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Estimation of the Angström coefficient over Ghardaïa city

Djelloul Djafer *

Unité de Recherche Appliquée en Energies Renouvelables, URAER
Centre de Développement des Energies Renouvelables, CDER
47433, Ghardaïa, Algeria

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Abstract - *Atmospheric turbidity over Ghardaïa city is investigated using the Angström coefficient. Its values are derived using five years (2004-2008) of data. They show a seasonal trend along the year with maximum values around summer months and minimum ones around winter months. The annual average value varied between 0.079 and 0.105. The daily average values were less than 0.1, between 0.1 and 0.2 and exceeded 0.2 for 64.6 %, 33.8 % and 1.6 % of the cloudless days respectively. This result reveals that for 64.6 % of the cloudless days the sky over Ghardaïa city was clean to clear, for 33.8 % was clear to turbid and for 1.6 % was turbid to very turbid.*

Résumé - *La turbidité atmosphérique sur la ville de Ghardaïa est étudiée en utilisant le coefficient d'Angström. Les valeurs sont calculées en utilisant cinq années de données (2004-2008). Ils montrent une tendance saisonnière le long de l'année avec des valeurs maximales pour des mois d'été et les minimales pour des mois d'hiver. La valeur moyenne annuelle varie entre 0.079 et 0.105. Les moyennes journalières sont inférieures respectivement à 0.1, entre 0.1 et 0.2 et plus de 0.2 pour dépassement de 64.6 %, 33.8 % et 1.6 % pour des jours sans nuages. Ce résultat révèle que pour 64.6 % des jours sans nuages, le ciel de la ville de Ghardaïa était propre à clair, pour 33.8 % le ciel était clair à trouble et que pour 1.6 %, il était trouble à très trouble.*

Keywords: Solar radiation - Turbidity parameters - Angström coefficient - Linke factor.

1. INTRODUCTION

The photovoltaic and solar thermal energy systems are usually designed considering their performance in standard test conditions without taking into account the state of the local atmosphere [1]. The reason is often the non-availability of atmospheric data for a specific location for which solar systems will be designed. The study of the efficiency in various atmospheric turbidity and weather conditions of solar cell/module is essential to optimize their performances since an increase in turbidity reduces the output current of solar cells [1].

Ground solar radiations are strongly dependent on the Earth's atmosphere. Its constituents (aerosols, water ...) absorb and diffuse significantly the direct solar radiation. Thus, it is important to quantify their temporal effects when recording solar radiation measurements in a local area.

The Atmospheric turbidity is associated with atmospheric aerosols. They can be in liquid or solid states suspended in the atmosphere with size ranging from 10^{-3} µm to several tens of microns [2]. Due to the relationship existing between aerosols and attenuation of solar radiation reaching the Earth's surface, different turbidity factors based on radiometric methods have been defined to evaluate the atmospheric turbidity.

* djafer.djelloul@uraer.dz

Among them, the Angström turbidity coefficient. It was introduced by Angström through the following equation [2]:

$$\tau_a(\lambda) = \beta \times \lambda^{-\alpha}$$

Where $\lambda^{-\alpha}$ is the aerosol optical thickness at wavelength λ (µm), β, the Angström turbidity coefficient defined at 1 µm and α the wavelength exponent [2].

The Angström turbidity coefficient is an important parameter (i) to predict the availability of solar energy under cloudless skies essential for the design of solar thermal power plants and other solar energy conversion devices with concentration systems, (ii) to study the performance of solar radiation devices at a particular location before their installation and (iii) in climate modeling and pollution studies [3].

In the present work, five years (2004-2008) of data will be used to estimate the Angström turbidity coefficient and to study its variation. I will recall first the definition of this turbidity coefficient, then I will present the used data and finally I will discuss the obtained results.

2. THE ANGSTRÖM COEFFICIENT

The Angström coefficient (β) is a measure of the presence of aerosols. It characterizes the amount of aerosols content in the vertical column of air with transversal unitary [3]. The typical values of this coefficient vary between 0 and 0.5 [3-8]. Its minimum value (zero) refers to an ideally dust free atmosphere, while values superior to unity refer to an extremely turbid atmosphere.

It can be determined with different methods and spectral measurements [2, 3, 9-13]. I will estimate the Angström turbidity coefficient using the empirical formula of Dogniaux [14] due to the non-availability of a photometric instrument to discriminate aerosols by means of spectral measurements. Many authors have used this formula to derive the Angström turbidity coefficient [2, 6, 8, 15-17]. This empirical formula is given by the following equation:

$$\beta = \frac{T_l - \left(\dfrac{h + 85}{39.5 \times \exp(-w_p) + 47.4} + 0.1 \right)}{16 + 0.22 \times w_p} \quad (1)$$

For the Sun's elevation angle (h), it is measured in degrees.

For the precipitation amount in centimeter (w_p), its value is calculated using the following equation:

$$w_p = 0.493 \times \phi \times \frac{1}{T} \times \exp\left(26.23 - \frac{5416}{T} \right) \quad (2)$$

where T is the temperature in (K) and ϕ the relative humidity in fractions of one.

For the Linke turbidity factor (T_l), the following equation is used for its calculation [3, 18, 19]:

$$T_l = T_{lk} \times \left(\frac{1}{\delta_{R_a}(m_a)} \Big/ \frac{1}{\delta_{R_k}(m_a)} \right) \quad (3)$$

where (T_{lk}), is the Linke factor according to Kasten [20], $\delta_{Rk}(m_a)$, the Rayleigh integral optical thickness and $\delta_{Ra}(m_a)$, the integral optical thickness given by Louche *et al.* [21] and adjusted by Kasten [22].

The Linke factor T_{lk} is related to the normal incidence solar irradiance by the following equation [3, 20]:

$$T_{lk} = (0.9 + 9.4 \times \sin(h)) \times [2\ln(I_0 \times (R_0 / R) - \ln(I_n)] \quad (4)$$

where (I_n), is the direct normal solar irradiance at normal incidence and I_0 the solar constant (1367 W/m^2). R and R_0 are respectively the instantaneous and the mean Sun-Earth distances. In our case, the (I_n) is measured directly through a pyrheliometer in (W/m^2).

The expression of $\delta_{Ra}(m_a)$ and $\delta_{Rk}(m_a)$ are given respectively by:

$$\frac{1}{\delta_{Ra}(m_a)} = 6.6296 + 1.7513 \times m_a - 0.1202 \times m_a^2 + 0.0065 \times m_a^3 + 0.00013 \times m_a^4 \quad (5)$$

$$\frac{1}{\delta_{Rk}(m_a)} = 9.4 + 0.9 \times m_a \quad (6)$$

where m_a is the air mass given by:

$$m_a = m_r \times \left(P / 101325 \right) \quad (7)$$

The parameter m_r is the air mass at the standard conditions [23] defined by the following equation:

$$m_r = [\sin(h) + 0.15 \times (3.885 + h)^{-1.253}]^{-1} \quad (8)$$

P is the local pressure in (Pa) given by [24]:

$$P = 10132 \times \exp(-0.0001184 \times z) \quad (9)$$

where (z), is the altitude in meter of the measurement location.

3. SITE LOCATION AND SOLAR RADIATION

The data used to perform the present work has been recorded at the Applied Research Unit for Renewable Energies (URAER) situated in the south of Algeria far from Ghardaïa city of about 18 km. The latitude, longitude and altitude of the URAER are respectively +32.37°, +3.77° and 450 m. The direct and the diffuse solar irradiance components, the temperature and the humidity used to calculate the Angström turbidity coefficient are recorded every 5 minutes.

A pyrheliometer instrument of type EKO installed since June 2004 measures the direct and the diffuse solar irradiance. Five years (2004-2008) of the above data is used to estimate the Angström turbidity coefficient and to study its variation.

A selection of the data that corresponds to clear sky conditions is applied for that reason. This criterion consists to choose data where the direct normal solar irradiance is greater than (200 W/m^2) and the ratio of the diffuse solar irradiance to the global solar irradiance is less than 1/3 [8, 25, 26].

4. RESULTS AND DISCUSSION

Equation (1) is used to calculate the Angström turbidity coefficient. Some algorithms were developed to obtain the solar ephemeris necessary for this calculation. The annual and the monthly average values of the Angström coefficient obtained from the data recorded between June 2004 and December 2008 are given in **Table 1**. The daily and monthly variations of this coefficient are shown on Fig. 1.

We can note the seasonal trend of the Angström coefficient along the year with a maximum and minimum values occurring respectively during summer and winter months. This phenomenon can be explained by a hot summer climate and winds of the south sectors (Sirocco) that characterize the region of Ghardaïa. This kind of winds brings with them particles of dust and sand which leads to increase the Angström coefficient [27].

Table 1: Monthly and annual average values of the Angström turbidity coefficient

	2004	**2005**	**2006**	**2007**	**2008**
January	-	0.030±0.021	0.030±0.015	0.024±0.020	0.036±0.015
February	-	0.042±0.027	0.042±0.026	0.058 ±0.049	0.070±0.039
March	-	0.058±0.039	0.047±0.031	0.110 ±0.102	0.071±0.038
April	-	0.076±0.038	0.091±0.040	0.166±0.076	0.090±0.045
May	-	0.118±0.051	0.116±0.039	0.122±0.051	0.114±0.039
June	0.120±0.035	0.118±0.036	0.114±0.050	0.153±0.045	0.139±0.035
July	0.095±0.023	0.155±0.024	0.133±0.032	0.155±0.035	0.186±0.024
August	0.139±0.029	0.120±0.045	0.142±0.022	0.142±0.039	-
September	0.075±0.051	0.099±0.040	0.138±0.045	0.145±0.037	0.129±0.036
October	0.075±0.025	0.067±0.022	0.121±0.042	0.082±0.035	0.094±0.035
November	0.023±0.014	0.065±0.025	0.062±0.037	0.054±0.043	0.051±0.027
December	0.028±0.019	0.036±0.020	0.048±0.028	0.048±0.033	0.051±0.021
Average	**0.079±0.028**	**0.082±0.033**	**0.090±0.034**	**0.105±0.047**	**0.094±0.032**

The variation of the Angström turbidity coefficient from June 2004 to December 2008 is represented on Fig. 2. The monthly average value varies between 0.023 and 0.166 and the annual one between 0.079 and 0.105. An annual average increase of about 0.015 (16 %) is observed between 2004 and 2008. This increase may be associated either to an increase of the pollution in the region or to atmospheric and solar property changes.

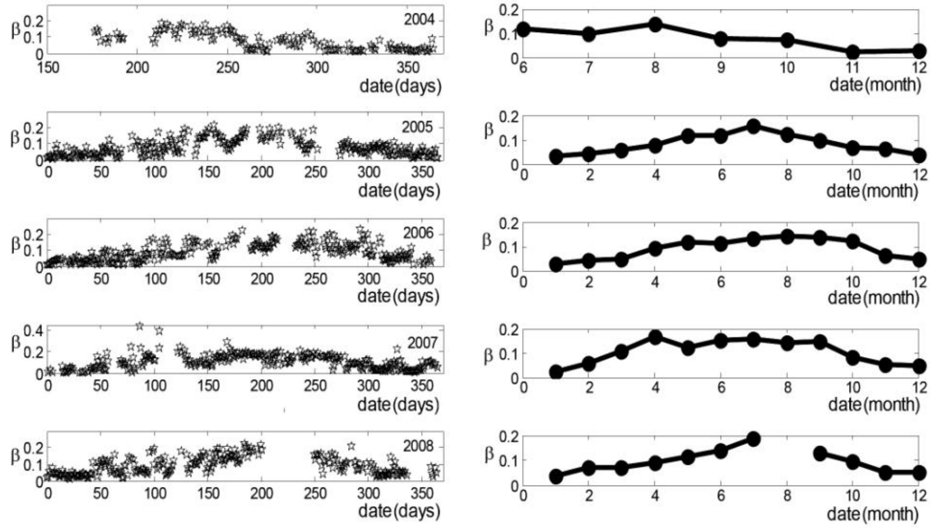

Fig. 1: The Angström turbidity coefficient β
left: daily variations, *right*: monthly variations

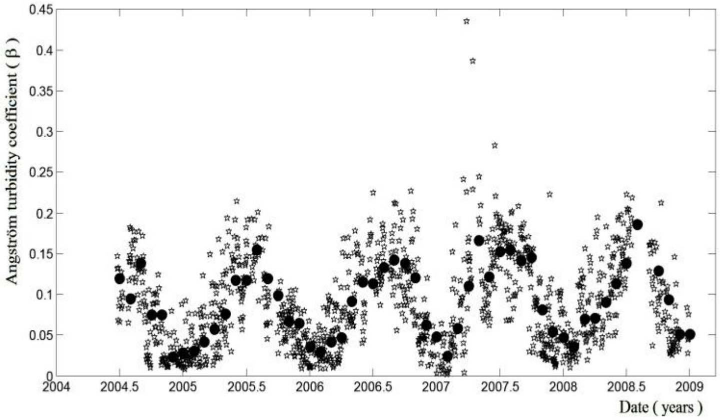

Fig. 2: Seasonal variation of the Angström turbidity coefficient.
The circles are the daily variations while the points are the monthly ones

The frequency of occurrence of the Angström coefficient values was computed and analyzed. The cumulative frequency of the turbidity values is adopted to indicate the percentage of clear days for which a given turbidity threshold is exceeded. Fig. 3 shows the frequency distribution of the Angström coefficient values with a sampling bin of 0.01. We observe that the maximum value of the Angström coefficient occurs near 0.02 with a frequency of 9.20 %.

Fig. 4 represents the cumulative frequency distribution of the Angström turbidity coefficient. We observe that for 64.6 % of the cloudless days, the Angström coefficient was less than 0.1, for 33.8 % it was between 0.1 and 0.2 and it exceeded 0.2 for only 1.6 % of the cloudless day. This result indicates that for 64.6 % of the cloudless days, the sky over Ghardaïa city was clean to clear, for 33.8 % it was clear to turbid and for 1.6 % it was turbid to very turbid [26, 28].

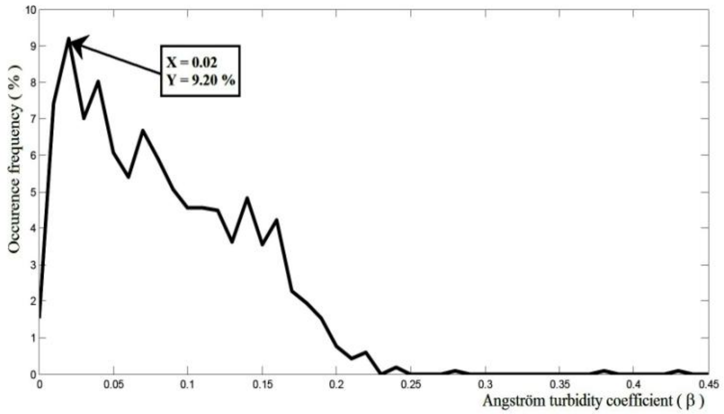

Fig. 3: The frequency of occurrences for the Angström turbidity coefficient values.

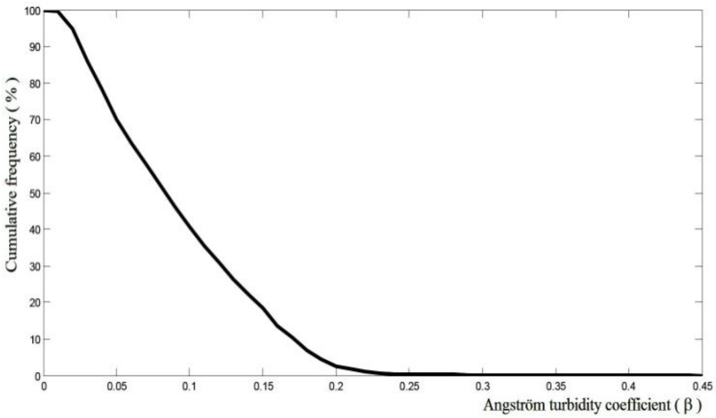

Fig. 4: Cumulative frequency distribution for the Angström turbidity coefficient

5. CONCLUSION

Five years (2004-2008) of measurements has been used to estimate the Angström coefficient over the region of Ghardaïa. We have computed the Angström coefficient using an empirical law due to the lack of spectral measurements at the URAER. The calculated values show a seasonal trend along the year with maximum and minimum attenuations occurring respectively during summer and winter months. This seasonal trend is related to the climate of the region which is characterized in summer by a hot weather and Sirocco winds that bring dust and sand particles and in winter by a dry weather and rains.

We found that the monthly average value of the Angström coefficient varied between 0.023 and 0.16 and the annual one between 0.079 and 0.105 with an increase of about 0.015 (16 %) between 2004 and 2008. This increase may be associated either to an increase of the pollution in the region or to atmospheric and solar property changes.

The frequency distribution of the Angström coefficient values shows a maximum near 0.02 with a frequency of about 9.20 %. The cumulative frequency distribution of these values reveals that the Angström coefficient values were less than 0.1, between

0.1 and 0.2 and exceeded 0.2 for 64.6 %, 33.8 % and 1.6 % of the cloudless days respectively. This result indicates that for 64.6 % of the cloudless days the sky over Ghardaïa city was clean to clear, for 33.8 % it was clear to turbid and for 1.6 % it was turbid to very turbid.

The tabulated results in the present work can be used (i) in the design and to check the performance of solar devices at any locality that has a similar climate to Ghardaïa city, (ii) to investigate and study the variation of efficiency of solar devices with the variation in the spectrum of incident radiation, (iii) to have a reference point for global studies of the evolution of atmosphere turbidity and aerosols.

The present study is a preliminary work that uses the global solar irradiance to estimate the effect of aerosols. Future spectral measurements should be done to determine the aerosols sizes and to estimate the effects of the other constituents of the atmosphere on the solar budget of a local area such as the presence of cirrus, ozone, water,…

The future spectral measurements will be necessary since the solar photons generate photo-chemical processes that are wavelength dependent such as photo-dissociation, photo absorption and photo-ionization which are the main drivers in terms of composition, thermal structure and dynamics of the atmosphere.

In the range of 300 - 600 nm, solar photons are partially absorbed by minor constituents such as ozone, nitric oxide, and water vapor in, more or less, narrow spectral bands. At longer wavelengths, the latter generates absorption, especially above 1 µm. Below 300 nm, all photons are absorbed in the terrestrial atmosphere by ozone in the range 180 - 350 nm, by molecular oxygen below 250 nm, and by molecular nitrogen and atomic oxygen below 100 nm [29].

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