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Monitoring of mirror and sensor soiling with TraCS for improved quality of ground based irradiance measurements

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Abstract

Meteorological stations for solar irradiance measurements are mainly utilized for resource assessment of possible sites for future solar power plants and for thermal efficiency calculation and control of operating power plants. These stations consist of a solar tracker, two pyranometers and a pyrheliometer (MHP) for irradiance measurements. The accuracy of the MHP instrumentation is usually specified to be better than 2 % if cleaned on a daily basis. However, soiling frequently exceeds other error influences significantly, reducing irradiance values and accuracy. Due to the high sensitivity to soiling shown by pyrheliometers, especially DNI measurements are affected. Reductions of measured DNI values exceeding 25 % in only a few weeks are not unusual. In order to improve this situation, the soiling level of each individual sensor can be determined by following a special sequence of sensor cleaning and brief breaks combined with a close examination of the sensor responses. This allows for an approximate post processing correction of the irradiance data measured since the last cleaning (if recent). The corrections applied are cross-checked by means of an improved version of the TraCS asset. It can be used to control the sensor soiling correction procedure. The TraCS's improvement consists in rotating the mirror within its plane with the pyrheliometer thus scanning its surface instead of just viewing the same small spot on the mirror. Hence, a better accuracy of the mirror soiling level is achieved by deriving more reliable average values. Finally, the results of an examination of sensor soiling rates at several meteorological stations set up in the MENA region and cleaned following the described protocol is presented. This gives an idea about the range of regional differences in soiling rates to be expected in the North African region.

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1. Introduction

In the course of the DLR EnerMENA project, there are 12 meteorological stations being set up in environments with different dust occurrences in the Near East / North African region. Most of these stations consist of a solar tracker with two pyranometers and one pyrheliometer measuring the solar resource at the sites. They are especially susceptible to soiling as has been shown in earlier publications [1, 2]. The deviations due to dirt can easily outrange the accuracy of the sensors specified by the manufacturer and thus be a showstopper for any resource assessment campaign relying on this specified accuracy for the irradiance data. Involved in daily data processing and quality control, we present some characteristics of irradiance sensor soiling and methods for their detection. Corresponding post-processing procedures for data quality improvement were developed and are intercompared to the response of an additional accessory named TraCS that allows a closer look on soiling behaviors.

The main issues encountered at remote sites are insufficient maintenance in terms of cleaning frequency and thoroughness of cleaning as well as faulty alignment of sensors. Also difficult communication channels between the station operators and the data quality controller far away from the actual measurement site may hinder the process. The cleanliness level of a pyrheliometer is most affected by the lack of cleaning which decreases the accuracy of the DNI measurement significantly. For post-processing procedures, it is crucial to find the best practices in order to minimize the errors caused by soiling of sensors and thus profit from the high precision of sensors that is achievable in controlled environments.

The new method for examining cleaning events could help improve that situation by a novel procedure for data correction that takes into account the soiling levels of each individual sensor detected during the station cleaning events. Comparing these levels from one site to another, the range of expected irradiance losses between two sites can be estimated. This can lead to valuable information on the soiling behaviors of sensors but also solar collectors in the region of interest. Comparing the sensor soiling levels to the soiling measured on a test mirror can pave the way to include the parameter into resource assessment procedures with the only effort of examining these cleaning events, limiting the huge inaccuracies caused by the parameter of soiling and its disproportionately high effect on power plants [3]. Although the parameter of sensor soiling cannot be applied directly to CSP plant efficiency, it can be used to narrow down the limits of possible mirror soiling rates.

This work describes the coincidence graph that allows for an identification of different soiling characteristics and detection of soiling levels of each individual sensor. Next, the recommended cleaning sequence is described and its advantages in terms of data flagging and correction are pointed out. Then a comparison of a cleaning analysis performed at various stations in the MENA region is presented. It shows local variations in sensor soiling rates. Finally the improved TraCS measurement setup is presented that allows for an intercomparison between sensor and mirror soiling rates measured in situ.

Nomenclature

DNI	Direct Normal Irradiance
DHI	Diffuse Horizontal Irradiance
GHI	Global Horizontal Irradiance
θ_s	Apparent solar zenith angle
Δ_{cl}	Irradiance signal step during a cleaning event
$DNI_{coincidence}$	Difference between measured and calculated DNI
I	Irradiance measurement signal
χ_{corr}	cleanliness correction factor
T	time interval between two cleaning events
t_0	time of last sensor cleaning
t_{cl}	time of current cleaning
t	current time

DNI_{calc}	DNI calculated from DHI, GHI and apparent sun elevation angle

2. Characteristics of irradiance sensor soiling

In the following paragraph, the different soiling behaviors and its effect on irradiance measurements are described. Soiling usually affects the pyrheliometers much more than the pyranometers as can be seen in Fig. 2, where such a typical cleaning event is displayed. In this case DNI is the most affected parameter and it is comparatively easy to estimate the measurement error caused by soiling. Nevertheless, dependent on ambient conditions there are other cases where the pyranometers are more affected by soiling, what makes identifying the inaccuracy for the DNI measurement impossible. We present a cleaning protocol that identifies the soiling levels of each sensor and thus allows for data qualification and subsequent correction.

2.1. The coincidence graph

The most important tool for deciding which sensor has suffered to what extent from soiling is the shape of the coincidence graph. This graph is given by subtracting the calculated DNI from the measured DNI. The calculated DNI is derived by

$$DNI_{calc} = (GHI - DHI)/\sin\gamma_s\,. \tag{1}$$

Where γ_s is the apparent solar elevation angle calculated by e.g. the Michalsky algorithm [4]. GHI and DHI are the irradiance values measured by the two pyranometers. The DNI coincidence value is calculated according to

$$DNI_{coincidence} = \mathrm{DNI}_{measured} - DNI_{calc}, \tag{2}$$

where $DNI_{measured}$ is the DNI measured by the pyrheliometer.

The coincidence graph proves very useful as it gives information on the status of the sensors. As a rule of thumb it can be stated that the DNI coincidence around solar noon in a well maintained station lies inside the interval ±20W/m². Values outside of this interval point to sensors that are either dirty or misaligned. This concept is very useful for remote quality control of the stations. In theory this calculation can be done for GHI and DHI as well, but the DNI coincidence is the most sensitive component, critical for CSP resource assessment. In the following we focus on this parameter.

An entire day of DNI coincidence with sensor cleaning is shown in Fig. 1 where the three step cleaning procedure described below is increased inside. In Fig. 2 the step in the coincidence graph and also in the DNI measurement graph is obvious. During cleaning DNI_{calc} increases less than the measured DNI value and thus increases the coincidence value. In this most frequent case, the absolute increase in the measured DNI is nearly the same as in the DNI coincidence proving the assumption that the pyrheliometer was more soiled than the pyranometers.

Once the step in the DNI and/or DNI coincidence has been detected well, the confidence level during the period before that cleaning event can be classified accordingly. For example, if the change in the coincidence value before and after a cleaning event is lower than the accuracy specified by the pyrheliometer manufacturer, the data can be classified as highly confident. There are also exceptions to this rule if the pyranometer and pyrheliometers are soiled just strong enough as to change DNI_{calc} and DNI by the same amount leaving the DNI coincidence constant. In this case other factors like the shape of the DNI coincidence curve have to be taken into account.

Experience with the DLR meteorological stations shows that these are rare cases and the normal case is an error smaller than the instruments accuracy. Singular events can make the influence of soiling exceed by far the clean instruments' accuracy. In any case, the values are corrected in post-processing procedures. These will be described in section 2.3.

2.2. Advanced cleaning

In order to gain all possible information from a sensor cleaning event and to simplify post processing, the cleaning should be performed in a standardized manner. The recommended sequence calls for a cleaning of the station only during sunny conditions, possibly at reasonably high sun elevations and fairly stable irradiance intensities to reach better accuracy. The main feature is not to clean the sensors at once but successively with a time delay between the cleanings: The DHI pyranometer is cleaned first, the GHI pyranometer after a few minutes. After another delay of at least three, better five minutes, the pyrheliometer is cleaned. This way the sensors are cleaned in an ascending order regarding their influence on the DNI coincidence.

With this cleaning sequence the soiling level of each single sensor is detected independently from the other. This makes confidentiality level flagging possible, individually for each sensor. The procedure of data examination becomes much easier if the timestamps of all cleaning events are registered automatically and directly at the station. The DLR and CSP Services stations are equipped with a pushbutton to be pressed by the operator when station cleaning is finished. The timestamps are registered by the data logger together with the measurement values of the station. This makes it quite easy to identify and read the cleaning steps necessary for confidence level assignment and DNI data correction. The latter will be described in the following chapters.

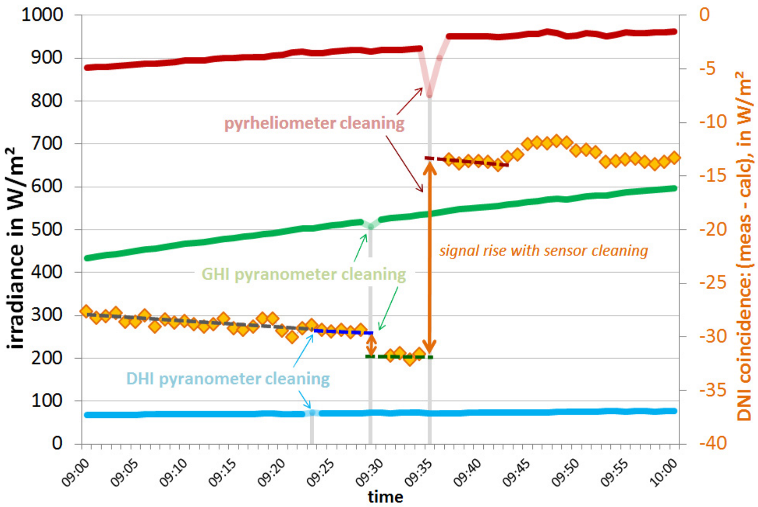

Fig. 1: (a) Irradiance sensor cleaning performed according to the proposed protocol with a time delay between the cleaning of one sensor and the next. Dashed lines show fits to the coincidence graph for data correction. Arrows show the signal step in the coincidence graph. Separating pyranometer and pyrheliometer cleaning avoid wrong reading of coincidence signal step (a).

2.3. Soiling characteristics

Fig. 1b shows a case where the pyrheliometer suffered from soiling and the pyranometers experienced nearly no soiling. In Fig. 1a, the pyranometers were also affected quite strongly. This can be seen in the enlarged three-step-cleaning: the signal step after the pyranometer cleaning is approximately a third of the whole step height and thus only two thirds of the cleaning step are caused by the pyrheliometer whereas in Fig. 1b the pyranometer step is negligible.

The general shape of the DNI coincidence graph is also different in both graphs. In Fig. 1b the shape resembles the cross section of a flat river bed (overlooking the cleaning step), characterized by a flat plateau over all day except the early morning and evening hours when dusk and dawn lights are registered by the pyranometers but not the pyrheliometer. This makes the coincidence less telling. During the day while the sun is shining at a near-constant rate, the formula for calculating the DNI from DHI and GHI works well.

If the pyranometers are soiled in a droplet pattern caused by red rain [5] or dew occurrence, the coincidence curve becomes more instable with multiple maxima and minima as can be seen in Fig. 1a. Due to the fact that the pyranometers are mounted on the tracker and thus follow the sun´s azimuth movement, the sun's point of passage through the GHI pyranometer's protective glass dome moves upwards until solar noon and then downwards again on the same line until sunset; see line in Fig. 1a for an illustration. This causes the curve to be symmetrical around solar noon. This DNI coincidence curve behavior is another indicator for a relatively high pyranometer soiling that cannot be neglected in cleaning event analysis.

If as in the case of Fig. 1b the pyranometer is soiled very little, the point of light passage through the glass dome does not matter much in the GHI measurement. The DNI measurement is affected in a constant manner by dirt on its entrance window because it is always oriented the same way towards the sun's position during a day leaving the coincidence curve more constant. Note that there are no dependencies between soiling levels and the absolute value of the coincidence curve: in Fig. 1 (a) the left graph returns -25 W/m2 in the clean state and the right one 0 W/m2. The absolute value of DNI coincidence depends on more (atmospheric, sensor calibration, leveling etc.) parameters and not only on the sensor soiling levels. Therefore only relative steps can be examined and absolute DNI coincidence values should never be compared directly, especially if measured at different stations. When cleaning all the sensors at once, the DNI coincidence curve steps up in both cases and it is not possible to quantitatively detect the soiling affecting only the DNI measurement.

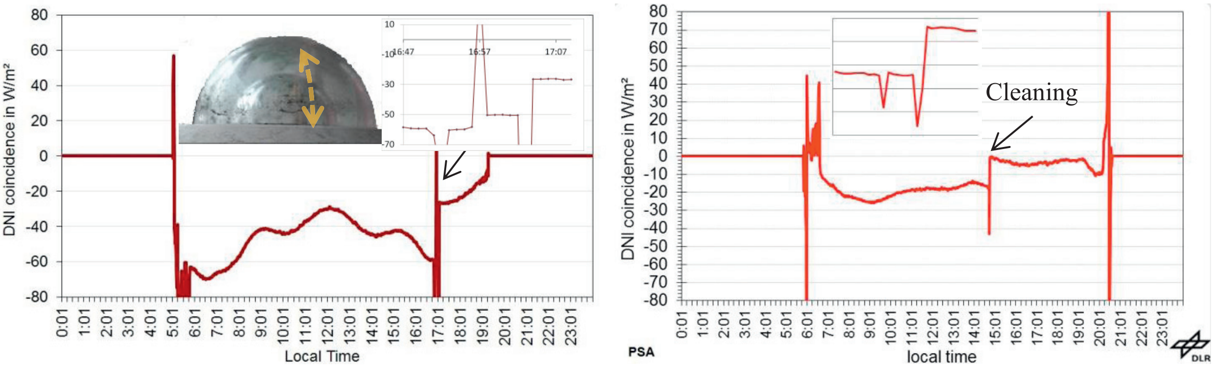

Fig. 2 (a) DNI coincidence graph of a station with heavily soiled pyranometers and pyrheliometer. The symmetrically oscillating shape is caused by dirt spots on the pyranometer dome. An example of such a dirty dome and the sun passage line depicted in the small photo.; (b) DNI coincidence of a station with a very dirty pyrheliometer. The curve's shape is generally more stable. 3-step cleaning enlarged in both graphs.

2.4. Direct Normal Irradiance data correction

Soiling is a non-linear statistical process that still poses a lot of open questions [6]. It can vary over time, from site to site, within the same site and with measurement instrument design [7]. As long as the soiling intensity is not too high and cleaning intervals, i.e. the time from one cleaning event to the next, are fairly short, linear soiling characteristics can be assumed. See section 4.3 for the justification of this statement.

A linear interpolation will result in a correction factor $\chi_{corr}(t)$ for each DNI measurement point in time within the cleaning interval. It is related to the "cleanliness" [8, 9] or "dust" [10] factor $\chi(t)$ defined as the reflectivity of a mirror divided by the same mirror's reflectivity in the clean state. In the case of sensor soiling the cleanliness definition will use the transmission through the sensor entrance window instead of the reflection at a mirror.

The correction factor for the measured DNI will be calculated according to the following formula:

$$\chi_{corr}(t) = 1 + \frac{\Delta_{cl}}{I(t_{cl})} \cdot \frac{t - t_0}{T} \tag{3}$$

Here Δ_{cl} is the difference in the DNI coincidence value from before to after the cleaning, $I(t_{cl})$ is the irradiance intensity measurement signal shortly after the time of cleaning, t_0 is the time of the last cleaning event and T the time difference between the last and the current cleaning event, t is the time of the cleaning of each sensor. These times have to be read from the measurement curves.

If cleaning events are too far apart, if soiling levels are very high or if the cleaning is performed during cloudy conditions, the quality of correction suffers or it cannot be performed at all. All the information available in these cases is that the operator has been at the station (because the pushbutton has been pressed), but if he/she cleaned the sensors well or incompletely or even left the sensors dirtier than before is not known to the data controller. Especially in the case of untrained local personal, the daily data control and regular feedback to the station maintenance personal is fundamental.

In the case where cleaning is performed on a cloudy day, the data cannot be used in this correction procedure: it has to be excluded from the correction procedure and left uncorrected. At these days the contributions to the yearly sum of DNI measurements is not very high, so the impact is comparably low. The issue becomes more significant though if the period without any information on the cleanliness level of the station is extended to more than a few days. In general the cleanliness correction procedure improves the irradiance measurements, but cannot guarantee perfect results.

3. Comparison of different sites and instruments regarding their soiling rates

The described data analysis procedures regarding sensor soiling have been performed at different sites throughout the MENA region allowing for a comparison of sensor soiling rates at the different measurement sites. This comparison permits an estimation of the dust loads to be expected during the operation of a future power plant.

Qualitatively, the soiling rates can be estimated if the DNI coincidence graphs of multiple stations are compared, as shown in Fig. 3.

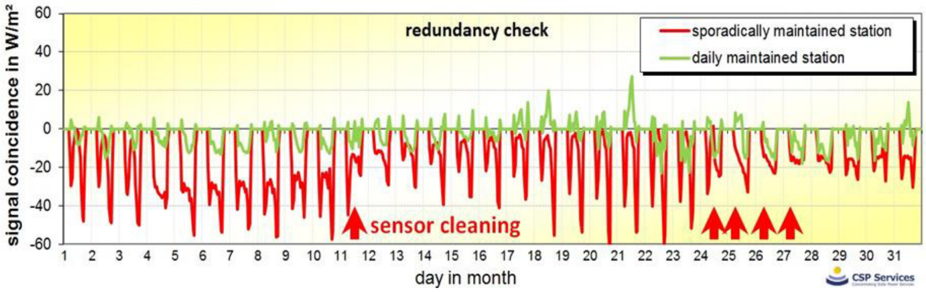

Fig. 3. Difference between a well-cleaned and a sporadically cleaned station as seen in long-term plots of the DNI coincidence

To determine the soiling rate exactly, one has to examine the DNI coincidence signal step during a pyrheliometer cleaning event and note time and signal change. Dividing the height of the signal step by the DNI measurement value at that time and by the time interval between subsequent cleaning events, the soiling rate is derived. The soiling rate is the most suitable parameter in order to compare the dirt loads at different sites. Time intervals exceeding five days have been excluded from this investigation. Once a cleaning event has been characterized the soiling rate λ_s is calculated using the formula

$$\lambda_s = \frac{\Delta_{cl}}{I(t_{cl}) \cdot T} \tag{4}$$

Fig. 4 shows a comparison of soiling rates on a logarithmic scale at 3 different sites, one in southern Spain at the Plataforma Solar de Almería (PSA), one in a Jordanian stone desert (Desert1) and one in a sand desert environment (Desert 2).

The data used for this graph covers one year of measurements for the two desert sites and more than three years for PSA. The data is screened for cleaning events using the signals from the cleaning control pushbutton installed at the stations. The three-step-cleaning events are analyzed manually to find Δ_{cl} and $I(t_{cl})$ by looking at the DNI coincidence graph and the DNI measurement at the time of cleaning. *T* is determined from the pushbutton data in combination with visual control to assure that the last cleaning has been executed correctly and no more than 3-4 days have passed since then. If, due to bad weather or incorrect cleaning, the data is ambiguous, the data point is discarded. This way and using equation (4) for the evaluation more than 300 soiling rate data points for PSA, 60 for Desert 1 and 70 for Desert 2 are examined. The highly different numbers are due to the many measurement points that had to be discarded at the desert sites due to unprofessional cleaning or bad weather. The frequencies of occurrence of the soiling rate values are plotted against the logarithm of the soiling rates.

Looking at Fig. 4, it is clear that at PSA soiling rates above 1% per day are found only sporadically. In 70% of all events the soiling rate does not exceed 0.3% per day. The stone desert environment behaves quite similar (70% below 0.6% daily soiling rate) with some peaks above 1% daily soiling rates supposedly caused by windblown dust events that are occurring less at PSA. The sand desert station has a much broader frequency distribution. At this station soiling rates of up to 9% per day were detected caused by singular events like sand storms. The main occurrence of soiling rates for this station lies between 0.6% and 1.6% per day, i.e. significantly higher than in the two other stations. A mean value for desert soiling rates derived in this study is not representative as more than half of the cleaning events had to be discarded. Nevertheless the mean soiling rates per day can be given to be 0.3% for PSA, 0.6% for Desert 1 and 1.6% for Desert 2. So, in sand desert sites regular cleaning of pyrheliometers is fundamental in order to keep the soiling-induced measurement error below the instrument's accuracy. In these regions daily cleaning is a must and has to be controlled steadily.

In former studies, a somewhat higher mean soiling rate of 0.7 % per day was derived for PSA. A series of factors may contribute to this: First of all a dirt road right next to the measurement site has been paved between the two measurement periods. The road is used multiple times a day by security personal. Such effects have been observed in several cases to have a significant effect on the soiling of optical sensors. Secondly the previous study was interpreting the data with a worst case scenario in mind filtering the data less critically towards high values as done here. Besides, the previous study was based on low statistics with only 9 months of data (excluding winter months) compared to 36 months in the present study.

Note that the results from pyrheliometer soiling analysis cannot be applied directly to efficiency losses caused by this parameter in CSP plants. Soiling behavior of pyrheliometers differs in general from mirror facet soiling [7] and can only be an orientation.

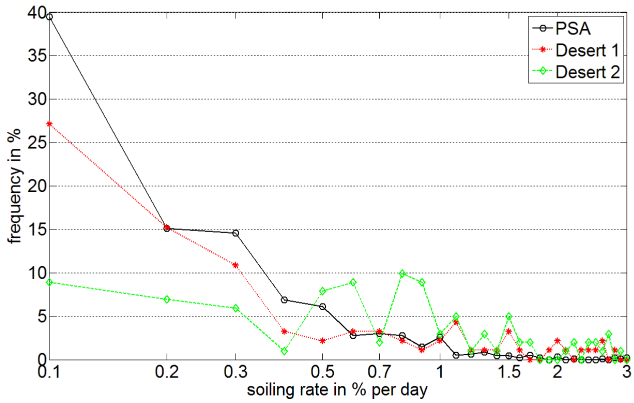

Fig. 4: comparison of soiling rates at three stations throughout the MENA region

4. Comparison of sensor soiling to mirror soiling

In order to compare solar mirror facet soiling and pyrheliometer soiling, the accessory TraCS is used. Here we present an advanced version currently installed at three sites in Spain and North Africa. It determines highly time resolved measurements of the soiling rates of sample mirrors exposed to the environment. With this accessory, not only information on the mirror soiling rates can be measured but also valuable information on the soiling levels of irradiance sensors and qualitative information on soiling patterns can be read.

4.1. TraCS 2.0

The TraCS accessory is mounted on a meteorological station described above. It consists of a second pyrheliometer that looks backwards through a sample mirror into the sun [11]. The measurement signal of the second pyrheliometer is divided by the DNI measurement signal resulting in a reflectivity value for the spot on the mirror where the sun is reflected. Because this spot is only some 15 mm in diameter local irregularities of the soiling pattern on the mirror can have an unwanted influence. For example dew drops that capture dust particles out of the air will leave them in a circular pattern on the mirror once the droplets have dried off. Or there was light rain that washed out the aerosols in the atmosphere and deposited them on the mirror, the so called “red rain” (compare Fig. 5d). This results in small spots of heavy soiling and others where the mirror is nearly clean. If the second pyrheliometer looks at one of these spots it will measure a lower cleanliness than the average cleanliness of the total mirror surface.

The new version of TraCS aims at reducing this error by scanning a larger surface on the mirror. This is realized by a motor that turns the mirror in its plane such that the original measurement spot is now scanning a circular shape (Fig. 5c) on the mirror surface thus enlarging the area that is being measured. An illustration of the improved setup is given in Fig. 5a and b. An example measurement curve of this new feature is depicted in Fig. 6a. It can be seen that the recurring pattern of reflectivity shows that the instrument is scanning always the same areas on the mirror at a constant velocity. It delivers additional information on the homogeneity of the soiling patterns on a mirror if the spread of the signal during one rotation is evaluated.

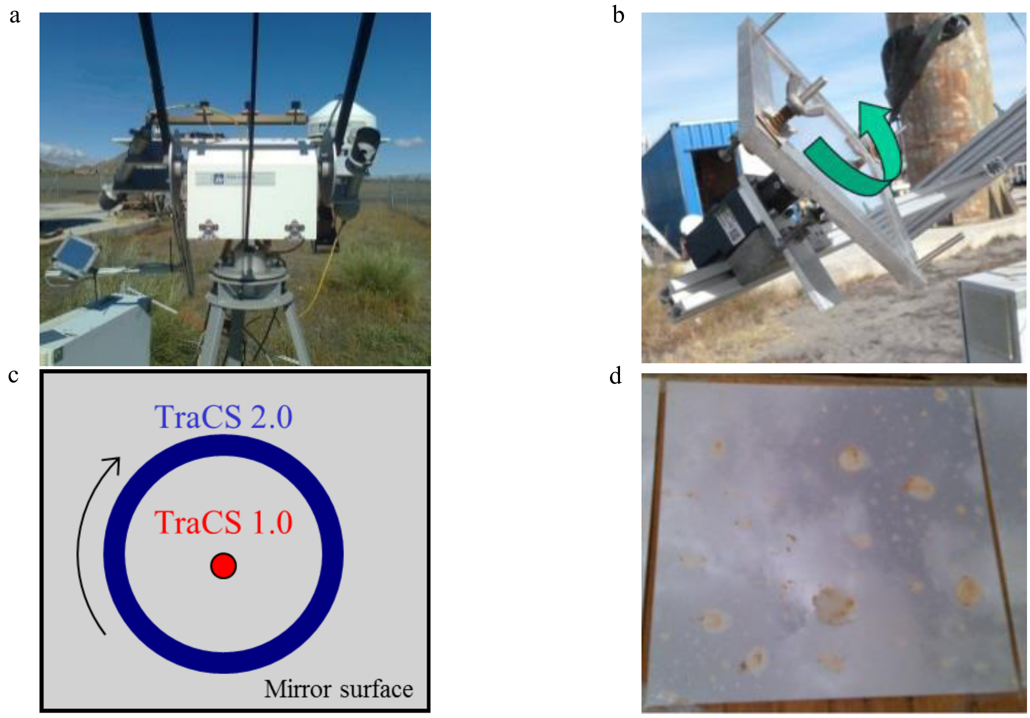

Fig. 5: TraCS2.0 measurement setup. (a) overview on the measurement setup with the main pyrheliometer on the right and the TraCS pyrheliometer with the sample mirror on the left; (b) detailed view of the sample mirror with the turning motor; (c) measurement area on the mirror of the old version of the TraCS in red and the new, turning version in blue. TraCS2.0 averages the cleanliness over a larger mirror surface area; (d) 10x10cm aluminium mirror surface after a red rain event.

4.2. Determining sensor soiling from TraCS

An additional functionality of the TraCS accessory is the possibility to cross check and compare the sensor soiling levels determined with the methodology described in section 2.3. In Fig. 6b we see a cleaning of both pyrheliometers, the main and the mirror pyrheliometer, while the sample mirror is left untouched. This means that the reflectivity value should stay the same if not the pyrheliometers showed soiling on their entrance windows. Because the reflectivity value measured with the TraCS at this point is only influenced by the soiling experienced by both pyrheliometers, the soiling level of the irradiance sensors can be estimated at a cleaning event. Comparing the relative signal step of both, the TraCS reflectivity measurement value and the DNI curve, it can be seen that they are nearly equal. The reason is that the second pyrheliometer that is looking downwards onto the sample mirror is much less affected by soiling than the main pyrheliometer that is looking upwards into the sun. Another fact is that the sample mirror's cleanliness (relative reflectivity) usually does not change rapidly with time. This means that an approximate detection of the signal step is possible even if the cleaning happened during the passage of clouds. This can be done comparing the reflectivity value of the sample mirror before the cloud passage to the value acquired afterwards. This avoids losing information on DNI data quality and soiling effects at the measurement site as was the case at the two Desert stations included in the soiling rate comparison depicted in Fig. 4.

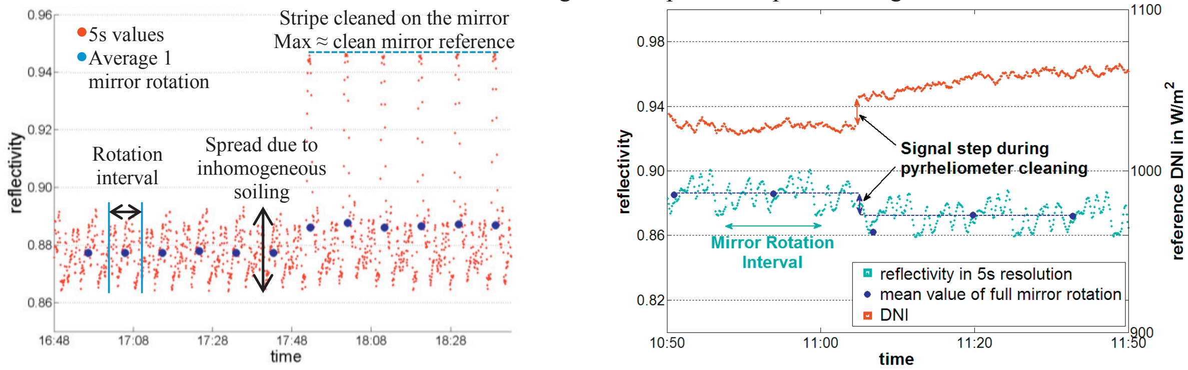

Fig. 6: (a) TraCS 2.0 measurement signal with a rotating mirror. The inhomogeneity of the soiling is in the range of 3 % on a mirror with a cleanliness of 93 %. At 17:50 a stripe on the mirror has been cleaned.
(b) signal step of TraCS reflectivity measurement and DNI measurement. Because the second pyrheliometer shows much lower soiling rates the step in reflectivity curve correlates well with the step in the DNI absolute value. Reflectivity remains constant while DNI changes

4.3. Soiling behavior measured with TraCS

A typical long term soiling curve taken with the TraCS accessory on a sample mirror is shown in Fig. 7. We see that the reduction in reflectivity can be fitted linearly between rain events. This graph serves to show that the assumption made in section 2.4 is quite reasonable assuming the pyrheliometer soiling behaves similar by trend to the sample mirror soiling. Even if the canopy is reducing the soiling rate of the pyrheliometer, the linear tendency will still be the same. Even though some studies showed different absolute soiling of exposed plant components and pyrheliometers [7] they did not show a non-linear behavior.

The higher the soiling rates are more likely it is that there is a deviation from the presented linear tendency. Therefore any soiling rates based on a cleaning interval *T* exceeding a few days have been excluded from the site comparison in section 3.

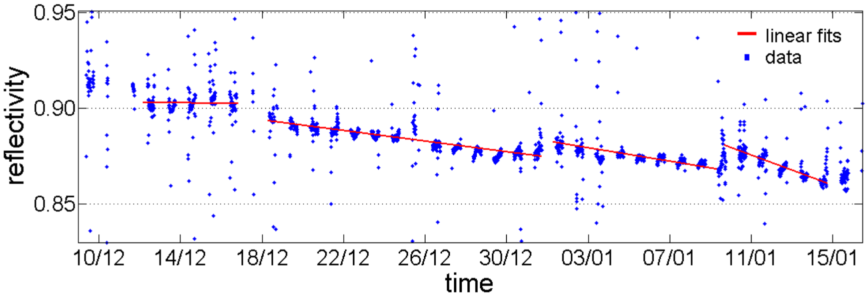

Fig. 7: soiling of a sample mirror measured with TraCS2.0 over five weeks. Linear fitting works well for limited time periods. Fitting time periods separated after rains.

5. Conclusion

In dusty environments the accuracy of irradiance measurements cannot be guaranteed to be the same as the instrument's specified measurement accuracy. Due to dust deposition on the entrance window of the pyrheliometer and protection domes of the pyranometers the measurement underestimates the solar resource depending on the amount of dust at the measurement site. This makes regular sensor cleaning indispensable in these regions. The error of measurement can be estimated and minimized by detecting the soiling load during the cleaning of the sensors and eventually correcting the irradiance values with an interpolation method. Using the sensor soiling information from different stations it is possible to compare the soiling loads from different sites. This investigation showed a loss in the DNI measurement due to soiling ranging from of 0.1% - 1.0% per day for one site each in Spanish semi-desert and Jordanian stone desert. Up to 9% per day and a mean of 1.6% per day were detected for the pyrheliometers at a station located in a sand desert.

The TraCS accessory (developed by DLR and commercially available from CSP Services) is a useful tool for monitoring soiling rates of a sample mirror in real time. The motor rotating the mirror around its optical axis delivers additional information on the homogeneity of soiling patterns on the mirror. The cleaning event can be analyzed for data correction and qualification even when performed during cloudy conditions and the linear interpolation method can be justified assuming similar behaviors of mirror and sensor soiling rates.

Future research on soiling shall aim at installing the TraCS2.0 to more meteorological measurement stations in order to gain a better global picture on the variation of sensor as well as mirror soiling in time and location. The results of such studies shall be applied to the case of real power plants and common cleaning strategies with the goal of reducing the investment risks that are highly dependent on this parameter. It is one of the least known and most influential parameters in CSP technology.

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References

[1] Geuder, N., V. Quaschning, Soiling of irradiation sensors and methods for soiling correction. Solar Energy, 2006. **80**(11): p. 1402-1409.
[2] Pape, B., et al., Soiling impact and correction formulas in solar measurements for CSP projects, in SolarPACES2009: Berlin.
[3] Cohen, G.E., D.W. Kearney, G. Kolb, FINAL REPORT ON THE OPERATION AND MAINTENANCE IMPROVEMENT PROGRAM FOR CONCENTRATING SOLAR POWER PLANTS*,* 1999, Sandia National Laboratories. p. 1-44.
[4] Michalsky, J.J., The Astronomical Almanac's algorithm for approximate solar position (1950–2050). Solar Energy, 1988. **40**(3): p. 227-235.
[5] Avila A., Q.-M.I., Alarcón M., Mineralogical composition of African dust delivered by red rains over northeastern Spain. Journal of

Geophysical Research, 1997. **102**(D18): p. 21.
[6] Sarver T., Al-Qaraghuli A., Kazmerski L., A comprehensive review of the impact of dust on the use of solar energy: History, investigations, results, literature, and mitigation approaches. Renewable and Sustainable Energy Reviews, 2013. **22**: p. 698-733.
[7] Bowman J., J.S., McDonald M. Analysis Of Soiling Rates At The Victor Valley Community College CPV Site. In: AIP conference proceedings. 2011.
[8] Meyen, S., E. Lüpfert, Measurement procedure for Direct Reflectance and Cleanliness of Solar Mirrors with D&S Reflectometer PMOD1, 2009, DLR QUARZ-CSP.
[9] Lüpfert, E., et al., Towards standard performance analysis for parabolic trough collector fields, in Solar PACES, DLR, Editor 2004: Mexico.
[10] Deffenbaugh D.M., G.S.T., Svedeman S.J., THE EFFECT OF DUST ACCUMULATION ON LINE-FOCUS PARABOLIC TROUGH SOLAR COLLECTOR PERFORMANCE. Solar Energy, 1986. **36**(2): p. 139-146.
[11] Wolfertstetter, F., et al. A Novel method for Automatic Real-Time Monitoring of Mirror Soiling Rates. in SolarPACES. 2012. Marrakesch.