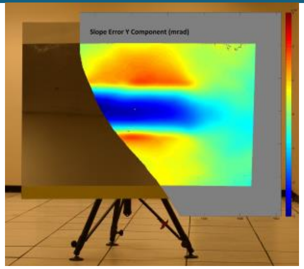
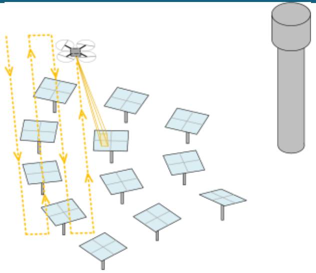
# Question-Based Gap Analysis of Heliostat Optical Metrology Methods


Randy C. Brost

September 30, 2022

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# Goal

In this presentation, we ask:

**What are the important optical metrology problems that heliostat developers face, with no readily available solution?**

By "solution," we mean something that is commercially available and supported, or nearly so.

Understanding this will help guide research directions.

Note that we are <u>not</u> trying to produce a comprehensive survey* of metrology research, or even all commercial solutions.

Instead, we are looking for key questions that are not covered by some existing system.

**<u>Note:</u>** This is a subjective study. It is imperfect. However, we hope it sparks productive discussion and thinking about research directions.

* Some excellent surveys already exist:

- J. C. Sattler *et al.*, Review of heliostat calibration and tracking control methods. *Solar Energy* **207**, pp. 110–132, 2020.
- A. Pfahl *et al.*, Progress in heliostat development. *Solar Energy* **152**, pp. 3–37, 2017.
- J. Coventry *et al.*, Heliostat Cost Down Scoping Study - Final Report. Australian National University Report STG-3261 Rev 01, December 2016.

# Back to the Basics

**Why do we do metrology?**

**…to help people answer important questions.**

**Who are we trying to help?**

**…people who design, manufacture, install, and operate heliostats.**

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**Why do we do metrology?**

**…to help people answer important *questions*.**

**Who are we trying to help?**

**…people who *design, manufacture, install, and operate* heliostats.**

# Brief Summary

Approach to gap analysis (highly abbreviated):

**Development Phases** →

1. Product Design
2. Process Design
3. Manufacturing
4. Field Installation
5. Operation

**Metrology Questions** →

Product Design
- Prototype optical shape?
- Prototype pointing accuracy?
- *more…*

Process Design
- Product meets tolerances?
- Tooling meets tolerances?
- *more…*

Manufacturing
- Instance meets tolerances?
- Statistical process control
- *more…*

Field Installation
- Facet canting, etc valid?
- Heliostat calibration?
- *more…*

Operation
- Which heliostats changed?
- Which need recalibration?
- Is this repair correct?
- Soiling?  Across field?
- *more…*

**Context Requirements** →

Product Design
- High-resolution map
- Available on demand
- All expected conditions
- *more…*

Process Design
- High-resolution mirror map
- High-resolution tooling map
- *more…*

Manufacturing
- High speed
- Very high reliability
- Statistical process control
- *more…*

Field Installation
- Outdoors
- High-volume
- During construction
- *more…*

Operation
- Outdoors
- High-volume
- Don't interrupt operation
- Support repairs
- *more…*

**Required Capabilities** →

Optical surface map, fast indoor

Optical surface map, flexible outdoor

Reflected beam direction and size

Surface map and pointing, fast in situ

Dynamic wind map and pointing

Soil assessment across field

Tool shape, surface map

Damage, degradation inspection

*(Associated requirements and constraints not listed)*

**Compare with State of Art**

A. Commercial products

B. Mature research results

C. Emerging research

If not adequately covered:

→ ***Gaps***

# Problems and Requirements

# Key Questions

Product Design

- (M) Given a prototype, what is its optical shape?
- (M) Where are errors?
- (M) Implications for reflected beam shape?
- (P) How accurately can we control pointing configuration?
- (M) How do above vary with expected conditions (range of motion, temperature,…)?
- (D) How do optical shape and pointing vary dynamically with wind?

Process Design

- (M) Does product meet specified tolerances? Over prescription changes?
- (T) Does tooling meet specified tolerances? Over prescription changes?
- (M) What process parameters are important to control? (feed quality, temperature, pressure, time,…)
- (M) How fast can we run the process?

Manufacturing

- (M) Does product meet optical tolerances? Over time? Across prescriptions? Across mass variation?
- (M) Continuous improvement: How can we improve product quality?
- (M) Continuous improvement: How can we improve production speed?

Field Installation and Commissioning

- (M) Did the heliostat change optical shape between manufacture and installation?
- (M) What canting adjustment is required?
- (P) What are corrections enabling accurate pointing, despite varying as-built parameters?
- (P) Do heliostats function properly temporally (i.e., executes tracking motion on time)?

Operation

- (S) What is soil level? Does it vary across the plant?
- (P) Are any heliostat tracking corrections out of date?
- (M) Have any heliostats changed their optical shape?
- (I) Are any heliostats damaged or degraded?
- (D) Have any heliostats loosened up, causing increased flutter? What is loose?
- (M) For a repaired heliostat, what canting adjustments are required?
- (P) For an out-of-date heliostat, what tracking corrections are required?
- (M) For heliostat with changed shape, what corrections are required?

All

- (G) Can we trust each measurement? How do we know they are accurate?

Related indirect questions:

What do measurement results imply:

- Interpretation?
- Significance?
- Impact on economic performance?

…Out of scope for this analysis. Our focus is first on whether it is possible to get the data in the first place.

# Optical Metrology Data Types

(M) Map of optical surface normals

(P) Pointing direction of reflected beam

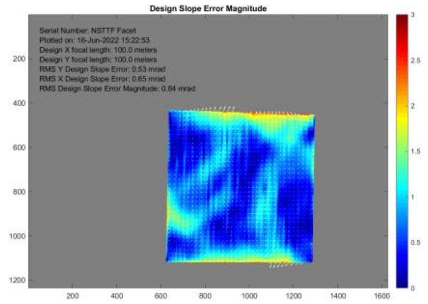
(D) Dynamic optical motion analysis

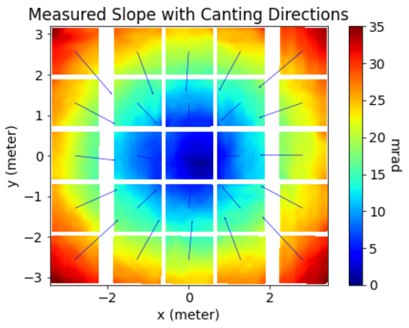
(T) Tool shape, surface normal

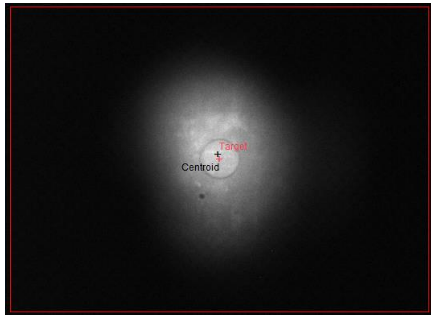
(S) Soiling

(I) Inspection

(G) Ground truth check




# Requirements Vary with Development Phase

Example: Optical Surface Map

- **Product design:** High resolution, high availability, evaluate all conditions (configuration, wind, temperature), low cost.
- **Process design:** High resolution (optic, tool), support process optimization, high availability, compatible with environment.
- **Manufacturing:** All specifications, high speed, high reliability, compatibility with factory, statistical process control, calibration check.
- **Installation:** Both shape and pointing, (accelerate calibration: span ($\theta_1$,$\theta_2$), without tower), sufficient up time.
- **Operation:** Outdoors, detect changes, fast enough, don't interrupt plant operation, low operating cost.

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Manufacturing
- Instance meets tolerances?
- Statistical process control
- *more…*

Field Installation
- Facet canting, etc valid?
- Heliostat calibration?
- *more…*

Operation
- Which heliostats changed?
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- Soiling? Across field?
- *more…*

**Context Requirements** →

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Process Design
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- High-resolution tooling map
- *more…*

Manufacturing
- High speed
- Very high reliability
- Statistical process control
- *more…*

Field Installation
- Outdoors
- High-volume
- During construction
- *more…*

Operation
- Outdoors
- High-volume
- Don't interrupt operation
- Support repairs
- *more…*

**Required Capabilities** →

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Soil assessment across field

Tool shape, surface map

Damage, degradation inspection

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**Compare with State of Art**

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If not adequately covered:

→ ***Gaps***

# Desired Characteristics

| # | Code | Question | Optical Surface Map | Pointing Accuracy | Surface Change Detection | Pointing Change Detection | Dynamic Motion Analysis | Tooling Geometry | Degradation and Damage | Soiling | Multi-Prescription | Multi-Mass | Multi-Elevation | Multi-Azimuth | Multi-Temperature | Single Facet | Full Heliostat | Full Heliostat Field | Distant Heliostats | Tower Not Required | Non-Intrusive | Full Working Envelope | High Speed | Very High Reliability | Limit Calibration Time | Statistical Process Control |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Product Design** | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1 | (M) | Given a prototype, what is its optical shape? | ✓ | | | | | | | | | | | | | ✓ | ✓ | | | | | | | | | |
| 2 | (M) | Where are errors? | ✓ | | | | | | | | | | | | | ✓ | ✓ | | | | | | | | | |
| 3 | (M) | Implications for reflected beam shape? | ✓ | | | | | | | | | | | | | ✓ | ✓ | | | | | | | | | |
| 4 | (P) | How accurate is pointing? | | ✓ | | | | | | | | | | | | | ✓ | | | | | | | | | |
| 5 | (M) | How do above vary with expected conditions? | ✓ | ✓ | | | | | | | | ✓ | ✓ | opt | ✓ | ✓ | ✓ | | | | | | | | | |
| 6 | (D) | How do shape and pointing vary with wind? | | | | | ✓ | | | | | ✓ | ✓ | ✓ | | | ✓ | | | | | | | | | |
| **Process Design** | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 7 | (M) | Does product meet specified tolerances? | ✓ | | | | | | | | ✓ | | | | | ✓ | ✓ | | | | | | | | | |
| 8 | (T) | Does tooling meet specified tolerances? | | | | | | ✓ | | | ✓ | | | | | ✓ | ✓ | | | | | | | | | |
| 9 | (M) | What process parameters are important? | ✓ | | | | | | | | | | | | | ✓ | ✓ | | | | | | | | | |
| 10 | (M) | How fast can we run the process? | ✓ | | | | | | | | | | | | | ✓ | ✓ | | | | | | | | | |
| **Manufacturing** | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 11 | (M) | Does output meet optical tolerances? | ✓ | | | | | | | | ✓ | ✓ | | | | ✓ | ✓ | | | | | | ✓ | ✓ | ✓ | ✓ |
| 12 | (M) | How can we improve product quality? | ✓ | | | | | | | | ✓ | ✓ | | | | ✓ | ✓ | | | | | | ✓ | ✓ | ✓ | ✓ |
| 13 | (M) | How can we improve production speed? | ✓ | | | | | | | | ✓ | ✓ | | | | ✓ | ✓ | | | | | | ✓ | ✓ | ✓ | ✓ |
| **Field Installation and Commissioning** | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 14 | (M) | Did the heliostat change optical shape? | ✓ | | | | | | | | | | | | | ✓ | ✓ | | ✓ | ✓ | | | | | | |
| 15 | (M) | What canting adjustment is required? | ✓ | | | | | | | | | | | | | ✓ | ✓ | | ✓ | ✓ | | | | | | |
| 16 | (P) | What are pointing corrections? | | ✓ | | | | | | | | | | | | | ✓ | ✓ | ✓ | ✓ | | ✓ | ✓ | | | |
| 17 | (P) | Do heliostats function temporally? | | ✓ | | | | | | | | | | | | | ✓ | ✓ | ✓ | ✓ | | ✓ | | | | |
| **Operation** | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 18 | (S) | What is soil level? Across solar field? | | | | | | | | ✓ | | | | | | ✓ | ✓ | ✓ | ✓ | | ✓ | | | | | |
| 19 | (P) | Heliostat tracking corrections out of date? | | | | ✓ | | | | | | | | | | | ✓ | ✓ | ✓ | | ✓ | | | | | |
| 20 | (M) | Heliostats optical shape changed? | | | ✓ | | | | | | | | | | | ✓ | ✓ | ✓ | ✓ | | ✓ | | | | | |
| 21 | (I) | Heliostats damaged or degraded? | | | | | | | ✓ | | | | | | | ✓ | ✓ | ✓ | ✓ | | ✓ | | | | | |
| 22 | (D) | Heliostats with increased flutter? | | | | | ✓ | | | | | | | | | | ✓ | ✓ | ✓ | | ✓ | | | | | |
| 23 | (M) | Repaired heliostat canting adjustments? | ✓ | | | | | | | | | | | | | | ✓ | | ✓ | | | | | | | |
| 24 | (P) | Required tracking corrections? | | ✓ | | | | | | | | | | | | | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | | | |
| 25 | (M) | Required shape corrections? | ✓ | | | | | | | | | | | | | ✓ | ✓ | ✓ | ✓ | | ✓ | | ✓ | | | |
| **All** | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 26 | (G) | Can I trust these measurements? | ✓ | ✓ | | | ✓ | | | | | | | | | ✓ | ✓ | | | ✓ | | | | ✓ | | |

Other perspectives:
Tolerances, and how they might be degraded by conditions.

# Core Capabilities

| | | Optical Surface Map | Pointing Accuracy | Surface Change Detection | Pointing Change Detection | Dynamic Motion Analysis | Tooling Geometry | Degradation and Damage | Soiling | Multi-Prescription | Multi-Mass | Multi-Elevation | Multi-Azimuth | Multi-Temperature | Single Facet | Full Heliostat | Full Heliostat Field | Distant Heliostats | Tower Not Required | Non-Intrusive | Full Working Envelope | High Speed | Very High Reliability | Limit Calibration Time | Statistical Process Control |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (M) | Optical surface map, fast indoor | ✓ | | | | | | | | ✓ | ✓ | | | | ✓ | ✓ | | | | | | ✓ | ✓ | ✓ | ✓ |
| (M) | Optical surface map, flexible outdoor | ✓ | | ✓ | | | | | | ✓ | ✓ | ✓ | opt | ✓ | ✓ | ✓ | | ✓ | ✓ | | | | | | |
| (B) | Reflected beam direction and size, slow | | | ✓ | ✓ | | | | | ✓ | ✓ | | | | | ✓ | | | | | | | | | |
| (M+P) | Surface map + pointing, fast | ✓ | ✓ | | | | | | | | | | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | | |
| (D) | Dynamic wind surface map and pointing | | | | | ✓ | | | | | ✓ | ✓ | ✓ | | | ✓ | | ✓ | | ✓ | | | | | |
| (T) | Tool shape, surface normal | | | | | | ✓ | | | ✓ | | | | | ✓ | ✓ | | | | | | | | | |
| (S) | Soil assessment across field | | | | | | | | ✓ | | | | | | ✓ | ✓ | ✓ | ✓ | | ✓ | | | | | |
| (I) | Damage/degradation inspection | | | | | | | ✓ | | | | | | | ✓ | ✓ | ✓ | ✓ | | ✓ | | | | | |
| (G) | Ground truth | ✓ | ✓ | | | ✓ | | | | | | | | | ✓ | ✓ | | | ✓ | | | | ✓ | | |

# Special Case:
# Single Facet, Closed-Loop Control

# The Effect of Single-Facet, Closed-Loop Control

No longer relevant:

Product Design
- (M) Given a prototype, what is its optical shape?
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All
- (G) Can we trust each measurement? How do we know they are accurate?

# The Effect of Single-Facet, Closed-Loop Control

## Core capabilities no longer relevant:

| | | Optical Surface Map | Pointing Accuracy | Surface Change Detection | Pointing Change Detection | Dynamic Motion Analysis | Tooling Geometry | Degradation and Damage | Soiling | Multi-Prescription | Multi-Mass | Multi-Elevation | Multi-Azimuth | Multi-Temperature | Single Facet | Full Heliostat | Full Heliostat Field | Distant Heliostats | Tower Not Required | Non-Intrusive | Full Working Envelope | High Speed | Very High Reliability | Limit Calibration Time | Statistical Process Control |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (M) | Optical surface map, fast indoor | ✓ | | | | | | | | ✓ | ✓ | | | | ✓ | ✓ | | | | | | ✓ | ✓ | ✓ | ✓ |
| (M) | Optical surface map, flexible outdoor | ✓ | | ✓ | | | | | | ✓ | ✓ | ✓ | opt | ✓ | ✓ | ✓ | | ✓ | ✓ | | | | | | |
| (B) | Reflected beam direction and size, slow | | | ✓ | ✓ | | | | | ✓ | ✓ | | | | ✓ | ✓ | | | | | | | | | |
| (M+P) | Surface map + pointing, fast | ✓ | ✓ | | | | | | | | | | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | | |
| (D) | Dynamic wind surface map and pointing | | | | | ✓ | | | | | ✓ | ✓ | ✓ | | ✓ | ✓ | | ✓ | | ✓ | | | | | |
| (T) | Tool shape, surface normal | | | | | | ✓ | | | ✓ | | | | | ✓ | ✓ | | | | | | | | | |
| (S) | Soil assessment across field | | | | | | | | ✓ | | | | | | ✓ | ✓ | ✓ | ✓ | | ✓ | | | | | |
| (I) | Damage/degradation inspection | | | | | | | ✓ | | | | | | | ✓ | ✓ | ✓ | ✓ | | ✓ | | | | | |
| (G) | Ground truth | ✓ | ✓ | | | ✓ | | | | | | | | | ✓ | ✓ | | | ✓ | | | | ✓ | | |

# Current State of the Art

# Current State of the Art Considered

Commercial:

- CSP Services/DLR:
  - Qfoto – Heliostat structure and mirror photogrammetry.[1]
  - QDec-M – High-resolution mirror deflectometry.[2]
  - QDec-H – High-resolution deflectometry of full heliostats in situ.[3]
  - Dynamic photogrammetry – Dynamic 3D measurements of heliostats in wind.[4]
  - HelioPoint II – Airborne calibration of tracking accuracy of heliostat field (in development).[5]
  - TRaCS – In-field automated soiling measurement.[6]

Mature Research:

- BCS – Beam Characterization System, analyzes sun beam reflected on tower (Many locations).[7]
- SOFAST – High-resolution mirror and heliostat deflectometry (Sandia).[8]
- [Goldberg and Zisken 2015] – Image of sun reflection while scanning (BrightSource).[9]

Emerging Research:

- Aerial soiling survey (Australian National University).[10]
- UFACET-NIO – High-speed airborne measurement of heliostat optical parameters (NREL, Sandia).[11,12,13]

Note: Recall that our goal is not to produce a comprehensive survey, but rather to identify which capabilities are not currently covered by commercial or near-commercial solutions.

Many thanks to international colleagues for their consultation and input.

Other perspectives:
Industry interest drives whether a metrology product is brought to market.
But data may be required to demonstrate need.

# Citations for the Previous Slide


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# Gaps

# Gaps

| | Technology | Development Stage | Optical Surface Map | Pointing Accuracy | Surface Change Detection | Pointing Change Detection | Dynamic Motion Analysis | Soiling | Multi-Prescription | Multi-Mass | Multi-Elevation | Multi-Azimuth | Multi-Temperature | Single Facet | Full Heliostat | Full Heliostat Field | Distant Heliostats | Tower Not Required | Non-Intrusive | Full Working Envelope | High Speed | Very High Reliability | Limit Calibration Time | Statistical Process Control | Notes |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Optical surface map, fast indoor** | CSPS QDec-M | C | ✓ | | | | | | ✓ | ✓ | ✓ | | | ✓ | ✓ | | | | | | ✓ | ✓ | ✓ | ✓ | All requirements demonstrated. Multi-camera enables screen size similar to mirror. |
| | Sandia SOFAST | M | ✓ | | | | | | ✓ | ✓ | ✖ | | | ✓ | ¾ | | | | | | ✓ | ✓ | ✓ | ¾ | Multi-facet measurement implemented. Outdoor full heliostat implementation in progress. Multi-elevation not demonstrated. |
| **Optical surface map, flexible outdoor** | Gap | | ✓ | ✓ | ✓ | | | | ✓ | ✓ | ✓ | opt | ✓ | ✓ | ✓ | | ✓ | ✓ | | ✓ | | | | | Not all requirements met. |
| | CSPS QDec-H | C | ✓ | | ✓ | | | | ✓ | ✓ | ✖ | ✖ | ✓ | ✓ | ✓ | ✓ | ✖ | ✖ | | ✖ | | | | | Limited elevation angles. Requires screen on tower. Difficult in large fields. |
| | BrightSource Tower Images | M | ✓ | ✓ | | | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | ? | ✖ | | ✓ | | | | | Does this degrades over long range? |
| **Reflected beam direction and size, slow** | BCS | M | | | | ✓ | | | ✓ | ✓ | | | | | ✓ | | | | | ✓ | | | | | Widely used. Is standard software available? |
| **Surface map + pointing, fast** | Gap | | ✓ | ✓ | | | | | | | | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | | | Systems not proven. |
| | Sandia UFACET | E | ✓ | ? | | | | | | | | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ? | ✓ | | | | Under development. |
| | NREL NIO | E | ✓ | ✓ | | | | | | | | | | ✓ | ✓ | ✓ | ✓ | ✖ | ✓ | ✖ | ✓ | | | | Under development. Initial published results. |
| | CSPS/DLR HelioPoint-II | E | ✓ | ✓ | | | | | | | | | | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | | | Under development. |
| **Dynamic wind surface map and pointing** | Gap | | | | | | ✓ | | | ✓ | ✓ | ✓ | | | ✓ | | ✓ | | ✓ | | | | | | Optical effects not measured. |
| | CSPS Dynamic | M | | | | | ✓ | | | ✓ | ✓ | ✓ | | | ✓ | | ✓ | | ✓ | | | | | | Not optical (dynamic photogrammetry). |
| **Soil assessment across field** | CSPS TraCS | C | | | | | | ✓ | | | | | | N/A | N/A | ✖ | ✓ | | ✓ | | | | | | Multiple copies or mobile to give spatial variation. |
| | ASTRI UAS | E | | | | | | ✓ | | | | | | ✓ | ✓ | ✓ | ✓ | | ✓ | | | | | | Initial published results. |
| **Ground truth** | Gap | | ✓ | ✓ | | | ✓ | | | | | | | ✓ | ✓ | | | ✓ | | | | ✓ | | | No method for detailed surface map of curved optics |
| | Water Pool | E | ½ | | | | | | | | | | | ✓ | | | | ✓ | | | | ½ | | | Horizontal only. No curvature. |
| | BCS | M | | | ✓ | ✓ | | | ✓ | ✓ | | | | ✓ | ✓ | | | ✓ | | | | ½ | | | Widely used. Not a detailed map of surface error. |

**Note:**
This is a subjective study, and we know it's imperfect.
Still, we thought it might promote useful discussion.

CSPS = CSP Services

- C Commercial product.
- M Mature research result.
- E Emerging research.
- New system needed.

For commercial products, the standard for a check mark is "part of the product functionality."
For mature research results, the standard for a check mark is "has been demonstrated multiple times."
For emerging research, the standard for a check mark is "is a designed part of the solution in progress."

**Other perspectives:**
Some gaps can currently be addressed, at least partially, by composite techniques that combine methods.

**Other perspectives:**
Many opportunities for improvement.