U.S. Department of Energy
HelioCon
Heliostat Consortium for Concentrating Solar-Thermal Power

An Undervalued Foundation for Heliostat Technologies: Optical Characterization, Modeling and Measurement

Guangdong Zhu, Ph.D.

February 16, 2022 • National Renewable Energy Lab • Virtual

conceptual design • components • integration • mass production • heliostat field

Outline

- Heliostats
  - Definition
  - Design diversity
  - Why optics matters?
- Fundamental requirements on optics
  - Sun shape
  - Opto-mechanical errors
  - Design shape and incidence angle
  - Solar mirror reflectance and its degradation
  - Reflected beam quality
- Measurement and modeling of heliostat optics
  - Measurement of heliostat optics
  - Ray-trace modeling
- HelioCon mission
  - Map the optics needs at the full development cycle
  - State of the art and gaps in the full development cycle

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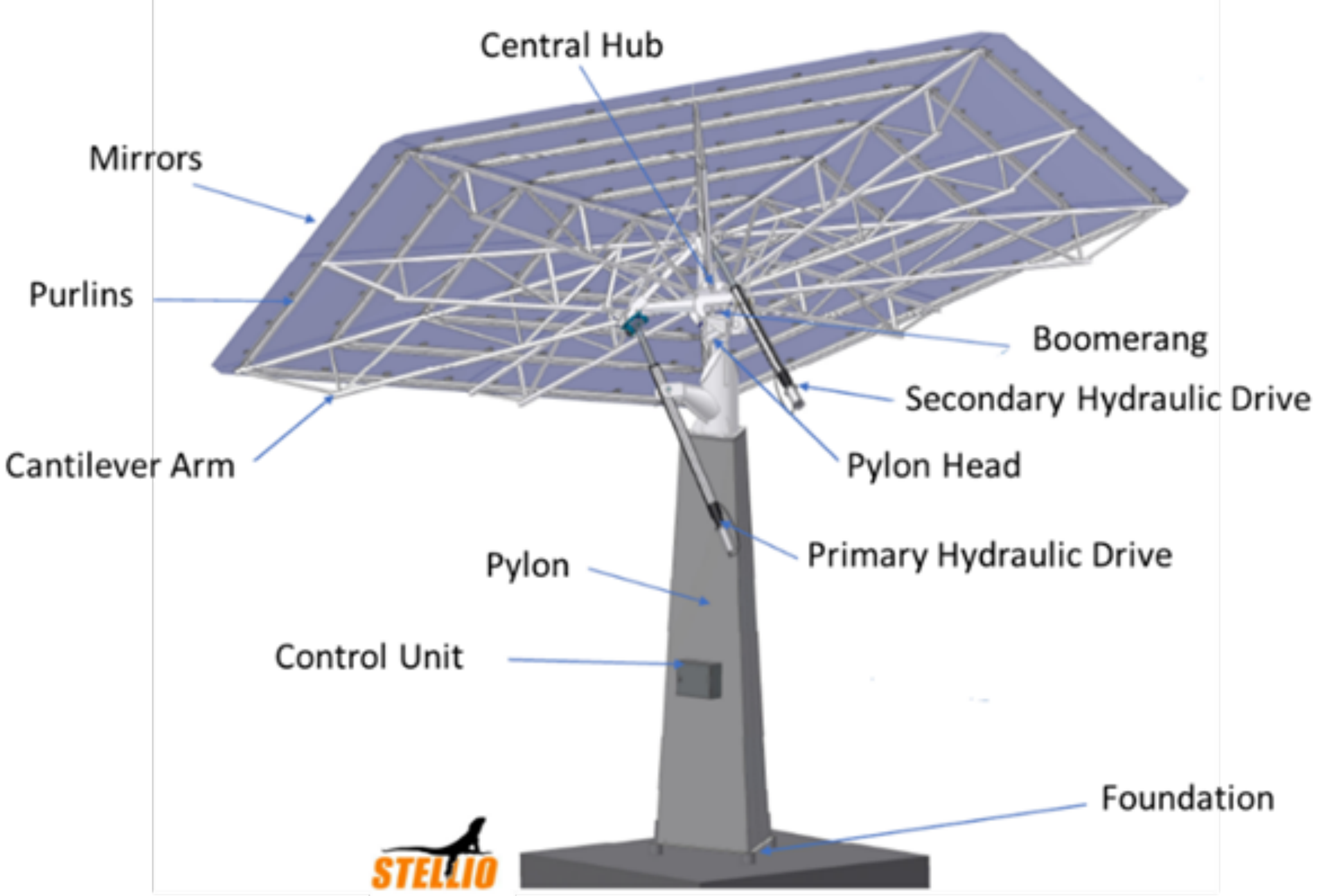
Heliostat

- Two-axis tracking reflector for CSP power generation (heat and electricity)

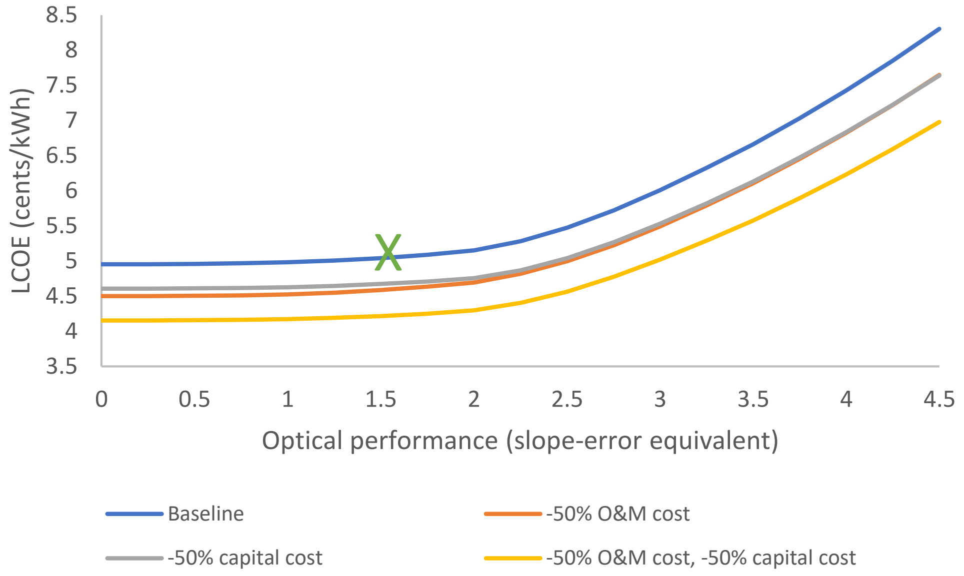
Diversity of Heliostat Designs

- Size & shape
- Mirror facets
- Drive
- Control
- Supporting structures
- Pylon
- Foundation
- Manufacturing process
- …



Optics Matters

- In a utility-scale solar field, a heliostat may be 1,500 m away from receiver.
  - Over 10,000 heliostats in a field
  - Optical precision: 1.5 ~ 2.5 mrad
    - Additional 2 mrad would result into 20% energy loss



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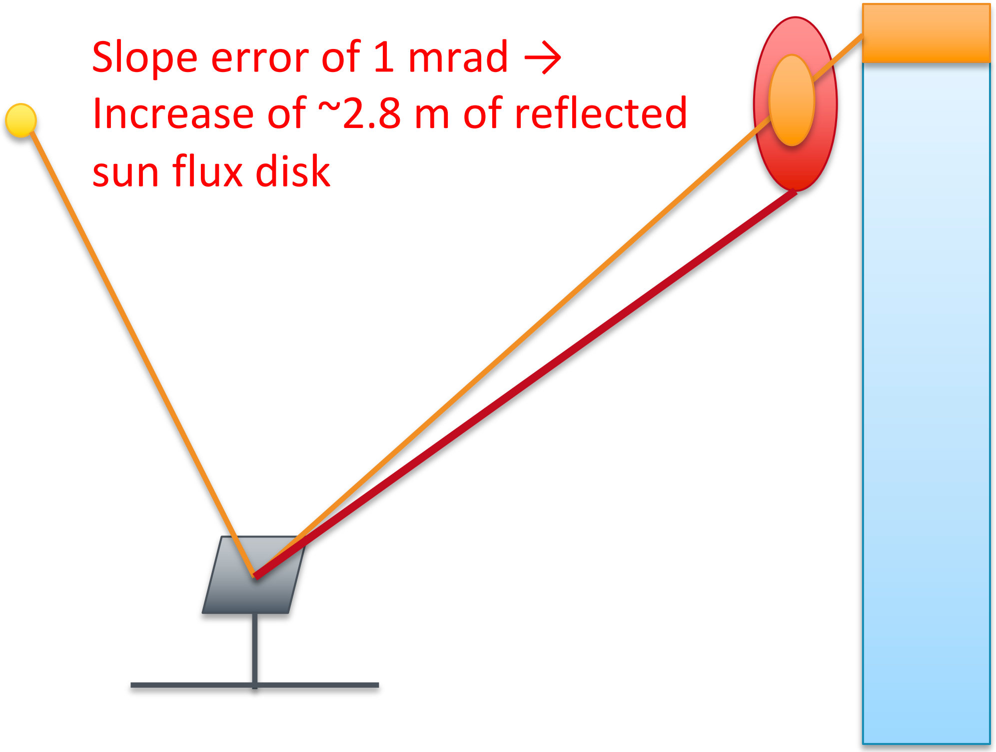
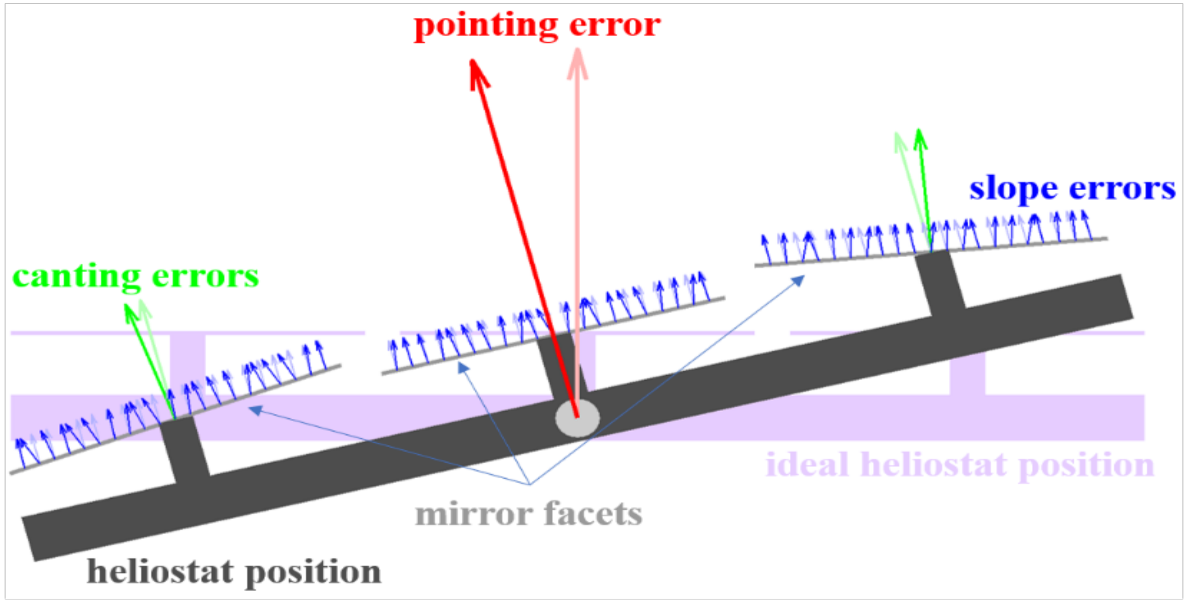
Sun Shape

- Sun has a finite shape
  - 4.7 mrad
    - Concentration ratio limit
      - 213 for line-focus
      - 213^2 for point-focus
  - Broadened by various collector optical errors
    - Reduced concentration ratio limit



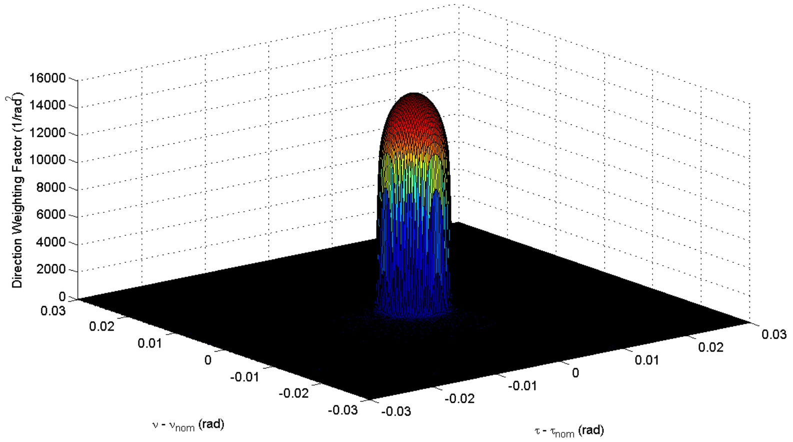
Opto-Mechanical Errors

- For a given design heliostat shape:
  - Slope error on mirror facet surface
  - Canting error of mirror facet
  - Pointing error of heliostat
- Will result into a broadened sun shape



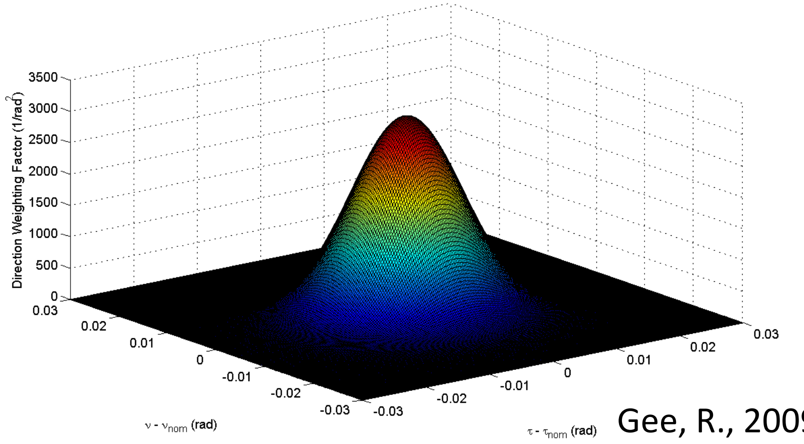
Error sources:

+ Sun shape



Error sources:

+ Sun shape
+ Specularity
+ Slope
+ Canting
+ Pointing

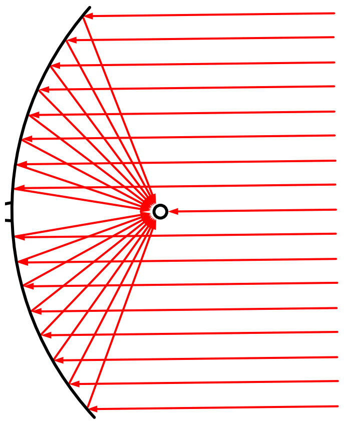


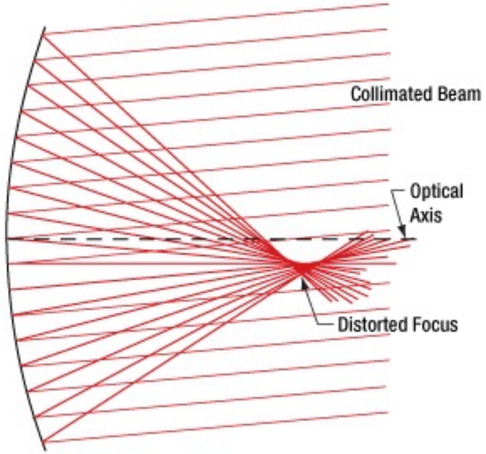
Gee, R., 2009, SolarPACES

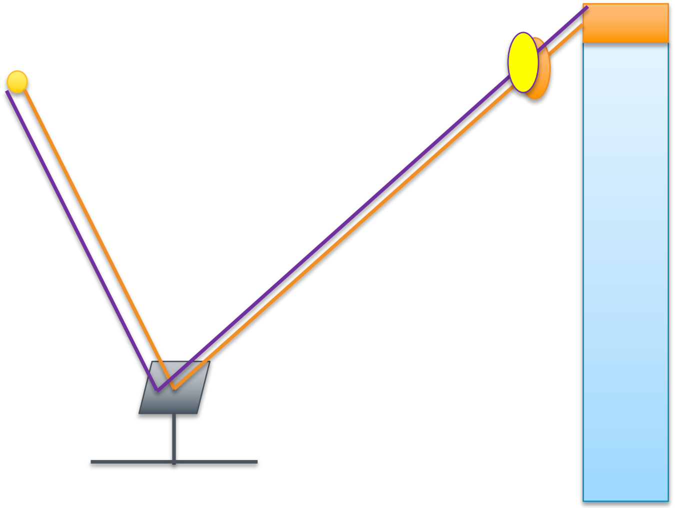
Impact of Design Shape and Incidence Angle

- **Additional error sources**
  - Heliostat design shape – often a parabolic approximation
    - Circular
    - Flat
    - Piece-wise parabola with multiple mirror facets
  - Incidence angle
    - Normal incidence of the sun is rare for heliostats
    - Resulting into additional astigmatic loss, even for a perfect parabola
- **Impact**
  - Further reduction of concentration ratio
  - Further reduction of optical efficiency
  - Less flexibility in flux control

https://www.thorlabs.com/

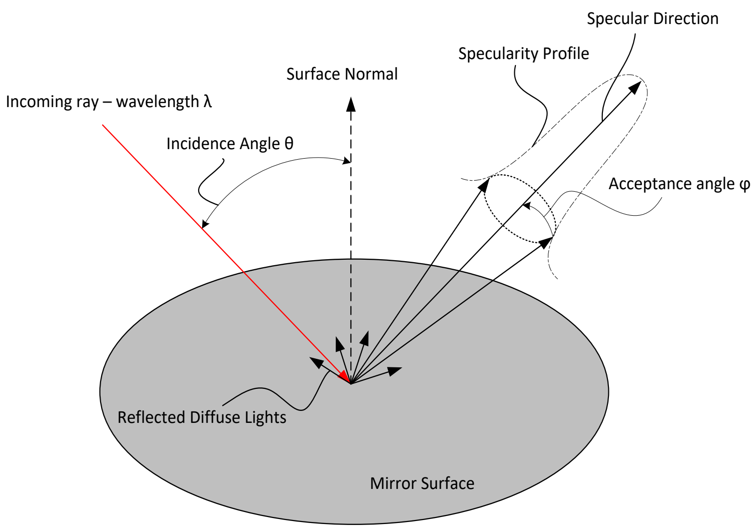


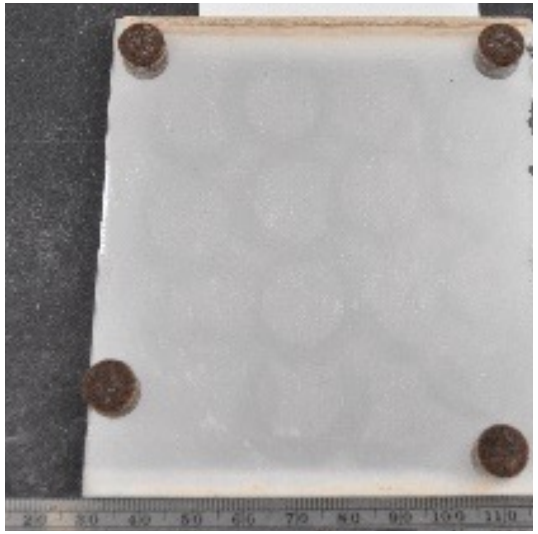




Mirror: Solar Reflectance and Its Degradation

- Solar reflectance
  - **Specular**
  - Solar spectrum
  - Beam incidence angle
- Degradation
  - Over 30 years of operation time
  - Accelerated aging test
  - Impact of soiling
- Impact
  - Requires washing optimization to balance the maintenance cost and solar field performance





Hemispherical: 92%
Specular reflectance: 74%

Reflected Beam Quality

- Contribution factors:
  - Sun shape
  - Opto-mechanical error
  - Heliostat design shape
  - Incidence angle
  - Solar-weighted specular reflectance
  - And…
    - Attenuation
    - Receiver geometry
    - Receiver coating properties
- Reflected beam quality
  - Operation requirements
    - Safety
    - Efficiency
    - Flux distribution
  - Control flexibilities
    - Accommodation of weather condition

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Measurements: Solar Reflectance

- Limited instruments available on market
  - Portable reflectometers are needed in field
  - Very few can measure specular reflectance at multiple acceptance angles
    - Essential to derive mirror specularity.
- Results of portable reflectometers may vary
  - Measurement parameters
  - Measurement protocol

Manufacturer	Surface Optics	Devices & Services Co	Aragon Photonics	Konica Minolta	CSP Services GmbH[a]	PSE AG
Developer	Surface Optics	Devices & Services Co	Abengoa & University of Zaragoza	Konica Minolta	DLR	Fraunhofer ISE
Model	410 Solar	15R-USB; 15R- RGB	Condor	CM-700d/600d	TraCS	pFlex 2.1

SolarPACES
Solar Power & Chemical Energy Systems

SolarPACES Task III
Solar Technology and Advanced Applications

Soiling Measurements of Solar Reflectors

Starting date of the project: 01/11/2019
Duration: 18 months

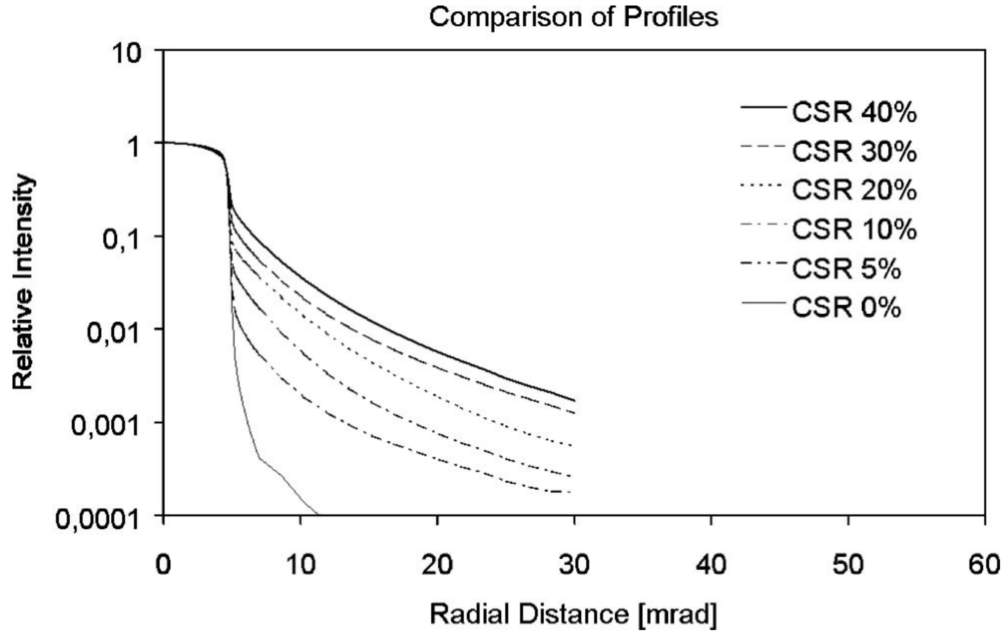
Deliverable: D1
Portable reflectometers to measure soiled reflectors in solar fields

Due date of deliverable: 30/04/2021 (M18)
Actual submission date: 29/06/2021

Responsible Workpackage Leader: Aránzazu Fernández García, CIEMAT
Revision: V9

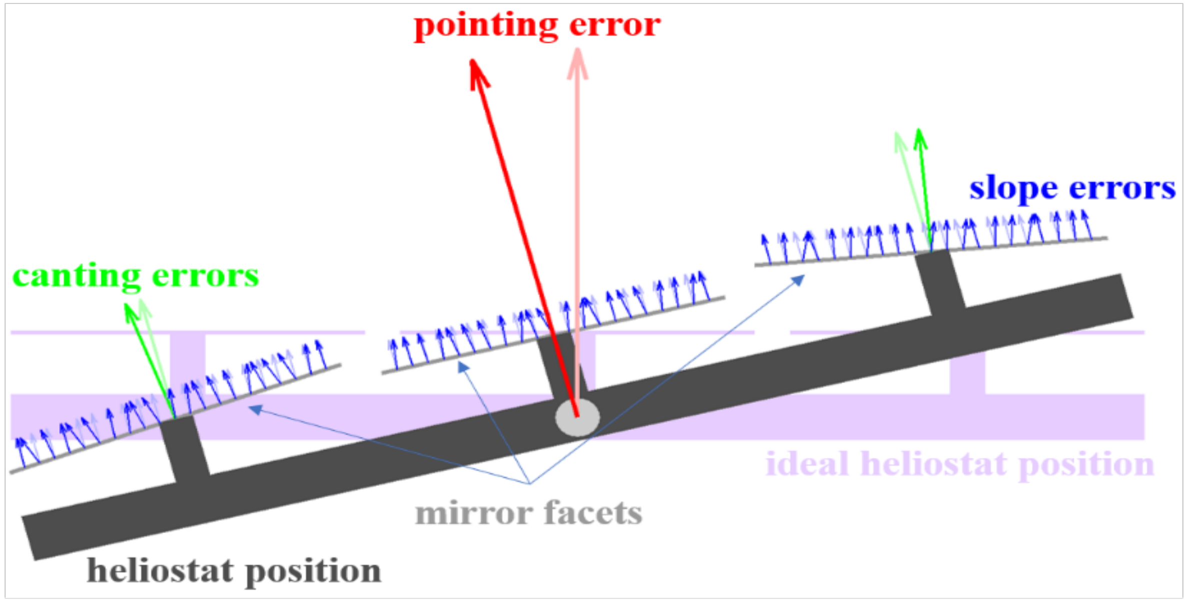
Measurements: Sun Shape

- Sun shape varies with local atmosphere conditions over a year
  - Air mass (1.5 is the standard value used now)
  - Clouds
  - Sun-to-earth distance (minor effect to CSP)



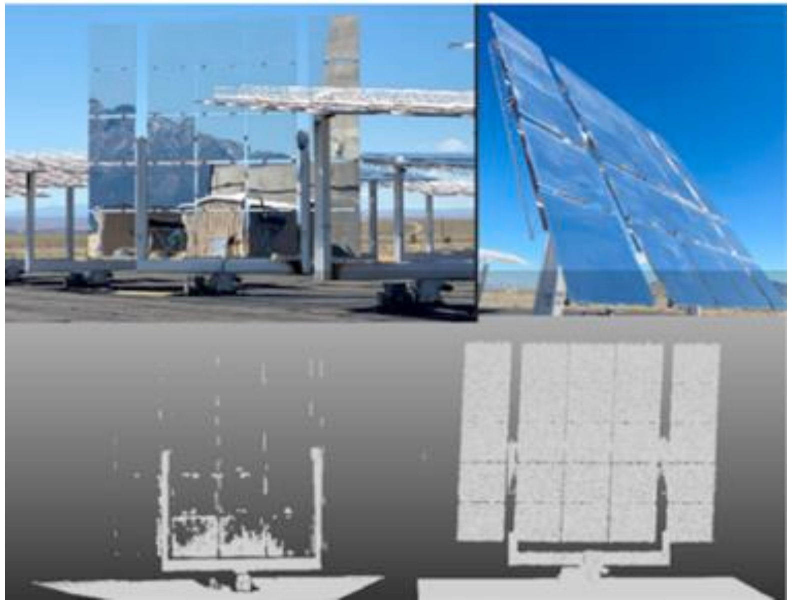
Measurements: Opto-Mechanics

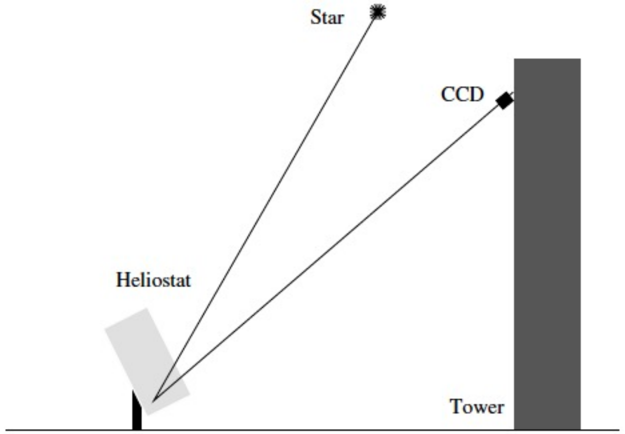
- To measure:
  - Mirror surface slope error
  - Mirror facet canting error
  - Heliostat tracking error
- Define what is measured
- Major requirements
  - sub-milliradian accuracy
    - 1 mrad = 0.06 degree
  - Environment (laboratory or in-situ)
  - Speed
  - Operation ease

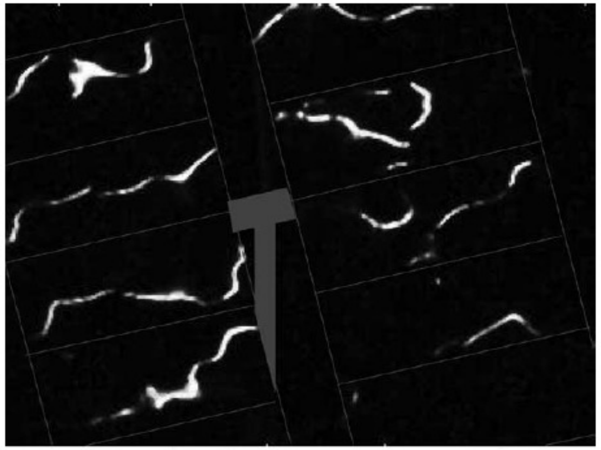


Measurements: Opto-Mechanics

- Laser-scanning techniques
- Reflection-based methodologies: sensitive to sub-milliradian slope change
  - Reflection on mirror surface
  - Reflection of objects on a separate target





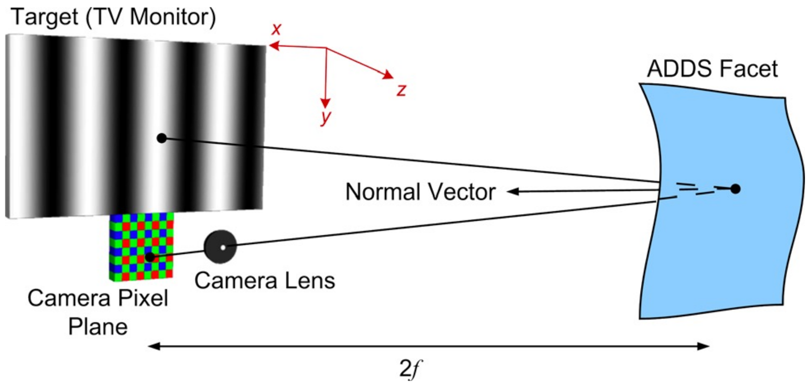


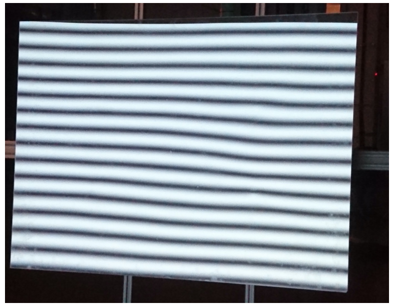
Little C., Small D., Yellowhair J., 2021, SAND2021-5732C

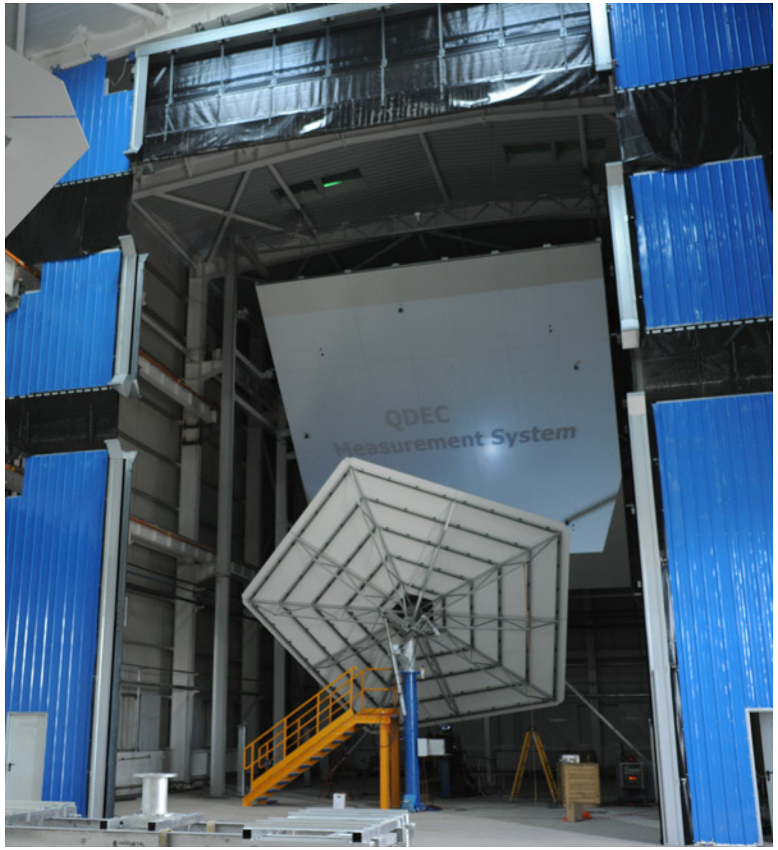
Arquerros, et. al, 2003. doi:10.1016/j.solener.2003.07.008

Measurements: Opto-Mechanics

- Reflection-based methodologies:
  - Laboratory metrology
    - Q-Dec
      - The only commercially available tool
    - SOFAST (and its derivation)
    - Similar deflectometry-based tools under development by others





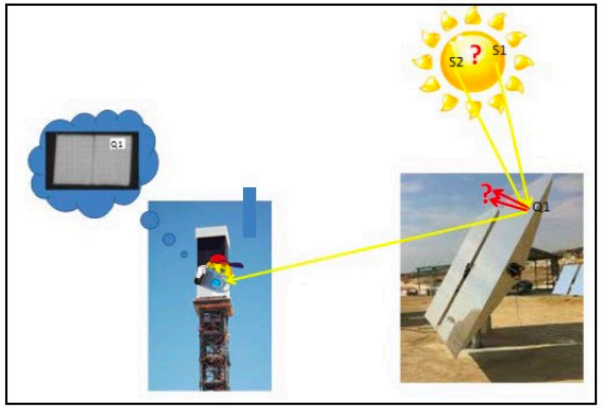


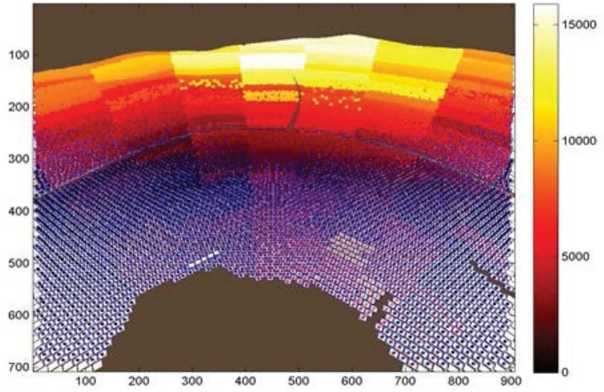
Andraka, et. al, 2014. doi.org/10.1115/1.4024250

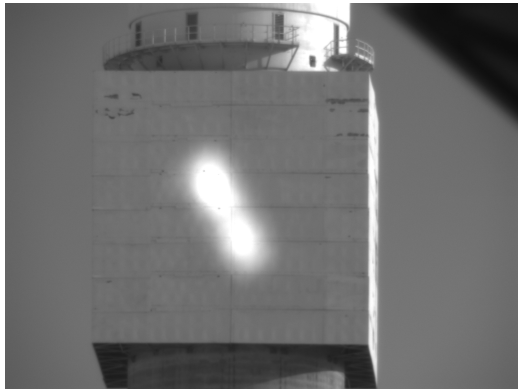
CSP Services: https://www.cspservices.de/quality-control/

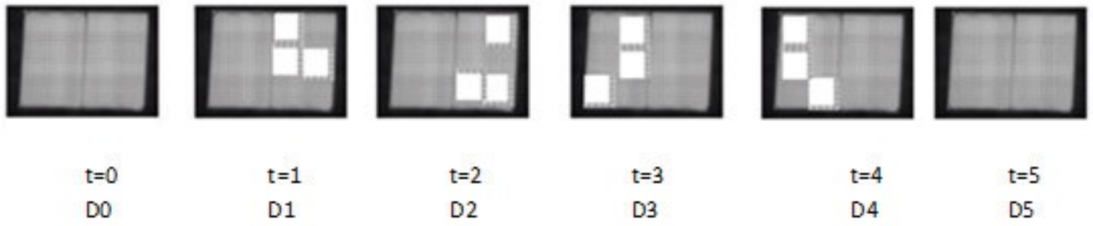
Measurements: Opto-Mechanics

- Reflection-based methodologies:
  - In-situ heliostat characterization
    - Beam characterization system
    - Camera-based heliostat-scanning method
  - Observation
    - Not directly measure surface slope error
    - Un-disclosed measurement uncertainty









Goldberg N., et. al., SolarPACES 2014 &2015

Measurements: Opto-Mechanics

- Reflection-based methodologies:
  - In-situ heliostat characterization (under development)
    - Through a SolarPACES funded effort, a round-robin test campaign is under planning.

ANU	The deformation of heliostats in operational conditions is characterised using a combination of measured flux maps (including stitched flux maps from images that are too large for the calibration target) and numerical inverse analysis to approximate heliostat shapes. The models derived can then be used to predict annual spillage using ray-tracing, calibrate heliostat tracking, etc.
CENER	Heliostat characterization system based on light detectors and cameras vertically distributed that scan the heliostat reflected beam offering detailed knowledge of the heliostat shape.
CENER + TEKNIKER	SHORT is a new heliostat calibration system, based on a low cost camera attached to each heliostat and a reduced number of targets along the filed (IR lights). The procedure allows parallel calibration of all heliostats and automatic verification and correction of the heliostat orientation.
CSIRO	An array of cameras are moved through the heliostat light beam, in front, or close to, the receiver, and the normal vector of each pixel-sized part of the heliostat across the entire field can be resolved. Alternatively, a camera array within a calibration target can be used to retrieve the same parameters up to the maximum thermal load of the target.
CSIRO	An array of retroreflectors with a tuned angular response are installed close to the receiver or within a calibration target. Ground based cameras can detect tracking/slope error signals from heliostats within the solid angle of the retroreflectors' response, allowing multiple heliostats to be measured simultaneously.
CyI	Airborne-based system for continuous monitoring and characterization of heliostat fields. The systems uses swarm of drones with specially design sensors to characterize the geometry of the heliostat's reflecting surfaces, estimate heliostats reflectivity, and other optical parameters and uses the information to continuously improve a digital model of the heliostat field that is used to predict the heliostat field optical behaviour.
DLR	A patented drone-based system (HELIOPOINT) which uses photogrammetry and deflectometry to measure the heliostat orientation in order to calibrate heliostat fields in less time than currently. Slope deviation is also measured.
DLR	A heliostat deflectometry system (QDec): camera is based on tower, images are provided by a beamer on tower surface Current project to work on a comprehensive methodology to achieve an agreed protocol to qualify (the performance of) heliostat fields.
IMDEA	Dynamic and real-time methodology for predictive heliostat field calibration. Activity to measure soiling on fields.
NREL	A non-intrusive optical tool (NIO) utilizes deflectometry and photogrammetry to measure mirror surface slope error, mirror facet canting error and heliostat pointing error by employing the state-of-the-art unmanned aerial system (UAS) for reflection image collections.

Measurements: Opto-Mechanics

- Reflection-based methodologies:
  - In-situ heliostat characterization (under development)
    - Example: Non-intrusive optical (NIO) in-situ characterization technology for heliostats

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Heliostat Field Information	**Data Collection**	**Raw Data Discretization**	**Image Processing**	**Data Management**

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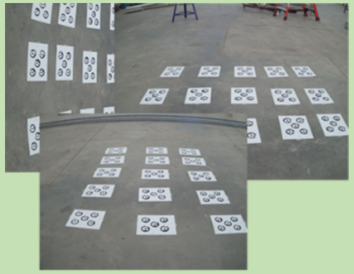
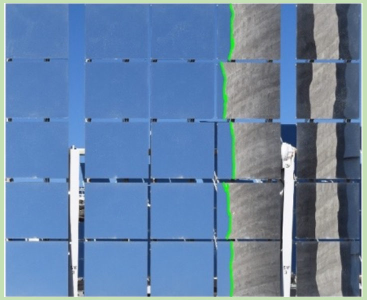
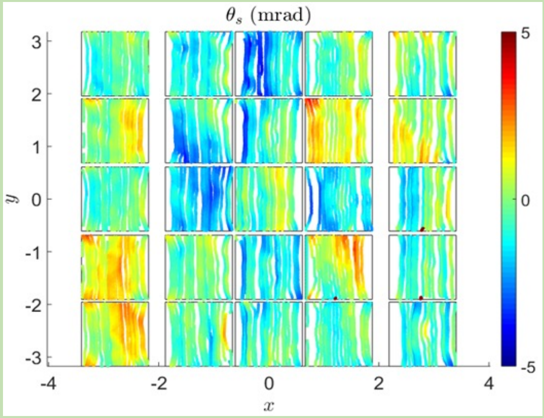
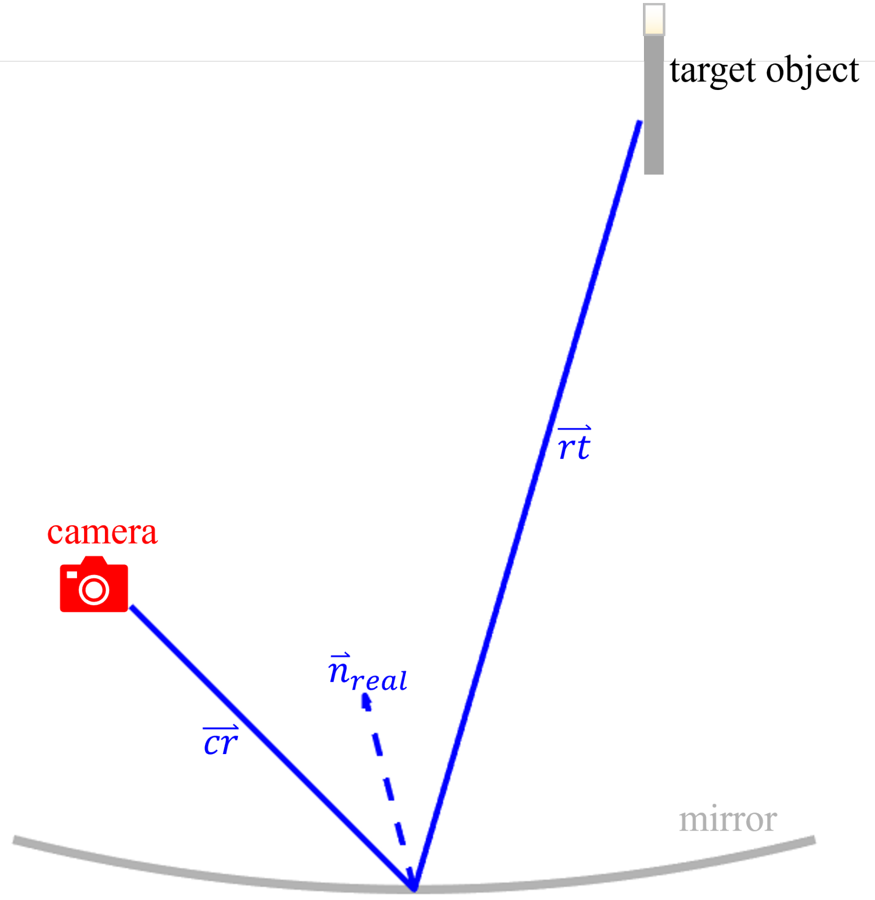






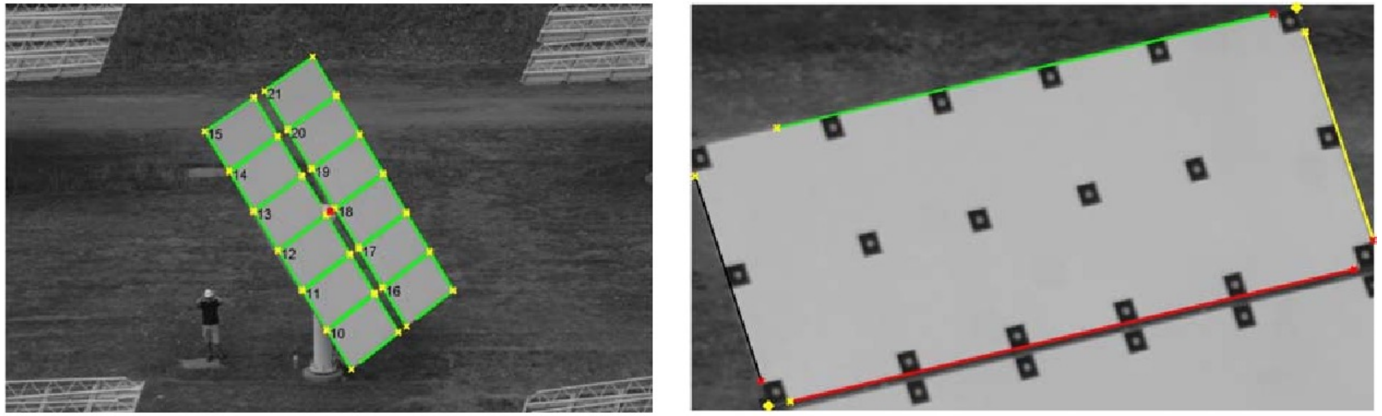
Measurements: Opto-Mechanics

- Reflection-based methodologies: **Working Principle**
  - How to determine position & orientation on the following three key elements
    - Mirror surface
    - Target
    - Reflection of target
  - Determine sensitivities of position & orientation on the same set of key elements
  - Additional elements
    - Projectors



Measurements: Heliostat Surface Shape

- Deviation of heliostat surface shape from the design shape
  - Photogrammetry



Roeger M., Prahl C., Ulmer S., J. Sol. Energy Eng.,
https://doi.org/10.1115/1.4001400

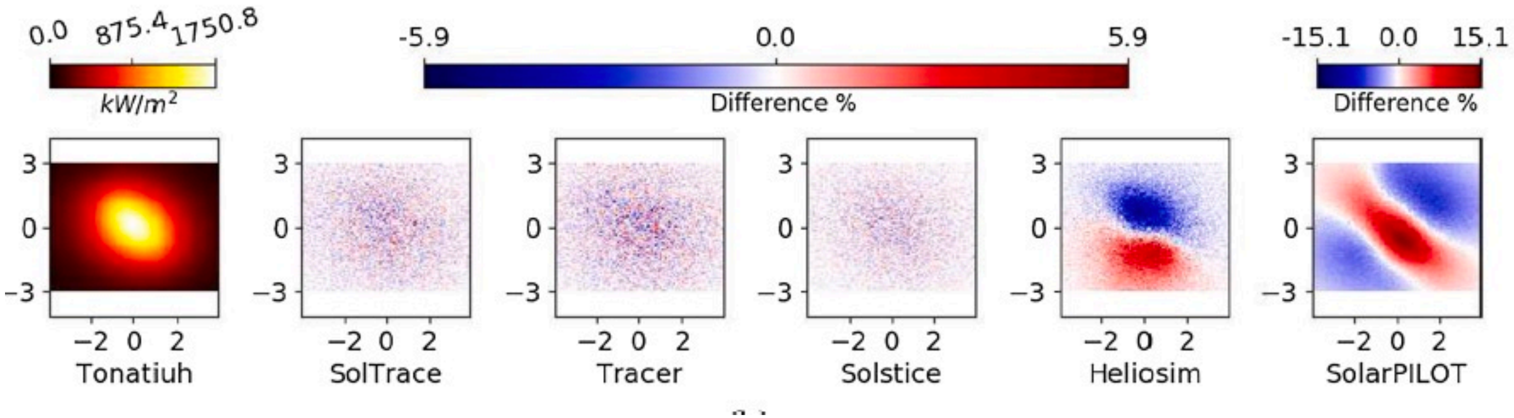
Reflected Beam Quality → Beam Quality Control

- Contribution factors:
  - Sun shape
  - Opto-mechanical error
  - Heliostat design shape
  - Incidence angle
  - Solar-weighted specular reflectance
  - And…
    - Attenuation
    - Receiver coating properties
    - Receiver geometry
- Beam quality control
  - Maximize efficiency
  - Minimize failures

Modeling of Heliostat Optics

- Analytical and ray-tracing modeling
  - Take into account
    - heliostat optics
    - Sun position
  - Calculate
    - Optical efficiency: instantaneous and annual
    - Reflected flux distribution
  - Solar field layout optimization
  - Solar field control

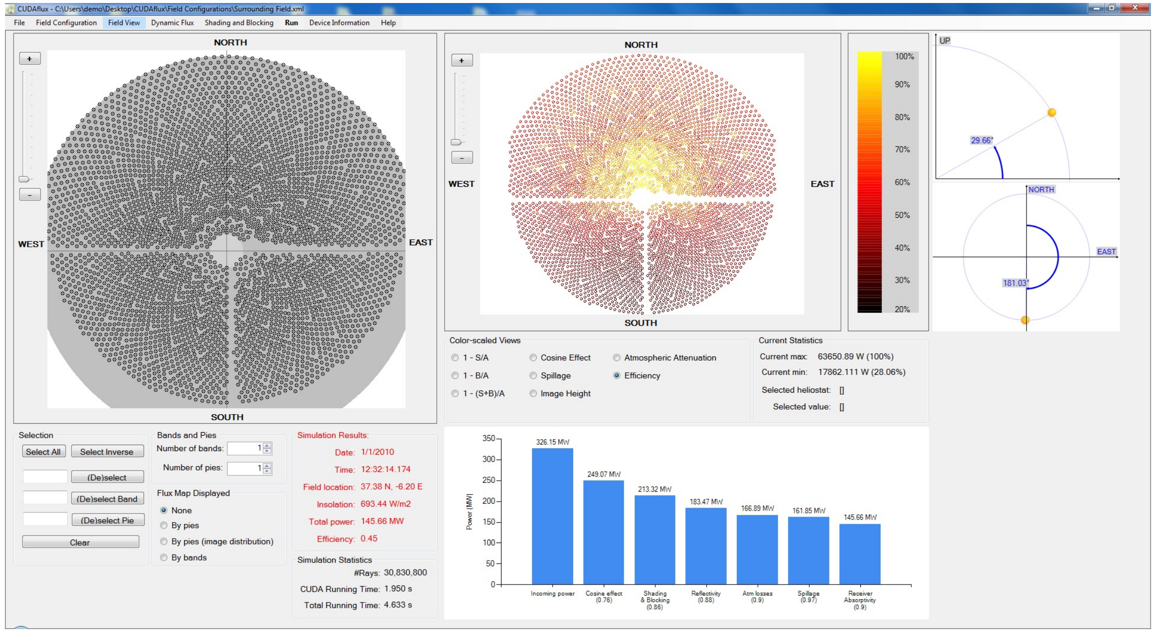
Name	Version	Open Source (URL)
Tonatiuh	2.2.3	http://iat-cener.github.io/tonatiuh/
Tracer	1.0.0	https://github.com/anustg/Tracer
Solstice	0.8.1	https://www.meso-star.com/projects/solstice/solstice.html
Heliosim	5.4.0	Closed source commercial product (trial version available on request)
SolarPILOT	1.2.1	https://github.com/NREL/solarpilot
SolTrace	3.0.0	https://github.com/NREL/soltrace



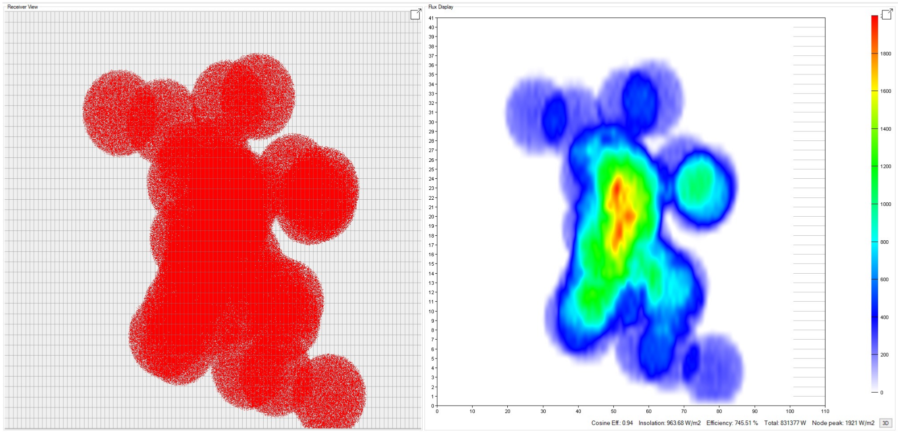
Wang, et. al., Solar Energy, 2020, https://doi.org/10.1016/j.solener.2019.11.035

Modeling of Heliostat Optics

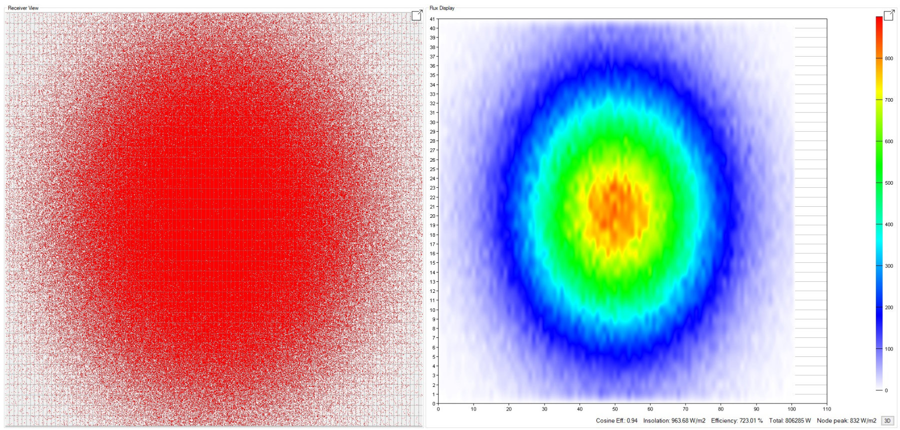
- Commercial software
  - Example: TieSol by TieTronix
    - GPU-based ray-trace model



Impact of Canting Error



Impact of Slope Error



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  - **State of the art and gaps in the full development cycle**

HelioCon Objectives and Scope

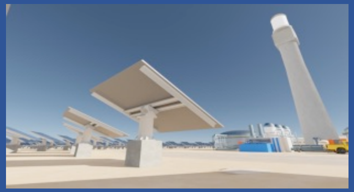
- **Heliostat Consortium (HelioCon): a DOE initiative to advance heliostat technologies**
  - 1/3 of the budget is allocated for the request for proposal (RFP) in order to expand the consortium member base
- **Objectives**
  - Form U.S. center of excellence focused on heliostat technologies to restore U.S. leadership.
  - Develop strategic core validation and modeling capabilities and infrastructure at DOE's national labs (NREL and Sandia).
  - Promote workforce development by integrating academia, industry, and all stakeholders.
- **Scope – 6 Topics**
  - Advanced Manufacturing
  - Metrology and Standards
  - Components and Controls
  - Field Deployment
  - Techno-Economics Analysis
  - Resource, Training and Education
- **Note**
  - Support but not develop specific heliostat designs

HelioCon: Metrology & Standards

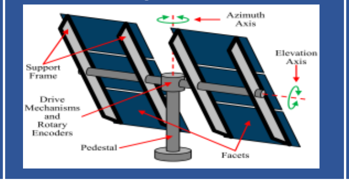
- **Objective: to complete a sustainable product development cycle**
  - Conceptual design
  - Heliostat components
  - Heliostat integration
  - Mass production
  - Heliostat field

Heliostat Development Cycle

Conceptual Design:



Heliostats Components:



An Integrated Heliostat:

Mass Production of Heliostats:

A Heliostat Field:

conceptual design • components • integration • mass production • heliostat field

HelioCon: Metrology & Standards

- **Optics**

Conceptual Design	Heliostat Components	Integrated Heliostat	Mass Production	Heliostat Field
• **Measurements - Site characterization** • Sun shape • Temporal solar irradiance file • Soiling characterization • Attenuation characterization • Weather forecasting • **Modeling** • High-fidelity energy/revenue prediction model • **Standards** • Site characterization • Heliostat design • Heliostat system design	• **Measurements - laboratory** • Optomechanical error measurement • Solar reflectance and its degradation with time and soiling • **Modeling** • Impact of wind load to optical performance • **Standards** • Definition of heliostat optics • Component life-cycle test – mirror	• **Measurements – *in-situ*** • Opto-mechanical error with wind load, temperature, and orientation • **Modeling** • High-fidelity energy prediction model under specific solar field control mechanism • **Standards** • Heliostat in-situ testing	• **Measurement – quality-control** • Opto-mechanical error • **Modeling** • Impact of manufacturing tooling to optical performance • **Standards** • Heliostat quality control	• **Measurement – in-situ** • Solar DNI • Weather forecast • Attenuation • Opto-mechanical error: pre and after installation • Solar reflectance and its degradation with time and soiling • Beam quality • **Modeling** • Energy production forecast • Impact of heliostat optics to operation (failure, environmental impacts) • **Standards** • Heliostat field performance testing • Heliostat field safe operation

HelioCon: Metrology & Standards

- **Optics – If not all, majority of needs are not fully addressed!**

Conceptual Design	Heliostat Components	Integrated Heliostat	Mass Production	Heliostat Field

• **Measurements - Site characterization**
  • Sun shape
  • Temporal solar irradiance file
  • Soiling characterization
  • Attenuation characterization
  • Weather forecasting
• **Modeling**
  • High-fidelity energy/revenue prediction model
• **Standards**
  • Site characterization
  • Heliostat design
  • Heliostat system design
	• **Measurements - laboratory**
	  • Optomechanical error measurement
	  • Solar reflectance and its degradation with time and soiling
	• **Modeling**
	  • Impact of wind load to optical performance
	• **Standards**
	  • Definition of heliostat optics
	  • Component life-cycle test – mirror
		• **Measurements – *in-situ***
		  • Opto-mechanical error with wind load, temperature, and orientation
		• **Modeling**
		  • High-fidelity energy prediction model under specific solar field control mechanism
		• **Standards**
		  • Heliostat in-situ testing
			• **Measurement – quality-control**
			  • Opto-mechanical error
			• **Modeling**
			  • Impact of manufacturing tooling to optical performance
			• **Standards**
			  • Heliostat quality control
				• **Measurement – in-situ**
				  • Solar DNI
				  • Weather forecast
				  • Attenuation
				  • Opto-mechanical error: pre and after installation
				  • Solar reflectance and its degradation with time and soiling
				  • Beam quality
				• **Modeling**
				  • Energy production forecast
				  • Impact of heliostat optics to operation (failure, environmental impacts)
				• **Standards**
				  • Heliostat field performance testing
				  • Heliostat field safe operation

HelioCon: Metrology & Standards

- **More than optics**

Conceptual Design	Heliostat Components	Integrated Heliostat	Mass Production	Heliostat Field

• **Measurements**
  • Wind profile
  • Relevant environmental factors
• **Modeling**
  • Wind load calculation model
• **Standards**
  • Wind measurement profile
	• **Measurements - laboratory**
	  • Structural load test
	• **Modeling**
	  • Wind load calculation model
	  • Structural design model
	• **Standards**
	  • Component life-cycle test
		• **Measurements**
		  • Wind load measurement
		  • Structural deformation under loads (in-situ and laboratory)
		• **Modeling**
		  • Wind load validation
		  • Correlation of opto-mechanical errors and structural deformation
		• **Standards**
		  • Heliostat load testing (in-situ and laboratory)
			• **Measurement**
			  • Tooling shape
			  • Non-optical quality
			• **Standards**
			  • Heliostat quality control – non-optical
				• **Measurement – in-situ**
				  • Wind load monitoring
				  • Corrosion and erosion monitoring
				  • Mechanical failure monitoring (mirror breakage, drive misfunctioning/degradation)
				• **Modeling**
				  • (need feedbacks)
				• **Standards**
				  • Heliostat solar field operation and maintenance - non-optical (such as drive reliability)

HelioCon: Metrology & Standards

- **Key observation**
  - Small industry
    - Need to grow the industry first: Call for collaboration where possible!!
  - Singular technology in many cases
    - Not cross-checked with other technologies
  - Standards to assess and ensure the heliostat and heliostat field performance are largely missing
    - Additional obstacles to convince investors
  - Devils in details
    - How to address each individual gap critical to heliostat development.

Highlight Gaps

- Standards
  - Site characterization
    - Soiling characterization
    - Impact soiling to mirror reflectance and soiling cycle
  - Standards of predictive energy generation model
  - Durability test standards of heliostat components and integration
- Metrology
  - Optomechanical error metrology – laboratory
    - Integrated heliostat with simulated load
  - Optomechanical error metrology - in-situ
    - Solar field performance monitoring and correction
  - Optomechanical error metrology – quality control in manufacturing
    - Heliostat production
    - Manufacturing tooling form quality
- Wind load
  - Wind measurement in solar field
  - Wind load modeling standards
  - Wing load model validation standards

HelioCon: Metrology & Standards

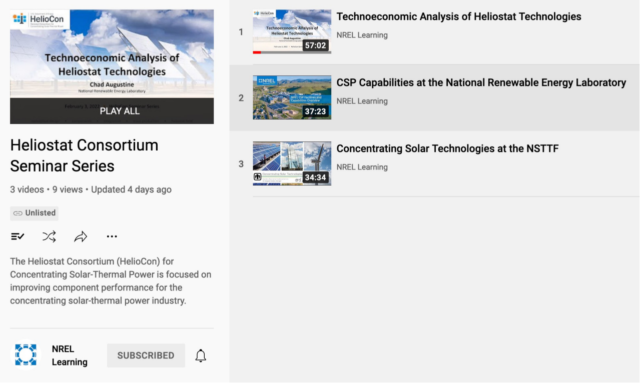
- Next steps
  - Roadmap development
    - Evaluate and rank the impact of gaps
    - Plan the scope of work for HelioCon
      - Core members: NREL, Sandia and ASTRI
      - New members through future request for proposals under HelioCon
  - Publish the roadmap
    - Six topics
      - Advanced Manufacturing
      - Metrology and Standards
      - Components and Controls
      - Field Deployment
      - Techno-Economics Analysis
      - Resource, Training and Education
  - Issue the first round of request for proposals in the summer.
- Feedbacks are always welcome!!

Questions?

- Guangdong Zhu
  - Guangdong.Zhu@nrel.gov
  - National Renewable Energy Laboratory
  - Director of HelioCon - an international consortium to advance heliostat technologies

More From the HelioCon Seminar Series

- Past seminar presentations now available on the NREL YouTube learning channel: https://www.youtube.com/playlist?list=PLmIn8Hncs7bGAK-hIf4qxuAbHUHK-xgZK
- Subscribe to the seminar series or get in touch: heliostat.consortium@nrel.gov



Next Seminar March 16th!

HelioCon Seminar Series: Resources, Training, and Education for the Heliostat Workforce

Speaker: Dr. Rebecca Mitchell, NREL

When: 1-2pm Wednesday March 16th

Zoom: https://nrel.zoomgov.com/j/1603280481?pwd=MjJKZkFZUG9pY1RqcS9TaUxFMjdRZz09