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Evaluation of the Global Horizontal Irradiation (GHI) on the Ground from the Images of the Second Generation European Meteorological Satellites MSG

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Abstract

The measurement of solar irradiation is still a necessary basis for planning the installation of photovoltaic parks and concentrating solar power systems. The meteorological stations for the measurement of the solar flux at any point of the earth's surface are still insufficient worldwide; moreover, these measurements on the ground are expensive, and rare. To overcome this shortcoming, the exploitation of images from the European meteorological satellites of the second generation MSG is a reliable solution to estimate the global horizontal irradiance GHI on the ground with a good spatial and temporal coverage. Since 2004, the new generation MSG satellites provide images of Africa and Europe every 15 minutes with a spatial resolution of about 1 km × 1 km at the sub-satellite point. The objective of this work was to apply the Brazil-SR method to evaluate the global horizontal GHI irradiance for the entire Moroccan national territory from the European Meteosat Second Generation MSG satellite images. This bibliographic review also exposed the standard model of calculation of GHI in clear sky by exploiting the terrestrial meteorological measurements.

Keywords

Global Horizontal Irradiation GHI, MSG Satellite Images, Brazil-SR Method

1. Introduction

Solar radiation is the only external source of energy of our planet.

The sun gives off a light energy of $6.3 \times 10^7\ \text{W/m}^2$. Because of its temperature of about 6000 K, the sun radiates mainly in the visible and near infrared (from 300 nm to 1200 nm) with a maximum around 500 nm. Above the atmosphere, the incident light energy of the sun varies with:

- The value of the solar constant ($G_0 = 1370\ \text{W/m}^2$ at a distance of one AU) dependent on solar activity (these variations are less than 1);
- The Earth-Sun distance (from $1325\ \text{W/m}^2$ in January to $1415\ \text{W/m}^2$ in July);
- The variation of the angle of incidence, depending on the time of day, the latitude and the season.

This energy, which descends in a straight line to the Earth, does not reach the Earth in its entirety, because it will undergo transformations by crossing the atmosphere: by absorption and by diffusion. The precise knowledge of solar radiation on the ground is important in the fields of energy, biomass, agriculture, climate, human health, etc. Satellite images are now an indispensable means for the evaluation of this radiation.

Direct solar radiation is the radiation that comes directly from the Sun, without diffusion through the atmosphere. This flow consists of rays that are parallel to each other and can be concentrated by mirrors.

The reflected solar radiation or **ALBEDO** is the part reflected by the ground. It depends on the environment of the site. The albedo is a dimensionless coefficient and represents the ability of a surface to reflect solar radiation. If the albedo is greater than 0.8, the surface will be perceived as white. On the contrary, it will be perceived as black if the albedo is less than 0.03.

The scattered solar radiation is the light scattered by the atmospheric constituents (ozone layer, clouds, oxygen, gas, dust, water vapor…). The phenomenon of atmospheric scattering splits a parallel beam into a multitude of beams going in all directions. Water droplets (clouds), air molecules, and dust are responsible for producing the burst of sunlight in the sky.

The global solar radiation is the sum of these various radiations. It reaches the value of $1000\ \text{W/m}^2$ in clear and cloudless weather. This radiation can be measured with a Pyranometer (**Figure 1**) or a solarimeter.

Generally, the solar energy is the sum of the cumulative radiation. **The daily global radiation** is the integral of the global radiation during one day at a given location with a slight tilt (usually horizontal). The cumulative radiation is in Wh/m^2 per day.

The absorption of solar radiation by the different gases in the atmosphere is highly selective and influences some parts of the solar spectrum.

GHI is the sum of the solar radiation coming directly from the sun DNI and the diffuse radiation DHI through the sky and the terrestrial albedo which arrive on a horizontal surface. The **GHI** is the main factor to evaluate the solar resource available for flat plate collectors. On the other hand, the **DNI** is the most important component of solar radiation for concentrating solar thermal systems.

The direct component depends on the height of the sun and the angle of inclination of the surface at the moment of consideration [1]:

Figure 1. Pyranometer to measure the global solar radiation on the ground (GHI).

$$\mathrm{BHI} = \mathrm{DNI} \cdot \sin(h)$$

$$\mathrm{BHI} = \mathrm{DNI} \cdot \cos(\theta_Z) \tag{1.1}$$

The global radiation on the ground is a function of the composition and thickness of the atmosphere through which the light rays pass during the day. It is broken down into direct and diffuse radiation. In the case of a horizontal surface, the global radiation is written in the following form [2]:

$$\mathrm{GHI} = \mathrm{DNI} \cdot \cos(\theta_Z) + \mathrm{DHI} \tag{1.2}$$

2. Evaluation of the Global Horizontal Ground Irradiation GHI

2.1. Calculation of the Attenuation of Solar Radiation by the Atmosphere

The calculation of the atmospheric attenuation of solar radiation is based on the evaluation of the atmospheric pressure and the optical mass of the air.

2.1.1. The Atmospheric Pressure

The atmospheric pressure is expressed as a function of altitude h (in meters):

$$P = P_0 \exp\left(\frac{-h}{8200}\right) \tag{2.1}$$

At sea level, the pressure is: P_0 = 101,325 Pa (or 1013.25 hPa or 1013.25 millibars or 1.013 bar). The standard temperature is 15˚C, or 288˚K. In the troposphere, which extends approximately from 0 to 11 km, the temperature decreases linearly by about 6.5˚C per km. For the calculation of atmospheric pressure, Piedallu & Gégout use the formulation proposed by the International Civil Aviation Organization [3]:

$$P_a = P_0 \left(1 - \frac{6.5}{288} \times \frac{h}{1000}\right)^{5.256} \tag{2.2}$$

2.1.2. The Optical Air Mass

To have an accurate measurement of the optical air mass, it must be realized at sea level of the length of the path traveled through the atmosphere by light rays from a celestial body; it is expressed as a multiple of the length of the path that corresponds to a light source located at the zenith.

According to the Glossary of Meteorology published by the AMS (American Meteorological Society), for zenith distances [recall that the zenith distance is the angle between the ray and the local vertical (**Figure 2**)] up to about 70˚, it is approximately equal to the secant of the angle defining the zenith distance of the given celestial body. For a more accurate calculation, the refraction of the light beam must be taken into account. To obtain a representative value at high altitude, these values must be multiplied by the ratio between the actual atmospheric pressure and the pressure at sea level.

$$m_0 = \frac{OM}{OA} = \frac{1}{\sin(h)} = \frac{1}{\cos(\theta_z)} \tag{2.3}$$

The second formula of Campbell [3] gives the optical mass of the air as a function of the zenith angle θ_z of the solar ray and the atmospheric pressure. This formula, commented above, corresponds to an atmosphere that would be modeled by a layer of constant thickness laid on a plane tangent to the earth's surface. The optical mass of air is related to the altitude by one of the Formulas (2.1) or (2.2) of calculation of the atmospheric pressure.

$$m = \frac{P_a}{P_0} \times m_0 \tag{2.4}$$

One can calculate m directly as a function of altitude using combinations of the formulations defined for the two entities: atmospheric pressure and optical mass number. By combining Formulas (2.1) and (2.3), for example, we obtain the following expression:

$$m = \exp\left(-\frac{h}{8200}\right) \times \frac{1}{\cos(\theta_z)} \tag{2.5}$$

The attenuation of solar radiation through the atmosphere can be expressed by the following relationship [4]:

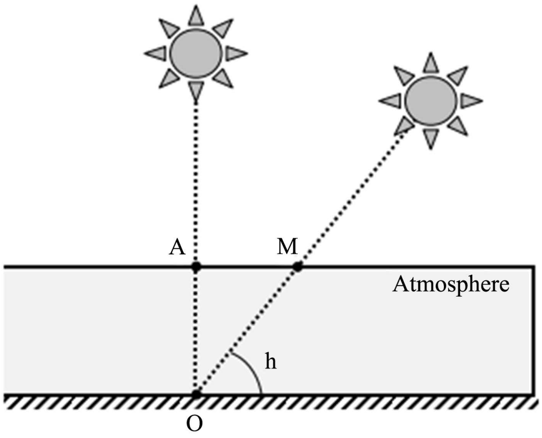

Figure 2. Definition of the relative optical air mass m_0.

$$I(\lambda) = I_0(\lambda) \cdot \exp\left[-m_{air} \cdot \tau(\lambda)\right] \tag{2.6}$$

where:

$\tau(\lambda)$ is the total optical thickness of the atmosphere

$I_0(\lambda)$ the extraterrestrial solar flux in w·m^{-1}

The atmospheric transmittance, equal to the fraction of incident radiation transmitted through the atmosphere, is represented by the exponential term in the above equation. It is thus a function of the total atmospheric optical thickness and the zenith angle θ_z through the mass relative m_{air}. This is equal to $(\cos\theta_z)^{-1}$ as a first approximation, for angles less than 75˚. On the other hand, for large values of θ_z a corrective term is added to account for the sphericity of the Earth (Kasten and Young, 1989).

$$m_{air} = \frac{1}{\cos(\theta_z) + a \cdot (b - \theta_z)^{-c}} \tag{2.7}$$

where: $a = 0.50572$, $b = 83.92005˚$, $c = 1.6364$.

The phenomena that contribute to the attenuation of solar radiation in a clear atmosphere are aerosol extinction, molecular scattering (or Rayleigh) and gas absorption. Thus, the total optical thickness $\tau(\lambda)$ is the sum of the terms characterizing these processes:

$$\tau(\lambda) = \tau_{aer}(\lambda) + \tau_{Ray}(\lambda) + \tau_{gaz}(\lambda) \tag{2.8}$$

$\tau_{aer}(\lambda)$: aerosol optical thickness (unitless);

$\tau_{Ray}(\lambda)$: optical thickness due to Rayleigh scattering;

$\tau_{gas}(\lambda)$: optical thickness due to gas absorption (O_3, NO_2, CH_4 and H_2O).

2.2. Standard Model for Direct Estimation of Global Solar Irradiance at Ground Level in Clear Sky

This model allows to estimate directly the average global irradiation received per day on a horizontal plane in clear sky [5]:

$$G_g = I_n \times (\cos(\theta_z) + C) \tag{2.9}$$

where:

θ_z is the solar zenith distance, $\theta_z = (90˚ - h)$;

C: the diffusion factor of the atmosphere.

In: being the illuminance due to direct radiation on a normal plane, given by:

$$I_n = A\exp(-B \cdot m \cdot r) \tag{2.10}$$

With: A the apparent solar constant outside the atmosphere

$$A = I_{sc} \cdot C_{dts} \tag{2.11}$$

I_{sc}: being the solar constant taken equal to 1367 W/m^2 and is the correction due to the variation of the Earth-Sun distance calculated by the relation:

$$C_{dts} = 1 + 0.034\cos(0.984\, j),$$

where j is the number of the day.

m: is the optical path of solar radiation; in this model, it is calculated by the following expression [6]:

$$m = \frac{35}{\sqrt{1224\cos\theta_z + 1}} \tag{2.12}$$

r: is the altitude correction factor, given by:

$$r = \left[1 - \frac{A_1}{44308}\right]^{5.257} \tag{2.13}$$

With A_1 being the elevation of the site considered in meters.

In the original model, the respective extinction and diffusion coefficients are given as follows:

$$\begin{aligned} B = &-1.99925\times10^{-15} j^6 + 2.22076\times10^{-12} j^5 - 8.33643\times10^{-10} j^4 \\ &+ 1.07543\times10^{-7} j^3 - 4.6\times10^{-7} j^2 - 131.45\times10^{-6} j + 0.1432 \end{aligned}$$

$$\begin{aligned} C = &-5.19886\times10^{-15} j^6 + 5.7539\times10^{-12} j^5 - 2.2713\times10^{-10} j^4 \\ &+ 3.70022\times10^{-7} j^3 - 2.1351\times10^{-5} j^2 - 0.000511 j + 0.05363 \end{aligned}$$

where: j is the jth day of the year.

2.3. The BRAZIL-SR Model for Calculating the Global Horizontal Irradiation GHI in Cloudy Skies

The Brazil-SR method provides solar irradiance maps, and was developed by the Brazilian National Space Research Center (INPE) and the Federal University of Santa Catarina (UFSC)/LABSOLAR (Martins *et al.* 2007). The method uses visible channel images from the GOES satellite to estimate solar radiation on the ground. It is based on the IGMK radiative transfer model of Moser & Raschke (1983), which allows for the consideration of multiple reflections of solar irradiance between the Earth's surface and the atmospheric layers. It uses a "double flux" approach developed by Schmetz (1984) to estimate atmospheric transmittance. Estimates of the solar irradiance at the ground, G_{ground}, are obtained from Equation (2.14), where G_0 is the extraterrestrial solar irradiance. The first term is associated with clear sky and the second is related to the overcast condition [7]. The clear_sky (τ_{skyclair}) and cloudy days (τ_{skycloud}) transmissions are obtained from an atmospheric parameterization using climatic data (temperature, relative humidity, surface albedo, visibility θ_z, and cloud properties) and geographical position (latitude, longitude, and altitude). The effective cloud cover coefficient, n is a weighting function of the linear relationship between clear and overcast conditions. Although a fairly simple approach, Equation (2.14) performs very well, as demonstrated by Colle and Pereira (1998).

The value of a pixel in an image is converted into a radiance value, ρ, and then transformed into a cloudiness index, n, above the pixel. This index is combined with the boundary values of atmospheric transmittance τ_{cloud} and τ_{clair} to provide an estimate of ground irradiance (G_{ground}) through equation:

$$G = G_0\left[\tau_{\text{skyclair}}(1-n) + \tau_{\text{skycloud}} n\right] \tag{2.14}$$

where:

G_0: is the solar irradiation from outside the atmosphere.

n: is called clouding index which is the key parameter to determine to obtain solar estimates with a good accuracy. The value of n contains information on the spatial distribution and optical thickness of clouds.

The methodology used to estimate direct beam irradiance (DNI) assumes that the contribution of cloud cover to direct transmittance can be added to the direct irradiance of clear sky.

$\tau_{\text{sky-clair}}$ due to aerosols, water vapor, and atmospheric gases.

Therefore, the direct solar estimate is calculated from the following equation:

$$\text{DNI} = G_0 \times \tau_{\text{atm-dir}} \times \tau_{\text{cloud-dir}} \tag{2.15}$$

where:

$$G_0 = G_{sc}\left(1 + 0.033\cos\frac{360\,j}{365}\right) \tag{2.16}$$

G_0 = extraterrestrial radiation measured on the plane normal to the radiation of the jth day of the year (W/m^2).

G_{sc} = solar constant (W/m^2). The last value of G_{sc} is 1366.1 W/m^2. This was adopted in 2000 by the American Society for Testing and Materials (ASTM), which developed an AM0 reference Spectrum (ASTM E-490) [8].

$\tau_{\text{cloud-dir}}$: represents the cloud transmittance for the direct component of solar irradiance.

$\tau_{\text{atm-dir}}$ is obtained by the following empirical relationship [9]:

$$\tau_{\text{atm-dir}} = \frac{1}{2}\left(\mathrm{e}^{-0.65m} + \mathrm{e}^{-0.95m}\right) \tag{2.17}$$

$\tau_{\text{cloud-dir}}$ is estimated from the cloud cover index, n, using the following approach (Stuhlmann *et al.* 1990):

$$\tau_{\text{cloud-dir}} = \left(1 - \tau_c\right) / \left(m - \tau_c\right) \tag{2.18}$$

where:

- $\tau_c = \left(n + 0.05\right) \quad \text{if:} \quad n < 0.95$,
- $\tau_c = 1.0 \quad \text{if:} \quad n \geq 0.95$.

With:

$$m = \frac{1}{\cos\left(\theta_z\right)},$$

the relative air-mass.

3. Method of Evaluating the Horizontal Global Solar Irradiance GHI on the Ground from Satellite Images

3.1. Atmospheric Remote Sensing

The main applications of atmospheric remote sensing are

- Weather forecasting
- Study of atmospheric gases

- Disaster prevention (storms, winds, etc.)
- Renewable energies (wind, solar)
- Air quality: pollution, aerosols, haze, etc.
- Greenhouse gases
- Climate change.

Among the main missions of remote sensing in the atmospheric domain are the geostationary meteorological satellites Meteosat provide data for climate monitoring in Europe and Africa since 1978, constituting one of the longest time series of climate data collected by satellite in the world. Meteosat imagery is crucial for nowcasting, which consists of detecting rapidly developing high-impact weather and predicting its evolution a few hours in advance, for the safety of people and property.

3.2. SEVIRI Image Data Level 1.5 High Throughputs-MSG-0 Degree

Rectified Meteosat SEVIRI image data (level 1.5). The data are transmitted as high-rate transmissions in 12 spectral channels (Table 1). Level 1.5 image data is geolocated and radiometrically pre-processed image data ready for further

Table 1. MSG SEVIRI spectral channel definition.

Channel	Bands	Centre Wavel. (μm)	Spectral Band (99% Energy limits) (μm)	Dynamic Range	Operating Temp (˚K)	Detectors Per Channel	Sample Distance at SST (km)
HRV	Visible & Near IR	0.75	Broadband (peak Within 0.6-0.9)	0 - 459 W/m^2 sr μm (scaled et centre frequency)	300	9	1
VIS0.6		0.635	0.56 - 0.71	0 - 533 W/m^2 sr μm		3	3
VIS0.8		0.81	074 - 0.88	0 - 357 W/m^2 sr μm			
IR1.6		1.64	1.50 - 1.78	0 - 75 W/m^2 sr μm			
IR3.9	window	3.92	3.48 - 4.36 (98 energy limits)	0 - 335 K	85 - 95		
IR8.7		8.70	8.30 - 9.10 (98 energy limits)	0 - 300 K			
IR10.8		10.80	9.80 - 11.80 (98 energy limits)	0 - 335 K			
IR12.0		12.00	11.00 - 13.00 (98 energy limits)	0 - 335 K			
IR6.2	Water Vapour	6.25	5.35 - 7.15	0 - 300 K			
IR7.3		7.35	6.85 - 7.85 (98 energy limits)	0 - 300 K			
IR9.7	Ozone	9.66	9.38 - 9.44	0 - 310 K			
IR13.4	Carbon dioxide	13.40	12.40 - 14.40 (96 energy limits)	0 - 300 K			

processing, e.g. extraction of meteorological products. All spacecraft-specific effects have been removed, and in particular, linearization and equalization of the image radiometry have been performed for all SEVIRI channels. The on-board blackbody data have been processed. Radiometric and geometric quality control information is included. Images are made available with different delays depending on their latency: quarter-hourly images if the latency is greater than 3 hours and hourly images if the latency is less than 3 hours (for a total of 87 images per day) [10].

3.3. Calculation of the Clouding Index n from the Image of the SEVIRI Radiometer of the MSG Satellite

The raw digital data, of the visible and infrared channels of the SEVIRI sensor of MSG, used are converted into reflectance values for the visible and near-infrared channels (0.6/HRV/1.6µm) into brightness temperature values for the thermal channel (10.8 µm), with the original contrast (clouds appear in black).

The calculation of the cloudiness index n from the second generation meteosat satellite image, which is the key parameter to be extracted to calculate GHI on the ground, requires the selection of a package of images taken over one month (30 images/month: 1 image/day) for the four seasons of the year at a specific time spanning a selected period of a few years. In the visible channels of SEVIRI, from the current raw image and two reference images. By exploiting the computer program **ERDAS IMAGINE** available at the Royal Center for Remote Sensing, which is programmed using the **Model Maker** to calculate the clouding index n from the geolocated and radiometrically corrected MSG image.

The clouding image is calculated, in the visible spectrum, from the current raw image and two reference images, the clear sky image and the fully cloudy sky image.

Therefore, for a single pixel, the radiance captured by the satellite is a combination of two components [11].

- Radiance reflected by the ground under clear sky which corresponds to it a minimum value named: $\rho_{\min}^{t}$
- Radiance reflected by the clouds that corresponds to him a maximum value named: $\rho_{\max}^{t}$

$$n(i,j)^t = \frac{\rho - \rho_{\min}}{\rho_{\max} - \rho_{\min}} \tag{3.1}$$

With:

$$\rho_{\min} = \rho_{\text{skyclear}}$$

$$\rho_{\max} = \rho_{\text{skycloud}}$$

where:

ρ: is the radiance measured by the visible channel of the SEVIRI sensor on the MSG satellite;

ρ_{clear} and ρ_{cloud}: are, respectively, the radiances from the SEVIRI visible channel measured in the same spectral range of wavelengths, under clear and overcast sky conditions.

The ρ_{clear} and ρ_{cloud} values for each image pixel are produced by a statistical analysis of satellite images (Martins *et al.* 2003).

Unlike the visible, for the thermal infrared channels IR3.9 or IR10.8 [12]:

- The minimum brightness image:

$T_{\min}^{t}$: corresponds to the reference image relative to the sky completely covered by clouds and

- The maximum brightness image:

$T_{\max}^{t}$: corresponds to the clear sky.

$$n(i,j)^{t} = \frac{T_{\max}^{t} - T^{t}(i,j)}{T_{\max?}(i,j)^{t} - T_{\min}(i,j)^{t}} \quad \text{(N. Bachari } et\ al.\text{, 2003)} \tag{3.2}$$

4. Conclusions

Solar radiation on the ground is generally affected by clouds that have a wide variety in time and space. The raw digital data, from the visible and infrared channels of the SEVIRI radiometer on board the MSG series of meteorological satellites, are valuable for evaluating the cloudiness index n. This index is the key parameter of all mathematical models for estimating the global horizontal irradiance GHI and the direct normal irradiance DNI on the ground.

The errors in the estimation of GHI by the Brazil-SR method can be determined from the mean bias error (MBE) and the root mean square error (RMSE). Lorenz *et al.* (2009) define MBE and RMSE as follows [13]:

$$\text{MBE} = \frac{1}{N}\sum_{1}^{N}\left(\text{GHI}_{\text{EST},i} - \text{GHI}_{\text{OBS},i}\right)$$

$$\text{RMSE} = \sqrt{\frac{1}{N}\sum_{1}^{N}\left(\text{GHI}_{\text{EST},i} - \text{GHI}_{\text{OBS},i}\right)^{2}}$$

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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