GEOMETRIC CALIBRATION OF ALL-SKY CAMERAS USING SUN AND MOON POSITIONS:

ACHIEVING SUB-DEGREE-ACCURACY WITHOUT ANY HANDWORK

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Agenda

- Introduction: Sky imaging and camera calibration
- Our novel approach: SuMo
- Experimental validation
  - Nominal accuracy
  - Influences on the method’s accuracy
- Conclusion

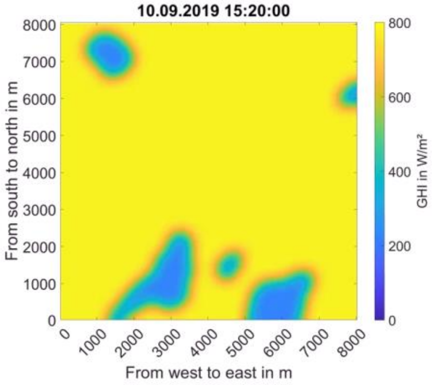
Motivation all-sky imaging

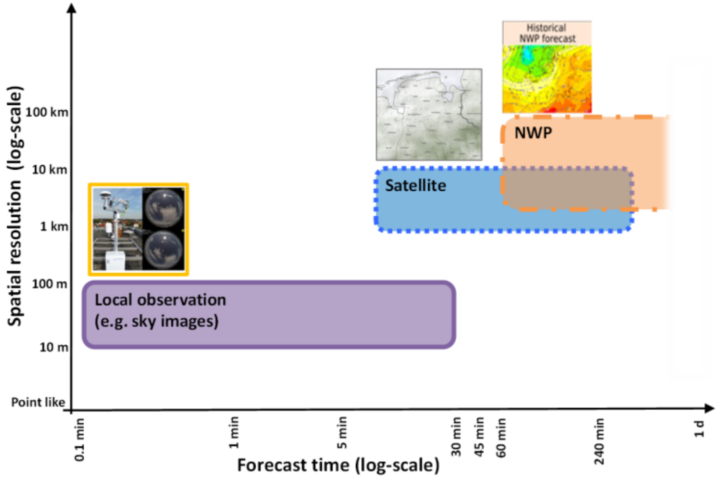
Why do we need sky imagers?

Motivation all-sky imaging
Applications

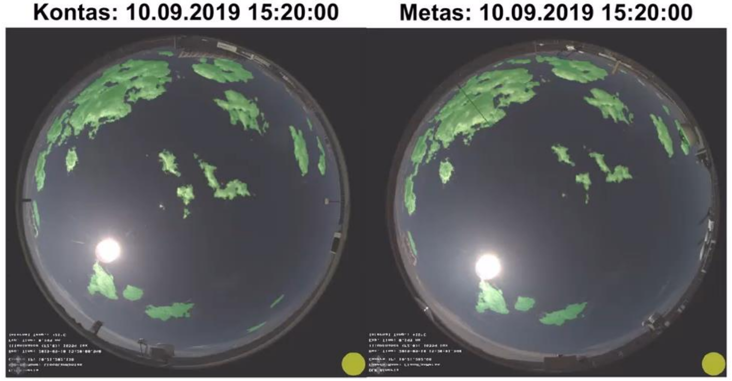
- Irradiance forecasts with highest resolution, e.g.:
  - 15-s update frequency and timestep
  - 10 m x 10 m spatial resolution
- Monitoring various parameters
  - Cloud cover and cloud location
  - Aerosol optical thickness
  - Radiance and irradiance measurement
- Applications:
  - Solar energy (e.g. management of PV-battery storage)
  - Automatic weather stations
  - Assimilation into weather models
  - …

64 km² irradiance map





Cloud detection



Motivation all-sky imaging

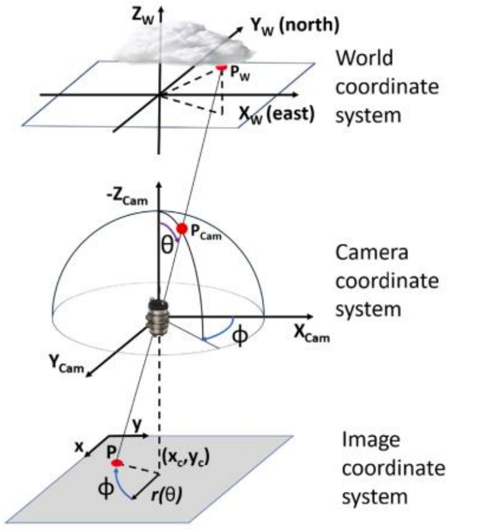
Why do we need geometric calibration?

Motivation all-sky imaging
Need for geometric calibration

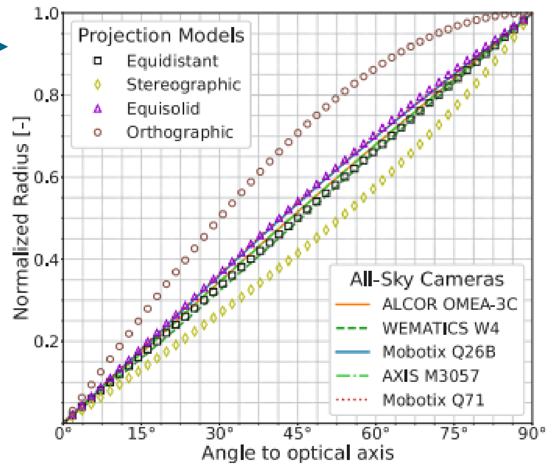
- Accurate mapping:

  Image (pixel) coordinates ↔ 3D- “world” coordinates of clouds, stars, …

  → camera model



- Camera models commonly describe:
  - Lens center coordinates (in pixels)
  - Radial lens distortion
  - External orientation (rotation of the camera around X, Y, Z)



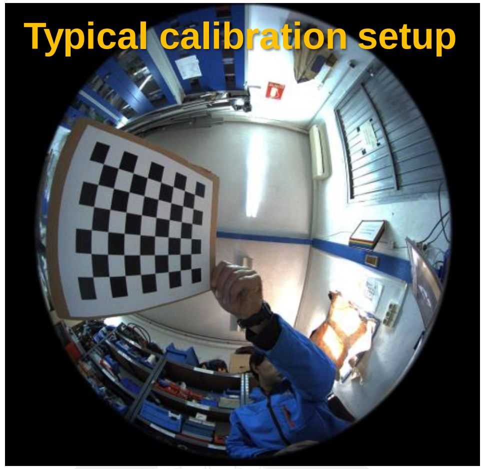
Contribution of this work

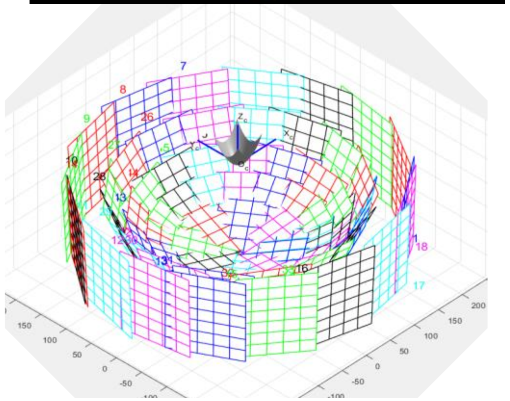
- Geometrical calibration increases workload when installing all-sky imagers:
  - Intrinsic calibration via specific setup (e.g. using checkerboards)
  - External orientation via separate procedure

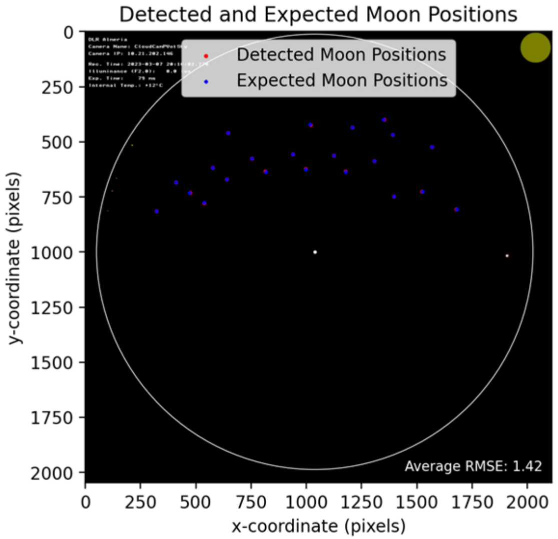
- Calibration should be enhanced:
  - No manual work on site
  - No overhead to plan calibration tasks
  - Retrospective creation should be possible
  - Automated as far as possible

- More details in our journal article:

  Blum, N., et al. (2025). "Geometric calibration of all-sky cameras using sun and moon positions: A comprehensive analysis." Solar Energy **295: 113476.**

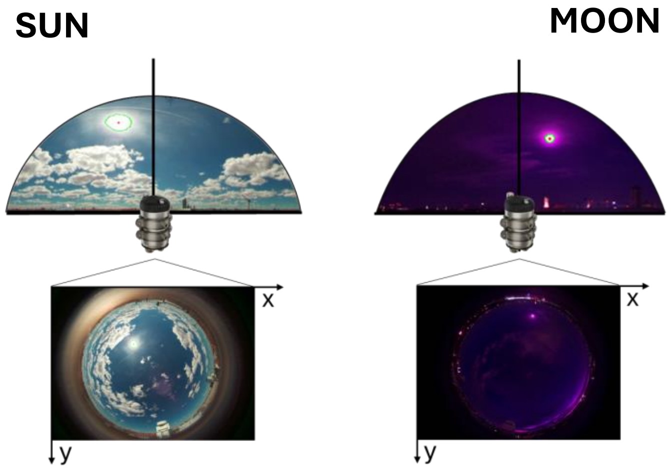






Our approach

Method – SuMo



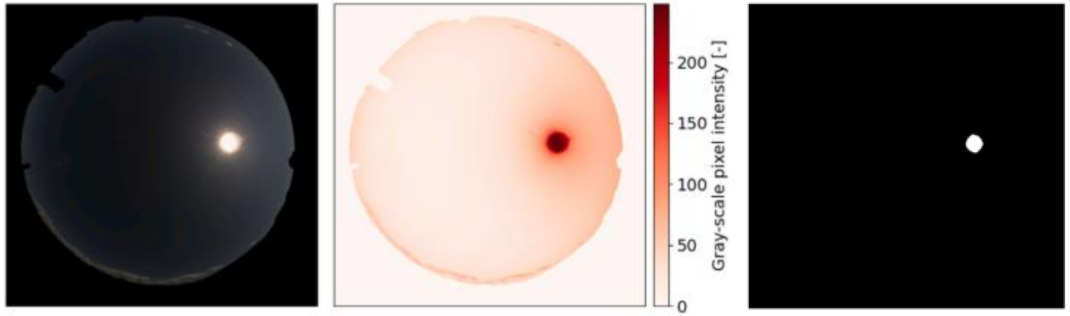
1. IMAGE-BASED ORB DETECTION

Observations of Sun and Moon selected for the calibration:

- Are the brightest celestial bodies (orbs) during day/night time
  → Simple criterion which avoids confusion
- Are easy to detect also using standard fisheye cameras

Detect largest circular bright dot as Sun / Moon via thresholding:

- *Pixel Intensity*
- *Circularity*
- *Aspect ratio*
- *Contour area*



Method – SuMo

2. ASTRONOMIC CALCULATION ORB POSITIONS

- GPS COORDINATES CAMERA
- TIMESTAMPS ALL-SKY IMAGES

↓

Common astronomic algorithms implemented in python

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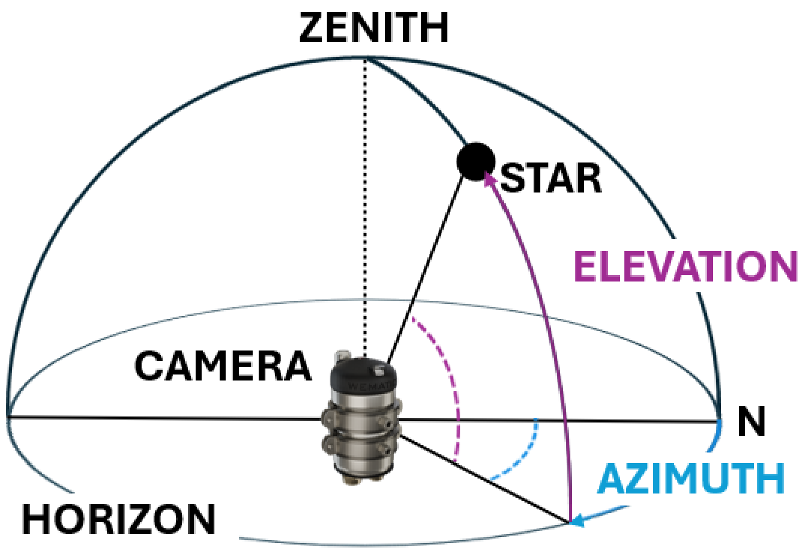
- ASTRONOMICAL ANGLES: Azimuth φ and Elevation ϑ
  $\varphi \in [0°, 360°); \vartheta \in [0°, 180°]$

World Coordinate System



Scaramuzza, D., et al. (2006). A Toolbox for Easily Calibrating Omnidirectional Cameras. RSJ International Conference on Intelligent Robots and Systems Beijing, China.

Method – SuMo

3. OPTIMIZATION MODEL PARAMETERS

Loss function computes root mean square average of cross product between “observed” (obs) and astronomically expected (exp) orb positions in world coordinates (3D):

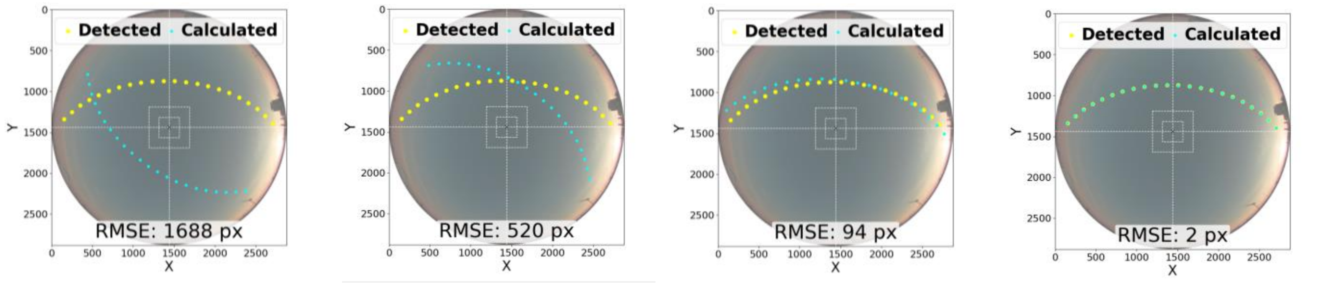
$$loss = \sqrt{\sum_{i=1}^{N} \frac{1}{N} (\|\underline{obs}_{3D,i} \times \underline{exp}_{3D,i}\|_2)^2}$$

Observed positions are calculated by applying the camera model to orb positions identified via image processing ($obs_{pixels,i}$):

Based on Scaramuzza et al. (2006)

$$obs_{3D,i} = \mathrm{rotation}(\underbrace{\mathrm{e_x}, \mathrm{e_y}, \mathrm{e_z}}_{\text{Rotation angles}}, \mathrm{intrinsic\_cam\_model}(\underbrace{\mathrm{x_c}, \mathrm{y_c}}_{\text{Lens center coords.}}, \underbrace{\mathrm{a_0}, \mathrm{a_2}, \mathrm{a_3}}_{\text{Lens distortion coefficients}}, obs_{pixels,i}))$$

Solver: Loss Minimization for Pixel Position Matching



Method – SuMo

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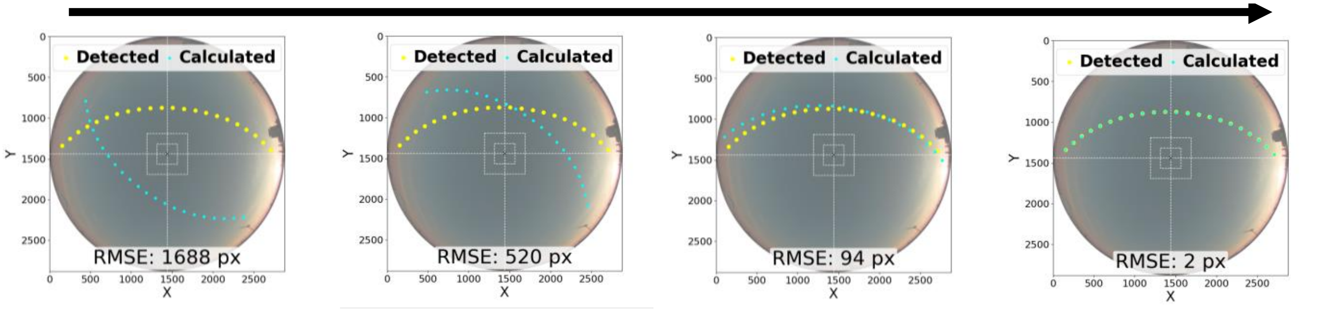
Solver minimizes loss

Solver: Loss Minimization for Pixel Position Matching



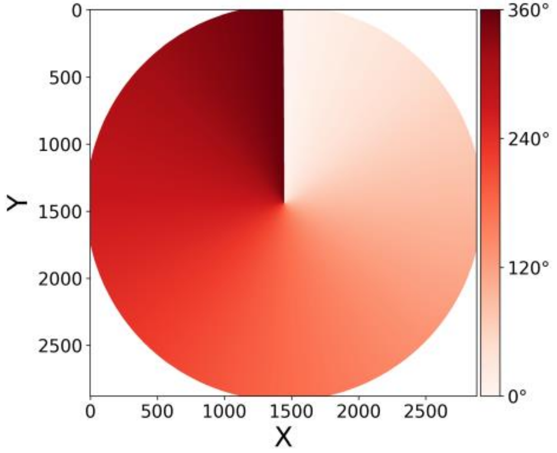
Method – SuMo

4. RESULT

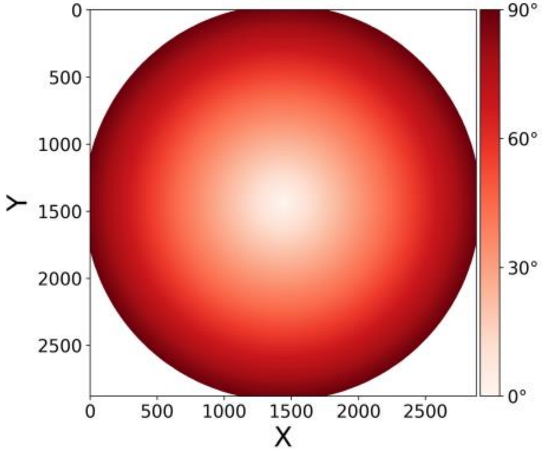
Calibration results enable mapping image pixels to world coordinates alternatively via …

MATRICES

AZIMUTH

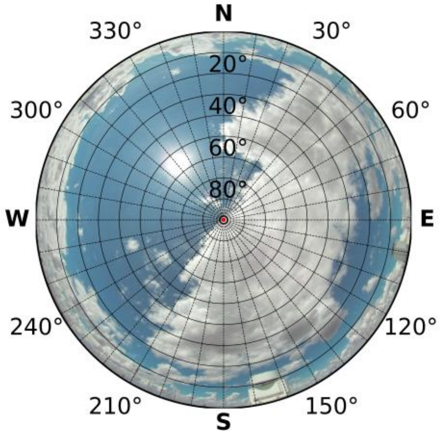


ELEVATION



azimuth and elevation angle (ϕ, θ) stored for every sky pixel (x, y)

CONVERSION FUNCTION



sky pixel (x, y) → azimuth and elevation angle (ϕ, θ)

Nominal accuracy

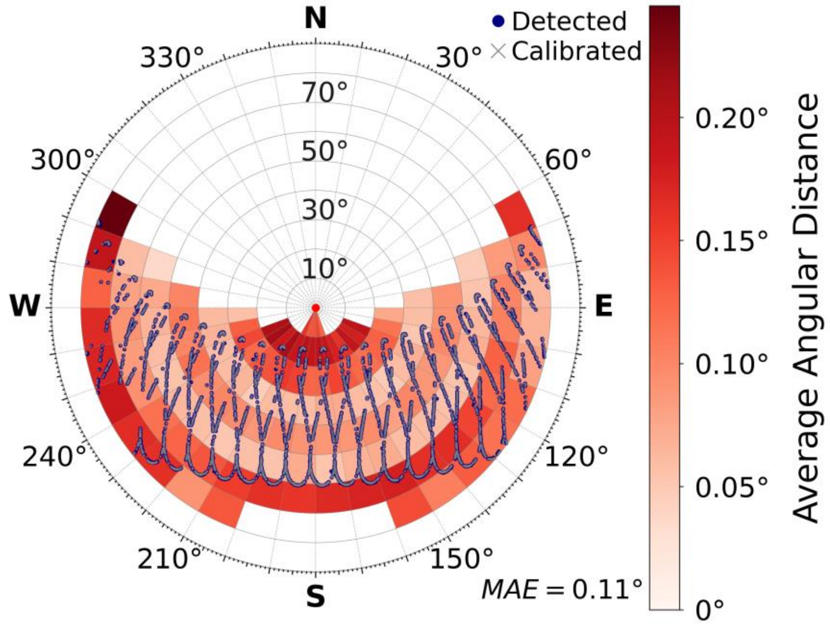
Results

Purpose	Period	Description
Calibration	03.02.2023-02.02.2024	Daytime images
Validation	04.03.2023-02.02.2024	12 full moon phases

- Calibration with sun positions (grey vs. blue)
- Validation with moon positions (color coded)
- Camera model reproduces astronomically expected moon positions well:

Calibrated with	#orbs	RMSE	MAE	Max. MAE in a grid cell
Sun	**3168**	**0.13°**	**0.11°**	**0.25°**

- Calibration determined from sun positions is transferable to predict moon positions

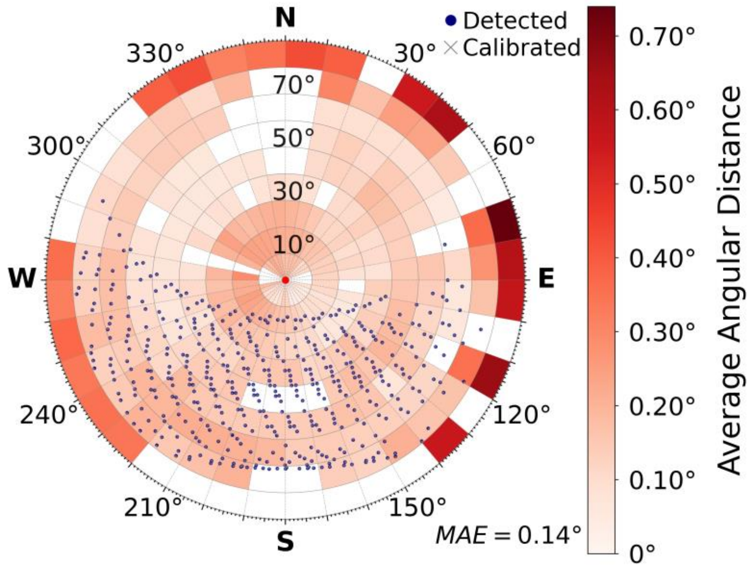


Results
Cross-validation with a state-of-the-art method

- Semi-automatic star-based calibration method ‘ORION’ used as reference
  - Orion includes star positions in entire sky dome
- Calibrated with SuMo → validated with ORION and vice versa
- Accuracy of SuMo confirmed
  - MAE = 0.14° on ORION star positions
  - Higher accuracy than ORION (MAE = 0.16°)
- Shortcomings of SuMo (and ORION) near horizon
  - θ <10° not included in SuMo calibration
  - Low quality of observations in this sky area

Calibrated with	MAE [°] (Validated on ORION star positions)
ORION	0.16°
SuMo	0.14°

Camera model calibrated via SuMo applied to predict star positions detected via ORION:



Results
Cross-validation with a state-of-the-art method

→Accuracy of the SuMo calibration confirmed in comparison to completely independent method and implementation

→Restriction of SuMo to observations from equator-pointing half of the hemisphere not problematic

→Handwork of ORION avoided, applicable to standard (non-astronomy) sky imagers

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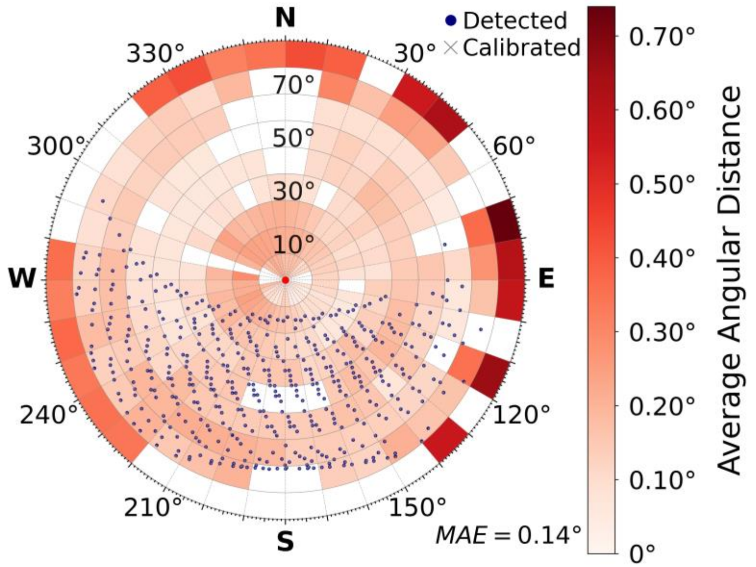
ORION	0.16°
SuMo	0.14°

Camera model calibrated via SuMo applied to predict star positions detected via ORION:



Influences on accuracy

Results – influences on accuracy
Calibration period

- Observed sun and moon elevation angles depend on season and latitude
- Shorter periods can lead to smaller variation in sun/ moon positions
- Calibration with single months of sun/moon observations
- Validation with an entire year of moon positions

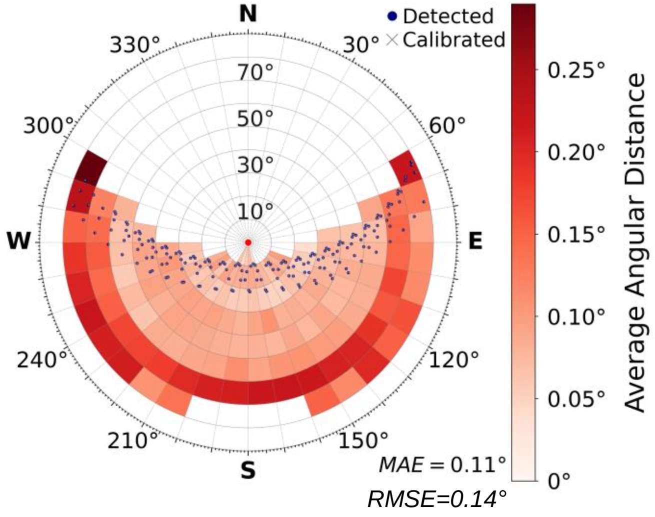
Dataset ID	Period	Description
Moon	04.03.2023–02.02.2024	12 full-moon phases
Sun	03.02.2023–02.02.2024	12 months, daytime
Sun, winter	01.12.–31.12.2023	Winter month, daytime
Sun, summer	01.06.–30.06.2023	Summer month, daytime
Moon, winter	22.12.–31.12.2023	Full moon phase in winter
Moon, summer	29.06.–07.07.2023	Full moon phase in summer
Moon, Sun, Summer	08.06.–07.07.2023	Summer month daytime and nighttime

Results – influences on accuracy
Calibration period

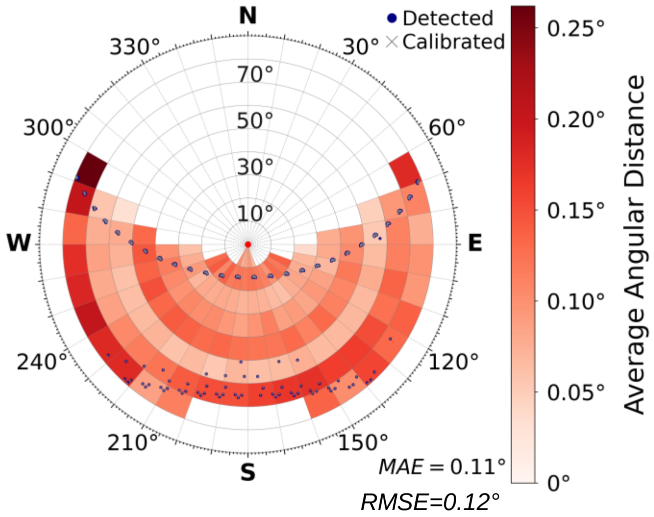
- A single moon phase in winter or a single month of sun and moon in summer yields accurate results!

- Own estimation: Combination of sun and moon positions will yield accurate calibration in any season and at latitudes between arctic circles

Moon in winter

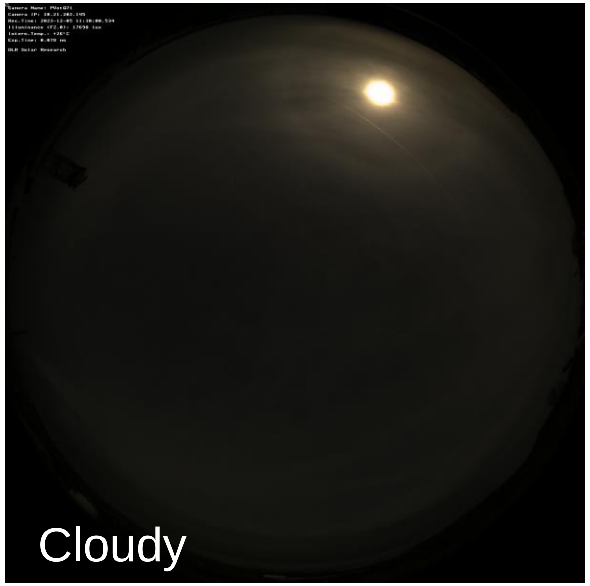


Moon & Sun in summer



Results

Application to different sky conditions



- Dataset classified into sky conditions by manually inspecting daily keograms
- Predicted and observed sun positions compared per subset

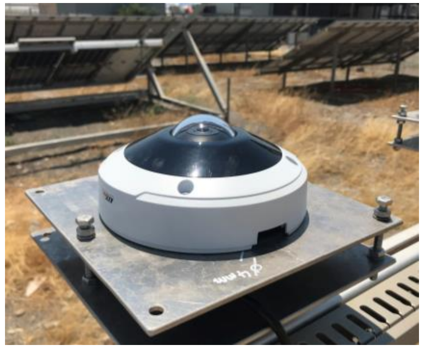
Results
Application to different sky conditions

	#days	#orbs/day	RMSE	Max. MAE in a grid cell
All	363	8.7	0.16°	0.56°
Clear	93	17.1	0.12°	0.59°
Turbid	19	0.6	0.32°	1.05°
Cloudy	85	2.1	0.38°	2.57°

- Filters effectively reject images from turbid or cloudy conditions
- On remaining turbid/ cloudy subsets RMSE increases around x3
- Timestamps from clear conditions will dominate calibration
- Only at extremely cloudy or turbid sites, these conditions will influence the calibration result
  → In these cases pre-filtering with automatic segmentation suggested

Results
Application to different camera hardware

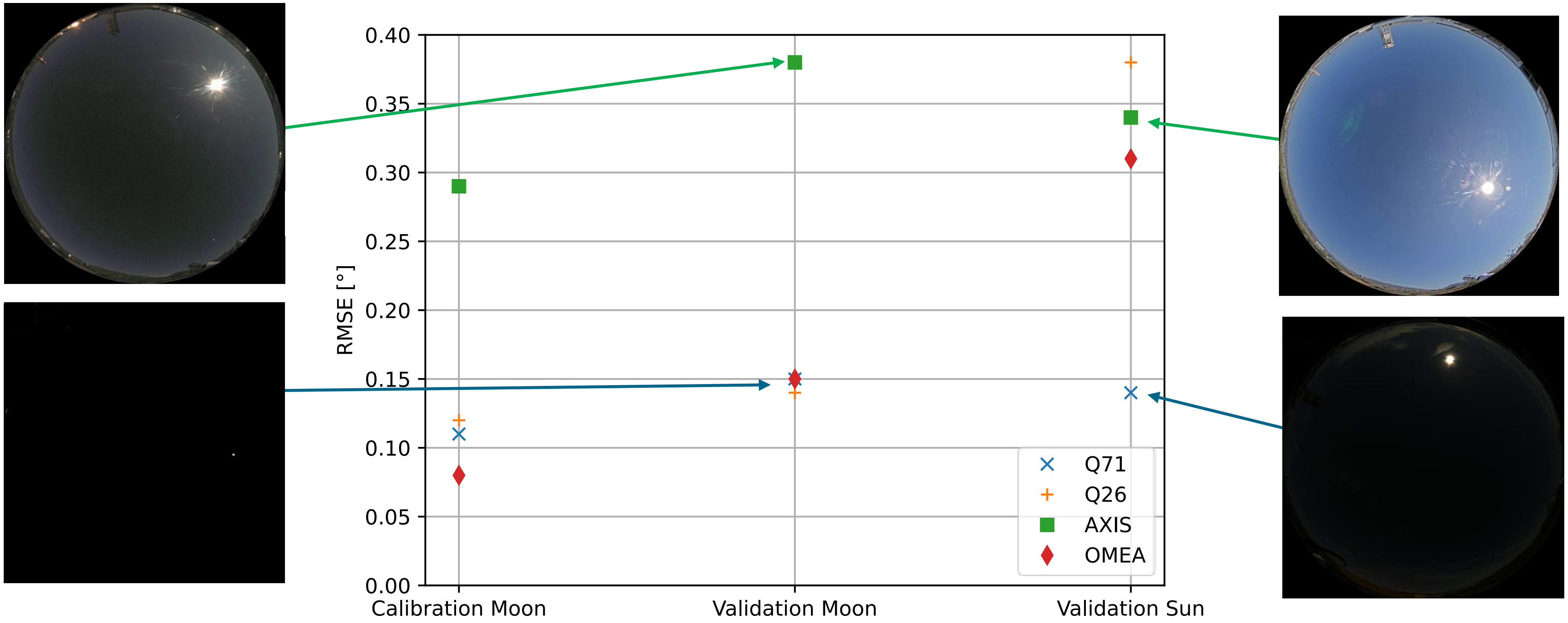
- Calibration applied to image datasets from different camera hardware / models
- Calibrated using moon positions
- Validated on separate period using
  1. Moon positions
  2. Sun positions




Camera	Calibration	Validation
Q26	24.06. – 21.12.2023	24.12.2023 – 20.06.2024
Q71	03.02. – 03.08.2023	07.08.2023 – 02.02.2024
AXIS	22.09.2022 – 21.03.2023	27.03. – 22.09.2023
OMEA	31.12.2023 – 31.03.2024	01.04. – 22.06.2024

Results

Application to different camera hardware



- RMSE < 0.4° for all cameras
- Optical artifacts are the main cause of the calibration‘s deviations
  → protective dome, “high-dynamic-range” 8-bit images disadvantageous
- Under-exposed images beneficial

Conclusion

Thank you for your attention! Questions? Niklas.blum@dlr.de

- New self-calibration method brings practical benefits:
  - Only inputs from regular operation
  - No manual work & planning overhead
  - Retrospectively applicable
  - Compatible with common camera model (Scaramuzza, Euler rotations)
- Accuracy of the method confirmed experimentally:
  - Accuracy equal/higher than state-of-the-art ORION method
  - Calibration feasible with $\leq$ 1 month of images
  - Cloudy/hazy conditions mostly sorted out automatically
  - Works robustly at 2 sites, on 4 camera types,
    - accuracy depends to some degree on image quality of the camera type
- Open-source Python package provided
  - Calibration tool
  - Image transformations etc.
- Datasets from PSA provided

Blum, N., et al. (2025). "Geometric calibration of all-sky cameras using sun and moon positions: A comprehensive analysis." Solar Energy **295: 113476.**

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

https://doi.org/10.1594/PANGAEA.980067

Impressum

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