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# Question-Based Gap Analysis of Heliostat Optical Metrology Methods

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**Abstract.** As part of the DOE Heliostat Consortium Roadmap study, we investigated optical metrology systems for heliostats, seeking areas where further research was needed. We began by considering optical metrology questions of interest across the heliostat development cycle and identified information types common across this spectrum. In addition to raising questions of interest, each development cycle phase implied specific operation requirements. Combining these yielded 13 core problem statements, four of which do not appear to have a readily available solution: (a) in-situ measurement of high-resolution maps of mirror surface normals, for all heliostat tilt angles and heliostats far from the tower; (b) accelerated heliostat calibration; (c) high-speed in situ measurement of heliostat surface normal maps and pointing directions; (d) ground truth methods for verifying the accuracy of surface normal map measurements. This analysis may provide input to the selection of future research goals.

**Keywords:** Heliostat Optical Metrology, Heliostat Consortium, Gap Analysis

## 1. Introduction

Concentrating solar heliostat fields can simultaneously achieve both high power and high temperature. High temperature is achieved by a high solar concentration ratio, and high power is achieved by a very large total mirror aperture. To accomplish this, heliostat mirrors must be precisely shaped, and precisely pointed. These factors combine to create an ensemble of challenging metrology problems, which span the entire heliostat field development cycle.

The DOE-funded Heliostat Consortium seeks to support the advancement of heliostat technology worldwide. In its first year, the consortium undertook a comprehensive study of heliostat technology, with the goal of identifying important current needs which would merit research and development investment [1]. This paper is a supplement to [1], and describes one aspect of that investigation, focused on optical metrology for heliostats.

We begin by describing primary phases of the heliostat development cycle, and then we identify metrology questions pertinent to each phase. In addition, we observe that context also varies across development phase, implying different operating constraints that must be satisfied. Reviewing the resulting ensemble of questions and constraints reveals a set of needed core metrology capabilities, which would cover most of the expected metrology problems. We express these as a set of key heliostat optical metrology problem statements, and comment on their solution status in the current state of the art.

## 2. Key Questions

Metrology systems perform measurements, and the purpose of these measurements is to answer questions of interest. Therefore to understand whether there are gaps in the current state of heliostat optical metrology, we should examine the related questions, and assess whether they are adequately addressed by currently available solutions.

Here is a list of example questions, grouped by phases of the heliostat development cycle:

Design
1. Given a prototype, what is its optical shape?
2. How accurately can a prototype reflect sunlight to a target point?
3. How do optical shape and pointing vary over heliostat position, temperature, and wind?

Manufacturing
4. Does this instance of the product meet optical shape tolerances?
5. What process parameters influence quality?

Field Installation
6. Did the heliostat change optical shape between manufacture and installation?
7. What corrections are required to enable accurate pointing?

Operation
8. What is the current mirror soiling level? Does it vary across the plant?
9. Do any heliostat tracking corrections need to be updated?
10. For closed-loop systems, what is each heliostat's real-time pointing angle?
11. Have any heliostat optical shapes changed?
12. Are any heliostats damaged or degraded?
13. Have any heliostats loosened up, causing increased flutter?
14. For heliostat needing repair, what adjustments are required?

All
15. Can we trust each measurement? How do we know they are accurate?

Note that the questions vary with heliostat development phase; later we will explain how the operating context constraints also vary with heliostat development phase. We do not assert that these are *all* the questions that arise, but it is clear that each of the above questions is important to answer.

## 3. Metrology Information Types

Reviewing the above questions, we see some common information requirements. For example, several questions concern optical shape, while several other questions concern pointing accuracy. After more careful study, we identified the following basic metrology information types required to address the above questions:

| | |
|---|---|
| Map | Map of surface normal directions across mirror surface (1,3,4,5,6,11,14). |
| Pointing | Direction of the reflected beam (2,3,9,10,14). |
| Calibration | Set of pointing corrections required for full-year accurate pointing (7). |
| Dynamics | Time-variation in optical shape or pointing (3,13). |
| Soiling | Reduction in reflectance due to soil on the mirror (8). |
| Inspection | Identification of defects and degradation (12). |
| Ground truth | Verification of measurement accuracy (15). |

The numbers in parentheses indicate which of the above questions are addressed by each information type. Figure 1 shows examples of four of the information types.

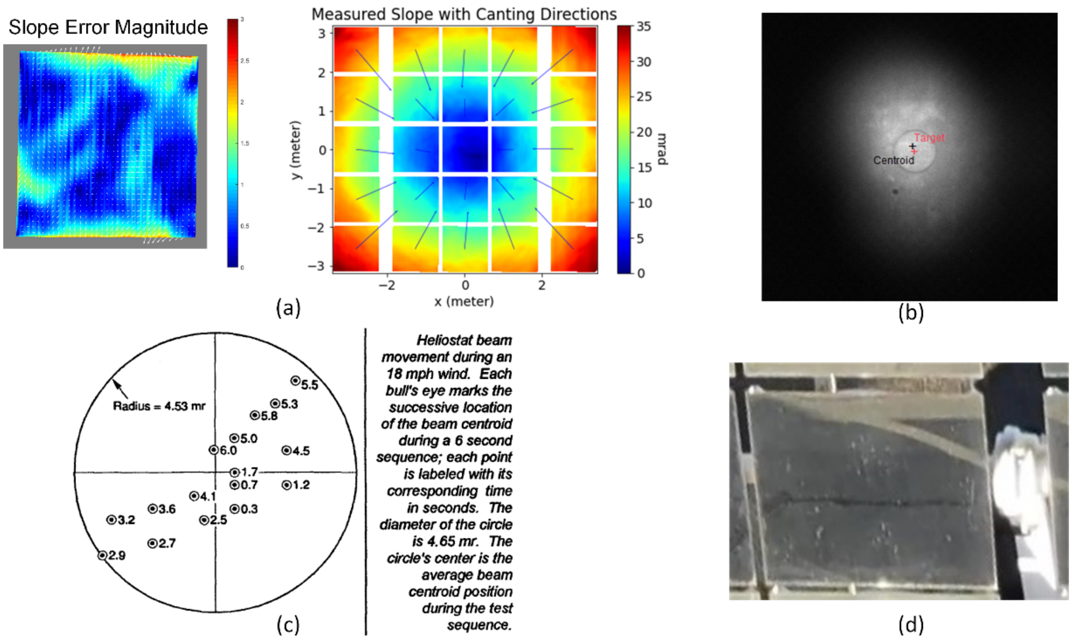

**Figure 1.** Information type examples. (a) Surface normal map results for a facet and full heliostat. (b) BCS measurement of pointing direction. (c) Beam pointing variation in wind, from [2]. (d) A soiled heliostat facet.

## 4. Requirements for Each Development Phase

Below we will express these information classes as outputs for metrology problem specifications. But first, we will review the context requirements of each heliostat development phase, because these determine the operating requirements for metrology systems intended to answer the above questions.

- Design. The goal is the best possible design for both the heliostat and its manufacturing process. Designs are refined in an iterative process, seeking the heliostat and process design which yields the best performance, both technically and economically. Each design learning cycle often involves hypothesizing an idea, analyzing its potential, and then fabricating and testing a prototype. Prototype testing is crucial, because experiments provide concrete evidence of design performance, and also can reveal “unknown unknowns” resulting from effects not considered in the analysis. Metrology is key to these tests. To maximize design quality, metrology should provide rich detailed measures such as high-resolution optical shape maps. To ensure the discovery of “unknown unknowns,” metrology for the prototyping phase must support testing under all conditions expected for the final heliostat; this includes the full range of positions, temperatures, and wind conditions. To maximize design quality, metrology should be available without delay, to minimize (prototype → test → data) time and thus maximize the number of cycles of learning possible within the limited design time. Thus on-site, on-demand metrology capability is desired for design support. Further, since capital is often limited during the design phase, low cost is desired, in addition to ease of use.
- Manufacturing. Many copies of the heliostat design are produced using the designed fabrication process. Primary goals are to maximize productivity while minimizing cost and maintaining high quality. For the best possible quality control, 100% inspection is preferred. To meet this requirement, metrology systems must be fast enough to measure within the production line cycle time, which can be on the order of seconds. (For example, the Crescent Dunes plant has roughly 10,350 heliostats with 35 facets each, or 362,250 facets total. To produce this many facets in six months using three shifts would require a takt time of 30 seconds per facet.) In addition to speed, metrology systems operating in factory environments must have very high reliability, since down time due to equipment failure can have huge economic consequences.

- Field Installation. Once installed, heliostats in the field are subject to harsh environments, and metrology systems used for measurement after installation must be able to cope with these environmental conditions. In addition, metrology systems must be able to successfully measure heliostats in widely varying geometric contexts, such as tightly packed heliostats near the tower, and sparsely packed heliostats a very long distance from the tower (e.g., 1.6 km). A key problem is heliostat calibration, which is the task of determining the configuration corrections required to achieve accurate pointing of the reflected beam to target points on the tower, for all sun positions through the year. If the field uses an open-loop control system, then these correction terms are needed before the solar field can operate at its maximum performance, which is a strong case for executing heliostat calibration as early as possible. However, calibration techniques that use the tower (for example, beam characterization system, or BCS, calibration techniques) may not proceed until the tower is constructed and construction workers have cleared the area. Thus metrology systems that can identify calibration parameters without using the tower are desired. Also affecting lead time, calibration techniques which require sampling over a full solar cycle (solstice → equinox → solstice) require a minimum of six months data collection before yielding calibration values; BCS-based estimation of as-built heliostat kinematic parameters is again an example. Metrology systems that can accelerate heliostat calibration without waiting for a full solar cycle would deliver an economic advantage to heliostat fields with open-loop control. Since many measurements are required for each heliostat to identify the aiming corrections for a full year, and because there are a large number of heliostats, metrology systems for accelerating heliostat calibration must operate at high speed.
- Operation. Heliostats are designed to be used for decades, and periodic assessment is required to identify heliostats requiring maintenance for optical performance. Metrology systems employed during operation must cope with harsh environmental conditions, and also the varying field packing context described above. The tower will exist, and during daylight hours will generally be brightly lit by concentrated solar flux. Metrology systems employed during operation must be able to take measurements without disrupting field operations, and if flying drones are utilized, they must avoid the hazardous regions of concentrated solar flux above the active heliostat field. Because of the large number of heliostats, such systems must also operate at high speed, although potentially not as high as the speed required for accelerated field calibration.
- Ground truth. At all development phases, metrology accuracy is essential. Errors in metrology could lead to high-consequence decisions made with incorrect information. The consumers of metrology data making high-consequence decisions must have confidence in the accuracy of the measurements. For this reason, heliostat metrology systems for commercial use must include some sort of verification method to confirm correct measurement performance, not only when the metrology system is first fielded, but also again at times when checking metrology accuracy is needed to support high-consequence decisions. Since heliostat metrology systems operate both indoors and outdoors, these ground truth verification systems must also work in both environments.

We can see that the requirements a metrology system must satisfy vary dramatically across development phases. For example, maps of optical surface normals are needed for questions in all phases. In the design phase, these must be captured on-demand by a low-cost system, capable of measuring across the full range of positions, temperatures, and operating wind conditions that the final heliostat will operate under. Meanwhile, in the manufacturing phase, one configuration under indoor factory conditions will likely suffice, but measurements must be made with high speed and very high reliability. In the field installation phase, measurements must be made outdoors in situ, preferably while the solar field is under construction and the tower not available, but moving heliostats desired test positions is allowed. During the operation phase, daytime measurements must be taken without disrupting field operations by modifying heliostat configurations, but the tower is available and brightly lit, with solar flux over the solar field that is hazardous in some locations.

## 5. Core Problem Statements

We can combine the information types with development phase requirements to formulate core problem statements that address the key questions listed above. Where appropriate we list the union of requirements across development phases; for example, if a system can measure surface normal maps indoors at low cost and high speed, then it could satisfy needs for both the design and manufacturing phases. We avoid specific numerical requirements, because these vary with context. All problem statements implicitly include requirements for safety, accuracy, ease of use, documentation, and other hallmarks of a quality metrology system.

### Map of Surface Normals – Indoor

Output: A high-resolution map of normal vectors across the mirror surface, captured indoors.

Questions addressed: 1, 4, 5

Phases addressed: Design, Manufacturing

Requirements: High-resolution slope map of both facets and full heliostats, allowing multiple prescriptions. For manufacturing, high speed, very high reliability, and support for statistical process control required. For design, on-demand, on-site access and low cost desired.

### Map of Surface Normals – Outdoor

Output: A high-resolution map of normal vectors across the mirror surface, captured in situ.

Questions addressed: 3, 6, 14

Phases addressed: Design, Field Installation, Operation

Requirements: High-resolution slope map of both facets and full heliostats. For design, ability to measure across the range of heliostat tracking configurations and expected operating temperatures required; on-demand availability at the development site and low cost desired. For field installation and operation, ability to operate in situ for heliostats both near and far from the tower required. For field installation, ability to operate without the tower available desired.

### Pointing Direction

Output: Reflected beam direction for a given sun position and heliostat configuration.

Questions addressed: 2, 14, can support 7

Phases addressed: Design, Field Installation, Operation

Requirements: High-accuracy measurement of full heliostat reflected beam pointing direction. Ability to measure across each heliostat's range of tracking configurations required. For field installation and operation, ability to measure heliostats both near and far from the tower required. For field installation, ability to operate without the tower available desired.

### Calibration

Output: Pointing corrections required for full-year accurate pointing, for all heliostats.

Questions addressed: 7

Phases addressed: Field Installation, Operation

Requirements: Data measured supporting calculation of aim point correction parameters for each individual as-built heliostat in situ, for all configurations it visits during full-year tracking. For field installation, ability to measure before the tower is available and ability to deliver correction parameters for the full solar field faster than a full solar cycle are required to shorten solar field lead time.

### Pointing Direction – Real Time

Output: Reflected beam direction for the current sun position and heliostat configuration, for all heliostats in the solar field.

Questions addressed: 10

Phases addressed: Design, Operation

Requirements: Measurement of data supporting calculation of closed-loop aim point correction parameters for individual as-built heliostats in situ, for the current sun position and heliostat configuration of each heliostat, both near and far from the tower. Ability to measure during on-sun operation required. To support closed-loop control, results must be calculated quickly enough to enable real-time correction. While primarily needed for operation, must be measurable during design to enable testing.

### Map of Surface Normals and Pointing Direction – Change Detection

Output: Whether each heliostat has changed either its optical shape or pointing direction compared to previous observations, for all heliostats in the solar field.

Questions addressed: 9, 11, 14

Phases addressed: Operation

Requirements: For a heliostat field that is already well-calibrated and the optical performance of each heliostat has been measured and recorded, periodically check each heliostat to detect whether its reflected beam departs from its expected shape or aim point, indicating that further diagnostic assessment is required. Ability to measure heliostats both near and far from the tower in situ, on-sun, with minimal operation disruption required. Note that this problem is easier than the following problem, because changes may be detected without constructing a full high-resolution surface map.

### Map of Surface Normals and Pointing Direction – Outdoor, High Speed

Output: High-resolution map of normal vectors across each heliostat, with associated two-degree-of-freedom pointing correction for one heliostat configuration, for all heliostats.

Questions addressed: 6, 9, 11, 14, can support 7

Phases addressed: Field Installation, Operation

Requirements: Ability to measure heliostats both near and far from the tower, in situ and at high speed required. For operation, ability to measure on-sun without disrupting energy production required. For field installation, ability to operate without the tower available and at very high speed to accelerate calibration desired.

### Dynamic Effects – Tracking

Output: Description of time performance of the heliostat tracking control system.

Questions addressed: 2, 7, 9

Phases addressed: Design, Field Installation, Operation

Requirements: Measurement of tracking time parameters, including motion period and its variation, motion duty cycle, ringing, and accuracy of synchronization with heliostat logs.

### Dynamic Effects – Wind

Output: Deviation of reflected beam pointing and optical shape in response to wind.

Questions addressed: 3, 13

Phases addressed: Design, Operation

Requirements: Measurement of beam variation on target required. For design, measurement of optical surface shape variation required.

**Soiling**

Output: Level of mirror soiling and its variation across the field.

Questions addressed: 8

Phases addressed: Operation

Requirements: Specular reflectance measured with an acceptance angle similar to receiver acceptance angle at multiple points across a mirror. Measurement at multiple locations across the solar field with a statistically significant sample size at each location required.

**Inspection**

Output: Whether a heliostat exhibits wear degradation, breakage, or mechanical problems.

Questions addressed: 12

Phases addressed: Operation

Requirements: Assess heliostat state-of-health; details are beyond the scope of this paper.

**Ground Truth – Surface Normal Map**

Output: Trusted reference for verifying accuracy of a surface normal map metrology system.

Questions addressed: 15, verifying 1, 3, 4, 5, 6, 11

Phases addressed: Design, Manufacturing, Field Installation, Operation

Requirements: A clearly correct measurement reference capable of verifying optical shape parameters of interest, for both facets and full heliostats, both indoors and in situ, with accuracy tighter than the target accuracy of the metrology system to verify is required.

**Ground Truth – Pointing Direction**

Output: Trusted reference for verifying accuracy of a pointing direction metrology system.

Questions addressed: 15, verifying 2, 3, 7, 9, 14

Phases addressed: Design, Manufacturing, Field Installation, Operation

Requirements: A clearly correct measurement reference capable of verifying beam pointing parameters of interest, for both facets and full heliostats, both indoors and in situ, with accuracy tighter than target accuracy of the metrology system to verify is required.

## 6. Remarks on the State of the Art

It is evident from the “questions addressed” and “phases addressed” entries that the above problem statements address the questions and development phases presented earlier. Next we consider the state of the art and ask: Does each problem have an available solution? We do not attempt a comprehensive review of heliostat metrology research; for that, see [3],[4]. Instead, we focus on commercial products and mature research results as candidate solutions.

Maps of mirror surface normals may be measured using CSP Services’ commercially available QDec-M system [5], or Sandia’s research SOFAST system [6]. These address the “Map of Surface Normals – Indoor” problem. For the “Map of Surface Normals – Outdoor” problem, CSP Services markets an outdoor QDec-H [7], which measures full heliostats in situ, for only one tilt angle. In addition, [8] reports an outdoor system which measures full heliostat surface normal maps in situ across a broader range of configurations. For heliostats far from the tower (e.g., 1.6 km), both methods may be vulnerable to errors due to atmospheric effects.

The basic “Pointing Direction” problem is solved by the Beam Characterization System (BCS) [2] in many situations. However, BCS signal strength decays with distance due to sun shape, so it can be difficult to measure heliostats far from the tower. BCS has been used to calibrate a commercial field [9], but this requires the tower and is time-consuming, so BCS calibration methods fall short of meeting the requirements of the “Calibration” problem.

Real-time measurement of heliostat pointing has been successfully performed by Heliogen's SOHOT system [10]; other approaches are reviewed in [4]. These provide exemplary solutions to the "Pointing Direction – Real Time" problem, although we have not ascertained their scope or whether they are readily available to industry.

The "Map of Surface Normals and Pointing Direction – Change Detection" problem pertains to solar fields where the operator desires to identify heliostats that have degraded performance requiring maintenance, compared to a database of recorded heliostat characteristics. Detecting change in optical shape or pointing accuracy is easier than ab initio analysis, because less information is required. For example, many measurements are required to construct a heliostat tracking correction model, but a single measurement may be sufficient to determine that heliostat tracking accuracy has degraded. BCS could be used for this, although additional software may be required to manage regular testing, result storage, and comparison of BCS images captured from the same heliostat at different times.

The "Map of Surface Normals and Pointing Direction – Outdoor, High Speed" problem is much more difficult. If the goal is to accelerate calibration during field installation, then a very large number of measurements must be taken, spanning many heliostats over multiple configurations. These measurements appear to require capturing detailed maps of surface normals, to correctly estimate the effective overall heliostat beam reflection. If the goal is to obtain a detailed measure of optical parameters during operation, then the total number of measurements may be smaller, but the task is complicated by the need to measure non-intrusively during solar field operation. This problem is an active area of research, with at least three groups pursuing a solution using unmanned aircraft systems (UAS) [11], [12], [13].

The "Dynamic Effects – Tracking" problem appears solvable using straightforward timing analysis. In contrast, measurement of dynamic deformations is required for the "Dynamic Effects – Wind" problem. BCS measurements of wind-induced beam deflections were reported as early as [2], but these data were not captured with a fine enough time resolution to support modal analysis. A recent detailed analysis was reported in [14], using backside dynamic photogrammetry methods to infer front-side optical slope deviations.

The "Soiling" problem has received significant attention. The CSP Services TraCS system is a commercial product that measures soiling automatically in a fixed location [15], and Bern, et al. reported a similar standalone instrument [16]. Both devices may be placed at multiple locations, reporting soiling data across the solar field. A UAS-based method for scanning soiling status over a wide area is reported in [17].

We are not aware of solutions to the "Ground Truth – Surface Normal Map" problem, other than use of a pool of water as a calibration standard, which does not have curvature and may only be used for systems that measure mirrors in a face up configuration. In contrast, BCS may be viewed as a solution to the "Ground Truth – Pointing Direction" problem, since it directly measures the phenomenon of interest – solar reflection onto a target [2].

## 7. Conclusion

We considered optical metrology questions of interest across the heliostat development cycle, and identified common information types and context requirements implied by development cycle phases. We combined these to yield 13 core problem statements, intended to address the questions of interest while meeting context requirements. We then considered the state of the art, to seek problems lacking a current solution. Noteworthy examples include (a) capturing high-resolution surface normal maps, for arbitrary tilt angles and heliostats far from the tower; (b) accelerated heliostat calibration; (c) high-speed in-situ measurement of heliostat surface normal maps and pointing directions; and (d) ground truth methods for verifying the accuracy of surface normal map measurements.

The surveys [3],[4] are comprehensive and rigorous. This paper attempts neither, but instead reports one author‘s analysis of the heliostat optical metrology problem space seeking topics in need of attention, along with solution characteristics that increase utility. We hope that sharing these observations may help other researchers as they select their goals.

## Data availability statement

There are no releasable data associated with this paper.

## Author contributions

Randy Brost contributed conceptualization, investigation, formal analysis, and writing.

## Competing interests

The authors declare no competing interests.

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