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THE METHOD HELIOSAT-2 FOR DERIVING SHORTWAVE SOLAR RADIATION FROM SATELLITE IMAGES

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ABSTRACT

This article presents the method Heliosat-2 that converts observations made by geostationary meteorological satellites into estimates of the global irradiation at ground level. This new version integrates the knowledge gained by various exploitations of the original method Heliosat and its varieties in a coherent and thorough way. It is based upon the same physical principles 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 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 method Heliosat-2 is applied to Meteosat images of Europe for the months of January 1995, April 1995 and July 1994. Pyranometric measurements performed by thirty-five meteorological stations are used to assess the performances that are close to those of Heliosat-1 found in the literature. Possible improvements are discussed.

Keywords: turbidity, atmosphere optics, radiation, image processing, meteorology, mapping, albedo, cloud, clearness index, software, Meteosat

1 NOMENCLATURE

t time.

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(i, j) space coordinates of a pixel in an image.

q_S sun zenithal angle for the pixel under concern.

I_0 solar constant, equal to 1367 W m^{-2}.

e correction used to allow for the variation of sun-earth distance from its mean value.

$G^t(i,j)$ and $D^t(i,j)$ respectively the horizontal global and diffuse irradiances at ground level, in W m^{-2}.

$G_c^t(i,j)$ and $D_c^t(i,j)$ respectively the horizontal global and diffuse irradiances at ground level under clear sky, in W m^{-2}.

$G_h(i,j)$ and $D_h(i,j)$ respectively the horizontal global and diffuse hourly irradiations at ground level for the hour, i.e. the integral of the irradiance observed during one hour (Wh m^{-2}). Similar notations hold for the daily irradiations, with a subscript *d*.

$G_{ch}(i,j)$ and $D_{ch}(i,j)$ respectively the horizontal global and diffuse hourly irradiations at ground level under clear sky for the hour *h* (Wh m^{-2}). Similar notations hold for the daily irradiations, with a subscript *d*.

$K_c^t(i,j)$ clear-sky index (unitless).

$T_L(AM2)$ Linke turbidity factor for a relative air mass *m* equal to 2 (unitless).

m relative optical air mass.

$d_R(m)$ integral Rayleigh optical thickness.

T_{rB} transmission function for beam radiation (unitless).

T_{rd} transmittance at zenith for the diffuse component and $F_d(q_S)$ the angular correction (unitless).

$L^t(i,j)$ radiance observed by the spaceborne sensor, expressed in W m^{-2} st^{-1}.

I_{0met} total irradiance in the visible channel for the various Meteosat sensors, that is the result of the convolution of the spectral distribution of I_0 by the spectral sensitivity curve of the radiometer.

$r^t(i,j)$ apparent albedo observed by the spaceborne sensor.

$r^t_{cloud}(i,j)$ apparent albedo observed by the spaceborne sensor over the brightest clouds (unitless) and is a quantity specific to the method Heliosat.

$r^t_{eff}(i,j)$ effective albedo for clouds (unitless).

$r^t_g(i,j)$ apparent albedo observed by the spaceborne sensor over the ground under clear skies (unitless).

q_v satellite viewing angle, formed by the normal to the ground and the direction of the satellite for the pixel under concern. It is the complement to 90° of the satellite altitude angle above horizon.

y difference between the sun and satellite azimutal angles.

b(t) calibration coefficient and is the radiance measured when viewing darkness (Rigollier *et al.* 2002), in W m^{-2} st^{-1}.

$n^t(i,j)$ cloud index (unitless).

2 INTRODUCTION

Several authors have shown the potentialities of the images of the Earth taken by the meteorological satellites for the mapping of the global irradiation impinging on a horizontal surface at the ground level. Zelenka *et al.* (1992, 1999) and Perez *et al.* (1997) demonstrate that for the best methods and for pixels of size of 10 km or so, the irradiation assessed by satellite is better than that estimated by the means of an interpolation technique applied to measurements performed at meteorological stations as soon as the distance to the stations is greater than 34 km for the hourly irradiation and 50 km for the daily irradiation.

Many methods were developed especially in the years '80s. Among them was the method called Heliosat-1 (Cano 1982; Cano *et al.* 1986; Michaud-Regas 1986; Diabaté 1989), one the most accurate as shown by several authors (Grüter *et al* 1986; Raschke *et al.* 1991). It was simple enough to widely disseminate in the world (Diabaté *et al.* 1988a b, 1989; Wald *et al.* 1992). It became popular and several modifications were proposed (Moussu *et al.* 1989; Obrecht 1990; Zelenka *et al.* 1992, 1999; Beyer *et al.* 1996; Fontoynont *et al.* 1997; Iehlé *et al.* 1997; Ineichen, Perez 1999).

There are several empirical parameters in the method Heliosat-1, especially in the computation of the apparent albedoes of the ground and clouds and normalization of the digital counts. The relationship between the cloud index and the clearness index is empirically defined and its parameters are computed by the means of a comparison between the cloud index and measurements made by meteorological stations in the area under concern. All these parameters were well tuned during the construction of the method or of its varieties using ground-based measurements and this explains the good results attained by the authors. Table 1 gives the root mean square error (RMSE) reported by authors having developed a variety of the Heliosat-1 method and using measurements for tuning parameters (Rigollier, 2000). In all cases, adjustment is made with a null bias. The errors are obtained by subtracting satellite-derived assessments from ground measurements performed in the meteorological network at a coincident location and coincident time.

Type	*Period*	*RMSE*	*Comments*
Hourly irradiation	May 1979	120 (16 %)	Cano (1982), France
	Year 1983	92 (10 %)	Michaud-Regas (1986), France
	Year 1984	98 (16 %)	
	Year 1983	64 (7 %)	Diabaté *et al.* (1988a), France
	May-June 1993	95 (N/A)	Beyer *et al.* (1996), Germany
	June-July 1996	58 (9 %)	Dribssa *et al.* (1999), Italy
Daily irradiation	Years 1983-1985	~ 370 (11 %)	Diabaté (1989), France
	Years 1994-1996	N/A (4-8 %)	Sidrach de Cardona *et al.* (2002), Spain

Table 1. Errors (RMSE, in Wh m^{-2}) reported by authors having developed a method using the Heliosat-1 principles. N/A: Not Available

However, when applied to other areas, or other periods, the accuracy, expressed as bias and RMSE in percentage of the mean irradiation, is usually lower than claimed by the inventors (Table 2). For example, one may note that the biases are not negligible in many cases. One may also remark in the first two rows that the biases found by Diabaté for two different periods over the same area differ largely: -7 % in 1983 and –1 % for 1984 and 1985. Using the same parameters than Diabaté, Obrecht and Raschke found biases in monthly means of daily irradiation that range from –8 to –29 % for various parts of Sahel. This table clearly shows that modifications of the method Heliosat-1 are necessary to ensure that any correct implementation should lead to similar performances.

Type	*Reference*	*Bias*	*RMSE*
Hourly irradiation	Diabaté (1989) (France, year 1983)	-7 %	14 %
	Diabaté (1989) (France, years 1984 and 1985)	-1 %	18 %
	Satel-Light project (CEC, DG 12) (various versions - 3 independent assessments per version) (Fontoynont *et al.* 1997)	~ 10 %	~ 30 %
	Zelenka *et al.* (1999) (Europe, Heliosat-1/Zelenka)	1 %	23 %
	Hammer (2000) (Germany, Heliosat-1/EHF)	5 %	30 %
	Olseth, Skarveit (2001) (Bergen, Norway, 1996-1997, Heliosat-1/EHF)	1 %	25 %
	Dumortier (2003) (one site in France, ½ hour, 1986-2000, Heliosat-1/EHF)	1 %	21 %
Daily irradiation	Obrecht (1990) (Sahel, June 1984)	-2 %	9 %
	Zelenka *et al.* (1992) (Heliosat-1/Zelenka)	- 10 %	16 %
	Perez *et al.* (2002) (USA, 1999, Heliosat-1/Zelenka)	- 1 %	16 %
	Hammer (2000) (Germany, Heliosat-1/EHF)	5 %	16 %
	Dumortier (2003) (Lyon, France, ½ hour, 1986-2000, Heliosat-1/EHF)	2 %	9 %
	Beyer (pers. communication, Brazil, GOES satellite)	~ 3 %	~ 14 %
Monthly mean of hourly irradiation	Heidt *et al.* (1998) (Germany)	N/A	19 %
	Diabaté (1989) (France)	N/A	10 %
Monthly mean of daily irradiation	Obrecht (1990) (Burkina-Fasso, year 1985)	-29 %	N/A
	Obrecht (1990) (Senegal, year 1986)	-9 %	10 %
	Solar Radiation Atlas of Africa (Heliosat) (Raschke *et al.* 1991)	-8 %	10 %
	Heidt *et al.* (1998)	N/A	10 %
	Petrarca *et al.* (1999) (Italy, 1994-1997)	N/A	7 %
	Hammer (2000) (Germany, Heliosat-1/EHF)	5 %	8 %

Table 2. Accuracy of the method Heliosat-1 (relative values of bias and root mean square error RMSE) as found in the literature. A positive bias means under-estimation. Heliosat-1/Zelenka means the version made by A. Zelenka, and Heliosat-1/EHF that of the EHF of the University of Oldenburg. Adapted from Rigollier (2000).

The purpose of the present paper is to present a new version, called Heliosat-2, which integrates the knowledge gained by these various exploitations of the original method and its varieties in a coherent and thorough way.

The various empirical parameters present in the method Heliosat-1 are now expressed using physical laws and there is no need for coincident pyranometric measurements to tune these parameters. The major motivations for creating this new version were to improve the capabilities of the method to process any type of data taken in the broadband visible range by geostationary meteorological satellites, including large time-series of images taken by different sensors, and to improve the implementation of the method by reducing the number of empirical parameters.

3 THE NEW METHOD HELIOSAT-2

Given the good fundamentals of the method Heliosat-1, it was decided to keep it principle, that is the construction of a "cloud index" resulting from a comparison of what is observed by the sensor to what should be observed over that pixel if the sky were clear, which is related to the "clearness" of the atmosphere. Actually, this principle is commonly adopted when the only inputs are images taken in the visible broad range (Pastre, 1981; Möser, Raschke, 1983, 1984; Cano *et al.* 1986; Stuhlmann *et al.* 1990; Delorme *et al.* 1992; Colle *et al.* 1999). Inputs to the method Heliosat-2 are not numerical counts of the satellite image, like in Heliosat-1. These counts are calibrated and thus converted into radiances L, in W m^{-2} sr^{-1}. This permits to take into account the change of sensor, gain and calibration in a time-series. Hence, large time-series spanning over several changes of sensors and satellites may be processed, enhancing the interest of the Heliosat method in climatology. It also contributes to reduce drastically the number of empirical parameters since many of them would now be expressed using known physical laws and parameters. For the Meteosat data, we adopted the calibration coefficients proposed by Rigollier *et al.* (2002) and available on the Web site www.helioclim.net.

3.1 The cloud index

The cloud index $n^t(i,j)$ is defined at instant t and for pixel (i, j) as:

$$n^t(i,j) = [r^t(i,j) - r^t_g(i,j)] / [r^t_{cloud} - r^t_g(i,j))] \quad (1)$$

In this equation, $r^t(i,j)$ is the reflectance, or apparent albedo, observed by the spaceborne sensor for the time t and the pixel (i, j): $r^t(i,j) = r^t(i,j) = p\, L^t(i,j) / I_{0met}\, e(t) \cos q_S\, (t,i,j)$, where $L^t(i,j)$ is the observed radiance, q_S is the sun zenithal angle, and I_{0met} is the total irradiance in the visible channel for the various Meteosat sensors (Rigollier *et al.* 2002). $r^t_{cloud}(i,j)$ is the apparent albedo of the brightest clouds, and $r^t_g(i,j)$ is the apparent albedo of the ground under clear skies.

Iehlé *et al.* (1997) and Rigollier (2000) showed the importance of the model used for modeling the clear-sky irradiation. Using different models, these authors found discrepancies larger than 200 Wh m^{-2} between the retrieved values of hourly global irradiation. The clearer the skies, the larger the discrepancies. Following the conclusions of Rigollier *et al.* (2000), we adopt the clear sky models of the 4th European Solar Radiation Atlas (ESRA 2000). The ESRA proposes two sets of models, each providing the global value *G* and the beam and diffuse components. One is best suited for the assessment of the irradiance. The other should be preferred for the computation of hourly irradiation and daily sum of irradiation. For the sake of conciseness, we direct the reader to the ESRA (2000) or Rigollier *et al.* (2000) for the detailed description of these models and their equations. This should be completed by the revision proposed by J. Page and J. Remund and reported in Geiger *et al.* (2002). The inputs to these models are the Linke turbidity factor for an air mass of 2, $T_L(AM2)$, and the elevation of the site, besides the parameters related to the solar geometry.

The reflectance observed by the sensor r^t under clear skies is a function of r^t_g, q_S, the satellite zenithal angle q_v, and the difference, y, of the sun and satellite azimutal angles. At the first order, given the large size of the pixel (> 1 km), the multiple reflection and scattering effects are negligible and we can write (Tanré *et al.* 1990):

$$r^t(i,j) = r^t_{atm}(q_S, q_v, y) + r^t_g(i,j)\, T^t(q_S)\, T^t(q_v) \tag{2}$$

where $r^t_{atm}(q_S, q_v, y)$ is the intrinsic reflectance of the atmosphere, $T^t(q_S)$ and $T^t(q_v)$ are the global transmittances of the atmosphere for respectively the incident and upward radiation.

The intrinsic reflectance of the atmosphere, also called the path reflectance, is caused by the scattering of the incident and upward radiation towards the sensor. If the scattering by the atmosphere is isotropic and homogeneous, it is conceivable that the path radiance L_{atm} reaching the sensor can be modeled in the same way than the path radiance reaching the ground. This was checked by Rigollier (2000) by the means of numerical simulations of the radiative transfer in the atmosphere. L_{atm} can be expressed using the expression of the diffuse irradiance under clear sky at ground level, D_c, obtained by the ESRA model:

$$L_{atm} = (D_c / p)\, (I_{0met} / I_0)\, (<\cos q_V> / \cos q_V)^{0,8} \tag{3}$$

The factor *p* permits to convert an irradiance D into radiance. The ratio (I_{0met} / I_0) normalizes the extraterrestrial irradiance I_0 to the Meteosat sensor case. Following Beyer *et al.* (1996), the ratio $(<\cos q_V> / \cos q_V)^{0,8}$ empirically corrects for the satellite zenithal angle without bias ($<\cos q_V> = 0.5$).

The global transmittance of the atmosphere T^t is the sum of the direct (or beam), Tr_B, and diffuse, Tr_D, transmittances that can be expressed by the means of the ESRA model as:

$$Tr_B(q_S) = \exp(-0.8662\, T_L(AM2)\, m\, d_r(m)) \tag{4}$$

$$Tr_D(q_S) = T_{rd}(T_L(AM2))\ F_d(q_S,\ T_L(AM2))$$

where m is the air mass, $d_r(m)$ the integral Rayleigh optical thickness, $T_{rd}(T_L(AM2))$ is the transmittance at zenith and $F_d(q_S,\ T_L(AM2))$ the angular correction.

According to the principle of reciprocity, the formulations of the downward and upward transmittances are identical:

$$T(q_S) = Tr_B(q_S) + Tr_D(q_S) \qquad (5)$$

$$T(q_v) = Tr_B(q_v) + Tr_D(q_v)$$

3.2 The apparent ground albedo r_g and apparent cloud albedo r_{cloud}

Using Equation 2, one may define a quantity $r^{*t}(i,j)$ that is a ground albedo if the sky were clear at the instant t.

$$r^{*t}(i,j) = [\ r^t(i,j) - r_{atm}(q_S,q_v,y)]\ /\ T(q_S)\ T(q_v) \qquad (6)$$

The ground albedo $r_g{}^t(i,j)$ is in principle the minimum value in a time-series of $r^{*t}(i,j)$ since it is assumed that the presence of a cloud increases the apparent albedo. However, some artifacts should be eliminated. The analysis of several years of images from Meteosat shows that it happens in day time that some pixels exhibit very low radiances $L^t(i,j)$, similar to those observed during the night, while the sun is well above the horizon. A constraint is imposed to avoid such cases; the radiance should be greater than 3 percent of the maximal radiance that can be observed by the sensor:

$$L^t(i,j)\ ³\ 0.03\ I_{0met}(t)\ /p + b(t) \qquad (7)$$

where $b(t)$ is the calibration coefficient, and more exactly the radiance measured when viewing darkness (Rigollier *et al.* 2002).

The time series of $r^{*t}(i,j)$ is restricted to the instants for which q_S is less than the maximum of 50° and (2 $q_S{}^{noon}$ / 3), where $q_S{}^{noon}$ is the angle observed at noon, remembering that q_S is less than 75° in any case. Once the time series established, the first and second minima are searched. The absolute minimum is subject to undetected defects in the original image and is more variable than the second minimum. Therefore, we set the ground albedo $r_g(i,j)$ for this period to the second minimum.

The period of the time-series should be the shortest as possible in order to take into account the rapid variations of the ground albedo, if any. In a real-time operational mode, a moving period may be adopted. Compared to the method Heliosat-1, wherein it is preferable to have one estimate of the ground albedo per slot (i.e., the instants of acquisition by the sensor), the accurate correction of the effects of the sun and satellite angles permits to merge all the slots into the time-series. Thus, the period may be shortened. There is only one map of r_g and this map may be used for all slots. Note that Equation 2 assumes that the ground is of Lambertian nature, i.e. the reflectance does not depend on q_S, q_V and y. Vermote *et al.* (1994) propose several bi-directional models to consider these effects. Following Hammer (2000) or Perez *et al.* (2002), defining r_g for each slot is a mean to take into account the non-Lambertian nature. Such elements may be accommodated into the method Heliosat-2.

The retrieved ground albedo is actually a ground albedo and not an approximate quantity like in Heliosat-1. This permits on the one hand to perform checking and monitoring of the method, even on an operational basis. On the second hand, it helps in solving the problem of the constant cloud cover over a pixel or a group of pixel. In that case, the minimal value will correspond to a cloudy instant. Using external knowledge of the expected albedo together with image processing techniques applied to the time-series of the checked ground albedoes, one may detect such cases and compute the likely value.

Solutions were proposed to tackle the case of the appearance of snow (Zelenka 2001, 2003) or the specular reflection on the sun on ground (Perez *et al.* 2002). They may be introduced in the method Heliosat-2. The specular reflection on the ocean is dealt with by Lefèvre *et al.* (2002) within the method Heliosat-2.

The apparent albedo of the clouds r_{cloud} is defined by Cano (1982) as the typical value for the brightest clouds. The effective cloud albedo r_{eff} depends upon the sun zenithal angle. We derive the following model from the drawings in Taylor, Stowe (1984a):

$$r^t_{eff}(i,j) = 0.78 - 0.13\ [1 - \exp(-4 \cos(q_S)^5] \qquad (8)$$

The parameter r_{cloud} is to be compared to the quantities $r^{*t}(i,j)$ to compute the cloud index n: r_{cloud} is not an actual albedo of cloud. For $r^{*t}(i,j) = r^t_{cloud}(i,j)$, the cloud index n should be equal to unity. Following Equation 6, we define the apparent cloud albedo $r^t_{cloud}(i,j)$ as:

$$r^t_{cloud}(i,j) = [\ r^t_{eff}(i,j) - r^t_{atm}(q_S,q_v,y)] \ /\ T(q_S)\ T(q_v) \qquad (9)$$

Two constraints are added, gained from Bauer (1996) and our own experience:

$$r^t_{cloud}(i,j) > 0.2, \text{ otherwise } r^t_{cloud}(i,j) = 0.2 \qquad (10)$$

$$\text{and } r^t_{cloud}(i,j) < 2.24\ r_{eff}(i,j), \text{ otherwise } r^t_{cloud}(i,j) = 2.24\ r^t_{eff}(i,j)$$

The value 2.24 is the largest anisotropy factor observed by Taylor, Stowe (1984b) for the present geometrical configuration sun-pixel-sensor and thick water cloud.

3.3 Computing the hourly and daily irradiation

The clear-sky index K_{ch} is equal to the ratio of the hourly global irradiation at ground on a horizontal surface G_h to the same quantity but for clear skies G_{ch}:

$$K_{ch} = G_h / G_{ch} \tag{11}$$

Rigollier and Wald (1998) propose the following relationship between n and K_{ch}:

$$\begin{aligned} n^t < -0.2 \quad & K_{ch} = 1.2 \\ -0.2 < n^t < 0.8 \quad & K_{ch} = 1 - n \\ 0.8 < n^t < 1.1 \quad & K_{ch} = 2.0667 - 3.6667\, n^t + 1.6667(n^t)^2 \\ n^t > 1.1 \quad & K_{ch} = 0.05 \end{aligned} \tag{12}$$

This Equation was introduced in the version Heliosat-1/EHF and led to satisfactory results (Hammer 2000). Thus, we also use this relationship in Heliosat-2.

The global daily irradiation $G_d(i,j)$ is computed from the set of hourly irradiations available for that day. The larger the number of images used per day, the lower the level of error. We use the model of Raschke *et al.* (1991) but applied to the clear-sky index instead of the clearness index. Let denote the horizontal daily irradiation for clear sky by $G_{cd}(i,j)$ and the daily clear-sky index by $K_{cd}(i,j)$. $G_d(i,j)$ is then computed from the N assessments of the hourly irradiation $G_h(i,j)$ made during the day:

$$G_d(i,j) = K_{cd}(i,j)\, G_{cd}(i,j) = G_{cd}(i,j) \sum_1^N w_h\, K_{ch}(i,j) \tag{13}$$

where $w_h = G_{ch}(i,j) / \sum_1^N G_{ch}(i,j)$

It comes

$$G_d(i,j) = G_{cd}(i,j) \sum_1^N G_h(i,j) \Big/ \sum_1^N G_{ch}(i,j) \tag{14}$$

For each hour h in the summation, the mean solar elevation for this hour should be greater than 15° for the clear-sky model to be valid.

4 COMPARISON BETWEEN RETRIEVED VALUES AND STATION MEASUREMENTS

Similarly to previous works, hourly and daily irradiations derived from satellite are compared to measurements performed at ground level by pyranometers in meteorological stations (Table 3). The 35 stations were selected in flat areas, in order to avoid the specific errors encountered in mountainous areas. We only used measurements of hourly irradiation greater than 10 Wh m^{-2}, a value typical of the diffuse hourly irradiation for the sunset and sunrise under clear-sky at 60° N. For these hours of very low solar elevation, the measured irradiation 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.

Station name	*WMO id.*	*Latitude*	*Longitude*	*Altitude*	*Country*
Aviemore	03063	57.20	-3.83	220	United Kingdom
Eskdalemuir	03162	55.32	-3.20	242	United Kingdom
Easthampstead / Bracknell	03763	51.38	-0.78	73	United Kingdom
Melle	06430	50.98	3.83	17	Belgium
Uccle	06447	50.80	4.35	100	Belgium
St. Hubert	06476	50.03	5.40	556	Belgium
Caen	07027	49.18	-0.45	78	France
St. Quentin	07061	49.82	3.20	98	France
Reims	07070	49.30	4.03	95	France
Bourges	07255	47.07	2.37	161	France
Macon	07385	46.30	4.80	221	France
Limoges	07434	45.87	1.18	396	France
Carcassonne	07635	43.22	2.32	130	France
Perpignan	07747	42.73	2.87	43	France
Valladolid	08141	41.65	-4.77	734	Spain
Hamburg - Sasel	10141	53.65	10.12	49	Germany
Bremen	10224	53.05	8.80	24	Germany
Seehausen	10261	52.90	11.73	21	Germany
Neubrandenburg	10280	53.55	13.20	73	Germany
Osnabrueck	10317	52.25	8.05	104	Germany
Braunschweig	10348	52.30	10.45	83	Germany
Potsdam	10378	52.37	13.08	107	Germany
Bocholt	10406	51.83	6.53	24	Germany
Kassel	10438	51.30	9.45	237	Germany
Dresden - Wahnsdorf	10486	51.12	13.68	246	Germany
Bonn - Friesdorf	10517	50.70	7.15	65	Germany
Weimar	10555	50.98	11.32	275	Germany
Trier	10609	49.75	6.67	278	Germany
Wuerzburg	10655	49.77	9.97	275	Germany
Coburg	10671	50.28	10.98	331	Germany
Saarbruecken	10708	49.22	7.12	325	Germany
Stuttgart	10739	48.83	9.20	318	Germany
Nuernberg	10763	49.50	11.08	312	Germany
Weihenstephan	10863	48.40	11.70	472	Germany
Budapest / Lorinc	12843	47.43	19.18	138	Hungary

Table 3. List of stations used for the comparison

The satellite data are high resolution images covering Europe and brought to the infrared resolution, that is 5 km at nadir. They are available every half-hour, between 0800 and 1500 UTC, from July 1994 to June 1995. We used only the images acquired for even slots (2, 4...). Only the instants for which the sun elevation is greater than 15°, were kept for the comparison, as it has been said that the description of the physical processes is not valid below that limit. The Linke turbidity factors are those of Angles *et al.* (1998, 1999).

Three months were used for the comparison: January 1995, April 1995 and July 1994. The estimate of the daily irradiation is said valid if at least 5 hourly irradiations are used in the computation in January and April and 8 in July. Note that the limited period for which satellite images are available every day and its asymmetry with respect to the local noon for our stations that are mostly located East of the longitude 0°, leads to bias in the retrieved daily irradiation, since the morning hours are more numerous than those in the afternoon. This is a limitation of our validation.

Most of the published works average the individual satellite assessments on a block of pixels centered on the location of the pyranometer. The size of this block has a strong influence on the comparison (Pinker, Laszlo 1991). Several other attempts, not published in international journals, found similar conclusions and demonstrated that there is not a unique size of pixel aggregate giving the best results. It is possible at one time to get better agreement with one size and at other times better agreement with a different size. Beyer *et al*. (1992) suggested that the local variance might be used as a measure of the spatial heterogeneity and may serve to determine the most appropriate size. Nevertheless, experience shows that compared to a single pixel, averaging over a block decrease the error significantly. Contrary to the other works, we are using a single pixel. The reason to do so is to obtain assessments of the accuracy that are independent upon the size of the aggregate.

Given the two time-series, we compute the difference (measured - estimated):

- for hourly irradiation for a given month, for all the hours, and for the monthly mean of hourly irradiation for a given hour, for all hours,
- for daily irradiation for a given month, for all the days, and for the monthly mean of daily irradiation,
- for the cumulative of the daily irradiation during 5 days and 10 days.

For the monthly means and sums of daily irradiation, we kept only the values that are made from at least 60 % of valid estimates. The differences have been computed and are summarized in Table 4 by the bias, RMSE and correlation coefficient for all stations together.

Information type	*Month*	*Mean value*	*Bias*	*RMSE*	*Correlation coefficient*	*Number of observations*
Hourly irradiation	Jan 95	137	-31 (-23%)	62 (45%)	0.83	5028
	Apr 95	361	2 (0%)	96 (27%)	0.90	8248
	Jul 94	569	1 (0%)	103 (18%)	0.87	8105
Monthly mean of hourly irradiation	Jan 95	142	-33 (-23%)	41(29%)	0.91	160
	Apr 95	361	1 (0%)	41 (11%)	0.94	280
	Jul 94	568	1 (0%)	48 (8%)	0.93	272
Daily irradiation	Jan 95	987	-54 (-5%)	199 (20%)	0.95	344
	Apr 95	3366	175 (5%)	534 (16%)	0.95	1044
	Jul 94	5817	143 (2%)	566 (10%)	0.94	887
Monthly mean of daily irradiation	Jan 95	891	-128 (–14%)	215 (24%)	0.88	20
	Apr 95	3367	175 (5%)	243 (7%)	0.97	35
	Jul 94	5776	192 (3%)	307 (5%)	0.92	34
5-days irradiation (at least 60 % of valid days)	Jan 95	4607	-333 (-7%)	898 (19%)	0.94	75
	Apr 95	16826	878 (5%)	1794 (11%)	0.96	209
	Jul 94	28736	1151 (4%)	2419 (8%)	0.91	202
10-days irradiation (at least 60 % of valid days)	Jan 95	8788	-742 (-8%)	1836 (21%)	0.93	43
	Apr 95	33675	1773 (5%)	3285 (10%)	0.96	104
	Jul 94	57680	2021 (4%)	3454 (6%)	0.92	101

Table 4. Differences between measured and estimated values in Wh m^{-2}. The mean value is that of the ground measurements. The percentages are expressed relatively to this mean value.

The number of observations is large enough, except for the assessment of the monthly mean of daily irradiation in January, where only 20 stations are retained. This may explain why the bias for the mean value (-128) is larger in absolute value than that for the single values (-54).

The bias is negative in January for both hours and days. It is positive in April and July. For these months, the fact that the bias is not equal to 0 for daily values while it is for hourly values may be explained by the limited period of available images as discussed above. The bias may be large in relative values in January (-23%); it indicates that Heliosat-2 overestimates the hourly irradiation for low sun elevations. In addition, one should note that $T_L(AM2)$ influences the bias. As we use typical values of $T_L(AM2)$ for each site and each month, the discrepancies between these values and the actual values lead to errors in assessing mean values of the irradiation. We performed the method Heliosat-2 on the same data but using different $T_L(AM2)$. We found that the bias was sensitive to the selected value of $T_L(AM2)$, the larger discrepancies being found when the sun is low.

The correlation coefficient is high in all cases, the lowest values being observed in January. The RMSE is not constant and increases with the mean value. In relative value, it is the largest in winter (45 % for hourly irradiation) and the smallest in July (18 %). Considering that using a block of 3 per 3 pixels would lead to a decrease of the standard-deviation by 3, thus decreasing the RMSE, we estimate the corresponding relative RMSE as 26, 9 and 6% for January, April and July instead of 45, 27 and 18% reported in Table 4 for hourly irradiation. For daily irradiation, the relative RMSE would be 8, 7 and 4% instead of 20, 16 and 10%. One notes that these values are close to those in Table 1.

5 CONCLUSION

The method Heliosat-2 meets the objectives set up before its development. It is more physically sound than the previous one. All parameters that needed to be tuned for each implementation of the method Heliosat-1 have been removed, set up to constant values, or automatically determined. No ground measurement is used for the development, contrary to the method Heliosat-1 and others. This should ensure a worldwide application of the method Heliosat-2.

The first comparison with ground measurements shows errors that are similar to those reported for Heliosat-1. Further investigations should be performed to better understand the performances and the limitations of Heliosat-2, especially for low sun elevations, and therefore bring possible improvements.

The method Heliosat-2 has the capabilities to process any type of data from geostationary meteorological satellites, including large time-series of images taken by different sensors. It is applicable in real-time or on archives of images, whatever their resolution. By suppressing empirically defined parameters, the implementation is the same for all cases. It facilitates exchange of knowledge and further collective improvements of the method Heliosat-2. Software is freely available at *www.helioclim.net*. Routines are written in C and documented. They permit to implement the method Heliosat-2 (Lefèvre *et al.* 2002).

The method Heliosat-2, as well as all other known methods, cannot perform accurately in areas where the scales of variability of the irradiation are smaller than 2-5 times the size of the pixel. This holds for the mountainous areas, for example.

The gains in accuracy obtained relative to the method Heliosat-1 are not coming from an increase of the dimensionality of the inputs originating from the satellite images, which remain the same. They come from external knowledge: the elevation and the Linke turbidity factor for each pixel of the area to process and some properties of the sensor for the day under concern. The value of the Linke turbidity factor is of primary importance in the method Heliosat-2 since it governs the clear-sky irradiation. It may be a problem, since it is known for a limited number of sites. Some empirical laws help in assessing a value for any place in the world. Remund *et al.* (2003) report on the creation of a database covering the whole world, available at *www.soda-is.com*. Several databases of terrain elevation are available in gridded format depending upon the requested size of the cell. The most known databases are ETOPO5 (5' of arc angle) and GTOPO30 (30" of arc angle) which are covering the whole world.

The method Heliosat-2 may be improved in several points. The clear-sky model does not take into account the diffuse part of the radiation that has been reflected once or more by the ground before impinging on the site under concern. It is known from previous works that this has a little impact for high sun elevations and large size of pixels. In any other cases, low sun elevation or pixel size smaller than approximately 1 km, this physical process should be taken into account (Tanré *et al.* 1990). This implies a modification of the model and the knowledge of the surrounding albedoes, including their bi-directional properties. It would help in solving the problem of the sun elevations less than 15°. Another major point of improvement is likely the relationship between the clear sky index and the cloud index (Equation 12). Gains will be reached if overcast skies may be better modeled.

The snow covering periodically the ground as well as permanent cloud coverage over a site creates problems in preventing from accurate determining the apparent ground albedo. Another source of information is necessary for the daily knowledge of the snow coverage; this is available in certain areas. Zelenka (2001, 2003) developed a promising method based on the observation of the time-series of apparent albedo. As for the permanent cloud coverage, one may use a climatological knowledge of the typical ground albedoes that would be observed without the clouds. These drawbacks were present in the method Heliosat-1.

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