# Solar ground measurements processing by automatic and manual tools (Spracovanie pozemných meraní slnečného žiarenia automatickými a manuálnymi nástrojmi)

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## Abstrakt

Merané dáta slnečného žiarenia sú cenným materiálom k spresneniu analýzy potenciálu danej lokality vyrábať elektrickú energiu, optimalizovať výrobu či identifikovať problémy pri výrobe. Chyby merania, chyby inštrumentov, či chyby spôsobené manipuláciou s dátovými tabuľkami spôsobuje znehodnocovanie meraných dát až na úroveň, kedy sú už nepoužiteľné. Použitie neskontrolovaných dát môže viesť k fatálnym následkom, ktoré ohrozujú financovanie, chod elektrárne či distribúciu elektrickej energie. Merané solárne dáta prechádzajú trojstupňovou kontrolou kvality: základnou numerickou kontrolou fyzikálnych limitov; rozšírenou numerickou identifikáciou systematických chýb dát; a manuálnou kontrolou kvality, ktorá je časovo náročná a vyžaduje dobre trénovaného operátora. K identifikácií systematických chýb je používaná štatistická analýza a metódy strojového učenia, ktorými je možné identifikovať problémy, ktoré základná numerická kontrola nezachytí, ako sú tienenie reliéfom alebo blízkymi objektami, rosa, námraza, znečistenie senzora, náklon senzora či nefunkčnosť slnečného sledovacieho zariadenia. Záznamy, ktoré prešli kontrolou kvality sú ďalej používané pri kalibrácií modelu slnečného žiarenia na báze satelitných snímok.

## Annotation

The estimation of solar irradiance is performed either by solar numerical modelling or by ground measurements of solar irradiance parameters. The objective is to obtain the best assessment of the local conditions for every location in question. For that reason the measurements undertake the quality control and only the reliable data are then exploited in the model site adaptation.

**Key words:** solar irradiance measurements, quality control, machine learning

## 1 Introduction

Solar irradiance is defined as the solar radiation emitted from the Sun surface coming to the Earth per unit area. In this work we consider only the shortwave component of solar irradiation. The irradiance at the top of the atmosphere depends on the mutual position of Sun-Earth and also on the geographical position. The irradiance measured on the Earth's surface is decreased by absorption, reflection and scattering on particles in the atmosphere.

The satellite observations combined with the knowledge of physical properties of the atmosphere are exploited for the simulation of solar irradiance coming to the Earth’s surface. Using these inputs, Solargis is capable of calculating reliable solar irradiance data for any location between latitudes 60N and 50S. These data do not suffer from many shortcomings of the ground measurements, but on the other hand they have limitations originating from the time and space resolution of satellite images and their coverage.

Since the specific properties of each site cannot be determined without proper understanding of the microclimate of the location, the importance of solar ground measurements is unquestionable. On the other hand, the ground measurements contain errors which influence the accuracy of the particular location conditions determination.

To achieve an accurate representation of the environment at the envisaged spot is to perform a robust quality control on the available solar measurements. Moreover, only the data that passed the quality check can be applied for the Solargis data site adaptation. This approach decreases the uncertainty of both the model and the measured data.

The data quality control method exploited by Solargis will be presented in the following section.

## 2 Data

Solar irradiance measurements are taken by e.g. pyrheliometers and pyranometers installed at meteorological stations. The stations are operated by institutes (Baseline Surface Radiation Network [1], National Renewable Energy Laboratory [7], Bureau of Meteorology [2], Southern African Universities Radiometric Network [8], etc.), universities or private companies. The public networks of solar ground measurements made the data available for research purposes. The requirements for the instruments follow the standard ISO 9060 [5].

The instruments installed at the meteorological stations measure the global, direct and diffuse component of solar irradiation. Their relation is determined by the following Equation 1:

$$GHI = DNI * \sin(\boldsymbol{\alpha}) + DIF \qquad \text{(Eq. 1)}$$

GHI = global irradiance; DNI = direct irradiance; DIF = diffuse irradiance; $\boldsymbol{\alpha}$ = sun elevation angle

The typical method of measuring the direct component of solar irradiance is by a pyrheliometer pointing to the sun in the sky and mounted on a rotating tracker set up for the particular location. A pyranometer fixed on a horizontal plane measures the global irradiance. The global tilted irradiance is usually measured by a pyranometer mounted on a tilted plane. This is the most representative parameter for photovoltaic power plants. Finally, a shaded pyranometer allows the measurements of diffuse irradiance. The shading is ensured by a shading ball mounted on a sun tracker or by a shading ring. Eventually, the pyranometers dome can be partially shaded by a black mask so the pyranometer with various sensors can measure direct and diffuse irradiance components at the same time. The quality control method presented in the following section are designed for these instruments and measuring methods.

Depending on the instrument accuracy announced by the manufacturer, there exist three quality classes of common instruments [5]. The uncertainty limits for pyranometers are listed in the Table 1 below.

*Table 1: Uncertainty limits for pyranometers.*

| | Class A | Class B | Class C |
|---|---|---|---|
| GHI | ±2% | ±5% | ±10% |

The temporal granularity of the processed data varies from 1-minute to 1-hour and the data are processed in the form of time series for at least several months long period to build on a robust data sample.

## 3 Methodology

Measurements of solar irradiation are affected by systematic and random error. The random error is normally distributed while the systematic error creates bias and it usually persists in time. The reasons of systematic errors are related shifts in instruments, miscalibration, inappropriate installation, computation error, data transfer etc. The quality control methods are focused to detect the systematic errors in data and eliminate them from further processing.

The degradation of irradiance measurements is often caused due to outer conditions. Different instrument types suffer from specific kinds of inconveniences.

The direct irradiance is very sensitive to shading from nearby objects or because of the orography of the site. Considering the relative sun position in the sky during the year the shading patterns are seemingly moving on the horizon from the perspective of the pyrheliometer.

The measurements are also affected by the local meteorological conditions such as dew, frost or snow collected on the pyranometer dome. Depending on the instrument class, pyranometers are equipped with heating or ventilation units which prevent the sedimentation of water drops or snow layers.

Pyrheliometers suffer from particular issues because the instruments are mounted on a moving tracker which follows the relative position of the sun in the sky. The tracker malfunction impairs the data and such measurements have to be filtered out.

Degradation of the measurements due to soiling accumulated on the pyranometer dome is frequent mainly in arid or dusty environments. A frequent maintenance and cleaning of the instruments improves the quality of the data. At the same time, the calibration must be carried out regularly and the instrument installation must be performed by a professional according to the instrument manufacturer's recommendations.

**Quality control**

The quality control exploited in this work consists of three steps. First the basic numerical quality control is performed to eliminate the rough errors. Then an extended numerical quality control removes specific issues in the data. Finally the visual quality control by an experienced operator is carried out.

We developed a software tool SDAT for data processing and analysis which includes the numerical quality control tests and allows the operator to visualize the measurements in order to inspect them visually. The development of further improvements is still ongoing. The aim is to fully automate the quality control with the exploitation of advanced quality control checks and machine learning.

**Basic numerical quality control**

First, basic numerical quality control [6],[9] is performed. The measured data of global, direct and diffuse irradiance are checked for consistency according to the Eq. 1. The incomplete datasets undergo a two component quality check. Physical limits are controlled to remove unrealistic values. Too long periods of consecutive static values are considered suspicious and eliminated.

### Extended numerical quality control

Extended numerical quality control methods are developed in-house by Solargis to detect specific issues. The approach is based on statistical analysis of the data and makes use of machine learning. These methods include time reference check which is a prerequisite for further correct data processing.

Secondly, the measurements degradation due to shading from static objects in the meteorological station surroundings can be detected from the analysis of the direct irradiance incident on the pyrheliometer during the year. The systematic decrement of the clearness index (the ratio between the global and extraterrestrial irradiance) is a reliable indicator of shading. The tracker malfunction can be detected from a typical intraday pattern on measured data. If the pyranometer is not mounted on a horizontal plane, the measured daily profile will be apparently misaligned. Though a specific tilt of the instrument can be convenient for more precise measurements when inclined solar power panels are installed at the plant.

Finally, the identification of dew or frost sedimented on the instrument is performed by the analysis of the oscillations of the daily solar irradiance profile and its incidence is limited by reaching the dew point temperature. The degradation of measurements due to sedimented soil or dust is usually observed during a longer period and can only be removed by instrument cleaning. The set of extended numerical quality control checks is still under development.

### Visual quality control

The final step of quality control is the visual inspection performed by the operator. It is a time consuming task and requires experience and knowledgeable interpretation. It will be substituted by advanced numerical quality control checks in the future.

## 4 Results

The quality control check application is presented in the current section. As mentioned above, the primary control is based on elimination of gross errors. The measurements taken at a single station have to fulfil the Eq.1. The discrepancy between direct, diffuse and global components of solar irradiance is shown in Fig. 1 representing the time series of the three components. The Y-axis represents the measured irradiance and the X-axis shows the date. Fig. 2 depicts the application of numerical test for consistency in a scatterplot.


*Figure 1: Inconsistency between direct, diffuse and global solar irradiance components.*

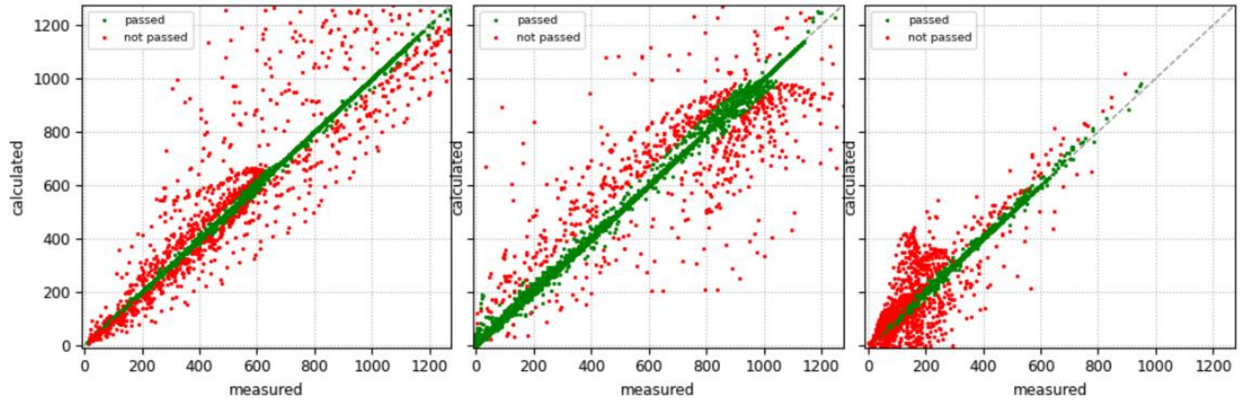


*Figure 2: Inconsistency between direct, diffuse and global solar irradiance components.*

Followingly, the unrealistic values under or above physical limits are recognized and removed from further processing. Fig. 3 shows a period of several weeks when the measurements were affected by systematic error and reached unphysical values.

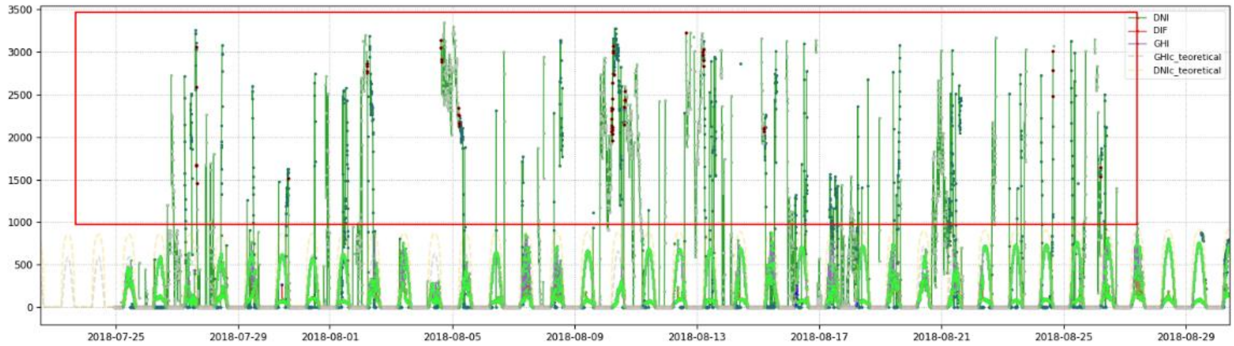


*Figure 3: Values above physical limits.*

The numerical tests identify consecutive static values (Fig. 4) of solar irradiance which usually do not represent real conditions. Such periods of measurements are excluded from the dataset.

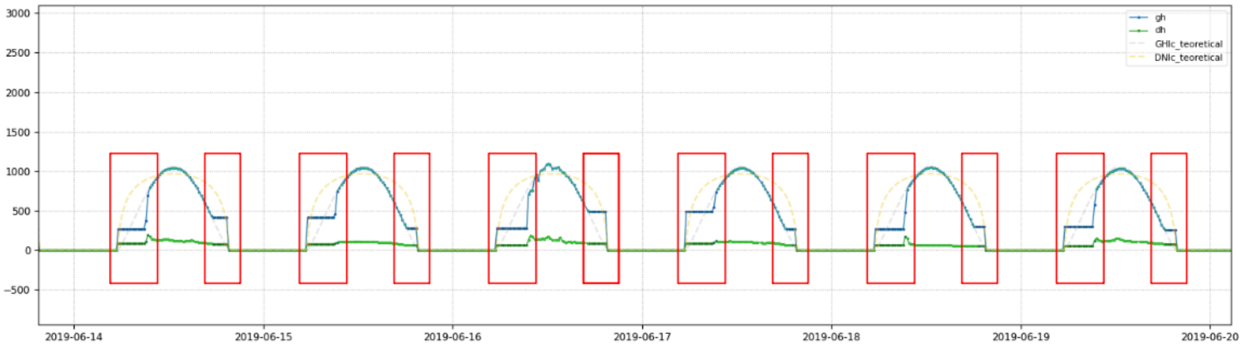


*Figure 4: Consecutive static values.*

If the direct component of solar irradiance is not available, the measured values of diffuse and global irradiance are also tested according to the Eq. 1. It is required that the measured diffuse irradiance values cannot exceed the global irradiance values. An example of such a test is depicted in Fig. 5.

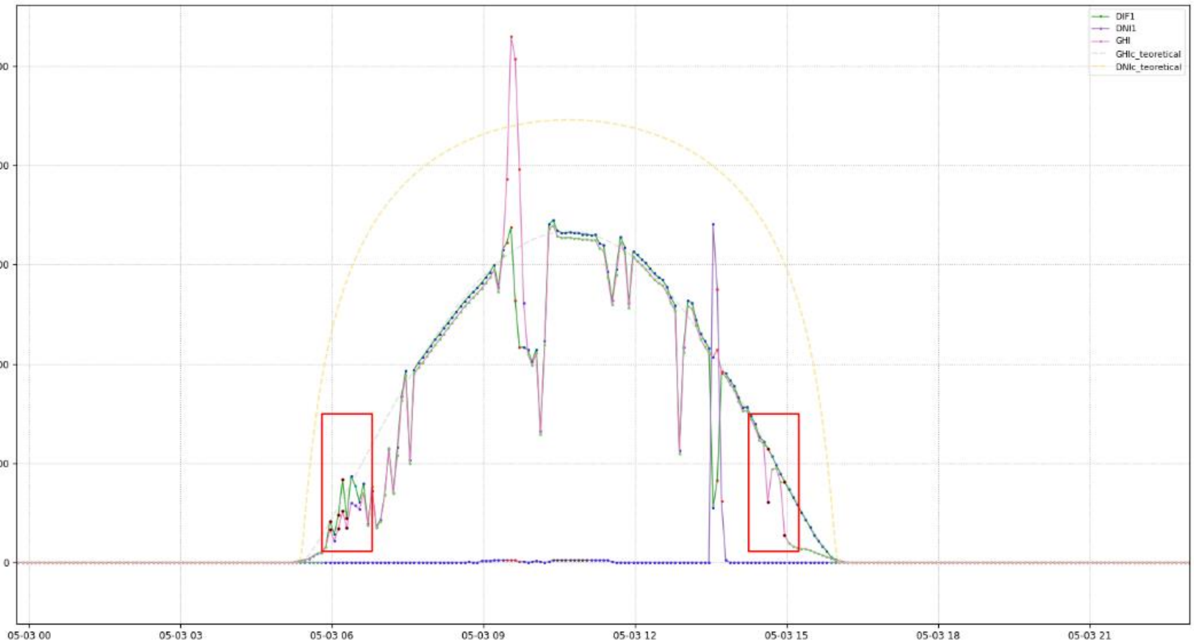


*Figure 5: Two-component test.*

Once the primary basic numerical quality control tests are performed, the resultant curtailed dataset undergoes the extended numerical tests based on statistical and machine learning approaches.

The shading detection is clearly notable in the clearness index plotted in sun azimuth and sun elevation plane as depicted in Fig. 6. The attached photographs confirm the existence of shading constructions and buildings on the horizon in the station surroundings. Thanks to the representation method the contours of those objects are visible in the clearness index plot.

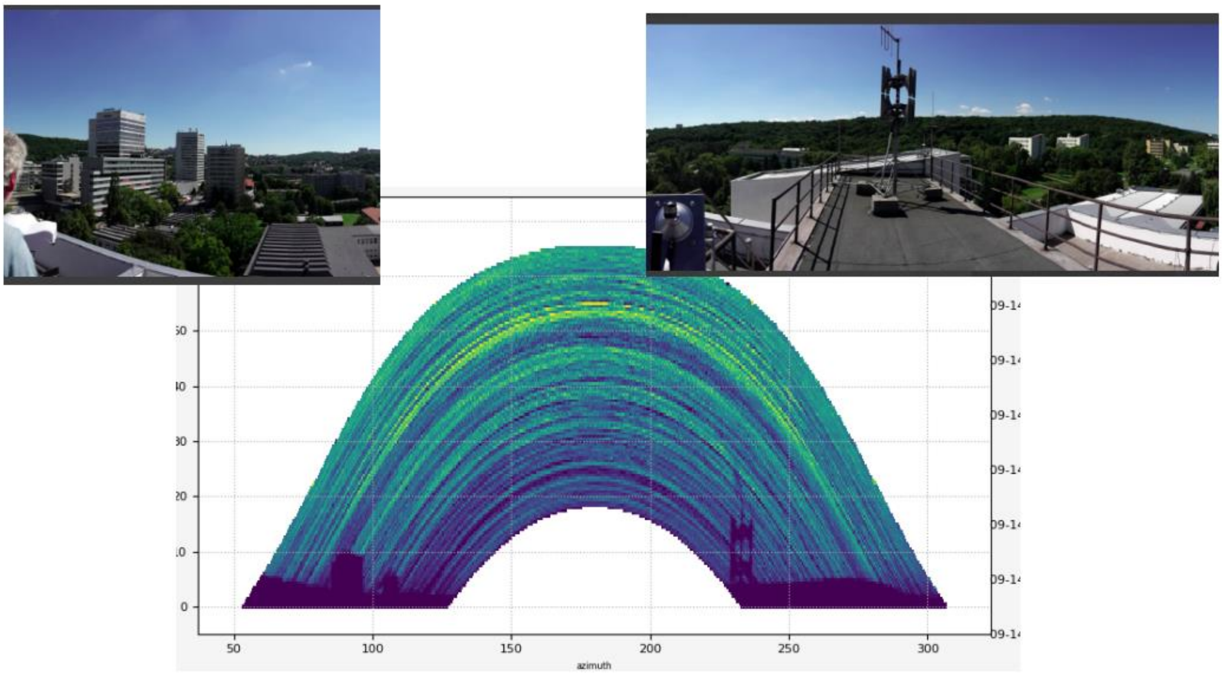


*Figure 6: Shading of the solar irradiance instruments caused by nearby objects.*

The issues related to a pyrheliometer mounted on a moving tracker are recognized by immediate and unrealistic changes of direct irradiance component measurements. The values of DNI either drop suddenly (Fig. 7) or remain static for a longer period of time (Fig. 8).

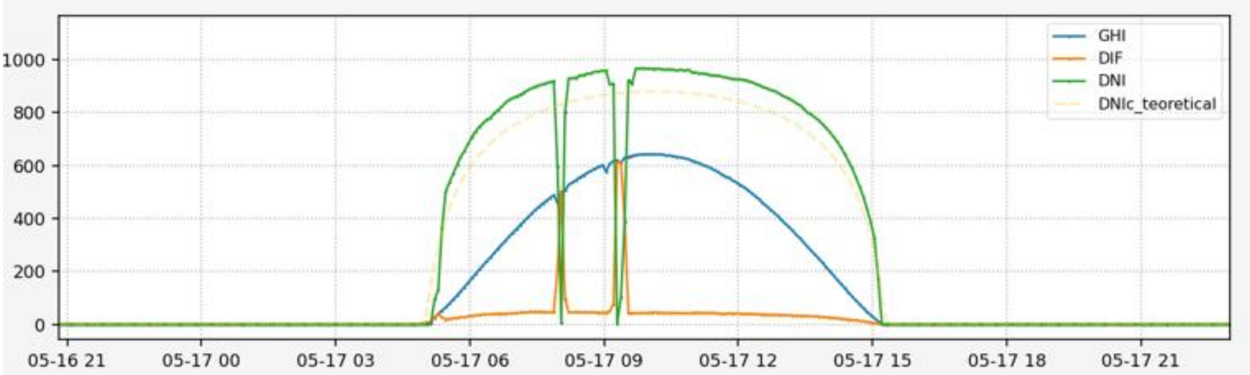


*Figure 7: Temporal tracker malfunction.*

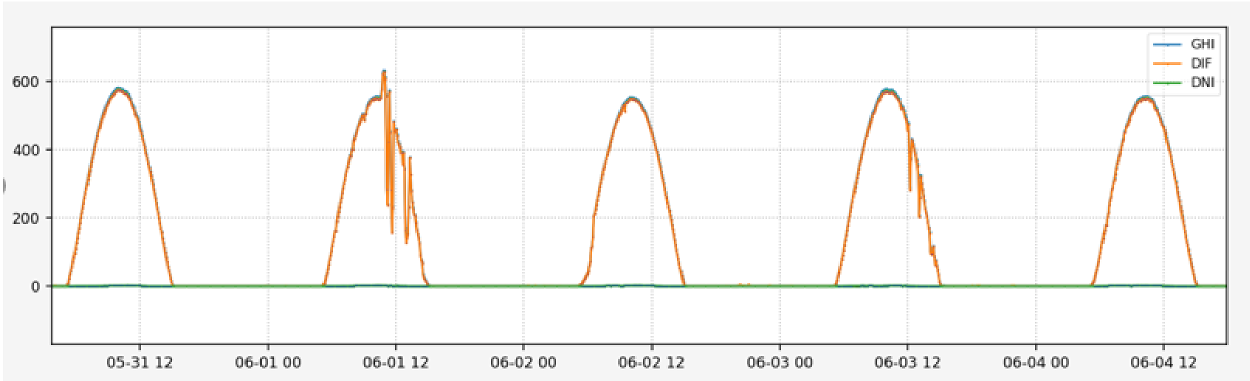


*Figure 8: Persistent tracker malfunction.*

The following Figure 9 represents the impact of misalignment of the instruments installed at the station. Here the results come from a modelled global tilted irradiance for different tilts and azimuths. The daily profiles indicate the inclination direction.

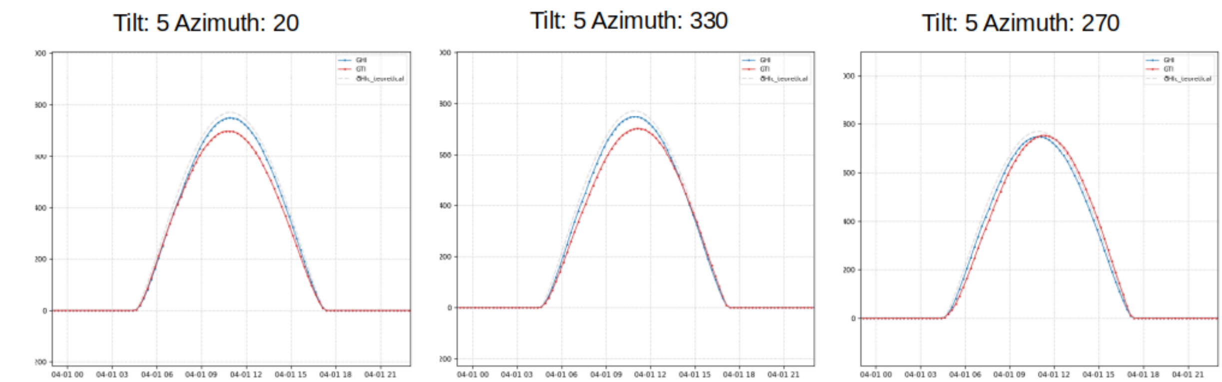


*Figure 9: Misalignment of the instruments.*

The water drops or frost collected on the pyranometer dome influence the refraction of the incoming solar irradiance. The magnifying glass effect is followed by increased scattering. A typical oscillating pattern can be observed on the global horizontal irradiance daily profile (Fig. 10). Due to the meteorological conditions, this effect is usually present during morning hours.

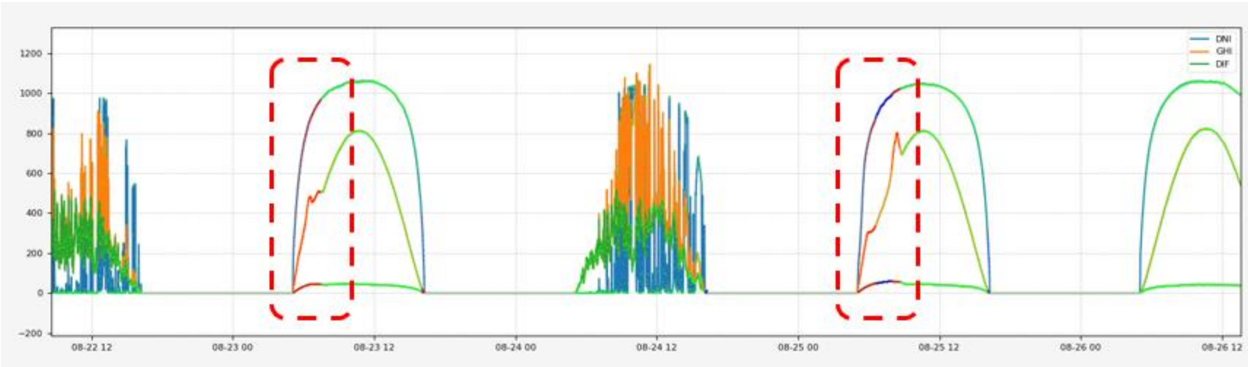


*Figure 10: Dew or frost on the instrument*

The soiling effect can manifest in two ways. Either the sedimentation of dust particles on the instrument is homogeneous and can be observed on measurements from a longer period when the measured values decrease continuously in time (Fig. 11). On the other hand, when the soiling effect is caused by heterogeneous particles (e.g. bird droppings, instruments irregularly covered by dust) the pattern is systematic but its shape is asymmetrical. The decreasing or asymmetrical pattern vanishes once the instrument is cleaned by the staff at the station or possibly by natural events such as rain.

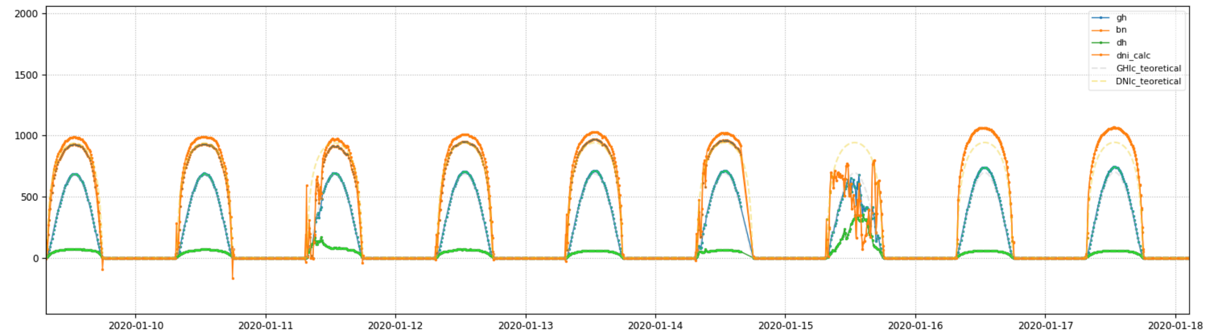


*Figure 11: Homogeneous soiling on the instrument.*

The extended numerical tests are still under development so the final check is performed by an experienced operator. The operator recognizes even minor issues which detection methods are not yet ready for daily usage.

# 5 Discussion and conclusion

The solar irradiance ground measurements reflect the local conditions on the site. The precise information contained can be used for solar model validation and calibration as well as for the TMY [3] (typical meteorological year) creation.

The TMY is a selection of the most representative conditions for the particular site. A multi-years time series is taken into account and long term statistical characteristics are computed for the whole dataset. Then a selection of data per month is performed so the resultant TMY is a combination of the most typical solar conditions over the year. Furthermore the TMY is considered a very accurate reference for the solar resource assessment.

The solar model operated by Solargis is based on satellite-derived data. The algorithm is based on atmospheric and cloud properties to simulate the radiation attenuation in the atmosphere. The result is presented in the form of computed irradiance parameters coming to the Earth's surface. Moreover, the solar power system production assessment can be carried out based on the modelled irradiance.

The accuracy of the satellite based solar model is enhanced by site adaptation [4] for particular locations. The solar ground measurements improve the description of the local climate conditions which cannot be detected otherwise. The instruments used in the measuring campaign have to accomplish recognized standards of accuracy [5]. A proper site adaptation requires at least 12 months of high quality solar ground measurements to cover the variability over the seasons. For that purpose an elaborated set of quality control checks was developed.

The understanding of the solar irradiance characteristics for a particular site are necessary for planning and designing of a solar power system. If the long term time series of solar ground measurements are not available a TMY is considered as the reference. Depending on the location a photovoltaic system or concentrated solar power system with a certain design is recommended.

During the operation a constant monitoring of a power plant and solar irradiance instruments installed on the site is necessary for early problem detection and efficient maintenance. Concurrently, the electricity production of a solar power plant is legally regulated therefore an accurate production forecast is inevitable.

In conclusion, the combination of in-house solar model development with the sophisticated quality control applied on solar ground measurements result in a high accuracy description of solar parameters at the considered site. At the end of the day, Solargis produces bankable data with a significantly reduced uncertainty which the investor of a solar power plant can rely on.

## 6 References

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