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Long term satellite global, beam and diffuse irradiance validation

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Abstract
In the field of solar energy applications, the use of geostationary satellite images becomes crucial, since they allow the retrieval of irradiance at the surface, with the best possible spatial and temporal coverage. This study, conducted on data from 18 European and Mediterranean sites, over 8 years of data shows that it is now possible to retrieve hourly global and beam irradiance data with a low uncertainty, typically 17% for the global, and 34% for the beam component, with a negligible bias.

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1. Introduction

Meteorological satellite images as data sources to evaluate the ground irradiance components become the state of the art in the field of solar energy systems. The strongest argument is the high spatial coverage, and the fifteen minutes temporal granularity. They also have the advantage to provide «real time» data used for example to assess the proper operation of solar plants. On the other hand, long term ground data are very scarce concerning the beam irradiance. The use of auxiliary inputs such as polar satellite data and ground information increases significantly the precision of the algorithms, mainly for the beam component. Following a paper from Zelenka [1] concerning the nuggets effect, the interpolation distance to the nearest ground measurement site is limited to 10 to 30 km, depending on the irradiance parameter; this strengthens the satellite derived data argument.

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Many Universities and private companies provide satellite derived data, freely or for pay, in “real time” or averaged over the last 8 years (Meteosat second generation is operational since 2004), and integrated over different time ranges. We choose six European data products to conduct a long term validation against ground measurements for both the global and the beam components. The study is based on hourly, daily and monthly values.

2. Ground data

Data from eighteen ground stations are used for the validation, with up to 16 years of continuous measurements; for the validation itself, due to the satellite variability, only data from 2004 to 2011 are used. The data acquired before the reference period are used to evaluate the interannual variability. The list of the stations is given in Table 1, with their characteristics. The climate range covers desert to oceanic, the latitude from 20°N to 60°N, and the altitudes from sea level to 1580 meters.

<table>
<thead>
<tr>
<th>Site</th>
<th>$G_{0}$</th>
<th>$B_{0}$</th>
<th>$D_{0}$</th>
<th>latitude</th>
<th>longitude</th>
<th>altitude</th>
<th>climate</th>
<th>network</th>
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<tbody>
<tr>
<td>Almeria (Spain)</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>37.092</td>
<td>-2.364</td>
<td>491</td>
<td>dry, hot summer</td>
<td>PSA</td>
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<tr>
<td>Bratislava (Slovakia)</td>
<td>x</td>
<td>x</td>
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<td>17.083</td>
<td>195</td>
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<td>CIE</td>
<td></td>
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<tr>
<td>Carpentras (France)</td>
<td>x</td>
<td>x</td>
<td>44.083</td>
<td>5.059</td>
<td>100</td>
<td>mediterranean</td>
<td>BSRN</td>
<td></td>
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<tr>
<td>Davos (Switzerland)</td>
<td>x</td>
<td>x</td>
<td>46.813</td>
<td>9.844</td>
<td>1586</td>
<td>alpine</td>
<td>PMO/SLF</td>
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<td>x</td>
<td>46.199</td>
<td>6.131</td>
<td>420</td>
<td>semi-continental</td>
<td>CIE</td>
<td></td>
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<td>x</td>
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<td>9.478</td>
<td>173</td>
<td>temperate humid</td>
<td>FhG</td>
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<td>x</td>
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<td>GAW</td>
<td></td>
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<tr>
<td>Lindenberg (Germany)</td>
<td>x</td>
<td>x</td>
<td>52.210</td>
<td>14.122</td>
<td>125</td>
<td>moderate maritim</td>
<td>BSRN</td>
<td></td>
</tr>
<tr>
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<td>x</td>
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<td>-3.730</td>
<td>650</td>
<td>semi-arid</td>
<td>UMP</td>
<td></td>
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<tr>
<td>Nantes (France)</td>
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<td>x</td>
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<td>-1.553</td>
<td>30</td>
<td>oceanic</td>
<td>CSTB</td>
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<td>Payerre (Switzerland)</td>
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<td>x</td>
<td>46.815</td>
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<td>490</td>
<td>semi-continental</td>
<td>BSRN</td>
<td></td>
</tr>
<tr>
<td>Sede Boker (Israel)</td>
<td>x</td>
<td>x</td>
<td>30.905</td>
<td>34.782</td>
<td>457</td>
<td>dry steppe</td>
<td>BSRN</td>
<td></td>
</tr>
<tr>
<td>Tamanrasset (Algeria)</td>
<td>x</td>
<td>x</td>
<td>22.780</td>
<td>5.510</td>
<td>1400</td>
<td>hot, desert</td>
<td>BSRN</td>
<td></td>
</tr>
<tr>
<td>Toravere (Estonia)</td>
<td>x</td>
<td>x</td>
<td>58.254</td>
<td>26.462</td>
<td>70</td>
<td>cold humid</td>
<td>BSRN</td>
<td></td>
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<tr>
<td>Valencia (Ireland)</td>
<td>x</td>
<td>x</td>
<td>51.938</td>
<td>-10.248</td>
<td>14</td>
<td>oceanic</td>
<td>GAW</td>
<td></td>
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<tr>
<td>Vaulx-en-Velin (France)</td>
<td>x</td>
<td>x</td>
<td>45.778</td>
<td>4.923</td>
<td>170</td>
<td>semi-continental</td>
<td>ENTP</td>
<td></td>
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<tr>
<td>Wien (Austria)</td>
<td>x</td>
<td>x</td>
<td>48.250</td>
<td>16.367</td>
<td>203</td>
<td>continental</td>
<td>GAW</td>
<td></td>
</tr>
<tr>
<td>Zilani (Letonia)</td>
<td>x</td>
<td>x</td>
<td>56.310</td>
<td>25.550</td>
<td>107</td>
<td>cold humid</td>
<td>GAW</td>
<td></td>
</tr>
</tbody>
</table>

High precision instruments (WMO 2008) such as Kipp and Zonen CM10 and Eppley PSP pyranometers, and Eppley NIP pyrheliometers, are used to acquire the data. A stringent calibration, characterization and quality control was applied on all the data by the person in charge of the measurements, the coherence of the data for all the stations was verified by the author and is described below.

3. Satellite irradiance products

Two kinds of products are analyzed in this study:

- “real time” long term time series
- average or typical years like TMY.

The first category of data is used for specific sizing and monitoring of power plants. The data are retrieved hour by hour (or 15 minutes by 15 minutes) from the satellite, and are representative of “real” data. The products are long term time series.

The second category of data is used as input for simulation software that are too heavy to be used with long term hourly data. The set of data is a single average year, evaluated from long term time series with specific conditions and algorithms.
3.1 “Real time” irradiance models

For the «real time» comparison, six different products are validated in the present study. The methodology and the input parameters are described in the following section.

3.1.1 SolarGis (GeoModel Solar)

The irradiance components are the results of a five steps process: a multi-spectral analysis classifies the pixels, the lower boundary evaluation is done for each time slot [2], a spatial variability is introduced for the upper boundary and the cloud index definition, the Solis clear sky model [3] is used as normalization, and a terrain disaggregation is finally applied [4].

3.1.2 Heliosat-3 (MineParisTech)

The Heliosat-3 method is based upon the same physical principles than Heliosat-2 but the inputs to the method are calibrated radiances, instead of the digital counts output from the sensor. This change opens the possibilities of using known models of the physical processes in atmospheric optics, thus removing the need for empirically defined parameters and of pyranometric measurements to tune them. The ESRA models [5,6,7] are used for modeling the clear-sky irradiation. The assessment of the ground albedo and the cloud albedo is based upon explicit formulations of the path radiance and the transmittance of the atmosphere. The turbidity is based on climatic monthly Linke Turbidity coefficients data banks. The Liu and Jordan [8] model is used to split the global irradiance into the diffuse and beam components.

3.1.3 IrSOLaV

In the IrSOLaV irradiance derivation scheme, the cloud index \( n \) is derived using the methodology developed by Dagestad and Olseth [9] with some modifications in the ground albedo determination. The ground albedo is computed from a forward and backward moving window of 14 days taking into account its evolution during the day, as function of the co-scattering angle.

The global horizontal irradiance \( G_h \) is then evaluated from the cloud index with the model proposed by Zarzalejo [10]. It uses as independent variables the cloud index \( n \), the 50-percentile of \( n \) for a given place, and the air mass. The normal beam irradiance \( B_n \) is calculated from the global irradiance with the help of Louche correlation [11].

In a second step, the clear sky conditions are identified with the algorithm proposed by Polo [12,13]; for these clear conditions, the irradiances are evaluated with the ESRA clear sky model [6], using the aerosol optical depth taken from Soda, MODIS or from a method proposed by Polo [12] depending on their availability.

3.1.4 S2m Solutions [14]

The first part of the process is to run a simulation on a numerical model for global weather prediction with data from the GFS (Global Forecast System) data base. Once the raw data have been obtained, they are used as inputs for the numerical meso-scale model, WRF (Weather Research and Forecasting).

To determine beam irradiance \( (B_n) \), S2m developed an algorithm based on the Meteorological Radiation Model (MRM) with the outputs from the WRF model. One of the inputs needed is the cloud index \( n \). Although this can be obtained from numerical simulations, a different methodology based on satellite images is used to obtain it. The values are approximated by the traditional Heliosat equation.

As it has been observed that ground albedo has a seasonal change. S2m Solutions has introduced a time dependent albedo in order to improve results.
3.1.5 Heliomont (MeteoSwiss) [15]

The Heliomont method is based on the basic Heliosat method. The all sky incident surface solar radiation fluxes at the earth’s surface are calculated by combining the clear sky surface radiation fluxes from a radiative transfer model with the radiative cloud forcing derived from satellite infrared and visible data. To take into account the diurnal time scale, Heliomont calculates a diurnal course of the clear sky reflectance and the clear sky brightness temperature from cloud masked reflectance and brightness temperature values of the previous days. This also enables to account for short-term changes in surface reflectance, such as during green-up or during periods of snow fall.

The clear sky radiative transfer model [16,17] is constrained by 6-hourly total column water vapor and ozone data from the European Centre for Medium-range Weather Forecast (ECMWF) and by use of a monthly aerosol climatology [18].

3.1.6 Solemi (DLR)

For the global irradiance $G_h$, an algorithm based on the Heliosat method (Hammer et al. [19]) is implemented. Contrary to the majority of the other schemes, the beam component is directly derived from the satellite images by the method of Schillings et al. [20]. Instead of using a general turbidity index like most other procedures, each important constituent is treated separately with the help of the Bird clear sky model [21].

The atmospheric water vapor $w$ is taken from the NOAA-NCEP (National Oceanic and Atmospheric Administration - National Centers for Environmental Prediction) NCDC data (National Climatic Data Center), and the impact of aerosols is taken from NASA-GISS (National Aeronautics and Space Administration – Goddard Institute for Space Studies) GACP-data (Global Aerosol Climatological Project). From these data sets the transmission of the cloud-free atmosphere is calculated.

The cloud parameterization scheme is a two-channel procedure, which uses the visible channel of Meteosat (0.45 μm to 1 μm) and the infrared channel (10.5 μm to 12.5 μm).

3.1.7 Satel-Light

The algorithms for retrieving global irradiance $G_h$ from satellite data are based on the Heliosat method (Cano [22]) which has been enhanced in several domains (Beyer [23], Hammer [19]). The clear sky index $K$ is defined as the ratio of the surface global horizontal irradiance $G_h$ to the corresponding clear sky irradiance $G_{hc}$ as derived by Page [24] and Dumortier [25] for respectively the beam and the diffuse components. The global irradiance is then derived from the cloud index $n$ following Fontoyont [26].

In the cloudless case the diffuse irradiance can be derived from Dumortier. Skartveit and Olseth [27] suggested an all sky model for the diffuse fraction $D_G/G_h$ of hourly global radiation, assuming that the diffuse fraction depends on the clearness index and the solar elevation. An improved version of this model also accounts for the hour-to-hour variability of the clearness index [28].

3.2 Average and typical year

Average and typical years are a solution as input to simulations. These are generally obtained from 10 to 20 years of measurements, averaged and partially interpolated between stations. Some of them are corrected with the help of meteorological and polar satellite data and/or ground information.

These data, included in the comparison, are derived within the following networks, programs or software:

WRDC: the World Radiation Data Centre Online Archive contains international solar radiation data stored at the WRDC, which is a central depository for data collected at over one thousand measurement sites throughout the world (available from http://wrdc-mgo.nrel.gov/).

RetScreen: the RETScreen Clean Energy Project Analysis Software is a unique decision support tool developed with the contribution of numerous experts from government, industry, and academia. The software, provided free-of-charge, can be used worldwide to evaluate the energy production and savings, costs, emission reductions, financial viability and risk for various types of Renewable-energy and Energy-efficient Technologies (RETs, available from http://www.retscreen.net).

NASA SSE is a renewable energy resource web site of global meteorology and surface solar energy climatology from NASA satellite data on one by one degree resolution (available from http://eosweb.larc.nasa.gov/sse/).

Meteonorm (v7) is a comprehensive meteorological reference software, incorporating a catalogue of meteorological data and calculation procedures for solar applications and system design at any desired location in the world. It is based on over 23 years of experience in the development of meteorological databases for energy applications (see http://www.meteonorm.com).

ESRA: the European Solar Radiation Atlas is oriented towards the needs of the users like solar architects and engineers, respecting the state of the art of their working field and their need of precise input data. From best available measured solar data complemented with other meteorological data necessary for solar engineering, digital maps for the European continents are produced. Satellite-derived maps help in improving accuracy in spatial interpolation (see http://www.helioclim.com/esra).

For the six modeled data sets described in section 3.1, the data are either averaged into monthly values, or directly retrieved from the provider in monthly values.

![Figure 1](image-url)

Fig. 1 Daily highest value of respectively the global and the beam irradiances reported versus the day of the year for the station of Carpentras. The corresponding modified clearness index and clear sky index are also represented.

4. **Data quality control**

A stringent quality control, including time stamp of the data, absolute and relative calibration coefficient, long term stability, components coherence etc., is applied on the data.

4.1 **Sensor calibration**

The absolute sensor calibration can be verified for clear sky conditions by comparison against data from a nearby site, or with the help of auxiliary measurements. To conduct this test, for each day, the highest hourly value of \( G_h \) and \( B_n \) are selected from the measurements and plotted against the day of the year. These points are representative of the clearest daily conditions. As the highest value for each day is selected, the upper limit normally represents clear-sky conditions. For the global component \( G_h \), it happens that higher-than-clear-sky values are obtained under partly
cloudy (scattered clouds), high-sun conditions, this is why this test should not be applied for data with time granularity lower than the hour. On such graphs, data from a nearby site, evaluated from auxiliary measurements, or for different years acquired at the same site can be compared as illustrated on Fig. 1. The $G_h$ graphs can be augmented by superimposing the modified clearness index $K_t'$, which was defined by Perez et al. [29].

4.2 Components consistency

When the three components, global, diffuse and beam, are available, the closure equation (global = beam + diffuse) can be applied. Due to the measurement methods for each of the components, the strict equality cannot be verified for all the values and acceptability limits are to be defined (as for example, BSRN QC, Seri QC, etc.). An illustration of the QC applied in this study is given on Fig. 2, where the blue dots are kept, whereas the brown dots are rejected.

The consistency test between the $G_h$ and $B_n$ components can be verified with the help of the global and beam clearness indices. The hourly beam clearness index is plotted versus the corresponding global clearness index as illustrated for the site of Carpentras in Fig. 3. On the same graph, the clear-sky predictions from the Solis radiative transfer model [3] are represented for four different a priori values of turbidity.

5. Comparison indicators

The comparison is done on an hourly, daily, monthly and yearly basis, on both the global and the beam component. Four indicators are used to describe the capability of the model to represent the measurements:
The first order statistics: the mean bias ($mbd$), the root mean square difference ($rmse$) and the standard deviation ($sd$). The visualization is made with the help of scatterplots of the modeled values versus the corresponding measurements.

Comparison in terms of frequency of occurrence and cumulated frequency of occurrence: for the irradiance, it gives an indication of the repartition for each level of radiation. For the clearness index, it assess that the modeled level of radiation occurs at the right time during the day.

The second order statistics defined by the Kolmogorov-Smirnov ($KS$) test [30]. It represents the capability of the model to reproduce the frequency of occurrence at each of the irradiance level.

The distribution of the difference between the model and the measurements around the 1:1 axis for hourly values is represented in term of frequency of occurrence as illustrated on Fig. 4. On the same graph, the cumulated frequency of occurrence is also represented.

6. Interannual variability indicator

The annual global and beam irradiation values are analyzed by comparison with an average reference period covering the years 2004 to 2010. The yearly total determined by the average over the reference period is used as normalization value for the annual totals. An illustration of the method is given on Fig. 5

Fig. 5 Total annual irradiation normalized to the average annual value over the reference period (2004-2010) for the site of Carpentras.

7. Results

7.1 Quality control

The stringent application of the quality control conducted to some slight calibration adaptations and value exclusions:

- Less than 2% difference with aeronet except a 5% for the site of Tamanrasset
- 70% to 90% of the data kept after application of the closure relation (when the three components are available)
- 10% to 20% difference for Davos, Vaulx-en-Velin and Zilani on the long term stability before 2004 (not included in the hourly, daily and monthly validation)
- The data of Lerwick, even with a good closure relation, are questionable, probably due to a very high turbidity
- The clearness test on the data from Madrid shows a strange behavior that could be an issue of sensor leveling problem.
When small differences (less than 2%) are pointed out by these tests, no correction is applied. Only the 10% to 20% over- and under-estimation before 2004 are corrected. These data are only used in the interannual variability study.

7.2 Hourly, daily and monthly validation

The number of points and the irradiance/irradiation values included in the comparison are the following:

- 475,000 hourly values
  \[ G_h = 340 \text{ [W/m}^2\text{]} \]
  \[ B_n = 350 \text{ [W/m}^2\text{]} \]
  \[ D_h = 135 \text{ [W/m}^2\text{]} \]

- 43,000 daily values
  \[ G_h = 3.69 \text{ [Wh/m}^2\text{ day]} \]
  \[ B_n = 3.78 \text{ [Wh/m}^2\text{ day]} \]
  \[ D_h = 1.46 \text{ [Wh/m}^2\text{ day]} \]

- 1,500 monthly values
  \[ G_h = 108 \text{ [Wh/m}^2\text{ month]} \]
  \[ B_n = 110 \text{ [Wh/m}^2\text{ month]} \]
  \[ D_h = 43 \text{ [Wh/m}^2\text{ month]} \]

The number of ground or satellite derived values differ from one site to the other; the covered periods are not always of the same length.

The general observation is that the global is retrieved with a negligible bias and a standard deviation ranging from 17% to 24% (57 to 81 [W/m²]), the beam component from 34% to 49% (119 to 174 [W/m²]) with a -10% to +12% bias, and the diffuse from 35% to 58% (57 to 81 [W/m²]) with a bias from -16% to 23%.

Fig 6. \( K_b \) versus solar elevation. Clear sky input: left: monthly turbidity values, right: daily turbidity values

SolarGIS method gives the best performance in term of bias and standard deviation for the global and beam components. The observation of the clearness index plotted against the solar elevation shows that this good performance is the result of the use of daily turbidity values instead of monthly climatological averages. This can be seen on Fig.6: on the left, monthly turbidity values, and on the right, daily turbidity values are used as input to the clear sky model. For high clearness indices, representative of clear sky values, the result of the use of monthly turbidity values can be seen by “discrete” point’s aggregations.

For the diffuse component, Heliomont presents a slightly higher standard deviation, but no bias. This can be an interesting option when diffuse irradiance is needed, as for example when evaluating the UV erythema [31].

The second observation is that all the models underestimate the beam irradiance under clear skies, and overestimate it for intermediate conditions. For clear conditions, this is due to an approximate knowledge of turbidity. In the case of intermediate cloud cover, the models do not identify with enough precision the type and thickness of the clouds.

The results are given on Fig. 7 and Table II.

7.3 Interannual variability

To conduct a significant interannual variability analysis, a long period of data is needed. These long time series have to be continuous and with no missing data. It is therefore necessary to circumvent the missing data as it is not possible to fill the gaps. The following strategy was used in the present study on a monthly basis: if the gaps’ length represents less than 10% of the month, a linear extrapolation is applied on the monthly values based on the
normalized number of hourly values aggregated in the considered month. If the gaps exceed 10%, the monthly value is replaced by the average of all the corresponding months over the considered period.

The comparison results are given in Table III. The blue columns represent the annual average and the corresponding standard deviation over the reference period 2004-2010. The results for the different products are expressed as mean bias differences; if the mbd is less than one standard deviation $sd$, the cell background is represented in green. This mbd are highly variable, even if the combined results for all sites are relatively satisfying.

### Table II

<table>
<thead>
<tr>
<th>Sites</th>
<th>Global irradiation</th>
<th>Beam irradiation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean annual bias difference</td>
<td></td>
</tr>
<tr>
<td>Yearly total [kWh/m²] 2004-2010</td>
<td></td>
<td></td>
</tr>
<tr>
<td>All sites</td>
<td>35% 0% -3% -3% -3% -3% -2% -1% 2% 0% 2% 0%</td>
<td>1383 0% 2% 0% -3% 4% 9% 3% 6% 8% 3%</td>
</tr>
</tbody>
</table>

8. Conclusions

When using solar irradiance data, satellite products are reliable if no ground site is situated in the vicinity of the considered site. They provide $G_{0s}$ at $\pm 17\%$ and $B_{0s}$ at $\pm 34\%$ with a negligible bias, on an hourly basis.

On an annual basis, the majority of the products are situated within one standard deviation $sd$ estimated on a nine year reference period (2004 to 2011).
Acknowledgements

The ground data were kindly provided by the the BSRN network, the GAW project, the CIE IDMP, the CSTB in Nantes, the UMP in Madrid, the ENTP in Lyon, the DLR (D), the FhG in Kassel, the SLF and PMOD (CH) and the SAS in Bratislava.

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References


