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

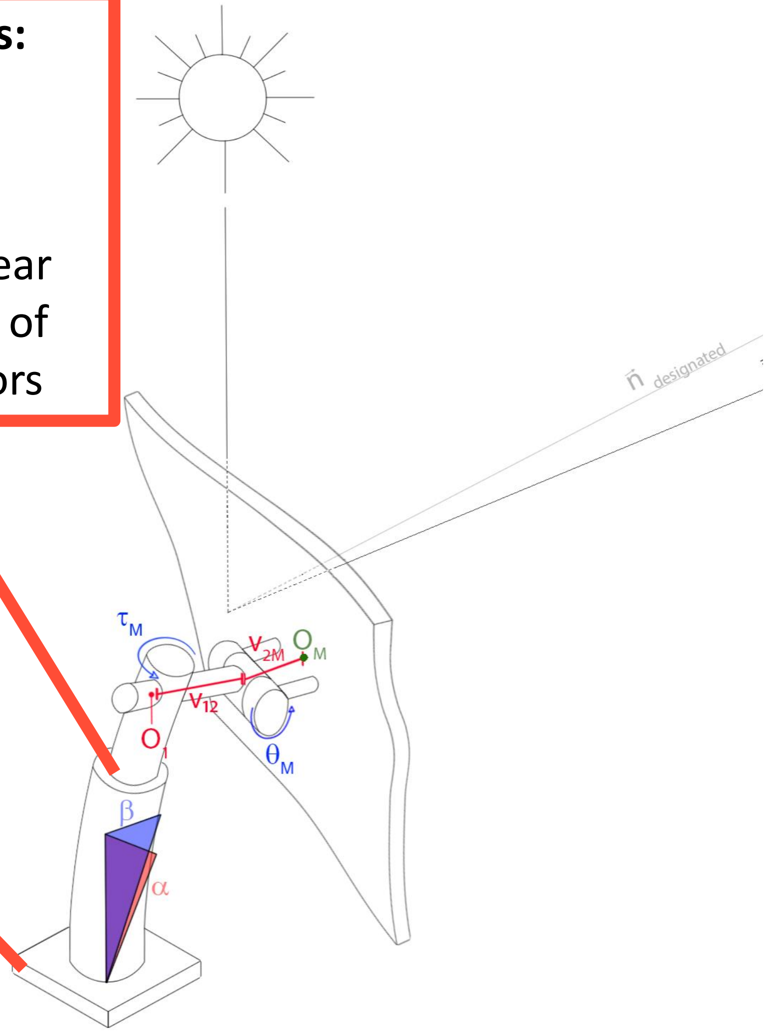
THIS PROJECT HAS RECEIVED FUNDING FROM THE EUROPEAN UNION'S HORIZON 2020 RESEARCH AND INNOVATION PROGRAMME UNDER GRANT AGREEMENT NO **823802**

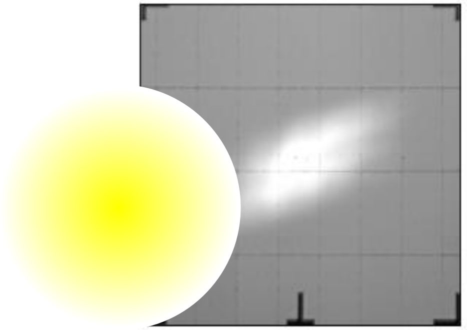
- Motivation
- Methods: Differentiable Raytracing
- Three Foundations of Automation
  - Diagnosis
  - Control
  - Predition
- Discussion

Motivation

SFERA-III
Solar Facilities for the European Research Area

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





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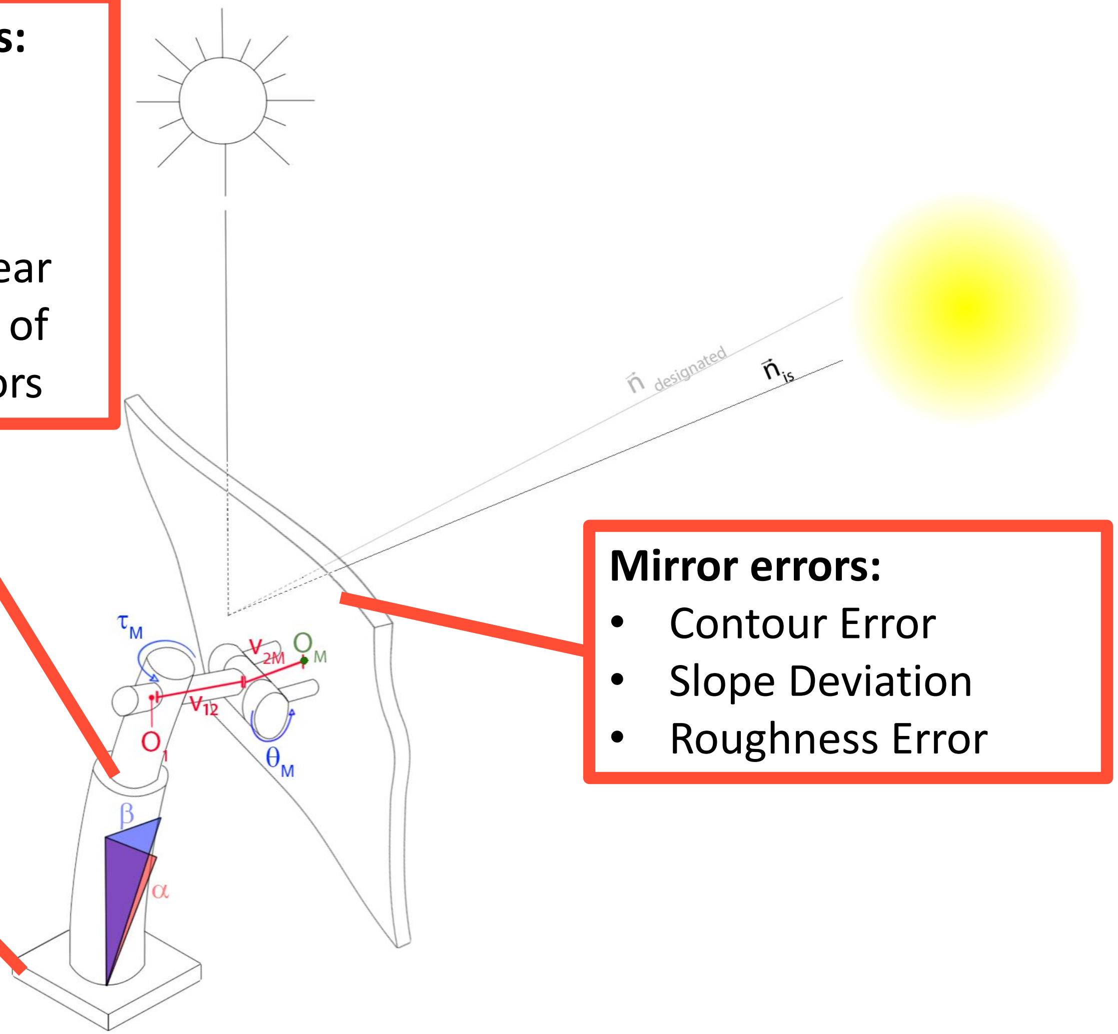

Mirror errors:

- Contour Error
- Slope Deviation
- Roughness Error

Alignment errors:
- Wind load
- Rigidity
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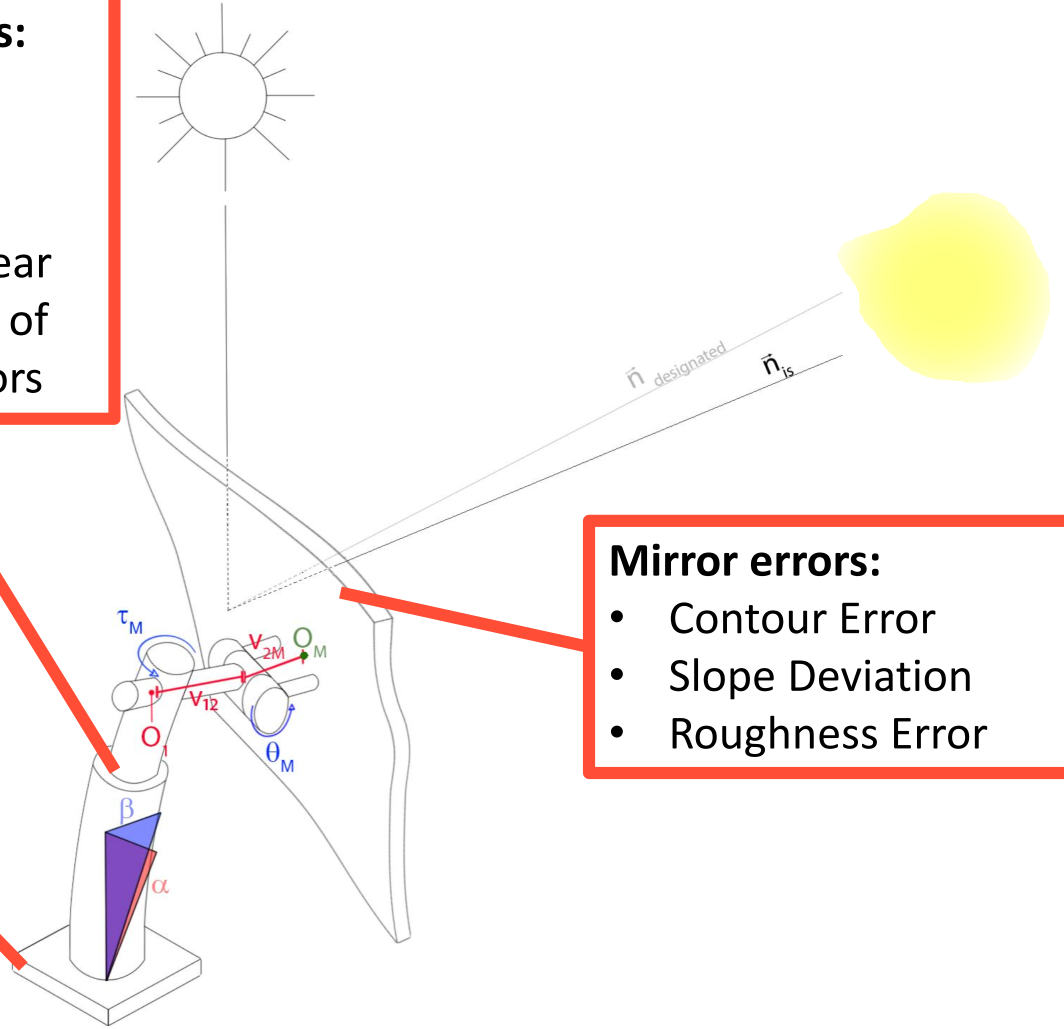
- Misscounting of Stepper Motors



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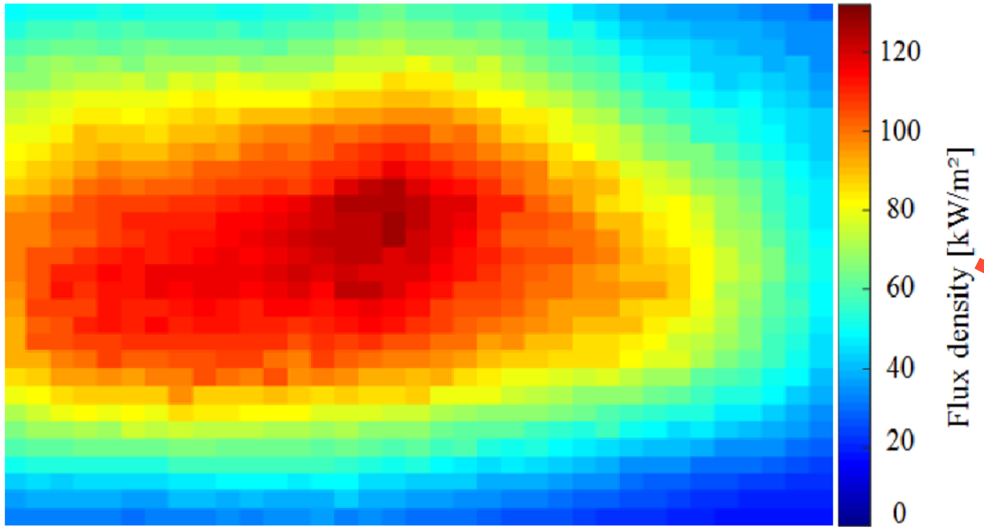

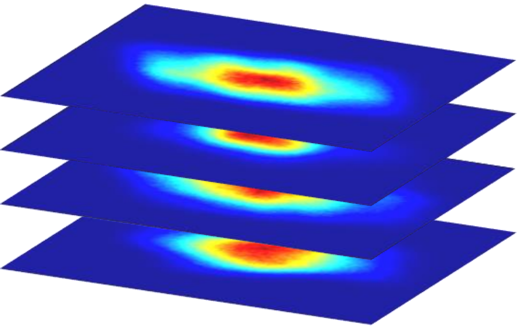

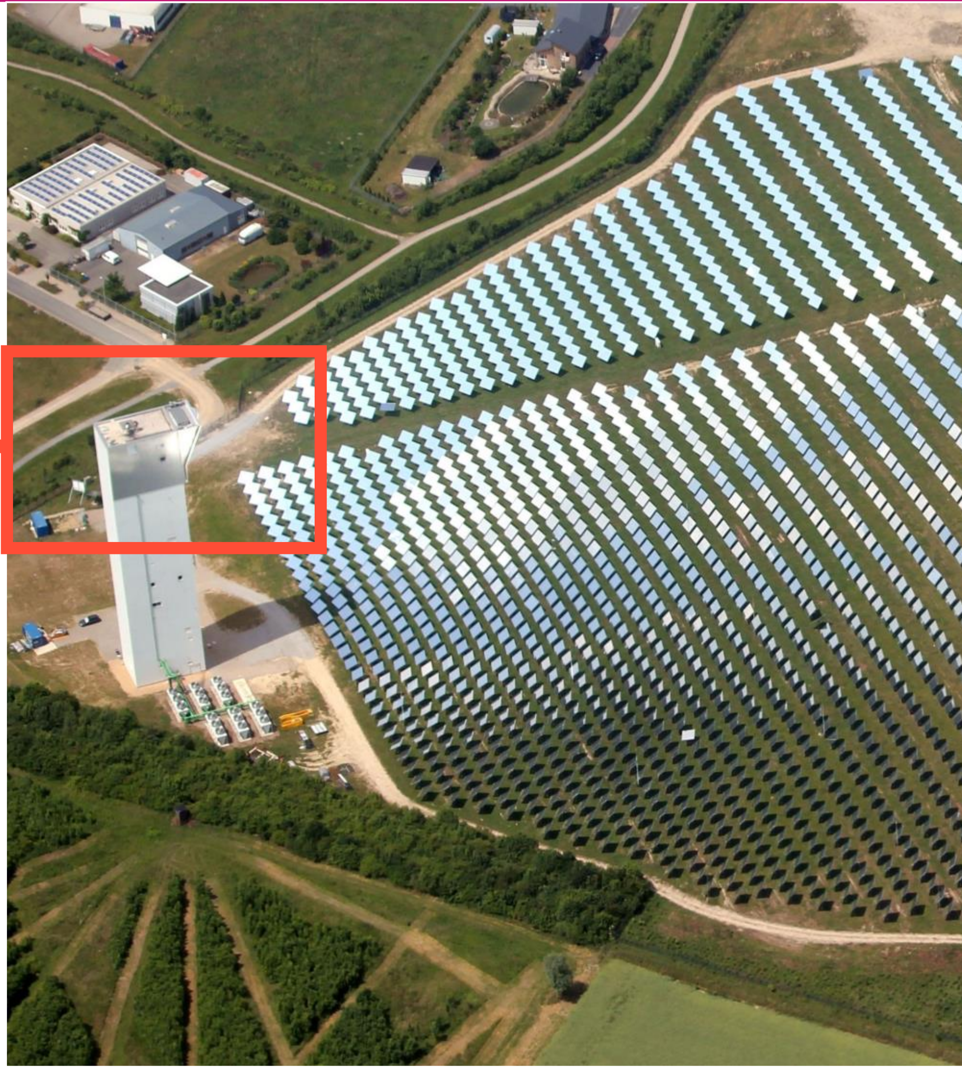

Difficulties:
- Unique Pointing Command
- Quality of Calibration
- Command Delay
- No Sensors
- No Measurement

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

Diagnosis

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

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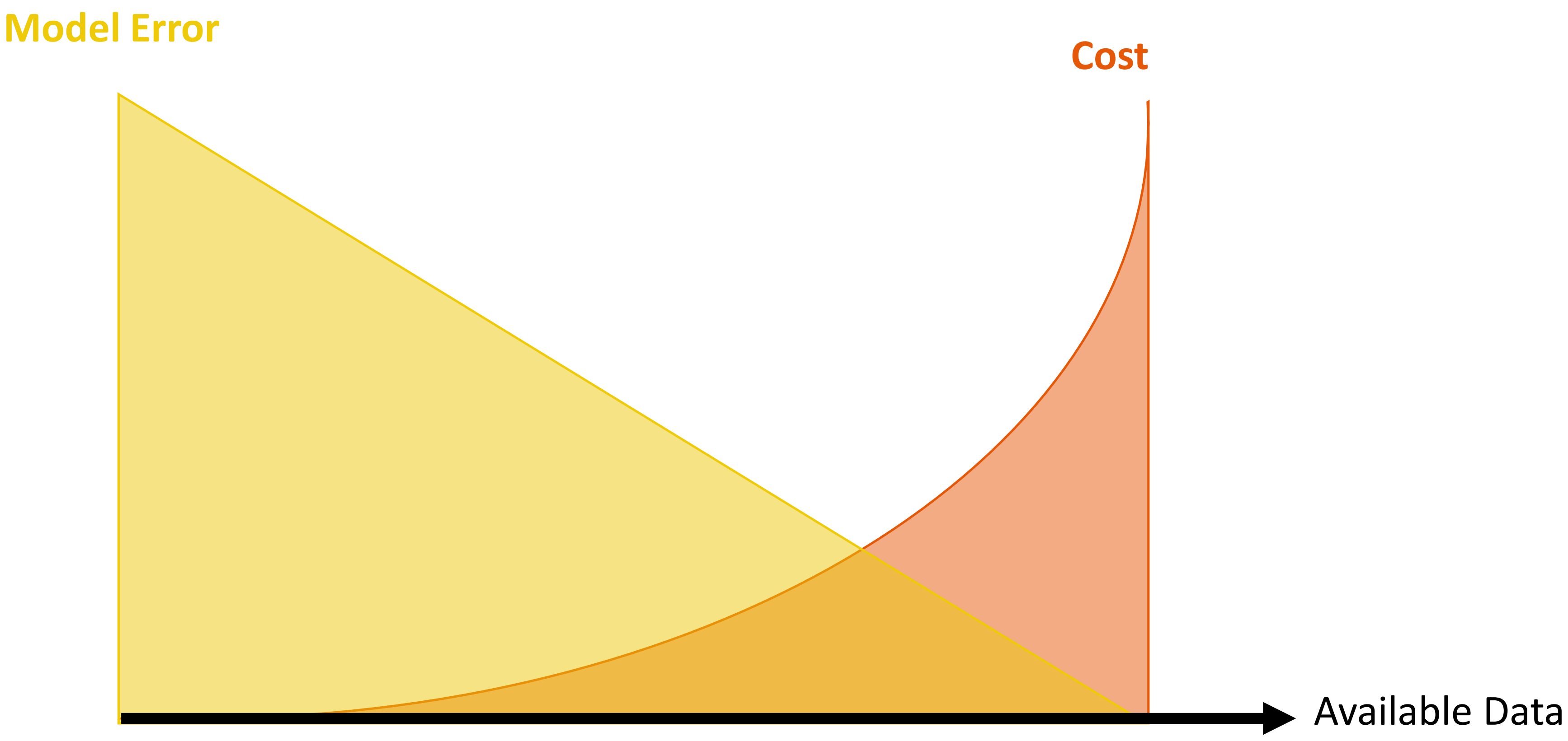
Difficulties:
- Open Loop Control
- Measurements for
  - Calibration are slow
  - Mirror deformations are unreliable and cost intensive
  - Flux measurements are experimental[1] or cost intensive

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
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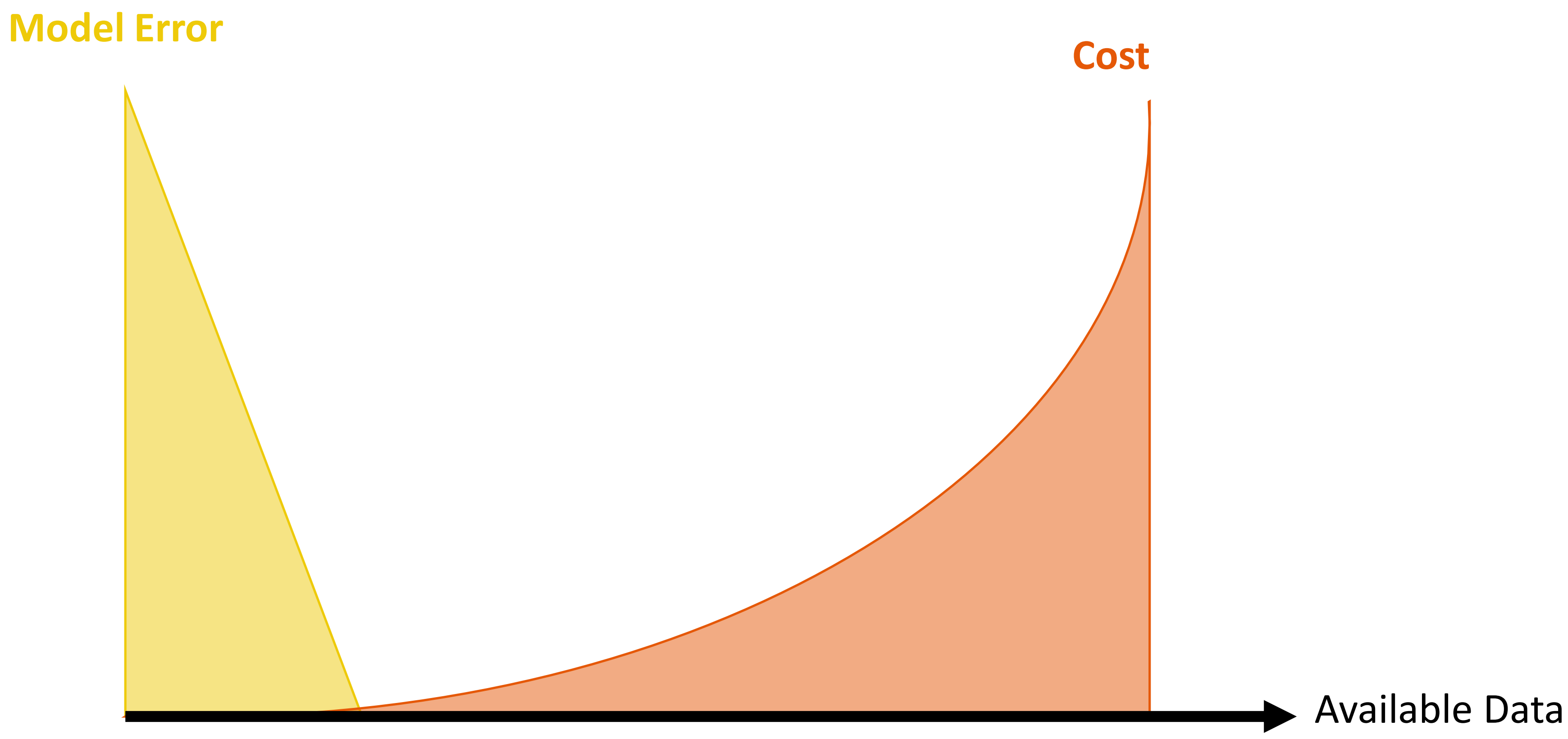
Solution:
- Closed Loop Control
- Install More Sensors
- **Use Modern Algorithms**



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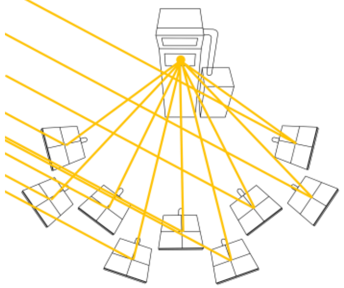
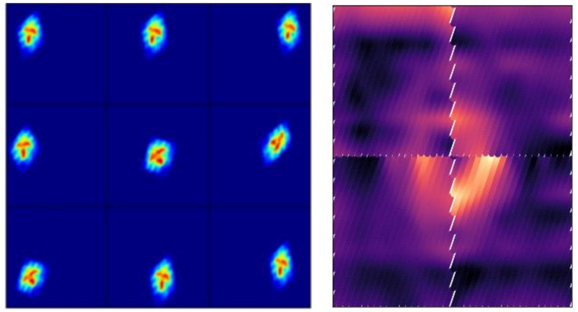
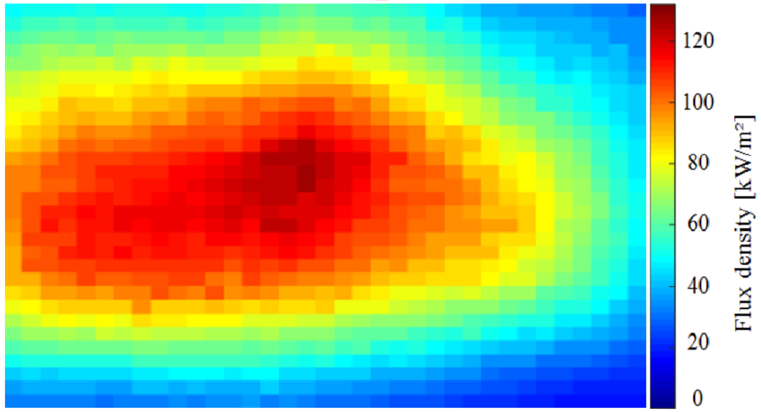
Methods

Heliostat Control



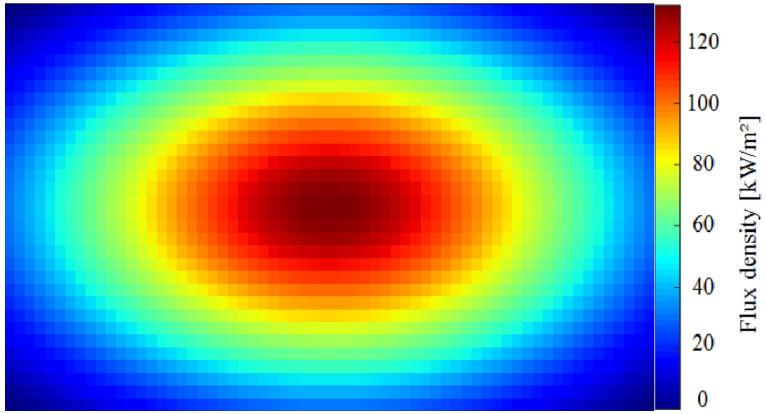


Heliostat Calibration /
Surface Information

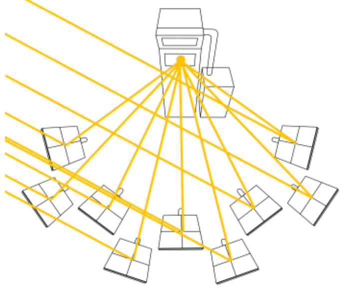


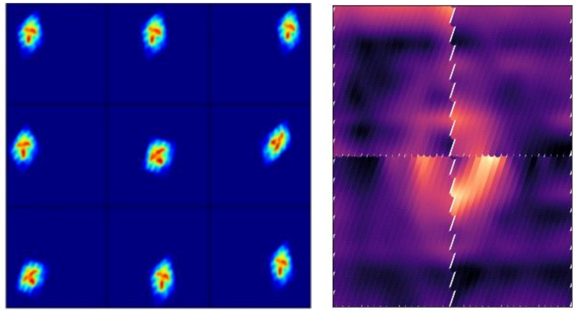
Simulation

(Commonly Raytracing)



Heliostat Control





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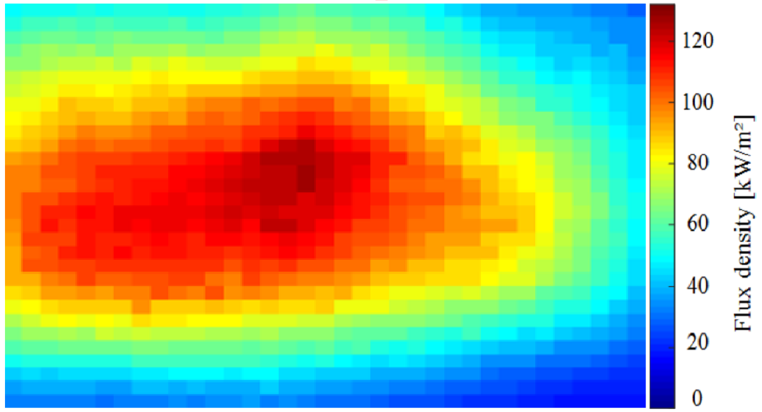

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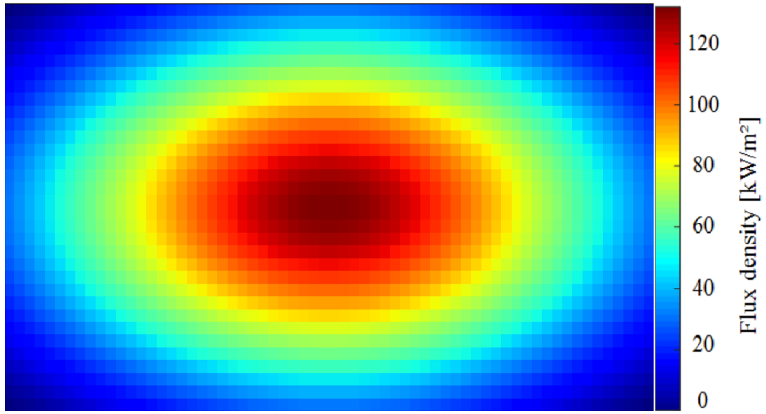

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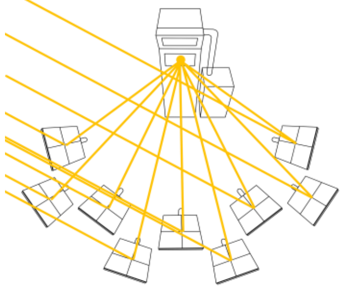

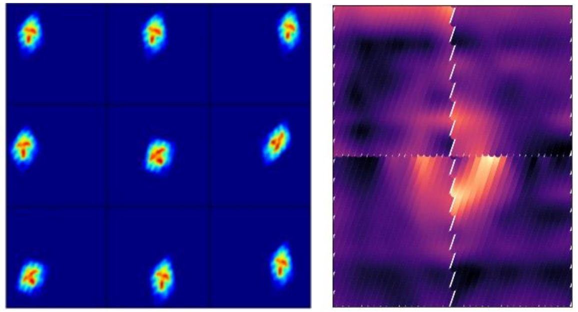

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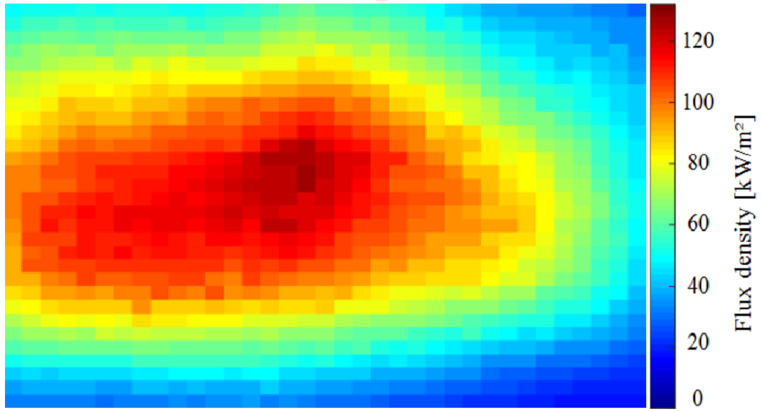
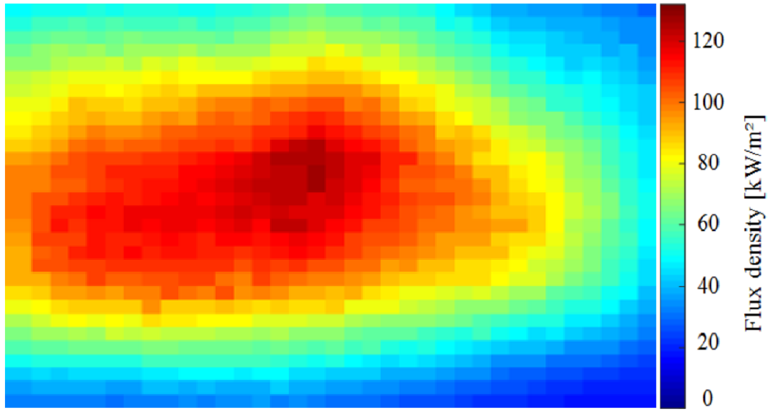
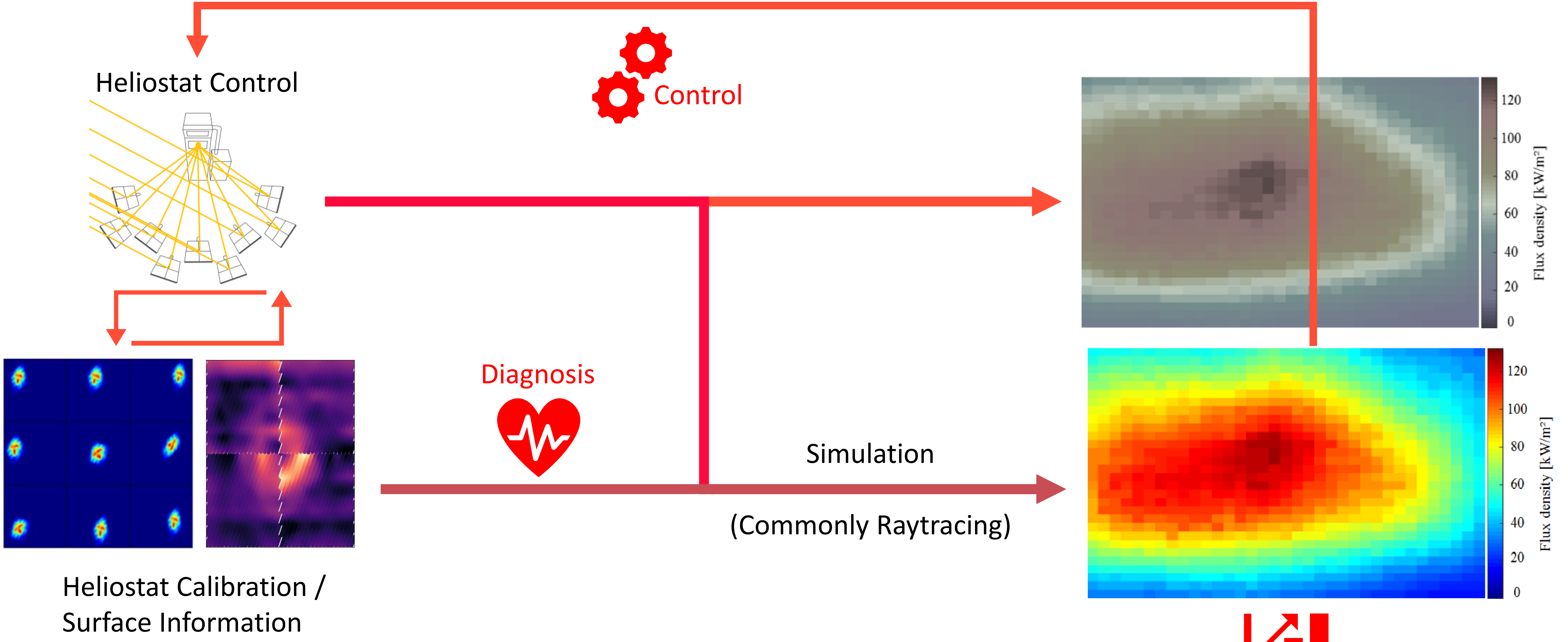
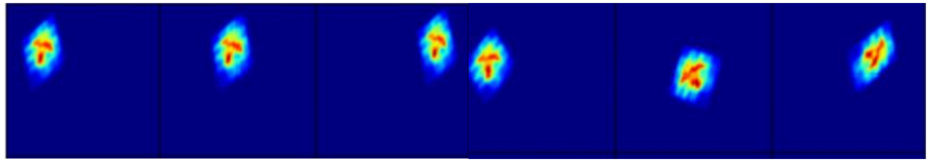




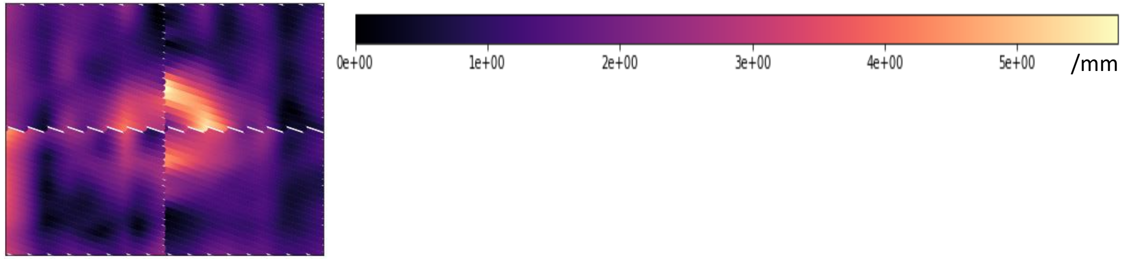

Heliostat Control
Control
Diagnosis
Simulation
(Commonly Raytracing)
Heliostat Calibration /
Surface Information
120
100
80
60
40
20
0
Flux density [kW/m²]
Prediction

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

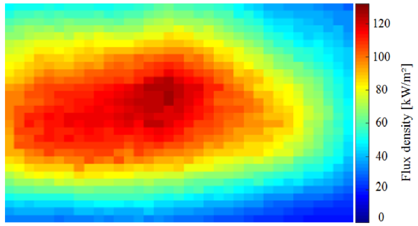
Calibration Data → ca 10-100 per Heliostat

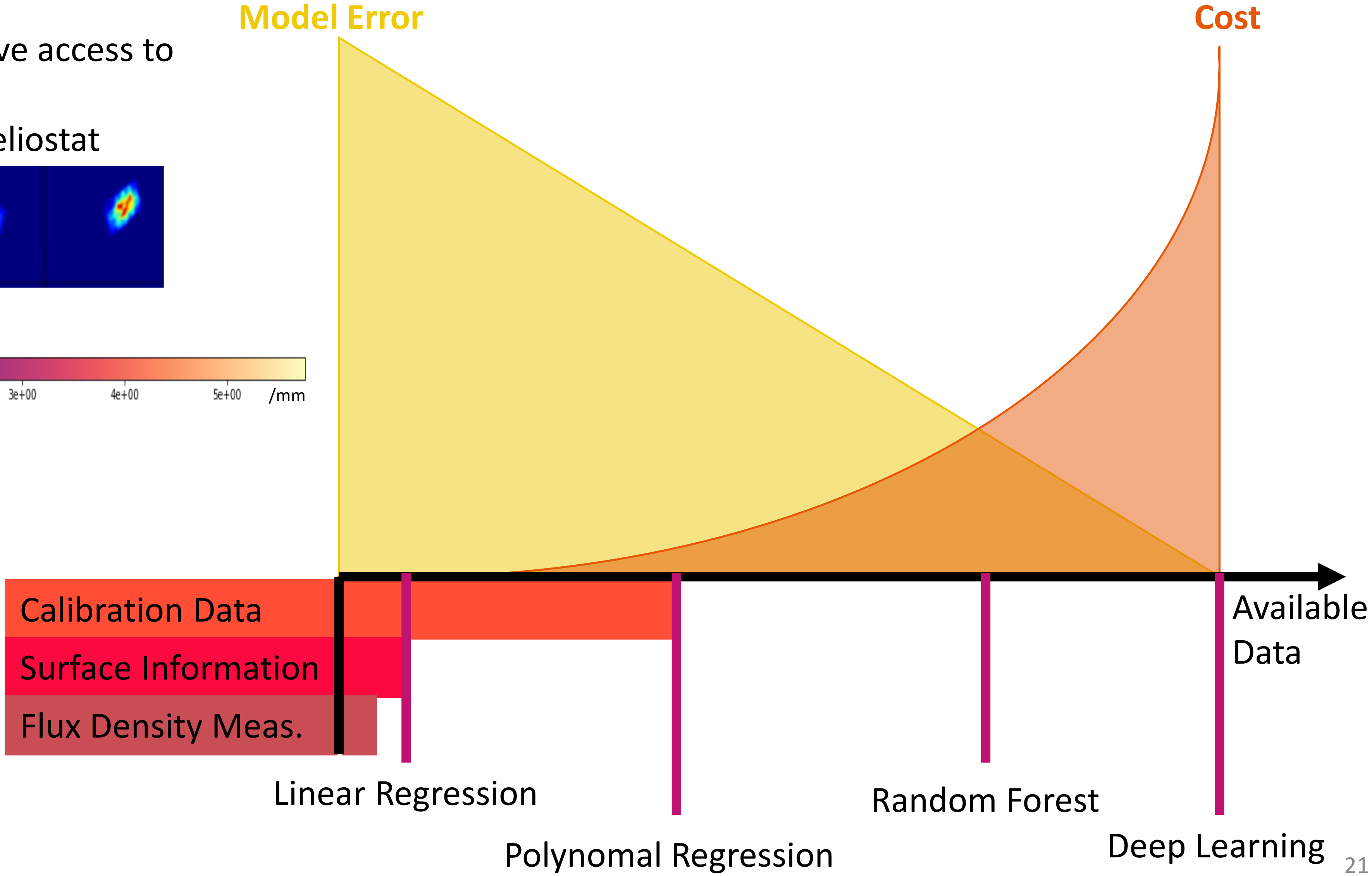


Surface Information → A few dozen



Flux Density Measurements
→ None (yet)





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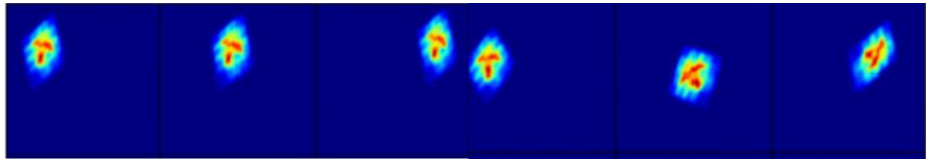

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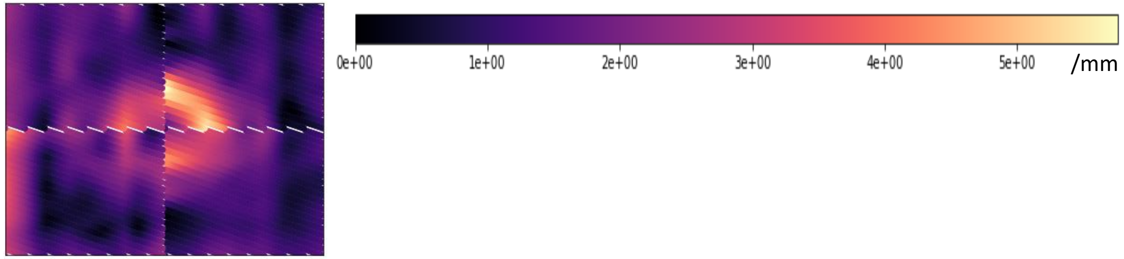

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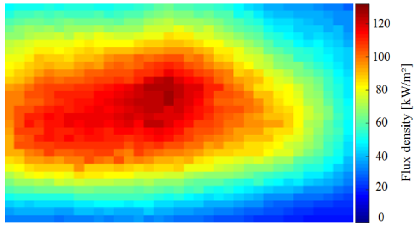
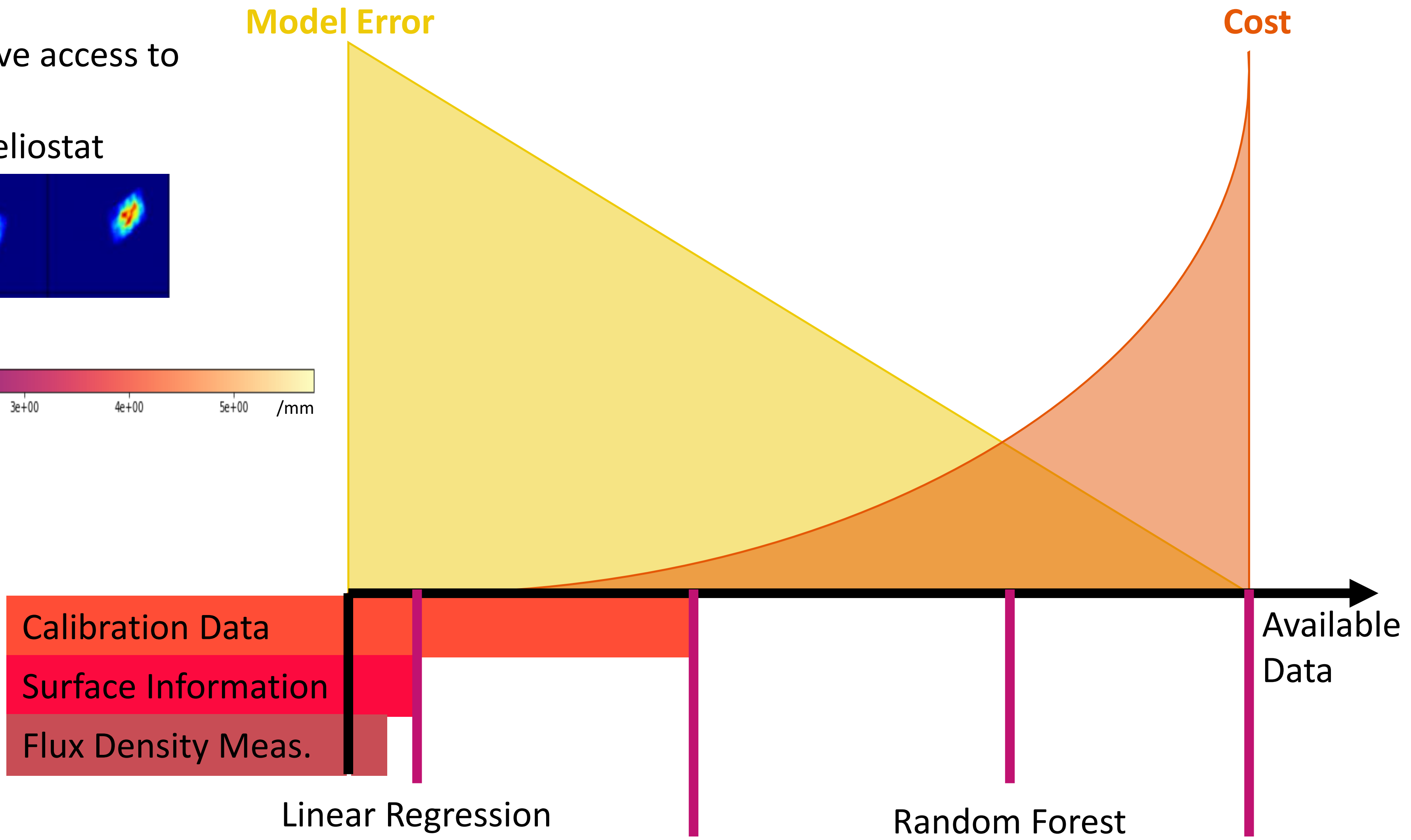
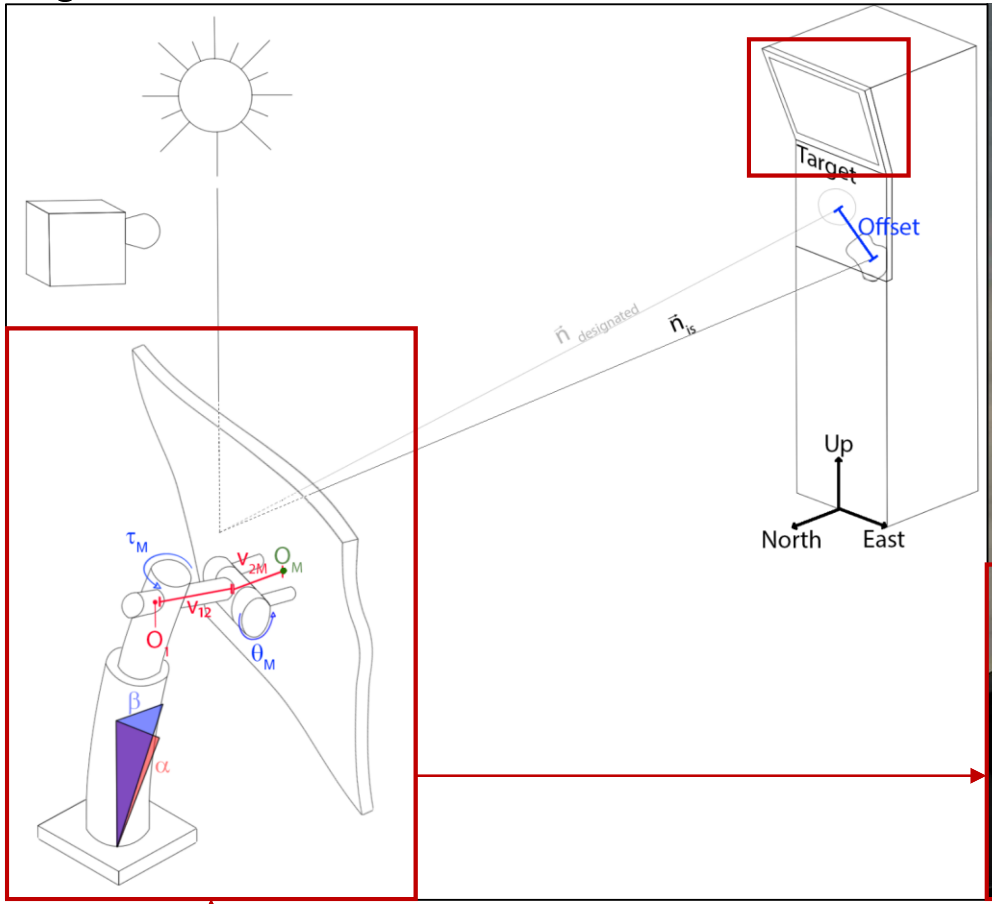
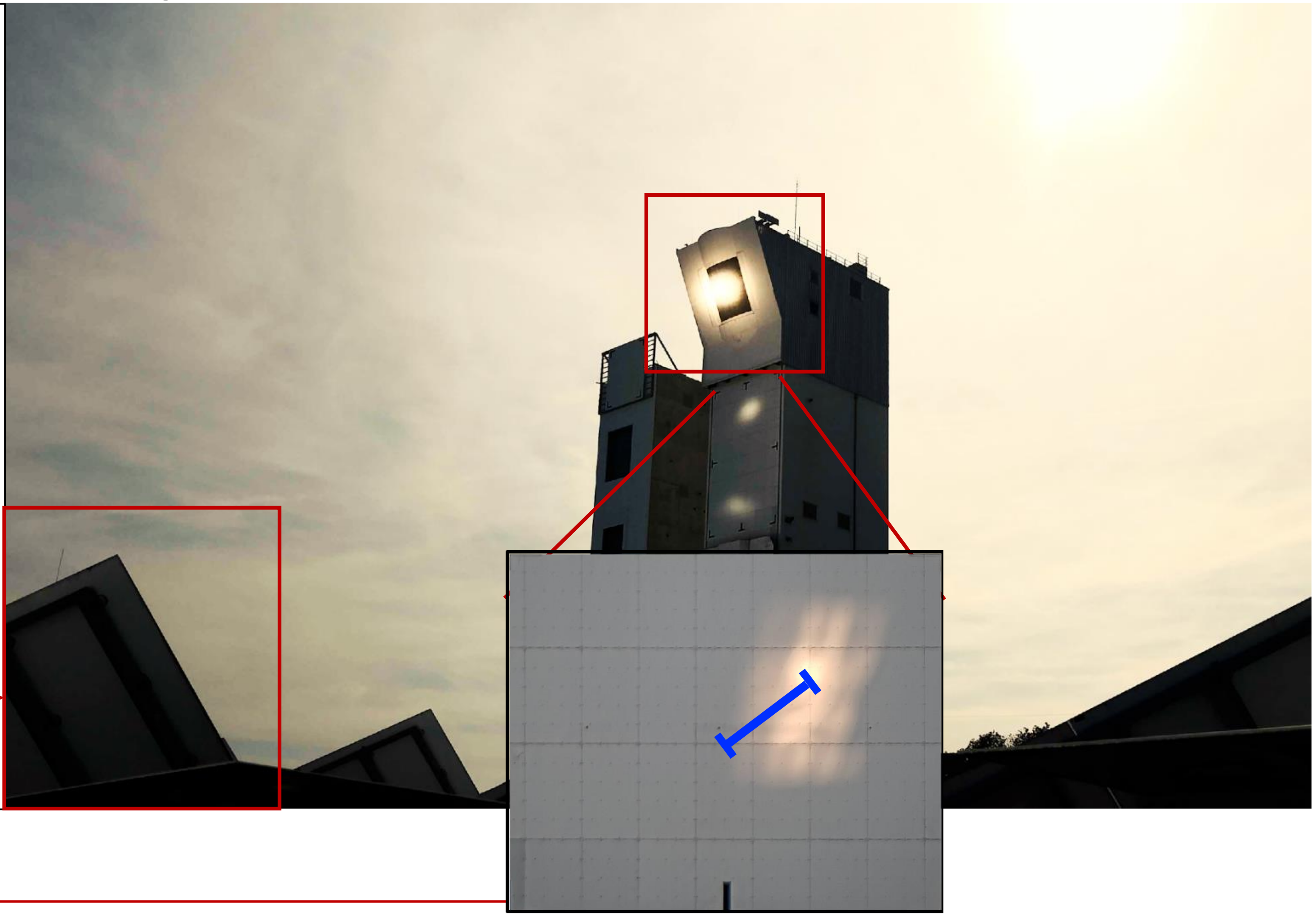




Digital Instance

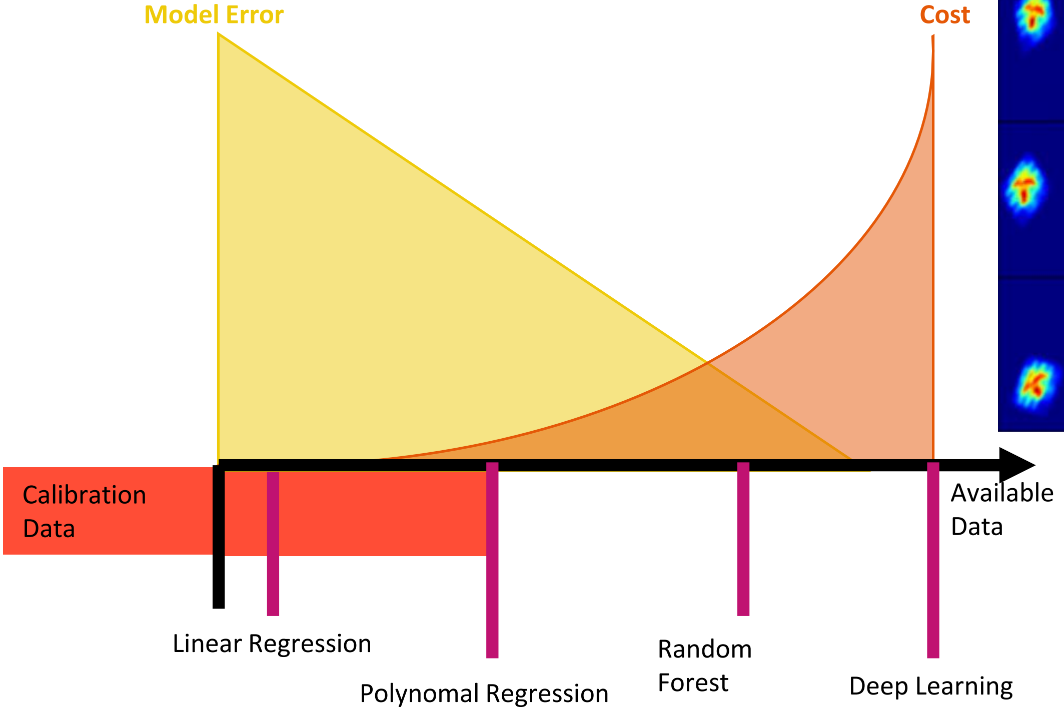
Real Object

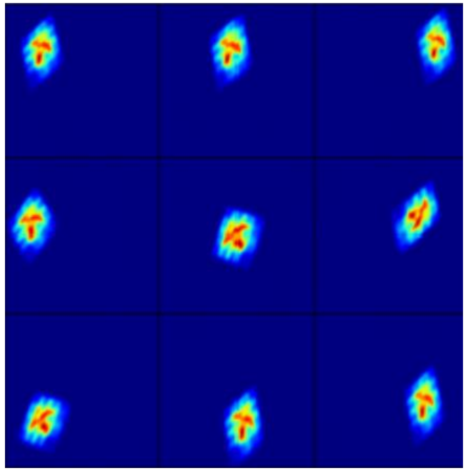


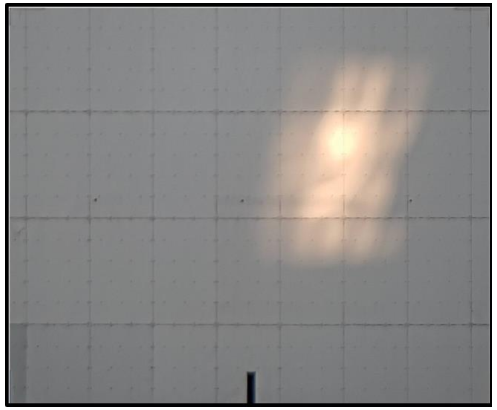


GANCSTR | ARTIST

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



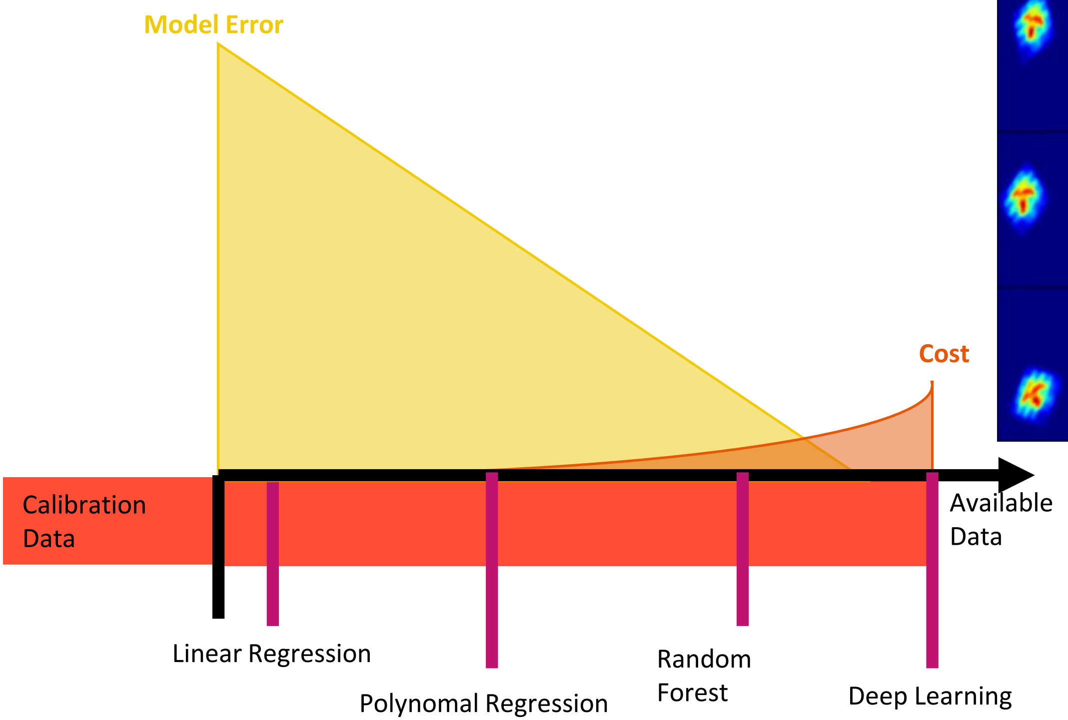


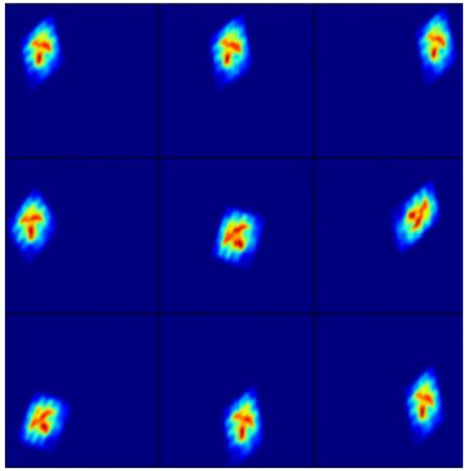


GANCSTR | ARTIST

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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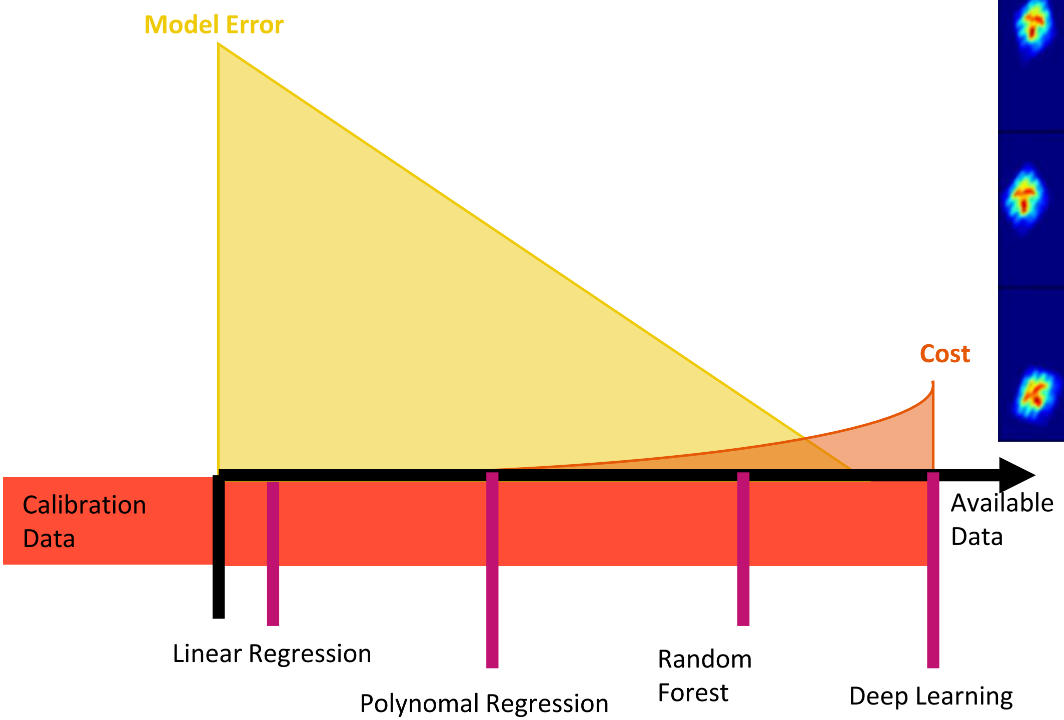

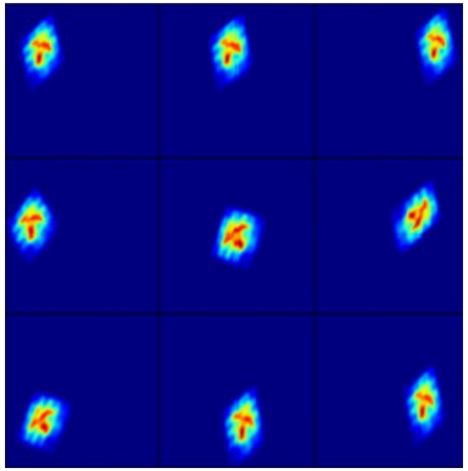

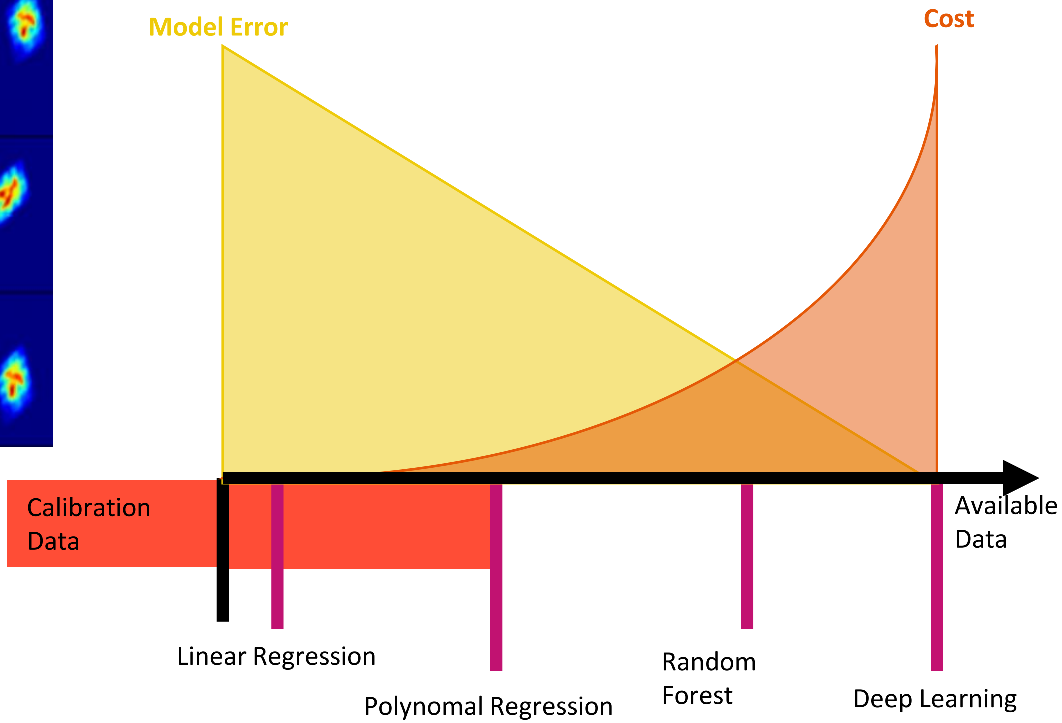

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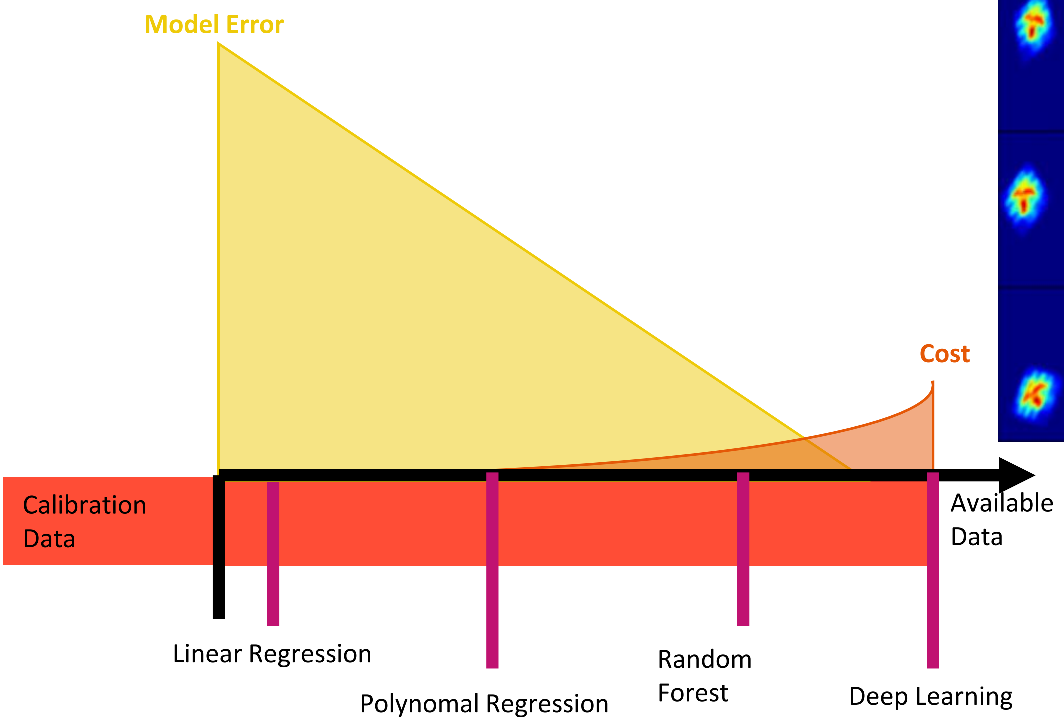
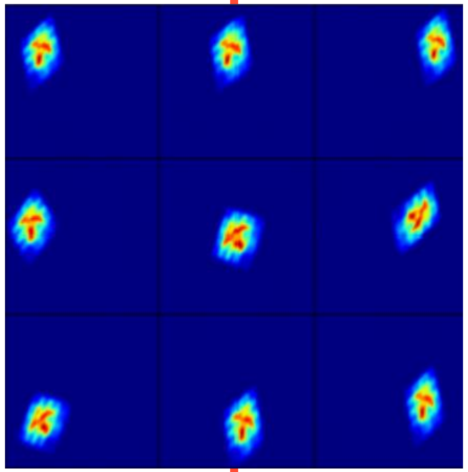
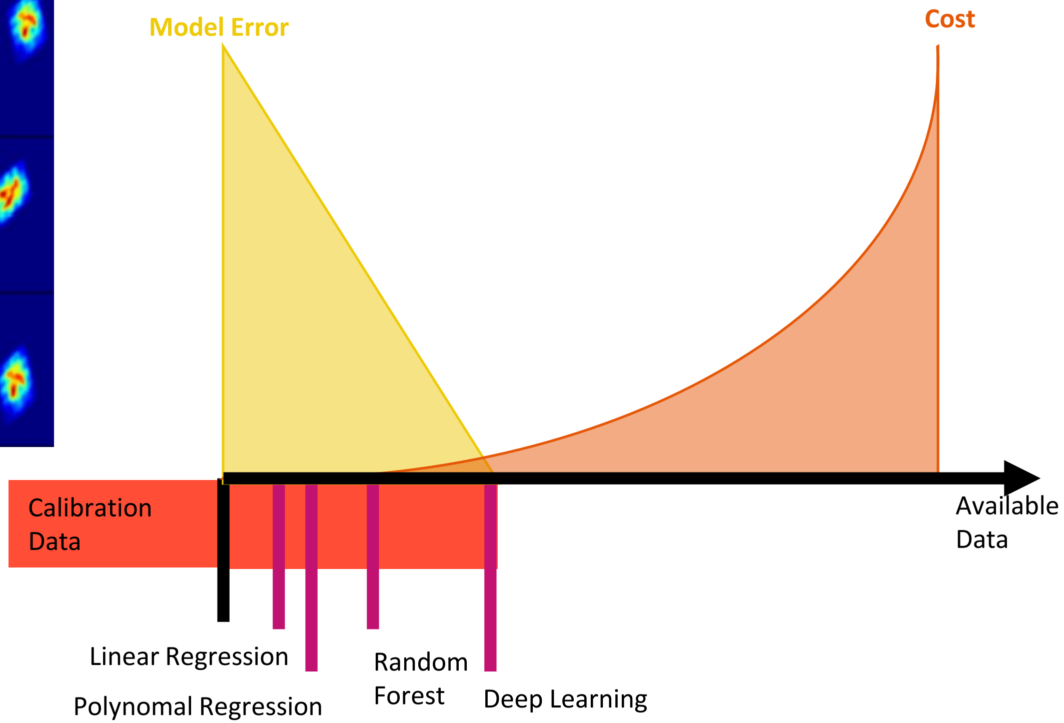
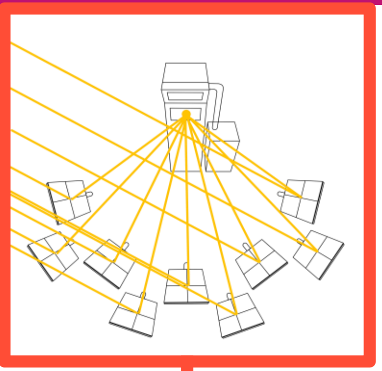
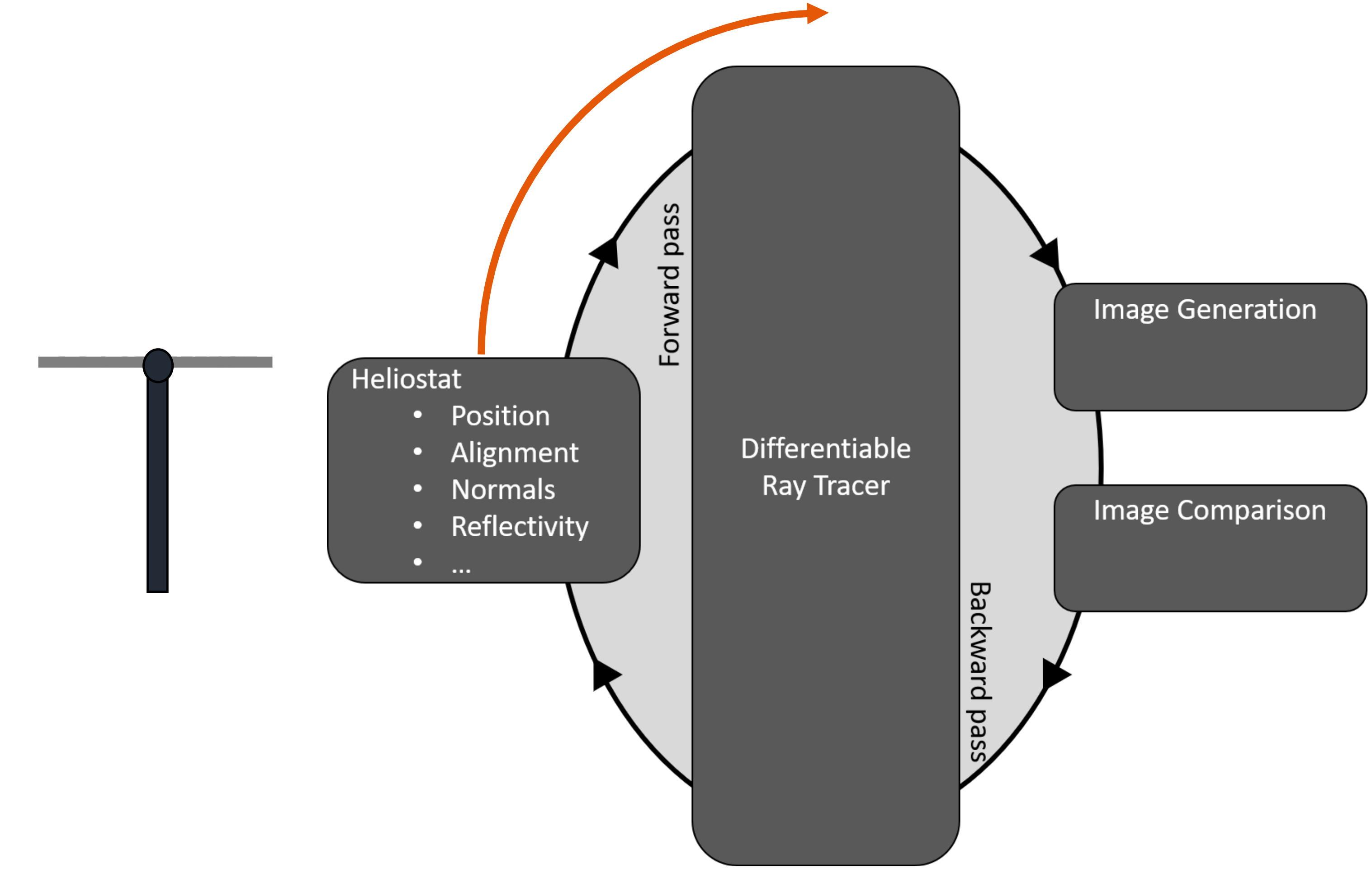


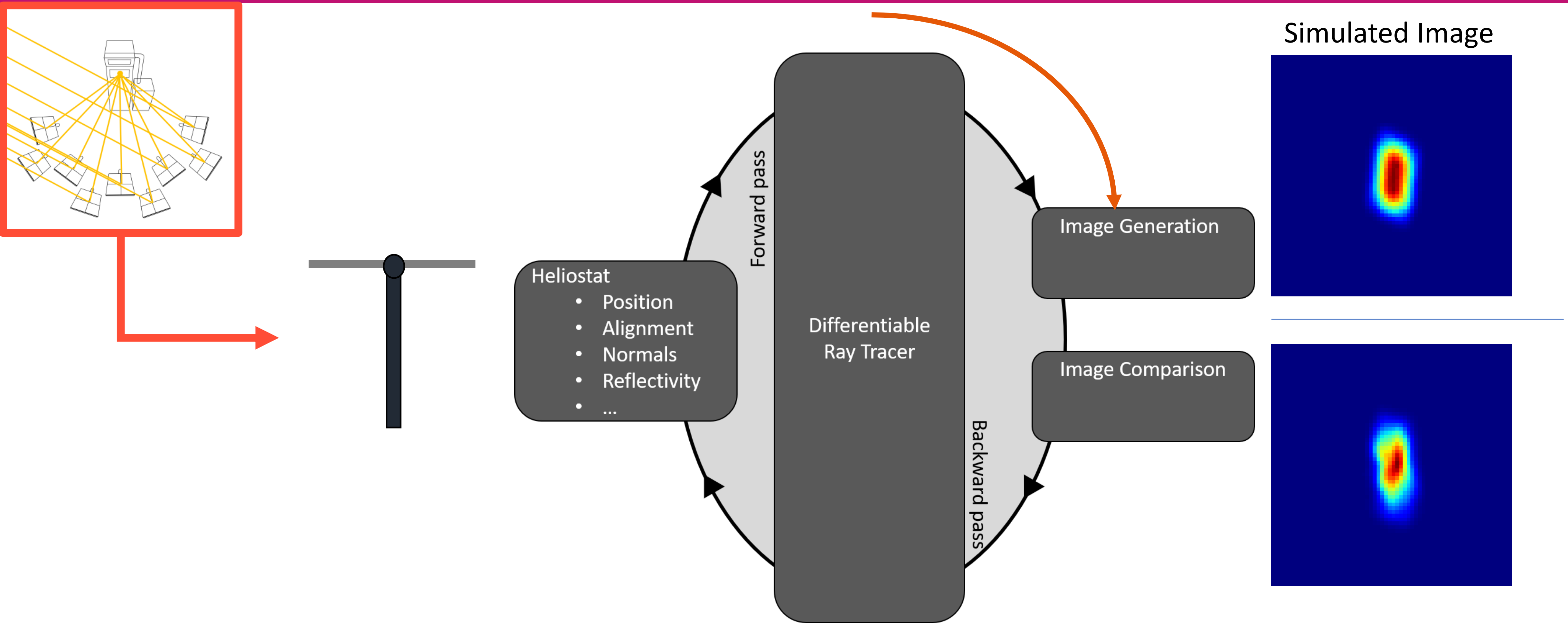


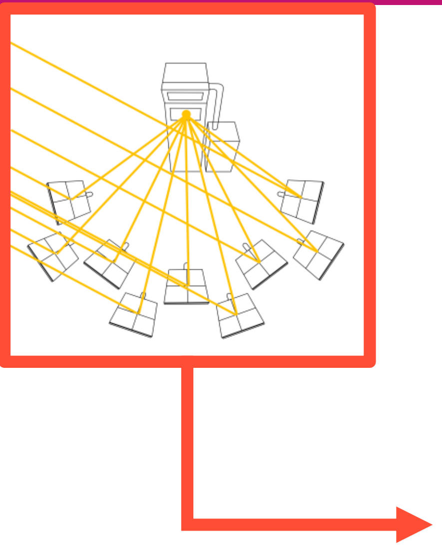


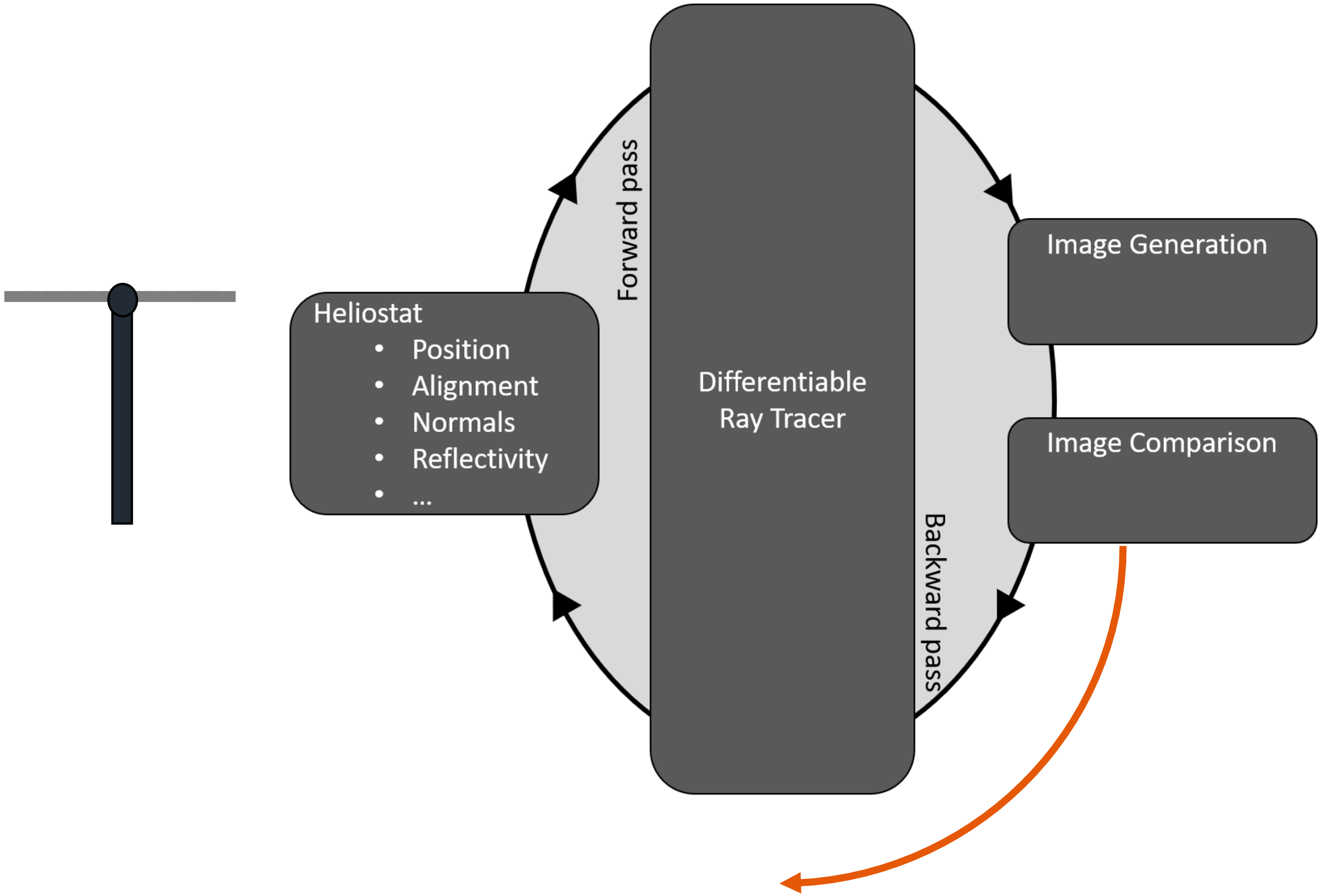
Methods: Differentiable Raytracing



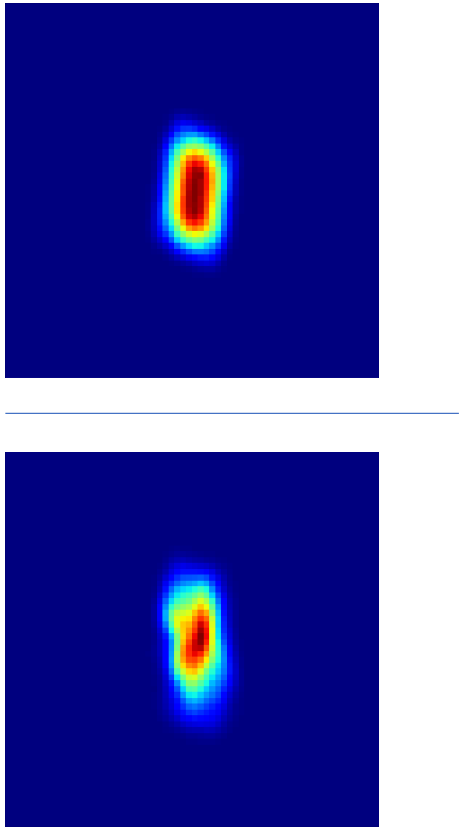

Heliostat
• Position
• Alignment
• Normals
• Reflectivity
• …
Forward pass
Differentiable Ray Tracer
Backward pass
Image Generation
Image Comparison

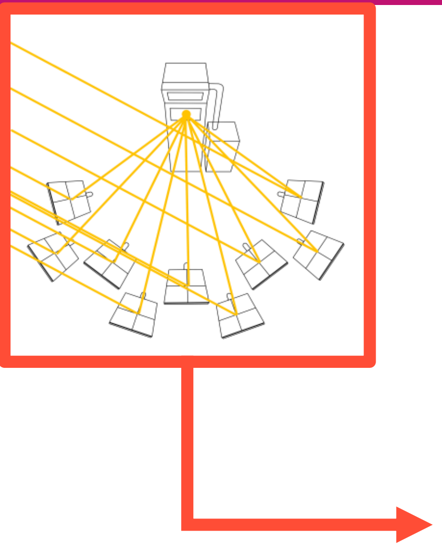

Heliostat
Position
Alignment
Normals
Reflectivity
...
Forward pass
Differentiable
Ray Tracer
Backward pass
Image Generation
Image Comparison
Simulated Image

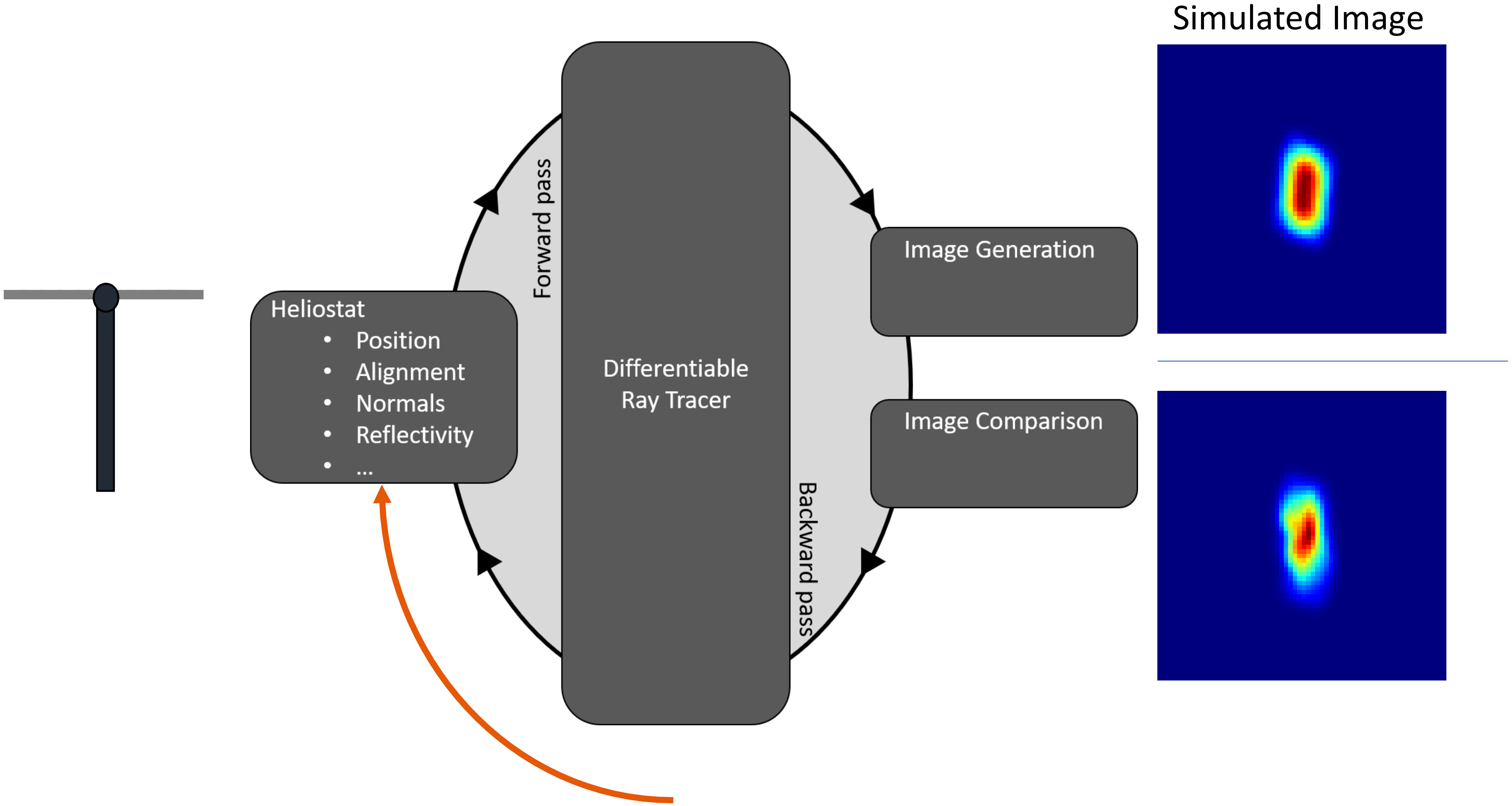




Simulated Image



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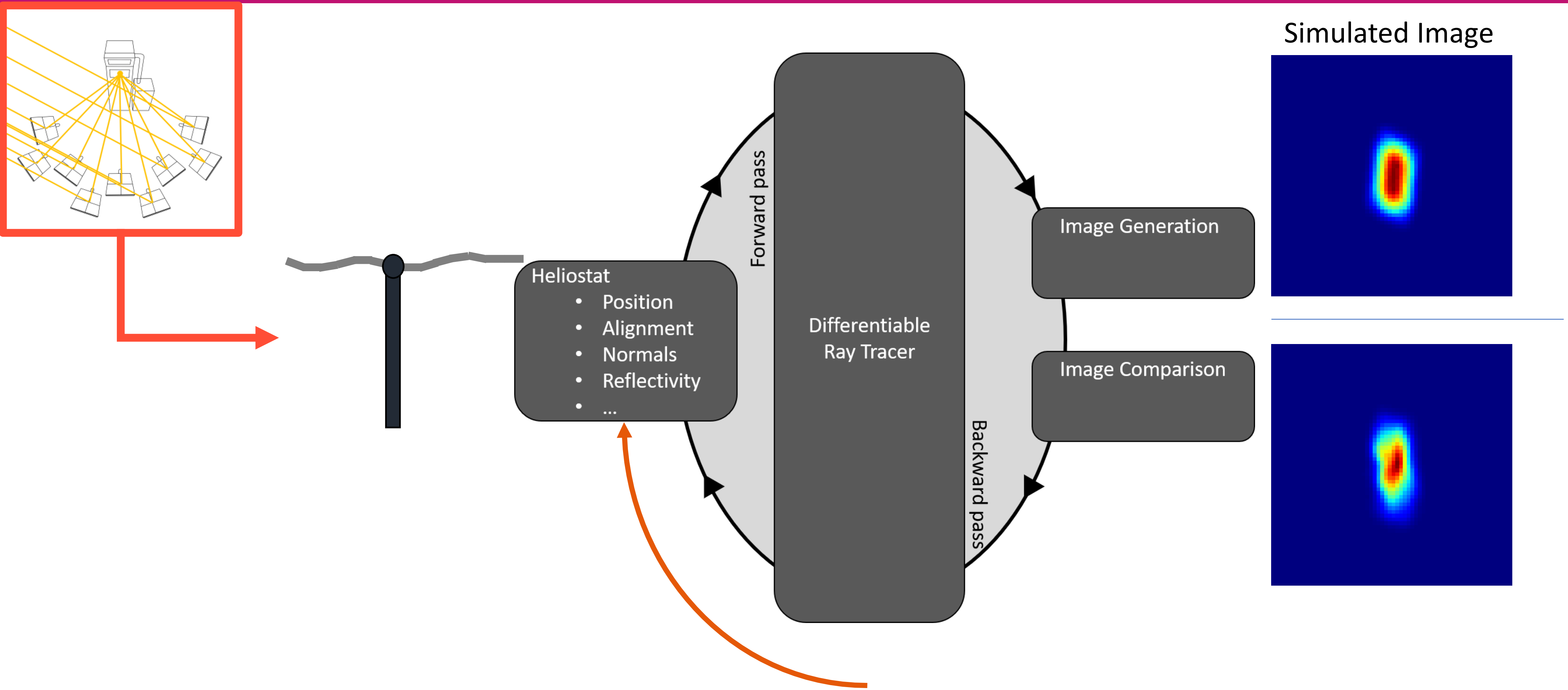
Simulated Image
Heliostat
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Forward pass
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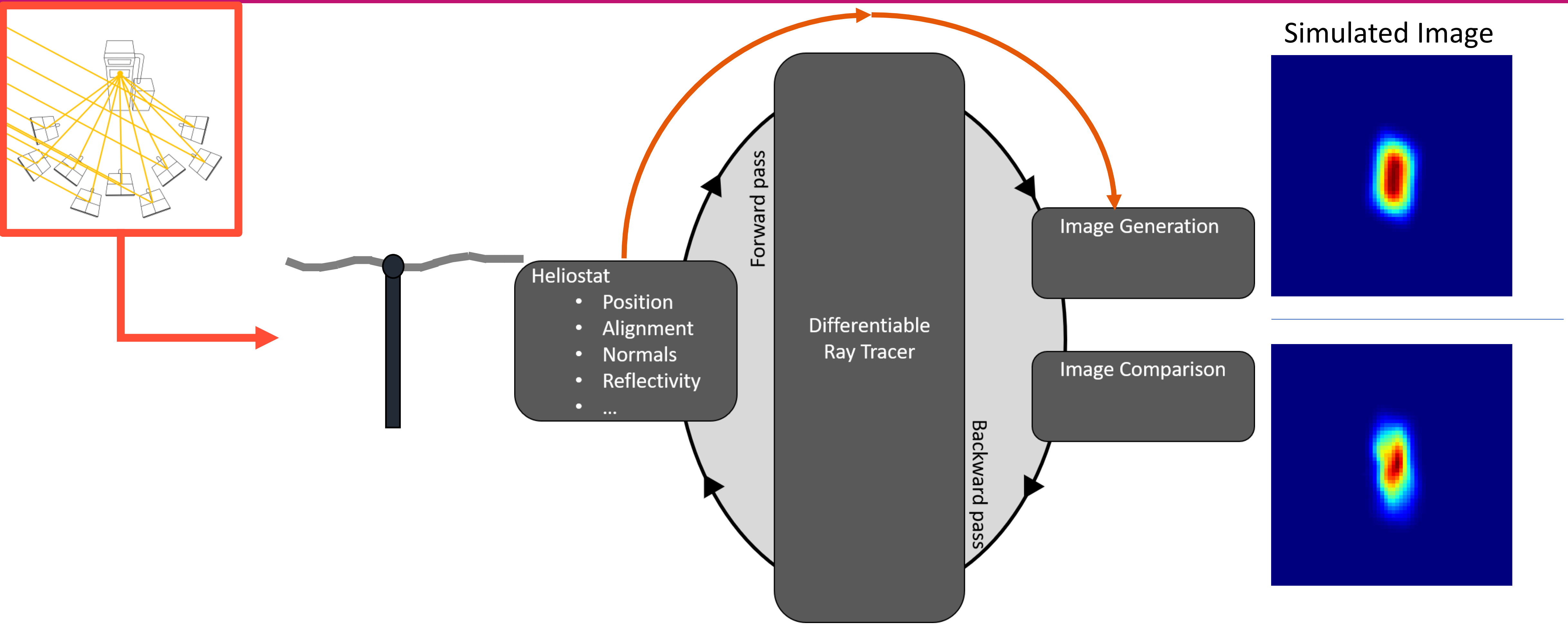
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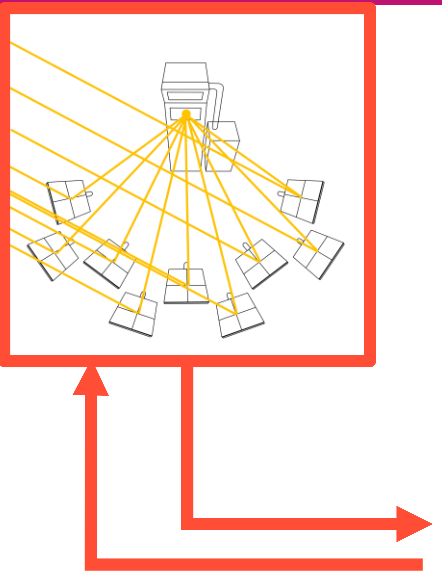

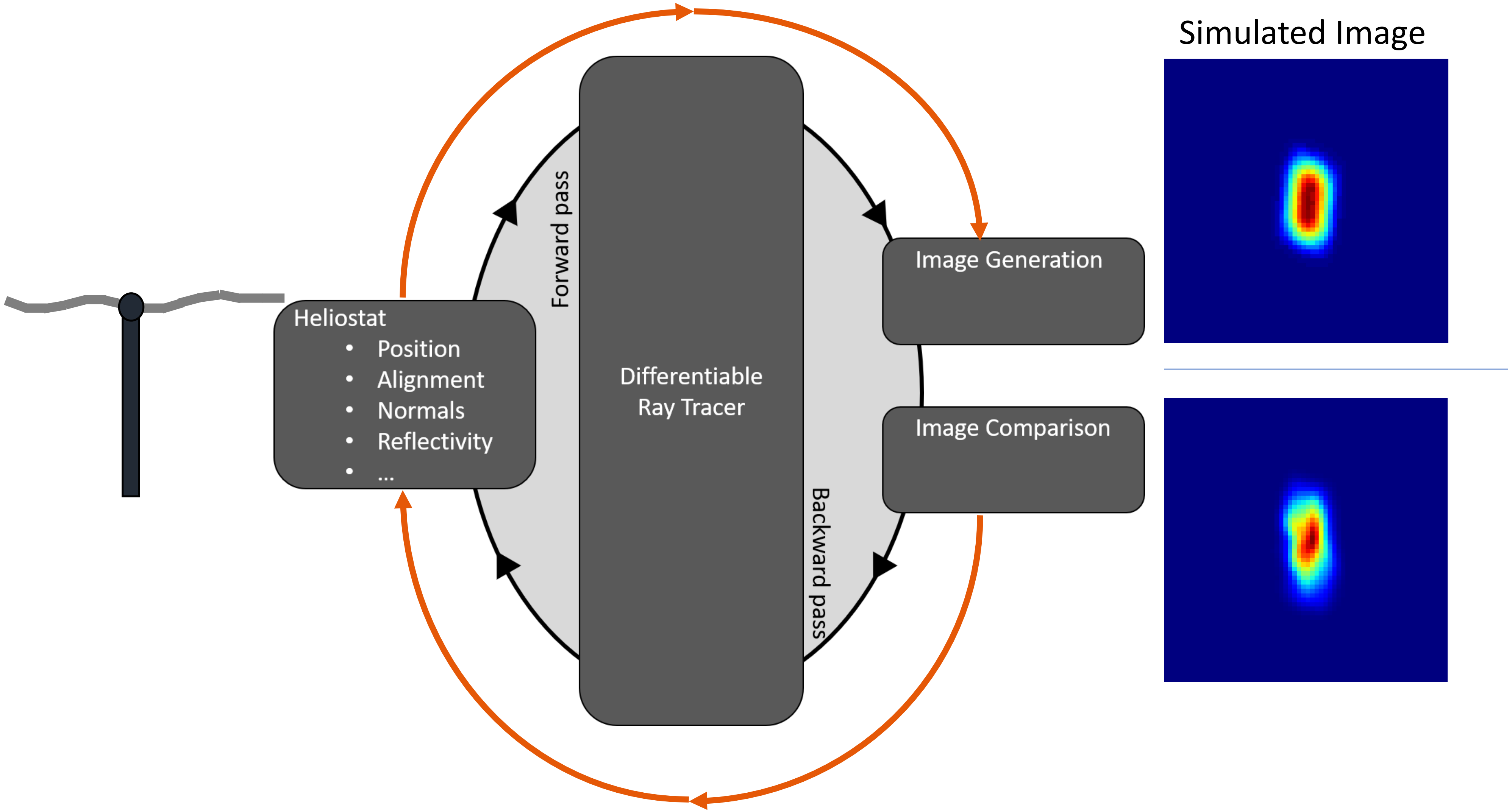
Forward pass
Heliostat
Position
Alignment
Normals
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…
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Image Comparison
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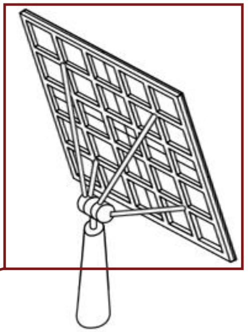
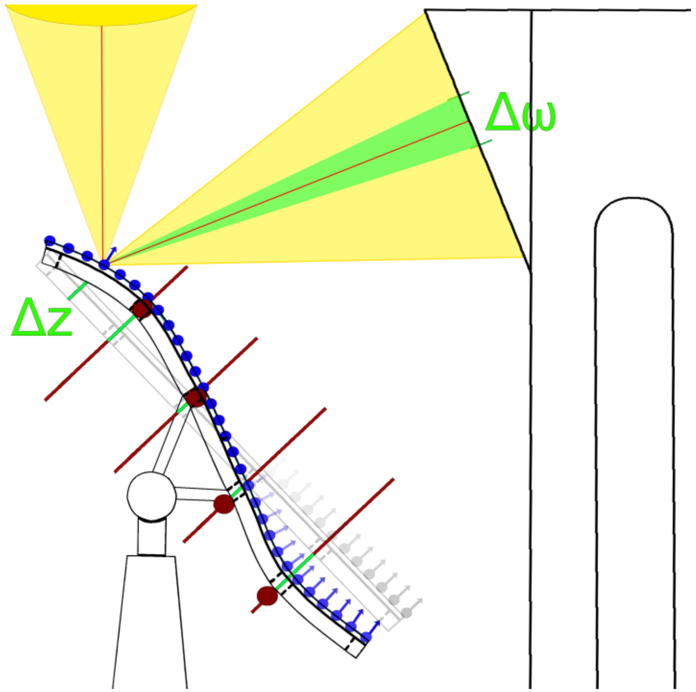
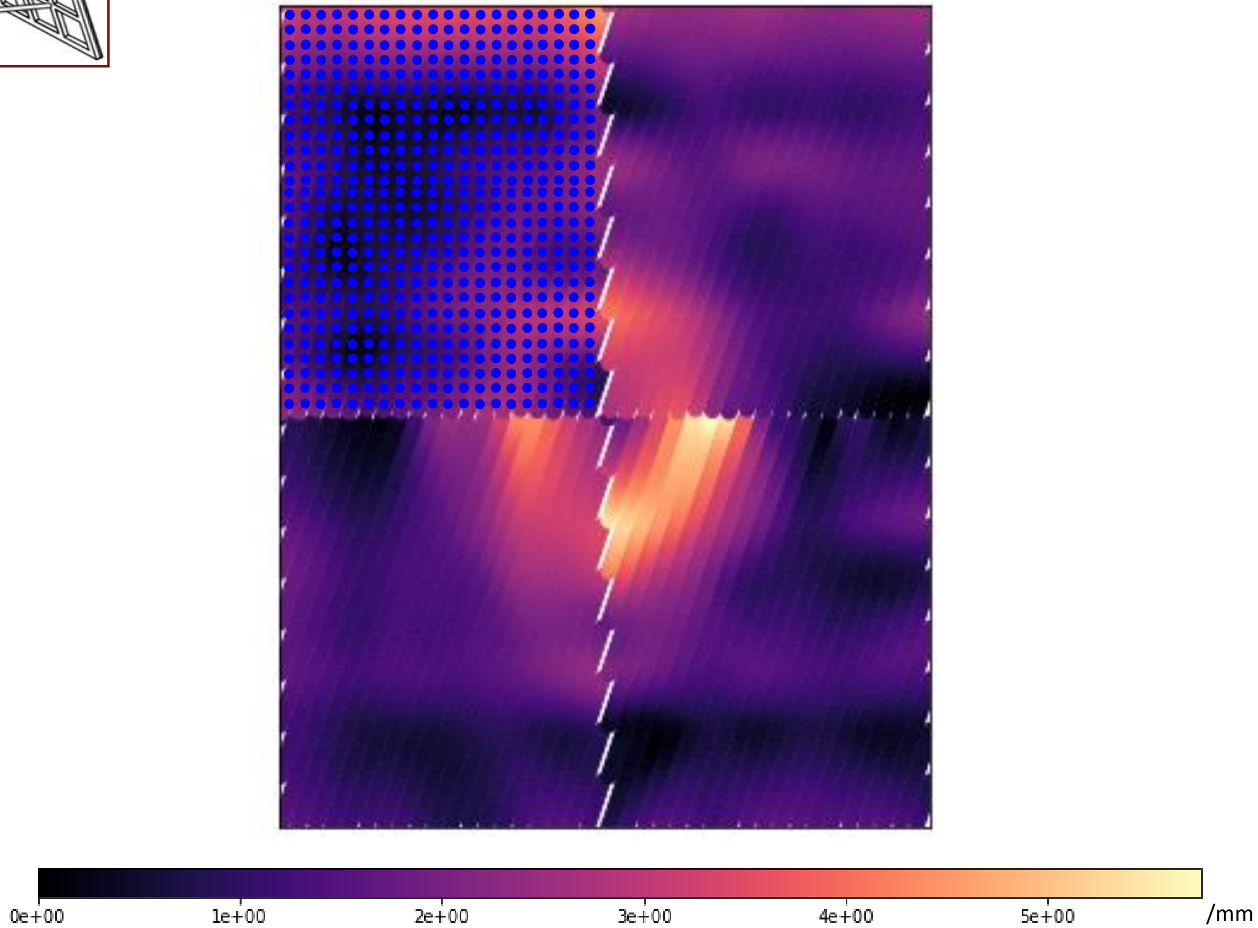
Diagnosis:
Detect Mirror Deformations

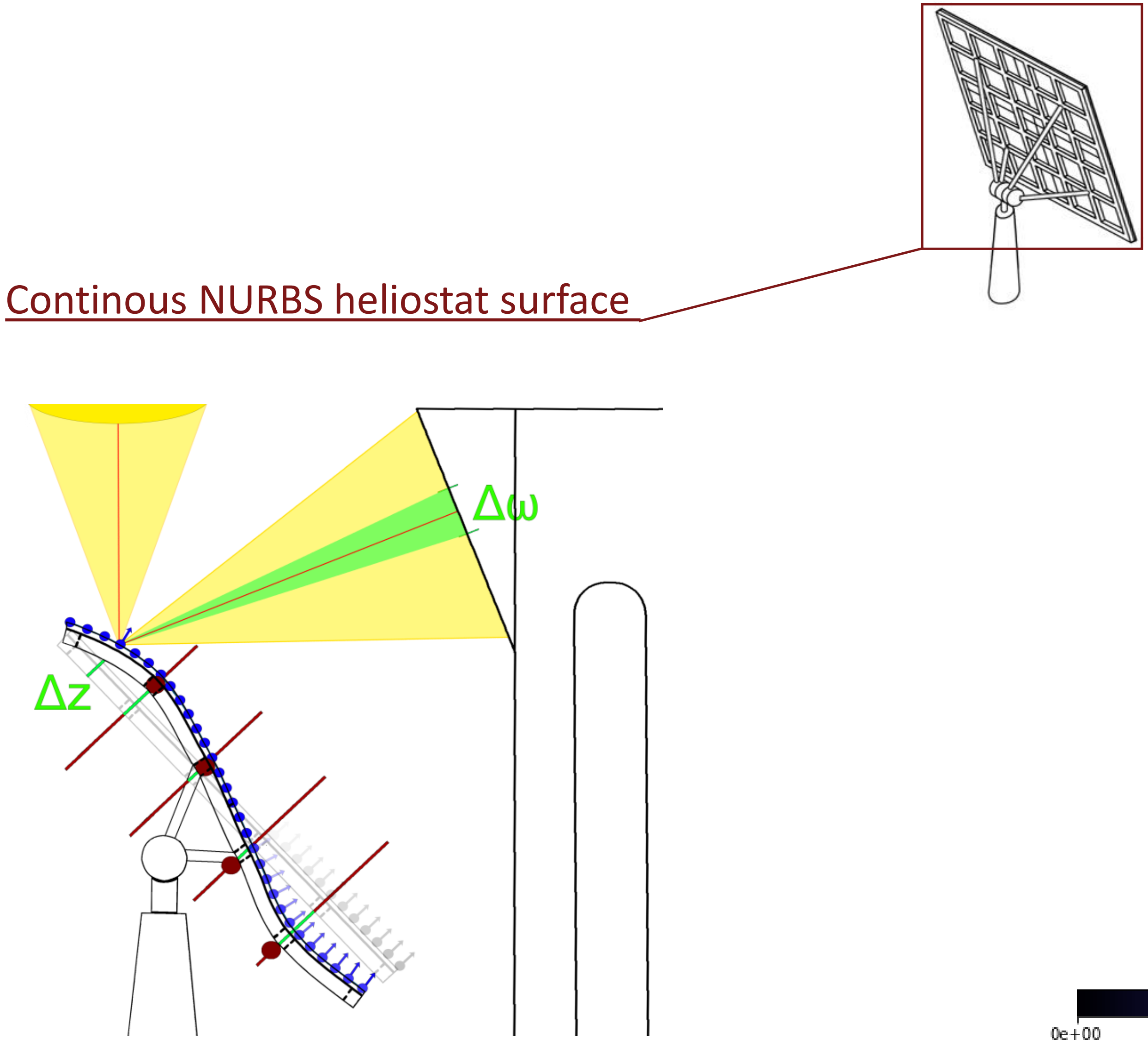


Continous NURBS heliostat surface



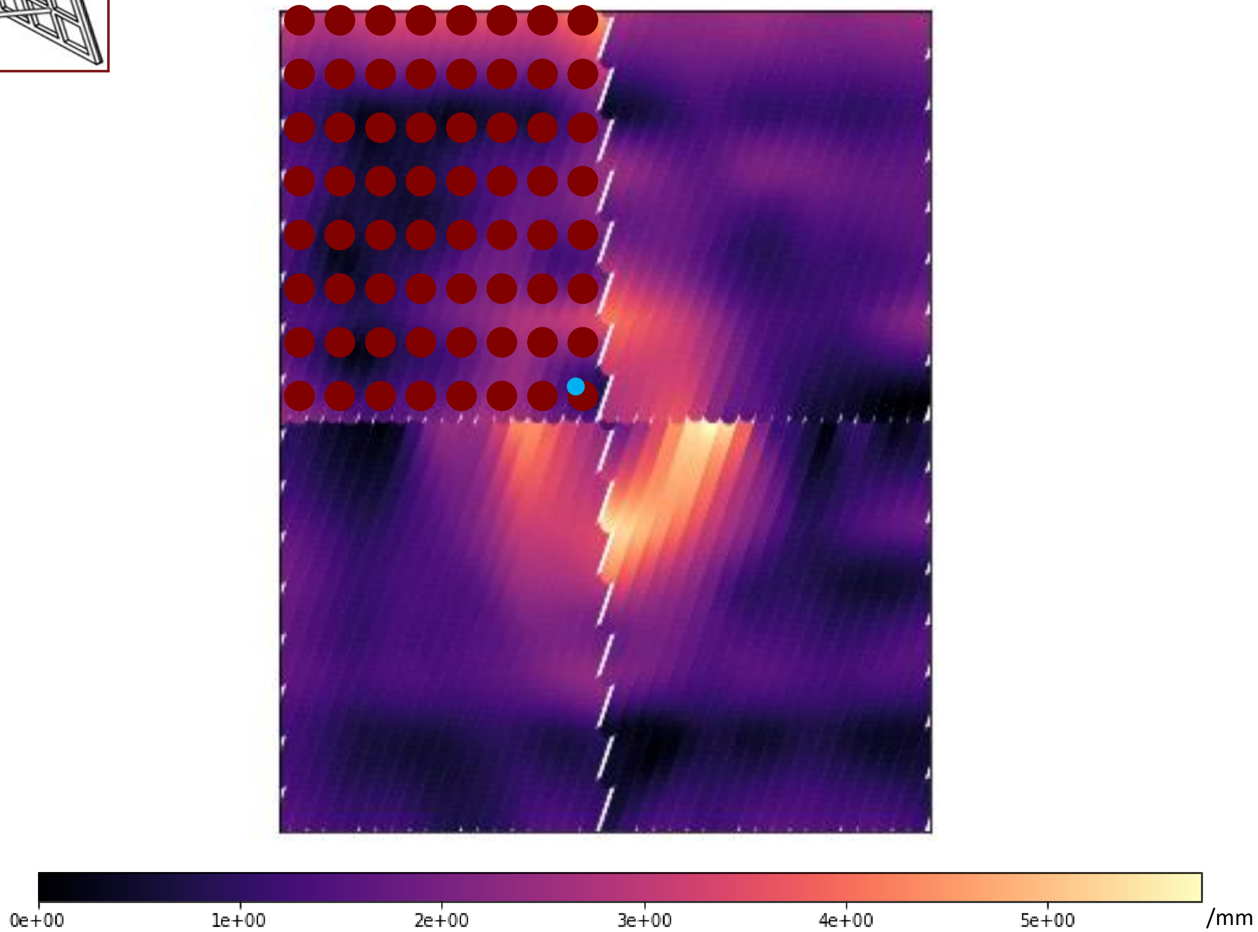
Ca. 25k points per facet

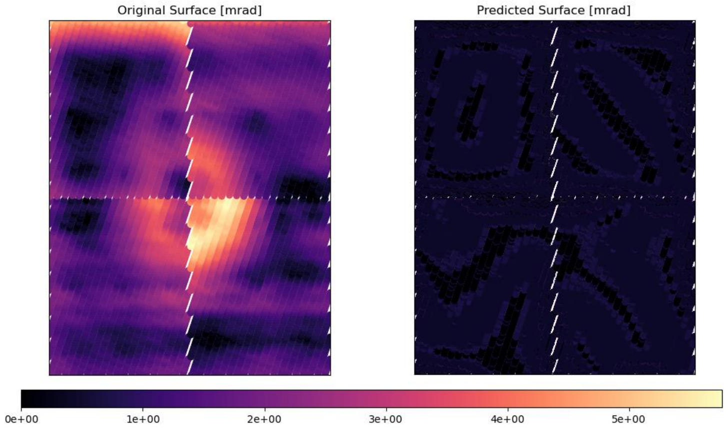


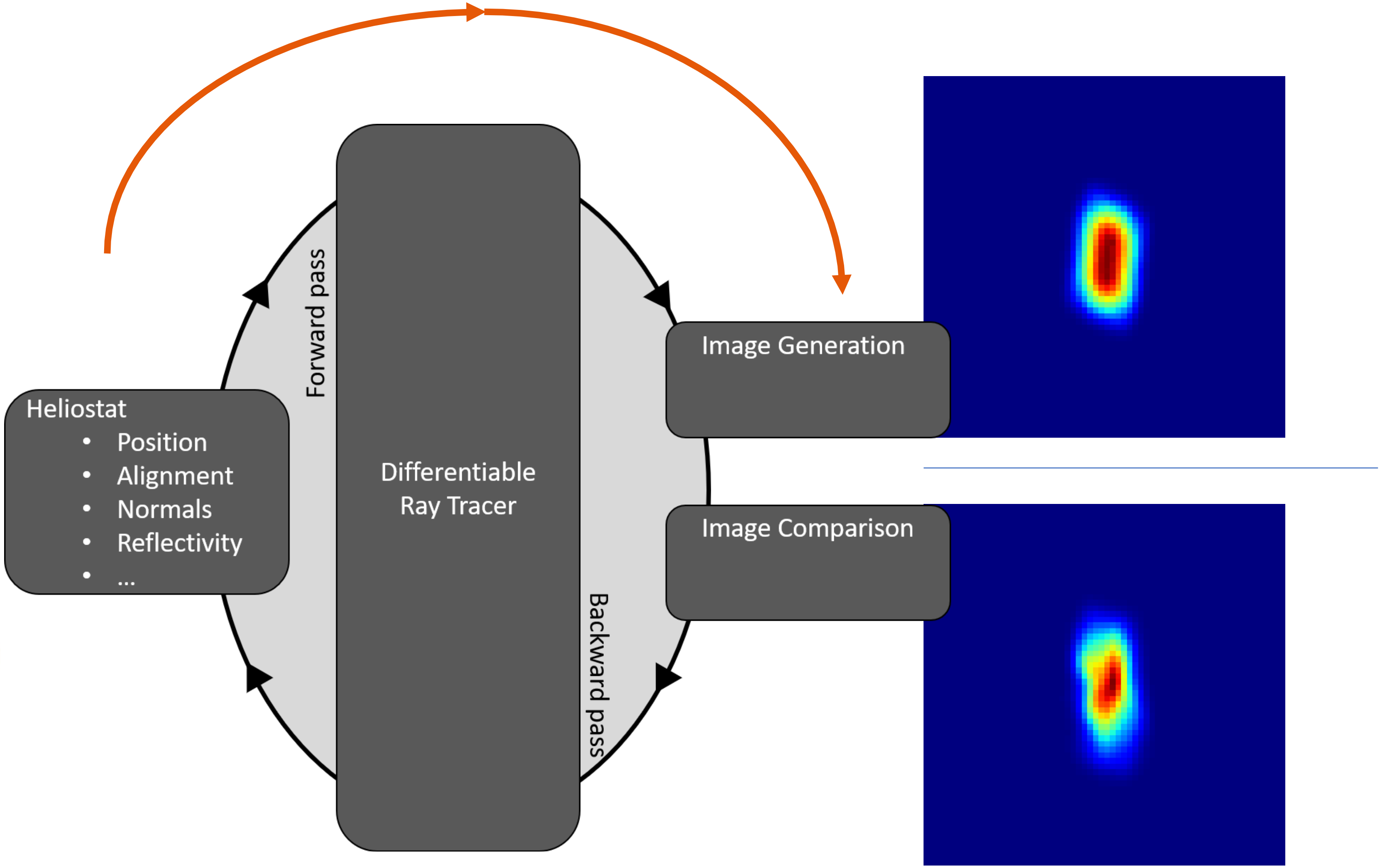


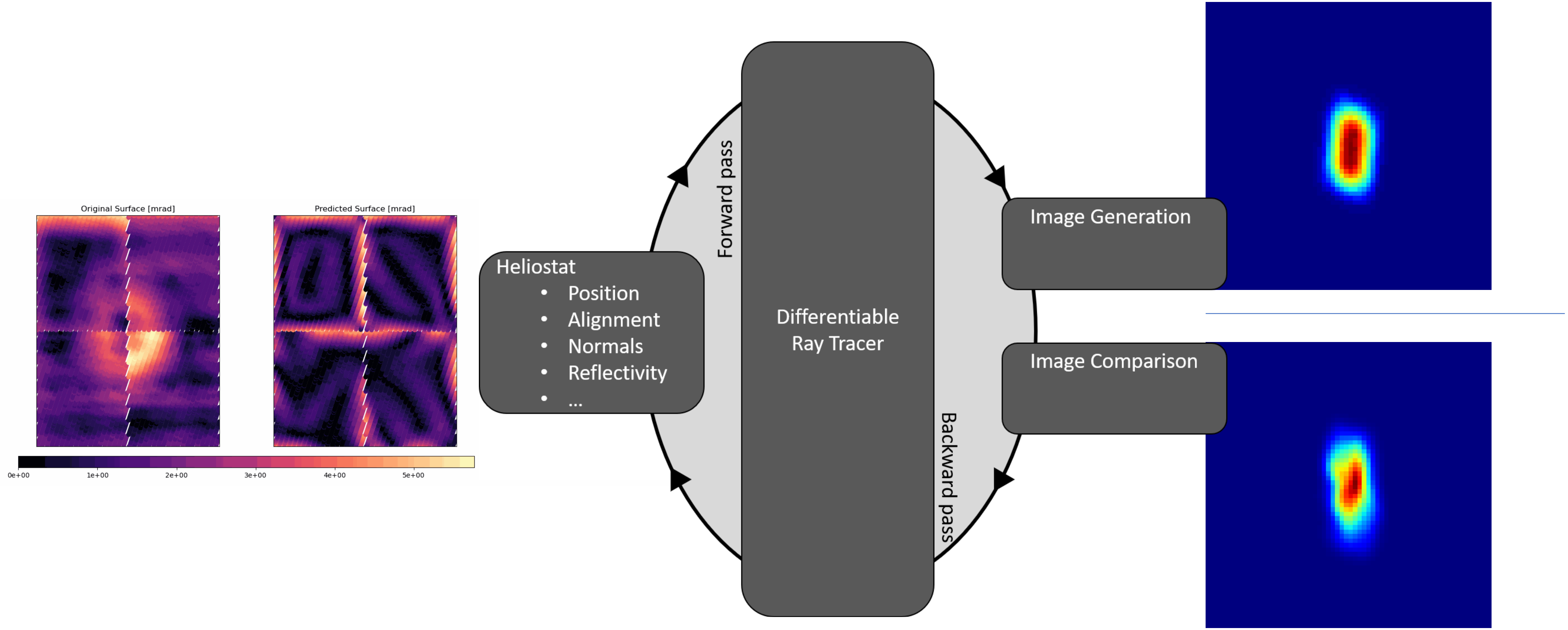
Ca. 25k points per facet

→ 64 points per facet with over 98% overlap

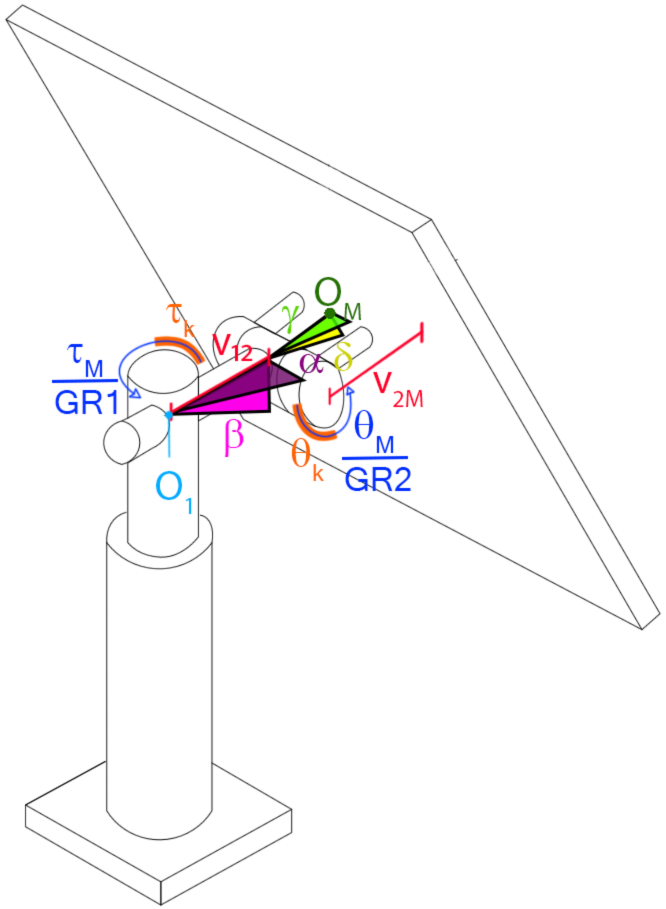


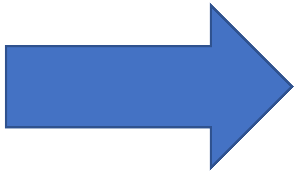

Original Surface [mrad]
Predicted Surface [mrad]
0e+00
1e+00
2e+00
3e+00
4e+00
5e+00

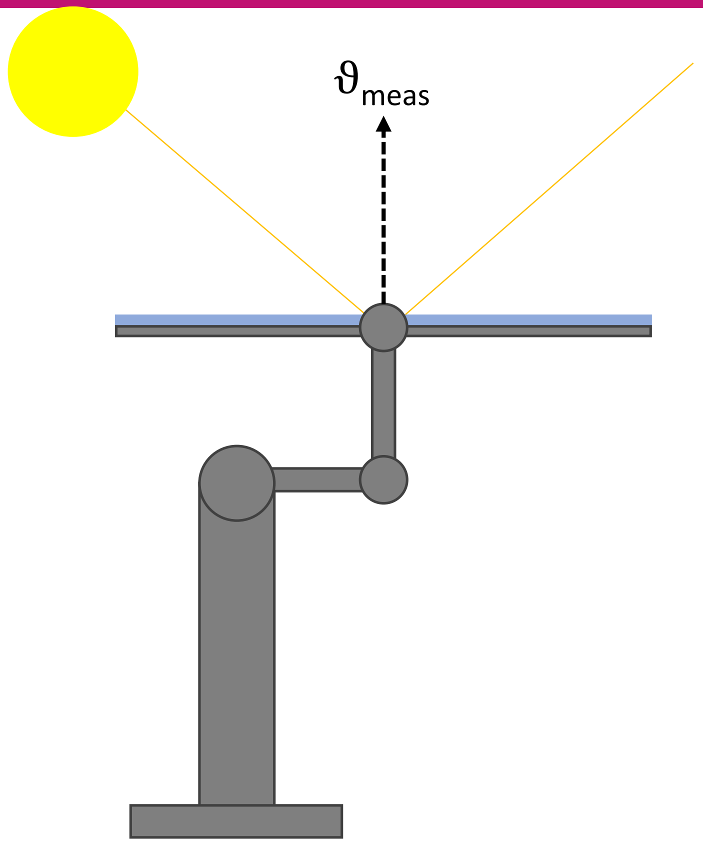

Heliostat
Position
Alignment
Normals
Reflectivity
...
Forward pass
Differentiable Ray Tracer
Backward pass
Image Generation
Image Comparison


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

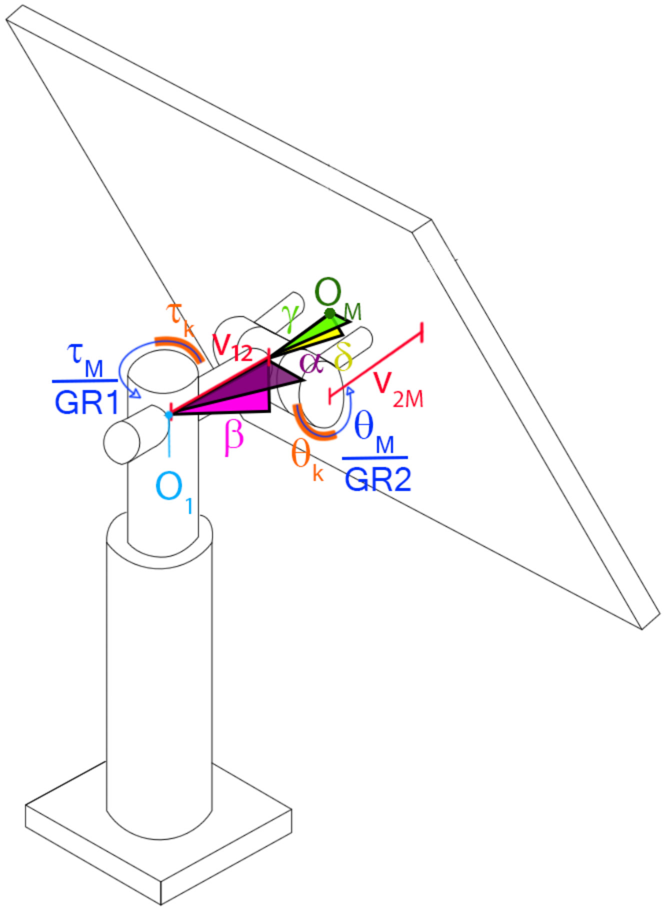
Control:
Heliostat Alignment

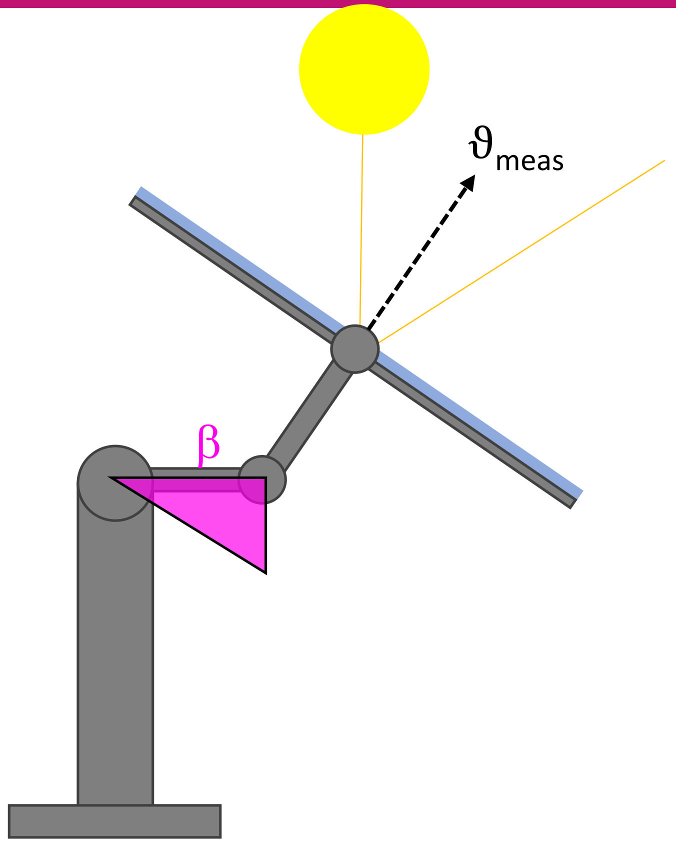




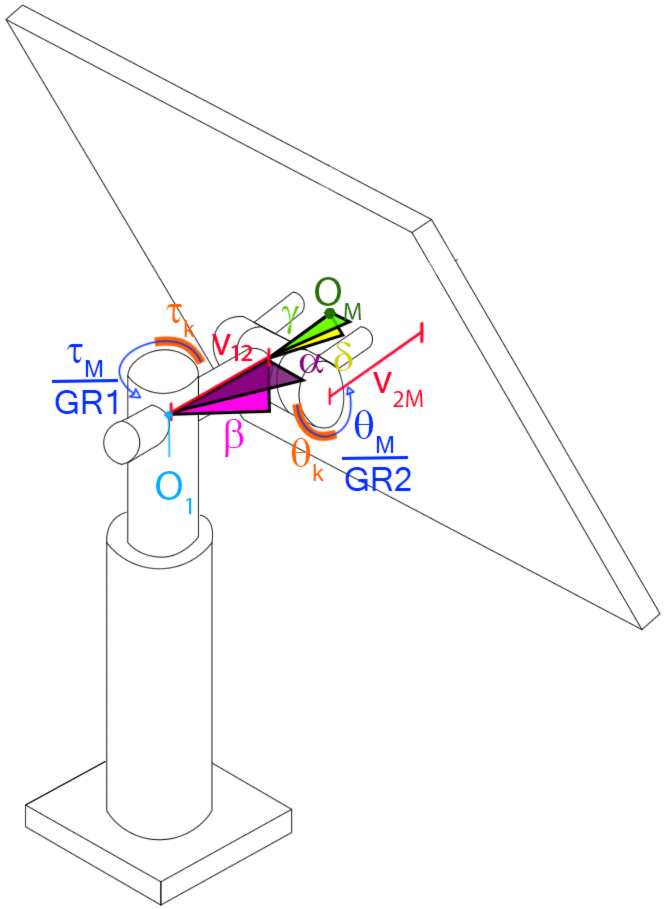


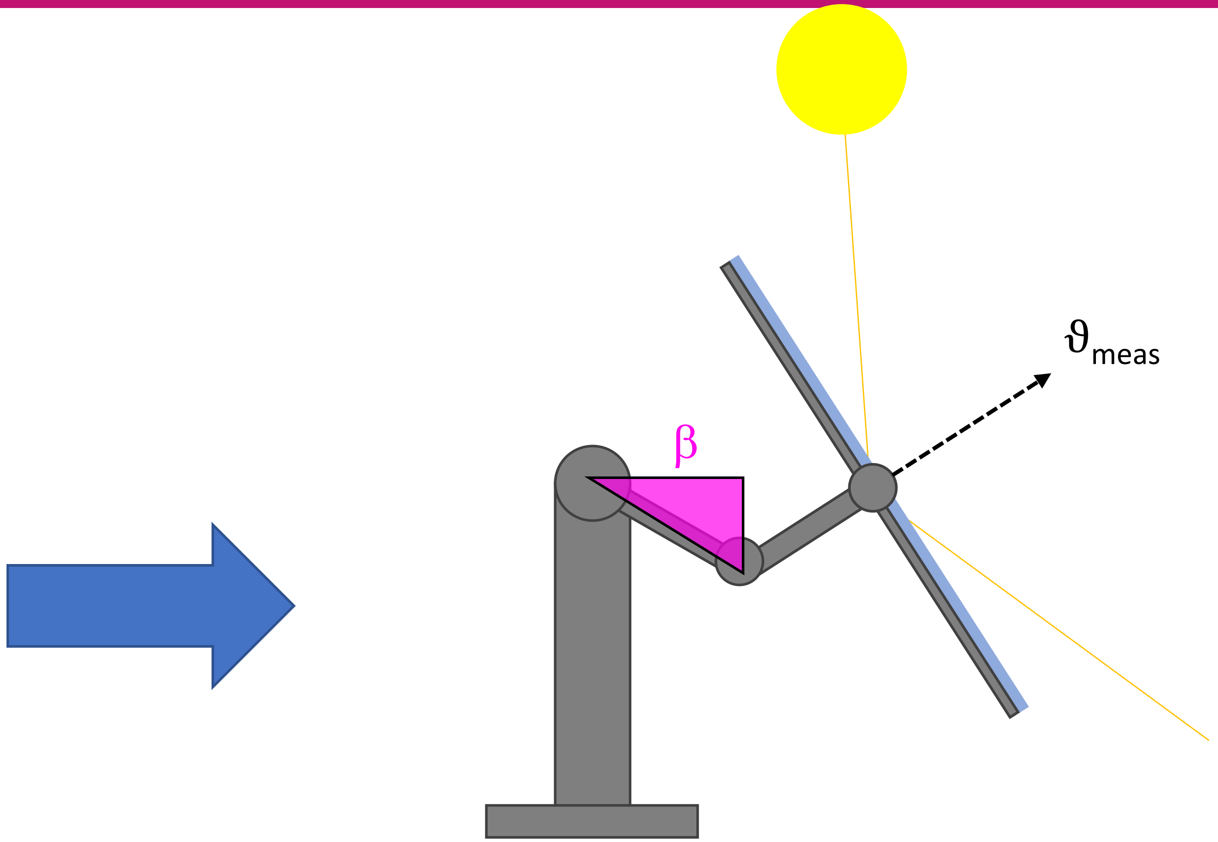
ϑ_{meas} = f(heliostat position, sun position, aimpoint)



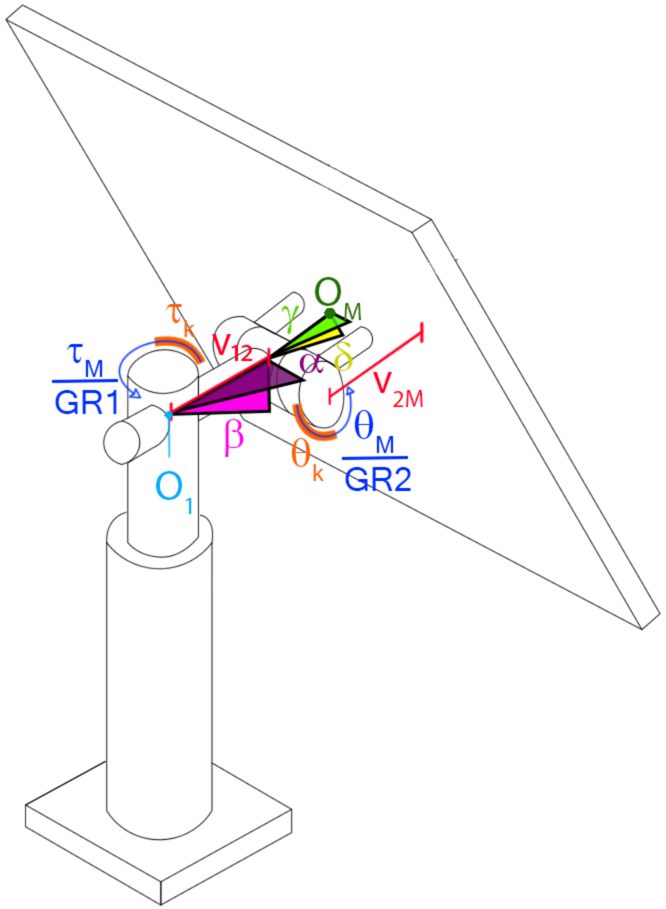


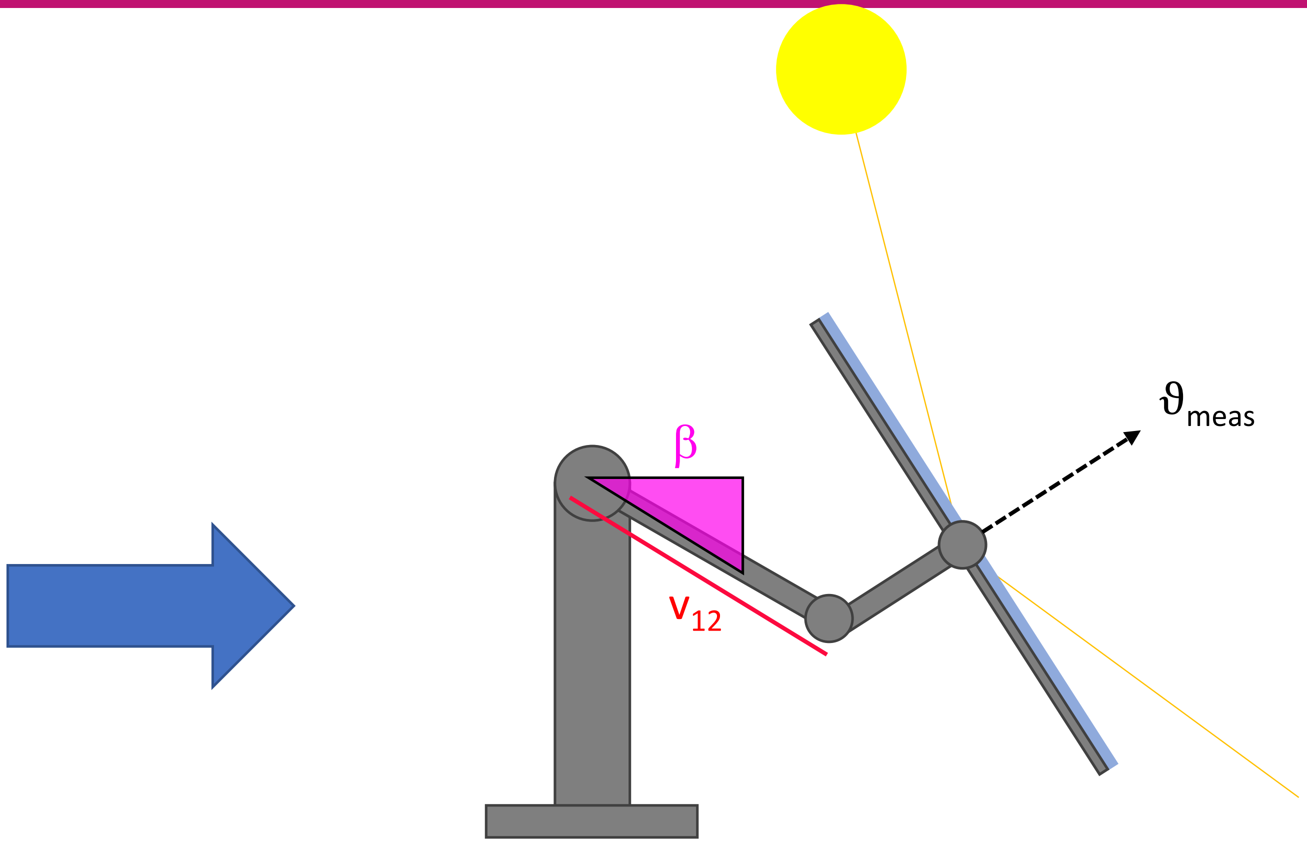
ϑ_{meas} = f(heliostat position, sun position, aimpoint)



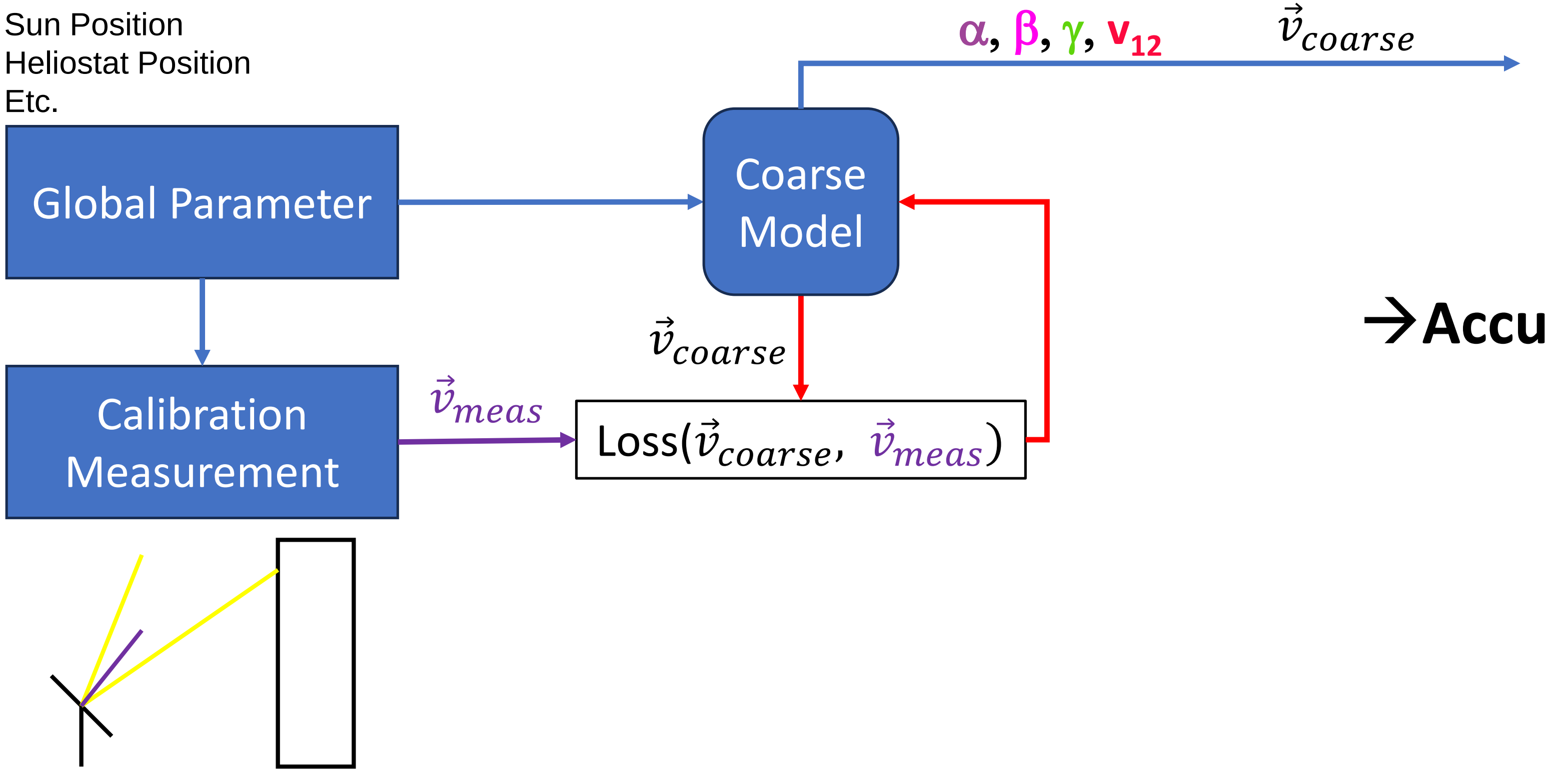


ϑ_{meas} = f(heliostat position, sun position, aimpoint)



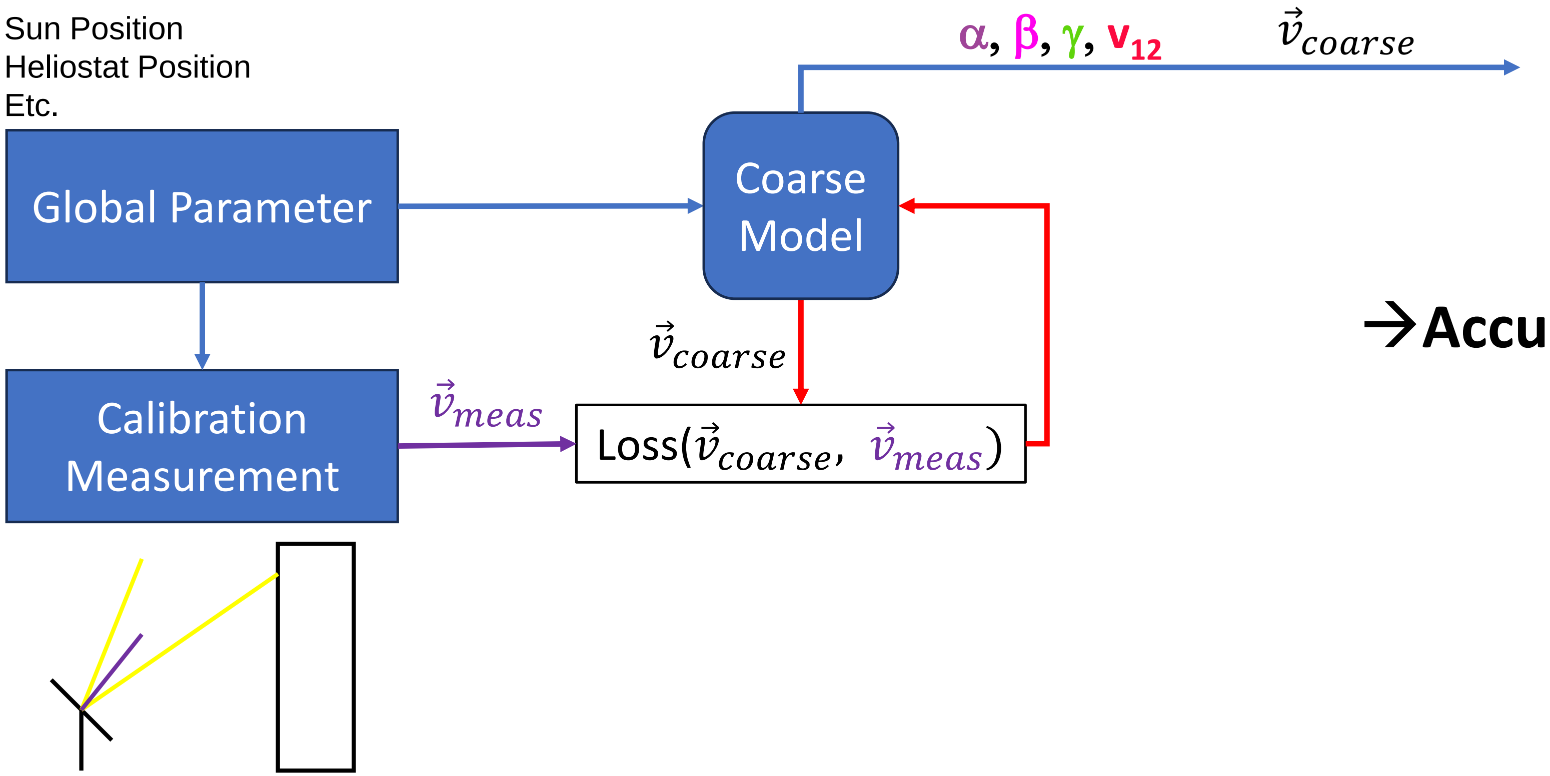


ϑ_{meas} = f(heliostat position, sun position, aimpoint
α, β, γ, v_{12} , …) → **20 independent parameters**



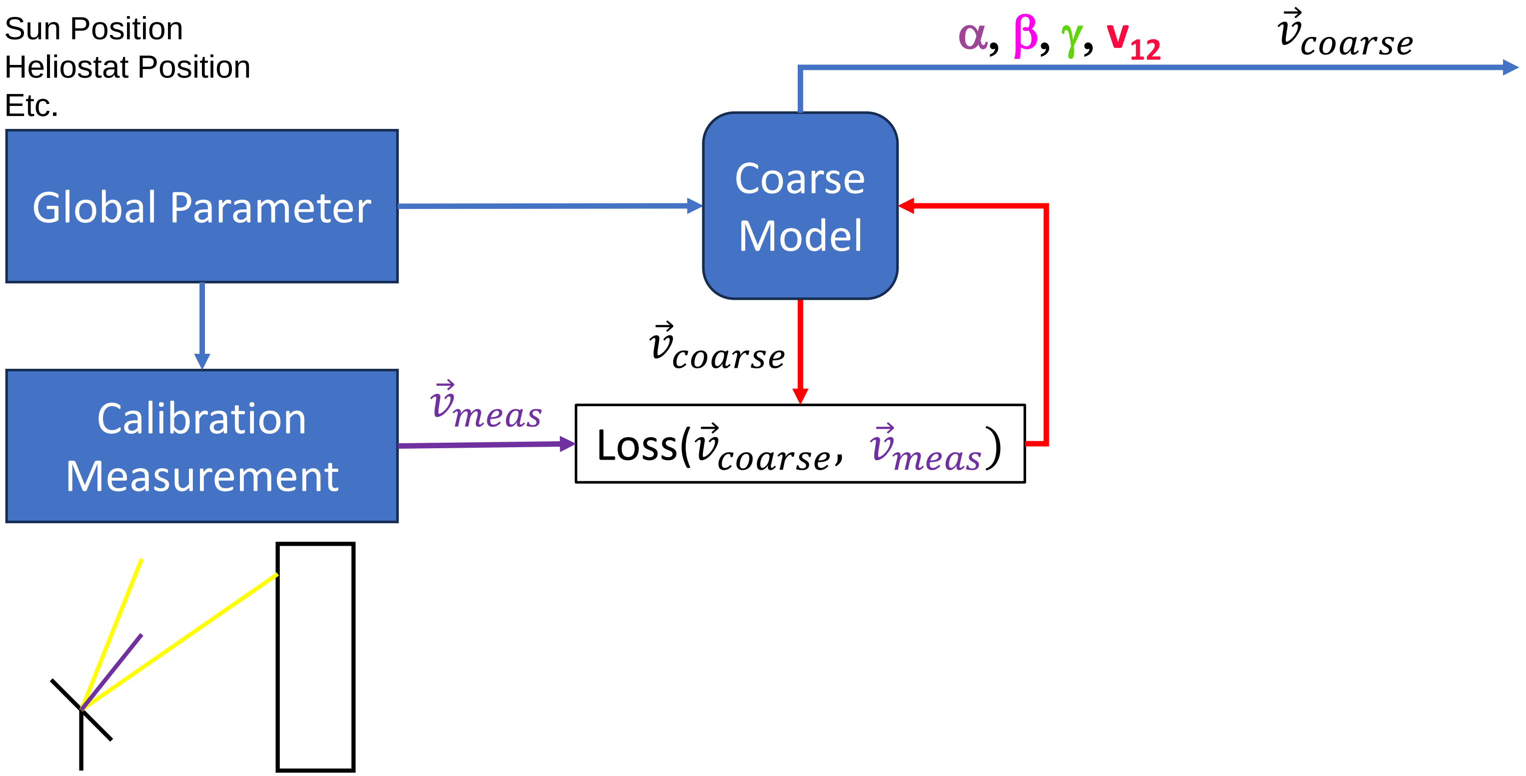
→Accuracy approx. 2 mrad

α = const

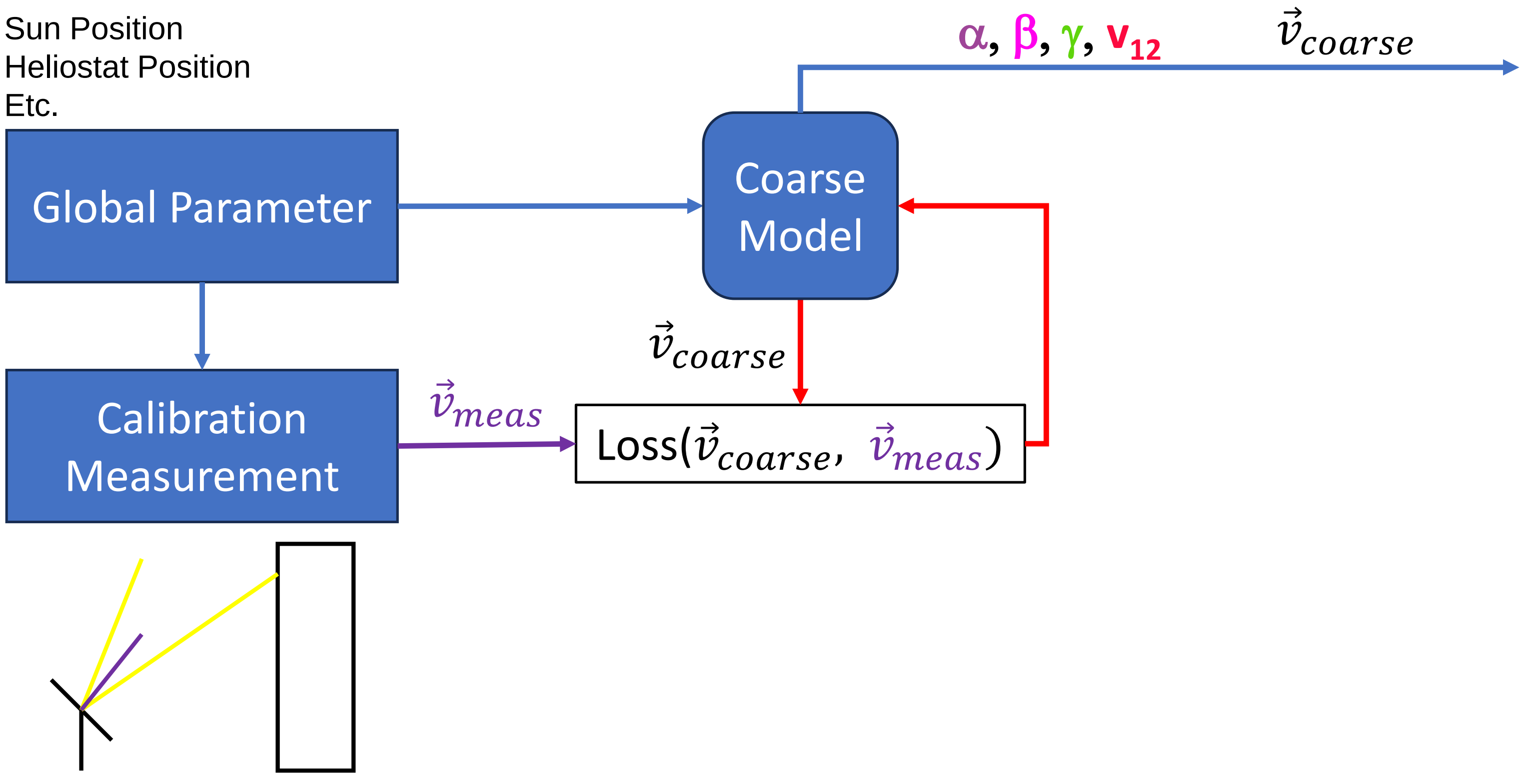


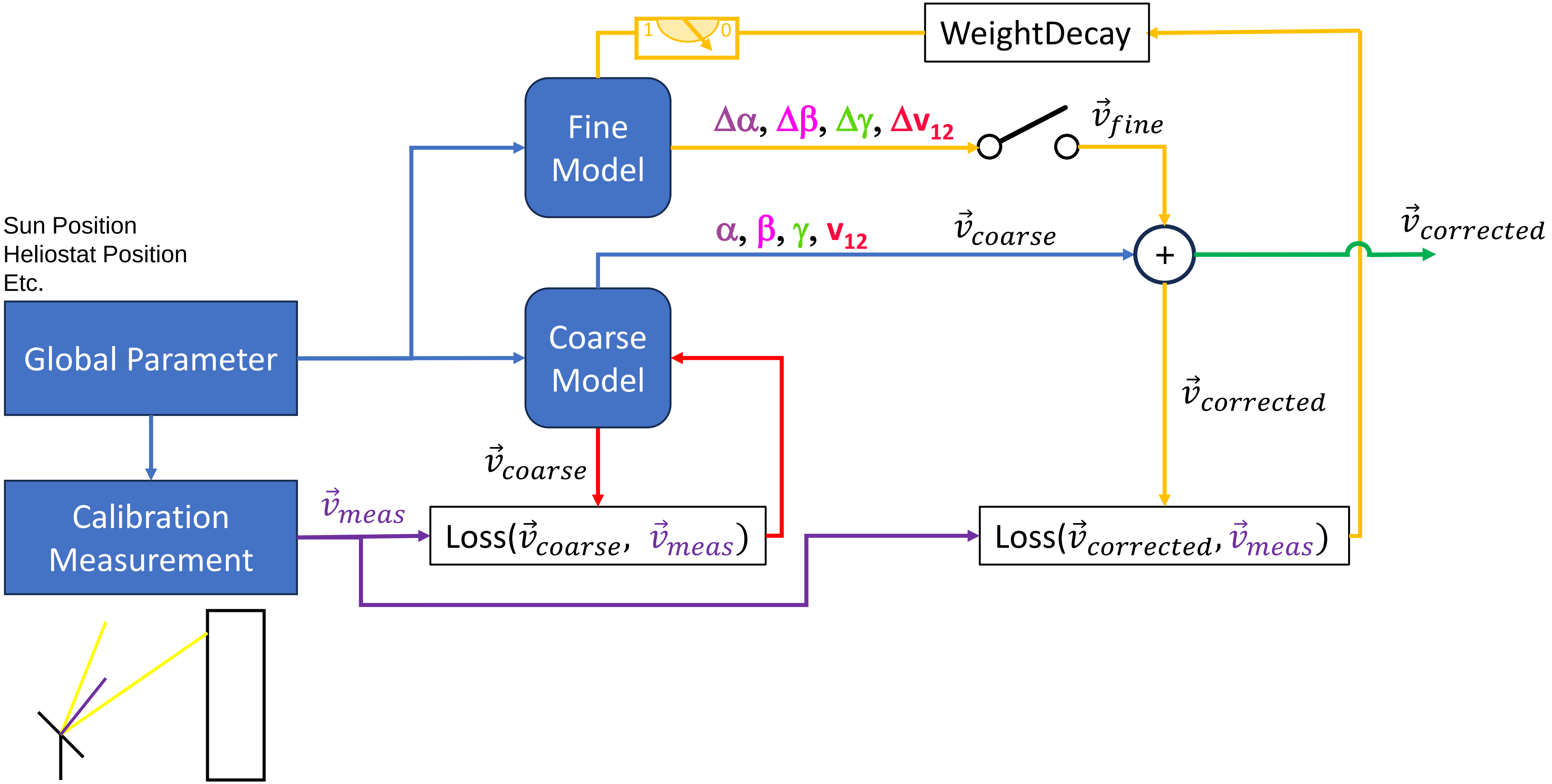
→**Accuracy approx. 2 mrad**

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

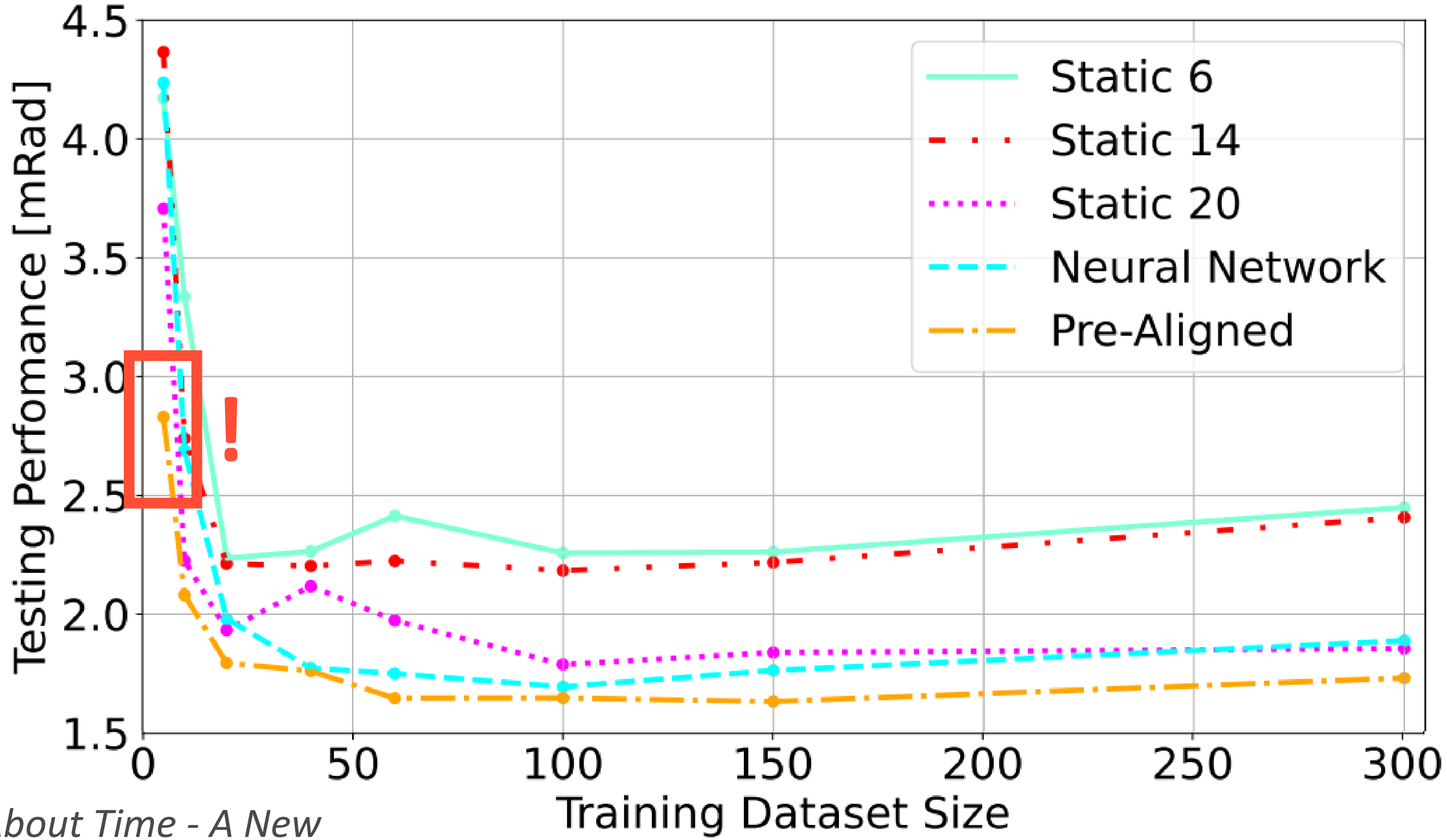


$$\alpha_{complete} = \alpha_{const} + \Delta\alpha_{dynamic} \text{ with } \Delta\alpha << \alpha$$




1
0
WeightDecay
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*

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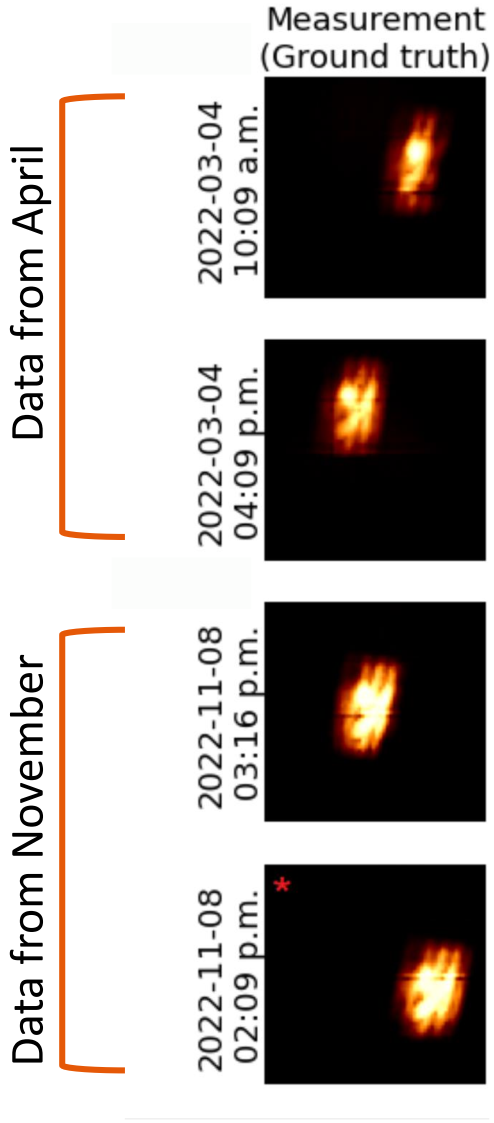
Prediction:

Single Heliostat Flux Density


Calibration Target
*
Receiver
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

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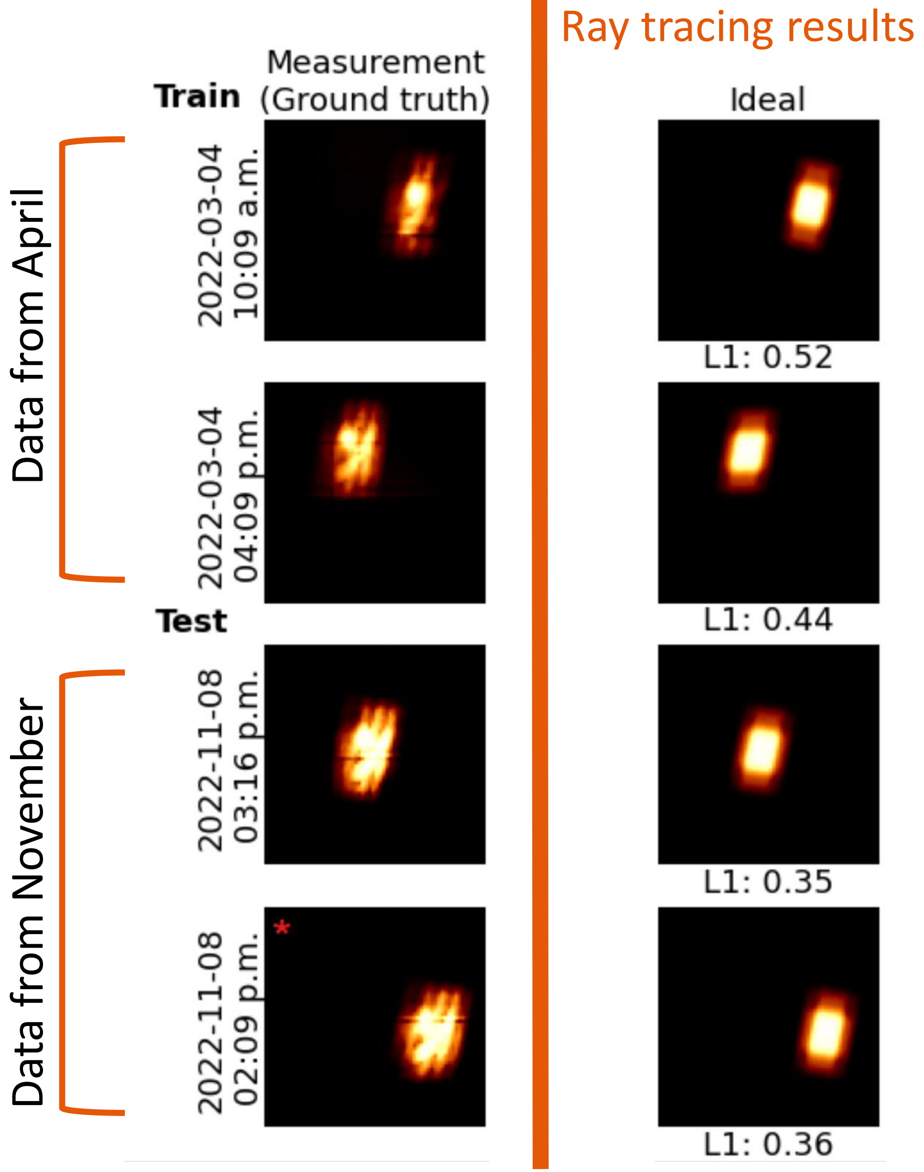
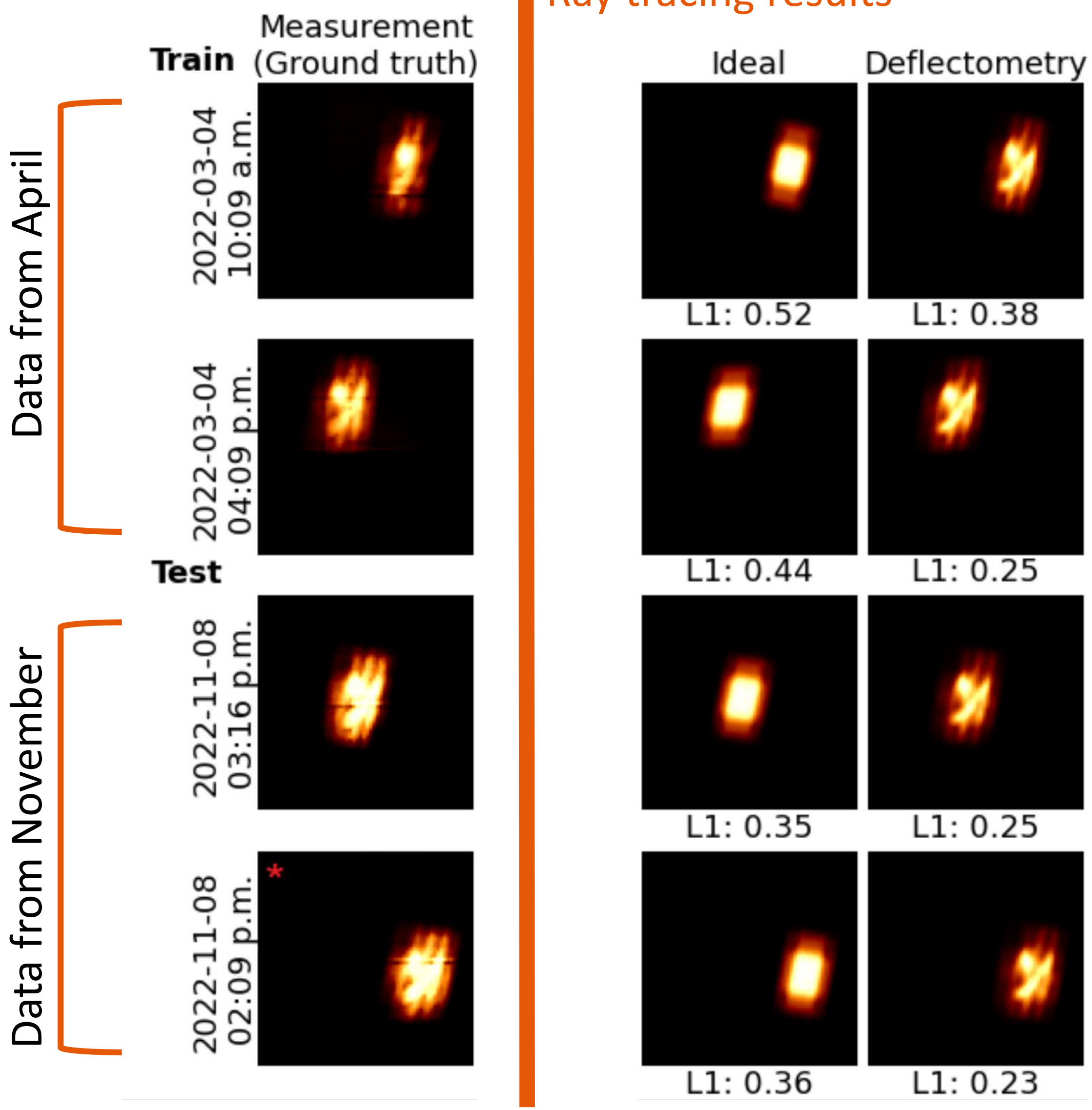


L1 = Mean Absolute Error

Ray tracing results



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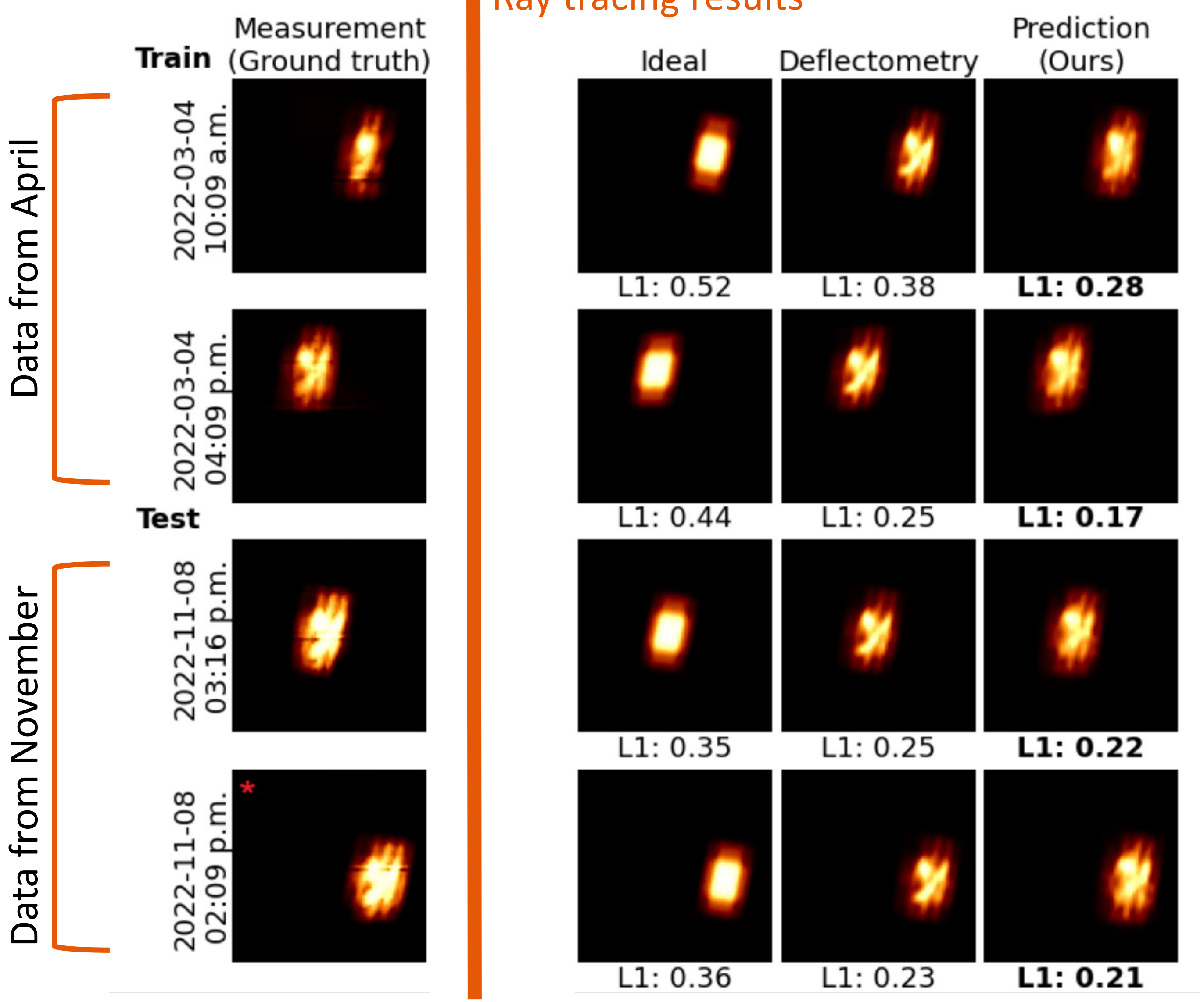
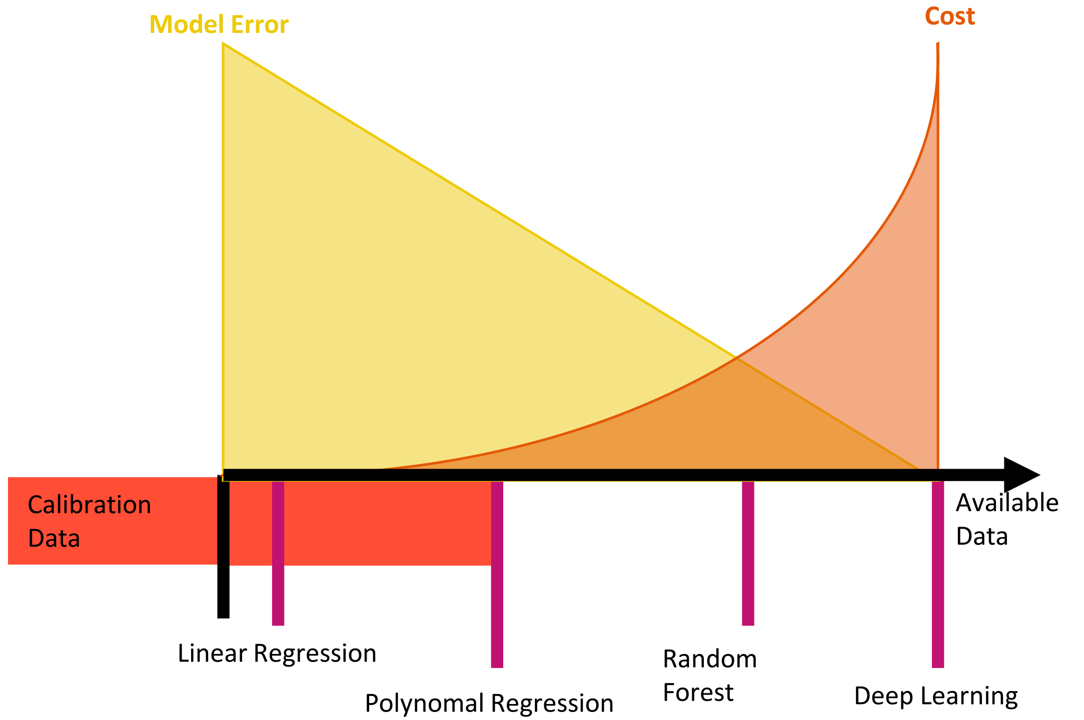
Ray tracing results



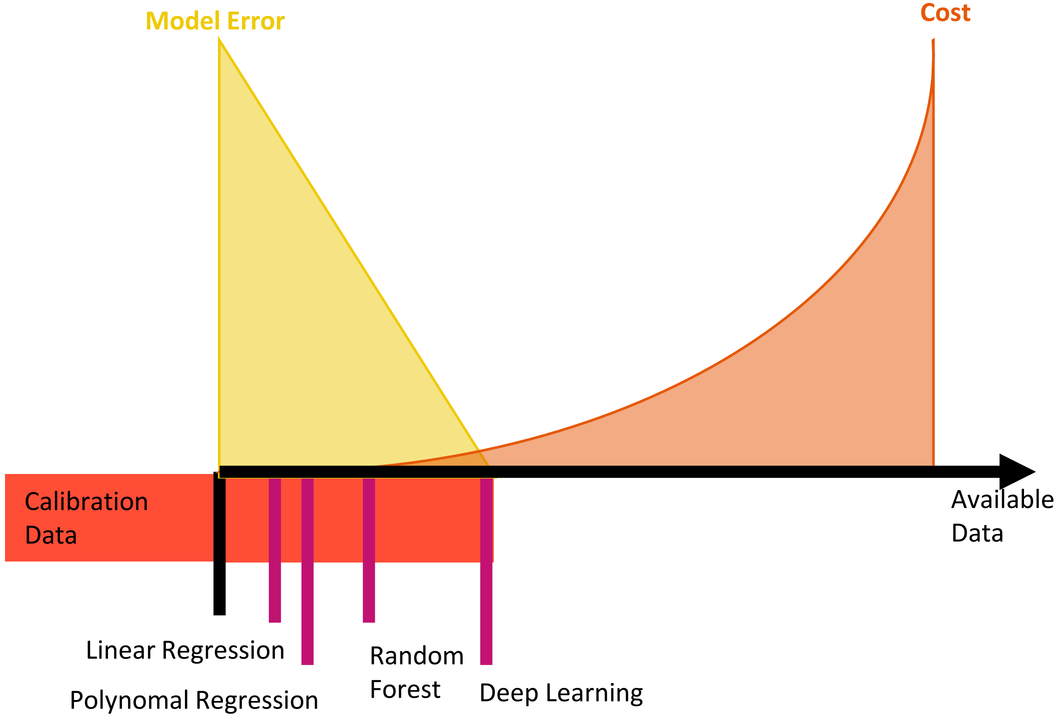
Outcomings

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



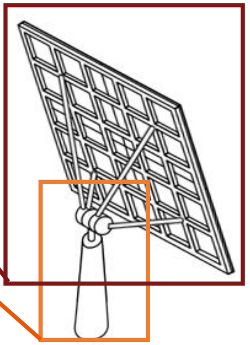
How to apply Deep Learning on small data sets at solar towers?

- 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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