Evaluation of a new model to calculate direct normal irradiance based on satellite images of Meteosat Second Generation

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Abstract

We present a method to derive the direct normal irradiance DNI from MSG data. For this we apply the Heliosat method to extract cloudiness from the satellite images. Clouds are causing high fluctuations in the DNI. A new model for the direct fraction of the irradiance is introduced to calculate DNI. The clear sky irradiance is mainly determined by the aerosol optical depth (AOD) and water vapour content, which are taken from suitable climatologies. The accuracy of satellite derived DNI data is analyzed here for Spanish sites.

1. Introduction

Measurements of the direct normal irradiance DNI are needed for the planning of a solar thermal power plant at a given site. Direct solar irradiance is highly variable in space and time. As ground measurements are expensive, such data are rare.

Meteorological satellites operationally scan the Earth's surface and clouds. So we can derive the direct normal irradiance from their data with a good spatial and temporal coverage. Since 2004, the satellites of the new generation MSG provide images of Africa and Europe every 15 minutes with a spatial resolution of approximately 1 km x 1 km at sub-satellite point.

In this document, we first present a method to derive the direct normal irradiance DNI from MSG data. A new model for the direct fraction of irradiance is used in combination with the Heliosat method applied to MSG data. In a second step we analyse the accuracy of the satellite derived DNI with ground measurements of six Spanish sites.

2. Direct Normal Irradiance from Satellite VIS Images

The calculation of the direct normal irradiance is performed in different steps. In a first step cloud information is derived from the satellite measurements using an enhanced version of the Heliosat method [1]. As a measure of cloudiness a dimensionless clear sky index k* is derived. Using a clear sky model the global irradiance is immediately related to the clear sky index, while our new beam fraction model allows for calculating the DNI. Fig. 1 represents the necessary process steps, which are described in this section.

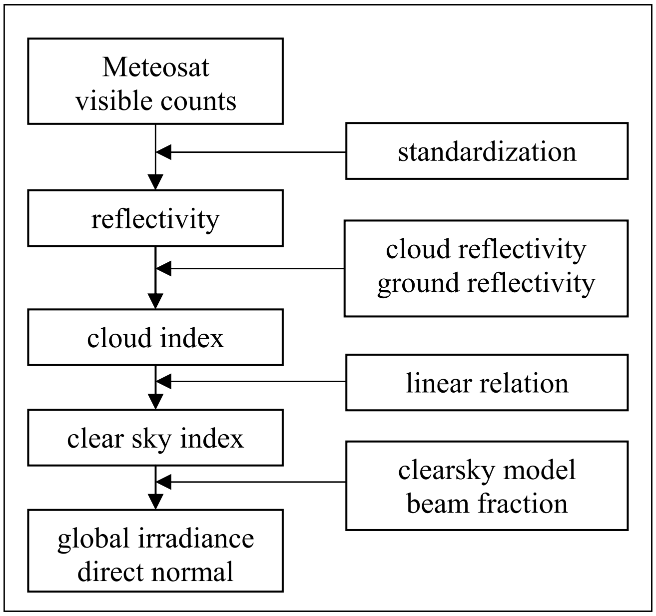

Fig.1: Significant process steps of the Heliosat method.

2.1. Heliosat Method

The Heliosat method is a technique of determining the global radiation at the ground by using data from a geostationary satellite.

In the Heliosat method it is assumed that the intensity of the visible solar irradiance which is scattered back to the satellite from the Earth and the atmosphere, behaves proportional to the atmospheric reflection. Also the isotropy of the atmospheric reflection is suppositional in order to disable the influence of the atmosphere's heterogeneity on the reflection properties.

Due to the dominating dependence of the reflection on the cloudiness, it is feasible to derive an important quantity characterizing the degree of cloudiness existing within a solid angle from the radiation measured by the satellite. Via this quantity it is possible to deduce the transmission properties of the atmosphere and then determine the global irradiance.

2.1.1 Standardization

The satellite measures the sunlight in the visible spectral region reflected by the earth. Hence the measurement signal depends on the irradiation hitting the reflecting layers. After subtraction of the radiometer offset C_o the remaining Count behaves proportionally to the irradiance I. Under utilization of these proportionalities the relative reflectivity ρ can be defined as standardized backscattering value:

$$\rho := C\text{-}C_o / I. \tag{1}$$

In the following only relative differences not absolute values of the reflecting properties are important therefore it is sufficient to divide by the cosine of the sun zenith.

2.1.2 Cloud Index

The standardized backscattering values of clouds usually exceed those of the Earth's surface, excluding the case of snow. Thus it is possible to identify the occurrence of clouds. If the reflectivity for a completely cloudy pixel ρ_c and the reflectivity of the unclouded ground (and ocean respectively) ρ_g is known, the cloud index n as a degree of cloudiness can be defined as

$$n = (\rho - \rho_g)/(\rho_c - \rho_g). \tag{2}$$

If the maximum and minimum of the standardized backscattering values of a pixel is selected as reference values, the Cloud index takes values in the range of $0<=n<=1$.

2.1.3 Reference values for ground reflectivity

In order to calculate the ground reflectivity ρ_g, in an iterative procedure values larger than the mean value of the distribution plus σ_g are filtered out, until convergence is achieved. The mean value of the new distribution is assigned to ρ_g.

In the original Heliosat method a constant value σ_g was used, $\sigma_g = 27$ is a suitable value for MSG. But an approach that accounts for the dependency of σ_g on the sun-satellite geometry leads to even better results. The bias of the clear sky irradiance is used as a measure to quantify the influence of σ_g. For clear sky situations, the quality of the ground reflectivity can be evaluated directly and there is little super imposition with other effects. If σ_g is chosen too small, the corresponding values of the ground reflectivity will be too small as well. This results in an underestimation of the irradiance. On the other hand, if σ_g is too high, an overestimation of the irradiance is the consequence. Best results were found for $15<=\sigma_g<= 50$ for different classes of solar and satellite zenith angles and the azimuth angle between sun and satellite.

2.1.4 Reference values for cloud reflectivity

The cloud reflectivity ρ_c also depends on the sun-satellite geometry. Therefore, different values of ρ_c are calculated using histograms of reflectivity values for classes with similar geometric configurations. Fig. 2 illustrates the approach to assign the cloud reflectivity to each class: The measured histogram is fitted by a superposition of two functions, the first is representing the ground reflectivity distribution fit_{ground} and the second the cloud reflectivity distribution fit_{cloud}. As cloud reflectivity we chose a value close to the reflection point $(\rho_{cloud} , a*max(fit_{cloud}))$.

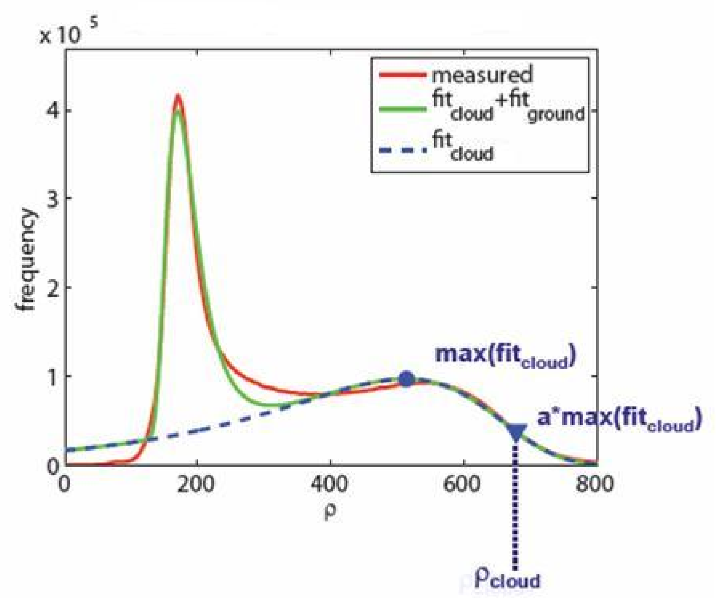

Fig. 2: Representation of the measured reflectivity distribution for one class of geometry (red line) by a superposition of two fit functions (green line). The fit representing the cloud reflectivity is illustrated by the dashed blue line. As cloud reflectivity we choose ρ_{cloud} which is a value close to the reflection point.

2.1.5 Relation between cloud index and clear sky index

The clear sky index is an appropriate and thus an established quantity for the description of the transmission properties of the Earth's atmosphere.

It is defined by

$$k^* = I_g / I_{clear} \tag{3}$$

where the current global radiation I_g is related to the expected clear sky radiation I_{clear}. In addition a model is needed, which describes the atmospheric conditions, a so called clear sky model, see sec. 2.2.

[Beyer et al. 96] introduced the relation

$$k^* = 1 - n \tag{4}$$

into the Heliosat method. This relation can be used without a previous calibration with ground data, but it is necessary that the clear sky model is optimally adapted to the regarded area. By Fontoynont et al. [2] relation (4) was improved in order to detail the case of complete cloudiness and to limit the clear sky index to meaningful values.

2.2. SOLIS Clear Sky Model

The SOLIS clear sky model [3] uses the radiative transfer model libRadtran [4] to calculate input parameters for a fitting function called the modified Lambert–Beer (MLB) relation. For this, only two radiative transfer calculations are needed for a given atmospheric state to get the irradiance for a full day. Since SOLIS can provide spectrally resolved irradiance data, it can be used for different applications. Beside improved information for the planning of solar energy systems, the calculation of photosynthetic active radiation, UV index, and illuminance is possible.

We use climatologies with monthly averages of AOD [5] and water vapour content [6] as input parameters for SOLIS and get the direct and global irradiance as output.

2.3. Direct model

We propose a new model [7] to calculate direct irradiance as a function of the clear sky index k^* and the direct irradiance at clear sky conditions b_{clear}. An appropriate clear sky model is the basis for this approach, see sec. 2.2.

For cloud events, described by $k^* < (1 - c(\theta))$ (whith $c(\theta)$ is a fit function), an exponentially rising parametrisation b(k*) for the direct irradiance was found empirically. It is given by

$$b(k^*) = b_{clear} \; k^{*P} \tag{5}$$

with P as a fit parameter.

Situations where $|k^* - 1|$ becomes smaller than $c(\theta)$, are defined as clear sky situations and the parametrisation results in

$$b(k^*) = b_{clear} + (k^*-1)\,\alpha \tag{6}$$

where α is a fit parameter.

If the clear sky index becomes greater than $(1 + c(\theta))$ we assume a special cloudy situation. In this case the global irradiance becomes more than I_{clear} in consequence of an increasing diffuse irradiance by reflection on clouds. The direct irradiance is then parameterised by

$$b(k^*) = b_{clear} \,/\, k^*. \tag{7}$$

In Fig. 3 the beam fraction as a function of clearsky index is given for satellite and ground derived values.

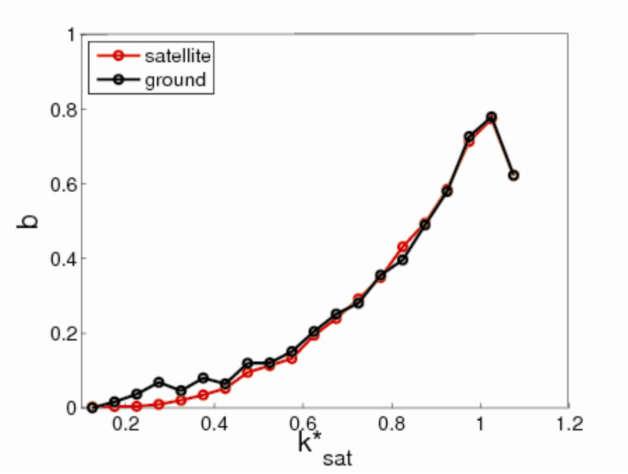

Fig. 3: Distribution of direct irradiance fraction once determined from satellite data and once evaluated from ground data versus the clearsky index.

3. Analysis and results

3.1. Yearly Sum and Frequency distribution of DNI

The accuracy of the proposed method to derive DNI was evaluated for the year 2005 for six stations of the Spanish Meteorological Service INM, see table 1. The evaluation was performed for all hourly values with the sun above horizon.

Table 1: INM stations with measurements of direct normal irradiance DNI.

Id	**Site**	**Latitude**	**Longitude**
1	Santander	43.49°N	3.80°W
2	Oviedo	43.35°N	5.87°W
3	A Coruna	43.37°N	8.42°W
4	Valladolid	41.65°N	4.77°W
5	Murcia	38.00°N	1.17°W
6	Madrid	40.45°N	3.27°W

Special focus of the evaluation was on the accuracy of yearly sums and on the investigation of frequency distributions of the time series, as these are relevant for yield estimates. Beside this, the relative bias *rBIAS* and the relative root mean square error *rRMSE* are used for quantitative comparisons.

For hourly values an *rRMSE* of 14.7% for global irradiance and of 31% for direct normal irradiance was found for the Spanish stations. The *rBIAS* is 1.5% for global irradiance and 1.1% for direct irradiance respectively.

Figure 4 displays *rBIAS* and *rRMSE* of DNI for the Spanish stations. The *rBIAS* for one year and one station is equivalent to the relative deviation of the annual sum for one station. In addition the *rBIAS* for clear sky situations $rBIAS_{clearsky}$ is provided. Hours are assigned as clear sky situations, if two criteria match: The clear sky index lies within $0.9<=k^*<=1.1$ and the variability of the cloud index in a small region of 3x5 pixel is small.

The comparison of *rBIAS* and $rBIAS_{clearsky}$ illustrates the strong influence of the quality of the clear sky model and the atmospheric input parameters on the quality of the annual sums. The deviation of annual satellite derived irradiance sums from the respective ground measured sums between -2% and 8.5% for DNI.

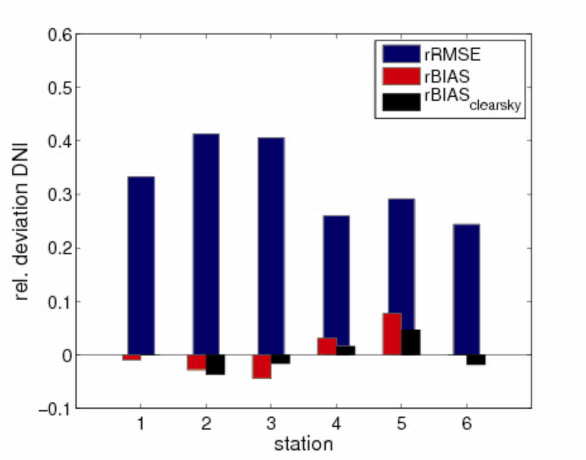

Fig. 4: Relative deviation of DNI. *rRMSE* represented by the blue bars, *rBIAS* represented by the red bars and $rBIAS_{clearsky}$ represented by black bars for the six Spanish stations.

In table 2 the accuracy information is given on different time scales which are relevant for solar energy applications. The deviation of annual satellite derived irradiance sums from the respective ground measured sums is between −2% and 4.5% for GHI and between −2% and 8.5% for DNI.

Table 2: Accuracy of satellite derived global horizontal irradiance GHI and direct normal irradiance DNI for different time scales.

	GHI	**DNI**
hourly mean	335 W/m²	366 W/m²
rRMSE hourly	14.5%	31.1%
rRMSE daily	7.5%	18.5%
rRMSE monthly	3.6%	6.3%
rBIAS	1.5%	1.1%

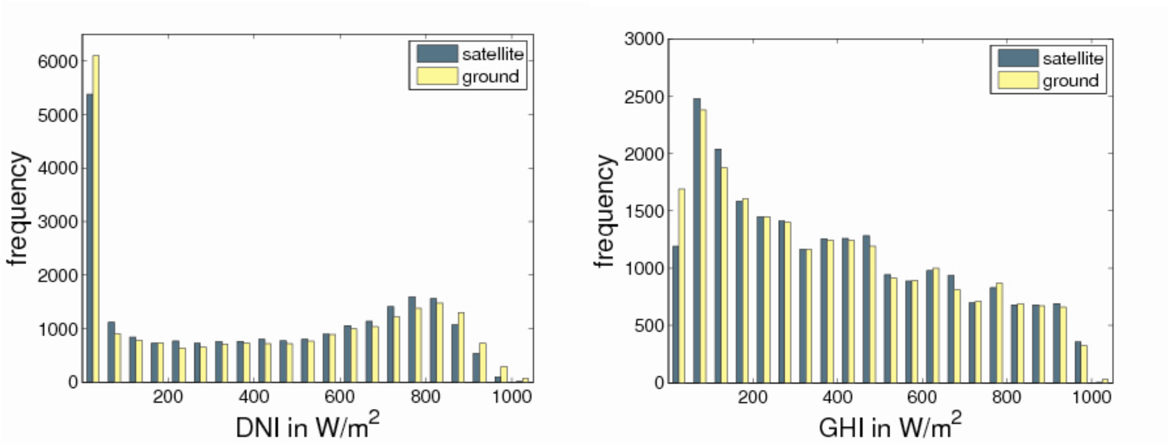

Fig. 5: Frequency distribution of calculated and measured direct normal irradiance (left) and of global irradiance (right) for the 6 spanish stations.

For energy conversion systems with non-linear response to the irradiance input a correct representation of the frequency distribution is of special importance. Figure 5 displays the frequency distribution of calculated and measured DNI and GHI for the Spanish stations; a fairly good agreement is achieved.

4. Conclusion

We developed a method to derive direct normal irradiance from MSG data. The influence of clouds on the direct normal irradiance is derived from MSG data with high quality. The quality for clear skies is determined by the accuracy of the aerosol climatology.

5. Acknowledgements

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References

[1] Hammer A., Heinemann D., Hoyer C., Kuhlemann R., Lorenz E., Müller R., Beyer H.G. (2003): *Solar energy assessment using remote sensing technologies*. Remote Sensing of Environment, 86, 423–432.

[2] Fontoynont, M., Dumortier, D., Heinemann, D., Hammer, A., Olseth, J. A., Skartveit, A., Ineichen, P., Reise, C., Page, J., Roche, L., Beyer, H. G. and Wald, L.: 1998, 'Satellight: A WWW Server Which Provides High Quality Daylight and Solar Radiation Data for Western and Central Europe', Proceeding of the 9th Conference on Satellite Meteorology and Oceanography, Paris, France, 25.-29.05.1998, 434-437

[3] Müller, R.W., Dagestad, K.F., Ineichen, P., Schroedter, M., Cros, S., Dumortier, D., Kuhlemann, R., Olseth, J.A., Piernavieja, C., Reise, C., Wald, L., Heinemann, D. (2004): *Rethinking satellite based solar irradiance modelling - The SOLIS clear-sky module*. Remote Sensing of the Environment, Volume 91, Issue 2, 160-174

[4] Mayer, B. and Kylling, A. (2005): Technical Note: *The libRadtran software package for radiative transfer calculations: Description and examples of use*. Atmos. Chem. Phys., 5:1855-1877, 2005

[5] Kinne et al. (2005): An AeroCom Initial Assessment – Optical Properties in Aerosol Component Modules of Global Models. In: Atmospheric Chemistry and Physics Discussions, 5, 8285-8330.

[6] Kalnay, E. et al. (1996): The NMC/NCAR 40-year reanalysis project. Bull. Am. Meteorol. Soc. 77 (3), 437–472.

[7] Kemper A. (2007): *Bestimmung der Diffusstrahlung unter Wolken aus Daten des Satelliten MSG*. Diploma thesis, Oldenburg Unversity, Germany.