# MINUTE RESOLUTION MEASUREMENT NETWORK
# FOR GLOBAL HORIZONTAL AND TILTED SOLAR IRRADIANCE
# FOR A TRANSMISSION SYSTEM CONTROL AREA IN SOUTHERN GERMANY

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ABSTRACT: Grid operators have to apply upscaling techniques to estimate the total power feed-in by PV systems in their control areas. In order to improve the real-time upscaling of PV power production in the control area of the German transmission system operator TransnetBW we set up a network of 40 solar irradiance measurement stations in the TransnetBW control area in Southern Germany. The measurement stations consist of a pyranometer, measuring global horizontal irradiance, and three silicon cells oriented east, south, and west with tilt angles of 25°. They measure irradiance in minute resolution and transfer the data in near real time. In order to ensure a good quality of our data we have developed a new quality control scheme exploiting the sensors with different orientations. Here we focus on our approaches for detection of horizons profiles and orientations by learning from measurements.
Keywords: Solar radiation, Quality Control, Monitoring, Shading, Pyranometer

## 1 INTRODUCTION

With the constantly increasing installation of PV power and its volatility due to weather, reliable predictions of PV power feed-in to the grid become increasingly important for a stable and cost-efficient electricity supply. In Germany, as in many other countries, only for a small fraction of PV systems PV power is monitored in real time. Grid operators have to apply upscaling techniques to estimate the total feed-in by PV systems in their control areas. Currently, these methods mostly rely on power output measurements of a set of reference PV plants. In order to improve the upscaling of PV power production in the control area of the German transmission system operator TransnetBW we set up a network of 40 solar irradiance measurement stations, measuring and transferring minute resolution irradiance data in near real time in the project PV-Live. Each measurement station consists of a pyranometer, measuring global horizontal irradiance and three silicon cells oriented east, south and west with tilt angles of 25°, measuring global tilted irradiance. These irradiance measurements are an additional high resolution input to the PV power upscaling and forecasting system of TransnetBW.

The use of irradiance data complementing PV power measurements is a new concept in PV power upscaling. The irradiance data are used as a basis to simulate the expected PV power of a typical PV plant, corresponding to the meteorological potential of PV electricity generation. This approach aims at a better understanding and modelling of the different effects influencing PV power generation. It allows distinguishing between meteorological effects and local, system-specific effects such as shading or self-consumption before the feed-in point.

Moreover, with the setup of our measurement network we create a new high resolution irradiance data set. Irradiance measurements play an important role in solar resource assessment, not only as input data for different applications, but also as a basis for model development, improvement and evaluation. Our minute resolution network covers the control area of TransnetBW with distances of 15 to 35 km between neighbouring sites and allows for evaluating spatial averaging and smoothing effects on this regional scale. The spatio-temporal resolution of our network is considerably higher than the typical resolution of irradiance networks by weather services, e.g. the German Weather Service DWD. Furthermore, the sensor combination is a unique feature of our stations and allows, e.g, to evaluate tilt conversion models. The measurement concept with four irradiance sensors also enables enhanced methods of data quality control, exploiting combinations of these sensors.

In this paper we describe our irradiance measurement network and the measurements stations. We give an overview of our quality control scheme with a focus on shadow detection with a machine learning approach and detection of station orientation based on the three silicon sensors. For orientation detection we analyse and compare the results of different configurations.

## 2 MEASUREMENT STATIONS AND NETWORK

### 2.1 PV-Live network

The network which was set up in the project PV-Live consists of 40 measurement stations in the control area of the transmission system operator TransnetBW, corresponding widely to the state of Baden-Württemberg (Fig. 1).

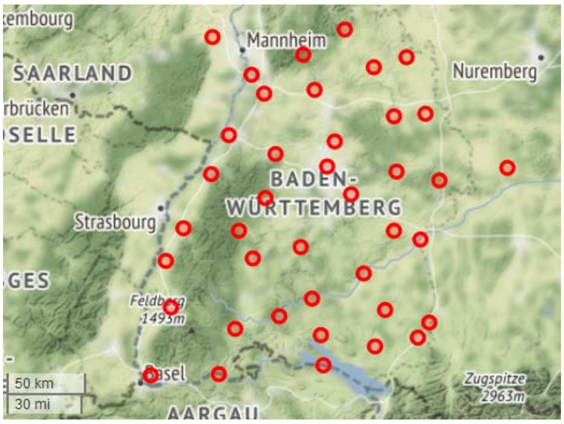


**Figure 1:** Locations of 40 PV-Live measurement stations in the control area of Transnet BW, widely corresponding

to the state of Baden-Württemberg.

In order to achieve a good representation of the mean irradiance in the network area, it is important that the measurement stations are distributed evenly. The stations are mostly installed close to PV power plants, some of them are also installed at outposts and buildings of TransnetBW, public utilities and other station partners. The distance between neighbouring measurement stations is between 15 and 35 km. Irradiance is measured and transferred in minute resolution in near real-time. The first stations started operating in summer 2017 and the complete network with 40 sites is operational since spring 2019.

2.2 Measurement stations

The measurement stations (Fig. 2) comprise of a pyranometer (SMP 10-V; ISO-9060 [1] Class A sensor) to measure global horizontal irradiance (GHI) and silicon photovoltaic reference cells (Mencke&Tegtmeyer Si-sensors) to measure global tilted irradiance (GTI) for east, south and west direction with tilt angles of 25°. The Si-sensors are calibrated in the ISE inhouse calibration lab with a measurement uncertainty of 1.3%.

The design of our measurement stations is motivated as follows:

- Measuring GHI with class A pyranometers aims at providing irradiance information with low uncertainty.
- Measurements of the tilted reference cells provide the basis for simulating the power output of typical, well-operating PV plants as complementary input to the PV power upscaling system of TransnetBW
- The usage of four irradiance sensors for each station allows for new quality control schemes, based on the comparison of the output of the different sensors.

The ground measurements are complemented by satellite derived irradiance values, derived from Meteosat Second Generation images with an advanced version of the Heliosat method [2].

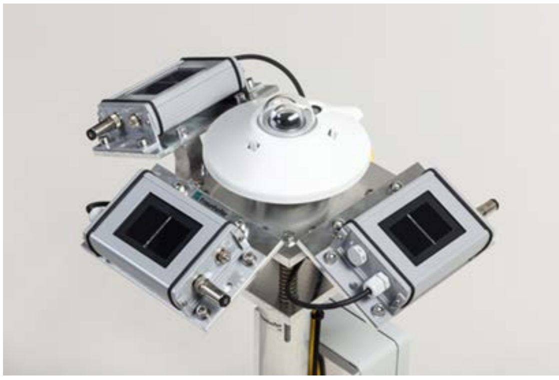

**Figure 2:** Measurement stations with a pyranometer to measure global horizontal irradiance and three silicon cells to measure global tilted irradiance, oriented towards east, south and west direction with 25° tilt angles.

## 3 QUALITY CONTROL

The operation of our irradiance measurement network includes maintenance of the stations, regular calibration of the instruments and continuous quality control in order to ensure a good quality of the data.

The PV-Live measurement stations are installed in field conditions. Regular onsite-maintenance is performed with a yearly schedule and involves a check of the instruments and installation as well as cleaning of the sensors. The sensors are recalibrated every three years. A maintenance concept for the stations based on the results of the quality control is currently under development.

Our quality control scheme aims at the detection of systematic effects like soiling, shading, calibration issues, and problems with data logging as well as the detection of outliers and faulty measurements, e.g. caused by snow or dew on the pyranometers.

Basic quality control of the irradiance measurements includes range limits as described e.g. in [3], [4] for GHI. In addition, we derive range limits for GTI measurements. Furthermore, exploiting different combinations of the four irradiance sensors enables enhanced quality control schemes, including sensor consistency tests. Snow or dew on the non-ventilated pyranometers are detected with a threshold procedure in comparison to measurements of the three silicon cells, additionally using temperature information.

Furthermore, our quality control includes labelling of measurements that are affected by shading. Even though when placing the stations we aimed at avoiding obstacles nearby, temporary shading of the sensors could not be completely avoided, especially for low solar elevations. To identify these shading events, we learn horizons from measurements.

Another aspect of quality control of irradiance measurements on tilted planes is to precisely determine the sensor orientation. The three tilted silicon reference cells should be oriented towards east, south and west respectively. However, we found from data analysis that some of the stations showed deviations from this aimed orientation. This is a well-known issue also for PV power plants, where often information on the systems' orientation does not agree with the actual orientation. Measuring PV system or measurement station orientation with a magnetic compass does not lead to reliable results in environments, where the Earth's magnetic field is disturbed by local magnetic fields, which is typically the case for PV systems and/or buildings. More elaborate methods are required to determine system or station orientations with low uncertainty, e.g. based on landmarks or on the analysis of shadows on a sunny noon. Here, we present and analyse an approach to detect station orientation based on the analysis of measurements.

Overall, our quality control can be split into three elements:

- Detection of horizon lines and station orientation by learning from measurements;
- Automated calculation of flags for single data points based on range limits or sensor inter-comparisons;
- Manual assignment of flags for persistent problems until the problem is solved;

Evidently, these elements of quality control are not independent of each other. Therefore they are determined in an iterative procedure. In this paper, we focus on shadow and orientation detection.

3.1 Shadow detection

Obstacles casting shadows on the measurement sensors have a strong impact on irradiance measurements. Fig. 3 shows measurements for three mostly clear sky days in winter with a drop of irradiance at the same time for all the days, indicating shading.

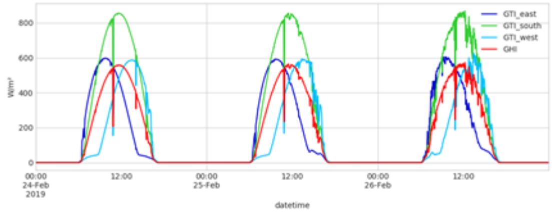


**Figure 3**: Irradiance Measurements of the PV-Live station in Wendlingen for three days in February 2019.

In order to flag shading events, we derive horizon lines for each station. Timestamps with the sun below these horizon lines are labelled as shaded. Horizons are learned directly from measurements in order to include shading by topography as well as shading by objects like trees or buildings.

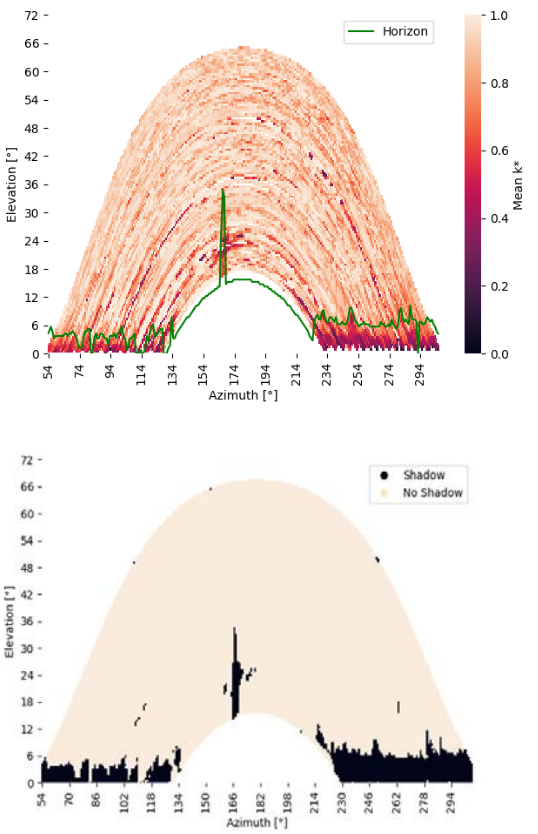


**Figure 4**: Clear sky indices derived from measurement data grouped by solar azimuth and elevation for clear sky situations with the detected horizon line for clear sky situations (top). Clusters derived with k-means clustering (k=2) corresponding to shadow and no shadow (bottom). Dataset: PV-Live station in Wendlingen, August 2017 – December 2018.

Our method for horizon detection consists of the following steps:

- Clear sky situations are identified using satellite derived irradiance values that are not affected by shading. We use a simple, not very strict threshold criterion based on clear sky index values:
  $k^*_{sat} = \frac{GHI_{sat}}{GHI_{clear}} \geq 0.75,$
  with $GHI_{sat}$ denoting satellite derived irradiance and $GHI_{clear}$ clear sky irradiance derived with a clear sky model [5].
- For these clear sky situations the ratio of the measurements to clear sky irradiance, i.e. measurement based clear sky index values $k^*_{meas}$, are grouped by solar azimuth and elevation (Fig. 4, top). Low values of $k^*_{meas}$ in clear sky situations indicate shadow.
- Data gaps are filled and the data is smoothed along the elevation axis to remove artefacts with a simple block smoothing.
- This smoothed data is used as input for k-means clustering with k=2. K-means is a well understood iterative clustering method [6] that consists of two repeating steps. Here we use the k-means implementation from [7]. The two resulting clusters can be thought of as shaded and unshaded. (Fig. 4, bottom). The line separating them is the horizon line.

An example of the calculated flags is shown in Fig 5. The irradiance drop before noon and the irradiance ramp in the evening correspond quite well with the calculated shading flag.

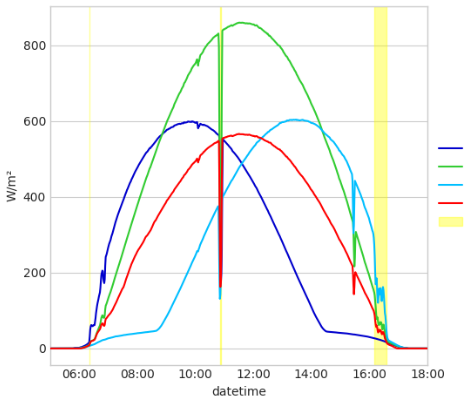


**Figure 5**: Irradiance Measurements of the PV-Live station in Wendlingen for a day in February 2019 with shadow flags.

3.3 Orientation detection and monitoring

The orientation of the measurement stations is determined by the silicon sensors, which should be oriented towards east, south and west respectively.

In order to detect deviations from this orientation, we adapt the approach proposed by Killinger et al. [8] as a part of their quality control algorithm for distributed photovoltaic array power output (QCPV). The QCPV approach aims at detecting azimuth and tilt angle as well as a loss factor for PV power plants lacking information of these parameters. Thereto, the difference of simulated and measured PV power for clear sky situations is minimized with respect to these parameters.

In our case we aim at detecting the station azimuth only, the tilt angle is known to be 25° and not subject of optimisation. As the three sensors have fixed 90° angles between them, the minimization can be done on all sensors combined. This leads to more stable results of the orientation detection than considering only one sensor, especially when only a short period of measurements is considered as input for the optimization (see section 4). Also, in a first approach the loss factor is neglected, which is motivated as follows: The sensors are regularly calibrated and the effect of soiling in Germany is expected to be reversible and variable, because of climatic conditions in Germany with rather frequent precipitation. Furthermore, periods, for which the consistency check between GHI and GTI reveals major deviations are flagged and not considered for orientation detection.

Since the stations measure both GHI and GTI, we can convert measured horizontal irradiance $\mathrm{GHI}_{\mathrm{meas}}$ to GTI and minimize its difference to measured tilted irradiance $\mathrm{GTI}_{\mathrm{meas}}$ to detect station orientation. Let $T$ be a combination of a diffuse/direct separation model and a transposition model for mapping GHI to GTI. Here we apply the DIRINT model [9] for direct /diffuse separation and the simplified version of the Perez diffuse irradiance model for tilted surfaces [10] for transposition, for both using their implementation in PVlib [11].

Using all three sensors together the angle $\Phi$ is detected, by which the stations differ from their ideal orientation with $\alpha_1 = 90°$ for sensor 1 (east), $\alpha_2 = 180°$ for sensor 2 (south), and $\alpha_3 = 270°$ for sensor 3 (west), respectively.

The optimization with respect to $\Phi$ is defined as:

$$\min_{\Phi} \sum_{i \in \{1,2,3\}} \| \mathrm{T}(\alpha_i + \phi, \mathrm{GHI}_{meas}) - \mathrm{GTI}_{\mathrm{meas,i}} \|.$$

The metric used for the optimization is the sum of the squared error. The minimisation is done using all of the data of a station in a given period, and additionally using clear sky situations only, because the effect of sensor orientation is most prominent for clear sky situations. The differences in the measurements of the four sensors for clear sky days are illustrated in Fig. 3. In contrast, Fig. 6 shows similar measurements of all sensors for overcast days. For clear sky detection here we deploy the method by Reno et al. [12].

The detected azimuth angles were used for tuning of stations orientation in maintenance. Accidental rotations of our stations, which are located out in the open, happened in a few cases. For a continuous monitoring of orientation angles, they are computed once a day using the data of the last thirty days in a moving window.


**Figure 6**: Irradiance Measurements of the PV-Live station in Freiburg for cloudy days in December 2018.

## 4 ANALYSIS OF ORIENTATION DETECTION

The data of our measurement stations with four sensors allows investigating quality control schemes for tilted irradiance measurements. Here we show an analysis of our approach for orientation detection and monitoring comparing different configurations.

We investigate

- the effectiveness of using three sensors over one,
- the effect of using only clear sky data in the minimization compared to using all of the data of a station in a given period,
- the influence of the period used to determine orientations.

For the analysis we determine a daily value for the orientation - by using time series of the respective past 30 days as input (rolling window approach). The data set used here spans the year of 2019 and includes data of the three stations Stuttgart, Freiburg, and Zwiefaltendorf. For each station an “all year reference” value of the orientation was calculated by using three sensors and the complete time series of the year 2019 based on all data and based on clear sky data only (Table 1). For the analysed sites the azimuth angles for the two configurations deviate less than 1°.

**Table I:** Azimuth angles of three stations determined using data of the full year 2019 with the three sensor approach using all available GHI data or clear sky GHI data only.

| | all | clear sky |
|---|---|---|
| Freiburg | 183.49° | 183.61° |
| Stuttgart | 181.42° | 181.70° |
| Zwiefaltendorf | 182.33° | 182.60° |

Fig. 7 shows the deviations of the orientation $\Phi$ derived from the rolling window approach of three sensors and the South sensor from the long term reference values depending on the fraction of clear sky situations. Fig. 8 shows the differences between orientations determined from all available data and from clear sky input only, respectively.

Both figures illustrate that using input from three sensors yields more reliable results than using input from one sensor when using a short period of 30 days as input. For the three sensor method (Fig. 7 top, Fig 8 top), the differences remain small, up to a few degrees. Deviations are much higher for the one sensor method, especially in winter (Fig. 7 bottom, Fig 8 bottom). In general, deviations are higher when the fraction of clear sky situations in the GHI input data is low, which is expected. This pertains to both, the one sensor and three sensor method, though deviations are much more pronounced for the one sensor method. Furthermore, a trend to positive deviations with decreasing fraction of clear sky situations in summer is visible for all configurations. A trend to negative deviations in winter is observed for the three sensor method (Fig. 7 top).

Different reasons can contribute to larger deviations in winter compared to summer. Winter months have less daylight hours and therefore less data points can be used in the optimization. Also overcast conditions occur more often during winter, which can lead to data sets with not sufficient clear sky data. Moreover, typically a larger share of the data is affected by shading in winter and the sensors may be covered by snow, further reducing the amount of data usable for orientation detection. Finally, also the spectral, angular and temperature characteristics of the Si-sensors can have an effect on orientation detection. Our analysis shows that the impact of these factors is mitigated when using the three sensors for orientation detection.

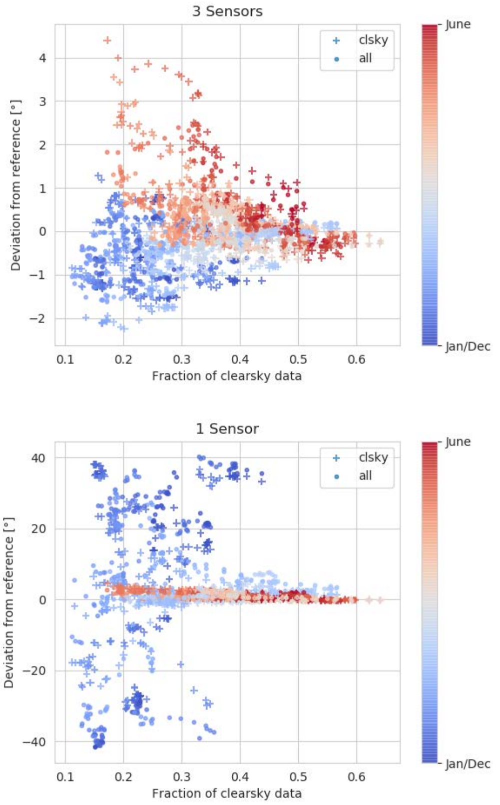


**Figure 7:** Deviation of detected azimuth angles for 30 day windows from a one year reference in dependence of the fraction of clear sky situations in the GHI input, using data of three sensors (east, south, west) (top) and using data of only one sensor (south) (bottom). The day of the year is colour coded to reflect the seasons. Results are using only clear sky GHI data (+) and all available GHI data (dots) as input. Data set: Stations in Stuttgart, Freiburg, and Zwiefaltendorf for the year 2019.

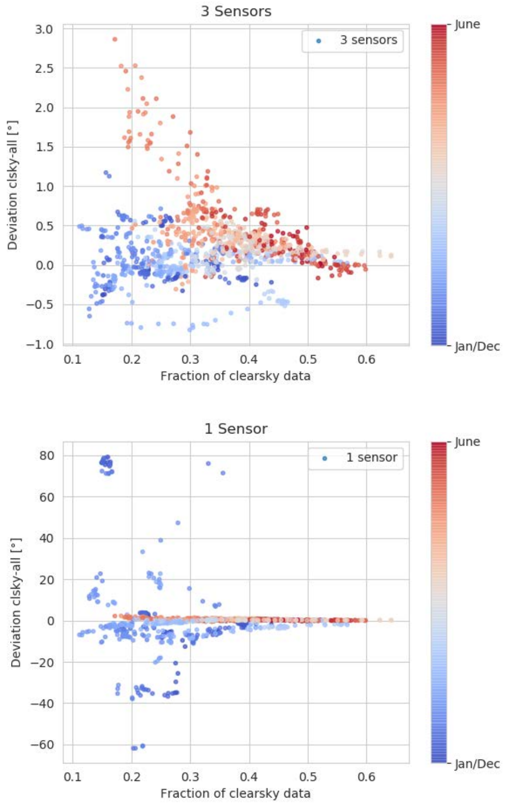


**Figure 8:** Differences of detected azimuth angles for 30 day windows found using all available GHI data or clear sky GHI data only. They are determined using data of three sensors (top) and using 1 sensor (south), bottom. The day of the year is colour coded to reflect the seasons. Data set: Stations in Stuttgart, Freiburg, and Zwiefaltendorf for the year 2019.

Based on the results of our analysis, we apply the three sensor method for orientation detection and monitoring. Fig. 9 shows histograms of the deviation of orientations determined with the rolling window approach from the all year reference value, using all available GHI data as input and clear sky GHI input only. The results derived from clear sky data exhibit a larger spread than the results derived from all data. This suggests that to obtain more stable results the input should not be limited to clear sky situations when using a short period of data for the optimisation. Still, for orientation monitoring we apply both configurations in parallel with larger differences between them indicating less reliable results.

Finally, as an independent reference, the orientation for the Freiburg stations was determined onsite by PV Performance Labs in Mai 2020, after maintenance in April 2020 with a fine tuning of the station orientation based on the results for the year 2019 given in Table I. Based on the observations of the shadow cast by the senor during noon the azimuth angle of the South sensor was estimated to lie between 178.2° und 179.2°. This is in good agreement with the result of our data analysis approach based on three sensors for the period May to September 2020, resulting in 178.2° when using clear sky data, and 178.5° when using all data.

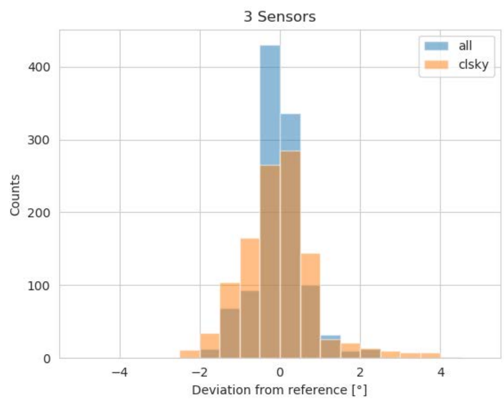


**Figure 9:** Histogram of the deviation of detected azimuth angles using 30 days windows from the all year reference, determined using all available GHI data or clearsky GHI data only and the three sensor method. Data set: Stations in Stuttgart, Freiburg, and Zwiefaltendorf for the year 2019.

Overall, the analysis of our approach for detection of station orientation angles gives insight in the performance of our method in different conditions. It indicates a reasonable performance of the three sensor method also when using only one month of data as input. We also show that orientation detection based on one senor may require periods longer than 30 days as input to obtain stable results, depending on the meteorological conditions. Still, open questions with respect to the uncertainty of our approach and potential for improvement remain.

## 5 SUMMARY AND OUTLOOK

We built and continue to operate an irradiance measurement network in the south-west German state of Baden-Württemberg, consisting of 40 measurement stations measuring both global horizontal and global tilted irradiance for east, south and west direction in minute resolution. We have developed a new quality control scheme including automated detection of horizon lines and station orientations.

A major result of our work is a quality controlled data set of irradiance measurements in minute resolution. To make the data set available for use in research, we plan to publish it along with detailed information on our quality control procedure. The published data set will include data from September 2020 onwards.

## ACKNOWLEDGEMEMTS

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