SolarPACES 2024, 30th International Conference on Concentrating Solar Power, Thermal, and Chemical Energy Systems

Measurement Systems, Devices, and Procedures

https://doi.org/10.52825/solarpaces.v3i.2369

Published: 26 Nov. 2025

OpenCSP: Collaborative Code and Data For CSP

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Abstract. We are announcing OpenCSP, an open-source platform including source code, applications, and data to enable collaborative development for the CSP community worldwide, supporting industry, research, and education. OpenCSP includes components of code, data, mechanical designs, tools, and documents, all provided under an open-source license allowing unlimited use. The OpenCSP code development environment is set up to enable collaborative team development of high-quality software, yet OpenCSP welcomes both polished code and rough code-in-progress. The goals of OpenCSP are to accelerate transfer of CSP metrology and analysis tools to industry, provide a resource for businesses supporting CSP, support CSP education, and to provide a community collaborative development environment to enable teams to build new advanced CSP applications more quickly, and to speed their deployment.

Keywords: CSP Optical Metrology, Open-Source Software, Open-Source Data

1. Motivation – Why Open CSP?

Concentrating solar power (CSP) has the potential to contribute significant heat for critical processes. However, CSP will only achieve this if solar collectors are properly designed and implemented with high optical accuracy. This requires good analysis and metrology tools.

We developed the OpenCSP collaborative development environment to increase access to CSP optical analysis and metrology tools, and to foster collaboration within the CSP community to increase the scope of optical tool coverage and the speed of tool deployment.

We are inspired by several previous collaborative open-source development projects. These include the Linux operating system [1], the Pyomo optimization package [2], and the pvlib toolbox for photovoltaic system analysis [3]. These are all examples where collaborative software development produced a result much stronger than could be achieved by individuals working alone, and where the result has had broad impact due to open source access. Open collaborative development also enabled these packages to improve over time, due to volunteer contributions from multiple authors.

We also recognize that effective CSP development requires not only code, but access to realistic, high-quality data. Without this, developers are limited to analytic studies based on first-principle assumptions, which can overlook significant real-world factors that influence performance. Acquisition of real data is relatively easy for those who have access to a functioning solar field, but inaccessible for most others. Therefore we aim to fill this “data gap” to make relevant real-world data readily available. The goals of OpenCSP are to:

- Accelerate transfer of state-of-the-art CSP metrology and analysis tools to industry, eliminating barriers to access.
- Provide a resource for businesses seeking to support CSP development.
- Enable the code and data to contribute to education.
- Provide a community collaborative development environment to enable teams to build new advanced CSP applications more quickly, and to speed their deployment.

2. What is OpenCSP?

OpenCSP is an open-source platform including source code, applications, and data to enable collaborative development for the CSP community worldwide, supporting industry, research, and education. It includes these main components:

- *OpenCSP_Code* – Foundation classes and functions for building new programs and also ready-to-run applications, including Sandia's SOFAST 2.0 code [4], [5], all in Python. The development environment includes several features to support effective team code development, including automatic testing, automatic document generation, a rich set of examples, issue tracking, and more.
- *OpenCSP_Data* – Large data sets for research, optical targets to support metrology ground truth tests, and test data for OpenCSP_Code.
- *OpenCSP_Mechanical* – Includes an interactive CAD tool for designing deflectometry layouts [6], [7], plus a gallery of CAD models to support collaborative CSP research.
- *OpenCSP_Tools* – Non-code tools to aid CSP analysis and understanding.
- *OpenCSP_Documents* – Documents supporting OpenCSP and related topics.

All of these are provided under an open-source license allowing unlimited use, requiring acknowledgement (see license files for details).

Because OpenCSP is intended to be a collaborative development environment, it contains both mature ready-to-run code, and code that is in various stages of development. Others are encouraged to join the effort, utilizing OpenCSP resources, contributing improvements, and participating in the team development process. New additions are also welcome.

3. OpenCSP Content

OpenCSP is informed by a long history of research results including the beam characterization system (BCS) system for measuring beam shape and pointing [8], [9], [10], deflectometry systems for measuring detailed slope maps [11], [12], [13], [14], [15], [4], airborne systems for assessing solar fields [16], [17], [18], [19], [20], [21], ground truth techniques [8], [12], laser methods [22], mechanical design for testing, and a full-year survey of reflected beam variation [23], and also previous open-source projects [1], [2], [3]. These prior results have informed the design of OpenCSP, and in some cases directly contributed OpenCSP content.

OpenCSP initially focuses on CSP optics, and currently includes over 50 foundation classes, >82,000 lines of code, and over 290 GB of data comprising over 130,000 files and directories. A brief summary of current OpenCSP content appears below.

OpenCSP Code:

- Foundation Classes (Figure 1(a)). Foundation classes include a Mirror base class, which can be defined by an arbitrary analytic function, or measured data, or a linear combination of either. Higher-level classes include Facet, FacetEnsemble, Heliostat, and SolarField, all of which support ray tracing (Figure 1(b)).

- SOFAST 2.0 (Figure 1(c)). Flexible code for performing high-resolution deflectometry measurement [4], [5]. Supporting hybrid deflectometry in either ambient light or darkness [24], SOFAST 2.0 has been used to assess the optical effects of temperature change on full heliostat facets [25], and to implement a simple educational installation using only the display and camera of a laptop computer.
- SpotAnalysis (Figure 1(d)). Generalized analysis of a light spot on a target. Useful for analyzing both BCS and laser measurements.
- TargetColor (Figure 1(e)). Generates optical targets with engineered color patterns.
- Utilities: VideoHandler class and automatic PowerPoint Slide Generation (Figure 2).
- Flight planner and data post-processing code for the UFACET system for scanning heliostat fields with a flying drone (Figure 3). Status: Rough.

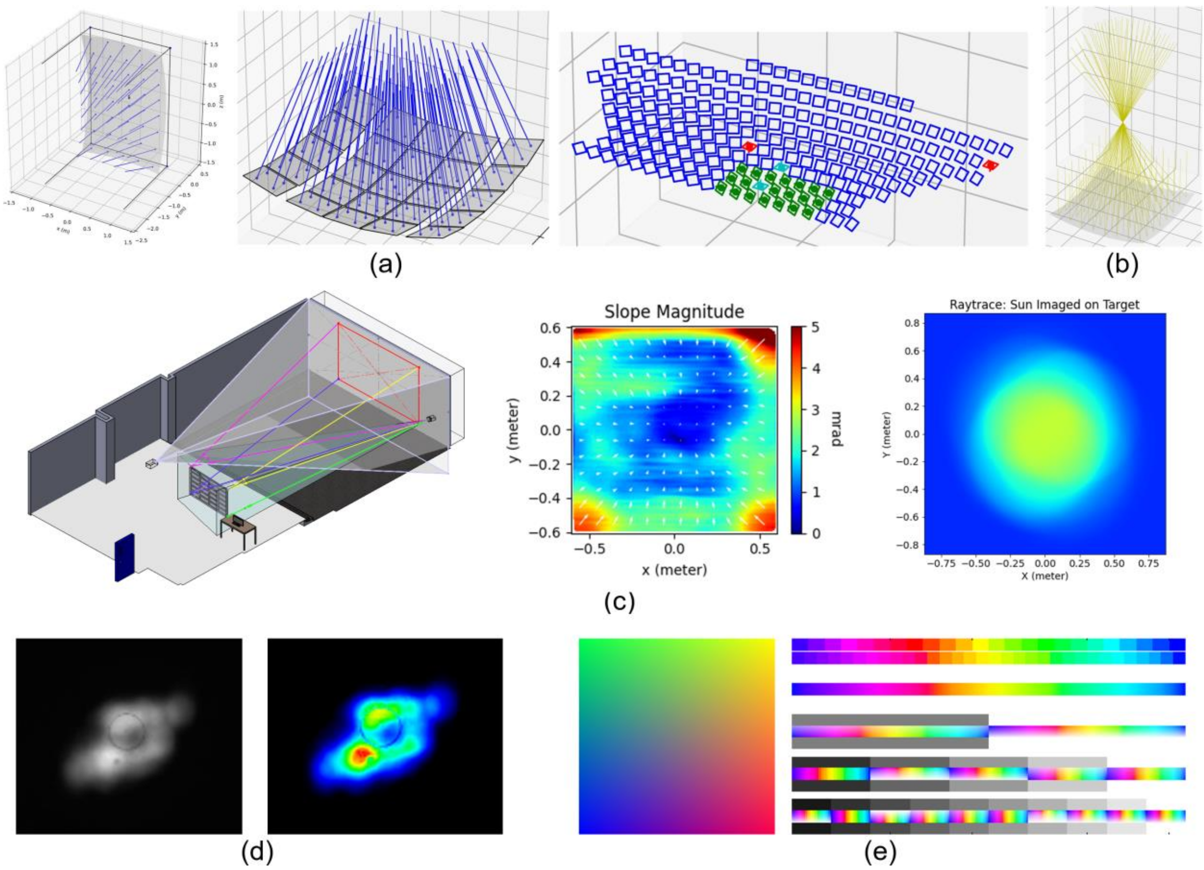


Figure 1. *Example OpenCSP output. (a) Facet, heliostat, solar field models. (b) Analytic ray tracing. (c) SOFAST layout, slope map, ray trace spot. (d) BCS raw image and analysis. (e) Optical targets.*

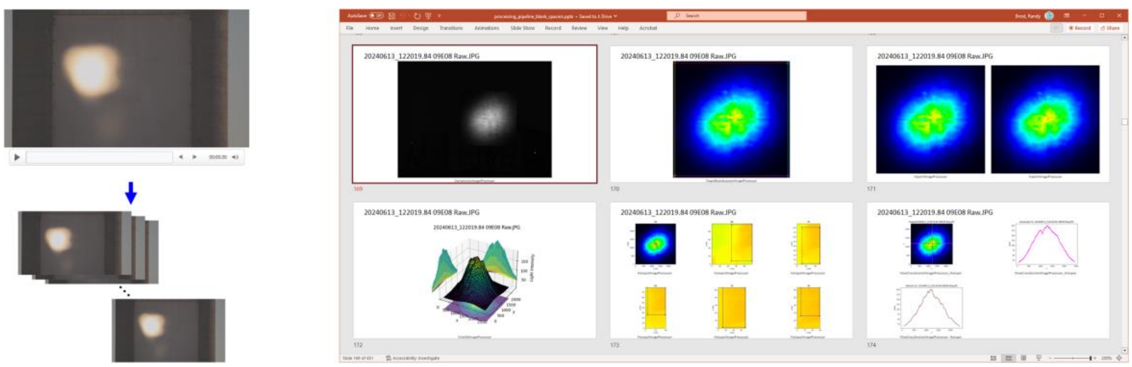


Figure 2. *Example OpenCSP utilities. Left: VideoHandler. Right: Automatic slide generation.*

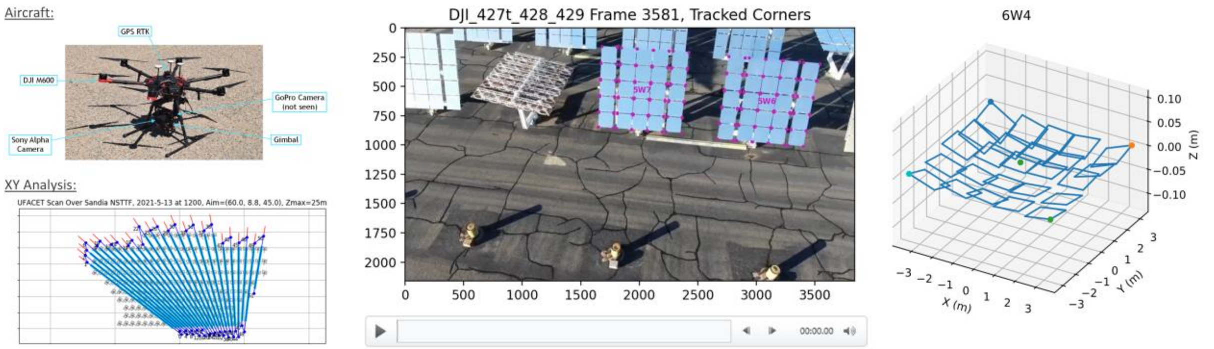
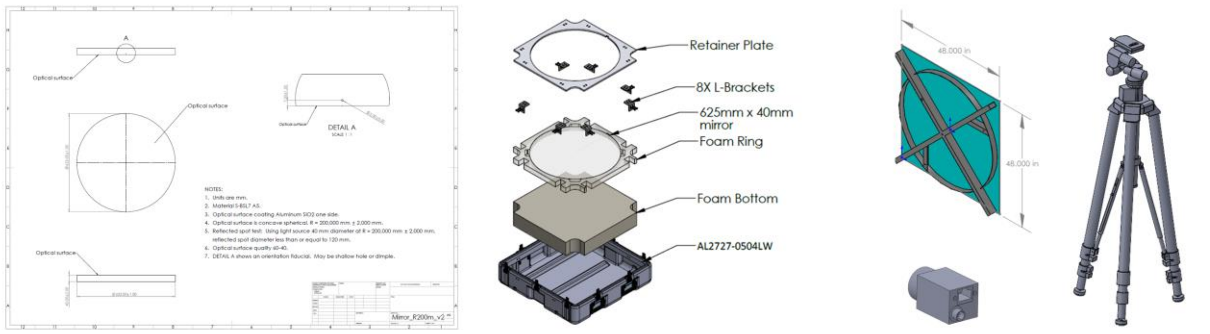


Figure 3. *UFACET was developed to scan a heliostat field with a flying drone. OpenCSP includes the flight planner and post-processing code (both rough), and we plan to release example data.*

OpenCSP Mechanical:

- SOFAST CAD Layout Tool (Figure 1(c)). Provides interactive visualization of optical constraints in deflectometry instrument layouts [6], [7].
- High-Precision Calibration Mirror Design (Figure 4(a,b)). Sandia acquired a very high-precision reference mirror with a 100 m focal length, for the purpose of cross-checking complex metrology systems like SOFAST and UFACET. OpenCSP includes full design information enabling others to replicate this.
- Metrology Support Models (Figure 4(c)). CAD models for modeling metrology setups, including hardware at the Sandia National Solar Thermal Test Facility (NSTTF).

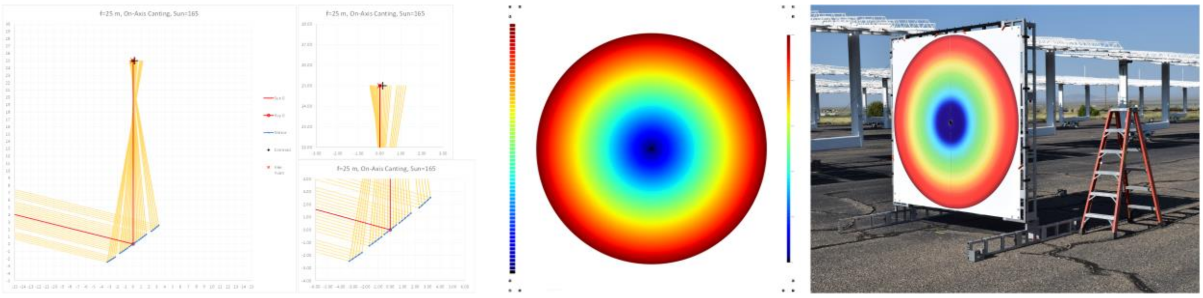


(a) (b) (c)

Figure 4. *(a) High-precision calibration mirror design.*
(b) Case for high-precision mirror. (c) Examples from the CAD gallery.

OpenCSP Tools:

- Interactive 2-d Ray Trace (Figure 5 (a)). An easy-to-use interactive 2-d ray-tracing tool for visualizing the effect of parameter changes in heliostat shape and sun position.
- Manually-drawn optical targets (Figure 5(b)). Some useful optical target designs.

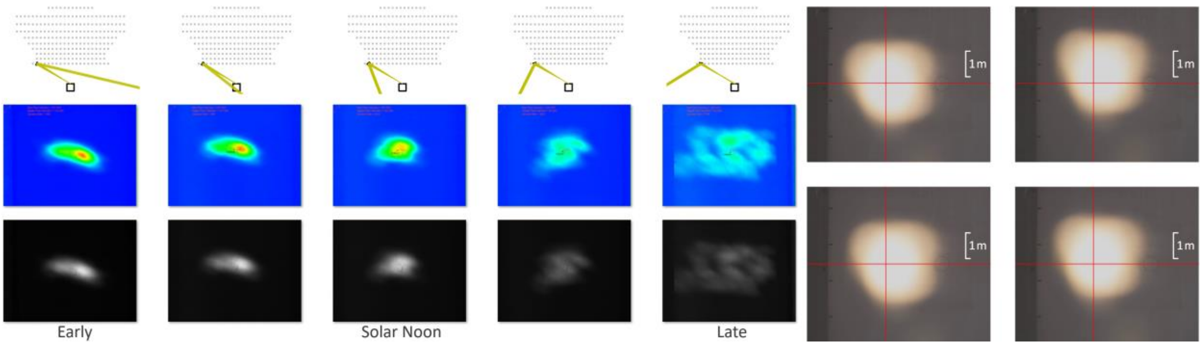


(a) (b)

Figure 5. *Example OpenCSP tools. (a) Interactive 2-d ray trace. (b) Manual optical targets.*

OpenCSP Data:

- BCS Data: Variation in beam shape and pointing error across time (Figure 6(a)) [23].
- BCS Data: Dynamic variation under wind (Figure 6(b)) [23].
- Sandia Heliostat Canting Prescriptions (Figure 7). Ideal canting data for heliostats in the NSTTF heliostat field, for both on-axis and off-axis canting schemes (in progress).
- SOFAST 2.0 Data Examples (Figure 1(c)). Example SOFAST data sets.
- UFACET flight data and post-processing results (Figure 3). Drone-captured video and post-processing analysis data for UFACET flight over the NSTTF heliostat field (planned).



(a) (b)

Figure 6. *Example OpenCSP data. (a) Variation in BCS beam shape through the day, year [23]. (b) Frames of BCS video of beam variation in wind [23].*

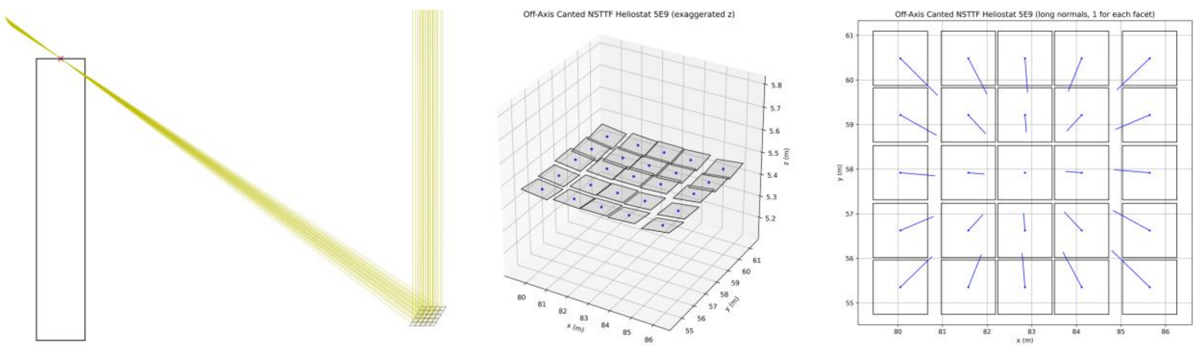


Figure 7. *Off-axis canting prescription for heliostat 5E09 at the Sandia NSTTF. (a) Looking north. (b) Exaggerated z-axis. (c) Surface normal. Rotation seen is due to maximizing flux at solar noon.*

OpenCSP Documents:

- OpenCSP portfolio, showing examples and where to find them.
- OpenCSP code documents, including getting started guide [26], plus auto-generated.
- Demonstration notebook, explaining foundation classes and how to use them.
- Sandia NSTTF technical information, providing context for data sets.
- Technical presentations, such as “Distortion Effects in CSP Mirrors,” and “Heliostat Metrology Challenges.”

4. How to Access OpenCSP

The primary entry to OpenCSP is the web site https://opencsp.sandia.gov. This contains an overview of OpenCSP and its content, and instructions on how to access and contribute. The web site also points to the code repository (https://github.com/sandialabs/OpenCSP), on-line documentation (https://opencsp.readthedocs.io/en/main/index.html), and the non-code site (https://sandia-csp.app.box.com/s/iftmhdkhgjnmfgefsfmkid011dtv8n3g) containing OpenCSP data, mechanical, tools, and documents.

OpenCSP code is written in Python, and code is managed using git. Some of the simpler tools are implemented in Excel. CAD models are constructed in SolidWorks 2022, and optical target artwork is constructed in Visio and available in exported pdf.

All OpenCSP code and data are available to the public for unlimited use, which includes incorporating either into commercial products with proper license acknowledgment and acknowledgement to OpenCSP (for example, “OpenCSP Inside”). The open-source license for code is the Apache 2.0 license [27] and for non-code is the Creative Commons license CC-BY-SA [28]. See the license files in the code repository and non-code site for details.

5. Conclusion

OpenCSP is intended to support rapid dissemination of high-quality CSP optical metrology and analysis capabilities, and also to foster effective global collaboration to develop improved and new technology. It includes both code and data components, and is geared to support CSP industry, research, and education.

OpenCSP is intentionally work in progress. We plan to add significant content in the future, and we hope it will provide a useful resource to the community. We invite others to contribute both code and data, and join the development effort.

Data availability statement

Data is a significant part of the OpenCSP collaborative development environment. It supports the automated testing of the code part of OpenCSP, provides detailed input to the OpenCSP use case examples, and also provides large data sets for direct study by other researchers. See Section 4 for access details.

Underlying and related material

OpenCSP provides an extensive source code library supporting both new code development and ready-to-run applications. See Section 4 for access instructions.

Author contributions

Author contributions to OpenCSP:

- Randy Brost – conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, software, resources, supervision, validation, writing.
- Benjamin Bean – conceptualization, data curation, formal analysis, methodology, software, validation, writing.
- Felicia Brimigion – conceptualization, data curation, investigation, software, writing.
- Margaret Gordon – conceptualization, funding acquisition, administration, resources.
- Evan Harvey – conceptualization, methodology, software, resources, writing.
- Madeline Hwang -- data curation, investigation, software, validation.
- Tristan Larkin – conceptualization, formal analysis, methodology, software.
- Miranda Mundt – methodology, software, resources.
- Nicholas Phelps – data curation, investigation, methodology, writing.
- Braden Smith – conceptualization, data curation, formal analysis, investigation, methodology, software, resources, validation, writing.
- Carly Tanaka-Lubensky – conceptualization, software, resources, writing.

Competing interests

The authors declare that they have no competing interests.

Funding

This work was funded by the U.S. Department of Energy Solar Energy Technologies Office, and by the Sandia National Laboratories LDRD Program.

Acknowledgement

We thank the DOE Solar Energy Technologies Office and the Sandia LDRD program for their financial support. We also thank Pavlos Apostolopoulos, Ryan Brost, Roger Buck, Robert Crandell, Mike Collins, Jim Crimmins, Anthony Evans, Luis Garcia Maldonado, Kevin Good, Sam Hastings, Rob Keene, Dane Kuhr, Doug Lujan, Dimitri Madden, Dave Novick, Gino Perez, Tess Ravick, Daniel Ray, Zac Ringer, Doug Robb, Estevan Rodriguez, Jon Sanchez, Steve Schell, Brian Sebastian, Bob Sleeper, Dan Small, Aaron Spieles, Eirini Tsiropoulou, Samantha Updegraff, Ye Wang, Bob Westervelt, and Jessica White for their many contributions toward OpenCSP and the results it includes.

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