1. Introduction

Networks of measuring stations of solar radiation at ground level which must provide well controlled measurements of the solar irradiation are only available in a limited number of sites. Moreover, the investments and the maintenance costs for each site are important. That is why in certain parts of the world, as in Africa, the stations are rare, whereas enormous profits in terms of effectiveness, costs, etc. should be reached by engineers, companies, agencies and institutes and research centers if suitable information were more easily and constantly available for practically any geographical place.

Atlas [Bachari et al. (2001), Wald et al. (2000), Diabate et al. (2004)] carried out from satellite data image processing and calibrated by time series of measurements in-situ of weather stations should make it possible to lay out available values of daily or hourly irradiations with a space resolution of roughly 10 kilometers and the relative errors (RMSE) of daily irradiation should be less than 20%. For that purpose, methods of interpolation/extrapolation are used to reach constantly the value at any geographical place, but they lead to evaluations of lower quality. Thus, since the setting on orbit of meteorological satellites (GOES, METEOSAT and NOAA), several methodologies of estimate global irradiation known as “exploitation of the satellite imagery” were born [Cano et al. (1986), Abdel Wahab et al. (2009)]. It is in this objective that methodology “Gistel” of estimate of the solar layer was focusing by using images of satellite METEOSAT on stations in France [Delorme et al. (1988)], Tunisie [Ben Djemaa et Delorme (1992)] and Côte d’Ivoire [Mohamed 1992), N’goran (2005)], within the
framework of an international collaboration. Gistel is a synthetic methodology (physical and statistical) initially elaborate with images of the types B2 (Gistel-B) [Lefèvre et al. (2007), 18] and WEFAX (Gistel-W) [Delorme C. et al., (1992)]. But with this version, it was impossible to have access to the average brightness of the ground from the methods of minima of the brightnesses used, more than great uncertainties are to be taken into account. Other similar methods were described with alternatives especially with regard to the choices of the parameters of entry, for example “Heliosat 1 or 2” [Dribssa et al. (1999), Rigollier et al. 2004)] which consists in ennum- gament calculating the index of correspondent to “a pixel image” from the apparent albedos of the ground and cloud.

This paper thus describes methodology Gistel-P, a new version improved of Gistel one, worked out from primary data images (P.D.U.S.) [N’goran (2005)] and its application to a comparative study of the values estimated with data of measurement collected on the site of university of Abidjan station (Southern of Côte d’Ivoire) during five months, from November 2001 to March 2002. Just as an outline on the turnover of the data of measurement (October 2009 to September 2010) of the new climatic weather station is provided.

2. Data and methodology

2.1. Data used

2.1.1. Data base of PDUS images of METEOSAT satellite

We acquired, on CD ROM support, data of five months images in the three channels “visible, infrared and steam” of satellite METEOSAT-7, with 11 images per day (1 image per hour of 7:30 to 17:30 TU). Only images of the channels “visible” are treated in this study. For each image, a portion smaller size 512x384 pixels useful centered on the Côte d’Ivoire country of 4° for 11° N and 2° to 9° W, was extracted to reduce quantity of data stored and also time of data processing. The result of this pre-treatment gives a database of 1650 images without defects. Figure 1 gives an example of presentation of these images obtained.

2. Data of ground measures

The data of measurement having been used for the validation of our methodology in wet tropical climate are those acquired on the site of the University of Cocody located at Abidjan (latitude 5°20’24” N, longitude 3°59’24” W). These data relate to two distinct periods: firstly from November 2001 to March 2002, with for ony measurement global solar radiation on horizontal level carried out using a pyranometer KIPP & ZONEN provided with a SEFRAM DATALOGER system of acquisition PC compatible which can receive 21,000 points of data. This station placed on the roof of the building of the Physics Laboratory of the Condensed Matter and Technology (elevation 70 m given using a GPS 38 GARMIN) and secondary since October 2009, a new site measuring is located at ground (elevation 46 m) in the course of same laboratory with “STATION VANTAGE PRO 2 PLUS” equipment of DAVIS INSTRUMENT which contains integrated sensors (speed and direction of wind, pressure, temperature, hygrometry, pluviometer, solar and UV radiations), a module of interface of sensor, a console of radio reception, a Data Logger suitable PC connection by USB cable, a software WeatherLink version 5.8.2, a computer allowing to data exploitation and a server of publication on Internet network. This unit constitutes the chain of the meteoclimatic station of the University of Cocody whose fitting is shown on Figure 2 with URL to Internet: http://meteo.univ-cocody.ci.

2.2. Gistel-P methodology

The total methodology of treatment (MGT) of Gistel-P used, taking into account the assumptions of original “Gistel” methodology, contains three models (Figure 3): “Data and Parameters of Entry” (ENTRE), “Atmospheric Transmission” (ATMOS) and “Estimate of global solar Irradiations” (IRRAD).
Figure 2. The chain of meteoclimatic at University of Cocody in Abidjan.

Figure 3. Synoptic of algorithm of Gistel-P method.
- **ENTRE model**: The model “ENTRE” considers a point image \( P_{i}(l, p, b_{i}, a, m, d, h) \) or \( P_{g}(\text{lat}, \text{long}, b_{i}, a, m, d, h) \) where the parameters are the line \( l \), the pixel \( p \), the value of the pixel called brightness \( b_{i} \), the year \( a \), the month \( m \), the day \( d \) and the hour \( h \) in a given site. The coordinates \( (l, p) \) of a point image are converted into their geographical equivalents \( (\text{long}, \text{lat}) \). Then, it also defines two other important parameters which are, for a completely cloud sky, the brightness \( S_{0} \) threshold (higher limit) and, for clear sky, the factor of disturbance of Linke \( (T_{L}) \) of the studied area.

- **ATMOS model**: The atmospheric model of transmission exploits also the O.M.M. model [1981] by clear sky to calculate global irradiance and the transitivity ground-satellite. The following formulas are used:

\[
G_{c} = \text{cor} \cdot (1300 - 57.7L) \cdot (\sin(h_{S})^{367 + T_{L}})^{33} \quad (1)
\]

for global irradiance by clear sky and,

\[
T_{v} = I_{v} / I_{0} = \left\{ \frac{(1390 - 31.7L) \cdot \exp(-T_{L} \cdot \sin(h_{S}) + 2)}{12.6 \cdot \sin(h_{V})} \right\}^{(1373 \cdot \text{cor})} \quad (2)
\]

for transitivity ground-satellite corrected by the factor of correction of the distance Ground-Sun, given by:

\[
\text{cor} = 1 + 0.034 \cdot \cos(360/365 \cdot (Q_{i} - 3)) \quad (3)
\]

where \( Q_{i} \) is the day of the month of the year since January 1°, with \( h_{S} \) the angular height of the sun, \( h_{V} \) the angular height of the satellite.

Then the model calculates three coefficients of reflection as given in the original methodology which is:

\[
C_{i}(\text{lat}, \text{long}, d, h) = \left[ B_{i}(\text{lat}, \text{long}, d, h) - B_{s} \right] / \left[ N_{k} \cdot G_{c}(\text{lat}, \text{long}, d, h) \cdot T_{v}(\text{lat}, \text{long}, d, h) \right] \quad (4)
\]

Where \( i=c \) for a clear sky, \( i=o \) for a cloudy sky and \( i=q \) for other intermediate sky, \( G_{c}(\text{lat}, \text{long}, d, h) \) and \( T_{v}(\text{lat}, \text{long}, d, h) \) are respectively obtained by the equations (1) and (2), \( d \) the date, \( N_{k} \) a numerical factor of calibration of the detector of METEOSAT equal to 0.554 and \( B_{s} \) the atmospheric component of the brightness (due to the Rayleigh diffusion), supposed constant \( =12 \) [Ben Djemaa and Delorme (1992)].

- **IRRAD model**: Finally, the attenuation coefficient \( K_{i}(\text{lat}, \text{long}, d, h) \), is deduced from the comparison between \( Cr_{q} \) and \( Cr_{c} \) and \( Cr_{o} \) according to the following relations:

If \( C_{r_{q}} \leq C_{r_{c}} \) then \( K_{i}(\text{lat}, \text{long}, d, h) = 1 \) (100% of irradiance by clear sky)

If \( C_{r_{q}} \geq C_{r_{c}} \) then \( K_{i}(\text{lat}, \text{long}, d, h) = K_{o} = 0.2 \) (of irradiance by clear sky)

If \( C_{r_{c}} < C_{r_{q}} < C_{r_{o}} \) then

\[
K_{i}(\text{lat}, \text{long}, d, h) = 1 - (1 - K_{o}) \frac{C_{r_{q}}(\text{lat}, \text{long}, d, h) - C_{r_{o}}(\text{lat}, \text{long}, m, h)}{C_{r_{o}}(\text{lat}, \text{long}, d, h) - C_{r_{c}}(\text{lat}, \text{long}, m, h)} \quad (5)
\]

This classification leads to the calculation of instantaneous global irradiance \( G_{i}(\text{lat}, \text{long}, d, h) \) such given by most methods [Delorme et al. (1988), Ben Djemaa and Delorme (1992)]:

\[
G_{i}(\text{lat}, \text{long}, d, h) = K_{i}(\text{lat}, \text{long}, d, h) \cdot G_{c}(\text{TL}, h_{S}) \quad (6)
\]

The total daily irradiation \( G_{d}(\text{lat}, \text{long}, d) \) is the summation of instantaneous global irradiance of day \( d \) (12 images per day):

\[
G_{d}(\text{lat}, \text{long}, d) = \sum_{k=1}^{12} G_{i}(\text{lat}, \text{long}, d, h) = \sum_{k=1}^{12} G_{i}(\text{lat}, \text{long}, d, 12) \quad (7)
\]

### 3. Results (period 2001 November to 2002 March)

The results presented and the discussion which follows relate to the application of Gistel-P methodology for period of November 2001 to March 2002 by observing the solar irradiations in two kinds of studies.

#### 3.1. Algorithm

Figure 3 illustrates the algorithm for a treatment sequence pixel by pixel imaged developed in language Turbo Pascal 7.0. All the results are stored in files format “.text” directly recoverable under Microsoft Excel for the statistical studies. The study leads to fix various parameters of reference which are: the basic component \( B_{s} \) fixed at 12, the brightness \( S_{0} \) threshold fixed at least 75 CN (Numerical Count: unit used to express the brightness) used to determine completely sky coefficient of reflection.

#### 3.2. Daily global solar irradiations

Figure 4 gives the synthesis of the curves of evolution of daily global irradiations from 2001 November to 2002
March. In general, the curves of the estimated values follow those of measurements. Some variations in November however are observed according to the value of $T_L$ or $S_O$. All global daily irradiations estimated are close to the measured ones. We represented (Figure 5) the graphs of the groups of dots of global daily irradiations calculated $IG_{cal}$ versus measured $IG_{mes}$. It arises for the totality of the 151 available couples a great dispersion of the points around the median. Determination of the statistical indicators: coefficient of correlation ($r$), mean bias (MBE), mean absolute (MAE) and root mean square (RMSE) errors, was made from the formulas suggested by Davies et al. [1988].

Table 1 shows the results of these indicators.

The coefficients of correlation vary from 0.60 to 0.80 and the better is obtained when mixing $T_L$ where $r_{syn} = 0.82$. The study of the

![Figure 4. Curve of evolutions of synthesis between estimated and measured global daily irradiations at University of Cocody in Abidjan from 2001 November 2001 to 2002 March ($r \approx 0.82$).](image)

![Figure 5. Dot representation of synthesis between estimated and measured global daily irradiations at University of Cocody in Abidjan from 2001 November 2001 to 2002 March ($r \approx 0.82$).](image)

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<th>TL</th>
<th>S0</th>
<th>$r_{Nov01}$</th>
<th>$r_{Dec01}$</th>
<th>$r_{Jan02}$</th>
<th>$r_{Fev02}$</th>
<th>$r_{Mar02}$</th>
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<td><strong>0.82</strong></td>
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Table 1. Coefficient of correlation ($r$) and mean bias (MBE), mean absolute (MAE) and root mean square (RMSE) errors belong to $T_L$ (2.5, 3.5 and 4.5) and $S_O$ (55 to 160 CN).
distribution of the mean bias error (MBE) shows that, for daily values fluctuating between 1 and 8 kW/m², a proportion of 80% is located between ±1.4 kWh/m². Seemly, the relative average deviations in mean absolute error (MAE), shows a proportion approximately 85% is lower than 1.4 kWh/m². But, the relatively low value of the coefficient of correlation obtained and especially its variability according to the month are probably due to strong disturbances observed in wet tropical area, because we are not any more in clear sky situation. So, we think that the results of our methodology are underestimated.

3.3. Instantaneous global solar irradiances

Studies were undertaken by looking at the daily profiles of the monthly averages, maxima and minima and days of better sunning of the instantaneous global solar irradiances between calculated and measured values with \( T_L \) (2.5, 3.5 and 4.5) and thresholds of \( S_0 \) brightness varying from 55 to 160 CN. Figure 6 shows an example of the curves of daily variations of the estimated monthly averages like those measured from 7:30 to 16:30 TU. Figure 7 represents the dots chart of the instantaneous global solar irradiances estimated according to those measured for these days. One observes a very good agreement between these curves. For profiles of the maxima values of global solar irradiances a triad is observed between measurement and estimate, while for the minima, it is a great dissension between measurement and estimate which is explained by the fact that one is in bad weather situation, sky completely covered by clouds. The statistics, concerning the distribution of the coefficient of correlation \( r \), are presented in Table 2.
These results confirm the theoretically announced classification of the days in three distinct classes: days of clear sky, days of sky completely covered and days of intermediate time. The mean bias (MBE), mean absolute (MAE) and root mean square (RMSE) errors calculated vary from 15 to 10% for the monthly averages, from 20 to 15% for monthly maxima and from 30 to 1% for the days of better sunning (1% for the 12/27/01) of instantaneous global solar irradiances. Deducting that our Gistel model is able to reproduce the form of daily irradiation by making a classification according time. But it needs more precisions on local conditions, This is why, since 2009 October, we have been considering a systematic locally acquisition of some parameters with ISESCO support.

4. Synthetic view of measure data of the new meteoclimatic station

A study of the daily profiles of the curves of daily global irradiations (averages, maxima and minima) from 2002 October to 2009 September has been conducted. It confirms a classification in three classes of days (Figure 8): days of clear sky (good weather), days of cloud cover (cloudy time) and days of other cases (intermediate time). This representation is important because it will be useful for the development of the models as well for the estimate and the prediction of the solar radiation as for dimensioning photovoltaic solar systems. However, it hides more realities because such data do not take into account the fluctuations in the local meteorological conditions, as observed in tropical climate, which can provoke large variation of solar radiation. The amplitude of these variations can reach 700 W/m² and occur within a short time interval, from a few seconds to a few minutes depending on the geographical location. These variations fundamentally depend on cloud size, speed and number. Although, it has been shown that, the fractional time distribution for instantaneous radiation differs significantly from that obtained with daily values. Thus, these important fluctuations, observed over one period of a few minutes (Figure 9), can cause instabilities in the distribution networks of energy to strong density of statement. Whereas the management of the electrical communication and the alternative energy sources require a better identification of these variations with small scales.

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<td>13</td>
<td>12</td>
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</tr>
</tbody>
</table>

Table 2. Statistical results of the distribution of the coefficient of correlation r.

![Figure 8. Curves of the evolutions daily irradiances (in W/m²) for three types of days pour 3 journées types (new station at University of Cocody in Abidjan latitude 5° 20' N, longitude 3° 59’ W et elevation 46 m).](image-url)
Figure 9. Comparative curves of theoretical extraterrestrial solar irradiance versus those of days of better sunning, low sunning and cloudy sky (new station at University of Cocody in Abidjan latitude 5° 20' N, longitude 3° 59' W and elevation 46 m).

Conclusions

At the end of this project, it was proven, through a methodology known as Gistel-P, that it is possible to evaluate rather correctly the daily global irradiation with an estimate of relative error of about 20%. Insufficiencies, moreover, were raised. It remains however that a good knowledge of the variation of the factor of Linke disturbance is essential, especially in tropical area. So, the established relations of estimate would be good quality provided that they take into account the seasonal formulas which with these latitudes, correspond to the dry season and the rainy season. A finer study of these data a longer period of time would be essential to validate the estimates by satellite imagery in order to be able to establish, by satellite, solar charts of these areas to weak density of measuring sites at the ground level. That is the reason, this work has been undertaken in Abidjan with ISESCO'S support. Whose preliminary result presented here is a good start which should in the future make it possible to improve these results by taking the pyranometric measurements adapted in wet tropical area. The advance to be followed will be then to carry out an estimate and/or a prediction of the solar irradiation by treatment of satellite images and to propose a set of strategies for the solar irradiation using the Gistel-P method.

References


