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Reconstitution of Solar Radiation on a Site of the Littoral in Côte D'ivoire

M. Sidibé[1], D. Soro[2], W.F. Fassinou[1] and S. Touré[1]

[1]*Universite Felix Houphouët Boigny Cocody 22 BP 582 Abidjan 22 Côte d'Ivoire*
[2]*Ecole Normale Supérieure (ENS) d'Abidjan, 08 BP 10 Abidjan 08, Côte d'Ivoire.*

Abstract

The solar energy available on the ground is generally a function of time, of geographical variability, but also of climate. On the littoral, cloudy periods are almost permanent. The functioning of converters such as solar thermal concentrators, photovoltaic concentrators, etc.... requires the use of the direct component of solar radiation on the ground. Given the insufficient number of solar radiation stations in our sub-Saharan countries, the reconstitution of solar radiation from theoretical models becomes inescapable. Among the theoretical models proposed in the literature, two were selected for our study because of their proven validity on several sites and also because of their numerical different techniques. In the first model, the numerical techniques of calculation used are based on the effects of diffusion and absorption. For this model, the transmission coefficients of the various atmospheric constituents are determined (the Bird & Hulstrom model). In the second model, the atmospheric disturbance of Linke is used (Capderou model). The different coefficients entering these models depend on the meteorological parameters (relative humidity, ambient temperature, atmospheric pressure). The numerical results of the global irradiance on the ground were obtained by Simulink simulation. On this basis, the literature proposes only the Simulink simulation of a model reconstituting solar irradiance. In our study, the simulation under Simulink of the two models reconstituting solar irradiance on the ground in clear sky was carried out simultaneously. The numerical results obtained were compared with the experimental results of the global solar irradiance measured on the site. It is the theoretical model based on the coefficients of transmission of the various atmospheric constituents, the Bird & Hulstrom model which presents the best agreement with the experiment carried out on the site.

Keywords: Solar radiation, littoral, theoretical models, simulation, transmission coefficient, Linke disturbance coefficient.

I- INTRODUCTION

The solar energy available on the ground is generally a function of time, geographical variability and also climate. Its knowledge on a given site is essential for the proper functioning of the solar thermal collectors. In Côte d'Ivoire the solar potential is enormous. As in most sub-Saharan countries, there is an insufficient number of solar radiation monitoring stations networks but also a laborious access to solar data. For this, reconstituting solar radiation from theoretical models for research purposes becomes inescapable. Our work is in this perspective. Thus, the study and the simulation are carried out under the climatic conditions of a site of Abidjan city in Cote d'Ivoire. Among the existing models in the literature, two were chosen and under clear sky conditions. Two factors characterized our choice: the validity proved on several sites in the world and the difference observed between their numerical techniques of calculation. Thus, for the first model, the transmission coefficients of the atmospheric constituents are directly used: the Bird & Hulstrom model [1- 2- 3-4]. Concerning the second model which is that of the Capderou model [5-6-7-8-9], it is mainly the atmospheric disturbance of Linke that is taken into account. The interest of this study is to determine a theoretical model of solar irradiance compatible with the climatic conditions of the littoral. For this, a modeling is done under Simulink. Both models are simultaneously simulated. This study will begin with the theoretical bases of solar radiation proposed by the different models. Then the materials and methods used follow. Finally, discussion and analysis of the results will complete this work.

II-THEORETICAL BASES OF THE MODELS

II.1- Model of Bird & Hulstrom [1]

II.1.1 Estimation of irradiance due to direct radiation by clear sky

The correlation proposed by Bird & Hulstrom for calculation of direct radiation in clear sky on a horizontal plane is expressed by equation (1):

$$I_{h1} = 0.975 \cdot I_{SC} \cdot \tau_r \cdot \tau_g \cdot \tau_o \cdot \tau_w \cdot \tau_a \cdot cos\theta_z \tag{1}$$

With:
τ_r: Transmission coefficient for Rayleigh scattering
τ_g: Transmission coefficient for the absorption of equilibrated gases (essentially O_2 and CO_2).
τ_o: Transmission coefficient for the absorption of atmospheric ozone
τ_w: Transmission coefficient for the absorption of water vapor
τ_a : Transmission coefficient for Aerosol Extinction.

θ_z: Zenithal angle, $\theta_z = 90° - h$ (2)

Where h is the height of the sun, given in **Annex A**.

I_{SC} : Extra-terrestrial Solar constant calculated by the following relationship:

$$I_{SC} = I_o \cdot \left(1 + 0.033cos(2\pi N/365)\right) \tag{3}$$

With I_o the average solar constant of 1367 W / m² and N, the day number in the year (N = 1 to January, 1[th] and N = 365 for December, 31[th]). The different transmission coefficients are characterized as follows:

- **Rayleigh scattering coefficient**

$$\tau_r = \exp[-0.0903 m_a^{0.84}(1 + m_a - m_a^{1.01})] \tag{4}$$

With m_a the optical air mass at local conditions, expressed in **Annex B**.

- **Ozone transmission coefficient**

$$\tau_o = 1 - 0.161(L_o \cdot m_r)\left(1.0 + 13948(L_o \cdot m_r)\right)^{-0.3035} - 0.00275(L_o \cdot m_r)(1 + 0.044(L_o \cdot m_r) + 0.003(L_o \cdot m_r)^2)^{-1} \tag{5}$$

Where, m_r and L_o denote respectively the relative optical mass of the air and the vertical thickness of the ozone layer in cm under normal conditions of temperature and pressure **NTP** (**N**ormal **T**emperature and surface **P**ressure) [2]. They are expressed in **Annex B**.

- **Water vapor transmission coefficient**

$$\tau_w = 1 - \alpha_w \tag{6}$$

Where α_w is the absorption coefficient by water vapor, given by equation (7) :

$$\alpha_w = 1 - 2.4959\, U_1[(1 + 7.034U_1)^{0.6828} + 6.385U_1]^{-1} \tag{7}$$

With U_1, the thickness of condensable water corrected by the length of the optical path. It is governed by the following relationship:

$$U_1 = w \cdot m_r \tag{8}$$

Where w is the height of condensable water:

$$w = \frac{0.493 \cdot H_r \cdot P_S}{T_a} \tag{9}$$

Where P_S is the saturated vapor pressure given by the following relation:

$$P_S = exp\left(26.23 - \frac{5416}{T_a}\right) \tag{10}$$

T_a The ambient temperature in K and H_r refers to the relative humidity in %.

- Coefficient of transmission by aerosols

In this model, the transmittance after aerosol scattering is based on the spectral attenuation of two wavelengths 0.38 microns and 0.5 microns, wavelengths whose absorption by ozone molecules is minimal.

$$\tau_a = exp[-k_a^{0.873} + m_a^{0.9108}(1.0 + k_a - k_a^{0.7088})] \tag{11}$$

Where:

$$k_a = 0.2758 k_{a\lambda/\lambda=0.38\mu m} + 0.35 k_{a\lambda/\lambda=0.5\mu m} \tag{12}$$

$k_{a\lambda/\lambda=0.38\mu m}$ and $k_{a\lambda/\lambda=0.5\mu m}$ are two coefficients of attenuation determined from experimental measurements derived by the following relationship [1]:

$$k_a(\lambda) = \beta \lambda^{-\alpha} \tag{13}$$

Where α is the granulometric distribution coefficient and β the atmospheric disturbance coefficient established by Angstrom. In this work, the measures used were provided by the **NCDC** (**N**ational **C**limatic **D**ata **C**enter) Asheville in North Carolina and cited by M. Mesri-Merad et al [1].

Note that α is close to 0 for small particles increases with the particle size and reached 4 to the larger particles. For our study α was taken equal to 1.3. For a very clear sky (deep blue), β is 0.02; for a polluted sky (milky blue) β is 0.2 [1].

II.1.2 Estimation of the irradiance due to diffuse radiation

To calculate the irradiance due to diffuse radiation on a horizontal plane (D_{h1}), three diffuse components due to various types of distribution of solar radiation by atmospheric film should be considered [4]:

$$D_{h1} = D_{r1} + D_{a1} + D_{m1} \tag{14}$$

Where :

D_{r1} : Irradiance due to diffuse radiation from Rayleigh scattering (W / m²)
D_{a1}: Irradiance due to diffuse radiation after diffusion by aerosols (W / m²)
D_{m1} : Irradiance due to the phenomenon of multi-reflection earth-atmosphere (W / m²).

- **The irradiance due to the diffuse radiation coming from the Rayleigh scattering**

$$D_{r1} = 0.79 \cdot I_{SC} \cdot cos\theta_z \cdot \tau_g \cdot \tau_o \cdot \tau_w \cdot \tau_{aa} \cdot 0.5 \cdot (1 - \tau_r)/(1 + m_a - m_a^{1.02}) \quad (15)$$

τ_{aa} Given by Bird & Hulstrom is written:

$$\tau_{aa} = 1 - (1 - \omega_0)(1 + m_a - m_a^{1.06})(1 - \tau_r) \quad (16)$$

With $\omega_0 = 0.9$ recommended.

- **The irradiance due to diffuse radiation after diffusion by aerosols**

$$D_{a1} = 0.79 \cdot I_{SC} \cdot cos\theta_z \cdot \tau_g \cdot \tau_o \cdot \tau_w \cdot \tau_{aa} \cdot F_C \cdot (1 - \tau_{as})/(1 + m_a - m_a^{1.02}) \quad (17)$$

With $F_C = 0.84$, the value recommended by this model, refers to the direct dispersion coefficient of the atmosphere.
τ_{aa}, the coefficient of transmission of the solar radiation after diffusion by the aerosols is estimated by the following relation:

$$\tau_{as} = {}^{\tau_a}/_{\tau_{aa}} \quad (18)$$

- **The irradiance due to the phenomenon of multi-reflection earth-atmosphere**

The irradiance due to radiation from the phenomenon of multi reflections earth - atmosphere is given by the following expression [1]:

$$D_{m1} = (I_{h1} + D_{r1} + D_{a1})\rho_g\rho'_a/\left(1 - \rho_g - \rho'_a\right) \quad (19)$$

With :
ρ_g : The Earth's albedo
ρ'_a, The clear sky's albedo given by:

$$\rho'_a = 0.0685 + (1 - F_C)(1 - \tau_{as}) \quad (20)$$

II.1.3 Estimation of irradiance due to global radiation on a horizontal plane

The irradiance due to the global radiation on a horizontal plane is given by the following expression:

$$G_{h1} = I_{h1} + D_{h1} \tag{21}$$

II.2- Model of Capderou [5]

It is based on the use of the atmospheric disturbance to calculate the direct and diffuse components of solar radiation.

II.2.1 Estimation of irradiance due to direct radiation by clear sky

To determine the solar irradiance by clear sky, knowledge of the atmospheric disturbance factor is required. This factor is the ratio between the extinction of the direct solar radiation passing through the atmosphere at a given incidence and that of the solar radiation passing through a reference atmosphere consisting only of pure and dry air under the same incidence [5]. Several mathematical formulations of atmospheric disturbance are proposed in the literature. In our work, the factor of atmospheric disturbance of Linke T_L^* by clear sky is given by [5-8-9]:

$$T_L^* = T_o + T_1 + T_2 \tag{22}$$

With:

T_o Disturbance due to gas absorption both by the fixed constituents of the atmosphere and by ozone, and especially by water vapor of variable quantity. It is given by the following relation:

$$T_o = \frac{9.4+0.9m_a}{m_a}\alpha_w \tag{23}$$

α_w Represents the extinction coefficient after absorption by water vapor.
In this model, the optical air mass m_a is expressed as:

$$m_a = \frac{1}{\sin(h)+9.4\cdot10^{-4}(\sin(h)+0.0678)^{-1.253}} \tag{24}$$

A modeling of the coefficient T_o as a function of the geo-astronomical parameters allowed Capderou to propose the following expression [9]:

$$T_o = 2.4 - 0.9\sin(\varphi) + 0.1(2+\sin(\varphi))A_{he} - 0.2Z - (1.22 + 0.14A_{he})(1 - \sin(h)) \tag{25}$$

With :

$$A_{he} = \sin\left(\left(\frac{360}{365}\right)(N - 121)\right)$$

And Z the altitude of the place in meters.
T_1 is the disorder corresponding to the absorption by atmospheric gases (O_2, CO_2 and O_3) and molecular Rayleigh scattering. T_1 is expressed by:

$$T_1 = 0.89^Z \tag{26}$$

T_2 is the disorder on the aerosol scattering coupled to a light absorption (it depends both on the nature and quality of aerosols). Depending on the Angstrom disturbance coefficient β, T_2 is given by:

$$T_2 = 16\beta \tag{27}$$

In the absence of measurements of the Angstrom disturbance coefficient, Capderou proposed the following formulation:

$$T_2 = (0.9 + 0.4A_{he})(0.63)^Z \tag{28}$$

The direct irradiance obtained in clear sky on a horizontal plane is given by:

$$I_{h2} = I_o \cdot \sin(\text{h}) \cdot I_{SC} \cdot exp\left[-T_L^*\left(0.9 + \frac{9.4}{0.89^Z}\sin(h)\right)^{-1}\right] \tag{29}$$

In this relation, I_o is the solar constant.

II.2.2 Estimation of the irradiance due to diffuse radiation

The diffuse irradiance incident on a horizontal plane is given by:

$$D_{h2} = I_o \cdot I_{SC} \cdot exp\left((-1 + 1.06 \cdot log\ (\sin(h))) + a - \sqrt{a^2 + b^2}\right) \tag{30}$$

With:

$$a = 1.1 \qquad b = log(T_L^* - T_o) - 2.8 + 1.02(1 - \sin(h))^2 \tag{31}$$

II.2.3 Estimation of irradiance due to global radiation on a horizontal plane

The overall irradiance received on a horizontal plane is given by:

$$G_{h2} = I_{h2} + D_{h2} \tag{32}$$

III- MATERIALS AND METHODS

The geographical coordinates of the place studied are represented by the latitude φ (degrees), the longitude λ_g (degrees) and the altitude Z (m). The geographical

coordinates of the site given by Google map are recorded in **Table 1**.
The geographical location of the site is given in **Figure 1**.

Table 1: Geographical coordinates of the site

Studied position	**Latitude φ (dégrées)**	**Longitude λ_g (°)**	**Altitude Z (m)**
Abidjan University Félix Houphouët Boigny of Cocody	5.3470499	-3.9852916	10

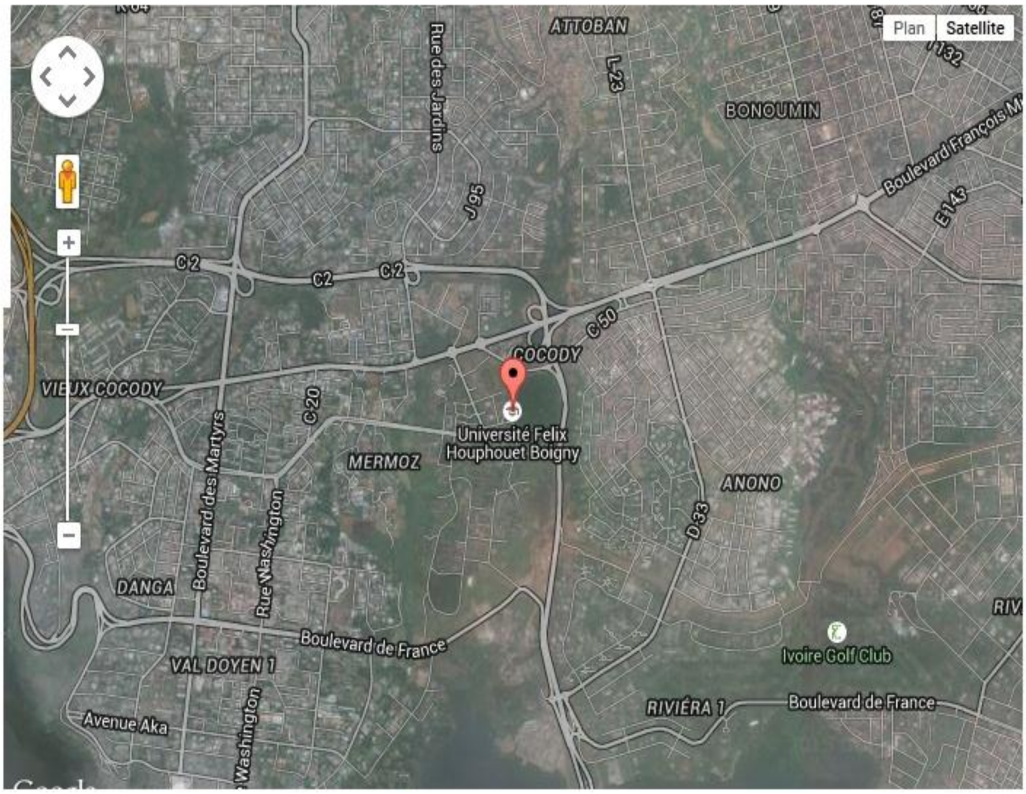

Figure 1 Geographical location of the site University Félix Houphouët Boigny of Cocody, Abidjan (Google map)

To validate the models, we performed simulation under Simulink. Simulink is a software with a graphical interface for modeling, simulation and analysis of dynamic systems. Being integrated with MATLAB, the two environments are perfectly compatible and the different functionalities of the latter are then directly accessible. The graphical interface, Simulink, allows easy and user-friendly construction of block diagrams. Each block composing the system is selected from a set of predefined libraries as shown in **Figure 2**.

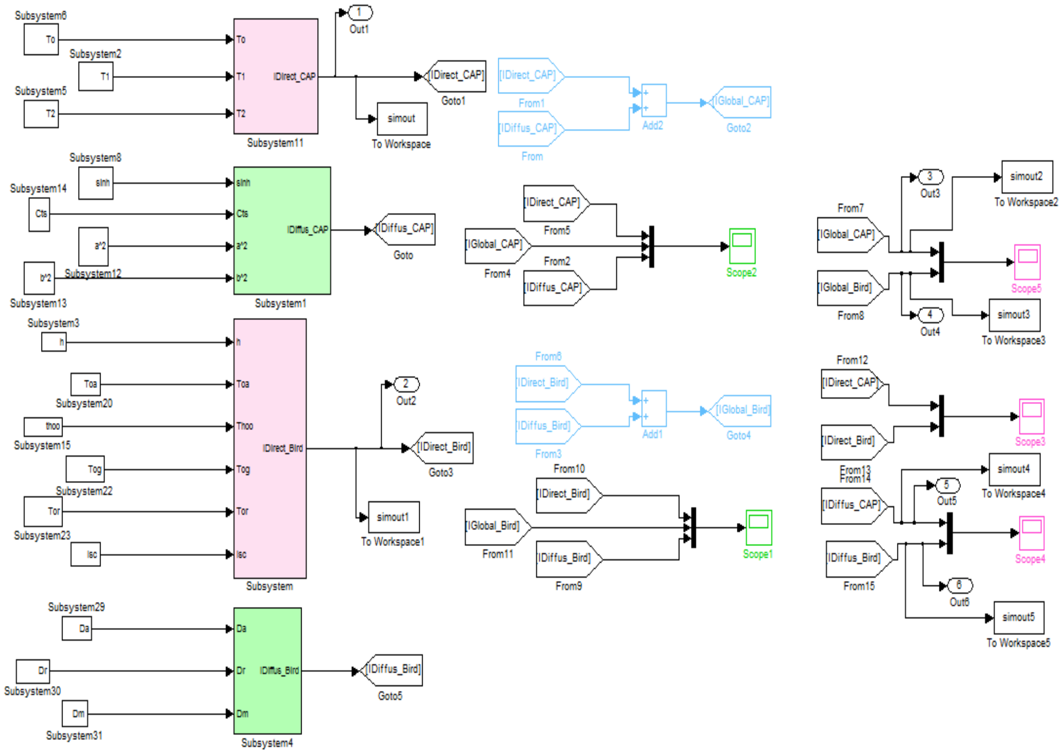

Figure 2: Modeling under Simulink.

The estimated values of the global irradiance obtained from the models are compared with the experimental values of the global irradiance measured on the site in Abidjan. To verify the validity of these models at all times, we chose two days with high solar activities on **April 23th, 1999** and **May 19th, 2015**. The choice of the first day because it belongs to a year for which the effects of the change are not noticeable. Unlike the second day belonging to the year where the effects of climate change are noticeable. It should be noted that the global irradiance measurements were performed by an Eppley PSP 43527-F3 pyranometer with an accuracy of ± 10W / m².

IV- RESULTS AND DISCUSSIONS

Figures 3 and **4** show the curves of variation in overall irradiance estimated and measured. We note that the distribution curves of the measured values and those estimated by the Bird & Hulstrom model are close despite the cloudy periods. On the other hand, the values estimated by the Capderou model overestimate the values measured experimentally**.**

As seen above, the two models are different by their numerical techniques used. In **Table 2**, the amplitudes of the irradiance from the models are recorded.

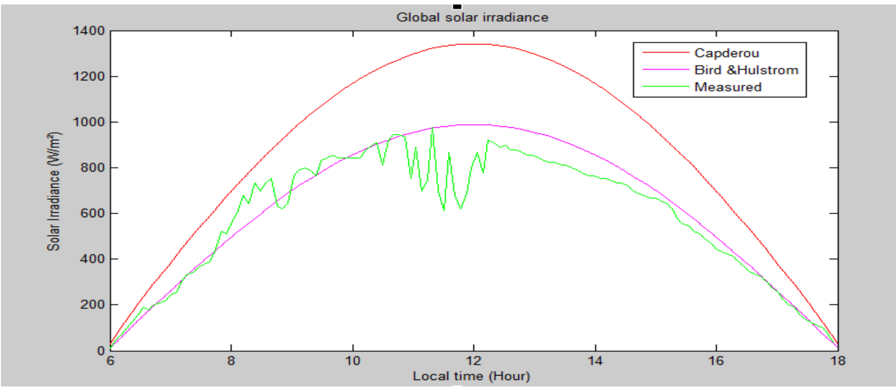

Figure 3 : **Global solar irradiance estimated and measured under Matlab / Simulink, day of 23/04/1999**

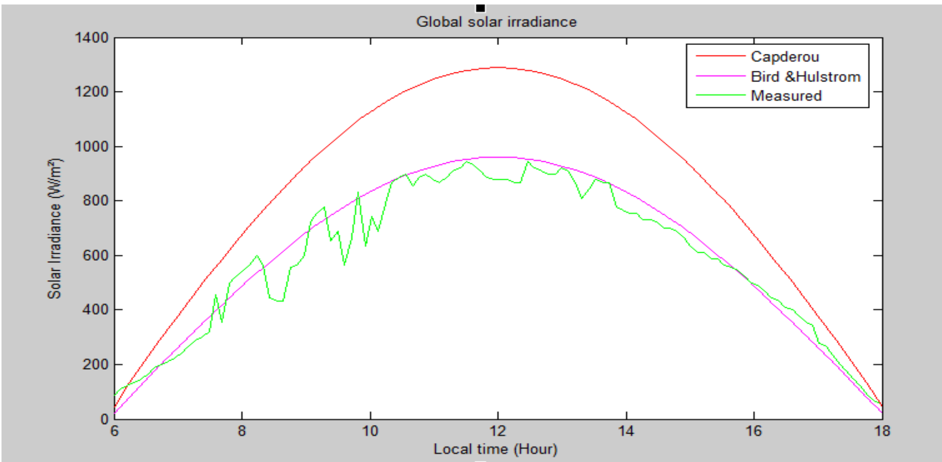

Figure 4 : **Global solar irradiance estimated and measured under Matlab / Simulink, day of 19/05/2015**

Table 2: Amplitude of the global solar irradiance estimated and measured.

Day	Models	Amplitude of the estimated global solar irradiance (W/m2)	Amplitude of the measured global solar irradiance (W/m2)
23/04/1999	Bird & Hulstrom	988,0	976,7
	Capderou	1340,9	
15/05/2015	Bird & Hulstrom	960,3	943,4
	Capderou	1289,0	

We remark on Figures **3** and **4** that the model of Bird & Hulstrom gives results that have better agreement with experiment. This can be explained by the fact that the Bird

& Hulstrom model actually takes more into account the different constituents of the atmosphere than the Capderou model.

Figures 5 and **6** show the curves of variation of the estimated direct solar irradiance. Direct solar irradiance from the Capderou model is and remains constantly above the Bird & Hulstrom model.

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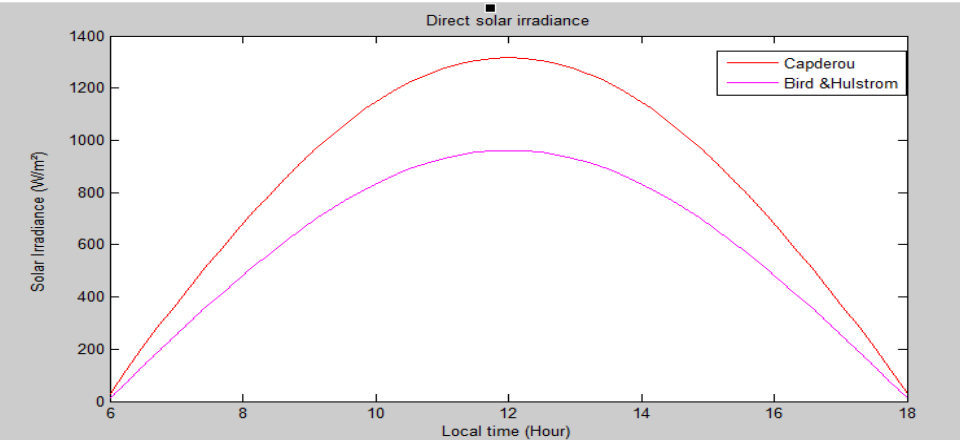

Figure 5 : **Direct irradiance estimated under Matlab / Simulink, day of 23/04/1999.**

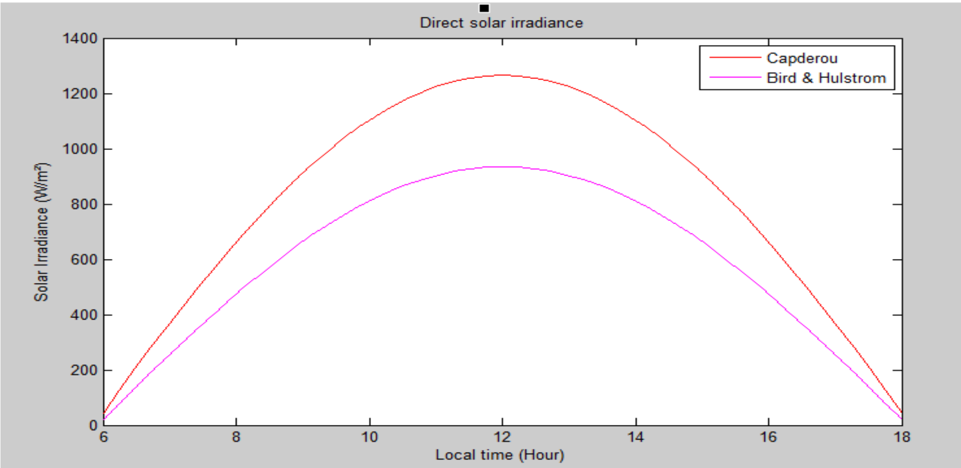

Figure 6: Direct irradiance estimated under Matlab / Simulink, day of 19 /05/2015

Figures 7 and **8** present the curves of variation of the estimated diffuse solar irradiance from the two models. They alternate. We note that the curve from the Capderou model is above that of Bird & Hulstrom from 6: 00 to 9: 00 then passes below at 15: 00 local time. Finally, it rises above until 18: 00.

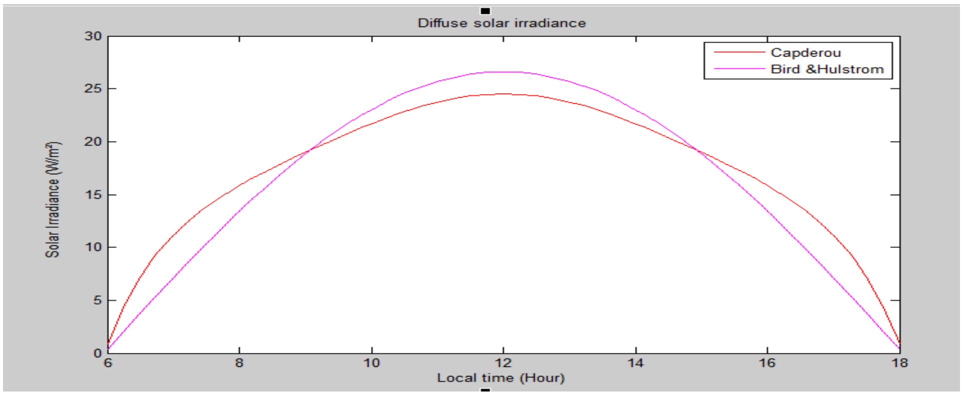

Figure 7: Diffused irradiance estimated under Matlab / Simulink, day of 23/04/1999

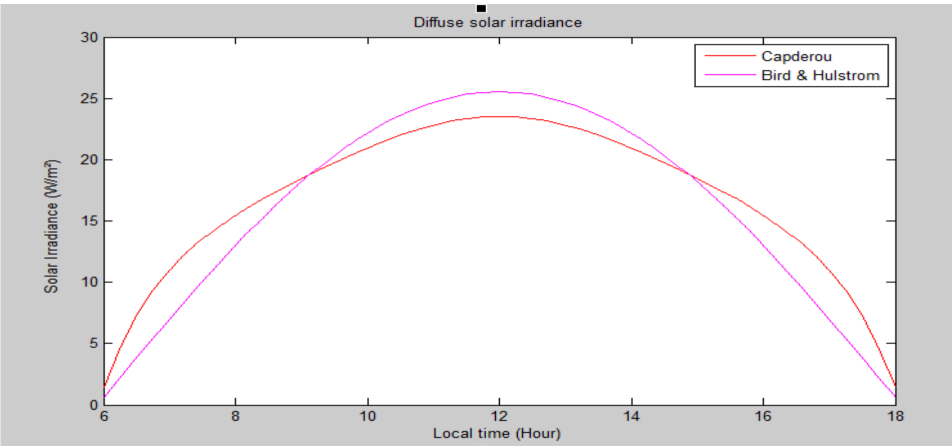

Figure 8: Diffused irradiance estimated under Matlab / Simulink, day of 19/05/2015

IV- CONCLUSION

Our work has consisted in reconstructing the solar irradiance on the ground of the littoral. For this, a simulation under Simulink of two models of solar irradiance with different numerical calculations was carried out. The analysis of the results has shown that for our site on the littoral, the values of the overall solar irradiance resulting from the theoretical model of Bird & Hulstrom presents a better agreement with the experimental values. The knowledge of a model specific to the littoral facilitates the dimensioning of the solar thermal collectors.

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ANNEX A

The height of the sun is the angle formed by the direction of the sun and its projection on the horizontal plane. It is given by the relation:

$$sin(h) = \cos(\delta) * \cos(\varphi) * \cos(\omega) + \sin(\varphi) * \sin(\delta) \quad \text{(A.1)}$$

Where φ is the latitude of the place; δ and ω denote respectively the declination of the sun and the hour angle. They are calculated by the following relations:

(A.2)

$$\delta = 23.45 * sin\left[\frac{360}{365} * (N + 284)\right]$$

$$\omega = 15(12 - \mathrm{T_{SV}}) \qquad \text{(A.3)}$$

T_{SV} is where the true solar time.

ANNEX B

- **Relative air mass m_r**

$$m_r = [cos\theta_z + 0.15(93.885 - \theta_z)^{-1.253}]^{-1} \qquad \text{(B.1)}$$

- **Corrected air mass m_a**

$$m_a = m_r[exp(-0.000184 * Z)] \qquad \text{(B.2)}$$

Z with the altitude of the site considered.

- **Thickness of the reduced ozone layer**

$$L_o = 235 + \{150 + 40sin[0.9865(N - 30)] + 20sin[3(\lambda_g)]\} * [(sin(1.28\varphi))] \qquad \text{(B.3)}$$

Where, λ_g denotes the longitude of the place.

NOMENCLATURE

D_a	Irradiance due to diffuse radiation after diffusion by aerosols (W / m²)
D_h	Diffuse irradiance incident on a horizontal plane (W/m²)
D_m	Irradiance due to the phenomenon of multi-reflection earth-atmosphere (W / m²)
D_r	Irradiance due to diffuse radiation from Rayleigh scattering (W / m²)
F_C	Direct dispersion coefficient of the atmosphere
H_r	Relative humidity (%)
h	Height of the sun (degrees)
I_h	Direct radiation in clear sky on a horizontal plane (W/m²)
I_{SC}	Extra-terrestrial Solar constant (W/m²)
k_a	Attenuation coefficient

L_o	Vertical thickness of the ozone layer (cm)
m_a	Corrected air mass
m_r	Relative air mass
P_S	Saturated vapor pressure (mb)
T_a	Ambient temperature (K)
T_L*	Factor of the disorder of Linke
T_{SV}	True solar time (hours)
U_1	Thickness of condensable water corrected
w	Height of condensable water
Z	Altitude of the place (m)

Greek letters

α	Absorption coefficient
β	Angstrom disturbance coefficient
δ	Solar declination (degrees)
φ	Latitude of the place (degrees)
λ	Wave length (m)
λ_g	Longitude of the place (degrees)
θ_Z	Zenithal angle (degrees)
ρ_a	Earth's albedo
ρ_a'	Clear sky's albedo
τ	Transmission coefficient
ω	Hour angle (degrees)

Indice

1	Model 1
2	Model 2

BIOGRAPHY

Sidibé, M., Maître-Assistant, Enseignant- Chercheur, Université FHB d'Abidjan Cocody, 22 BP 582 Abidjan 22, Côte d'Ivoire, Laboratoire d'Energie Solaire.
E-Mail : sidibmo20@gmail.com

Soro, D., Maître-Assistant, Université Nangui Abrogoua, UFR-SFA, 02 BP 801 Abidjan, Côte d'Ivoire. Enseignant à l'Ecole Normale Supérieure (ENS) Abidjan, Côte d'Ivoire 08 BP 10 Abidjan 08.
E-Mail: donafologosoro@yahoo.fr

Fassinou, W., F., Maître de Conférences, Enseignant- Chercheur, Université FHB d'Abidjan Cocody, 22 BP 582 Abidjan 22, Côte d'Ivoire, Laboratoire d'Energie Solaire.
E-Mail: faswaniferd@yahoo.fr

Touré, S., Professeur Titulaire, Enseignant- Chercheur, Université FHB d'Abidjan-Cocody, 22 BP 582 Abidjan 22, Côte d'Ivoire, Laboratoire d'Energie Solaire.
E-Mail: siakaahtoure@yahoo.fr