Software correction of angular misalignments of tilted reference solar cells using clear-sky satellite open data

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SOFTWARE CORRECTION OF ANGULAR MISALIGNMENTS OF TILTED REFERENCE SOLAR CELLS USING CLEAR-SKY SATELLITE OPEN DATA

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ABSTRACT: In-situ measurements for photovoltaic systems are very sensitive to angular misalignments. It can lead to errors in many steps of a photovoltaic (PV) project. In this paper, we propose a simple and robust method to estimate and correct a posteriori the angular misalignment of tilted reference solar cells or pyranometers. The method uses output of the clear-sky irradiance model McClear, a free Copernicus Atmospheric Monitoring Service. We applied the method in 6-month data composed of 7 different tilted reference solar cells. We find that angular misalignment estimation found in the case study are meaningful. Finally, we showed the angular correction found improves satellite-based estimation of GTI for the 6 following months of data for clear sky days, for both RMSE and bias indicators.
Keywords: in-situ measurements, angular misalignment, satellite data

1 INTRODUCTION AND CONTEXT

In 2018, world photovoltaic (PV) installed capacity crossed the 500 GW_p mark [1]. The growth is exponential and is expected to continue in the following years [1].

Due to this high growth, the market is becoming more competitive, and PV stakeholders are improving more and more the resource assessment, PV production characterization and forecast. All of this relies on accurate solar irradiance data, using *in-situ* measurements with thermopile pyranometers, photodiode pyranometers, and photovoltaic reference cells [2].

In-situ measurements for photovoltaic systems are very sensitive to angular misalignments. For example, they increase errors in solar resource estimation or nowcasting [3]. They also reduce the accuracy of cloud tracking algorithms (e.g. in [4]). Angular misalignment can occur e.g. during the installation or the operation, notably due to temperature gradients, wind efforts, birds, etc.

In parallel to *in-situ* measurements, satellite-derived irradiance databases can provide complementary and easily available data (e.g. [5]). Satellite data provide a stable measurement that can be compared with *in-situ* measurements to detect and correct angular misalignments, to avoid the important errors described previously.

In this paper, we propose a method for estimating the angular misalignment of tilted reference solar cells or pyranometers using output of the clear-sky irradiance model McClear, a free Copernicus Atmospheric Monitoring Service.

2 DESCRIPTION OF THE METHOD

The proposed method needs preliminary *in-situ* measurements of global tilted irradiance (GTI) of reference solar cell or pyranometer. The goal is to estimate the angular misalignment of the sensor and eventually correct it. For that purpose, we compare the measurements with output of the clear-sky irradiance model McClear, a free Copernicus Atmospheric Monitoring Service [6].

An illustration of the method is given in Figure 1. The comparison of measurements and satellite data is done using Perez luminance transposition model [7] applied on the global and diffuse horizontal irradiation coming from McClear model. It is done by knowing the solar azimuth and elevation angle, ground albedo as well as azimuth and tilt angle of the *in-situ* instrument (noted respectively α and β). If the measurement is from a reference solar cell, incident angle modifier (IAM) model of the reference cell is applied in the direct and circumsolar component of the solar irradiance. Then, once the simulated global tilted irradiance $(GTI_{sim}(\alpha,\beta))$ is computed, the root mean square error is computed on selected clear sky days from the measured GTI:

$$RMSE(\alpha,\beta) = \sqrt{\frac{\sum_{i=1}^{n}\left(GTI_{sim,i}(\alpha,\beta) - GTI_{meas,i}\right)^2}{n}}$$

Where i is the time index, n the number of samples. Finally, tilt and azimut angle are optimised in order to minimise the RMSE and the resulting azimuth and tilt angles $\hat{\alpha}$ and $\hat{\beta}$ are the corrected angles from misalignments.

$$\left(\hat{\alpha},\hat{\beta}\right) = argmin[RMSE(\alpha,\beta)]$$

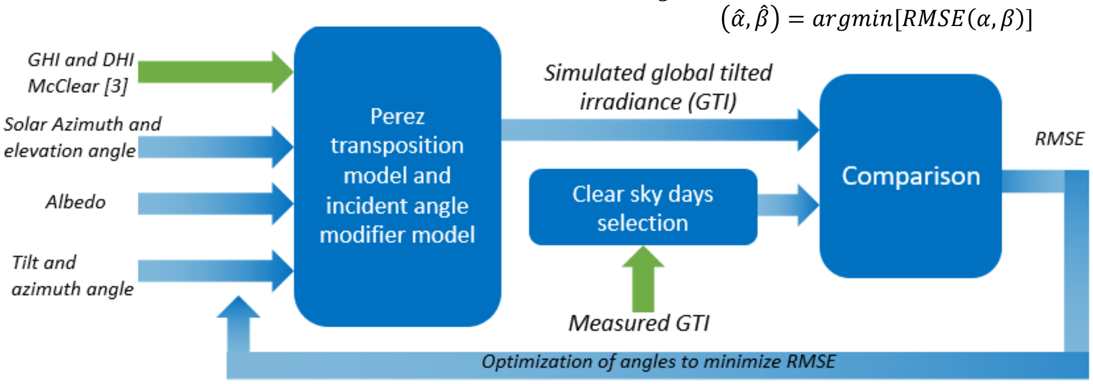

Figure 1: Illustration of the different steps of the software correction method for angle misalignments

3 CASE STUDY

3.1 Description of the data and method application

In order to test the method, one-year data (2017) from Opti-SkyControl© sensors developed by Optimum Tracker company are used. Data are recorded at 1min time step for a site located in South Est of France. Opti-SkyControl© is derived from an Optimum Tracker's patent [4] and is designed for North-South 1 axis solar trackers, in order to estimate the PV production at any angle. Opti-SkyControl© is composed by 7 reference cells with different tilts: -35°, -20° and -10° facing East, 0° horizontal cell and 10°, 20° and 35° facing West. Reference cells were calibrated by meteocontrol before the commissioning. Opti-SkyControl© also includes a pyranometer and a hemispheric camera that are not used in this case study.

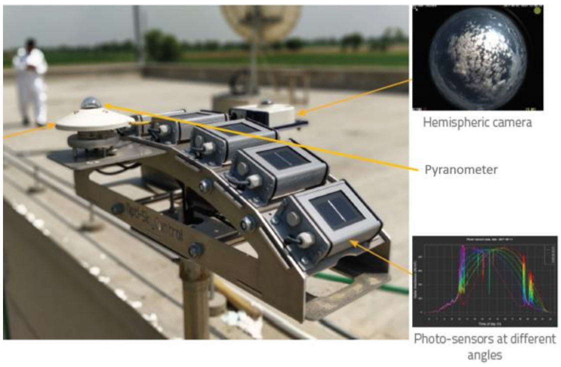

Figure 2: Opti-SkyControl© Sensors developed by Optimum Tracker company

For the comparison, CAMS McClear data are downloaded for the corresponding site with clear sky global horizontal irradiance (GHI) and clear sky diffuse horizontal irradiance (DHI). Cloud-free days are selected manually using in-situ measurements and used for the misalignment correction (9 full clear sky days in the first six months, and 8 full clear sky days in the last 6 months in the dataset).

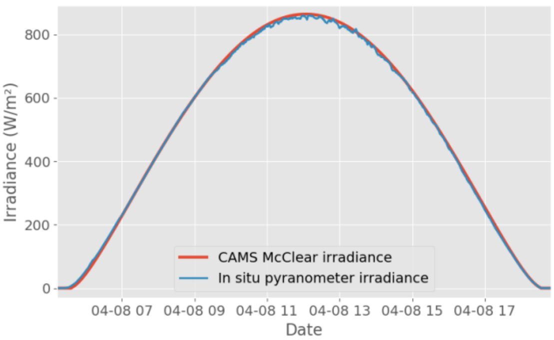

Figure 3: Example of clear sky day irradiance plot showing both *in-situ* pyranometer measurement and irradiance from clear sky McClear model.

Solar azimuth and elevation are computed at every time step using pvlib python library [8]. Ground albedo is set to a standard value of 0.15.

3.1 Results and discussion

Perez transposition model together with IAM model on the direct irradiance component part is applied on satellite data for the first 6 months of data (from January to June 2017). Different tilt and azimuth angles are tested for each solar cell, and the correct angle is chosen by minimizing the root main square error between satellite irradiance projection and in situ measurements.
Resulting angles are put in Table I.

Table I: Value of the correction of the different angles

Reference cell tilt angle (°)	Correction angle to add in azimut (°)	Correction angle to add in tilt (°)
-35	4,88	1,81
-20	5,02	1,34
-10	4,96	1,31
0	5,12	2,85
10	5,32	0,32
20	5,53	0,45
35	4,62	1,18

We can notice the corrected angles in azimuth found to be added are all between 4.62° and 5.53° to add. It means the Opti-SkyControl© must be shifted of around 5° to in the North direction when facing the East direction.
Tilt angle corrections have a maximum deviation of 2.85°for 0° tilted sensor. Deviation found is between 1.81° and 0.32° for other sensors. Regarding these results, the mast holding the Opti-SkyControl© must face a small deviation from the horizontal.

In order to test the interest of the method, the simulated GTI is computed from the satellite derived irradiance for a priori azimuth and tilt angles, and for the new corrected angles. The simulation is done in the 6 next months of data (from July to December 2017) to ensure a cross-validation and is compared to *in-situ* measurements.
Results are displayed in Figure 4 and Figure 5.

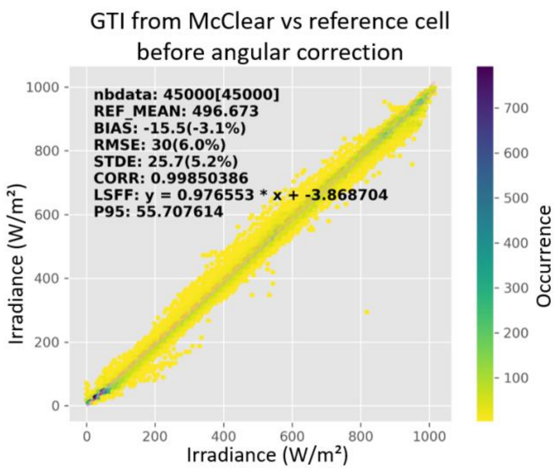

Figure 4: All sensors measurements in the second 6-months 2017 period in clear sky days vs GTI from McClear model, with a priori tilt and azimuth angles.

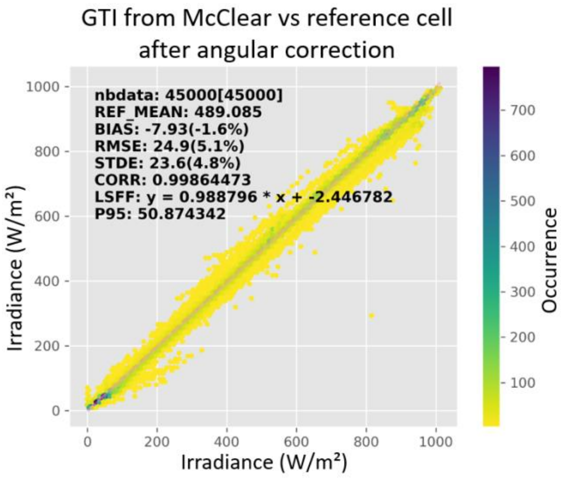

Figure 5: All sensors measurements in the 6 last-months 2017 period in clear sky days vs GTI from McClear model, with corrected tilt and azimuth angles. Correction was done in the first 6-month 2017 period.

The results show significant reduction of the RMSE (-5.1W/m²) and Bias (-7.6W/m²) indicators for all sensors included. Table II details the results for each reference cell.

Table II: RMSE and bias values and improvement in the comparison of the 6 last-months 2017 period dataset

Reference cell tilt (°)	RMSE before correction (W/m²)	RMSE after correction (W/m²)	RMSE improvment (W/m²)
-35	32,50	20,90	11,60
-20	29,50	17,60	11,90
-10	39,5	33,70	5,80
0	31,50	27,60	3,90
10	23,60	21,60	2,00
20	21,90	21,50	0,40
35	27,90	27,70	0,20

Reference cell tilt (°)	Bias before correction (W/m²)	Bias after correction (W/m²)	Bias improvement (W/m²)
-35	-11,5	2,38	13,88
-20	-17,5	-3,2	14,3
-10	-28,1	-20,7	7,4
0	-17,9	-11,7	6,2
10	-15	-9,32	5,68
20	-8,28	-4,96	3,32
35	-10,3	-8,09	2,21

When analysing results in Table II, we can see that the best RMSE and bias improvments are obtained for -35° and -20° reference cells. Then comes -10 and 0° reference cells. These results are coherent with the value of the angle corrected in Table I : these 4 sensors have higher tilt angle correction than the 3 others.
We clearly see the improvment of the 6 months for the 7 sensors, from 11.9W/m² to 0.2W/m² for the RMSE improvement, from 14.3W/m² to 2.21W/m² for bias improvement. Figure 5 illustrates temporally the improvement obtained in the satellite-derived GTI before and after correction in a particular day.

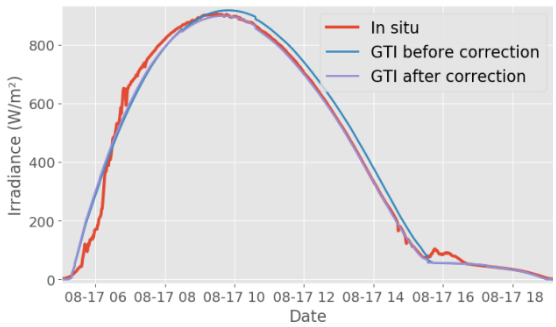

Figure 6: Comparison with -35° tilted reference cell and satellite-derived GTI before and after correction

4 CONCLUSION AND PERSPECTIVES

In this paper, we proposed a simple and robust method to estimate and correct *a posteriori* the angular misalignment of tilted reference solar cells or pyranometers using output of the clear-sky irradiance model McClear, a free Copernicus Atmospheric Monitoring Service.

We observed that angular misalignment estimation found in the case study are meaningful. Then, we showed angular corrections improve satellite-based estimation of GTI for the 6 following months for clear sky days, for both RMSE and bias indicators.
A next possible step is to make a dynamic correction to detect significant misalignment variations. Also, the angles found by the method can be compared with on-site precise azimuth and tilt measurements of the sensors.

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