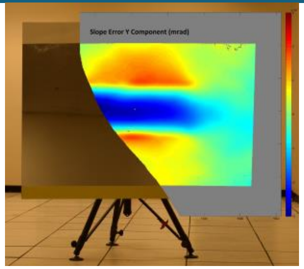
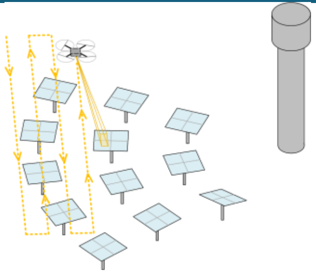
Robust Deflectometry





Braden Smith and Randy Brost

October 9, 2023

SAND No. 2023-10537C

Deflectometry in CSP

Deflectometry is well suited for use in CSP

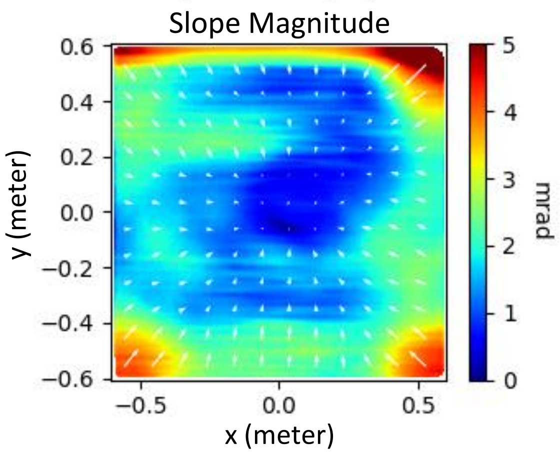
- A metrology method that measured the surface shape of reflective surfaces
- Sensitive to small magnitudes of surface slope
- Can easily accommodate physically large optics

Deflectometry systems in use in CSP

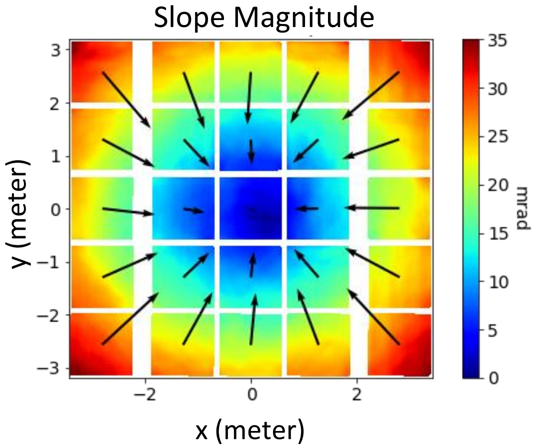
- CSP services' QDec[1] is a commercially available product.
- Sandia's SOFAST system was first created in 2011.
- Many others…

Deflectometry can measure optics from single facets to entire heliostats

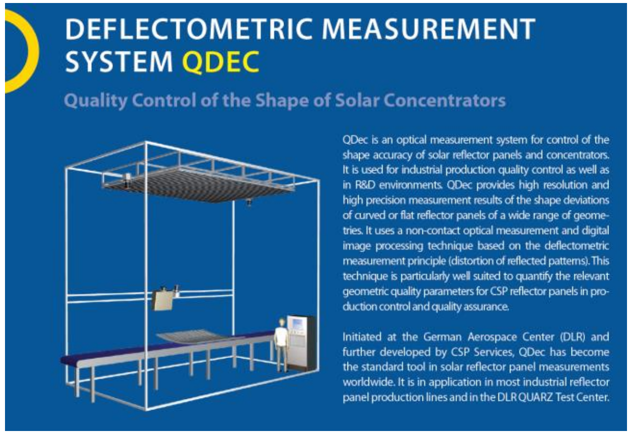
Example SOFAST measurement of mirror facet



Example SOFAST measurement of entire heliostat



QDec System[1]



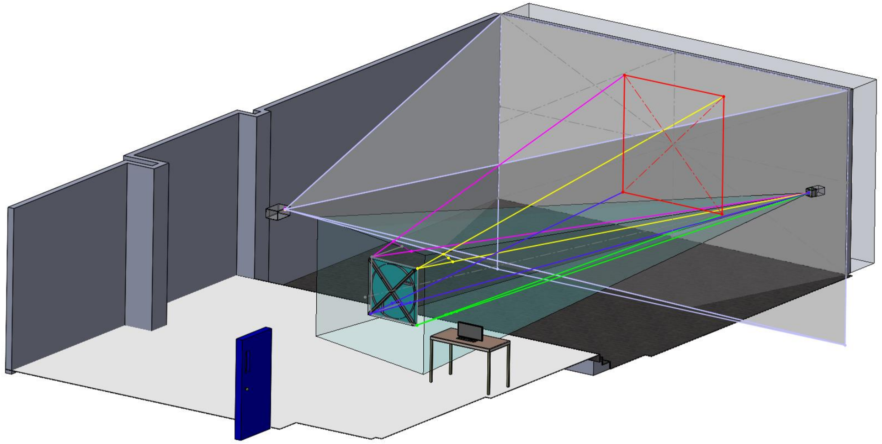
DEFLECTOMETRIC MEASUREMENT SYSTEM QDEC

Quality Control of the Shape of Solar Concentrators

QDec is an optical measurement system for control of the shape accuracy of solar reflector panels and concentrators. It is used for industrial production quality control as well as in R&D environments. QDec provides high resolution and high precision measurement results of the shape deviations of curved or flat reflector panels of a wide range of geometries. It uses a non-contact optical measurement and digital image processing technique based on the deflectometric measurement principle (distortion of reflected patterns). This technique is particularly well suited to quantify the relevant geometric quality parameters for CSP reflector panels in production control and quality assurance.

Initiated at the German Aerospace Center (DLR) and further developed by CSP Services, QDec has become the standard tool in solar reflector panel measurements worldwide. It is in application in most industrial reflector panel production lines and in the DLR QUARZ Test Center.

SOFAST CAD Layout



[1] CSP Services. QDec system. https://www.cspservices.de/wp-content/uploads/CSPS-QDec.pdf.

Citations for High-Resolution Slope Measurement

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- N. S. Finch and C. E. Andraka. Uncertainty Analysis and Characterization of the SOFAST Mirror Facet Characterization System. *Journal of Solar Energy Engineering* **136**, February 2014.
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- CSP Services. QDec-M. https://www.cspservices.de/wp-content/uploads/CSPS-QDec.pdf.
- D. Kesseli, et al. A New Reflected Target Optical Assessment System - Stage 1 Development Results. *SolarPACES 2022.* Also NREL Report NREL/CP-5700-84142, August 2023.

DLR/CSP Services Accomplishments

DEFLECTOMETRIC MEASUREMENT SYSTEM QDEC

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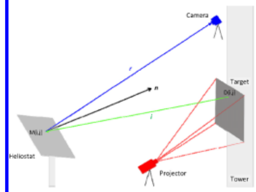
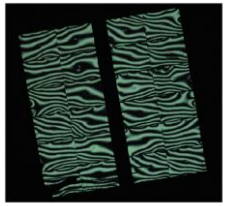
QDec System Features

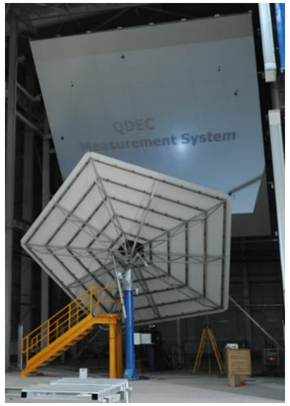
	QDec Offline	QDec Inline
Measurement time	< 30 s	< 5 s
Evaluation time	< 40 s	< 10 s
Number of measurement points (standard / maximum)	≈ 250´000 / ≈ 1´000´000	≈ 250´000 / ≈ 1´000´000
Measurement uncertainty local spot / global value (RMS)	< 0.5 mrad / < 0.2 mrad	< 0.5 mrad / < 0.2 mrad
Numerical output	SDx, SDy, FDx, FDy, IC, ICsun, etc.	SDx, SDy, FDx, FDy, IC, ICsun, etc.
Graphical output	local slope deviation (x/y), local focus deviation, local intercept factor, local height deviation, standard quality report (pdf)	local focus deviation
Output database formats	standard: .csv optional: .xls / SQL	standard: .csv optional: .xls / SQL
Optional output (with increase of evaluation time)	Flux distribution, reverse ray tracing, matrix data in ASCII file (.csv)	graphical output of local slope deviation (x/y), local focus deviation, local intercept factor, local height deviation, standard report (pdf), flux distribution, reverse ray tracing, matrix data in ASCII file (.csv)

https://www.cspservices.de/wp-content/uploads/CSPS-QDec.pdf





Ulmer, et al. 2014.



https://www.cspservices.de/quality-control/

Principles of Deflectometry

How deflectometry works

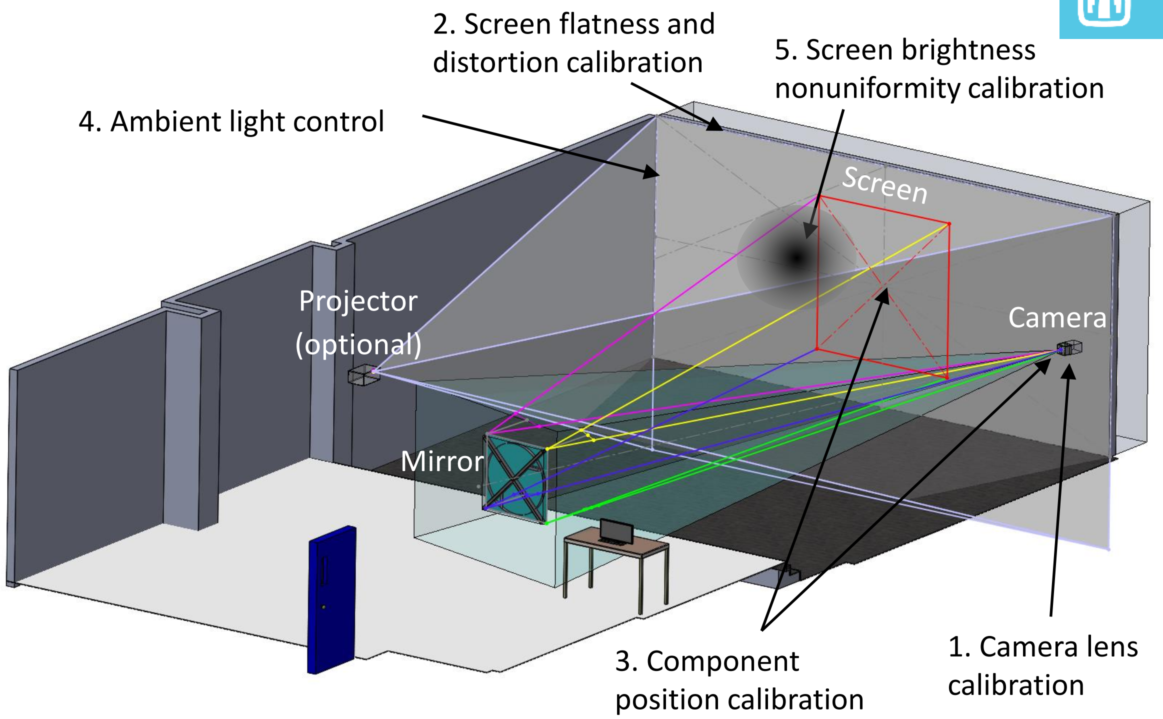
1. A known pattern is displayed on a screen, typically sinusoidal fringes in X and Y separately
2. A calibrated machine vision camera views the reflected image of that pattern
3. The deviations from the perfect pattern are interpreted as curvature of the mirror

System calibration is critical for an accurate measurement.

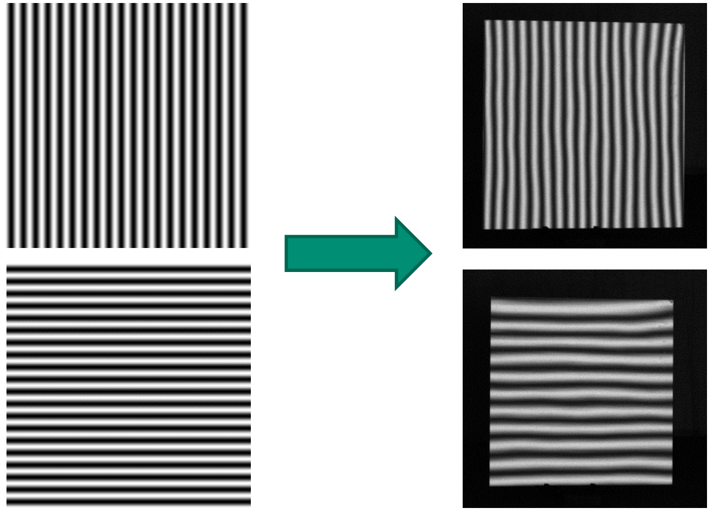
Calibration components include:

1. Camera lens calibration
2. Screen flatness and distortion calibration
3. Component position calibration
4. Ambient light control
5. Screen brightness nonuniformity calibration

Example SOFAST Setup



Displayed Fringes | Viewed Reflected Fringes



Robust Deflectometry

Characteristics of a "Robust Deflectometry" system:

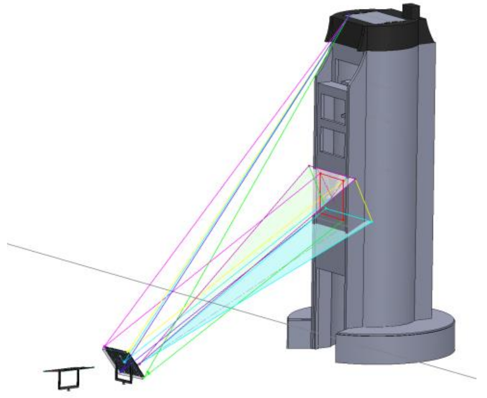
- Can be quickly deployed to new locations
- Can be quickly calibrated
- Quick calibrations will still yield accurate results
- System can yield accurate results outside of a laboratory settings
- Can measure very small to very large sized optics

Sandia's SOFAST has recently undergone a development effort to improve the accuracy, ease, and speed of calibration.

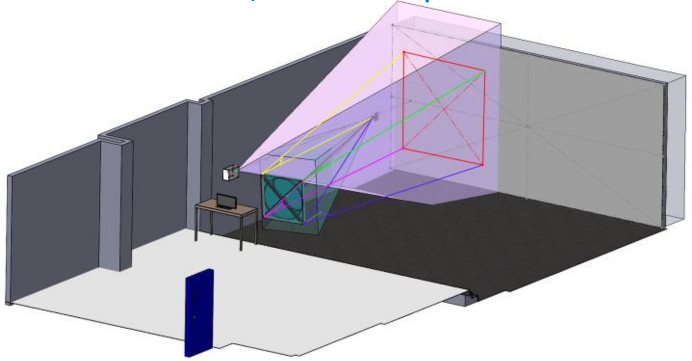
The next section describes the following improvements:

1. Camera lens calibration optimization tool
2. Screen shape measurement tool
3. Component position measurement tool
4. Ambient light analysis
5. Screen brightness nonuniformity calibration

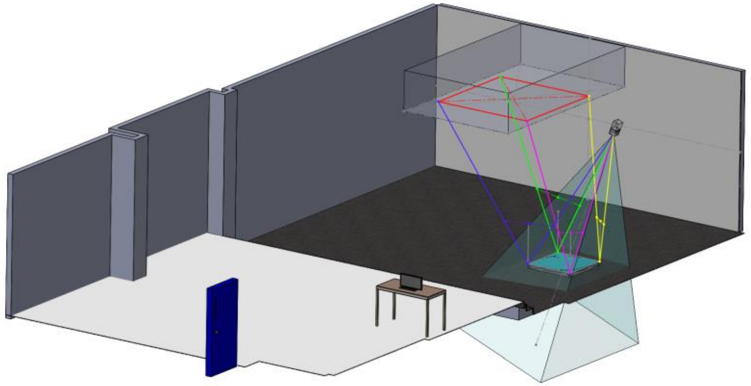
Outdoor, tower-based SOFAST



Indoor, small-footprint SOFAST



Indoor, vertical-pointing SOFAST

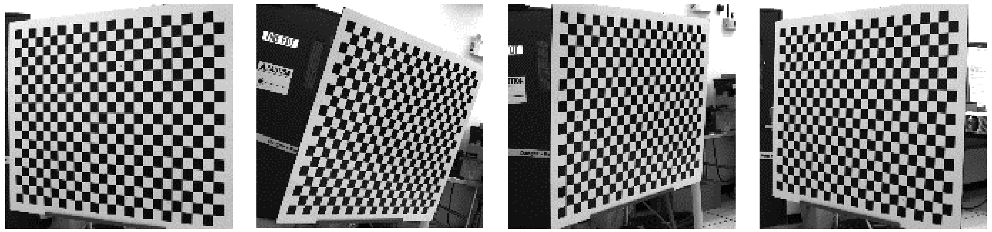


1. Camera Lens Calibration Optimization Tool

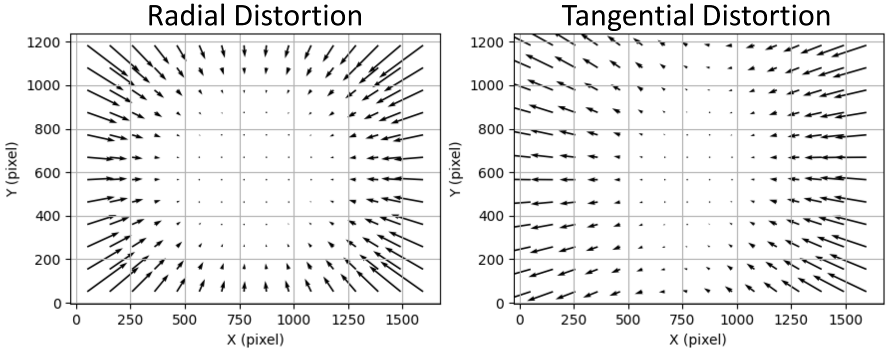
Calibration step

Lens calibration quantifies the optical distortion present in a camera lens

1. Capture N images of a flat, regular checkerboard that is presented at a variety of angles to the camera



2. Algorithm solves for best fit focal length and fits residual error to a distortion model



What users need to know

- How flat must the checkerboard be?
- At what angles should the checkerboard be presented?
- How many images should be taken?

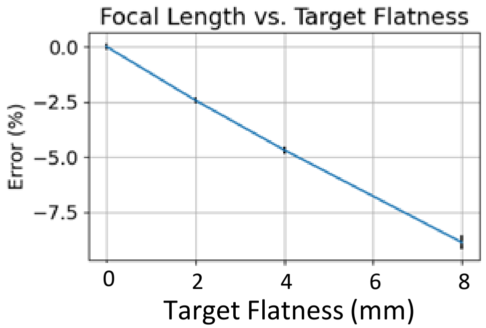
Developments to improve SOFAST's robustness

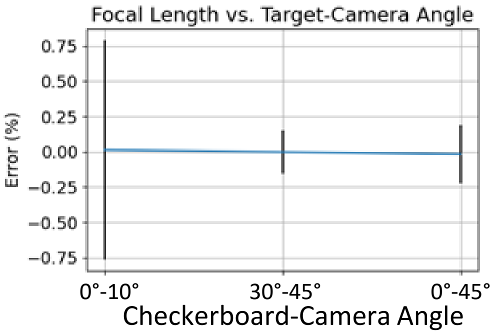
We made a camera calibration simulation to inform the user on what calibration parameters are required as a function of calibration accuracy.

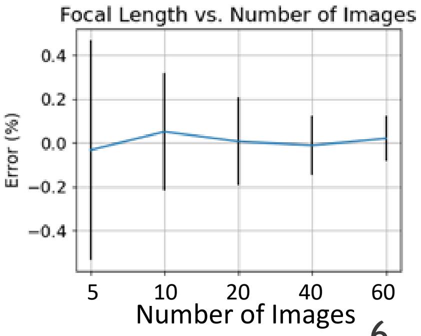
Simulation Parameter	Value
Number of checkerboard squares	19x22 squares
Checkerboard size	0.95 x 1.1 meters
Number of trials per configuration	50
Nominal camera focal length	50 mm
Nominal checkerboard to camera distance	13 meters
Checkerboard corner location uncertainty	0.5 pixels STDEV

Results of calibration simulation performed for Sandia lab SOFAST camera*

(Basler acA1600-20gm with a 50mm lens)







* Error bars represent 2 standard deviations

2. Screen Shape Measurement Tool

Calibration step

Deflectometry relies on knowing the XYZ location of every point on the display

Original SOFAST procedure

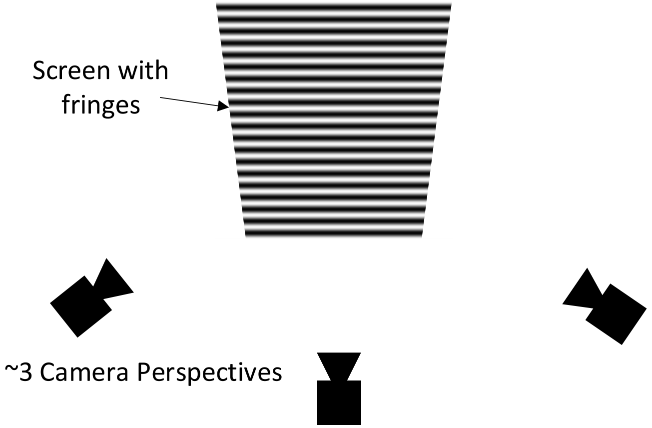
The user manually measures a grid of points displayed on the screen

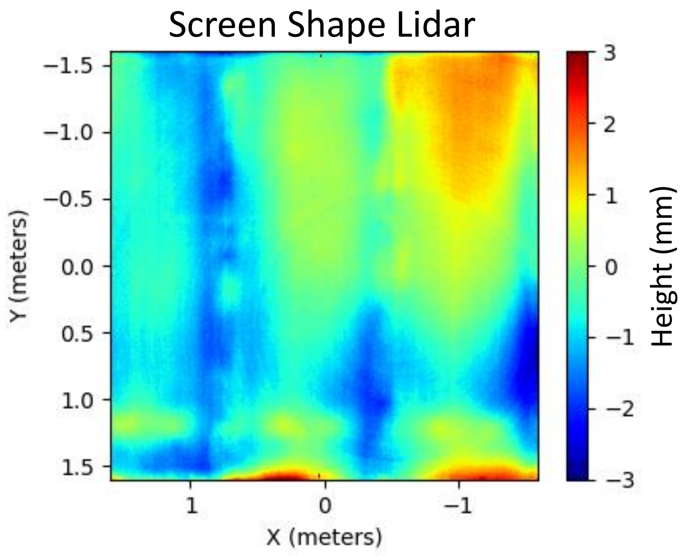
- Relies on having physical access to the screen
- Physically and time intensive
- Difficult if the screen is not flat

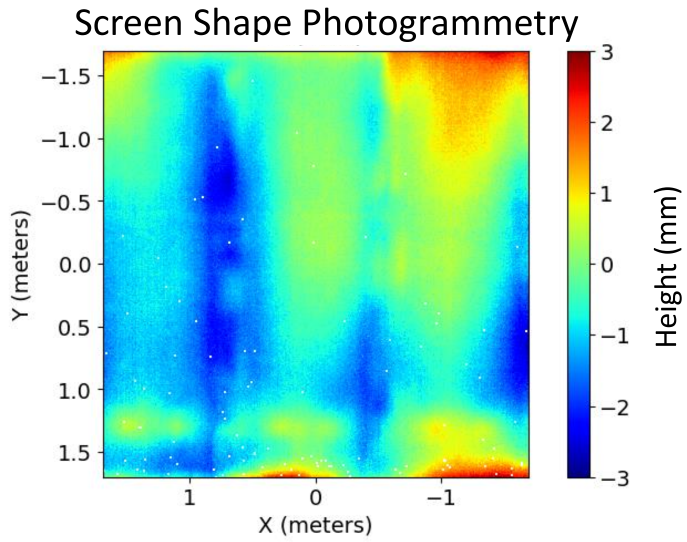
Developments to improve SOFAST's robustness

Developed a photogrammetric surface flatness measurement tool

- A calibrated camera captures sinusoidal fringes from ~3 different angles
- The photogrammetric algorithm reconstructs the 3D shape of the screen area to high accuracy
- We validated the accuracy of this method by comparing against a FARO LIDAR scanner







3. Component Position Measurement Tool

Calibration step

Deflectometry needs to know the position of the camera's entrance pupil relative to the screen to high accuracy

Original SOFAST procedure

The user manually measures the relative XYZ distance between the camera and the deflectometry screen

- Relies on having physical access to the screen and camera
- It is difficult to manually measure the location of a camera's entrance pupil as it is a virtual point inside the lens

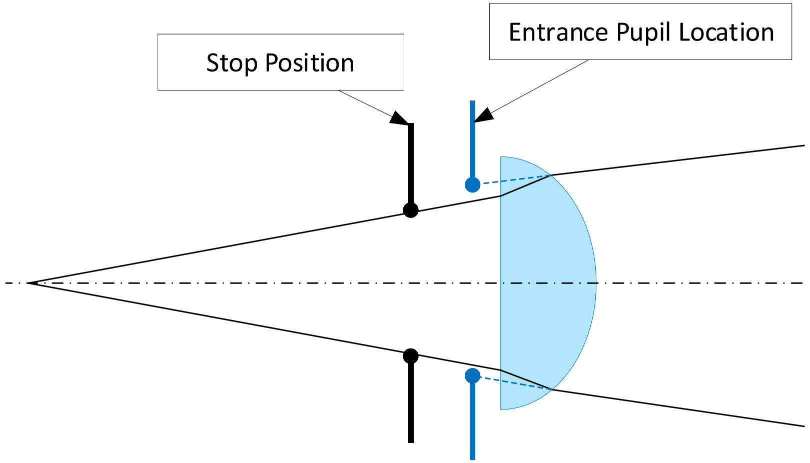
Developments to improve SOFAST's robustness

Developed a photogrammetric component location tool

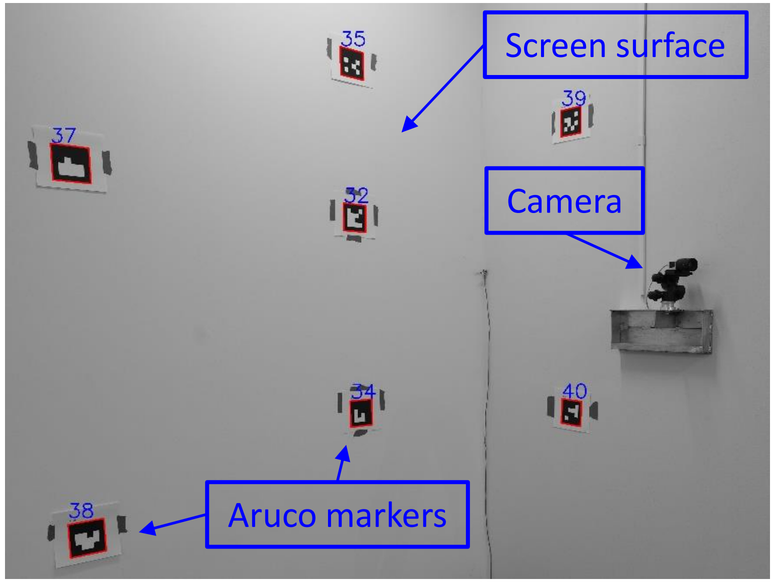
- A calibrated camera captures images of the setup area with Aruco[1] markers spanning the area from the screen to the camera's field of view.
- The photogrammetric algorithm reconstructs the 3d marker positions and thus the relative positions of the screen and camera.
- High accuracy calibration is possible with one person in ~2 hours.

Cross section of simple optical system

The physical location of the stop and the entrance pupil are not the same



Example Calibration Setup



[1] S. Garrido-Jurado, et. al., "Automatic generation and detection of highly reliable fiducial markers under occlusion," *Pattern Recognition*, vol. 47, no.6, pp. 2280-2292, 2014, https://doi.org/10.1016/j.patcog.2014.01.005.

4. Ambient Light Analysis

System setup step

- Deflectometry relies on detecting projected patterns on a screen.
- Uncontrolled ambient light can cause measurement errors.

Original SOFAST procedure

The user operates in a completely dark room

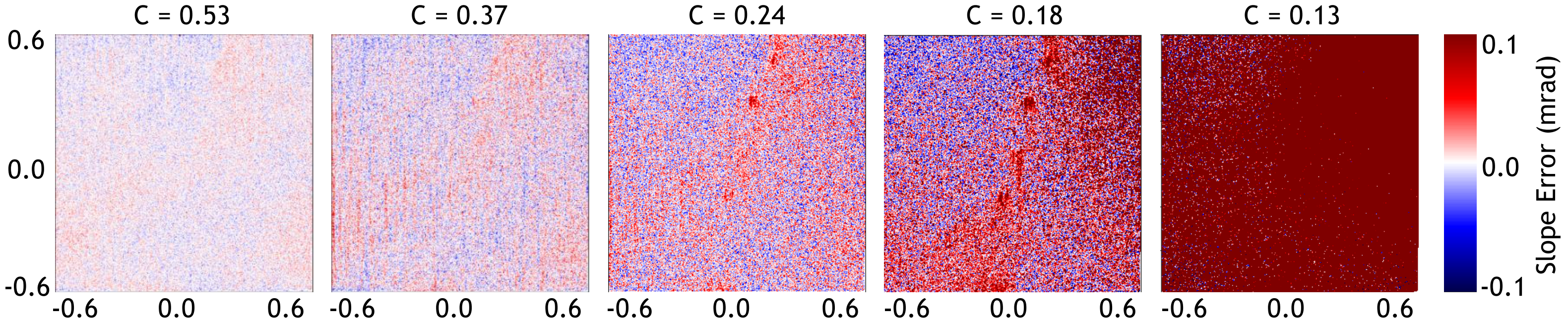
- Sometimes not possible outside of laboratory settings
- The user would likely want to know if a system will work prior to construction

Developments to improve SOFAST's robustness

We characterized SOFAST's sensitivity to varying levels of ambient light

- Characterized measured slope error as a function of fringe contrast, $C = \frac{I_{max}-I_{min}}{I_{max}+I_{min}}$.
- Given a specific camera/projector/screen type, allows the user to determine if a setup is viable before it is built.

Slope error as a function of fringe contrast



5. Screen Brightness Nonuniformity Calibration

System operation

- SOFAST expects sinusoidal fringes when performing phase unwrapping
- Typical camera/projector responses are nonlinear, which causes sinusoidal fringes to appear warped.
- Nonuniformity in the screen surface, commonly found when using a projector/screen system, can exacerbate this effect.

Original SOFAST procedure

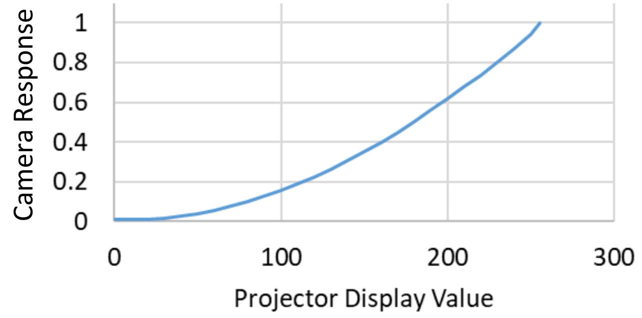
- The user can take pains to use a perfectly white wall and use high quality white paints.
- However, this is not always possible outside of laboratory settings.

Developments to improve SOFAST's robustness

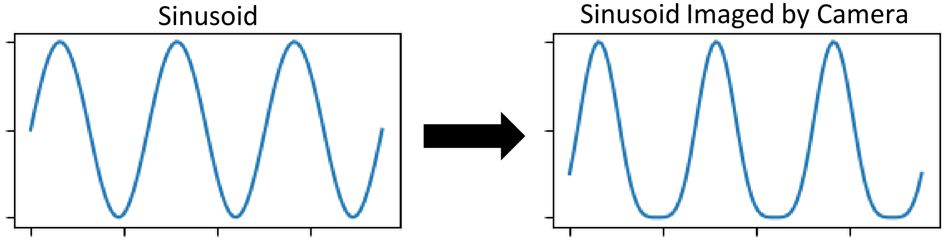
Developed a calibration step internal to SOFAST that accounts for nonlinear responses and screen brightness.

- Characterizes background illumination levels
- Characterizes brightness nonuniformity
- Characterizes camera-projector response on a per-pixel level

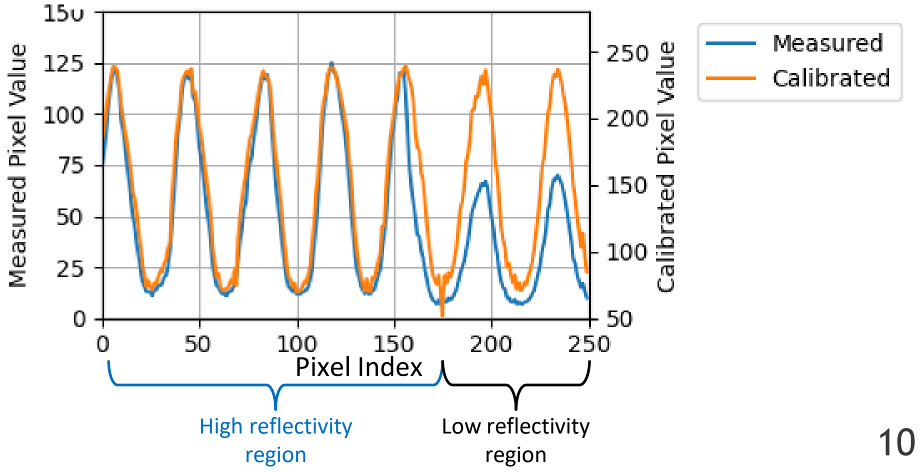
Typical Camera-Projector Response



Nonlinear projector-camera responses causes fringe warping



Uncalibrated vs. Calibrated Fringes



Conclusions and Acknowledgements

Conclusions

- We have discussed a series of improvements implemented to Sandia's deflectometry tool, SOFAST, which as made it a more robust tool.
- These improvements allow us to use it in scenarios previously incompatible with SOFAST.
- Robust CSP metrology tools can be calibrated accurately in non-ideal or inaccessible settings in and outside of the laboratory.
- All source code will soon be available as part of OpenCSP. Email OpenCSP@sandia.gov for details.

Acknowledgements

- Thanks to U.S. Department of Energy, Solar Energy Technology Office (SETO)/HelioCon for funding
- Thank you to colleagues Anthony Evans, Roger Buck, and Robert Crandell for help with data collection and collaboration

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