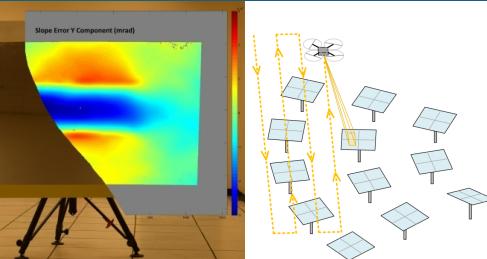




Sandia
National
Laboratories

Question-Based Gap Analysis of Heliostat Optical Metrology Methods



Randy C. Brost

September 30, 2022



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SAND2022-????

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 not 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.

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

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?

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.

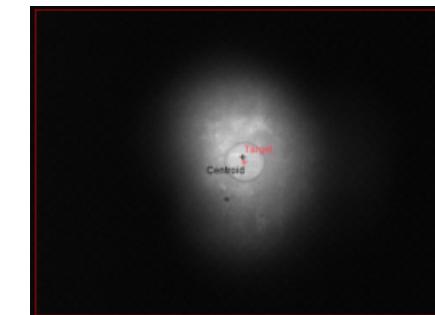
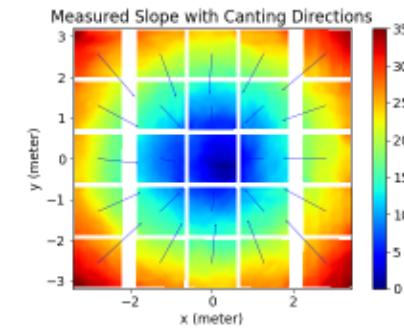
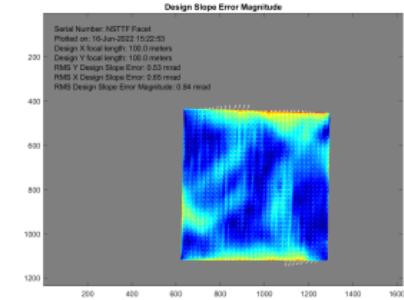
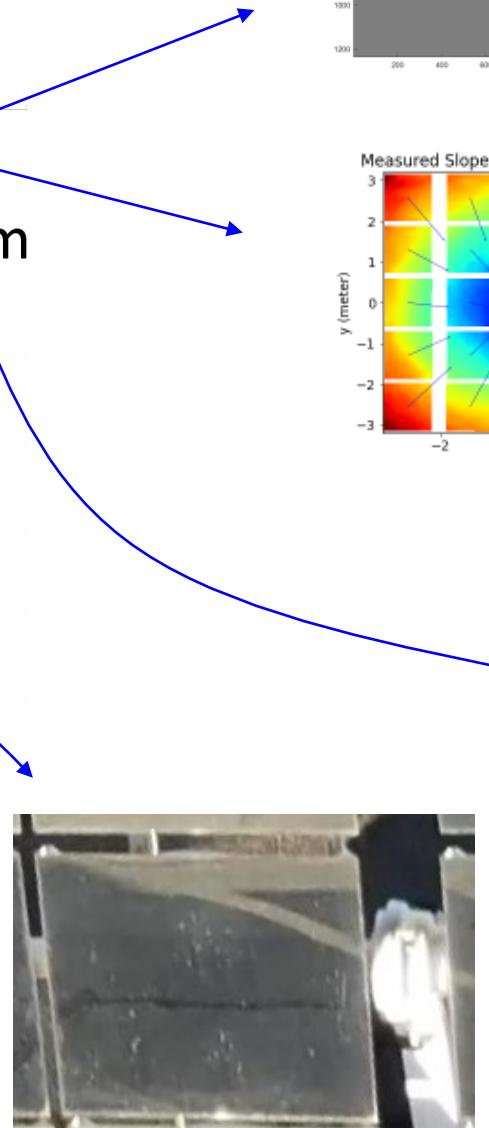
All

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

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 (θ_1, θ_2) , without tower), sufficient up time.
- **Operation:** Outdoors, detect changes, fast enough, don't interrupt plant operation, low operating cost.

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(Associated requirements and constraints not listed)

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If not adequately covered:
→ **Gaps**

Desired Characteristics



		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	SingleFacet	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?
- (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?
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- (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?
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- (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?

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.
 - QDec-M – High-resolution mirror deflectometry.
 - QDec-H – High-resolution deflectometry of full heliostats in situ.
 - Dynamic photogrammetry – Dynamic 3D measurements of heliostats in wind.
 - HelioPoint II – Airborne calibration of tracking accuracy of heliostat field (in development).
 - TRaCS – In-field automated soiling measurement.

Mature Research:

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

Emerging Research:

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

Other perspectives:

Industry interest drives whether a metrology product is brought to market.

But data may be required to demonstrate need.

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.

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	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 ✓							✓ ✓ ✗					✓ ^{3/4}					✓ ✓ ✓ ^{3/4}					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	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 ^{1/2}							✓		✓			✓				1/2						Horizontal only. No curvature.
	BCS	M ✓ ✓		✓ ✓					✓ ✓		✓			✓		✓		1/2						Widely used. Not a detailed map of surface error.

Other perspectives:

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

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:

Many opportunities for improvement.



Backup Slides

Coverage



Technology		Development Stage														Notes						
		Optical Surface Map	Pointing Accuracy	Surface Change Detection	Pointing Change Detection	Dynamic Motion Analysis	Tooling Geometry	Degradation and Damage	Solling	Multi-Prescription	Multi-Mass	Multi-Elevation	Multi-Azimuth	Multi-Temperature	Single Facet	Full Heliostat	Distant Heliostats	Tower Not Required	Non-Intrusive	Full Working Envelope	High Speed	Very High Reliability
Optical surface map, fast indoor	CSPS QDec-M	C ✓								✓ ✓ ✓					✓ ✓				✓ ✓ ✓ ✓	All requirements demonstrated. Multi-camera enables screen size similar to mirror.		
	Sandia SOFAST	M ✓								✓ ✓ ✗					✓ ¼				✓ ✓ ✓ ¼	Multi-facet measurement implemented. Outdoor full heliostat implementation in progress. Multi-elevation not demonstrated.		
Optical surface map, flexible outdoor	CSPS QDec-H	C ✓ ✓								✓ ✓ ✗ ✗ ✓ ✓ ✓ ✓ ✓ ✗ ✗ ✗										Limited elevation angles. Requires screen on tower. Difficult in large fields.		
	BrightSource Tower Images	M ✓ ✓								✓ ✓ ✓ ✓ ✓ ✓ ✓ ? ✗ ✓										Industrial implementation. Degrades over long range (?)		
Reflected beam direction and size, slow	BCS	M	✓							✓ ✓					✓			✓		Widely used. No standard software (?)		
Surface map + pointing, fast	Sandia UFACET	E ✓ ?														✓ ✓ ✓ ✓ ✓ ✓ ? ✓				Under development.		
	NREL NIO	E ✓ ✓														✓ ✓ ✓ ✓ ✗ ✓ ✗ ✗ ✓				Under development.		
	CSPS/DLR HelioPoint-II	E ✓ ✓														✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓				Under development.		
Dynamic wind surface map and pointing	CSPS Dynamic	M	✓							✓ ✓ ✓					✓ ✓ ✓					Not optical (dynamic photogrammetry).		
Tool shape, surface normal							✓		✓						✓ ✓							
Soil assessment across field	CSPS TraCS	C				✓				N/A N/A ✗ ✓ ✓										Multiple copies or mobile to give spatial variation.		
	ASTRI UAS	E				✓				✓ ✓ ✓ ✓ ✓										Published results.		
Damage/degradation inspection						✓				✓ ✓										Not implemented. Possible add to UFACET or NIO.		
Ground truth	Water Pool	E ½								✓					✓	✓	½			Horizontal only. No curvature.		
	BCS	M ✓ ✓								✓ ✓					✓ ✓	✓	½			Widely used. Not a detailed map of surface error.		

Other perspectives:

Soiling is complex,
not fully understood.

CSPS = CSP Services

C Commercial product.

For commercial products and mature research results, the standard for a check mark is "has been demonstrated."

M Mature research results

For mature research results, the standard for a check mark is "has been demonstrated multiple times."

E Emerging research.

For emerging research, the standard for a check mark is "is a designed part of the solution in progress."

HelioCon Objectives and Scope



HelioCon Objectives and Scope

Objectives

- Form U.S. center of excellence focused on heliostat technologies.
- Develop strategic core validation and modeling capabilities and infrastructure at DOE's national laboratories (NREL and Sandia).
- Promote workforce development by integrating academia, industry, and all stakeholders.

Scope – 6 Topics

- Metrology and Standards
- Components and Controls
- Advanced Manufacturing
- Resource, Training and Education
- Field Deployment
- Techno-Economics Analysis

HelioCon Objectives and Scope

- 1/3 of the budget is allocated for external funding in order to expand the consortium member base.
- A request for proposal (RFP) was recently issued to solicit proposals for this funding.

Support but not develop specific heliostat designs

HelioCon Request for Proposals



HelioStat Consortium (HelioCon):

www.heliocon.org

HelioCon Roadmap Report:

www.heliocon.org/roadmap_report.html

HelioCon Request for Proposals (RFP):

https://heliocon.org/request_for_proposal.html

RFP Webinar:

October 10, 2022 4:00 p.m. MDT

https://nrel.zoomgov.com/meeting/register/vJltcu-prjMiHtbz5Pw_5yEkaELwEprnOGg