Comments on Quality Control of Solar Radiation Data Measured at a Ground Station in Hot and Dry Zone

D. Kumar and B. Ravindra

Abstract Ministry of New and Renewable Energy, Govt. of India has set a target of 100 giga watts (GW) power from solar power till 2022. Hence, the importance of solar radiation resource assessment. Ground-based solar radiation measurement and its quality plays an important role in the study of estimation of solar radiation and forecasting of solar power produced. In this paper hourly averaged solar irradiance data on a horizontal surface, measured at Indian Meteorological Department weather station for the hot and dry region, Jodhpur (India) is analyzed for the month of August, 2015. Data quality check is done in two stages where, at the first stage, solar irradiance is taken in original form, and then in the second stage BSRN standard guidelines, coherence and correlation tests are applied. Data quality check of ground-based solar radiation data for Jodhpur during rainy season (month having highest error/disturbances) highlights the need to include other weather parameters such as rainfall data. The results are compared with other available data, and some suggestions for data quality improvement are discussed.

Keywords IMD · Irradiance · NREL SERI-QC · BSRN

Symbols

ε Earth Eccentricity Factor
I_E Extraterrestrial Radiation
W Watts
Z Zenith Angle

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Abbreviations

AMS	Advance Measurement Station
BSRN	Baseline Surface Radiation Network
C-WET	Centre for Wind Energy Technology
CIEMAT	Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas
DHI	Diffuse Horizontal Irradiance (W/m^2)
DLR	Deutsches Zentrum Für Luft- und Raumfahrt
DNI	Direct Normal Irradiance (W/m^2)
ETR	Extraterrestrial Radiation
GHI	Global Horizontal Irradiance (W/m^2)
IMD	Indian Meteorological Department
ISO	International Organization for Standards
JNNSM	Jawaharlal Nehru National Solar Mission
K	Diffuse Horizontal Transmittance (DHI/GHI)
K_n	Direct Beam Transmittance (DNI/I_E)
K_t	Clearness Index (GHI/(I_E x cos(z)))
MESOR	Management and Exploitation of Solar Resource Knowledge
MNRE	Ministry of New and Renewable Energy
NIP	Normal Incidence Pyrheliometer
NREL	National Renewable Energy Laboratory
PSP	Precision Spectral Pyranometer
RMIB	Royal Meteorological Institute of Belgium
SERI-QC	Solar Energy Research Institute Quality Control software package
SRRA	Solar Radiation Resource Analysis
WMO	World Meteorological Organization

1 Introduction

Due to rapid consumption of fossils fuels and huge demand for power, MNRE, Govt. of India, has introduced a solar power generation plan named Jawaharlal Nehru National Solar Mission (JNNSM) [1]. Currently, the ministry has updated its solar target to 100 GW till 2022 [2]. To achieve this target, solar radiation resource assessment is needed. The solar radiation data can be obtained from several sources. The first one is the IMD-Pune (National Data Centre) [3], which is around for the last 100 years, from where we can take satellite as well as ground data. Next is C-WET Chennai which has installed 111 ground-based SRRA stations and 4 AMS which provide solar radiation data with very fine frequency (1 min). To achieve the given solar power generation target mentioned above, the most important knowledge required is good quality solar radiation data, with no missing values and free from all errors.

In this paper, the solar radiation data quality is demonstrated for one Indian location. It is known that climate classification may also play a role in solar resource assessment. Here we have taken classification provided in MNRE handbook: Energy Conscious Buildings [4]. This is based on the work of Bansal et al. [5] who have proposed five climatic zones [6].

For any location-specific analysis, the first thing required is the long-term time-series solar radiation data of that location. The available data can be of three types: satellite data, time-series data, and ground-based data. The satellite data is basically used for preliminary site analysis, but for any detailed assessment, ground-based data is required for at least 1 year [7]. In this research article, we will use only ground-based solar radiation data.

The accurate measurement of ground-based solar radiation data requires great care. The instruments required for solar measurement: Pyranometers for the DHI and GHI, and Pyrheliometer for DNI, require careful operation and maintenance and only best class instruments which follow (ISO-9060) [8] are selected for actual research grade databases. On-line data checking is required for getting best class data. Such tests routinely used for checking the data quality will be discussed later in this article.

The reasons behind errors occurring in solar radiation measurement are equipment error, uncertainty, and operational errors [9]. On equipment side, the errors usually are cosine and azimuth response, temperature response etc. out of which maximum error is caused by cosine error. Usually all these errors are controlled and checked by manufacturer and by the calibration center. A routine check-up is done for instrument's sensitivity and its quality standard, which certifies them for further use on ground. Reading, cleaning, alignment or other operational errors such as natural errors are also not uncommon.

To study the effects of natural errors Gender and Quashing [10] have worked on the response of dust/sand layers on measuring instruments and made some suggestions for correction of data. They suggested use of Si-based sensors, if the site is in a remote place and regular operation and maintenance is not possible. It may be noted that poor quality of solar radiation data may lead to erroneous solar resource assessment and can lead to project failure [11].

One of the earliest approaches used in the solar radiation data quality analysis is given by, NREL SERI-QC [12]. Here they have introduced some dimensionless components like transmittance coefficients for global, diffuse and direct radiation components. If we plot beam and global coefficients, then we can easily verify the quality of data. Some possible plots for different sky conditions and alignment errors are described in detail later on. Many researchers across the world have contributed to this field: Some have worked on filtering of the GHI and some on combination with DHI and DNI [13]. These GHI, DHI, and DNI data sets are our prime inputs, and the basic approaches, tests, and limits which check the authenticity of data, are discussed in this article. Due to huge variation in data across the world, standard guidelines are established (BSRN) [7]. Tests and guidelines discussed above also involve some meteorological data, which help the data manager to verify the actual problem of disturbed radiation data. The final objective of this research is to provide best class data, which will be free from all errors and shows the real environmental picture of location being analyzed.

2 Database and Site Selection

According to the solar radiation map generated by MNRE and C-WET [4, 14], the north-west region of India is having very good quality of solar radiation and the area is also barren with highest clear sky and sunshine hours (around 300 days). The location selected in this work is Jodhpur (Rajasthan) as many solar installations are expected to come up in this region. The solar radiation data for the month of August, 2015 is selected, as in this month we get the highest variability due to sand-storms, rain and heavy cloud overcast conditions. The detailed description of selected location can be seen in Table 1.

3 Methodology

For ground-based solar radiation data, quality tests to be used are explained below. The tests and procedures follow international practices developed by NREL SERI-QC [12] and WMO BSRN [7]. These standards and tests are elaborated by MESOR [15] and further improved by experience gained by CIEMAT [13], DLR [16] and other ground-based radiation measuring networks. This work is followed by RMIB [17], MNRE C-WET [18] and many more groups around the world. The mathematical approach described in the next section is taken from these sources.

Quality control tests are applied on ground data measured at IMD Jodhpur station.

Table 1 Description of test location

S. No.		
1.	Location	Jodhpur (Rajasthan) Climate: Hot and Dry (MNRE handbook) Latitude/Longitude: 26.25° North/73.04° East
2.	Data Source	IMD, Ground Measurements 10 min (Frequency) High/Medium Maintenance Schedule
3.	Equipment's	Pyranometer (First Class Standard (PSP)—Eppley) Pyrheliometer (Secondary Standard (NIP)—Eppley) Ultrasonic Wind, Pressure, Temperature, Relative Humidity Sensor and Rain Gauge

3.1 Physical Limit Tests [16]

It is the maximum and minimum limit which can be achieved by solar radiation at the most optimal climate conditions. The maximum value which can be achieved is extraterrestrial radiation (1365 W/m^2), but it is affected by the latitude and orientation of the location. The minimum value may go below zero (i.e., −4 W/m^2) due to radiative cooling at night. These limits for various solar radiation components are given below in Eqs. (1)–(3):

$$\mathrm{GHI_{max}} = \mathrm{DNI_0} \times 1.5 \times (\cos(z))^{1.2} + 100, \quad \mathrm{GHI_{min}} = -4 \; (\mathrm{W/m^2}) \tag{1}$$

$$\mathrm{DNI_{max}} = \mathrm{DNI_0}, \quad \mathrm{DNI_{min}} = -4 \; (\mathrm{W/m^2}) \tag{2}$$

$$\mathrm{DHI_{max}} = \mathrm{DNI_0} \times 0.95 \times (\cos(z))^{1.2} + 50, \quad \mathrm{DHI_{min}} = -4 \; (\mathrm{W/m^2}) \tag{3}$$

$$\mathrm{DNI_0} = I_E \times \varepsilon$$

where $\mathrm{GHI_{max}}$, $\mathrm{DNI_{max}}$, $\mathrm{DHI_{max}}$ are maximum theoretical radiation and $\mathrm{GHI_{min}}$, $\mathrm{DNI_{min}}$, $\mathrm{DHI_{min}}$ are minimum theoretical radiation received on selected location.

3.2 Extreme Rare Limit Tests [16]

Here the limit is more refined and these limits are calculated for the most possible radiation values obtained under clear sky conditions in the clear and dry atmosphere (see Eqs. 4–6). The diffuse (Rayleigh) limit is calculated using the work of Long and Shi [19]. Maximum and minimum limits possible for clear sky are given below in terms of the extraterrestrial radiation (ETR):

$$0.03 \times I_E \times \cos(z) < \mathrm{GHI} < \left(1.2 \times I_E \times (\cos(z))^{1.2} + 50\right) \; (\mathrm{W/m^2}) \tag{4}$$

$$0 < \mathrm{DNI} < \left(0.95 \times I_E \times (\cos(z))^{1.2} + 10\right) \; (\mathrm{W/m^2}) \tag{5}$$

$$0.03 \times I_E \times \cos(z) < \mathrm{DHI} < \left(0.75 \times I_E \times (\cos(z))^{1.2} + 30\right) \; (\mathrm{W/m^2}) \tag{6}$$

3.3 Coherence and Correlation Between Radiation Components [16]

The two radiation components (DHI and DNI) are correlated to GHI. Their mutual ratios and correlation with extraterrestrial and theoretically calculated values are also used for data quality analysis. The relations shown in Eqs. (7)–(10) are valid for all types of environmental conditions, and standard limits are calculated. These indicate the quality status of the solar radiation data.

$$\mathrm{DHI}/\mathrm{GHI} > 1.05, \quad \text{for } z < 75^\circ \tag{7}$$

$$\mathrm{DHI}/\mathrm{GHI} > 1.1, \quad \text{for } 93^\circ > z > 75^\circ \tag{8}$$

$$\left|1 - \frac{\mathrm{GHI}}{\mathrm{DHI} + \mathrm{DNI} \times \cos(z)}\right| > 0.08, \quad \text{for } z < 75^\circ \tag{9}$$

$$\left|1 - \frac{\mathrm{GHI}}{\mathrm{DHI} + \mathrm{DNI} \times \cos(z)}\right| > 0.15, \quad \text{for } 93^\circ > z > 75^\circ \tag{10}$$

3.4 Tracking Error Test [18]

For measuring DNI, the device used has to be kept at constant tracking mode, so that equipment is always in direct focus of sun. The angular misalignments leads to tracking error and the effect of this error can be easily seen by making relevant plots of the given time-series. If equipment is not tracking properly then DNI values go down and DHI tends to meet the value of GHI. The change in radiation for DHI and DNI are identified by using Eq. (11) given below:

$$\begin{aligned} &\frac{\mathrm{DHI} + \mathrm{DNI} \times \cos(z)}{\mathrm{GHI}_{\mathrm{clear}}} < 0.85, \quad \text{for } z < 75^\circ \quad \mathrm{GHI} > 50 \left(\mathrm{W/m^2}\right) \\ &\frac{\mathrm{DHI}}{\mathrm{DHI} + \mathrm{DNI} \times \cos(z)} < 0.85, \quad \text{for } z < 75^\circ \quad \mathrm{GHI} > 50 \left(\mathrm{W/m^2}\right) \end{aligned} \tag{11}$$

where $\mathrm{GHI}_{\mathrm{clear}}$ is the GHI on a clear sky day.

3.5 Visual K-Test [16]

Radiation Transmittance values are defined as follows: Clearness index (K_t) is the ratio of measured global radiation component with product of extraterrestrial radiation and solar zenith angle. Direct beam transmittance (K_n) is ratio of measured direct radiation component received on horizontal surface with theoretical possible radiation (ETR). Diffuse horizontal transmittance (K) is ratio of measured diffuse radiation component with measured global radiation component. These are calculated by following NREL SERI-QC approach [12]. The location-specific transmittance ratio ranges can be evaluated by either taking standard guidelines of climate types or manual calculation from clear sky days (see Eqs. 12–14). The data produced after this analysis is further visualized and fit in suggested envelops.

$$
\begin{aligned}
&K_n > K_t, \quad \text{condition for sensor cleaning case} \\
&K_n (= DNI/I_E) \text{ ratio range } (0\text{–}0.8) \\
&K_t (= GHI/I_E \times cos(z)) \text{ ratio range } (0\text{–}1.0)
\end{aligned} \tag{12}
$$

$$K(= DHI/GHI) > 1.05 \text{ for} \quad \text{zenith angle}(z) < 75^\circ \tag{13}$$

$$K(= DHI/GHI) > 1.10 \quad \text{for} \quad \text{zenith angle}(z) > 75^\circ \tag{14}$$

4 Data Analysis

In the selected location (Jodhpur), detailed analysis was done for the month of August, 2015. The available data frequency is 10 min, which is then averaged to hourly values. Only sunshine hours (7 AM to 5 PM) are selected for analysis.

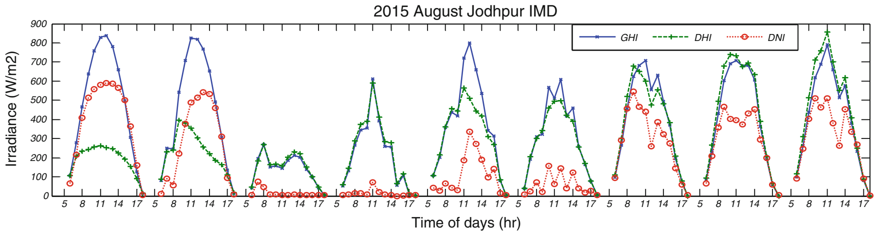

Fig. 1 Time series plot Jodhpur, Aug-2015 (selected days-clear, rainy, cloudy and measurement error, where sunshine duration: 7 AM to 5 PM selected)

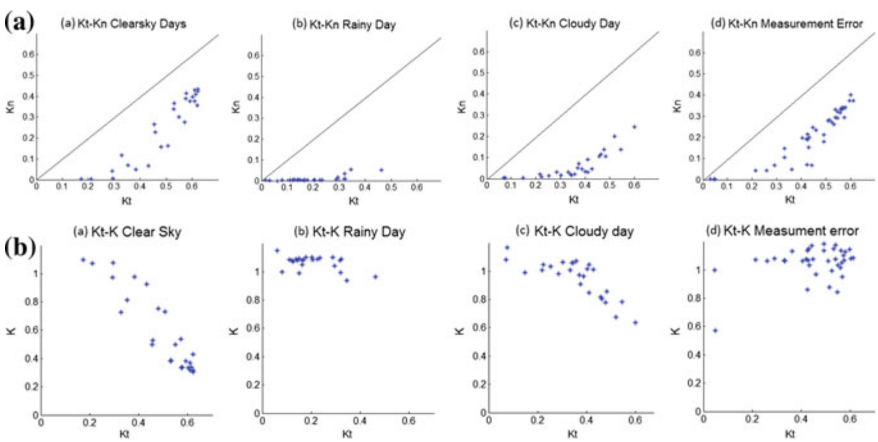

Fig. 2 **a** Transmittance plot (Kt-Kn) for *a* clear, *b* rainy, *c* cloudy and *d* measurement error days, **b** transmittance plot (Kt-K) for *a* clear, *b* rainy, *c* cloudy and *d* measurement error day

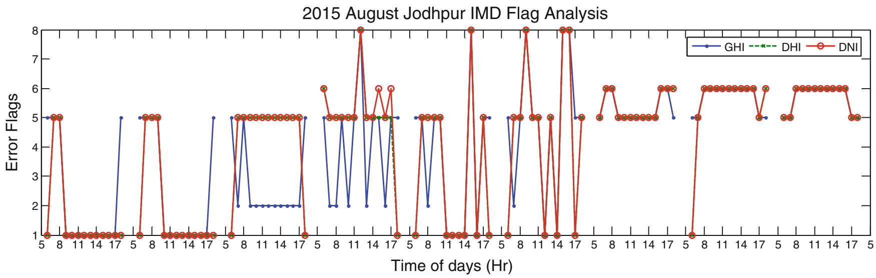

Fig. 3 Associated errors flags for selected days (clear, rainy, cloudy and measurement error)

Table 2 Quality control plot analysis (August 2015 analysis, all results are in %)

	Missing values	Correct values	Min. limit	Max. limit	Clear sky limit	Coherence test	Co-relation	Rayleigh limit	Track error
Flags	0	1	2	3	4	5	6	7	8
DNI	0	36.65	0	1.7	5.8	28.4	7	0	20.2
GHI	0	36	0	0	15.8	25.8	7	0	14.9
DHI	0	37.5	0	2.0	0	31.41	7	0	21.7

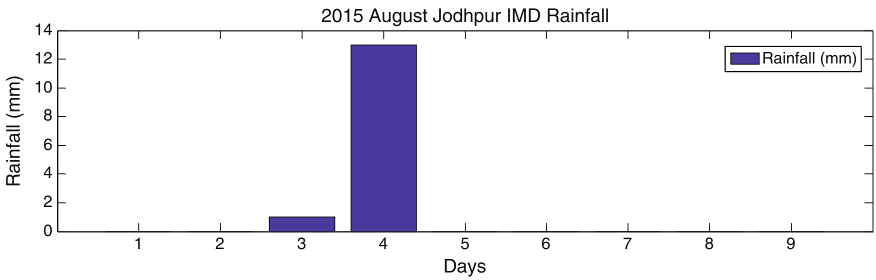

Fig. 4 Rainfall data plot for selected days of August 2015 (IMD Jodhpur)

All quality control guidelines are discussed above and for determining extreme diffuse range, Rayleigh clear sky limit is calculated [19]. Each test is given a specific flag number, and in visual test only basic criteria are checked. The flagging approach is taken from Mitra et al. [18]. Now the complete data quality analysis is applied on the selected data (see Figs. 1, 2 and 3). The results obtained after analysis can easily be understood by referring to Table 2. It may be noted that in Fig. 1, the first 2 days refer to the clear sky, the 3rd and 4th days refer to the rainy days, the 5th and 6th days refer to the cloudy days and the last three days depict the error in measured DHI due to a possible instrument error. The transmittance values shown in Fig. 2, quality test error flags shown in Fig. 3 and rain fall data shown in Fig. 4 also confirm this.

5 Discussion

The results obtained are compared with the rainfall data, taken from IMD and NASA rainfall database (Fig. 4). Based on the detailed visualization of the data plots shown in Figs. 2 and 3 following observations can be made:

(i) On the clear sky days, the data quality is acceptable for further use.
(ii) Rainy days can be seen in month of August. On typical days like this, the usual condition of variable cloud intensity may be present. These are shown as third and fourth days (as rainy days) and 4th and 5th (as cloudy days) in Figs. 1, 2 and 3. By correlating the rain fall data with the solar radiation components during this period further conclusion can be drawn. Unfortunately, cloud cover data was not available for this period. It is suggested that additional weather inputs such as these should be used to identify the source of missing values when standard quality control tests fail.
(iii) For the last 3 days shown in Figs. 1, 2 and 3, the DHI values are constantly increasing, and there is no climatic event present. The reason for this type of response from measuring instrument is probably due to shade-ring correction problem. This can also be seen from the transmittance plots as given in Fig. 2.

The identification of missing values in solar radiation databases and their gap filling is an ongoing area of research. Data visualization can help in identifying various anomalies. If the source of missing values is correlated with additional weather parameters such as rain fall and cloud cover etc., then best-filling procedure can be applied, which satisfies the standard characteristics of that location.

The most important factors due to which measurement error arises are less frequent cleaning and maintenance schedules. So if we clean the equipment frequently (cleaning interval decided according to station location) and the operator is well-acquainted with the system, the majority of the data problems will be solved.

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