PYRANOCAM
A NOVEL, ACCURATE AND ROBUST MEASUREMENT SYSTEM OF DNI, DHI AND GHI

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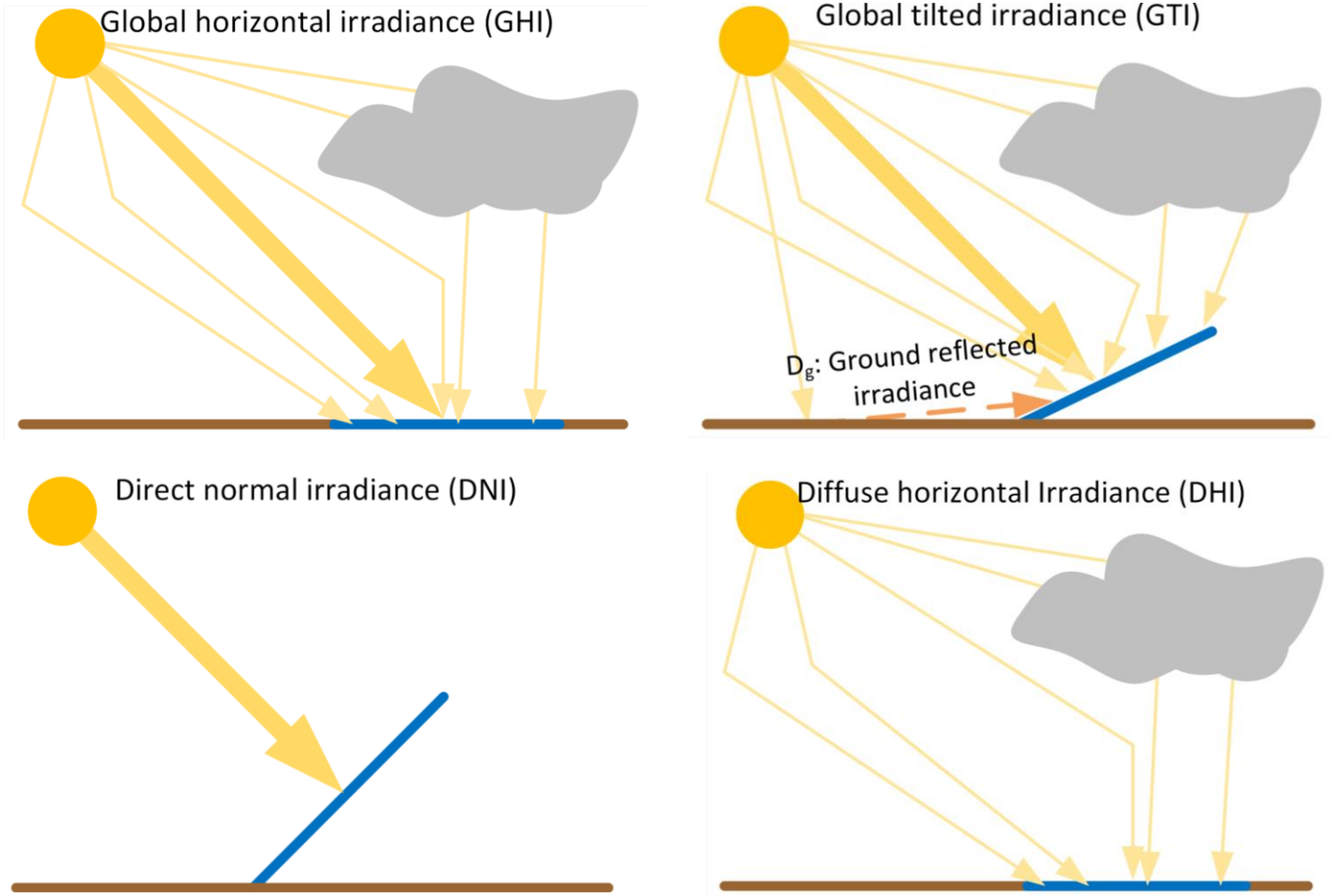
Content

- Introduction – Measurement systems of direct, diffuse and global irradiance
- Working principle of the PyranoCam method
- Worldwide validation
- Conclusion

Irradiance parameters for solar energy applications



On-site DHI measurement recommended for bifacial PV plants [1]

[1] International Electrotechnical Commission (2021). *Photovoltaic System Performance - Part 1: Monitoring* (IEC 61724-1:2021). IEC. iec.ch

Measurement systems of direct and diffuse irradiance

- **Sun tracker**
  - Expensive
  - Prone to failures
  - Permanent data checks
  - High cleaning demand

    → Good reference system if operated properly – otherwise reduced accuracy

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Measurement systems of DNI and DHI

- **Sun tracker**
  - Expensive
  - Prone to failures
  - Permanent data checks
  - High cleaning demand

    → Good reference system if operated properly
    – otherwise reduced accuracy

  - **Simpler sensors**
    - Intend to avoid the above shortcomings

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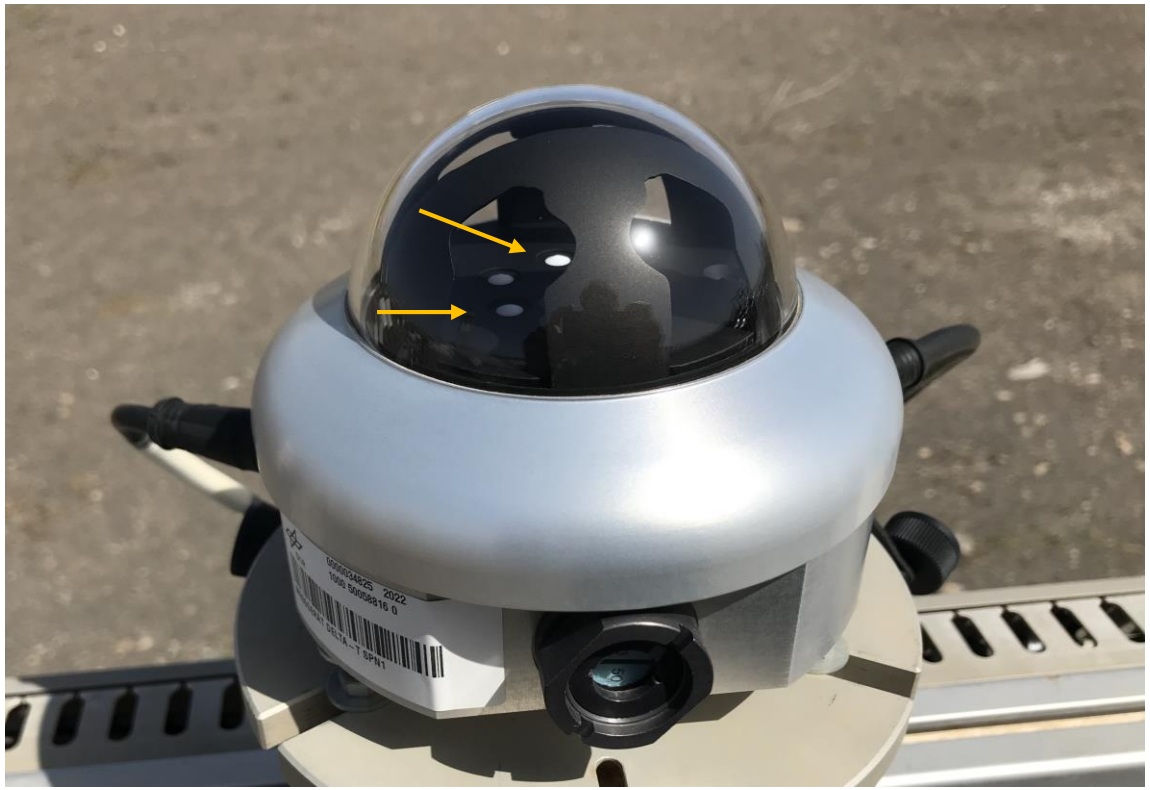
Simple measurement systems of DNI, DHI

Delta-T SPN1



- 7 thermopile pyranometers
- Special shading mask
- Calculates GHI, DHI, DNI from pyranometer readings

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Simple measurement systems of DNI, DHI

Rotating Shadowband Irradiometer (RSI)

- Fast-response photodiode pyranometer
- Rotating shadow band
- GHI, DHI measured
- DNI calculated

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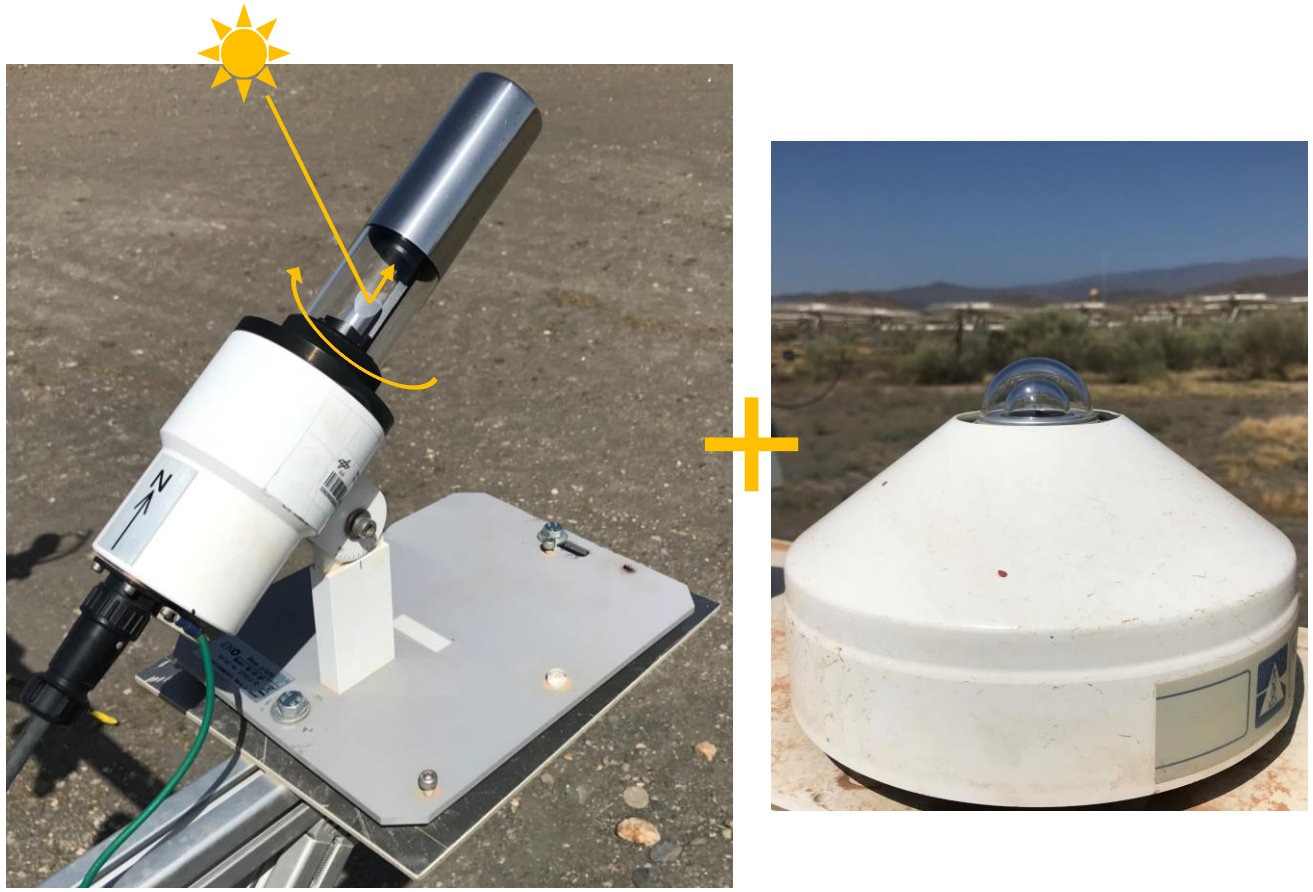
Simple measurement systems of DNI, DHI

EKO MS-90



- Special rotating mirror
- Pyroelectric sensor
- measures DNI, thermopile pyranometer for GHI
- DHI calculated

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Simple measurement systems of DNI, DHI
PyranoCam (own development [2,3])

Thermopile pyranometer → GHI

Sky imager

Combined evaluation

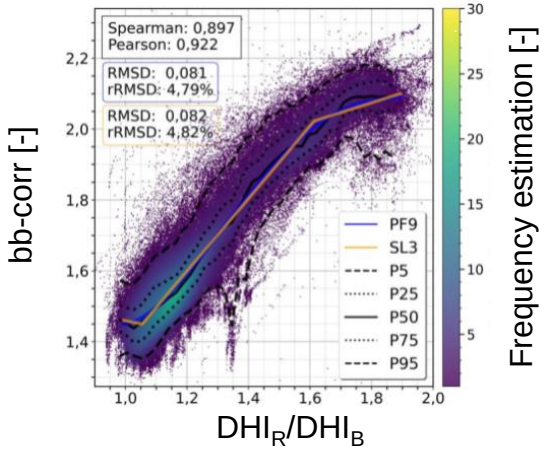
[2] Blum, N., et al. (2022). "Measurement of diffuse and plane of array irradiance by a combination of a pyranometer and an all-sky imager." Solar Energy 232: 232-247.

[3] Blum, N. et al. (2024). “Bewertung von Messsystemen der Direkt- und Diffusstrahlung unter unterschiedlichen Klimabedingungen”. PV-Symposium, 27-29.02.2024, Bad Staffelstein.

PyranoCam
Working principle – physical component

Camera model relates R,G,B intensities to radiance

- Contribution of infrared irradiance to DHI depends on atmospheric conditions (situation)
- Indicators for bb-corr investigated via spectroradiometer data [4]
  → DHI_R/DHI_B strong indicator of bb-corr
  → Piece-wise linear fit



R,G,B intensity
Linearization
Weighted sum based on white balancing
Apply radiometric calibration factor
Visible-range Radiance
Mask out sun disk and pixels below horizontal plane
Weighted sum based on projection into horizontal plane
Visible-range DHI
Situationally-dependent Broadband correction (bb-corr)
Raw broadband DHI

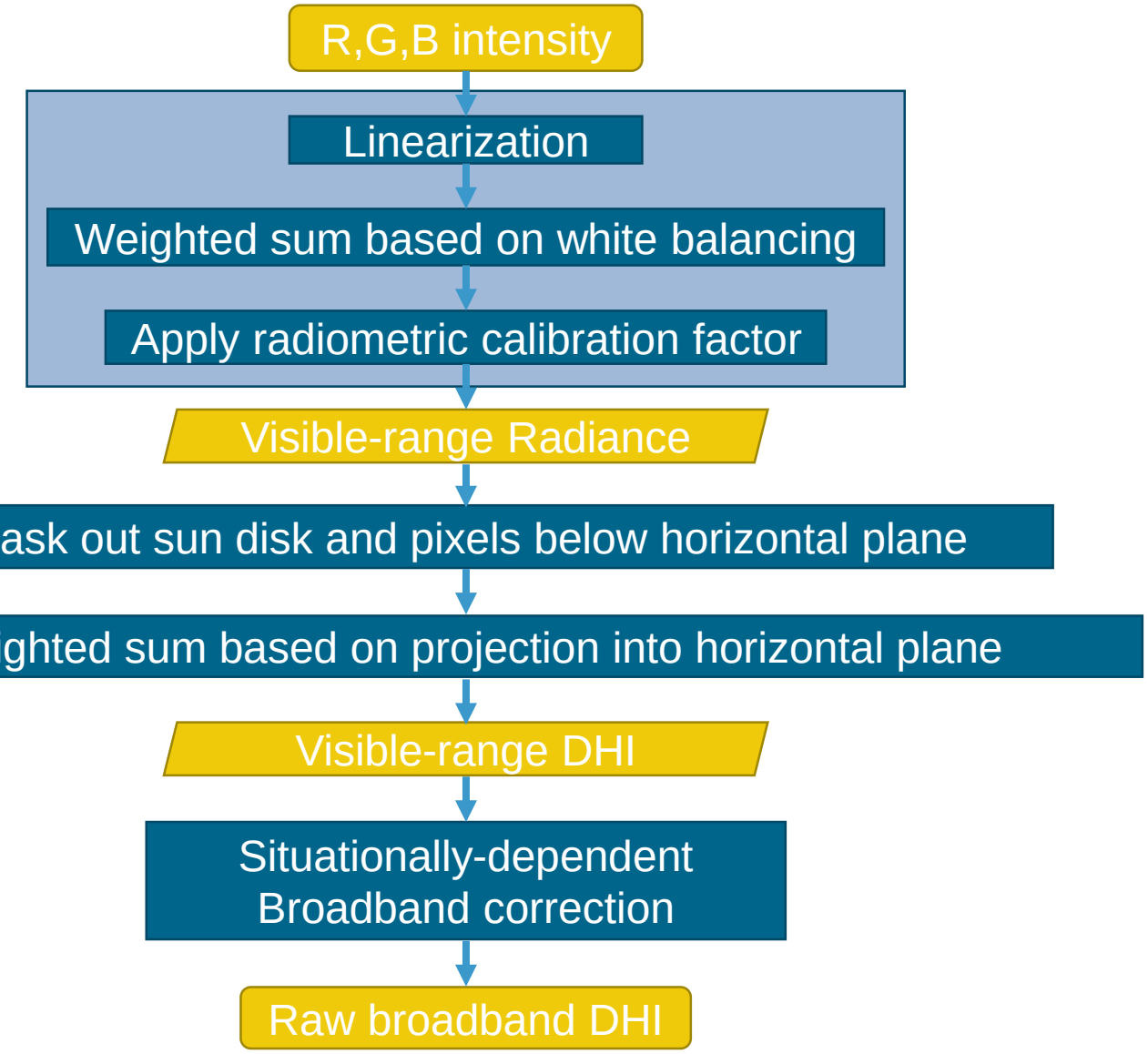
[4] Matteschk, P. (2024). Physikalische Weiterentwicklung einer Wolkenkamera-basierten Messmethode für Diffusstrahlung. Diplomarbeit, Technische Universität Dresden.

PyranoCam
Working principle – physical component

Calibrations required!

Radiometric

Geometric



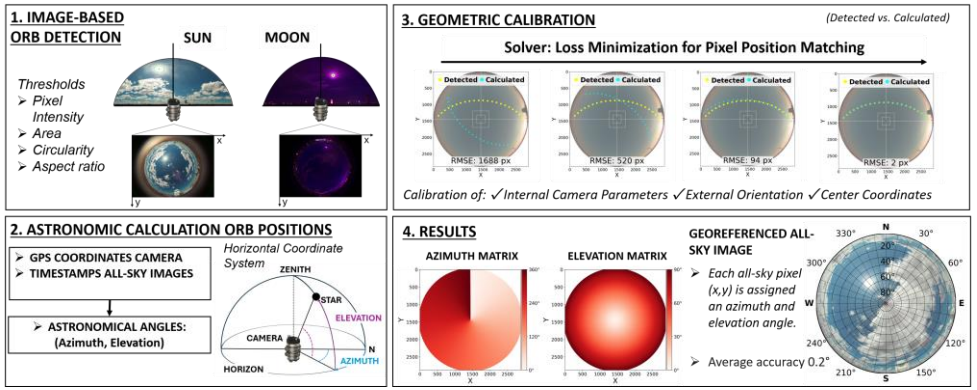
PyranoCam
Working principle – self calibrations

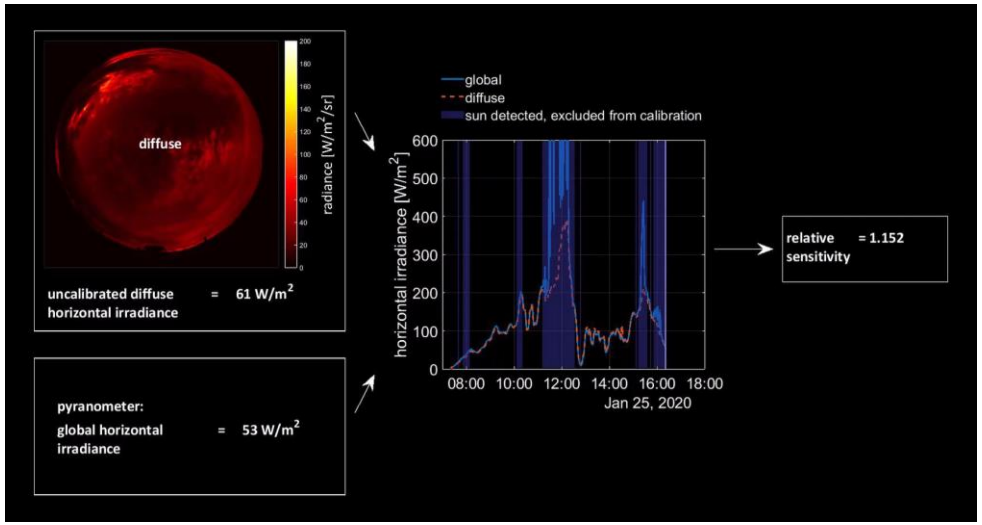
Calibrations realized as self calibrations:

- Geometric
  - see presentation of Yann Fabel yesterday
  - Only based on Sun or preferably Moon positions
  - All intrinsic camera parameters (lens distortion) and external orientation determined

- Radiometric
  - In situations without direct irradiance, we should have GHI = DHI
    - → ASI detects such situations reliably
    - → Sun disk not visible
  - PyranoCam‘s pyranometer provides GHI

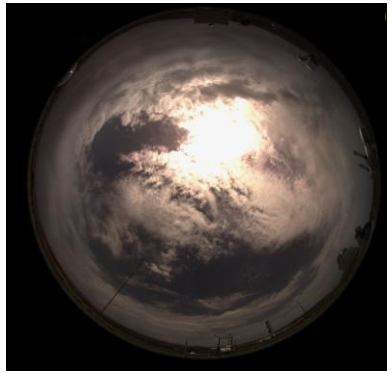
Blum et al. (under review)



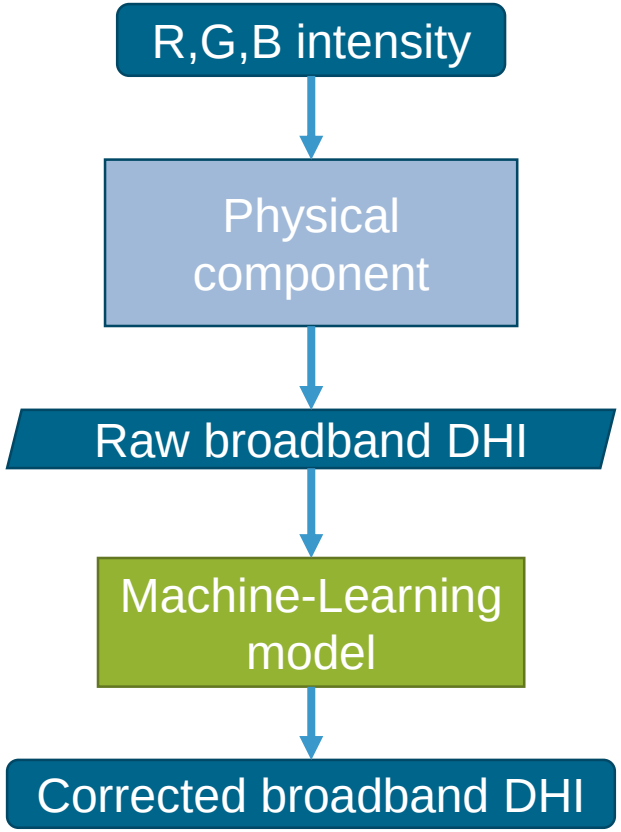


PyranoCam
Working principle – Machine-Learning correction

- Camera-based irradiance measurement exhibits disturbances, in particular in “circumsolar” region:
  - Image saturation
  - Glare effects



- **Machine learning model** trained to correct for these [5]



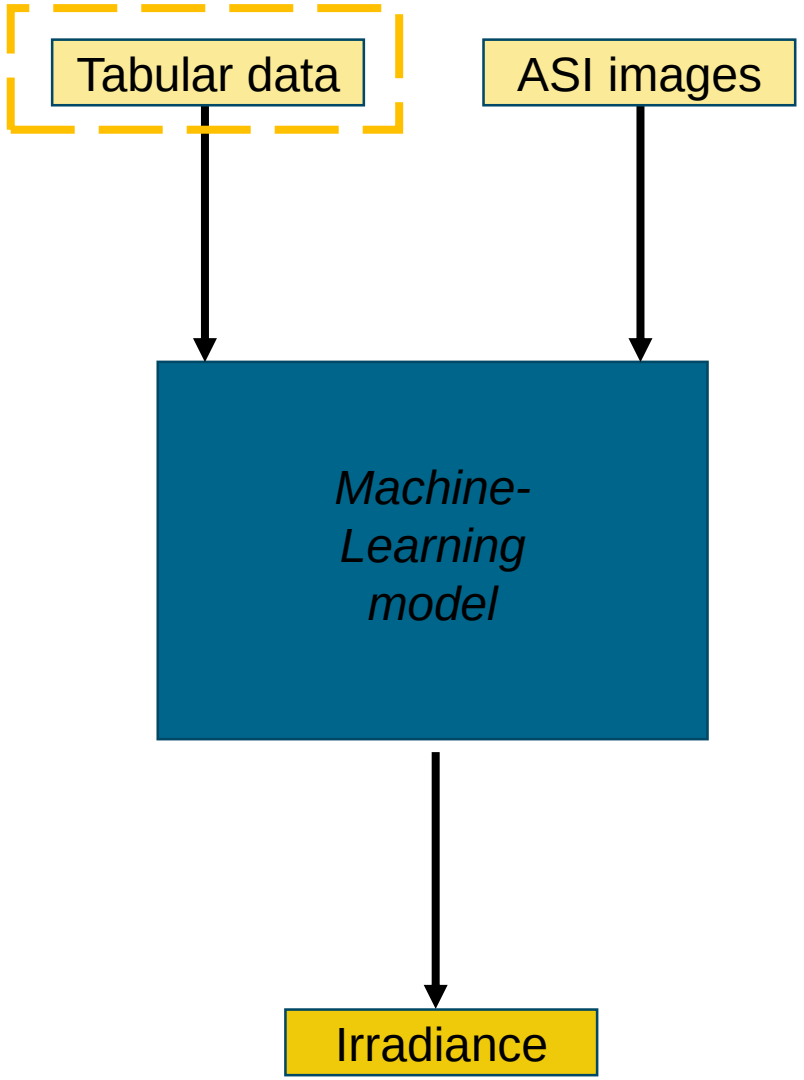
[5] Broda, R. (2022). Development of A Machine-Learning-Based Correction for Cloud-Camera-Based Solar Radiation Measurement. Masterarbeit, RWTH Aachen.

Images taken at PSA. The research site Plataforma Solar de Almería (PSA) is owned and operated by the Spanish CIEMAT

PyranoCam
Working principle – Machine-Learning correction

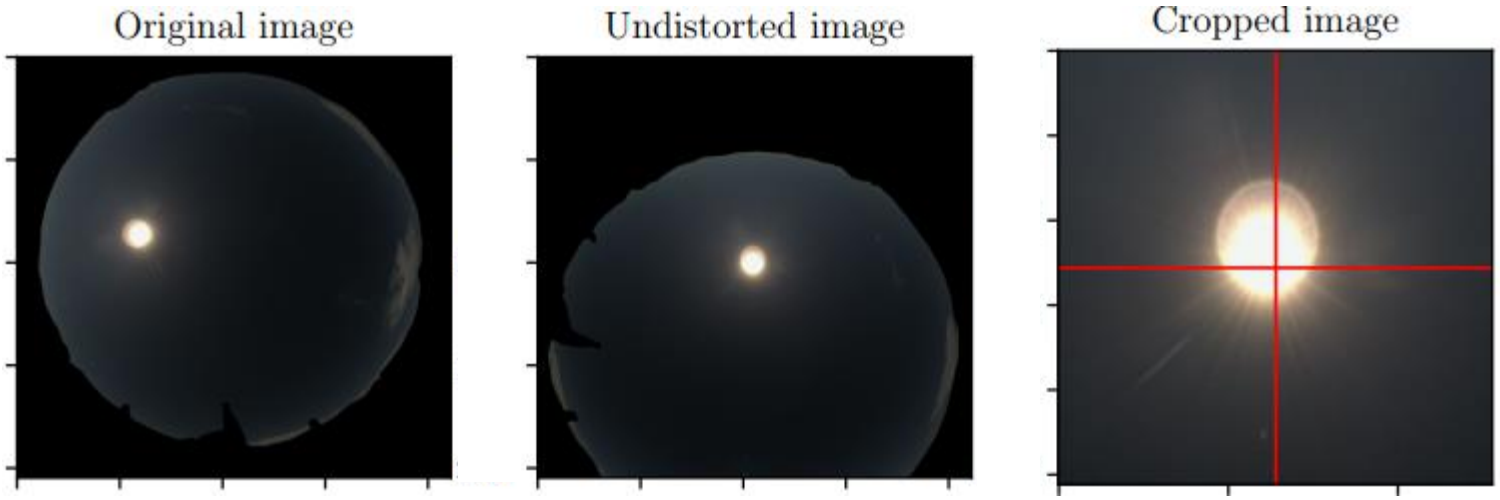
- Tabular data
  - Features were identified/ designed which indicate disturbances:

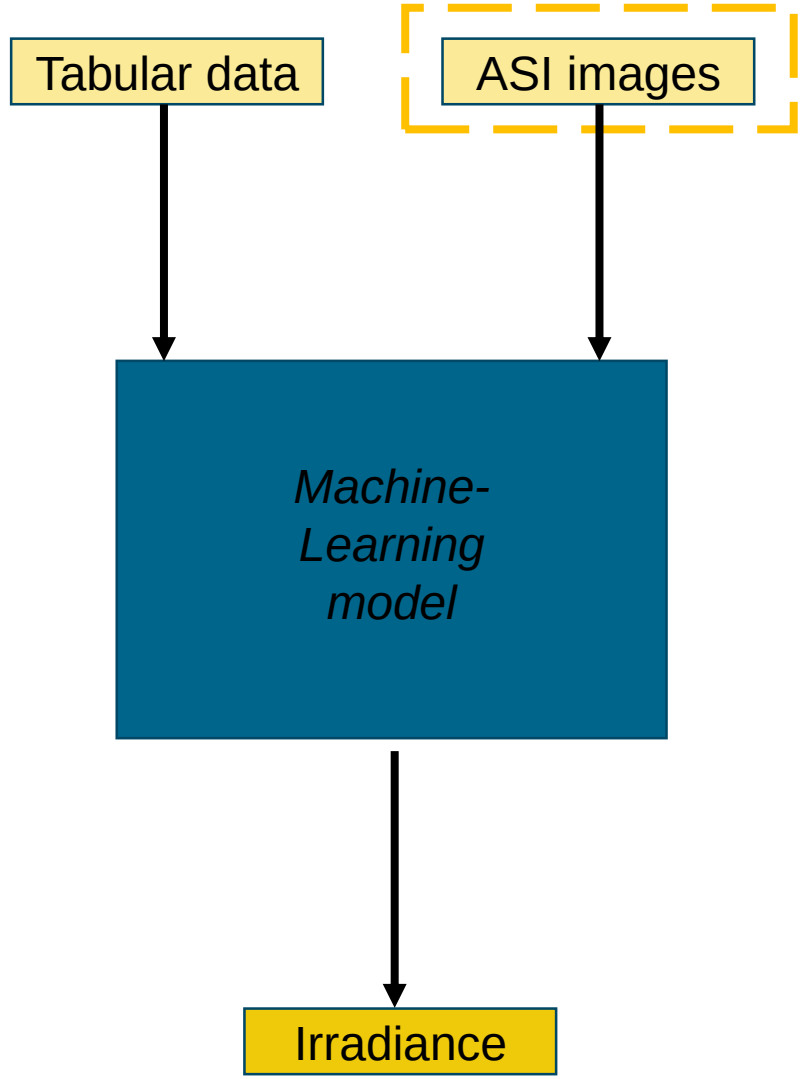
Variable	Explanation
GHI	From Pyranometer
Raw DHI	--
Raw DNI	From raw DHI and GHI
DHI_cs25	Contribution circumsolar irradiance to DHI
DHI_horizon	Contribution of horizon brightening to DHI
DHI_iso	“isotropic” contribution to DHI
Illuminance_R	Illuminance calculated from R channel
Illuminance_G	Illuminance calculated from G channel
Illuminance_B	Illuminance calculated from B channel
#saturated pixels	Number saturated pixels in ASI image
Sun elevation	Sun elevation angle



PyranoCam
Working principle – Machine-Learning correction

- ASI images
  - Transformed and cropped dynamically to show the “circumsolar” region
    - 25° around sun under clear conditions
    - Larger area e.g. if very turbid





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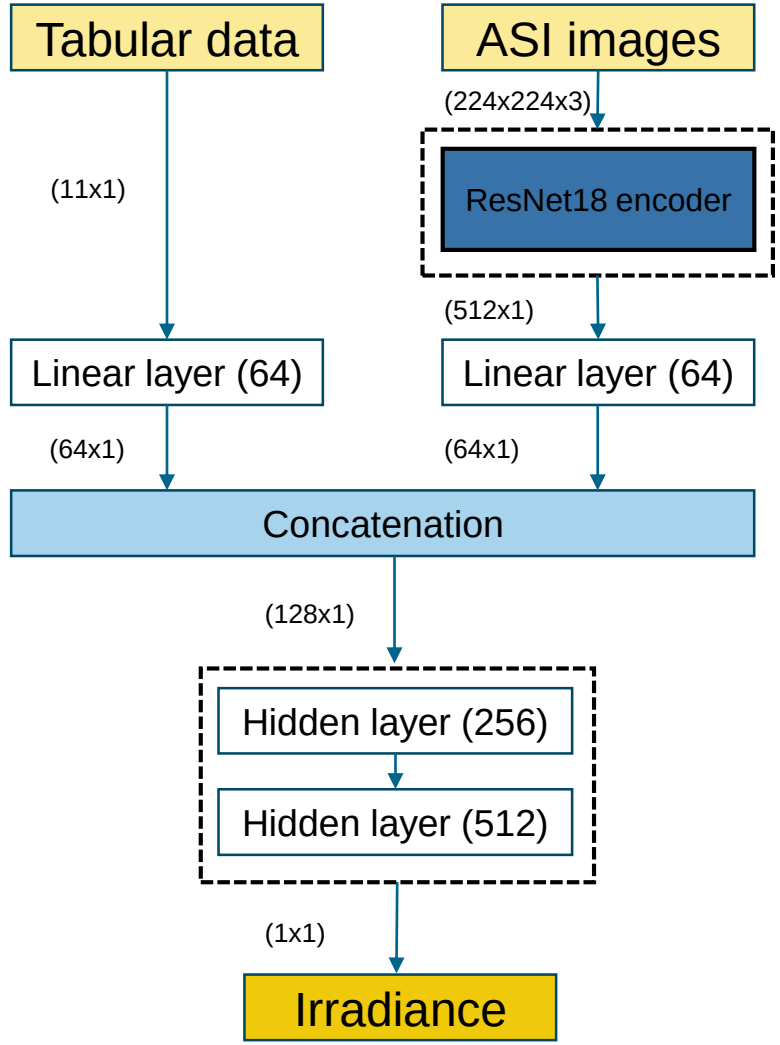
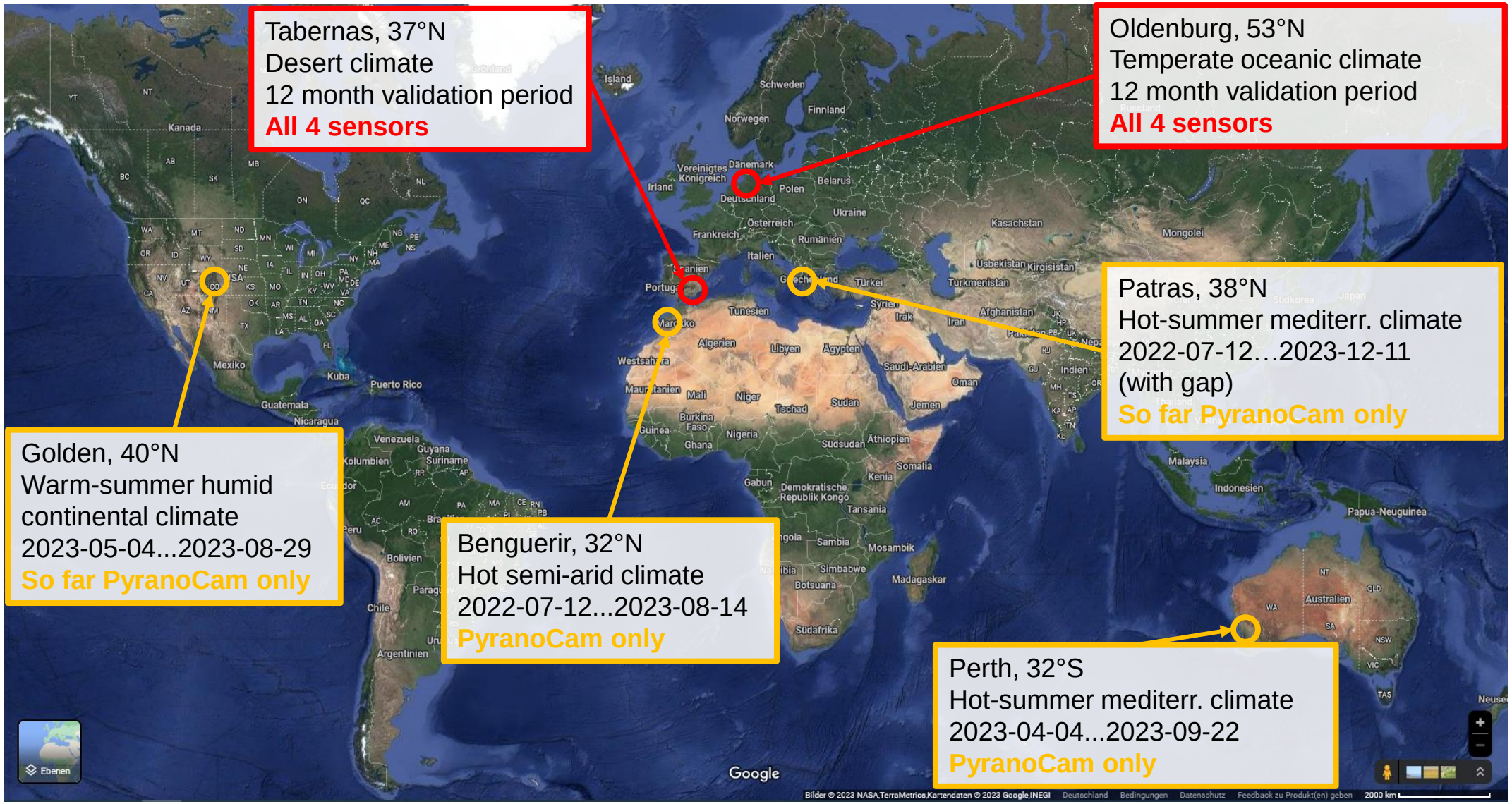
PyranoCam
Working principle – Machine-Learning correction

- CNN encodes ASI image information
- Fully connected layers perform regression task
- Suited self-supervised pre-training
- Model architecture and hyperparameters tuned for highest performance
- Training with data from 2 sites (Tabernas, Oldenburg)

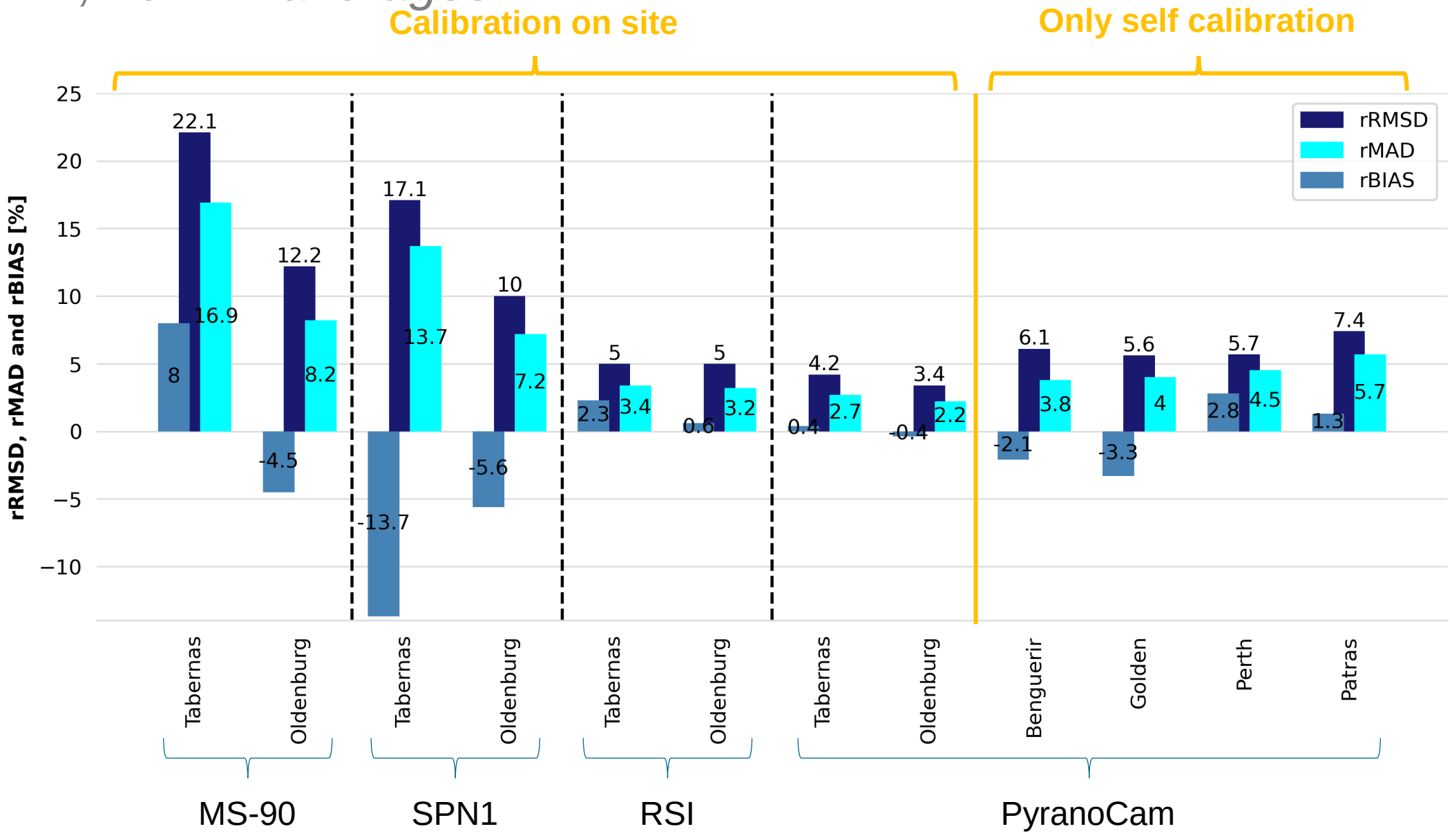


Setup of the validation and benchmark campaign
Validation at 6 sites, 4 continents



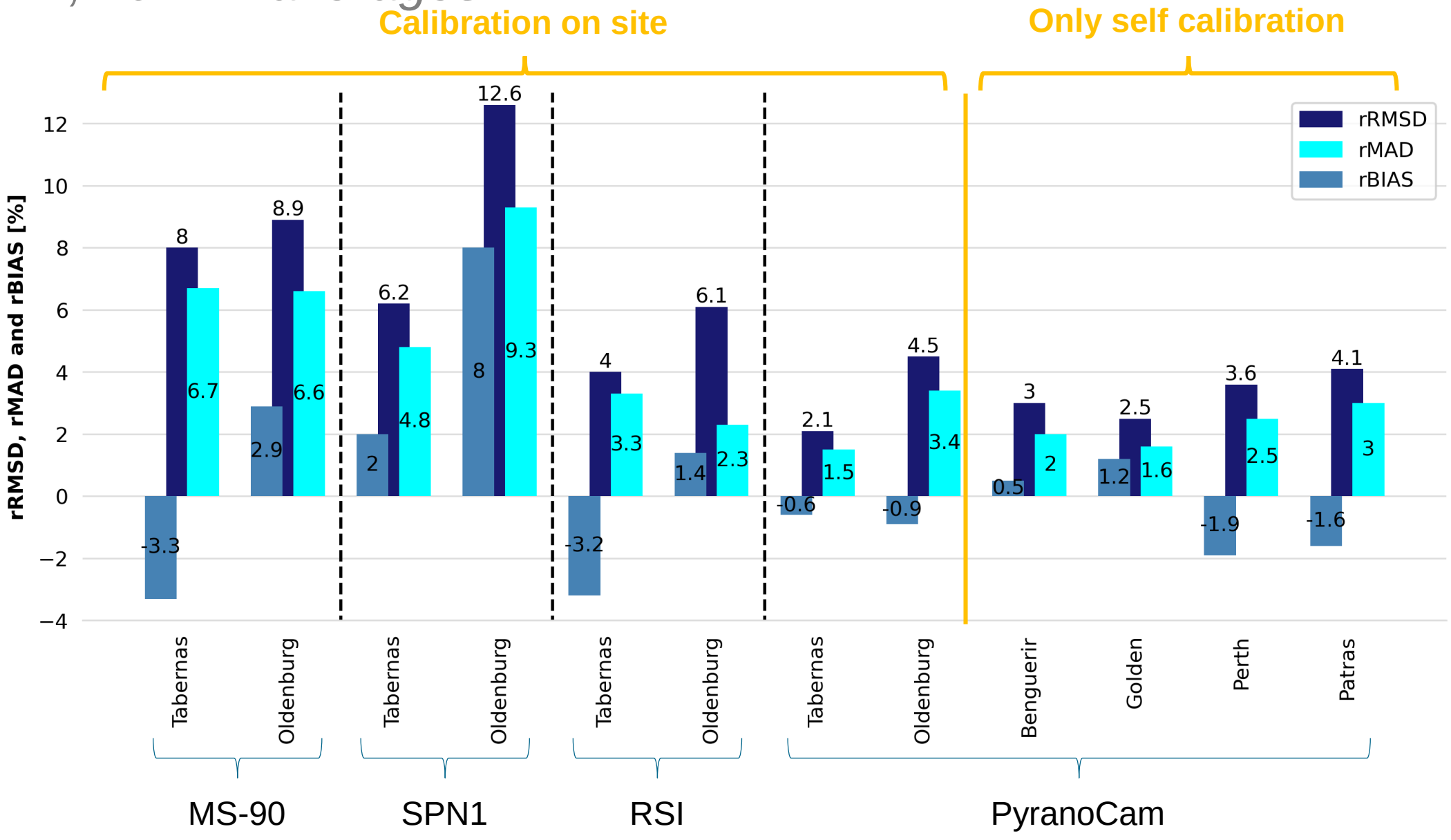
Experimental comparison of sensor accuracies

DHI, 10-min averages



Experimental comparison of sensor accuracies

DNI, 10-min averages



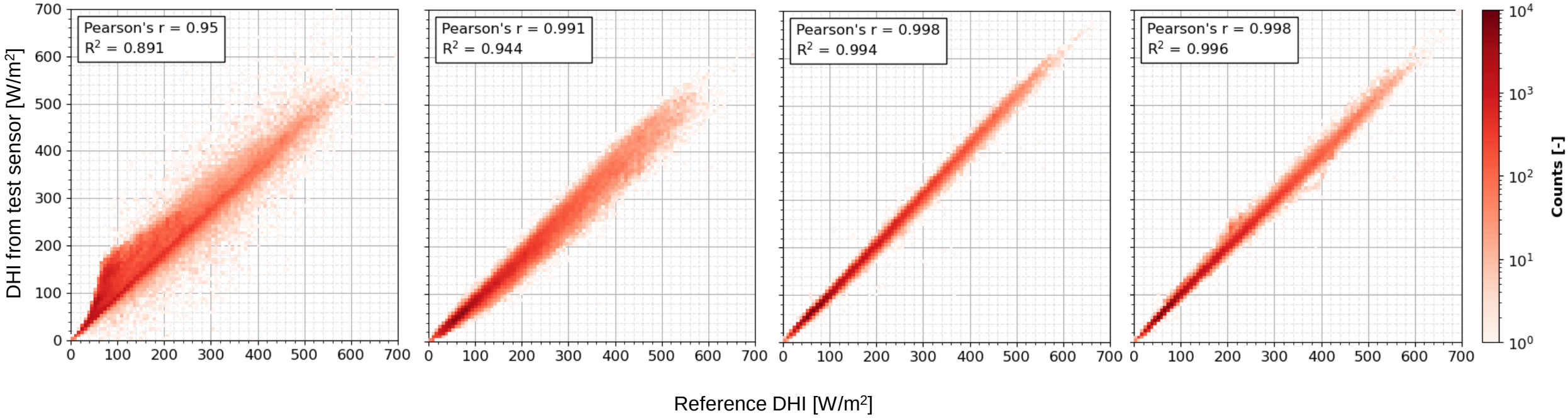
Experimental comparison of sensor accuracies

MS-90

SPN1

RSI

PyranoCam

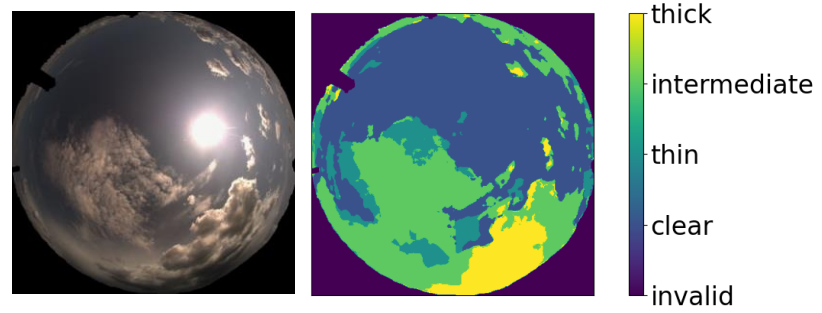


Reduced scattering
Higher correlation with reference

Images partly taken at PSA. The research site Plataforma Solar de Almería (PSA) is owned and operated by the Spanish CIEMAT

Influences on the accuracies of simple sensors

- Linke turbidity
- Sun elevation & azimuth angle
- Reference DNI & DHI
- Hourly average Clear-Sky-Index
- Cloud cover per cloud class and sky part
- Spectral composition of GHI, DHI, DNI
- Circumsolar irradiance



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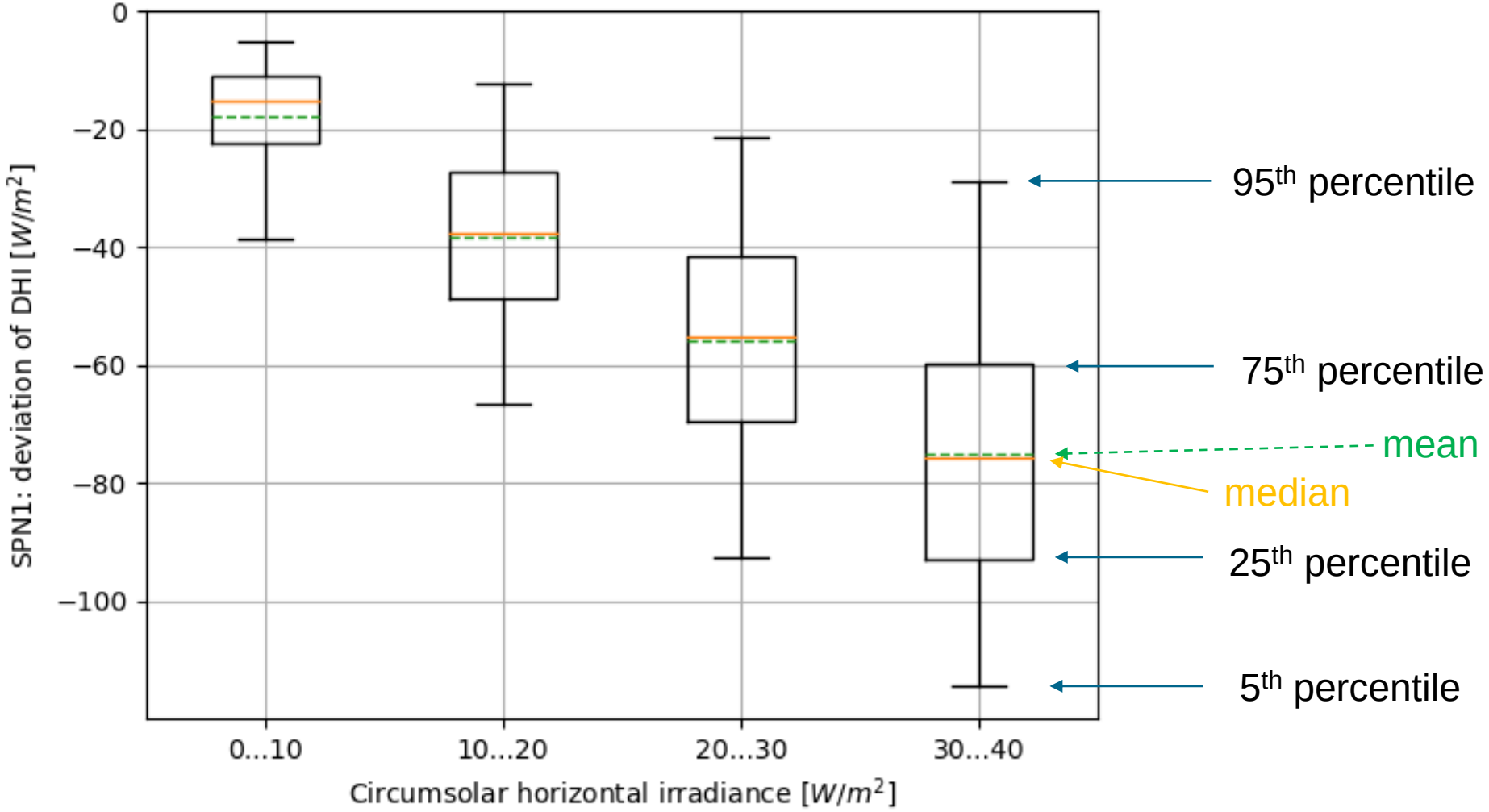
Influences on the accuracies of simple sensors
SPN-1

Largest influence on SPN1's DHI measurement – circumsolar irradiance
(sun distance angle 2.5°…5°, ρ=-0.63)



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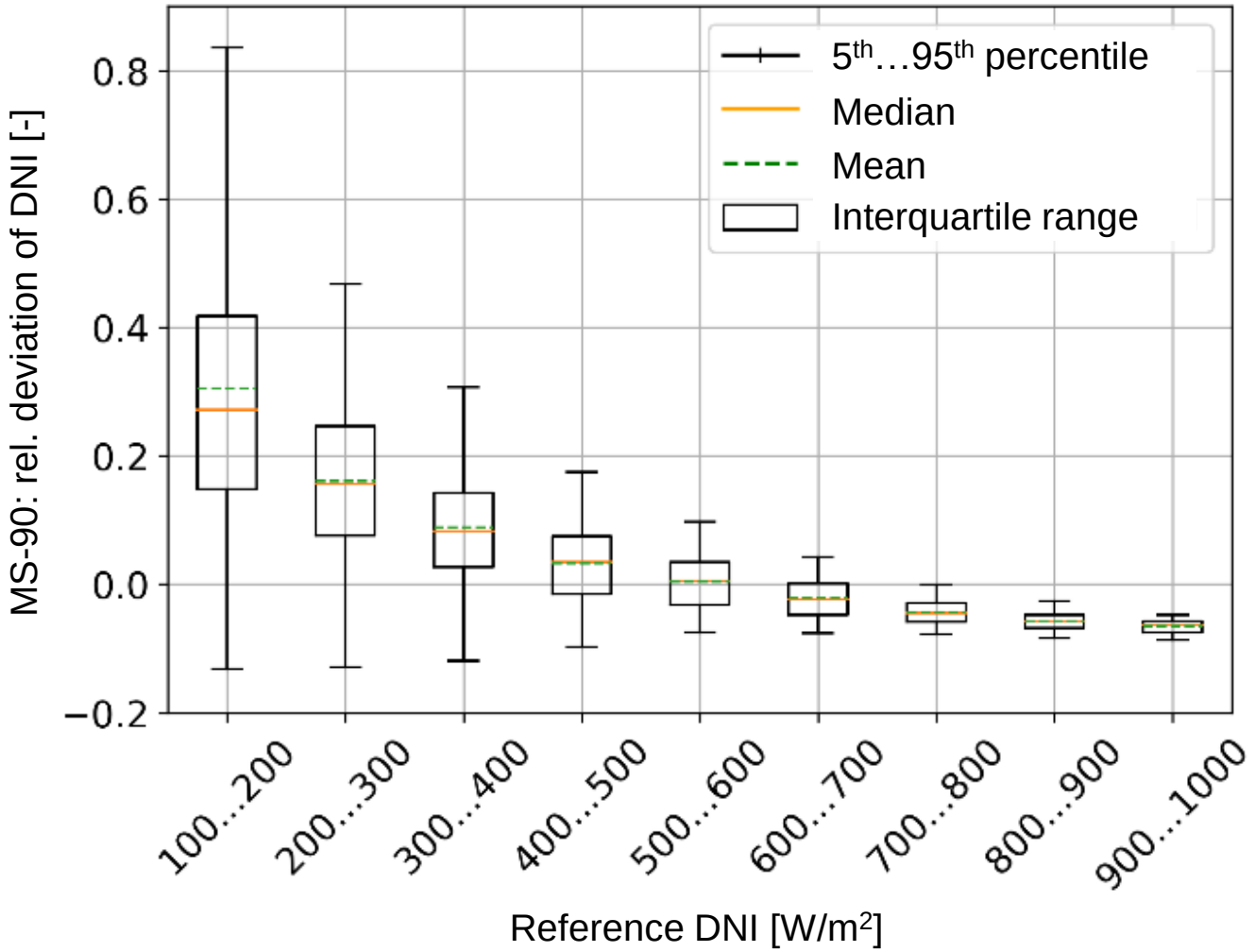
Influences on the accuracies of simple sensors
MS-90

Largest influence on MS-90's DNI measurement – reference DNI (ρ=0.73)



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Influences on the accuracies of simple sensors
RSI & PyranoCam

- Rather small influences on DHI measurement:
  - RSI: Reference DHI largest influence (ρ=0.42)
  - PyranoCam: Reference DNI largest influence (ρ=0.41)

- RSI: calibrated in Tabernas, corrections developed with data from Tabernas

- PyranoCam developed with data from Tabernas, Oldenburg
  → Accuracy confirmed at other sites

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Conclusion (sensor comparison)

- Sensor comparison shows that PyranoCam‘s accuracy very competitive with other simple sensors.
- E.g. PyranoCam‘s rRMSD is slightly smaller than the one of the RSI and much smaller than the one of SPN-1 and MS-90 (Comparison of the sites of Tabernas and Oldenburg):

	DHI	DNI
PyranoCam	3-4%	2-5%
RSI	5%	4-6%
SPN-1	10-17%	6-13%
MS-90	12-22%	8-9%

- Accuracies of SPN-1, MS-90 depend strongly on conditions on site
- RSI and PyranoCam high accuracy under all conditions
- PyranoCam‘s high accuracy confirmed at all 6 sites

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Conclusion (PyranoCam)

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

- PyranoCam combines a number of advantageous features
  - Geometric, radiometric self-calibration
  - Dedicated broadband correction enabled by trichromatic (R, B) information
  - Corrections using combination of ASI and pyranometer
  - GTI provided also
  - Provides input data (GHI, DHI, DNI) for nowcasting with basic hardware

Outlook

- There is potential for further improvement of PyranoCam
  - High dynamic range images will reduce disturbances connected to glare effects and image saturation
  - Training data from >2 sites available and will further increase generalization
- Sensor benchmark being extended for further use cases

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