A BENCHMARK OF SIMPLE MEASUREMENT SYSTEMS FOR DIRECT IRRADIANCE

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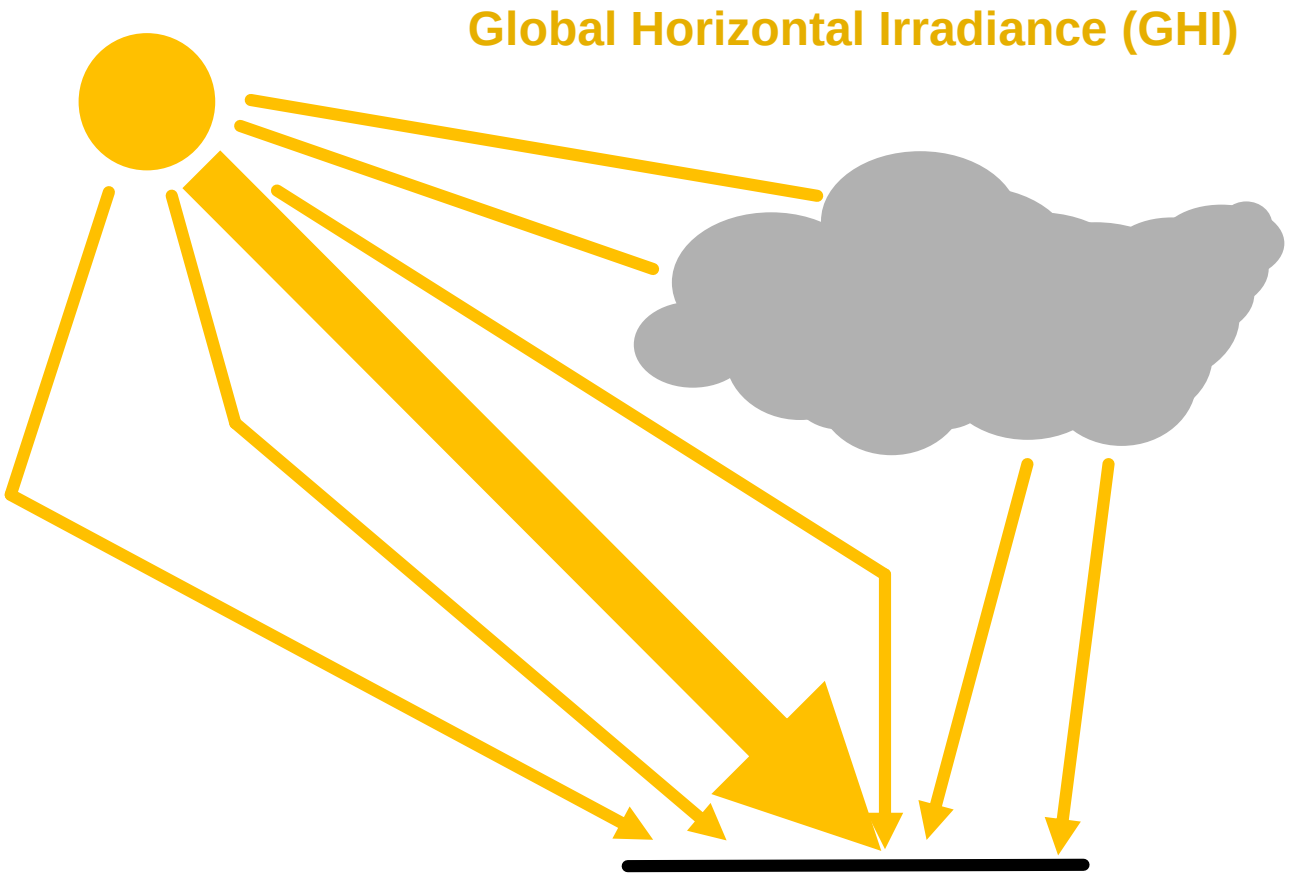
8 EKO Instruments Europe, Middle East, Africa, South America
9 CIEMAT Energy Department, Renewable Energy Division

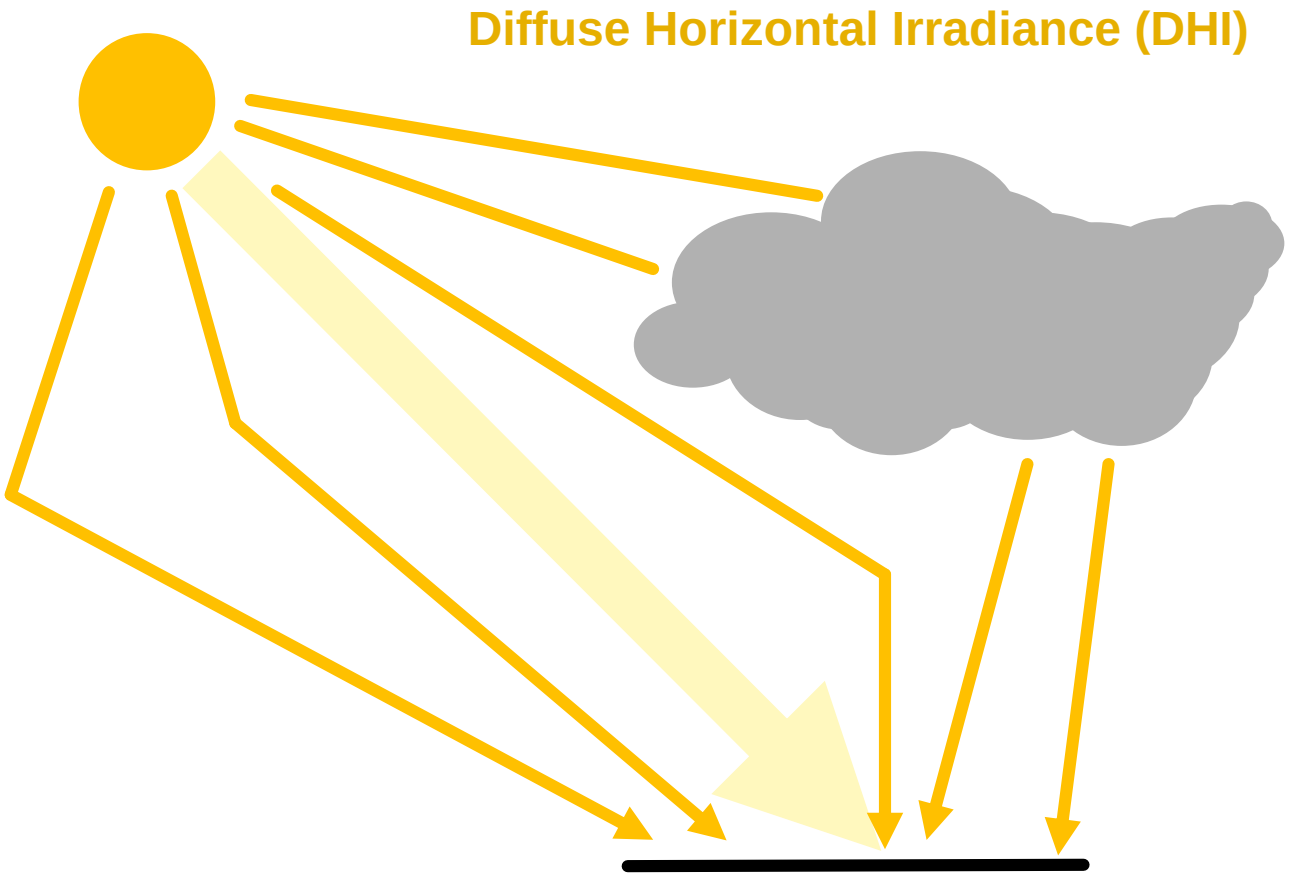
Outline

- Motivation: Overview of options to determine direct irradiance
- Are some sensors more accurate than others?
- Which sensor is suited for a given application / site?

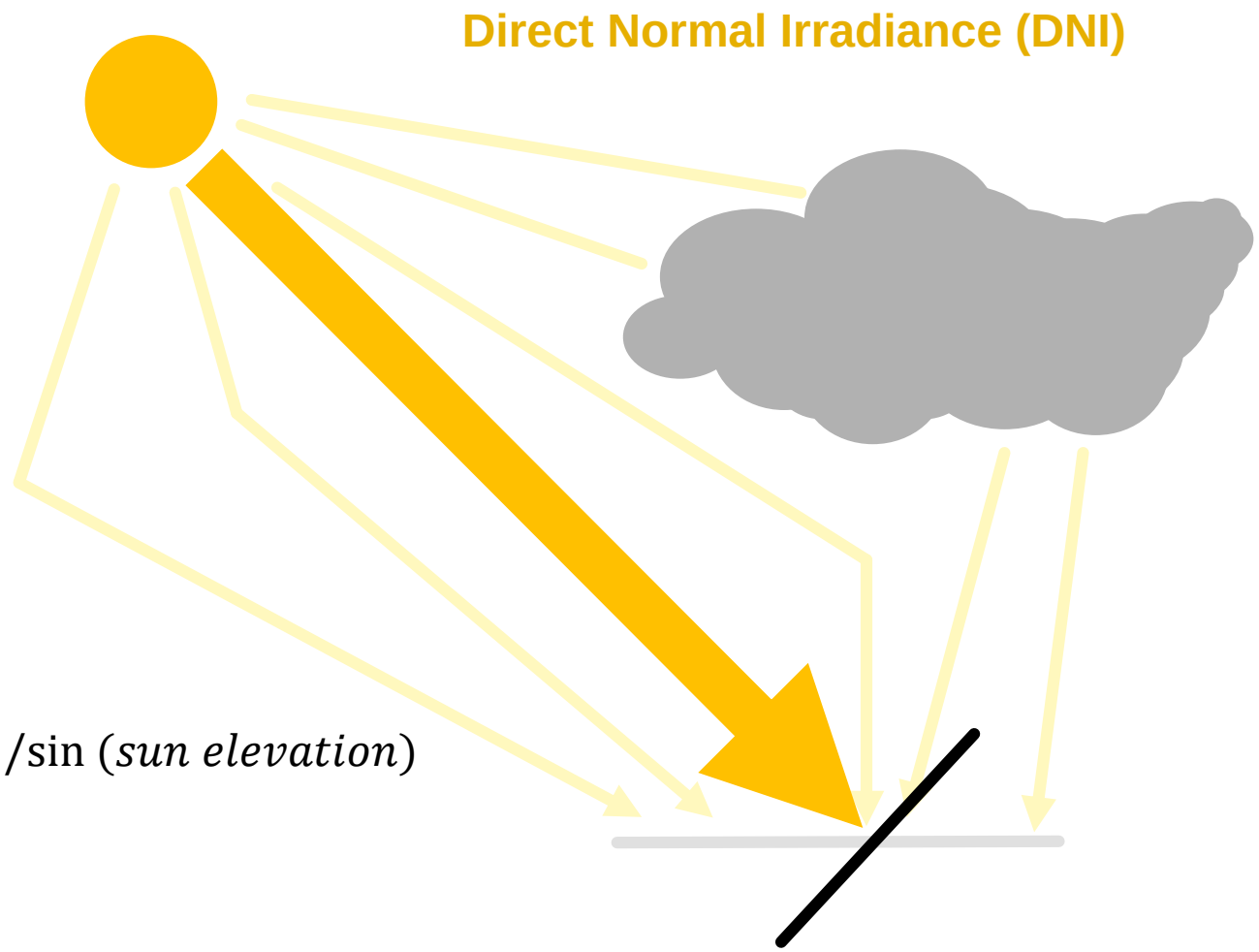
Irradiance parameters for solar applications



Irradiance parameters for solar applications



Irradiance parameters for solar applications



$$DNI = (GHI - DHI)/\sin(sun\ elevation)$$

What options do we have to determine DNI?

- Remotely-sensed

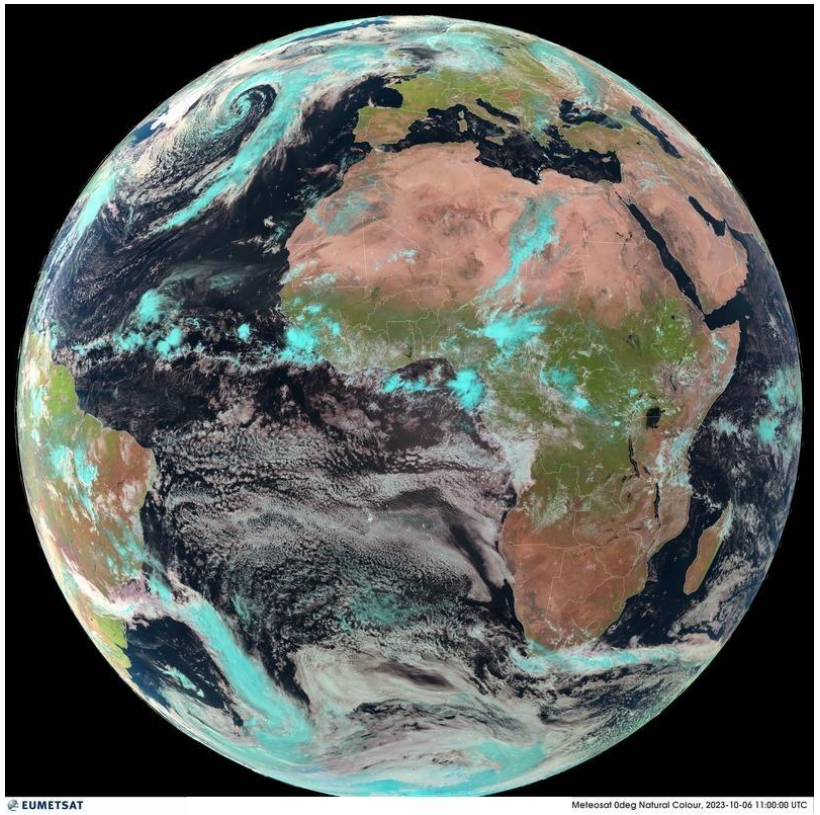


image credit: ©EUMETSAT 2023

Example image of Meteosat Second Generation

What options do we have to determine DNI?

- Remotely-sensed
- Estimated from GHI by decomposition

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

What options do we have to determine DNI?

- Remotely-sensed
- Estimated from GHI by decomposition

  Often too inaccurate, in particular for high-resolution real-time data e.g. to control power plant

- Measurement on-site

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What options do we have to determine DNI?

- Remotely-sensed
- Estimated from global irradiance (decomposition)
- **Measurement on-site**
  - 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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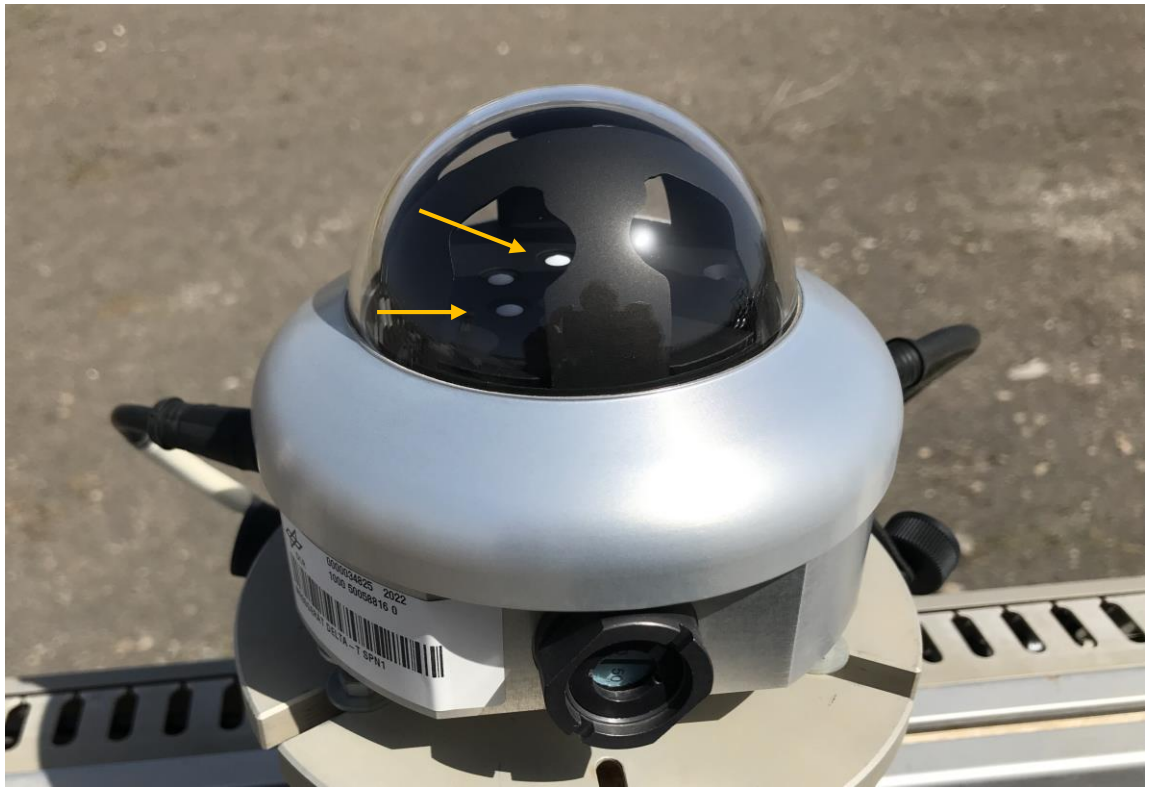
  - **Simpler sensors**
    - Intend to avoid the above shortcomings

Simple sensors for DNI

Delta-T SPN1



- 7 thermopile pyranometers
- Special shading mask obscures 50% of sky for each pyranometer
- Always ≥1 pyranometer shaded & ≥1 unshaded
- Determines GHI, DHI → calculates DNI

Simple sensors for DNI

Rotating Shadowband Pyranometer (RSP)

- Fast-response photodiode pyranometer
- Shadowband
- When pyranometer unshaded: GHI; shaded: DHI
- DNI calculated

Simple sensors for DNI

EKO MS-90

- Special rotating mirror
- Pyroelectric sensor
- Measures DNI

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Simple sensors for DNI

Sunto CaptPro

- 11 R,G,B,IR photodiodes measure GHI and global tilted irradiance in 10 planes
- Proprietary algorithm → DNI, DHI

Simple sensors for DNI

PyranoCam
(own development
[2,3])

[2] Blum, N. B., 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.

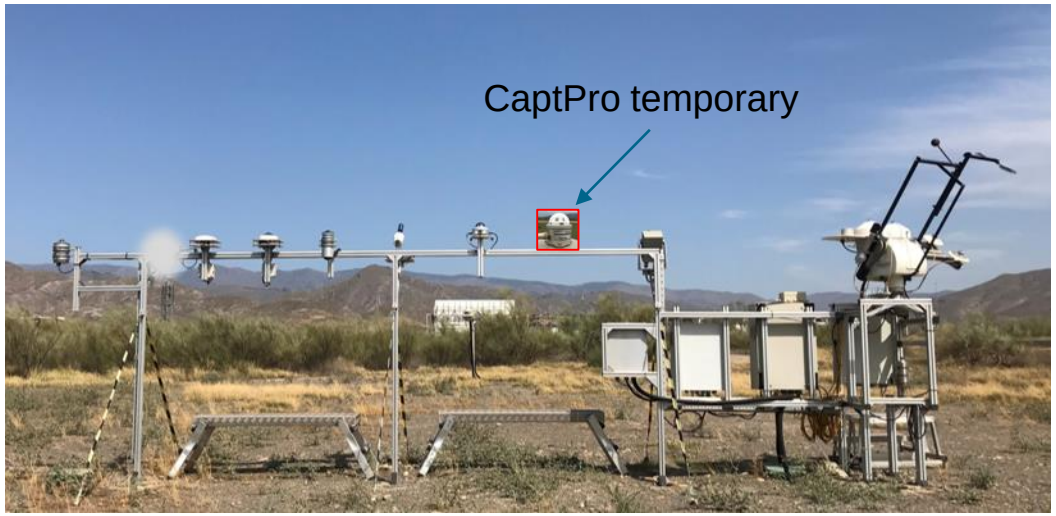
[3] Broda, R. (2022) Development of A Machine-Learning-Based Correction for Cloud-Camera-Based Solar Radiation Measurement. Master thesis, RWTH Aachen.

- Pyranometer → GHI
- All-Sky Imager sky radiance → raw DHI
- Corrections by combination → more accurate DHI
- DNI calculated

Benchmark setup

*The research site Plataforma Solar de Almería is owned and operated by the Spanish CIEMAT

- Tabernas*, southern Spain (37°N)
- Cold-desert climate
- 12 months measurements
- Mean irradiances over dataset:
  - 456 W/m² (GHI)
  - 541 W/m² (DNI)
  - 144 W/m² (DHI)



- Oldenburg, northern Germany (53°N)
- Temperate oceanic climate
- 12 months measurements
- Mean irradiances over dataset:
  - 279 W/m² (GHI)
  - 269 W/m² (DNI)
  - 135 W/m² (DHI)

In the images some sensors masked to comply with NDAs

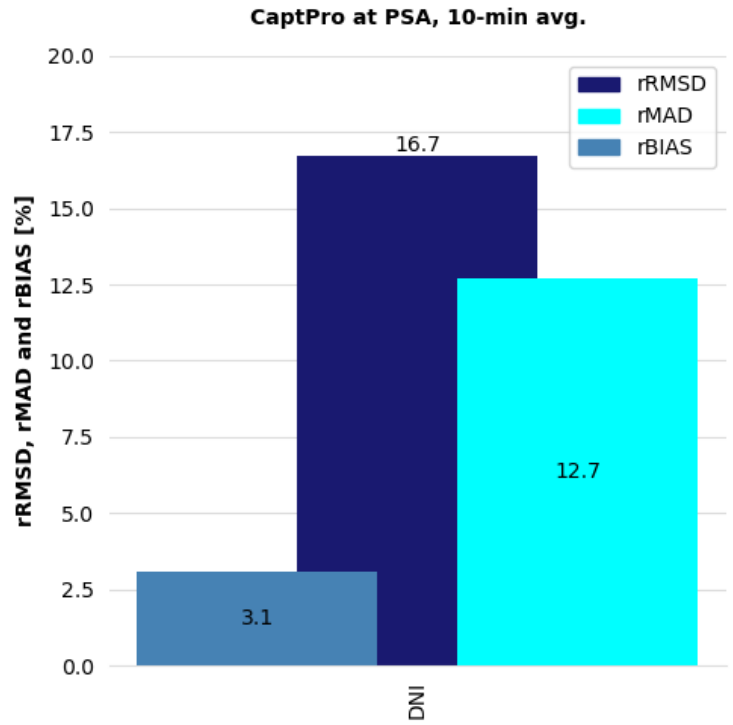
Are some sensors more accurate than others?
Sunto CaptPro

- Sensor broke after 4th month of the benchmark in Tabernas
- Repair attempt by manufacturer failed

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

Are some sensors more accurate than others?
Sunto CaptPro

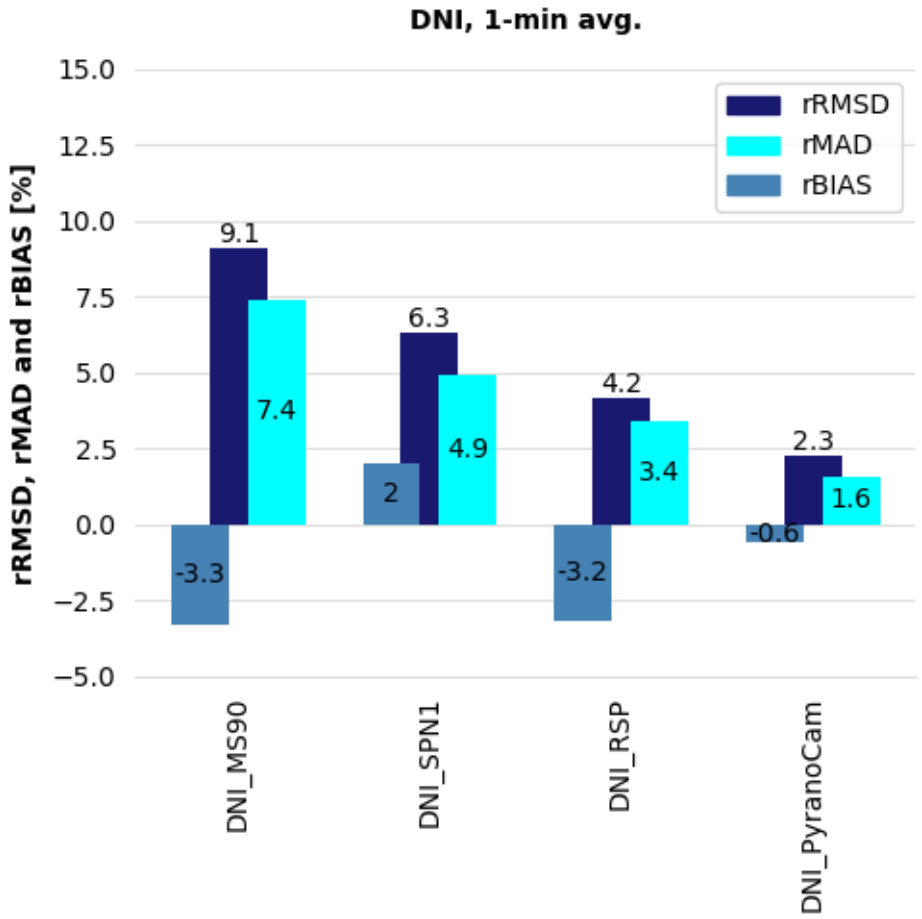
- Limited database of 4 months from Tabernas
- Overall accuracy unsatisfactory
- Maybe useful if global tilted irradiance with spectral correction for PV required



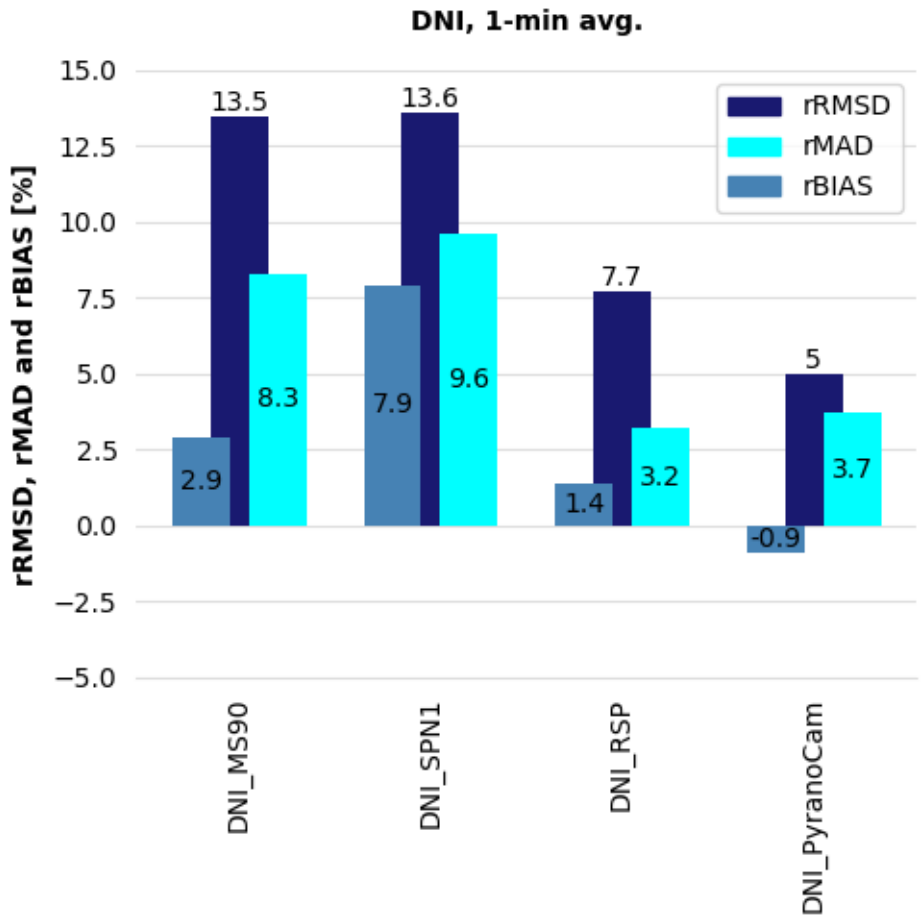
$$rRMSD = \frac{100\%}{\overline{ref}}\sqrt{\overline{(test - ref)^2}} \qquad rMAD = \frac{100\%}{\overline{ref}}\overline{|test - ref|} \qquad rBIAS = \frac{100\%}{\overline{ref}}\overline{test - ref}$$

Are some sensors more accurate than others?

Evaluation in Tabernas



Evaluation in Oldenburg



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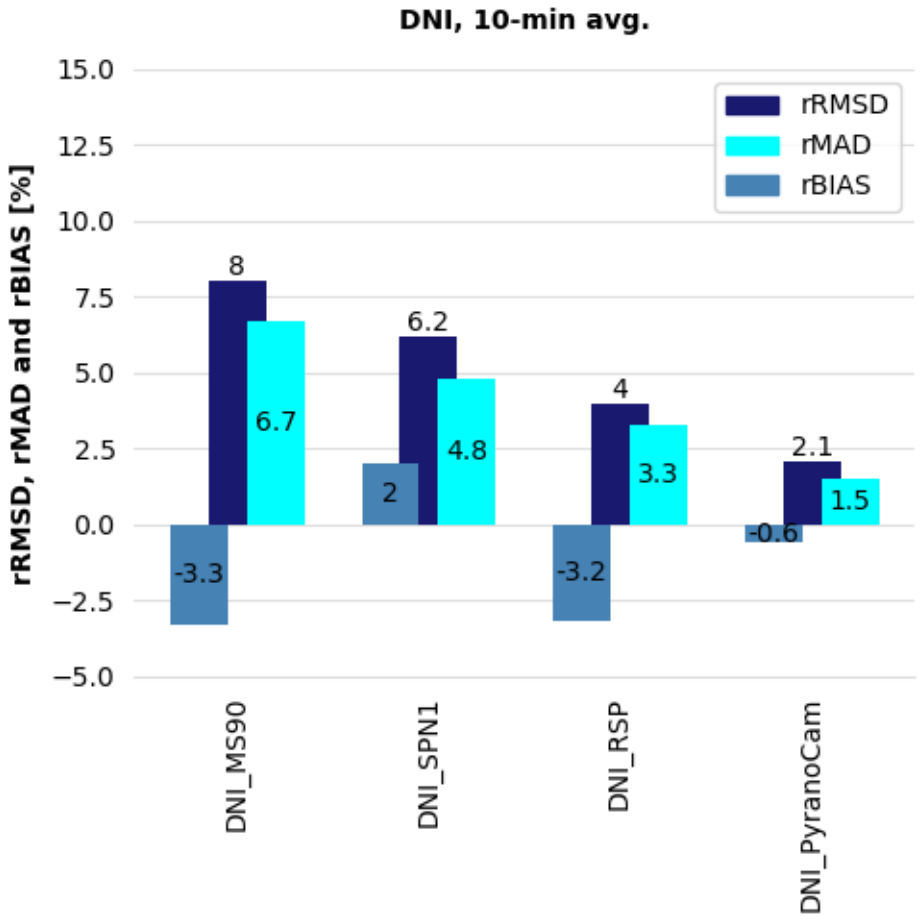

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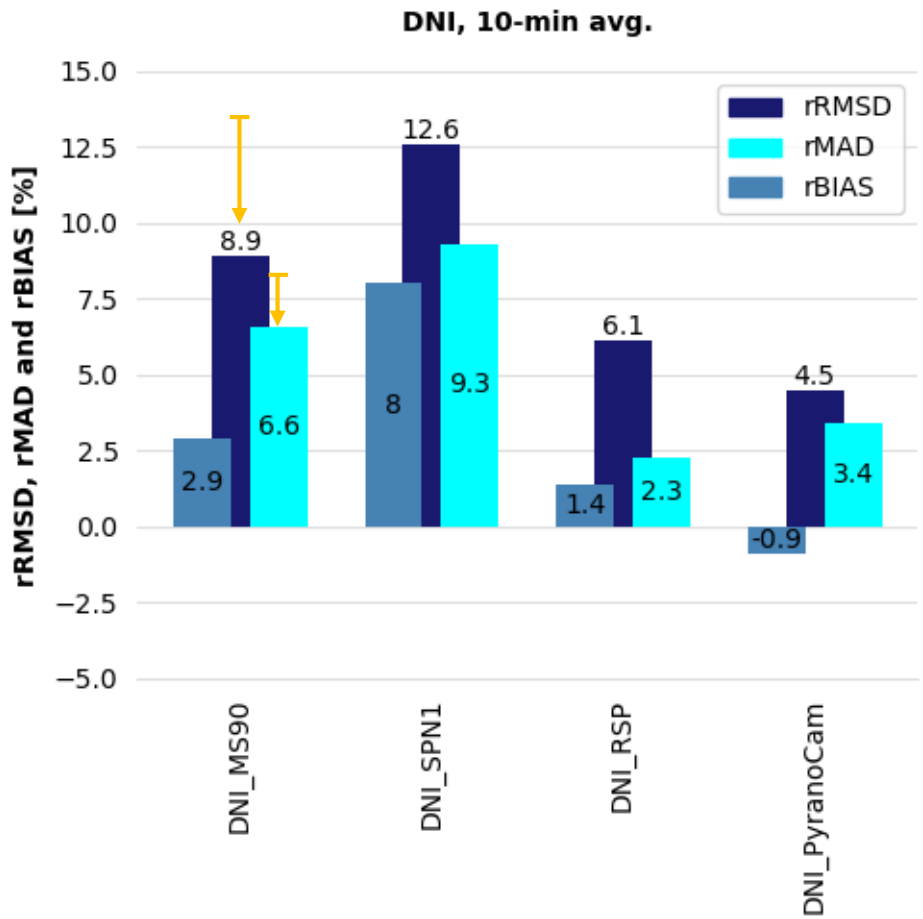
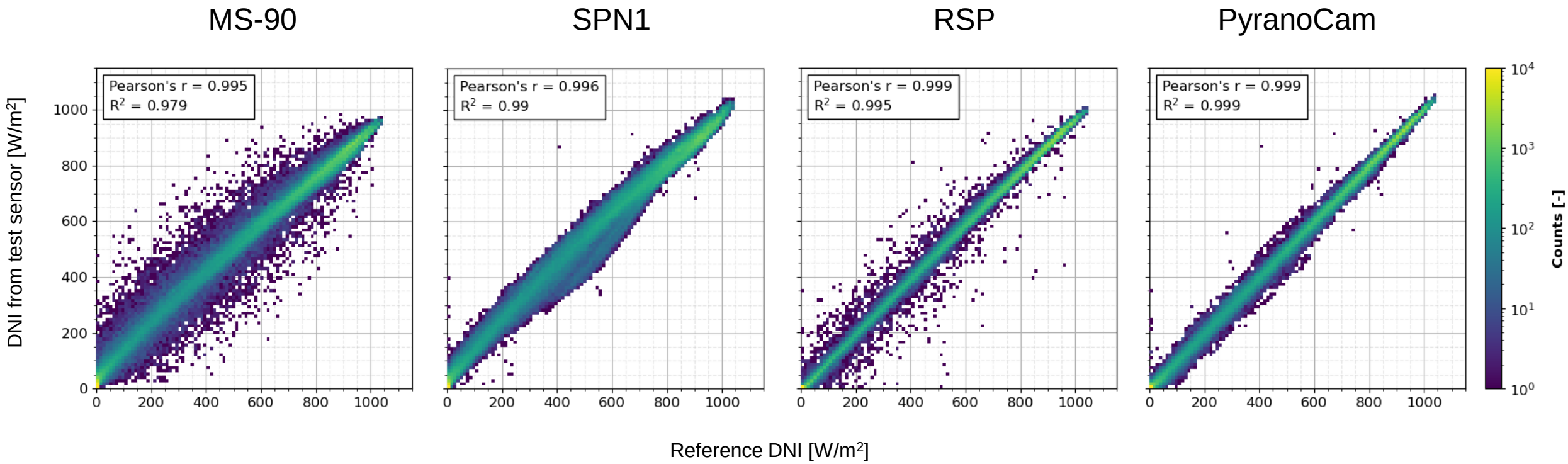


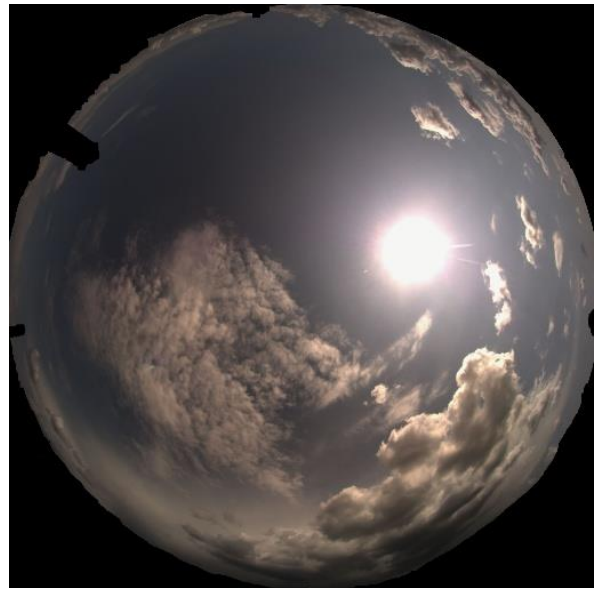
Which sensor is suited for a given application / site?

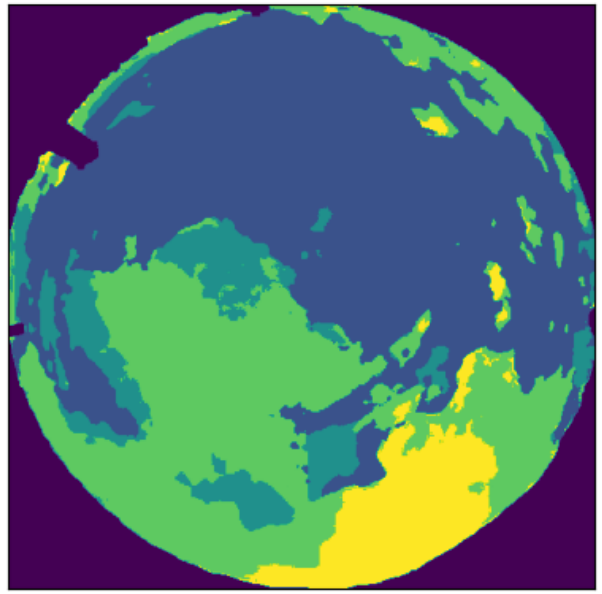
Reduced scattering



Which sensor is suited for a given application / site?

- Linke turbidity
- Sun elevation
- **Cloud cover**





Which sensor is suited for a given application / site?

- Linke turbidity
- Sun elevation
- Cloud cover
- **Spectral composition of GHI, DNI**

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

Influences on the sensors‘ accuracies

- Linke turbidity
- Sun elevation
- Cloud cover
- Spectral composition of GHI, DNI
- **Circumsolar irradiance**

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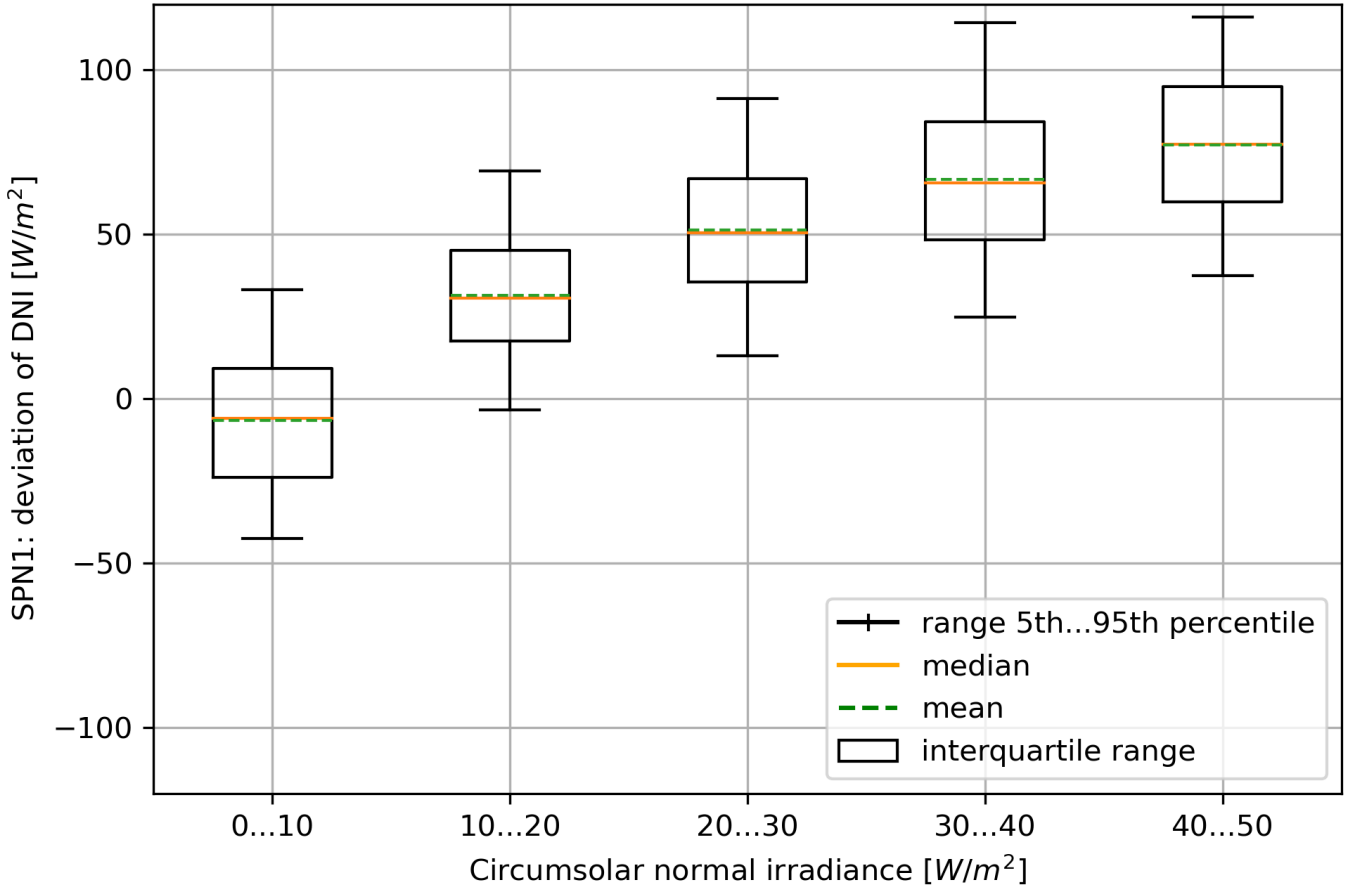
Which sensor is suited for a given application/ site?
SPN-1

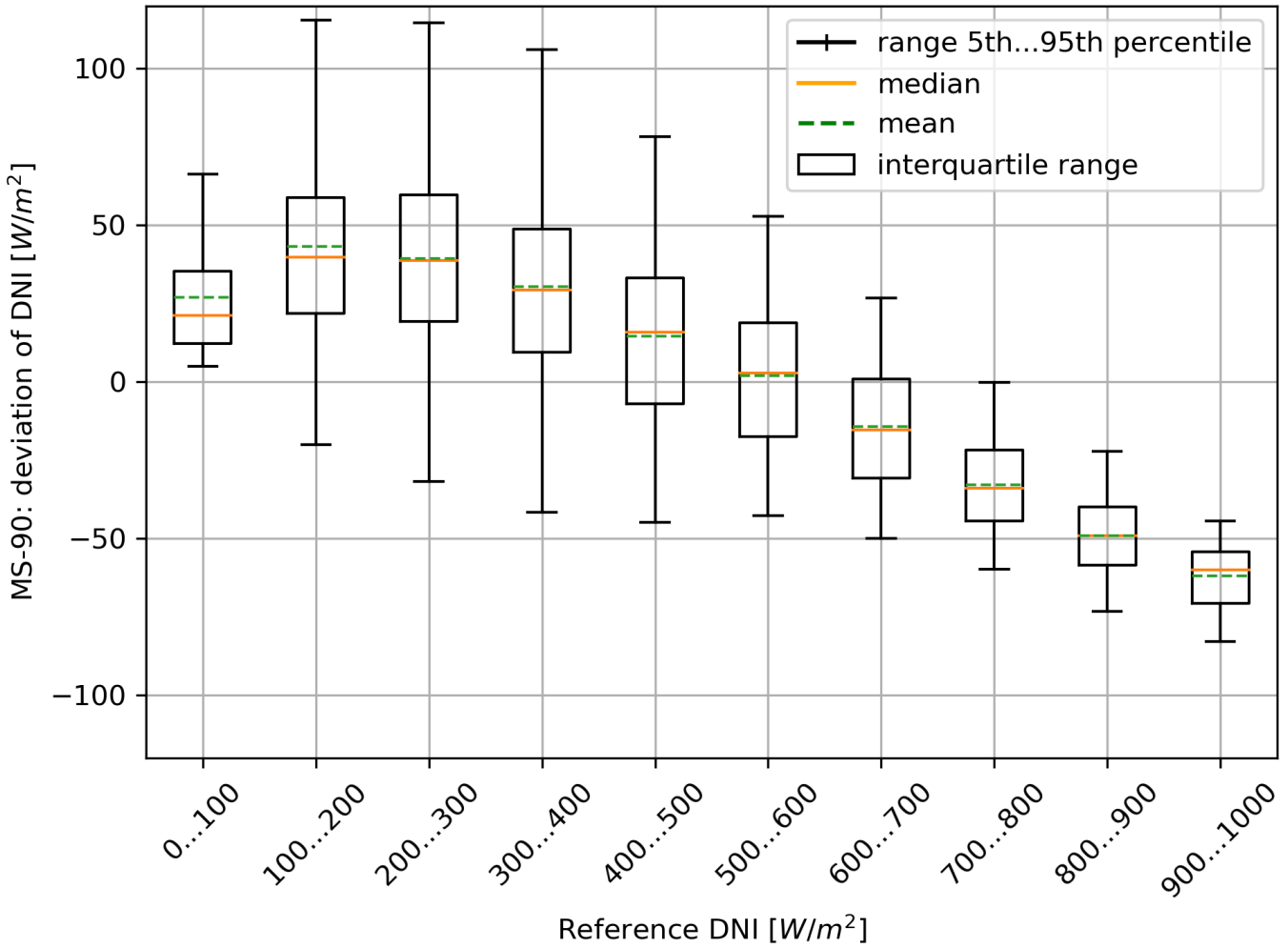
Largest influence on SPN1, DNI: circumsolar normal irradiance (sun angular distance 2.5° to 5°)



→ Positive bias increases strongly with circumsolar normal irradiance

Which sensor is suited for a given application/ site?
MS-90

Largest influence on MS-90, DNI: reference DNI



→ Overestimation and increased scattering at DNI in 100…500 W/m²

→ On-site calibration compensates the MS-90's bias partly
→ underestimation if DNI in 600…1000 W/m²

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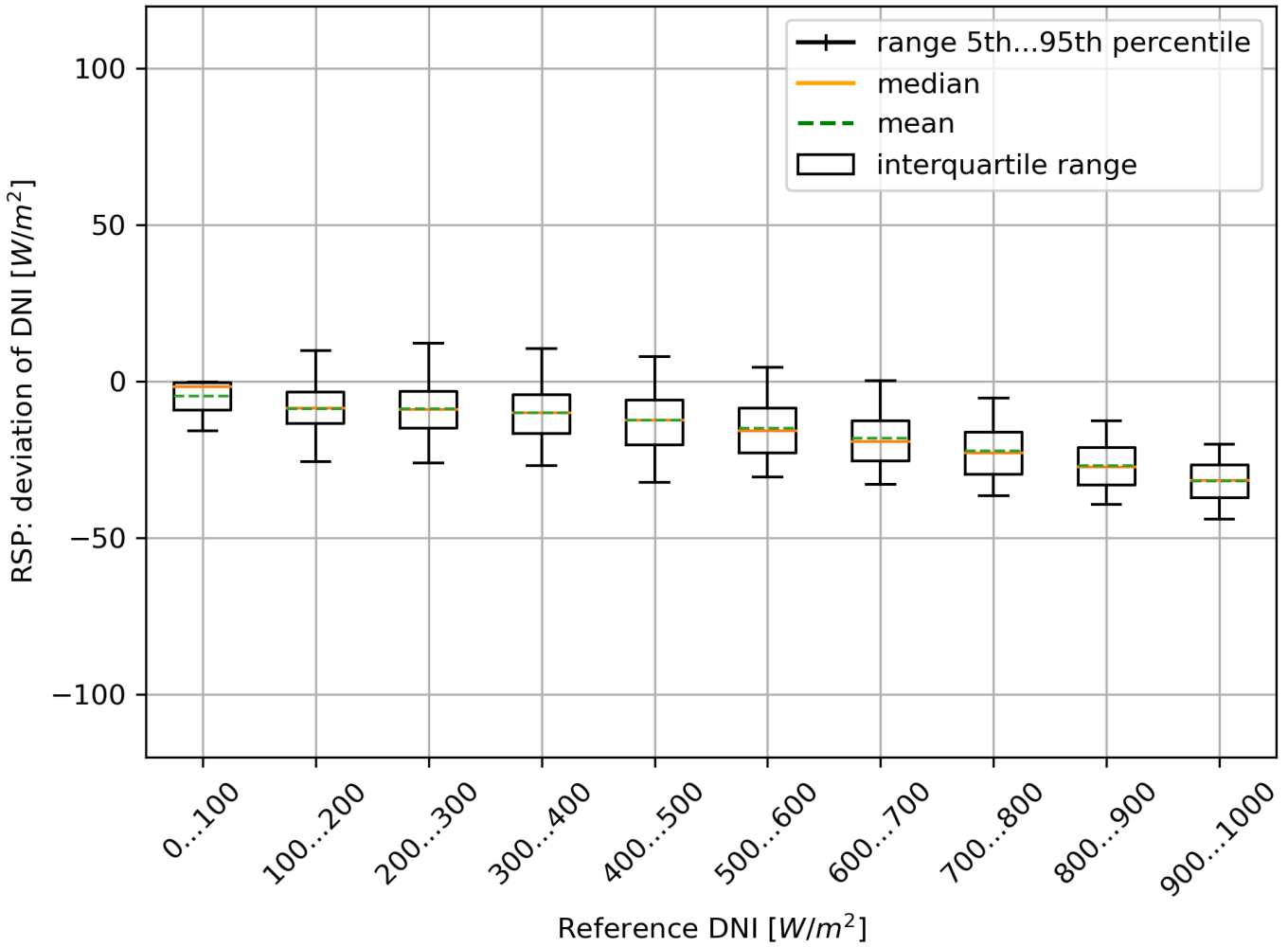
Which sensor is suited for a given application/ site?
RSP

Largest influence on RSP, DNI: reference DNI

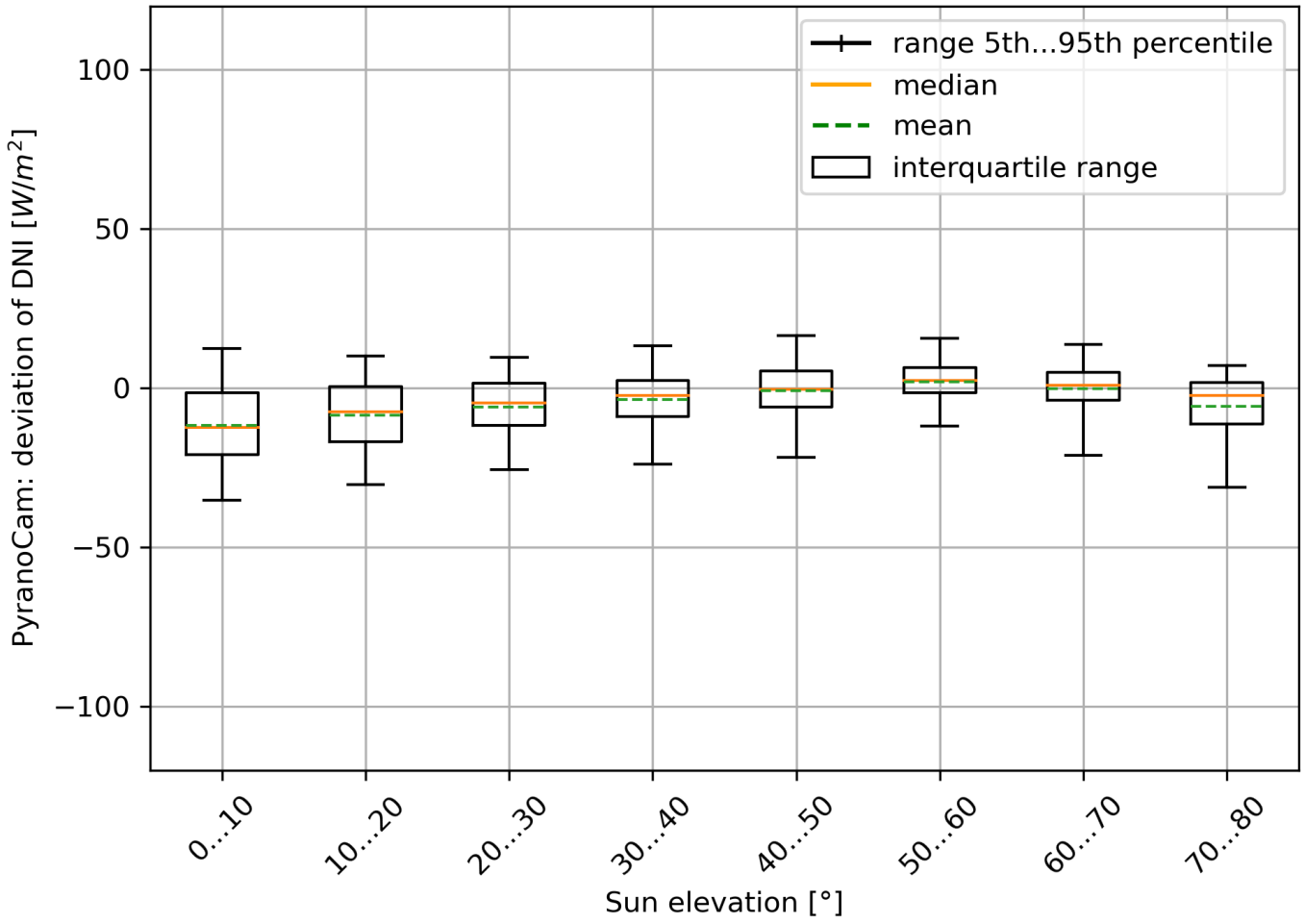


→ No strong influences on accuracy

→ Underestimation at larger DNI

Which sensor is suited for a given application/ site?
PyranoCam

Largest influence on PyranoCam, DNI: sun elevation



→ No strong influences on accuracy

→ Slight underestimation at low sun elevation

Which sensor is suited for a given application/ site?
Findings

Specifics of a site and application need to be considered when choosing a sensor:

- SPN1 considerable shortcomings if more circumsolar irradiance present (clouds, aerosols)
- MS-90 only recommended if exclusively longer clear periods of interest
- RSP 4G high accuracy in our test

  → But deviations known when calibration transferred to different atmospheric conditions due to narrowband spectral response
- PyranoCam performs well under all conditions tested so far

Conclusion

- 3 accuracy groups identified, e.g. by rRMSD (10-min avg., DNI):
  - RSP, PyranoCam in high accuracy group:
    - RSP: 4-6%
    - PyranoCam: 2-5%
  - SPN1, MS-90 larger deviations:
    - SPN-1: 6-13%
    - MS-90: 8-9%
  - CaptPro based on our experience problematic for DNI
    - CaptPro: 17%

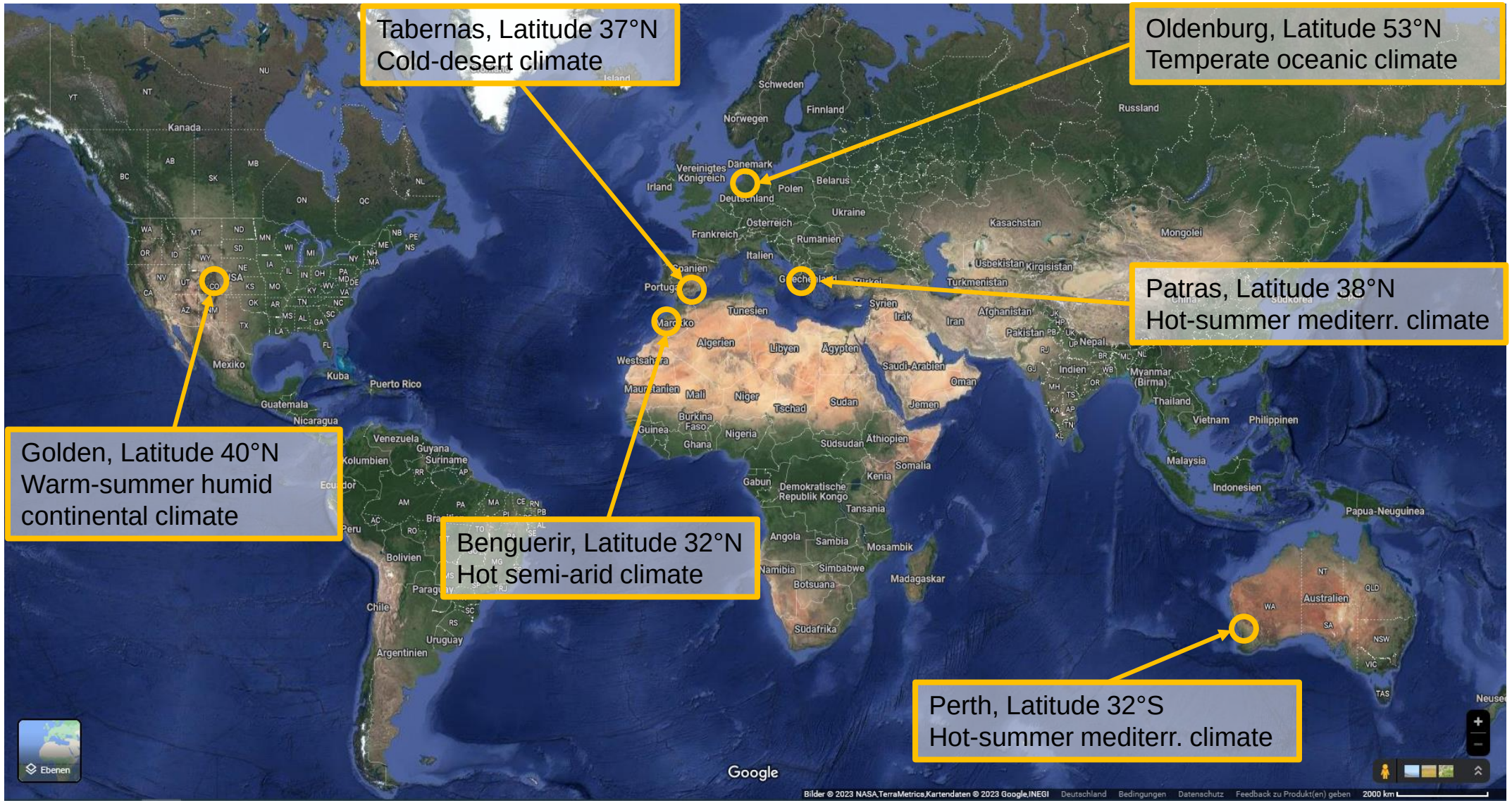
- RSP, MS-90, SPN1 have shortcomings in certain atmospheric conditions
  - e.g. high circumsolar irradiance for SPN1

- PyranoCam provides promising accuracy

  → Should be verified at further validation sites

Outlook

Validation of PyranoCam: 6 sites, 4 continents



Outlook

- Validation of PyranoCam is ongoing at 6 sites worldwide
  - Preliminary results suggest similar accuracy as in Tabernas and Oldenburg
  - Detailed analysis with 1-year datasets planned/ required
- Further evaluation of atmospheric influences for SPN1, RSP, MS-90, PyranoCam
  - will allow users to estimate a sensor‘s accuracy at their site
- Journal publication under preparation

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Thank you for your attention!
Further questions? niklas.blum@dlr.de