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Measurement Systems, Devices, and Procedures

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Agile Deflectometry

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Abstract. Concentrating Solar Power (CSP) systems use mirorrs to focus light onto a receiver, and high optical slope accuracy is required to achieve high concentration. Deflectometry is a technique for measuring optical slope directly, at fine spatial resolution across a miror surface. In this paper we report techniques for making an existing deflectometry system, SOFAST, more flexible and easier to deploy across a wide range of application scenarios. Example applications include mirror prototype development, high-volume manufacturing, outdoor in situ heliostat inspection, and education. We report using the resulting system to measure mirrors ranging in diameter from 0.13 m to 9.3 m, a range of nearly two orders of magnitude. Hardware implementations vary from a simple laptop computer to a system combining a computer, projector, screen, and camera. These efforts pursue a goal of making deflectometry easier to use, applicable to a wider range of problems, and widely available to the CSP community.

Keywords: Deflectometry, Sofast, Concentrating Solar Power, Agility

1. Introduction

Concentrating Solar Power (CSP) facilities need accurate and versatile ways to measure the quality of their mirrors. This includes measuring the surface slope of single mirror facets as well as measuring the canting directions of multifaceted heliostats. Surface slope is the direction of the mirror surface normal at each point on the mirror. Surface slope, not surface shape, is the primary metric used when measuring the quality of a CSP mirror, because over long distances associated with CSP, optical quality is more sensitive to mirror surface slope, not surface position. Although surface slope is defined as the derivative of the surface shape, information is inherently lost during the conversion between the two when measuring mirrors in discrete spatial increments. Deflectometry is an optical metrology method that can measure the surface slope distribution of mirrors at fine spatial resolution and high accuracy. Deflectometry based tools have been demonstrated to measure single CSP mirror facets [1] as well as multifaceted heliostats [2]. CSP deflectometry systems have been demonstrated outdoors measuring full solar fields [3] and are available as a commercial product [4].

Deflectometry can support multiple use cases throughout the heliostat development cycle:

- **Design.** During the design phase, deflectometry can be used to obtain high-resolution slope maps of prototype mirrors, yielding insight into mirror performance and aspects requiring improvement. Figure 1 shows a simple example. This prototype mirror appears smooth to visual inspection (left), but deflectometry reveals that it contains slope errors of up to 5 mrad (middle). The derivative of slope (right) reveals where the backside supporting structure causes deformations that “print through” the mirror glass. This information suggests where to focus attention for improving the design and its associated fabrication process.

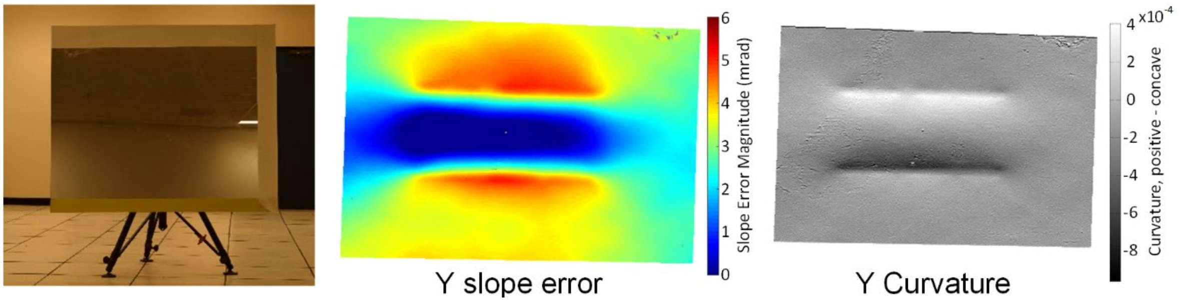


Figure 1. SOFAST measurement showing y slope error and y curvature of a test mirror.

- **Manufacturing.** Because deflectometry is completely automated, deflectometry systems can be used in manufacturing lines to obtain detailed measurements of manufactured mirrors, assessing product quality in real time.
- **Field assessment.** Either at installation or periodically during solar field operation, there is a need to assess heliostat shape, to determine whether both individual mirrors and their ensemble have the optical shape required to achieve high concentration [3].
- **Education.** One challenge in learning about CSP is gaining an appreciation of the role of optical precision and its effect on system performance. Deflectometry can provide an accessible means to gain hands-on experience with high-precision measurement of mirrors, which can then be used in experiments.

To address these use cases, deflectometry systems must be flexible, easy to use, and meet the requirements of the context. For example, to support prototyping, a system should be available on site and provide high-resolution data to support cycles of learning. Manufacturing systems should be fast, reliable, and support statistical process control. Field assessment systems must operate outdoors where heliostats are installed. Education systems must be low-cost and easily accessible to students. Deflectometry software must be flexible enough to handle each of these scenarios.

About a decade ago, Chuck Andraka and his team at the Sandia National Laboratories National Solar Thermal Test Facility (NSTTF) developed a deflectometry system designed to measure CSP mirrors [1]. This system was used to measure dish mirrors both indoors and outdoors, and its indoor laboratory implementation has been used many times since then. In this paper we report improvements to this system which increase its flexibility, range of applications, and ease of use.

This system is named SOFAST [1]. In its indoor laboratory implementation, it projects a series of fringes onto a screen. The mirror to measure is placed facing the screen, and a camera is placed viewing the mirror so it can see the screen’s reflection. The projector and camera are coordinated so that a series of images is captured which view the reflection of each projected fringe pattern. The SOFAST software then analyzes the resulting time-sequence of images to deduce the relationship between points on the mirror and their corresponding reflected point on the screen. The resulting reflection map then provides the basis for a wide variety of post-processing calculations, including mirror slope across its surface, difference between measured slope and the desired mirror design, computed predictions of solar flux under various solar incidence conditions, and other metrics describing mirror accuracy and performance. A companion program named AIMFAST was produced to measure canting angles of facets within multi-facet collectors [2].

Recently, we initiated an effort to improve SOFAST. Goals include improving its utility for high-volume manufacturing, adding new analysis, and making it easier to apply to new problems. We also developed tools to accelerate the system design and setup. These improvements enable SOFAST to be applied more easily to a wide range of CSP problems.

2. Areas of Improved SOFAST Agility

2.1 Code Base

We refactored the SOFAST software to make it easier to maintain, test, and extend. In addition to bringing SOFAST up to modern software engineering standards, we constructed a modular structure that makes every sub-process and intermediate data product accessible to the user. This facilitates automatic unit and integration tests to support reliable code extensions, and makes the tool much less rigid in how it is used to collect and process data.

We changed the code structure to separate the data acquisition, data processing, and data visualization functions into separable processes which can run independently. SOFAST can be run using scripts, or through its graphical user interface. If quick feedback on a mirror's optical performance is desired, data can be captured, analyzed, and visualized using SOFAST's graphical user interface within seconds. This workflow is particularly friendly to prototype development and research settings. Alternatively, data can be automatically collected and saved to disk for later automatic processing, a workflow that is well suited for industrial manufacturing lines performing trend analysis and statistical process control.

Version control is now implemented using a code repository and the code now contains a unit test suite that compares current SOFAST outputs to a separate curated repository of sample data. The test suite fully exercises SOFAST's functionality to ensure that changes made to the code have not affected its accuracy. These improvements enable accelerated development and collaboration while ensuring the fidelity of SOFAST.

2.2 Multi-Facet Measurements

We extended SOFAST to handle either single mirror facets or multifaceted heliostats. The previously reported Sandia tool AIMFAST measured facet canting angles [2], but SOFAST is now capable of simultaneously measuring high-resolution slope maps and facet canting angles of multifaceted heliostats. SOFAST can output either slope maps for individual facets, or an overall slope map for the entire heliostat. Figure 2 shows an example SOFAST measurement of an NSTTF heliostat including canting directions. In the plot on the right, the needles are projections of very long surface normal vectors, standing perpendicular to the center of each facet, viewed from the front of the heliostat. As facet canting angle increases, the projected needle appears longer.

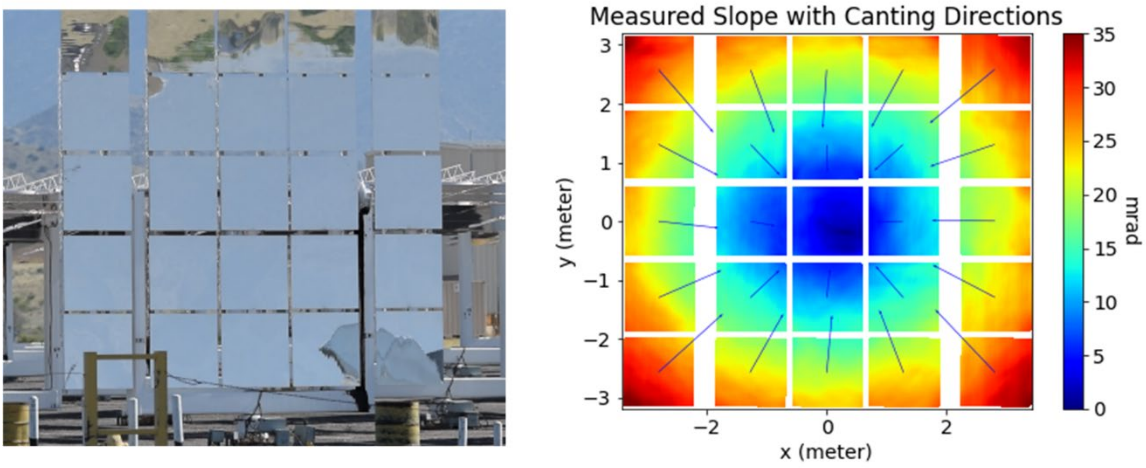
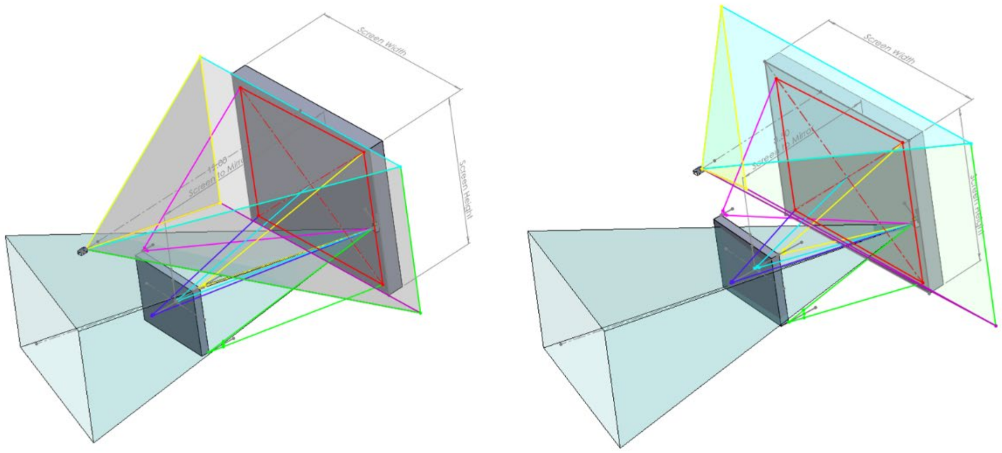


Figure 2. Example SOFAST measurement of a multifaceted NSTTF heliostat (5W01) with calculated facet canting directions.

2.3 System Layout

Proper layout is essential for correct deflectometry performance. The location of the screen, projector, camera, and mirror under test must satisfy a strict set of geometric constraints. The core requirement is that when the camera views the mirror, it must see a reflected image of a region that is completely contained within the screen. Further, the projector's projected image must fully contain this region. In addition, the camera's field of view must contain the entire mirror surface. Finally, view interference must be avoided.

We developed a computer-aided design (CAD) layout tool built in SolidWorks to design configurations of the projector, screen, camera, and test mirror. The tool provides an abstract view and a concrete view. In the abstract view, functional aspects of SOFAST components are rendered, enabling designers to ensure that all required optical constraints are satisfied. The reflected screen region seen by the camera is automatically updated when the screen, mirror, or camera positions are modified. The camera field of view and projector's field of projection are also shown. This tool enables designers to explore design alternatives and resolve challenges due to space limits or other factors. For example, Figure 3 shows two abstract setup configurations. By replacing the projector lens in layout (a) with a projector lens with a wider field of view, a more compact layout is achieved (b). The SOFAST CAD layout tool also supports a concrete view showing detailed components; Figure 4 shows an example.



(a) (b)

Figure 3. Example abstract layouts produced with the SOFAST CAD tool.

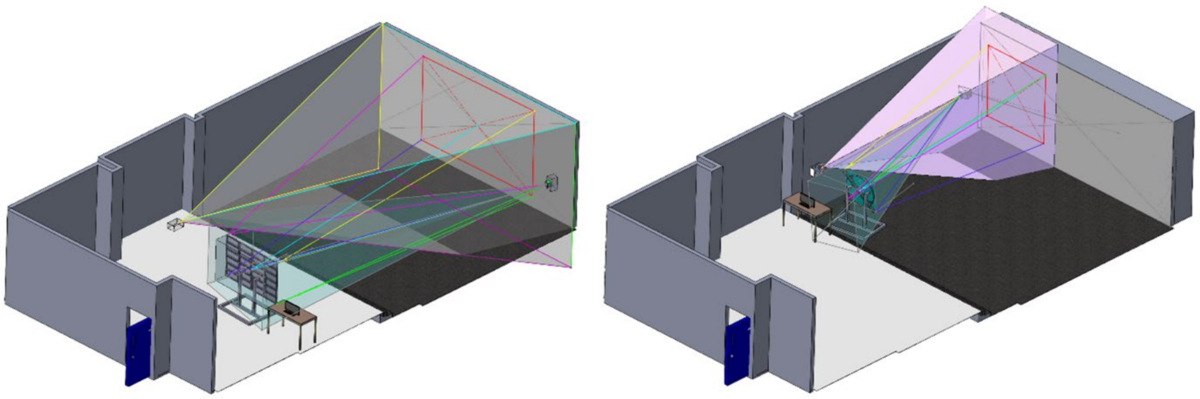


Figure 4. Two SOFAST configurations in the Sandia NSTTF Optics Laboratory. These configurations exist simultaneously, demonstrating two layouts.

2.4 Calibration

One of the most time-consuming steps of installing an original SOFAST system is the calibration of the projected image. The distortion of the projected image on the screen must be characterized to achieve accurate results. We developed tools that accompany SOFAST to help users efficiently calibrate new SOFAST systems.

Images projected on screens generally contain some degree of optical distortion due to optical inaccuracies in the projector lens and misalignments between the projector and the screen. SOFAST requires an accurate calibration of projector distortion. The early by-hand distortion characterization process required hundreds of measurements and could not account for keystone distortion, which is caused by the projector pointing off normal to the screen.

SOFAST now has an accompanying photogrammetric screen calibration tool that requires much less manual labor and can account for keystone distortion. The user captures images of a regular grid projected onto the screen and photogrammetric algorithms automatically create a screen distortion model for use internal to SOFAST, illustrated in Figure 5(a) and (b). This accelerates the setup time of SOFAST systems and enables quick measurement of mirrors in situ. Additionally, this tool enables characterization of screens unable to be characterized before, such as screens in inaccessible locations as illustrated in Figure 5(c).

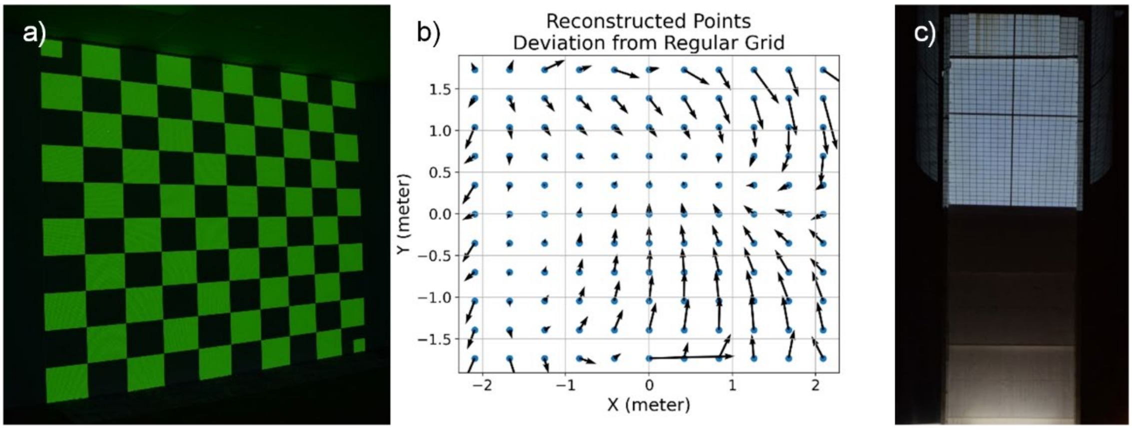


Figure 5. The projector distortion calibration tool enables distortion characterization to be done quickly, even in inaccessible screen locations, such as the side of a solar tower. Note the keystone distortion in (c).

2.5 Scalability

SOFAST was originally developed as a laboratory tool primarily used in fixed locations indoors. Our recent improvements have enabled both much larger and much smaller scales of feasible SOFAST systems. We have demonstrated SOFAST measurements of mirrors ranging from 0.13 m to 9.3 m diagonal on screens ranging from 0.32 m to 14.7 m diagonal, respectively.

We demonstrated a large-scale outdoor SOFAST system capable of measuring full NSTTF heliostats, using an outdoor approach previously reported in [3]. So far, we have measured three heliostats (6.8 m × 6.4 m) in size, up to 190 m from the projector screen. We used the flat front face of the solar tower shown in Figure 5(c) as the projector screen. A camera on top of the solar tower captured images of heliostats in the solar field, as shown in Figure 6(a). Because we did not have communication cables that were long enough, SOFAST's data acquisition system could not be used in this initial test. Instead, we used a digital camera to capture images, manually coordinating with fringe projection. The resulting reflected fringe images were then processed by SOFAST's data processing modules. SOFAST output a variety of analysis visualizations, including plots of slope error measured relative to an ideal heliostat assumed to have all facets canted towards a single location one focal length away.

Figure 6 and Figure 7 show results for two different heliostats in the NSTTF field.

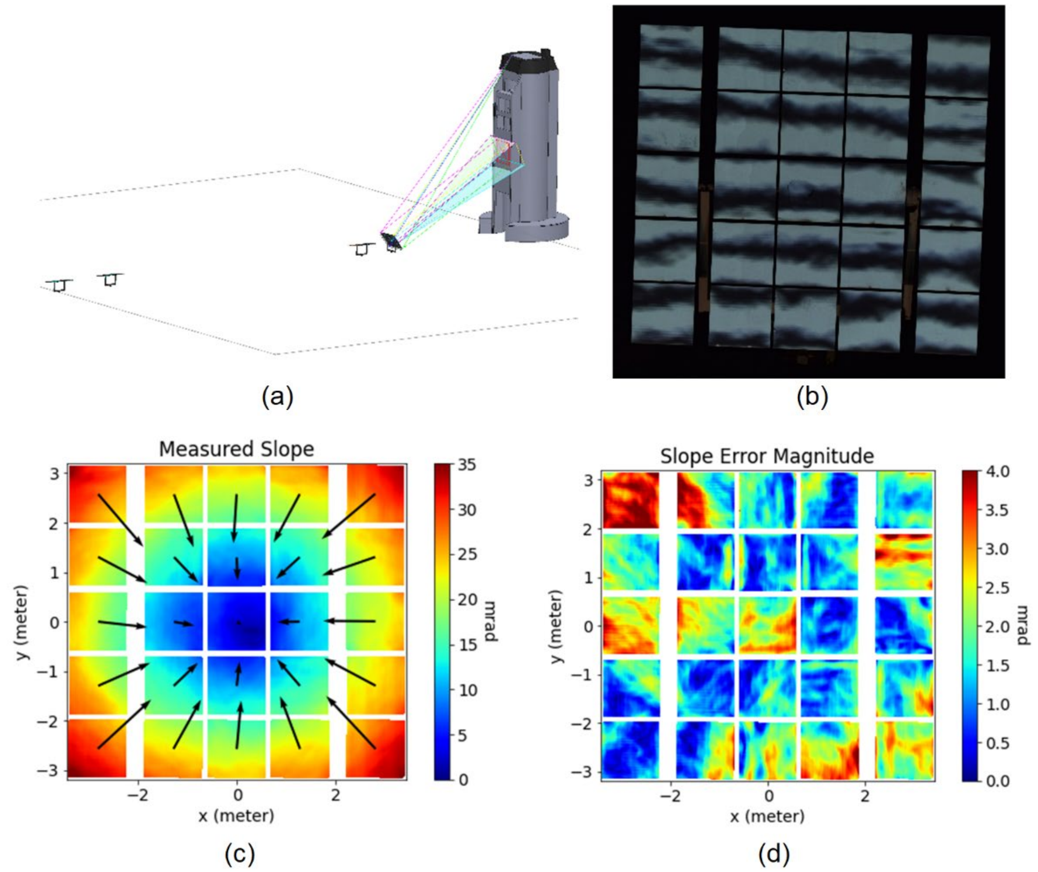


Figure 6. Measurement of heliostat 5W01, with 55 m slant range.

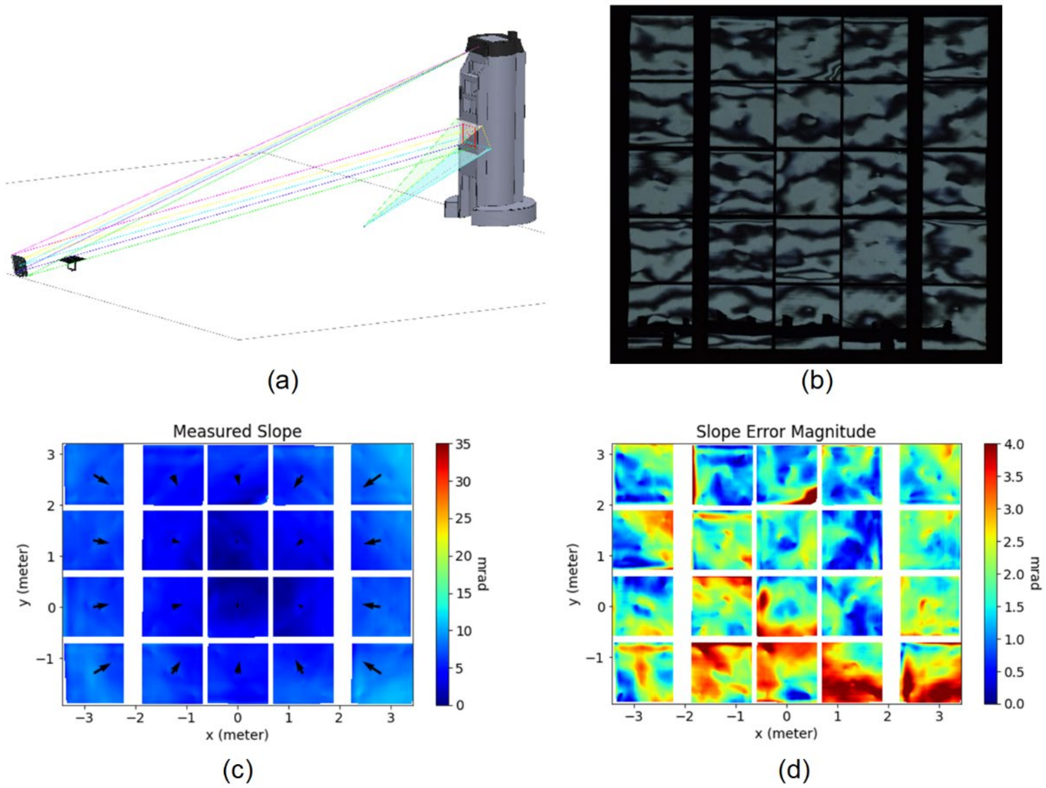


Figure 7. Measurement of heliostat 14W01, with 188 m slant range.

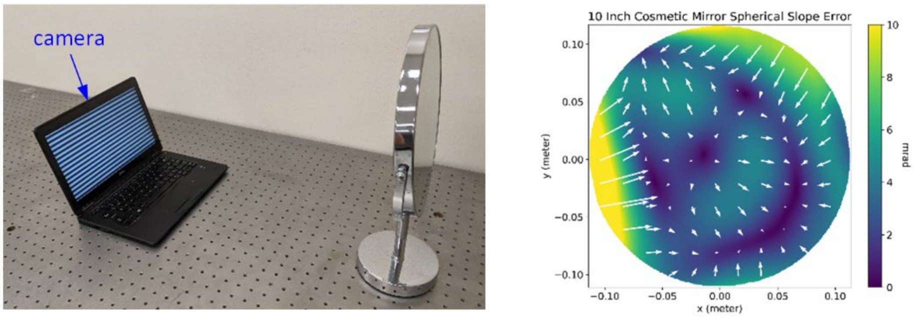
In both Figure 6 and Figure 7, (a) shows the measurement setup, (b) shows an example fringe image, (c) shows the overall measured slope and canting angles, and (d) shows the slope error, compared to a reference heliostat appropriate for the heliostat location. Corresponding plots in Figures 6 and 7 have identical color bar scales.

Figure 6 shows results for 5W01, a heliostat with a slant range of 55 m from the tower target. Figure 7 shows measurement results for 14W01, a heliostat 188 m from the target. Note in Figure 7(b) that the bottom row of facets are occluded by the heliostat 13W01 in front; this is why the plots in Figure 7(c) and Figure 7(d) have only four rows of tiles. This occurred because our screen is too low to obtain a full view of heliostats in the back of the field.

Because 5W01 is closer to the tower than 14W01, it has a shorter focal length and thus its facets are more steeply canted. This can be clearly seen in the measurement data by comparing part (c) of each figure.

Comparing Figure 6(b) and Figure 7(b), we notice increased distortion of the fringes in Figure 7(b). This is not due to a difference in optical quality, but rather due to a difference in the observed distortion as a function of distance from the mirror to the tower and camera. For a full discussion of this effect, see [5]. We note that SOFAST is not fazed by this distortion, since it does not require recognition of reflected features.

On the other end of the scale spectrum, we also demonstrated a small-scale SOFAST system capable of measuring mirrors a few centimeters in size. We used a laptop with an integrated camera to produce a mobile, small-scale SOFAST system. The laptop screen displays the fringes, and the integrated webcam captures the images. We used the setup in Figure 8(a) to measure a small ten-inch diameter cosmetic mirror. The SOFAST calculated slope error relative to a spherical surface is shown in Figure 8(b).



(a) (b)

Figure 8. Small-scale SOFAST setup and measured slope error of a small cosmetic mirror.

2.6 Documentation

At the beginning of our improvement effort, SOFAST lacked complete documentation. We augmented SOFAST's documentation with substantial additional content. SOFAST documentation now contains a detailed list of required equipment, a complete system setup instruction manual, software installation instructions, programmer's documentation, operating instructions, and a set of example data acquisition and data processing scripts. This documentation package serves to increase the flexibility and ease of use of SOFAST.

3. Discussion

Deflectometry is a proven technique for high-resolution mirror slope measurement, and our improvements to one deflectometry system, SOFAST, have helped us appreciate its wide range of potential applications. Our goal in making these improvements is to make deflectometry easier to apply to a wide range of CSP metrology problems, spanning prototype design, high-volume manufacturing, field operation, and education. We have demonstrated SOFAST application to problems ranging in mirror size from 0.13 m to 9.3 m, in both laboratory settings and outdoors, and the software includes features designed to support high-volume manufacturing.

Key elements missing in the work reported here are validation against ground truth and an analysis of measurement uncertainty and how it varies with configuration. We intend to address these problems in future work, extending the uncertainty analysis reported in [6].

Data availability statement

Access to the data presented in the paper is restricted. SOFAST source code and measurement data is Sandia proprietary information.

Author contributions

Randy Brost contributed conceptualization, investigation, formal analysis, software, funding acquisition, project administration, and writing. Braden Smith contributed software, data curation, formal analysis, investigation, and writing. Felicia Brimigion contributed software, investigation, and review & editing.

Competing interests

The authors declare no competing interests.

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