Solar irradiation retrieval in Cameroon from Meteosat satellite imagery using the Heliosat-2 method

Donatien Njomo, Lucien Wald

ISESCO Science and Technology Vision
Volume 2 - Number 1 - August 2006 (19-24)

Solar Irradiation Retrieval in Cameroon from Meteosat Satellite Imagery Using the Heliosat_2 Method

Donatien NJOMO[1], Lucien WALD[2]

[1]Environmental Energy Technologies Laboratory (EETL)/ University of Yaoundé I / PO Box 812 Yaoundé - Cameroon.

E-mail : dnjomo@usa.net

[2]Groupe Télédétection & Modélisation - Centre d'Energétique / Ecole des Mines de Paris

BP 207 - 06904 Sophia Antipolis Cedex - France

E-mail : lucien.wald@ensmp.fr

Abstract

The radiation climate of Cameroon is not well known. Measurements of global and diffuse incident solar irradiations were carried out from 1982 to 1987 in ten meteorological stations throughout the country using Eppley PSP pyranometers. The distance between two neighboring stations was about 200 km. This ambitious program of collecting solar radiation data throughout the Cameroon territory was abruptly stopped in 1987 because the maintenance of the pyranometers network together with the monthly field data collection became too cumbersome and costly. It therefore became necessary to look for a valuable tool to retrieve incident solar irradiation from low cost satellite imagery such as the geostationary Meteosat satellite data. In this work we use a method referred to as Heliosat_2, well documented in [12, 13], and developed by Wald and his co-workers Rigollier and Lefèvre. This method, which uses known models of physical processes in atmospheric optics, consists of first calculating the atmospheric cloud index for each pixel from images acquired in the visible band of the Meteosat sensor. The cloud index is then related to the pixel clear sky index defined as the ratio of the observed irradiation to the clear sky irradiation that should be observed at the pixel site at that instant. The computation of the clear sky irradiation is done by solving the radiative transfer equation in a cloud free atmosphere as documented in the European Solar Radiation Atlas (ESRA 2000). We have performed calculations of incident solar irradiations over the Cameroon territory using 5 km resolution Meteosat imagery of the year 1997 available from the Modeling and Remote Sensing Group of the Ecole des Mines de Paris based at Sophia Antipolis. A real advantage with the Heliosat method is that we can calculate the incident solar radiation for contiguous pixels. To assess the performances of the method for African sites we have compared the solar irradiation values derived from Meteosat data using the Heliosat_2 method to ground measurements available in Yaoundé (3°52' N ; 11°32' E) and Garoua (9°20' N ; 13°23' E). We observed that the accuracy of the Heliosat method is very satisfactory for the monthly variations of the daily solar irradiations in sahelian sites, while in forest sites the variations of the retrieved irradiations do not fit the measurements. The accuracy of the Heliosat_2 method could be greatly improved if the method was implemented using all the "high resolution" Meteosat data received every half an hour in a day; the computations of the daily irradiations might therefore be more accurate.

Keywords *: Meteosat imagery - Solar irradiation retrieval - Heliosat_2 method - Atmospheric optics.*

1. Introduction

There is a growing interest all over the world for solar energy mainly because the general public became aware of the harmful effects on the environment from the use of fossil energy sources. The air and water pollution problems, ecological disruptions observed owing to the climate changes are as much consequences of the current consumer methods of energy.

Solar energy is generally considered as a well adapted energy source to developing countries because these countries receive high solar irradiation, on the order of 6 kWh/m^2 per day together with a daily sunshine duration the longest one, about 8h, compare to daily values of 2.5 kWh/m^2 for irradiation and of 3h for sunshine duration in average for the industrialized countries [1].

In the special case of Cameroon, with a triangular territory spreading itself between the latitudes 2°N and 13°N and between the longitudes 8°E and 16°E, one observes two climatic zones: a southern rainy zone, very humid, between 2°N and 5°N and a northern lightly arid zone, dry, occurring between the latitudes 5°N and 13°N. Measurements of global and diffuse solar irradiations were carried out in Cameroon between 1982 and 1987 using Eppley pyranometers in ten meteorological stations at least 200 km apart and distributed across the whole Cameroonian territory [1]. Costly maintenance problems and malfunction of these devices placed on irregularly visited sites ended this program of measurements that ultimately furnished a series of complete measurements only for the year 1984. The solar radiation climate of Cameroon is therefore poorly known. In addition, the large distance between stations precludes all reasonable possibility of interpolation or of extrapolation of the currently available data in a mapping study of solar irradiance of Cameroon.

Several researchers have shown the feasibility of the extraction of the global solar irradiation incident on the ground from image data from geostationary satellites such as Meteosat. A good review of these methods can be found in [6]. The geostationary satellites observe the state of the atmosphere as well as the cloud cover above the targeted surface. This information can be used to retrieve the solar irradiation reaching the ground. In the simple models, one calculates at each instant a cloud index for the atmosphere using the digital data in the visible channel of the observed site. This cloud index is then linked to a clear sky index that is defined as the ratio between the global irradiation reaching on the observed site and that which would have reached on this site if the atmosphere was clear and without clouds. One real advantage of this type of method is to be able to determine the solar irradiation across contiguous areas.

The method of retrieval on which we worked referred to as the Heliosat_2 method was developed by Wald, Rigollier, Lefèvre and Albuisson and is described in the main publications and technical reports dealing with this method [2 - 12] and released by these authors. We present in the following the general principle of this method as recently recalled by Wald et al. in [13, 14]. We then apply the method to the Meteosat imagery of the year 1997 for the region of Cameroon.

2. Overview of the Heliosat_2 Method

2.1 Fundamentals of the method

The Heliosat_2 method is built around the generally accepted idea that every radiance variation observed by the satellite sensor is necessarily due to the variation of the apparent albedo, itself caused by the variation of radiances leaving the atmosphere and the scene towards the satellite.

In this method we use the cloud index n to characterize the irradiation level of a scene; this index compares how clear the state of the atmosphere above the scene is compared to what it would be for a perfectly clear atmosphere. We thus write :

$$n^t(i,j) = \frac{\left[\rho^t(i,j) - \rho_g^t(i,j)\right]}{\left[\rho_{cloud}^t - \rho_g^t(i,j)\right]} \qquad (1)$$

where

ρ^t (i, j) represents the apparent albedo observed by the satellite at the instant t for the pixel (i,j); it reads

$$\rho^t(i,j) = \frac{\pi L^t(i,j)}{I_{0met}\,\varepsilon(t)\cos\theta_s(t,i,j)} \qquad (2)$$

L^t (i, j) being the radiance measured by the sensor of the satellite

ρ_{cloud}^t (i, j) is the albedo of the clouds more brilliant and is calculated from the relationship

$$\rho^{*t}(i,j) = \frac{\rho_{sat}^t(i,j) - \rho_{atm}(\theta_s,\theta_v,\psi)}{T(\theta_s)T(\theta_v)} \qquad (3)$$

with ρ_{sat}^t being the reflectance more high observed by the satellite for the temporal series of images of the pixel under consideration; a value close to 0.8 should be used here

ρ_g^t (i, j) is the apparent albedo of the ground for a cloudless sky and is calculated with the same relationship as previously used but with the minimum value of ρ_{sat}^t observed by the satellite for the temporal series of illuminated images of the pixel (i,j).

The other terms are defined in the Nomenclature.

It is important to note that the cloud index n as defined here is not the same as the cloud cover of the atmosphere.

For a clear sky, the apparent albedo ρ^t (i, j) observed by the satellite is noticeably equal to the apparent albedo of the ground and the cloud index is then close to 0 (and even sometimes negative). On the other hand when the sky is covered, the cloud index n is close to 1 (sometimes lightly bigger). The cloud index n can therefore be considered as an adequate parameter for describing the attenuation of the radiation due to the atmosphere (globally speaking n would be equal to 1 minus the transmittance of the atmosphere).

The implementation of the method uses the following constraints :

for

$$\rho^t(i,j) < 0.01 \text{ then } n^t(i,j) = 0. \qquad (4)$$

for

$$-0.01 < \left[\rho^t(i,j) - \rho_g^t(i,j)\right] < 0.01 \text{ then } n^t(i,j) = 0.0 \qquad (5)$$

for

$$\left[\rho_{cloud}^t(i,j) - \rho_g^t(i,j)\right] < 0.1 \text{ then } n^t(i,j) = \qquad (6)$$

Values of the cloud index vary between -0.5 and 1.5 [12].

The cloud index n next will be linked up to the clear sky index K_c of the atmosphere that is defined as the ratio between the incident global irradiation on the considered pixel and the global irradiation that would be incident on this pixel if the atmosphere was perfectly clear; this is expressed as :

$$K_{ch} = \frac{G_h}{G_{ch}} \Leftrightarrow G_h = K_{ch} \quad G_{ch} \qquad (7)$$

The following constraints are used during the implementation of the method

$$
\begin{aligned}
& n^t < -0.2 \Rightarrow K_{ch} = 1.2 \\
& -0.2 < n^t < 0.8 \Rightarrow K_{ch} = 1 - n \\
& 0.8 < n^t < 1.1 \Rightarrow K_{ch} = 2.0667 - 3.6667 n^t \\
& \qquad\qquad + 1.6667 \left(n^t\right)^2 \\
& n^t > 1.1 \Rightarrow K_{ch} = 0.05
\end{aligned} \tag{8}
$$

The index h in these relations stands for hourly values.

The daily global irradiation incident to the ground is calculated using the relationship

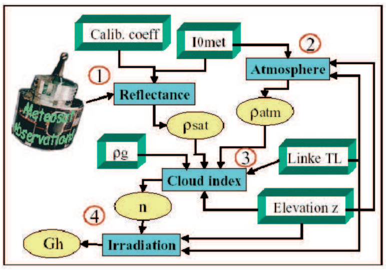
$$
G_d(i,j) = G_{cd}(i,j) \frac{\sum_{h=1}^{N} G_h(i,j)}{\sum_{h=1}^{N} G_{ch}(i,j)} \tag{9}
$$

where N represents the number of hours in the day during which the irradiation values were determined. Note that an assumption is made in this study that the physical processes behind this method are valid only for sun elevations γ_s greater than 15°.

The albedo values used in the equations above are constructed from a temporal series of satellite image data. As for the optical state of the atmosphere in clear skies, it is described in the European Solar Radiation Atlas (ESRA) project, documented in [6], where the spatial and temporal distributions of direct and diffuse irradiances are calculated together with the corresponding transmittances of a cloudless atmosphere for different values of the visibility.

2.2 Implementation of the Heliosat_2 method

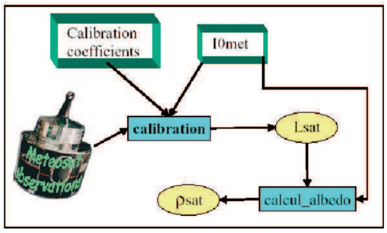
The four steps implementing the Heliosat_2 method are illustrated in the simplified diagram shown below :



General outline of the Heliosat_2 method

1 - Assessment of the reflectance observed by the satellite

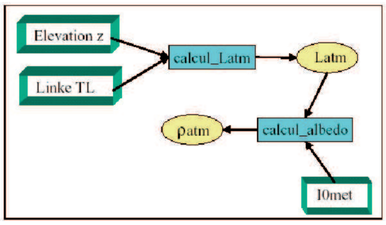
The first unit "reflectance" the flowchart of which is shown below reads the Meteosat data and calibrates them using external information including calibration coefficients and the total irradiance I_{omet} in the visible channel [0,3 - 1,1µm] of the Meteosat sensor. The resulting radiances L_{sat} are then converted into reflectances ρ_{sat} by means of the procedure *calcul_albedo*.



Flowchart of unit «reflectance»

2 - Assessment of the intrinsic reflectance of the atmosphere

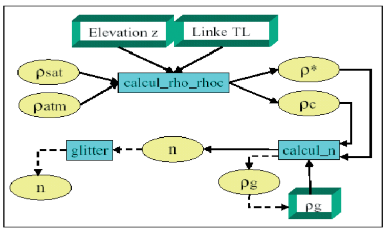
The second unit "atmosphere" shown below computes the radiances of the atmosphere L_{atm} for a clear sky for each pixel, by the means of the procedure *calcul_Latm*, using the clear sky library generated by the ESRA model and external information such as the elevation *z* and the Linke turbidity factor T_L. Then the resulting radiances L_{atm} are converted into reflectances ρ_{atm} by means of the procedure *calcul_albedo*.



Flowchart of unit «atmosphere»

3 - Assessment of the cloud index

The third unit "cloud index", which flowchart is presented below, computes the cloud index n. The reflectances ρ_{sat} and ρ_{atm} are inputs to the procedure *calcul_rho_rhoc* that uses the elevation *z* and the Linke turbidity factor T_L as external information. The outputs are the reflectance ρ^* and the cloud reflectance ρ_{cloud}, which are inputs to the procedure *calcul_n* to produce the cloud index n. This procedure calls upon external data: the ground reflectance ρ_g. In cases where the map of ground albedo needs to be updated, the value ρ^* is combined with ρ_g if the sky is clear to produce a new ρ_g value.

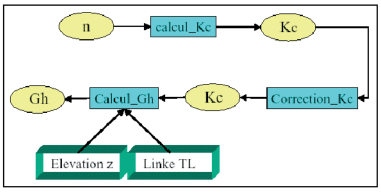


Flowchart of unit «cloud_index»

4 - Assessment of the irradiation

The fourth unit "irradiation" shown below converts the cloud index n into clear sky index K_c by the means of the procedure *calcul_Kc*. The clear sky index is defined as the ratio of the observed irradiation G_h to the clear sky irradiation G_{ch} that should be observed at that site and that instant. The formula proposed by Rigollier and Wald in 1999 in the first version of the model is corrected in the procedure *correction_Kc*. The clear sky index is an input to the procedure *calcul_Gh* that delivers the global hourly irradiation G_h.

The procedure calls upon the clear sky library and the elevation and Linke turbidity factors as external information.



Flowchart of unit «irradiation»

The reader wishing to obtain more details on this Heliosat_2 method will consult with great profit the publications by Wald, Rigollier, Lefèvre and Albuisson quoted in References.

2.3 Data format used by the model

The Heliosat_2 method was written to be independent of the choice of the data model. However the software has been tested until now only with Meteosat images. The method uses degraded B2 images formed by pixels that are effectively pixels of original size of 5 km but with a sub-sampling of 6 in each direction. Note that only 8 slots are available per day. Computations are all made in the true solar time system. The original structure of the data as images is kept until the computation of the cloud index. Then, another structure is adopted; for each pixel, a time-series of all cloud indices for a full year is stored. This change of structure appears in the software dealing with the cloud index for the computations of clearness index and irradiation. The irradiation output is obtained for a single pixel in the software.

3. Application of the Heliosat_2 method to Meteosat images of Cameroon

The Environmental Energy Technologies Laboratory at the University of Yaounde I in Cameroon recently acquired from the European Organization for the Exploitation of Meteorological Satellites (Eumetsat) 540 numerical «high resolution» Meteosat images covering the Central Africa region (5°E - 25°E; 10°S - 20°N) and consisting of 15 slots in each of the spectral bands VIS, IR, WV for the average day of every month of the year 1999. Among these images, only 180 of them in the visible channel are consistent with the Heliosat method. Such a temporal series proves itself insufficient for an accurate implementation of the method. We therefore chose to carry out our irradiation calculations for the Cameroon territory using the B2 images of the year 1997 available from the Modeling and Remote Sensing Group of the Ecole des Mines de Paris based at of Sophia Antipolis. The monthly variations of daily global irradiations in Cameroon extracted from Meteosat satellite images are presented in the figures that follow.

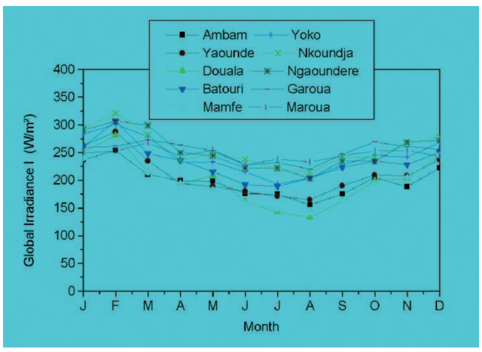
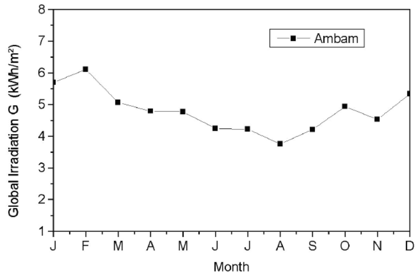
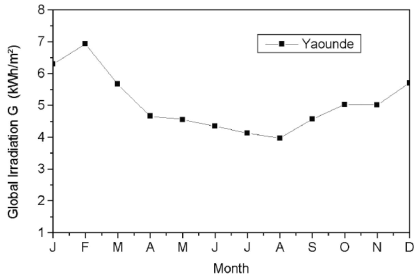


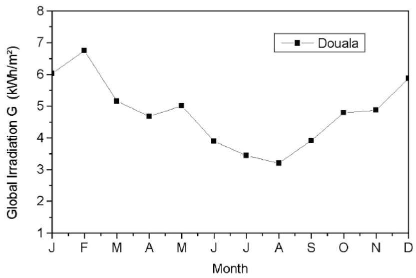
Figure 1 : Irradiances estimates for all the stations



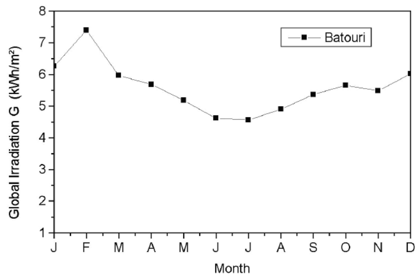
Locality of Ambam



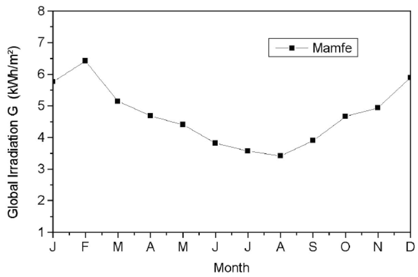
Locality of Yaounde



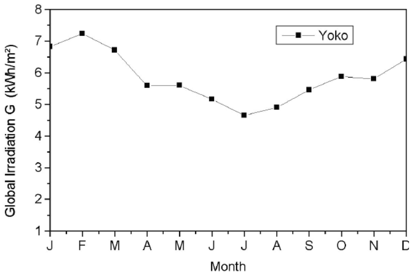
Locality of Douala



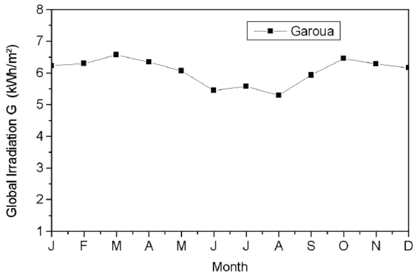
Locality of Batouri



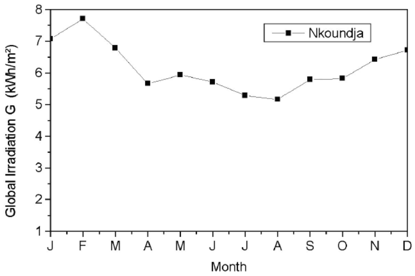
Locality of Mamfe



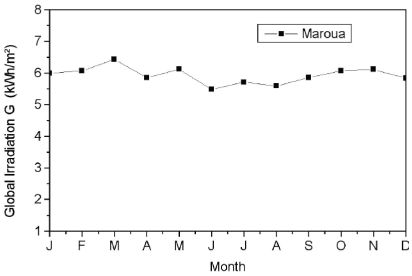
Locality of Yoko



Locality of Garoua

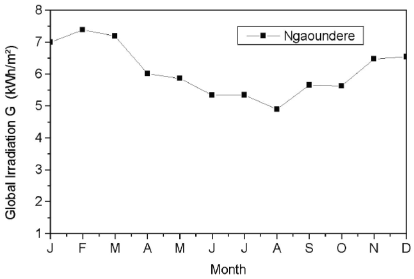


Locality of Nkoundja



Locality of Maroua

Figure 2 : Irradiations calculated for the ten stations



Locality of Ngaoundere

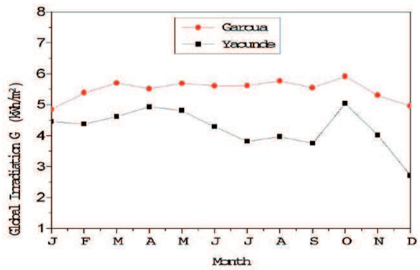


Figure 3 : Irradiations measured at Yaounde and Garoua

4. Discussion and conclusion

Inspection of the results from this study leads to the following observations :

● A comparison of the computed results coming from the Heliosat_2 method with measurements of solar irradiations currently available at Yaounde (3°52' N; 11°32' E) and Garoua (9°20' N; 13°23' E) shows that the monthly variations of the global irradiation incident on the site of Garoua as retrieved with the Heliosat method compare well with the measured values; on the other hand the correspondence is less robust for the site of Yaounde. The reason probably comes from the fact that the site of Garoua is a sahelian type and therefore presents a nearly lambertian surface and the atmosphere above this region is uniformly dry, whereas the site of Yaounde is a forest type layered with a humid and persistently cloudy atmosphere.

● The empiricism of the Linke turbidity factor, that besides is determined for the single value 2 of the air mass number, remains a limiting factor for the Heliosat method. The quality of the method would therefore be substantially improved if one used an atmospheric defined transmittance in the visible spectral band that had been validated before using for example a line by line radiative transfer code.

● The quality of the Heliosat_2 method also would have clearly been improved if it was implemented with all the «high resolution» HR Meteosat images available every half an hour in the day. The calculation of the daily mean values would be significantly more accurate.

Nomenclature

B_h	hourly value of the incident direct solar radiation
D_h	hourly value of the incident diffuse solar radiation
G_h	hourly value of the incident global solar radiation
I_o	solar constant = 1367 $W.m^{-2}$
I_{omet}	extra-atmospheric value of the solar radiation in the visible band for Meteosat sensor
K_c	clear sky index
L	radiance
n	cloud index
S_λ	Meteosat sensor spectral response in the visible band
T_L	Linke turbidity factor
T	atmospheric transmittance
Greek Symbols :	
ε	correction for the variation of the Sun-Earth distance
ρ	apparent albedo observed by the Meteosat sensor
θ_s	sun zenithal angle
θ_v	view angle
ψ	difference between sun and satellite azimuth angles
Subscripts :	
θ	extra-atmospheric value
g	ground value
c	clear sky value
b	cloudy sky value
λ	spectral value

References

[1] Njomo D., 2003, Analyse de sensibilité des systèmes héliothermiques dans un climat solaire tropical, Thèse d'Habilitation à Diriger des Recherches, Energétique et Génie des Procédés, Université de Perpignan, France, 104 p.

[2] Lefèvre M., Bauer O., Iehlé A., Wald L., 2000, An automatic method for the calibration of time-series of Meteosat images, International Journal of Remote Sensing, 21 (5), 1025-1045.

[3] Lefèvre M., Remund J., Albuisson M., Wald L., 2002, Study of effective distances for interpolation schemes in meteorology. European Geophysical Society, 27th General Assembly, Geophysical Research Abstracts, vol. 4, April 2002, EGS02-A-03429.

[4] Lefèvre M., Rigollier C., Cros S., Wald L., 2002, Toward a solar climatological database: the HelioClim project. In Proceedings, EARSeL Symposium 2002.

[5] Lefèvre M., Rigollier C., Cros S., Albuisson M., Wald L., 2002, A shortwave radiation database to support GODAE-related activities. Proceedings of the International Symposium "En route to GODAE", 13-15 June 2002, Biarritz, France. Published by CNES, Toulouse, France, 2002, pp. 157-158.

[6] Rigollier C., 2000, Vers un accès à une climatologie du rayonnement solaire : estimation de l'irradiation globale à partir d'images satellitales. Thèse de Doctorat en Sciences et Technologies de l'Information et de la Communication, Université Nice - Sophia Antipolis, France, 194 p.

[7] 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.

[8] Rigollier C., Lefèvre M., Blanc Ph., Wald L., 2002. The operational calibration of images taken in the visible channel of the Meteosat-series of satellites. Journal of Atmospheric and Oceanic Technology, 19(9), 1285-1293.

[9] Rigollier C., Wald L., 1999, The HelioClim Project: from satellite images to solar radiation maps. In Proceedings of the ISES Solar World Congress 1999, Jerusalem, Israel, July 4-9, 1999, volume I, pp 427-431.

[10] Rigollier C., Wald L., 1999. Towards operational mapping of solar radiation from Meteosat images. In Proceedings, EARSeL Symposium 1998 "operational remote sensing for sustainable development", Enschede, The Netherlands, Nieuwenhuis G., Vaughan R., Molenaar M. eds, Balkema, Rotterdam, pp 385-391.

[11] Rigollier C., Wald L., 2000. Selecting a clear-sky model to accurately map solar radiation from satellite images. In : Proceedings, EARSeL Symposium 1999 "remote sensing in the 21st Century: economic and environmental applications", Valladolid, Spain, Casanova J.-L., Vaughan R. eds, Balkema, Rotterdam, pp 131-137.

[12] Rigollier C., Lefèvre M., Wald L., 2001, Heliosat version 2. Technical Report D3.2.

[13] Rigollier C., Lefèvre M., Wald L., 2004, The method heliosat-2 for deriving shortwave solar radiation from satellite images. Solar Energy, vol. 77, pp. 159-169.

[14] Wald L., Albuisson M., Best C., Delamare C., Dumortier D., Gaboardi E., Hammer A., Heinemann D., Kift R., Kunz S., Lefèvre M., Leroy S., Martinoli M., Ménard L., Page J., Prager T., Ratto C., Reise C., Remund J., Rimoczi-Paal A., Van der Goot E., Vanroy F., and Webb A., 2002, SoDa: a project for the integration and exploitation of networked solar radiation databases. In: Environmental Communication in the Information Society, W. Pillmann, K. Tochtermann Eds, Part 2, pp. 713-720. Published by the International Society for Environmental Protection, Vienna, Austria.