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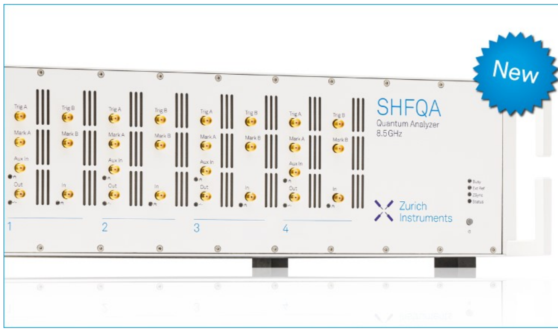

Parallel Soiling Measurements for 4 Mirror Samples during Outdoor Exposure with TraCS

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Abstract. The upgraded version of the Tracking Cleanliness Sensor, the so-called TraCS4, which determines the real-time cleanliness and soiling rate of four mirror samples simultaneously is presented. Using this device, different materials can be intercompared at the site of interest which is the main advantage as the performance of anti-soiling-coatings is usually dependent on local weather conditions. A detailed uncertainty analysis of the TraCS4 device results in a cleanliness measurement uncertainty of about 0.019 cleanliness points. The uncertainty for the intercomparison of different materials is derived to be 0.012 cleanliness points. Exemplary soiling measurements with different anti-soiling and reference coatings at PSA are presented.

INTRODUCION

Mirror soiling in solar fields is receiving more and more attention as projects are going into operation in regions with high dust loads such as the Middle East and North Africa. Mirror manufacturers and coating developers are working on anti-soiling coatings to reduce the soiling susceptibility of the mirror surfaces. There is, however, a lack of automatic long term measurement methods to quantify the effectiveness of these coatings under outdoor conditions. The performance of anti-soiling coatings depends on the local ambient conditions (e.g. dust composition, humidity level, rainfall and dewfall frequency). Therefore it is best to test them at their future site of installation.

In this work we present an updated version of the previously presented Tracking Cleanliness Sensor (TraCS) [1] that has been adapted to measure up to 4 different mirror samples simultaneously (called TraCS4) as well as a detailed uncertainty analysis of the measurement. In [1], a comparison to the reference D&S R15 has been presented with good agreement to the TraCS results. The here presented upgraded version of the TraCS can be used to directly compare different anti-soiling coatings at the site of interest and enables a characterization of the site's soiling characteristics.

MEASUREMENT PRINCIPLE AND MAINTENANCE

The measurement principle of TraCS has been published previously [1]. A solar tracker with the standard measurement equipment for Concentrated Solar Power (CSP) solar resource including a pyrheliometer for direct normal irradiance (DNI) measurements is used. Additionally to this pyrheliometer (Pyr_{dir}), a second pyrheliometer (Pyr_{refl}) is installed on the tracker pointing onto a solar mirror that reflects the DNI into the pyrheliometer's opening

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window. Comparing the DNI measurements of Pyr_{dir} and Pyr_{refl} enables the determination of the mirror reflectance dependent on the current solar spectrum at the time of measurement. Furthermore, the pyrheliometer's uncertainties are well understood and their application at remote sites and under harsh environmental conditions has already been tested. Further, pyrheliometers measure broadband irradiance within almost the whole solar spectrum, which is the important parameter for input to yield analysis tools. TraCS for one mirror sample has been commercialized by CSP Services GmbH, Suntrace GmbH and others for more than 4 years.

To derive the cleanliness, ξ, of the mirror sample the reflected DNI measured by the TraCS pyrheliometer (DNI_{refl}) is divided by the DNI measured by the main pyrheliometer (DNI_{dir}):

$$\xi(t) = \frac{DNI_{refl}(t)}{k_c \cdot DNI_{dir}(t)}\bigg|_{DNI_{dir} > DNI_{lim}} \tag{1}$$

Where k_c is the TraCS calibration factor of each mirror:

$$k_c = \frac{1}{N}\sum_{n=1}^{N}\frac{DNI_{refl}^{clean}(t_n)}{DNI_{dir}(t_n)} = constant \tag{2}$$

N is the number of calibration measurement points taken at times t_n during the calibration measurements. DNI_{refl}^{clean} is DNI_{refl} of the clean mirror. The calibration is performed upon every mirror cleaning over at least one hour on clear sky conditions with measured DNI larger than 200 W/m^2 (DNI_{lim}) and a temporal resolution of one minute [1, 2].

TraCS4

TraCS has been upgraded to measure 4 mirror samples simultaneously in order to compare different anti-soiling coatings during outdoor exposure. This simultaneous measurement is facilitated by a mirror frame, that holds 4 mirror samples that rotate 360° within 20 minutes (see Fig. 1). The reflectance of each mirror is therefore measured once per complete rotation on a measurement area of more than 40 cm^2. The mirror samples mounted on the upgraded TraCS4 have to be plane, smaller than 10x10 cm^2 and can be any reflector material such as thick silvered-glass, thin silvered-glass, polymer films, aluminum, etc.

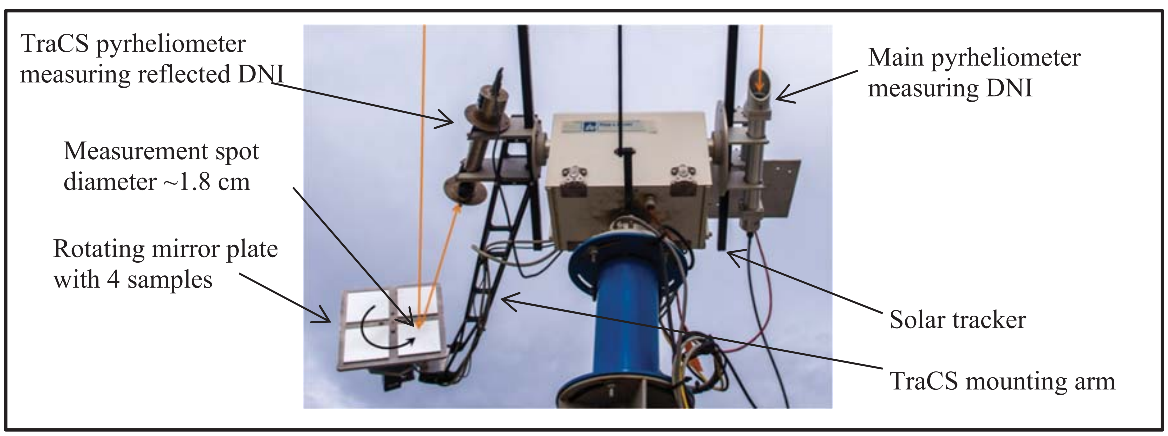

FIGURE 1. Updated TraCS4 measurement system at Plataforma Solar de Almería (PSA, Spain).

Each measurement value is assigned to one mirror sample according to the rotational position of the mirror plate. The start and end positions of each mirror sample on the plate are determined in a test rotation run. During the regular measurement routine, the mirror plate stops 15 seconds at the measurement starting position to accompensate the pyrheliometer's reaction time. Measurements are only performed for DNI values larger than 200 W/m^2 in order to reduce noise.

Maintenance of TraCS4

Additionally to the usual maintenance of the solar tracker and all mounted irradiance sensors (cleaning of the sensors as well as alignment and leveling inspection), the entrance window of the TraCS4 pyrheliometer has to be cleaned daily or week-daily to assure high quality of the reflected DNI measurements. Further, the adjustment of the sample mirrors is controlled and corrected if misalignment is noted. The mirror alignment can be controlled using the pyrheliometer alignment pinholes of the TraCS pyrheliometer. The mirror samples are cleaned every few weeks depending on the level of dust deposited. As a rule of thumb, the cleanliness should stay above 90 % for most of the measurement time, because lower values are not representative for operating solar fields. All cleaning and adjustment activities are recorded.

UNCERTAINTY ANALYSIS

In the following, several contributions to estimate the measurement uncertainty of the cleanliness measurement of the updated TraCS4 measurement system are analyzed. Note that all of the uncertainty influencing factors are also valid for the previous version of the TraCS system if it is not otherwise stated.

Calibration

In [2], the variation of k_c at PSA between April 2013 and the end of 2014 has been analyzed. The main impact on the drift of k_c during this period has been identified to be caused by the drifting calibration constants of the pyrheliometers as well as the decreasing reflectance of the mirror sample. Exluding these two effects, the uncertainty of the cleanliness derived with TraCS4, u_{cal}, has been estimated by calculating the root mean square deviation (RMSD) of k_c during April 2014 and results in u_{cal} equal to 0.009 cleanliness points.

Mirror Plate Alignment

Additionally to the correct alignment of solar tracker and pyrheliometers, the mirror samples have to be oriented towards the pyrheliometer Pyr_{refl} in a way that the main reflection of the sun enters completely into the aperture of Pyr_{refl} during the whole rotation of the mirror plate. Throughout the whole rotation the normal vector of the mirrors has to be parallel to the axis of the rotating motor as well as tilted with the same angle to the optical axis of Pyr_{refl} as the latter is tilted respective the suns position vector. The mirror plate alignment can be controlled using the pinhole alignment tool of Pyr_{refl}. If this is not the case, the measured DNI_{refl} as well as ξ are affected as the reflection of the irradiance does not enter the aperture of Pyr_{refl} uniformly. In [1] and [2], different, slight misalignments of the sample mirror of TraCS have been analyzed during clear sky periods concerning the effect on ξ. It has been found that in more than 75% of the test measurements, the deviation in ξ in comparison to a perfectly aligned mirror sample lies below 0.008. The uncertainty caused by the mirror alignment, u_a, is therefore estimated to be 0.008.

An added misalignment risk is introduced in the TraCS4 version due to potentially unparallel glueing of mirrors to the mirror plate. This could result in canting between the individual mirror samples. If the glueing is performed on an optical table this risk can be easily minimized to the extent that there is no orientation difference visible in the pyrheliometer pinhole when rotating the plate.

Field of View of Pyrheliometer and Circum Solar Irradiance

Raw reflectance and cleanliness measurements with TraCS4 show a natural diurnal course throughout the day (see Fig. 2) [1, 2]. This course is mainly caused by the circum solar irradiance (CSR) and relative humidity changes throughout the day. For decreasing relative humidity, an increase of ξ of up to 0.02 troughout the day can be observed.

Pyr_{refl} can only capture the irradiance which is reflected by the mirror sample. The circum solar contribution which is not reflected by the mirror due to its limited size is therefore not included in DNI_{refl}. This effect reduces the measured ξ in comparison to the theoretical one if all CSR would be measured by Pyr_{refl}. As the clearsky CSR is systematically changing throughout the day with the air mass (AM) [2], this results in a diurnal fluctuation of ξ.

To estimate the uncertainty of ξ due to CSR (u_{CSR}) of TraCS4, a theoretical example of a CSR (α_{out}=3.2°) of 10% (see also [4]) is considered at the beginning and the end of one measurement day which decreases to 0% at midday. α_{out} is the maximum angular distance from the center of the sun that is interpreted as the circumsolar region. Assuming a distance of 3 cm between the center of the field of view of Pyr_{refl} on the mirror and the edge of the mirror, results in an angle of 2.8°. For larger angles, the CSR is not reflected into Pyr_{refl}. Less than 10% of CSR contribute to CSR between angles of 2.8° and 4.0° from the center of the sun [3] for this exemplary case. The rotation of the mirror sample as well as the penumbra function of the pyrheliometer further reduces the percentage of CSR which is not reflected by the mirror [2]. This results in ξ deviating maximal 0.0025 from ξ at midday for this exemplary case. CSRs larger than 10% usually result in DNI levels of less than 200 W/m^2 (DNI_{lim}) [3] which is the lower limit of the measurement range of TraCS and don't have to be considered. Therefore, u_{CSR} is estimated to be not larger than 0.0025.

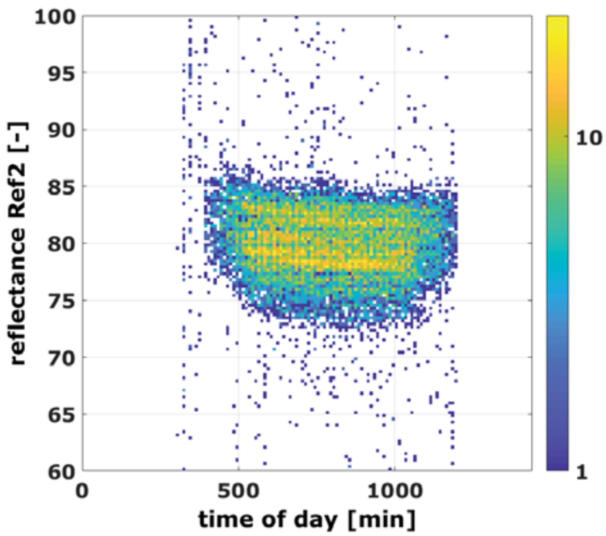

FIGURE 2. Reflectance measurement of mirror sample Ref2 (see Section "Exemplary measurement results") versus minute of the day from May 18th 2018 until February 6th, 2019 with TraCS4 at PSA.

Spectral Reflectance of the Mirrors

The spectral distribution of the incoming solar irradiance changes throughout the day and with the AM. All mirror samples have different wavelength dependent spectral reflectance. The spectrum of the reflected irradiance is therefore different from the incident solar spectrum. The TraCS4 software is performing a spectral correction for the reflectance measurements [2]. The applied correction factors have been derived with the help of hemispherical reflectance measurements of the mirror sample, taken with a Perkin Elmer spectrophotometer, and simulated solar spectra with the SMARTS software (Simple Model of the Atmospheric Radiative Transfer of Sunshine, [4]), for different AM. The broadband DNI_{dir} registered by Pyr_{dir} can be calculated by the integral over the elementwise multiplied spectra of the incident irradiance, the spectral transmittance of the entrance window of Pyr_{dir} and the spectral sensitivity of the thermal sensor. To calculate the broadband irradiance DNI_{refl} reaching Pyr_{refl}, the spectral correction factor for the mirror sample has to be also considered [2]. Applying the spectral correction to the raw ξ measurements results in a smoothing of the diurnal fluctuations seen in the raw cleanliness signal.

The measurement of the spectral reflectance of a mirror sample is performed for a wavelength range from 280 to 2500 nm. The reflected irradiance outside that wavelength range can therefore not be considered in the spectral correction of the TraCS software.

The integrated irradiance in this wavelength range covers about 0.04% of the fully integrated irradiance for AM 1 up to AM 10 for the simulated spectra. This deviation of 0.0004 in ξ is therefore neglected in the spectral correction [2]. The uncertainty of ξ due to the spectral correction, $u_{sp,1}$, is estimated to be 0.0004.

If the corrected measurements of ξ are applied in plant simulations in which a different reflector material is used than in the study of [2], u_{sp} could be increased. To estimate this increase of u_{sp}, DNI_{refl} has been simulated with

SMARTS for two different aerosol optical depths (AOD) (0.5 and 0.084) and AM levels. The standard deviation of the ratio between DNI_{refl} for these two AOD levels is calculated to be 0.0028 and can then be considered as $u_{sp,2}$ for plant simulations with other reflector materials.

The total uncertainty due to the spectral correction, u_{sp}, within the TraCS software can then be calculated with $u_{sp,1}$ and $u_{sp,2}$:

$$u_{sp}=\sqrt{0.0028^2+0.0004^2}\cong 0.0028 \quad (3)$$

Moreover, it has to be noted that the aluminium plate on which the mirrors are mounted could reflect within the acceptance angle of Pyr_{refl}. This effect is neglected in this uncertainty calculation.

Pyrheliometer Uncertainties

Additionally to the already mentioned uncertainties of the TraCS4 concerning ξ measurements, the uncertainties which are caused by the pyrheliometer measurements have to be considered. In the following, these uncertainties are discussed.

Zero Offset

The measurement signal of a pyrheliometer is influenced by the ambient temperature (T_{amb}). The generated heat flows within the instrument affect the reference temperature of the thermopile. The uncertainty due to this zero offset is called Type B and is specified with 1(W/m^2)/5(K/h) by the manufacturer [5]. Variations of 5 K/h of T_{amb} (ΔT_{amb}) are most probable during the hours shortly after sun rise or before sun set, when DNI rarely exceeds 200 W/m^2. During these periods, the zero offset uncertainty, u_0, can be calculated as:

$$u_0\left(DNI_{lim},\Delta T_{amb}=\frac{5K}{h}\right)=0.005 \quad (4)$$

For periods with higher DNI, ΔT_{amb} is usually smaller. For DNI of 1000 W/m^2, u_0 is equal to 0.0002, for ΔT_{amb} of 1 K/h which can be expected during midday. Additionally, these periods with small ΔT_{amb} are most common throughout the day. A mean u_0 can therefore be estimated to be around 0.002 [2]. As this effect is the case for both pyrheliometers that are used in TraCS4 and the measurement principle is based on relative ratios of both pyrheliometer signals, u_0 is estimated to be around 0.001.

Inclination Angle

Depending on the inclination angle of the pyrheliometer, convective flows within the pyrheliometer housing affect the temperature of the thermopile. The standard ISO9060:1990 [6] norm defines the uncertainty for first class pyrheliometers due to the inclination angle, u_i, equal to 0.005.

The difference in inclination angles of the two pyrheliometers in TraCS4 is largest for high sun elevation angles. During solar noon, Pyr_{refl} is pointing to the ground. This case of convective temperature flows is not considered within the norm. The norm only considers inclination angles where the pyrheliometer points upwards and the heat flow moves away from the thermopile. Uncertainties due to the inclination angles for pyrheliometers pointing downwards have not been investigated so far. Therefore, u_i can only be estimated to be around 40% higher than the standard value for Pyr_{refl} and thus u_i is equal to 0.007.

Housing Temperature

The influence of the housing temperature on the measurement signal is specified to be less than 0.5% of the signal for a CHP1 pyrheliometer (Pyr_{dir}), according to the manufacturer [5]. These deviations can partly be corrected by the implemented temperature sensor and a sensor specific temperature correction curve. For the CH1 pyrheliometer (Pyr_{refl}), a value of 1% DNI measurement uncertainty is given for the temperature range between -20 and 50°C [7]. Therefore, the uncertainty of the Pyr_{dir} and Pyr_{refl} due to the housing temperature for the cleanliness measurement, u_T, can be estimated to be 0.005 and 0.01, respectively.

Non-Linerarity

The dependency of the mV measurement signal of a pyrheliometer and the corresponding DNI shows a slightly non-linear relationship which is not accounted for by the calibration constant of the sensor. This results in an uncertainty due to the non-linearity (u_{lin}) for both pyrheliometers which is specified to be equal to 0.002, according the manufacturer [5, 7].

It has to be mentioned that the traceability of the TraCS4 DNI measurements to the international reference has not to be assured as the TraCS4 measurement principle is not based on absolute measurement values but on the comparison of two measurement signals. Therefore, no additional uncertainty is added.

The same accounts for the longterm drift of the pyrheliometer calibration constants which is compensated by the calibration of TraCS4. The calibration constant, k_c, is derived upon every cleaning of the sample mirrors, i.e. every few weeks.

Summary of Uncertainty Analysis

The total relative uncertainty of the TraCS4 cleanliness measurement (u_ξ) is a superposition of all the previously mentioned uncertainties (listed also in Table 1) and can be calculated applying the Gauß error propagation. The uncertainties which directly affect the cleanliness ξ (u_{cal}, u_a, u_{CSR}, u_{sp} and u_0) can be added quadratic. The relative uncertainties concerning the pyrheliometers can be referred to the uncertainty of cleanliness ($u_{\xi,pyr}$):

$$u_{\xi,pyr}=\frac{1}{k_c}\cdot\sqrt{\left(\Delta DNI_{refl}\cdot\frac{1}{DNI}\right)^2+\left(\Delta DNI\cdot\frac{DNI_{refl}}{DNI^2}\right)^2}=\frac{DNI_{refl}}{k_c\cdot DNI}\cdot\sqrt{{u'_{pyr,refl}}^2+{u'_{pyr,dir}}^2} \quad (5)$$

with

$$\Delta DNI=u'_{pyr,dir}\cdot DNI \quad (6)$$

$$\Delta DNI_{refl}=u'_{pyr,refl}\cdot DNI_{refl} \quad (7)$$

$u'_{pyr,dir}$ and $u'_{pyr,refl}$ can be calculated by quadratic addition of the values in Table 1:

$$u'_{pyr,dir}=\sqrt{u_{T_1}^2+u_{i1}^2+u_{lin}^2}=0.007 \quad (8)$$

$$u'_{pyr,dir}=\sqrt{u_{T_1}^2+u_{i1}^2+u_{lin}^2}=0.012 \quad (9)$$

Assuming a mean ξ of 0.948 in the measurement interval from April 2013 until End of 2014 at PSA, $u_{\xi,pyr}$ results in 0.014.

The total uncertainty of the cleanliness measurement with TraCS4 is then estimated to be:

$$u_\xi=\sqrt{u_{\xi,pyr}^2+u_a^2+u_{cal}^2+u_{CSR}^2+u_{sp}^2+u_0^2}=0.019 \quad (10)$$

for u_{sp}=0.0004 (the case of u_{sp}=0.0028 does not change the end result up to the given decimal places).

Additionally, the influence of the pyrheliometer on the uncertainty, the spectral correction and the CSR affect all 4 mirror measurements in the same way. This means that an intercomparison of the different mirror materials is possible with a higher accuracy of approximately 0.012 (only taking into account the calibration and mirror plate alignment uncertainty contributions).

In general, it can be concluded that the TraCS4 measurements are sufficiently accurate given the variations within an operational solar field. This can be demonstrated considering the cleanliness in an exemplary solar field of the type Andasol. For this exemplary solar field, cleaning intervals are usually about two weeks between two cleanings of a distinct mirror [2]. Assuming average soiling rates measured at PSA, this results in a mirror cleanliness of about 0.93 after two weeks assuming the cleanliness being 1 directly after the cleaning. The difference of 0.07 lies above u_ξ and can therefore be resolved with the TraCS4 device.

TABLE 1. Estimated and calculated relative uncertainties contributing to the total uncertainty of cleanliness measurements with TraCS and TraCS4 [2].

Parameter	Cause	Relative uncertainty
ξ	Calibration (u_{cal})	0.009
	Mirror plate alignement (u_a)	0.008
	CSR (u_{CSR})	0.0025
	Spectral correction (u_{sp})	0.0004 or 0.0028
	Pyrheliometer zero offset for temperature changes (u_0)	0.001
DNI_{dir} and DNI_{refl}	Pyrheliometer inclination angle (u_i)	0.005 for Pyr_{dir}; 0.007 for Pyr_{refl}
	Pyrheliometer housing temperature (u_T)	0.005 for Pyr_{dir}; 0.01 for Pyr_{refl}
	Pyrheliometer non-linerarity (u_{lin})	0.002
ξ	**u_ξ total**	**0.019**

EXEMPLARY MEASUREMENT RESULTS

The updated TraCS4 delivers one cleanliness time series for each mirror sample. Figure 3 shows an example graph of 12 days of measurement at CIEMAT's Plataforma Solar de Almería (PSA). Two sample mirrors with anti soiling coating 1 (ASC1) and ASC2 as well as two uncoated standard solar mirrors (Ref1 and Ref2) have been installed at the PSA TraCS4 device on the 2nd of February 2017. Continuous measurements have been acquired since then. Outage times occurred during the measurement campaign due to a TraCS4 motor failure or positioning errors. During these example measurements, one coated sample, ASC1 performs slightly better (higher ξ), while ASC2 performs worse compared to Ref1 and Ref2. A Saharan dust episode between the 11th and 13th of February 2017 [8] resulted in a cleanliness loss of 2 – 10%, depending on the sample material. The anti-soiling coatings ASC1 and ASC2 showed a mean absolute ξ drop of 2% and 10% while the uncoated reference samples Ref1 and Ref2 suffered a mean ξ drop of 6.6% and 3.7%, respectively. The soiling impact could thus be reduced by ~45% by the anti-soiling coating ASC1 in comparison to Ref2 for this soiling event.

The soiling rate can be calculated as the difference in cleanliness from one day to the next for each mirror in TraCS4. A comparison of the soiling rate over time of the different mirror materials over the available measurement period from May 18th, 2018 until February 6th, 2019 is shown in Fig. 4. Ref1 and Ref2 denote the uncoated standard mirrors, ASC1 and ASC2 the different anti soiling coated mirrors. The soiling rate is shown on the y axis in units of %/day. No significant difference between the mirror materials can be seen in the soiling rate plot over time. There are periods where the ASCs perform better and those where they perform worse than the reference mirrors.

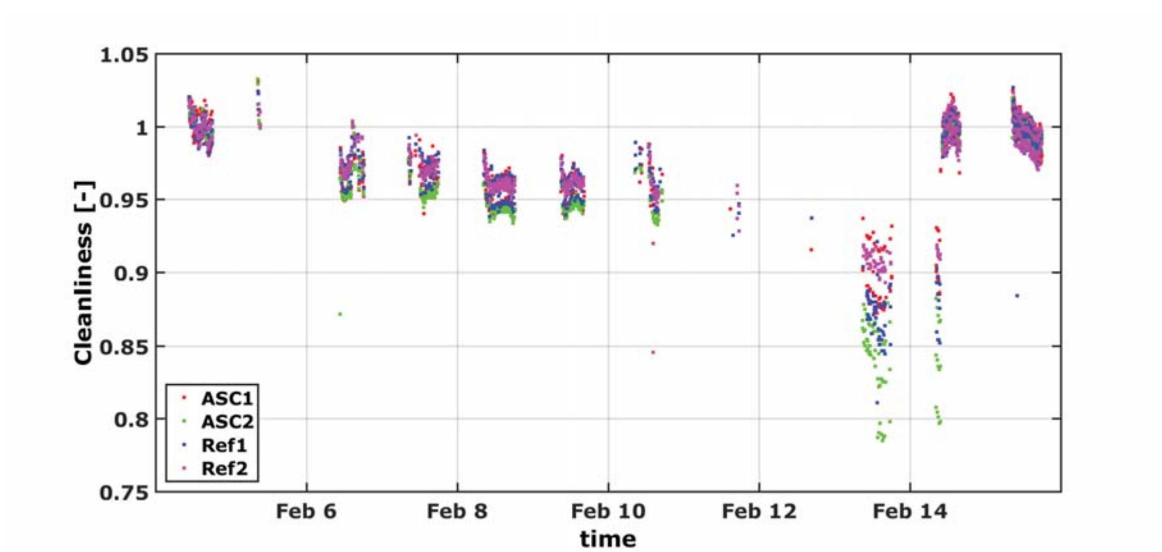

FIGURE 3. Example cleanliness measurements of 4 mirror samples from February 2017 with TraCS4 at PSA.

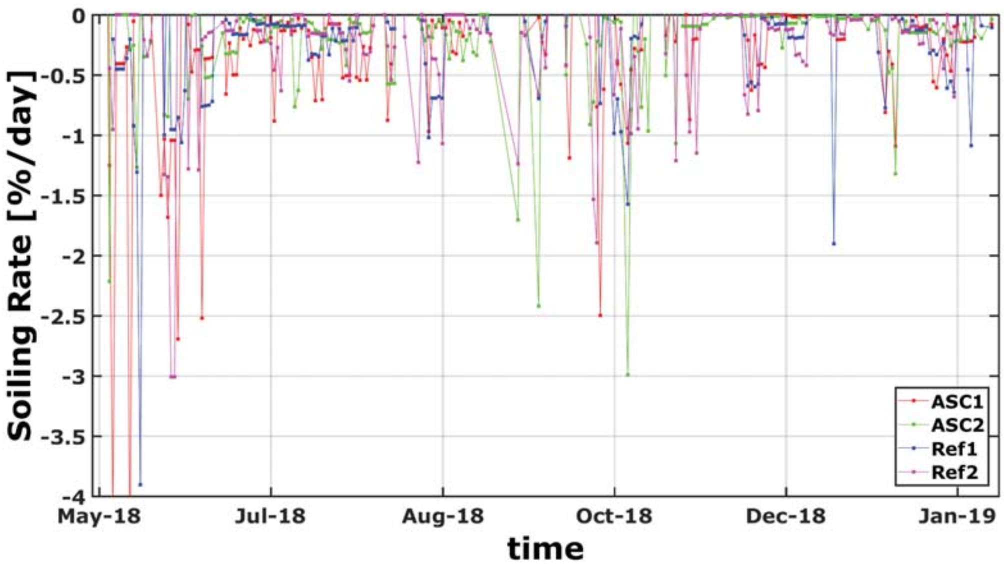

FIGURE 4. Soiling rate for four sample mirrors as measured with TraCS4 at PSA between May 18th, 2018 until February 6th, 2019.

TABLE 2. Average soiling rate measurements and their standard deviations at PSA between May 18th, 2018 until February 6th, 2019. Values are given in units of %/day.

Mirror sample	Average soiling rate	Standard deviation
ASC1	-0.424	0.648
ASC2	-0.235	0.398
Ref1	-0.362	0.474
Ref2	-0.318	0.476

The average soiling rate and its standard deviation are shown in Table Table 2 for the four mirror samples. It can be seen that ASC1 behaves worse in comparison to the other samples at PSA with an average soiling rate of -0.424 between May 2018 and February 2019. ASC1 also shows a larger standard deviation which indicates that it is more sensitive to changing soiling conditions. ASC2 behaves even better than the uncoated samples also with a lower standard deviation compared to the uncoated samples. It can be seen in Fig. 4 that during some distinct weather conditions ASC1 soils more than ASC2 and the reference mirrors (e.g. during various events in July 2018) while during other periods ASC1 soils less (e.g. at the beginning of 2019). These different soiling conditions could be characterized by humidity and dew inducing aerosol particles to deposit and attach to the mirror surface as compared to dry deposition conditions. The standard deviations of the uncoated mirrors and ASC2 are lower than for ASC1. This might be an indicator for a more steady soiling behaviour in comparison to the ASC1.

Reference [9] investigated the same anti-soiling coatings at PSA during the period of February 2017 until the end of 2018. They examined the degradation and anti-soiling behavior of both coating applying two different cleaning techniques (pressurized water and contact brush cleaning). During the evaluation period in which ASC1 and ASC2 have been mounted on the TraCS4, cleaning has been performed by dry contact cleaning with a tissue which might have a similar effect as the contact cleaning with a brush in comparison to pressurized water cleaning. Reference [9] showed that although the ASC1 shows better anti-soiling properties at the beginning of the test period in comparison to ASC2 (see also Fig. 3), this coating has a poorer durability if cleaned by a brush over a longer time period. This result is also confirmed by the longterm evaluation with TraCS4 (Table 2).

CONCLUSION

An upgraded version of the TraCS (Tracking Cleanliness) sensor, the so-called TraCS4 has been developed which can determine the real-time cleanliness and soiling rate of four mirror samples simultaneously. The advantage of this device is its capability to intercompare materials under outdoor exposure in the climate of interest. This is specifically interesting in the light of the dependency of anti-soiling-coatings on local weather conditions.

A detailed uncertainty analysis of the measurements conducted with the TraCS4 device is presented in this work. The uncertainty of the cleanliness measurement is approximated to be about 0.019 cleanliness points, which is sufficiently accurate to measure cleanliness drops between two cleaning cycles. The uncertainty for the intercomparison of different materials is lower due to influences affecting all samples in the same way. It is derived to be 0.012 cleanliness points.

Further, exemplary soiling measurements of more than 7 months of two mirror samples with different anti-soiling coatings and two reference mirrors recorded at PSA are presented. It can be seen that one anti-soiling coating performs worse than the other anti-soiling coating and the reference mirrors in terms of averaged soiling rates caused by anti-soiling and durability properties. This result is also confirmed by D&S reflectance measurements presented in [9].

The novel TraCS4 measurement system enables material comparison and the testing of anti-soiling coatings under distinct realistic meteorological conditions at the site of interest.

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