Satellite-Based Techniques for the Retrieval of Solar Radiation Data – A Review of Current European Activities –

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The paper reviews the current status of satellite-based techniques for the retrieval of solar surface irradiance. Main emphasis will be the reporting on recent and current joint European research projects related to the development of satellite-based methods and their application in various fields of solar energy.
Satellite-derived data benefit from a high temporal resolutions of30 minutes and the almost continuous spatial coverage with a resolution of less than 5 kilometers, if resulting from geostationary satellites as the European Meteosat. Achievable current accuracies are comparable to data from ground stations on a monthly time scale, hourly data actually show some more potential for improvements.
Satellite data not only show potential for replacing ground-based pyranometer data as a data source for most standard applications in a foreseeable future. They also can provide various solar energy specific irradiance quantities which are currently not supplied at all or with extraordinary high efforts only: spectral irradiance, direct normal irradiance, directionality of diffuse irradiance, irradiance on arbitrarily oriented surfaces, to mention only some.
In the framework of a newly started project by a European consortium completely revised algorithms will be developed to retrieve the solar irradiance from the new Meteosat satellite generation MSG which will be launched in 2002. This platform will show resolutions increased by a factor of two both in time and in space. The main improvement however will be the availability of more detailed information on atmospheric constituents affecting the atmospheric transmittance of solar radiation (clouds, water vapor, aerosols, ozone) through the use of twelve spectral radiometer channels. This information is expected to significantly increase the accuracy of the retrieval algorithms.
In addition, the potential of satellite data for short-term forecasting of solar irradiance is briefly demonstrated.

1. INTRODUCTION

The increasing use of solar energy implies new challenges for the supply of application-specific solar radiation data. Especially the integration into energy structures makes availability of special information necessary.
Traditional data often not adequate: no real-time, coarse density, poor accuracy, time resolution, „new“ quantities
Necessary: new data sources, new instruments, new methods, new services for data supply, integrated approaches
Idea of using satellite information for surface solar irradiance estiumation is not new
Largely applied for climate research, global radiative balance, large scale (typically one degree), monthly averages

Operational use: geostationary satelite: Meteosat

The projects to be presented are:

- Satel-Light — Processing of Meteosat Data for the Production of High Quality Daylight and Solar Radiation Data Available on a WWW Internet Server *(www.satel-light.com)*
- SoDa — Integration and Exploitation of Networked Solar Radiation Databases for Environment Monitoring *(www.jrc.soda.it)*
- PV-SAT — Remote Performance Check for Grid Connected PV Systems Using Satellite Data *(www.pvsat.de)*
- Heliosat-3 — Energy-Specific Solar Radiation Data from Meteosat Second Generation (MSG): The Heliosat-3 Project *(www.heliosat3.de)*

All projects are funded within research programmes of the European Community.

2. THE METHOD

The HELIOSAT method was originally proposed by Cano (1986) and later modified by Beyer et al. (1996) and Hammer (2000). For the calculation of the clear-sky irradiance it uses the direct irradiance model of Page (1996) and diffuse irradiance model of Dumortier (1995). Both use the Linke turbidity factor for atmospheric extinction. The direct irradiance is:

$$G_{dir,clear} = G_0 \cdot \varepsilon \cdot e^{-0.8662 T_L(2) \cdot \delta_R(m) \cdot m}. \qquad (1)$$

where G_0 is the extraterrestrial irradiance, ε the eccentricity correction, $T_L(2)$ the Linke turbidiy factor for air mass 2, δ_R(m) the Rayleigh optical thickness and m the air mass. For the diffuse irradiance, an empirical fit by Dumortier (1995) is used:

$$\begin{aligned} G_{diff,clear} = {} & G_0 \cdot \varepsilon \cdot \big(0.0065 + (-0.045 + 0.0646 T_L(2)) \cdot \cos\theta_z \\ & + (0.014 - 0.0327 T_L(2)) \cdot \cos^2\theta_z\big). \end{aligned} \qquad (2)$$

Here θ_z is the solar zenith angle. For the Linke turbidity factor, a climatological relation is used:

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

T_0, u and v are site-specific parameters, J is the day of the year. The turbidity model divides Europe in 13 zones. Within each zone, the variations of the turbidity at sea level are described by u and v. The sea level turbidity is then corrected to take into account the influence of altitude (-0.65 per 1000 m).
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

$$n = \frac{\rho - \rho_{\min}}{\rho_{\max} - \rho_{\min}} \quad (4)$$

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 $n \to 0$ and $n \to 1$.
The ground irradiance is obtained from

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

3. THE PROJECTS

3.1. Satel-Light

Within the framework of the *Satel-Light* project, a data base of solar radiation and daylight data for Western and Central Europe has been made available on the Internet. The data is completely derived from Meteosat satellite imagery. Irradiances and illuminances covering a two year period (1996-1997) can been calculated on an half-hourly basis and a spatial grid of 10 km. For this purpose the Heliosat method has been largely modified and improved as described in chapter 2.
The Satel-Light web server basically consists of pre-calculated cloud index values (Eq. 4) and a set of numerical routines for the calculation of global and diffuse irradiance and illuminance values on horizontal and tilted surfaces, frequencies for the occurence of sky types, probabilities for exceeding given threshold values on different time scales. Data can be supplied by the server either as site-specific time series or statistics, or as graphical output in customized maps. For the latter purpose the server also features a basic set of GIS functionality.
A special motivation for the Satel-Light project was in the scarcity of available daylight measurements. A good understanding of the site-specific daylight climate is essential for an optimum use of natural lighting in buildings for a reduction of overall energy consumption and a more comfortable indoor climate.

The period covered by Satel-Light will be extended to five years (1996-2000) within the ongoing SoDa project (chapter 3.2).

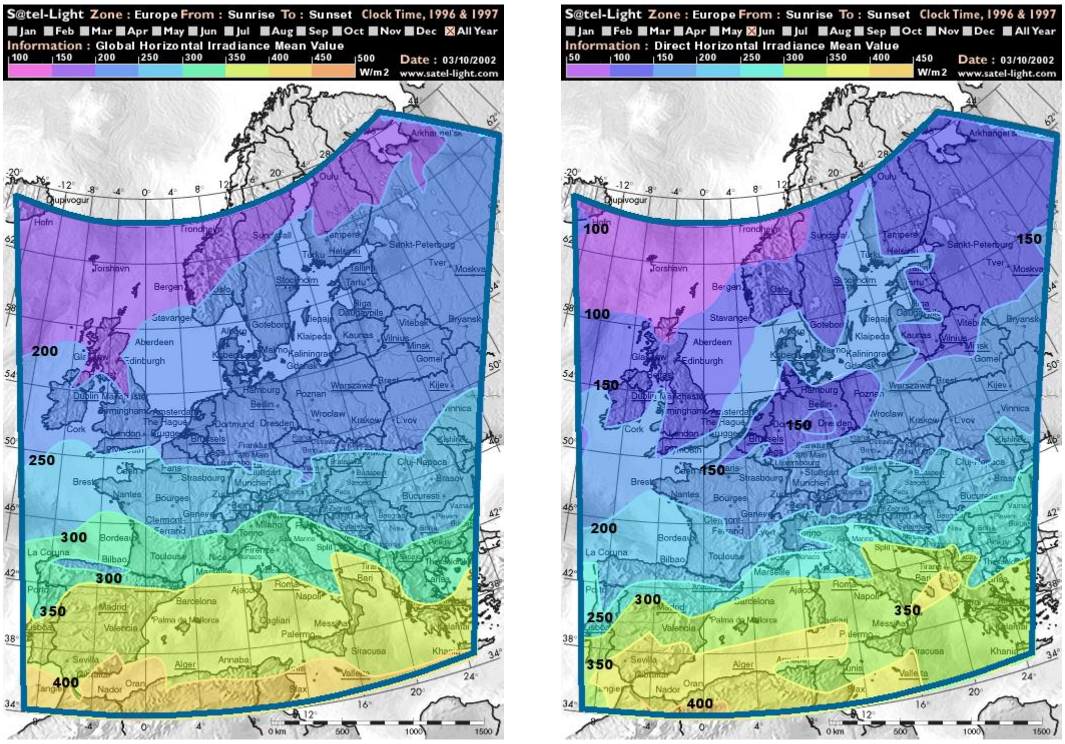

Figure 1 Maps representing spatial information retrieved from the Satel-Light data base. The annual mean of global irradiance on a horizontal surface (left) and the monthly (June) mean of direct horizontal irradiance (right) are shown. Both maps are based on 1996-1997 data averaged over sunshine duration.

3.2.SoDa

The project *SoDa* aims at responding to the strong multi-disciplinary needs for information on solar radiation. It represents a real innovation. Advanced information and communications technologies will be used to supply high quality value-added information that match the actual customer needs. The methodology is also user-driven with a large involvement of users in the project. A WWW-based service is being developed and demonstrated which realise the integration of information sources of different natures within a smart network. These sources include databases containing solar radiation parameters and other relevant information, including algorithms and end-users applications; some of them may originate from an advanced processing of remote sensing images. Before the SoDa service was made available, these resources were available separately.

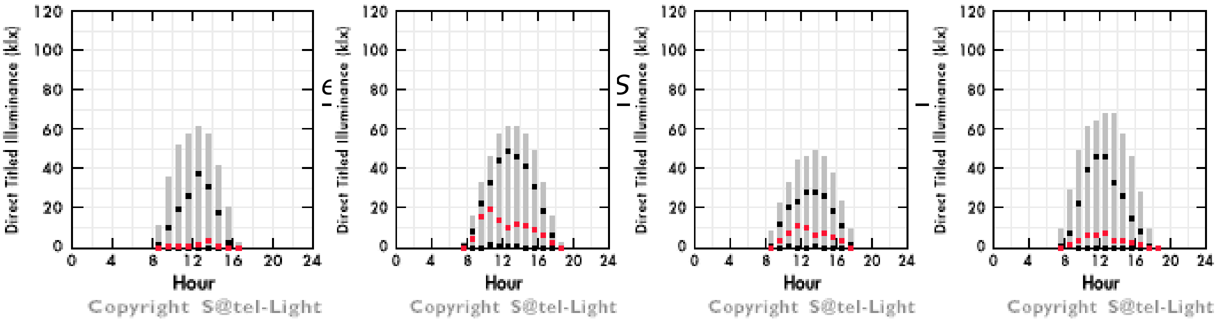

Figure 2 Monthly frequencies of direct illuminance on a vertical, south-oriented surface for Berlin, Germany retrieved from the Satel-Light data base. The months are January, April, July and October 1996-97 (from left to right) showing hourly results (max (100%), 75%, 50% and 25%)

The information sources also include application-specific user-oriented numerical models and advanced algorithms. Algorithms based on innovative techniques in data fusion, data mining, data processing, and data assimilation in numerical models are being developed and tested to supply value-added information on solar radiation. The service is being validated through users trials, and its benefits are assessed. The project SoDa focuses on several applications in environment and connected domains: air quality in cities, vegetation, coastal zones, energy-conscious building design and daylighting, and industrial use of renewable energies.

Providers, outside the Consortium SoDa, are using the SoDa service to disseminate information on solar radiation. One example is the MARS (monitoring agriculture by remote sensing), a component of the Common Agricultural Policy of the European Commission.

A multi-disciplinary consortium has been assembled, which gathers companies and researchers with the necessary expertise in solar radiation and information and communications technologies. Customers and potential users are also represented as partners in the consortium via the involvement of commercial vendors of solar radiation databases and of representatives of large international or local environmental research and development programmes.

The objectives of the project SoDa are:

- to answer the needs for high quality user-specific information on solar radiation
- to integrate diverse sources of information presently available separately within a smart integrating network
- to develop and operate a prototype service, which efficiently exploits this network
- to increase the quality of the delivered information through improved modelling of time and space structures of the solar radiation, and improved matching to actual customer needs
- to disseminate the achievements of the project, and assess the sustainability of a permanent commercial service

Figure 3 Structure of the PV-SAT procedure for the remote surveillance of photovoltaic system performance.

3.3. PV-SAT

The installed power of small grid-connected PV systems continues to increase with large growth rates. Typically, these systems do not include any long term surveillance mechanisms and failures of system components and performance decrease will probably not recognized.

The PV-SAT method is based on the derivation of site-specific solar irradiance data from Meteosat images rather than ground measurements. Based on the system configuration data, a generic PV system model is used to estimate the monthly yield of the system. This figure is communicated to the system operator for comparison with the actual system performance. To gain information on the overall applicability of the procedure, a test phase including more than 70 systems in Germany, Switzerland and the Netherlands has been performed. It may be concluded that an accuracy of about +/- 15 kWh/kWp can be expected for the estimation of the specific yield of systems operating without srious technical failures.

3.4.The Future: HELIOSAT-3

A successful integration of solar energy technologies into the existing energy structure highly depends on a detailed knowledge of the solar resource. HELIOSAT-3 will supply high-quality solar radiation data gained from the exploitation of existing Earth observation technologies and will take advantage of the enhanced capabilities of the new Meteosat Second Generation (MSG) meteorological satellites (see table below). The expected quality represents a substantial improvement with respect to the available methods and will better match the needs of the users of the resulting products.
In particular, HELIOSAT-3 will provide

- solar irradiance data with high accuracy and space-time resolution necessary for solar energy applications, plus a large geographical coverage
- additional solar-energy specific data (direct and spectral irradiance, angular distribution of diffuse irradiance, spatial structure of irradiance) according to the needs of end-users
- information on HELIOSAT-3 products, its sustainability as a service and its potential benefits to end-users.

With HELIOSAT-3, solar energy applications will benefit from the huge potential of Earth observation technologies in an optimum manner: It is the first time that solar energy users will have access to satellite-based solar radiation data with a quality, that allows an optimised planning of solar energy systems and performance monitoring of these systems with respect to meteorological conditions. The harmonisation with the needs of the solar energy community will be secured through the close co-operation with users inside and outside the HELIOSAT-3 consortium.
The establishment of the methodology will be the basis of new services to the growing solar energy industry providing near-real-time solar radiation data serving the specific needs of the customers. Similarly, the climate community will be served by HELIOSAT-3 with data appropriate to their special needs.
The main components of HELIOSAT-3 are:

- Retrieval algorithms for the MSG-based estimation of major atmospheric parameters modifying the radiative transfer: clouds, water vapour, aerosols, and ozone
- Physically based calculation schemes for (i) solar irradiance based on MSG and the atmospheric parameters and (ii) additional parameters relevant in solar energy applications
- Implementation of an operational processing chain from MSG data to end-use oriented solar radiation data
- Prototype applications assessing the economic benefit of the derived new or improved products for the solar energy sector.

In benefiting from the new satellite technology HELIOSAT-3 will enhance the recent efforts made by the European Commission and its outcomes will be integrated into the follow-ups of the projects Satel-Light, PVSAT, SolarGIS, ESRA, SoDa. These projects will directly benefit as customers from the outcomes of HELIOSAT-3.
To give an example, in the remote performance control of photovoltaic systems the expected increase in accuracy due to better irradiance products will lead to an increase in the number of detected system failures by at least 20% compared to current accuracies. This directly results in an overall increase in system efficiencies.

Benefits for solar irradiance retrieval
Improved cloud detection and classification (broken clouds!?)
Estimation of relevant atmospheric parameters: water vapor, aerosols, ozone
physical modeling of atmospheric radiative transfer
direct calculation of solar energy specific quantities

Table 1. Improvements in METEOSAT Resolution

	1st Generation (MOP)	2nd Generation (MSG)
Radiometric	8 bit	10 bit
Spatial (high resolution VIS)	2.5 km	1 km
Spatial (all other channels)	5 km	3 km
Temporal	30 min	15 min
Spectral channels	3	12

Figure: MSG channels

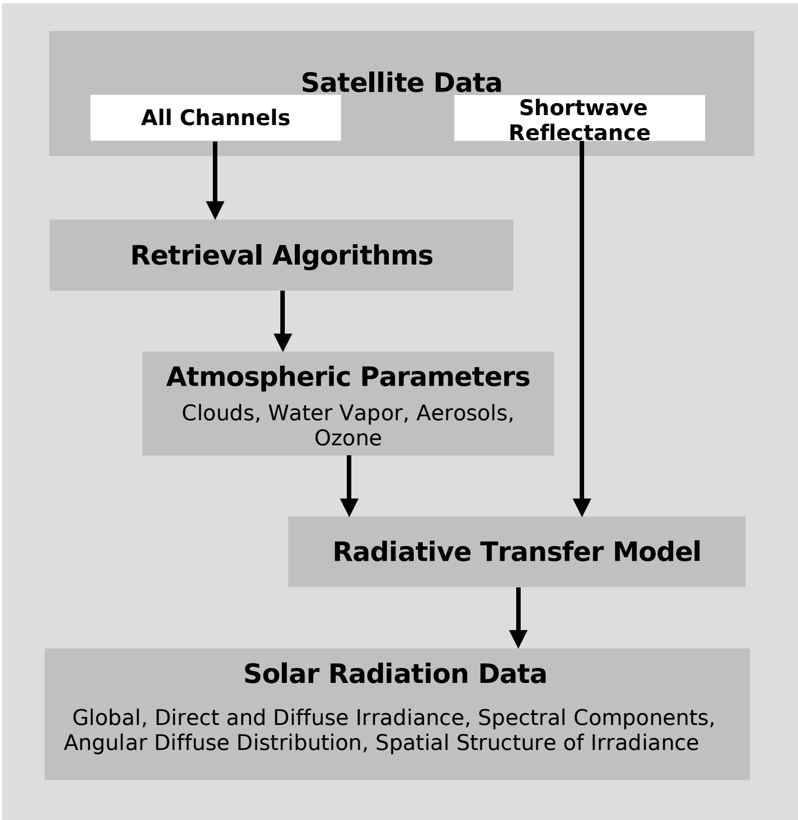

Figure 4 Components of the HELIOSAT-3 calculation scheme. The availability of additional atmospheric data from MSG enables an advantageous use of radiative transfer calculations.

further applications which will benefit: solar thermal power plants, forecasting

4. CONCLUSIONS

Satellite data are reliable data source for solar surface irradiance. Current applications already benefit.
They provide „new“ solar energy specific information.
They are unrivaled for most remote locations.
They show promising potential with next generation satellites.
Will they replace ground-based pyranometer networks in the future?

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5. ACKNOWLEDGMENTS

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