SKY-IMAGING: AN OPEN-SOURCE PYTHON PACKAGE FOR ASI PROCESSING

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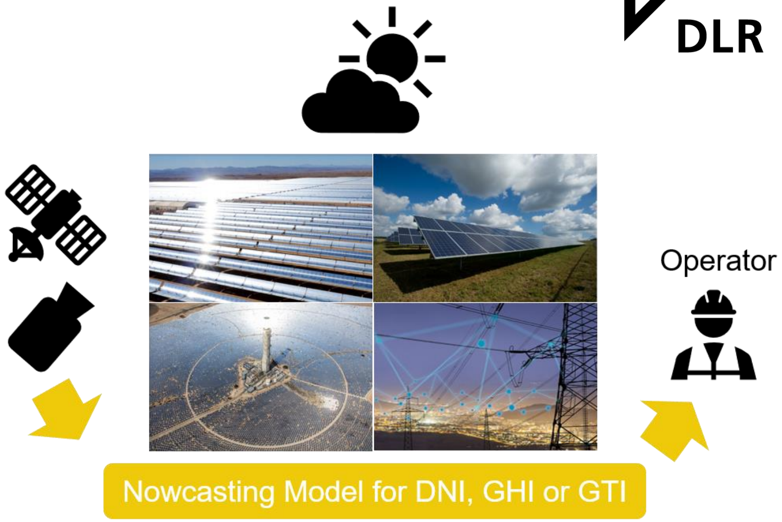
Agenda

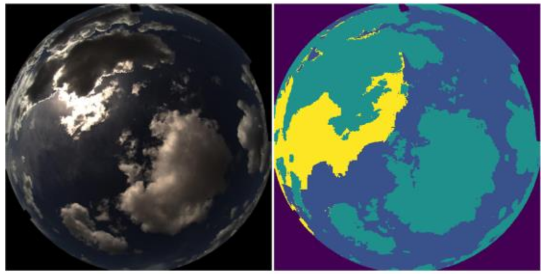
- Introduction Sky-Imaging
- Autonomous Geometric Calibration
- ASI Anomaly Detection
- Dataset publication: SolarVision Almería
- Conclusion & Outlook

Introduction

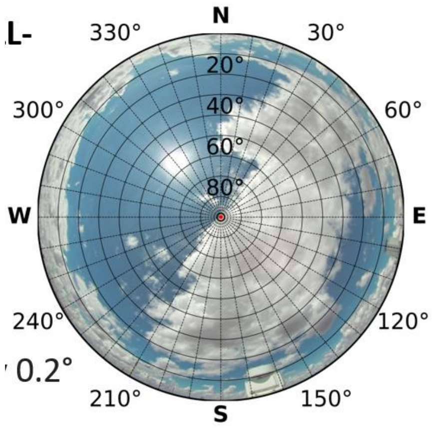
- Increased interest in all-sky imagers due to potential of enhancing the integration of solar energy:
  - Short-term solar forecasting
  - Image-based measurements of the solar resource (PyranoCam)
  - Detection of clouds and aerosols
- Automated processing/analysis essential to deal with large data quantities
- Many image (pre-)processing techniques are independent of application

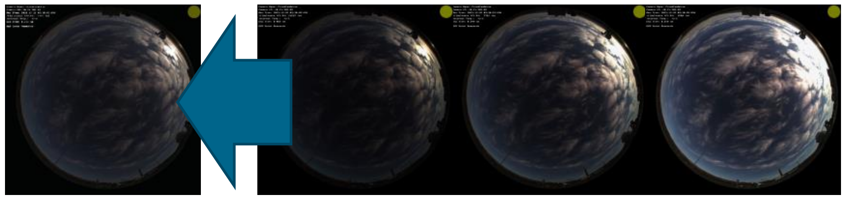
→ Development of an open-source python package as toolbox for ASI processing

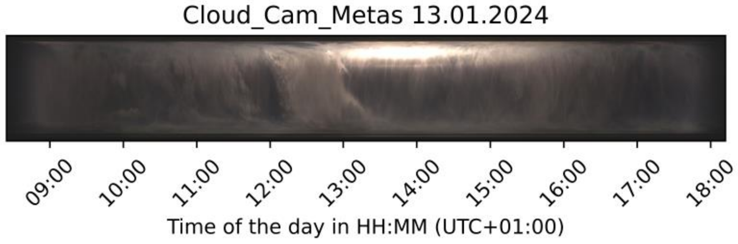




Sky-Imaging
A Toolbox for ASI Processing







Automated geometric calibration of ASIs

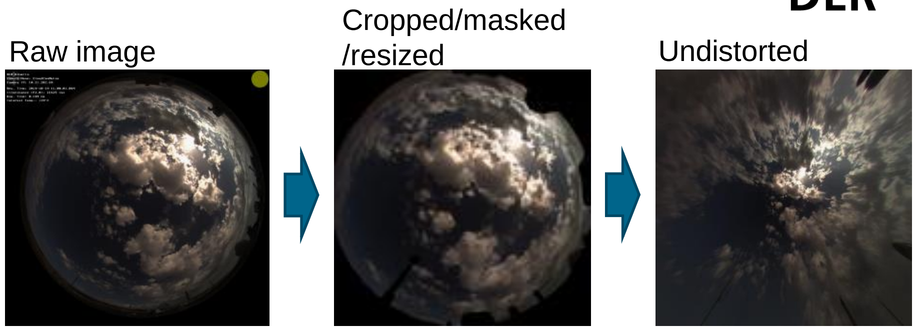
Image pre-processing for ML tasks

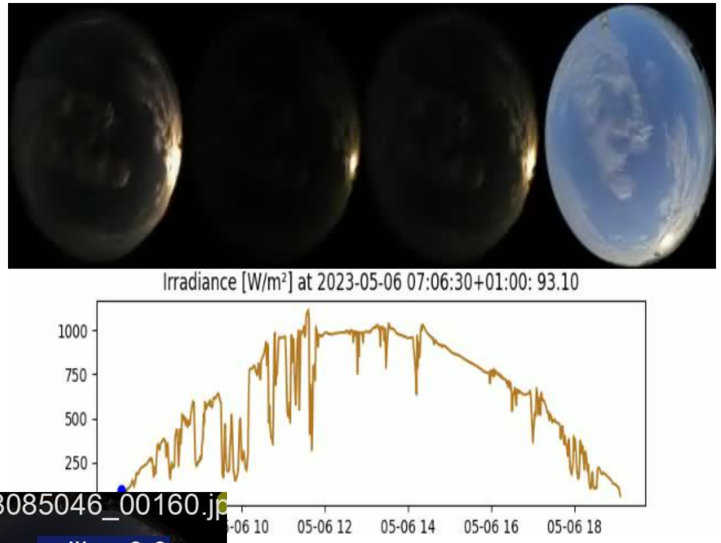
Image-merging (multiple exposure times)

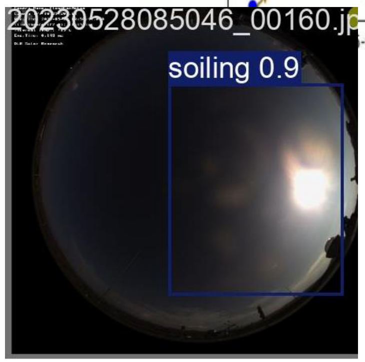
Combination of sensor and image data

Data analysis and visualization

Anomaly detection in sky images





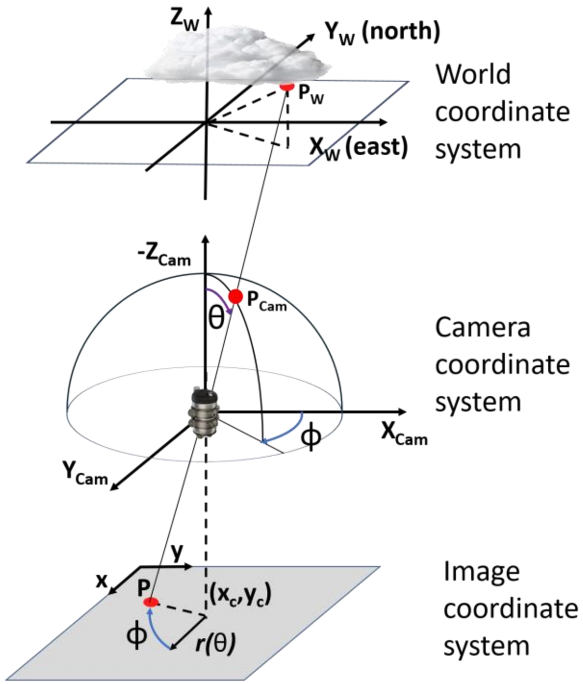


Geometric Calibration: Introduction

- In sky imaging positions of clouds in the sky, radiance information etc. need to be reconstructed from images

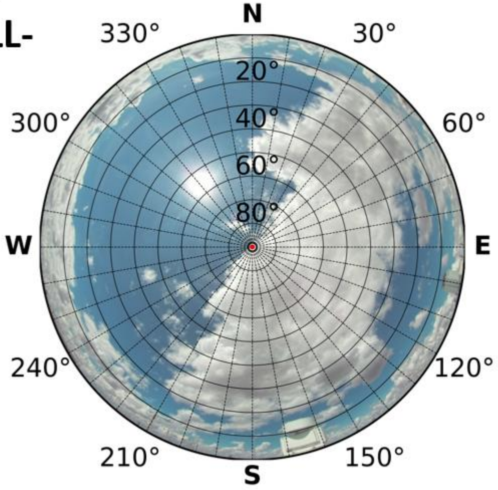
- **Geometric Camera Models enable this:**
  - Intrinisic part maps of image pixel coordinates (x,y) to 3D-cartesian coordinates $(X_{cam}, Y_{cam}, Z_{cam})$
    - Lens distortion described by coordinates of lens center and polynomial coefficients
    - e.g. Scaramuzza model
  - External orientation (3 rotation angles) maps $(X_{cam}, Y_{cam}, Z_{cam})$ to world coordinates (X_w: east, Y_w: north, Z_w: zenith)

- **Our novel tool SuMo:**
  - Automatically determines calibration parameters (intrinsic/ external) based on sun and/or moon positions detected in all-sky images
  - No need for manual interference on-site
  - Allows for retrospective calibration
  - Continuous monitoring of ASI's geometric calibration possible, e.g., to detect (unintended) changes of external orientation
  - Independent of camera hardware



GEOREFERENCED ALL-SKY IMAGE

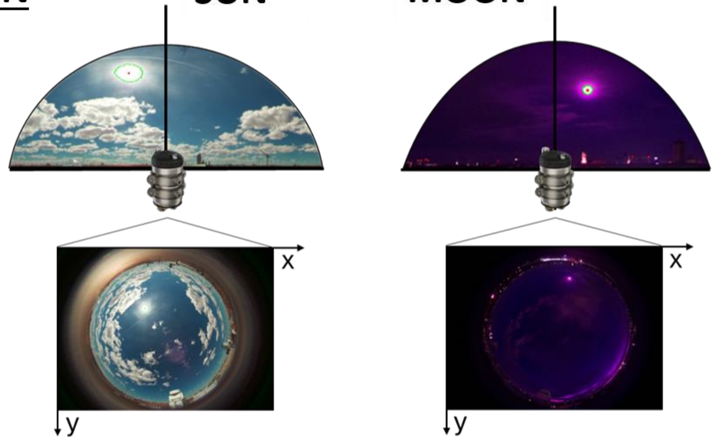
- *Each all-sky pixel (x,y) is assigned an azimuth and elevation angle.*



Geometric Calibration: Method

1. IMAGE-BASED ORB DETECTION

Thresholds
- *Pixel Intensity*
- *Area*
- *Circularity*
- *Aspect ratio*



2. ASTRONOMIC CALCULATION ORB POSITIONS

- GPS COORDINATES CAMERA
- TIMESTAMPS ALL-SKY IMAGES

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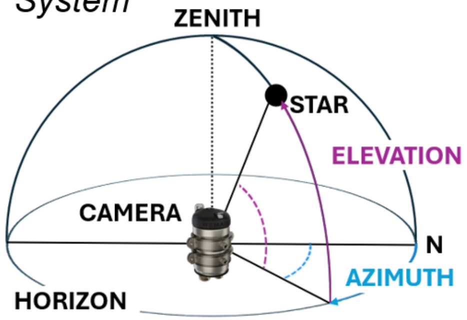
- ASTRONOMICAL ANGLES: (Azimuth, Elevation)

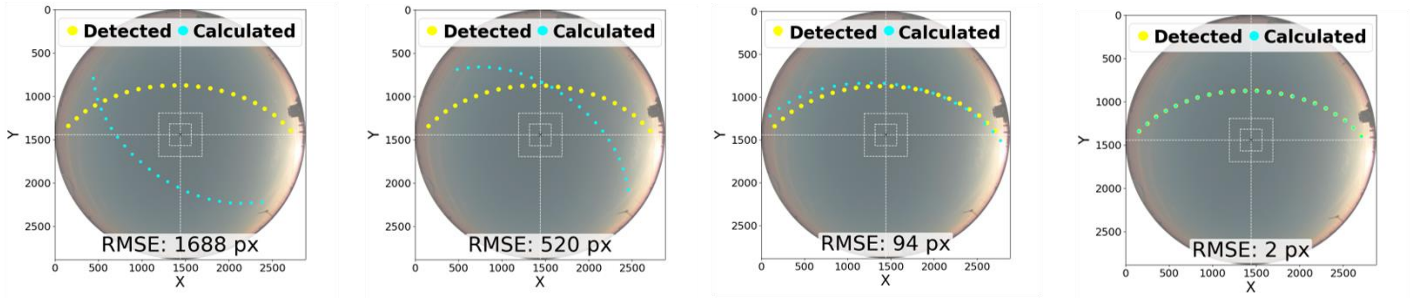
Horizontal Coordinate System



3. GEOMETRIC CALIBRATION

(Detected vs. Calculated)

Solver: Loss Minimization for Pixel Position Matching



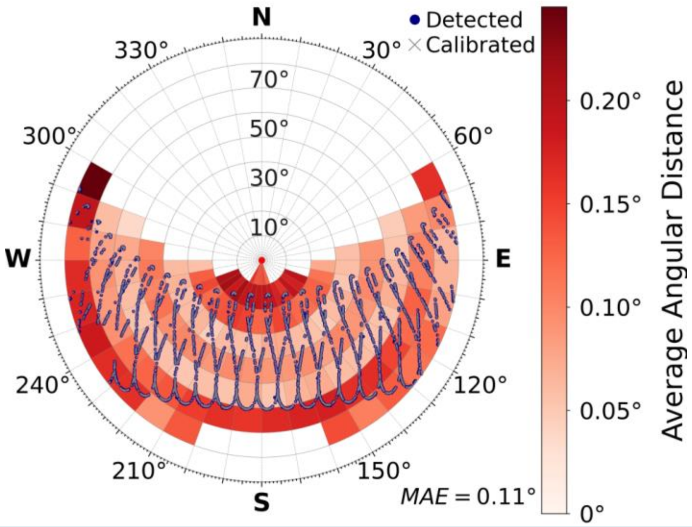
Calibration of: ✓Internal Camera Parameters ✓External Orientation ✓Center Coordinates

Geometric Calibration: Validation

- Validation with 5 camera types at three locations:
  - RMSE ≤ 0.38° achieved for each camera
- Influence of orb type (Sun/ Moon), period duration, season, latitude, atmospheric conditions and image quality evaluated:
  - Best case: *RMSE* 0.14° – moon images of regular quality
  - Worst case: *RMSE* 0.98°– sun images of low quality (for one camera)
- Cross-validation with semi-automatic calibration method (ORION) demonstrates improved usability & accuracy
- Journal paper currently in review:

  N. Blum et al., "Geometric Calibration of All-Sky Cameras Using Sun and Moon Positions: A Comprehensive Analysis", Solar Energy (in review).

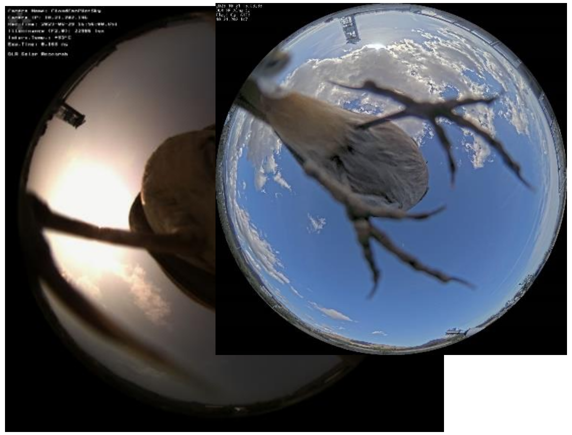
Orb positions detected in image vs. astronomically expected:
- **Grey/ blue** dots: strong coincidence in calibration (Sun)
- **Color code**: Small angular deviations in validation (Moon)



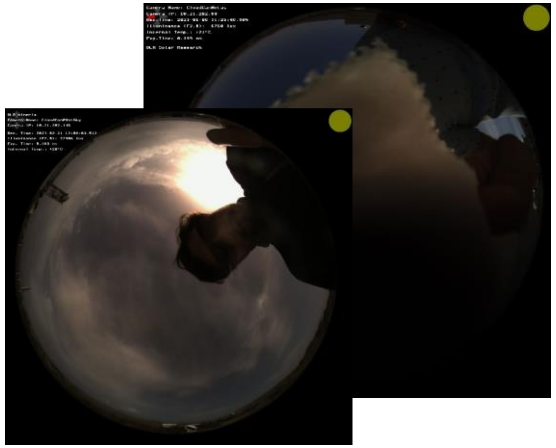
ASI Anomaly Detection
Introduction

- Motivation:
  - In autonomous ASI operation corrupted images may impact the performance if not detected
  - Warnings can be issued when anomalous images were detected
  - Required actions may be identified (e.g., cleaning, scarecrows)
  - Retrospective data cleaning for benchmark purposes
- Possible Anomalies

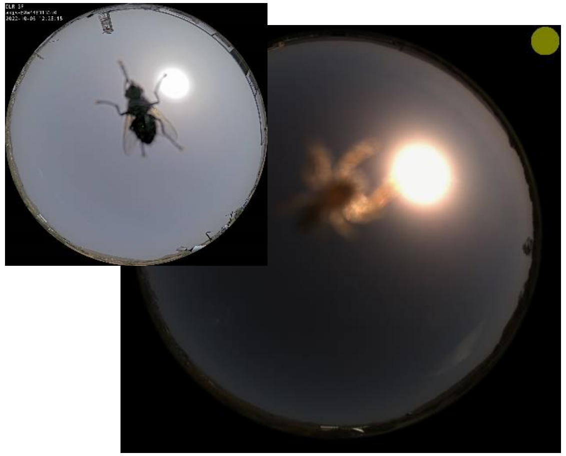
Birds



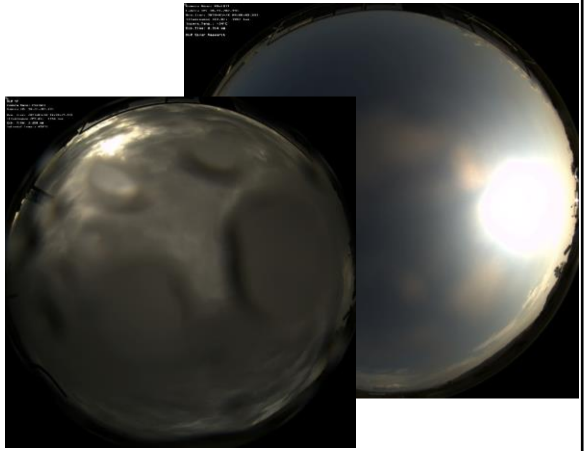
People/Maintanance



Insects/Spiders



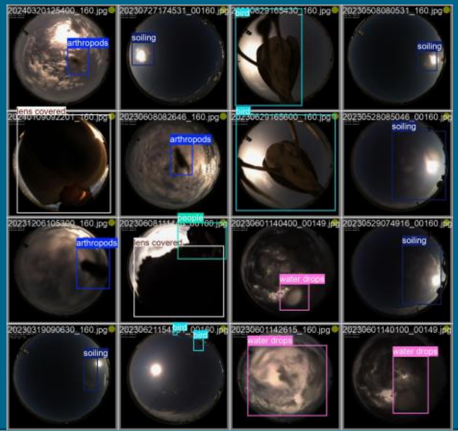
Water drops/Soiling



ASI Anomaly Detection
YOLO Fine-Tuning

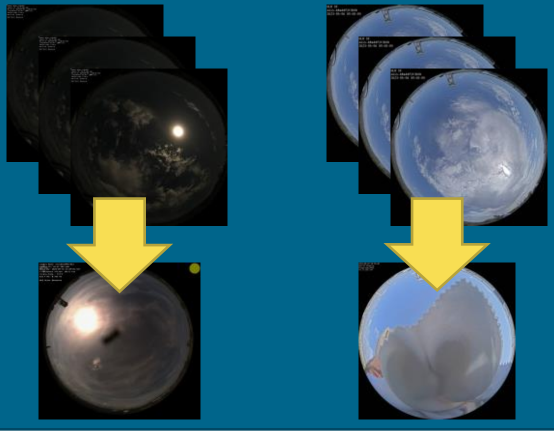
- Anomaly detection via object detection model (YOLOv11) :
  - Create dataset by searching camera logbooks and labeling images via label-studio
    → 390 labeled images
  - Fine-tune pretrained YOLO model to detect anomalies using ultralytics software
  - Apply inference on large datasets to extend anomaly dataset and repeat procedure

Dataset Creation



Model Fine-Tuning

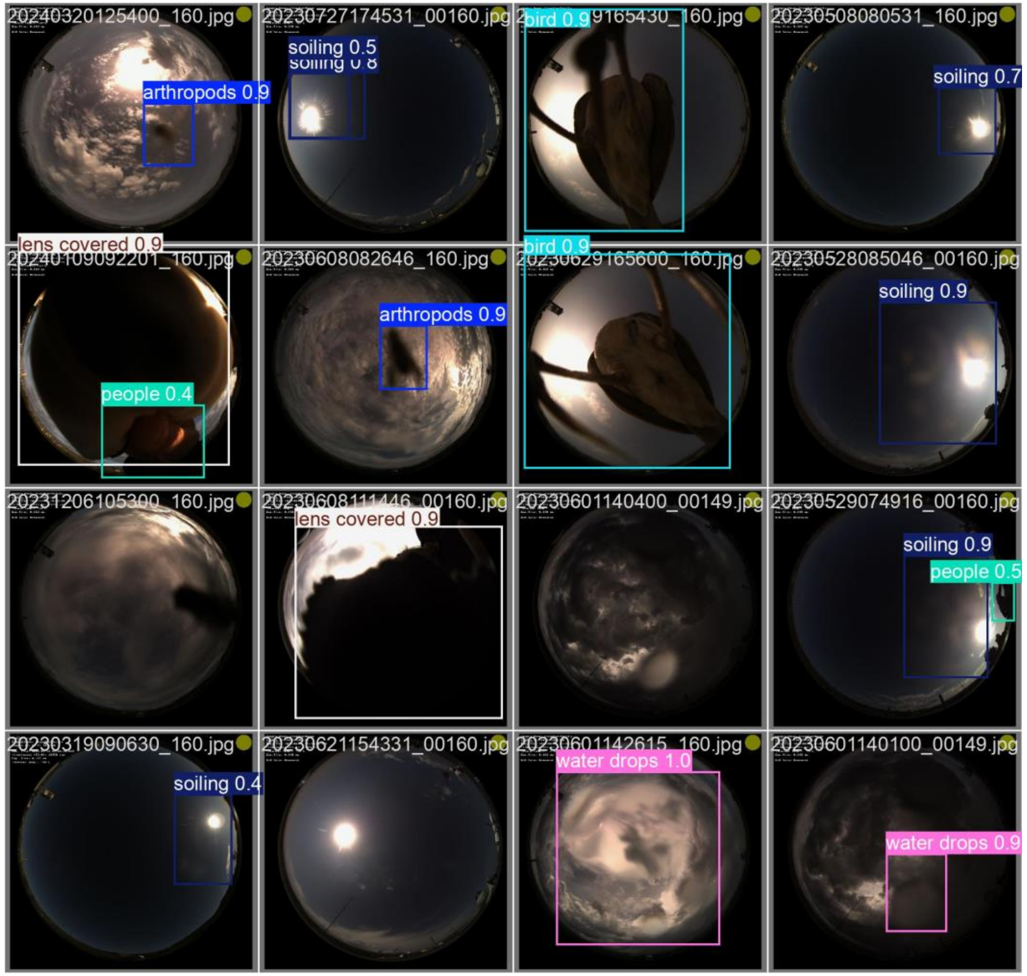
Inference



ASI Anomaly Detection Validation

- Evaluation after 1st iteration
- Train/validation split (80/20)
  - Train: 302 images
  - Valid: 78 images

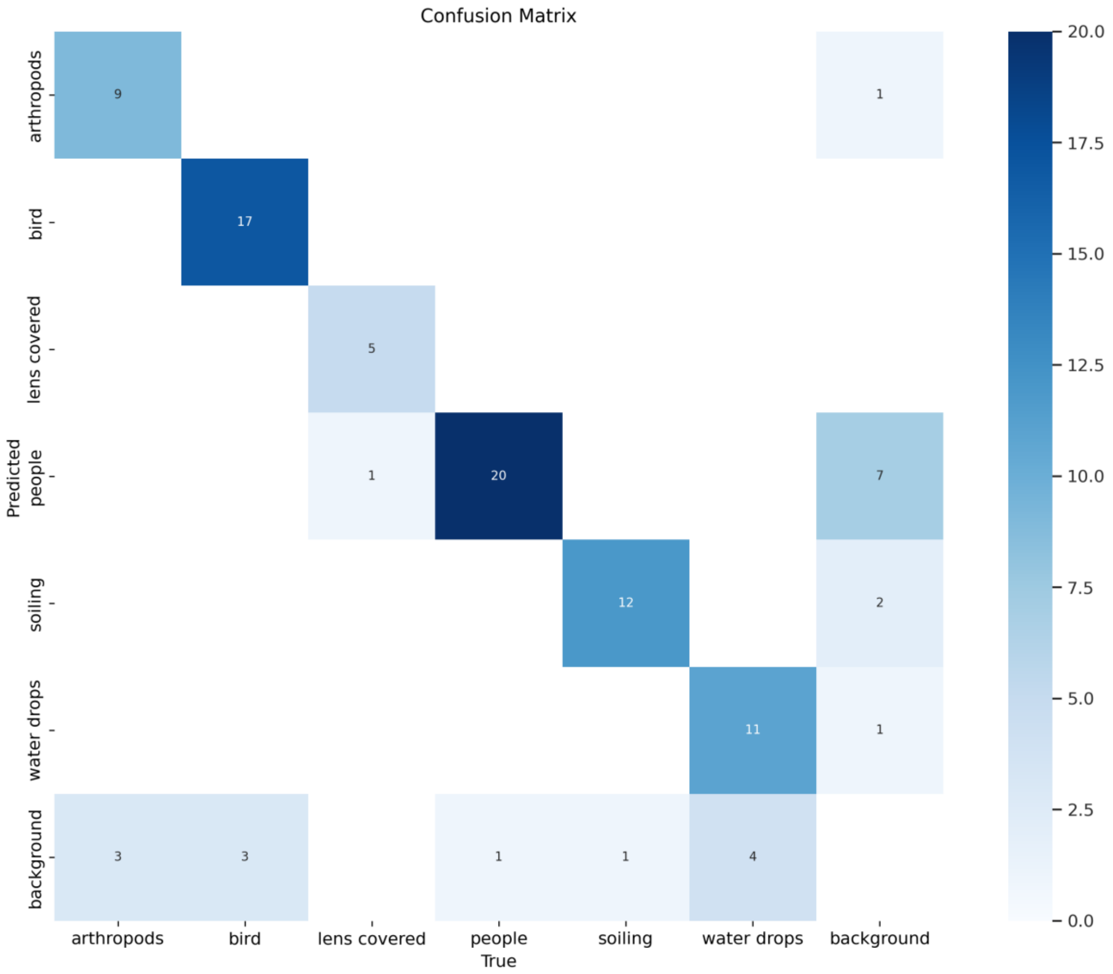
Examplary results on validation set



ASI Anomaly Detection Validation

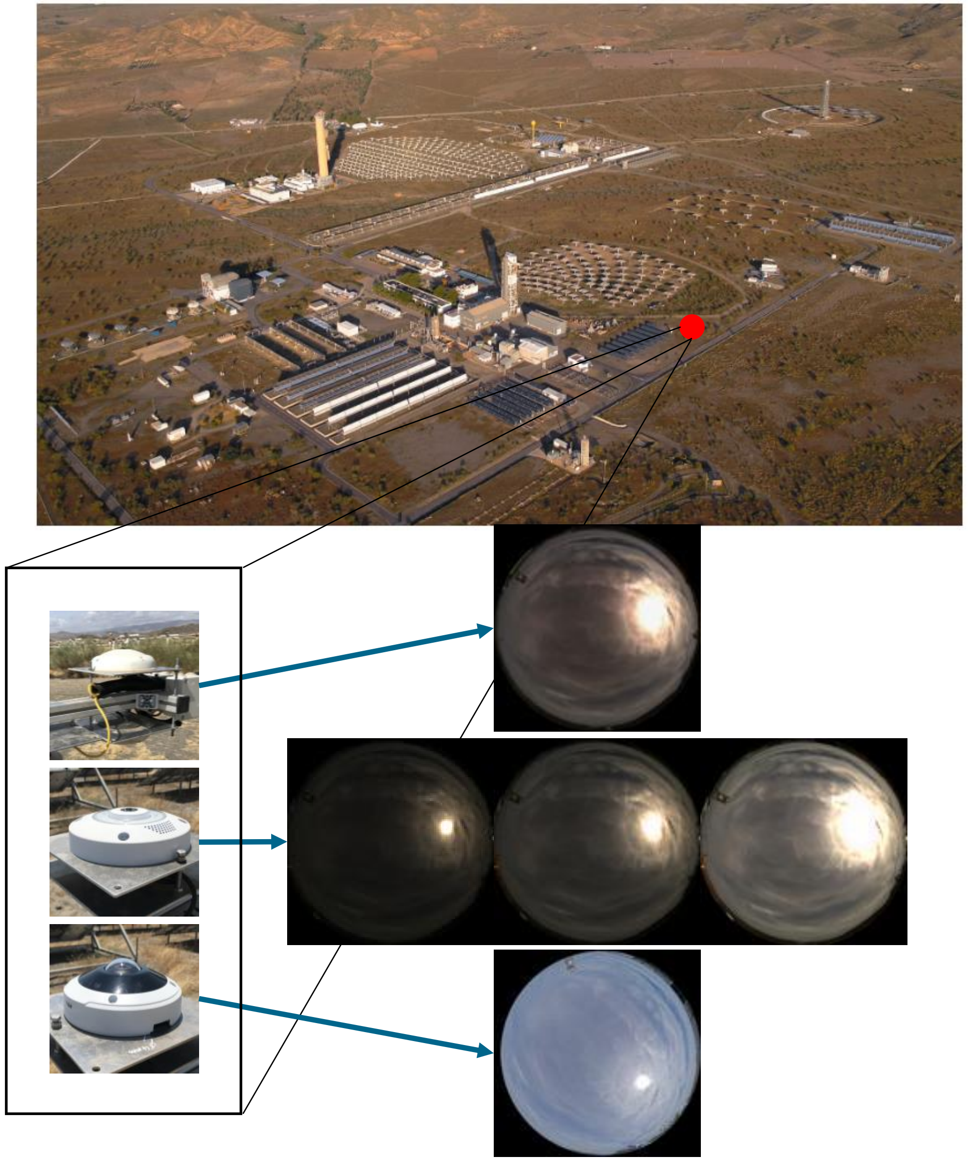
- Object detection metrics of predicted boxes on validation set
  - Precision: TP/(TP+FP)
    → how many detected objects are actually correct
  - Recall: TP/(TP+FN)
    → how many real objects were detected
  - mAP50: average precision for Intersection over Union
    → how well do predicted and ground truth boxes match

Class	Instances	Precision	Recall	mAP50
All	87	0.96	0.78	0.91
Arthropods	12	0.97	0.75	0.96
Birds	20	0.99	0.85	0.87
Lens cov.	6	1	0.72	1
People	21	0.9	0.84	0.96
Soiling	13	0.98	0.77	0.86
Water drops	15	0.9	0.73	0.84



Dataset Publication

[1]Plataforma Solar der Almería (PSA) is owned and operated by CIEMAT



- SolarVision Almería Dataset
  - 2 years-dataset (August 2022 – July 2024) from PSA[1]
  - 3 All-sky imagers
    - Mobotix Q26: Single-exposure times (160µs)
    - Mobotix Q71: Multiple-exposure times (80-320µs), HDR
    - AXIS M3058-PLVE: HDR
  - Additional measurements from meteorological station
    - Irradiance (GHI, DNI, DHI)
    - Temperature, relative humidity, pressure, wind speed/direction
- Motivation
  - Reproducibility of published works
  - Perform benchmarks for model comparison
  - Application of sky-imaging toolbox

Conclusion

- **Sky-Imaging Python Package:**
  - Toolbox for ASI Processing:
    - Autonomous geometric calibration
    - Anomaly Detection
    - Data analysis and visualization
    - …
- **SolarVision Almería Preview:**
  - 2-Years dataset of 3 ASI + irradiance measurements from PSA
  - Current publication process on Pangaea (until then dataset can be shared on request)
- **Outlook**
  - Planned data article on SolarVision Almería dataset
  - Planned publishing of anomaly dataset and cloud segmentation masks
  - Further community development of open-source software for all-sky imagers and open-data plattforms (e.g., SkyImageNet)

https://github.com/DLR-SF/sky_imaging

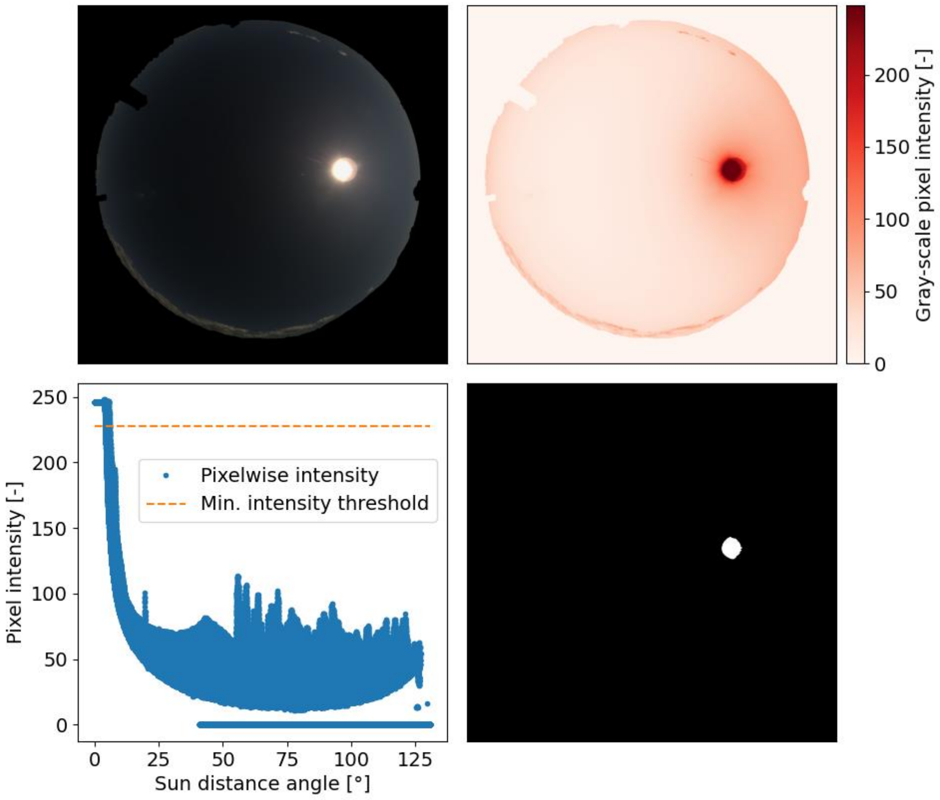
https://gigamove.rwth-aachen.de/en/download/880e69f789d0445b434be6d292973b74

Thank you for your attention! Questions? yann.fabel@dlr.de

BACKUP SLIDES

Geometric Calibration: SuMo Method

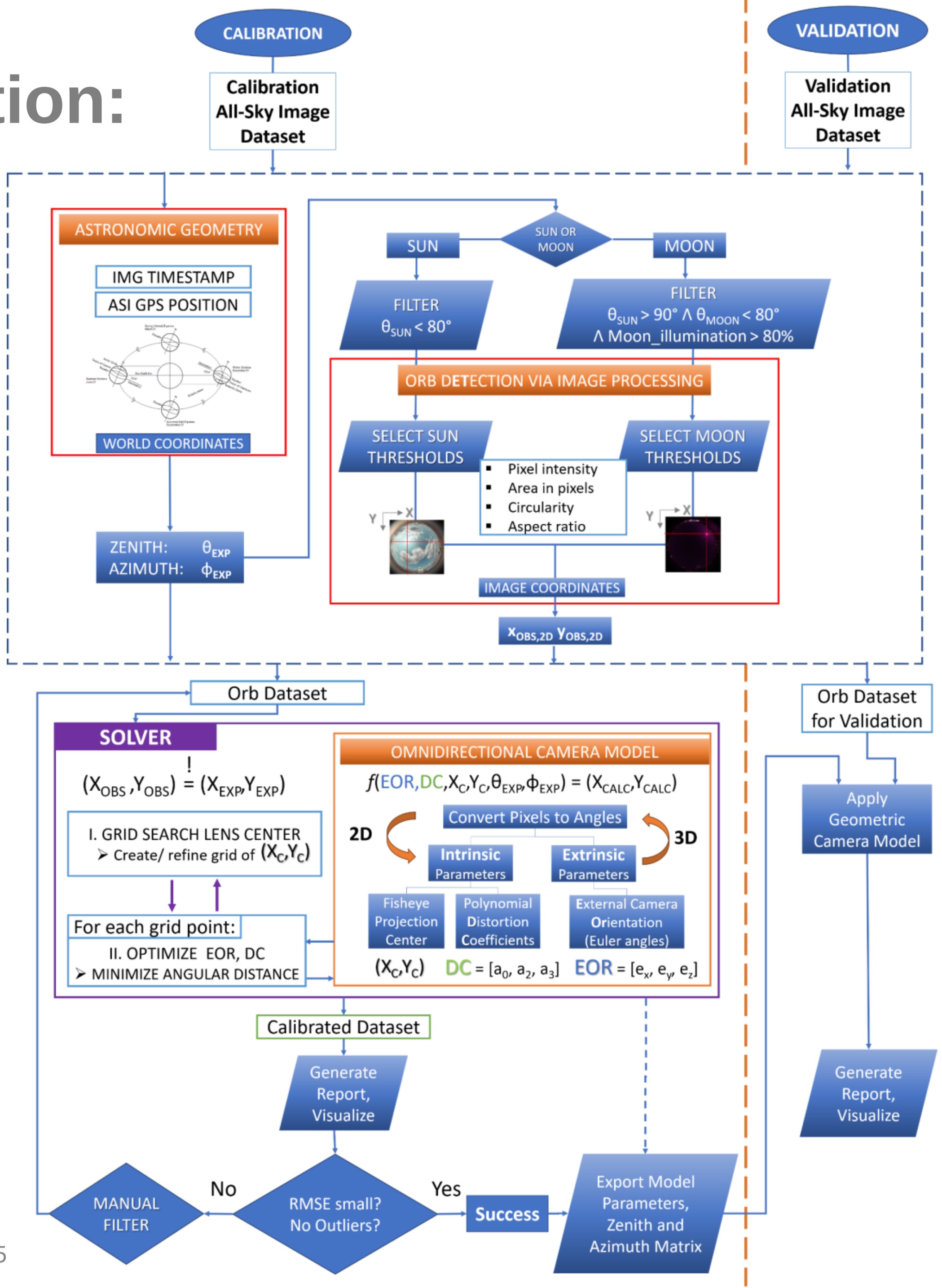
- Image-based Orb Detection:
  1. A Camera mask is applied to neglect all pixels not representing the sky
  2. Image is transformed into gray-scale
  3. Image is transformed into binary image by applying Otsu algorithm:
     - Split pixels into two classes by an intensity threshold
     - Minimize weighted within-class variance
     - (Threshold adjusted to comply with specific minimum)
  4. Consider contour of largest white region in binary image (should be small and circular) that must fulfill these criteria:
     - Area limited by contour must be within certain range
     - Aspect ratio of fitted ellipse should be close to one
     - Circularity of contour should be close to 1



Geometric Calibration:
SuMo Method

- Astronomic Calculation of Orb Positions
  - pyEphem python package used for astronomical calculations
  - Spherical coordinates of Sun and moon calculated from timestamp and the camera's geolocation (considering atmospheric refraction)
  - Only periods where respective orb can be observed theoretically
    - Sun: solar elevation at least 10°
    - Moon:
      - Moon elevation at least 10°
      - Solar elevation not exceeding -6°
      - Moon phase at least 80%

Geometric Calibration: SuMo Flow Chart



Impressum

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