scan 2	0.05	0.07	0.08
Scan3	0.01	0.07	0.03



Next Steps

- Flat water testing – difficult on printed targets, as only ~2% of light is reflected, necessitating high ISO, “noisy” images.
- Further validation against other systems on heliostat mirrors, for different layouts.
- System improvements for parabolic trough facet measurement.





Thank You!

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Error in Deflection Measurement

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