COMBINING SOLAR IRRADIANCE MEASUREMENTS AND VARIOUS SATELLITE-DERIVED PRODUCTS TO A SITE-SPECIFIC BEST ESTIMATE

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Abstract

Energy yields of concentrating solar thermal power plants depend strongly on the availability of beam irradiance. Direct solar irradiance is highly variable in space and time and thus, requires in-depth analysis of measurements with high quality, well tracked calibrations and approved quality control to achieve reliable results. Strong variability from year to year makes it necessary to combine precision data, available from limited measurement periods with long-term data, which should cover at least 10 years. For most places this may only be reached by application of historic satellite data. For sites around the Mediterranean region, Africa and the Mideast solar products based on data from the Meteosat First Generation so far have been used. Since mid 2006 this satellite generation is out of service and replaced by Meteosat Second Generation. Therefore, recent measurements can not be inter-compared to the satellite-series, which is used to retrieve long-term time-series. In this paper, a satellite-retrieval for beam irradiance from the new generation is introduced and inter-compared with data derived from the first generation satellite for an over-lapping 2 year time period. Applying more than one satellite data set has the further advantage to incorporate several independent data sets and thus strengthens credibility of the final result. A new procedure which combines the value of independent data sets is introduced: A quality-weighted average is produced depending on the individual uncertainties of each data set. By the help of long-term data the most representative climatological values are determined for the final best estimate, which is required for bankable simulations of energy yields.

Keywords: solar radiation, rotating shadowband radiometer, satellite data, measurement uncertainty, data fusion, direct normal or beam irradiance, Plataforma Solar de Almería -PSA, concentrating solar power - CSP.

1 Introduction

This paper introduces a new method to combine measurements of solar irradiance and satellite derived data of solar irradiance to a best estimate. This best estimate shall represent the solar irradiation conditions at a certain site as accurate as possible. The main goal is to derive the long-term average of the direct normal irradiance (DNI), which gives a first estimate of the profitability of a site for concentrating solar power (CSP). For small changes the achievable yields at a site are roughly proportional to the annual average or sum of DNI. Thus, a 1% change in irradiance leads to a similar change in power output.

In case of a CSP plant in Spain with a nominal power of 50 MW_e it is expected that annual yields are in the order of 100 GWh to 200 GWh depending on irradiance conditions, sizing of solar field and thermal buffer. A 1% difference in annual DNI under the current feed-in tariff leads to differences in economic yields in the range from 200 000 € to 600 000 € each year for a single plant. Therefore, a reliable method to calculate the best estimates for the long-term DNI conditions at a certain site is of high importance for project development and financing of CSP-plants. As the availability of DNI at a CSP-site also has influence on the specific layout of a plant at a certain site the topic is also relevant for site-specific engineering of the plant.

From the analysis conducted by Lohmann[1,2] it is known that DNI is highly variable from year to year. To bring the deviation from the actual long-term average below 5% in most regions of the world it is required to have at least 10 years of data available[3,4].

Up to now, often a single source of solar irradiance data is taken to fix the average irradiance conditions at a site. Compared to global irradiance the direct irradiance derived from satellites usually has a higher uncertainty as small changes in the state of the atmosphere have strong influence on attenuation of beam irradiance. Therefore it makes sense to increase reliability of the DNÌ conditions by taking measurements at potential CSP-sites additionally to satellite products. These measurements in some cases were used to adapt the satellite-derived data giving the measurements full weight in the time these are available. But DNI measurements often also show moderate accuracy. If measured by a pyrheliometer, they might suffer from bad sun-tracking or soiling of the instruments. If derived from shaded and un-shaded pyranometer measurements, cosine-effects, limits of shadow-band corrections and the lower accuracy of pyranometers compared to pyrheliometers introduce uncertainties.

Further, the mostly rather limited time-coverage of solar resource data introduces uncertainties when fixing a solid long-term average. Measurements at a site usually are not available before project development reaches a certain degree of maturity. Therefore for most CSP-sites only short measured time-series can be taken into account. Site specific measurements offer some additional advantages, they measure the local effect of atmospheric conditions during the measurement period and they have a much higher temporal resolution. So they are usually the better input for simulations, but the solar radiation level during the measurement period may be far from the long term average due the natural variability of the weather conditions. Satellite data enable to derive such long-time series, which are required to cancel out as good as possible deviations from high year to year variability. The goal is to make use of the strengths of both worlds. Higher accuracy of on-site measured data shall be transferred to the time-series from the satellite.

As all related DNI data have significant uncertainties, it seems not adequate to take e.g. the measurements as the one and only truth. Likely all differ by a certain degree from the true value. A combination of various data sources likely leads to more realistic data. Open question is to find a procedure how to combine various data.

This paper starts by characterizing the solar resource products taken into account here. Then the method for a combined best estimate is presented. The discussion leads to a preliminary method to calculate also the uncertainty of the new combined values. To give an example of application the procedure is executed for data of the Plataforma Solar de Almería (PSA).

2 Available solar irradiance data

In principle solar radiation may be derived either by measurements at the site under consideration, by interpolation of measurements in some distance from the site or from knowing the actual state of the atmosphere at the site and calculating the radiative transfer. The later can be derived either from atmospheric models or from satellite data. So far atmospheric models like numerical weather models or climate models are not adapted to derive beam irradiance at all. For weather or climate models deviations of beam irradiance against high quality measurements often exceed 10% by far. But measurements in meteorological networks seldom are site-specific: only 25 km distance often lead to significantly different results[5]. Satellite-derived solar irradiance data are usually more site- and time-specific than distant ground measurements. There are several different satellite methods available. For this paper two are selected, for which we expect the highest accuracy for DNI, while most others mainly are designed to derive primarily global horizontal irradiance.

Interpolation of measurements at the ground can lead to high deviations from the true irradiance conditions especially, if DNI shall be derived in regions with microclimatic effects. As excellent radiation measurements can reach accuracies in the range of 1% this is the most accurate, but also most expensive method. A combination of measurements and satellite data is the practical way to reach reliable long-term estimates.

2.1 Satellite-derived data

In this paper two different satellite procedures working with two different types of satellites are taken into account. Both work with data from the Meteosat satellite series operated by Eumetsat.

The method SOLEMI developed by DLR[6,7] is mainly applying data derived from Meteosat First Generation (MFG). This satellite series delivers operational data since the early 1980s – at least for the main mission, which is serviced by a geostationary satellite positioned at 0°. This covers Africa, Europe as well as parts of Brazil and Asia. Repetition rate for the whole field of view is half hourly from which hourly averaged products of DNI are derived. Since 1998 an additional mission from around 60° longitude covers most of Asia, but this paper only applies data of the main mission. The advantage of this satellite series is that data are available over a long time period, which is required to derive valid long-term estimates. However, it is not possible any more to receive up to date products from MFG since in June 2006 with Meteosat-7 the last satellite of the MFG series quit service at the 0°-position. Thus, no chance nowadays to inter-compare with measurements, which have been set up just recently for qualification of large solar energy projects.

Fortunately, since 2005 the successor satellite series MSG (Meteosat Second Generation) is now operational. It has the same viewing geometry as MFG, but with 15 min a higher temporal resolution and increases in the visible spectral range the maximum spatial resolution from around 3 km to approximately 1 km. Meanwhile, several methods exist to derive solar irradiance from this new satellite. The method Heliosat-3[8,9,10] is regarded as one of the most promising procedures for retrieval of solar irradiance from MSG.. A modified approach to calculate DNI as proposed by Kemper[11] is used for the calculations in this paper.

For this paper MSG-derived DNI data reaching from 2004 to 2007 is made available for a site in Southern Spain. From MFG a time-series reaching from January 1999 to June 2006 is processed up to now and several more years will be available soon. This allows for direct inter-comparison of the two satellite data sets for a period of more than 2 years. Combining both data sets leads to a continuous hourly time-series of 9 years. The pixels selected cover the Plataforma Solar de Almería (PSA), for which also high quality measurements are available.

2.2 Measurements at the ground

Several measurement sites are used for the validation of the satellite procedures, which is subject of separate papers. The procedure introduced in this paper benefits from additional measurement data to increase accuracy of a combined time-series. This takes into account several different independent data sources. The method here will be applied to data for the Plataforma Solar de Almería (PSA) in the Southeast of the Iberian Peninsula. There several irradiation sensors are operating. Since 2006 CIEMAT set up a reference station following the standards of BSRN (Baseline Surface Radiation Network)[12]. Currently data from this station are not applied yet.

Figure 1. Left: Reference station of DLR at PSA. Right: Meteorological station of EPURON operated at a site in Spain.

In parallel DLR operates its own reference station there[13]. This station (fig. 1) is equipped with a 2D tracked Kipp&Zonen pyrheliometer of type CH1, which reaches first class quality according to WMO[12]. In parallel two pyranometers of type Kipp&Zonen CM11 reaching secondary standard are operated. From the combination of the shaded and unshaded pyranometer DNI can be derived in redundancy. This DLR station is operated since more than 5 years and logs data in 1 min time resolution. Further, for calibration purposes EPURON SLU operates a measurement station at PSA equipped with a rotating shadowband radiometer of type RSR-2 manufactured by Irradiance Inc. The data are also logged with a 1 min interval. This station is working there since May 2007. This type of station is important to include in the presented work as such kind of instruments are often used in project development. Those sensors are less affected by dirt and work with low power consumption compared to a tracking device[13].

2.3 Uncertainty of the various data sources

The instruments of the DLR reference station are regularly re-calibrated by the manufacturer according to its recommendation. The station receives almost daily maintenance. Its data are screened on a daily base. If possible errors are corrected, otherwise they get blanked. The rate of data flagged "good" is 99.5%. Following the Kipp&Zonen documentation it is assumed that this reference station with its current intense maintenance reaches an overall absolute uncertainty of 1.5%. This is related to 1 sigma, which is the standard in science to express measures of uncertainty. For all following measures of uncertainty in this paper the same statistical definition is used assuming that the values are normally distributed as it is shown in figure 3.

The EPURON station's sensor type usually experiences less soiling than pyrheliometers[9], which makes it a good choice for remote continuous operation on potential sites. At PSA this station is - just like those operated in the field (fig.2) – checked for correct operation through remote access via GSM modem by the project developers on a daily base. The EPURON meteorological stations are calibrated initially against the reference station at PSA. In the field stability of the calibration is checked every 6 months against a traveling standard. All measured data are corrected mainly for effects of temperature and angular sensitivity of the used pyranometer. Before application the data undergo a scrupulous quality control using the SERI QC[14] software to flag erroneous data. When applying this full QC chain, it is assumed that the absolute uncertainty of long-term data derived from these stations is 3% or better. From the comparison to the reference station at PSA it is found that the RMS of corrected monthly values is 9 W/m², equivalent to an average of 4%.

To derive the average uncertainty of the satellite data many different sites shall be analyzed. Satellite algorithms to derive solar irradiance usually are optimized by minimizing the average deviation from a set of good measurement stations. In the ideal case the bias of the method then approaches zero over all stations. In reality this can not be reached as there are always obstacles, which lead to deviations of the satellite-derived data from measurements. However, the measurements at the ground also do not resemble the truth. Further, pin-point measurements are not representing the same entity as the satellite pixel, which covers many km². Also the sampling rate of the satellite with 15 min for MSG or 30 min for MFG usually causes deviations from the hourly averages calculated on base of 1 min sampling, which is applied for the measurement stations here.

Common measures expressing the deviation of satellites from measurements at the ground are the following:
$\Delta I_i(t) = I_{i,sat}(t) - I_{i,mes}(t)$ describes the individual deviation of satellite derived irradiance values $I_{i,sat}$ at the time t for the site i from ground-based measurements at this site $I_{i,mes}$ for the same time interval. Positive values here shall mean that the satellite-derived values are above the measured ones. Usually many individual values average out. The mean bias MB expresses the remaining deviation over N samples

$$MB = \frac{\sum_{t=1}^{N} I_{sat}(t) - I_{mes}(t)}{N}.$$

To obtain the uncertainty of the long-term average derived from a certain data set the standard deviation σ_{MB} of the mean biases MB_i over several sites i should be taken. This shall be based on as many full years as available. If a data set approaches an overall MB, the resulting σ_{MB} is regarded as the uncertainty of the annual averages to take, in case e.g. a satellite data set shall be applied without any additional proof by measurements at a new site.

The current version of SOLEMI reaches for DNI a 1-sigma uncertainty of $\sigma_{MB,DNI,,SOLEMI}$ = 5%, the current version of Heliosat-3[11] $\sigma_{MB,DNI,Heliosat3}$ = 4% based on a validation with 6 sites of the Spanish Weather service INM in Spain. These values refer to annual averaging. For shorter term averages the uncertainty is significantly larger. If shorter term values are applied, the root mean square deviation RMS related to the specific averaging period shall be taken as the measure of uncertainty. From inter-comparison with the reference data measured with the pyr-

heliometer of DLR the following RMS-values for monthly means of DNI are derived: 36 W/m² with SOLEMI, 17 W/m² with Heliosat3, and 9 W/m² for the corrected RSR2-measurements.
Combining several data sources could increase accuracy, especially if they can be regarded as independent sources not tending to deviate towards the same direction. Combining MFG and MSG-derived data can be a promising approach. Combination with good DNI-measurements at the site helps to further improve the best estimate.

3 How to combine the various input data?

The idea is to calculate a weighted average of all input data, which is regarded as an independent source of information with known quality. The question is how to combine. Which weighting makes sense? Equal weights would be appropriate, if the data sets are assumed to have similar quality. But what shall be applied, if one data set is significantly better than the other? Estimated weights may be a solution, but this can be highly subjective. The uncertainty of the combined product can not be calculated. Therefore a quantitative approach shall be developed.

3.1 Calculating the best estimate

We propose to take the inverse of the uncertainty measure *σ??* of each data set *j* as a weight. The best estimate for the irradiance during a certain parallel period of measurements or satellite observations can be calculated from

$$I = \frac{1}{\sum \delta_j^{-1}} \sum_{j=1}^{n} \delta_j^{-1} I_j$$

where *j* indicates the individual data set of a site and *n* is total number of independent data sets. This approach combines proportional to the quality expressed by the individual 1-sigma uncertainty δ_j. When calculating the combined best estimate, it must be assured that all temporal averages I_j refer to the same time-period. When one of the data sets has gaps in the averaging period, the missing data must be filled or the corresponding times in the other data sets must be cancelled out. If the gaps are filled in, the type and quantity of the gap filling must be taken into account when indicating the quality of this data set.

3.2 Resulting uncertainty of combined data sets

The combination of data sets with various qualities should improve the overall quality of the resulting combined data set. If the additional data sets taken into account are of equal or better quality an improvement is obvious. But often additional data sets also will have moderate or low quality. Quantification of the uncertainty of the combined data set is required to support the decision process.

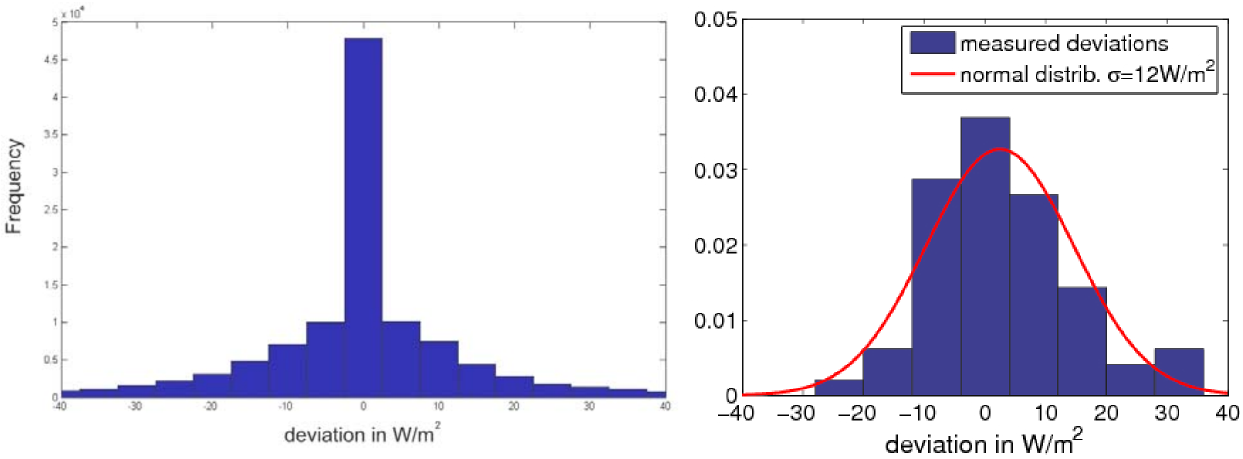

Figure 2. Distribution of the mean bias around the reference for monthly averages (left: corrected RSR2, PSA; right: Heliosat-3, 6 Spanish sites of INM).

It is assumed that the deviations follow a normal distribution and are statistically independent (fig. 3). Then the Gaussian law for error propagation can be applied. Results for the combination of two data sets are displayed in figure 3. This reveals that e.g. for a base data set with 4% uncertainty it makes sense to combine it with an additional data set if the uncertainty of this additional set is better than 7%. For a base uncertainty of 6%, an additional data set should have accuracies of up to 10%. This reveals that the proposed method taking a quality-weighted average adds value even if the additional data set is not of top quality.

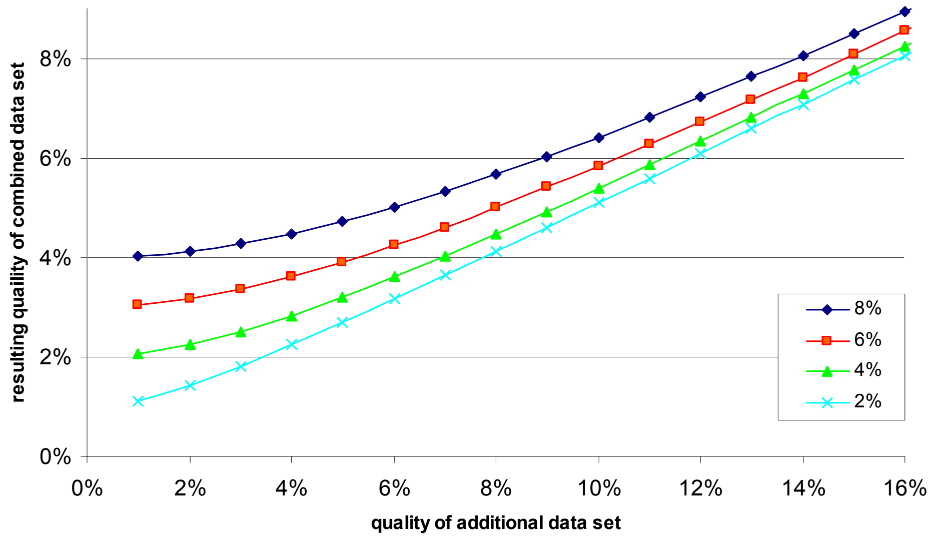

Figure 3. Resulting uncertainty when combining a base data set of 2%, 4%, 6% or 8% overall uncertainty with an additional data set of various quality.

When using more than two parallel data sets, the situation might get even better. Table 1 gives the resulting uncertainty for a case where the base data set has an uncertainty of 4%. This e.g. reveals that it makes sense better to add two data sets with a moderate 7%-quality than only 1. Adding two data sets of only 10% uncertainty should be avoided.

σ_{base}=4%	σ_{set}=1%	2%	3%	4%	5%	6%	7%	8%	9%	10%	11%	12%
σ_{set1}=1%	1,4%	1,5%	1,7%	1,9%	2,2%	2,4%	2,7%	3,0%	3,3%	3,6%	3,9%	4,2%
2%	1,5%	1,6%	1,8%	2,0%	2,2%	2,5%	2,8%	3,1%	3,3%	3,7%	4,0%	4,3%
3%	1,7%	1,8%	1,9%	2,1%	2,4%	2,6%	2,9%	3,1%	3,4%	3,7%	4,0%	4,3%
4%	1,9%	2,0%	2,1%	2,3%	2,5%	2,7%	3,0%	3,3%	3,5%	3,8%	4,1%	4,4%
5%	2,2%	2,2%	2,4%	2,5%	2,7%	2,9%	3,2%	3,4%	3,7%	4,0%	4,2%	4,5%
6%	2,4%	2,5%	2,6%	2,7%	2,9%	3,1%	3,3%	3,6%	3,8%	4,1%	4,4%	4,7%
7%	2,7%	2,8%	2,9%	3,0%	3,2%	3,3%	3,6%	3,8%	4,0%	4,3%	4,5%	4,8%
8%	3,0%	3,1%	3,1%	3,3%	3,4%	3,6%	3,8%	4,0%	4,2%	4,5%	4,7%	5,0%
9%	3,3%	3,3%	3,4%	3,5%	3,7%	3,8%	4,0%	4,2%	4,4%	4,7%	4,9%	5,2%
10%	3,6%	3,7%	3,7%	3,8%	4,0%	4,1%	4,3%	4,5%	4,7%	4,9%	5,1%	5,4%

Table 1. Resulting uncertainty for a case where the base data set has 4% uncertainty and is combined with two other data sets of various uncertainties. Good combinations, which shall improve the quality, are indicated in green, yellow for indifferent situations, and red for combinations, which are not recommended as they would decrease quality.

4 Deriving the best estimate of the solar irradiance at the Plataforma Solar de Almería

The proposed method is being applied to derive the best estimate of the long-term average of beam irradiance for the Plataforma Solar de Almería (PSA). The following steps are taken:

1. All time-series receive quality control, which leads to estimates of the individual uncertainty.
2. For a 'calibration time-period', which is the span during which values are available in parallel to the reference, the biases against the reference are derived. This bias shall be derived from at least a full year of data.
3. For each monthly value a bias-corrected value is calculated using a linear correction.
4. According to chapter 3.1 the best estimate is calculated for each month.
5. The remaining overall uncertainty is calculated according to the Gaussian law of error propagation taking the monthly RMS as measure of uncertainty.

From the 9 years of data so far available a best estimate of 244 W/m² for the long-term average of direct normal irradiance at the PSA is derived. This is equivalent to an annual DNI sum of 2135 kWh/m² or 5,8 kWh/m² mean daily sum. The uncertainty of the combined best estimate for the monthly values ranges from 6 W/m² (2%) to 29 W/m² (23%) depending on the actual quality and amount of available data for each month.

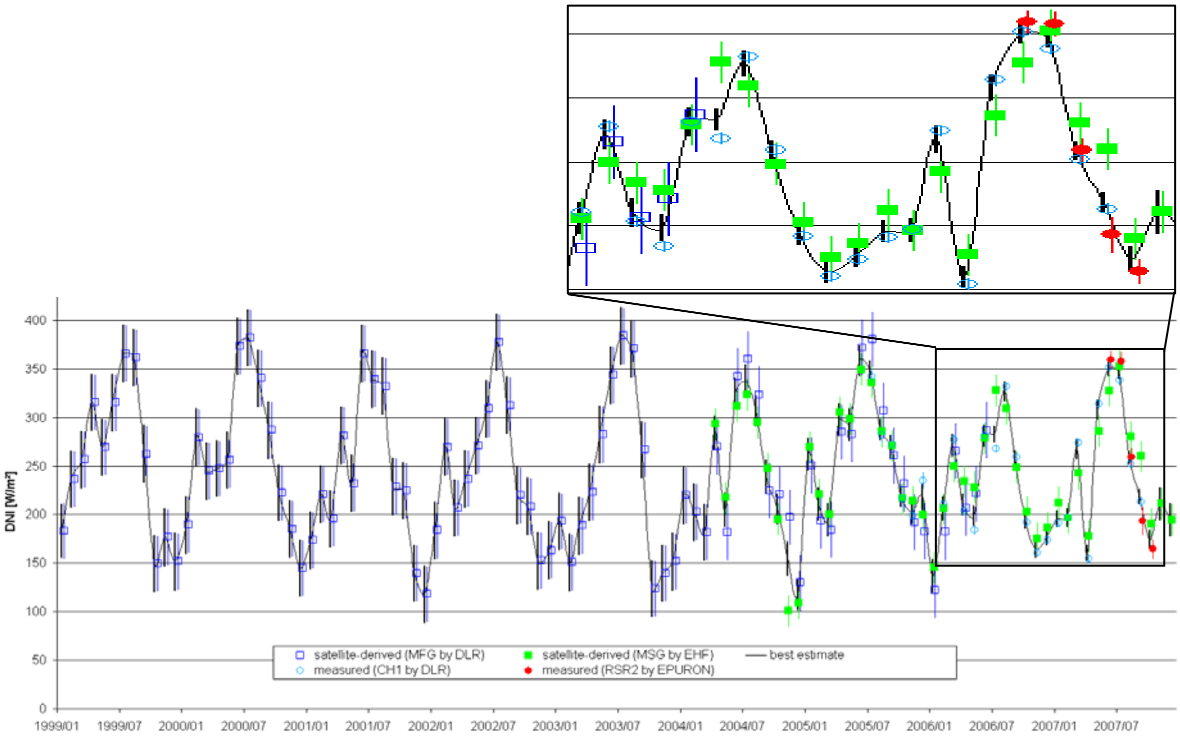

Figure 4. DNI-time-series over the past 9 years at PSA. Error bars indicate 1-sigma bands of monthly values for each data type. The black line and bars show the best estimate.

5 Conclusions & Outlook

In this paper a method is developed that provides a best estimate of site-specific solar irradiance conditions. The procedure is shown for direct normal irradiance, but it can be applied in principle in the same manner for global horizontal irradiance or other site-specific parameters, which have approximately a normal distribution.

Major findings are:

- If the various input data are of comparable quality, the proposed method to combine various input data sets to a new best estimate should lead to results, which should be closer to the true values than using only single data sets. The accuracy of the best estimate is usually better than that of single data sets.
- If there are data of very limited quality, the resulting best estimate can be worse than without applying the additional information. The decision on using a data set or not shall be guided by thorough analysis of the quality of the individual data set and calculation of the influences on the remaining uncertainty.
- Thus, each data provider shall do the best to achieve high accuracy, so that it actually makes sense to use the data. All data sets should be corrected as far as possible to eliminate biases. Otherwise the best estimate gets biased.
- The best estimate for the long-term average of direct normal irradiance at the PSA is 244 W/m².

Currently, for the presented best estimate time-series at PSA only measurements data from DLR and EPURON are applied. Since 2006 CIEMAT has joined the BSRN-network, which shall provide highest possible standards for operational measurements. In the future this data shall also be taken to further improve the quality of the PSA-time-series. This will allow checking how the proposed method works using more different time-series.

To achieve more experience under various natural conditions, the new method shall be applied to several other sites to see how it behaves in other situations. Preferable these additional investigations will cover different climates, altitudes and satellite observing geometries.

Several general relevant issues covering the field of site-specific best estimates remain open. E.g., how does the length of the parallel time-period affect the reliability of the final result? In the future it is planned to take this additionally into account. The accuracy of all data both of ground-based as well as satellite-based irradiances is highly variable in time. A more sophisticated procedure should try to take into account individual uncertainty measures for each date.

For more accurate yield predictions of solar thermal power plants, it would be an advantage to retrieve also realistic high resolution DNI time-series for in-depth site investigations based on hourly or better time resolution as input to detailed simulations. This issue is not covered yet by the proposed method. As this second order characteristics of solar resources have significant impact on yields of solar thermal power plants, this topic shall be investigated in the future. E.g. for more detailed inter-comparisons of satellite data against measurements, other measures like the Kolmogorow-Smirnow-integral are recommended[15]. These give information on the higher statistical moments and differences in the distribution functions, which also can have significant influence on energy yields of solar thermal power plants. In this paper only a fast basic approach is presented. In the future the influence on those parameters and on differences in energy yields should be analyzed.

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