A Novel Method for Automatic Real-Time Monitoring of Mirror Soiling Rates

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Abstract

The effect of soiling of solar concentrators influences the output of solar thermal power plants significantly. The literature values estimate the loss in specular reflectivity due to dust on the mirrors to be as high as 14% or even 26% after a few months [1], [2]. It varies significantly with location [3]. Given the fact that these numbers are quite high and very broadly spread in the literature, project planners and plant operators demand better methods to measure soiling loads in running power plants as well as in resource assessment measurement campaigns. In this paper we introduce a new measurement setup named "TraCS" (Tracking Cleanliness Sensor) that allows for an easier, supposedly more precise and more cost effective measurement of the soiling level of solar mirrors. It will assist power plant operators and maintenance teams to optimize their cleaning cycles based on a real time measurement. At the same time the setup paves the way to including cleanliness as a standard parameter in solar resource assessment. It enables more sophisticated research on the most important weather parameters influencing the soiling rates at different plant sites and on upcoming new coating materials [4].

Keywords: soiling, cleanliness measurement, site assessment, cleaning optimization, resource assessment.

1. Introduction

Once a power plant has passed commissioning and is running at the best possible level from the engineering point of view the most efficiency-limiting parameter during its operation is the decreasing cleanliness of solar reflectors and receivers caused by soiling, i.e. the accumulation of dust and smaller particles on its surfaces. The loss in reflectivity or transmittance correlates linearly with the thermal output of the solar field of the power plant assuming a constant direct normal irradiance (DNI) as input to the power plant. It can cause an efficiency loss well above 10% as mentioned earlier.

The losses due to soiling of power plant components are reduced by cleaning. However, cleaning causes an increase in maintenance costs and water use even using sophisticated cleaning robots [5]. Therefore, researchers and maintenance teams of power plants are aiming at cost optimization for cleaning measures [6]. At least two input values are needed for this optimization: the cleaning cost for a unit mirror surface and the actual optical efficiency reduction and thus profitability loss of the whole power plant due to soiling. The cleaning costs are known pretty well for each plant site after some time of operation, but the efficiency reduction due to reflectivity losses is not known in a continuous manner.

Current procedures depend much on the plant operator's experience with the local weather: if an obvious sandstorm event significantly soils the mirrors, some might hire local workers to clean the whole power plant's mirrors during a few nights. This is costly but usually worth the increase in reflectivity. If one calculates the reflectivity threshold value at which such a cleaning effort makes sense, the power plant's efficiency could be increased even if the mirrors lose their reflectivity due to more subtle effects, less obvious than a sandstorm.

2. State of the art of reflectivity measurements

The currently employed methods to measure the parameter of soiling allow very few measurement points in time and are rather tedious. Either they measure the soiling rate at the time of the cleaning event once at the end of each exposure period [1] assuming a constant direct normal irradiance (DNI) and comparing the output values of e.g. a concentrating (photovoltaic) device before and after the cleaning. Or they use the D&S Portable Specular Reflectometer Model 15R, or other handheld measurement devices that has to be handled by an operator at the reflector in question. This procedure requires a lot of operator time due to the large distances in a power plant and the rather long procedure to obtain good measurement values [7].

Figure 1 shows the D&S 15R reflectometer and the optical pathways determining the working principle of the measurement: a high intensity LED lamp emits light at one fixed wavelength of 660 nm and is focused onto a sample mirror with a system of collimator lens and aperture. The same optics are found at the receiver side, limiting the light that reaches the Si-Photodiode to a selectable acceptance angle between 7 and 46 milliradians. The acceptance angle is defined as a solid angle φ around the vector of direct reflection from one point on the mirror to the center of the receiver aperture.

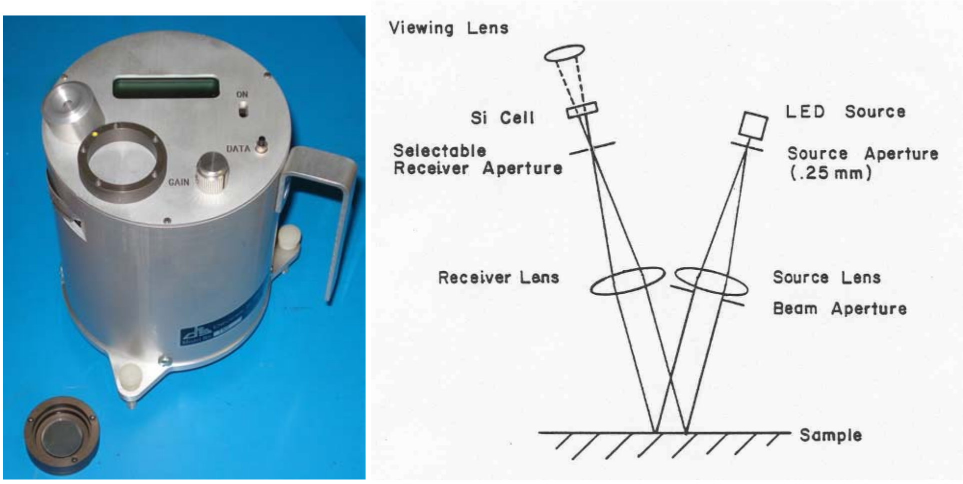

Figure 1: D&S Portable Specular Reflectometer 15R device and its optical pathways

For the application in CSP plants, this device is very flexible regarding the acceptance angle. The acceptance angle is a characteristic of different CSP plant types and should thus be taken into account in reflectivity measurements in order to obtain the most accurate measurement. In a concentrating collector the acceptance angle is

$$\varphi = \arctan\left(\frac{d_r}{d_{mr}}\right)$$

with d_r the diameter of the receiver and d_{mr} the distance from incoming solar ray on the reflector to the receiver. 25 mrad were chosen for all D&S measurements made in the course of this work as this comes closest to the situation in a parabolic trough power plant. In the EuroTrough collector for example, the full acceptance angle ranges from 23 to 40 mrad at normal incidence angle, not considering corrections for atmospheric influences like the sunshape. The fixed reflectance angle of the D&S 15R device is 15° and the diameter of the illuminated measurement spot is 10 mm. To achieve a representative mean value for the mirror's reflectivity, a large number of measurements have to be taken.Note that the mean reflectance angle in a typical power plant is greater than the 15° of the D&S 15R.

3. Setup design and working principle

3.1. Working principle

The working principle of the new setup uses already well-established measurement equipment. A precise meteorological station as used in resource assessment or in a running power plant serves as a basis for the installation. Such a station usually consists of a solar tracker with two pyranometers for measuring the diffuse and global irradiance (DHI and GHI) and one pyrheliometer for the measurement of the direct normal irradiance (DNI). As accessory on the same tracker, a second (“TraCS”) pyrheliometer is mounted such that it looks backwards into a mirror that reflects the direct solar irradiance into the TraCS pyrheliometer. See Figure 2 for an impression on the setup’s appearance.

Overview of MHP Station **Details of TraCS accessory**

Figure 2: Meteorological Station High Precision (MHP) with TraCS accessory installed at the rooftop of the University of Oujda, Morocco

Dividing the measurement signal from the TraCS pyrheliometer by the value from the main pyrheliometer a measurement of reflectivity is obtained. This value is a quantity for the absolute reflectivity of the sample mirror measured with the sun’s spectrum and the geometry of the sun´s natural direct radiation at present atmospheric conditions. Because we are interested in measuring the cleanliness factor in the most representative way and independent of the specific mirror material, coating or shape we introduce a constant calibration factor C_{clean}. The calibration factor is measured using the clean sample mirror at preferably clear sky conditions during a time span t_{clean} in which the state of the mirror can be considered as clean and in which N measurement values are taken. The inverse of the calibration factor is multiplied to the quotient of reflected DNI and direct normal irradiation, $DNI_{reflected,soiled}(t)$ and $DNI_{sun}(t)$. The thus resulting value is the cleanliness factor, calculated in real time by the following formula:

$$\frac{1}{N}\sum_{n=1}^{N}\frac{DNI_{reflected,\,clean}(t_n)}{DNI_{sun}(t_n)} = C_{clean} = const$$

$$cleanliness(t) = \frac{DNI_{reflected,\,soiled}(t)}{C_{clean} * DNI_{sun}(t)}$$

Because $DNI_{sun}(t)$ and $DNI_{reflected,soiled}(t)$ are measured simultaneously with the same instrumentation, variations in the sun’s intensity are cancelled out.

Once the system is installed correctly and the sample mirror aligned to the TraCS pyrheliometer, there are no additional moving parts involved. The measurement can be taken automatically and continuously just as in an ordinary meteorological station, using the same data acquisition system.

3.2. Experimental setup

3.2.1 Sun tracker and Pyrheliometer

The solar tracker in the test setup is the Kipp & Zonen Solys2 tracker. Its tracking accuracy is given by the manufacturer to be better than 0.1° with passive tracking. In the DLR stations, the trackers are usually equipped with the K&Z sun sensor for active tracking to reach a tracking precision of better than 0.02°.

The pyrheliometers used are the Kipp & Zonen CHP1 and CH1. Both models of pyrheliometers employ a thermopile sensor in the inside of a tube housing that defines the opening angle of the instrument. One side of the thermopile consists of a blackened surface where the solar radiation is completely absorbed, independent of the wavelength of the incoming light. The temperature difference between this solar heated absorber and the interior of the pyrheliometer body defines the incoming solar irradiance. The opening angle of the pyrheliometer is 2.5°, i.e. the pyrheliometer receives radiation from a region of 2.5° around the center of the sun in the case of perfect tracking. Deviations from the optimum angle cause the percentage of received light to decrease following the penumbra function [8]. The total uncertainty for the measurement of DNI while tracking the sun perfectly is given to be 1% for daily total values and 2% for hourly total values.

3.2.2. Pyrheliometer and mirror mounting

The mirror mounting support is made from 20 mm aluminum profiles that are attached to the mounting disk at the lateral end of the horizontal axis of the solar tracker. The mirror panel itself is inclined by 15° respective the horizontal axis of the tracker such that the reflection angle is the same as in the reference system. A metal plate supports the mirror panel to avoid its bending due to the small points of high stress caused by the adjustment screws below the mirror panel. The distance from the pyrheliometer's entrance window to the mirror surface is adjustable in the range from 160 mm to 620 mm for the purpose of validation of the experimental setup. As long as not stated otherwise the standard distance used for measurement is 360 mm.

3.3. Sample mirror panels on ambient soiling pole

One mirror panel is mounted permanently in the TraCS and is used as the sample mirror for continuous soiling measurements.

Apart from that, 36 additional mirror panels are exposed to ambient conditions in separate mountings on a soiling pole for several one-week periods. Each is differently orientated versus the horizon and the geographic North and is mounted at different heights from 0.7 m to 10 m. This produces realistically soiled mirror panels that can be put into the setup for a few minutes each in order to be able to validate the measurement setup using the whole range of possible soiling characteristics.

The mirrors were cut to 100 x 100 mm rectangular samples. The size was chosen large enough to illuminate the pyrheliometer's aperture window as well as the pinhole mounting control system at its top. Furthermore, the mirror surface covers the complete imaginary area defined by the limit angle of the pyrheliometer and the working distance. This means that all light detected by the TraCS pyrheliometer has been reflected by the mirror and cannot come from the background. At the maximum working distance of 620 mm and the limit angle of 4° of the pyrheliometer [8], this area describes a circle of 86 mm diameter. This leaves enough tolerance for imperfect, off-center placement of the sample mirrors.

All used mirrors are plane solar mirror panels manufactured by the Flabeg GmbH, Germany, protected by a standard solar mirror coating.

3.4. Location

The setup was first designed, manufactured and installed at Université Mohamad I in Oujda, Morocco and after some improvements at the Plataforma Solar de Almería (PSA). The working distance from the pyrheliometer to the sample mirror is only variable in the PSA-design. The Oujda version has a fixed working distance of 360 mm. The mounting pole for the exposure of the 36 sample mirrors is installed at the PSA.

4. Validation of the setup

Figure 3 shows a cleanliness measurement taken over one week at the rooftop of Oujda University in June 2012. It shows some interesting weather phenomena that highly influenced the cleanliness of the test mirror. This graph points out the possibilities of the new setup and serves as a motivation for the validation that is shown in the following paragraphs. All corrections and exclusions described below have been applied to this measurement. The main advantage is to be seen in the continuous manner that the device delivers measurement values and that short-term changes in the cleanliness can be detected with such a high time resolution. However, some effects like the slightly higher values measured during mornings and evenings are still under investigation.

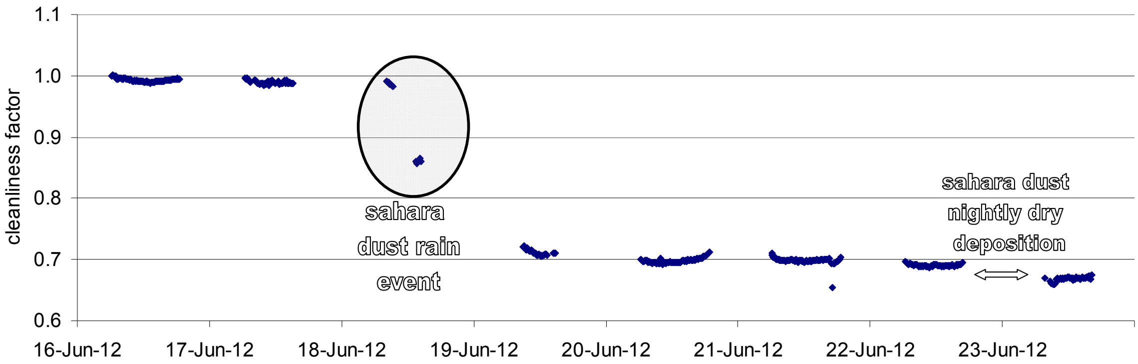

Figure 3: Continuous cleanliness measurement of a test mirror during one week of exposure in TraCS. The atmosphere was highly dust loaded during measurement period

4.1. Comparison to reference

Figure 4 shows a graph of the 36 exposed mirrors measured for a few minutes each at four different measurement spots with the TraCS. The same mirrors were then measured with the D&S 15R device at eight different spots to create a reference value. The precision corresponds to the inhomogeneity of the soiling of the sample mirror.

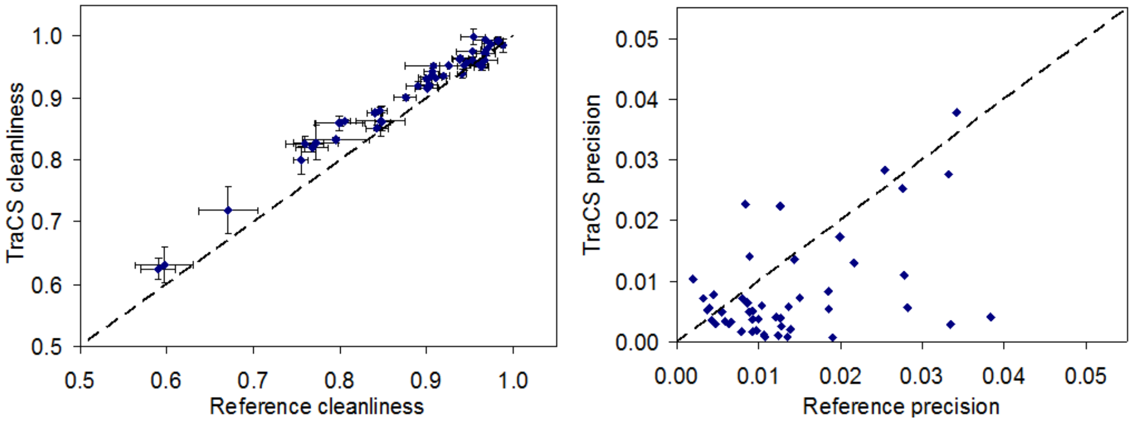

Figure 4: Intercomparison of naturally soiled mirrors measured with TraCS and reference device. Left: TraCS overestimates the cleanliness compared to the reference system. Right: TraCS measurement precision is better due to the larger measurement spot

The TraCS systematically overestimates the cleanliness of the sample mirrors by some percent. This deviation may be caused by the different measurement spectra used for the measurements. Different wavelengths are scattered with different efficiencies. This would result in a different slope of the measurement curve. Another explanation could be the fact that in the D&S the illuminated spot on the mirror is smaller (10 mm) than the viewing field of the detector (22 mm) [9] resulting in less light being scattered into the receiver optics of the device in addition to the directly reflected light. This would result in a lower measurement value compared to the TraCS, where the viewing field is being illuminated entirely by the sun.
It can be argued that the optical, geometric and spectral properties of the TraCS come closer to the situation

of CSP as it does not use lenses or other optical elements that are not intrinsic to CSP plants. In this way the light reflected by the sample mirror perfectly maintains its properties until it hits the thermopile.

4.2. Cleaning of pyrheliometers

The specifications of the pyrheliometer manufacturer suggest a daily cleaning of the pyrheliometer in order to fulfill the 2% hourly accuracy specification. The different soiling levels before and after a cleaning event were estimated by the jump of the measured DNI from before to after the cleaning.

An example graph of such a cleaning event is depicted in Figure 5.

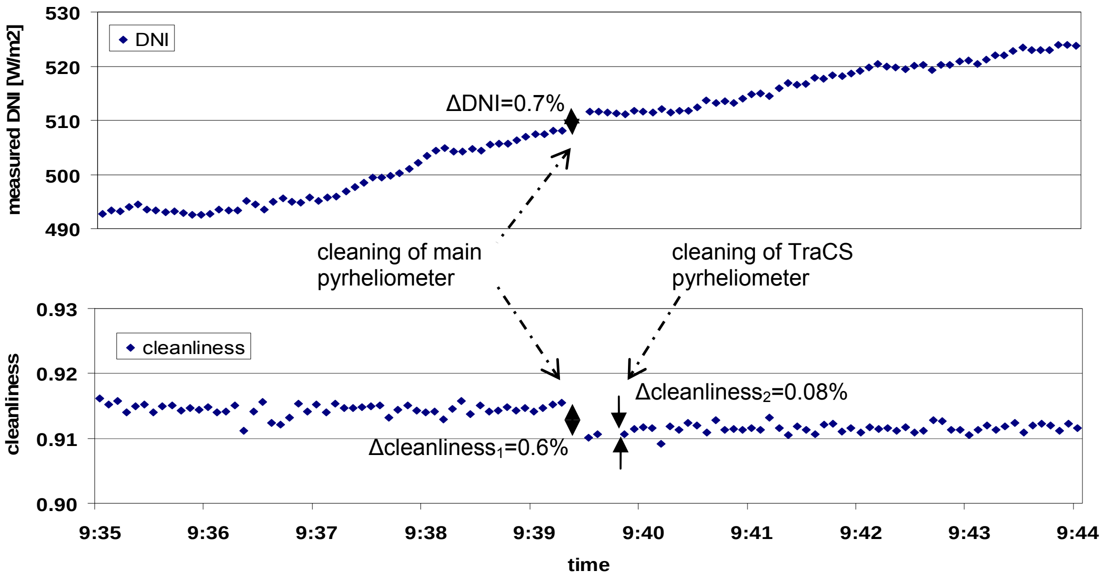

Figure 5: Cleaning of main pyrheliometer increases measured DNI and decreases the cleanliness by very similar relative values. Cleaning of mirror pyrheliometer has a much smaller effect on cleanliness signal. Cleanliness remains constant at changing DNI

Typically, the main pyrheliometer that measures the DNI directly soils much quicker than the one looking downwards into the mirror. It can be concluded that the total jump in the cleanliness value during pyrheliometer cleaning is a good measure for the soiling of the main pyrheliometer.

The decrease in cleanliness of the sample mirror must be corrected after a cleaning event. Only values measured with two clean pyrheliometers are reliable. To correct the measurement in between two pyrheliometer cleaning events the value of the total pyrheliometer cleaning jump is interpolated linearly back to the last cleaning event to correct the cleanliness values as proposed in [11]. The linear interpolation is a strong assumption. Nevertheless, single fast soiling events can still be detected (Figure 3) presumably because the sample mirror is not protected by a canopy like the pyrheliometer entrance window and thus soils at a different rate than the sample mirror itself.

4.3. Mounting tolerance of sample mirror

In order to determine the required mounting accuracy of the mirror inside the mirror holder, the same clean sample mirror was intentionally placed imperfectly in its support and the measurement was taken with the inaccurate positioning of the system.

There are two pinholes at the top of the pyrheliometers that are perfectly aligned with its optical axis. The sunlight falling through the upper pinhole should hit the bottom pinhole perfectly central in order for the pyrheliometer to be pointed exactly at the center of the sun and measure with the highest possible precision. In the following examination, the quality of the mounting was documented by taking pictures of the bottom pinhole of the TraCS pyrheliometer. The manufacturer of the pyrheliometer specifies that the pyrheliometer should be pointed at the sun with a deviation of less than 0.75° from its center. This means that the light spot should not deviate by more than 2 mm from ideal position.

The measurement values shown in Figure 6 have been averaged over a few minutes in order to give a good mean value with a negligible standard deviation. Measurements are taken during same weather conditions.

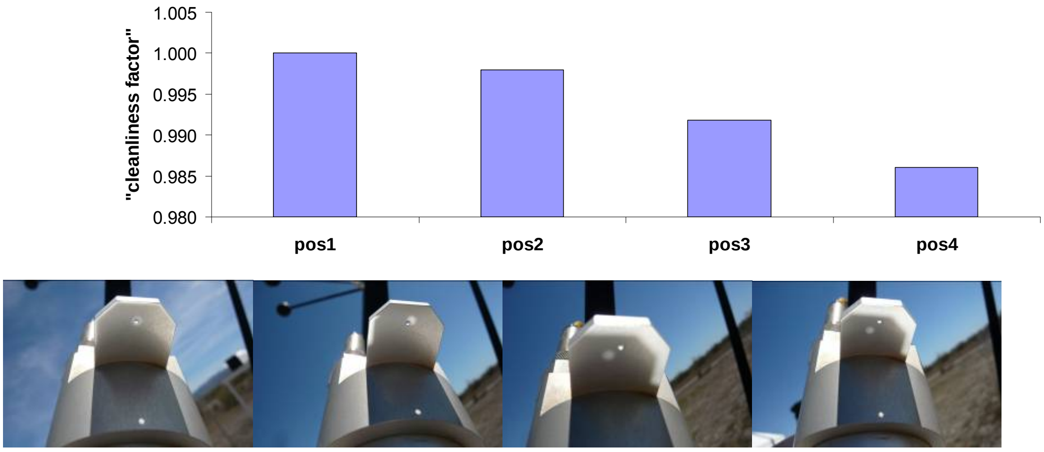

Figure 6: Light spot reflected by the sample mirror through top pinhole and seen at the bottom pinhole of the mirror pyrheliometer. The pictures correspond to positions in the graph above

The test proves that the mounting accuracy of the TraCS accessory is not very relevant to the measurement result: As the light spot at the bottom pinhole falls more than 2 mm off the perfect position, the measurement value decreases less than 1% from the expected value (pos3). This obviously incorrect mounting can be avoided easily even by an inexperienced operator.

4.4. Acceptance angle

In order to modify the acceptance angles of the measurement system we changed the distances from the pyrheliometer to the sample mirror. In the Figure 7 the values for the different working distances are plotted against the reference cleanliness values measured at same mirrors.

The acceptance angle is calculated from the diameter of the thermopile at the bottom of the pyrheliometer and the working distance plus the pyrheliometer length.Changing the acceptance angle in the range from 19 to 46 mRad does not systematically affect the measurement results.

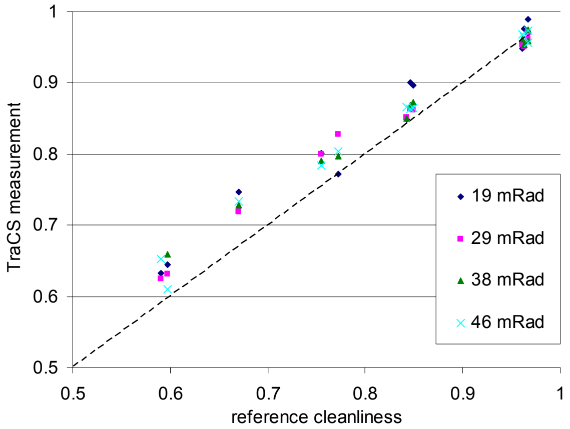

Figure 7: Exposed mirrors measured with the D&S reflectometer (reference) and the TraCS device at different measurement distances that correspond to different acceptance angles. TraCS values plotted against reference. Different working distances have no obvious effect on the measurement results

4.5. Meteorological limits for measurement

The cleanliness measurement becomes less reliable with decreasing DNI values. In order to determine the lower boundary for a reasonable measurement the cleanliness measured at a day with partly cloudy conditions was plotted in Figure 8 against the absolute DNI value at which the value has been measured. For DNI values down to 250 W/m^2 the measured cleanliness lies within a relatively narrow range. If the DNI drops below this value, the measured cleanliness becomes more and more noisy and thus unreliable. The relatively large spread of values is due to the short measurement time of 5 s for each data point.

All cleanliness values measured at a DNI below 250 W/m² should not be used in further evaluations.

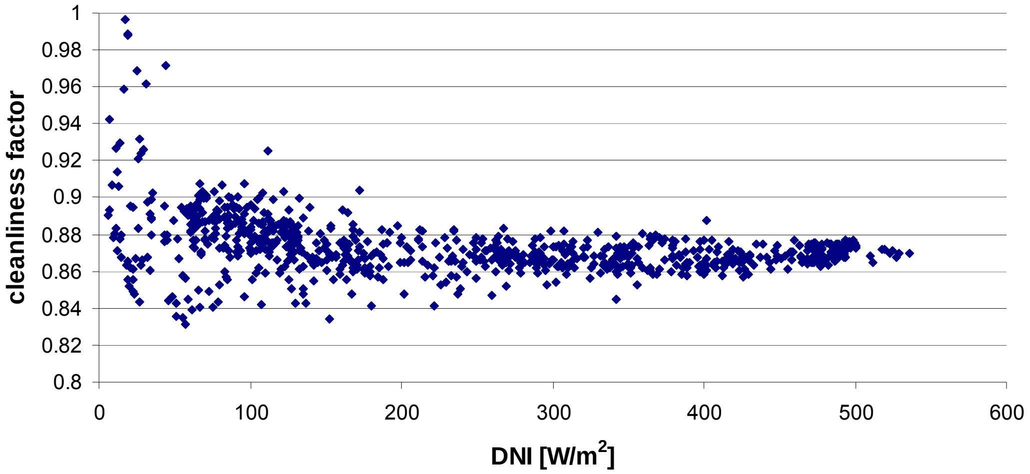

Figure 8: Cleanliness of the same mirror measured at different absolute DNI levels. The measurement interval was 5 s. The values begin to diverge from roughly 250W/m^2

5. Measurement results for sample mirrors exposed in different orientations

In Figure 9 some results from the exposure experiments measured with the TraCS accessory are shown. The graphs give the cleanliness values of mirrors that were exposed in different directions towards the geographic North and the horizon as well as at different heights. Surprisingly, in this example the cleanliness decreases with increasing height above ground which gives reason for a more thorough investigation on the topic of soiling of solar mirrors.

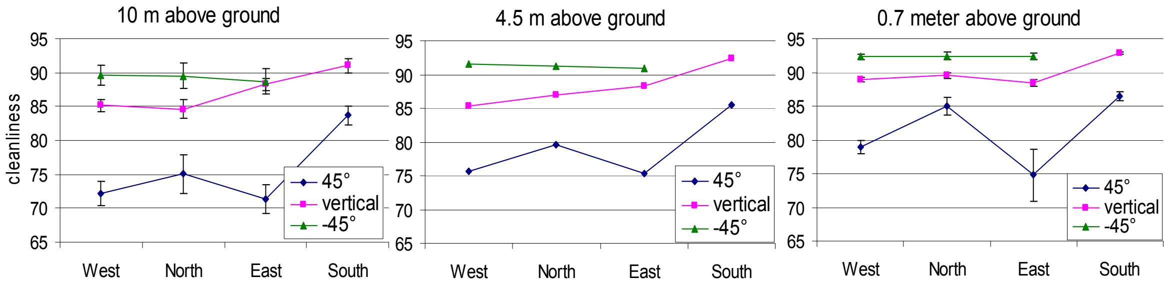

Figure 9: Sample mirrors exposed at different orientations, heights and angles against horizon. Values taken with the TraCS system

6. Conclusion

A new method to determine cleanliness levels of solar mirrors has been validated and the limits for the best measurement conditions are given. The system is easily integrable to high precision meteorological stations consisting of a solar tracker and radiation sensors like pyrheliometers and pyranometers that are already used in resource assessment and running power plants. The TraCS is an accurate measurement system for the cleanliness of a solar mirrors. It has the advantage of measuring with the natural sun spectrum and at a high time resolution. It can be adapted to power plant conditions regarding the acceptance and reflectance angles. The reproducibility of measurement is just as good as with the D&S 15R although the latter can be used directly at a solar reflector in a running power plant, which is not yet possible with the TraCS.

7. Outlook

One possible improvement of the TraCS would be to enlarge its measurement spot. To achieve that, we test a mechanism that moves the mirror in its holder by a simple rotation in the mirror's plane, enlarging the measurement area to a measurement ring with 14 mm thickness and arbitrary diameter.

Furthermore, integration onto a heliostat is feasible. The heliostat would serve as a solar tracker with some pyrheliometers mounted in a fixed or even moveable manner such that they look into the sun via the heliostat mirror when the latter is in the measurement position. During the day, the heliostats in question can track the sun as required by power plant operation and several times a day they go into measurement position. This procedure could make it a tool for cleaning cycle optimization in running power plants and overcome its disadvantage of not being able to measure directly at the reflectors of a running power plant.

In the course of further investigations on the topic, attempts will be made to correlate cleanliness values measured with the TraCS to simultaneously measured weather parameters in order to identify the most influencing parameters responsible for the soiling of solar mirrors.

Acknowledgements

EnerMENA funds provided by the German Federal Foreign Office assisted in the procurement of the experimental instrumentation. The collaboration between DLR and Université Mohamad I of Oujda was made possible by the Morocco Meteonet Solar Project co-financed by the German Federal Ministry of Education and Research and the Université Mohamad I Oujda, Morocco. Sample mirrors were provided free of charge by Flabeg.

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