# Improving satellite-derived solar resource analysis with parallel ground-based measurements

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## Abstract

Satellite-derived solar radiation products often have strong deviations from ground-measured solar irradiance data. Common problems include a systematic over- or underestimation, which can be expressed by calculating the mean bias. As in first order energy produced by a solar plant roughly depends on the total incoming irradiation this simple number gives a first hint on potential error of energy production. Moreover, due to limited usability of low and very high irradiance values and non-linear effects also the frequency distribution of solar time-series data have a relatively strong influence on potential yields and its uncertainty. Thus, for detailed engineering and financing of solar power plants it is advisable to not rely simply on site-specific satellite derived solar resources products, but also to do measurements at the site and use those for validating and improving the satellite-derived time-series. This paper presents a method, which embosses the features of frequency distribution of ground-based measurements onto two different satellite-derived time-series. The method presented shows good improvement of systematic over- or underestimation: in one example it is shown, that if at least 3 months of parallel measurements are available at a site, even strong biases beyond 25 % can be reduced below 10 %. But the quality of results applying only a quarter year of overlap for training is still quite variable. Applying half a year of data usually already gives significantly better results – at least if all sun angles are covered, by a start of measurements at summer or winter solstice. In most cases, a complete parallel year of measurements is sufficient to reach very good improvements at sites. Inter-comparing the improvement effect on beam irradiance versus global horizontal irradiance shows that direct normal values from satellite can be far better improved than on global horizontal irradiance. However, the initial analysis shows that the need to correct global horizontal is also much smaller.

KEYWORDS: Ground-measured, satellite-derived, *DNI*, *GHI*, solar irradiance, inter-comparison, method, uncertainty, mean bias, fitting

## 1. Introduction

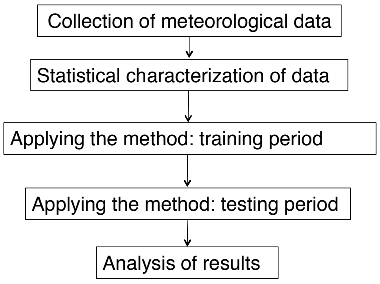
Financing of solar power plants requires highly accurate information about the solar conditions at a site. Today, it is common to apply satellite-derived time-series of global horizontal irradiance (*GHI*) for photovoltaic (PV) and direct normal irradiance (*DNI*) for performance simulation of concentrating solar power (CSP) plants. Satellite data have the advantage that they are easily available for a long-term period contrary to ground-based measurements. The inter-annual variability of solar irradiation can be very high depending on location of the sites and hence stable and reliable long-term averages shall not be based on measurement from a few years only. Today satellite-derived time-series covering more than 10 years can be made available for every site worldwide. Such long-term time-series help reducing uncertainty of the long-term best estimate. However, as earlier studies - and also this paper - show, differences between various satellite-derived and ground-measured data sets can be high indicating a remarkable uncertainty associated with these techniques. Despite having more than a decade of satellite data, uncertainty of the long-term average often is in the range of 5 % to 15 %, especially for *DNI*. As such high uncertainty can be a showstopper for solar energy projects or at least can cause severe difficulties in financing, it is common practice in CSP industry to measure at least over one year at the site. However, limited period of ground-based solar radiation measurements are available during project development, often due to sharp deadlines for subsidy programs and late decision to install a station.

Ground-based solar radiation measurements may be used to correlate satellite-derived solar radiation data. Carow (2008) presented methods for using ground-based measurements to improve the performance of satellite-derived algorithms to determine solar irradiation from satellite images. Although three different methods are presented, the influence of the length of overlapping data is not taken care of in Carow (2008). It is a common practice in wind energy industry to use Measure-Correlate-Predict (MCP) methods such as regression, Weibull scale, Matrix method etc. to determine wind resource at a site from short-term measurements. Hoyer et al. (2009) describes a method to create a Typical Meteorological Year using one year of ground-based measurements and long-term satellite-derived time series.

However, quantitative analysis relating the uncertainty and length of measurement period is still not known. In addition in case of short-term measurements covering less than one year of overlap, information about the duration and period of the year to be used for improvement of satellite-derived data is also missing. The repercussion of these limits to the uncertainty of the resource estimate is not analyzed until now. This paper aims to improve the quality of satellite-derived time-series data by using ground-based measurements with special consideration of the length of the overlapping period between satellite and ground-based data sets. Thus, this paper systematically determines the influence of the length of the measurement period – and the accuracies of both satellite and ground measurements on the uncertainty of the long-term best estimate of solar radiation. For one site with accurate measurements over at least 3 years, it is shown how taking only a subset of the measurements affects the accuracy.

## 2. Methodology

The methodology followed in this study can be summarized by the flowchart given below.



### 2.1 Collection of meteorological data

To study the effect of improving satellite-derived solar irradiance data using ground-based measurements a site is selected, for which long-term and precise ground-based solar radiation measurements are available. These multi-year measurements are taken as the reference. To guarantee high quality stations are selected, which fulfill the requirements of the Baseline Surface Radiation Network (BSRN). Here the BSRN-station of Tamanrasset in Algeria is taken, which in the following is indicated by the site code DZTAM. Tab. 1 lists the data sets used in this study.

For all sites satellite-derived solar radiation data from German Aerospace Center (DLR-SOLEMI 2011) and University of Oldenburg, Energy and Semiconductor Research Laboratory (EHF) are available over a long overlapping period. DLR provided its Solemi data in version 1.1 in hourly time-resolution, which is derived from

Meteosat First Generation (MFG), EHF provided its EnMetSOL data in version 3.2 based on Meteosat Second Generation (MSG) data. The MFG data have the advantage of covering a longer time-span, while the MSG-derived data generally should be of higher quality due to higher time resolution of 15 min and spatial resolution together with better radiometric specifications.

**Tab. 1: Overview of available measurement and satellite-derived solar radiation data. Coordinates and elevation are according to WGS84.**

| site, country, site code, coordinates | data set | temporal resolution | solar radiation parameters | start time | end time | time span |
|---|---|---|---|---|---|---|
| Tamanrasset, Algeria, DZTAM<br>lat.: 22.78<br>lon.: 5.51<br>elev.: 1385 m | BSRN measurements | 1 min | *GHI*, *DNI*, DHI | 2001-01-01 | 2009-12-31 | 10.0 a |
| | DLR-Solemi V1.1 11.2007 | 60 min | *GHI*, *DNI*, DHI | 1991-01-01 | 2006-06-30 | 16.5 a |
| | EHF Heliosat Version 3.2 | 15 min | *GHI*, *DNI* | 2004-07-01 | 2009-10-31 | 6.3 a |

To make results well comparable from both data sets 4 years of data have been taken. However due to cease of service of MFG in 2006 and incompleteness of 2004 in MSG only the year 2005 is overlapping. Results therefore are not fully comparable.

### 2.2 Statistical Characterization of data

To quantify the improvement of overlapping measurements, first the quality of un-corrected satellite data is analyzed by the following measures: The Mean Bias *MB* (eq.1) describes the average systematic deviation of the average of the satellite derived irradiance $G_{sat}$ from the ground-measured irradiance $G_{ground}$ over the same overlapping time period by:

$$MB = \frac{\sum G_{sat} - \sum G_{ground}}{\sum G_{ground}} \qquad \text{(eq. 1)}$$

The Standard Deviation *SDD* of the differences of $G_{ground}$ - $G_{sat}$ in each time-step describes the variability of the deviations while the Root Mean Square Deviation *RMSD* gives a combined indication of *MB* and *SD*.

As the frequency distribution of solar radiation time-series has strong influence on the annual power production of a CSP plant (Chhatbar and Meyer, 2011) the Kolmogorov-Smirnov Integral (KSI) acc. to Espinar, et al. (2008) is also calculated for each uncorrected and corrected data set.

### 2.3 Description of method used

There are various methods to correct satellite-derived data with the common aim to reach a new data set showing reduced error measures as compared to the measured data sets. Basic example for this is given by a simple linear correction for bias removal. In contrast, Carow (2008) applied and discussed three different approaches finding that the "feature transformation" is the method leading to best results. The feature transformation is based on the adaption of the frequency distribution of the modeled set to the one of the ground data by using information of the relative distortion of the distribution of the satellite data from parallel sets. For this process Carow (2008) uses a presentation of the cumulative distribution functions by fitted polynomial curves. Carow (2008) could prove that this procedure may lead to reduced KSI values for two of the three stations.

Beyer et al. (2010) developed a similar feature transformation procedure using look up tables. For the application parallel sets of measured and satellite data are used to derive the difference of the respective distribution functions, The functions of the differences is then applied to correct new sets of measured data, As Beyer et al. (2010) explained, the method only works as long as differences of the cumulative frequency distributions show sufficient similarly from year to year or from site to site when used for spatial extrapolation, In method applied in this paper the difference of the cumulative frequency distributions are presented by polynomial functions. The correction step involves lookup tables for the presentation of the values of cumulative distribution function of the set to be corrected, In the following, we applied this method to overlapping time series of ground measurements and satellite derived data for 3, 6, 12 and 24 months.

For the evaluation of the cumulative distributions of satellite and ground data, the time series of ground and satellite data is filtered by sorting out all values for elevation and azimuth less than or equal zero to keep only day values and skip night values. The cumulative frequency distributions are calculated with a bin size of 1 W/m$^2$ as functions for irradiance independent of cumulative frequency distribution. For the polynomial representation polynomial fit of 4th degree is used. Carow (2008) and our tests showed that a fitting of 4th degree comes out with the best and most stable results.

The quality of the original and resulting time series is given by the parameter mean, mean bias, root mean square deviation and KSI. These parameters are always calculated for complete data sets, including night values. Fig. 1 shows schematic example for the described method. *DNI* data from satellite data and ground measurement is used as input. The upper left image illustrates the determination of the difference of both cumulative frequency distributions. The determined difference is applied to the test satellite data set and the corrected data set is calculated (upper right image). The lower images show the mapping steps. Input is the irradiance data from satellite data, which has a certain value of cumulative frequency distribution (lower left image). In the lower right picture the corrected/adjusted irradiance value for the same cumulative frequency distribution is determined.

The horizontal arrow describes the difference of irradiance of both curves for the same frequency distribution value. The difference between the curves is reduced. With the adjusted frequency distribution the corresponding irradiance values can be determined.

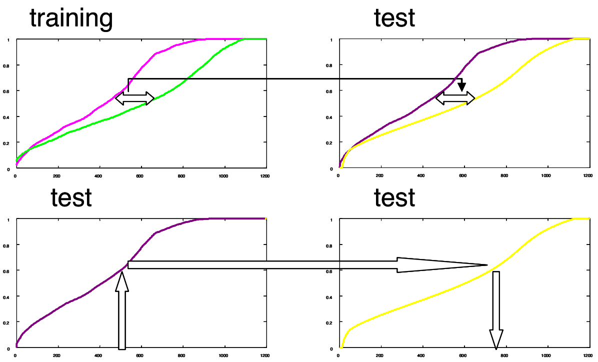


**Fig. 1: Top left: cumulative frequency distribution for training time of overlapping ground and satellite time series, the arrow illustrates the difference between both curves. Top right: corrected satellite cumulative frequency distribution for test period; Bottom left: mapping of original satellite irradiance values to original cumulative frequency distribution; arrow and bottom right image: first, mapping of original cumulative frequency distribution to corrected cumulative frequency distribution, second, mapping of corrected cumulative frequency values to adjusted satellite values. Green: ground data from trainings set, magenta: satellite data from trainings set, purple: satellite data from test set, yellow: corrected satellite data**

Polynomial equation of the difference is calculated by subtracting the polynomial coefficients of the fitted ground polynomial from the coefficients of the fitted satellite polynomial for training time series. Thus, the difference polynomial (or deviation of cumulative frequency distribution curves) is obtained, which is applied to the testing years by subtracting it from the satellite polynomial. The result is the corrected satellite polynomial.

The next step is to implement the lookup table method to find the adjusted satellite values for the corrected satellite cumulative frequency distribution. For this all irradiance values in cumulative frequency distribution are treated in 1 W/m$^2$ bins. The first step is to assign the original cumulative frequency distribution values to the time series of satellite irradiance data. In the second step this time series of cumulative frequency distribution values is used to receive adjusted satellite irradiance values by evaluating it on the corrected values for cumulative frequency distribution. As values are interpolated linearly within the data range given by the training year, values outside this range, which may occur in the new data set have to be set to the maximum of original satellite irradiance. Similarly night values have to be set to zero.

## 3. Results

The results presented in this chapter are divided into results for *DNI* and *GHI* to show the effects the method has on both kinds of irradiance. The values of statistical parameters – mean bias, standard deviation of differences, root mean square deviation and KSI – for both DLR and EHF time-series is shown in tables and figures below for 3, 6, 12 and 24 month of overlapping training data. This training sets is applied to the whole overlapping time of ground measurement and satellite-derived data for DLR and EHF for four years. To gain a reliable statistical base, several permutations for the combinations of 3, 6, 12 and 24 month have been analyzed. The following tables give the average results for all sets characterized by a given combination of season (3 month), half year (6 month), one year (12 month) and two years (24 month).

### *3.1 Results for DNI*

Tab. 2 summarizes the uncorrected statistical parameters for DLR and EHF for the available overlapping time period. The results for DLR and EHF respectively are given in Tab. 3 and Tab. 4.

**Tab. 2: Values of statistical parameters for *DNI* at site DZTAM for overlapping time period of BSRN and DLR respectively EHF. To calculate these parameters BSRN values are used as reference.**

| | ***time*** | ***MB*** | ***rMB*** | ***SDD*** ***60min*** | ***rSDD*** ***60min*** | ***RMSD*** ***60min*** | ***rRMSD*** ***60min*** | ***KSI*** |
|---|---|---|---|---|---|---|---|---|
| | **[a]** | **[W/m$^2$]** | **[%]** | **[W/m$^2$]** | **[%]** | **[W/m$^2$]** | **[%]** | **[%]** |
| DLR | 2002 – 2005 | 7 | 3 | 165 | 31 | 165 | 31 | 219 |
| EHF | 2005 – 2008 | 73 | 27 | 256 | 42 | 266 | 50 | 1005 |

**Tab. 3: Overview of main results for site DZTAM for various time periods for *DNI* from DLR.**

| ***Δt*** | ***MB*** | ***rMB*** | ***SDD*** ***60min*** | ***rSDD*** ***60min*** | ***RMSD*** ***60min*** | ***rRMSD*** ***60min*** | ***KSI*** |
|---|---|---|---|---|---|---|---|
| **[a]** | **[W/m$^2$]** | **[%]** | **[W/m$^2$]** | **[%]** | **[W/m$^2$]** | **[%]** | **[%]** |
| ¼ | -16.0 | -6 | 184 | 33 | 186 | 35 | 408 |
| ½ | -6.6 | -2 | 172 | 33 | 173 | 33 | 208 |
| 1 | -1.0 | 0 | 172 | 32 | 172 | 32 | 101 |
| 2 | -1.9 | -1 | 172 | 32 | 172 | 32 | 45 |

**Tab. 4: Overview of main results for site DZTAM for various time periods for *DNI* from EHF.**

| ***Δt*** | ***MB*** | ***rMB*** | ***SDD*** ***60min*** | ***rSDD*** ***60min*** | ***RMSD*** ***60min*** | ***rRMSD*** ***60min*** | ***KSI*** |
|---|---|---|---|---|---|---|---|
| **[a]** | **[W/m$^2$]** | **[%]** | **[W/m$^2$]** | **[%]** | **[W/m$^2$]** | **[%]** | **[%]** |
| ¼ | -10 | -3.6 | 234 | 44 | 235 | 45 | 377 |
| ½ | -5 | -2 | 233 | 44 | 233 | 44 | 243 |
| 1 | -5 | -2 | 236 | 44 | 236 | 45 | 159 |
| 2 | -3 | -1 | 236 | 45 | 236 | 45 | 80 |

Fig. 2 and Fig. 3 show the effect of increasing overlap time on the relative mean bias for satellite data from DLR and EHF, respectively. Fig. 4 exemplary presents the effect of increasing overlap time for the relative standard deviation of differences rSDD and Fig. 5 the KSI in both cases only for DLR data. In Tab. 5 and Tab. 6 the effects for quarterly and half yearly, respectively, are given. In this case, the results are averaged over DLR and EHF.

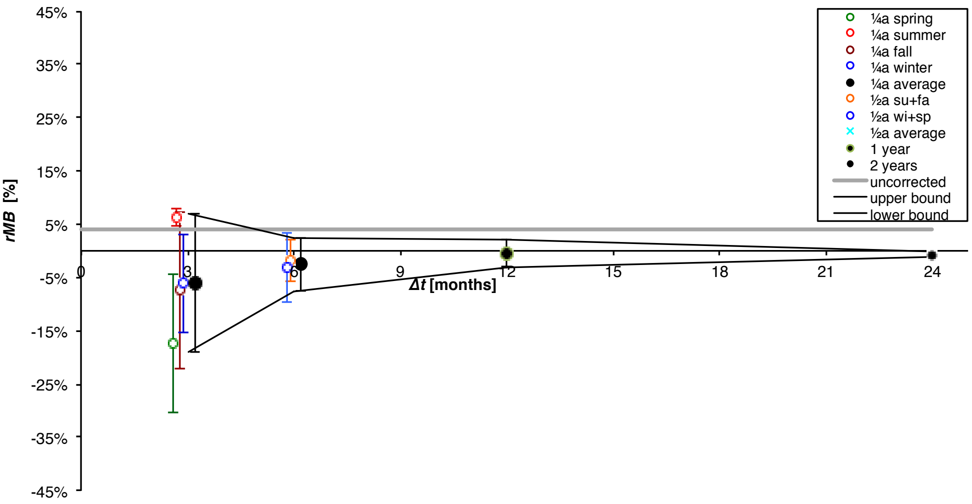


**Fig. 2: The effect of increasing overlap time on the relative mean bias of corrected DLR-Solemi in relation to the long-term average derived from long-term precise ground-based measurements at Tamanrasset, Algeria**

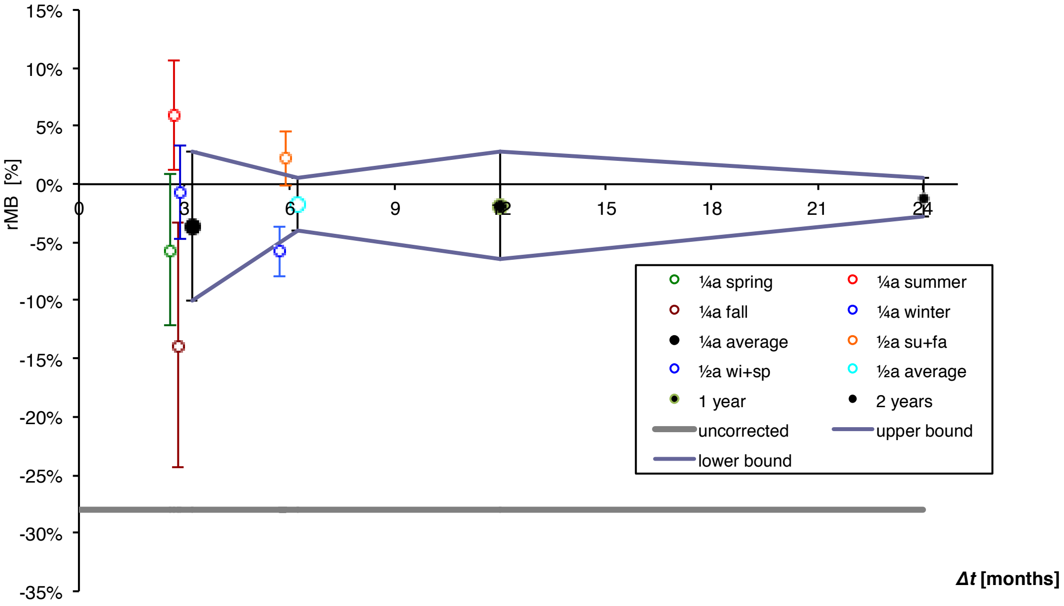


**Fig. 3: The effect of increasing overlap time on the relative mean bias of corrected EHF in relation to the long-term average derived from long-term precise ground-based measurements at Tamanrasset, Algeria.**

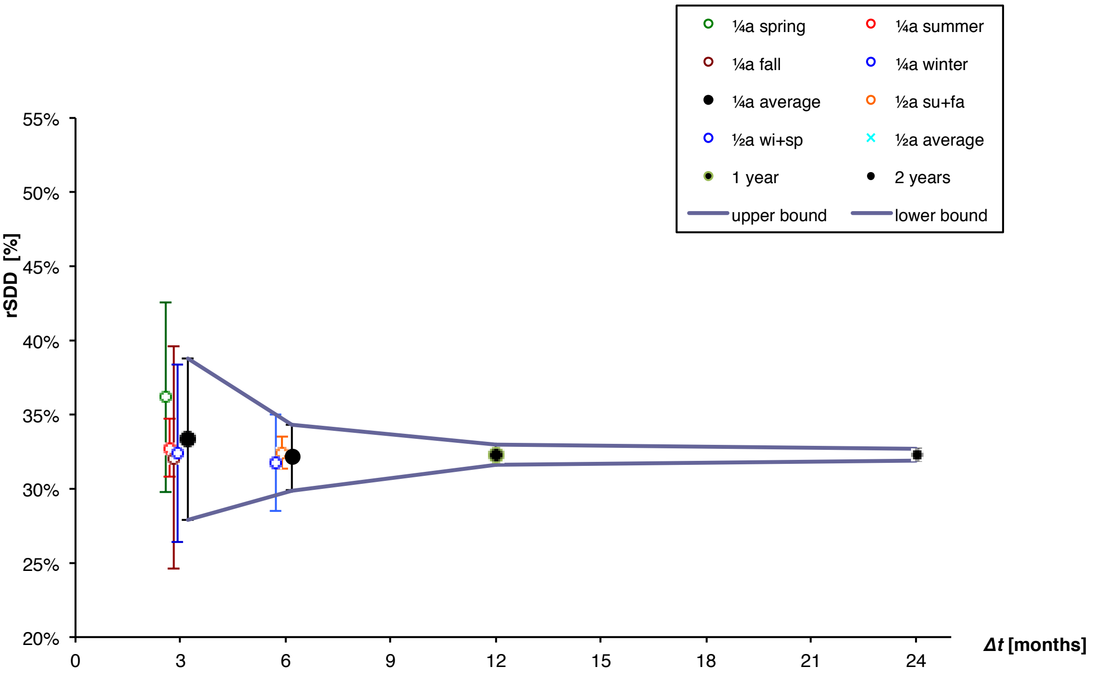


Fig. 4: The effect of increasing overlap time on the relative standard deviation of differences between corrected DLR data sets and the reference measurements in 60 min time resolution.

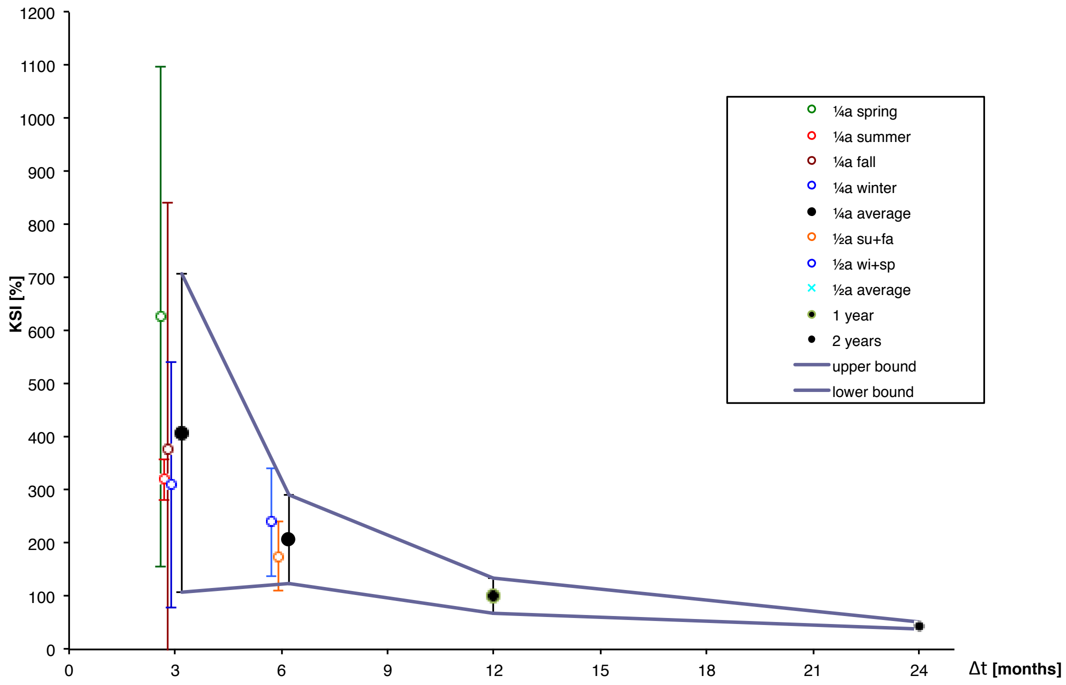


Fig. 5: The effect of increasing overlap time on the KSI of corrected DLR data sets.

**Tab. 5: The seasonal effect of improvement for *DNI*, if only 3 months of measurements are available averaged over all available sites.**

| **season** | ***MB*** | ***rMB*** | $SD_{60min}$ | $rSD_{60min}$ | $RMSD_{60min}$ | $rRMSD_{60min}$ | ***KSI*** |
|---|---|---|---|---|---|---|---|
| **units** | **[W/m²]** | **[%]** | **[W/m²]** | **[%]** | **[W/m²]** | **[%]** | **[%]** |
| **spring** | -31 ± 30 | -11 ± 11 | 219 ± 20 | 40 ± 5 | 221 ± 29 | 42 ± 6 | 448 ± 379 |
| **summer** | 16 ± 9 | 6 ± 3 | 203 ± 8 | 38 ± 3 | 204 ± 32 | 38 ± 6 | 351 ± 92 |
| **fall** | -28 ± 33 | -11 ± 12 | 213 ± 25 | 39 ± 6 | 216 ± 39 | 41 ± 7 | 466 ± 367 |
| **winter** | -9 ± 19 | -3 ± 7 | 202 ± 12 | 38 ± 4 | 203 ± 17 | 38 ± 5 | 305 ± 163 |

**Tab. 6: The seasonal effect of improvement for *DNI*, if only half a year of measurements are available averaged over all available sites.**

| **season** | ***MB*** | ***rMB*** | $SD_{60min}$ | $rSD_{60min}$ | $RMSD_{60min}$ | $rRMSD_{60min}$ | ***KSI*** |
|---|---|---|---|---|---|---|---|
| units | [W/m²] | [%] | [W/m²] | [%] | [W/m²] | [%] | [%] |
| **summer+fall** | 0 ± 10 | 0 ± 4 | 204 ± 9 | 38 ± 1 | 204 ± 33 | 39 ± 6 | 203 ± 67 |
| **winter+spring** | -12 ± 13 | -4 ± 5 | 201 ± 11 | 38 ± 2 | 202 ± 32 | 38 ± 6 | 248 ± 74 |

### *3.2 Results for GHI*

Tab. 7 summarizes the uncorrected statistical parameters for DLR and EHF for the available overlapping time period. The results for DLR and EHF respectively are given in

Tab. 8 and Tab. 9. In Fig. 6 and Fig. 7 the effects of increasing overlap time for *GHI* are exemplary shown for the relative mean bias of corrected data sets for DLR and EHF.

**Tab. 7: Values of statistical parameters for *GHI* at site DZTAM for overlapping time period of BSRN and DLR respectively EHF. To calculate these parameters BSRN values are used as reference.**

|  | ***time*** | ***MB*** | ***rMB*** | ***SDD*** ***60min*** | ***rSDD*** ***60min*** | ***RMSD*** ***60min*** | ***rRMSD*** ***60min*** | ***KSI*** |
|---|---|---|---|---|---|---|---|---|
|  | **[a]** | **[W/m²]** | **[%]** | **[W/m²]** | **[%]** | **[W/m²]** | **[%]** | **[%]** |
| DLR | 2002 – 2005 | -1 | 0 | 68 | 13 | 68 | 13 | 118 |
| EHF | 2005 – 2008 | 23 | 9 | 106 | 19 | 109 | 20 | 316 |

**Tab. 8: Overview of main results for site DZTAM for various time periods for *GHI* from DLR.**

| ***Δt*** | ***MB*** | ***rMB*** | ***SDD*** ***60min*** | ***rSDD*** ***60min*** | ***RMSD*** ***60min*** | ***rRMSD*** ***60min*** | ***KSI*** |
|---|---|---|---|---|---|---|---|
| **[a]** | **[W/m²]** | **[%]** | **[W/m²]** | **[%]** | **[W/m²]** | **[%]** | **[%]** |
| ¼ | 0 | 0 | 71 | 13 | 71 | 13 | 94 |
| ½ | -4 | -2 | 70 | 13 | 71 | 13 | 74 |
| 1 | 0 | 0 | 69 | 13 | 69 | 13 | 45 |
| 2 | 0 | 0 | 69 | 13 | 69 | 13 | 40 |

**Tab. 9: Overview of main results for site DZTAM for various time periods for *GHI* from EHF.**

| *Δt* | *MB* | *rMB* | *SDD*<br>*60min* | *rSDD*<br>*60min* | *RMSD*<br>*60min* | *rRMSD*<br>*60min* | *KSI* |
|---|---|---|---|---|---|---|---|
| [a] | [W/m$^2$] | [%] | [W/m$^2$] | [%] | [W/m$^2$] | [%] | [%] |
| ¼ | 0 | 0 | 101 | 17 | 101 | 18 | 115 |
| ½ | -5 | -2 | 101 | 19 | 101 | 19 | 83 |
| 1 | 0 | 0 | 100 | 19 | 100 | 19 | 60 |
| 2 | 0 | 0 | 100 | 19 | 100 | 19 | 47 |

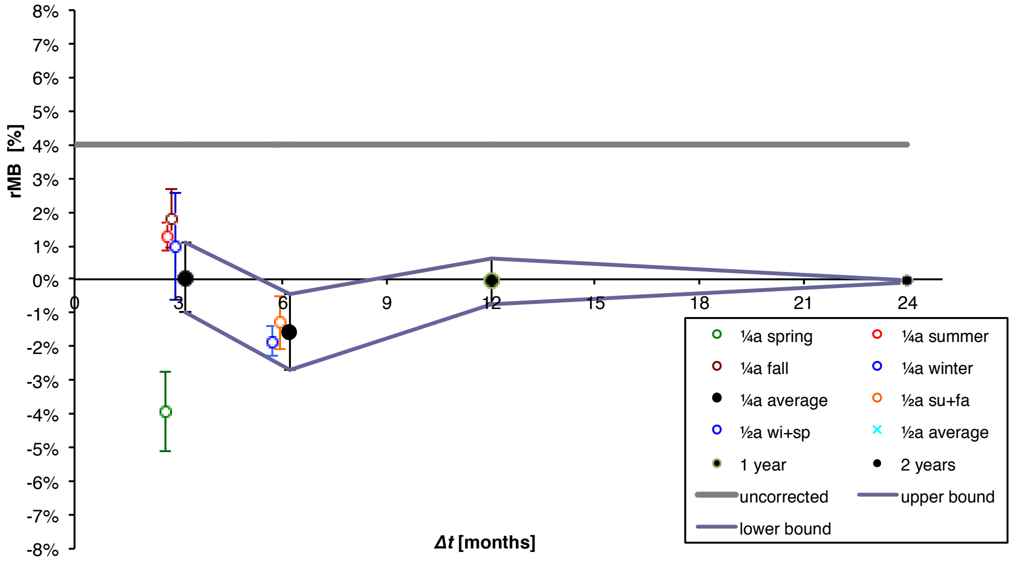


**Fig. 6: The effect of increasing overlap time on the relative mean bias of corrected DLR in relation to the long-term average derived from long-term precise ground-based measurements at Tamanrasset, Algeria.**

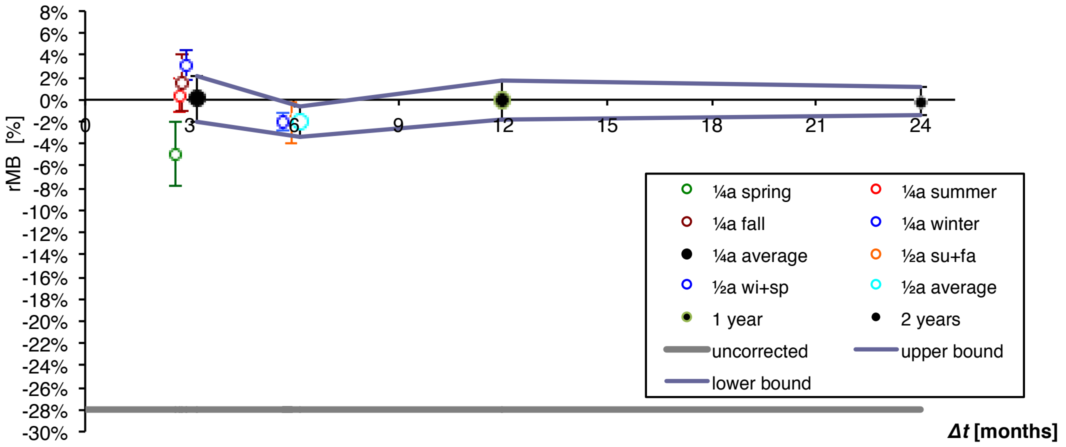


**Fig. 7: The effect of increasing overlap time on the relative mean bias of corrected EHF in relation to the long-term average derived from long-term precise ground-based measurements at Tamanrasset, Algeria.**

## 4. Discussion of results

rMB and KSI are improved for DLR and EHF. For EHF at this site the rMB of the original data is -28 %. For the adjusted data sets it slightly fluctuates around 0 % for the different lengths of training periods. Only the average of the spring season shows higher rMB of -5 %. The values for DLR show similar behavior. The uncorrected rMB is 4 % and the corrected rMB approaches 0 %. Also the average of the spring season has a greater rMB with -4 %. Differently to the EHF the average for six month of parallel measurement is with -2 % below the average but still an improvement to the uncorrected data.

The values for rSDD do not show significant improvement for both DLR and EHF. It describes the average deviation between two datasets. With the developed method we do not eliminate errors like phase distribution by clouds.

It is shown that for both satellite data sets the adaption of the frequency distribution can work already well with a short time period such as ¼ year. The KSI is greatly improved from 219 % to 186 % and from 1005 % to 377 % for *DNI* for quarterly overlap for DLR-Solemi and EHF respectively. For the same overlap period the average effect on *GHI* is from 118 % to 94 % and from 316 % to 115 %. For a full year of parallel data sets the KSI is improved for *GHI* to 45 % and for *DNI* to 101 %.

Deviations in SDD and KSI occur, because the resulting cumulative frequency distributions differ slightly from the measured cumulative frequency distributions. Both curves do not exactly match. The fit significantly improves with increasing the overlap period. This observation is explained by the fact that few months cannot map the full natural variability. Therefore, the recommendation is confirmed to use at least a full year of measurements to incorporate the annual variability of the atmosphere. The full year of data also has the advantage that the variation of sun elevation, which also can cause significant systematic errors of the satellite procedure, can be well compensated.

Shorter time-periods than one year already improve the resulting corrected data set. To cover all sun angles it is an advantage, if an overlapping half-year period starts at winter solstice and last until summer or covers the second half of the solar cycle. If the measurement starts in spring and lasts until fall, the improvement usually is also expected to be good, because the higher irradiance during that time of the year has a stronger overall effect. Worst results are usually achieved, if the available half-year period covers mainly winter season. This might be different in monsoon regions, where often a major amount on annual irradiation is gathered during winter.

The findings shown here for EHF results shall not be generalized. Meanwhile University of Oldenburg further improved their method so that a better fit of original data can be expected.

For *GHI* it is concluded that for many satellite data products at many sites *GHI* could be used without site-specific adaption. As the improvements for *DNI* are far greater than for *GHI* and deviations from measurements usually far greater it is strongly recommended to do site-specific measurements and adapt satellite data during the overlapping period. To reach sufficient overlap periods measurements shall be started early in project development. However, it is obvious that only high quality measurements actually shall be used for the proposed improvement process. If the quality of measurements is moderate or even poor, it is better to avoid spoiling good satellite data.

## 5. Conclusions and Outlook

The hypothesis that the quality of potential improvements of satellite-derived irradiance data depends strongly on the length of the overlap with measurements is confirmed. A single month of overlap is of no or very limited help, because the characteristics of ground-based measurements are much more diverse, and hardly are covered within a single month' timespan. Using 3 continuous months for improvement of satellite data in some cases largely improves the corrected data set, while in others it worsens the quality of the long-term satellite-derived time series. This is observed especially at site like Tamanrasset, where an uncorrected satellite-data-set like DLR-Solemi already matches well the measurements in terms of the long-term best estimate. If an uncorrected satellite-data-set like that of EHF in the case of the site Tamanrasset shows a strong bias, already few months of overlapping precision data significantly help reducing this bias.

The study demonstrates that already few months of parallel measurements are of help. It shows, in which season measurements help best to improve overall results. Results are given for *DNI* and *GHI* to indicate also which sort of solar resource has which benefit from measurements in parallel to satellite data. Besides, regarding the accuracy of the long-term averages, the quality of the representation of the distribution function of the data – of special importance for non-linear reacting systems as CSP – is discussed.

In this paper the method is applied only to a single site and two sorts of satellite-derived data sets. The developed procedure can be universally used to modify any satellite-derived time-series with ground-based data of the same time-resolution. To verify the found phenomena it is recommended to extend the study by applying it to several more sites and other satellite products. Similar to the site used in this study, additional sites shall have at least 4 years of high quality overlapping measurement data. To show that the behavior of the method is similar sites in different climates shall be selected, but also other subtropical sites, to confirm the findings.

This study is using only hourly-integrated values, where satellite and ground-based time-series are given in the same time resolution. For more sophisticated performance simulations of solar thermal systems, but also for PV there is the need to have time-series in resolutions down to the 10 min scale or even finer. Today's satellite observation systems are not capable of such high time-resolutions. Therefore, it is proposed to extend the whole methodology, so that the often much higher time resolution of measurements can be embossed to satellite data.

Corrections, which differ from season to season might lead to even better matches of satellite to ground data. A seasonal dependent correction procedure would have the advantage that incomplete measurement years might be of higher value. It is not shown, but expected by the authors that e.g. the method used in this paper leads to better results, if a single but complete year is applied than applying e.g. 1.5 years of the same quality. A correction-method, which is taking into account different seasonal characteristics, might overcome the assumed short-coming. However, such modified procedures then would be difficult to apply, if not at least one year of data is completed.

## 6. Acknowledgements

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