Estimation of the global horizontal solar irradiation GHI for the Moroccan national territory from meteorological satellite images of the Second Generation Meteosat series MSG

AHMED. EL OUIQARY[1], EL'MKADDEM KHEDDIOUI[1], MOHAMED. FAOUZI. SMIEJ[2]
[1] Laboratory of Atmospheric Physics, Materials and Modeling (LPAMM), Faculty of Science and Technology of Mohammedia, Hassan II University of Casablanca, Morocco.
[2] Royal Center for Space Remote Sensing, Rabat (CRTS), Morocco.
ahmed.elouiqary-etu@etu.univh2c.ma

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Abstract
Illuminance is the power of radiation per unit area (W/m^2). Its projection on the ground on a horizontal plane named GHI (Global horizontal irradiance) is the meteorological quantity commonly used to estimate and forecast photovoltaic production. The GHI at a given location varies mainly according to the zenithal solar angle and the transparency of the atmosphere. The first variable can be calculated with good accuracy, the second depends on the cloud cover and the concentration of optically active atmospheric components. Apart from clouds, solar radiation modeling for solar energy generally retains aerosols, water vapor and ozone as significant components. A few Moroccan researchers have been able to estimate the global horizontal GHI irradiance using ground-based measurements. These data are insufficient because the measurement stations are located in well-defined geographical sites and therefore do not cover all the Moroccan national territory. The scientific literature specifies that images taken by geostationary satellites are a reliable source to obtain solar irradiance data with a quasi continuous spatial coverage. The objective of the present work is to evaluate the GHI for the whole Moroccan national territory from the images of the second generation MSG meteorological satellites by the procedure of the two methods Heliosat-2 and ARSC (Atmospheric Science Research Centre).

1. Introduction

The energy demand of countries is extremely increased in our modern era and this is considered as a level of development. Clean energy sources are getting more and more attention due to this increasing energy demand and the reduction of fossil fuels. As the demand for energy increases, the interest in renewable energy resources has increased with the decrease in fossil fuels. It is obvious that clean energy resources such as solar, wind, marine and biomass should be used in the future due to environmental effects such as global warming, climate change and carbon emissions. The sun has the greatest energy potential of all renewable energy resources. According to the researchers, the solar energy, which arrived to the earth's surface during the year, is more than 160 times more than the energy of fossil fuels [Özdemir (2012); Varınca and Talha (2006)]. Researchers are making progress in forming this huge potential for the benefit of humanity.

The Earth is located at 150 million km from the Sun. This one permanently emits 1026 Watt in the form of radiation and the Earth receives 178 million billion Watt on its illuminated side or 350 Watt per m^2 at the equator. The solar radiation is all the electromagnetic waves emitted by the Sun. The level of irradiance measured at the Earth's surface depends on the wavelength of solar radiation. The part of the solar spectrum that is visible to the human eye is generally in the range of 380-780 nm, which is also the range in which the radiation emitted by the sun is maximum (the absolute value is about 500 nm). This part of the spectrum is called the visible spectrum. Radiation in wavelengths below 380 nm is known as ultraviolet and radiation occurring in wavelengths above about 780 nm is called infrared radiation. The majority of solar radiation reaching the top of the atmosphere is in the spectral range of 300-3000 nm.

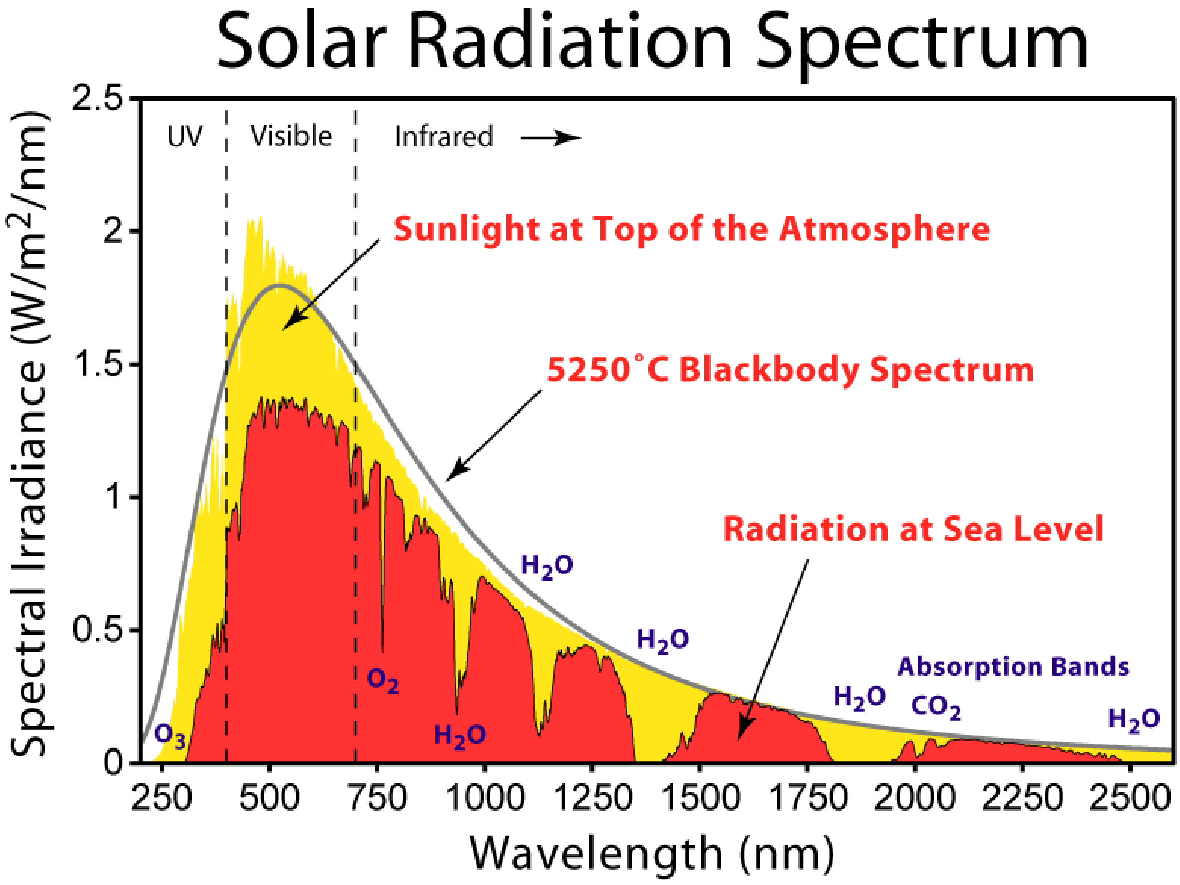

Figure 1: Spectrum of solar radiation

When solar radiation propagates through the atmosphere, it interacts with its gaseous constituents and with all the particles present in suspension (aerosols, water droplets and ice crystals). The particles we are talking about here have dimensions ranging from a hundredth of a µm to a few hundred µm. Solar radiation can be reflected, scattered or absorbed.

Incident solar irradiance at the ground is a relative measure of solar radiation at the Earth. It is defined as the energy flux per unit area from incident solar radiation, expressed in W/m^2.

In 2010, solar irradiance was identified by the World Meteorological Organization (WMO) Global Climate Observing System as a key climate variable for understanding and monitoring the global climate system. In addition to its interest in the field of climatology, solar irradiance is also of primary importance for fields as varied as solar energy, health, architecture, agriculture or forestry. By analogy with other energy sources, solar irradiance can indeed be considered as a deposit or a resource.

There are several possible ways of converting energy into use:

- direct conversion into electrical energy by photovoltaic cell;
- direct conversion into thermal energy by solar thermal collector, for example, for the production of domestic hot water;
- thermodynamic conversion into electrical energy by combining a solar thermal collector, a turbine or a thermal engine and an electrical generator;
- the conversion into chemical energy by photochemical way with the production of hydrogen by photolysis of water.

For a given location on Earth, the solar radiation received by a surface varies according to different phenomena :

- ✓ the cyclic variations of position and orientation of our planet in relation to the Sun (at the origin of seasonal variations),
- ✓ the diffusion and absorption, in particular because of the clouds, (at the origin of daily variations).

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Due to its geographical location, Morocco has a considerable solar deposit with a capacity of 20,000 MW, with more than 3,000 h/year of sunshine and an average potential of 5.5 kWh/m²/day.
The global irradiation received on a horizontal surface or horizontal plane, called by its acronym GHI for (Global horizontal irradiance) is a meteorological quantity. It can be broken down into three components whose proportions and intensity vary according to location, time of day and season. The global radiation is obtained by adding three types of radiation:

- **The normal direct radiation (DNI**) which has made a path in the atmosphere without geometric deviation, and thus corresponds to the portion of the incident radiation in the direction of illumination of the Sun, which varies with the height of the sun above the horizon.
- **The diffuse radiation** which results from the diffraction of direct radiation by clouds and atmospheric particles,
- **The reflected radiation due to the albedo** which results from the reflection of radiation by nearby surfaces. The albedo of a medium considered is the ratio between the reflected radiation flux and the incident radiation flux. This coefficient is higher than the surface is clear (water, snow, ...).

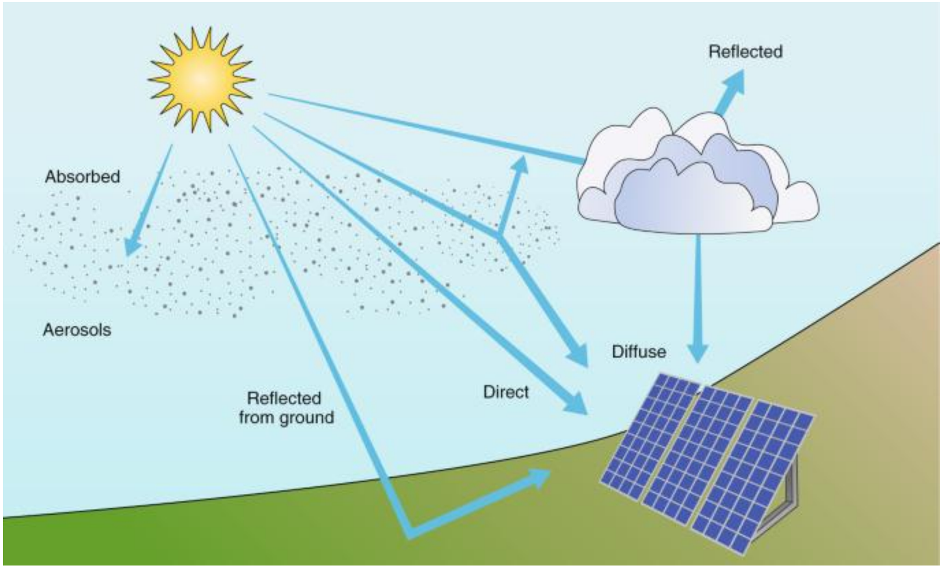

Figure 2: The three components of solar radiation

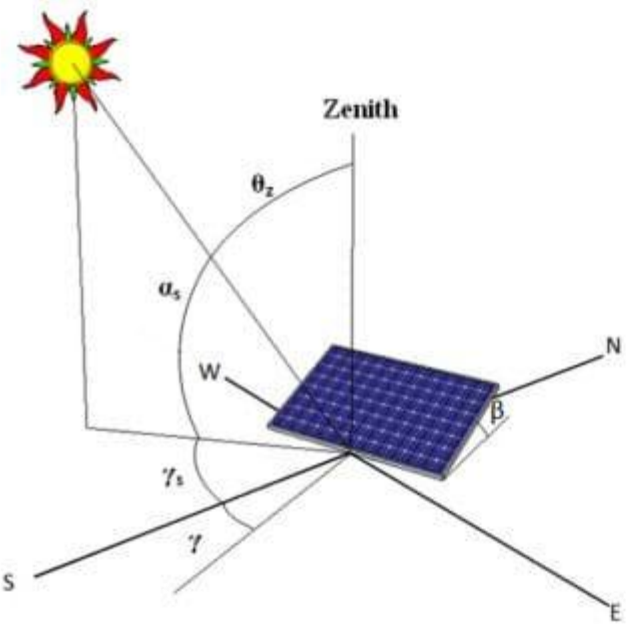

Figure 3: Commonly used angles for solar radiation: ϴz is the zenith angle.

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$$GHI = DNI\cos(\theta_z) + DHI$$

It is extremely important to make a correct measurement of the global, diffuse and direct solar irradiation in the sense of productivity analysis and cost accounts when planning energy systems. Basically, solar irradiance is determined in two ways:

- The first is the measurement of the irradiation intensity by means of conventional weather stations and sophisticated measuring equipment. With this method, it is possible to make an accurate and reliable measurement of irradiance. As a result, the lack of measuring stations in the world, expensive equipment, the need for human strength, the use of incorrect devices, geodetic measurements have failed to satisfy.
- The second way is the use of estimation methods that use images acquired by meteorological satellites to obtain an estimate of the global solar irradiation at any point on the ground and at any time. Meteorological satellites such as Meteosat Second Generation (MSG) produce images in which clouds are clearly visible. These clouds are generally more reflective than the ground they cover. The occurrence of a cloud results in an increase in the signal perceived by the satellite compared to what the same satellite should perceive if the sky was clear. This increase can be related to the attenuation of solar radiation from the top of the atmosphere to the ground. This simple principle, indirect in nature, has been adopted by many methods for estimating solar radiation incident on the ground. The cloudiness index, which modulates the atmospheric transmittance under clear sky conditions (Kasten et al. 1984), will allow to evaluate the global illuminance on a horizontal plane for a given pixel and at a given time. It is possible to link the cloudiness index n to a transmission factor Kc defined by :

$$K_c = \frac{GHI}{GHI_C}$$

With :
K_C : Atmospheric Transmission Index for clear skies (without unit)
GHI : Horizontal Global Radiation (in W/m²)
GHI_C : Global Radiation by clear sky (in W/m²)
The clear sky index (K_C) is related to the cloudiness index n by the following relationship:

$$K_c = 1 - n$$

The context of this research work is part of a series of works started at the Royal Center for Remote Sensing (CRTS), of quantitative evaluation of the cloud cover index n from data acquired by the two visible spectral band channels, the near infrared spectral band channel, and the high resolution visible HRV channel of the SEVIRI (Spinning Enhanced Visible and Infrared Imager) radiometer embarked on board the Meteosat second generation MSG weather satellites. The cloud cover index is the key parameter to determine the global horizontal irradiance GHI. The values of GHI thus obtained will have to be compared with those measured by the ground weather stations during the same period and for the same region. The second main objective of this work is to identify the physical and climatic parameters that most affect the normal direct radiation DNI, in the Moroccan national territory.

2. Methodology

2.1. The Meteosat Second Generation MSG weather satellites

The Meteosat family of meteorological satellites, placed in geostationary orbit, developed under the responsibility of the European Space Agency on behalf of the European meteorological organization EUMETSAT. The MSG program is the successor to the first generation of Meteosat satellites, with four such satellites built and launched between 2002 and 2015. These satellites are to be replaced by the third generation Meteosat satellites starting in 2019.

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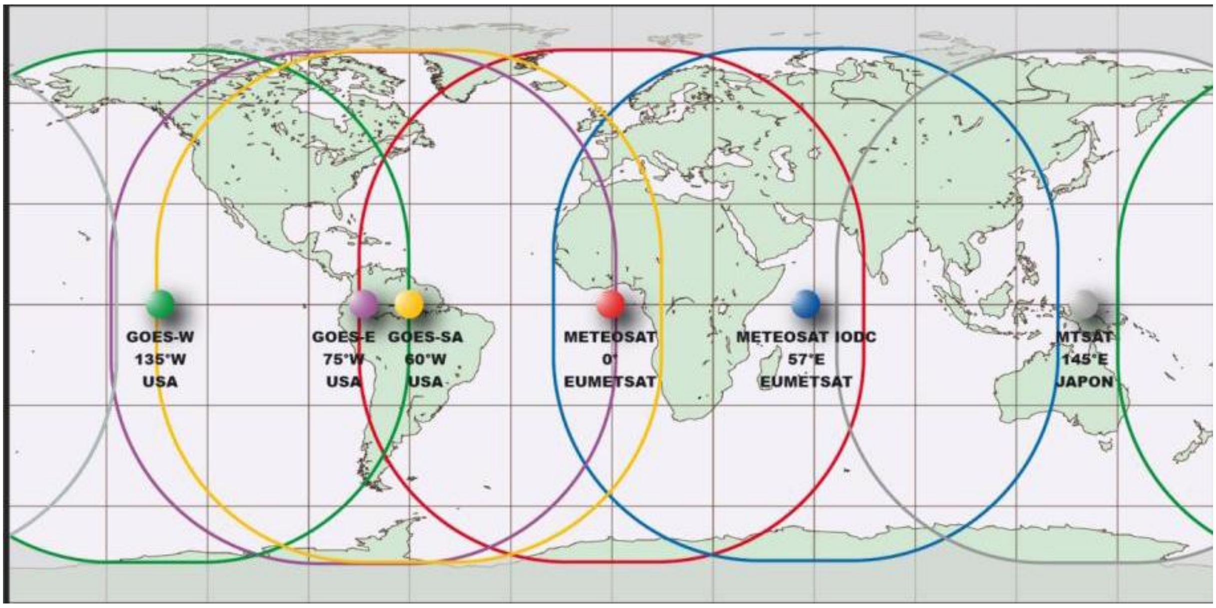

The objectives of satellite meteorology are:

- Have essential data for numerical weather prediction
- Is a real-time observation tool :
  - ✓ **Of the clouds** (classification, temperature and altitude of the top, detection of convective cells, liquid water content, precipitating character,...).
  - ✓ **Atmosphere** (temperature, humidity, aerosols, volcanic ash plumes, concentration of some gases, ...)
  - ✓ **From the surface** (temperature, radiative fluxes, vegetation index, snow, forest fires, vegetation mapping, sea ice, wind strength and direction,...)
- CLIMATE monitoring: long-term data archiving and exploitation (radiation balance, cloud and precipitation statistics,...), validation of climate models

2.2. Solar radiation measurement by satellite

The EUMETSAT company operates the MSG meteorological satellites placed in geostationary orbit at an altitude of 35800 km, in the equatorial plane and moving at a speed of 3 $km.s^{-1}$. It turns on itself, around its axis of inertia, at an angular speed of 100 revolutions per minute. At each rotation, its imaging radiometer SEVIRI detects the solar radiation reflected by the Earth for a given latitude and scans from the North Pole to the South Pole (figure 4). The images obtained have an excellent resolution: 2500 pixels by 2500 pixels for half a terrestrial hemisphere. The spatial resolution of the MSG satellite series has been improved, since it is 3km for the multispectral bands (compared to 5km for the first generation) and 1km for the high-resolution visible HRV channel (compared to 2.5km previously).

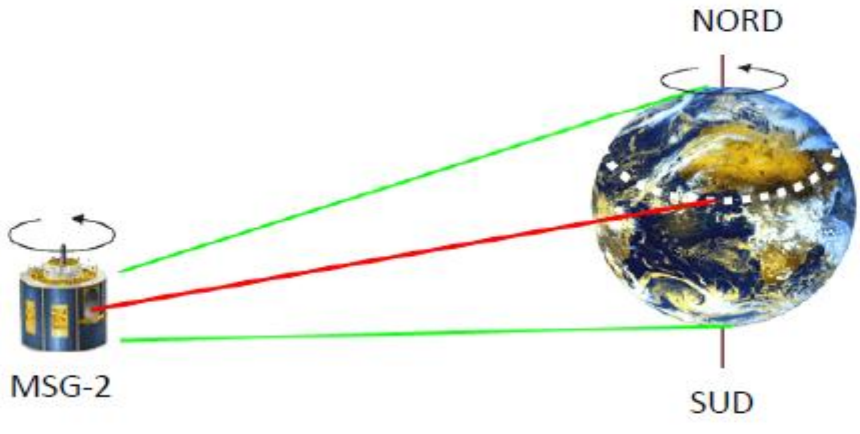

Figure 4: Principle of acquisition of an image line by MSG-2

An image of the reflected radiation exiting at the top of the atmosphere is then constructed every quarter of an hour. For each pixel of the image, SEVIRI associates a digital count on 8 bits. We then obtain a raster map in gray levels. A calibration operation allows to convert them into radiance level. The radiance is the light intensity emitted per unit solid angle and per unit area of a source in a given direction. It is expressed in Watt per steradian per square meter ($W.sr^{-1}.m^{-2}$).
EUMETSAT has been receiving and archiving these raster maps since 1981 and makes them available to users such as meteorologists, geologists and companies working in the field of renewable energy, climate change studies, tourism, etc….

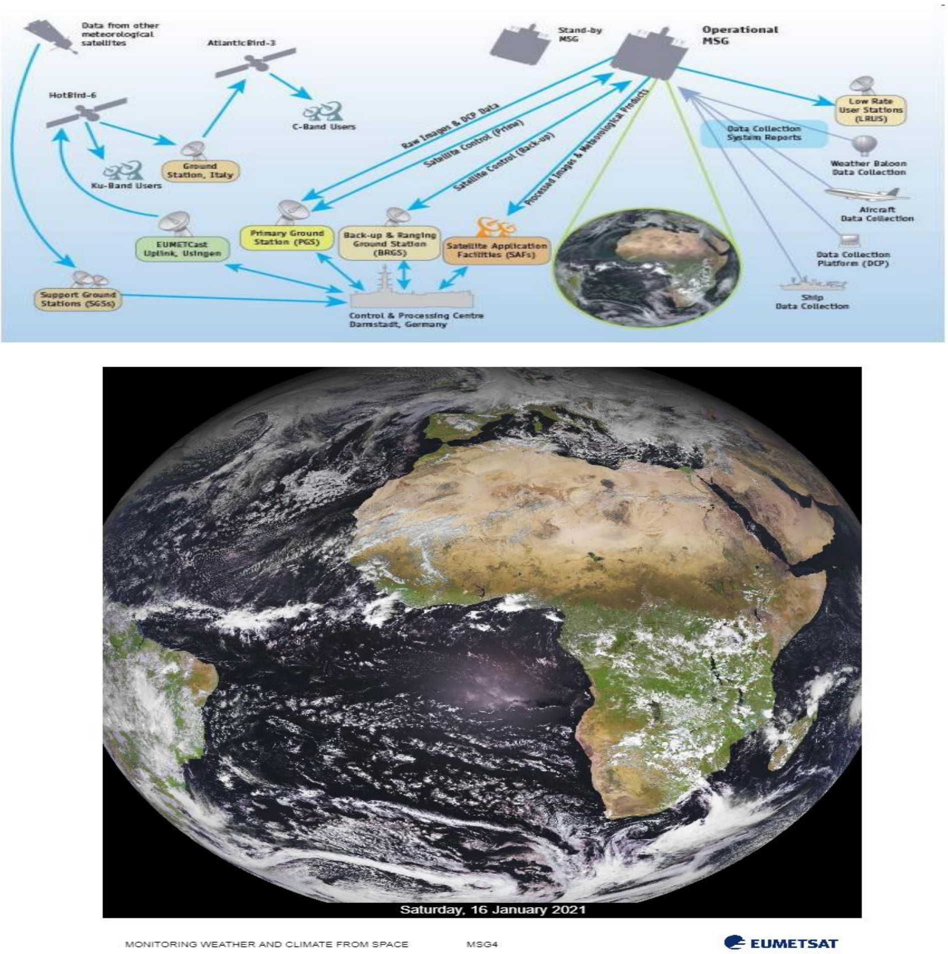

Figure 5: MSG weather satellite image

2.3. Derivation of solar radiation from satellite images

2.3.1. The predictive models of the calculation of irradiance

The irradiance that reaches the Earth's surface cannot be measured directly from space, but is estimated from images taken in the visible spectrum by SEVIRI. This calculation is based on an algorithm that takes into account factors such as atmospheric transmittance, cloud properties, surface albedo, atmospheric water vapor, satellite viewing angle and solar elevation.
Having an image at time h of a day j of the radiance Li(x,y,j,h) of each pixel i of position (x,y) on the image we obtain an estimate of the value of the global solar irradiation Gi (x,y,j,h) received at the point of geographical coordinates (X,Y) on the ground. Many models of solar radiation have been developed from these images according to different algorithms and assumptions: Heliosat, MeteoNorm, CalSol, SatelLight, r-sun.

2.3.2. The Heliosat-2 method

Rigollier et al. (2000) proposed several improvements to evolve the original Heliosat method. The Heliosat-2 version (Cano et al. 1986; Rigollier et al. 2004) is an inverse method that derives the solar radiation from the luminance perceived by the satellite. It combines a model for calculating the

radiation under clear skies at each geographical point and at any time, and a model for extinguishing the radiation obtained due to the presence of clouds. It has been developed at MINES ParisTech in collaboration with several European partners and is considered as one of the most efficient among the different methods using visible spectrum images from meteorological satellites (Cano et al. 1986).
Heliosat-2 only processes data that have been calibrated and converted into luminance, which is a recognized physical quantity that can be used by atmospheric radiative transfer models. In each pixel of coordinates (i, j) the luminance L perceived by the satellite sensor at time t is converted into apparent reflectance (or albedo):

$$\rho^t(i,j) = \frac{\pi L^t(i,j)}{I_{0met}\varepsilon(t)\cos\theta_s(t,i,j)} \quad (1)$$

with :

$\rho^t(i,j) =$ Apparent reflectance observed by the sensor at time t
$L^t(i,j)$: Luminance observed by the sensor at time t
I_{0met} : Solar irradiance (W/m2) at the top of the atmosphere in the visible band of Meteosat, also called the solar constant.
ε(t): Earth-Sun distance correction.
Θ_S: Zenith angle of the sun at time t, at point (i, j)
We consider **n**, **the clouding index**, which is the key parameter of the Heliosat-2 method, as resulting from a ratio between what is observed by the sensor and what would be observed if the sky were clear (without clouds). This is expressed as :

$$n^t(i,j) = \frac{\rho^t(i,j) - \rho^t{}_{ground}(i,j)}{\rho^t{}_{cloud}(i,j) - \rho^t{}_{ground}(i,j)} \quad (2)$$

With :

$\rho^t(i,j)$: Apparent reflectance observed by the sensor at time t (equation.1).
$\rho^t{}_{ground}(i,j)$: Clear-sky apparent ground reflectance at time t determined from a reference map of a time series of satellite images to incorporate possible seasonal variation.
$\rho^t{}_{cloud}(i,j)$: Apparent reflectance of the brightest clouds at time t.

$$n^t(i,j) = \frac{\rho^t{}_{eff}(i;j) - \rho^t{}_{atm}(\theta_s,\theta_v,\emptyset)}{T_{atm}(\theta_s)T_{atm}(\theta_v)} \quad (3)$$

With :
$\rho^t{}_{eff}(i;j)$: Effective cloud reflectance.

$$\rho_{eff} = 0.85 - 0.13\left[1 - e^{-4\cos(\theta_S)^5}\right] \quad (4)$$

$\rho^t{}_{atm}(\theta_s,\theta_v,\emptyset)$: Reflectance of the atmosphere
$T_{atm}(\theta_s)$: Downward transmittance
$T_{atm}(\theta_v)$: Ascending transmittance
θ_s: Zenith angle of the sun at time t at point (i, j)
θ_v: Boresight angle of the satellite at time t at point (i, j)

If the sky is clear, the apparent albedo is close to the apparent albedo of the ground and the index of cloudiness n is close to 0. Conversely, if the sky is completely covered, n is close to 1. This basic principle is not always exactly verified when, for example, multiple layers of clouds are involved, or when the albedo of the ground varies abruptly (snowfall, cast shadows). The cloudiness index perceived by the sensor should not be confused with the cloudiness that would be observed by an observer on the ground. n can be considered as a measure of the attenuation of solar radiation by the

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atmosphere, and related to the global radiation through K_c , quotient of the irradiation observed by the irradiation that should be observed by clear sky :

$$K_c = \frac{G(i,j)}{G_c(i,j)} = f(n) \quad (5)$$

With :
G(i,j): Global irradiation (direct + diffuse components) observed
G_c (i,j): Global irradiation (direct + diffuse component) observed by clear sky
f(n): Empirical relation linking n to K_c ((Rigollier and Wald, 1998) (fig. 3))

$$K_C(n) \begin{cases} n < -0.2, K_c = 1.2 \\ -0.2 \le n \le 0.8, K_c = 1-n \\ 0.8 \le n \le 1.1, K_c = 2.0667 - 3.6667n + 1.667n^2 \\ n \ge 1.1, K_c = 0.05 \end{cases}$$

G is therefore computable from n and G_c at each pixel and at each time:

$$G(i,j) = K_C \, G_c(i,j) \quad (6)$$

G_c : is computed by the ESRA 2000 clear sky model; (Rigollier et al. 2000).
This model requires information on the optical properties of the atmosphere: absorption due to water vapour and aerosols, and scattering by aerosols.Heliosat-2 relies on the Linke turbidity coefficients (TL) which integrate these two pieces of information (Kasten, 1996; Jacovides, 1997). The TL describes the optical thickness of the pure atmosphere without clouds that would attenuate direct radiation as the real atmosphere does by absorption and scattering.

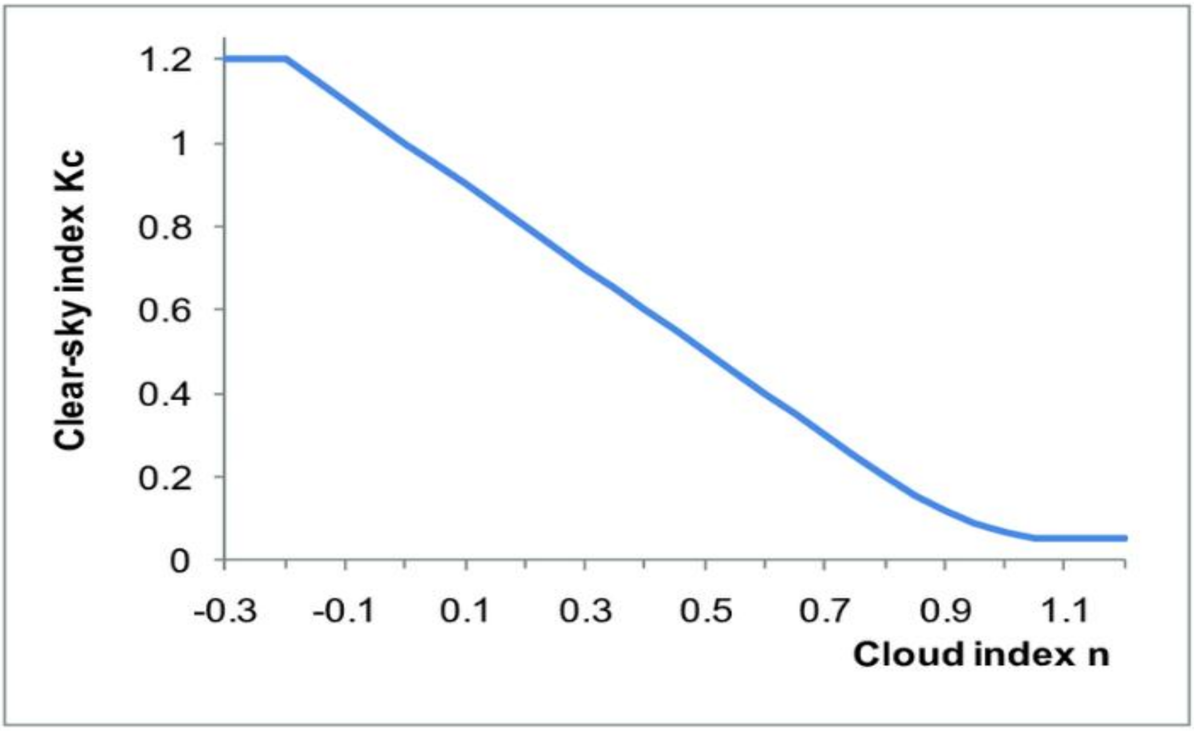

Figure 6[6] : Relationship between the cloud index n and the clear-sky index Kc

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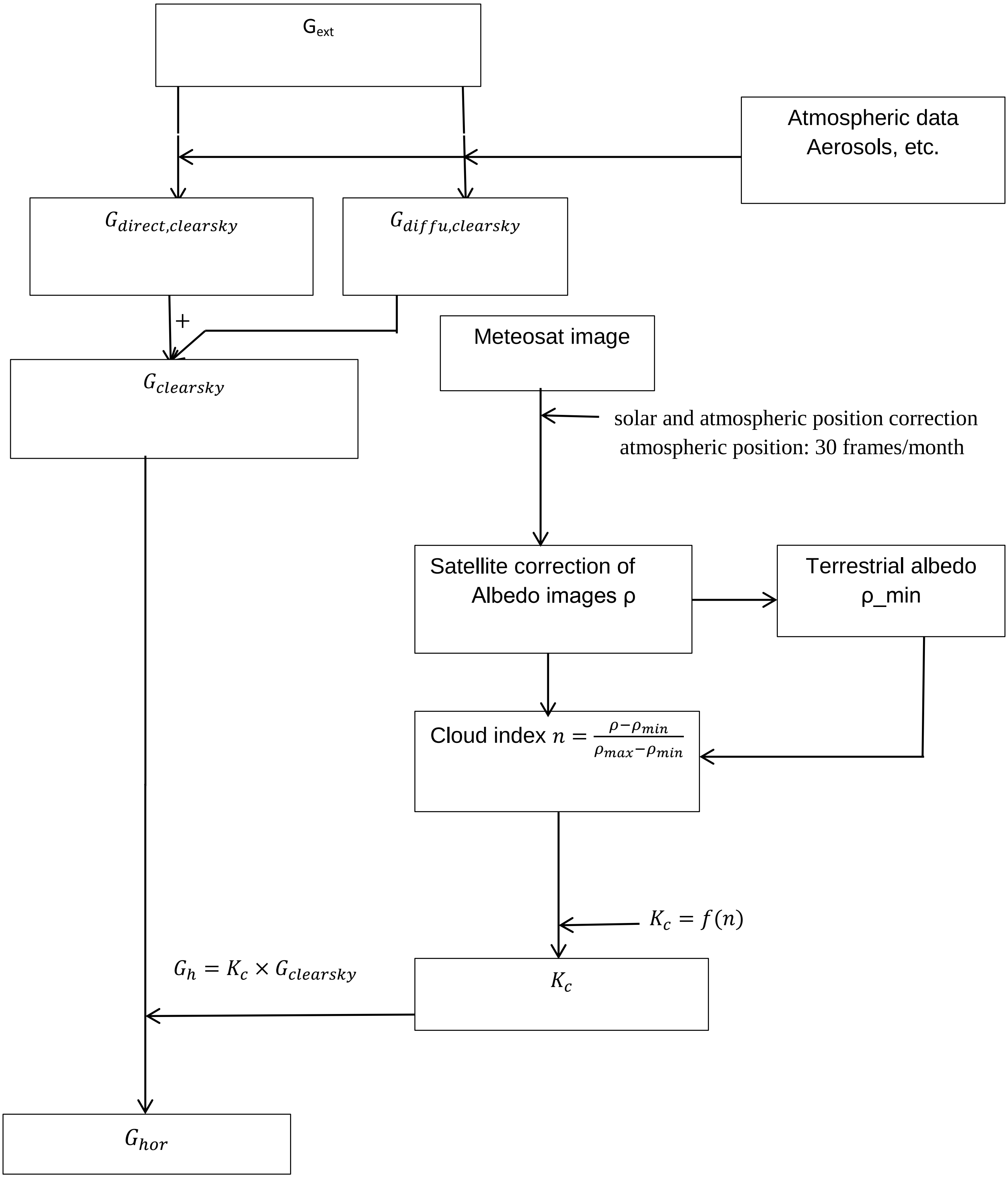

Figure 7 [7]: Overview of the Heliosat-2 method

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2.3.3. The Atmospheric Science Research Centre (ARSC) method Richard Perez (State University of New York at Albany)

Principle:

Techniques for obtaining ground irradiance values from satellite observations are based on the quasi-linear relationship between extra-atmospheric radiation flux and ground irradiance as a function of cloud cover (Schmetz .1989).

The atmospheric transmittance for a cloud cover index n is given by the relation

:

$$\tau(n) = \tau_{atm}(0) \cdot (1 - n)$$

The cloud cover index n is a quotient of the global albedo:

$$n = \frac{\rho_{toa} - \rho_{toa,min}}{\rho_{toa,max} - \rho_{toa,\,min}}$$

n: cloud cover index;

ρ_{toa} : Instantaneous observed planetary albedo above the atmosphere (top of atmosphere

$\rho_{toa,min}$: Minimum observed value for planetary albedo;

$\rho_{toa,max}$: Maximum observed value for planetary albedo.

The Kasten model (Kasten et al. 1984) is used to represent the transmittance of the atmosphere (for a clear sky, n = 0).

$$\tau_{atm}(0) = 0{,}84 \times \exp(-0{,}027 \times T_L \times m)$$

$\tau_{atm}(0)$: Atmospheric transmittance for a clear sky

m : relative optical air mass;

$$m = [\cos(\theta_z) + 0{,}50572 \times (6{,}07995 + (90 - \theta_z))]^{-1}$$

TL: Linke turbidity factor, obtained from climatology data

The horizontal global irradiance G is expressed by the following relationship:

$$G = \frac{I_0}{R^2} \times \mathrm{COS}(\theta_z) \times 0.84 \times \exp(-0.027 \times T_L \times m) \times (1 - n)$$

Where:

I_0: solar constant, i.e., the radiation flux normal to the radiation beam from the sun for an average earth-sun distance, I_0=1367 W/m^2

θ_Z: apparent zenith angle of the sun as seen from the observed pixel

R: earth-sun distance in astronomical units.

m: relative optical air mass;

TL: Linke turbidity factor, obtained from climatology data.

The direct solar radiation, which reaches the ground is a function of the direct clear sky irradiance "DNI_clear" and the cloudiness index n. Its formulation is given by the following relation [Schillings et al. 2004]:

$$\mathrm{DNI} = \mathrm{DNI}_{clear} \cdot \frac{100 - n}{100}$$

With :

$$DNI_{clear} = E_0 . \tau_R . \tau_{gas} . \tau_{ozone} . \tau_{WV} . \tau_{Ae}$$

n : Cloud Index
DNI : Direct Normal Irradiation
τ_R : Rayleigh transmittance
τ_{gas} : Transmittance of gas (CO_2, O_2, CH_4, N_2O)
τ_{ozone}: Transmittance of ozone (O_3)
τ_{WV} : Transmittance of water vapor ((H_2O)
τ_{Ae} : Transmittance of aerosol
E_0 : The solar constant corrected for the eccentricity effect

$$E_0 = \overline{E}_0(1 + 0.033 \cos \frac{2\pi \times j}{365})$$

$\overline{E}_0 = 1367\ W/m^2$: The solar constant
j: day of the year
Concentration thermodynamic systems use only the normal direct irradiation (DNI), they can only be installed in areas with high sunshine. Thus, a sunshine of 1 800 kWh/m^2/year is the minimum threshold estimated necessary to obtain a sufficient output [Institut de l'énergie et de l'environnement de la francophonie: IEPF].

3. Results

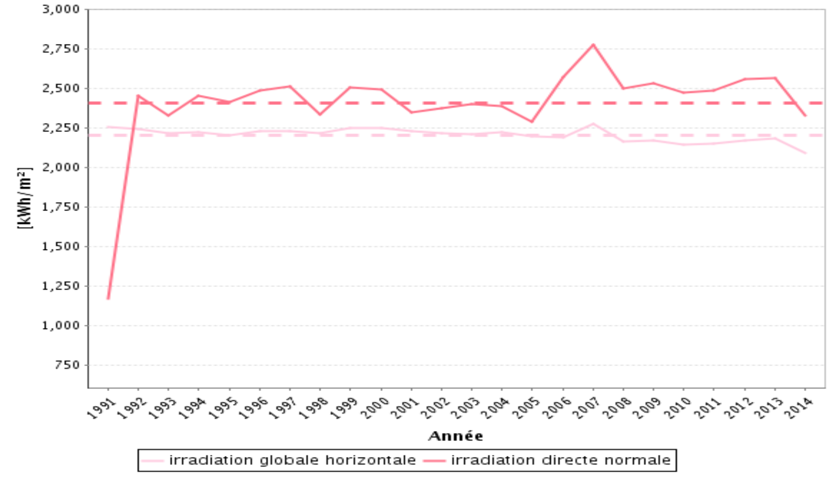
The results expected after completion of the practical phase of these methods should be of considerable accuracy than the data from **[14]**, given the spatial resolution of the SEVIRI radiometer of the MSG satellite series. These data will be compared with in-situ measurements obtained with the help of meteorological instruments specific to GHI and DNI measurements. To evaluate the performance of the estimation of the global horizontal GHI irradiance using these methods, the researchers use the following statistical indicators; bias error (MBE) and root mean square error (RMSE).

$$MBE = \frac{1}{N}\sum_{i=1}^{N}(GHI_{EST,i} - GHI_{OBS,i})$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(GHI_{EST,i} - GHI_{OBS,i})^2}$$

Where:
GHI_{EST} and GHI_{OBS}: Are the estimated and observed values of GHI.
Data from the Solar Atlas for the Mediterranean (case of Morocco)

1. Interannual values



Année	GHI	DNI
1991	2253	1169
1992	2241	2453
1993	2213	2329
1994	2223	2453
1995	2201	2411
1996	2229	2481
1997	2227	2508
1998	2212	2334
1999	2245	2504
2000	2250	2493
2001	2229	2344
2002	2215	2369
2003	2208	2400
2004	2221	2387
2005	2191	2286
2006	2187	2569
2007	2271	2771
2008	2159	2497
2009	2169	2531
2010	2141	2471
2011	2145	2485
2012	2168	2559
2013	2180	2563
2014	2087	2324
Moyenne	**2203**	**2404**

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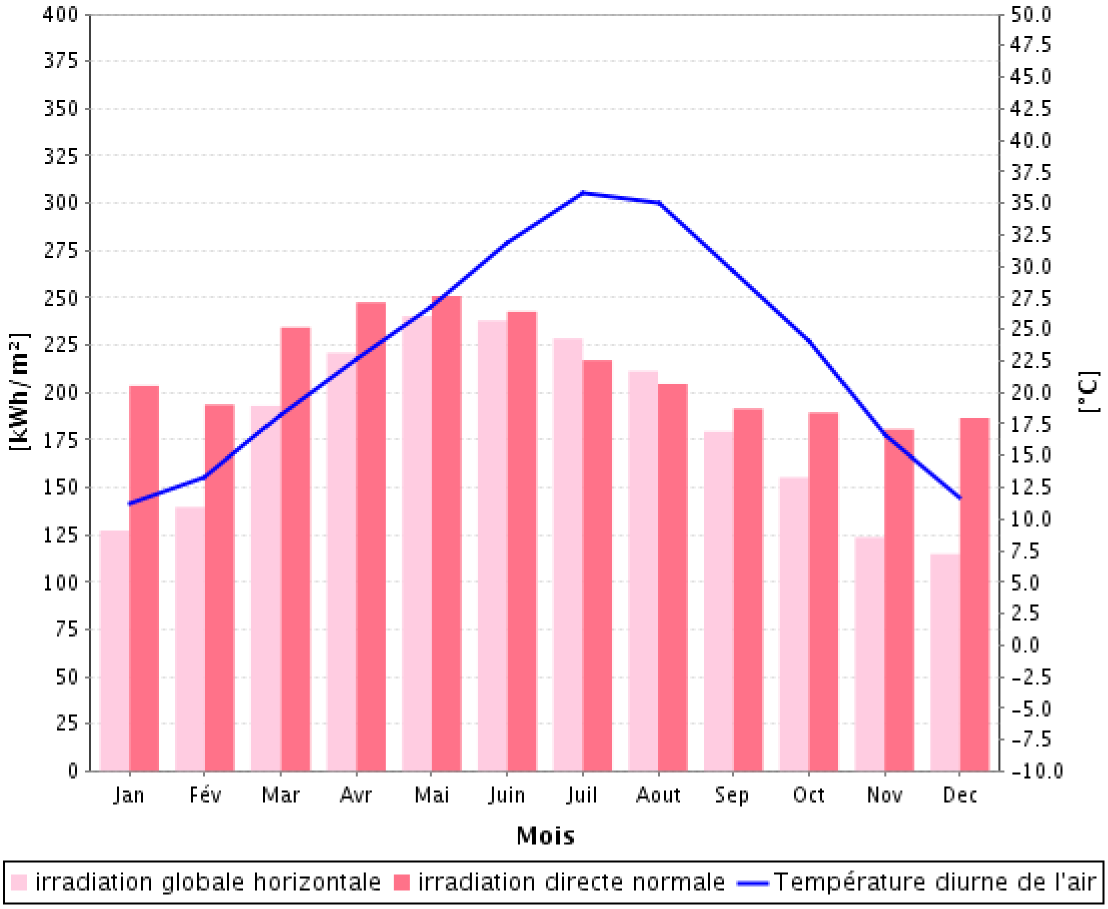

GHI: global horizontal irradiation [kWh/m²].
DNI: direct normal irradiation [kWh/m²]
TEMPER: Diurnal air temperature [°C]

MONTH	GHI	DNI	TEMPERATURE
Jan	132	217	9,4
Feb	143	202	11,0
Mar	200	254	15,0
Apr	227	265	18,6
May	252	282	22,3
Jun	248	271	27,3
Jul	241	249	31,6
Aut	220	230	30,8
Sep	190	218	25,5
Oct	161	206	20,5
Nov	129	195	14,1
Dec	118	198	10,0
Year	**2262**	**2787**	**19.7**

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