Site-adaptation of satellite-based DNI and GHI time series: overview and SolarGIS approach

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Abstract. Site adaptation is an approach of reducing uncertainty in the satellite-based longterm estimates of solar radiation by combining them with short-term high-accuracy measurements at a project site. We inventory the existing approaches and introduce the SolarGIS method that is optimized for providing bankable data for energy simulation in Concentrating Solar Power. We also indicate the achievable uncertainty of SolarGIS model outputs based on site-adaptation of projects executed in various geographical conditions.

INTRODUCTION

Solar resource (Direct Normal Irradiance, DNI, and Global Horizontal Irradiance, GHI) is needed for accurate planning, engineering and financing of a solar energy project. Solar resource (solar radiation) may change dramatically over a distance of few kilometres, especially close to sea and large water bodies, urbanized and industrial areas, in the mountains and in fast-changing geography. Due to year-by-year weather variability, a longer history of measurements is needed.

Solar resource data is required for various sites, but **meteorological stations** accurately measuring solar resource over a longer time are just few. The historical data are therefore acquired by the use of solar models that read inputs from geostationary satellites and atmospheric databases.

The accuracy of state-of-the-art **satellite-based models** is acceptable for design and financing of small and medium size solar power systems, while for larger solar power plants, a good practice is to start running solar measurement campaign at the site of interest, in parallel already with the project development and construction. The meteorological station at (or nearby) the project site provides detailed and accurate solar resource data, which is than used for improved characterisation of historical solar resource computed by models. Operation of solar models in real time provides systematically updated data that can be compared value-by-value with local ground measurements. In general, the **modern solar resource data** should have the following **attributes**:

- *Site-specific*: they should represent the exact geographical conditions of the site of interest. It is to be noted that any interpolation or approximation by the measurements form a nearby station are not acceptable for solar resource assessment of large solar power projects;
- *Climatologically representative*: the data should cover long period of time;
- *Systematically updated*: by continuous measurement and computation.

The satellite-based models and high-accuracy ground measurements fulfil the requirements above, and a combination of both approaches is used as an industry standard for achieving bankable solar resource assessment of large-scale solar power projects.

For the mathematical procedure, combining ground measurements with modelled data, various terms are used: (i) correlation of the ground-measured and modeled data; (ii) calibration of the solar model (its inputs and parameters) or (iii) site adaptation of satellite data (satellite model). The third term “site adaptation” is more general and best explains the concept of adapting the content of the satellite-based data (by correlation, calibration, fitting, recalculation) to the local measurements. Therefore, we prefer using the term “**site adaptation**”.

This publication has three objectives: (i) to provide an inventory of existing approaches for site adaptation of satellite-based DNI and GHI time series (ii) to present the SolarGIS method optimized for providing data for energy simulation in Concentrating Solar Power (CSP) and (iii) to generalize our experience about achievable uncertainty from many site-adaptation projects done in various geographical conditions, worldwide.

REQUIREMENTS FOR THE GROUND MEASUREMENTS AND SATELLITE DATA

Successful site adaptation requires two components: accurate ground measurements and satellite data. Both data sets should be collected at the same site (or nearby) and should follow the minimum standards mentioned below.

Ground Measurements

To achieve accurate results, the solar measurements should be acquired by high-standard sensors:

- First class **pyrheliometers** for Direct Normal Irradiance (DNI);
- Secondary-standard **pyranometers** for Global Horizontal Irradiance (GHI) and Diffuse Horizontal Irradiance (DIF).

As an alternative to pyrheliometer, a **Rotating Shadowband Radiometer** (RSR) instrument can be used, as it offers more robust measurements in harsh environments, where daily maintenance cannot be guaranteed. A trade-off is higher uncertainty of the measured data. It is good practice to use instruments in a combination so that measurements can be acquired at least for two parameters and the internal consistency test can be performed.

Use of the state-of-the-art instruments does not alone guarantee good results. All measurements are subject to uncertainty and the information is only complete, if it is accompanied by a statement of the associated uncertainty. Sensors exhibit different specific features that must be considered, and appropriate correction techniques must be applied to obtain correct results. Errors of the measuring equipment come from the **instrument** itself (cosine and azimuth effects, temperature response, spectral sensitivity, stability, non-linearity) or from the whole **system setup** (sun tracking or shade-ring misalignment, instrument levelling, cabling, data logging and problems in data transfer or storage). In addition, **operation related problems** (dust, snow, water droplets, frost, bird droppings, shading by surrounding structures or vegetation, mechanical or electrical field effects, system shutdowns) are sources of errors that have to be considered.

Therefore, prior to further processing, the ground-measured irradiance has to be quality-assessed. Quality assessment (QA) tests are described in number of publications, e.g. in [1, 2]. In QA, two types of tests are run: (i) first, the automatic tests are run to identify the obvious issues by set of numerical criteria; next (ii) the visual inspection is used to identify issues, which are of more complex nature and difficult to describe by general numerical criteria. Visual inspection is time-consuming process requiring experienced operator.

The **automatic QC tests** include:

- Identification of missing values;
- Identification of time shifts;
- Evaluation of measurements against sun position (Sun below and above horizon);
- Comparing the data with possible minimum and maximum irradiance limits;
- Evaluation of consistency of GHI, DIF and DNI by comparing the redundant measurements.

The **visual quality control** aims to identify and flag the following erroneous patterns:

- Shading from nearby objects (near shading) or mountains (far shading);
- Regular data error patterns;
- Sensor calibration issues;
- Irregular anomalies.

Data readings not passing QA tests are flagged and excluded from further analysis. The data that pass are aggregation into hourly time step.

Important is length of ground measurements: optimally, the data should be measured for a period of at minimum 12 months. In case of a tight time schedule, a shorter period (9+ months) may be considered for the preliminary site-adaptation, however such data may not cover all seasonal deviations. Data covering a shorter period (e.g. 3 to 6 months) may provide false indication of the relationship between satellite data and local measurements.

The **time series acquired by ground sensors** should have the following parameters to be considered for site adaptation of satellite data:

- Time resolution: 1 to 10 minutes (hourly resolution may hide some of the measurements issues);
- Data from two or more high-standard instruments should be available (for quality assessment and redundancy tests);
- Time series should cover at least one year, optimally several years of data should be available.

Satellite Data

In solar resource assessment, by satellite data we consider an output of a solar model that uses high resolution satellite images, aerosols, water vapour, terrain and other data on the input to calculate historical and recent time series of primary solar resource parameters: DNI and GHI. Other parameters (diffuse, tilted, irradiance, etc.) can be derived from the primary ones.

The **satellite-based time series** should have the following **features** (Table 1):

- Time series should represent the exact site of interest;
- Time resolution: 15 or 30 minutes (determined by the satellite scans);
- Spatial resolution: typical grid cell size is 3 to 5 km (determined by the satellite grid cell); this resolution can be enhanced by the use of high-resolution terrain data. Spatial resolution of atmospheric data is lower;
- The time series should cover, optimally, the history of recent 10 to 20 years.

In industry, often a term *satellite data* is used although it is clear that the modelling procedure includes also the use of other data, such as: aerosols, water vapour, terrain and others. Therefore we keep this convention.

Optimally the satellite data should be computed from atmospheric inputs with high frequency of update (e.g. daily); the reason is that as aggregation to monthly values reduces important short-term variability.

In this paper SolarGIS satellite-based model is used. The modeled time series represents up to 21 years of historical data at high spatial resolution (approx. 3 km at the equator) and temporal resolution (15 and 30 minutes). The data is accessible online [http://solargis.com], for any site on a land between latitudes 60 North and 50 South. Solar radiation is calculated by numerical models, which are parameterized by a set of inputs characterizing the cloud transmittance, state of the atmosphere and terrain conditions. A comprehensive overview of the SolarGIS model is made available in [3, 4]. The related uncertainty and requirements for bankability are discussed in [5, 6].

TABLE 1. Input data used for the SolarGIS solar radiation model (example of Stellenbosch, South Africa)

Inputs into the SolarGIS model	Source of input data	Time representation	Original time step	Approx. grid resolution
Cloud index	Meteosat MFG (PRIME) satellites (EUMETSAT)	1994 to 2004	30 minutes	3.0 - 3.1 km
	Meteosat MSG satellites (EUMETSAT)	2005 to present	15 minutes	3.6 - 3.8 km
Atmospheric Optical Depth (aerosols)	MACC (ECMWF)	2003 to present	6 hours (monthly averages for a period 1994 to 2002)	85 and 125 km
Water vapor	CFSR/GFS (NOAA)	1994 to present	1 and 3 hours	35 and 55 km
Elevation and horizon	SRTM-3 (SRTM)	-	-	250 m
SolarGIS primary data outputs (GHI and DNI)	-	1994 to present	15 minutes	250 m

MISMATCH BETWEEN SATELLITE AND MEASURED DATA

The fundamental difference between a satellite observation and a ground measurement is that signal received by the satellite radiometer integrates an area (a footprint of visible and infrared channels in the satellites represents an area of about 3.0 to 4.5 km, in semi-desert and desert climate) while a ground station represents a pinpoint measurement. This results in a mismatch when comparing instantaneous values from these two observation instruments, mainly during intermittent cloudy weather and changing aerosol load.

Nearly half of the hourly Root Mean Square Deviation (RMSD) for GHI and DNI can be attributed to this mismatch (value at sub-pixel scale), which is also known as the "**nugget effect**" [7]. The satellite grid cell is not capable describing the inter-grid-cell variability in complex regions, where within one grid cell diverse natural conditions mix-up (e.g. fog in narrow valleys or along the coast). In addition, the coarse spatial resolution of atmospheric databases such as aerosols or water vapour is not capable to describe local patterns of the state of atmosphere (Table 1).

Especially DNI is strongly sensitive to variability of cloud information, aerosols, water vapour, and terrain shading. The relation between uncertainty of global and direct irradiance is nonlinear. Often, a negligible error in global irradiance may have high counterpart in the direct irradiance component. This is not the case of analyzed local measurements.

Even the best-available satellite-based solar radiation data have imperfections given by limitations of the input data and the underlying models:

1. **Input data**: Main inputs influencing the accuracy of solar radiation modelling are satellite images from geostationary satellites used to analyse cloud dynamics and other atmospheric data (aerosols, water vapour). Accuracy of input data is mainly determined by the (i) underlying measuring or modelling techniques and (ii) by the their spatial and temporal resolution.
2. **Solar models**: Even the best available solar models have limits determined mainly by their capacity to capture extreme effects, such as low sun angle, extremely high aerosol load, specific types of cloudiness, high reflectance surfaces. The operational satellite-based models may not able to capture high-frequency dynamics of clouds at a local scale.

As a result, a systematic deviation between satellite data and ground measurements is observed, driven by the ability of models to correctly simulate the following factors:

- **Aerosols**: systematic deviation of aerosols in a location of interest occurs frequently, given the fact that grid cell in the atmospheric data represents a coarse region (e.g. 85 or 125 km in case of MACC-II data [8, 9]). Often a grid cell of aerosol data integrates very heterogeneous geographical landscapes (seas, land, urbanisation, forest, mountains). The ability of aerosol models to represent complexity of atmospheric aerosols is limited.
- **Clouds**: systematic under- or overestimation of cloud attenuation effect can occur in deserts, complex terrain, along the land/water boundary, or during specific cloud situations (thin high clouds). In deserts, high-reflectance areas (e.g. dry salty lakes) may contribute to high systematic error. In complex mountains, and in period of low sung angle, the frequency of changes of cloud patterns and related shading effects, may not be captured accurately in the cloud models.
- **Water vapour**: similarly to aerosols, imperfection and low resolution of water vapour data contributes to systematic deviations. Yet, the sensitivity of DNI and GHI to the imperfections of water vapor data [10, 11] is lower compared to aerosols.
- **Terrain**: systematic errors may originate also from terrain shading and steep elevation changes. These errors can be eliminated to a large extent by implementation terrain correction algorithm in the satellite model by (see [12]).

The mismatch between satellite data and ground measurements may be partially attributed also to the **insufficiencies of ground measurements**. Even after quality assessment and flagging of erroneous measurements, some residual issues exist in the measured data (such as slight miscalibration or misalignment of the instrument). These issues together with nominal instrument uncertainty form measurement uncertainty. **Methods of site-adaptation are based on the assumption that the measurement uncertainty is substantially lower than the uncertainty of satellite data.** This condition can be fulfilled only with ground-measured data collected by high quality instruments during measurement campaign following high standards of operation and maintenance.

Above-mentioned limitations of both measurement and modelling approaches result in the occurrence of systematic and random deviations when satellite-based data are compared to ground observations. Deviations in the satellite data, which have systematic nature, can be reduced by site adaptation methods.

METRICS TO EVALUATE SUCCESS OF SITE ADAPTATION

For site-adaptation to be successful, there must exist a systematic difference between satellite and measured data. Systematic difference can be stable over the year or it can slightly change seasonally or during the certain meteorological conditions (e.g. typical cloud formation during a day). The data analysis should distinguish systematic differences from those arising at occasional events, such as extreme sand storms or forest fires. Such episodically occurring differences may mislead the results of adaptation, especially if short period of ground measurements is only available.

For the assessment of the enhancement procedures, the following metrics is used [13]:

- Metrics based on the comparison of the all pairs of the hourly daytime data values: Mean Bias, and Root Mean Square Deviation (RMSD), histogram, in an absolute and relative form (divided by the daytime mean DNI values);
- Metrics based on the difference of the cumulative distribution functions: KSI (Kolmogorov-Smirnov test Integral).

The normalized KSI is defined as an integral of absolute differences of two cumulative distribution functions *D* normalized by the integral of critical value $a_{critical}$:

$$KSI\% = \frac{\int_{x\,min}^{x\,max} D_n dx}{a_{critical}} * 100$$

$$a_{critical} = V_c * (x_{\max} - x_{\min})$$

$$V_c = \frac{1.63}{\sqrt{N}}, \quad N \geq 35$$
,

where critical value depends on the number of the data pairs N. As the KSI value is dependent on the size of the sample, the KSI measure may be used only for the relative comparison of fit of cumulative distribution of irradiance values.

METHODS

Two approaches exist for the adaptation of satellite data to the conditions represented by the ground measurements:

- Adaptation of satellite-based GHI and DNI values,
- Adaptation of the input parameters and data used in the solar radiation model.

Adaptation of Satellite-based GHI and DNI Values

This approach is good enough if only small and stable deviations occur. It has unreliable performance if large inconsistencies between ground measured and satellite-based data exist. Site-adaptation can be realized using GHI or DNI with daily or hourly aggregation. In general, methods using daily data are less accurate compared to the use hourly data. Two methods can be used:

1. *Ratio method*: This method is easy to manage, but it only removes mean bias, the distribution of values will be changed only uniformly over the whole range of values.
2. *Fitting cumulative distribution function* improves the local accuracy of the satellite-based data by reduced mean bias, RMSD and KSI. This method is more accurate compared to the ratio method, as it improves also representation of typical and extreme situations.

The **ratio method**, known also as rescaling method (Method 1), re-calculates DNI and GHI long-term monthly and annual averages by simple correction of bias (systematic deviation). It was used e.g. by [14]. The method is based on the calculation of ratios of the measured and satellite-derived solar radiation for the overlap period between measured and satellite data. In a second step, these ratios are applied to calibrate the long-term satellite dataset to the short-term ground measurements. This method is easy to manage, but it only removes mean bias, and does not enable to benefit from a complete information potential of the ground-measured data. Another disadvantage is separate treatment of DNI, DIF and GHI values, which may lead to discrepancy of irradiance components, if the deviation is too large. Variation of this method is linear fitting, where in addition to scale (ratio) also data offset is calculated. This method must be used with care as it can result in negative irradiance values that must be subsequently resolved.

Site adapted time series can be produced by **fitting cumulative distribution function** (Method 2) of the satellite-based DNI and GHI to cumulative distribution function derived from the ground measurements [15]. For the period with overlap of ground measured and satellite data, frequency distribution of the ground-measured data is derived and considered as a reference, to which frequency distribution of satellite-based data is adapted. Mean value of satellite data is also adapted to the mean value of ground-measured data. RMSD between ground-measured and the original satellite values are most often reduced.

This method is mentioned also in [16]. It can be also characterized as a post-processing (adaptation) of already computed GHI and DNI data. The post-processing improves the local accuracy of the satellite-based data in all three aspects (reduced mean bias, RMSD and KSI), however the resulting time series may suffer from inconsistencies between GHI, DNI and DIF components, regardless whether they are statistically harmonised.

Adaptation of Input Parameters of Solar Radiation Model

This approach is based on the adaptation of the parameters or inputs to the solar model. Two methods can be mentioned:

3. A simplified version of this approach is based on *adaptation of clearness index*. Clearness index integrates all properties of the atmosphere attenuating solar irradiance in one number: in other words effects of aerosols, water vapour and clouds are not separated from each other. This correction may be applied to high frequency data (hourly or sub-hourly) or to daily data.
4. Methods based on *adaptation of the model input data* (Atmospheric Optical Depth, Water Vapour and/or Cloud Index) and control parameters of the satellite model with subsequent recalculation of the model, which result in more accurate and consistent GHI and DNI parameters. Hourly (or sub-hourly) data are typically used. If good-quality DNI measurement exists, this is typically used as the principal parameter for site adaptation.

Adaptation of clearness index (Method 3) approach is similar to the Method 1, as it aims to reduce mean bias, RMSD and KSI (difference between frequency distributions). However, the focus is on site-adaptation of the determining model inputs − in this case clearness index. The method consists of three steps:

- Using solar radiation model, the primary model input parameters are derived from the ground measurements. In this case *clearness index* is considered (defined as the ratio of the surface radiation and the corresponding top of the atmosphere radiation);
- Calibration/correlation of the input parameters – in this case *clearness index* − by a least-square regression (or similar method) of hourly (or daily) difference between the input parameters derived from the ground measurements and the corresponding satellite-based parameters;
- Recalculation of GHI, DIF and DNI, with the solar model using site-adapted inputs.

The site-adaptation can consider hourly or daily values. Wey et al. [17] propose to use daily values of clearness index. As the DNI and GHI components are treated separately an inconsistency in adapted components may arise.

Adaptation of the model input data (Method 4) uses the same three steps as in Method 3, just in the first step clearness index is substituted by more complex parameters, such as *Aerosol Optical Depth* and/or *Cloud Index*, as the key analytical data inputs. Cebecauer et al. [18] demonstrated procedure, which used hourly satellite data and daily aerosol (AOD) values. In this case the model is completely recalculated thus the consistency of GHI, DNI and DIF components is maintained.

In semi-arid and desert conditions, clouds are of relative low importance and it is mainly AOD, which determines the mismatch between ground-measured and satellite data. However, AOD has strong non-linear effect, especially on the DNI output. Therefore more accurate results (reduction of RMSD and KSI) can be achieved in the second step (mentioned in Method 3, and valid also for Method 4), especially when adaptive weighting to different ranges of AOD values is considered. For example extreme episodes of AOD are adapted with different weight compared to typical or very low values. This method also allows removing specific seasonal problems in AOD description that are common in some regions. This procedure is delicate and good results can be only achieved if the expert fully understands the underlying physics and its impact on the results.

As a result of this approach, mean bias stays close to zero (typically within ±1% of the ground measurement), thus it correspond to the expected uncertainty of the measuring instruments. If procedure is successful, RMSD and KSI parameters should be also reduced. The graph shown in Figure 2 is used for a visual control of results.

Comparison of Methods

Methods 1 and 2 are statistical, and have limited capabilities compared to Methods 3 and 4. A disadvantage of the above-mentioned methods is a separate treatment of DNI and GHI values which may lead to discrepancy between irradiance components, unless they are statistically harmonized (which is not a trivial task). However, they do not require use of any special algorithms. If high quality data is used, Method 2 gives better results over Method 1. Good results can be achieved only for satellite data with small differences to ground measurements.

Method 3 does not have capability of specific treatment of atmospheric attenuation factors. If applied on daily basis, can relatively well preserve the shape of diurnal profiles, but unlike Method 4 it does not preserve consistency between GHI and DNI components. Method 3 requires tools for solar radiation calculation, especially for sun geometry.

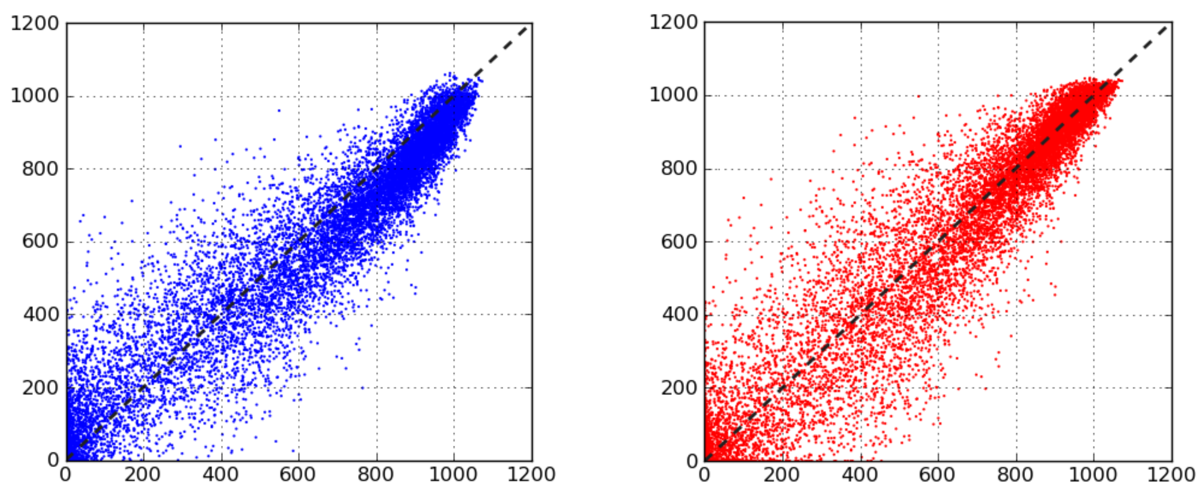
Method 4 is the most accurate if run by knowledgeable expert. Its advantage is preserving consistency of GHI and DNI components for high frequency data (hourly or sub-hourly). However it requires a full computational chain of the satellite model, and can be run only by the satellite data supplier. This method is highly adaptive and if run by experienced professional it yields the most accurate results. To be applied appropriately a more knowledge is needed and specific computational tools must be used. This method can be used in combination with other methods. In such a case, Method 4 is used for correction of main sources of discrepancies (such as limitations in aerosol description) and small residual deviations are removed in the next step by one of the simpler statistical Methods 1 or 2.

SOLARGIS APPROACH - EXAMPLE

Site adaptation by a combination of Methods 4 and 1 is shown on an example of Stellenbosch site in South Africa (Source:, STERG, University of Stellenbosch):

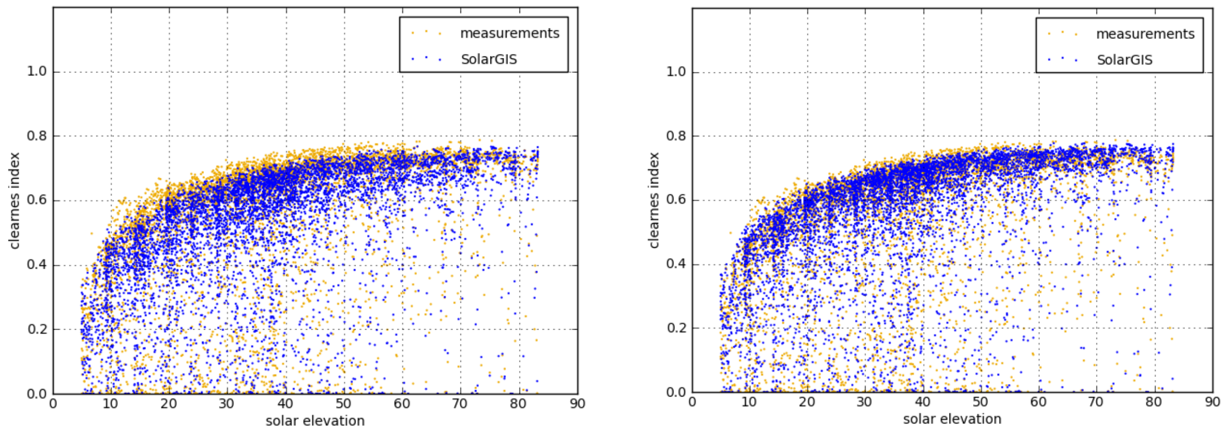
- The ground measurements, which passed the quality assessment, were used for adaptation of the aerosol data (Method 4). Based on the adapted aerosol data, DNI and GHI was recomputed by the site-adapted SolarGIS model scheme.
- In the second step the DNI and GHI values were corrected for discrepancies in the cumulative distribution of values and residual bias of approximately 1% has been removed by Method 1.

Preliminary inspection of the original SolarGIS satellite data indicates slight underestimation of Direct Normal Irradiance (Figure 1 left). The site-adapted values better represent the local conditions and show improved distribution and match of individual pairs of values (Figure 1 right).



Original DNI DNI after adaptation

FIGURE 1. Correction of SolarGIS DNI hourly values (Stellenbosch, South Africa).
Left: original, right: site-adapted data. X-axis represents the measured DNI, Y-axis the satellite-derived DNI.



Original DNI DNI after adaptation

FIGURE 2. Clearness index vs. solar elevation for original and site-adapted SolarGIS DNI (Stellenbosch, South Africa). Left: original, right: site-adapted data.

Figure 2 shows a comparison of the DNI hourly values in two-dimensional space described by the DNI clearness index and sun angle. A fit between measured (yellow) and satellite-adapted values (blue) demonstrates that the site-adapted satellite-derived hourly values very well match the distribution of the ground-measured values for all types of weather conditions for the range of sun elevation angles 5 degrees and higher. The plot on the left shows, that also original SolarGIS data are capable to represent various solar radiation situations: this is a result of the use of daily aerosol data controlling majority of variability during cloud-less situations.

Table 2 documents the accuracy gain of site-adaptation is documented by statistical measures, which show improvement in all aspects.

TABLE 2. Comparison of the original satellite-derived DNI and GHI with the site-adapted values. The daytime irradiances are assumed only (Stellenbosch, South Africa).

	Bias		RMSD hourly	RMSD daily	RMSD monthly	KSI
	[W/m^2]	[%]	[%]	[%]	[%]	[-]
DNI original	-16	-3.0	24.2	17.8	6.3	266
DNI site-adapted	0	0.0	24.1	16.5	3.1	31
GHI original	5	-1.0	10.5	4.8	2.2	45
GHI site-adapted	0	0.0	10.4	4.5	1.5	10

UNCERTAINTY OF SITE ADAPTATION

Combining high-quality ground measurements and satellite data can result in significant reduction of uncertainty of the DNI and GHI estimates. The results from South Africa confirm our experience from site-adaptation of sites across all continents.

Figure 3 generalizes this experience and indicates how the uncertainty of the SolarGIS DNI and GHI yearly estimates can be reduced by having several years of ground measurements. Site adaptation, based on accurate and quality-controlled ground measurement may provide historical time series, where uncertainty of longterm values is close to the uncertainty of measuring instruments.

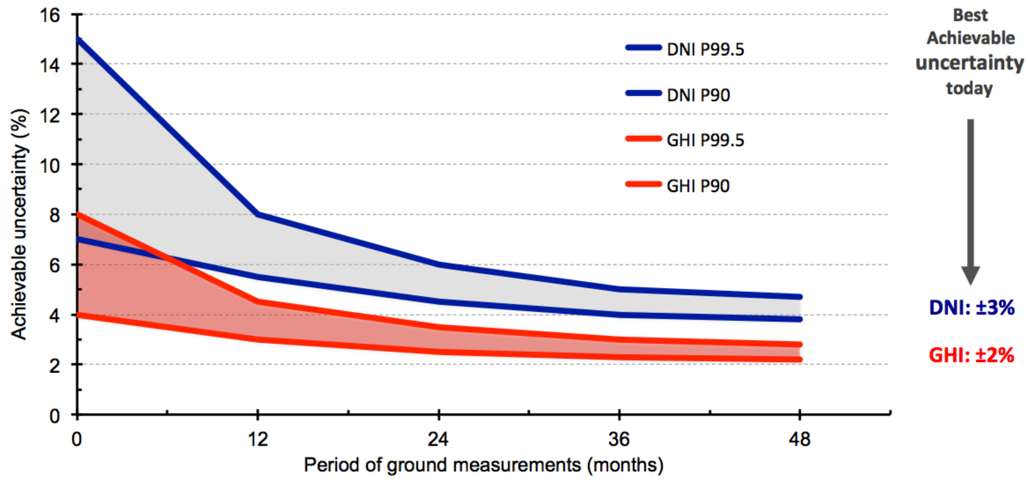


FIGURE 3. Potential of reducing uncertainty of yearly GHI and DNI estimates by SolarGIS approach (values are indicative)

In general, the uncertainty of the resulting data depends on:

- Accuracy and quality of ground and satellite data (assuming rigorous quality control of both data sets)
- Length of ground measurements (2 to 3 years are optimal)
- Magnitude and type of systematic deviation between ground and satellite data
- Applied method and experience of the expert.

It is expected that systematic uncertainty of site-adapted yearly DNI value remains by about ±1% to ±3% higher than the uncertainty of the ground measurements. In case of GHI, it can be expected that the residual uncertainty relative to the uncertainty of the instrument remains higher − in the range from ±0.5% to ±1.5%. Thus, for example, if uncertainty of pyrheliometer is assumed to be in the range of ±2%, the uncertainty of annual DNI value, after site-adaptation by the best method and using 3 years of measurements, could stay ±3.5%.

DISCUSSION

The site-adaptation methods are used to adapt satellite-derived DNI and GHI to the local climate conditions. Site adaptation is effective for mitigating *systematic* problems in the satellite-derived data, such as under/over-estimation of local aerosol loads, especially when the magnitude of this deviation is invariant over the time or has a seasonal periodicity. It is to be noted that presence of *non-systematic deviations* or use of *less accurate ground data* may lead to accuracy degradation of the primary satellite-derived dataset. This strengthens even more the importance that must be absolutely given to keeping of the best possible quality of in-situ measurements.

The most accurate is the method based on the adaptation of the model input data, namely *AOD* (Method 4), especially if larger differences exist. If complete solar modelling tools are not available, than simplified correction of *clearness index* (Method 3) or ratio and fitting methods (Methods 1 and 2) can be used.

The higher deviation between satellite and ground data, the more problematic result can be achieved, especially with Methods 1 to 3. If the differences are larger (bias is higher than 4% for GHI and 7% for DNI) the use of simple methods may introduce strong inconsistencies into the results. If only small differences are to be corrected (bias up to 2 to 3% and only small difference in the distribution of values) all methods may provide satisfactory results.

If more ground-measured data is available in a region, site-adaptation can be extended into a regional model adaptation [19].

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