PyranoCam: Simple measurement system for all components of solar irradiance in arbitrary planes

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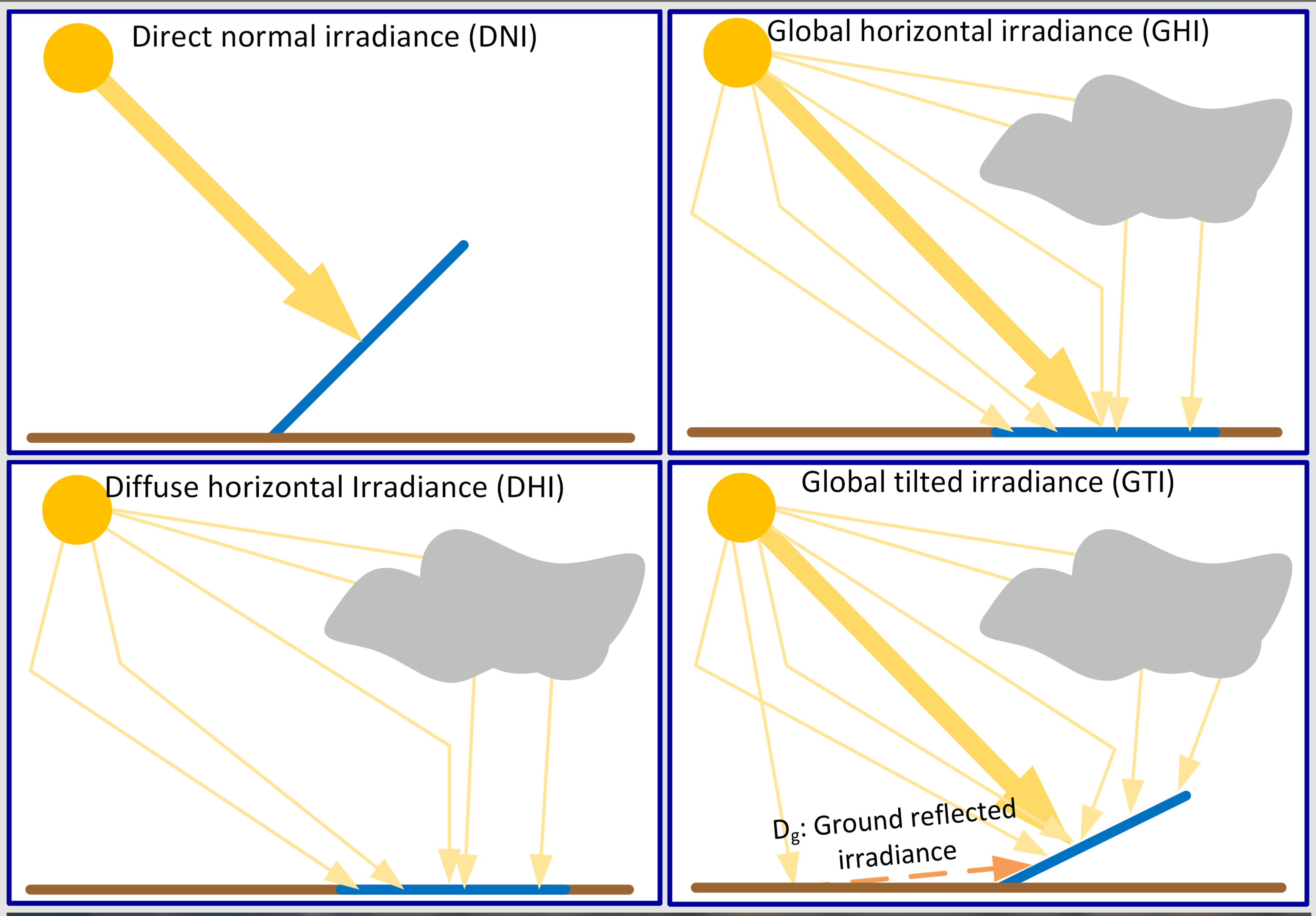
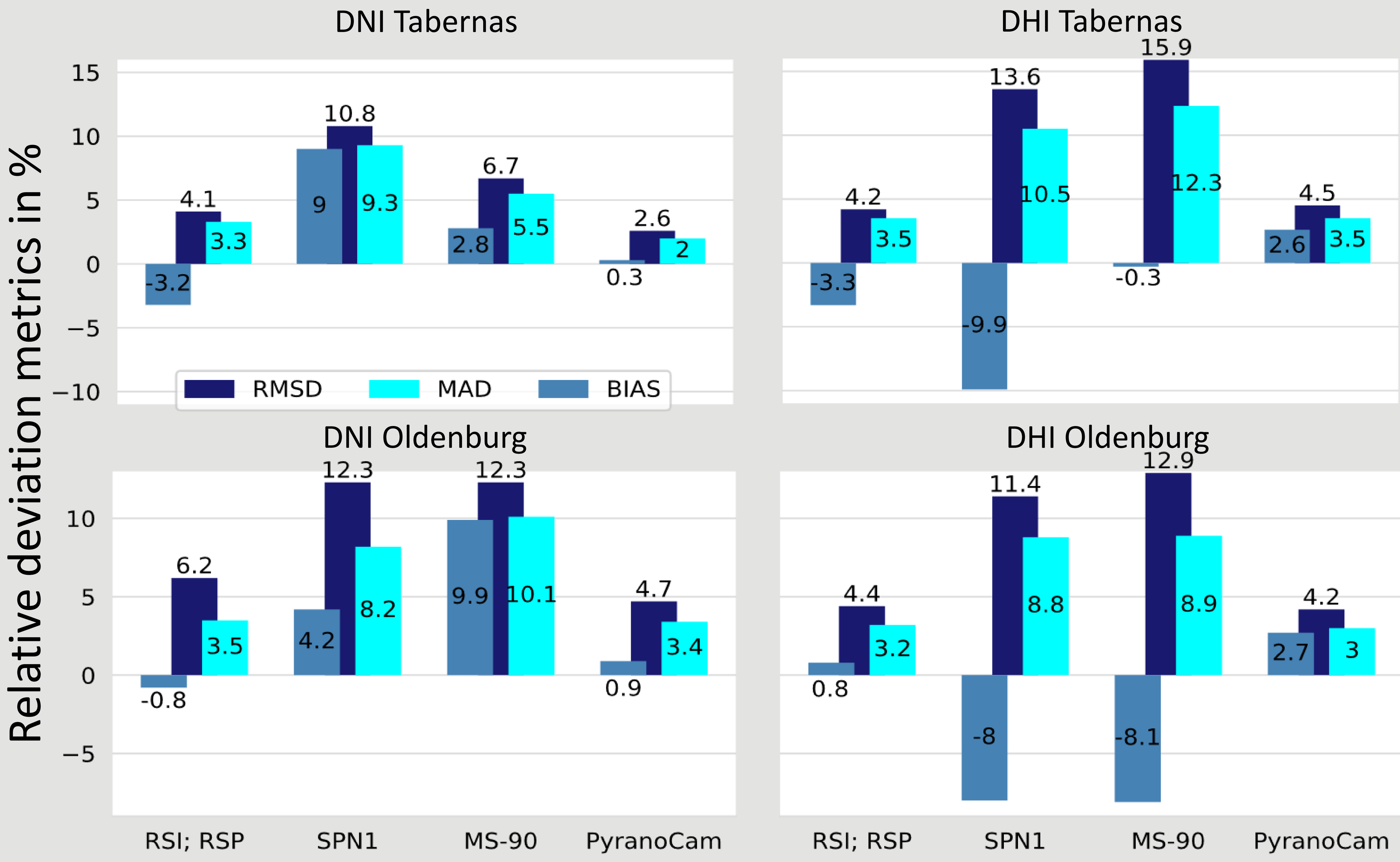


Parameter	Tabernas	Oldenburg
Latitude	37.1°N	53.2°N
Typical sky conditions	clear to cloudy	scattered to overcast
Köppen climate class	semi-arid	temperate oceanic
Mean DHI; DNI (used dataset)	155 W/m²; 566 W/m²	132 W/m²; 360 W/m²



Sensor	Strongest influence on measured irradiance component (DNI, DHI)		
	Situations with DNI > 100 W/m²		All-sky conditions
	DNI	DHI	DHI
RSP	Sun elevation angle, ρ=-0.33	Sun elevation angle, ρ=0.2	Sun elevation angle, ρ=0.24
PyranoCam	DNI clear sky index, ρ=0.40	Circumsolar irradiance, ρ=-0.47	DNI clear sky index, ρ=0.51
MS-90	Circumsolar irradiance, ρ=0.68	Circumsolar irradiance, ρ=-0.72	Circumsolar irradiance, ρ=-0.68
SPN1	Circumsolar irradiance, ρ=0.76	DNI clear sky index, ρ=-0.27	DNI clear sky index, ρ=-0.50

Motivation

Accurate, robust and cost-efficient measurements of different solar irradiance components in arbitrary planes are of great interest for solar energy applications. A wide range of cost-effective and robust measurement systems are currently available on the market.

Available measurement techniques exhibit at least one of these shortcomings: intensive maintenance, high acquisition cost, increased deviations or restrictions to single planes (global tilted irradiance).

PyranoCam is a robust and inexpensive setup of a thermopile pyranometer and an all-sky imager (ASI) for measurements of GHI, DHI, DNI and GTI (for any arbitrary plane) [1].

Objectives

- Benchmarking of PyranoCam and different established systems:
  - Rotating Shadowband Irradiometer/Pyranometer (RSI/RSP 4G)
  - Delta-T SPN1
  - EKO MS-90
- Evaluation at two sites with distinct conditions
  - Tabernas (Spain) & Oldenburg (Germany)
  - Analysis of distinct atmospheric conditions on the measurement performance → dedicated auxiliary measurements are used for this purpose: e.g. spectroradiometers, tracked and shaded pyranometers, …
- Benchmark limited to DHI and GHI
  - PyranoCam uses a ISO 9060:2018 class A pyranometer for GHI
  - The superior performance of PyranoCam for GTI against transposition based models was shown in [1]
    - Transposition models based on DNI and DHI measured by ISO 9060:2018 class A pyrheliometer and shaded pyranometer
  - Reference systems use sun tracker with sun sensor equipped with ISO 9060:2018 Class A pyrheliometers (DNI) and shaded pyranometers (DHI)

Overview of the PyranoCam method

- The PyranoCam method can be divided into two main sections, as depicted in the flowchart.
  - Physical model [1]
  - Machine learning based corrections [2]

Results

- Benchmark over 117 days lasting data set
- Used error metrics
  - Root mean square deviation (RMSD)
  - Mean absolute deviation (MAD)
  - Bias
- RSI/RSP and PyranoCam show a similar performance and both clearly outperform the remaining radiometers at both sites
- SPN1 and MS-90 show significant variations between the sites
  - Indicating impacts of the prevailing atmospheric conditions
- The influence of atmospheric conditions on the observed relative deviations is evaluated via the spearman coefficient of correlation
  - Circumsolar irradiance is found to be the strongest influence on the often noticeable DNI deviations of MS-90 and SPN1

Summary & Outlook

- PyranoCam is operational
- Benchmark showed best performance in terms of DNI and DHI for PyranoCam and RSI/RSP
- PyranoCam outperforms transposition based models in terms of GTI
- Future publications will present validation results from six measurement sites located in various climates
- The PyranoCam hardware can additionally be used to derive cloud coverage/classification and short-term deterministic and probabilistic forecasts of the solar irradiance [4, 5]

Physical PyranoCam Model [1]

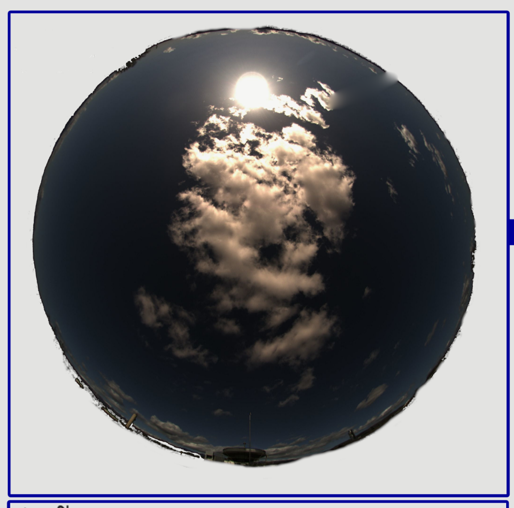
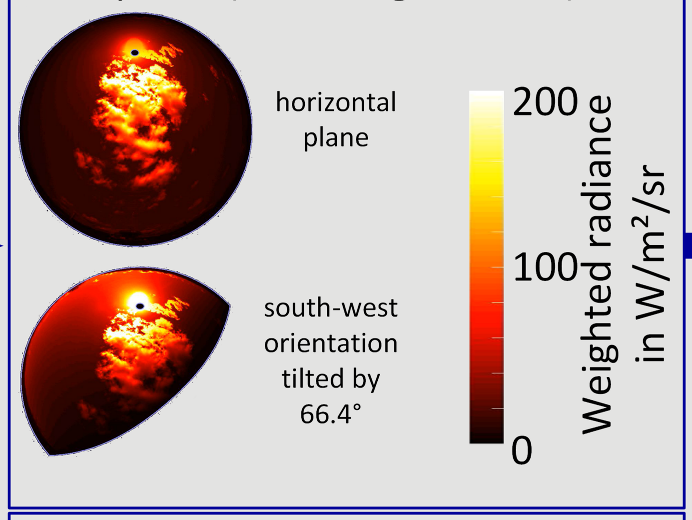


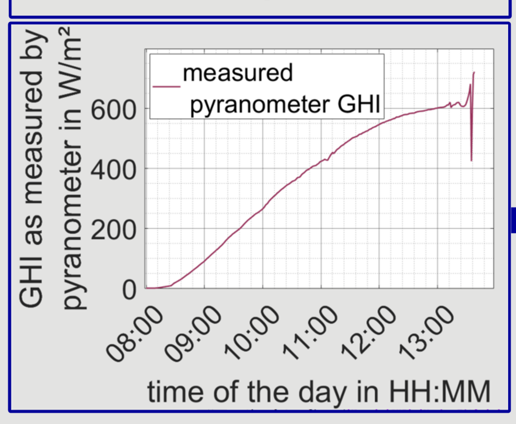
Image analysis for any arbitrary plane (excluding sun disk)



$\int$ *weighted radiance = DHI*

$\int$ *weighted radiance* $= D_t$

D_t: diffuse sky irradiance in arbitrary plane



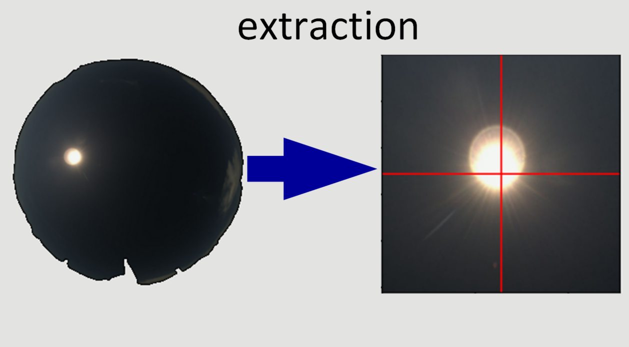
Physical corrections based on image exposure and saturation as well as automatized calibration under diffuse conditions [1]

Corrected *DHI*
Corrected D_t
Measured *GHI*
Calculated *DNI(GHI, DHI, θ)* [1]
Calculated *GTI* (DNI, D_t, D_g, θ) [1]
Calculated $D_g(\rho, GHI)$ with ρ as ground albedo [3]

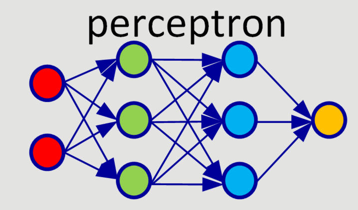
Machine learning based corrections [2]

Tabular features from physical PyranoCam Model

Image transformation (rotation and cropping) & convolution neural network based feature extraction



Data concatenation & multilayer perceptron



Improved: *DHI, GHI, DNI & GTI*

References

[1] 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.
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