TOWARD AIRBORNE REAL-TIME CONDITION MONITORING SYSTEMS OF SOLAR TOWER POWER PLANTS

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Agenda

- Motivation
- Simulation Environment – Overview
- System-Under-Development – Overview
- Simulation-Based Analysis of System-Under-Development
- Transfer to Real Data
- Conclusion and Outlook

MOTIVATION

CESA-1 experimental solar tower power plant at Plataforma Solar de Almería (PSA), owned and operated by CIEMAT (Photo: Marc Röger, DLR).

Motivation

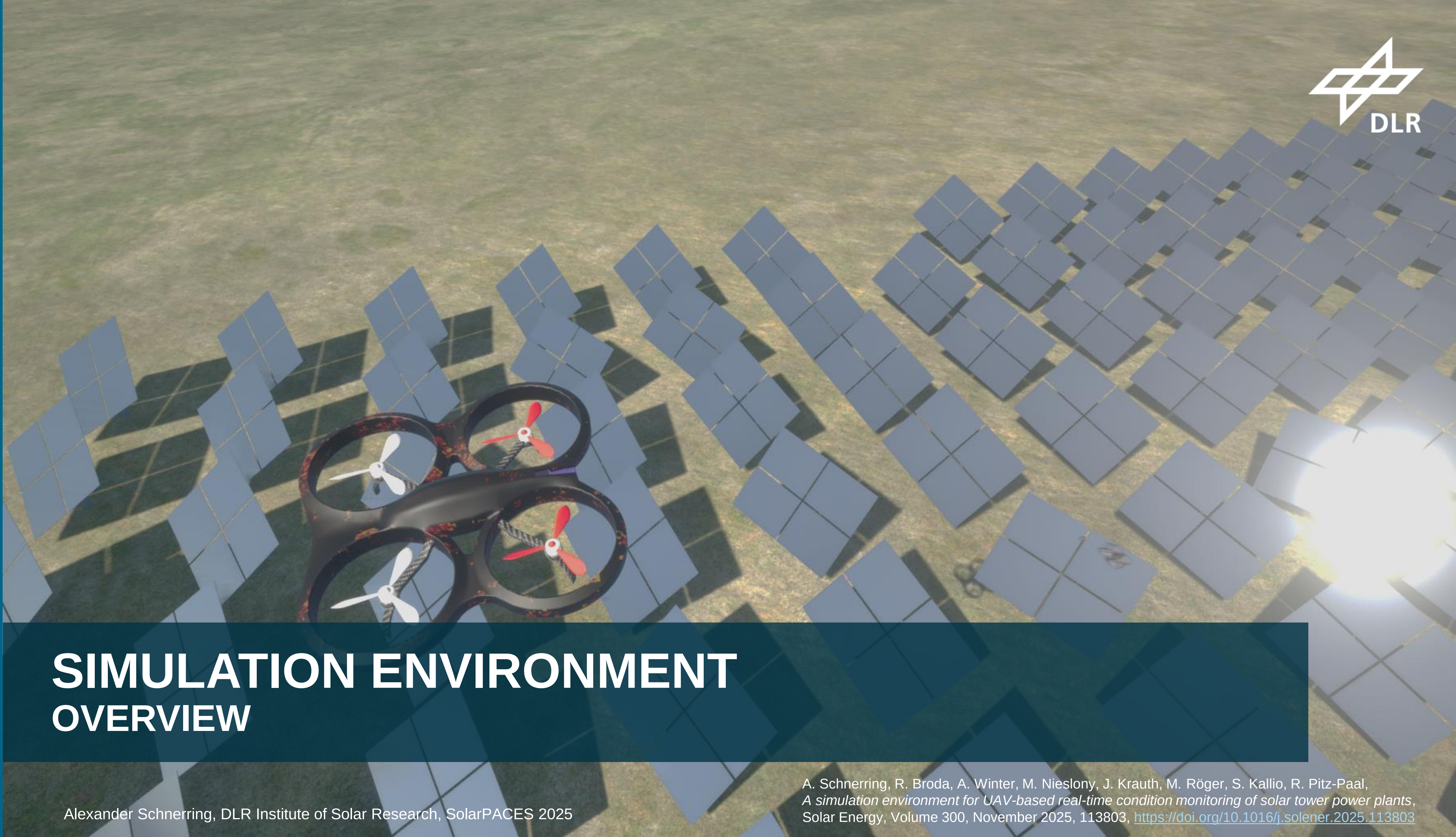
- Heliostat calibration is necessary to maintain efficient operation of solar tower power plants [1]
- The camera-target method [2] is still considered the golden standard but comes with several disadvantages
- Unmanned Aerial Vehicles (UAVs) can be used to overcome these issues [3,4,5]
- Real-time data analysis opens up new possibilities for autonomous condition monitoring, such as dynamic route planning

Aerial image of the heliostat field at the solar test facility in Jülich, Germany, owned and operated by DLR

Motivation

- The development of autonomous UAV-based condition monitoring systems comes with several challenges
  - Testing in the real world, making adaptions etc. slows down the development cycle significantly
  - Measurement campaigns often fall short of their potential due to unexpected/unplannable circumstances
  - (Autonomous) UAV-flights always come with safety-issues

- A simulation environment enables us to…
  - … speed up the development cycle
  - … prepare better for measurements in real world
  - … test our real-time algorithms cheaply and safely

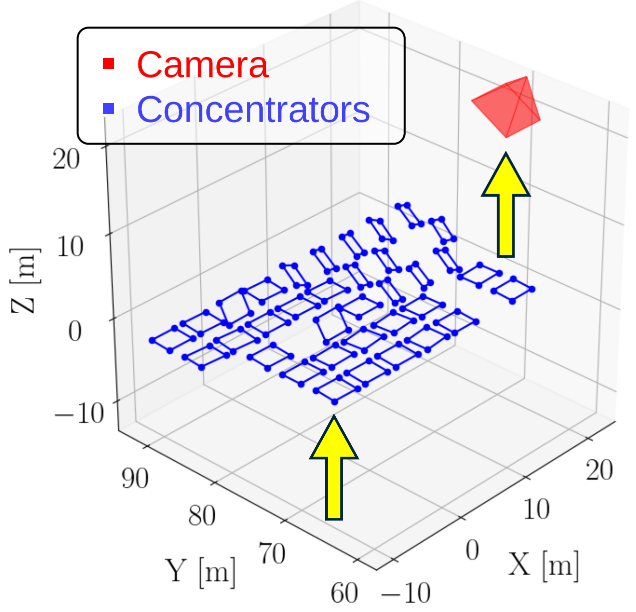


SIMULATION ENVIRONMENT
OVERVIEW

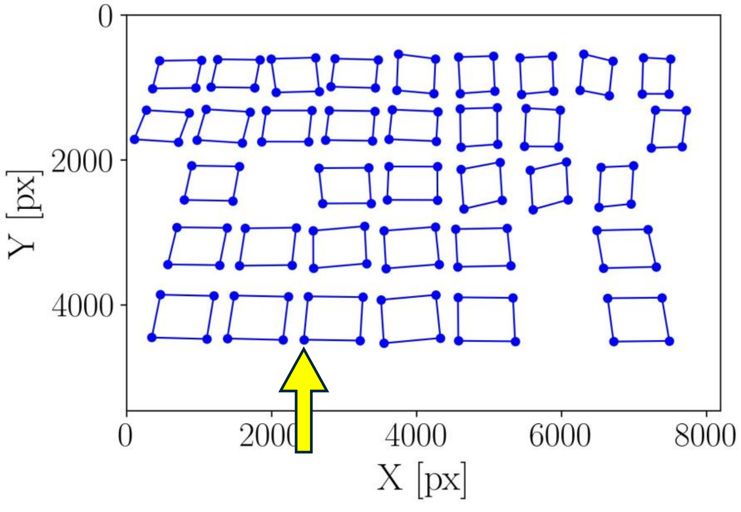
A. Schnerring, R. Broda, A. Winter, M. Nieslony, J. Krauth, M. Röger, S. Kallio, R. Pitz-Paal,
A simulation environment for UAV-based real-time condition monitoring of solar tower power plants,
Solar Energy, Volume 300, November 2025, 113803, https://doi.org/10.1016/j.solener.2025.113803

Simulation Environment
Overview

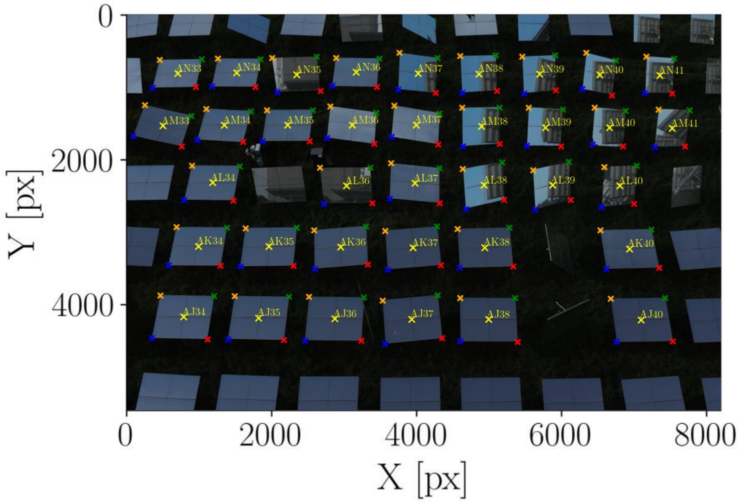
- *Python* backbone enables the computation of ground truth image features [6]



Simulated 3D scene

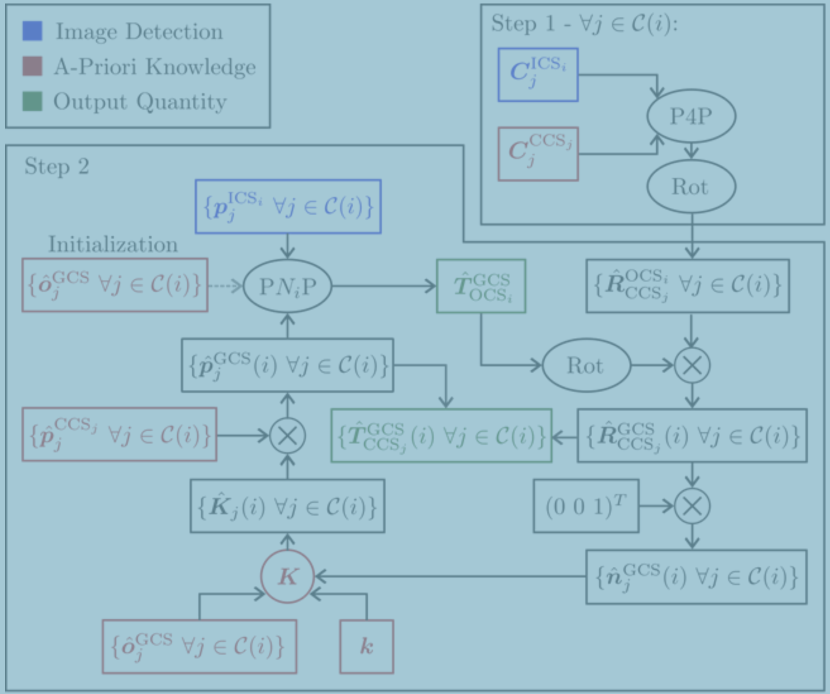


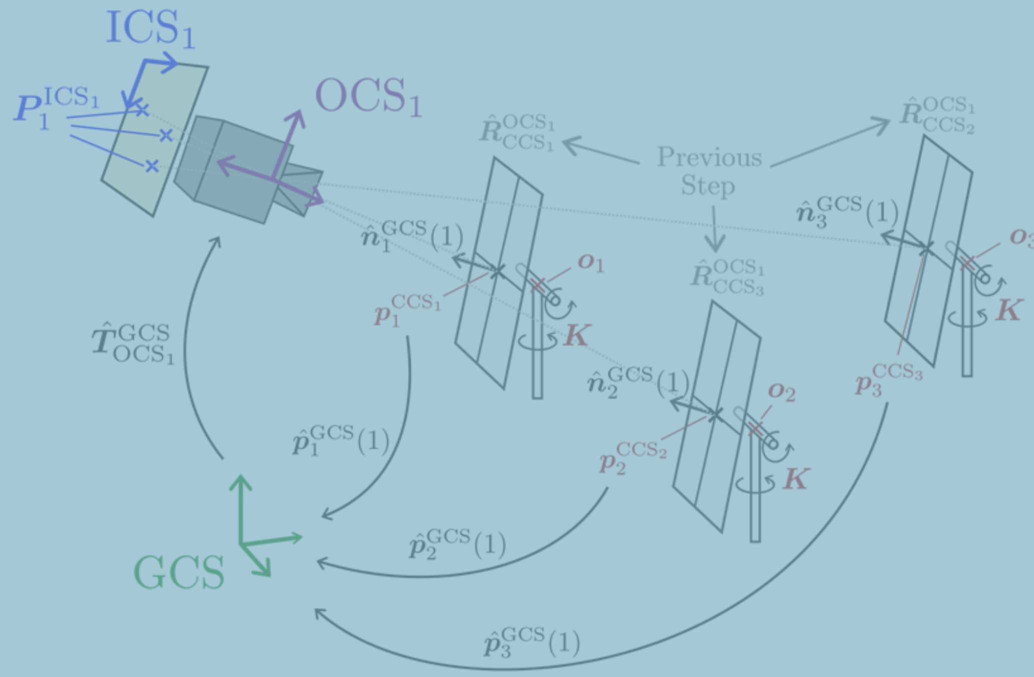
Simulated image

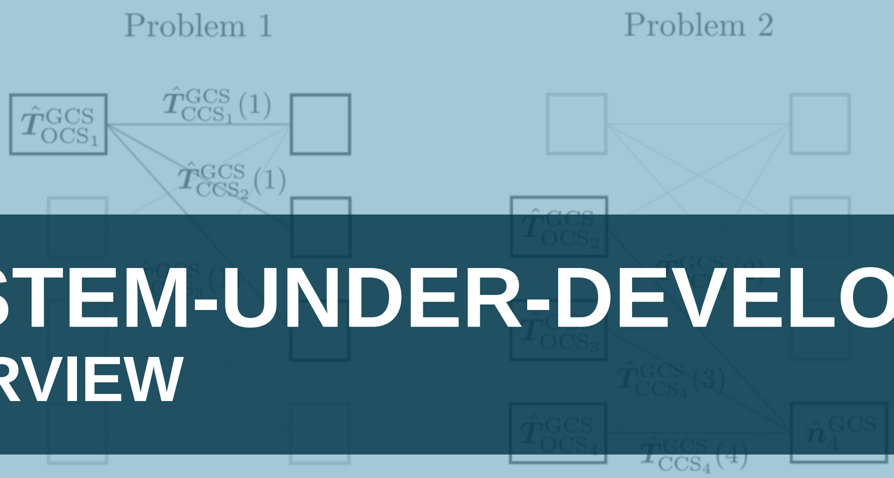


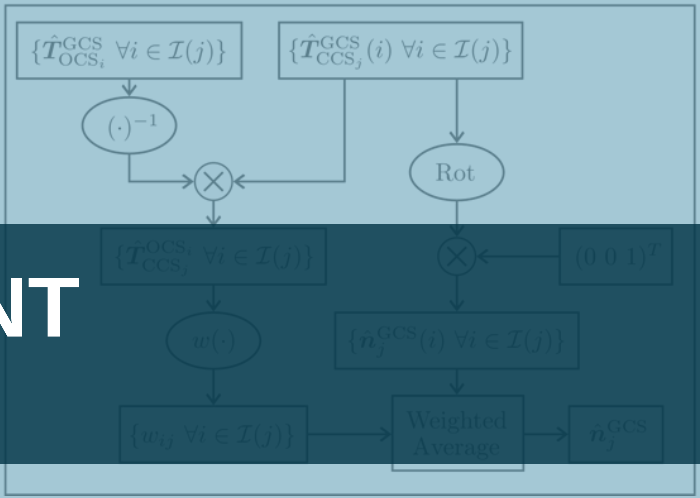
Real image

- Allows to simulate image-based systems independent of perception module
- Allows precise control of noise level in different parts of the system and analysis of their effect on the system output









SYSTEM-UNDER-DEVELOPMENT

OVERVIEW

Schnerring A., Broda R., Nieslony M., Algner N., Saez E., Röger M., Kallio S., Pitz-Paal, R., *ARTSCORE: Airborne Real-Time Solar Concentrator Orientation Estimation*, paper, in preparation

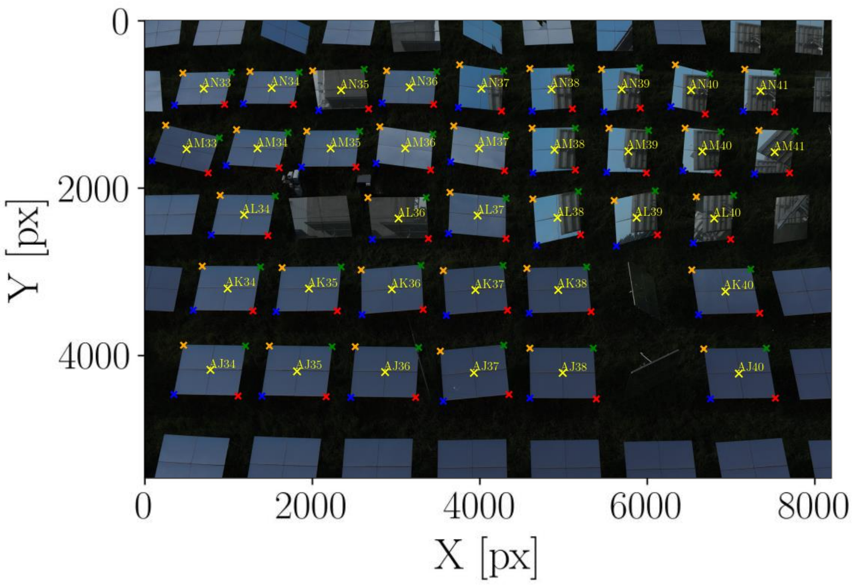
System-Under-Development
Concentrator Orientation Estimation

- Detecting heliostat tracking errors and outliers requires concentrator orientation estimation
- Corner-based methods: Estimate concentrator orientations from concentrator corner points, detected in image data

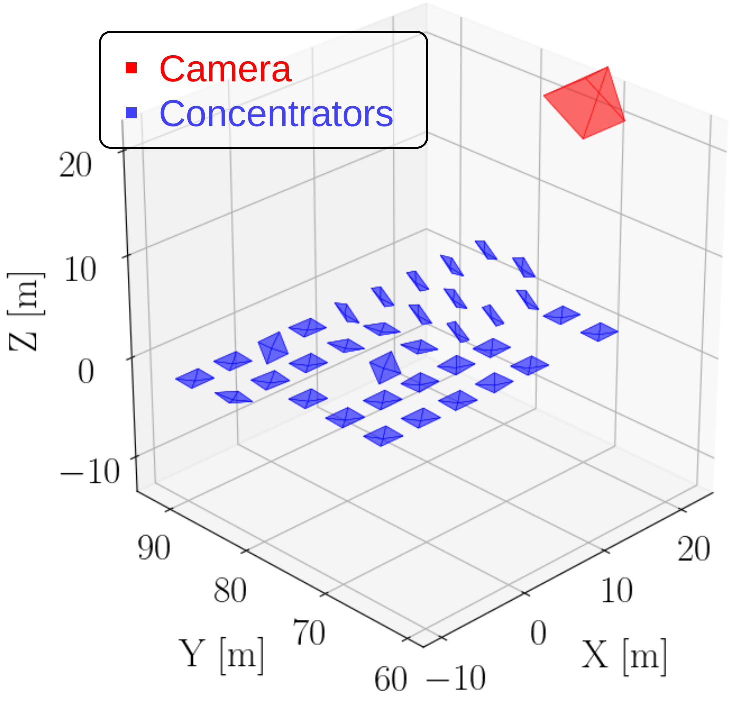
- Previous bundle adjustment approach [5]:
  - Jointly estimates camera poses and 3D corner point positions from a series of images
  - Derives concentrator orientations from 3D corner point positions
  - Computationally expensive (difficult to apply in real-time)
  - Requires static field

System-Under-Development
ARTSCORE

- New approach: **ARTSCORE** (Airborne Real-Time Solar Concentrator ORientation Estimation) [7]
- Step 1:
  - Jointly estimates camera pose and concentrator orientations from a single image
  - Leverages a-priori knowledge of heliostat positions, kinematic system, and concentrator geometry

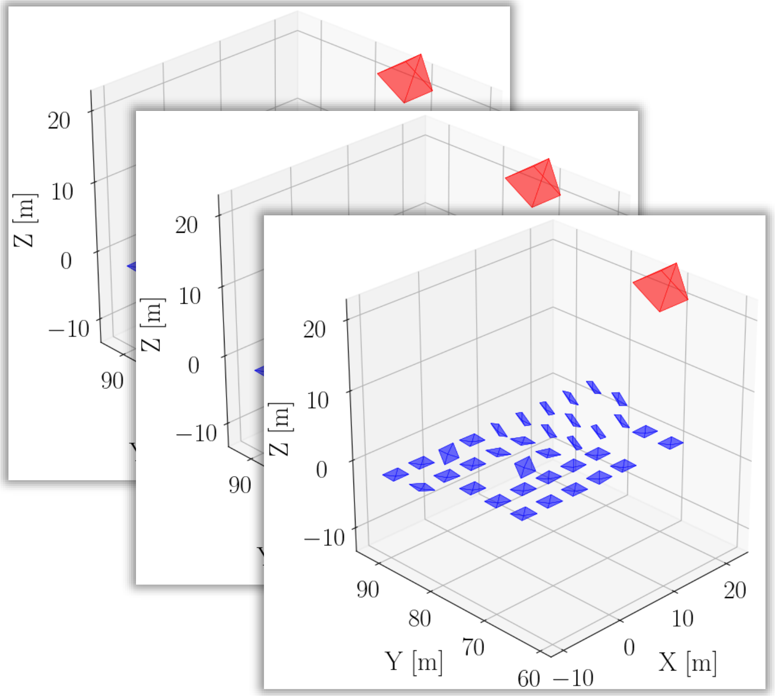


Step 1:
Imagewise concentrator orientation estimation

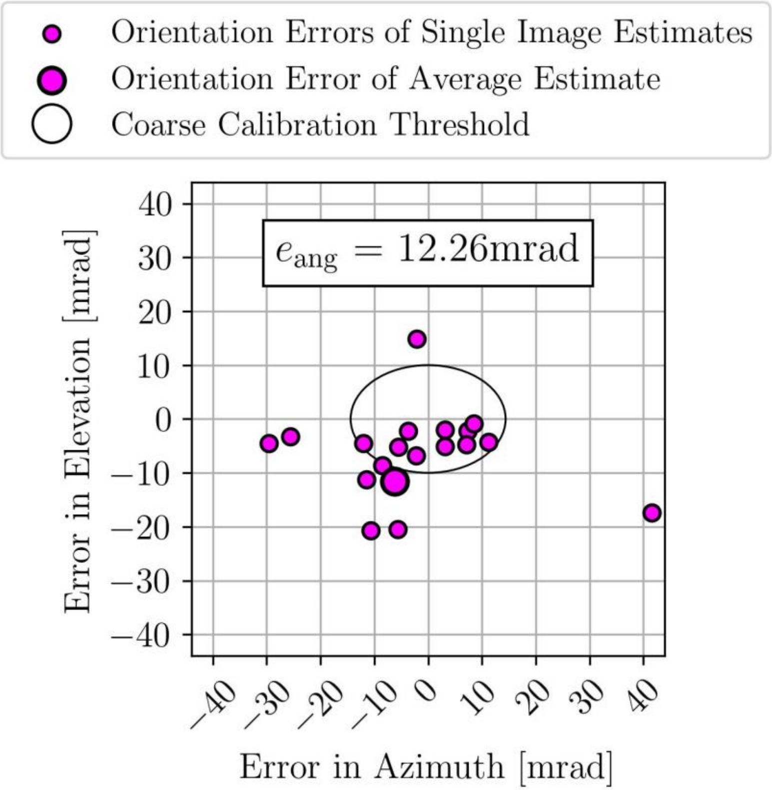


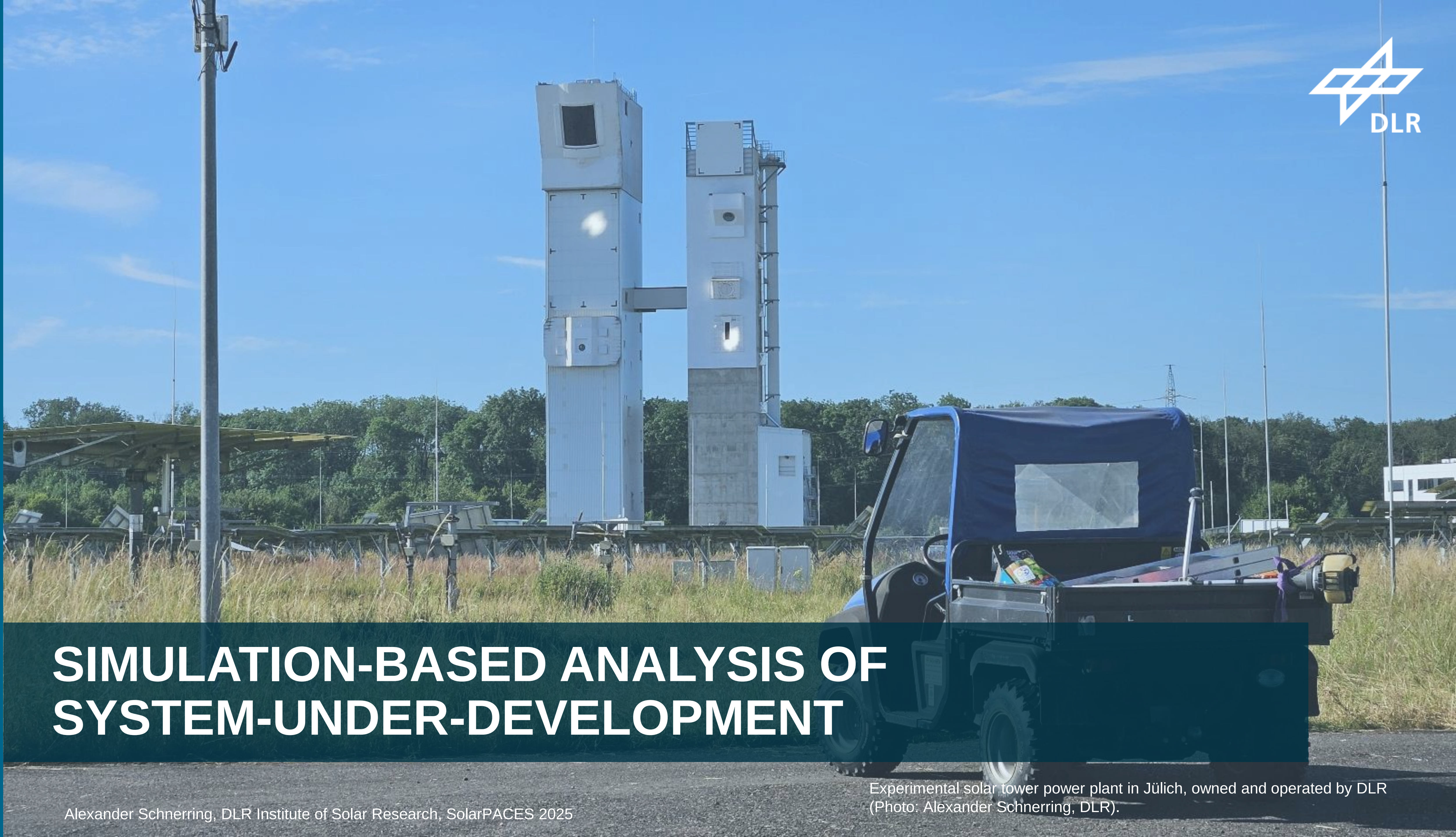
System-Under-Development
ARTSCORE

- New approach: **ARTSCORE** (Airborne Real-Time Solar Concentrator ORientation Estimation) [7]
- Step 2:
  - Per concentrator: Average estimates of multiple images to obtain final concentrator orientation estimate



Step 2: Concentratorwise averaging over multiple images



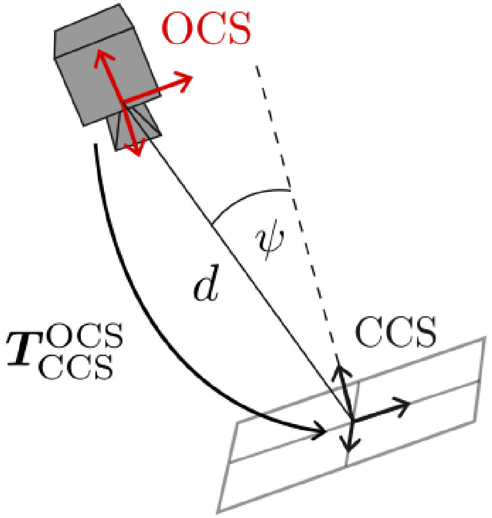


SIMULATION-BASED ANALYSIS OF SYSTEM-UNDER-DEVELOPMENT

Experimental solar tower power plant in Jülich, owned and operated by DLR (Photo: Alexander Schnerring, DLR).

Simulation-Based Analysis

- Quality of the image-based concentrator orientation estimate is well predicted by the descriptor (d, ψ) (two DOFs) of the relative perspective $T_{\text{CCS}}^{\text{OCS}}$ (six DOFs) between camera (**OCS**) and concentrator (**CCS**):



$$d = |t_{\text{CCS}}^{\text{OCS}}|, \qquad \psi = \cos^{-1}\left(\frac{t_{\text{CCS}}^{\text{OCS}} \cdot n}{|t_{\text{CCS}}^{\text{OCS}}| \cdot |n|}\right)$$

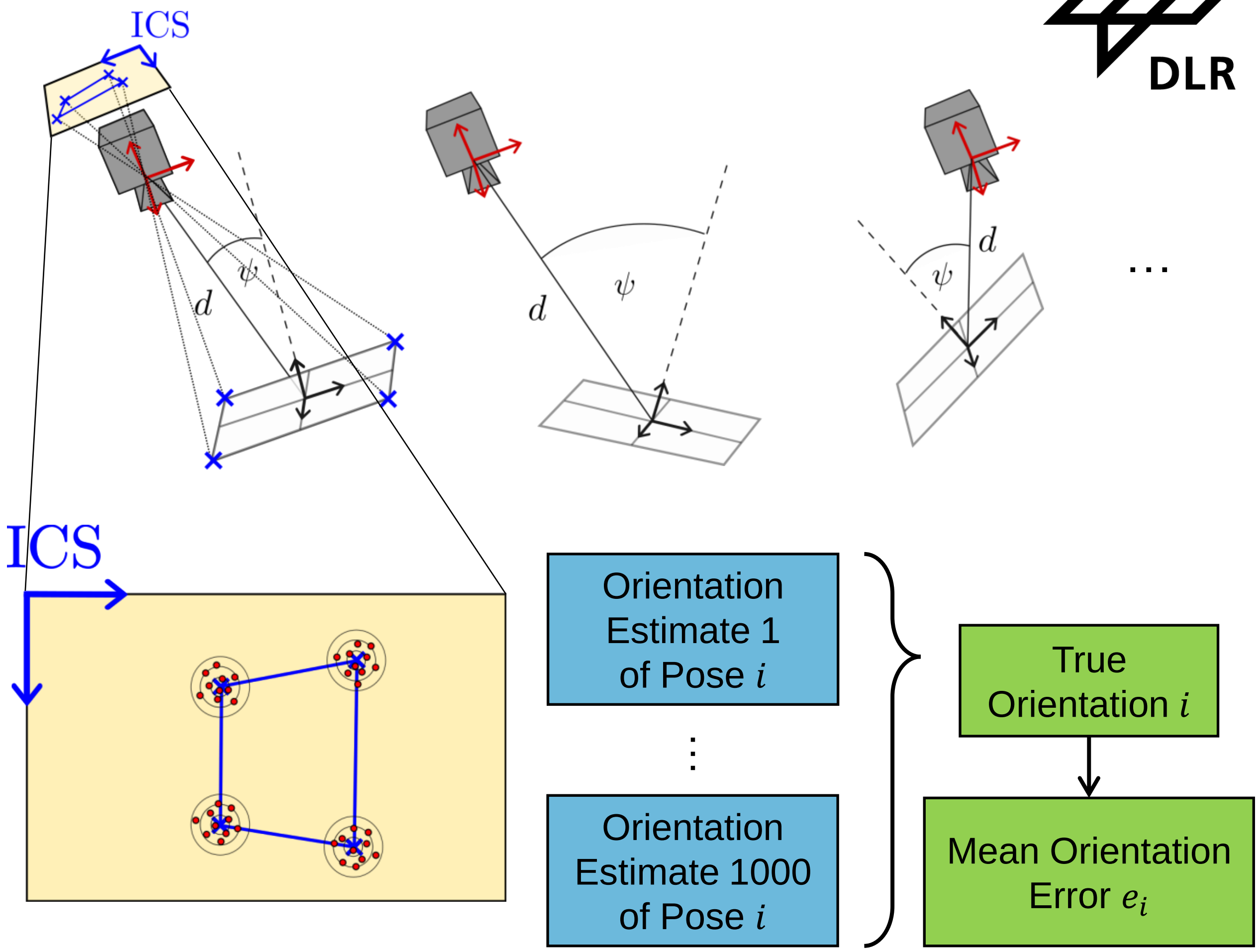
with

$$t_{\text{CCS}}^{\text{OCS}} = \text{Trans}(T_{\text{CCS}}^{\text{OCS}}), \qquad n = \text{Rot}(T_{\text{CCS}}^{\text{OCS}}) \cdot (0\ \ 0\ \ 1)^T$$

- Idea: Analyze orientation estimation quality as a function of (d, ψ) in simulation and derive modifications accordingly

Simulation-Based Analysis
Monte-Carlo Experiment

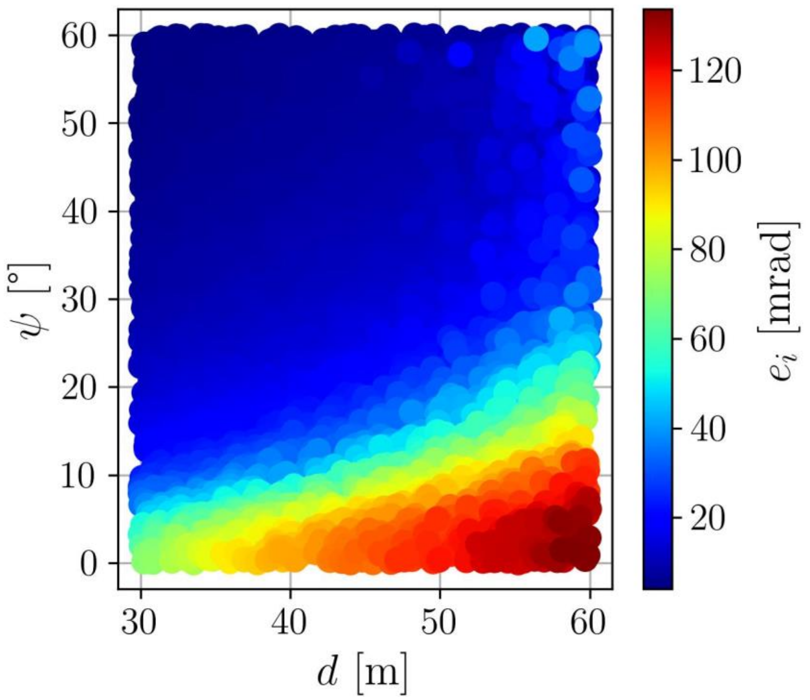
- In simulation, sample 5000 relative poses
- For a given pose i, project the four concentrator corner points on the virtual camera sensor, using the camera model
- For every projection of a given pose i, sample **1000 noise vectors** four times and add them to the corner point projections
- Based on the noisy projections, estimate 1000 concentrator orientations for a given pose i



- Compute mean orientation error e_i for every sampled relative pose → 5000 mean orientation errors overall

Simulation-Based Analysis
Monte-Carlo Experiment

- For every sampled pose i, plot ψ_i over d_i and color with e_i
- Observations with high ψ and low d result in lowest mean orientation errors
- Conclusion: Concentrators should preferably be observed from close distances and using oblique perspectives
- Problem: Concentrator orientations may not be known a-priori



→ Simulation-Based Modification: When averaging the estimates from different images, include only those images with high ψ

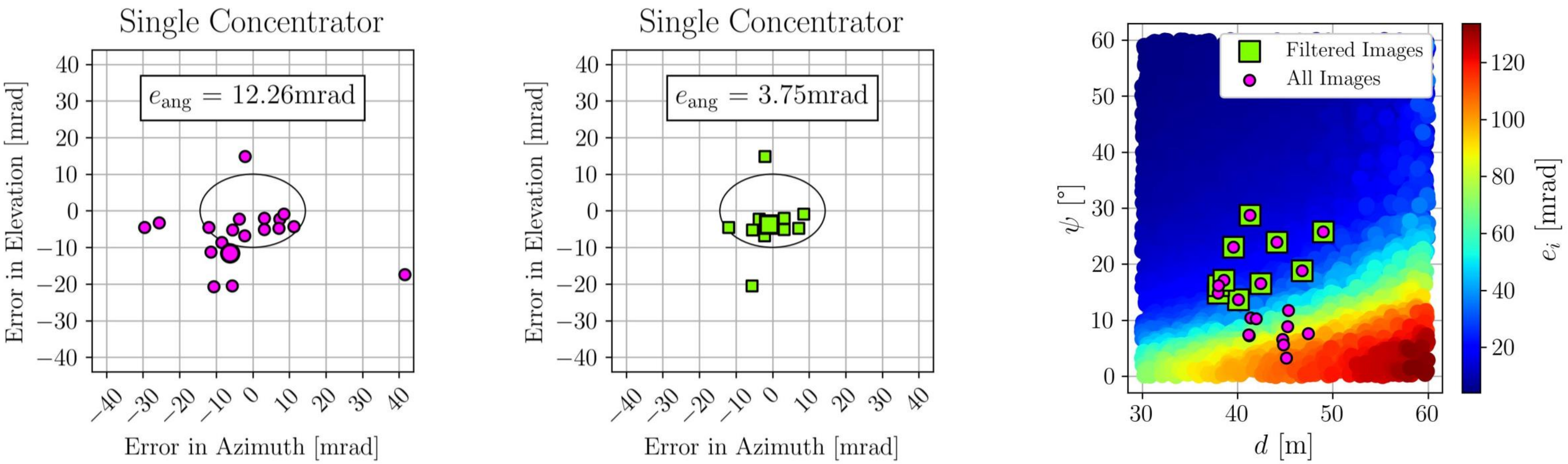
TRANSFER TO REAL DATA

Experimental solar tower power plant in Jülich, owned and operated by DLR (Photo: Alexander Schnerring, DLR).

Transfer to Real Data

Only include high-ψ-images – Single Concentrator

- Considering estimates for a single concentrator
- Before modification: Average all 20 images (●)
- After modifcation: Average those 10 images (■) with highest value ψ



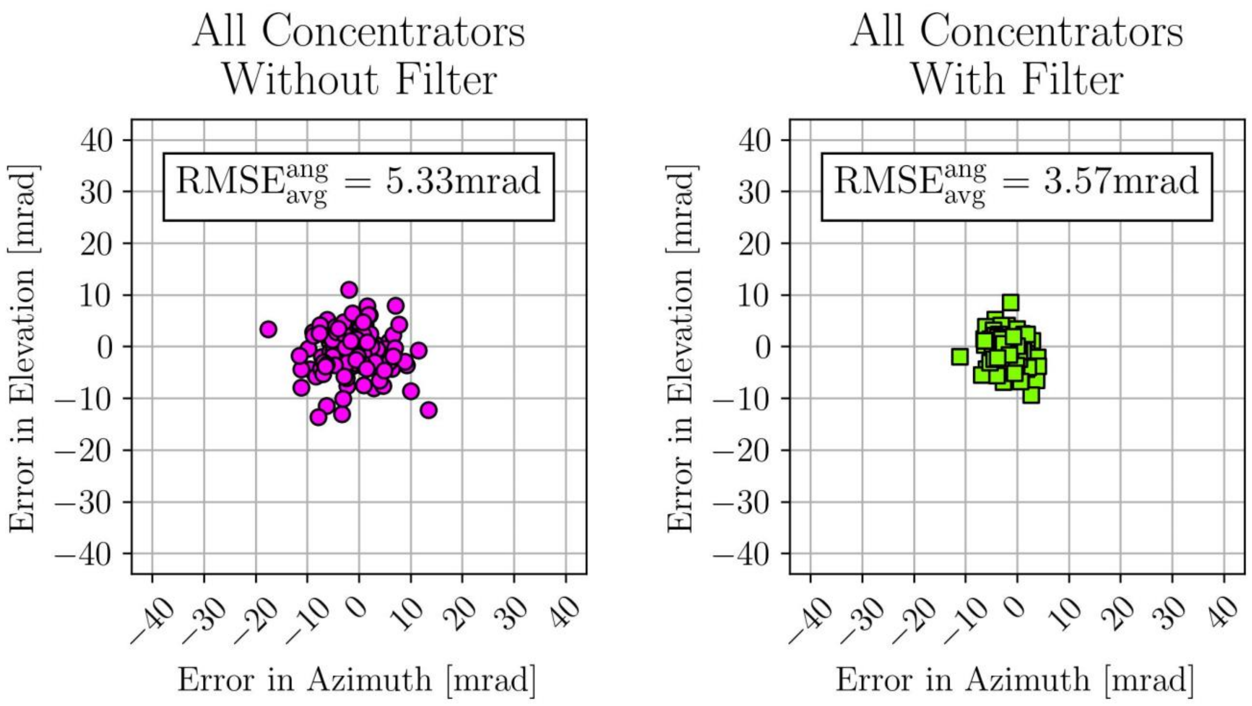
Transfer to Real Data

Only include high-ψ-images – All Concentrators

- Considering estimates for 146 concentrators (each averaged over multiple images)
- Before modification: Average all 20 images (●)
- After modifcation: Average those 10 images (■) with highest value ψ

→ Reduction of overall error $\mathrm{RMSE}_{\mathrm{avg}}^{\mathrm{ang}}$ from $5.33\mathrm{mrad}$ to $3.57\mathrm{mrad}$

→ Modification identified in simulation leads to improvements on real data!



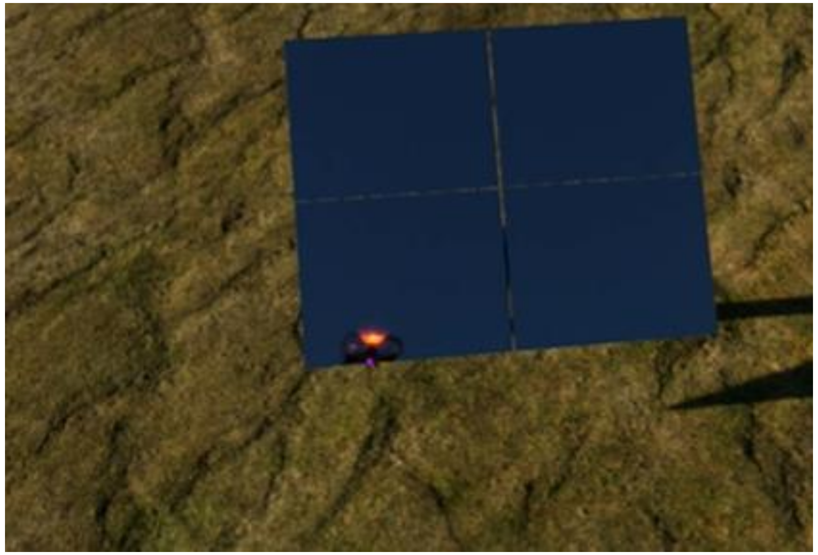
CONCLUSION AND OUTLOOK

Image recorded at Plataforma Solar de Almería (PSA), owned and operated by CIEMAT (Photo: Marc Röger, DLR).

Conclusion and Outlook

- Conclusion:
  - A simulation environment is used to model camera observations of a heliostat field
  - Component of a novel heliostat coarse-calibration algorithm is evaluated within this simulation
  - Simulation-based insights lead to a refined modification of this algorithm
  - The modified algorithm demonstrates enhanced performance on real-world data

- Outlook:
  - Use *Unreal Engine* + *AirSim* + *ArduPilot SITL*
    - → Real-time rendering of images
    - → Simulation of UAV flight dynamics
  - Development of a reflex-based fine calibration algorithm with dynamic route planning



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[7] A. Schnerring, R. Broda, M. Nieslony, N. Algner, E. Saez, M. Röger, S. Kallio, R. Pitz-Paal, ***ARTSCORE: Airborne Real-Time Solar Concentrator Orientation Estimation***, paper, in preparation

THANK YOU FOR YOUR ATTENTION!

Image recorded at Plataforma Solar de Almería (PSA), owned and operated by CIEMAT (Photo: Marc Röger, DLR).

Imprint

Topic: **Toward airborne real-time condition monitoring systems of solar tower power plants**

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