A new method for estimating solar energy resource

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A new method for estimating solar energy resource

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Abstract – This paper presents the first prototype of a new method –called Heliosat-4– for assessing solar surface irradiance. The Heliosat-4 method is based on the radiative transfer model libRadtran and benefits from advanced products derived from recent Earth Observation missions. It will provide direct and diffuse components and spectral distribution of solar surface irradiance every 3 km and ¼ h over Europe and Africa. The outcomes of this first prototype of the method are compared to ground measurements made at 8 stations in Europe and Northern Africa. The results show that RMSE attained by the Heliosat-4 method is fairly similar to that attained by current methods. A large overestimation is observed. Nevertheless these tests are very encouraging.

Keywords: solar irradiance, atmospheric optics, radiative transfer, cloud, Envisat, MetOp, MSG.

1. NOMENCLATURE

z, z_0, z_H	altitude (km) above mean sea level
I_0	irradiance at the top of the atmosphere (W m^{-2})
I, I_B, I_D	global, direct, diffuse irradiance on horizontal plane (W m^{-2})
$I^{clearsky}$, $I_B^{clearsky}$	global, direct irradiance on horizontal plane under clear sky (W m^{-2})
$T_{cloud+albedo}$	cloud extinction and ground albedo contribution (unitless)
$A(z)$, $A_B(z)$	attenuation coefficients of the atmosphere for global, direct irradiance (unitless)
α, α_B	parameters of the double-z fitting function (m^{-1})
ρ	ground albedo (unitless)
ρ_{sph}, ρ_{sph}'	spherical albedo for clear and cloudy sky (unitless)
a, b	empirical parameters for modified Lambert-Beer relation (unitless)
τ_0, τ_{0B}	optical depths for modified Lambert-Beer relation (unitless)
τ_c	cloud optical depth (unitless)
$\tau_{aer550nm}$	aerosol optical depth at 550 nm (unitless)
α	Angstrom coefficient (unitless). It characterizes spectral variation of aerosol optical depth
vis	visibility at ground level (km)
θ_s	solar zenith angle (°)

2. INTRODUCTION

World energy consumption is sharply rising (Martin-Amouroux, 2004) when we are witnessing a gradual depletion of fossil resources. Other sources of energy should be better exploited to meet demand. Among them, solar energy offers a great potential. Solar energy resources have been for long estimated from measurements made within meteorological stations networks (WMO, 1981). However, such networks do not offer a dense nor sufficient coverage to provide an accurate description of spatial variations of the resource. As an alternative, several methods have been developed in the past years to assess the solar surface irradiance (SSI) from images taken by satellites (Rigollier et al. 2004). Most current methods are inverse, i.e. the inputs are satellite images whose digital counts result from the ensemble of interactions of radiation with the atmosphere and the ground during the downward and upward paths of the radiation. The authors believe from experience that limits of such methods are presently reached in terms of accuracy, except for those are specialized to a specific region using empirical fittings (Polo et al., 2006). Consequently, a new paradigm is studied based on a direct modeling. This would permit to deliver knowledge on direct, diffuse components and spectral distribution, which is seldom offered by current methods.

Recent satellite missions such as Meteosat Second Generation, Envisat and MetOp combined with recent data assimilation techniques into atmospheric modeling offer a favorable context for the design and exploitation of a method based on a direct modeling. In this approach, the various optical processes occurring along the path of the light from the outer space towards the ground are modeled by the means of a radiative transfer model (RTM).

In this work, we propose a prototype of a direct method –called Heliosat-4– for assessing the SSI; it exploits advanced products derived from recent satellite data and is based on a radiative transfer model. Our final goal is to integrate it into an operational system for providing operationally direct and diffuse components and spectral distribution of the SSI for the usable Meteosat image pixels (9 million pixels, 3 km resolution at nadir of the satellite and each quarter-hour). This SSI data will be disseminated by the means of the SoDa Service (www.soda-is.com, Gschwind et al. 2006). This communication deals with the SSI integrated over the spectral interval [0.3 µm, 4 µm].

3. METHOD

3.1 Background

The Heliosat-4 method is under joint development by the DLR (German Aerospace Center) and MINES ParisTech. The libRadtran RTM has been selected for this development. libRadtran was originally developed for modelling UV irradiance. Its accuracy has also been demonstrated for actinic fluxes and total irradiance (www.libradtran.org, Mueller et al., 2004).

There are many inputs to RTMs. Oumbe et al. (2008) performed an inventory of the variables (e.g., cloud) and their attributes (e.g., optical depth) available in an operational mode and assessed to

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which degree the uncertainty on an attribute of a variable – including the absence of value– leads to a variation on the SSI. They found a number of significant inputs:

- solar zenith angle (θ_s) and number of the day in the year,
- cloud optical depth (τ_c),
- cloud type,
- water vapor amount,
- aerosol optical depth and its spectral variation ($\tau_{aer550nm}$, α),
- aerosol type,
- ground albedo (ρ) and its spectral variation,
- atmospheric profile,
- ground altitude (z).

Another result of this sensitivity analysis is that the influences of vertical position and the geometrical thickness of clouds in the atmosphere are negligible. Thus, the SSI I for a cloudy atmosphere can be considered as equal to the product of the irradiance obtained under a clear sky ($I^{clearsky}$) and a function of the cloud extinction and ground albedo contribution ($T_{cloud+albedo}$):

$$I \approx I^{clearsky} \; T_{cloud+albedo} \qquad (1)$$

3.2 Scheme

For our objectives, look-up tables can be used (Gimeno-Ferrer and Hollmann, 2002). The look-up tables are cumbersome to compute and then to implement in the routine operations. If new descriptions of atmospheric properties are available, the look-up tables should be recomputed for the new conditions and re-implemented in the processing software. They have the advantage of making the subsequent operations much faster. Here, we have opted for another approach by using libRadtran and a combination of simpler approached models that run fast enough for our purposes.

Considering Eq. 1 and taking into account that *i)* the variations with the altitude z of the term $T_{cloud+albedo}$ are negligible and *ii)* the cloud parameters may be known in an operational mode every ¼ h and 3 km and the clear-sky parameters only every day and 50 km, the concept of the Heliosat-4 method is that the SSI I can be computed by the products of three models as follows:

$$I = \underset{\text{daily and 50 km}}{I^{clearsky}} \quad f(z) \quad \underset{\text{¼ h and 3 km}}{T_{cloud+albedo}} \qquad (2)$$

where each model differs from the others with respect to space and time scales. The first model computes the clear-sky irradiance $I^{clearsky}$; it takes into account all atmospheric parameters but clouds and ground albedo and focuses the bulk of computation resources. The second model *f(z)* corrects for ground elevation for a given site and the third model take into account the clouds extinction and the contribution of the ground albedo to the SSI ($T_{cloud+albedo}$). The second and third models are much simpler and run faster than the first one. A sketch of the scheme is given in Fig. 1.

3.3 The clear-sky part of the scheme

The Heliosat-4 method exploits a clear-sky model which is in this case the RTM libRadtran combined with the modified Lambert-Beer (MLB) relation proposed by Mueller et al. (2004). The MLB relation is a fitting function modelling the influence of the solar zenith angle in order to save computing time:

$$I^{clearsky}(\theta_s) = I_0 \exp(-\tau_0 / \cos^a \theta_s) \qquad (3)$$

$$I_B^{clearsky}(\theta s) = I_0 \exp(-\tau_{0B} / \cos^b \theta_s)$$

where τ_0, τ_{0B} and *a, b* are determined from the knowledge of the global and direct irradiances at solar zenith angles equal to 0° and 60°. This knowledge is obtained by two runs of libRadtran.

Inputs to libRadtran are the optical depth and type of the aerosols, the water vapour and ozone content, which are themselves assessed from data provided by the satellites Envisat and MetOp (Holzer-Popp et al. 2002; Schroedter-Homscheidt et al. 2008). These inputs are provided for cells of 50 km in size.

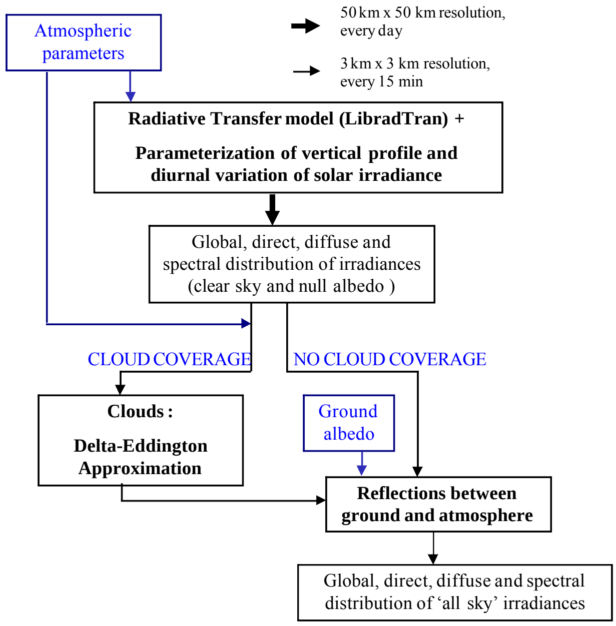

Figure 1. Heliosat-4 scheme

3.4 Double-z fitting function for vertical profile of irradiance

The mean terrain altitude for each cell, z_0, is also an input to libRadtran. The altitude of the terrain has a large influence on the irradiance and it is necessary to take into account the actual altitude of the site of interest in the assessment of the clear-sky irradiance and consequently of the SSI. It would be too time-consuming to run libRadtran for each altitude. Given the fact that libRadtran can run with two altitudes (z_0 and z_H) as inputs in one call, we have designed the use of the double-z fitting function described below to perform the altitude correction. Knowing values of clear-sky irradiances at two different altitudes $I^{clearsky}(z_H)$ at z_H and $I^{clearsky}(z_0)$ at z_0, this fitting function allows to determine clear-sky irradiances at other altitudes. It is called "double-z fitting function" because it needs as inputs the clear-sky irradiances at two altitudes. The form of this function has been defined from the typical vertical profile of direct irradiance but was then found suitable to the global irradiance, i.e., the sum of the direct and diffuse components. Two attenuation coefficients, *A(z)*, for global and, $A_B(z)$, for direct irradiances are defined:

$$I^{clearsky}(z) = I_0 (1 - A(z)) \qquad (4)$$
$$I_B^{clearsky}(z) = I_0 (1 - A_B(z))$$

We assume that *A(z)* and $A_B(z)$ have the following forms:

$$A(z) = A(z_0)\ exp[-\alpha(z - z_0)] \quad (5)$$
$$A_B(z) = A_B(z_0)\ exp[-\alpha_B(z - z_0)]$$

$A(z_0)$ and α can then be computed:

$$A(z_0) = 1 - (I^{clearsky}(z_0) / I_0) \quad (6)$$
$$\alpha = -ln[(I_0 - I^{clearsky}(z_H))/(I_0 - I^{clearsky}(z_0))] / (z_H - z_0)$$

z_H has been empirically defined to obtain the best results for elevations between 0 and 8 km and is set to, in km:

$$z_H = max(3, z_0 + 2) \quad (7)$$

The same equations hold for $A_B(z_0)$ and α_B, where $I_B^{\ clearsky}(z_H)$ and $I_B^{\ clearsky}(z_0)$ are the direct clear-sky irradiances at z_H and z_0:

$$A_B(z_0) = 1 - (I_B^{\ clearsky}(z_0) / I_0) \quad (8)$$
$$\alpha_B = -ln[(I_0 - I_B^{\ clearsky}(z_H))/(I_0 - I_B^{\ clearsky}(z_0))] / (z_H - z_0)$$

The outcomes of the double-z fitting function are compared for several altitudes to the outcomes of libRadtran and 6S (Vermote et al., 1997) which serve here as references. libRadtran was run for several input conditions, e.g., different solar zenith angles (0, 10, 20, 40, 50, 60, 65, 70, 75, 80) °, four different aerosol types, different visibilities (15, 20, 25, 30, 40, 50, 60, 80, 100) km, different amounts of precipitable water (10, 15, 30, 60, 80) kg m^{-2}, different standard atmospheres and different ground albedos (0.0, 0.2, 0.3, 0.6, 0.9). Similar runs were made with 6S. Similar conclusions and values were obtained, ensuring that the comparison is not biased by the use of a single RTM. Deviations between the results of the RTM and the double-z fitting function were computed. The relative value of the deviation is less than 1 % (global) or 2 % (direct) for current visibilities, i.e. greater than 30 km (WMO 1981) (Fig. 2). It may amount to respectively 3 % and 5 % for very low visibilities of 15 km. For larger visibilities, the relative deviation is almost zero for altitudes from sea level up to 6-7 km. There is little influence of the solar zenith angle on the deviation. We conclude that this function is accurate enough to be used in the Heliosat-4 method.

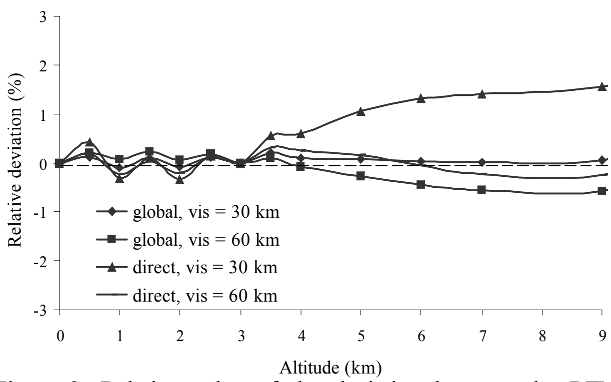

Figure 2. Relative value of the deviation between the RTM libRadtran and the double-z fitting function. Main inputs to the RTM are solar zenith angle (30 °), precipitable water (15 kg m^{-2}), number of the day in the year (170), and ground albedo (0.2).

3.5 Clouds extinction and ground albedo contribution

Since the geometrical thickness of clouds has a negligible effect on the SSI, it is set up to a fixed value of 1 km. Then, we assume that the irradiance passing through the clouds is divided into downward and upward irradiances. Therefore, we use the well-known two-stream and delta-eddington approximations (Paris and Justus, 1988) to model the extinction due to clouds:

$$I_B = I_B^{\ clearsky}\ exp(-\tau_c / cos\theta_s) \quad (9)$$
$$I_D = t_D\ (I_D^{\ clearsky} + R_c\ \rho_{sph}) + (t_B - t_D)\ I_B^{\ clearsky}$$

where R_c is the irradiance reflected by the cloud and is given by:

$$R_c = (r_D\ I_D^{\ clearsky} + r_B\ I_B^{\ clearsky}) / (1 - r_D\ \rho_{sph}) \quad (10)$$

The effective diffuse and the direct-to-diffuse transmissivities and reflectivities –respectively r_D, t_D and r_B, t_B– are determined from the radiation boundary conditions (Paris and Justus, 1988). The spherical albedo ρ_{sph} is computed previously in the clear-sky part of the scheme.

If we consider that an infinite series of reflection and scattering takes place between the ground and the atmosphere, the SSI computed for a null ground albedo can be corrected for the actual ground albedo ρ:

$$I(\rho) = I(\rho{=}0) / (1 - \rho\ \rho_{sph}') \quad (11)$$

where ρ_{sph}' is the spherical albedo for the cloudy atmosphere. The input to the cloudy part of the scheme is the cloud optical thickness derived from an appropriate processing of the Meteosat images made at DLR. Presently, the ground albedo is set arbitrarily; a database should be found for operation.

4. COMPARISON BETWEEN RESULTS AND STATION MEASUREMENTS

We have applied the Heliosat-4 method to data provided by the DLR for the year 2004. Values of irradiance for every quarter-hour were averaged to yield hourly means of irradiance. These assessed SSI are compared to measurements performed by pyranometers at 8 meteorological stations (Table 1). We only use measurements with irradiance greater than 50 W m^{-2}. For lower values, the measured irradiance is mainly of diffuse nature and is influenced by local conditions, including orography and the presence of nearby obstacles. By removing these values, we ensure better conditions for understanding the results at this preliminary stage. For the same reason, we avoid measurements taken at solar zenith angle greater than 70°. Above this angle, atmospheric parameters are not well estimated.

Table 1. Stations used for validation

Site	Station	Country	Latitude / Longitude(°)	Altitude (m)
1	Carpentras	France	44.05 / 5.05	110
2	Dresden	Germany	51.13 / 13.78	214
3	Freiburg	Germany	48.04 / 7.87	241
4	Geneva	Switzerland	46.25 / 6.13	407
5	Ispra	Italia	45.82 / 8.60	191
6	Payerne	Switzerland	46.81 / 6.94	492

7	Tamanrasset	Algeria	22.78 / 5.51	1368
8	Vaulx-en-Velin	France	45.78 / 4.93	173

The discrepancies between the SSI measured and assessed are computed. Table 2 displays the mean value of the SSI measured at ground level, the bias, i.e., the mean difference, the root mean square error (RMSE) and the correlation coefficient between the two series of values. The bias is positive for all sites. This means that the method over-estimates the SSI in general. The bias may be small as in the case of Tamanrasset (station 7) or large as in the case of Vaulx-en-Velin (station 8). The correlation coefficient is large in all cases: the changes in radiation are well reproduced by the Heliosat-4 method. The root mean square error ranges from 70 $W\,m^{-2}$ to 133 $W\,m^{-2}$; in relative values, it is close to 20 % in all cases, except for Tamanrasset for which it is 10 %. The solar zenith angle has an important impact on quality of the estimation: the greater the solar zenith angle, the greater the relative bias and RMSE. A similar comparison is under way for direct irradiance.

Table 2. Performance of Heliosat-4 for global SSI. RMSE means root mean square error, *Num* is the number of observations and *Corr* means correlation coefficient.

Site	Num	Mean ($W\,m^{-2}$)	Bias ($W\,m^{-2}$)	RMSE ($W\,m^{-2}$)	Corr
1	2627	566.5	37.7 (7 %)	87.9 (15 %)	0.948
2	1916	451.0	58.2 (13 %)	111.1 (25 %)	0.901
3	936	528.7	81.5 (15 %)	121.0 (23 %)	0.932
4	2427	491.8	23.0 (5 %)	106.5 (22 %)	0.917
5	2405	499.9	59.6 (12 %)	101.4 (20 %)	0.942
6	1985	556.0	61.8 (11 %)	110.0 (20 %)	0.918
7	2747	714.9	15.5 (2 %)	69.4 (10 %)	0.966
8	1605	542.4	87.1 (16 %)	132.5 (24 %)	0.917

5. CONCLUSION

Compared to current methods (Rigollier et al., 2004), the Heliosat-4 method should not only produce total global irradiance, but also direct and diffuse components, and spectral distribution. First results show that the RMSE attained by the Heliosat-4 method is fairly similar to that attained by current methods. These tests are very encouraging. A strong drawback is the overestimation. Several causes may be invoked: the ground albedo was set to an arbitrary value that may not be the correct one, the spectral variation of the aerosol optical depth is not taken into account as we used only $\tau_{aer550nm}$, as well as the aerosol type. It is also believed that a better modeling of the cloud extinction can be done if cloud effective radii are known with subsequent more accurate assessments.

This first prototype of the Heliosat-4 method shows promises. It demonstrates that principles are sound. There is space for improvements and the authors are confident that the Heliosat-4 method will reach a satisfactory quality.

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