SFERA-III

Solar Facilities for the European Research Area

"Towards a fully automated flux density prediction using data driven models"

Max Pargmann, German Aerospace Center (DLR)

NETWORKING

Summer School: "Smart CSP: How Smart Tools, Devices, and Software can help improve the Design and Operation of Concentrating Solar Power Technologies" - WP1 Capacity building and training activities - Cologne, Germany, September 14th-15th 2023

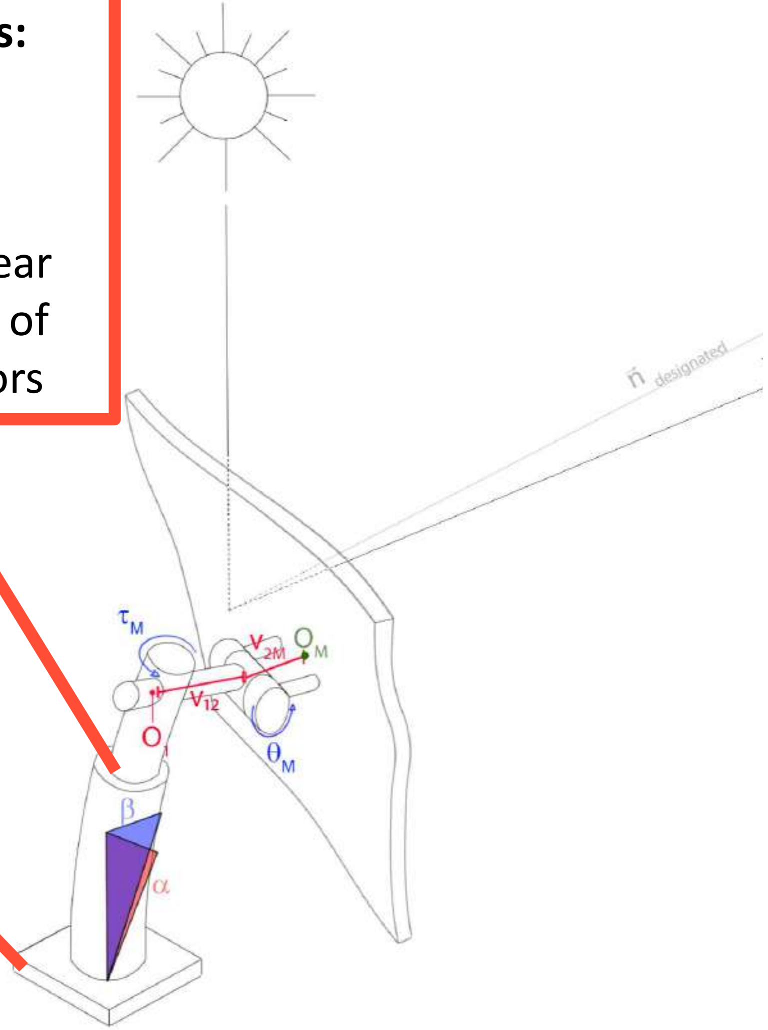
THIS PROJECT HAS RECEIVED FUNDING FROM THE EUROPEAN UNION'S HORIZON 2020 RESEARCH AND INNOVATION PROGRAMME UNDER GRANT AGREEMENT NO **823802**

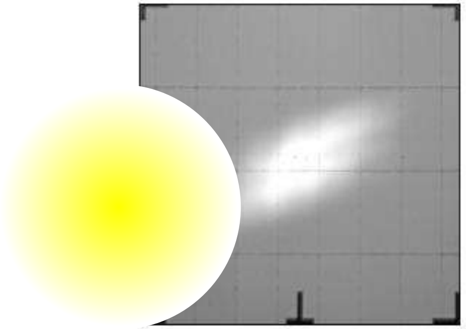
- Motivation
- Methods: Differentiable Raytracing
- Three Foundations of Automation
  - Diagnosis
  - Control
  - Predition
- Discussion

Motivation

Alignment errors:

- Wind load
- Rigidity
- Sag
- Backlash / Wear
- Misscounting of Stepper Motors





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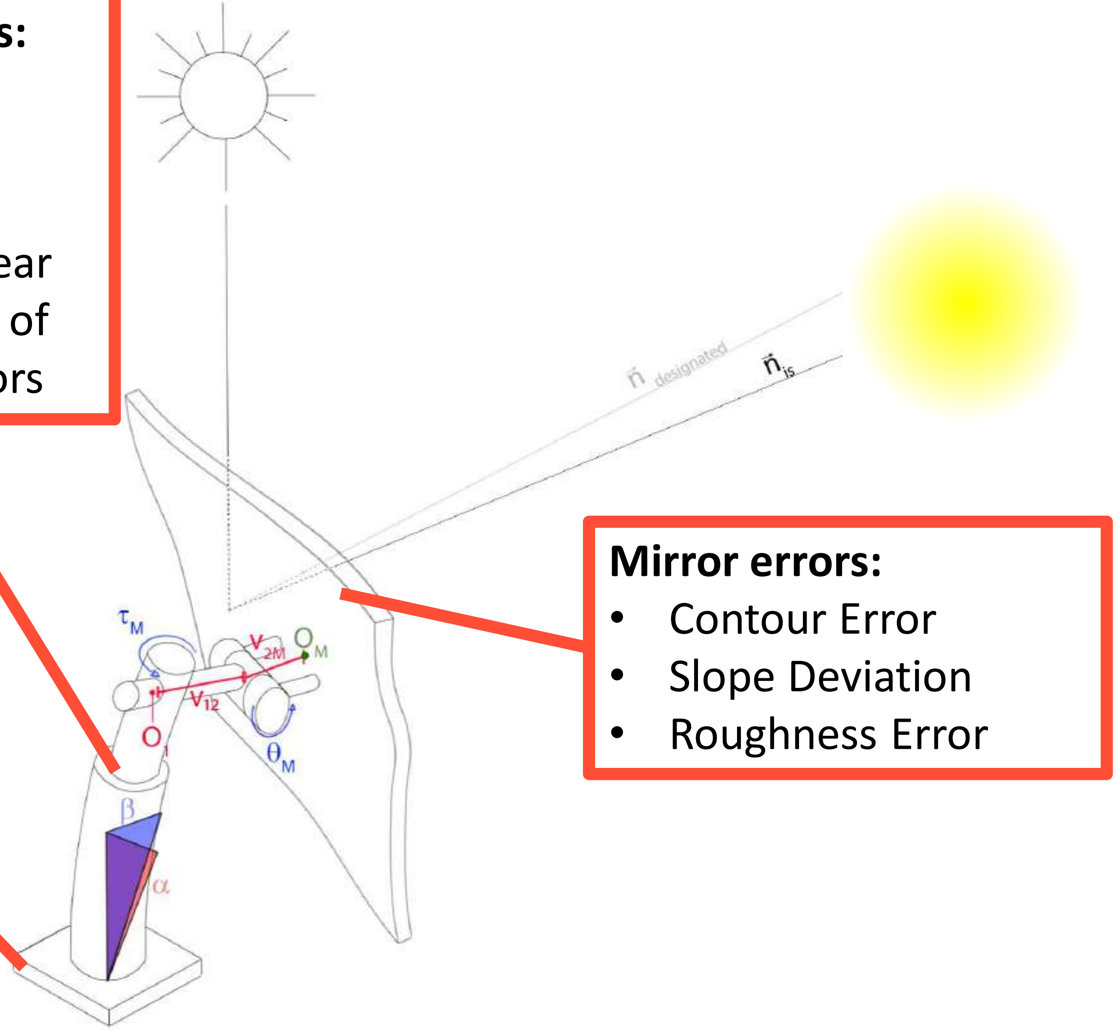
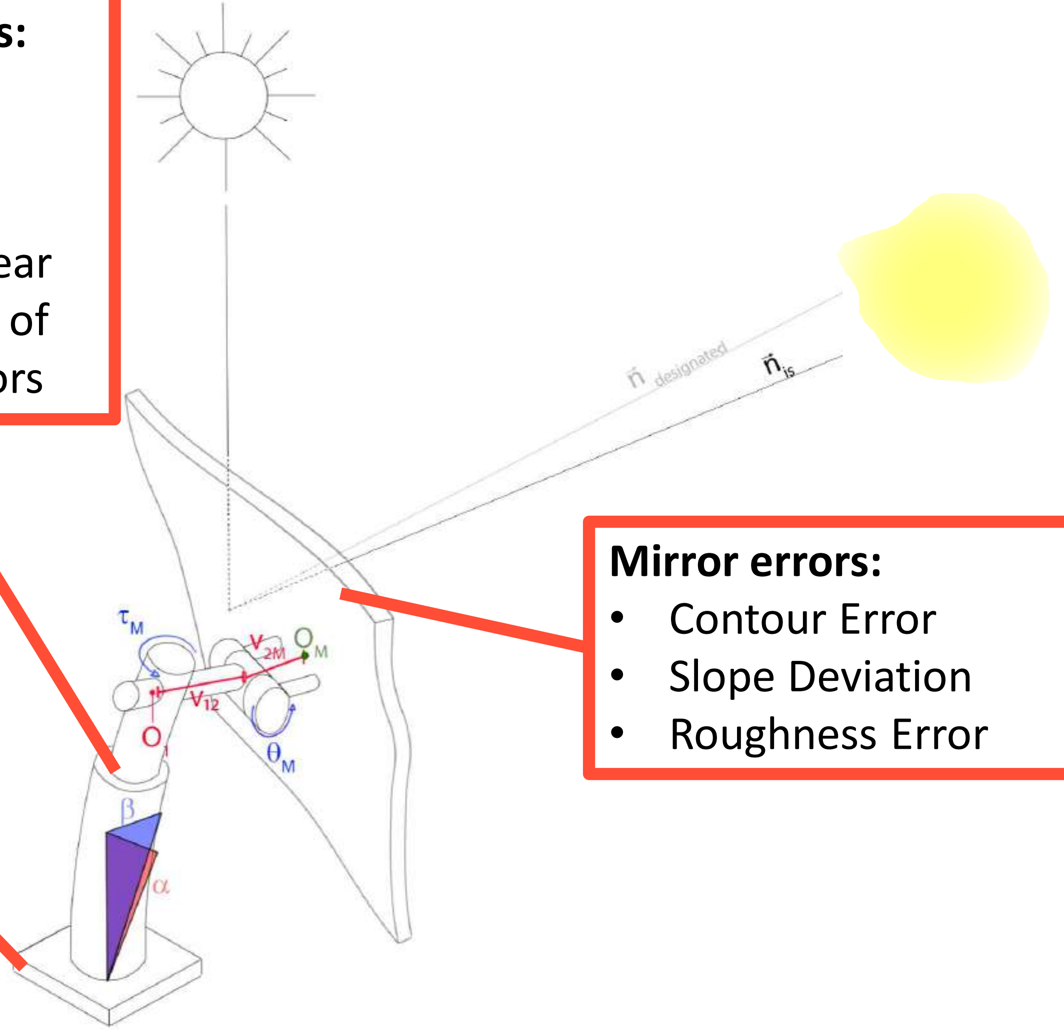


Mirror errors:
- Contour Error
- Slope Deviation
- Roughness Error

Alignment errors:
- Wind load
- Rigidity
- Sag
- Backlash / Wear
- Misscounting of Stepper Motors



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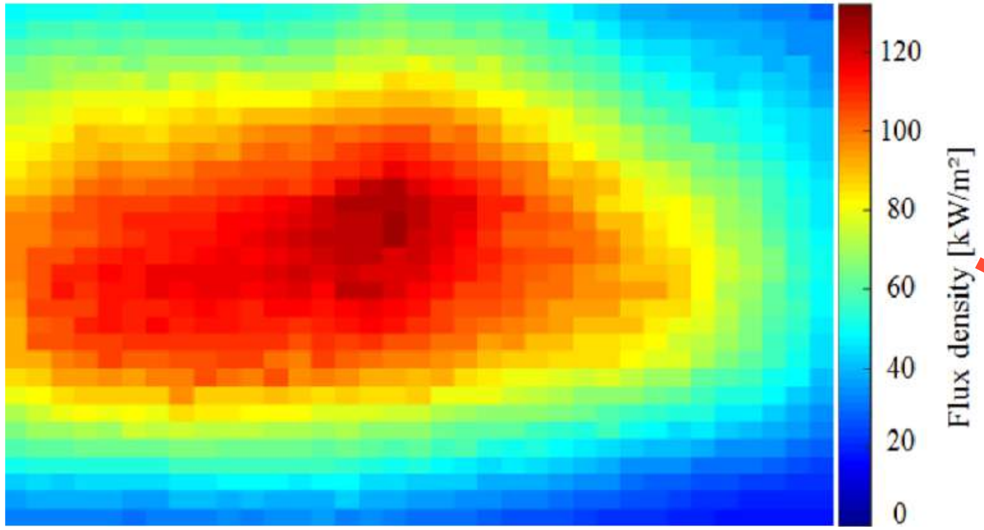

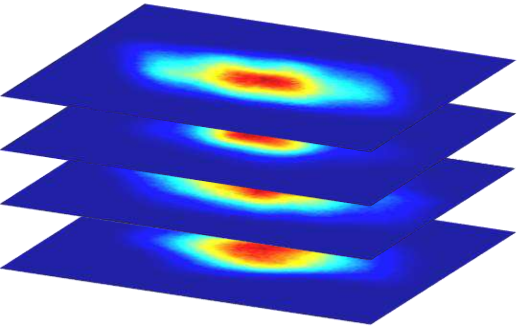

Difficulties:

- Unique Pointing Command
- Quality of Calibration
- Command Delay
- No Sensors
- No Measurement

Diagnosis

Heliostat soiling; changes in alignment and mirror curvature; Receiver heat spikes

Control

Aimpoint Assignment/Optimization; in dependency of; Lacky Calibration, Mirror Defomrations

Prediction

Optimized control strategies for upcoming weather condtions

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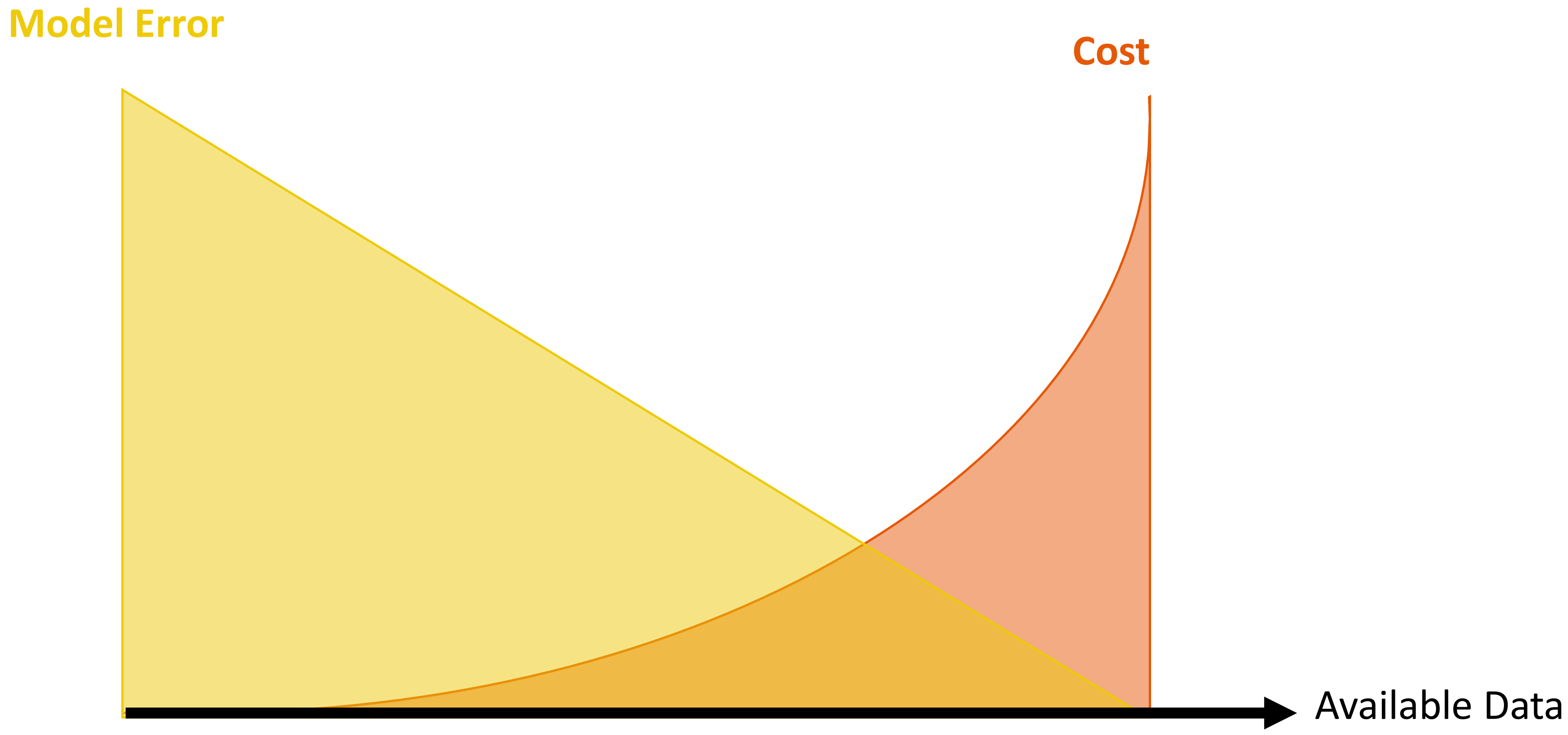
Prediction

Optimized control strategies for upcoming weather condtions

Difficulties:
- Open Loop Control
- Measurements for
  - Calibration are slow
  - Mirror deformations are unreliable and cost intensive
  - Flux measurements are experimental[1] or cost intensive

Solution:
- Closed Loop Control
- Install More Sensors



[1] Offergeld, Matthias, et al. "Flux density measurement for industrial-scale solar power towers using the reflection off the absorber." *AIP Conference Proceedings*. Vol. 2126. No. 1. AIP Publishing, 2019.

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- Open Loop Control
- Measurements for
    - Calibration are slow
    - Mirror deformations are unreliable and cost intensive
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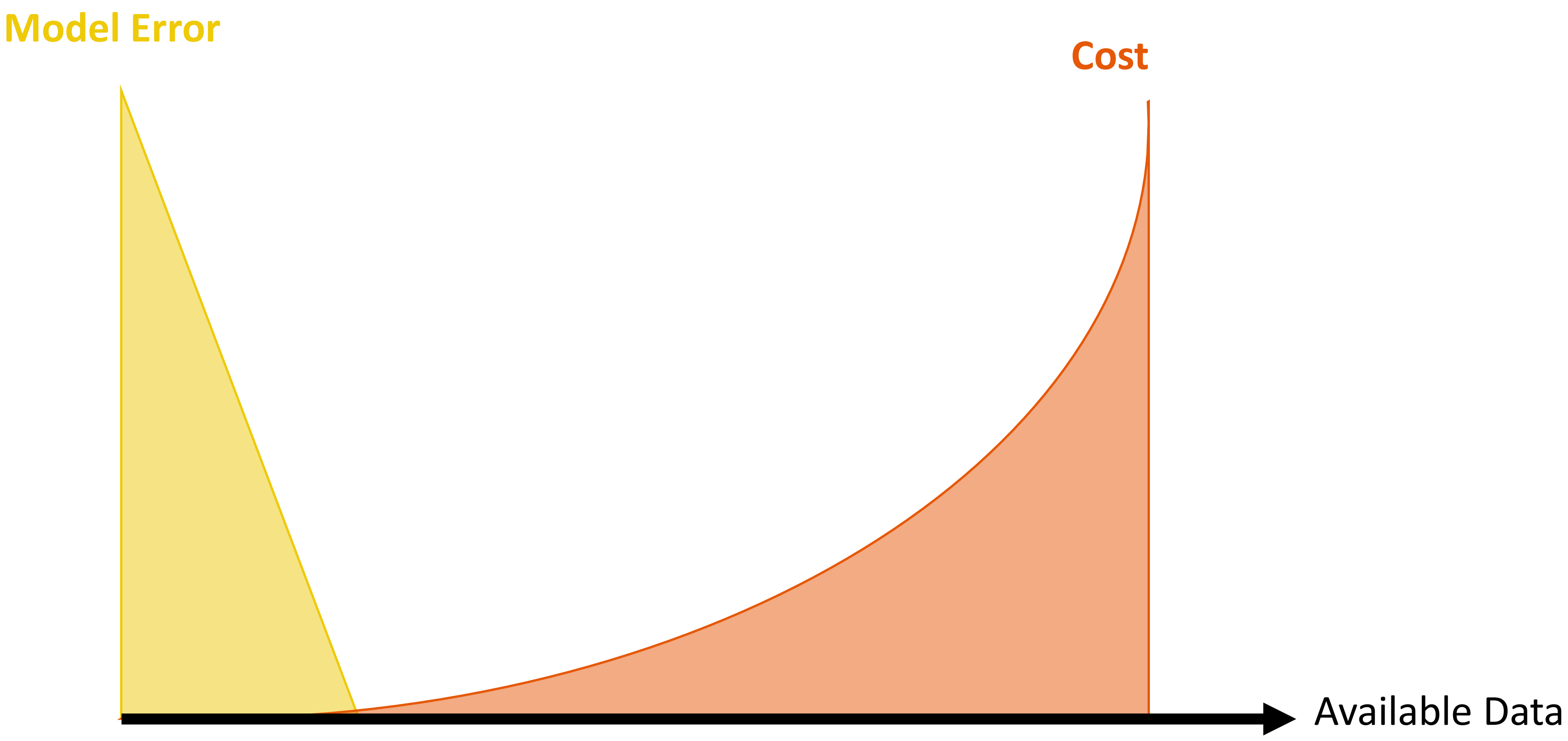
Solution:
- Closed Loop Control
- Install More Sensors
- **Use Modern Algorithms**



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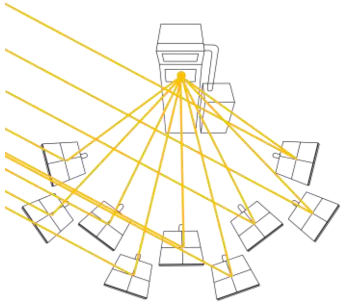
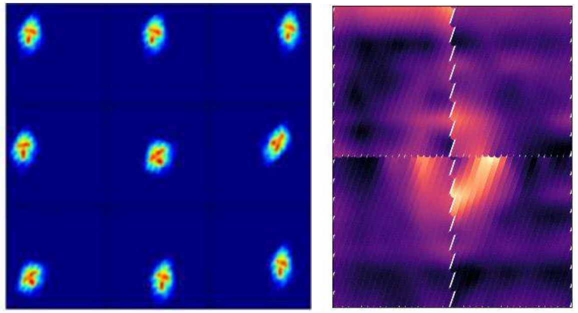
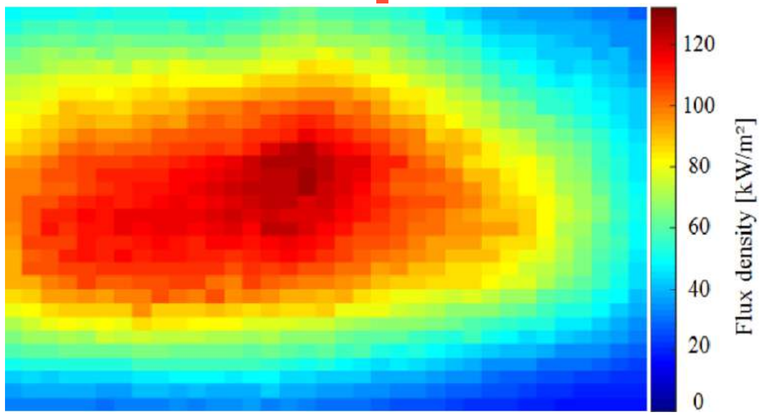
Methods

Heliostat Control



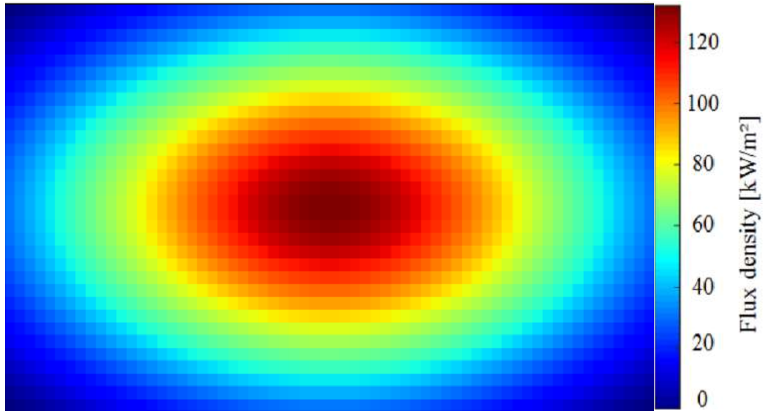


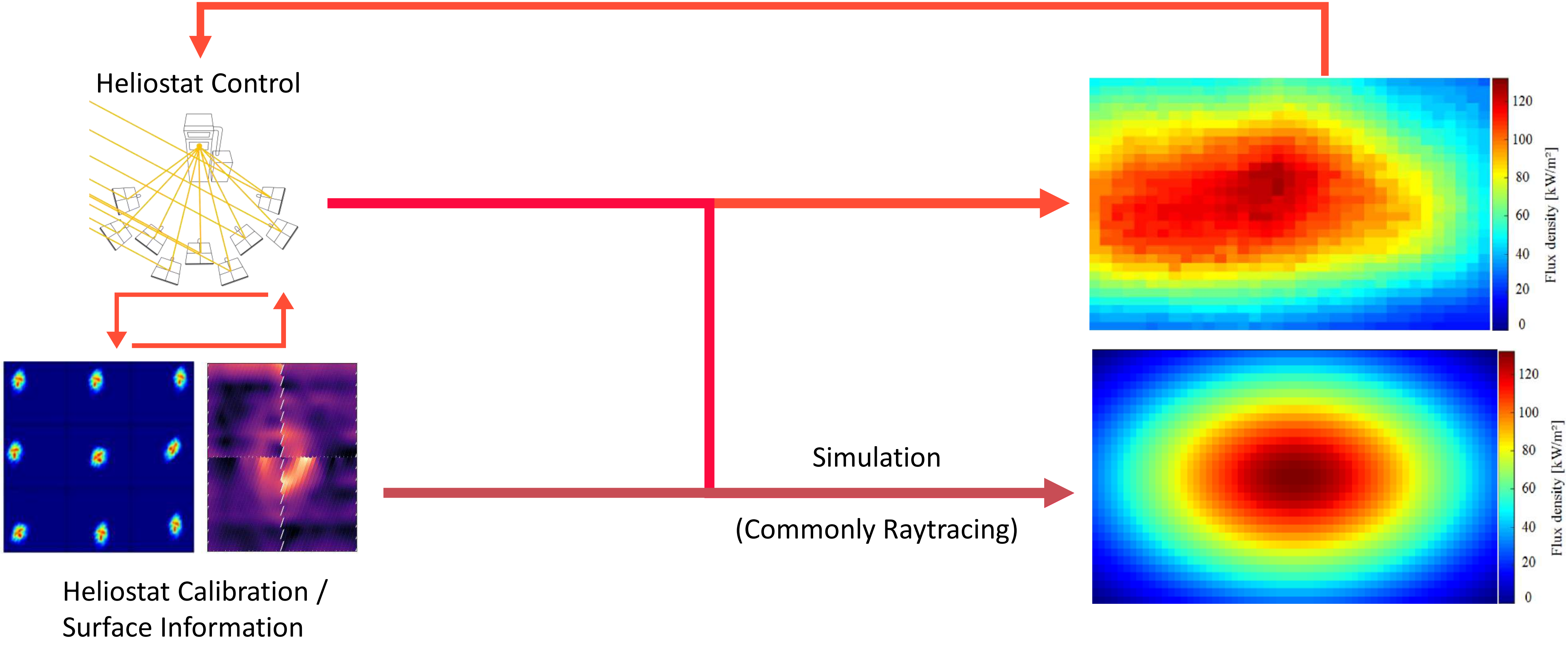
Heliostat Calibration /
Surface Information



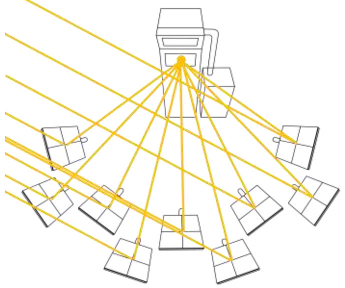
Simulation

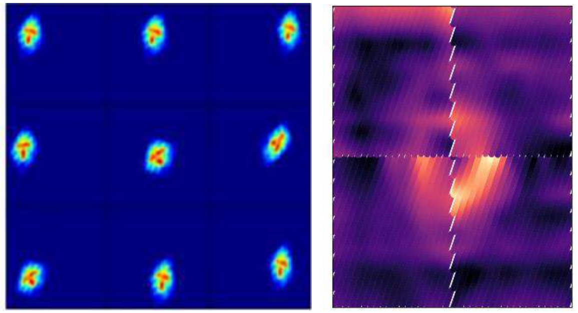
(Commonly Raytracing)




Heliostat Control
Heliostat Calibration /
Surface Information
Simulation
(Commonly Raytracing)
120
100
80
60
40
20
0
Flux density [kW/m²]

Heliostat Control





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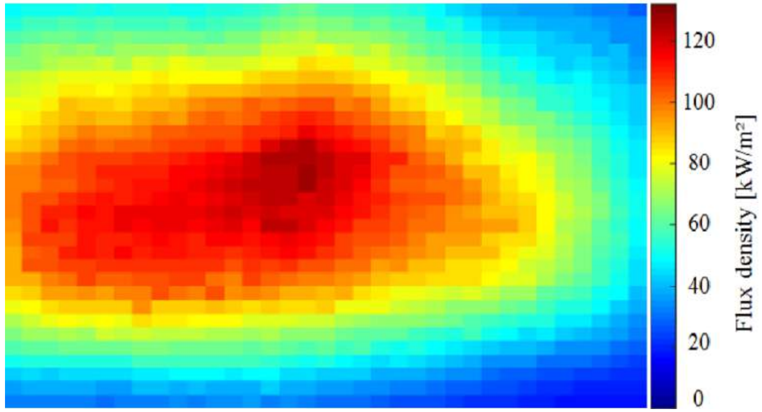
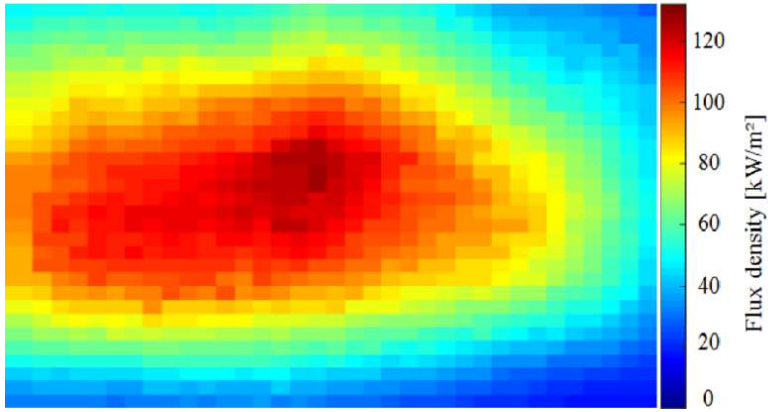
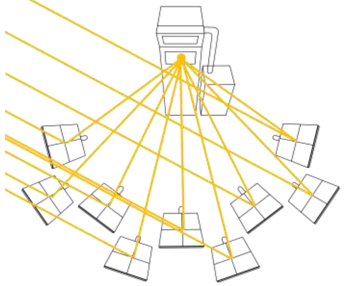




Heliostat Control



Control

Diagnosis

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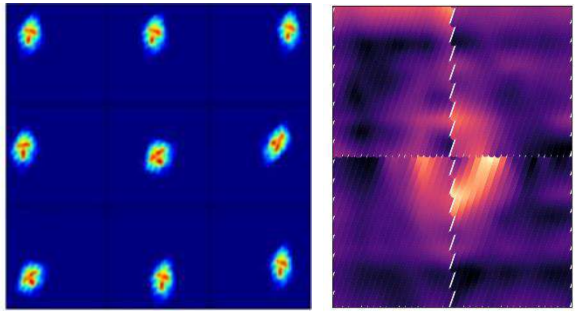
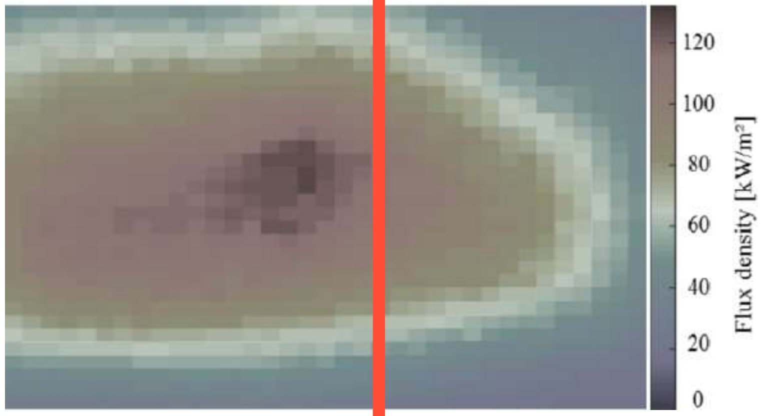
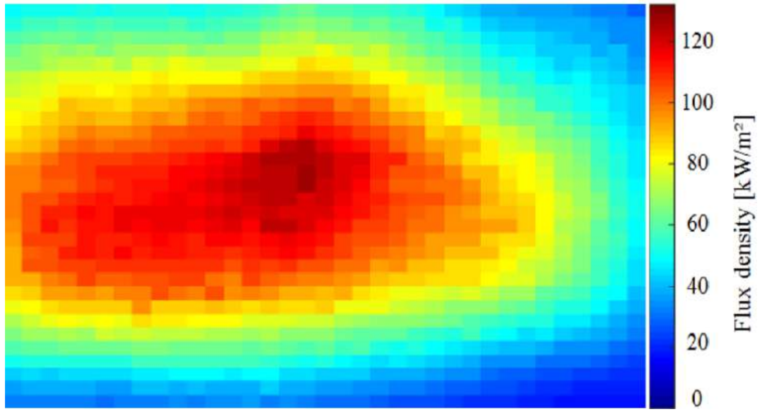


Heliostat Calibration / Surface Information

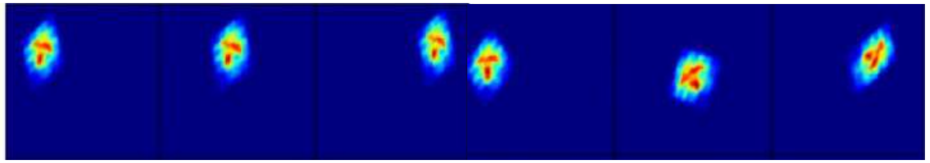




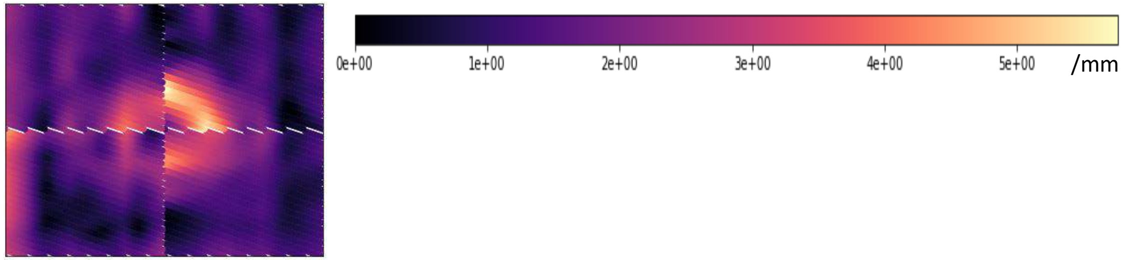
Prediction

In a commercial power plant, we have access to a maximum of:

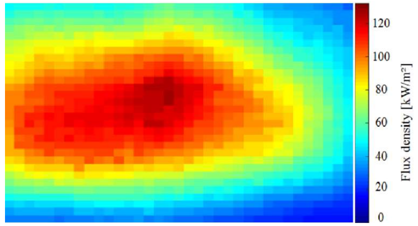
Calibration Data → ca 10-100 per Heliostat

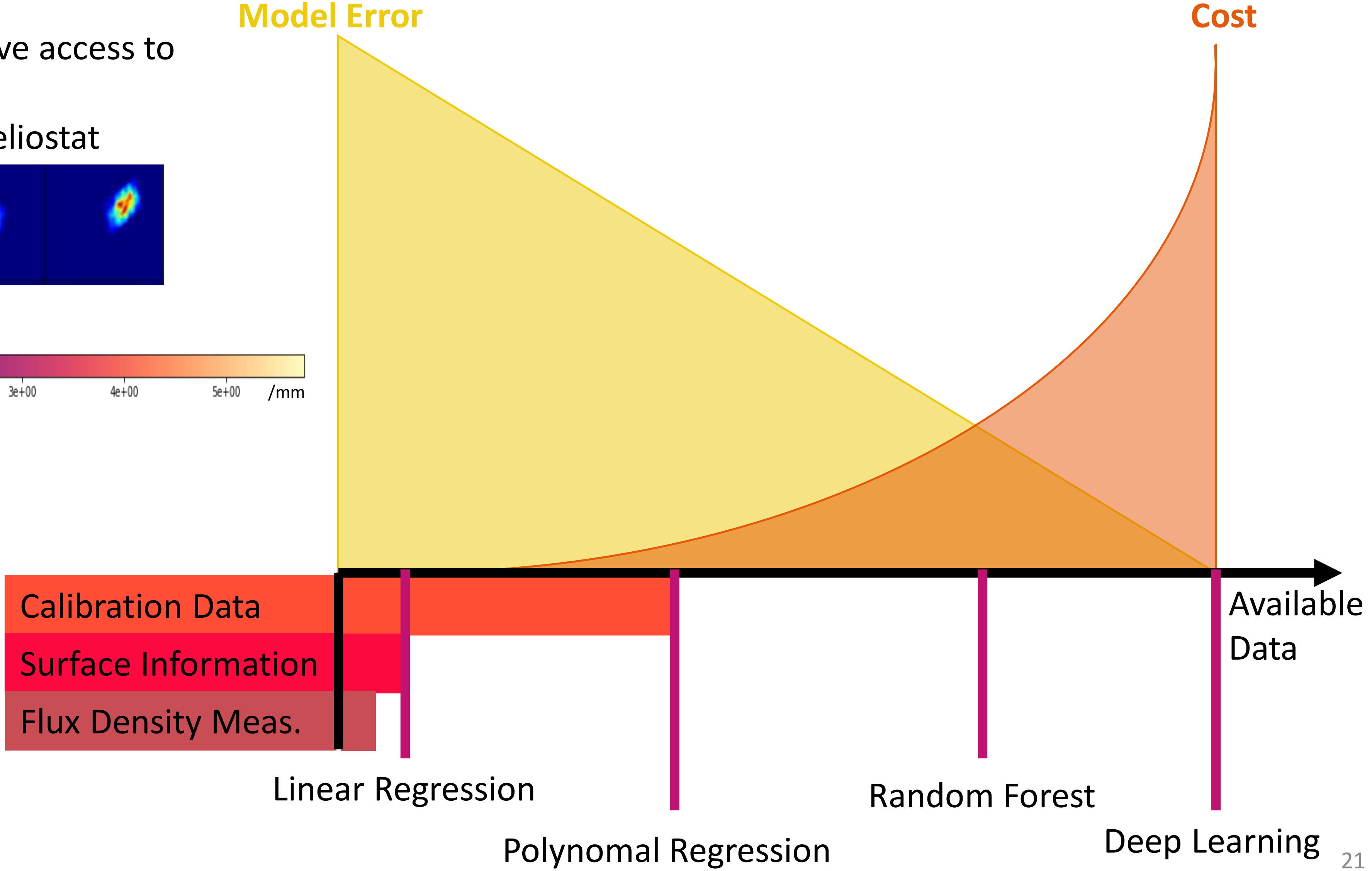


Surface Information → A few dozen



Flux Density Measurements
→ None (yet)





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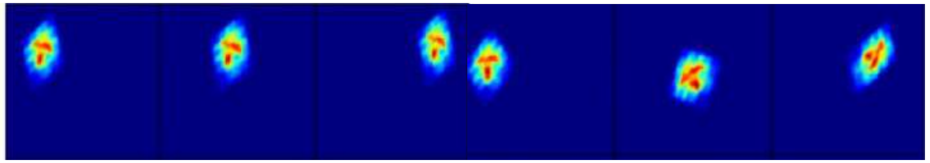

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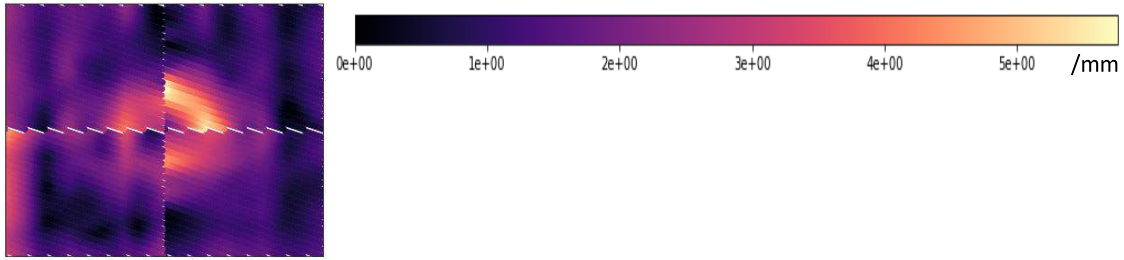

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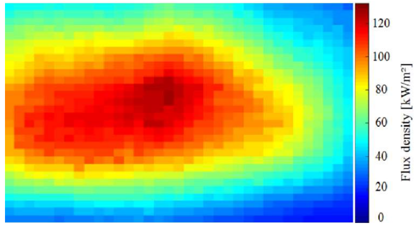
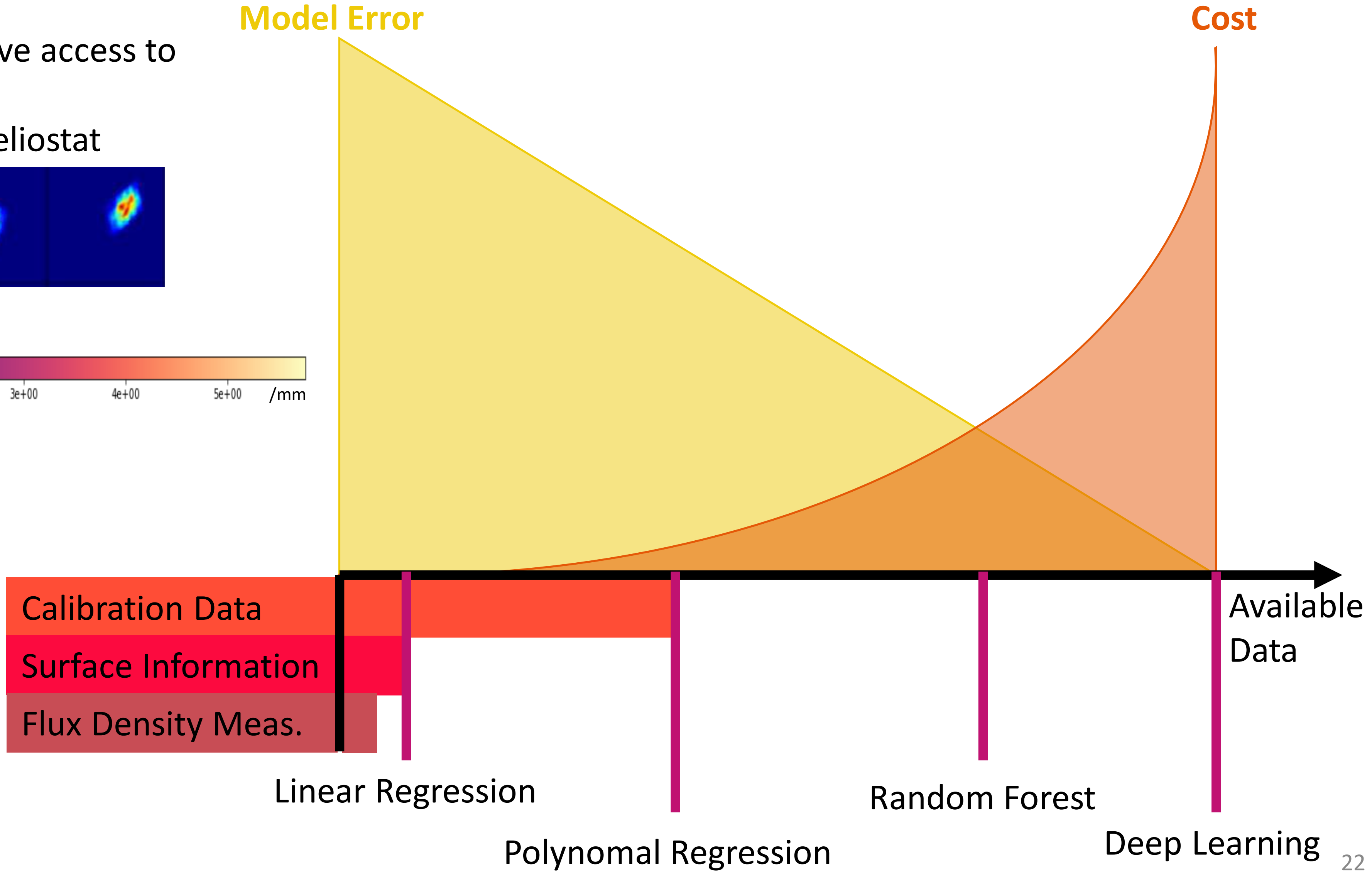
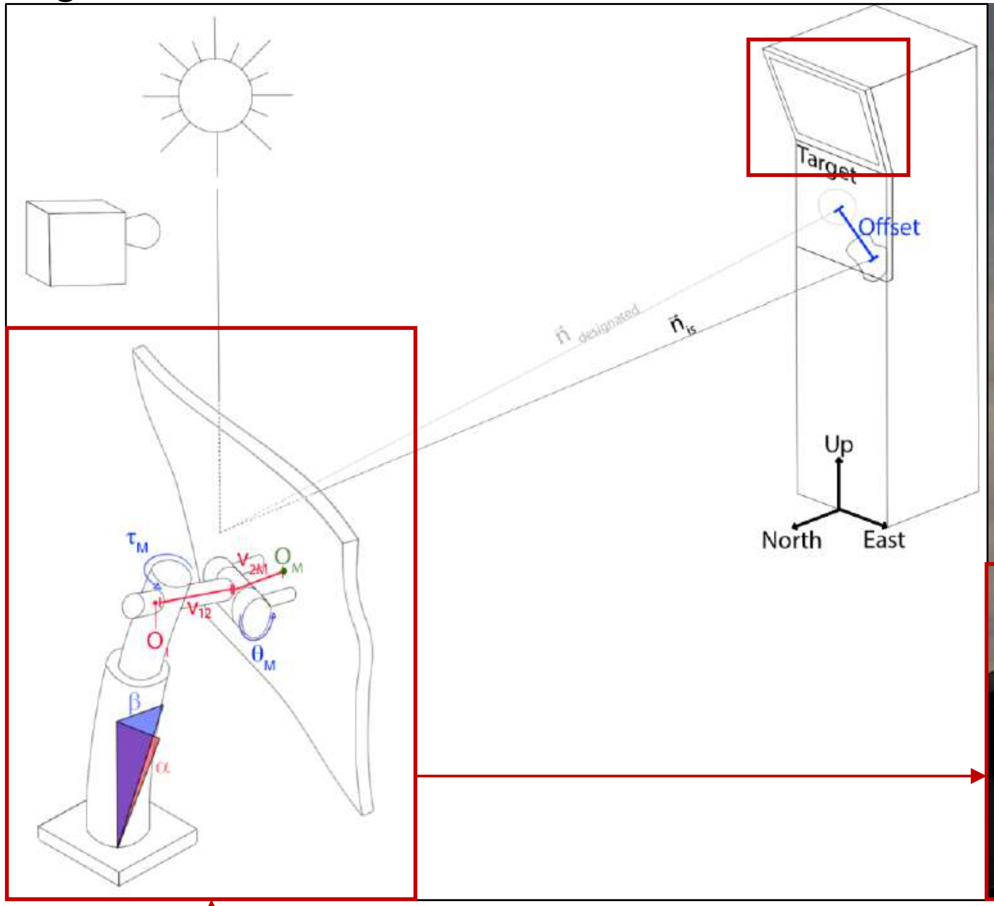
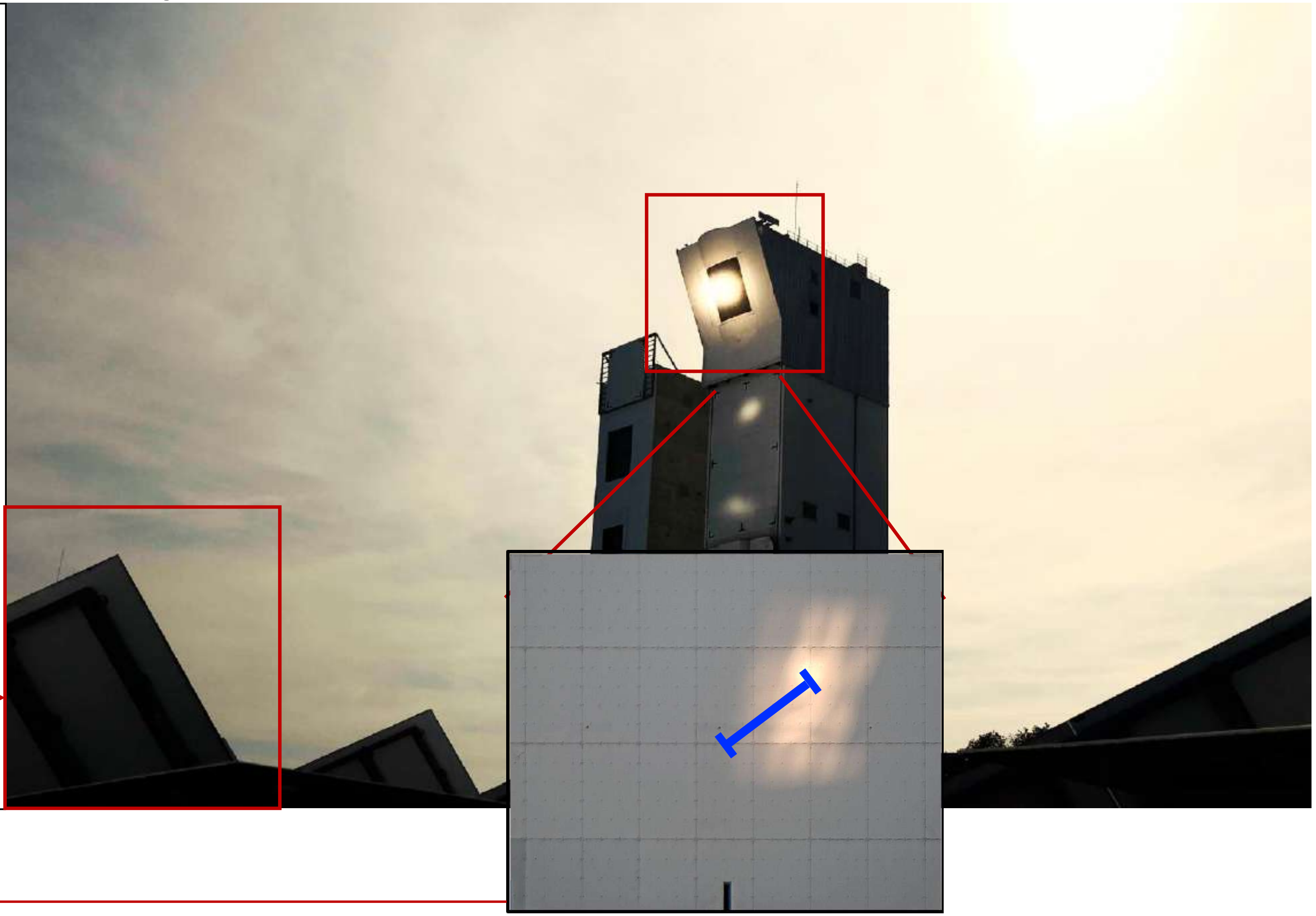




Digital Instance

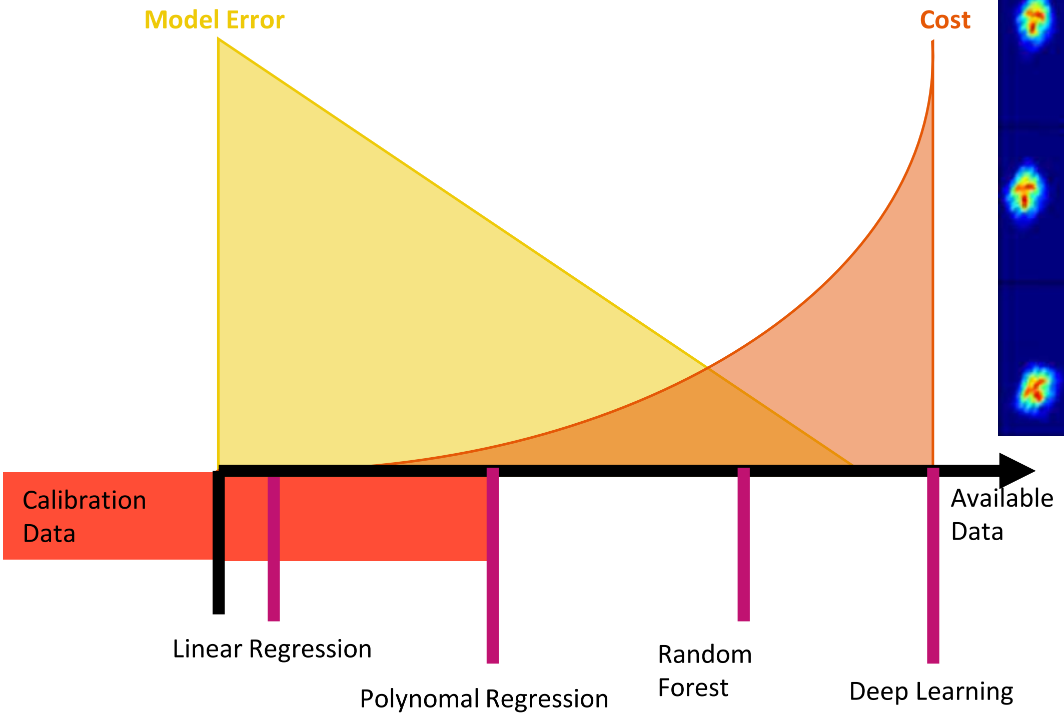


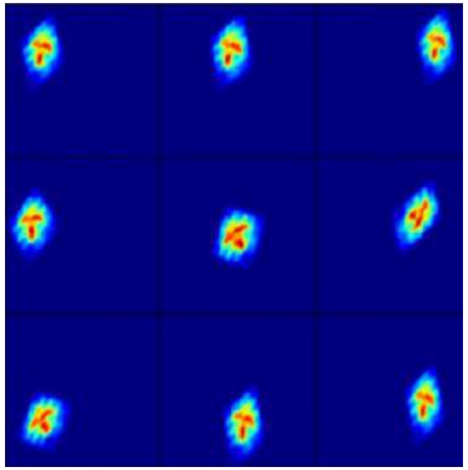
Real Object

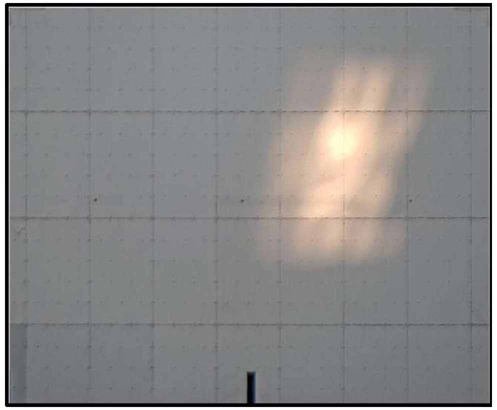


GANCSTR | ARTIST

How much information about each heliostat can be deduced from field data?



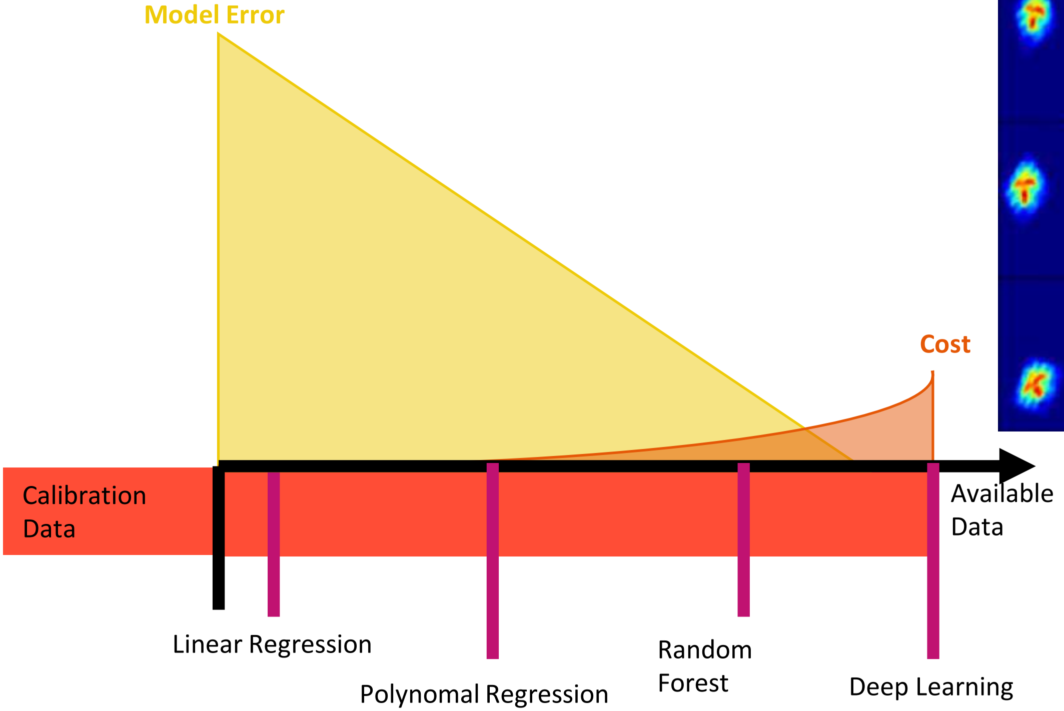


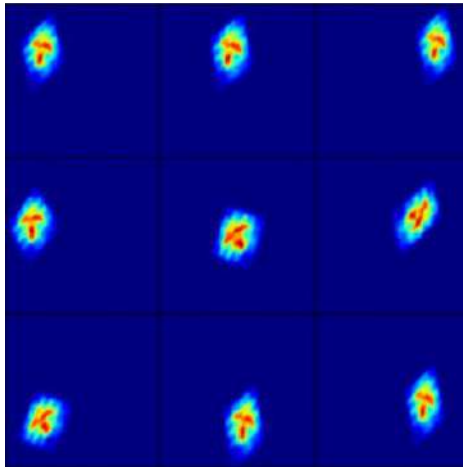


GANCSTR | ARTIST

How much information about each heliostat can be deduced from field data?

How much information can be deduced with as few data as possible?





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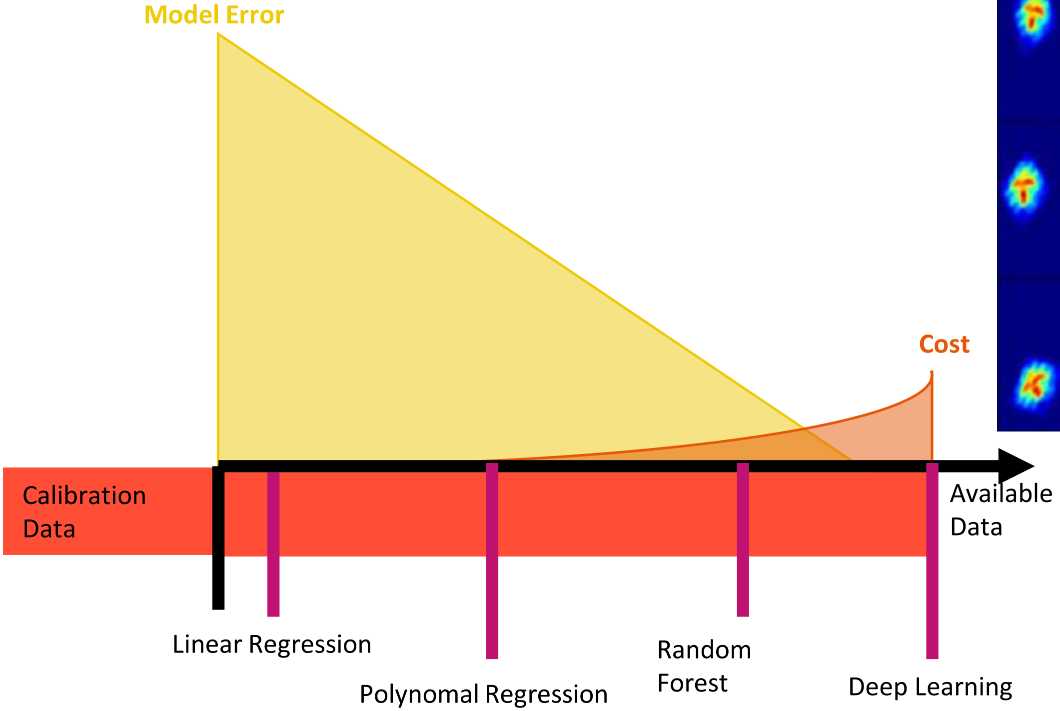

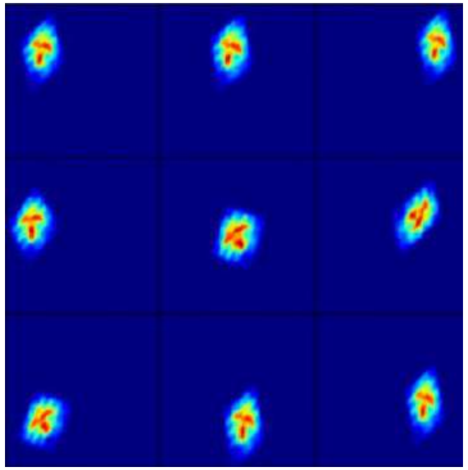

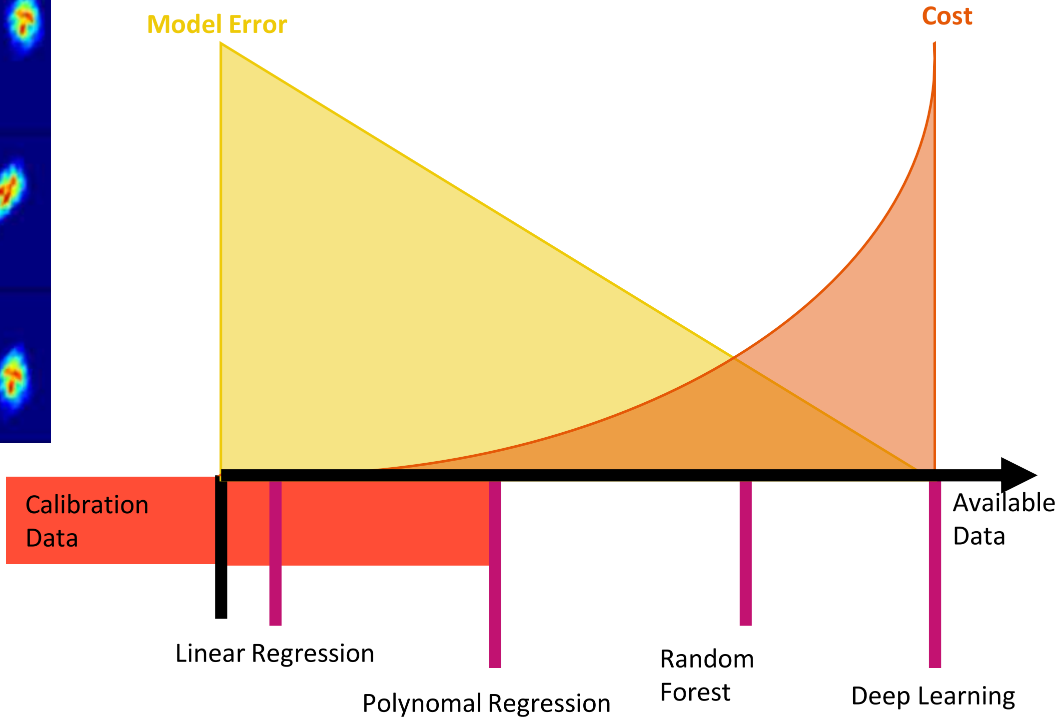

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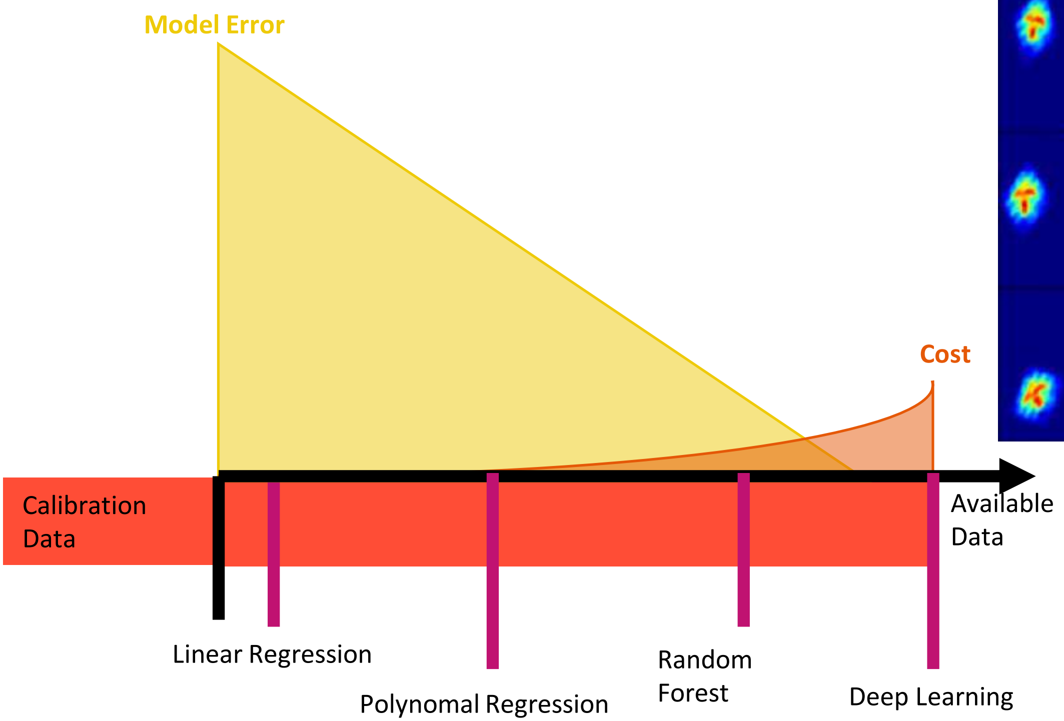
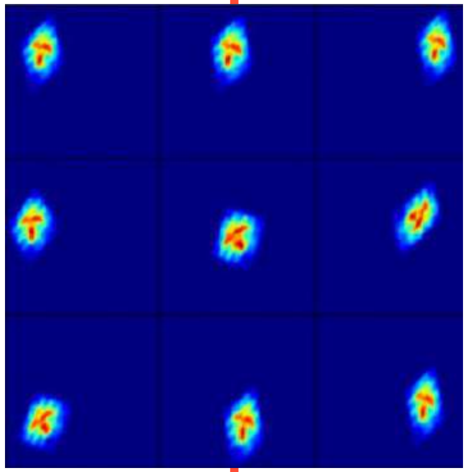
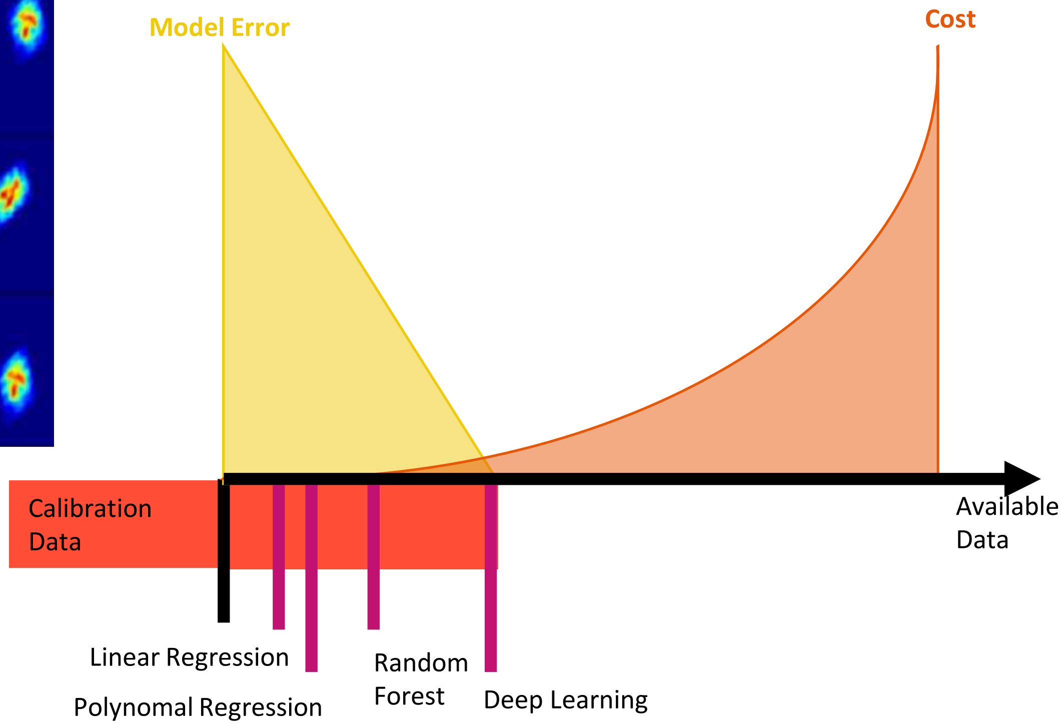
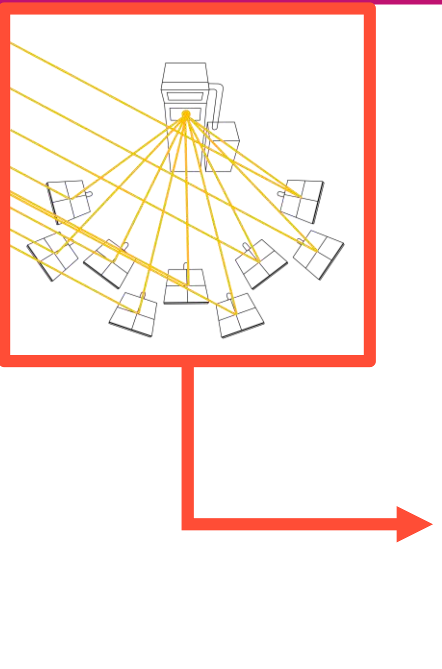
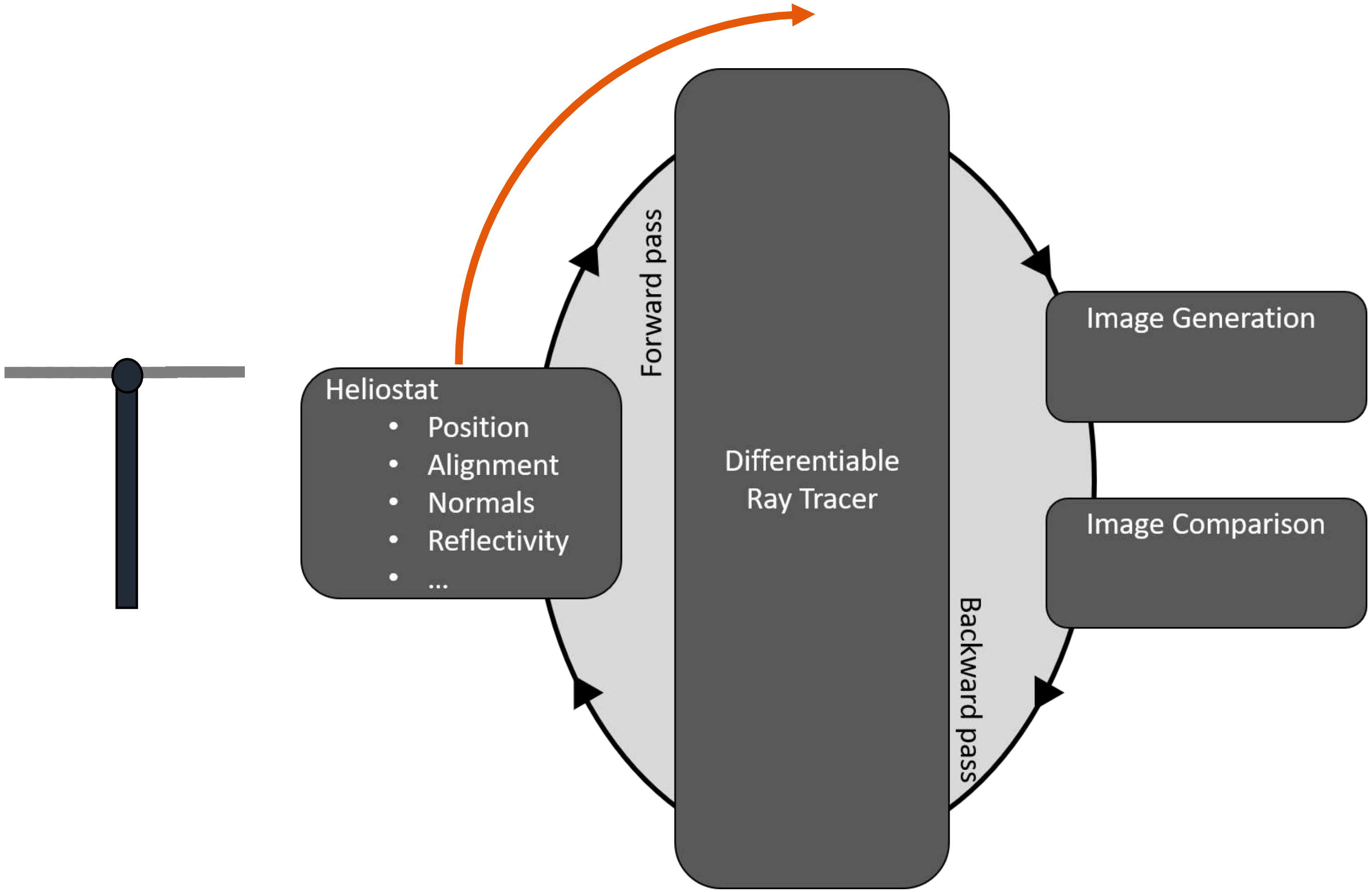


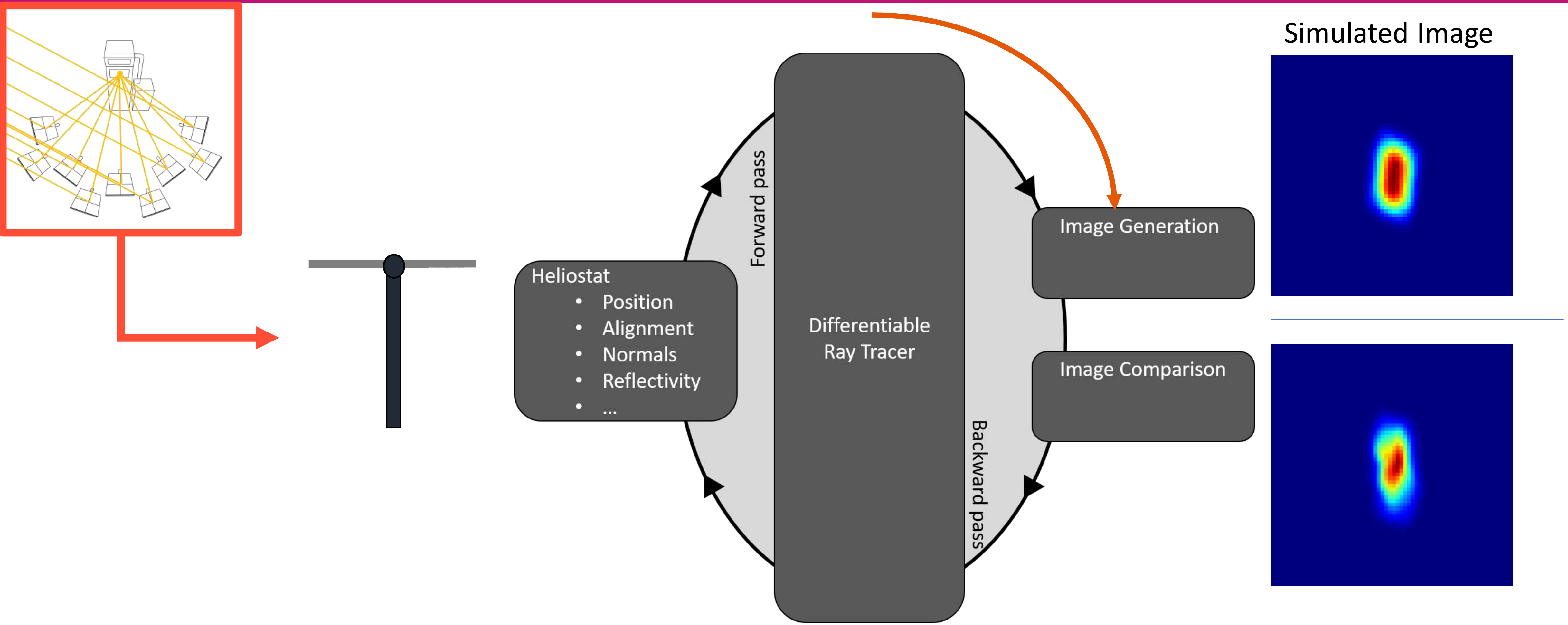




Methods: Differentiable Raytracing




Forward pass
Heliostat
• Position
• Alignment
• Normals
• Reflectivity
• ...
Differentiable
Ray Tracer
Image Generation
Image Comparison
Backward pass


Simulated Image
Heliostat
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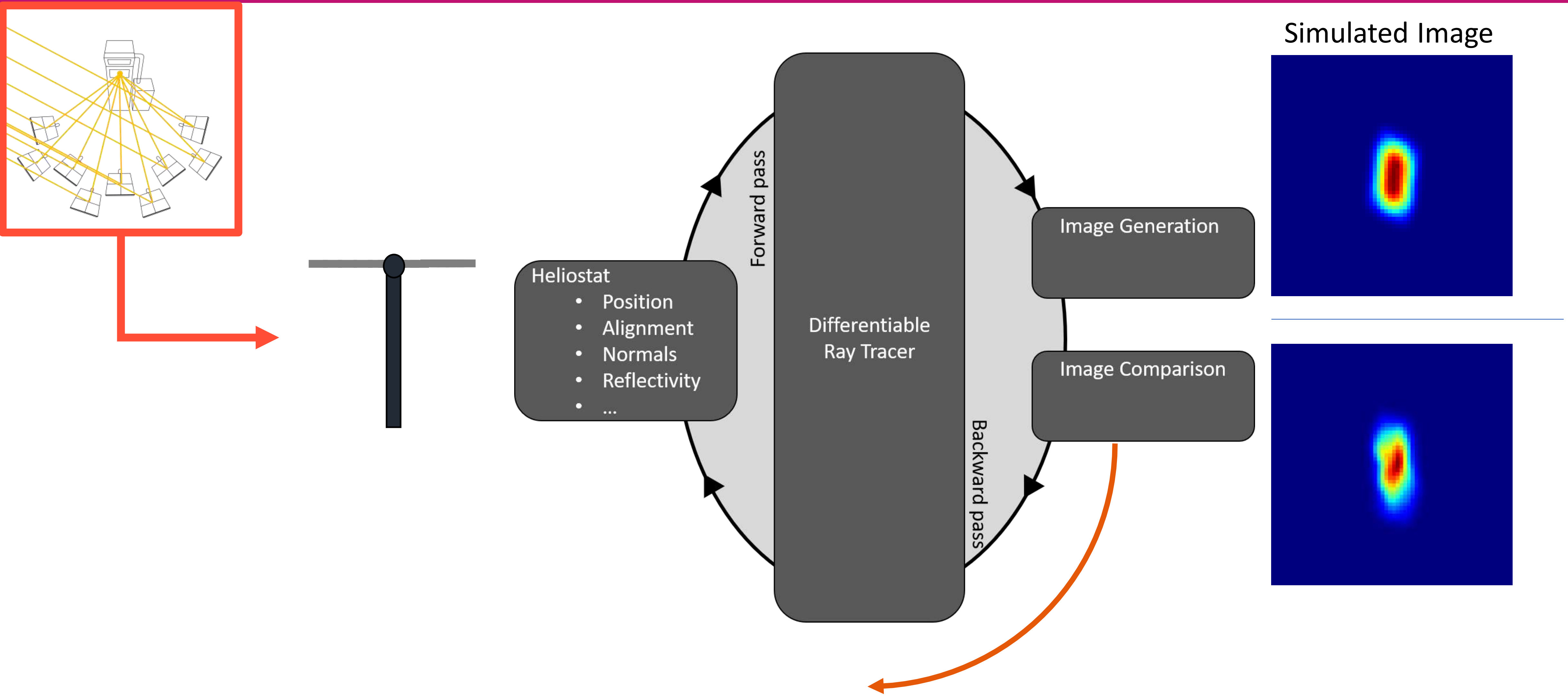
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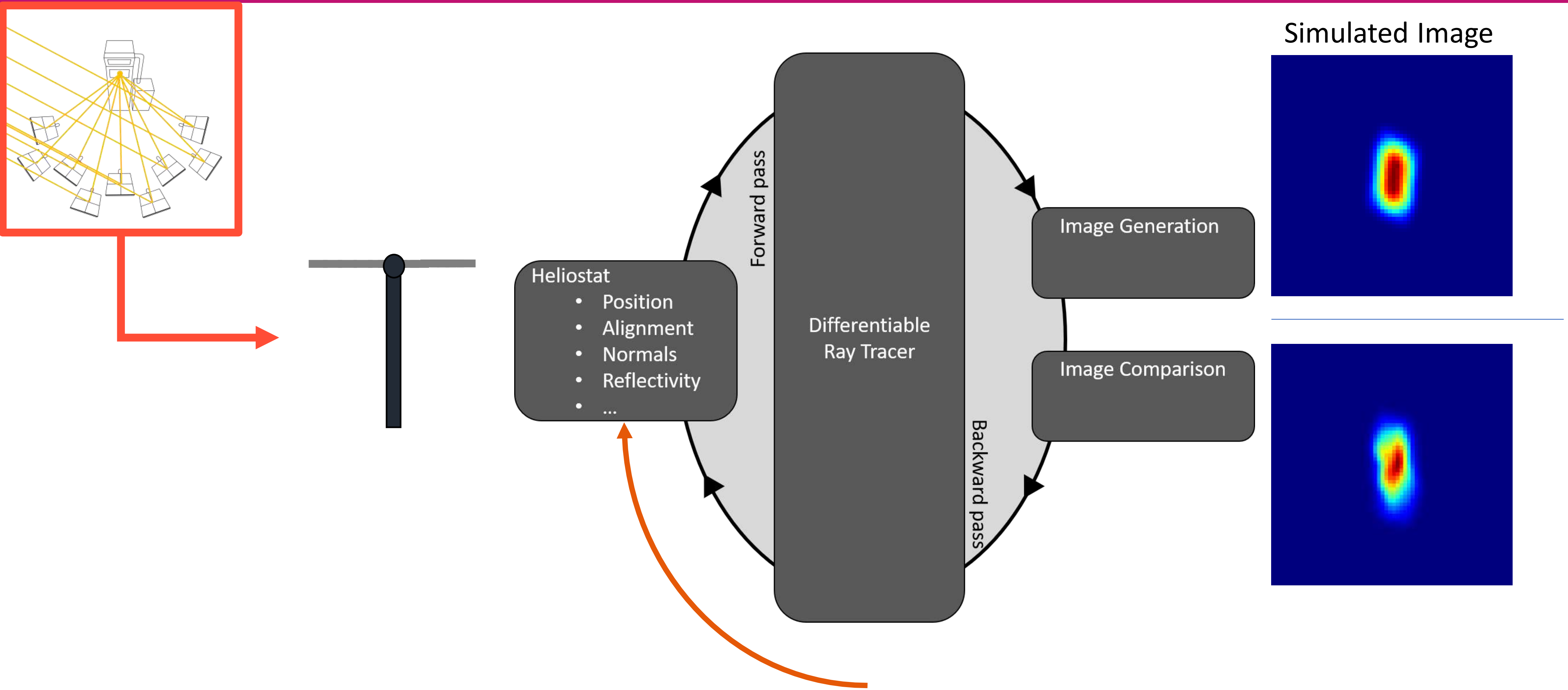
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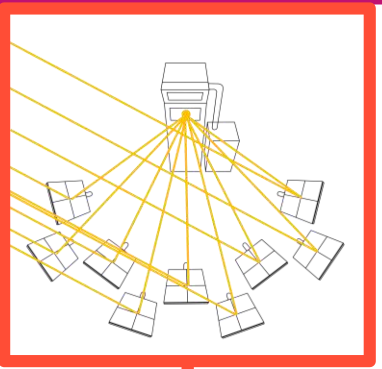

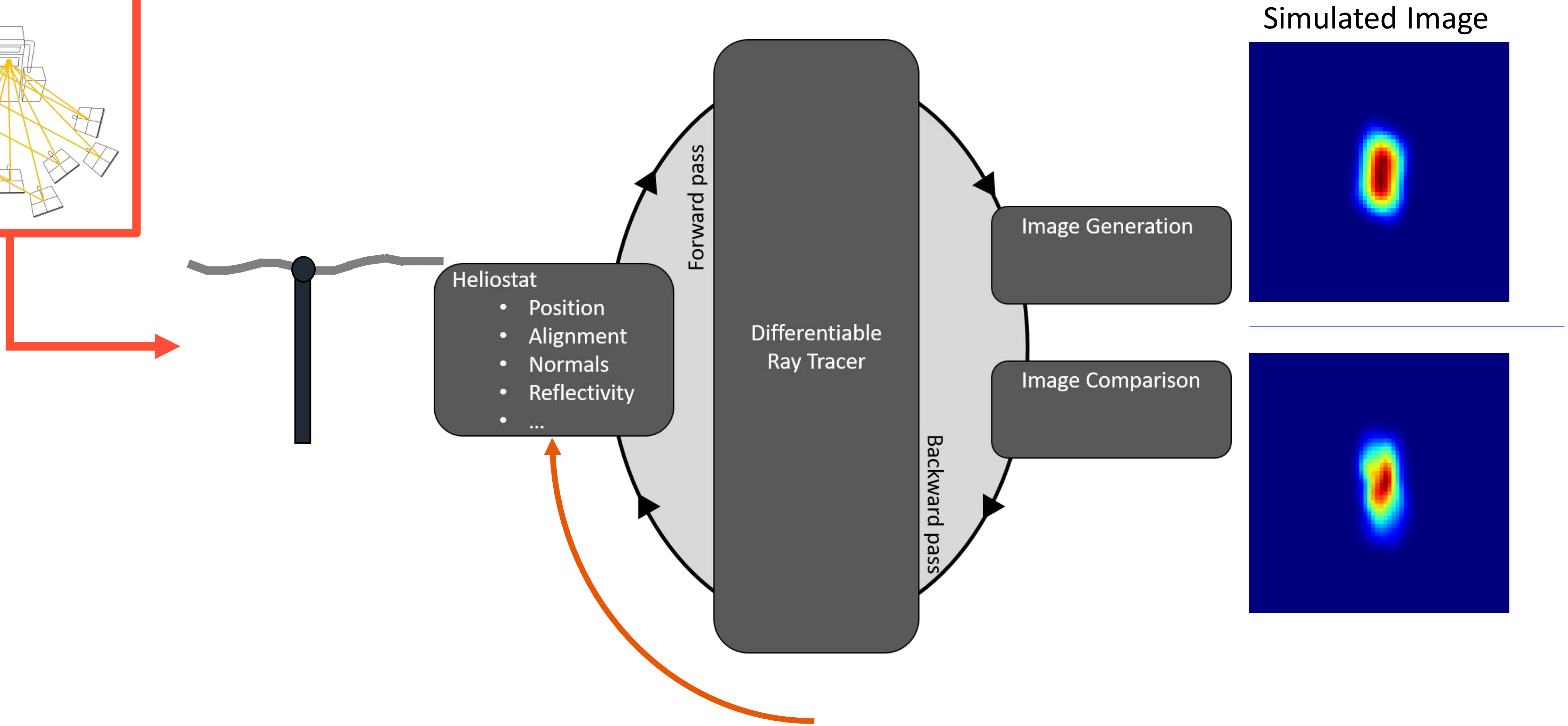
Heliostat
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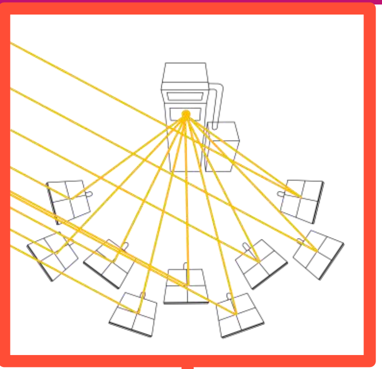
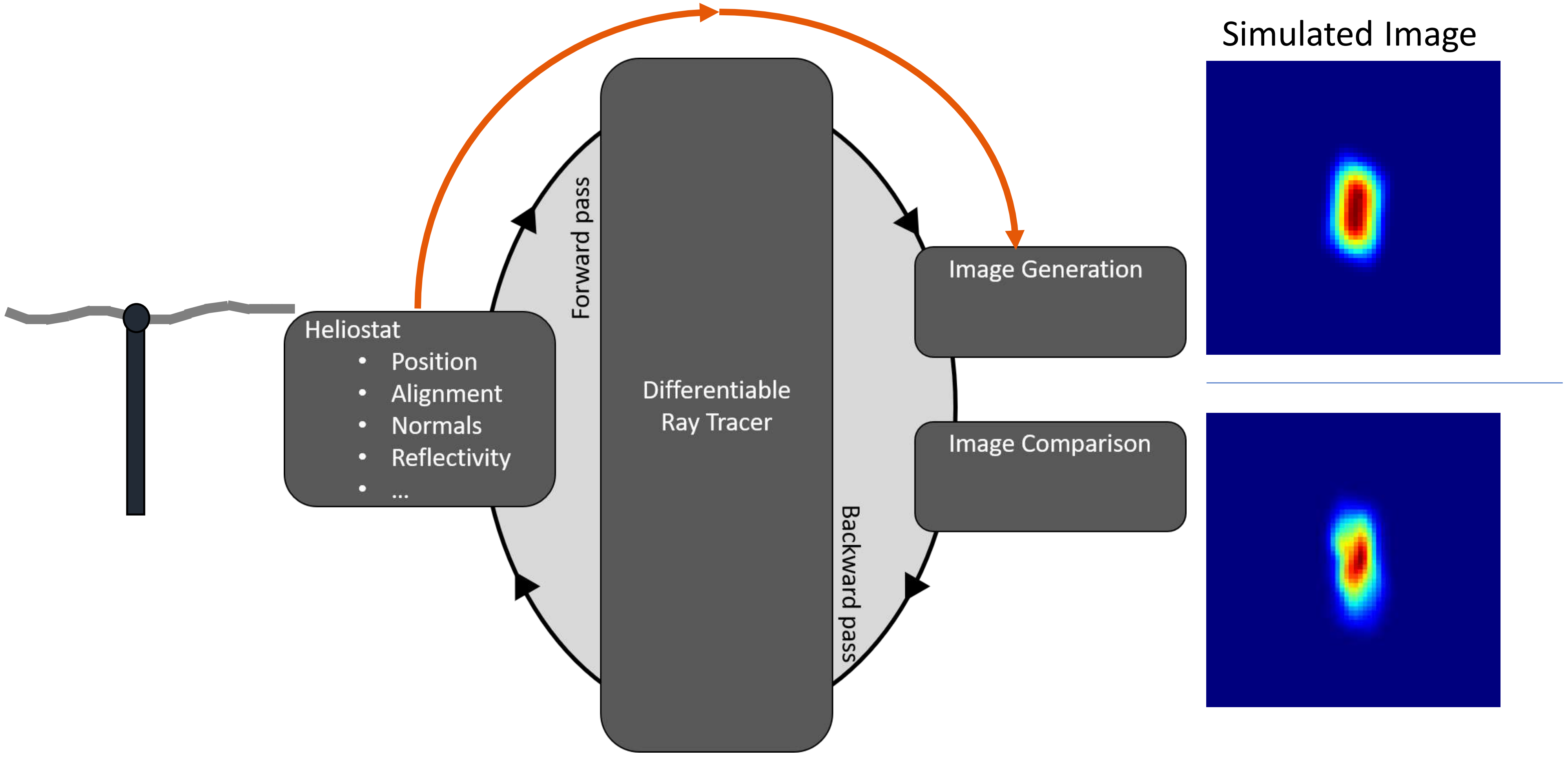
Simulated Image

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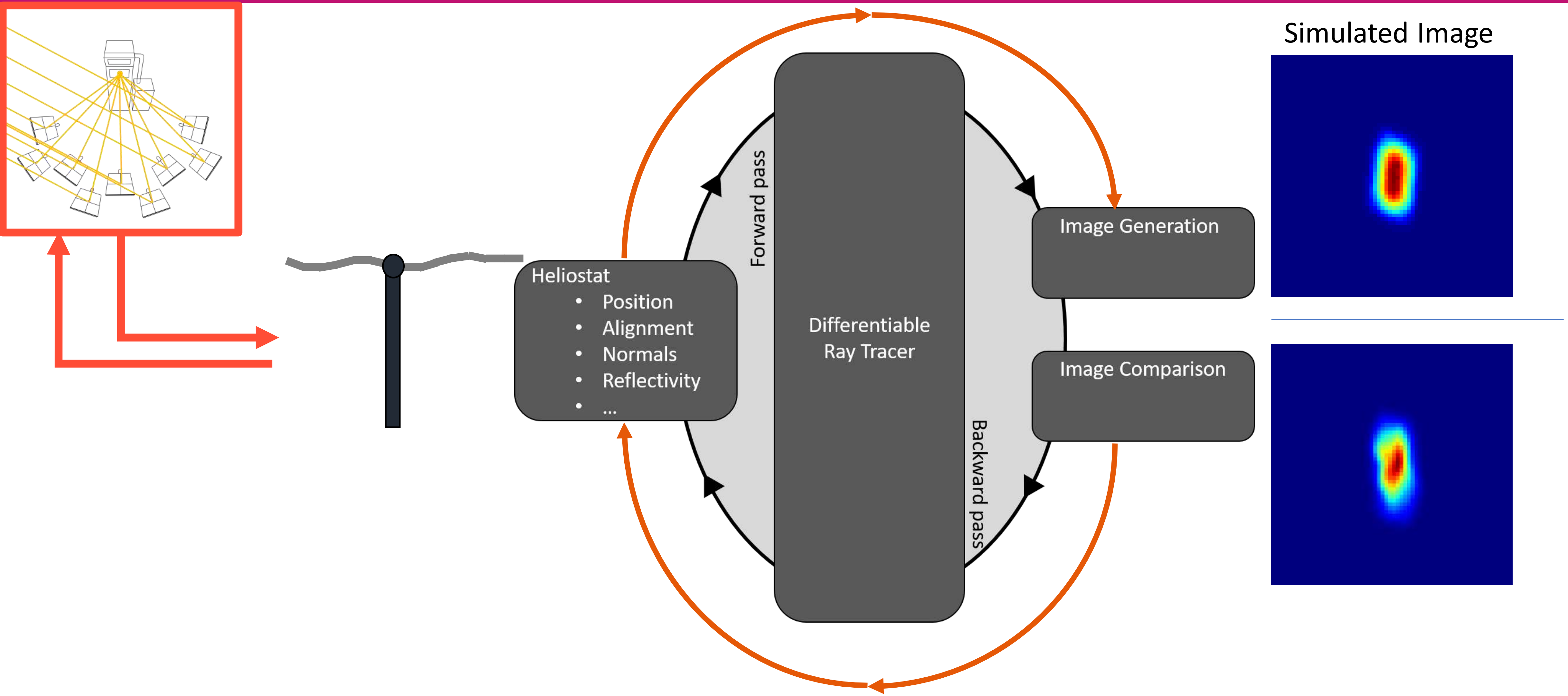
Simulated Image
Heliostat
Position
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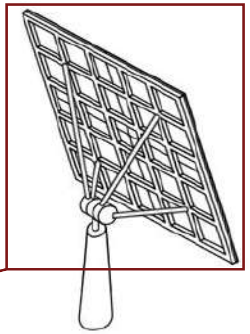
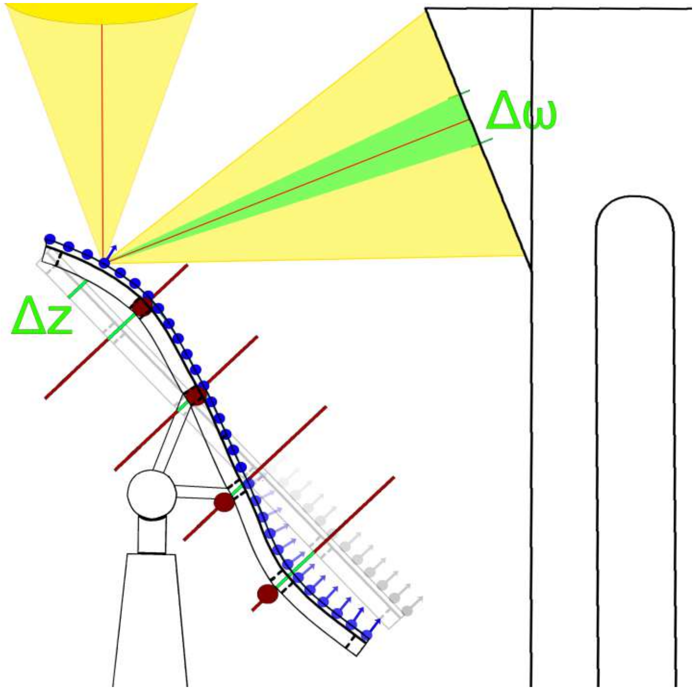
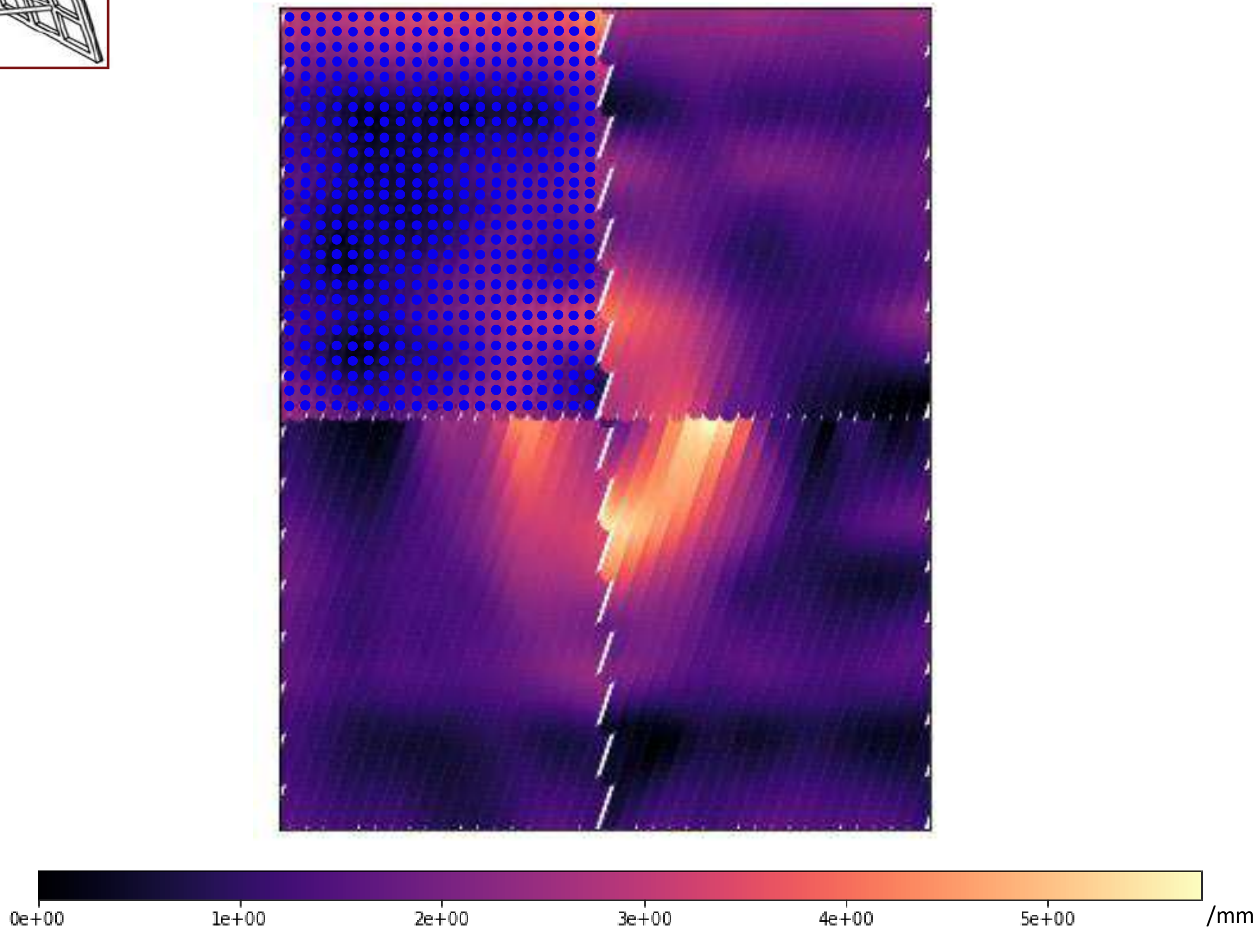
Diagnosis:
Detect Mirror Deformations

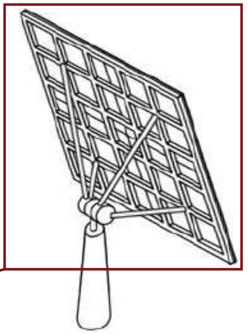


Continous NURBS heliostat surface



Ca. 25k points per facet





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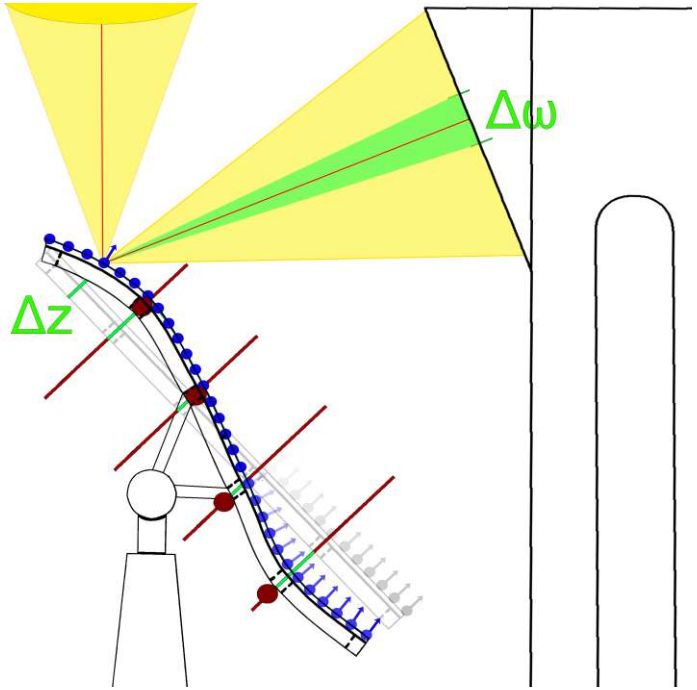
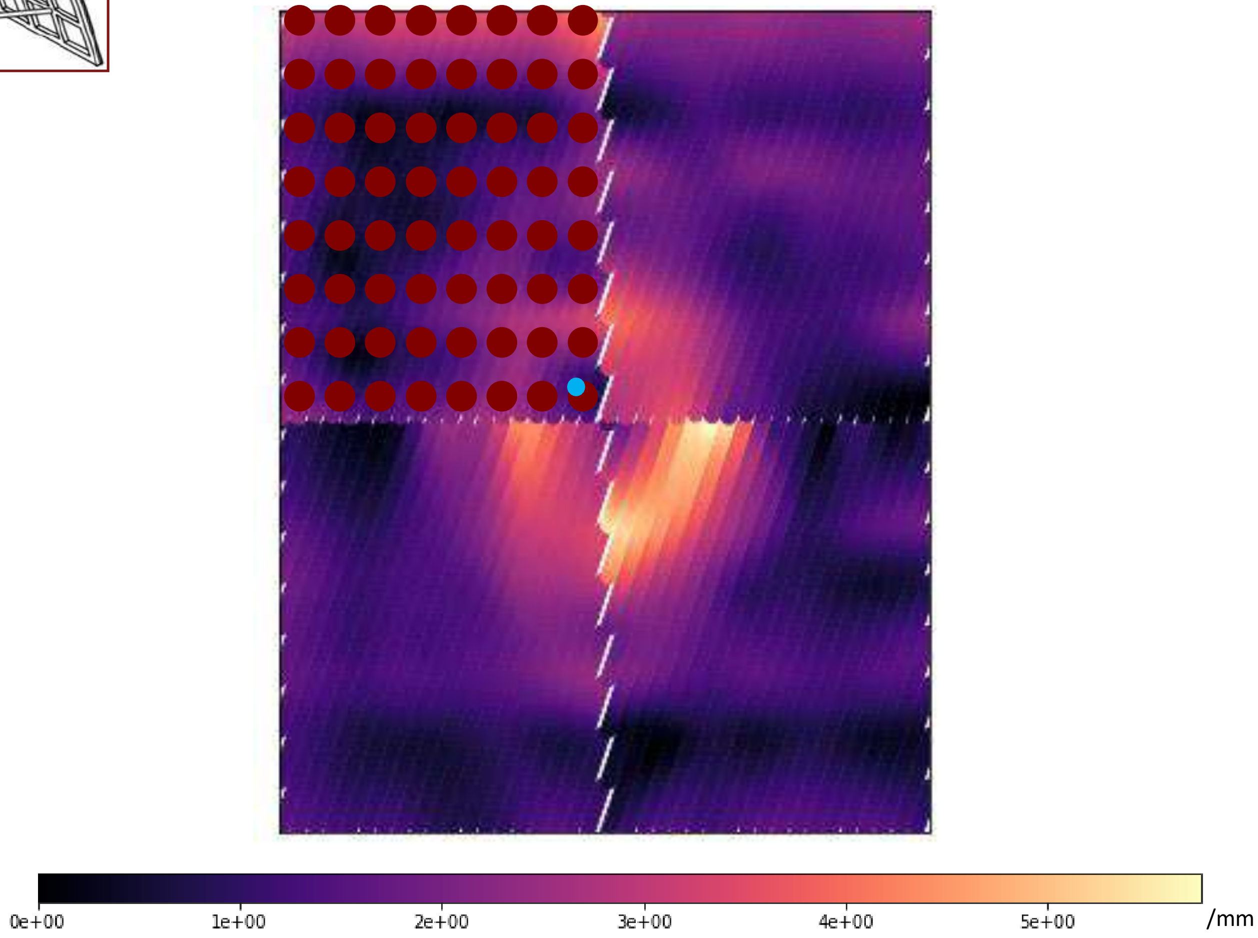


Ca. 25k points per facet

→ 64 points per facet with over 98% overlap



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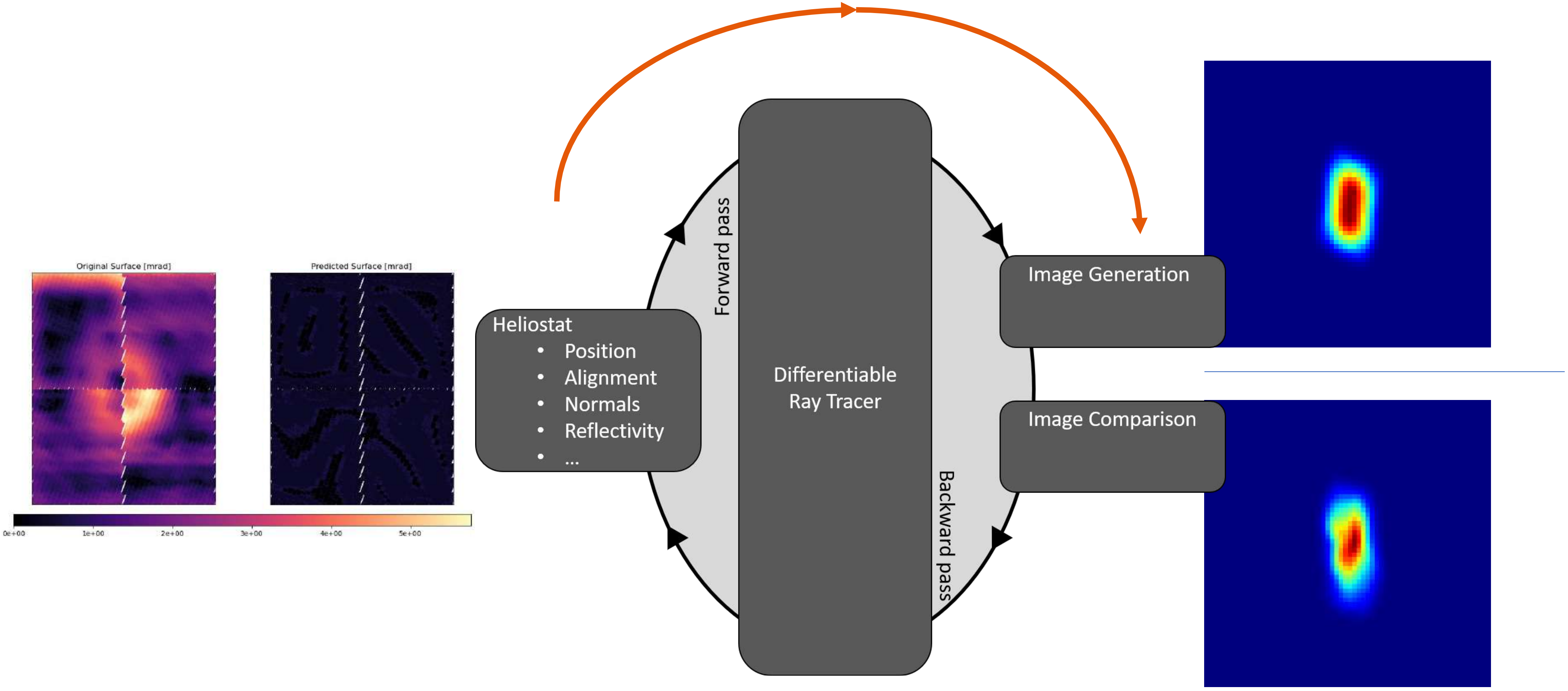
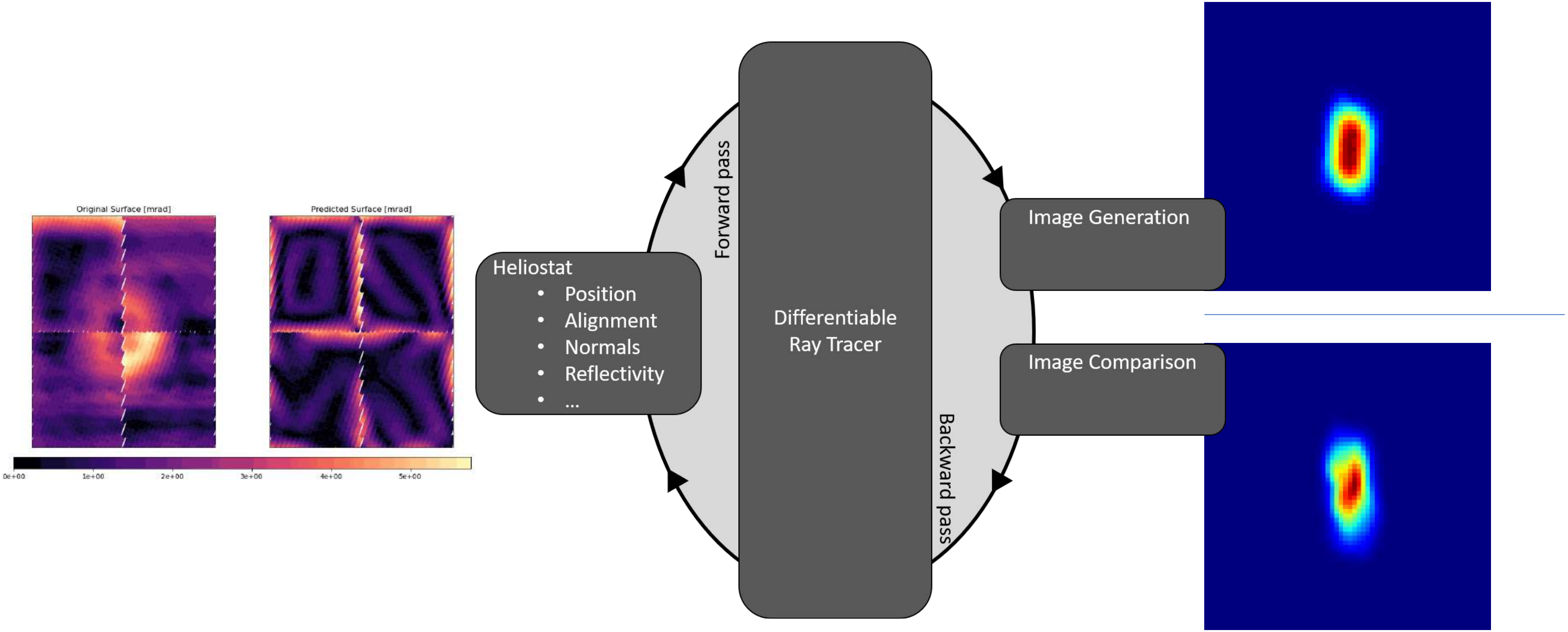
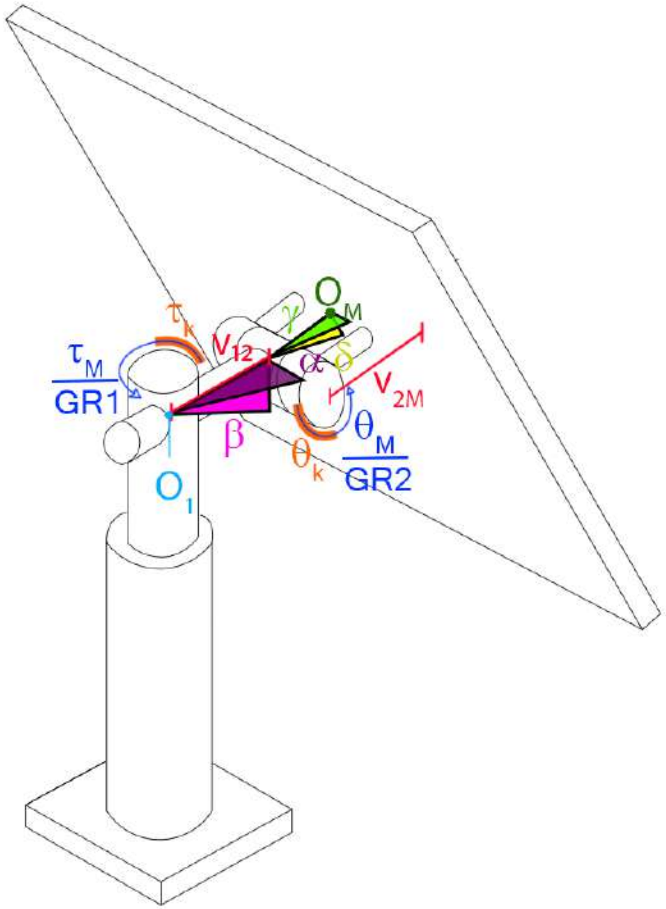
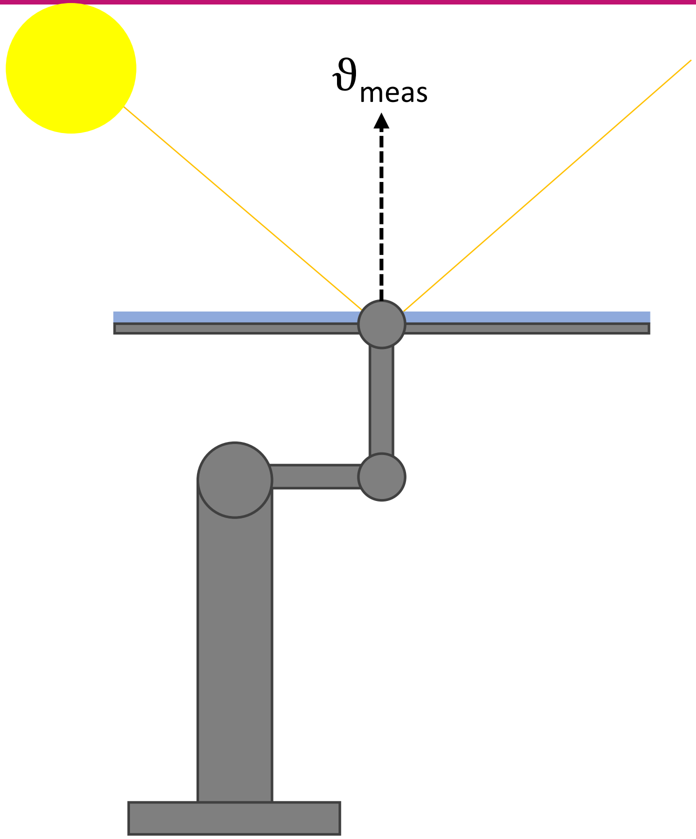


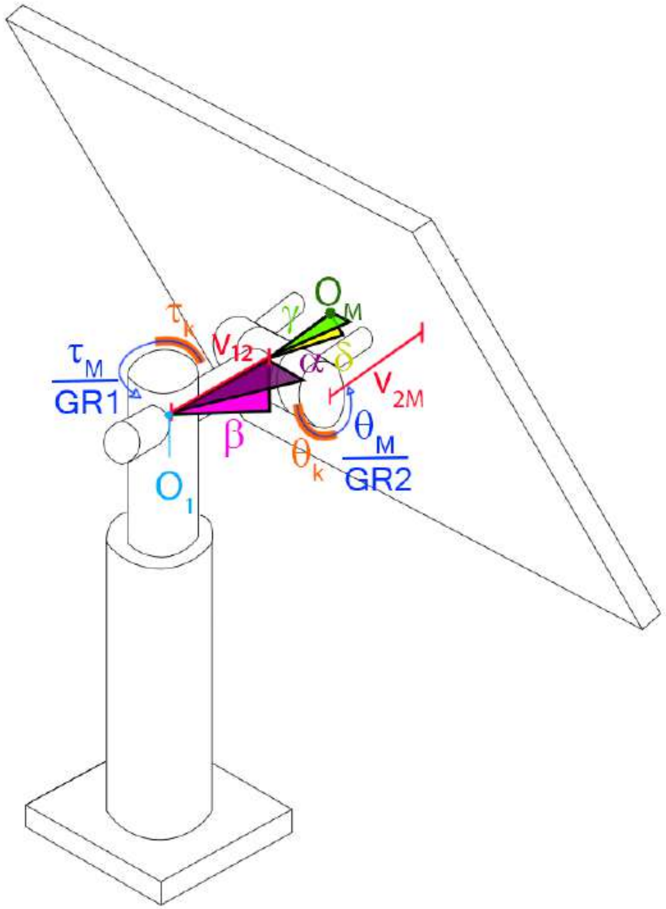

Original Surface [mrad]
Predicted Surface [mrad]
0e+00
1e+00
2e+00
3e+00
4e+00
5e+00
Heliostat
Position
Alignment
Normals
Reflectivity
...
Forward pass
Differentiable Ray Tracer
Backward pass
Image Generation
Image Comparison

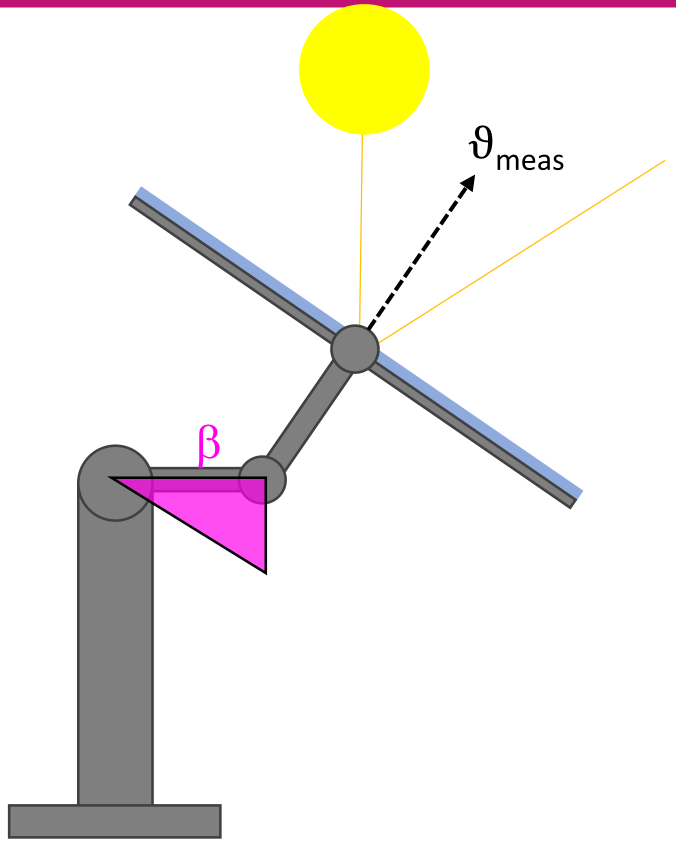
Control:
Heliostat Alignment





ϑ_{meas} = f(heliostat position, sun position, aimpoint)





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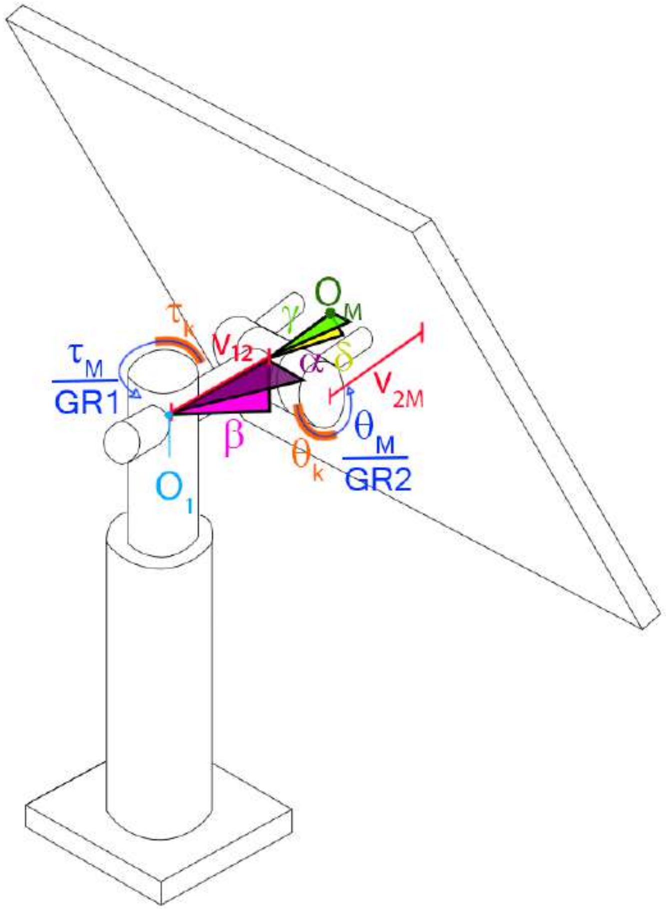

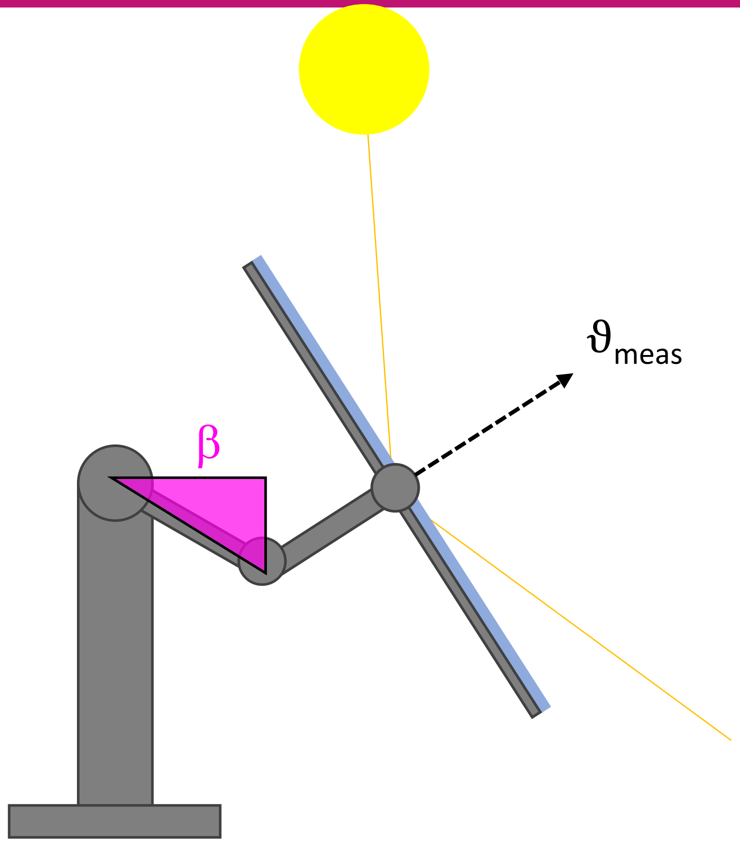

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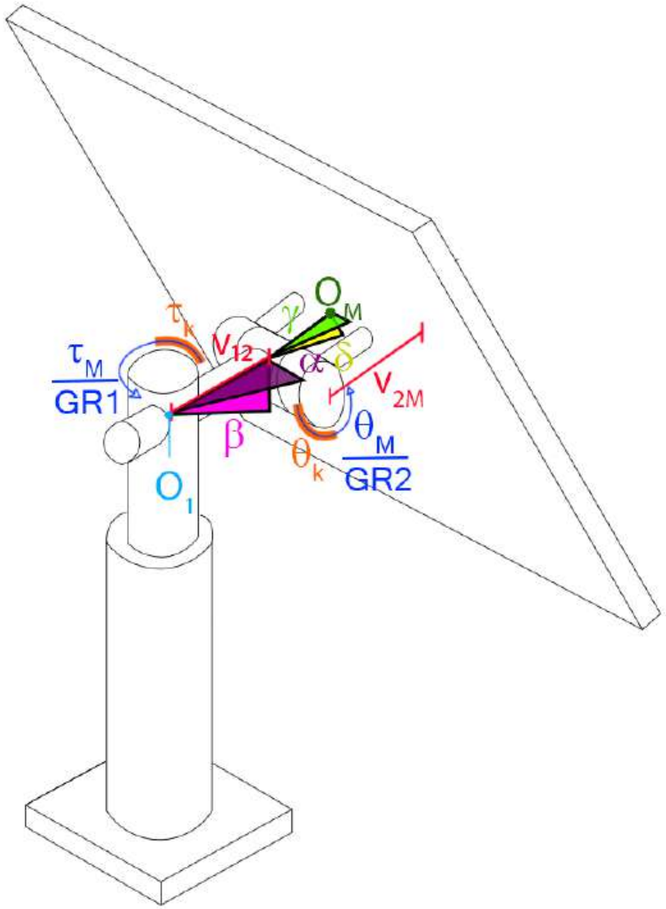
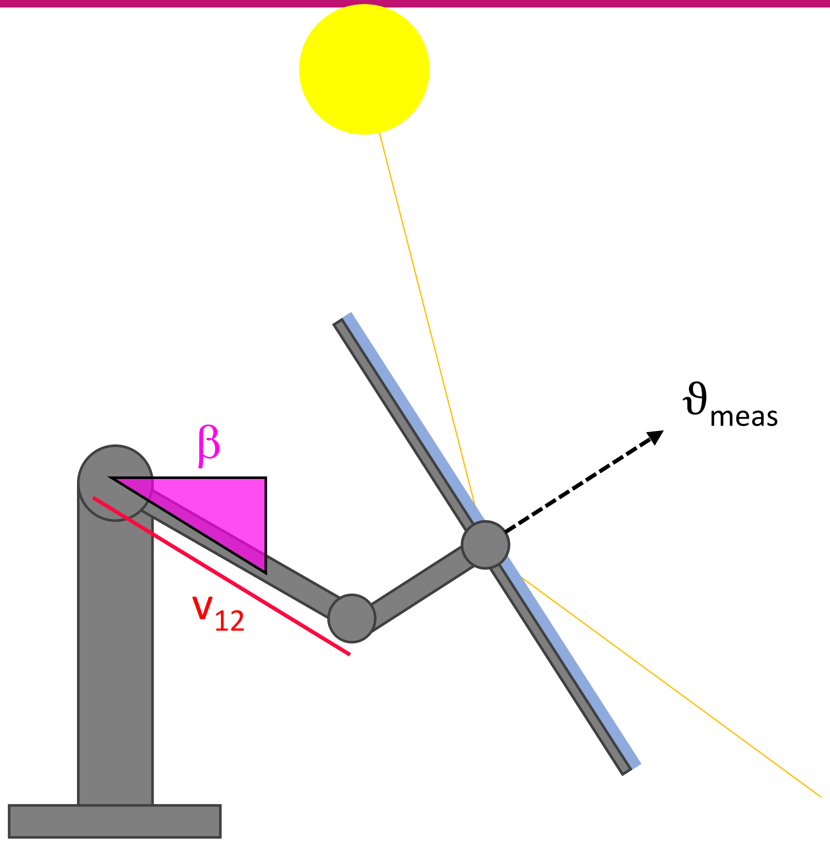
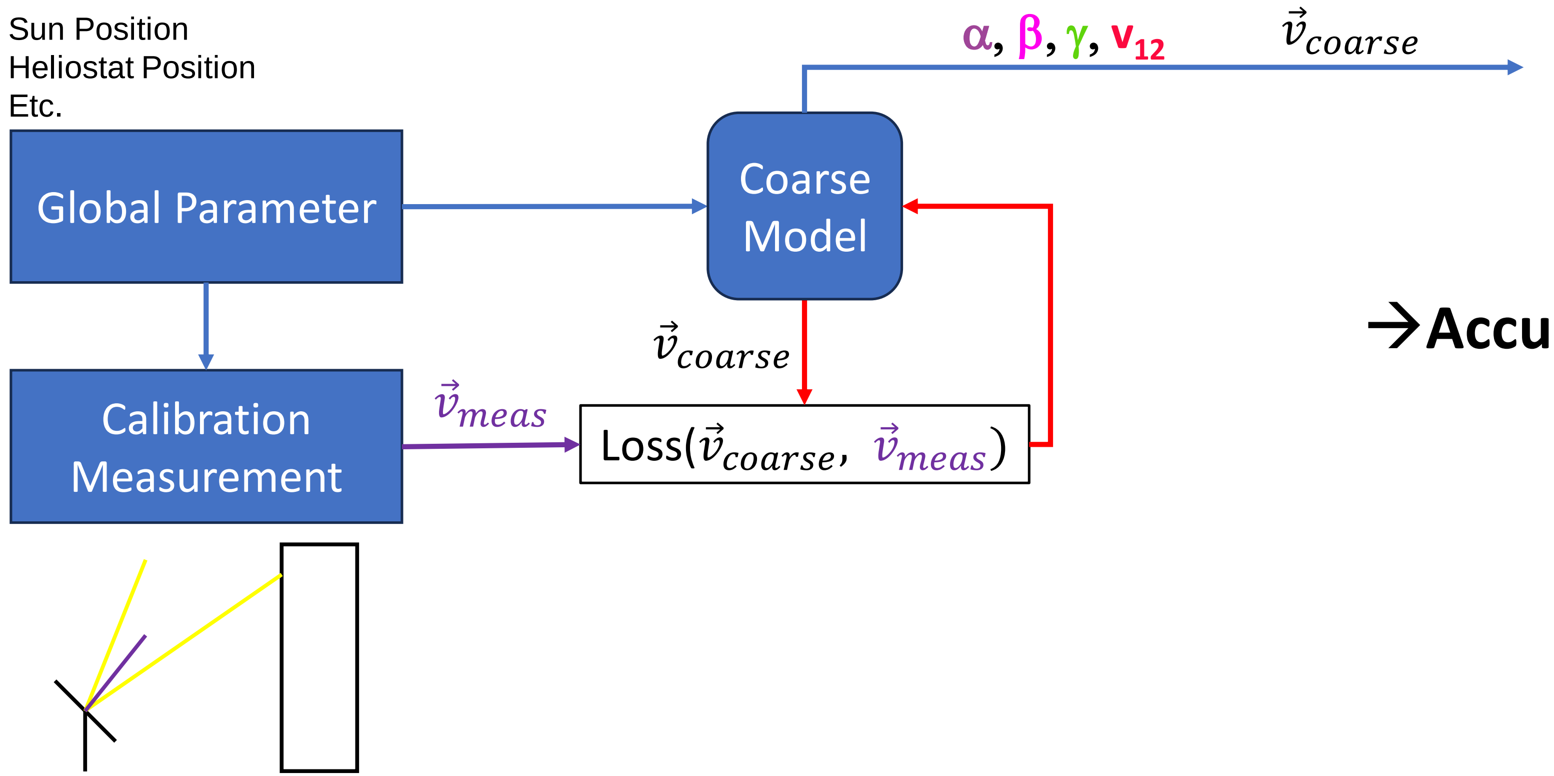
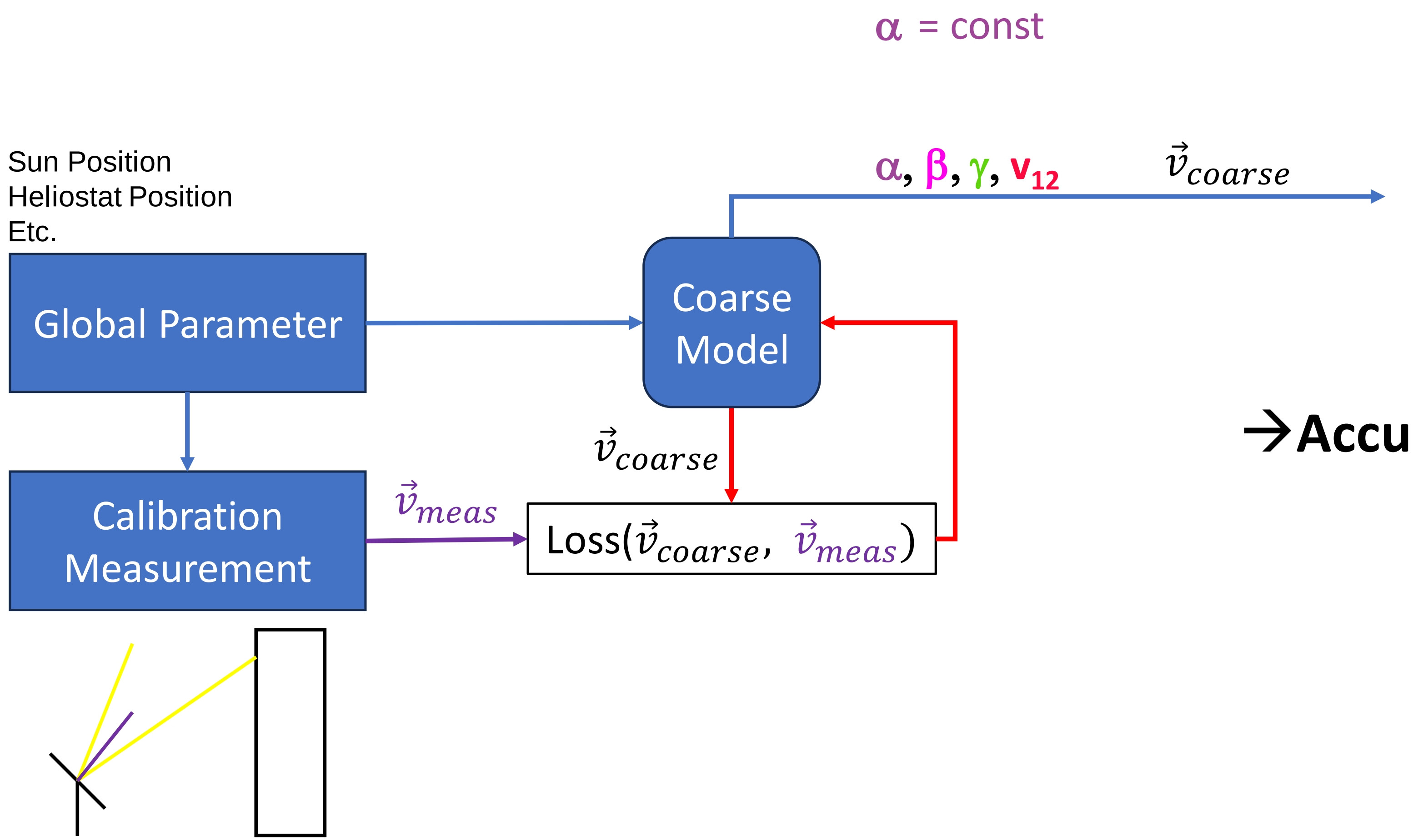




ϑ_{meas} = f(heliostat position, sun position, aimpoint
α, β, γ, v_{12} , …) → **20 independent parameters**

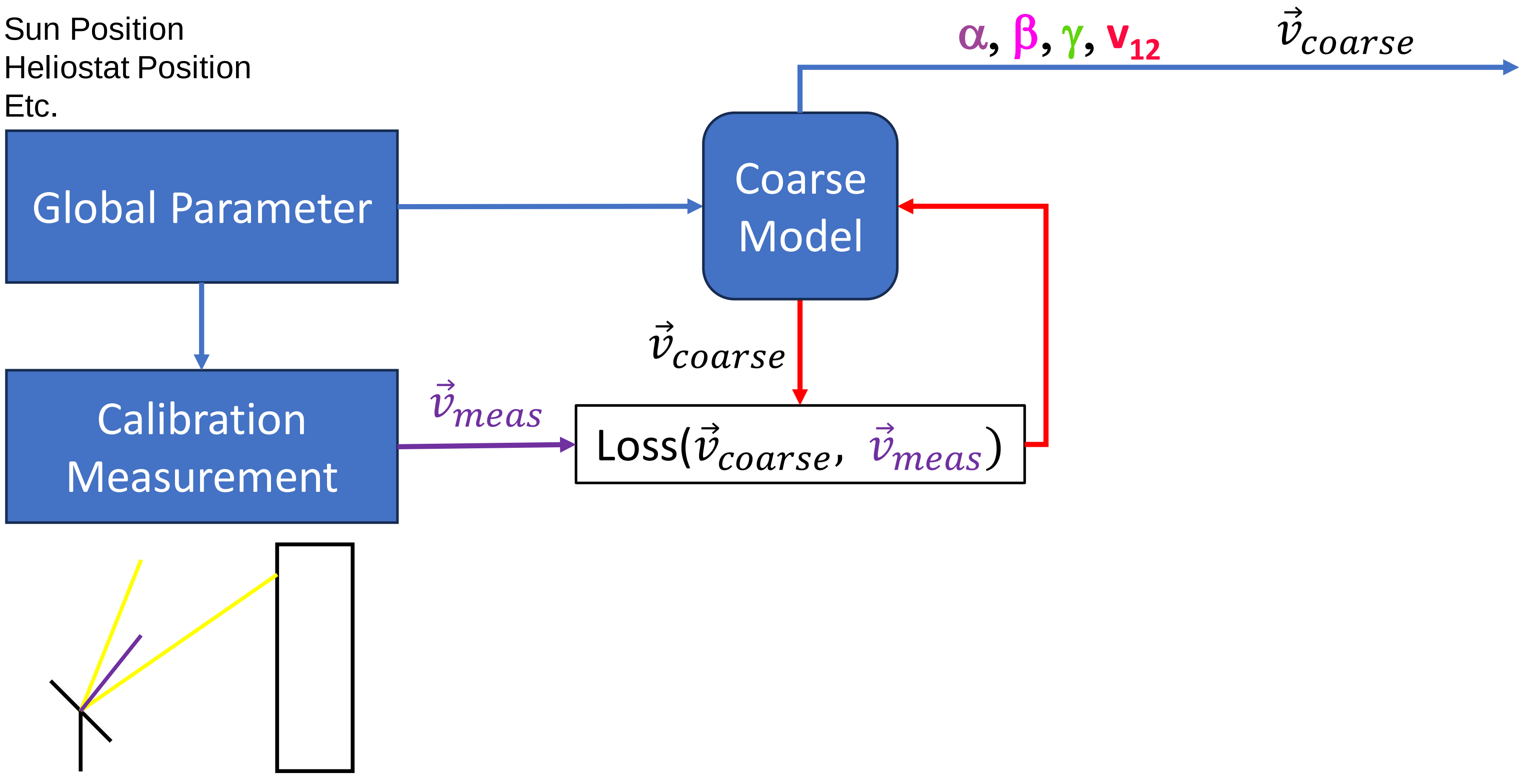


→**Accuracy approx. 2 mrad**

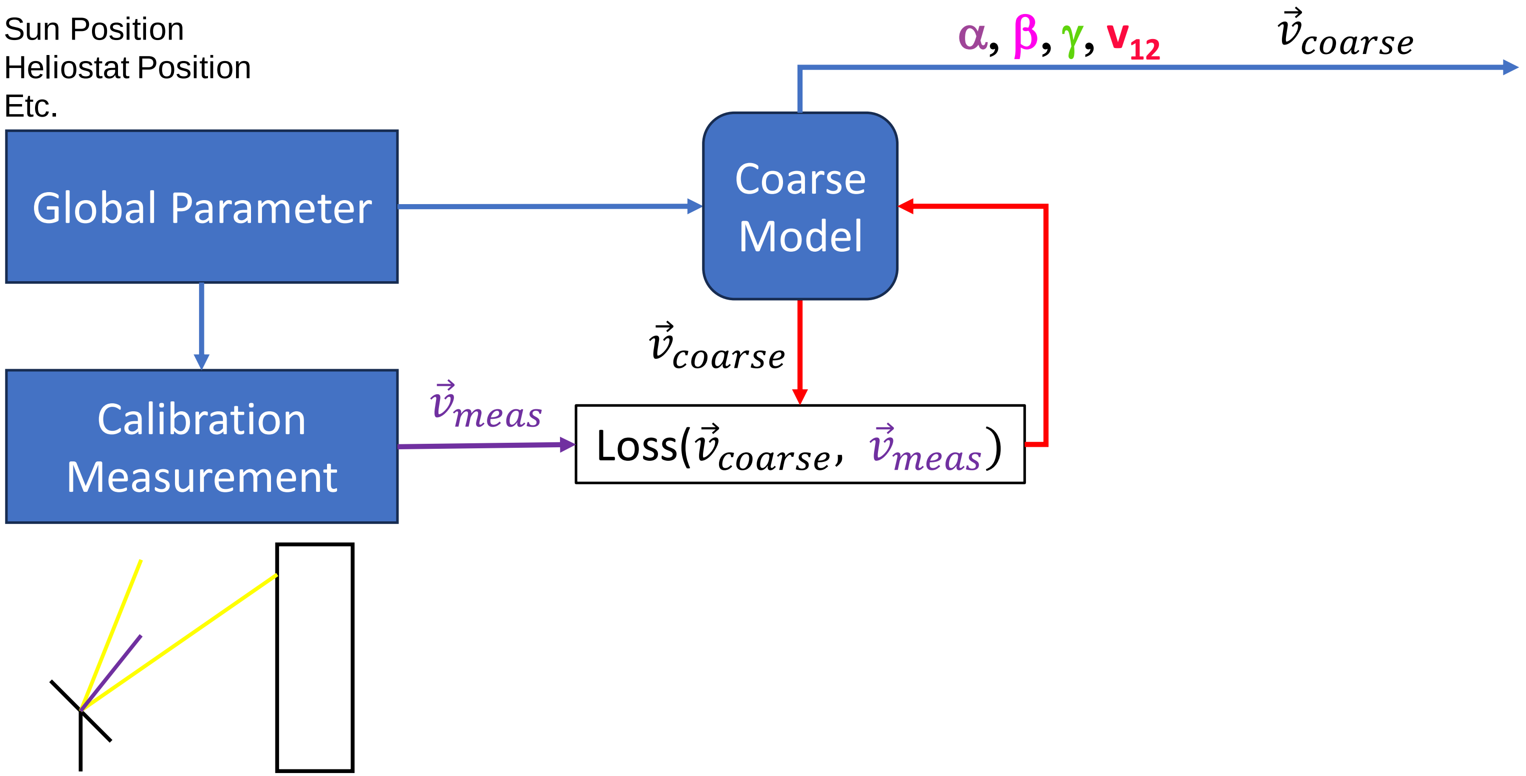


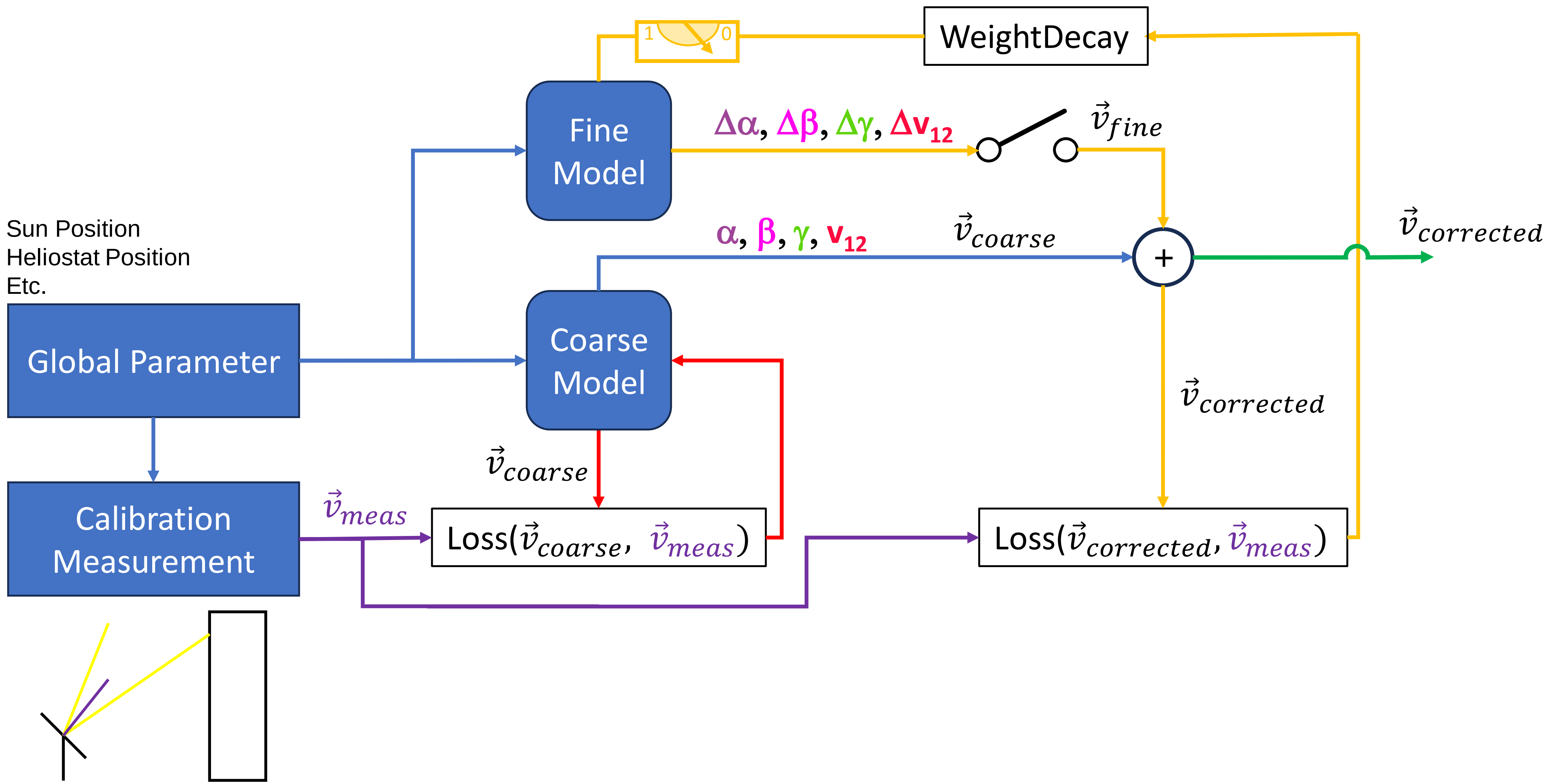
→**Accuracy approx. 2 mrad**

α (alignment, temp., time, wind, rigidity) = ???

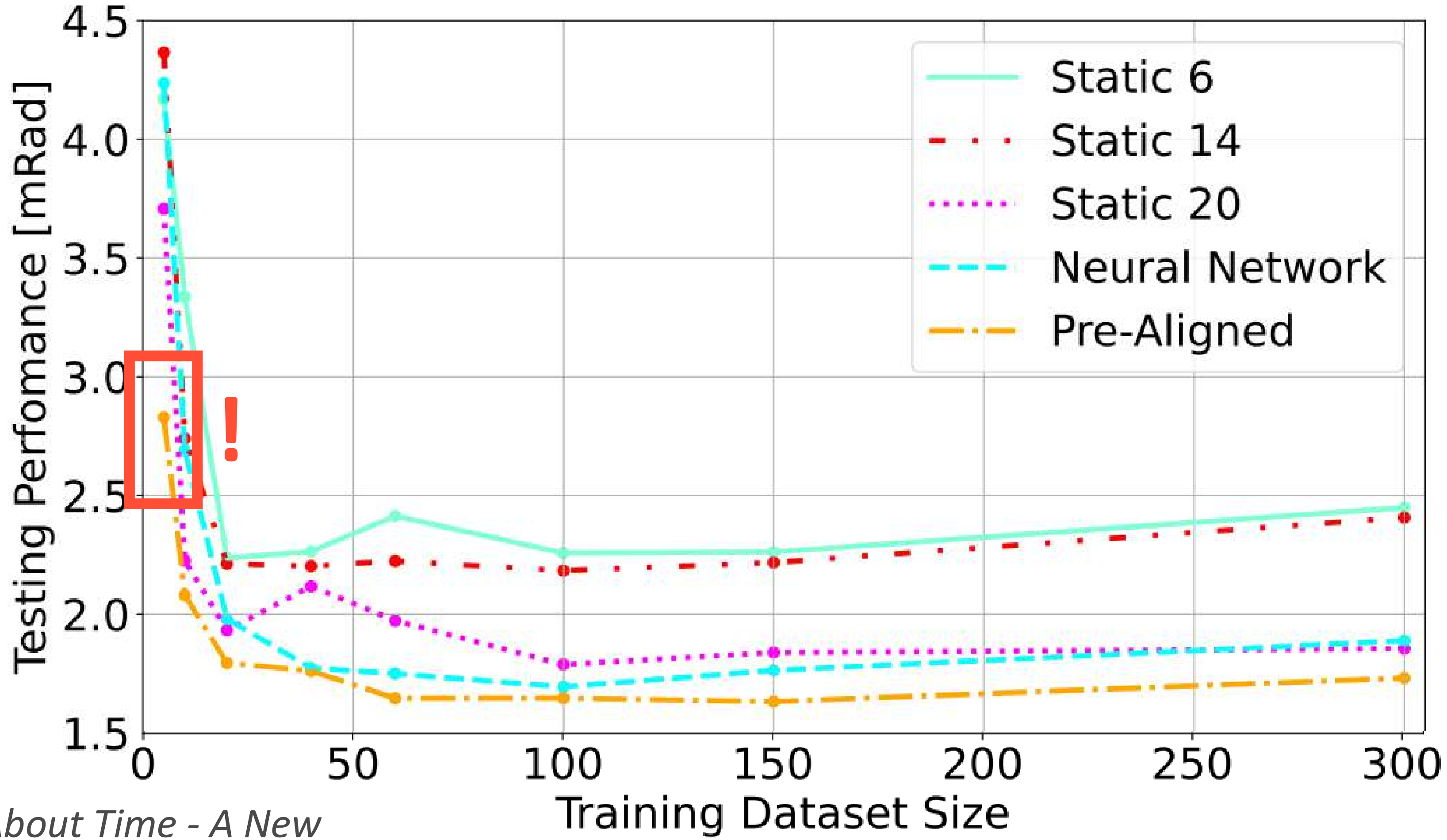


$\alpha_{complete} = \alpha_{const} + \Delta\alpha_{dynamic}$ with $\Delta\alpha \ll \alpha$




WeightDecay
1
0
Fine Model
$\Delta\alpha, \Delta\beta, \Delta\gamma, \Delta v_{12}$
$\vec{v}_{fine}$
Sun Position
Heliostat Position
Etc.
$\alpha, \beta, \gamma, v_{12}$
$\vec{v}_{coarse}$
+
$\vec{v}_{corrected}$
Global Parameter
Coarse Model
$\vec{v}_{corrected}$
$\vec{v}_{coarse}$
Calibration Measurement
$\vec{v}_{meas}$
$Loss(\vec{v}_{coarse}, \vec{v}_{meas})$
$Loss(\vec{v}_{corrected}, \vec{v}_{meas})$

- The models are evaluated on the basis of a special data set training/test split, which provides information about the worst-case performance. Details in [1]
- The combination of rigid body and neural network model prediction is always best

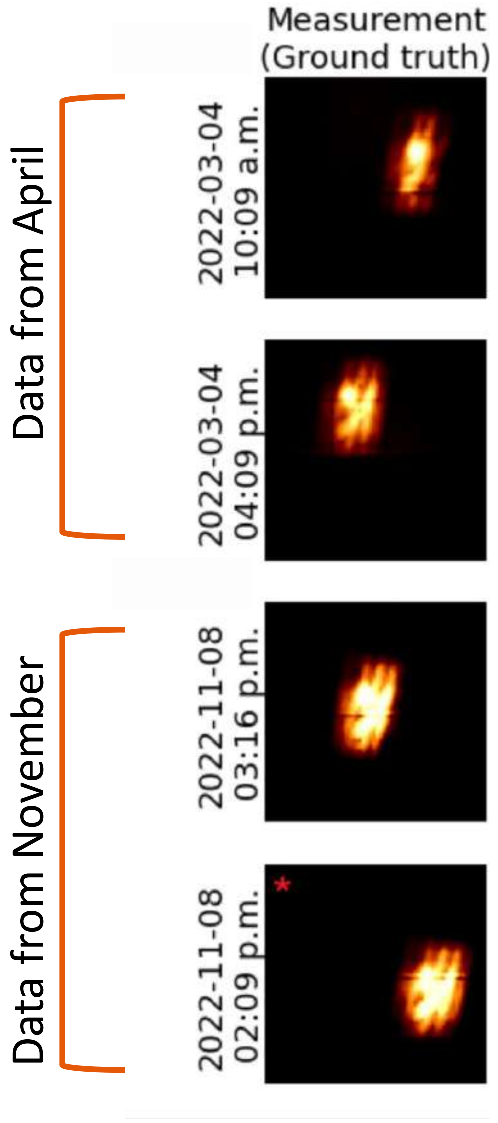


[1] Pargmann and Leibauer et al. *It is Not About Time - A New Standard for Open-Loop Heliostat Calibration Methods*

Prediction:

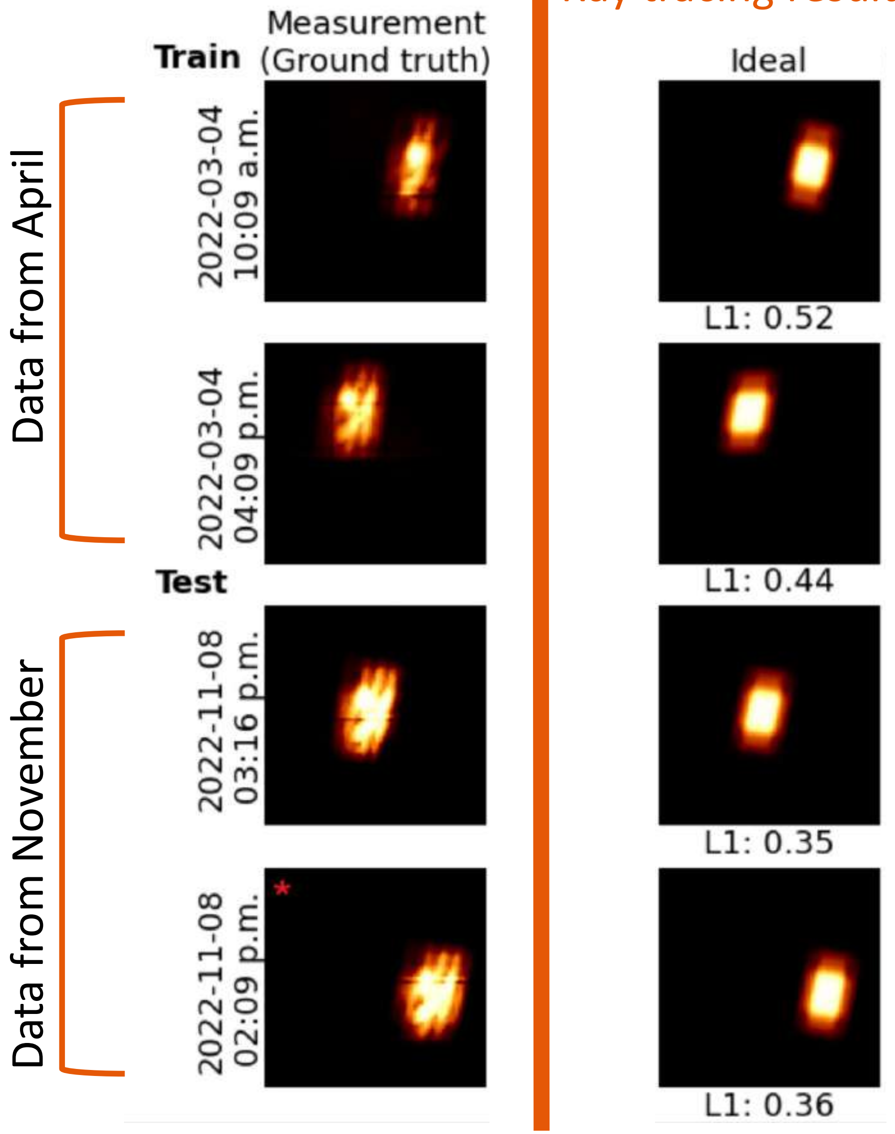
Single Heliostat Flux Density


Receiver
Calibration Target
Heliostat

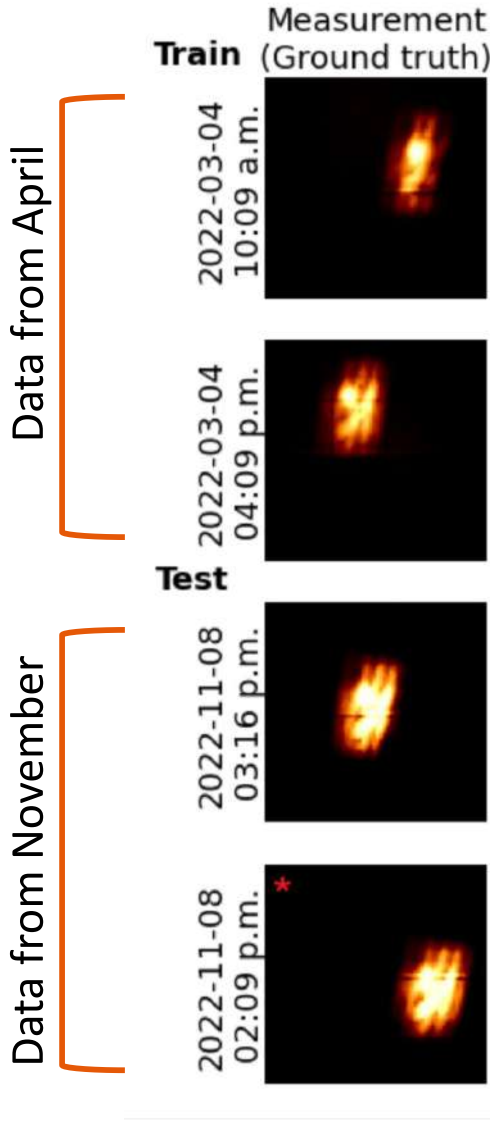

Measurement
(Ground truth)
Data from April
2022-03-04
10:09 a.m.
2022-03-04
04:09 p.m.
Data from November
2022-11-08
03:16 p.m.
2022-11-08
02:09 p.m.

53

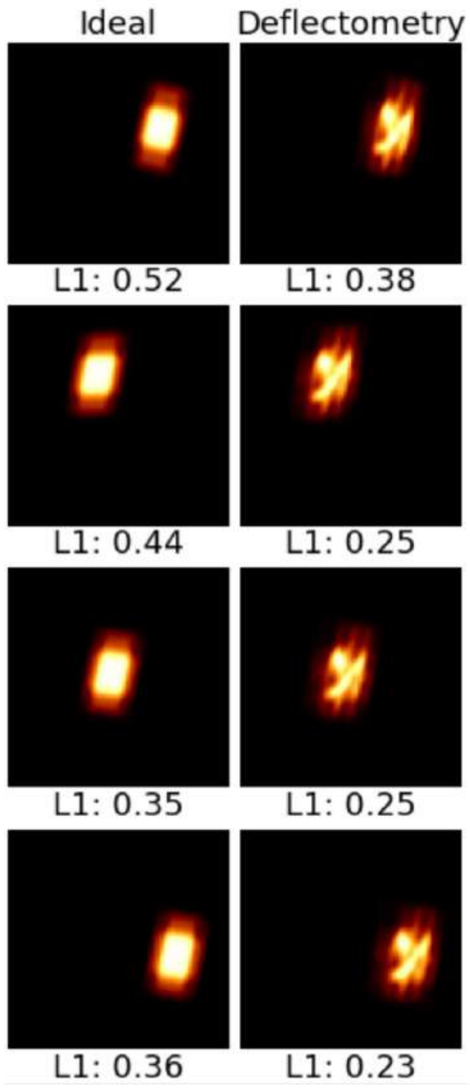
Ray tracing results



L1 = Mean Absolute Error



Ray tracing results



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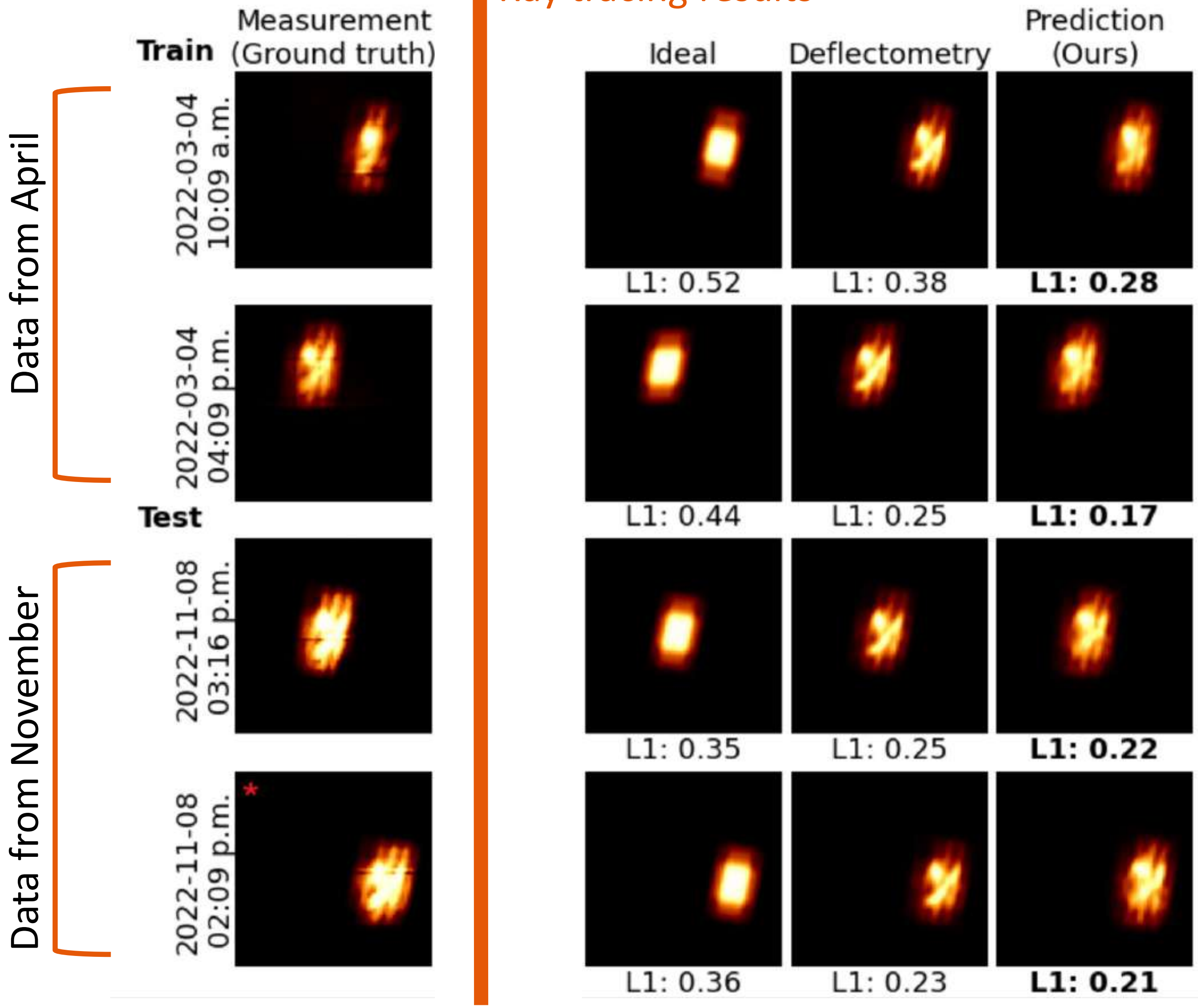
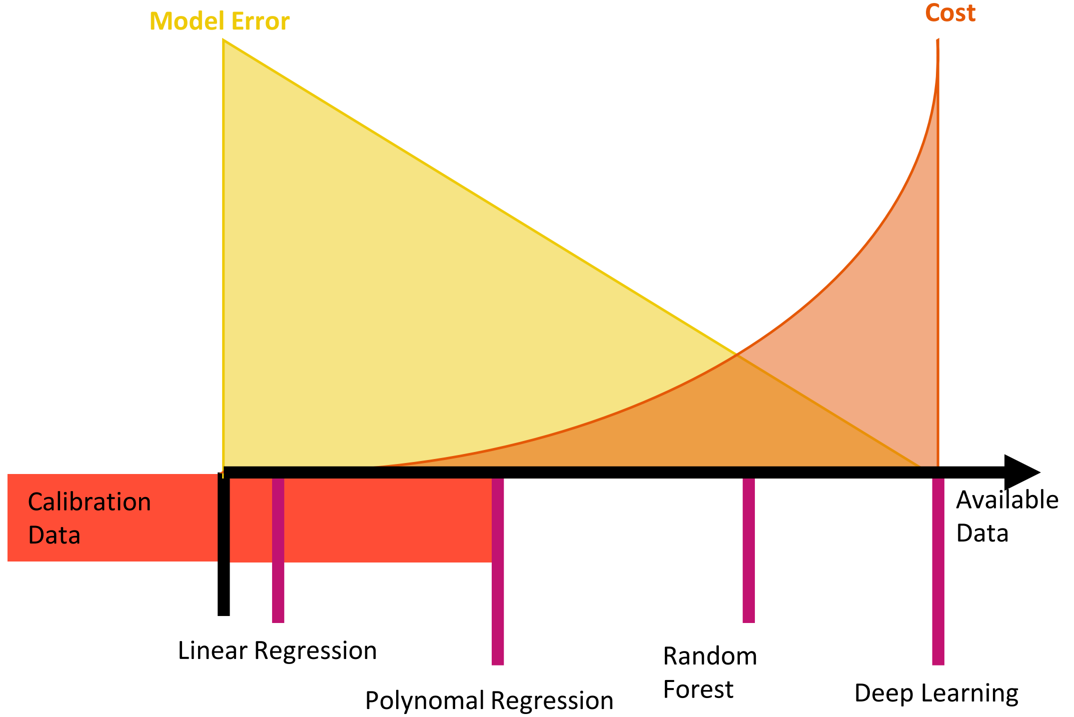
Ray tracing results



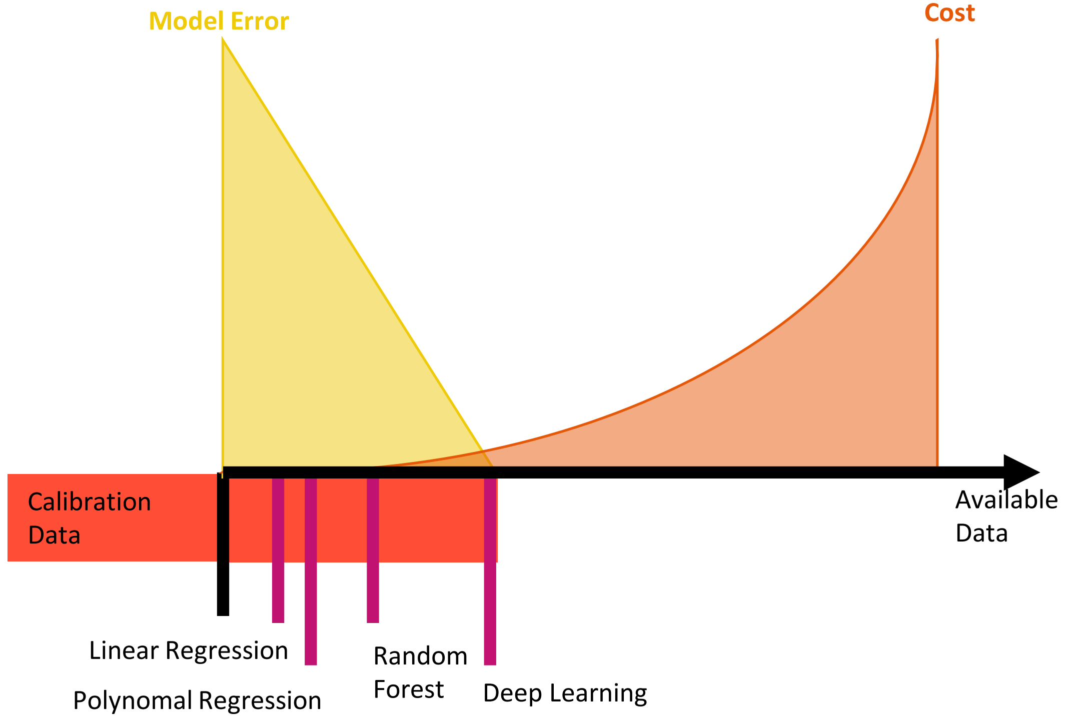
Outcomings

How to apply Deep Learning on small data sets at solar towers?



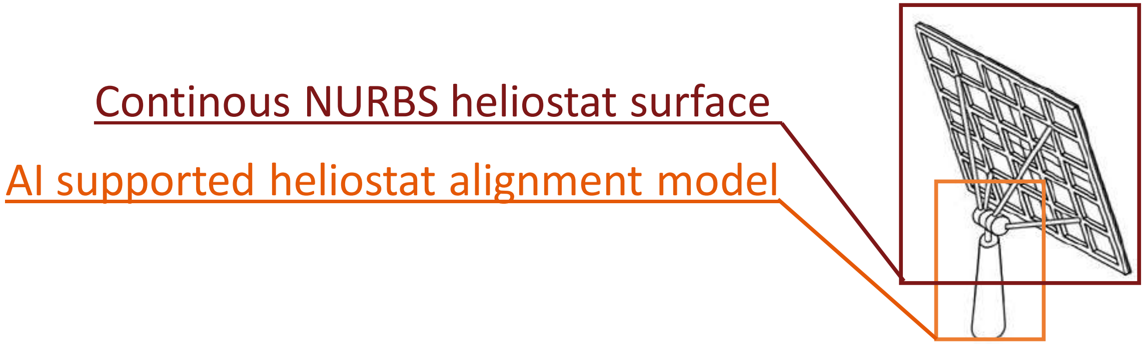
How to apply Deep Learning on small data sets at solar towers?

- Data is scarce, but physical Information isn't!
- Ways to reduce the data usage at the solar tower:
  - Use Physical Information for Initialization (eg. Heliostat Alignment)
  - Use Simulation/Augmentation data to pretrain Networks
  - Use a physics informed Loss function to smooth your optimization function
- Use images instead of tabular data



When to choose AI models over physic at solar towers (at small data sets)?

- Most processes at the solar tower are very good approximated by physical simulations
- AI can be used to close this gap when the error source is unknown
- Estimate unknown error:
  - Example Heliostat Alignment Model:
    - Potential optimal accuracy approx. 0.03mrad
    - Heliostatfield accuracy approx. 2.1mrad
    - Measurement and Hardware errors approx. 1mrad
  - Example Heliostat Surface Model
    - NURBS can fit Mirror to 100% (even with broken edges)



→ AI can reduce model error by half the absolute error

→ Physical model‘s parameter space is sufficient

Conclusion

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