Screening and Flagging of Solar Irradiation and Ancillary Meteorological Data

Norbert Geuder, Fabian Wolfertstetter, Stefan Wilbert, David Schüler, Roman Affolter, Birk Kraas, Eckhard Lüpfert, Bella Espinar

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Screening and flagging of solar irradiation and ancillary meteorological data

N. Geuder[a]*, F. Wolfertstetter[b], S. Wilbert[b], D. Schüler[b], R. Affolter[a], B. Kraas[a], E. Lüpfert[a], B. Espinar[c]

[a]CSP Services, 04001 Almería, Spain, and 51143 Cologne, Germany
[b]DLR German Aerospace Center, Institute of Solar Research, Plataforma Solar de Almeria, 04200 Tabernas, Spain
[c]MINES ParisTech, Centre Observation, Impacts, Energie (O.I.E.), CS 10207, F-06904, Sophia Antipolis cedex, France

Abstract

Solar irradiance and ancillary meteorological data is frequently measured by automatic weather stations for use within solar resource assessment for solar power plants. High accuracy measurement data are required for comparison and adjustment of satellite data and derivation of the expectable long-term mean value of the solar resource. Thus, utmost diligence must be taken during the measurement process and data evaluation to achieve data quality required for project financing. The combination of automatic data screening and manual flagging by an expert in at least daily frequency in close collaboration with a local station operator is the most recognized way to detect impacts on measurement data and paves the way for post-correcting data treatment where necessary and reasonable. This is the preferred and recommended procedure, resulting in highest data quality. The presented work is also understood as a basis for ongoing development and discussion among the corresponding expert group about screening of irradiance and ancillary meteorological data and its corresponding flagging. A common understanding and wide conformity about the screening process and flagging of data would be aspired.

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Keywords: Meteorological data, flagging, screening, solar irradiation, data treatment, Automatic Weather Station, monitoring, supervision

* Corresponding author. Tel.: +49-2203-9590030.
E-mail address: n.geuder@cspservices.de

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1. Introduction

Solar irradiance with further ancillary meteorological data is the basis for solar resource assessment studies and indispensable in project development of solar power plants. A variety of sources exists for such data: they may originate from measurements with Automatic Weather Stations (AWS), be derived from satellite observations or result from weather models. Accuracy and corresponding quality of the data vary strongly depending on the data source. In the case of measured data, a variety of instrument types is available for use in AWS, having different uncertainty performance. However, the true data quality is to a by far higher extent determined by how thoroughly the measurements are performed. This includes how continuous the equipment is maintained, how diligent the measurements are controlled and if the data consistency is supervised.

Differing measures exist to check the data quality and detect influenced or erroneous measurements. Performing a thorough Quality Check (QC) of the data is therefore required to evaluate the quality of a data set and assign its validity for its prospected utilization. This should comprise both automatic data screening as well as the visual inspection of the data by an expert, preferably in high resolution time series (e.g. 1 minute) and at a daily frequency. A number of QC measures for automatic tests have been described by different institutions (see e.g. references [1-6]). In most cases, they contain automatic screening of the data on certain mathematical or logical conditions, delivering as result that the data point either passes or fails the test condition. The results are documented with one combined or several flags according to the particular format of each institution.

Further influences on the data potentially known by the supervisor are in most cases only included as text comments or even omitted. Such influences may be for instance damaged or misaligned sensors, maintenance works on the instruments, detection of soiled sensors and subsequent sensor cleaning, obstructed sensors, temporarily erroneous calibration constants in the program code, etc. These events are frequently not detected or sometimes not even detectable by automatic QC screening tools, however they contain important and valuable information. Useful QC measures for an automatic data screening and a complementary manual flagging user interface were implemented in the Meteorological Data Management System (MDMS). The MDMS has been developed and is used by Concentrating Solar Power Services (CSPS) and DLR's Institute of Solar Research within their daily collection and revision of meteorological data, which they gather for their own purposes or on customer order. Meanwhile, the MDMS tool has been requested also by further institutions. The scheme of the data screening and data flagging will be presented in this publication. Scientists and experts in that topic are encouraged to exchange their opinion and experience with the authors in order to develop a common understanding as far as possible and certain standardized methods for data screening.

Nomenclature

AWS	Automatic Weather Station
BSRN	Baseline Surface Radiation Network
DHI	Diffuse Horizontal Irradiance
DNI	Direct Normal Irradiance
GHI	Global Horizontal Irradiance
ETR	Extra-Terrestrial Radiation
K	diffuse fraction or effective diffuse horizontal transmittance
K_t	clearness index or effective global horizontal transmittance
K_n	direct beam transmittance
MDMS	Meteorological Data Management System
p	barometric pressure
QC	Quality Check
t	time
T_{air}	ambient air temperature
z	solar zenith angle

2. Automatic data screening

Several particular errors of meteorological data can be detected by automatic screening algorithms. Corresponding tests are documented in a number of publications [1-5]. Exemplary categories of such tests are the comparison with natural physical or improbable limits. We summarize existing checks in combination with the list of the ones implemented in the MDMS. Flags produced in such a way usually deliver fast and rough information about the data quality. However, dependent on how strict the screening parameters and their corresponding values are chosen; too many or too few events may be detected. Moreover, the values of some parameters are site-dependent according to corresponding weather conditions. Therefore, the results of the automatic screening always demand a manually check of an expert to ensure their validity. A number of reasonable automatic checks and data screening approaches are presented subsequently.

2.1. Missing data values

Data sets usually refer to regular time intervals. Due to various reasons (e.g. power outage during the measurement process), data from certain time stamps or intervals can be missing. An automatic filter should check, detect and mark the time stamps of a gap in the analyzed data set.

2.2. Lower irradiance limit: GHI, DNI and DHI

The physical lower limit for solar irradiance is strictly speaking 0 W/m². However, negative values in the order of -2 to -5 W/m² occur at night for thermopile sensors due to the net long-wave radiation exchange between the sensor and the cold sky. The lower limit of -4 W/m² cited in the MESOR report [6] seems too strict for pyranometers as still a high number of time stamps were flagged with values slightly below -4 W/m² due to natural fluctuations. Values exceeding -5 W/m² however occur scarcely and thus are probably a sign of measurement errors or – at ventilated pyranometers – may be a sign that the air filter of the fan is clogged with dirt. Thus a lower limit value of -5 W/m² is proposed and used for measurements of GHI and DNI with pyranometers.

As pyrheliometers do not sense the negative net long-wave radiation exchange to that extent due to their construction and orientation during night (usually to the horizon), their lowest response remains over -1 W/m². Also, Si-photodiode sensors do neither detect the negative long-wave net radiation. They merely may show slightly negative values due to small imperfections of their electrical connection and/or the measurement device. Therefore, a lower limit of -1 W/m² is appropriate for both, pyrheliometers and Si-photodiode sensors.

2.3. Upper irradiance limit for DNI

An upper limit for DNI is the extraterrestrial radiation (ETR), also known as Solar Constant. It has a mean value of 1367 W/m² according to WMO [7] but varies over the year with the sun-earth distance. The DNI is further reduced by the earth's atmosphere. Its maximum values at clear skies can be estimated with the Bird clear sky model [8]. The values with the input parameters set to values representing absolutely clear skies serve well as an upper DNI limit. The values used in MDMS are listed in Table 1.

Table 1: Parameters used for upper DNI threshold and Bird's clear sky model [8]. 'Forward scattering rs' prescribes what proportion of scattered radiation is sent off in the same direction as the incoming radiation ("forward scattering"). Bird [8] recommends a value of 0.85 for rural aerosols.

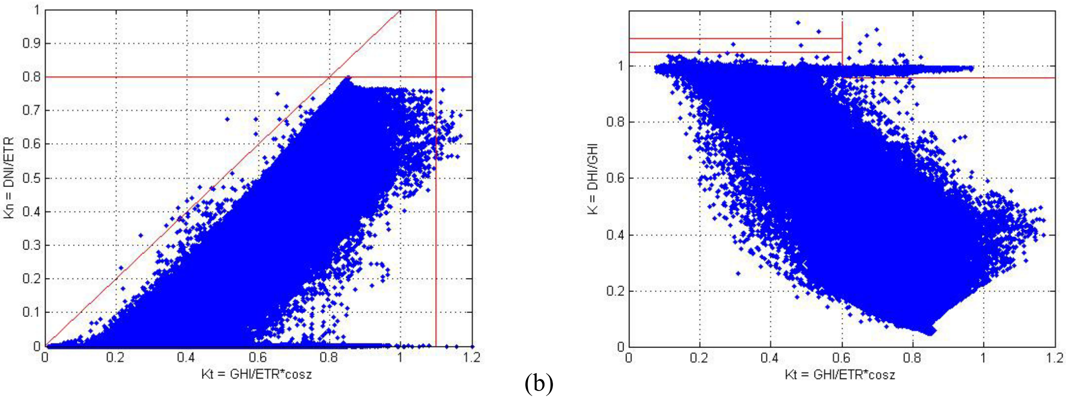
Parameter	Dimension	Possible values	Setting in MDMS
Total column ozone	atm cm	0.05 … 0.04	0.05
Total precipitable water vapor	cm H_2O	0.01 … 6.5	0.01
Intermediate computation of the broadband aerosol optical depth	-	0.02 … 0.5	0.02
Forward scattering rs.	-	0.85 recommended	0.85
Albedo	-	Between 0.2 (earth) and 0.9 (snow)	0.2

2.4. K-value tests

Clear upper limits for GHI and DHI are hardly definable: DHI is usually below 600 W/m² but in certain cases with thin clouds, haze and/or aerosols higher values are observed. GHI may easily exceed the ETR in the case when DHI is rather high and at once the cloud cover has a clearance allowing the direct beam and thus DNI rise suddenly. Such high GHI values exceeding ETR usually are only of short duration. The consistency and plausibility of the irradiation data can be analyzed by means of the combination of the three irradiance components GHI, DNI and DHI at a given time. Therefore, transmittances calculated from their values according to [4] and plotted against each other (see Table 2 and Figure 1).

Table 2: Definition of K-values with z as the solar zenith angle

K_t, the clearness index or effective global horizontal transmittance	K_n, the direct beam transmittance	K, the effective diffuse horizontal transmittance
$K_t = GHI/(ETR \cdot \cos(z))$ (1)	$K_n = DNI/ETR$ (2)	$K = DHI/GHI$ (3)



(a) (b)

Figure 1: Scatter plots of the K-values where red lines mark the applied limits. (a) K_t-K_n-space and (b) K_t-K-space

There are two main tests for the K-values. Checking limits in the K_t-K_n-Space (Figure 1a) and checking limits in the K_t-K-space (Figure 1b). The K_t-K_n-space is checked for the following limits:

- $K_n > K_t$: Such a situation can occur due to a cleaning event of the GHI-Pyranometer
- Upper Limit for K_n: empirically chosen, 0.8. In [4] a limit of 1 is suggested, but with this value almost never events are detected. Therefore, this limit was decreased.
- Upper Limit for K_t: 1.0 as recommended in [4].

The K_t-K-Space (Figure 1b) is checked for this limit:

- $K > 1.05$ for $z < 75°$ and $K > 1.10$ for $z > 75°$ [4]: although the DHI cannot be higher than the GHI, both sensors have an inaccuracy and for low irradiations and sun heights, the inaccuracy is even bigger.
- (K_t is already checked in the K_t-K_n space)

2.5. Operational check of sun tracker alignment or shadowband rotation

GHI and DHI both at high levels as with prevailing direct irradiance component and at once DNI zero frequently is a sign that the tracker is not working or the shadowband not rotating correctly. So with K_t over 0.6 and K over 0.96, a flag for the tracker/shadowband-malfunction is set.

2.6. BSRN/Endorse tests

Also commonly used tests from BSRN/Endorse are implemented. Tests for rare observations in irradiance data are performed with the limits from Espinar [5]. The conditions for GHI, DNI and DHI for not being flagged are:

$$0.03 \cdot ETR \cdot \cos(z) < GHI < 1.2 \cdot ETR \cdot (\cos(z))^{1.2} + 50 \text{ W/m}^2 \quad (4)$$

$$0 < DNI < 0.95 \cdot ETR \cdot (\cos(z))^{1.2} + 10 \text{ W/m}^2 \quad (5)$$

$$0.03 \cdot ETR \cdot \cos(z) < DHI < 0.75 \cdot ETR \cdot (\cos(z))^{1.2} + 30 \text{ W/m}^2 \quad (6)$$

Also consistency tests are performed. The following conditions need to be fulfilled for the set of a flag:

$$DHI/GHI > 1.05 \quad \text{for} \quad z < 75° \qquad \text{and} \qquad DHI/GHI > 1.1 \quad \text{for} \quad 93° > z > 75° \quad (7)$$

Furthermore consistency tests are applied that work like the consistency tests above, but with slightly different, less restrictive, constants:

$$\left|1 - \frac{GHI}{DHI + DNI \cdot \cos(z)}\right| > 0.08 \quad \text{for} \quad z < 75° \qquad \text{and} \qquad \left|1 - \frac{GHI}{DHI + DNI \cdot \cos(z)}\right| > 0.15 \quad \text{for} \quad 93° > z > 75° \quad (8)$$

Errors in this test are often an indication for a cleaning event.

2.7. Irradiance gradients or change rates

GHI, *DHI* and *DNI* are checked for quick changes in irradiance values. For thermopile sensors and Δt = 10 min temporal resolution the suggested limits are [4]:

$$\left|GHI(t)/\cos(z(t))/ETR - GHI(t-\Delta t)/\cos(z(t-\Delta t))/ETR\right|/\Delta t < 0.75 \text{ min}^{-1} \quad (9)$$

$$\left|DNI(t)/ETR - DNI(t-\Delta t)/ETR\right|/\Delta t < 0.75 \text{ min}^{-1} \quad (10)$$

$$\left|DHI(t)/\cos(z(t))/ETR - DHI(t-\Delta t)/\cos(z(t-\Delta t))/ETR\right|/\Delta t < 0.35 \text{ min}^{-1} \quad (11)$$

Although these values are tested with 10 min time resolution in [4], we use it for Δt = 1 min time resolution as well. The time dependency of ETR is not shown, because it does not change observably in such a small time difference as one or ten minutes.

2.8. Artificial intervention on DNI signal (cleaning)

Aim of this test is to find artificially generated high gradients in the DNI data caused by cleaning of the pyrheliometer, sensor shading (e.g. by maintenance staff) or tracker errors. It makes use of the DNI-coincidence, which is defined as the difference $DNI_{coin} = DNI_{meas} - DNI_{calc}$ between the measured DNI and the DNI that is calculated from DHI and GHI. A step test for the DNI-coincidence basically works as the irradiance gradient tests described above. However, large variations within two consecutive coincidence values in 1 min resolution can also be caused by clouds and shall not be flagged. Hence, the detection is only applied in time intervals that are surrounded by nearly constant DNI coincidence gradients as explained in the following.

First, intervals between phases with rather constant DNI coincidence are defined as intervals of 15 min length that are preceded and followed by 2 min intervals with DNI coincidence gradients of less than 4 W/m²/min. Only the 15 min intervals that are surrounded by nearly constant DNI coincidence gradients are checked for high DNI coincidence gradients (see Figure 2). A timestamp is flagged when a DNI-coincidence gradient of 15 W/m²/min is detected within such a 15 min time interval. The interval has been set to 15 min empirically in order to cover the cleaning events completely.

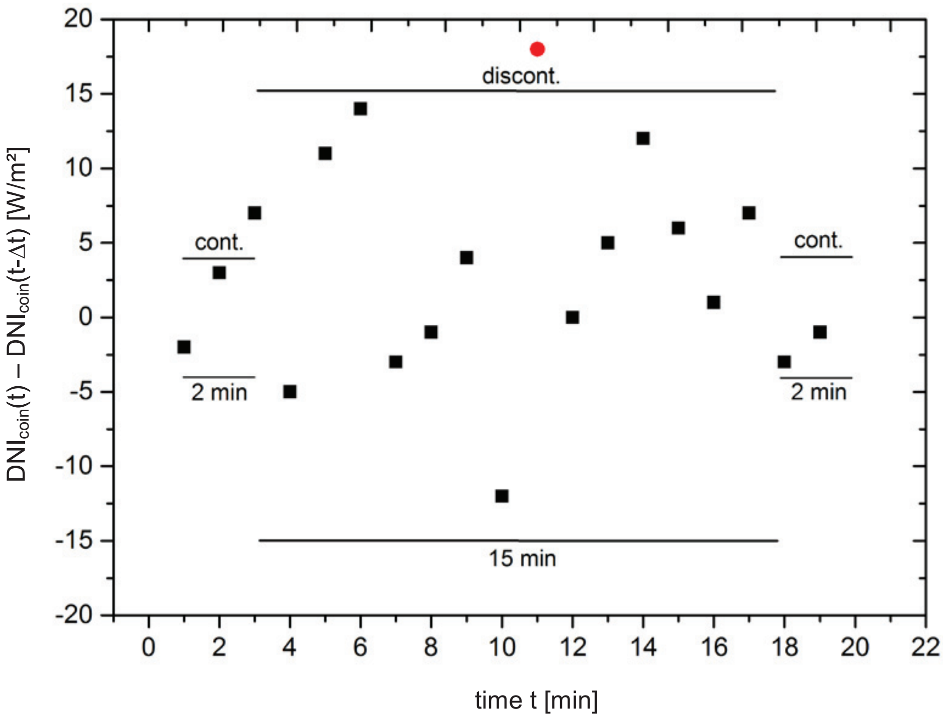


Figure 2: Visualization of detection and selection of artificial impacts on DNI by screening of the DNI-coincidence gradient. The red circle marks the flagged timestamp.

2.9. Temperature screening

Temperature is recommended to be measured multiply in AWS: if possible, at least dry bulb air (or ambient) temperature, temperatures of the irradiance sensors and the logger temperature should be recorded. This allows the performance of several checks:

1. Maximum/minimum thresholds: For AWS at many sites values of -10°C as lower threshold and +60°C as upper threshold have been chosen. However these values require to be adapted for other climate zones where lower temperatures may occur (e.g. to -30°C in winter or even less).
2. Coincidence: the individual temperature values are compared to each other. If the difference between them is over a certain threshold (15 K for logger and air temperature and 20 K for irradiance sensor and air temperature), an error flag is set.
3. Change rate: temperature should not change more than ±2°K/min for data in one minute time resolution and not more than ±0.4 K/min for 10 min time resolution.

2.10. Wind data screening

Wind speed and wind direction data are checked for maximum and minimum limits:

- 0 m/s < Wind speed < 50 m/s
  The upper limit is empirically derived, higher values are not necessarily erroneous but should be reviewed on correctness by skilled persons potentially together with locals.

- 0° < Wind direction < 360°

Furthermore, wind speed and direction are checked for its variability using limits from ENDORSE [5]. For wind speed a flag is set if the values change less than 0.5 m/s within intervals of one hour. For wind direction a minimal change of 5° is assumed. If it is less and the wind speed is greater than 0 m/s a flag is set. These tests help detecting sensor failures.

2.11. Barometric pressure screening

The expected mean value of barometric pressure can be calculated using the altitude of the site over mean sea level and knowledge of the air temperature T_{air} as:

$$p = 1013.25 \cdot \left(1 - \frac{0.0065 \cdot altitude}{273.15 + T_{air}}\right)^{5.255} \tag{12}$$

According to CSP Services observations, the measured pressure values usually remain within a range of ±30 hPa from the calculated average value. Furthermore, the maximum change rates have been derived from our data sets to ±2 hPa for data with one-minute time resolution and to ±4 hPa for 10 min data.

2.12. Screening of atmospheric humidity

Most AWS usually determine atmospheric humidity as relative humidity values. They are checked for its limits and change rate (as in ENDORSE [5]):

- 0 % < relative humidity < 100 %
- Change rate: < 10 %/min for 1-minute time resolution and
  < 15 %/10 min for 10-minute time resolution (this limit by CSP Services)

2.13. Screening of precipitation data

Precipitation is checked for minimum and maximum values. The following values are regarded as reasonable for most situations and sites interesting for solar energy applications according to observations from CSP Services:

- 0 < precipitation < 4 mm/min for 1-minute data
- 0 < precipitation < 3 mm/min for 10-minute data

Nevertheless, the upper limit may be exceeded easily at tempests and very heavy rainfalls; the occurrence of such a case should be revised on correctness. Depending on the type and mounting of the precipitation sensor, precipitation may be recorded erroneously due to strong winds triggering accidentally the precipitation sensor. A visual check by skilled personnel on recorded precipitation in combination with high wind speed (>17 m/s) indicated by a corresponding flag is therefore recommended for tipping bucket rain sensors. Depending on the contemporaneous sunshine pattern and relative humidity profile as well as potentially information from local personnel, the recorded precipitation is to be disregarded or stated as correct.

2.14. Screening for dew on irradiance sensors

Formation of dew on the irradiance sensors usually has an impact on the measurement signal. The form of the impact depends on the sensor type: a reduction of the signal is usually observed at pyrheliometers and pyranometers due to reflection, scattering or blocking of the sensitive surface by water droplets; at photodiode sensors, it may cause augmentation of the sensor signal because forming dew droplets can combine on the usually flat, (constructional) smaller and mostly diffuse-translucent photodiode cover, thus forming bigger or just one singular droplet. They may act as a collecting lens, increasing the sensor response instead of reducing it.

The formation of dew occurs when the sensor's outer surface temperature (not the measured sensor body temperature!) falls below dew point. In MDMS, it is assumed to be possible when the air temperature is less than

3.5 K over the calculated dew point [9]. For AWSs with 3 separate thermopile sensors for measurement of GHI, DNI and DHI, additionally the coincidence of the measured and calculated DNI is screened and flagged correspondingly: occurrence of dew is assumed when contemporaneously the measured DNI is more than 50 W/m² lower than its calculated value (from GHI, DHI and the solar elevation angle).

At RSIs using one single sensor for determination of the three irradiance components and usually showing the increased sensor signal with the occurrence of dew, its automatic detection via a computational algorithm is hardly possible. Thus it is recommended to be performed via a visual check by an expert.

2.15. Battery voltage screening

Many AWS at remote sites are operated on batteries, charged by PV panels. To prevent outages due to broken power supply, battery voltage should be recorded and checked. The following tests are recommended:

- Check for the minimum daily battery voltage. If the value drops below 11.0 V (valid for a 12 V system, to be adapted for systems with other voltages), a flag is set to notice low battery power and/or a damaged battery.
- Check for correct battery charging with two different ways:
  - The daily data set is screened for GHI values over 200 W/m² and corresponding battery voltage analyzed on increasing or decreasing values in subsequent timestamps if the battery voltage is below a threshold of 12.5 V.
  - The minimum and maximum battery voltage is determined for an interval of at least 12 hours (to assure inclusion of a charging period during daylight). The difference between both voltages must be greater than 0.5 V, otherwise a charge error flag is set.

AWS connected to grid power usually have an uninterruptable power supply. The availability of grid power should be checked by the measurement system and a flag set at power outages to be able to react and prevent data losses. The battery voltage of the uninterruptable power supply should be checked and a flag set if it drops below a system-defined threshold to enable detection and reaction by data reviewing and local staff.

2.16. Screening on manual comments or entries to the data set by a supervisor

The recorded data set should be checked for manual entries or comments that a supervisor entered in the database and a corresponding flag is set. This allows the user easy detection of special events or potential explanations for certain data peculiarities.

3. Visualization of data flags and interactive data treatment

The above described flags should be included in the meta data when exchanging data or for manual data monitoring. Figure 3 shows exemplary erroneous DNI measurements due to dew, where the flag is illustrated as vertical orange lines at the affected timestamps. Furthermore, MDMS offers a tool for data treatment which allows correcting such apparently erroneous data. Different methods are included depending on the affected parameter and the detected error (further details see section 4). Whereas the above mentioned automatic screening flags do not need to be stored, any type of data treatment or other important observations definitely require being stored with the data.

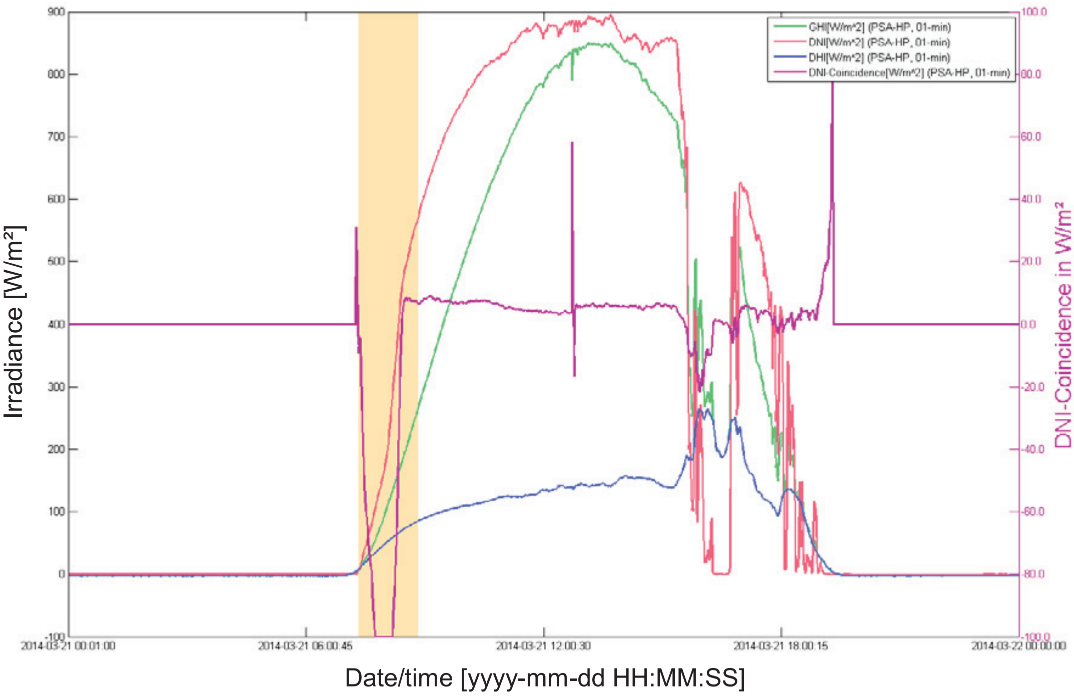


Figure 3: Visualization of flagging done by automatic data screening, here for erroneous DNI data due to dew in the morning hours.

4. Semi-automatic flagging

A typical example for semi-automatic flagging is a flag for gap filling, which is one of the data correction tools of MDMS. One can select gaps graphically by clicking in the figure or by selecting the gap limits from the data table. Within the interval marked by red lines in the graph, one can e.g. choose between a linear interpolation and data from another source to fill this gap. Possible methods for gap filling are described in e.g. [10].

During the interpolation process, the MDMS sets the corresponding flags automatically to the affected timestamps. Therefore it is called semi-automatic flagging. The flags already used are:

- data taken from other station
- data linearly interpolated
- interpolated using average daily variation from other existing data points
- data replaced by redundancy
- data replaced by hand (enter values in the data tables)
- data replaced from other day, exact day written in comment
- interpolated as clear sky scenario with turbidity according to Linke from existing DNI data
- interpolated as clear sky scenario with Bird model and standard parameters
- interpolated as clear sky scenario with Bird model and parameters estimated from irradiance curves
- sensors wet
- data loaded manually
- data quality unclear
- ‘negative’ cleaning event corrected

The notation of ‘negative’ cleaning events denotes situations when the sensor seems to be dirtier after the cleaning than before. It has to be stated and intonated that such data treatment needs to be performed by experts and skilled persons only. Data manipulation has to be done diligently and in order to correct and improve erroneous or deviating data. However, in order to do so, data treatment is often necessary in measurements due to measurement errors which may be caused by maintenance, sensor failure or other reasons. The scrupulous documentation of all performed data treatment is of utmost importance.

5. Manual flagging

Further flagging information has to be set manually. This can be a description of technical errors, e.g. 'soiled sensor' or 'ventilation unit failure'. Other errors shall be documented as well, e.g. 'shadow on sensor' (for example due to a cable of an electric power line, which shadows the sensor daily but at slightly different day hours).

6. Creation of user info

A detailed documentation of data quality with flags only makes sense if this information can be used later on for sorting out or filtering data, depending on its purpose. So a number of flags are used to decide which data passes certain filters for further use. Combinations of flags can be defined to describe the following exemplary groups:

- Use data for calibration
- Use data for DNI sum but not for calibration purposes
- Do not use this data at all

7. Summary and outlook

The combination of automatic data screening and manual flagging by an expert in at least daily frequency in close collaboration with a local station operator is the most recognized way to detect impacts on measurement data and paves the way for post-correcting data treatment where necessary and reasonable. This is the preferred and recommended procedure, resulting in highest data quality. The presented work is also understood as a basis for ongoing development and discussion among the corresponding expert group about screening of irradiation and ancillary meteorological data and its corresponding flagging. A common understanding and wide conformity about the screening process and flagging of data would be aspired.

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