PRECISE MEASUREMENTS OF SOLAR BEAM IRRADIANCE THROUGH IMPROVED SENSOR CALIBRATION

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Abstract

Solar beam irradiance is measured for solar energy applications due to two reasons: to determine the available amount of the solar resource and energy yield at sites selected for an installation or to evaluate efficiency and proper operation of a concentrating solar power plant. However, the requirements on data and devices are different for both applications. In this paper, the equipment and methods used at DLR for improved solar beam irradiance measurements are presented with reachable accuracy for both applications. Different thermal irradiance sensors are compared among each other and to an absolute cavity radiometer. The sensors are calibrated with the absolute cavity radiometer to get utmost accuracy for precise field measurements. Besides, they are subsequently used for the calibration of RSP sensor heads for remote automatic weather stations, which reach a mean accuracy of 3%.

Keywords: solar irradiance, pyrheliometer, absolute cavity radiometer, Rotating Shadowband Pyranometer, accuracy.

1. Introduction

There are two main reasons in Concentrating Solar Power to measure solar beam irradiation: first of all, to determine the available amount of the solar resource at selected sites in order to perform a diligent planning and thorough design of a solar power plant on site, and secondly to evaluate efficiency and thus prove and finally monitor proper operation of an yet existing solar power plant. However, requirements on the measured data and even more on the conditions for the realization of maintenance of the measuring devices are different. Whereas actual data with utmost accuracy is required to supervise an operational power plant, rather typical meteorological data for the selected site is needed for determination of the solar resource and plant layout.

Standard sensors for plant surveillance are precise thermal sensors like pyrheliometer and pyranometer. Properly installed, they yield at their best an accuracy of between 1 and 2% when cleaned daily at least. However, this accuracy may still represent up to 80% of the total measurement error for plant efficiency. One feasible way to improve the pyrheliometer accuracy is by direct field calibration against an absolute cavity radiometer (which itself is very costly and normally not adequate for continuous field operation).

To determine the solar resource for solar power plants at mostly remote locations, usually a long-term series of satellite data in combination with a shorter measurement period on ground is applied. For solar resource assessment neither the costs of equipment with thermal sensors nor its installation effort nor the necessary on-the-spot support to maintain the accuracy are reasonable. Rotating Shadowband Pyranometers (RSP) or Radiometers (RSR) are most suitable for remote measurements with respect to sensor soiling and power supply. However, their sensors need to be calibrated thoroughly and their readings corrected for systematic measurement errors.

The accuracy of satellite data is still too low to rely just on them for solar resource assessment whereas ground measurements usually lack the necessary duration to predict the expectable long-term mean with sufficient accuracy.

In this paper, the equipment for improved solar beam irradiance measurements and methods used at DLR are presented for both applications. Different thermal irradiance sensors are compared with each other and to an absolute cavity radiometer. The sensors are calibrated with the absolute cavity radiometer for utmost precise field measurements. Besides, they are subsequently used for the calibration of RSP sensor heads for remote automatic weather stations.

2. Enhanced equipment for accurate irradiation measurements

2.1. Precise equipment

DLR operates several meteorological stations for precise irradiation measurements: Two fixed equipments are situated at the Plataforma Solar de Almería (PSA) and taking continuous measurements of irradiation and further meteorological data to obtain a reliable set of historical data as well as for field calibration of the RSP sensors and for determination of the efficiency of investigated solar devices tested on site. Besides, DLR operates two precise mobile stations for the purpose of proper field measurements at solar power plant installations of project partners as support in the development of new technologies (see Figure 1).

The stations are equipped with Kipp&Zonen CMP21 and/or CM11 pyranometers for measurements of global and diffuse irradiation as well as with CHP1 and CH1 pyrheliometers for measurement of the solar beam radiation, DNI. The irradiation sensors are mounted on 2AP or the new SOLYS-2 tracker, both from Kipp&Zonen, equipped with a sun sensor to ensure steady proper orientation towards the sun. The pyranometers are mounted on corresponding CV2 ventilation units for better coupling of the sensor body to the ambient temperature and for reducing the infrared radiation exchange with the cold sky. Furthermore, the sensor body temperature can be measured, allowing for further temperature corrections.

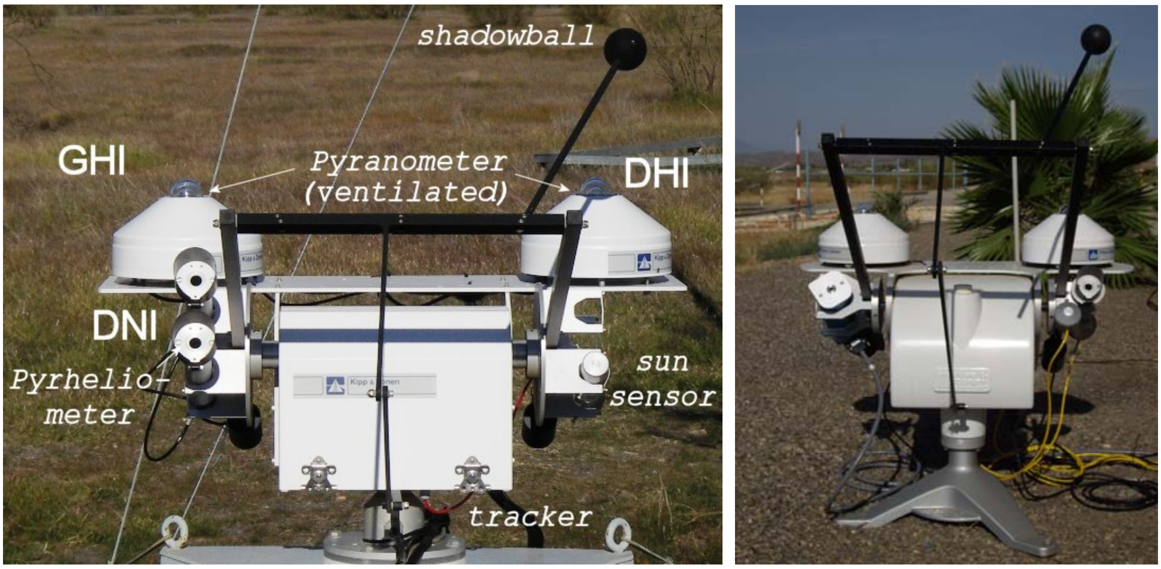

Figure 1. Precise irradiance measurement equipment (left picture) and Solys 2 tracker with PMO6-cc absolute cavity radiometer (right picture) of DLR at Plataforma Solar de Almería.

2.2. PMO6-cc absolute cavity pyrheliometer

The PMO6-cc developed and manufactured by the PMOD/WRC (Physikalisch-Meteorologisches Observatorium Davos / World Radiation Center) consists of a radiometer head with a blackened cavity and a control unit. It is operated on the principle of substituting radiative by electrical power and hence measuring radiation as electrical power in absolute in units of W/m². While in operation, the (front) cavity is orientated towards the sun and heated up by radiation incident through a hole with an exact defined size (“open phase”). Its back being connected to a heat sink yields a temperature difference across the thermal impedance, which is proportional to the incoming radiative power and which is measured. In a following “closed phase”, this power is then substituted by an integrated electrical heater controlled to obtain the same temperature difference. Hence the cavity has to be irradiated and shaded alternately, meaning that the instrument cannot be operated continuously but in chopped mode with the measurement taken at the end of every phase. In order to compensate for changes in heat sink (ambient) temperature, a second equivalent cavity (viewing the ambient without being irradiated) is included with the temperature difference measured across a second thermal impedance likewise.

The open cavity, the high price and discontinuous operation make the PMO6-cc unsuitable for field operation. In terms of calibrating other instruments like pyrheliometers, it implies that irradiation conditions need to be very constant with time. Changes in irradiation are integrated.

3. Accuracy of pyrheliometer measurements

To get an impression on which accuracy is reached with commercial pyrheliometers, three available devices were analyzed at the PSA by comparing measurements and besides two pyrheliometer readings were compared to absolute cavity radiometer measurements.

3.1. Comparison of simultaneous CH1 pyrheliometer readings

A descriptive demonstration of the uncertainties of First Class Normal Incidence Pyrheliometers was achieved by comparing the measurements of three different CH1. During one year starting from November 2007, two of them were operated simultaneously at a time. They were mounted on a 2AP sun tracker at the PSA on the same side of the tracker using the upper and lower mounting clamp (see right picture of Figure 1). Both pyrheliometers were cleaned every working day.

With both sensors properly mounted and oriented to the sun, we stated slightly differing signals in the order of several W/m² at otherwise equal conditions. For the analysis only DNI values greater than 700 W/m² were used and the relative deviations δ_R between the two DNI readings determined. Furthermore, the average of the relative deviations was calculated for $|\delta_R|<2\%$ and DNI values corresponding to a δ_R differing more than 1% from this average were rejected. $\sigma(\delta_R)$, the standard deviation of the remaining δ_R, and their average $\delta_{R,M}$ were determined. The three comparisons are summarized in Table 1.

	$CH1_A$ - $CH1_B$	$CH1_A$ - $CH1_C$	$CH1_C$ - $CH1_B$
$\delta_{R,M}$ [%]	0.24	0.70	-0.36
$\sigma(\delta_R)$ [%]	0.08	0.19	0.24

Table 1. Comparison of three CH1 pyrheliometers ($CH1_A$, $CH1_B$, $CH1_C$). Standard deviation $\sigma(\delta_R)$ and average $\delta_{R,M}$ of the relative deviations δ_R.

One main cause for slight deviations within the readings of two different pyrheliometers is the decreasing accuracy with the transfer of the device sensitivity within the calibration chain from the World Radiation Reference (WRR) in Davos (accuracy of 0.17%) to purchasable devices which may sum up to 0.88%.

In Figure 2 the relative deviation δ_R of DNI readings of pyrheliometers $CH1_A$ and $CH1_C$ is plotted versus the time starting from the beginning of the comparison. The average $\delta_{R,M}$ is marked as a green line, the red lines give the average increased/decreased by $\sigma(\delta_R)$. Besides the offset, a characteristic daily decline of δ_R can be stated. This can be seen in more detail in Figure 3. It could be observed that the lower CH1 is less affected by dew and soiling due to the attenuated radiation exchange with the sky. This also yields temperature effects which both are supposed to be reasons for the daily decline. The installation of a protection shield above the pyrheliometer is therefore recommendable.

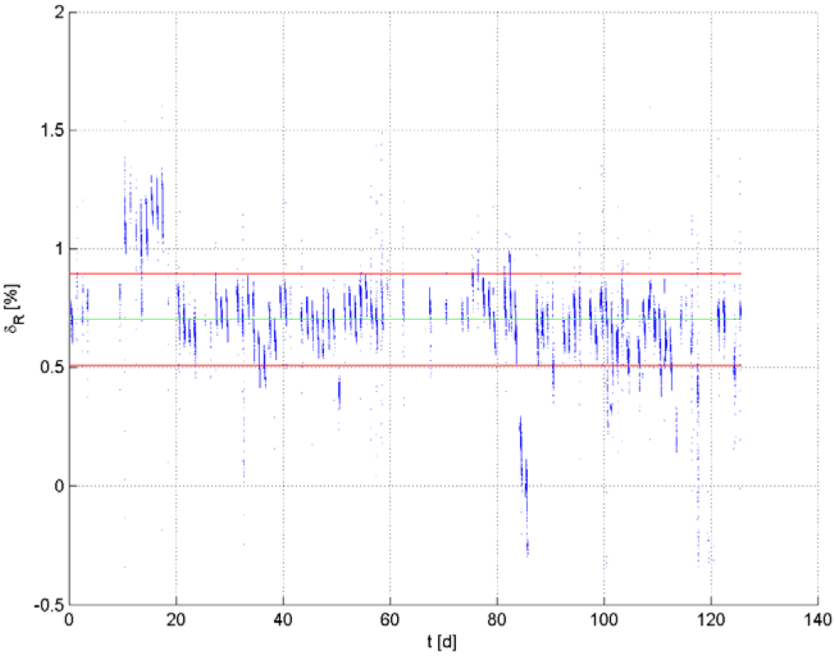

Figure 2. Relative deviation δ_R of DNI readings for pyrheliometers CH1$_A$ and CH1$_C$.

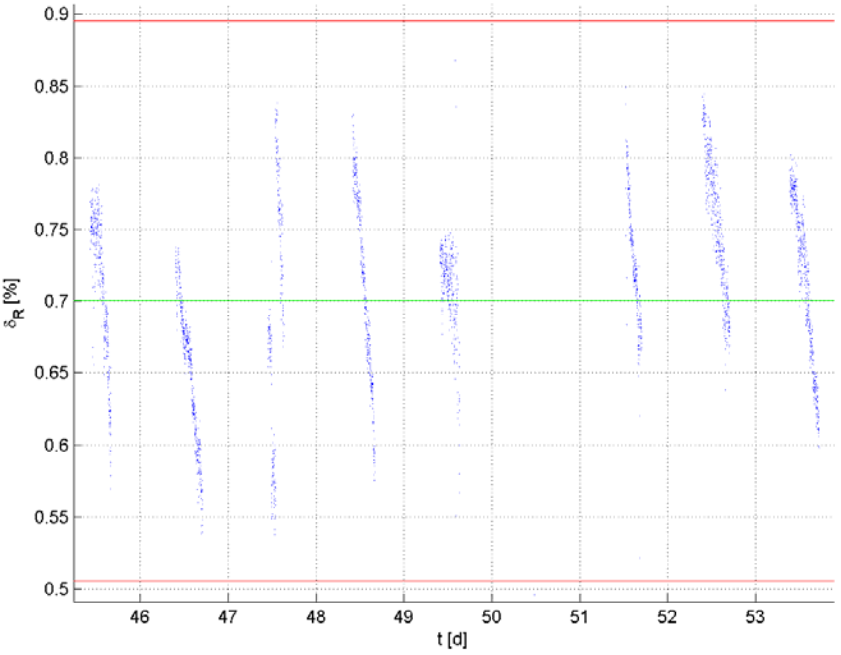

Figure 3. Detailed view of the relative deviation δ_R between DNI readings for pyrheliometers CH1$_A$ and CH1$_C$.

3.2. Comparison of field pyrheliometer to absolute cavity pyrheliometer readings

To reduce the problematic length of the calibration chain and get utmost accuracy, a PMO6-cc absolute cavity radiometer (see bottom left sensor of the right picture in Figure 1) with an accuracy of 0.3% and traceability to the WRR of 0.1% was acquired from the World Radiation Center (WRC).

First comparisons of the readings of the absolute cavity radiometer to a CHP1 and a CH1 pyrheliometer were carried out in June 2009. Similarly to DNI readings of pyrheliometers the relative deviations were calculated for DNI values greater than 700 W/m². Figure 4 shows the DNI measurements of the three radiometers and the corresponding relative deviations plotted versus the time. Furthermore the standard deviation of the CHP1 signal during every open phase of the absolute cavity measurement is depicted.

Variations of the incoming irradiance during the measurement time of the absolute cavity radiometer reduce the reliability of the comparison. The red line in the lower diagram of Figure 4 marks the maximal accepted standard deviation.

The offset of the DNI given by the CH1 is obvious. Its average relative deviation is 1.3%, for the CHP1 no offset was found. In addition to the uncertainty of the calibration itself, a non-stability of ±0.5% per year has to be considered according to the manufacturer. That is relevant since the CH1 was calibrated about 1.5 years before the comparison while the CHP1 was calibrated only 7 months before the measurements.

The standard deviations of the relative deviations are 0.22% or the CH1 and 0.24% for the CHP1. Thus the accuracy of our pyrheliometers will be improved notably below 1% by direct calibration.

In the course of the development of the calibration procedure the accuracy of the comparison will be fully assessed. The mere accuracy of recording the measurements lies well below the offset detected for the CH1. Furthermore, the direct comparison is expected to better characterize the instruments in use in order to quantify the influence of different measurement conditions beyond the manufacturers information and standard limits set by ISO 9060.

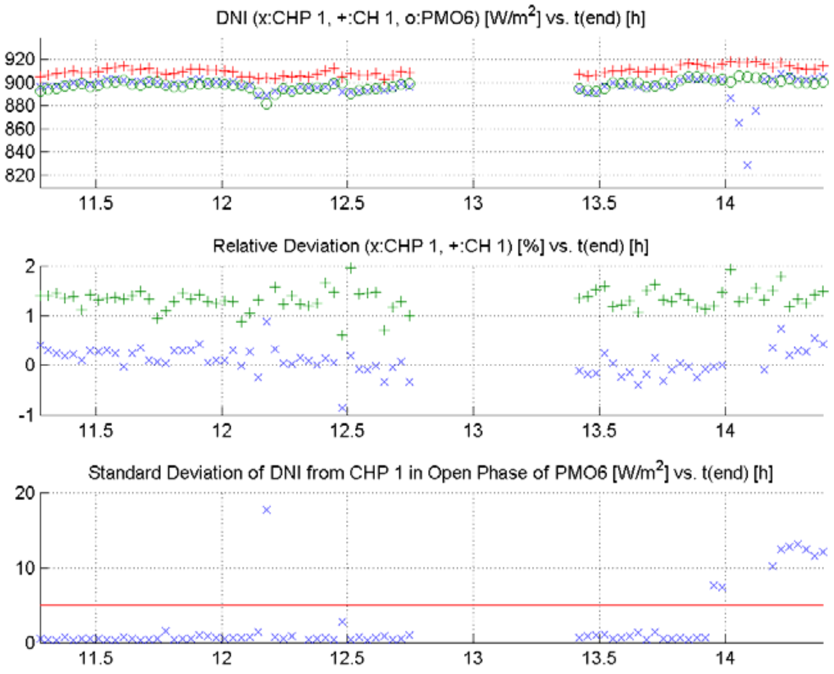

Figure 4. DNI measurements of a CHP1 and the CH1$_C$ pyrheliometer in comparison to those of a PMO6-cc absolute cavity radiometer. DNIs, relative deviations and standard deviation of the CHP1 signal during the open phase of the PMO6-cc plotted versus the time t(end) at the end of the open phase of the PMO6-cc.

3. Improved Rotating Shadowband Pyranometer for Solar Resource Assessment

Parallel to the precise irradiance sensors, several Rotating Shadowband Pyranometers (RSPs, see Figure 5) were operated for a duration between several weeks until more than one year, thus providing an ample data base for a proper analysis of systematic signal deviations and measurement accuracy. Due to the systematic errors of the RSPs, additional corrections are necessary to improve their primary fair accuracy. With parallel measurements of several weeks, a thorough calibration of the RSP sensor is obtained. Recently developed functional corrections [1] are now validated at various sites, different climate zones, environmental conditions and altitudes.

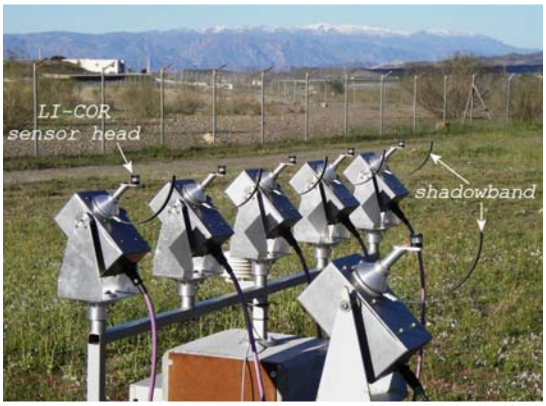

Figure 5. RSP calibration mount of DLR at Plataforma Solar de Almería.

The quality of the correction algorithm has finally been analyzed on its capability to reproduce the reference irradiation from the precise sensors. Therefore the deviation between the precise and corrected RSP irradiance measurements were compared as well as integral measures like mean bias (MB), root mean square deviation (RMSD), standard deviation, the correlation coefficient and the total irradiation sum within each comparative period.

Figure 6 shows the deviation between the corrected RSP and the reference beam irradiance values, plotted against the intensity of the reference irradiation. To see the improvement by the correction, also the original response ("raw data" with bright color) is shown. The shown data set refers to 23 analyzed RSP sensor heads. The distribution of the corrected RSP direct beam irradiation data is spread mainly within a range of ±25 W/m² with deviations of several data points until 100 W/m², single values even more; its absolute RMSD is 17.3 W/m². The uncorrected DNI on the contrary shows a clear overestimation by the RSP of up to 150 W/m², mainly at intensities around 550 W/m². This is reflected in an absolute RMSD value of 53.7 W/m².

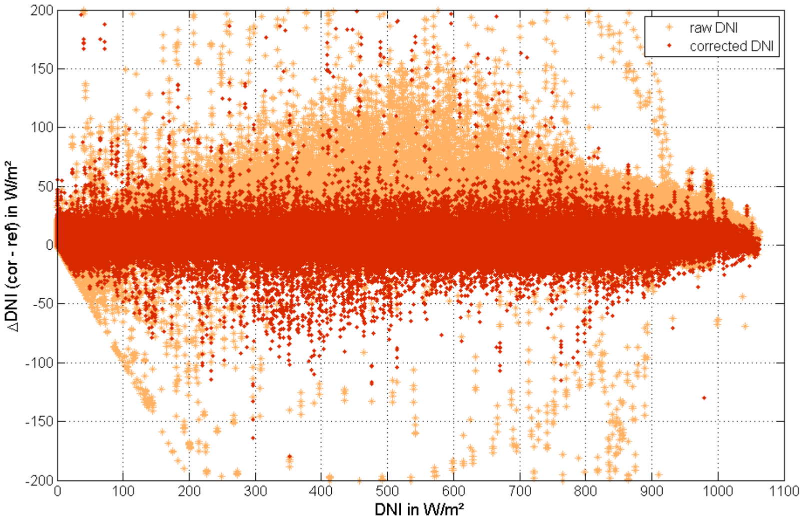

Figure 6. Deviation of the corrected RSP direct normal irradiation values to reference DNI including measurements from 23 analyzed RSP.

For global irradiance, the distribution of the corrected data is reduced to within a range from -20 to 30 W/m² over its entire intensity with an RMSD of ±10.2 W/m² whereas the original global response of the LI-COR clearly underestimates true irradiance with increasing values up to 40 W/m² at over 800 W/m² and at an RMSD of 13.7 W/m². For diffuse irradiance, the corrections achieve a reduction the original RMSD from 16.3 W/m² to a significantly lower value of 6.1 W/m² mainly due to the spectral corrections. Deviations of originally -40 W/m² are reduced to less than 20 W/m².

However, these denoted RMSD values refer to the complete set of 23 different sensors and represent the accuracy for the determination of the correction functions. They are not representative for the resulting accuracy reachable with one particular RSP. In order to obtain the accuracy of one device, the MB and the RMSD have to be determined for all devices separately and then averaged. These values are listed in Table 2 for uncorrected data as well as corrected data. The “ref” column denotes the accuracy of the reference of the precise sensors data via the redundant consistency of its three measured components. Here only data sets with direct irradiation above 200 W/m² were evaluated as usually very low DNI is typically not relevant for concentrating solar power plants.

	GHI		**DHI**		**DNI**		**ref**	*unit*
	uncor	*cor*	*uncor*	*cor*	*uncor*	*cor*		
average MB	-10.3 *±4.0*	0.3 *±1.3*	-17.3 *±1.6*	-0.4 *±0.7*	24.6 *±10.5*	1.0 *±0.5*	1.0 *±3.9*	*W/m²*
RMSD	14.2	7.6	18.9	4.5	33.3	14.5	5.3	*W/m²*
Sum	-1.9%	0.0%	-14.2%	-0.4%	3.5%	0.1%	0.2%	

Table 2. Average values of Mean Bias, Root Mean Square Deviation and relative deviation of the irradiation sum of the 23 RSP data sets: for the uncorrected raw data and for corrected data, as well as the accuracy of the reference data set (“ref”).

The mean bias of the uncorrected raw DNI data shows a value of 25 W/m² as the average of the 23 sensors, several of them however differed by even more than 37 W/m². Maximum values for GHI and DHI were around -17 W/m² and 21 W/m² with average values of -10 W/m² and -17 W/m², respectively. The correction algorithm reduces these values considerably to around the accuracy of the reference data of 1.0 W/m², most notably the variation spread. The RMSD decreases with the corrections from 33 to below 15 W/m² for direct normal irradiation (from 14 to 8 W/m² for global and from 19 to 5 W/m² for diffuse irradiation) as shown in Figure 7. Thus, a relative standard deviation of the RSP data of 3% is reached for Direct Normal Irradiation beyond 200 W/m² and 2.4% for DNI beyond 300 W/m², taking into account an inaccuracy of 1.5% of the reference data.

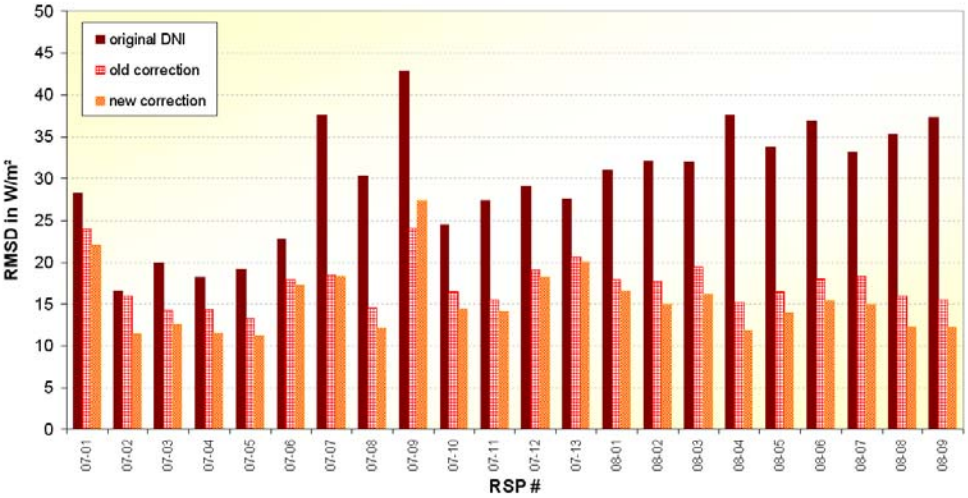

Figure 7. RMSD of DNI from uncorrected data as well as for both corrections.

Without corrections, the sum of the measured uncorrected irradiation results in more than 3% too high for DNI (2% too low for global and 14% too low for diffuse irradiation). By applying the correction formulas, the deviation falls within the accuracy of the reference data.

5. Conclusion

With the high quality of beam irradiance measurements approved with the absolute cavity radiometer, the equipment is ready for use in improved field measurements and evaluation of collector performance or even whole plant efficiency on site. However the comparison of DNI measurements of different pyrheliometers shows that the remaining uncertainty is not negligible. Calibration of each pyrheliometer with the PMO6-cc absolute cavity radiometer promises a reduction of the uncertainty to a value below 1%.

Applying corrections on the measured RSP irradiance achieves to reduce the root mean square error of its direct normal beam irradiance from more than 30 W/m² to below 15 W/m². Thus the inaccuracy of direct solar beam irradiation with RSPs drops for solar resource assessment for concentrating solar power plants to values below 2.5% at comparatively low installation and maintenance costs, avoiding the problem of high pyrheliometer soiling at remote sites. The meanwhile comprehensive data base from the RSP sensor calibrations is used for determination of the necessary time period and conditions to perform a thorough calibration. Furthermore, the corrections are to prove good results for all climate zones and sites and will be trimmed or adjusted if necessary.

Common DNI measurements do not consider the influence of circumsolar radiation caused by atmospheric scattering. Due to the relatively high field of view angles of pyrheliometers, the amount of solar irradiation that is usable for CSP-technologies can be overestimated. Further investigations of the influence of sunshape variations on direct beam measurements are planned in consideration of different intercept factors for different technologies and collectors.

Acknowledgements

Part of the equipment was financed by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU).

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