Heliosat 2: an improved method for the mapping of the solar radiation from Meteosat imagery

Christelle Rigollier, Mireille Lefèvre, Sylvain Cros, Lucien Wald

Rigollier C., Lefèvre M., Cros S., Wald L., 2003, Heliosat 2: an improved method for the mapping of the solar radiation from Meteosat imagery. In Proceedings of the 2002 EUMETSAT Meteorological Satellite Conference, Dublin, Ireland, 1-6 September 2002. Published by EUMETSAT, Darmstadt, Germany, pp. 585-592.

HELIOSAT 2: AN IMPROVED METHOD FOR THE MAPPING OF THE SOLAR RADIATION FROM METEOSAT IMAGERY

C. Rigollier, M. Lefèvre, S. Cros and L. Wald

Groupe Télédétection et Modélisation, Ecole des Mines de Paris
B.P. 207 F-06904 Sophia Antipolis, France

ABSTRACT

Solar irradiance at the ground level can be determinated from Meteosat images by the means of several methods. The purpose of this work is to present the method Heliosat 2, an improved version of the well known Heliosat 1 method. Heliosat 1 converts observations made by geostationary meteorological satellites into estimates of the global irradiation at ground level. It was implemented in many places and is routinely used to produce maps. It suffers from some drawbacks, which come from several empirically defined parameters inside the method. The accuracy of the estimates is very sensitive to their tuning during the implementation phase. This method cannot cope with changes in spaceborne radiometers. Consequently, parameters have to be tuned at each change. Four points of improvements were identified. Values in images were calibrated, hence large time-series spanning over several changes of sensors and satellite may be processed. It also permits to adopt known models of the physical processes in atmospheric optics; thus removing the need of empirically defined parameters. A new model of clear sky irradiation was used for a better accuracy of the estimates performed by the method. The computation of the ground albedo and the cloud albedo makes use of recognised models of the radiance and the atmospheric transmittance. The relationship between the cloud index and the hourly global irradiation was modified to better represent the cloudy skies. This new method Heliosat 2 exhibits results that are more accurate than those provided by the method Heliosat 1 by approximately 30 %. Comparisons were made with ground measurements obtained at 35 sites in Europe. For daily irradiation we observed a relative mean square error of less than 200 J. cm^{-2} and 110 J.cm^{-2} for the monthly mean of daily irradiation.

1 INTRODUCTION

Mapping solar radiation at the ground level is an important issue for several applications. The solar energy technologies as the photovoltaic system, thermal solar power plant or optimisation of daylight usage in building need accurate information in solar radiation earth surface repartition. This knowledge is also essential for primary production forecast, photo chemical, meteorological and climatological studies.

Processed with an appropriate method, images from meteorological geosynchronous satellite can produce maps of solar radiation, which are more accurate than those obtained from interpolation of measurements of radiation made at ground level (Perez *et al.* 1997). Among the existing irradiance calculation schemes, the Heliosat algorithm can estimate solar radiation from Meteosat satellite image with satisfactory results (Cano *et al.* 1986, Diabaté *et al.* 1989, Heidt *et al.* 1998). This method was simple enough to be widely disseminated in the world (Diabaté *et al.* 1988, 1989; Wald *et al.* 1992). Nevertheless, this method Heliosat 1 suffers from several drawbacks, which come from several empirically defined parameters inside the method.

Moreover, it cannot cope with changes in spaceborne radiometers, which occur periodically in operational meteorological programmes. Consequently, parameters have to be tuned at each change. To overcome these drawbacks, we developed a new method called Heliosat 2. This method is based on the same physical principles with the possibilities of using known models of the physical processes in atmospheric optics.

First, this paper presents the method Heliosat 1 in its general principles and its potential improvements. It then describes the several developed improvements, which define the method Heliosat 2. Finally, it presents comparisons with ground measurements, which quantify the accuracy of these satellite estimations.

2 THE METHOD HELIOSAT 1

The principle of the method Heliosat 1 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 that commonly adopted when the only inputs are images taken in the visible broad range. It is the one used by several method of proven quality (Pastre, 1981; Möser, Raschke, 1983, 1984; Cano *et al.* 1986; Stuhlmann *et al.* 1990; Delorme *et al.* 1992; Colle *et al.* 1999). At each pixel (*i, j*) of the current image at time *t*, a normalised count $CN^{*t}(i,j)$ is computed as:

$$CN^{*t}(i,j) = (CN^t(i,j) - CN0^t) / [I_0\ \varepsilon(t)\ (\sin \gamma_S(i,j))\ (\sin \gamma_S(i,j))^{0,15}]$$

Where

- $CN^t(i,j)$ is the numerical count observed by the sensor at time *t* for this pixel *(i, j)*, $CN0^t$ being what can be called the sensor zero (the numerical counts are not necessarily calibrated),
- $(\sin \gamma_S)^{0,15}$ is the clear sky transmittance (model of Perrin de Brichambaut, Vauge 1982).

This normalised count $CN^{*t}(i,j)$ is related to the apparent albedo $\rho^t(i,j)$ observed by the spaceborne sensor. In preparation to the determination of the cloud index $n^t(i,j)$, a reference map of the normalised count for clear sky is constructed (Moussu *et al.* 1989). It is also called the normalised count for ground, $CN^*_g(i,j)$. Given a time-series of images, it is evaluated at each pixel in a recursive fashion by minimising the variance between the digital counts and those resulting from the clear sky model, the cloudy cases being eliminated at each step (Cano *et al.* 1986). The cloud index is defined as a function of $CN^*_g(i,j)$, $CN^{*t}(i,j)$, and the typical normalised count of the brightest cloud tops CN^*_{cloud}:

$$n^t(i,j) = [CN^{*t}(i,j) - CN^*_g(i,j)] / [CN^*_{cloud} - CN^*_g(i,j)]$$

The computation of CN^*_{cloud} is performed using the inverse of the algorithm used for determining the reference albedo map and retaining only the cloudy areas. The histogram of this "only cloud" image provides an estimation of CN^*_{cloud}.. The clearness index $KT_h(i,j)$ may be defined for the hour *h* centred on *t* as:

$$KT_h(i,j) = G_h(i,j) / G_{0h}(i,j)$$

where $G_{0h}(i,j)$ is approximated by $I_0\ \varepsilon(t) \sin \gamma_S$, where γ_S is for the middle *t* of the hour. Care should be taken of the sunset and sunrise. Several previous studies did show a linear relationship between the cloud index and the clearness index, where the parameters *A* and *B* are positive and have been determined once for ever (Diabaté *et al*. 1988, Diabaté 1989):

$$KT_h(i,j) = -A\ n^t(i,j) + B$$

This relationship between $KT_h(i,j)$ and $n^t(i,j)$ leads to the computation of the global hourly irradiation $G_h(i,j)$. 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. A model has been proposed by Diabaté (1989), using an analytical law fitted onto climatological hourly values. However most users adopted the following model. Let denote the horizontal daily irradiation outside the atmosphere by $G_{0d}(i,j)$ and the daily clearness index by $KT_d(i,j)$. $G_d(i,j)$ is then computed from the *N* assessments of the hourly irradiation $G_h(i,j)$ made during the day:

$G_d(i,j) = KT_d(i,j)\ G_{0d}(i,j) = G_{0d}(i,j)$ **Erreur !** where w_h = **Erreur !**, it comes: $G_d(i,j) = G_{0d}(i,j)$ **Erreur !**

The method Heliosat 1 is currently used by several institutes in Europe and elsewhere with geostationary satellites like Meteosat (Europe), GOES (USA) or GMS (Japan). This method contains several empirical parameters, especially in the computation of the apparent albedoes of the ground and the clouds. The clear sky model the atmosphere is also expressed by the sole exponent wherever the location. The parameters *A* and *B* in the relationship between $KT_h(i,j)$ and $n^t(i,j)$ may be adjusted by comparison with measurements made at meteorological stations. These parameters were well tuned during the construction of the method or of its varieties and this explains the good results attained by the authors when performing a comparison with ground observations. For example, according to Diabaté (1989), Diabaté *et al.* (1988) or Grüter *et al.* (1986), the typical relative error (RMSE) is about 7-18 percent for the assessment of the hourly irradiation and 10-15 percent for the assessment of the daily irradiation,

3 THE METHOD HELIOSAT 2 DESIGN

The empirically defined parameters in Heliosat 1 should be expressed using physical laws. We propose a new version of this method by introducing external knowledge on the optical state of the atmosphere for each location as supplementary inputs, given the fact the inputs should still be images taken in the visible range of the radiometer. This new version, called Heliosat 2 should improve the capabilities of the method in order to process any type of data from geostationary meteorological satellites, including large time-series of images taken by different sensors. Its implementation should be improved and applicable in real-time or archived data and its accuracy should be improved. Given the good fundamentals of the method Heliosat 1 with respect to the objectives, it was decided to keep its principles, that is the computation of a cloud index *n* from the apparent albedo, the albedo of the ground (*i.e.* without clouds or minimal albedo) and the albedo of the very bright clouds (or maximum albedo). Four points of improvements were identified, in order to meet the objectives expressed above. They are detailed as in the following paragraph. The efforts were aiming at a better quality on a global sense, which means that operational aspects and accuracy of the assessed irradiation were equally treated.

3.1 *Images calibration*

An operational method has been developed, tested and validated for the calibration of the visible channel of the series of satellites of the Meteosat Operational Programme (Rigollier *et al.* 2002). It performs on an automatic basis and is well suited for the processing of large volume of data. It is based upon the analysis of the content of the satellite images. It can likely be used for the calibration of other geostationary satellites having spectral bands similar to Meteosat, such as GOMS, GMS, Insat, and the first GOES series. Daily sets of calibration coefficients are obtained by this method and are used to convert Meteosat digital counts in to radiances.

3.2 *Modelling the clear sky irradiation*

Studies of several clear sky models were performed. Of particular interest are the models of the European Solar Radiation Atlas (ESRA). Rigollier *et al.* (2000) demonstrate that these models could be used in the framework of the Heliosat method. The accuracies of these models are among the best, and the constancy of their performances with respect to different conditions are a clear advantage with the aim of producing a robust method. The accuracy (RMSE) in the assessment of the diffuse hourly irradiation ranges from 11 Wh m^{-2} to 35 Wh m^{-2} for diffuse irradiations up to 250 Wh m^{-2}. The accuracy in the ESRA model is mostly gained by the introduction of the Linke turbidity factor. This factor provides a reasonable estimation for the water vapour and aerosols optical effects. From an operational point of view, the use of the ESRA model implies the knowledge at each pixel of the image, of the Linke turbidity factor and of the ground elevation. Both data can be found on line at *http://www.soda-is.org*.

3.3 *Computation of the cloud index*

The computation of n^t is pending to the determination of the reflectances or albedoes ρ^t_g and ρ^t_{cloud}. In turn, these reflectances are computed from the analysis of a time-series of the reflectance observed by the sensor ρ^t. The reflectance observed by the sensor ρ^t under clear skies is a function of the reflectance of the ground, ρ^t_g, the sun zenithal angle, θ_S, the viewing angle, θ_v, and the difference, ψ, of the sun and satellite azimuth angles. At the first order, given the large size of the pixel, the multiple reflection and scattering effects are negligible. Assuming a Lambertian ground, the reflectance observed by the sensor is (Tanré *et al.* 1990):

$$\rho^t(i,j) = \rho^t_{atm}(\theta_S, \theta_v, \psi) + \rho^t_g(i,j)\, T^t(\theta_S)\, T^t(\theta_v)$$

where $\rho^t_{atm}(\theta_S, \theta_v, \psi)$ is the intrinsic reflectance of the atmosphere, caused by the scattering of the incident and upward radiation towards the sensor. The parameters $T^t(\theta_S)$ and $T^t(\theta_v)$ are the global transmittances of the atmosphere for the incident and upward radiation. The principle of reciprocity implies that the same formulation applies to both transmittances. Numerous works show that the ground is not exactly of Lambertian nature. Vermote *et al.* (1994) propose several bi-directional models to consider these effects in the simulation of $\rho^t(i,j)$. From an operational point of view, the method Heliosat 2 cannot consider these effects by lack of information. In particular, it would imply the knowledge of the landuse for each pixel of the field of view of the satellite Meteosat and of the associated model. The present approach is based upon the modelling of the intrinsic reflectance of the atmosphere, also called the path reflectance, and the atmospheric transmittance. Each term, ρ^t_{atm} and $T^t(\theta_S)$ or $T^t(\theta_V)$ is modelled, resulting into the explicit formulation of ρ^t as a function of θ_S, θ_V, ψ and ρ^t_g. Inversely, this permits to compute ρ^t_g and ρ^t_{cloud}. Assuming that the scattering by the atmosphere is isotropic, it is conceivable that the path radiance L_{atm} reaching the sensor is proportional to the path radiance reaching the ground. Taking account the results, Beyer *et al.* (1996), the path radiance can be expressed using the expression of the diffuse irradiance under clear sky at ground level, D_c:

$$L_{atm} = (D_c / \pi)\ (I_{0met} / I_0)\ (<\cos\theta_V> / \cos\theta_V)^{0,8}$$

Various tests show that the approach is satisfactory, provided it is restricted to zenithal angles and viewing angles less than 75°, as was the case with the method Heliosat 1 (Diabaté 1989; Bauer 1996). It follows that the method Heliosat 2 will be unable in principle to accurately estimate the irradiation north of the latitude 65° N, and south of the latitude 65° S.

3.3.1 *Computation of the ground albedo*

The ground albedo $\rho_g(i,j)$ may be assessed from a time-series of Meteosat observations converted into radiances $L^t(i,j)$. The analysis of several years of images from Meteosat shows that it happens that some pixels exhibit very low radiances, similar to those observed during the night, while the sun is well above the horizon. A constraint is imposed on radiances to avoid such cases; they should be greater than 3 percent of the maximal radiance that can be observed by the sensor:

$$L^t(i,j) \geq 0{,}03\ \textbf{Erreur !} + b(t)$$

where $b(t)$ is the calibration coefficient, and more exactly the radiance measured when viewing darkness. Knowing the Linke turbidity factor and the site elevation, the path radiance is computed:

$$L^t_{atm}(i,j) = \textbf{Erreur !} \quad \text{and} \quad \rho^t_{atm}(\theta_S,\theta_v,\psi) = \textbf{Erreur !}$$

Finally, we get a quantity $\rho^{*t}(i,j)$ that is a ground albedo if the sky were clear at the instant *t*.

$$\rho^{*t}(i,j) = [\ \rho^t(i,j) - \rho_{atm}(\theta_S,\theta_v,\psi)]\ /\ T(\theta_S)\ T(\theta_v)$$

This operation is performed for several images. For each pixel, a time series of $\rho^{*t}(i,j)$ is obtained. To eliminate artefacts in assessing the ground albedo, the time series is restricted to the instants for which the sun zenithal angle θ_S is less than the maximum of 50° and (2 θ_S^{noon} / 3), where θ_S^{noon} is the angle observed at noon, remembering that θ_S is less than 75° in any case. The second minimum of the series of retained reflectances is the ground albedo $\rho_g(i,j)$ for this period. 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. Compared to the method Heliosat 1, 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. In an operational mode, especially when real time is at stake, a moving period may be adopted.

This possibility to have only one albedo map for a period permits to create a background map that allows overcoming the case where at a pixel, no cloudless instant is observed. In that case, the smallest reflectance is that of a cloud and should not be considered as the ground albedo. Prior being declared a ground albedo, the second minimum is compared to the background value. It cannot be less to half this value and cannot be greater than twice this value. If it is the case, it is set to one of these limits. The result is the ground albedo.

3.3.2 *Computation of the cloud albedo*

The albedo of the clouds ρ_{cloud} has been defined by Cano (1982) as the typical value for the brightest clouds. The histogram of cloud albedoes is flat and it is very difficult to characterise this parameter ρ_{cloud} by a statistical quantity, such as a mode or a percentile. Costanzo (1994) or Hammer *et al.* (1997a, b) compute the mean value of the brightest albedoes observed in a time-series of images. The results may depend upon the length of the time-series and of the selected threshold. It should be added that some sites exhibit clear skies during several months (e.g. the Mediterranean basin), making it difficult to find very bright clouds.

The above-mentioned difficulties disappear if one is using calibrated radiances. In this case, we may adopt an actual albedo of the brightest clouds. Rigollier (2000) refers to the maximum value given by Grüter *et al.* (1986) that is 0.9. The effective cloud albedo depends upon the sun zenithal angle. We follow the model proposed by Taylor, Stowe (1984a):

$$\rho_{eff}(i,j) = 0.78 - 0.13\ [1 - exp(-4\ cos(\theta_S)^5]$$

However, the parameter ρ_{cloud} is to be compared to the quantities $\rho^{*t}(i,j)$ that derive from the observed radiances to compute the cloud index n. For $\rho^{*t}(i,j) = \rho^t_{cloud}(i,j)$, the cloud index n should be equal to unity. It follows that the same equation should apply to the effective cloud albedo, leading to the apparent cloud albedo $\rho^t_{cloud}(i,j)$:

$$\rho^t_{cloud}(i,j) = [\ \rho_{eff}(i,j) - \rho_{atm}(\theta_S, \theta_v, \psi)]\ /\ T(\theta_S)\ T(\theta_v)$$

Two constraints are added, gained from experience:

$\rho^t_{cloud}(i,j) > 0.2,$ otherwise $\rho^t_{cloud}(i,j) = 0.2$ and $\rho^t_{cloud}(i,j) < 2.24\ \rho_{eff}(i,j),$ otherwise $\rho^t_{cloud}(i,j) = 2.24\ \rho_{eff}(i,j)$

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.

3.4 *Relationship between the cloud index and the hourly global irradiation*

A linear relationship was assumed between the clearness index KT_h and the cloud index in the method Heliosat 1 (Grüter *et al.,* 1986; Michaud-Regas, 1986) and others (Raschke *et al.,* 1991).
The hourly irradiation is computed as:

$$G_h(i,j) = KT_h(i,j)\ G_{0h}(i,j) = (-A\ n^t(i,j) + B)\ G_{0h}(i,j)$$

According to Diabaté (1989), the coefficients A and B do not depend upon the geographical location but on the time of the day. Three sets of values were defined: one for the morning, one for mid-day and one for the afternoon. Though satisfactory results are obtained, Diabaté (1989) stresses that there is no explanation of the variability of the parameters A and B during the day while their variability along the year or with the latitude is negligible, and questions the validity of this relationship. Beyer *et al.* (1996) underline that the parameter KT_h is not well describing the optical state of the atmosphere: a cloudy sky may have the same KT_h than a turbid clear sky though the radiative flux reaching the spaceborne sensor may be different because of the higher albedo of the cloud or the backscattering effects. They propose to use instead the clear-sky index K_{ch}, which is equal to the ratio of the hourly global irradiation at ground on an horizontal surface G_h to the same quantity but for clear skies G_{ch}:

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

Furthermore, Beyer *et al.* (1996) show that the relationship may be simply written as:

$$K_{ch} = 1 - n$$

with a negligible loss in accuracy. The gain in terms of operating the method is large since it is not necessary to use ground measurements to establish or correct the parameters A and B of the relationship. However, this relationship has some drawbacks that need to be corrected. First, since the apparent albedo of the ground, ρ_g, is not the smallest value that can be observed, it happens that the cloud index n is negative. The relationship predicts a value of K_{ch} greater than 1, which is physically sound up to a limit of approximately 1.2 according to the observations. Secondly, the apparent albedo of the cloud, ρ_{cloud}, is not the greatest value that can be observed and the cloud index n may be larger than 1. It also predicts a value of K_{ch} negative, which is impossible. Actually, observations of the smallest clearness index in Europe for several years show that the minimal value is approximately 0.04 (ESRA, 1984 and 2000). Since

$$K_{ch} = KT_h\ (I_0\ \varepsilon\ sin\ \gamma_S\ /\ G_{ch})$$

Using the model for clear skies of Perrin de Brichambaut, Vauge (1982), we find the minimal value of the clear-sky index, K_{ch}, of approximately 0.05, with an error of approximately 0.01. A careful analysis of many comparisons between measured global hourly irradiations and cloud indices n made in the framework of the project Satel-Light (Fontoynont *et al.*, 1997) show that for overcast skies ($n \geq 0.8$), a linear relationship is inappropriate and underestimates K_{ch}. It is therefore proposed to use instead a quadratic relationship up to $n>1.1$ where the minimal value of K_{ch} of 0.04 is reached. Taking into account these remarks and constraining the relationship and its first derivative to be continuous everywhere, except in $n = 0.2$, the new relationship is the following:

$n^t < -0.2 \quad K_{ch} = 1.2$
$-0,2 < n^t < 0.8 \quad K_{ch} = 1 - n$
$0,8 < n^t < 1.1 \quad K_{ch} = 2.0667 - 3.6667\ n^t + 1.6667(n^t)^2$
$n^t > 1.1 \quad K_{ch} = 0.05$

Figure 4.1 exhibits this relationship, which is made of four parts. The continuity is ensured as well as that of the derivative, except in n = -0.2.

The University of Oldenburg adopted this model in their current version of the method Heliosat 1. Compared to the standard method Heliosat 1, it provides better results (Olseth and Skarveit 1998).

However, though this relationship is more satisfactory than the previous one, the limitation of the cloud index *n* to characterise the optical state of the atmosphere remains. The principle of the method Heliosat 1 is that a difference in global radiation perceived by the method is only due to a change in apparent albedo, which is itself due to an increase of the radiation emitted by the atmosphere towards the sensor. This principle is not always verified. Other parameters may intervene, such as multiple cloud layers and dramatic changes in the ground albedo due to the snowfall or the shadow created by a neighbouring cloud.

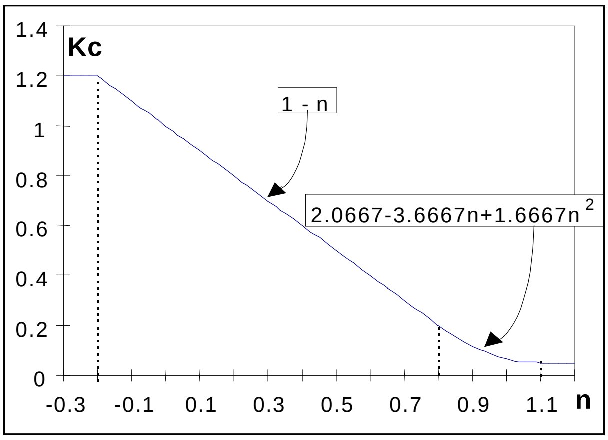

Figure 4.1. Relationship between the clear-sky index K_{ch} and the cloud index n

4 COMPARISON BETWEEN RETRIEVED VALUES AND STATION MEASUREMENTS

A comparison between irradiation values retrieved by the processing of Meteosat images and measured by ground stations is performed. It permits to measure the accuracy of the method Heliosat 2 Thirty-five stations from Europe were selected for the comparison. They were selected in flat areas, in order to avoid the specific errors encountered in mountainous areas. These countries are Belgium, France, Germany, Hungary, Norway, Spain and United Kingdom. The meteorological offices provided global hourly irradiation values. These offices perform a screening for quality check. The formats and units were unified before comparison. Measurements are performed in mean solar time or true solar time. The time of the meteorological measurements is that of the end of the measure. For example, the hourly irradiation at 11 hours is the integral of the irradiance from 10 to 11 hours. The satellite observations are performed in universal time co-ordinated (UTC). Consequently, the initial time series of measurements are converted into other time series expressed in universal time. The time for the satellite observation depends upon the position of the site within the field of view; it can be computed exactly knowing the characteristics of the observing system and is expressed in UTC. For each meteorological station, knowing its longitude, the UTC of the satellite observation T_{sat} is converted into local time t_{sat}. By weighting the two consecutive irradiation values centred on this local time t_{sat} and by assuming that the irradiance is constant within the hour, the estimated hourly value in universal time, $G*_h^{meas}(T_{sat})$, was computed:

$$G*_h^{meas}(T_{sat}) = G*_h^{meas}(t_{sat}) = (t_1 - t_{sat} + 0.5)\, G_h(t_1) + (t_{sat} - t_1 + 0.5)\, G_h(t_1 + 1)$$

where t_1 and t_{sat} are local time expressed in hours, t_1 = Round(t_{sat}), and Round is the rounding operator such as (Round(10.4)=10; Round(10.5)=11 etc.).

The time series of estimated measurements $G*_h^{meas}(T_{sat})$ are hereafter considered as actual measurements. Only were used the measurements of hourly irradiation greater than 10 Wh m^{-2}. This value corresponds to the level of diffuse hourly irradiation for the sunset and sunrise under clear-sky at 60° N in Norway. 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 the validation process.

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, from July 1994 to June 1995. We used only the images acquired for even slots. The satellite data were processed using the method Heliosat 2 Estimates of the global hourly irradiation were thus obtained. Only the estimates, for which the solar zenithal angle is lower than 78°, were kept for the comparison, as it has been said that the description of the physical processes is not valid below that limit.

Three months were used for the comparison: January 1995, April 1995 and July 1994. From each data set of hourly irradiation, and for a given month, the daily irradiation was computed as follows. For the station measurements, we sum up all the hourly irradiations greater than 10 Wh m^{-2}. The estimate is said valid if at least *N* hourly irradiations are used in the computation. *N* is equal to 6 in January and April and to 12 in July. For the high-resolution images, we use the above-described algorithm. The estimate is said valid if at least *N* hourly irradiations are used in the computation. For each hourly irradiation, the mean solar elevation should be greater than 12°. *N* is equal to 5 in January and April and to 8 in July. Given the two time-series, and for all stations together, we compute the difference (measured - estimated). For each parameter, the differences have been computed and are summarised in the table 5.1. The bias is usually useful for assessing the accuracy. For example, it ranges from 23 Wh m^{-2} in July 1994 to -10 in January 1995. However, it strongly depends upon the selected stations and the selected period and has no great statistical significance in this context because the field is not stationary. Consequently, only the RMSE is dealt with in the following. This parameter is more stable. The results are good compared to the expected accuracy for the Heliosat-II method The correlation coefficient is high in all cases. The relative increase in accuracy is approximately 30 % compared to that observed with the Heliosat 1 method.

Information type	Month	Mean value	RMSE	Correlation coefficient	Number of observations
Hourly irradiation	Jan 95	137	62	0.83	5028
	Apr 95	361	96	0.90	8248
	Jul 94	569	103	0.87	8105
Daily irradiation	Jan 95	987	199	0.95	344
	Apr 95	3366	534	0.95	1044
	Jul 94	5817	566	0.94	887
Monthly mean of hourly irradiation	Jan 95	142	41	0.91	160
	Apr 95	361	41	0.94	280
	Jul 94	568	48	0.93	272
Monthly mean of daily irradiation	Jan 95	891	215	0.88	20
	Apr 95	3367	243	0.97	35
	Jul 94	5776	307	0.92	34

Table 5.1 Differences between measured and estimated values in Wh m^{-2}

5 CONCLUSION

We developed a new version of the Heliosat algorithm. It presents results that are more accurate than the previous method. 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. By suppressing empirically defined parameters, the implementation is the same for all cases and the gain in operation is important. Only one map of the ground albedo will be necessary, instead of having one map per slot as presently in the most advanced versions of the method Heliosat 1. The parameterisations of the cloud and ground albedoes request the knowledge of the Linke turbidity factor and the elevation for each pixel of the Meteosat image to be processed. This constraint is not an additional one, since the model of the clear sky irradiation also requests these information. The development of this method did not use any ground measurement contrary to the method Heliosat 1 and others. This ensures a worldwide application of the method Heliosat 2. It is currently operative on the series of Meteosat images in B2 format, spanning from 1985 awards and covering Europe, Africa and Atlantic Ocean (Lefèvre *et al.* 2002). The times series are available on line at http://www.soda-is.org.

The method Heliosat 2 may be improved in several points. Similarly to the method Heliosat-I, the assessments are satisfactorily for sun zenithal angles larger than 75 - 78°. Though applicable, it produces larger errors. The clear sky model does take into account the diffuse part of the radiation that has been reflected by the ground before impinging on the site under concern. This knowledge could help in solving the problem of low sun elevation. Another major point of improvement is the relationship between the clear sky index and the cloud index. Gains will be reached if superimposed cloud layers may be identified. Determination of ground albedo creates problem when the snow covers periodically a site as well as a permanent cloud coverage. Areas where the scales of variability are really smaller than the pixel size like mountainous areas cannot be treated accurately. 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. They come from external knowledge, that is the elevation and the Linke turbidity factor for each pixel.

References:

BEYER H.G., COSTANZO C., HEINEMANN D., 1996, Modifications of the Heliosat procedure for irradiance estimates from satellite images. *Solar Energy*, **56**, 3, 207-212.
CANO D., MONGET J.M., ALBUISSON M., GUILLARD H., REGAS N., WALD L., 1986, A method for the determination of the global solar radiation from meteorological satellite data, *Solar Energy*, **37**, 31-39.
COLLE S., LUNA DE ABREU S., COUTO P., MANTELLI S., 1999, Distribution of solar irradiation in Brazil derived from geostationary satellite data, In Proceedings of the Solar World Congress ISES 1999, Jerusalem, July 4-9 1999.
COSTANZO C., 1994, Bestimmung der solaren Einstrahlung am Boden aus Meteosat-Daten-Untersuchung und Erweiterung einer empirischen Methode. Diploma thesis, Physic Dept., Carl von Ossietzky University, Oldenburg, Germany.
DELORME C., GALLO A., AND OLIVIERI J., 1992, Quick use of Wefax images from Meteosat to determine daily solar radiation in France, *Solar Energy*, **49** (3), 191-197.
DIABATÉ L., DEMARCQ H., MICHAUD-REGAS N., WALD L., 1988a, Estimating incident solar radiation at the surface from images of the Earth transmitted by geostationary satellites: the Heliosat Project, *International Journal of Solar Energy*, **5**, 261-278.
DIABATÉ L., MOUSSU G., WALD L., 1988b, An operational tool for the fine-scale mapping of the incident solar radiation using satellite images : the Heliosat station. In : Proceedings of the 1988 annual meeting of the American Solar Energy Society, pp. 11-17.
DIABATÉ L., MOUSSU G., WALD L., 1989, Description of an operational tool for determining global solar radiation at ground using geostationary satellite images, *Solar Energy*, **42**, 201-207.
ESRA, *European solar radiation atlas*, 1984. Second and Extended Edition, Vols I et II. Edited by Palz W., Commission of the European Communities, DG Science, Research and Development, Report N° EUR 9344, Bruxelles.
ESRA, *European solar radiation atlas*, 2000. Fourth edition, includ. CD-ROM. Edited by J. Greif, K. Scharmer. Scientific advisors: R. DOGNIAUX, J. K. PAGE. AUTHORS: L. WALD, M. ALBUISSON, G. CZEPLAK, B. BOURGES, R. AGUIAR, H. LUND, A. JOUKOFF, U. TERZENBACH, H. G. BEYER, E. P. BORISENKO. Published for the Commission of the European Communities by Presses de l'Ecole, Ecole des Mines de Paris, Paris, France.
FONTOYNONT M., DUMORTIER D., HEINEMANN D., HAMMER A., OLSETH J.A., SKARVEIT A., INEICHEN P., REISE C., PAGE J., ROCHE L., BEYER H.G., WALD L., 1997, Satel-Light, Processing of Meteosat data for the production of high quality daylight and solar radiation data available on a World Wide Web Internet server, Mid-term progress report JOR3 - CT 95 - 0041, Project Satel-Light, for the Commission of the European Communities, Ecole Nationale des Travaux Publics de l'Etat, Vaulx-en-Velin, France.
GRÜTER W., GUILLARD H., MÖSER W., MONGET J.M., PALZ W., RASCHKE E., REINHARDT R.E., SCHWARZMANN P., WALD L., 1986, Solar Radiation Data from Satellite Images, Solar Energy R&D in the European Community, Series F, Volume 4, D. Reidel Publishing Company, 100 p.
HAMMER A., HEINEMANN D., WESTERHELLWEG A., 1997a, Normalisation of Meteosat counts - an investigation basing on ocean pixels, Satel-Light project for the Commission of the European Communities. Carl von Ossietzky University, Oldenburg, Germany.
HAMMER A., DEGNER T, HEINEMANN D., WESTERHELLWEG A., 1997b, Modifications of the Heliosat method coud index improvements, detection of snow cover and results of radiative transfer calculations, Satel-Light project for the Commission of the European Communities. Carl von Ossietzky University, Oldenburg, Germany.IEHLÉ A., LEFÈVRE M., BAUER O., MARTINOLI M., WALD L., 1997, Meteosat: A valuable tool for agro-meteorology, Final report for the European Commission, Joint Research Centre, Ispra, Italy.
LEFÈVRE M., RIGOLLIER C., CROS S., WALD L., Toward a solar climatological database: the HelioClim project, *In* Proceedings of the EARSeL conference: Geoinformation for European wide integration, June 4-6 2002, Prague, Czech Republic.
MICHAUD-REGAS N., 1986, Mise en oeuvre et validation d'une méthode opérationnelle et automatique pour l'évaluation d'atlas solaires en Europe à l'aide de mesures satellitaires Meteosat. Thèse de Doctorat, Université Paris VII, Paris, France.
MÖSER W., RASCHKE E., 1983, Mapping of global radiation and of cloudiness from Meteosat image data: theory and ground truth comparisons, *Meteorologische Rundschau*, **36**, 33-41.
OLSETH, J.A., A. SKARTVEIT 1998, High latitude global and diffuse radiation estimated from METEOSAT data. In: proceedings. of the 2nd European Conference on Applied Climatology, ECAC 98, 19-23 October 1998, Vienna, Austria
PASTRE C., 1981, Développement d'une méthode de détermination du rayonnement solaire global à partir des données Meteosat, *La Météorologie*, VIe série N°24, mars 1981.
PEREZ R., SEALS R., ZELENKA A., 1997, Comparing satellite remote sensing and ground network measurements for the production of site/time specific irradiance data, *Solar Energy*, **60**, 89-96.
PERRIN DE BRICHAMBAUT C., VAUGE C., 1982, *Le gisement solaire : Evaluation de la ressource énergétique*, Paris: Technique et documentation (Lavoisier).
RIGOLLIER C., BAUER O., WALD L., 2000, On the clear sky model of the 4th European Solar Radiation Atlas with respect to the Heliosat method, *Solar Energy*, **68** (1), 33-48.
RIGOLLIER C., LEFÈVRE M., BLANC P., WALD L., 2002, The operational calibration of images taken in the visible channel of the Meteosat-series of satellites. To be published by Journal of Atmospheric and Oceanic Technology..
STUHLMANN R., RIELAND M., RASCHKE E., 1990, An improvement of the IGMK model to derive total and diffuse solar radiation at the surface from satellite data, *Journal of Applied Meteorology*, **29**, 596-603.
TANRÉ D., DEROO C., DUHAUT P., HERMAN M., MORCRETTE J.J., PERBOS J., DESCHAMPS P.Y., 1990, Description of a computer code to simulate the satellite signal in the solar spectrum: the 5S code, *International Journal of Remote Sensing*, 11(4), 659-668.
TAYLOR V.R., STOWE L.L., 1984a, Reflectance characteristics of uniform Earth and cloud surfaces derived from Nimbus 7 ERB, *Journal of Geophysical Research*, **89**(D4), 4987-4996.
TAYLOR V.R., STOWE L.L., 1984b, Atlas of reflectance patterns for uniform Earth and cloud surfaces (Nimbus 7 ERB – 61 days), NOAA Technical Report NESDIS 10, July 1984, Washington, DC, USA.
VERMOTE E., TANRÉ D., DEUZÉ J.L., HERMAN M., MORCRETTE J.J., 1994, Second Simulation of the Satellite Signal in the Solar Spectrum (6S), 6S User Guide, NASA-Goddard Space Flight Center - Code 923, Greenbelt, USA.
WALD L., WALD J.-L., MOUSSU G., 1992, A technical note on a low-cost high-quality system for the acquisition and digital processing of images of WEFAX type provided by meteorological geostationary satellites. *International Journal of Remote Sensing*, 13, 5, 911-916.
ZELENKA A., CZEPLAK G., D'AGOSTINO V., JOSEFSON W., MAXWELL E., PEREZ R., 1992, Techniques for supplementing solar radiation network data, Technical Report, International Energy Agency, # IEA-SHCP-9D-1, Swiss Meteorological Institute, Krahbuhlstrasse, 58, CH-8044 Zurich, Switzerland.