Comparison between SolaRes estimates of the tilted solar irradiance and measurements by the PV-Live network

Thierry Elias, Mustapha Moulana, **HYGEOS, Lille, France**
Nicolas Ferlay, Gabriel Chesnoiu, Isabelle Chiapello**, LOA, Villeneuve d''Ascq, France**
Yves-Marie Saint-Drenan**, Mines Paris, Sophia-Antipolis, France**
Swen Metzger, **ResearchConcept Io, Freiburg, Germany**
Gregor Feigel, **University of Freiburg, Germany**

2024/09/06 09:45, Barcelona, EMS2024

HYGEOS

OUTLINE

1. Introduction
2. SolaRes validated for GHI and DNI in clear-sky
3. Modeling the spectral and angular specifities of Silicon sensors
4. Performances in GTI
5. Tests with a parameterization method
6. Influence of the cloud properties
7. Conclusions

1. Introduction
Solar resource and meteorology

One of the main sources of uncertainty in solar energy <- meteorology

-> clouds, local and transported aerosols

Solar resource is the solar radiation collected by the solar set-up = f(atmosphere, surface, and collecting technology)

Performances with GHI (horizontal and broadband spectrum),

while solar radiation usually collected in **a non horizontal plane and in a restricted spectrum**

Performances = comparison scores between estimates and reference high quality observation -> root mean square difference (RMSD) and mean bias difference (MBD)

Clear-sky conditions for validating, because input data are known with smallest uncertainty

Validation with AERONET (ground-based network measuring aerosol optical properties)

But not available everywhere -> testing the influence of global data set as CAMS

Then, computing the **performances in all-sky conditions, with cloud influence**

1. Introduction

PV-Live network [Lorenz et al., 2021], and satellite cloud-screening

E. Lorenz et al. — *Solar Energy 231 (2022) 593–606*

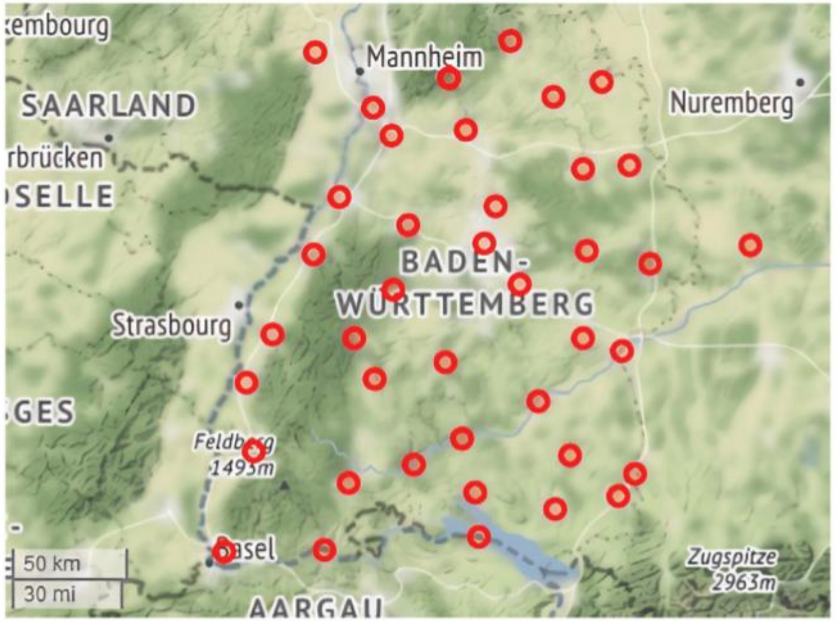
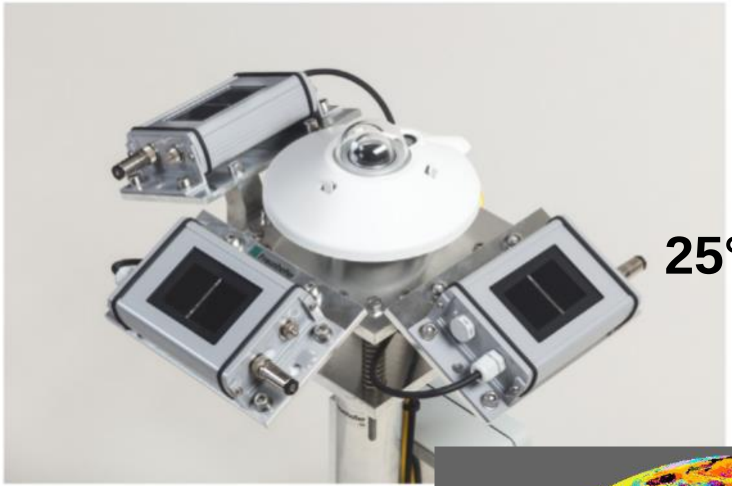


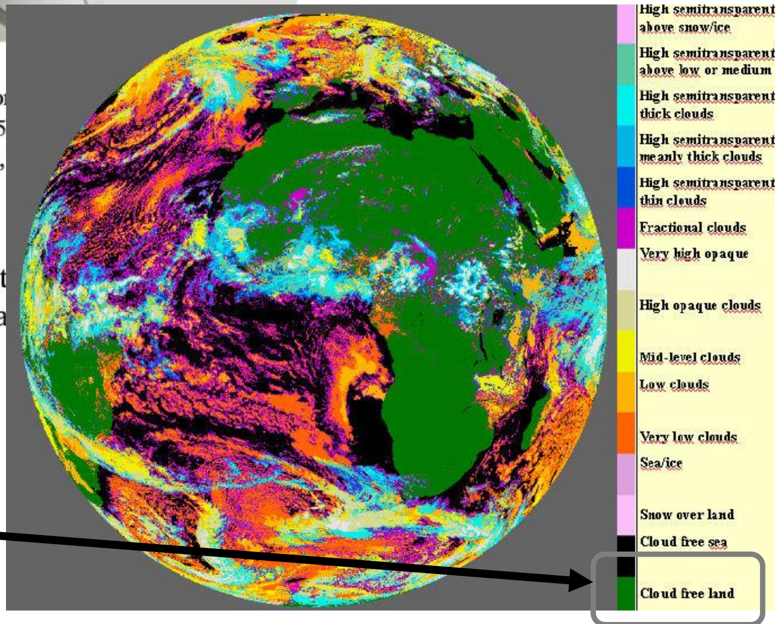
Fig. 1. The PV-Live network consists of 40 measurement stations distributed over the control area of TransnetBW, corresponding widely to the state of Baden-Württemberg in Germany, which covers an area of about 35.751 km^2 (Map tiles by Stamen Design (https://stamen.com), under CC BY 3.0. Data by OpenStreetMap, under ODbL (https://www.openstreetmap.org/copyright)).



25°-tilt

Fig. 2. PV-Live measurement station with a ho three silicon reference cells with tilt angles of 25 orientation of the Si Sensors towards east, south,

are not equipped with ventilation unit caused considerable additional costs a consumption.



Cloud-screening: NWCSAF cloud type = 1, and constant over 1 hour

https://www.nwcsaf.org/ct_description

2. SolaRes validated for GHI, and DNI in clear-sky

Description of SolaRes (Solar Resource Estimate) [Elias et al., 2024]

$GHI_{spectrum}$ = $DirHI_{spectrum}$ + $DifHI_{spectrum}$

atmosphere-surface coupling, & anisotropy, by the SMART-G radiative transfer code [Ramon et al., 2019]

Spectrum = BB for solar broadband spectrum, Si for the Silicon sensor

Also: $GTI_{Si} = DirTI_{Si} + DifTI_{Si}$ (T for Tilted)

SolaRes adapted to solar resource estimates of bifacial panels, semi-transparent sensors, CSP, …

SolaRes described and validated in clear-sky conditions in Elias et *al.* [2024]

Input data here:

Aerosols and water vapor by CAMS-NRT (spectral aerosol optical thickness AOT)

(AERONET for validation [Elias et *al.*, 2024])

Clouds by NWCSAF (cloud optical thickness COT)

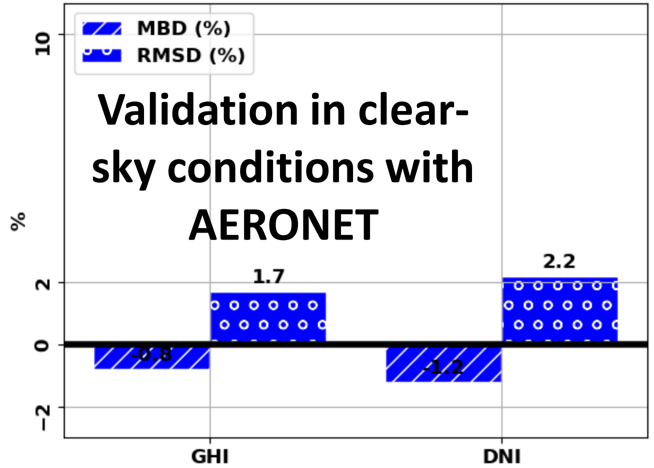
Surface by MODIS (surface albedo)

2. SolaRes validated for GHI, and DNI in clear-sky
<2% MBD and RMSD in GHI and DNI

2 years, 1-minute resolution, Lille and Palaiseau (France) [Elias *et al.*, 2024]

1. Validation with AERONET

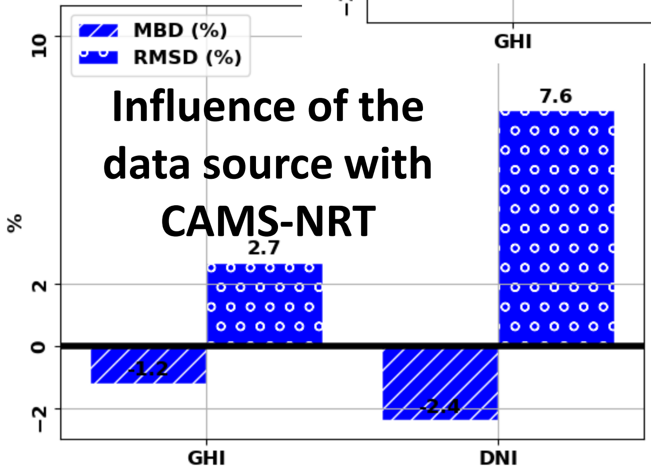
Cloud-screening: from ground-based obs + AERONET Level 2.0



2. Influence of the data source

With CAMS-NRT (Copernicus Atmosphere Monitoring Service)

Cloud-screening: from ground-based obs + CT=1



Confirmation at Freiburg (**1 year, 1-hour,** AOT=0.15+-0.09**)**

0.5%/3.1% of MBD/RMSD in GHI

Cloud-screening: only SAFNWC cloud type CT=1, and constant CT over 1 hour)

2. SolaRes validated for GHI, and DNI in clear-sky
Example of GHI on 1 date at Freiburg

clear-sky at Freiburg on 2021/06/14

GHI observed by a **thermopile pyranometer**

Input data: CAMS-NRT

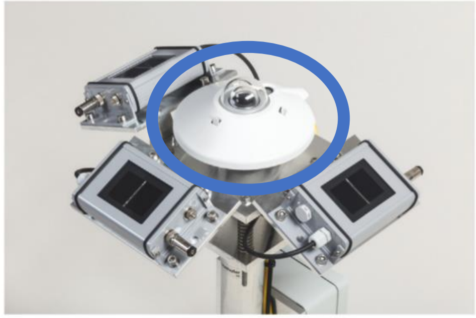
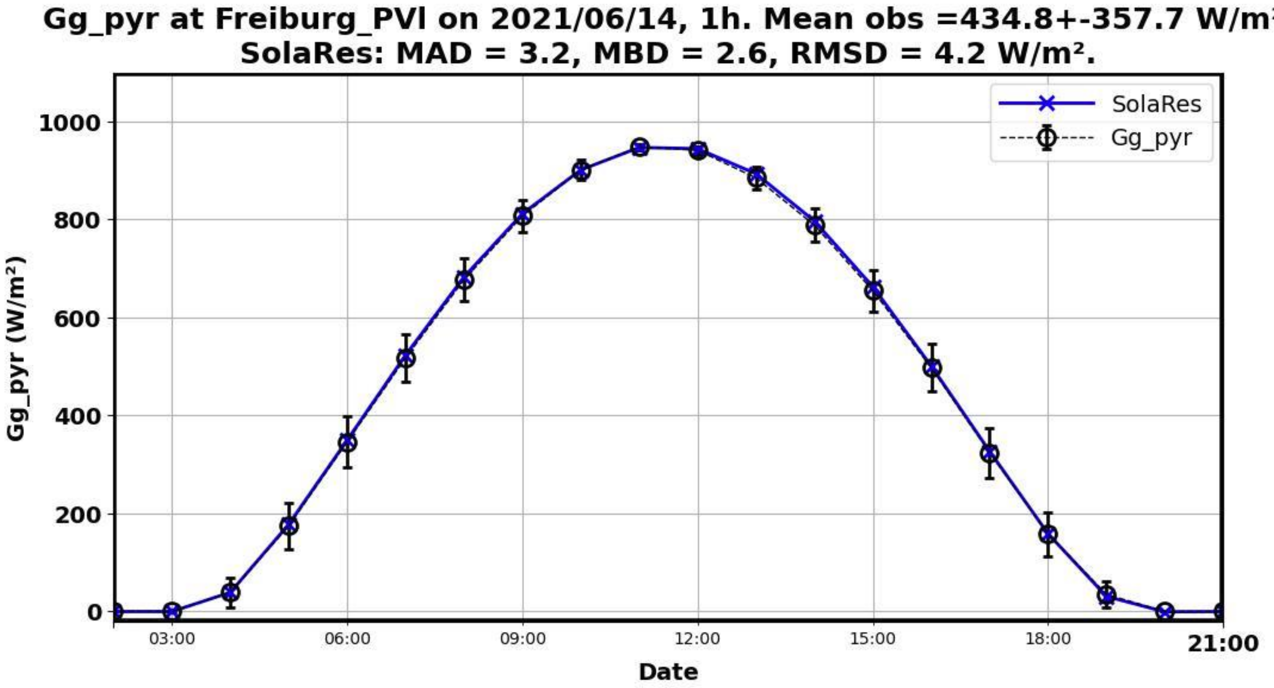


Fig. 2. PV-Live measurement station with a horizontally mounted pyranometer and three silicon reference cells with tilt angles of 25°. The stations are installed with the orientation of the Si Sensors towards east, south, and west.

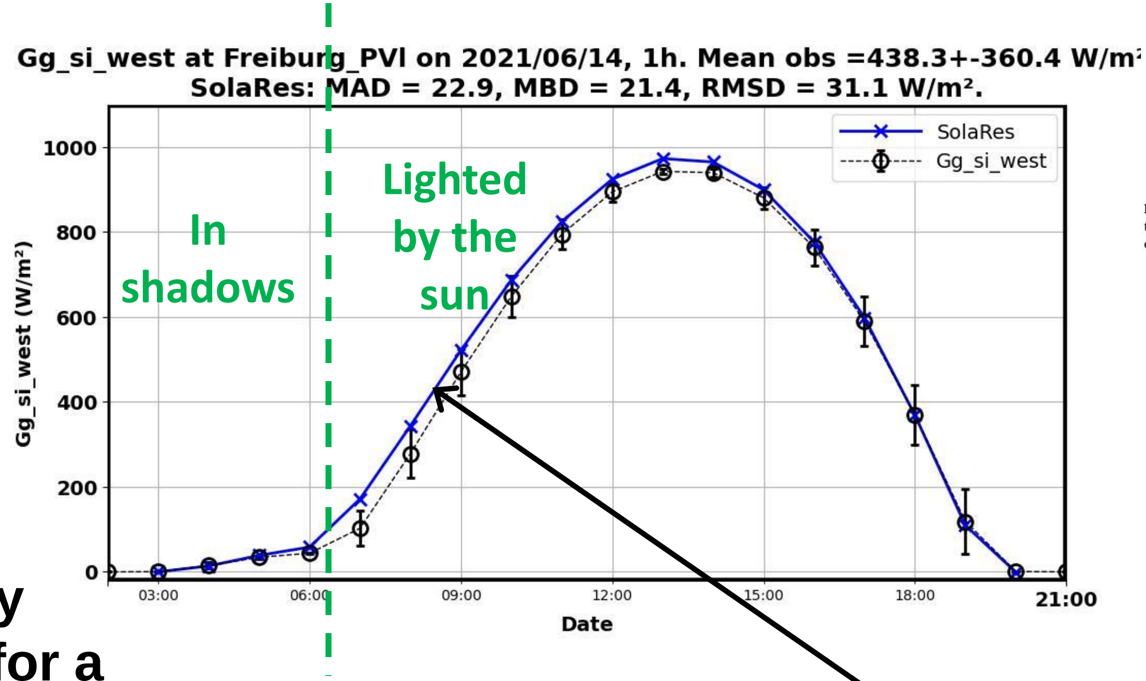


These are the scores that we would like to reach by comparing estimated GTI with measurements by a Si sensor

2. SolaRes validated for GHI, and DNI in clear-sky

Beware ! Observations by a Silicon sensor

First test at Freiburg, with observation by the westwards 25°-tilt Si sensor



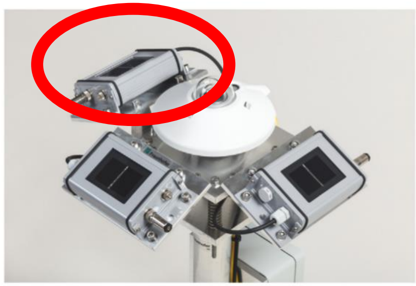


Fig. 2. PV-Live measurement station with a horizontally mounted pyranometer and three silicon reference cells with tilt angles of 25°. The stations are installed with the orientation of the Si Sensors towards east, south, and west.

The scores in GTI are degraded compared to scores in GHI, partly because the simulation is made for a thermopile pyranometer, while the measurements are made by a Si sensor. → Spectral and angular specificities need to be considered

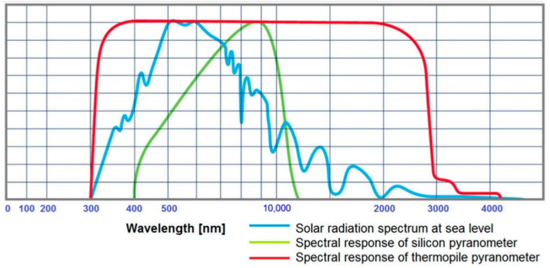


Figure 3. Spectral response curves of silicon, thermopile pyranometers, and solar spectrum at sea level [20].

Diurnal variability of GTI affected by the sensor

3. Modeling the spectral and angular specifities of the Silicon sensor
The spectrum

$GTI_{Si \rightarrow BB} = GTI_{Si} * K_{cal}$

$GTI_{Si \rightarrow BB} = (DirTI_{Si} + DifTI_{Si}) * K_{cal}$

$K_{cal} = GHI_{BB} / GHI_{Si}$

K_{cal} on 2021/06/14:

	only bandwidth	*non-flat SR*
GHI	**1.29+-0.01**	**2.31+-0.02**

[Mubarak *et al.*, 2017; 2021]

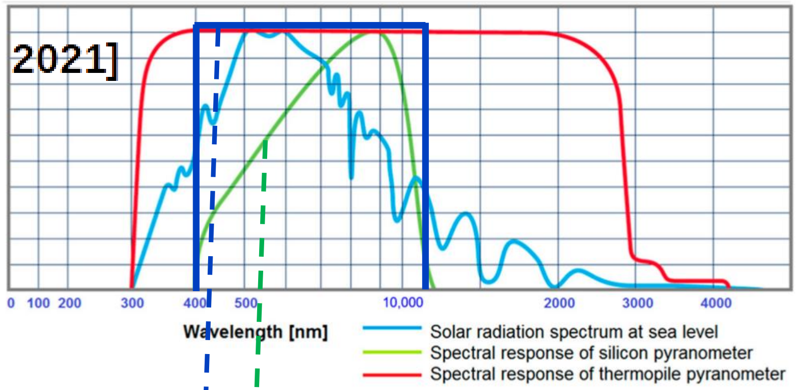
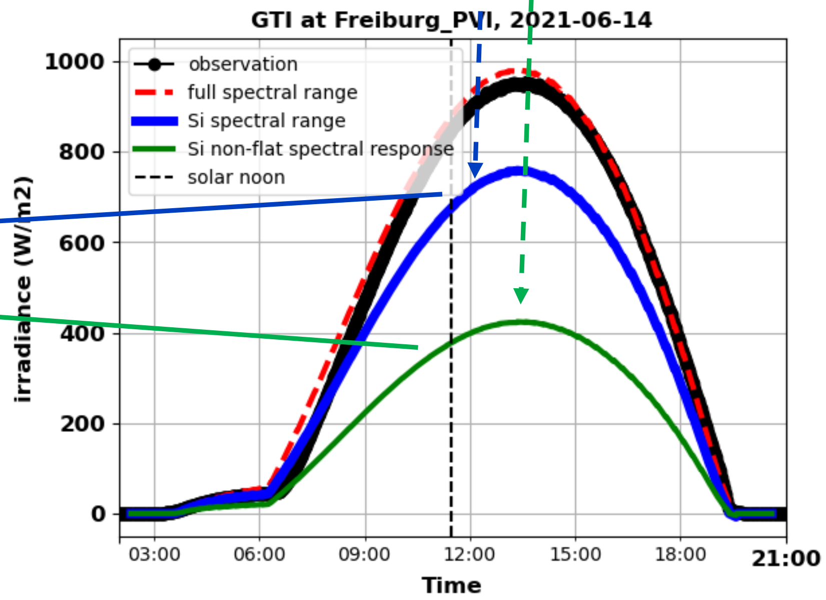


Figure 3. Spectral response curves of silicon, thermopile pyranometers, and solar spectrum at sea level [20].



3. Modeling the spectral and angular specifities of the Si sensor
Applying the Martin and Ruiz [2001] solar incident angle correction

$$GTI_{Si \rightarrow BB} = (K_{sia,dir} \ DirTI_{Si} + K_{sia,dif} \ DifTI_{Si}) * K_{cal}$$

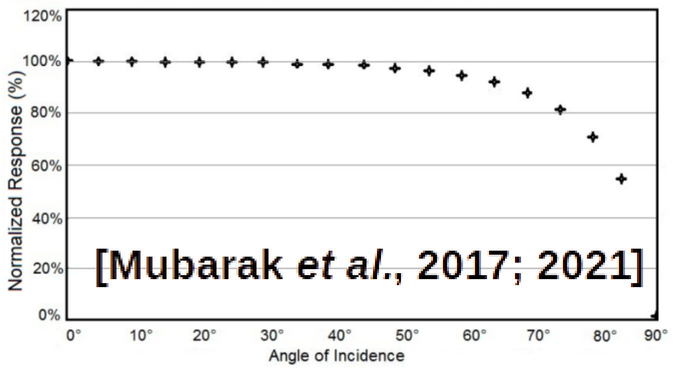
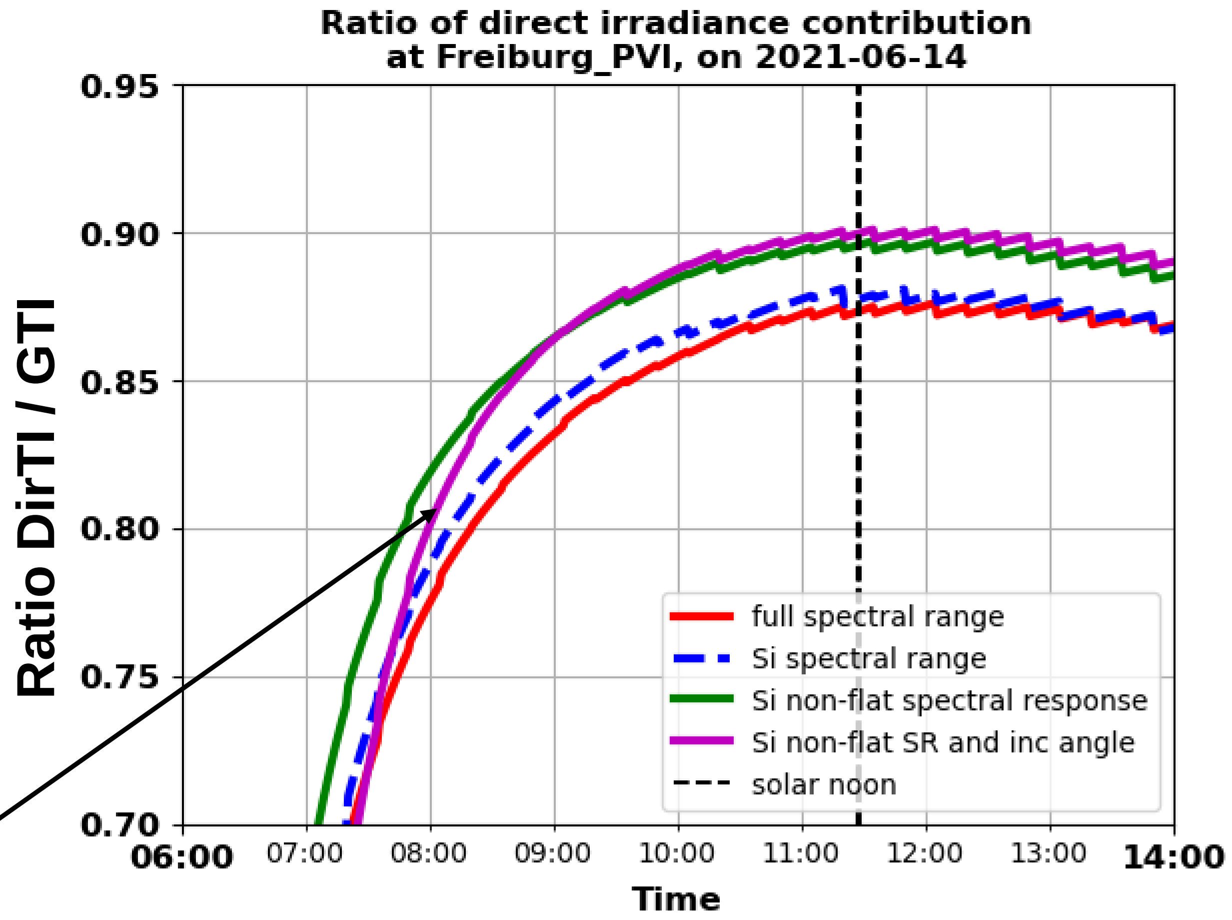


Figure 4. Normalized angular response of SiS versus solar angle-of-incidence measured by the manufacturer [25] under STC.



Strong impact of the solar incident angle (SIA) correction before 09:00 (-> diurnal variability)

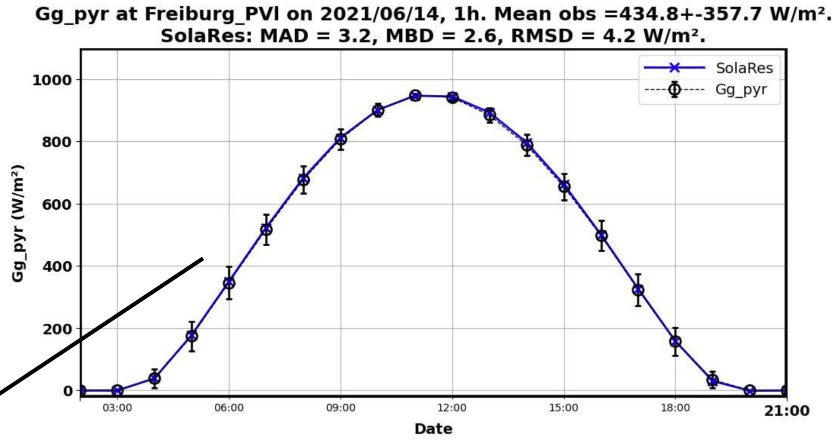
4. Comparison scores with SolaRes: clear-sky, 1 day

Similar comparison scores in GHI and GTI

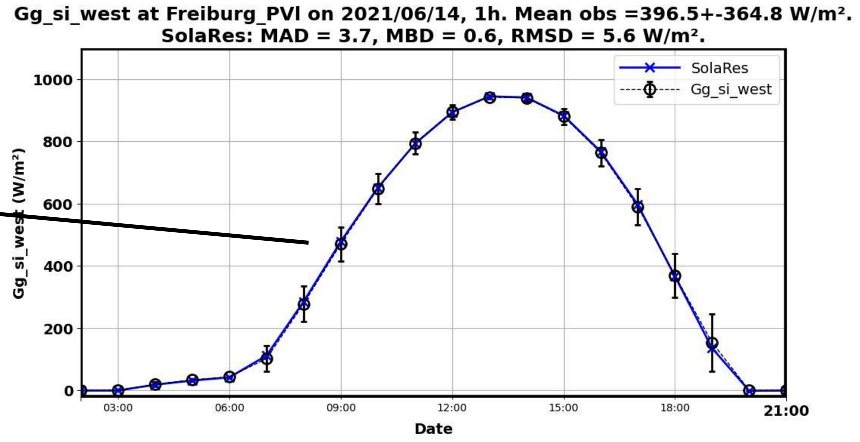
$$GTI_{Si \rightarrow BB} = (K_{sia,dir} \, DirTI_{Si} + K_{sia,dif} \, DifTI_{Si}) * K_{cal} * K_{cal,cor}$$

Freiburg, 2021, 1 day, $K_{cal} = 2.31$; $K_{cal,cor} = 0.98$

param	*spectrum*	*sia+cal*	*cal,cor*	*MBD*	*RMSD (W/m2)*
GHI	pyr	/	/	3	4
GTI	pyr	/	/	21	31
GTI	Si	yes	/	9	14
GTI	Si	yes	yes	1	6



Similar comparison scores in GHI and GTI



4. Comparison scores with SolaRes : clear-sky, 1 year

Success: similar comparison scores in GHI and GTI

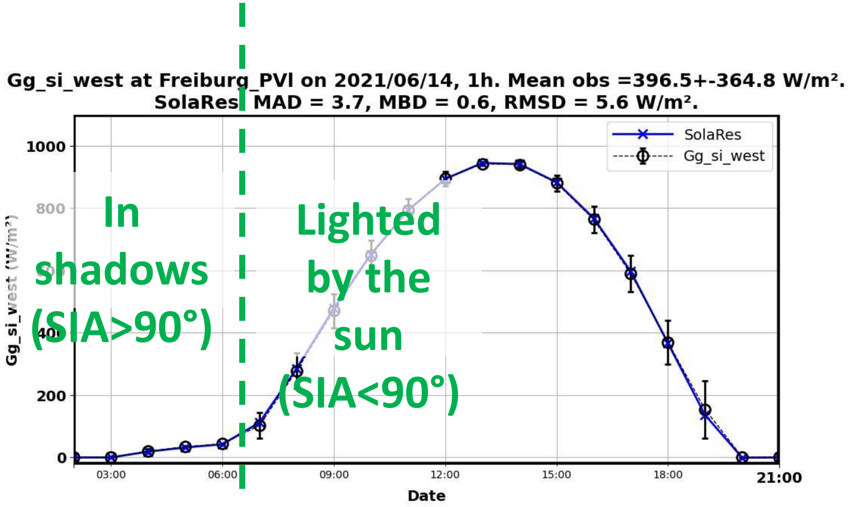
HYGEOS

Freiburg, 2021, 1-h, K_{cal} = 2.31; $K_{cal,cor}$ = 0.98

clear-sky: cloud type CT = 1 & constant CT over 1 h (and SZA < 80°)

param	*Lighted conditions*	*MBD (%)*	*RMSD (%)*
GHI	**All**	**0.5**	**3.1**
GTI-west	All	0.4	3.5
GTI-west	**Only lighted**	**0.5**	**3.2**

Success ! Similar results in GHI and GTI



4. Comparison scores with SolaRes : clear-sky, 1 year

Success: similar comparison scores in GHI and GTI

Freiburg, 2021, 1-h, $K_{cal} = 2.31$; $K_{cal,cor} = 0.98$

clear-sky: cloud type CT = 1 & constant CT over 1 h (and SZA < 80°)

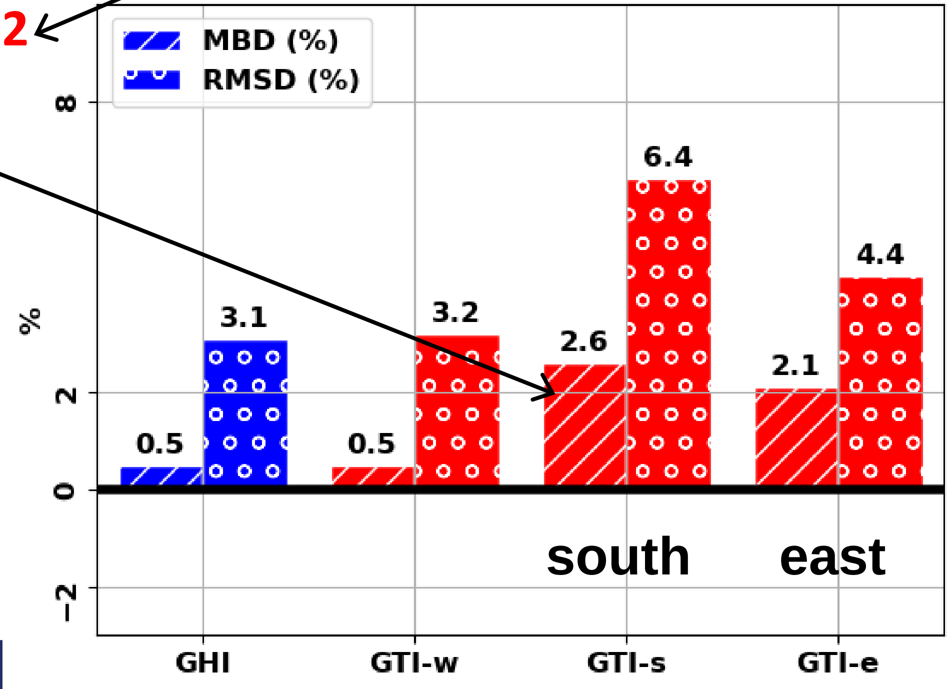
TODO: bar fig

param	*Lighted conditions*	*MBD (%)*	*RMSD (%)*
GHI	All	0.5	3.1
GTI-west	All	0.4	3.5
GTI-west	Only lighted	0.5	3.2

Success ! Similar results in GHI and GTI

More bias than westwards

Si calibration uncertainties ? Surface reflection contribution ?

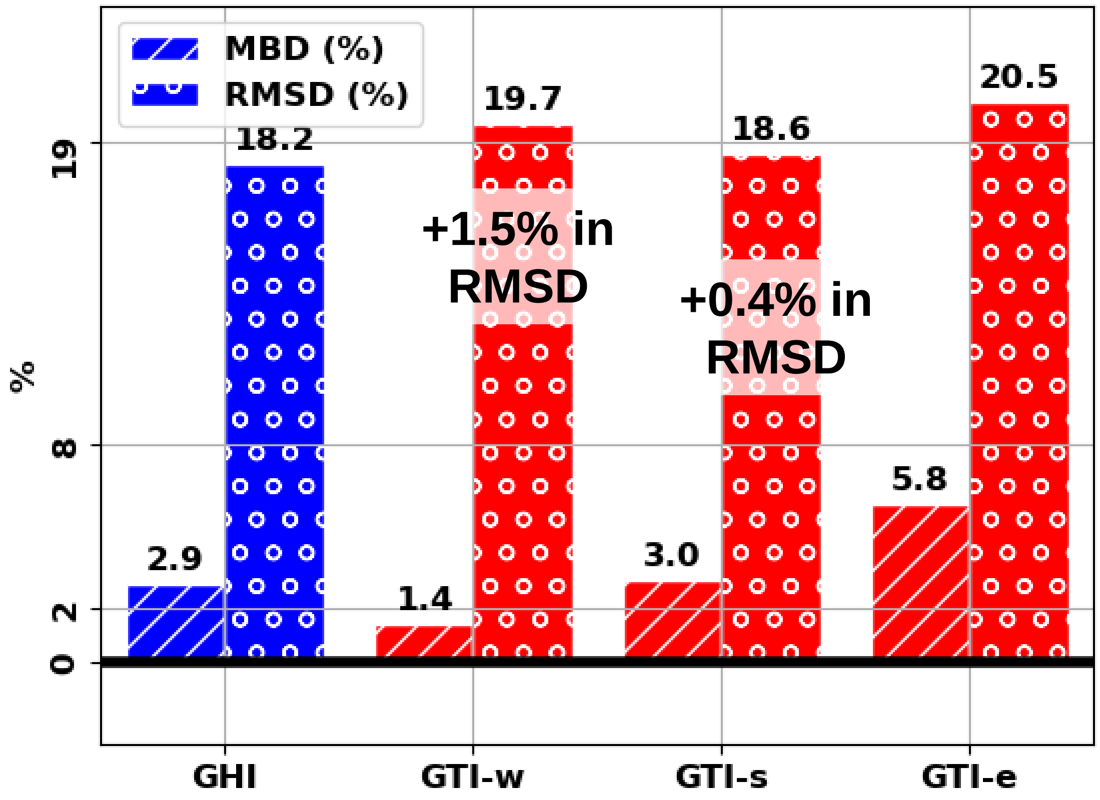


4. Comparison scores with SolaRes : all-sky, 1 year

+1.5% RMSD in GTI than in GHI

All CT

SIA < 90°



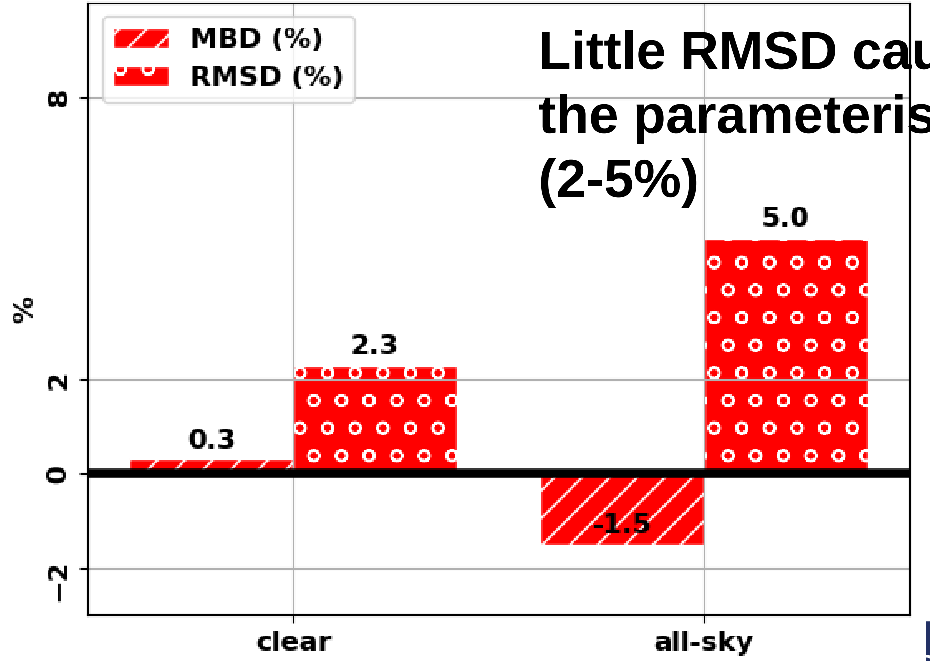
5. Tests with a parameterisation method. From GHIobs
Same calibration issue of 2% for the western instrument

Parameterisation of GTI-west from $\mathbf{GHI_{obs}}$, in 2021:

Sky	*cal,cor*	*MBD*	*RMSD (%)*
Clear	/	2.3	3.4
Clear	Yes	0.3	2.3

The same calibration issue, but with independent method and measurements

From PVlib:
1. decomposition
2. transposition
3. sia corr
4. spectral mismatch

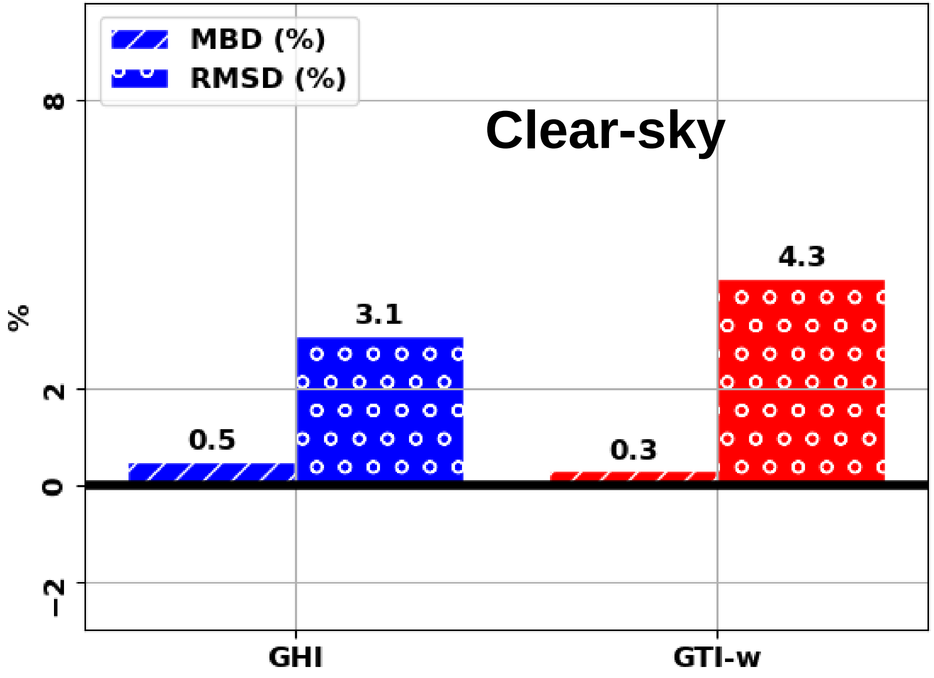


Little RMSD caused by the parameterisation (2-5%)

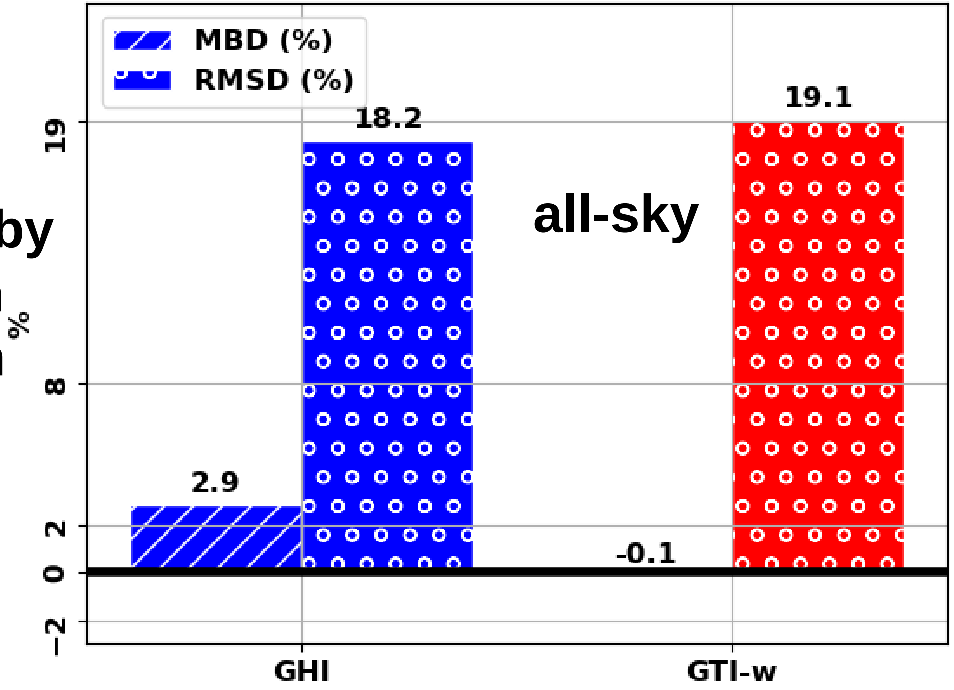
5. Tests with a parameterisation method. From $GHI_{SolaRes}$

1% RMSD caused by the parameterisation

Parameterisation of GTI-west from **$GHI_{SolaRes}$**, in 2021:

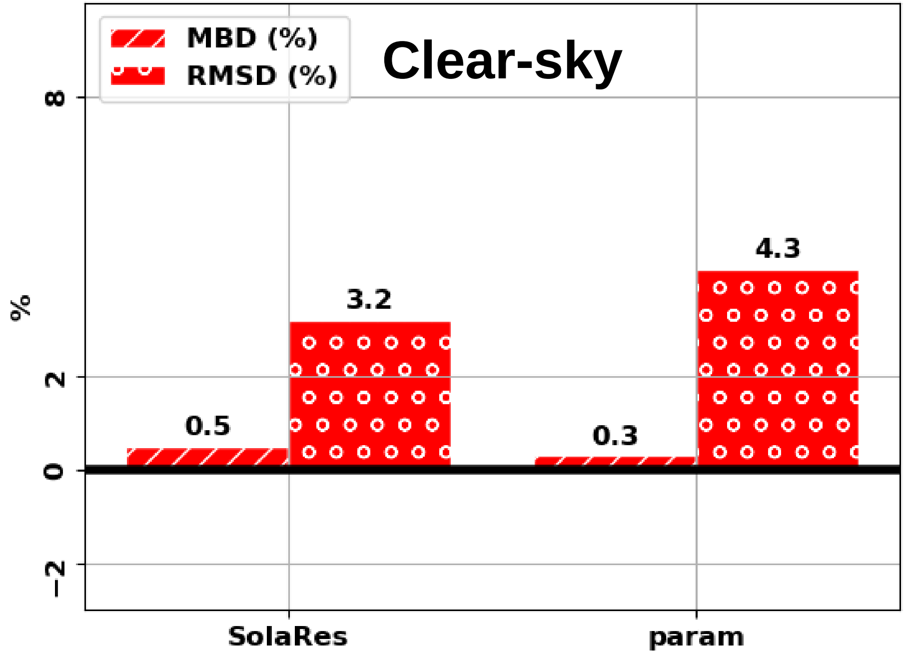


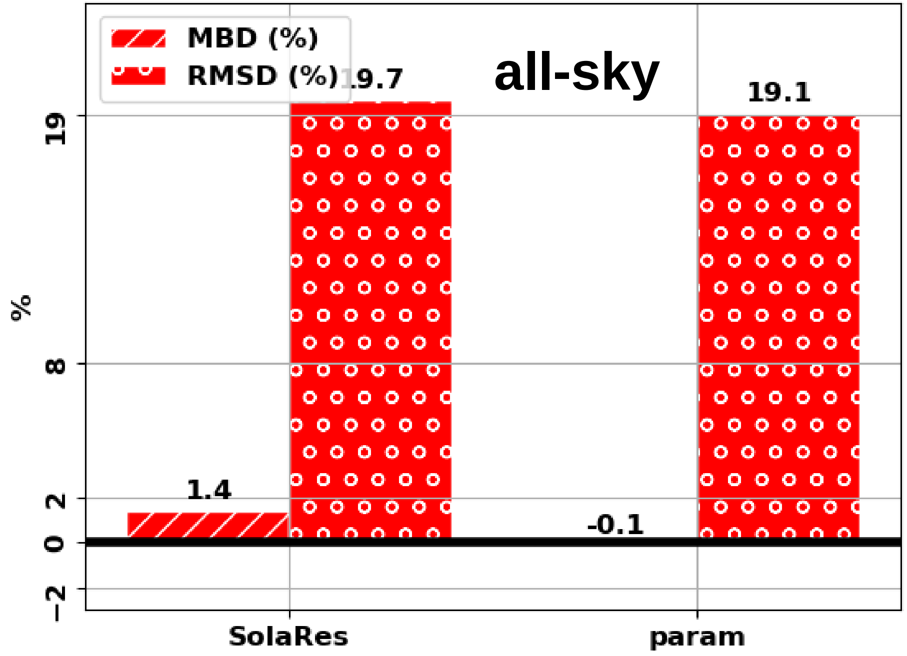
Little RMSD caused by the parameterisation (2-5%), or 1% in both clear and all-sky



parameterisation: +1% in clear-sky conditions, -0.6% in all-sky

GTI-west.





SolaRes 1% better than the parameterisation in clear-sky, but 0.6% worse in all-sky

-> Should focus in improving the SolaRes scores in cloudy situations

6. Influence of the cloud properties

Over estimation by SolaRes of the diffuse contribution by clouds

Western GTI by SolaRes

lighted

Clouds	***MBD (%)***	***RMSD (%)***		
CT=1	0.5	3.2		
COT < 0.5	0.4	6.4	}	45% of the situations
COT in 0.5-2	-4.0	17.4	}	
COT > 5	9.6	38.3		41%

(DNI=0, only diffuse)

(CT = cloud type, COT = cloud optical thickness)

RMSD significantly increases with mean COT
-> over estimation by SolaRes of the diffuse contribution by clouds

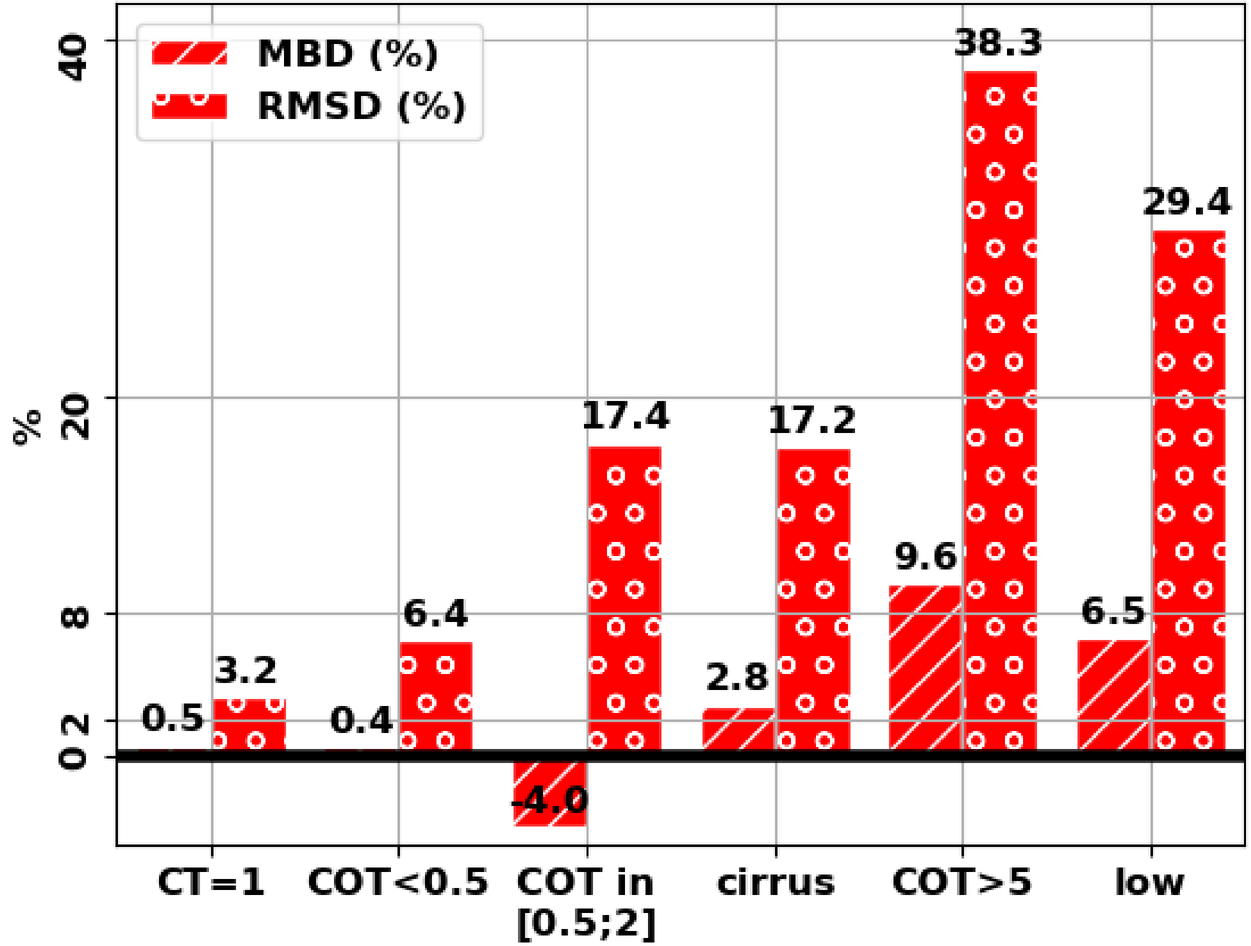
6. Influence of the cloud properties

Over estimation by SolaRes of the diffuse contribution by clouds

Western GTI by SolaRes

lighted

Clouds	*MBD (%)*	*RMSD (%)*	
CT=1	0.5	3.2	
COT < 0.5	0.4	6.4	}
COT in 0.5-2	-4.0	17.4	}
COT > 5	9.6	38.3	



Mean COT: **5+-11** **22+-32**

Mean CDER(um): **12+-10** **7+-5**

CDER = cloud droplet effective radius, given by SAFNWC

7. Conclusions

PV-Live : observation of standard GHI + GTI in PV conditions with Silicon sensors

Definition of calibration coefficients on 1 clear-sky day

→ equal RMSD in GHI and GTI-west over 1 year in clear-sky

→ +1-3 % RMSD in south and east

2 % correction for GTI-west probably because of calibration uncertainties,

but may need 4 % correction for GTI-south and GTI-east

→ +1.5 % RMSD in GTI-west over 1 year in all-sky

+1 % RMSD by a parameterisation model in both clear and all-sky conditions

→ better results with SolaRes in clear-sky but slightly worse in all-sky

→ possible improvement in cloudy cases with SolaRes ?

7. Conclusions

PV-Live : observation of standard GHI + GTI in PV conditions (spectral and angular)

+1 % RMSD by a parameterisation model in both clear and all-sky conditions

→ better results with SolaRes in clear-sky but slightly worse in all-sky

→ possible improvement in cloudy cases with SolaRes ?

With SolaRes, RMSD increases with COT

For example, 17 % RMSD for cirrus with mean COT=5+-11, but

29 % RMSD for low clouds with COT=22+-32

Perspectives : sensitivity study on SolaRes performances with cloud optical thickness, droplet effective radius, phase and cloud typology.

THANK YOU

te@hygeos.com