SOLAR RESOURCE ASSESSMENT AND SITE EVALUATION USING REMOTE SENSING METHODS

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ABSTRACT

In this paper we describe and compare two methods used by the University of Oldenburg and DLR Stuttgart to calculate surface solar irradiance from METEOSAT 7 imagery. We examine the consistency of the two methods and compare the results with ground measured data. As a result we show the differences between the methods and the errors relative to ground measurements. The benefit of such satellite derived solar irradiance is shown by a brief presentation of two example applications. Finally an outlook is given into potential improvements resulting from the enhanced possibilities of the METEOSAT Second Generation (MSG) satellite which is due to start in 2002.

INTRODUCTION

An efficient world wide expansion of solar power requires reliable data on the solar energy resource. The assessment of the available solar irradiance is of particular importance for planning and performance evaluation. Ground based measurements are expensive and are rarely available for most sites, especially in the solar belt. Geostationary satellites like METEOSAT 7 provide the opportunity to derive information on the solar irradiance for a large area at a temporal resolution of up to 30 minutes and a spatial resolution of up to 2.5 km.

THE METHODS

The general idea of both methods is to deal with atmospheric and cloud extinction separately. In a first step the clear-sky irradiance for a given location and time is calculated. The methods use different models, assumptions and input data to account for the atmospheric state. Details will be given for each of the methods below. In a second step a cloud index is derived from METEOSAT imagery. This step uses the fact that the planetary albedo measured by the satellite is proportional to the amount of cloudiness. The so derived cloud index is then correlated to the cloud transmission. The clear-sky irradiance is then diminished by the cloud transmission to infer the ground irradiance.

The HELIOSAT Method

The HELIOSAT-Method was originally proposed by Cano [1] and later modified by Beyer et al. [2] and Hammer [3]. For the calculation of the clear-sky irradiance it uses the direct irradiance model of Page [4] and diffuse irradiance model of Dumortier [5]. Both use the Linke turbidity factor for atmospheric extinction. The direct irradiance is:

$$G_{direct,clearsky} = G_0 \cdot \varepsilon \cdot e^{-0.8662 \cdot T_L(2) \cdot \delta_R(m) \cdot m} \tag{1}$$

where G_0 is the extraterrestrial irradiance, ε the eccentricity correction, T_L the Linke turbidiy factor for airmass 2, δ_R(m) the Rayleigh optical thickness and m the airmass. The diffuse irradiance is an empirical fit by Dumortier [5]:

$$G_{diffus,clearsky} = G_0 \cdot \varepsilon \cdot (0.0065 + (-0.045 + 0.0646 \cdot T_L(2)) \cdot \cos\theta_z + (0.014 - 0.0327 \cdot T_L(2)) \cdot \cos\theta_z^2 \tag{2}$$

Here θ_z is the solar zenith angle. Since there is no information on the atmospheric turbidity from METOSAT, a climatological relation is used:

$$T_L(2) = T_0 + u \cdot \cos\left(\frac{2\pi}{365 \cdot J}\right) + v \cdot \sin\left(\frac{2\pi}{365 \cdot J}\right) \tag{3}$$

T_0, u and v are site specific fit parameters, J is the day of the year. A map with the parameters for Europe has been set up during the EU-funded Satel-Light project [6].

For the derivation of the minimum and maximum values of the cloud index albedo values are needed. The minimum ρ_{min} corresponds to the reflectance of the ground and the maximum ρ_{max} to optically thick clouds. For the minimum ground albedo maps are computed on a monthly basis. The maximum is derived from a statistical analysis of satellite images and is commonly done only once for each satellite sensor. The cloud index n is then given by

$$n = \frac{\rho - \rho_{\min}}{\rho_{\max} - \rho_{\min}}. \tag{4}$$

This cloud index is then empirically correlated to the clear sky index k_T^*. This relationship is basically $k_T^* = 1 - n$ with minor modifications for $n \rightarrow 0$ and $n \rightarrow 1$.

The ground irradiance is obtained from

$$G = k_T^* \cdot (G_{direct,clearsky} \cdot \cos\theta_z + G_{diffus,clearsky}) \tag{5}$$

The direct and diffuse component of the ground irradiance is then calculated using a statistical model of Skartveit/Olseth [7].

The DLR Method for Direct Normal Irradiance (DNI)

The method for the DNI is developed by DLR using the clear sky parameterization model by Bird [8] that uses transmittances for the individual atmospheric constituents. We added a transmission coefficient to take into account the attenuation of clouds. DNI is defined as follows:

$$\mathrm{G_{direct}} = \mathrm{G_0} \cdot \varepsilon \cdot \tau_{\mathrm{R}} \cdot \tau_{\mathrm{Gas}} \cdot \tau_{\mathrm{Ozon}} \cdot \tau_{\mathrm{WV}} \cdot \tau_{\mathrm{Ae}} \cdot \tau_{\mathrm{Cl}} \tag{6}$$

with the eccentricity corrected extraterrestrial solar irradiance (G_0) and the transmittance functions τ_i of the Rayleigh atmosphere, mixed gases (CO_2 and O_2), O_3, water vapor, aerosols and clouds, respectively. This method needs information about atmospheric ozone, water vapor and aerosol. The cloud index τ_{Cl} is calculated by using the IR and VIS channels from the METEOSAT satellite based on self adjusting, local thresholds which represent the daily variation of the surface properties [9]. The reference land surface temperature is described as a function of time for every pixel:

$$T = a_0 + a_1\left(\cos\left(\chi - a_3 + \sin\left(a_2\right)\times\sin\left(\chi - a_3\right)\right) + 0.1\times\sin\left(\chi - a_3\right)\right) \tag{7}$$

with $\chi = t/24\times 2\pi$ and t = decimal hours of the satellite (UTC). a_0 gives the daily mean temperature, a_1 the temperature amplitude, a_2 influences the width and steepness of the daily temperature wave and a_3 gives the phase shift, which is dominated by the local solar time.

COMPARISON TO GROUND DATA

We have compared results of both methods to ground data from Girona, located in north-eastern Spain, 30 km off the Mediterranean Sea. The data is global and diffuse horizontal irradiance from 1st Jan. 1998 to 15th Nov. 1998. We have computed the root mean square error (RMSE) and the mean bias (MBE). The relative errors are with respect to the ground measured values. The ground data averages were calculated separately for each method, since they show different gaps in the satellite image series. This results in different relative RMSE values even for similar RMSEs. For the computation of the errors night-time values, ground measurement errors and missing satellite images have been eliminated. The errors are given in table 1.

Direct Irradiance

We start with the comparison of the direct irradiance calculated by both methods. Figure 1 shows the results of the methods compared with ground measured data. Both methods show consistent results. The DLR method shows a slight overestimation, whereas the HELIOSAT derived data are slightly below the ground data. The scatter of the DLR method is larger than of the HELIOSAT method.

To compare the clear sky models we have chosen clear sky periods. The selection criteria were, that the direct irradiance had to be at least twice as large as the diffuse irradiance and there had to be at least four consecutive values which fulfil these criteria. This leads to about 1000 values for each of the methods. The results are shown in Figure 2. The scatter is significantly smaller for both methods, the HELIOSAT method has a larger negative bias, many of the points below 500 W/m² are below the diagonal, whereas the DLR method is nicely centered around the line.

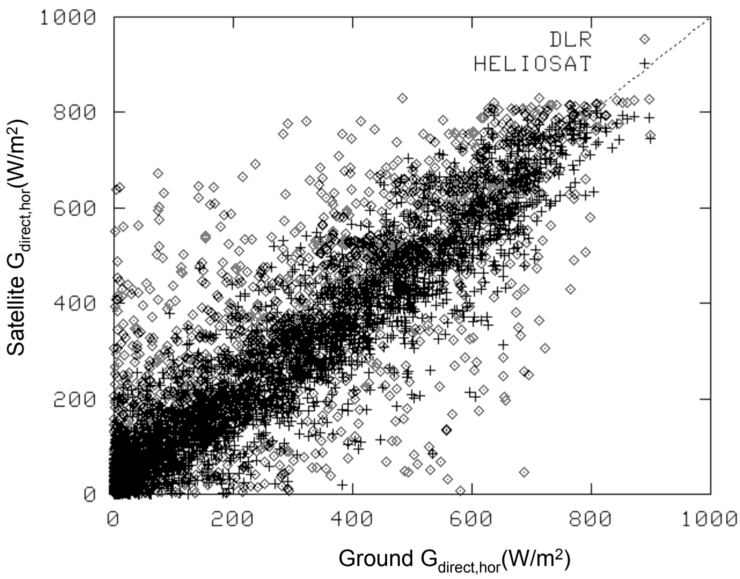

Figure 1: Comparison of ground measured and calculated direct horizontal irradiance, all days.

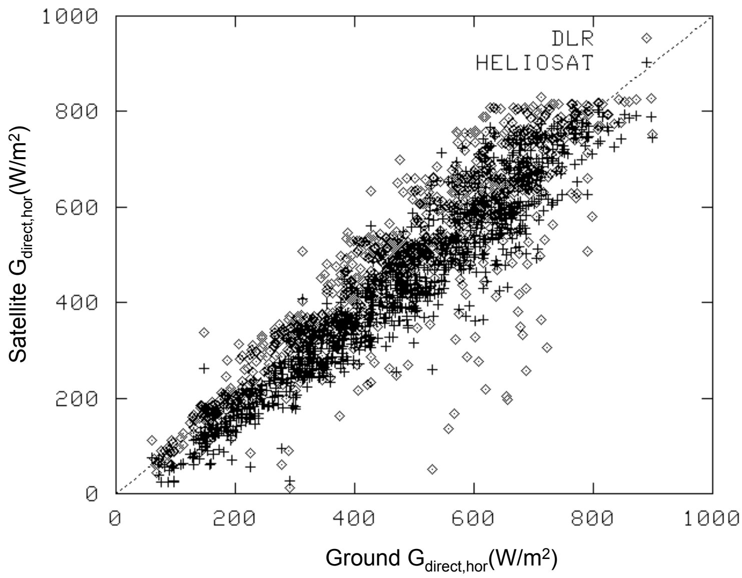

Figure 2: Comparison of ground measured and calculated direct horizontal irradiance, clearsky periods

TABLE 1

ERROR VALUES: HORIZONTAL IRRADIANCE

Method	RMSE	rRMSE	MBE	rMBE
DLR direct	130.6	44.4%	14.6	5.6%
HELIOSAT direct	79.7	28.6%	-2.7	-0.6%
DLR direct (clear sky)	81.8	17.7%	4.5	1.0%
HELIOSAT direct (clear sky)	73.8	17.8%	-47.1	-10.1%
HELIOSAT global	62.8	16.6%	-2.3	-0.6%

Gobal Irradiance

Since only the HELIOSAT method calculates global irradiance, no comparison is made for the DLR method. Figure 3 shows a scatter plot for global irradiance. The scatter is smaller than for the direct irradiance.

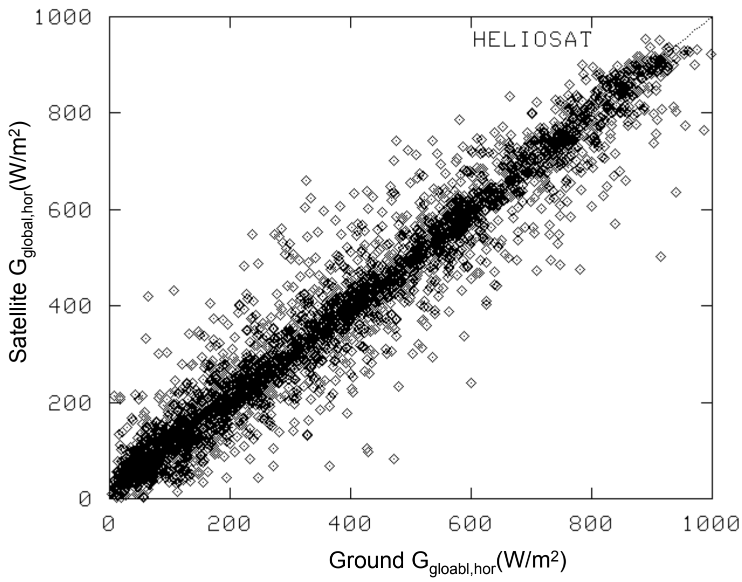

Figure 3: Comparison of global irradiance for the HELISOAT method, all days.

Conclusion

Both methods show good results for calculating direct and global irradiance with a high temporal and spatial resolution. The quality of the derived values is comparable to a ground station at 25 km distance [10]. The HELIOSAT method performs better in all-day cases, whereas the DLR method is preferable in clear sky situations. This is probably due to the different focus settinggs of the two methods. The HELIOSAT method focuses on all-day global irradiance. The DLR method is designed for solar thermal power plant evaluation, where clear sky direct irradiance is most important. Here the DLR method can use the advantage of a much more detailed clear sky model using atmospheric input data for ozone, water vapor and aerosol.

APPLICATIONS

Remote Performance Check of PV Systems: PVSAT

The idea of the PVSAT procedure is to evaluate the performance of grid connected photovoltaic (PV) systems on a monthly basis and to detect failures, which lead to losses in the energy yield. The yield strongly depends on the incoming solar irradiance making location and time specific irradiance information absolutely necessary. Remote sensing techniques have a strong advantage over ground based measurements due to its high spatial coverage. Ground based measurement networks are very expensive and satellite derived data have shown to be preferable to ground measurements of more than 25 km distance [10]. The PVSAT procedure calculates a hourly time series of global irradiance using the HELIOSAT method. This time series is used to simulate the yield of the PV system. The so calculated yield can be compared to the yield of the actual system. Significant differences between both figures are a strong indication of a malfunction of the PV system.

Site Evaluation for Solar Thermal Power Plants: STEPS

Solar thermal power plants will provide a major share of the renewable energy sources needed in the future. STEPS [11,12], an Evaluation system for Solar Thermal Power Stations, was designed to calculate the performance of such power stations as function of solar direct irradiance, geographical conditions (land slope, land cover, distance from cooling water resources, etc.), infrastructure (pipelines, electricity grids, streets etc.) and the configuration and performance of a selected solar thermal power plant concept. A geographic information system (GIS) is used to combine and process all the parameters for site assessment as shown in Figure 4. One of the most important input parameter is the solar direct irradiance. To provide geographically continuous information over several years about the solar resource in remote regions, the irradiance is calculated using remote sensing methods described above. Results were obtained with high spatial and temporal resolution.

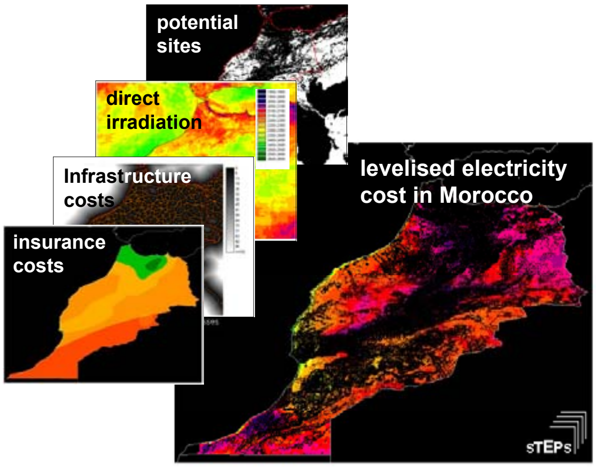

Figure 4: Combining satellite derived direct irradiance with geographical, technical and economical data to calculate the levelised electricity costs, for example in Morocco.

OUTLOOK: PERSPECTIVES OF MSG

The new European meteorological satellite MSG (METOSAT Second Generation) which is due to start in summer 2002 offers additional spectral channels and a higher spatial and temporal resolution. The added channels will allow for a better of the atmospheric state, especially regarding clouds. This enables the use of radiative transfer models instead of parameterized models for e. g. the turbidity in HELIOSAT. A further benefit is the determination of atmospheric constituents (e.g. water vapor, ozone, ...) from only one satellite platform which reduces the dependency of external data. Overall a significant increase in accuracy is expected.

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