Solar Irradiance Measurements for the Monitoring and Evaluation of Concentrating Systems

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Abstract. Precise solar radiation measurements are essential for monitoring and evaluation of concentrating solar systems. In this paper the quality of irradiance measurements from the low cost systems SPN1 and Rotating Shadowband Irradiometer (RSI) are compared to reference measurements from a Pyrheliometer, a Pyranometer and a Shadow Ring Pyranometer. A graphical and statistical analysis of the measurement differences has been conducted. The investigation is based on data of nearly one year and focuses mainly on deviations regarding the Direct Normal Irradiance (DNI). Furthermore, estimations for the expected errors are given. It is shown, that the mean deviation of DNI measurements from the RSI are rather small. However, large short time variability can lead to considerable measurement inaccuracies. The SPN1 shows a strong non-linear bias that should be corrected.

INTRODUCTION

In order to meet the global CO2 emission reduction targets, one task is to replace fossil fuel consumption for the production of process heat between 100 °C and 300 °C with concentrating solar collectors. The SPF Institute for Solar Technology is currently monitoring several solar process heat systems in Switzerland. The work presented in this paper is part of the PVPS Task 16 “Solar resource for high penetration and large scale applications” of the international energy agency (1). The main goal of the task is to enhance the quality of forecast and resource assessments. While it is mainly focused on PV applications, the correct assessment of solar resources is also a key element for thermal systems. Performance evaluation of concentrating solar systems requires a precise measurement of Direct Normal Irradiance (DNI). The state of the art device for detailed measurements of the DNI is the bi-axially tracked Pyrheliometer. However, due to its high investment cost and need of maintenance, cost-efficient alternatives are of strong interest especially for monitoring of small systems. In this work, performance and reliability of two low cost alternatives, the SPN1 and the Rotating Shadowband Irradiometer (RSI), are investigated and compared to the tracked Pyrheliometer.

Comparing observations resulting from different methods is a widely encountered task in applied science. Most related research was done in the field of clinical medicine in which cheap, fast and non-invasive measurements often are required to replace the most precise laboratory methods, usually called the ‘gold standard’ method. A guideline to a graphical evaluation of the agreement is given in (2). In this work, the authors suggest to calculate and plot the differences d between the compared measurement results. The mean of differences $\bar{d}$ is further interpreted as an overall bias between the two measurement methods. The standard deviation s_d of the differences shows the variability of the measurement deviation. The authors define a band of measurement differences that is limited to $\bar{d} \pm 1.96\, s_d$. Assuming normal distributed differences, 95 % of all data points will be within this band. The authors extend this method to cases in which the deviation between the measurement methods vary with the values of the measurement (3). In this paper, we adapt this method for the comparison of radiation measurement devices using the 95 % limit of agreement in order to estimate how performance evaluation of solar installations can be affected by measurement inaccuracies.

DATA ACQUISITION

All three measurement devices are mounted on the roof of the laboratory building of the University for Applied Science HSR in Rapperswil, Switzerland. The maximum distance between the instruments is less than 5 meters which ensures that spatial effects play a minor role. The presented data was consecutively measured between 8th of August 2016 and 15th of July 2017.

Technical Characteristics of the Investigated Measurement Devices

In total five different measurement devices have been used (Figure 1). The reference measurements have been taken with three complementary devices. The global horizontal irradiation (GHI) has been measured with a horizontally installed Pyranometer. Within the setup of the Pyrheliometer a tracked tube assures that only Direct Normal Irrradiace (DNI) reaches the sensor. In the two low cost alternatives, different measurement principles allow the determination of the DNI without tracking. In the SPN1 seven sensors are placed behind a complex shading mask. The shape of the shading mask ensures that one of the sensors is always completely shaded while another one is always fully exposed to the solar irradiation. The direct fraction of the radiation can then be calculated according to (4). The sensor of the RSI is shaded every 30 s by a rotating shadow band. Based on the resulting irradiation curve, an algorithm calculates the DHI, the GHI, and the DNI. Except the RSI, all used measurement devices have an analog output and are sampled in time steps of 10 s. The RSI measurement results correspond to values averaged over the timespan of one minute.

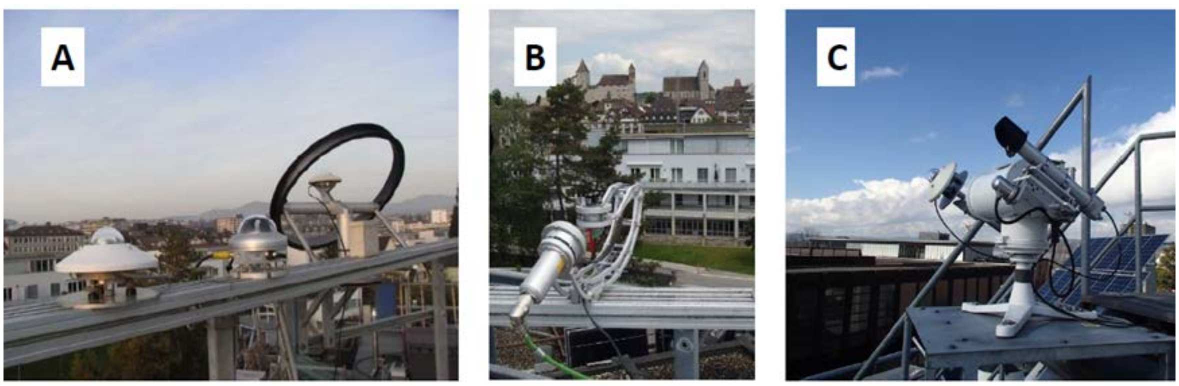

Figure 1. (A) Pyranometer for the measurement of the horizontal global radiation (left), “Sunshine Pyranometer SPN1” (center), Pyranometer with shadow-ring for measurement of the horizontal diffuse radiation (right). (B) “Rotating Shadow band Irradiometer RSI”. (C) Tracking Pyrheliometer for DNI measurements used as reference. All instruments are installed at the SPF Institute for Solar Technology in Rapperswil, Switzerland

Data post-processing

The measurement devices are not completely synchronous. They are, however, all connected to the same logging and database system. Measured values are logged whenever the system detects the measurement to exit the dead band. Based on this database, measurement values with time steps of 60 s were extracted. This gives an additional uncertainty due to the definition of the dead band. The dead band is defined to be 0.1 W/m^2. As shown later, this has a minor effect on the overall analysis. Therefore, it is save to consider the exported data as the original output of the measurement device.

Before the main evaluation the acquired data was analyzed in order to identify unrealistic values. Reasons for the presence of bad data can be occasional complete or partial shading of the measurement devices due to maintenance work, snow covering of a device, errors in manually adjusting the shadow band of the shadow band Pyranometer or, in the case of the RSI, mechanical problems of the rotating component. The quality control criteria proposed in (5) have been partially adapted whenever they were thought to be applicable to the given data. The lower boundary of the acceptance interval was set to 10 W/m^2 for the direct irradiation. In addition, measurements with a solar elevation less than 10° were omitted to remove the night time emasruements. Furthermore, the test for consistency between diffuse and global radiation was done.

$$\frac{I_{DHI}}{I_{GHI}} < 1.05 \text{ for } I_{GHI} > 50\ Wm^{-2} \quad (1)$$

The RSI provides a measurement every minute that is calculated from consecutive global irradiation measurement and a shading of the sensor by the rotation every 30 s. Therefore the RSI measurement can be interpreted as an estimation of the averaged irradiation over one minute. When comparing the RSI results with the Pyrheliometer and Pyranometer reference measurement, this has to be taken into consideration. The RSI results were therefore compared to the mean of the logged reference data values of the last minute.

RESULTS

Plots comparing GHI and DNI measurements can be found in Figure 2 and Figure 3. The graphs show a two dimensional histogram of the logarithmic count. Furthermore, the best fitting linear regression slope through the origin and R^2 correlation coefficient are given. The results of the RSI show that both the GHI as well as the DNI are affected by a similar amount of deviation from the line of equality. The variability of the measurement difference increases for larger radiation values. Their R^2 coefficient is 0.95413 and 0.96414 respectively. It can be seen, that the SPN1 gives a high quality measurement of the GHI with a R^2 value of 0.9947 while the DNI exhibits a non-linear bias that results in an R^2 value of 0.97746. It is important to note that the R^2 coefficient only provides information about correlation, in other words how well the data points can be approximated by any straight line. The bias of the measurement has to be analyzed separately.

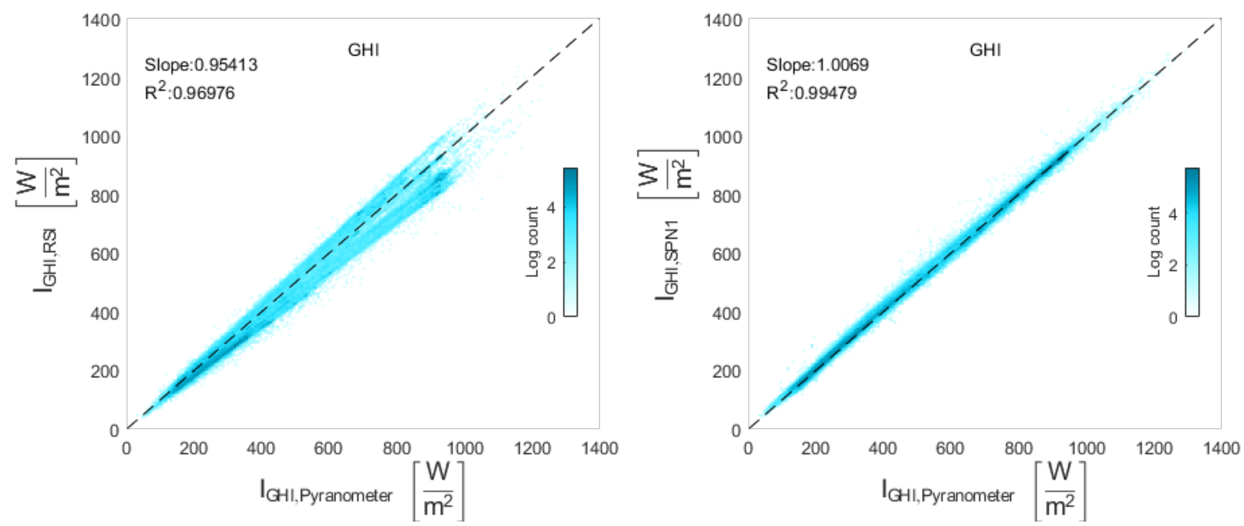

Figure 2. Log count histogram plots of GHI for SPN1 and RSI in comparison to the pyranometer.

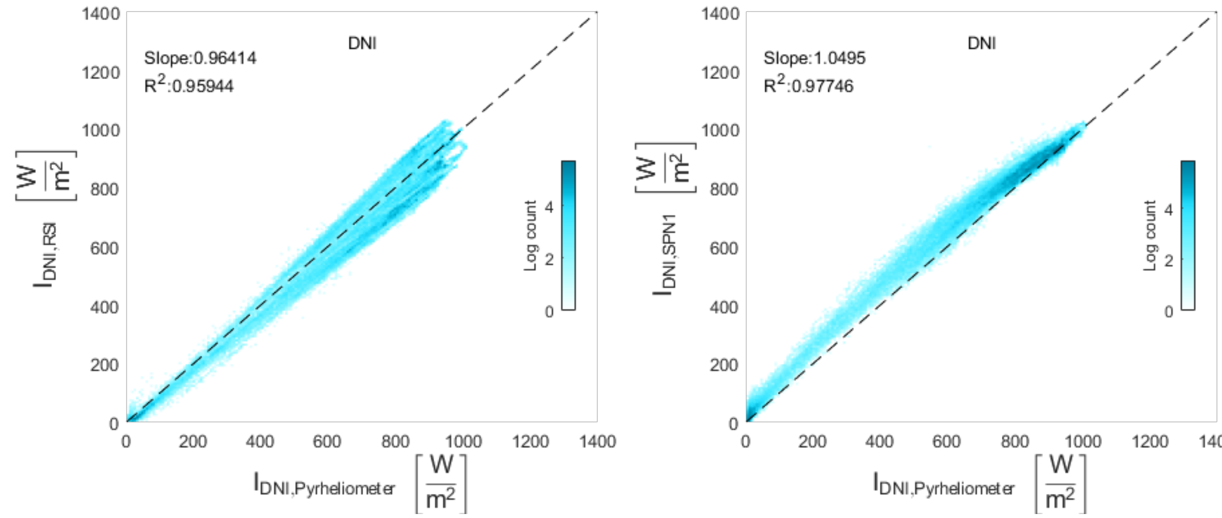

Figure 3. Log count histogram plots of DNI for SPN1 and RSI in comparison to the bi-axial tracking pyrheliometer.

A more detailed analysis of the difference between the DNI measurement of the RSI and the Pyrheliometer is shown in Figure 4. In the left hand side plot, the linear mean difference and the 95 % limit of agreement line according to (3) are given as solid and dashed lines. The mean difference is negative in the whole data range indicating that, on average, the RSI is biased to slightly underestimate the DNI in the range of 15-31 W/m^2. The largest relative deviation of the 95 % limit of agreement line can be found at small irradiation values while the absolute deviation is largest at high irradiation values. On the right hand side of Figure 4 the data points of the difference plot are colored according to their occurrence in the year. From this representation, it becomes clear that the variability of the difference is not random over time. A seasonal dependence can be identified as well as distinct lines that are assumed to be caused by continuous changes of the measurement deviations.

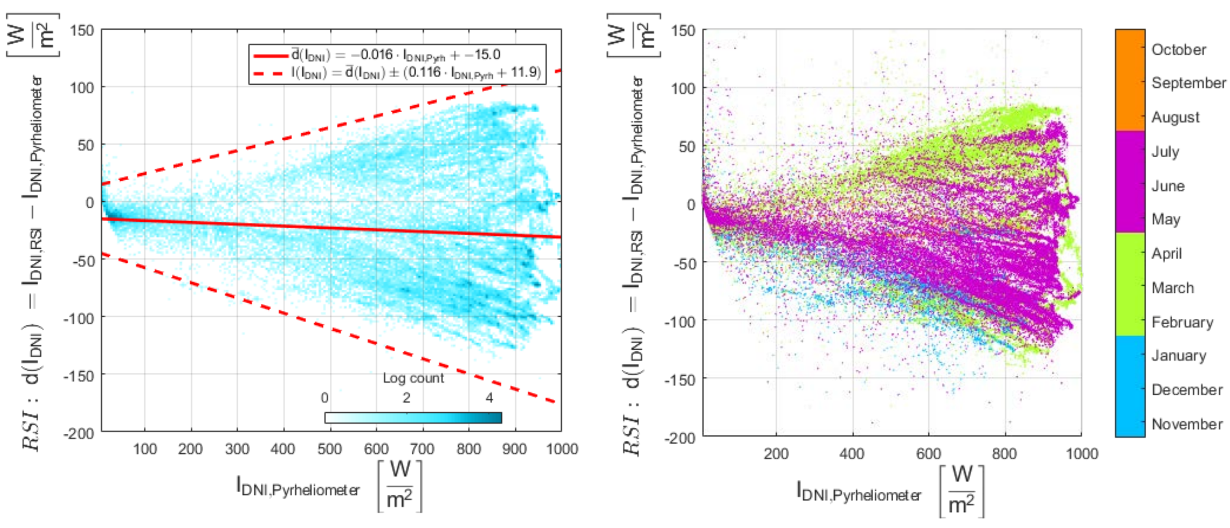

Figure 4. Left: Difference plot of the DNI measurement of the RSI. Right: yearly dependence of the RSI measurements.

The analogous plots for the SPN1 are given in Figure 5. The difference plot shows that the SPN1 exhibits a non-linear bias when compared to the Pyrheliometer. The measurement differences are smallest for very low and very high irradiation values. In the middle range the SPN1 tends to overestimate the DNI. Due to the non-linearity of the data, the linear regression analysis cannot be applied in this case. A small seasonal dependency of the measurement difference can be seen in the plot on the right hand side. However, if compared to the RSI results, the seasonal influence is much smaller.

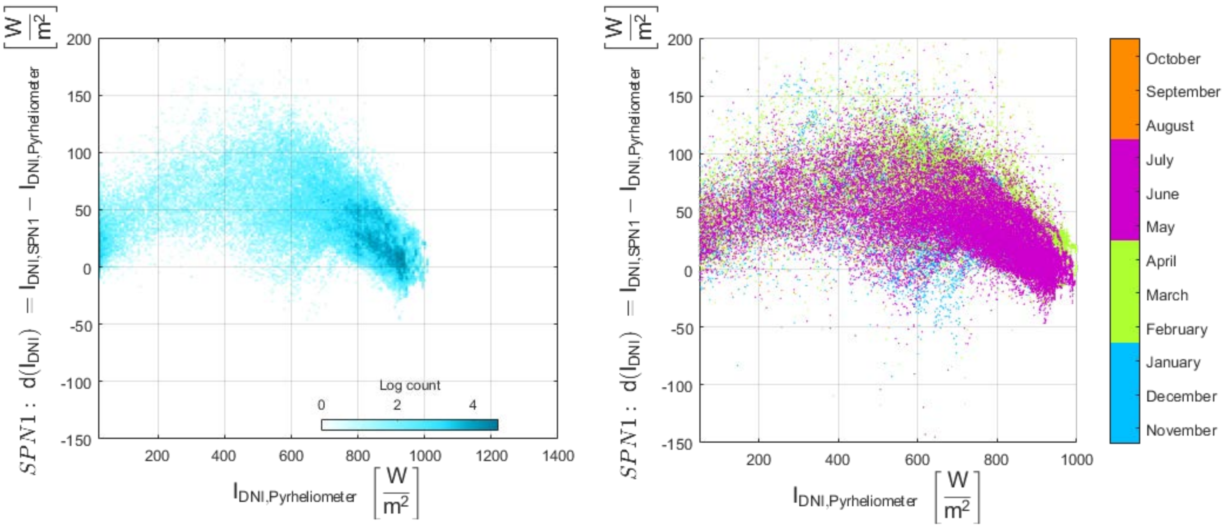

Figure 5. Left: Difference plot of the DNI measurement of the SPN1. Right: yearly dependence of the SPN1 measurements.

DISCUSSION

The comparison of the DNI measurement of the threedevices shows, that overall the RSI exhibits a higher variability when compared to the reference measurements. However, the mean difference in DNI of the RSI measurements over a whole year shows only a small systematic bias smaller than 5 % of the maximum irradiation value. Therefore, if only yearly sums are of interest, the RSI can be used for the evaluation without causing large errors in the analysis. Additionally the average bias could be corrected to get even more precise results. However, the measurement error is highly time dependent. When short time periods are of importance the 95 % limit of agreement states that relative errors up to 11.6 % have to be expected. This relative error can directly be estimated from the slope of the 95 % limit line with the simplification of neglecting the offset at 0 W/m^2 radiation. In absolute numbers, the deviations can reach up to 100 W/m^2 which is in agreement with other publications (6). In summary, it can be deduced from the chosen analysis that 95 % of the time the error of the RSI will be smaller than 11.6 %.

The GHI of the SPN1 shows a good correspondence to the reference measurement while the GHI measurement of the RSI shows a variability similar to the DNI values. A possible conclusion is that the main reason for measurement inaccuracies is not the algorithm of the RSI that calculates the DNI from the irradiation curve during rotation. The similar characteristics of the GHI and the DNI measurements indicates that the reason is likely to be either the sensor of the RSI or the smaller sampling rate due to the 30 s time gap between rotations.

The DNI measurement of the SPN1 shows a non-linear bias. Thus, the same linear bias and error analysis does not apply. This corresponds well with the earlier comparisons (4), where different SPN1 devices have been tested in different locations. However, due to the strong bias at irradiation values between 200 and 800 W/m^2 a correction is necessary in order to get reasonable results for yearly analysis. Without this correction the SPN1 measurement will overestimate the irradiation and consequentially lead to an underestimation of the performance of the solar installation. Such a correction function has to be non-linear and will be subject to subsequent work.

CONCLUSION

In this work, we compared two low cost alternatives for solar irradiance measurements to the reference methods which are the Pyrheliometer for the DNI and Pyranometers for both the DHI and the GHI. The evaluation was done following a graphical method widely used for measuring agreement in method comparison. It has been shown that there are various characteristics of the measurement devices that have to be taken into account when using this alternatives instead of the standard devices. The RSI has a small average bias but a high variability in the quality of the measurement. Therefore, cumulated irradiations with a big sample size are likely to give good results. On the other hand, if the measurement period is short, the SPN1 is the better low cost alternative for irradiation measurements. In order to correct for the bias a correction function for the SPN1 measurement has to be developed.

ACKNOWLEDGEMENTS

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