A Digital Twin Environment for In-Situ Solar Tower Plant Optimization

By Max Pargmann

Agenda

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[redacted]

- Motivation
  - Raytracing – a perfect tool for power plants?

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- Differentiable Raytracing: Bringing Raytracing to the next level

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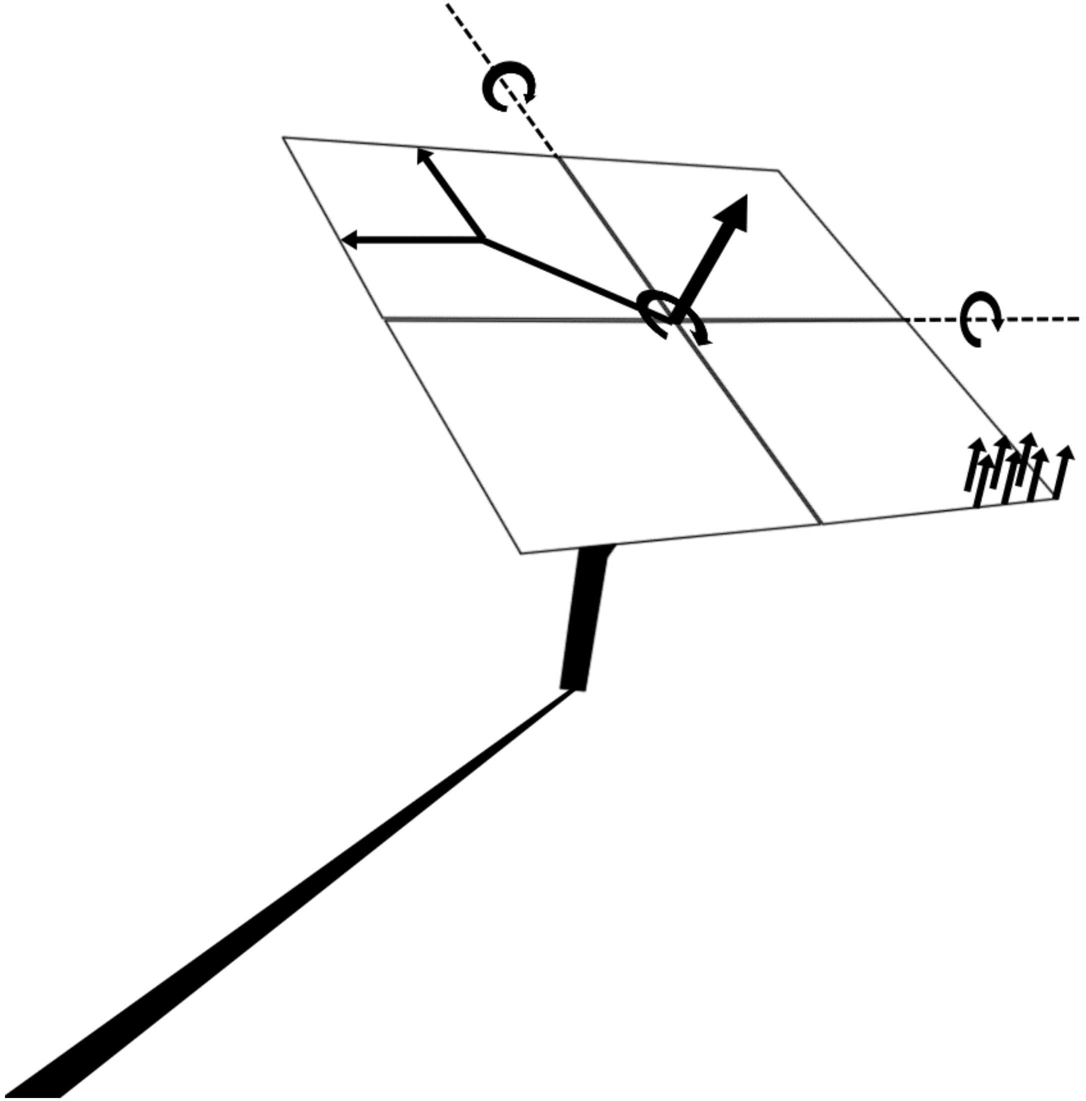
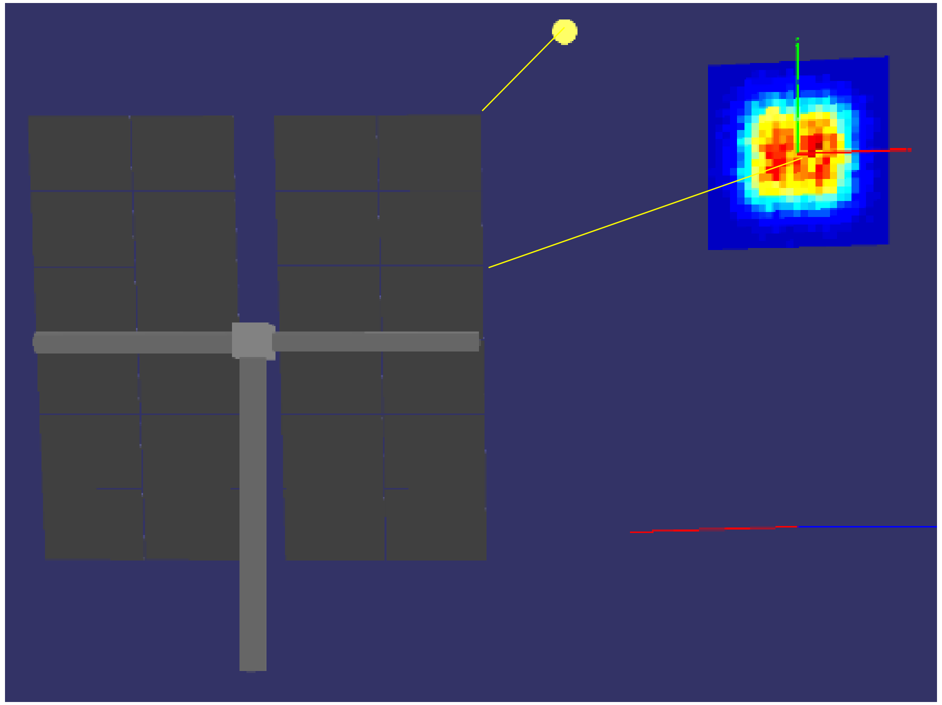
  - Raytracing – a perfect tool for power plants?
- Differentiable Raytracing: Bringing Raytracing to the next level
- Results on:
  - Heliostat Calibration
  - Heliostat Surface Reconstruction
  - Flux Density Prediction
- Conclusion & Outlook



Motivation

Motivation - Raytracing

- Raytracing is one of the most common tools for solar tower power plants due to its realistic physics
- It is mainly used to predict the irradiance at the receiver
- Rays are emanated from a light source and reflected inside a defined volume until they get absorbed by the receiver/target



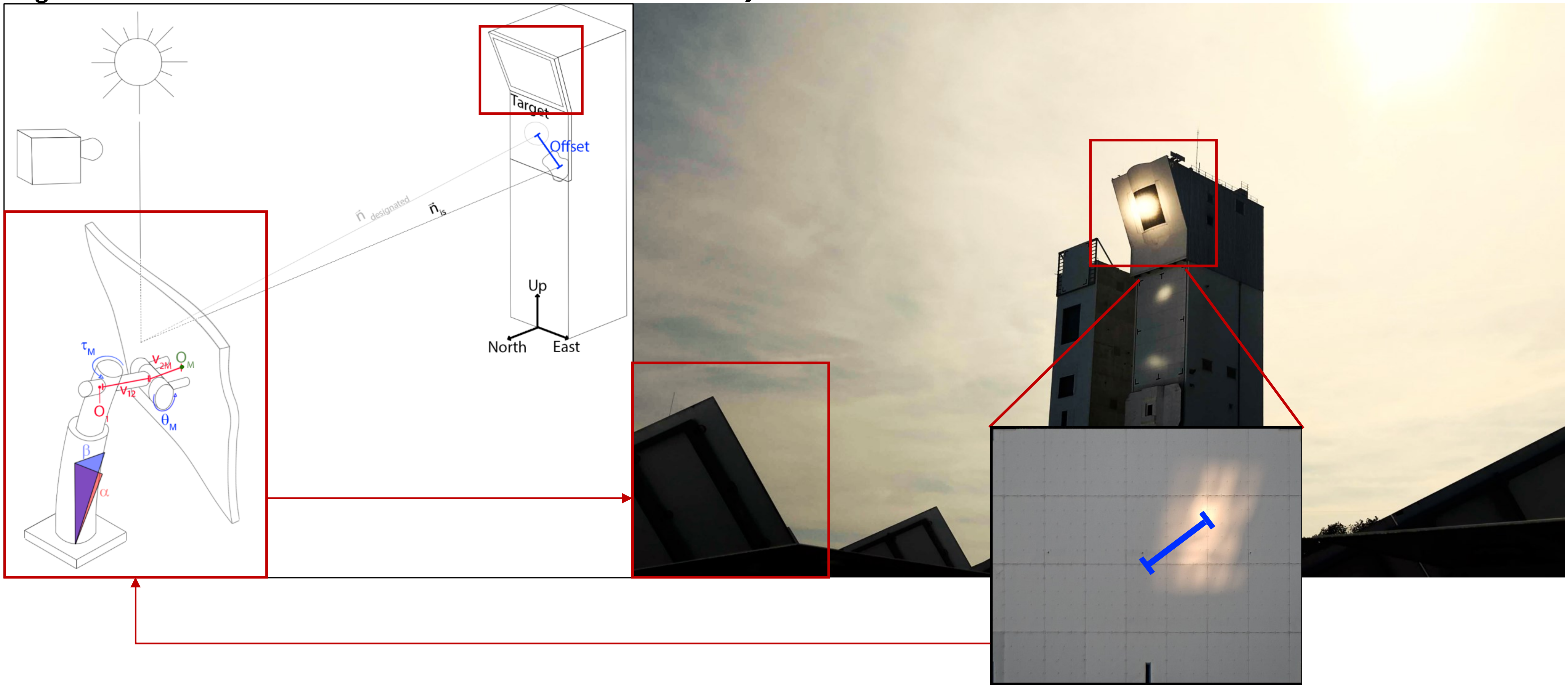
Motivation - Raytracing

- Heliostat errors can reduce the power plants efficiency and can damage components
- Pure simulations neglect:
  - Misalignment
  - Mirror Deformations

Motivation – Heliostat Calibration

Digital Instance

Real Object



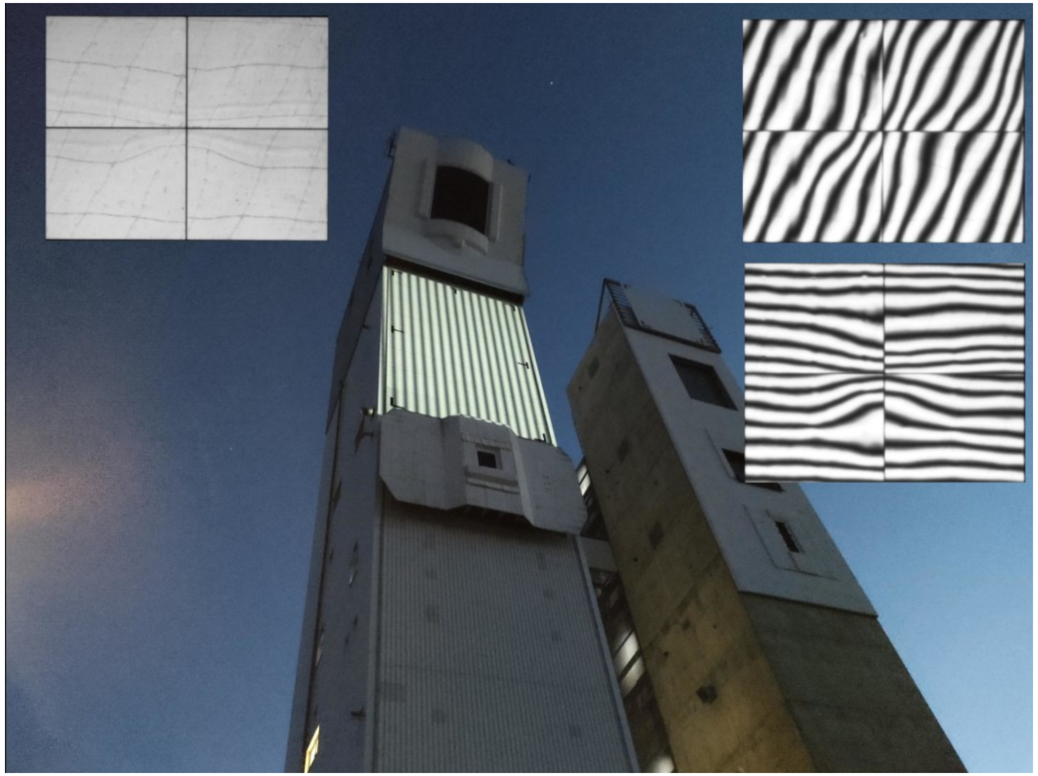
Motivation – Heliostat Calibration

[redacted]

- Fully automated
- **BUT:**
- Underlying geometry model is not accurate enough
  - Neglects time, angle dependencies
- Mean dataset size is to small for accurate heliostat control

Motivation – Stripe Pattern Deflectometry

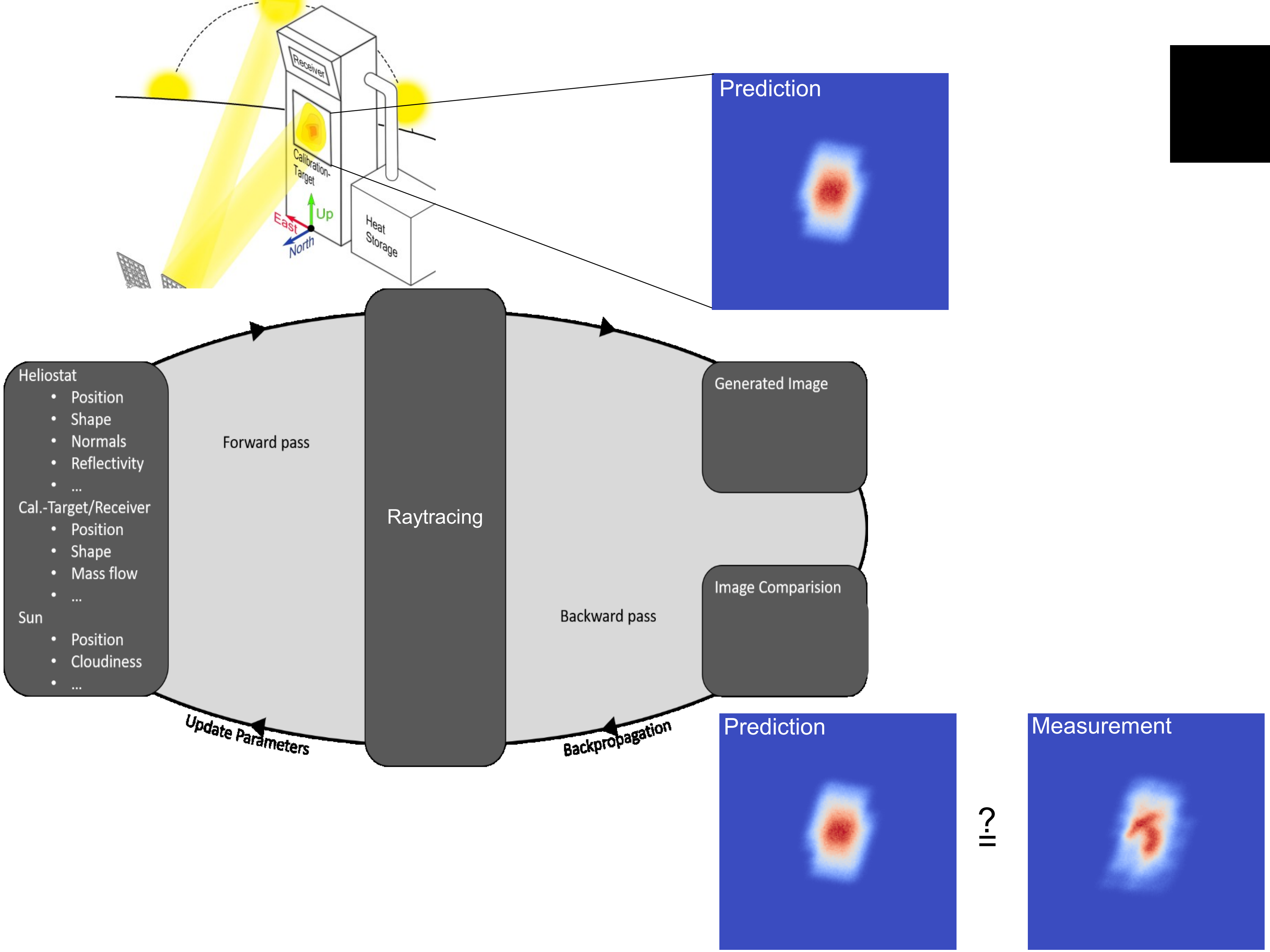
- Stripe pattern is projected onto the calibration target
- From multiple images the surface is reconstructed
- Extremely accurate surface measurement
- **BUT:**
  - Automation is pending since over 10 years



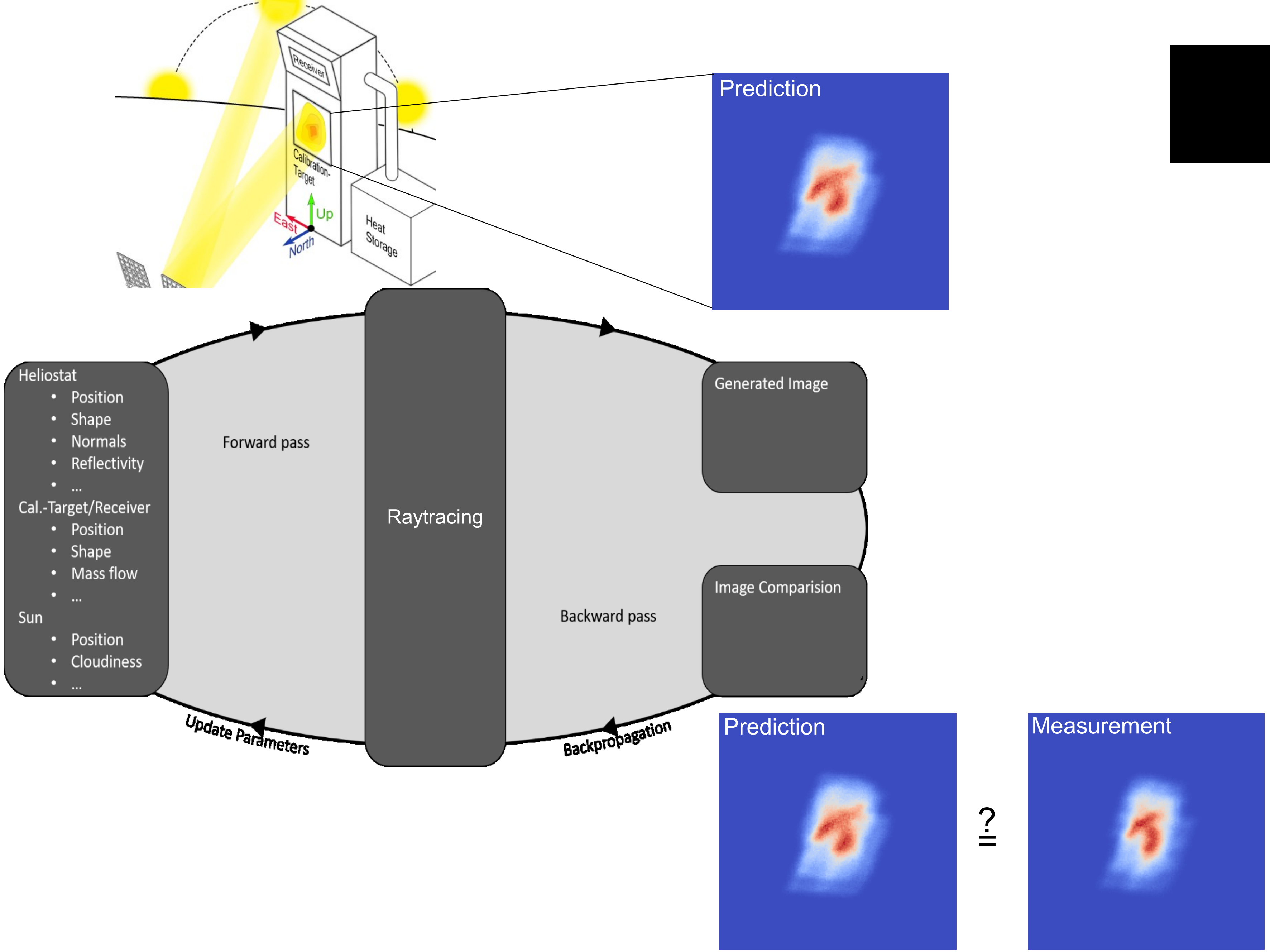
Motivation – Raytracing a Perfect Tool for Solar Tower Plants?

- Supplied by external data, raytracing can
  - predict a realistic flux density map
  - enable semi-closed loop heliostat control without additional sensors
- **But:**
  - Data supply chains are unreliable
  - Data set size is to small
  - Model parameters are inaccurate
  - Can only predict flux density map other parameters must be given
- **Solution:**
  - Integration of ray tracing into a machine learning pipeline

The New Differentiable Raytracing Environment


Receiver
Calibration-Target
Up
East
North
Heat Storage
Prediction
Heliostat
Position
Shape
Normals
Reflectivity
...
Cal.-Target/Receiver
Position
Shape
Mass flow
...
Sun
Position
Cloudiness
...
Forward pass
Raytracing
Generated Image
Image Comparision
Backward pass
Update Parameters
Backpropagation
Prediction
?=
Measurement

[redacted]



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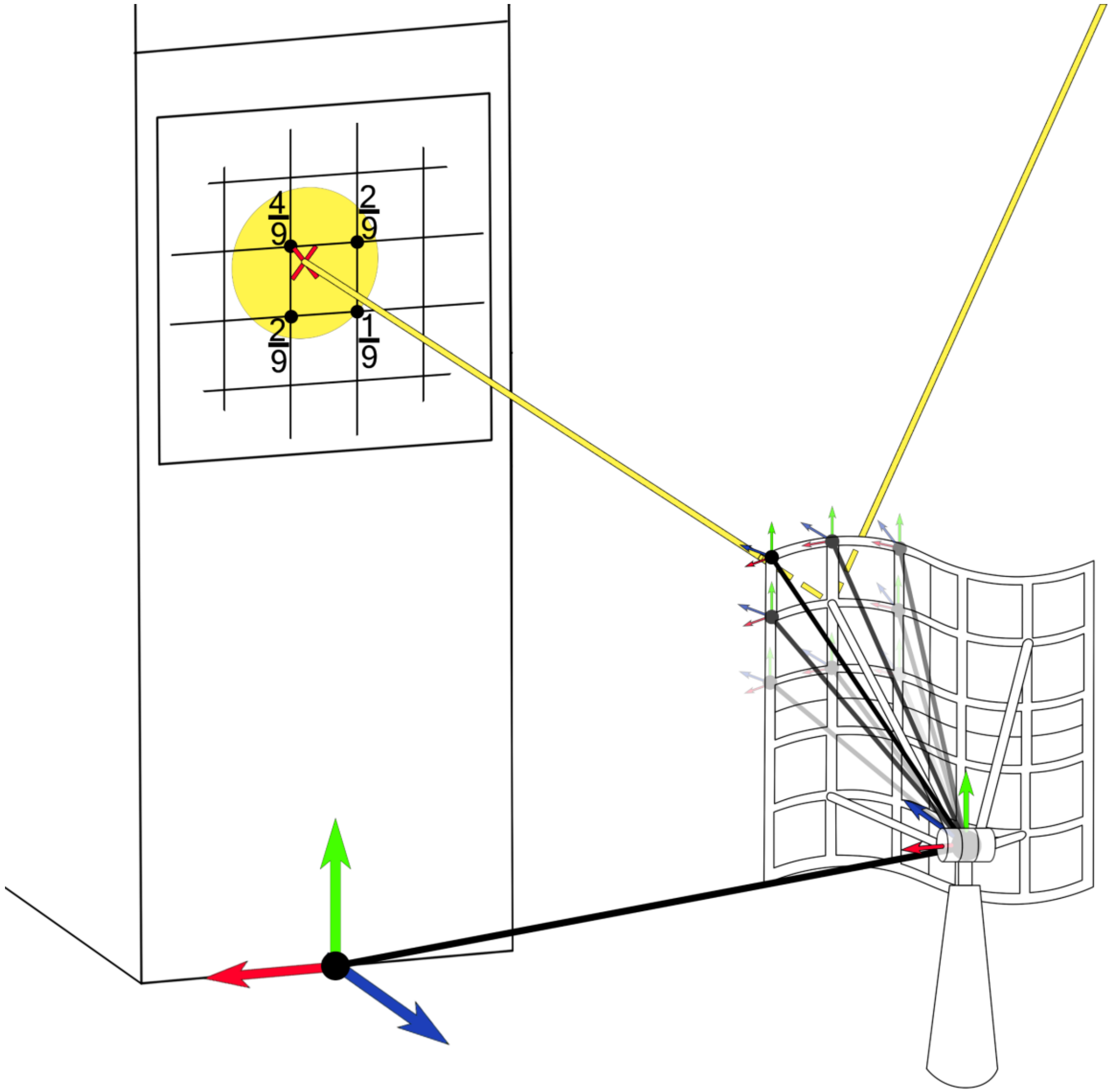
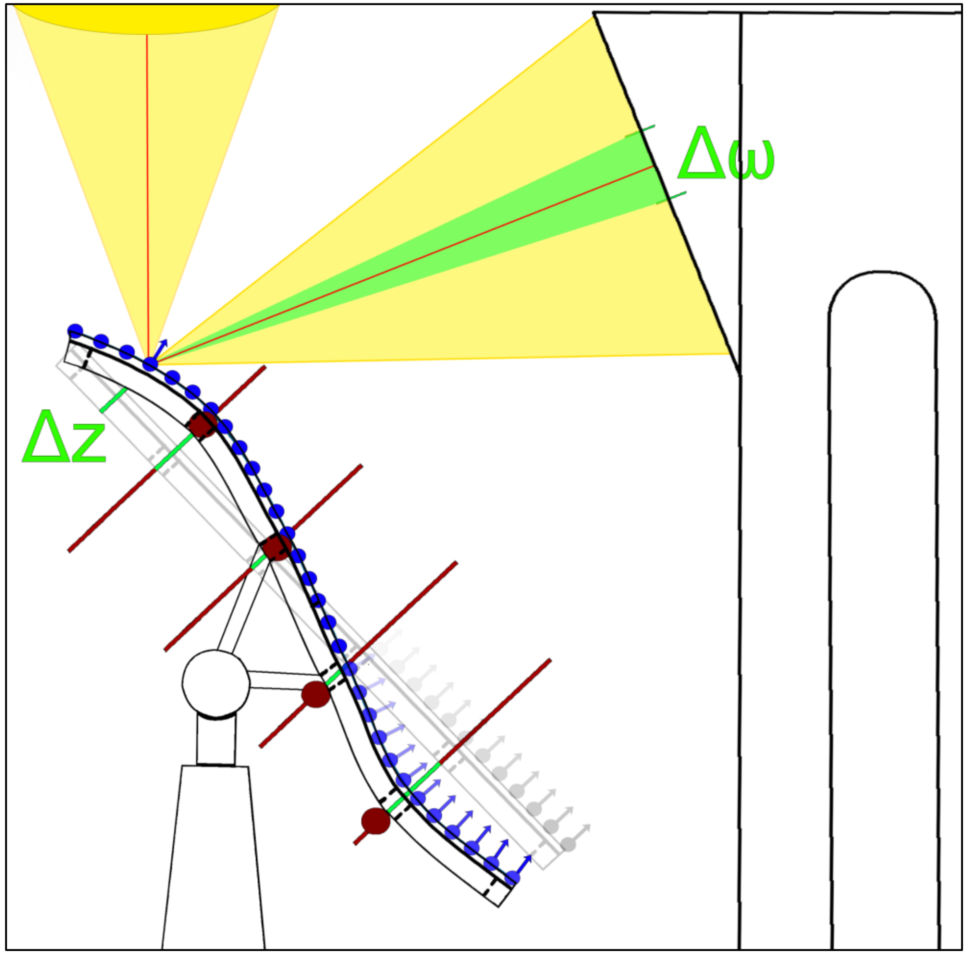
The New Differentiable Raytracing Environment

- For this the raytracing environment has to be differentiable
  - Diff. coord systems
  - Inverse bilinear extrapolation for ray distribution



The New Differentiable Raytracing Environment

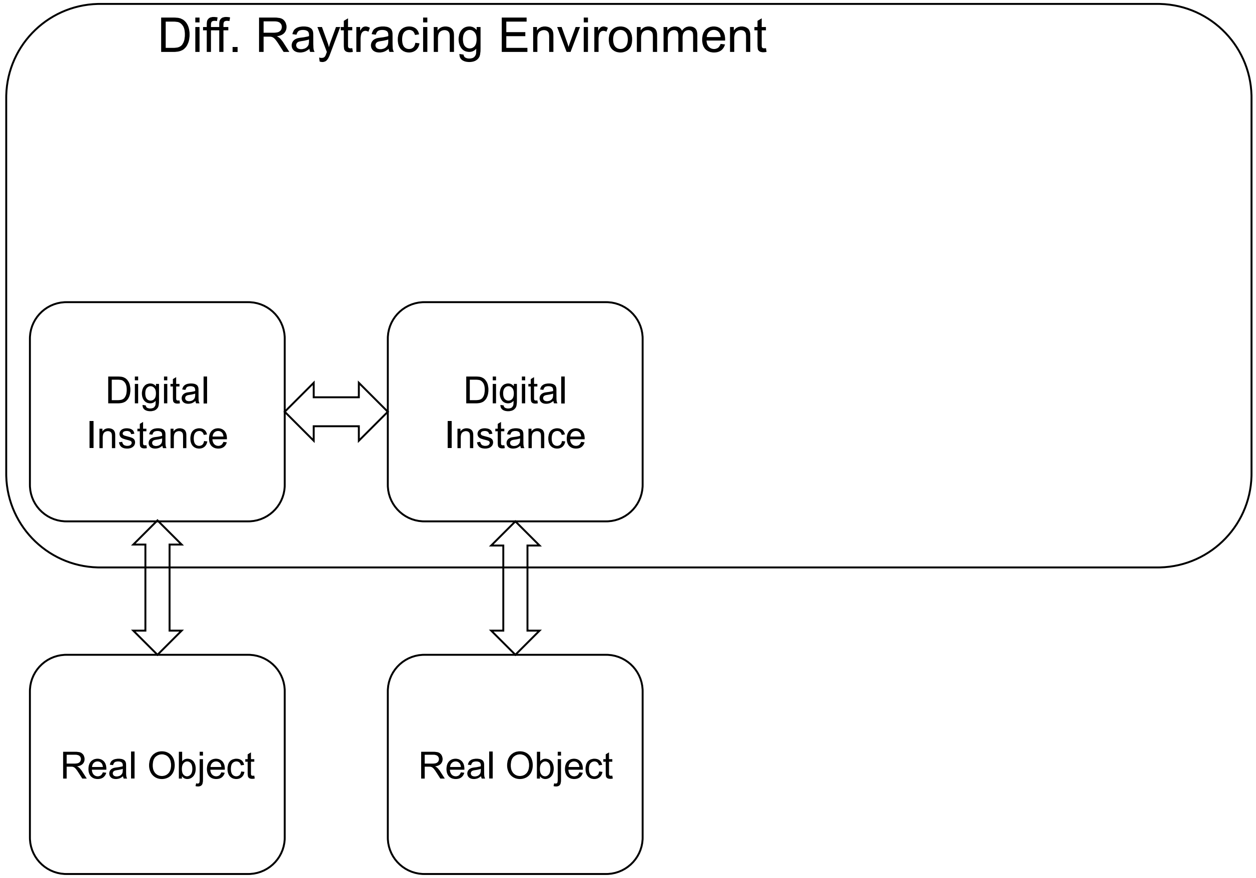
- Not necessary but helpful:
  - Degrees of Freedom of Surfaces (blue dots) can dynamically reduced by using diff. NURBS (Non-Uniform Rational B-Spline) (red dots)



The New Differentiable Raytracing Environment

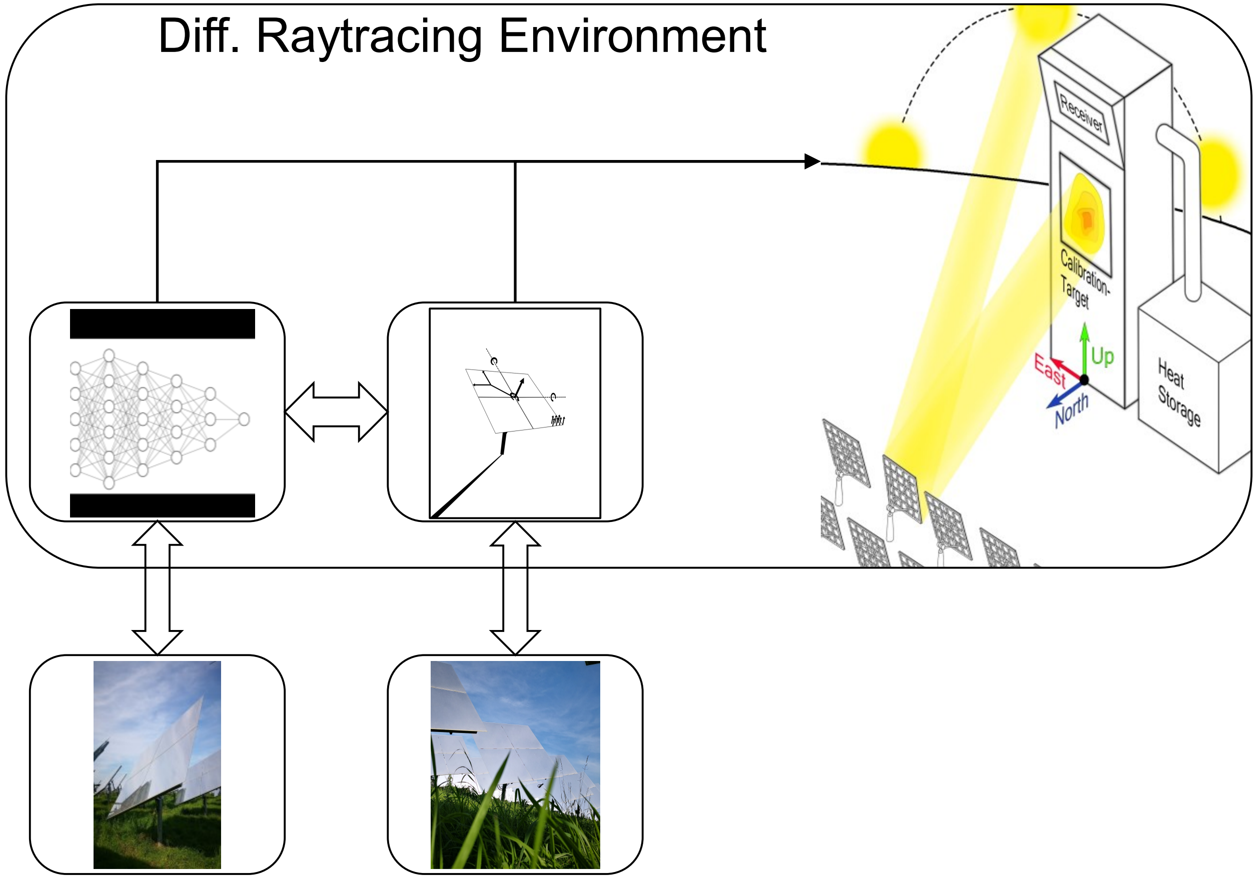
- Optimization of (almost) arbitrary object parameters using AI Routines (*Autodiff.*, *Backprop.*, *Adam*, etc.)

- Objects inside this Environment can be treated as Digital Twin Instances



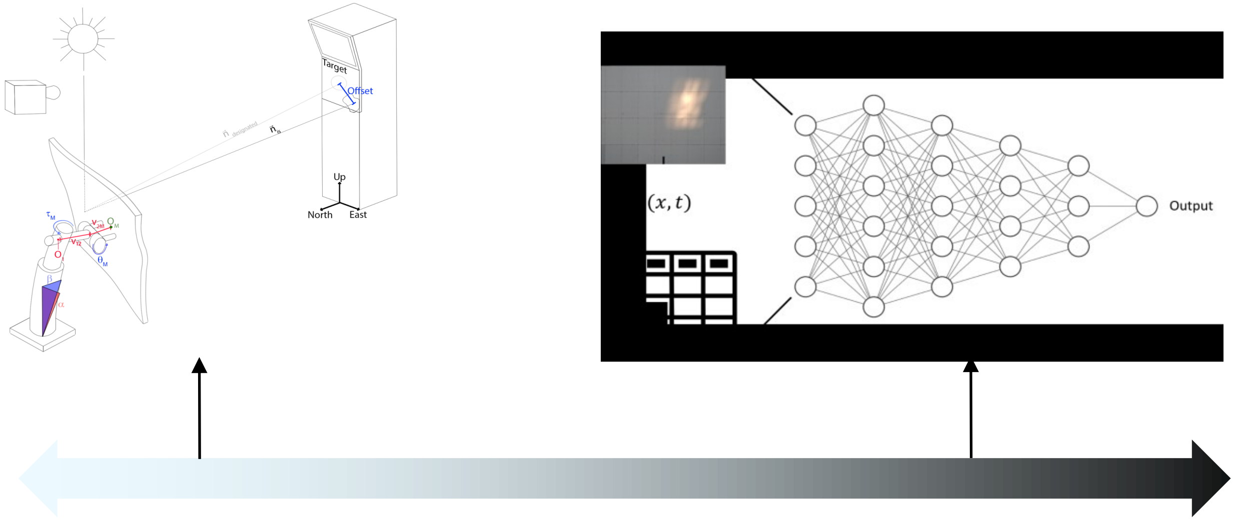
The New Differentiable Raytracing Environment

- Optimization of (almost) arbitrary object parameters using AI Routines (*Autodiff.*, *Backprop.*, *Adam*, etc.)
- Objects inside this Environment can be treated as Digital Twin Instances
- Differentiability allows integration and training of neural networks



The New Differentiable Raytracing Environment

- Optimization of (almost) arbitrary object parameters using AI Routines (*Autodiff., Backprop., Adam,* etc.)
- Objects inside this Environment can be treated as Digital Twin Instances
- Differentiability allows integration and training of neural networks
- Enables continuously improvement



Small Datasets

Big Datasets

Results

Results

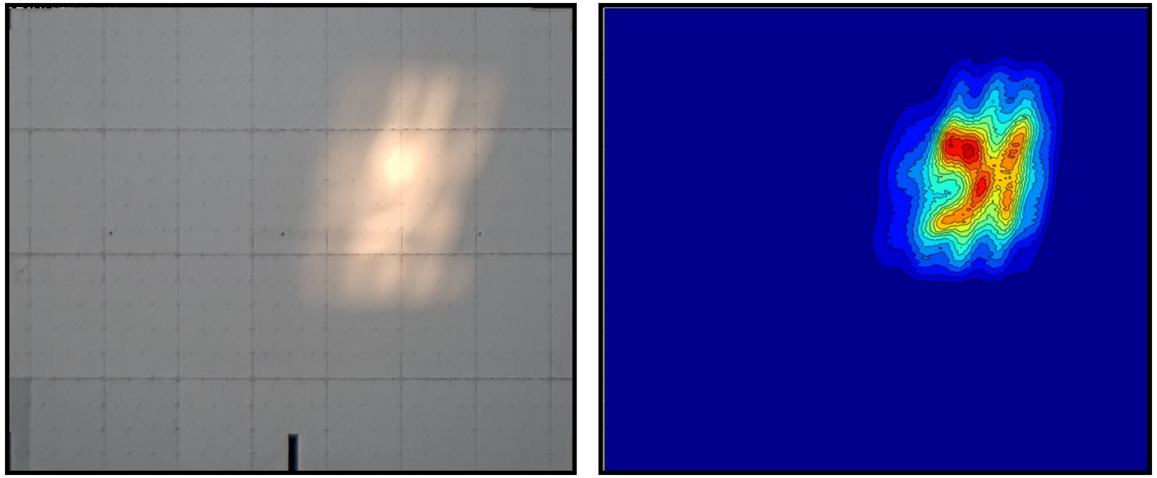
- Raytracing Environment was tested on three different tasks
  - Heliostat Calibration (Toy Example)
  - Heliostat Surface Reconstruction
  - Heliostat Flux Density Prediction

- All 3 uses the images from the heliostat calibration

- Works in a data range of 1 to 5 Images

- No external preprocessing

Real Image Simulated



Results – Heliostat Calibration

[redacted]

- Toy Example with reduced geometric model has average accuracy of few mrad
- Test on real data still pending

$$\begin{pmatrix} \alpha \\ \beta \\ \gamma \end{pmatrix} = \pm \begin{pmatrix} 0.0052 \\ 0.0085 \\ 0.011 \end{pmatrix} \mathrm{rad}$$

Results – Heliostat Calibration

[redacted]

- Toy Example with reduced geometric model has average accuracy of few mrad
- Test on real data still pending
- Raytracer can use the same Loss as standard calibration algorithms (e.g. Levenberg Marquardt)

  →If not a single ray is generated algorithms can behave identical

$$F = \min_{\alpha,\beta,\gamma,\delta,\theta_k,\tau_k,\mathrm{GR1},\mathrm{GR2}} \sum_{i=1}^{N} \arccos(\vec{n}_{\mathrm{is},i} \cdot \vec{n}_{\mathrm{model},i}).$$

Results – Heliostat Calibration

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- Toy Example with reduced geometric model has average accuracy of few mrad
- Test on real data still pending
- Raytracer can use the same Loss as standard calibration algorithms (e.g. Levenberg Marquardt)
  - →If not a single ray is generated algorithms can behave identical
  - →Image Loss Terms (L1, L2, Hausdorff-Distance) provide additional information
  - →Can include surface information data, and rotational displacements

$$F = \min_{\alpha,\beta,\gamma,\delta,\theta_k,\tau_k,\mathrm{GR1},\mathrm{GR2}} \sum_{i=1}^{N} \arccos(\vec{n}_{\mathrm{is},i} \cdot \vec{n}_{\mathrm{model},i}).$$

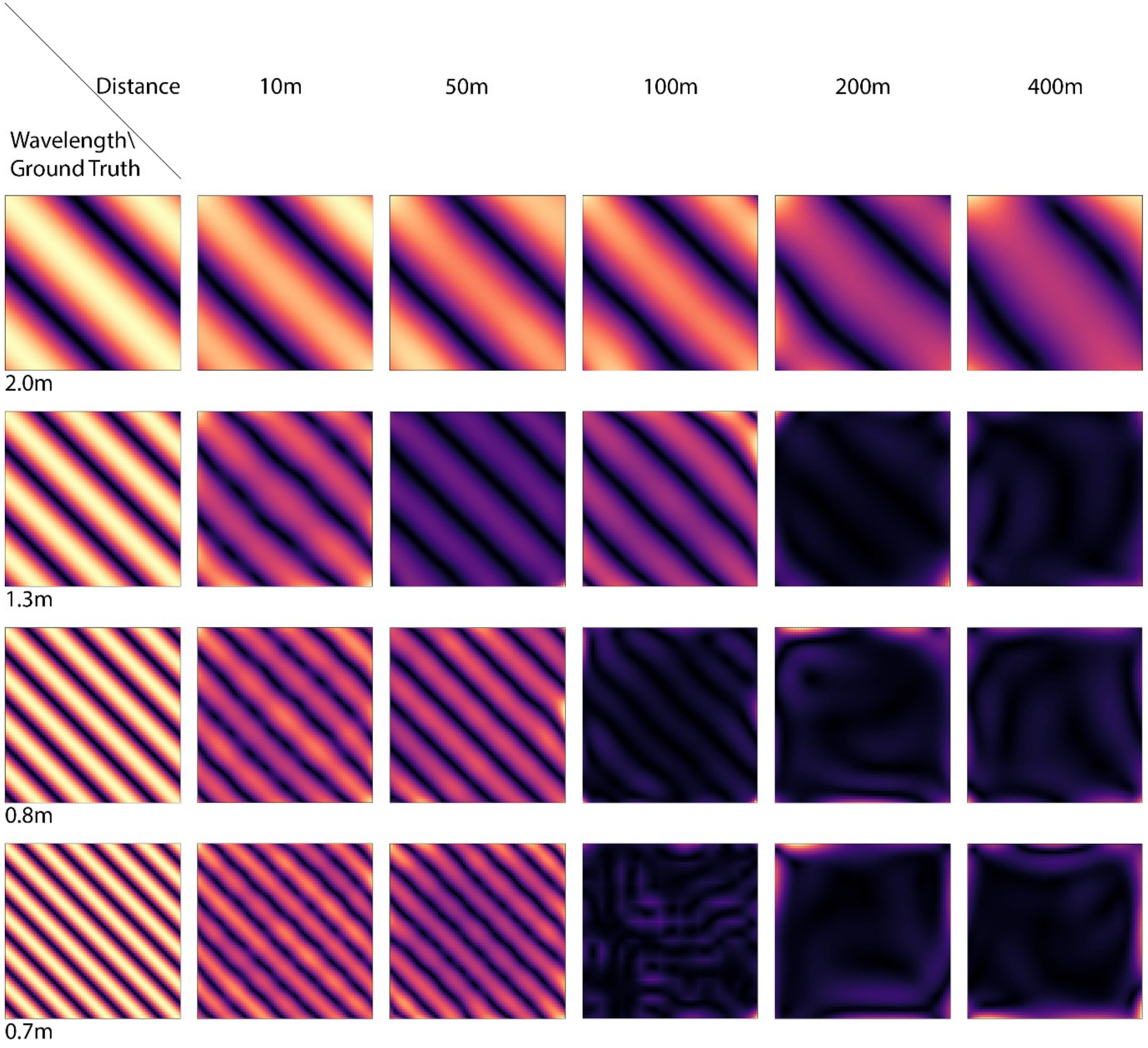
$$L1LossFunction = \sum_{i=1}^{n} |y_{true} - y_{predicted}|$$

$$L2LossFunction = \sum_{i=1}^{n} (y_{true} - y_{predicted})^2$$

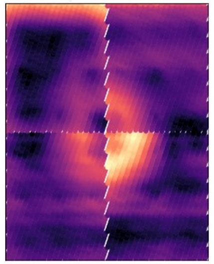
$$d_{\mathrm{H}}(X,Y) = \max\left\{ \sup_{x\in X} d(x,Y), \sup_{y\in Y} d(X,y) \right\}$$

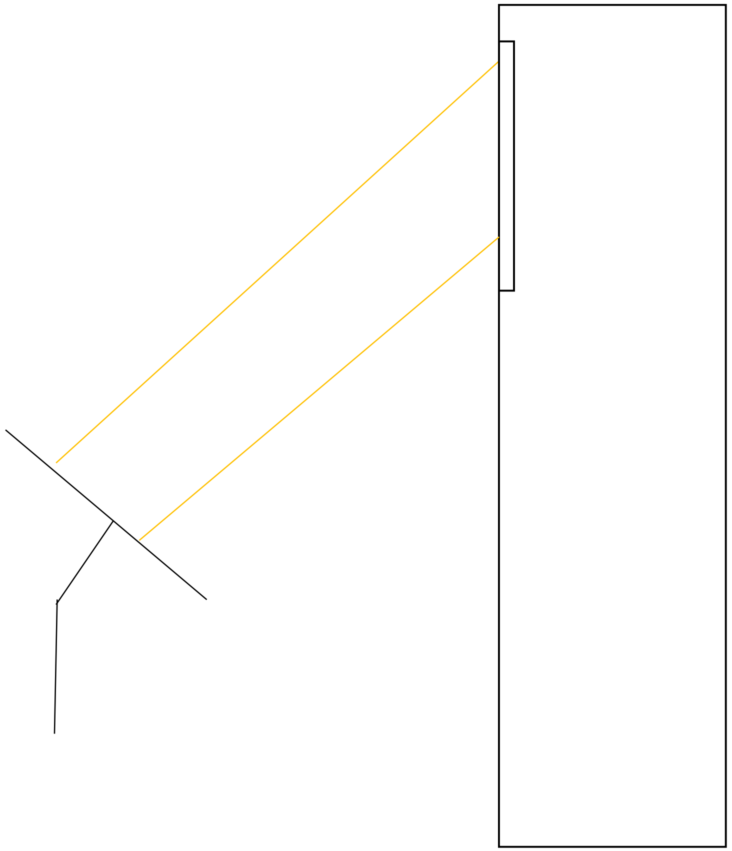
Results – Heliostat Surface Reconstruction

- Sun blur makes reconstruction ambiguous
- NURBS act as regularization
- Can reconstruct coarse surfaces up to 400m (and more)
- Can reconstruct fine surfaces up to 100m

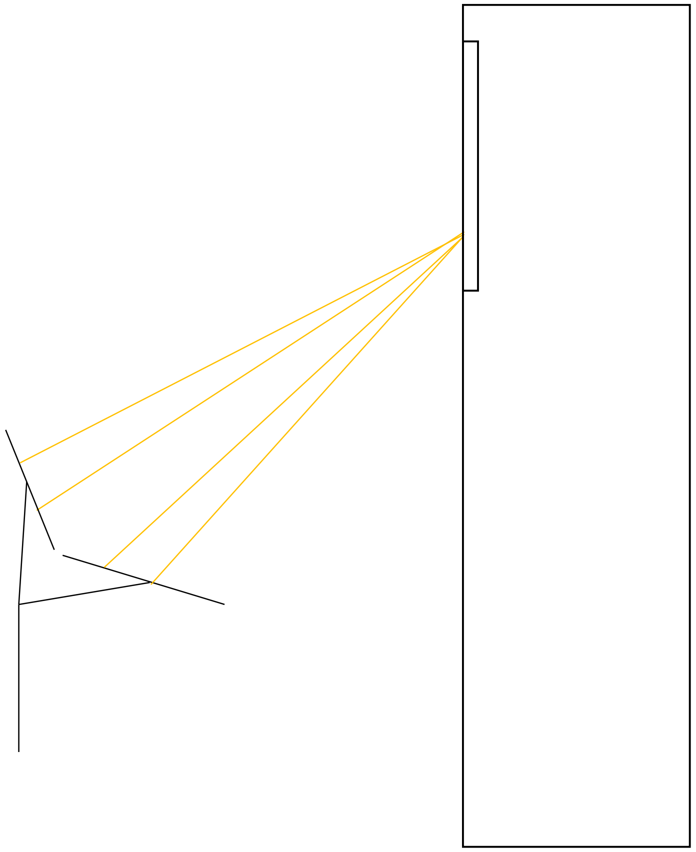


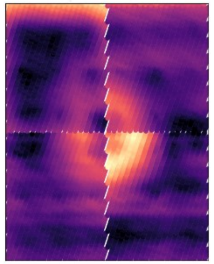
Results – Heliostat Surface Reconstruction

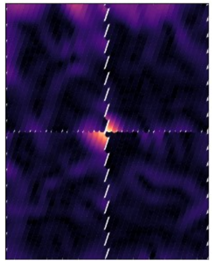
Deflectometric measured surface:  @ ca. 50m



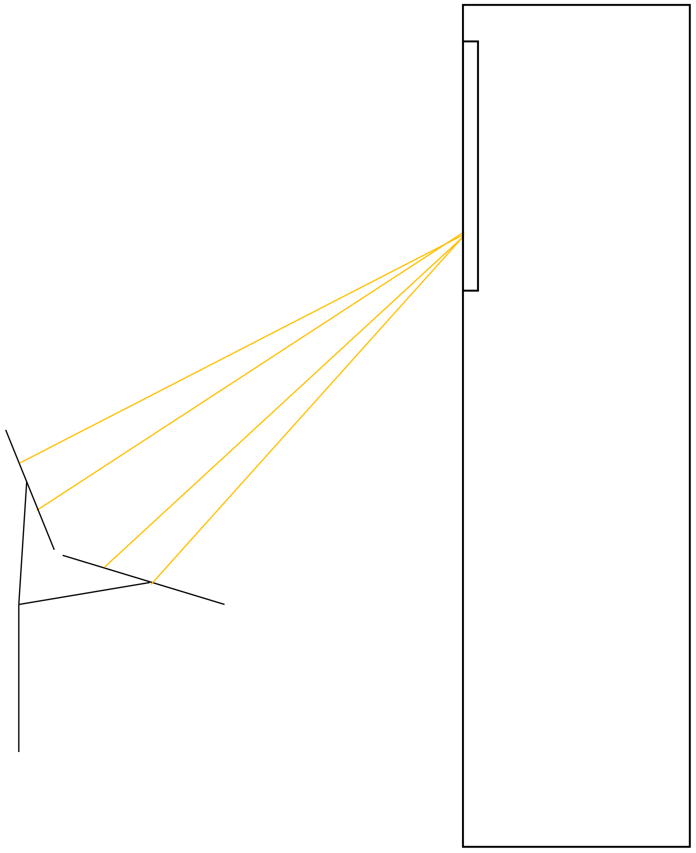
Results – Heliostat Surface Reconstruction



Deflectometric measured surface:  @ ca. 50m

Reconstruction in focal length:  @ ca. 50m

Results – Heliostat Surface Reconstruction



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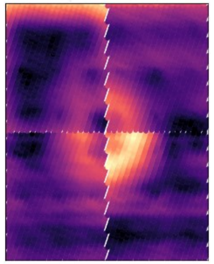

@ ca. 50m

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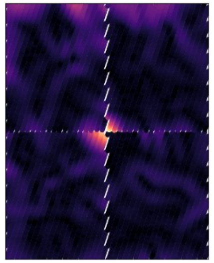
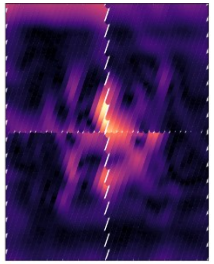


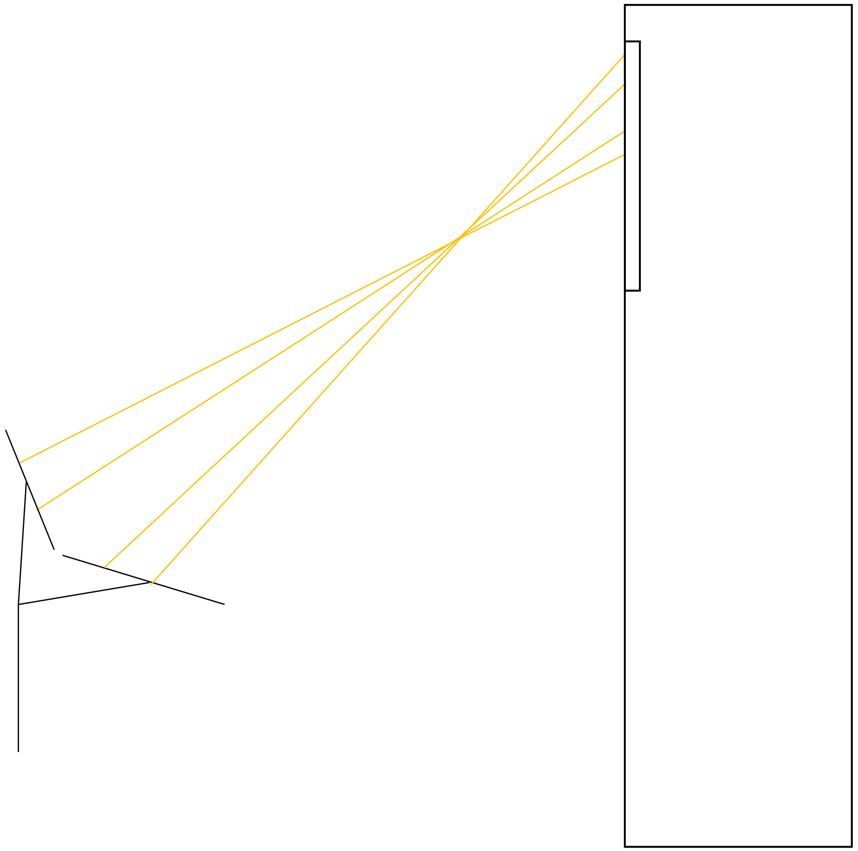
@ ca. 50m

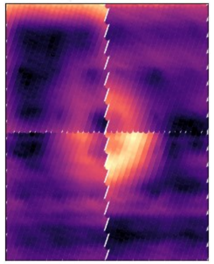
Reconstruction in focal length with 5 images:

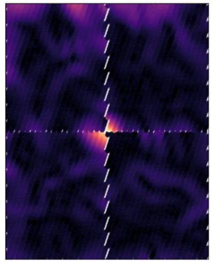


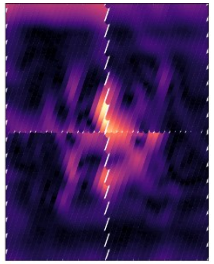
@ ca. 50m

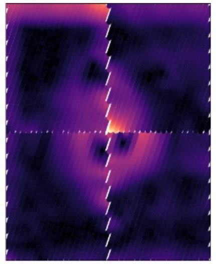
Results – Heliostat Surface Reconstruction



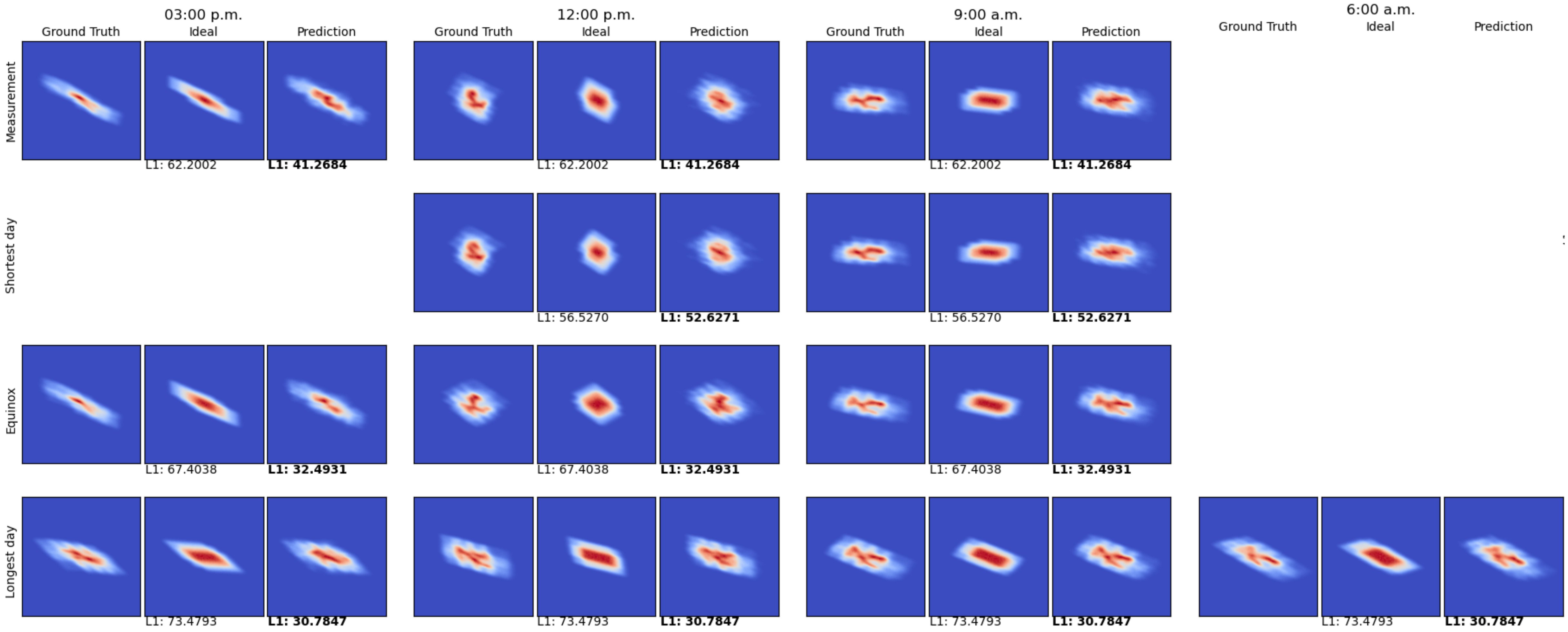
Deflectometric measured surface:  @ ca. 50m

Reconstruction in focal length:  @ ca. 50m

Reconstruction in focal length with 5 images:  @ ca. 50m

Reconstruction in higher distance:  @100m

Results – Flux Density Prediction



Conclusion & Outlook

Conclusion

- Mathematical Proof that diff. Raytracing can improve heliostat calibration → Validation still pending
- Reconstruction of surface defects possible up to a few hundred meters
- Reconstruction is worse in exact focal length due to higher underdetermination
- “Wrong” surface is still able to improve the prediction throughout the year

Outlook

- Heliostat calibration has do be evaluated with real data
- Apply at the solar tower for multiple heliostats
- Neural network integration for higher data set sizes
- Optimization of other solar field parameters, e.g.:
  - Heliostat field design
  - Receiver design
  - Gradient based aimpoint management

Thanks for your attention!

Impressum

Thema: A Digital Twin Environment for In-Situ Solar Tower Plant Optimization

Datum: 22.06.2022

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Institut: Institute of solar research, DLR