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Turbidity Coefficient

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Abstract

This paper intents to study the Angstrom Coefficient from data measured by stations and compare that with the NREL modeled data to find utility of the Angstrom coefficient in measuring attenuation of solar radiation. First, The Coefficient and Angstrom constant was calculated using empirical equations and measured data. Second, results was studied and Coefficient's utility as measure of attenuation of solar radiation and other patterns was found out. And finally, this will be evaluated against the modeled data from NREL.

The variation in Turbidity is a factor in attenuation of the radiation. From the study it was found out that solar irradiation is highly dependent on the Turbidity coefficient. The variations observed in the plotted data is well inline with the irradiance measured for the two locations under consideration in this study.

The results varied from the modeled data considerably, but the trend of fluctuation in the plots were similar due to reasons not fully established under this study.

1.Introduction

Solar panels being dependent on the amount of solar radiation incident on them generates interest to look for various phenomenon that reduces the incoming radiation. As a fact, radiation passing through the atmosphere is faced with scattering, absorption by particles, aerosols and other gaseous content. In order to measure the radiation at the clear sky, it is important to study their effects on recording solar measurement data. This will help with predicting the radiation conditions at the given location and assess the degree of atmospheric haze caused due to pollution, particles and/or aerosols. This practice is important for solar energy, climatology and metrology.

Among the common measures, atmospheric turbidity shows the attenuation of solar radiation that reaches the earth’s surface under clear sky and so gives the optical thickness of the atmosphere.

Of the several turbidity parameters, the most frequently used are the Linke turbidity factor and the Angstrom turbidity coefficient. As already mentioned before, the knowledge of these turbidity parameters is important to optimize the performances of solar radiation devices installed at a particular location but it is also important in climate modeling and in pollution studies to predict the availability of solar energy under cloudless skies essential for the design of solar thermal power plants, for other solar energy conversion devices with concentration systems and to compute the amount of spectral global irradiance for the design of photovoltaic systems and calculation of the photosynthetic energy for plant growth.

2.General Objectives

The following will be the general objective of the current study:

- Evaluate the utility of the Angstrom turbidity coefficient for describing the attenuation of insolation due to aerosols in the atmosphere.

Specifics

- Collect measured atmosphere data for a USA city/region with developed solar PV (Boston for example).
- Apply NREL insolation data using MATLAB for measured data.
- Correlate how changes in the atmosphere turbidity affect the insolation in a specific city/region.

3.Bibliographic Revision

Study of the atmosphere has been a field of interest among the science community. Case studies carried out during the 1920's still hold valid. The practices have advanced due to the current sophistication of the available technology. The following will elaborate on the most pronounced terms associated with the study.

1.Linke Turbidity Factor

According with Irbah (2013) atmospheric turbidity conditions has been quantified with the Linke turbidity factor *Tl* since 1922. It is defined as thenumber of clean dry atmospheres necessary to have the sameattenuation of the extraterrestrial radiation produced by the realatmosphere. Modeling of the absorption and scattering of the solar radiation during clear skies has done using the Linke turbidityfactor. TheLinke factor depends on the air mass and most popular methodsnormalize the measured values of *Tl*to an air mass equal to 2. This turbidity factor describesthe optical thickness of the atmosphere due to both theabsorption and scattering by the water vapor and aerosol particlesrelatively to a dry and clean atmosphere.

More specific definition was put forward by Irbah (2013) and claimed that it expresses the atmosphereturbidity or equivalently the attenuation of the direct solar radiation flux. The value of the Linke factor may then be derived from the direct component of the solar radiation. Typical values of the Linke factor vary between 1 and 10. High values of the Linke factor mean that the solar radiations are more attenuated in a clear sky atmosphere.

Equation 01 was used byIrbah (2013) to calculate the Linke factor Tl.

$$Tl = Tlk^{*\frac{\frac{1}{\delta Ra(ma)}}{\frac{1}{\delta Rk(ma)}}} \quad \text{Eq.1}$$

As described in the original papers: Tlk is the Linke factor according Irbah (2013), $\delta Rkma$ the Rayleigh integral optical thickness and $\delta Ra(ma)$ the integral optical thickness the subscript k stands for the author ”Kasten” (Kasten,1996) and the subscript a for the word

”adjusted”. The Equation 02 relates the Linke factor T to the normal incidence solar irradiance.

$$Tlk = (0.9 + 9.4 \sin h) * (2 * \ln (Io(\frac{}{@}))\text{-}\ln(I_n))^{@A} \quad \text{Eq.2}$$

Where according to the author *h* is the Sun’s elevation angle in degrees, *In*the direct normalsolar irradiance at normal incidence and $I_0$the solar constant (1367W/m^2). *R* and *R*0 are respectively the instantaneous and mean Sun-Earth distances. The value of *I* is measured directly through a pyrheliometer in ( ) (W/m^2). The expression of $\delta Rkma$ and $\delta Rama$ are given by the equations 3 and 4.

$$C@D^{B}(ma) = 6.6296 + 1.7513ma - 0.1202m_D^K + 0.0065m_D^K - 0.00013m_D^L \quad \text{Eq.3}$$

$$\frac{B}{}(ma) = 9.4 + 0.9\,(ma) \quad \text{Eq.4}$$

C@M where $ma$is the air mass

given by the equation 5: $ma = mr($

______^{0}) Eq.5

BPBQKR

According to Canada (1993) the parameter mr is the air mass at the standard conditions defined by equation 06:

$$mr = [\sin(h) + 0.15(3.885 + h)^{UB.KRQ}]^{UB} \quad \text{Eq.6}$$

Asmentioned by Irbah (2013) the local pressure P (in Pascal) is given by equation 07.

$$P = 101325e^{UP.PPPBBYLZ} \quad \text{Eq.7}$$

where z is the altitude in meter of the location above sea level.

2.The Angstrom coefficient

According to Canada (1993) and Irbah (2013) the Angstrom turbidity coefficient β proposed by Angstrom is a function of the aerosol loading of the atmosphere. It is also used to describe the dependency of the aerosol optical thickness Ion wavelength and is a useful tool to measure the particle size of atmospheric aerosols/particles. Angstrom Coefficient's minimum value is 0 for an ideally dust free atmosphere, while >1 have been estimated in extremely turbid climates. The typical values vary from 0 to 0.5. Angstrom's turbidity formula also gives an index, α, a function of the aerosol size: low α values correspond to large particles, and vice versa.

For most natural atmospheres α= 1.3±0.5. Canada (1993) says the aerosol optical depth is given by the Angstrom relation, shown in the equation 08.

$Ka\lambda = \beta\lambda^{\mathrm{UD}}$ Eq. 8

Where $Ka\lambda$ is the aerosol optical depth in the vertical direction, also called the monochromatic aerosol attenuation coefficient, and λ is the wavelength in µm. According to Canada (1993) parameters β and a can be determined from a number of measurement techniques. With a dual wavelength sun photometer, β and a can be determined simultaneously, by measuring aerosol attenuation at two wavelengths where molecular absorption is either absent or is minimal. However, β and a can be measured at $\lambda = 1$ µm with a single wavelength Voltz instrument.

4.Methodology

For this study we opted to find the Angstrom Coefficient using the methodology for the parameters that will give us the values of the coefficient and the exponent. Based on the data from NREL that had measured the Angstrom optical depth at a number of wavelengths, averaged for each day we calculated the values.

Taking the average of the AOD for the given wavelengths and applying equation 8 for two wavelengths and solving for β , we can find the Angstrom Exponent. Substituting the value of a in equation 8 will give us the coefficient β.

Plotting the modeled data with actual data will elaborate on the viability of the model. Also a study of how variation in turbidity values affects the irradiance will be conducted by matching the monthly irradiation at the location against the variations in the turbidity coefficient and exponent. Finally pattern of variation over the seasons will be studied and common features will be interpreted from the findings.

1.Collecting measured Data

In order to determine the a and β, the measured data was collected using the NREL

(2014) as shown in the table 01. The data is from 2013 to 2014 and is the Aerosol Optical Depth (AOD) in 400, 500, 675, 870, 1020nm wavelengths. The average a (alpha) and β (beta) were also measured using the data.

Below is the data for our in consideration Location 01 :

Baseline Measurement System

BMS

Latitude: 39.742^{o} North

Longitude: 105.18^{o} West

Elevation: 1828.8 meters AMSL

DATE (MM/DD/YYYY)	Avg AOD [400nm]	Avg AOD [500nm]	Avg AOD [675nm]	Avg AOD [870nm]	Avg AOD [1020nm]	Avg Alpha [Angstrom exp]	Avg Beta
11/14/2013	0.0446	0.0429	0.0297	0.0181	0.0117	1.4379	0.0142
12/8/2013	0.1144	0.0967	0.0633	0.0302	0.0375	1.4291	0.0328
12/9/2013	0.0245	0.0348	0.0292	0.0112	0.0192	0.7133	0.0164
12/11/2013	0.0315	0.0354	0.0275	0.0121	0.0167	0.9941	0.015
12/29/2013	0.0314	0.0382	0.0332	0.0173	0.0131	1.026	0.0159
1/1/2014	0.0297	0.034	0.024	0.0087	0.0062	1.834	0.0077
1/10/2014	0.026	0.0353	0.0281	0.0087	0.0062	1.7324	0.0081
1/23/2014	0.1367	0.1099	0.0702	0.0305	0.0273	1.8716	0.0278
1/28/2014	0.0391	0.0429	0.0313	0.0073	0.011	1.8537	0.0098
4/10/2014	0.1026	0.0831	0.0627	0.0515	0.0507	0.7801	0.0483
4/11/2014	0.0869	0.0918	0.0944	0.0985	0.1036	-0.1423	0.102
4/14/2014	0.0941	0.0803	0.0618	0.0379	0.069	0.6195	0.0505
4/18/2014	0.0313	0.029	0.0246	0.024	0.0229	0.3366	0.0226
4/23/2014	0.0651	0.0564	0.0473	0.038	0.0387	0.5995	0.0372
5/1/2014	0.031	0.0509	0.0426	0.0405	0.0281	0.1511	0.0353

5/6/2014	0.0594	0.0709	0.0616	0.0643	0.0488	0.1855	0.056
5/13/2014	0.0341	0.0445	0.0313	0.028	0.0242	0.4762	0.0259
5/15/2014	0.1449	0.1198	0.0799	0.0666	0.0473	1.1561	0.0519
5/19/2014	0.0686	0.0786	0.0723	0.0741	0.0562	0.1689	0.0647
5/26/2014	0.1689	0.1742	0.1626	0.166	0.1611	0.0597	0.1623
5/30/2014	0.2106	0.1534	0.087	0.061	0.0456	1.6428	0.0474
6/2/2014	0.0723	0.0673	0.0522	0.0523	0.0435	0.5185	0.0453
6/4/2014	0.0861	0.0773	0.0629	0.0499	0.0607	0.4846	0.0538
6/9/2014	0.0446	0.0463	0.0368	0.0272	0.0385	0.3694	0.0324
6/10/2014	0.1197	0.1084	0.0884	0.0698	0.0747	0.5821	0.0705
6/12/2014	0.2657	0.2101	0.1385	0.0923	0.088	1.2625	0.0845
6/13/2014	0.0544	0.0575	0.0519	0.0478	0.0563	0.0631	0.052
6/14/2014	0.1056	0.099	0.0882	0.0794	0.0908	0.2267	0.0837
6/16/2014	0.0473	0.0561	0.0533	0.0494	0.0588	-0.1282	0.0555
6/17/2014	0.0676	0.0729	0.0727	0.0676	0.0769	-0.066	0.0735
6/18/2014	0.086	0.0923	0.0922	0.0888	0.1012	-0.1093	0.0963
6/19/2014	0.0474	0.0469	0.0384	0.029	0.0425	0.3239	0.0351
6/26/2014	0.1928	0.1748	0.1533	0.1391	0.1385	0.3604	0.1351
7/1/2014	0.3431	0.2579	0.1664	0.1172	0.1014	1.3332	0.1006
7/2/2014	0.286	0.2168	0.1355	0.0891	0.0735	1.4902	0.0747
7/3/2014	0.2405	0.1747	0.1138	0.0861	0.0783	1.229	0.0751
7/9/2014	0.165	0.1077	0.0659	0.053	0.0462	1.3535	0.0439
7/10/2014	0.0893	0.0568	0.0348	0.0294	0.0288	1.2181	0.0256
7/16/2014	0.2282	0.1591	0.0917	0.0637	0.054	1.5757	0.0526

7/18/2014	1.4865	1.4321	1.3581	1.3418	1.3649	0.1009	1.3371
7/19/2014	0.4641	0.3184	0.1732	0.1031	0.0766	1.9515	0.0797
7/22/2014	0.0993	0.0656	0.0442	0.0374	0.0381	1.0385	0.034
7/28/2014	0.4558	0.3922	0.3457	0.3364	0.3436	0.3126	0.3273
9/15/2014	0.1327	0.1083	0.0696	0.0544	0.0523	1.0638	0.0494
9/20/2014	0.0568	0.058	0.0384	0.0326	0.0328	0.7041	0.0314
9/26/2014	0.0455	0.0434	0.0314	0.0322	0.0328	0.3968	0.0308
9/27/2014	0.0254	0.0344	0.029	0.032	0.0331	-0.1949	0.033
10/16/2014	0.0276	0.0287	0.0228	0.0224	0.0247	0.2021	0.023
10/17/2014	0.3682	0.3951	0.4191	0.4449	0.4692	-0.2471	0.464
10/21/2014	0.0138	0.018	0.0155	0.0158	0.0199	-0.2247	0.0181
10/31/2014	0.0136	0.018	0.0159	0.019	0.0225	-0.4185	0.021

Table 01. Aerosol Optical Depht (AOD), alpha and beta coefficients by several months.

2.Mathlab Modeling to correlate the data

Using the system of equations described in methodology, the evaluation was conducted agains the data obtained. The results were plottedfor Beta found using Angstrom formula and that according to modeled data by NREL.

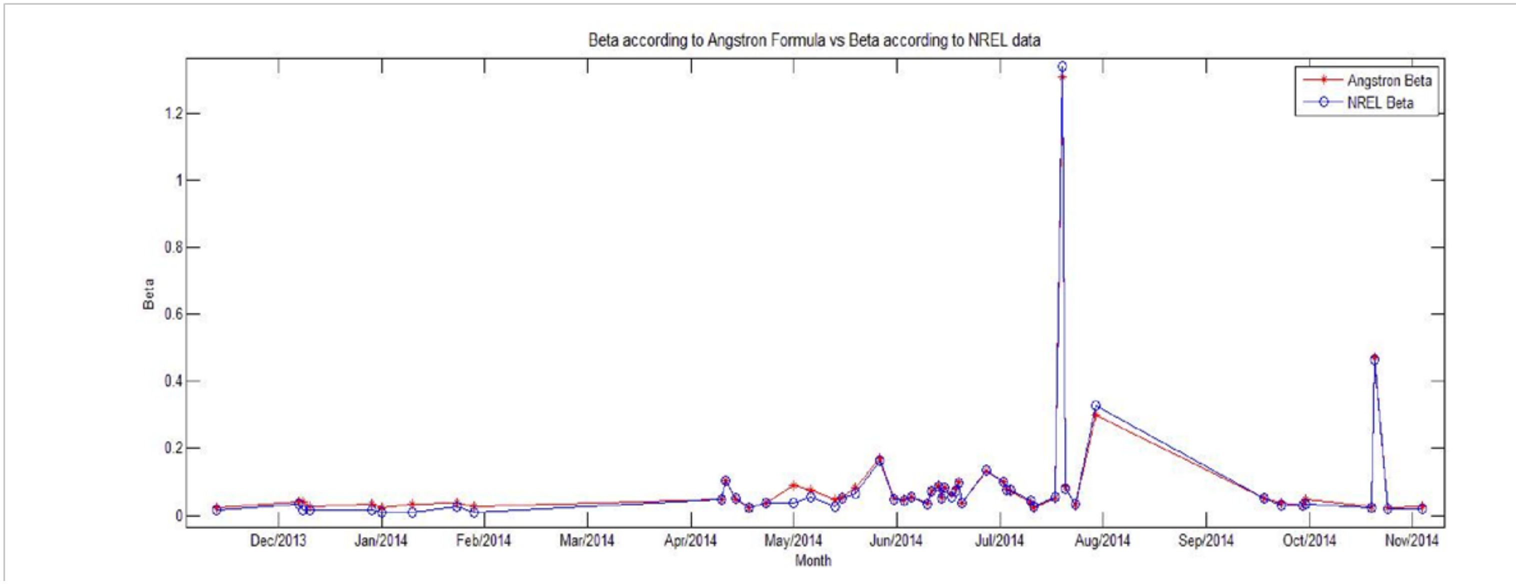

Figure 01. Beta according to Angstrom Formula using measured data and Beta According to NREL data.

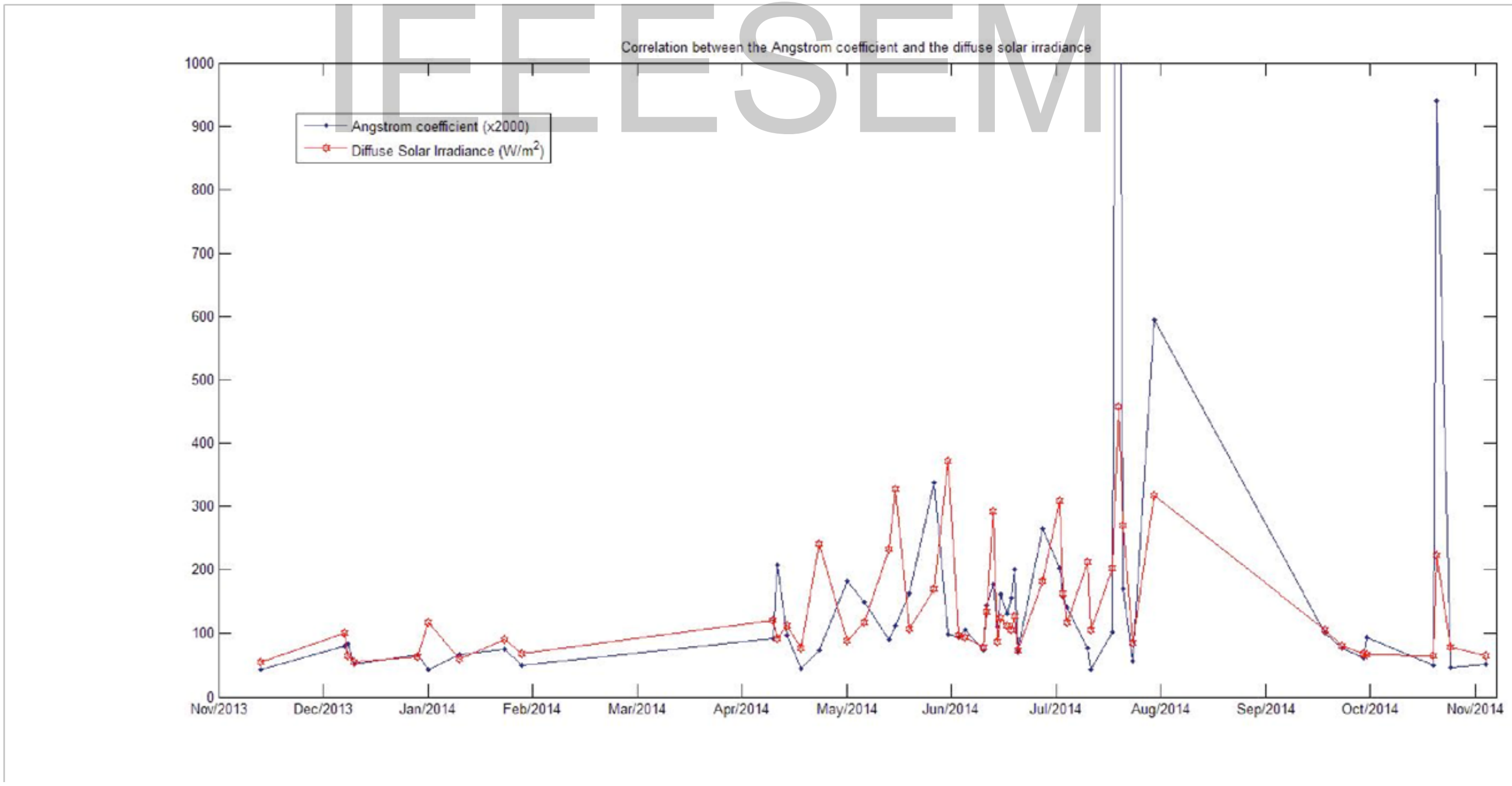

Figure 02. Correlation between Angstrom coefficient and diffuse solar irradiance.

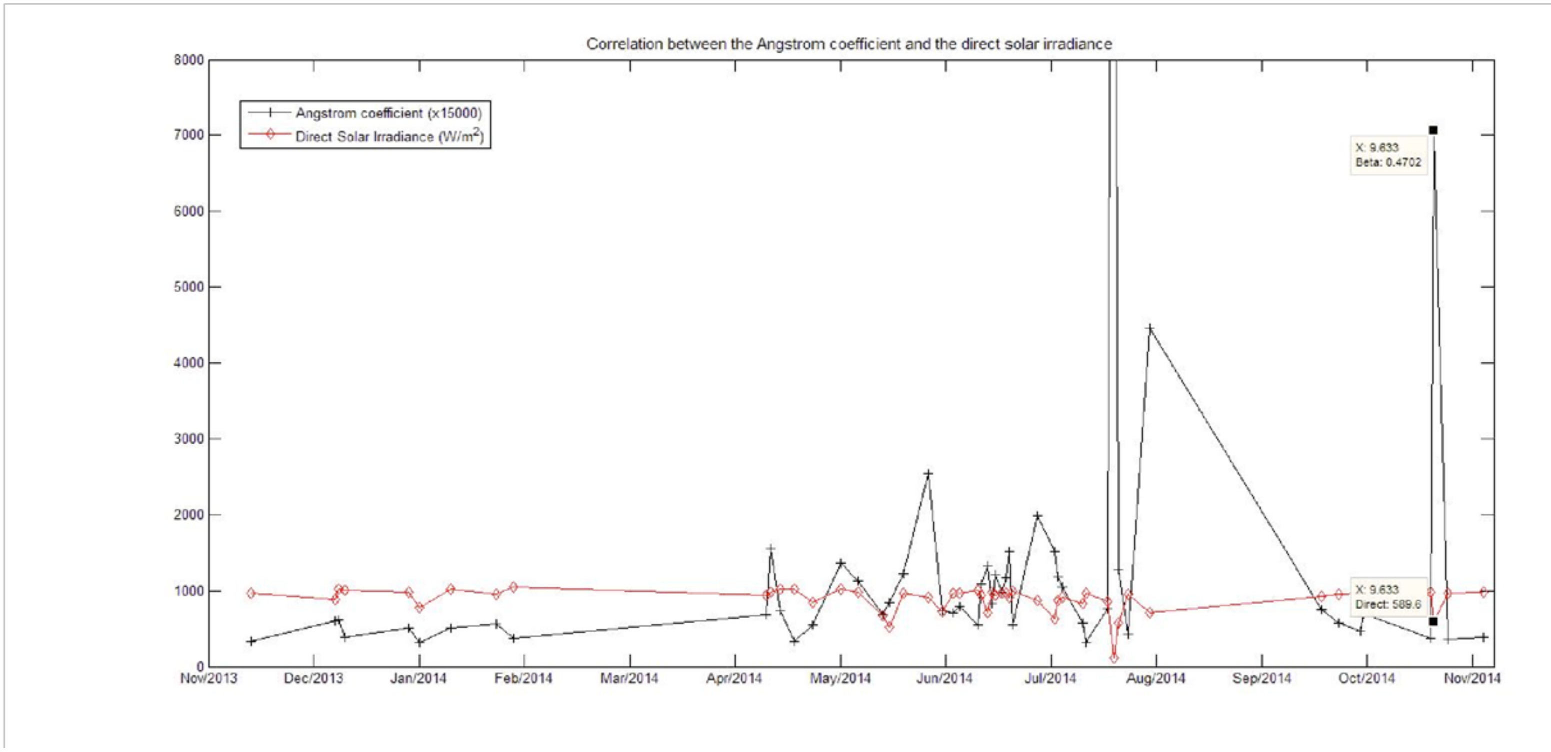

Figure 03. Correlation between Angstrom coefficient and direct solar irradiance.

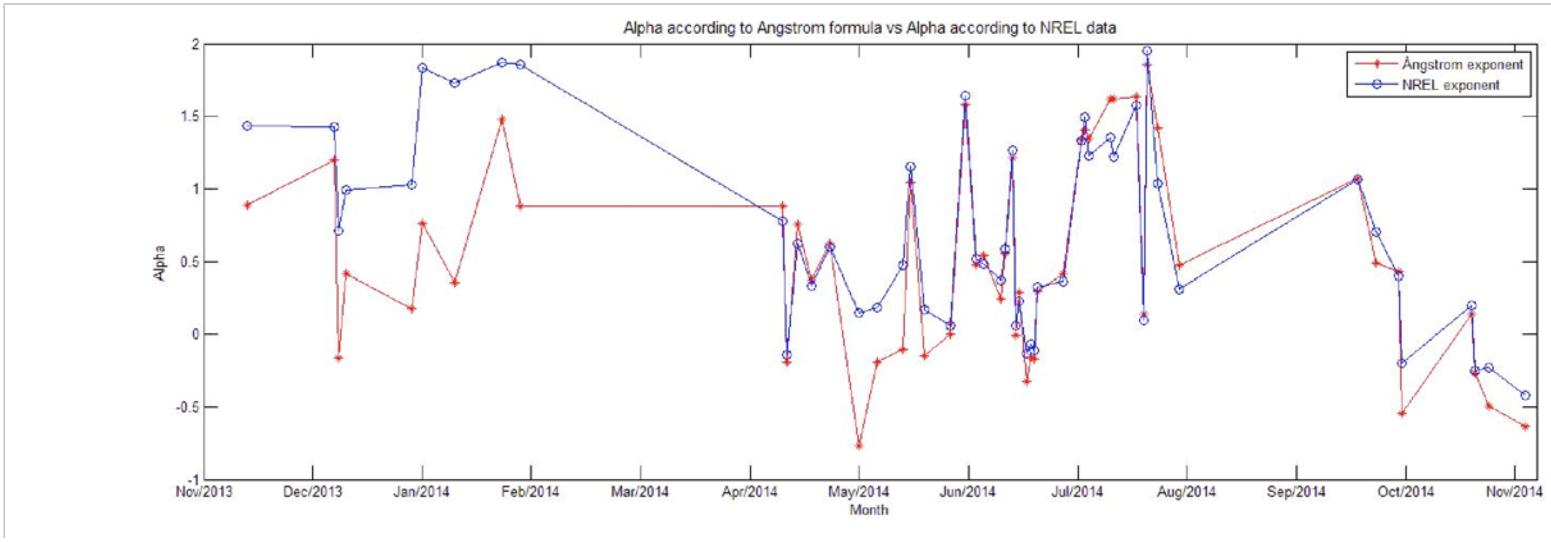

Figure 04. Alpha according to Angstrom Formula using measured data and Alpha According to NREL data.

Below we have conducted the above analysis for the our in consideration Location 02 :

Solar Resource & Meteorological Assessment Project (SOLRMAP)

Aurora, Colorado

Latitude: 39.75685oNorth

Longitude: 104.62025oWest

Elevation: 1674 meters AMSL

Time Zone: -7.0

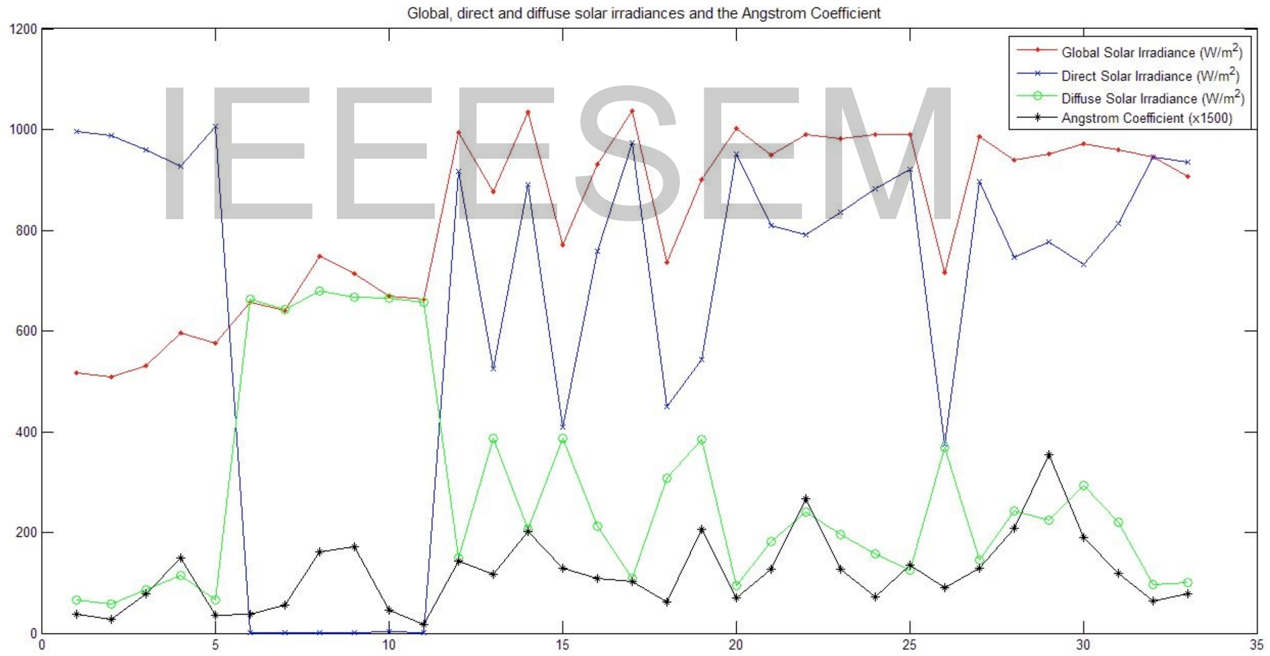

Figure 05. Global, direct and diffuse solar irradiances and the Angstrom Coefficient.

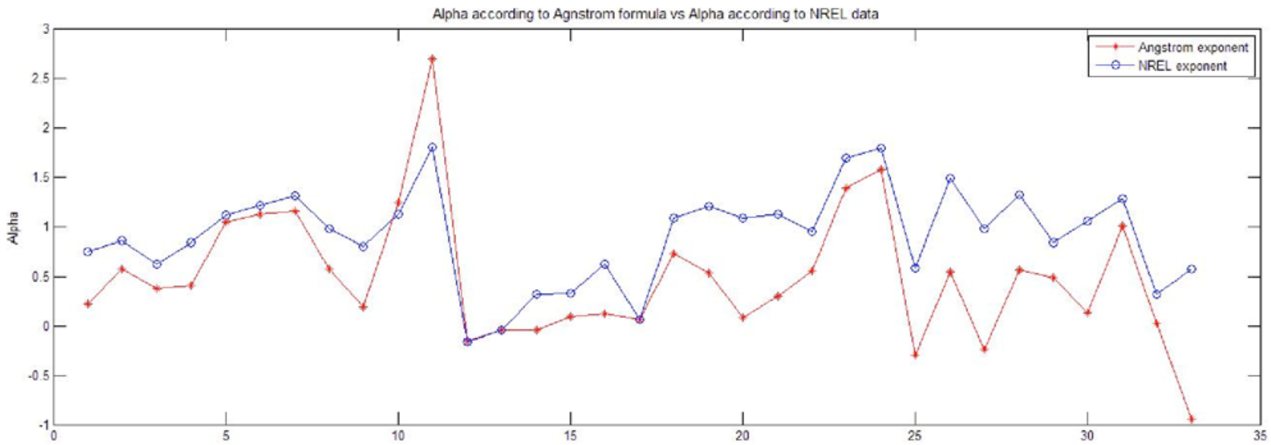

Figure 06. Alpha according to Angstrom formula and Alpha according NREL data

3.Presentation of seasonal variation of tubidity coefficient

Based on the assessment conducted it was found out the Amstrong Turbidity is the lowest during the November-December time period. This takes an increasing trend where during the months of April-May the values tend to distort and show greaterfluctuations. This can be witnessed with great ease in Fig. 2

4.Valuation and presentation of insolation as a function of turbidity coefficient

The irradiance data is closely related to the Beta. Following the seasonal trend, with an increase in Beta the direct solar irradiation decreases. The patern of changes for the values of Beta over the horizon of many months is closely folled by changes in the Solar irradiation which is clearly understood from Fig. 3

5.Results and discussion

Based on the evaluation conducted it is said that there is a difference between the actual turbidity data and that modeled by NREl. The values of the Beta (Angstrom Coefficient) is lowest during the month of November with a increasing trend reaching the fluctuating pattern April onwards and is inversely proportional to the direct solar irradiance. It was also witnessed that some abrupt deviation in the curves exsisted and it is believed that it can be associated with the mixture of various factors.

Although very different than the solar irradiance data, values of Beta can be used to estimate the good potential of a region for solar energy generation and other related aspects.

While measuring the difference in values of Angstrom exponent, it was found out that drastic differences exist between the data measured and that obtained from the NREL. Although significant, the trend is followed by curves obtained from both.

6.Conclusion

In this model an adopted approach was used to find the turbidity coefficient and constant from the Angstrom optical depth measured against various wave lengths. This data was plotted and compared to what was obtained from data by NREL.

It was found that the data have a similar pattern are close but they do deviate considerably from each other. This indicates a discrepancy between the data sets. It could not be established as to why the deviations occur but it can be hinted that the unpredictable nature of atmosphere can play a big part. A reason to this can be that in summer vertical convection is enhanced and can induce a turbid atmosphere. And in line with our finding, in summer months the turbidity coefficient is considerable higher than that the winter months.

Form the data it was also noted that the Angstrom coefficient is inversely related to the global irradiance.

Higher Coefficient values indicate lower irradiance.

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