SOILING OF IRRADIATION SENSORS AND METHODS FOR THEIR CORRECTION

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Abstract – Access to exact solar irradiation data is indispensable for planning and dimensioning of applications as e.g. solar power plants. The expectable amount of yearly solar irradiation has an over-proportional impact on the financing and therefore has to be known very precise. For this reason, investigations at DLR and the PSA concern also improvements of the accuracy of measured irradiation data, which we take at some locations in southern Spain and Morocco. Devices as Rotating Shadowband Pyranometers (RSP) as well as thermal pyranometers and pyrheliometer are used. In this paper we present our findings of soiling characteristics of these sensors and corresponding methods for soiling correction.

1 INTRODUCTION

For planning of projects and applications like solar power plants, knowledge of the spatial distribution of the expectable solar irradiation in suitable regions is necessary in order to find the most promising site. Unfortunately, valid data there is rare and the accuracy of the data from several accessible sources [Quaschning00, Quaschning02] is low as they show a wide spread comparing their yearly sums [Geuder04]. Measurements of irradiation data have to be taken to get reliable and trustworthy data at a selected site. As small variations of the annual irradiation take strong influence on the outcome of the plant and successively also on the costs, they have to be known very precisely. Irradiation measurements may decide whether a plant at a selected site is either economically reasonable and might be built or if it is unattractive.

For taking solar irradiation data, different possibilities exist using sensors as e.g. Rotating Shadowband Pyranometers (RSP) and more precise thermal sensors. [Geuder04] gives an overview including the corresponding experiences with the devices. Because of a different measuring principle they show also differing accuracies. Measurements from the less precise RSP can be corrected by functional coherences and accordingly the accuracy improved [Geuder03b]. In contrary to the intrinsic accuracies of the sensors, soiling is a further cause of signal deviation and because of its statistical nature an inaccuracy of a different nature.

In this paper, after a short description of the used sensors, we present our findings on the soiling characteristics of the different sensors as well as a method for the correction of the deviation caused by soiling.

2 DESCRIPTION OF SENSORS

After a short description of the devices and principles of measurements, we present the accuracies and error specifications of the sensors. More detailed information on the sensors can be found in [Geuder03a, Geuder03b].

2.1 Rotating Shadowband Pyranometer (RSP)

Most of the meteorological stations, which are under operation in the south of Spain and in Morocco, are equipped with Rotating Shadowband Pyranometers (RSP) from Ascension Technologies Inc., USA (Figure 1).

Figure 1: Rotating Shadowband Pyranometer (RSP) in normal position (left) and during rotation (right).

The RSP consists of a horizontally mounted LI-COR radiation sensor, a semiconductor, and a shadowband mounted on a motor. In normal position GHI is measured. After a start signal coming once every minute from a steering device, the motor drives the shadow-band rotating once around the sensor (see right picture in Figure 1). Then diffuse horizontal irradiation (DHI) can be determined during the drop of the signal when a shadow is implied on the sensor. Subsequently, direct normal irradiation (DNI) is calculated from GHI, DHI and the solar height angle (which is known with time).

A Campbell CR10X data-logger is used for measuring, steering, pre-processing and storage of the data. Data collection is initiated automatically every night by a computer, connecting to the data-logger via a GMS modem. Further data processing steps are carried out automatically and finally graphically illustrated results are sent via e-mail to experienced controllers for surveillance.

2.2 High precision instruments with thermal sensors

A further station in southern Spain is running with thermal sensors for high precision measurements (Figure 2). It is equipped with a ‘first class’ Kipp&Zonen pyrheliometer CH1 for measurement of DNI and two horizontal mounted ‘secondary standard’ Kipp&Zonen pyranometers CM11 for the measurement of GHI and DHI. ‘First class’ and ‘secondary standard’ means that the devices are calibrated along ISO 9060 of the World Meteorology Organization (WMO) at the World Radiation Center in Davos, Switzerland. The devices are mounted on a Kipp&Zonen 2AP two-axis tracker, which is following the suns path on the sky with an accuracy of 0.1°. This ensures that the CH1 is always pointing in exact direction to the sun. For a steady shading of the DHI sensor, a shadow ball is fixed on the sun tracker. The two pyranometers stay horizontally mounted all the time. For correct measurements, the whole device has to be installed very precisely. Data read-out and processing is carried out in the same way as it is described in chapter 2.1.

Figure 2: Meteorological station with highly precise instrumentation: 2 pyranometers (GHI, DHI), pyrheliometer (DNI) and shadow ball, mounted on a 2AP solar tracker.

Thermal sensors convert the absorbed irradiation into heat; the arising temperature difference between frontside and backside is measured by a thermo-coupling device and yields a voltage, which is proportional to the irradiation. In order to get the specified accuracy of the sensors, leveling of the solar tracker and the sensors has to be carried out very accurate and carefully.

GHI, DHI and DNI are measured separately with three sensors here. As one of the three values can be calculated from the two others (e.g. DNI from GHI and DHI), the calculated and the measured value have to be within the range of the error specification. This offers two facilities: a) to check if levelling has been done correctly and b) to validate the measurements. Assuming that the sensors are clean the measurements are accurately calibrated and correct if calculated and measured value fits within the error range. Levelling is accurate if a remaining deviation stays constant during the day.

2.3 Error specifications of the sensors

The pyranometers CM11 and the pyrheliometer CH1 as thermal sensors show nearly constant sensitivity for the whole spectrum of solar and celestial irradiation. Existing sources for inaccuracies are listed with their corresponding values in Table 1. The maximal error is within 2% for the pyrheliometer and 4% for the pyranometer.

The LI-COR radiation sensor of the RSP, a silicon photodiode, shows as every semiconductor a systematic dependence on temperature in a range of 0.15%/K. It furthermore lacks constant spectral response in its sensitive range between 0.4 and 1.2 µm. Therefore its signal varies remarkably up to 10% with spectral variations in irradiation. Some major changes can also be detected at low solar elevations when a significant part of the near infrared solar radiation is absorbed by water vapor. As the calibration of the RSP radiation sensor is carried out for some days under real daylight conditions against an Eppley Precision Spectral Pyranometer, the determined calibration constant may have an error of up to 5%. Detailed error specifications are also listed in Table 1. Over all, errors might sum up in worst case to 25% for sun height angles above 10°, for lower sun angles even higher. As DHI is only measured punctually at the rotation once a minute, at quickly changing irradiation conditions like a halfway cloudy sky and fast moving clouds, the DHI and subsequently DNI might deviate from true irradiation values.

However, as some of these characteristics represent systematic deviations, they can be corrected by applying correction functions [Geuder03b]. After correction, the signal deviation for sun height angles higher than 10° is within 4%, annual sums of GHI are within 0,4%, sums of DNI within 1,5% and of DHI within 1,4% whereas before correction the annual sum of DNI deviated by more than 10% [Geuder03b].

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Table 1: Specifications of the sensors.

	CH1	CM11	LI-COR
Response time (95%)	7 s	< 15 s	10 µs
Zero off-set (T_{amb}-drift by 5 K/h)	±3 W/m²	±2 W/m²	—
Non-stability	< ±1%/a	±0.5%/a	< ±2%/a
Non-linearity (<1000 [3000] W/m²)	±0.2%	±0.6%	±1%
Spectral selectivity (0.35...1.5 µm)	±0.5%	±2 %	-5 ... +10%
Temperature response (-10...+40°C)	±1%	±1 %	0.15%/K
Directional response	—	±10 W/m²	< ±5%
Calibration error	±0.1%	±0.4 %	±3 ... ±5%
Viewing angle	5°	2π sr	2π sr

3 SOILING CHARACTERISTICS

Another source for falsification of the irradiation values is soiling of the sensors. In contrast to the influences described in chapter 2.3, soiling is a more statistical process correlated to ambient conditions which are physically hardly measureable neither predictable but usually reducing the signal. It is correlated on weather conditions like the actual amount of dust in the air (influenced by the prevailing nature and present state of the ground around the station), corresponding with air velocities at the location, humidity or dew on the sensors, adhesion properties of the sensor surface etc. Rain may both clean the sensors during heavy rainshowers or with slightly rainfalls deposit even more dust. Soiling affects all three types of sensors, but in fact to a different extent because of different shape and construction.
To study the soiling characteristics of the sensors, we cleaned them at several locations in southern Spain and Morocco after different time periods and took notes of the rise of the signal (Figure 3). The left graphics shows DNI signal, the right graphics GHI. As soiling is supposed to depend exponentially on time, it is plotted against a logarithmic time scale. PSA1 and PSA2 represents the same location (Plataforma Solar de Almería), both equipped with a RSP, however at PSA2 additionally thermal sensors are installed. The site in Morocco has only been staffed with a RSP whereas at the further location GU1 and GU2 in the south of Spain RSP as well as thermal sensors have been installed.

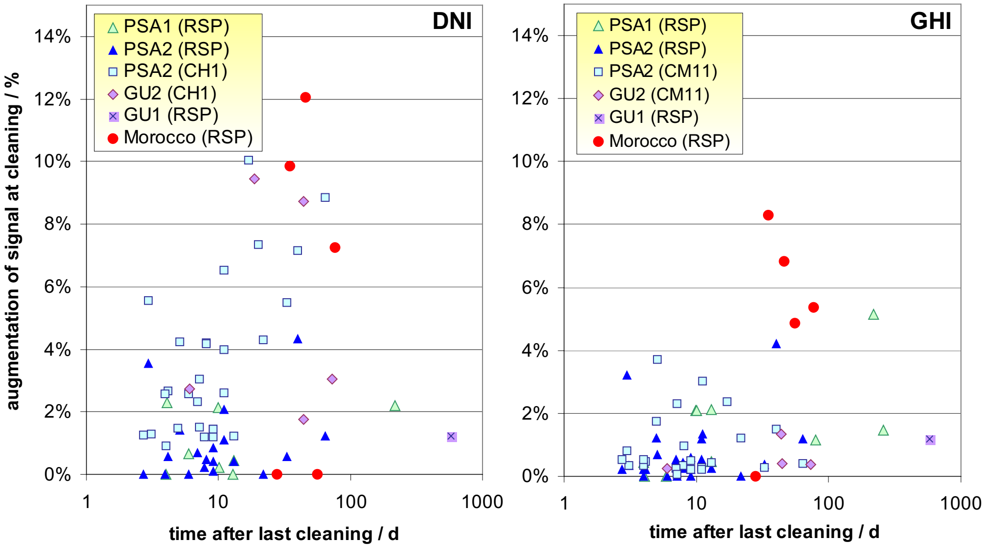

Figure 3: Soiling characteristics: augmentation of the irradiation signal (left: DNI, right: GHI) when cleaned in dependence of the cleaning interval for several sensors at different locations.

Although so far there is only a small amount of samples disposable, some characteristics yet can be seen: Comparing the different DNI sensors at the same location (PSA), the CH1 thermal sensor with an augmentation of the signal of up to 10% is much more sensitive to soiling than the LI-COR sensor of the RSP. An explanation might be that dust particles easily settle down at the front glass plate which is surrounded by a shield serving as rain protection and so preventing high air velocities there. Incoming radiation is scattered by the particles and therefore misses the sensor mounted in a certain distance. The LI-COR sensor of the RSP instead is covered by a diffusor, so additional scattering

does not have significant influence. At location GU, which is about 100 km away from PSA and has a similar nature of ground in the environments, the thermal sensor CH1 and the RSP show a similar soiling sensivity as at PSA. Whereas the signal decrease of the RSP due to soiling usually seems to be under 2% with some single peaks up to 4%, the decrease of the CH1 signal seems to be equally spread over the whole range of 8%.
Taking a look to the Morocco site however, although it is equipped with a less-sensitive LI-COR sensor, shows increase of the DNI signal at cleaning of even up to 12%. This location is near to the Sahara and therefore more exposed to deposits of dust as there is a higher affinity to sand storms. But of course with the few number of samples no proved statement can be deduced here.
Soiling characteristics at GHI is slightly different: The CM11 pyranometer with signal augmentations of up to 4% is less sensitive to soiling as the CH1 pyrheliometer but also has an even distribution of the samples over that range. The LI-COR sensor on the contrary shows for the Spanish sites single peaks of also up to a range of 5%, but its core is centered to values under 2%. For Morocco again it shows significantly higher soiling values.

4 METHOD FOR SOILING CORRECTION

With the high susceptibility of the thermal sensors to soiling, especially the DNI sensor, they need to be cleaned daily to guarantee the high precision of the measured values. Otherwise their better accuracy compared to RSP does not hold. However, as measurements here are taken separately by three different sensors, this offers a possibility to correct the signals reduced by soiling. As outlined in chapter 2.2, by comparing the measured signal of DNI with the calculated from GHI and DHI, we are able to observe the accurate calibration of the sensors. This, of course, is only valid with clean sensors. The other way round, assuming that the calibration of the sensors stays accurate within the period until accuracy is proven by the next cleaning, the deviation between the measured DNI signal and the calculated value gives information about the soiling of the sensors. A comparison of this signal deviation with the noted signal increase of chapter 3 is presented in Figure 4: One curve shows the daily deviation between measured and calculated DNI, which is calculated once for each day at solar noon, when the irradiation has been sufficiently stable. The calculations have been performed for these conditions because of the high inaccuracy for low sun height angles or unstable irradiation conditions and additionally because soiling is supposed to be a slow and roughly steady process. For cloudy days no calculations could be done.

The second data points drawn in Figure 4 are the values of signal increase, which we noted when cleaning the CH1 DNI sensor. As Figure 4 shows, both values are mostly matching within 0.5%. Using a daily determined deviation between the calculated and the measured DNI gives a rough estimation for correcting the DNI signal due to soiling of the CH1 sensor.

Probably there must be some correlation between the soiling of the CH1 pyrheliometer and the CM11 pyranometer although they show a different susceptibility to soiling. The correlation of the soiling of the pyranometers to the CH1 DNI sensor is presented in Figure 5 separately for GHI and DHI. The data originate from the taken notes at the cleaning process. The figure shows a very weak correlation with a high spread of around 4%. Furthermore, although soiling of both pyranometers should be very similar, its influence to the GHI signal is higher in the mean than to DHI. As an rough estimation, soiling for GHI can be calculated to be 17% of the value determined for DNI respectively a value of 15% for DHI.

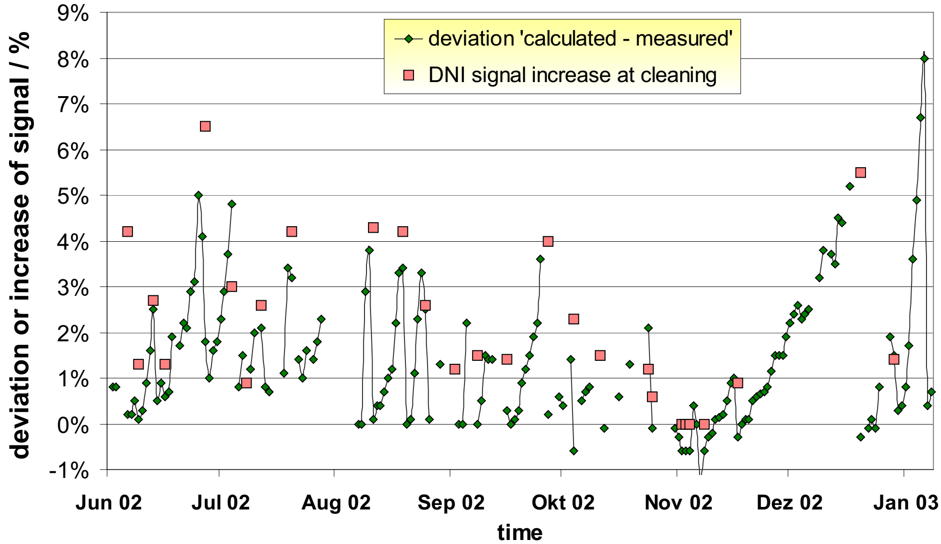

Figure 4: Rise of DNI signal by cleaning the CH1 pyrheliometer as well as the deviation of the calculated DNI to the CH1 signal.

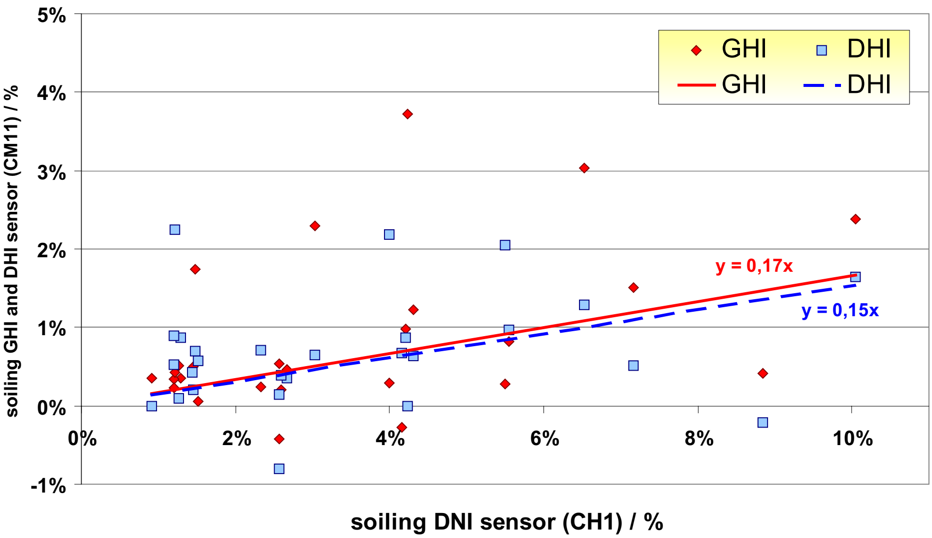

Figure 5: Correlation of the soiling of the CH1 DNI sensor in dependence on the soiling of the CM11 GHI and DHI sensor.

For the RSP there is no direct possibility to determine its decrease of the signal due to soiling. Therefore, as rough estimation only a constant factor can be used for correction of the reduced signal. The chosen value, however, has to be site-specific.

5 CONCLUSIONS

Different sensors for measurements of irradiation have been examined for their soiling characteristics. As we could show in this paper, different sensors show different susceptibilities to soiling. Whereas the reduction of the signal of the RSP at the location in southern Spain was usually under 2% for DNI and 1% for GHI, with single peaks up to 5%, the CH1 pyrheliometer shows a spread of reduction until 10% for DNI. The GHI signal of the CM11 pyranometer was reduced to up to about 4%.

Furthermore, the extent of soiling also is depending on the location respectively probably on geomorphologic structure of the ground in the environments. For the site in Morocco soiling losses of up to 12% have been measured for DNI and 8% for GHI.

For stations separately measuring GHI, DNI and DHI, the DNI signals can be corrected with the deviation of the measured value to that calculated from GHI and DHI. Correction of GHI and DHI can be done according to a existing weak correlation: soiling of GHI shows a value of about 17% of the DNI soiling value, DHI about 15%. For the soiling of the RSP there is no possibility to detect intrinsically the actual amount within the measurement. Soiling has to be corrected with a constant factor, which value must be depending on the location. This seems valid as self-cleaning effects could be observed over a long-term period.

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