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Solar Radiation from Solar Disc and its variability in Terrestrial Region

H.N. Singh*, Kanishka Singh[1] and Drishti Singh[2]
**Associate Professor, R.S.S. P.G College, Pilkhuwa, C.C.S University, Meerut, Uttar Pradesh, India.*
1.Graduate student, Delhi College of Arts and Commerce, University of Delhi, New Delhi, India.
2.Graduate student, Thakur Ram Narayan College of Law, University of Mumbai, Mumbai, Maharashtra, India.
**Corresponding Author*

Abstract
Solar energy on earth is the source of all the activities extending from natural to the engineered solar energy applications. In this age of industrialization, now the climate change and pollution of conventional engineered system for industrialisation urges the utmost evolution of the engineered solar energy systems which are free from pollution on one hand and everlasting on the other. Under this sanctity of solar energy and its applications, it is of fundamental importance to estimate the solar radiation intensity in broad-band and spectral-band both in the terrestrial region because of being input energy for all solar energy engineered devices. Theoretically, it is completely characterised in the extra-terrestrial region in form of: radiation emitted by the solar disc, sun-earth angles due to revolution and rotation of the earth along with surface orientation and tilt being outside the earth's atmosphere. The challenging task to the scientists and researchers is the building of precise and accurate models to estimate the solar radiation intensity in the terrestrial region because the terrestrial region is unstable in terms of both vertical height in form of composition of the atmosphere at a station and horizontal spread from stations to stations due to changes of climate, weather conditions, cloudiness type and extent, albedo of the surfaces, etc. In this communication, an attempt has been made to identify the variability factors in terrestrial region under both the categories: qualitative physical phenomena and quantitative radiation model to quantify the variability factors.
Keywords: *Solar Radiations; Terrestrial Atmospheric Phenomena, Radiation Models.*

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I. Introduction

The solar radiation, reaching on earth's surface after reflection and absorption in the real atmosphere, is the source of nearly all the natural activities on earth extended from sea - waterto the surface of the earth. But, under the governance of solar energy itself, the various processes and results on earth makes it being variable non-linearly at a station, namely: cloud formation, raining, evaporation, density variability of aerosols due to natural activities along with transportation by wind. In addition, with these, the man-made activities of industrialization which emits greenhouse gases and aerosols in the pure atmosphere gives additional variability in the solar irradiance available at a station at a particular time on a specific day of the year. So, modelling to estimate the solar radiation at a station has an in-built challenge because the variability factors are mainly produced by solar radiation itself. But as a scientist and researcher we have to accept it because the actual data present at a station is very important in all the engineered solar energy application, namely: daylighting, animal husbandry, solar drying, photo-biology, agricultural- meteorology,building sciences as solar architecture, comfort air-conditioning, photovoltaic applications and solar thermal applications.All require an accurate estimation of solar radiation available as accurate as possible.

II. Solar Radiation in the Extra-terrestrial Region

2.1 Radiation Emitted by Solar Disc:

The sun is an entity which produces and processes all the dynamic processes within it to sustain and radiates out to allow us to exist and sustain. The consciousness is the ultimate entity which covers the whole cosmos. The sun receives consciousness from the galaxy in form of vibrations which translates into energy which further converts into matter and reverses to convert into energy, then vibrations and finally the consciousness to its components in the solar system inform of: broad-band radiation spectrum, microwaves, radio waves, X-rays, γ-rays and cosmic rays. Within the core, the temperature is of the order of 10^6K which decreases outward till the surface of the sun known as photosphere, commonly called the "solar disc". The solar disc is at the temperature of around 6000K and has a stable and sharply defined outer boundary. But above this, the plasma density decreases while temperature increases upto the order of 10^5K in the outermost layer known as coronal layer. For any activity within the sun, the boundaries of its different layers are not opaque and they communicate in form of energy exchange, transportation and circulation within it.

Considering, the solar disc as a black body at about 6000K, it gives a broad band spectrum spread which is found in the range of 0.25μm to 2.5μm which includes the ultra-violet (UV), visible and Infra-red (IR) regions of the electromagnetic spectrum.

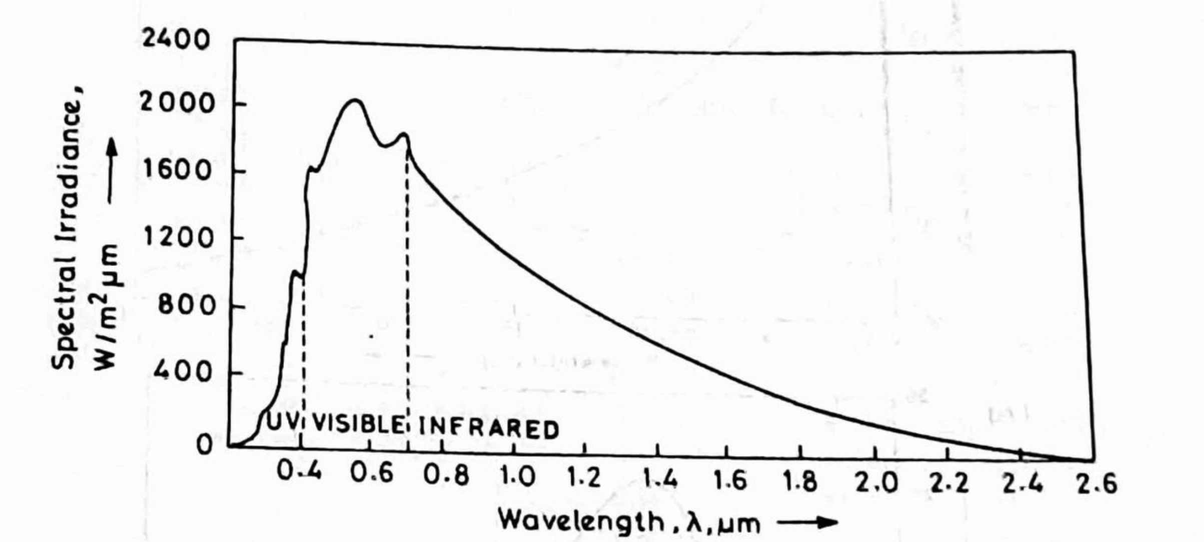

Fig.1: Solar Spectral Irradiance [1].

As shown in the fig.1[1], the spectral intensity is different for different wavelengths. It is these two parameters: the spectral intensity and its variation and the wavelength- range, which governs the fabrication and performance of various engineered solar energy devices in the process of solar energy exploration for mankind with the clean environment.

2.2 Radiation received in the Extra-terrestrial Region:

Assuming sun to be at rest at one of the foci of the earth's elliptic orbit, there is a variation in the intensity of solar radiation received in the extra-terrestrial region with the n^{th} day of the year. This problem was overcome with the introduction of the concept of solar constant I_{ON} (which is the total solar energy received at mean earth-sun distance by a surface outside earth's atmosphereof an astronomical unit (1AU) per unit time per unit cross-section with respect to the direction of solar beam) by***A. Pouillet in 1837*** and ***Langley in 1881***, first gave the method for its quantitative determination. At present, internationally, the accepted value of solar constant (I_{ON}) is 1367W/m^2 where, 1AU= 1.496x10^{11}m. Its variability on the earth's surface in absence of atmosphere is parameterised in form of: astronomical factors, geographical factors and geometrical factors which are given in [1], [2], [3]. At any general sloped surface, in absence of atmosphere it is given by the relation,

$$I_{EN} = I_{ON} \bullet [\,1.0 + 0.033 \cos(\tfrac{360n}{365})] \quad (1)$$

$$I_S = I_{EN} \bullet \cos\theta_i \quad (2)$$

where,

$$\cos\theta_i = [\cos\phi \bullet \cos\beta + \sin\phi \bullet \sin\beta \bullet \cos\gamma] \bullet \cos\delta \bullet \cos\omega$$
$$+[\sin\phi \bullet \cos\beta - \cos\phi \bullet \sin\beta \bullet \cos\gamma] \bullet \sin\delta$$
$$+ [\cos\delta \bullet \sin\omega \bullet \sin\beta \bullet \sin\gamma] \quad (3)$$

$$\omega = (\text{Solar Time} - 12)\, 15^o \quad (4)$$

Solar Time = Local time ± Longitude correction + ellipticity correction (EOT)

$$\delta = 23.45 \bullet \sin [\tfrac{360}{365}(284 + n)]$$

Till here it looks like that there is no problem to estimate I_S in real atmosphere at the ground, but it is a problem. As soon as I_{EN} reaches in the atmosphere, it undergoes the physical processes of: reflection, absorption and scattering. The reflected part by clouds and large aerosols is back to the extra- terrestrial region itself. The earth's surface finally receives the radiation in form of: transmitted beam radiation through atmosphere from the incident direction known as beam radiation (I_B), the scattered part from the hemispherical dome of the atmosphere in form of diffuse radiation known as diffuse radiation (I_D) and solar radiation reflected from the ground and the surroundings as reflected radiation (I_R). Therefore, we have:

$$I_B = f_b \cdot I_S, I_D = f_d \cdot I_S \text{ and } I_R = f_r \cdot I_S \quad (6)$$

where f_b, f_d and f_r are transmittance, diffusivity of the atmosphere and reflectivity of the surrounding surfaces respectively.

The crux of the problem and challenges are: **the estimations off$_b$, f$_d$ and f$_r$** requiring the models (theoretical, experimental or both) to estimate the hourly, daily, monthly and annual averages of the solar radiation for a given orientation and tilt of the surface at a particular station.

III. Variability factors for Solar Radiation in Terrestrial Region

3.1 Physical Factors:

The physical factors responsible for the attenuation of I_{EN} are: by pure atmosphere (Rayleigh Scattering); by water content of the atmosphere (expressed in centimetres of precipitable water), the turbidity- coefficient of Angstrom Schiiepp, the exponent α in Angstrom's turbidity formula and the ozone content of the atmosphere (expressed in cm NTP). The attenuation in terrestrial region due to these factors is studied under: ***atmosphere without clouds***. In this we consider the transmittances of: Rayleigh scattering (τ_r), Mei scattering (τ_m), mixed gases (τ_g), ozone (τ_o) and water vapour (τ_w). Since these transmittances are less than one hence the direct solar radiation on the earth's surface is less than the total extra-terrestrial radiation I_{EN}, which is the direct solar radiation.

The natural pure atmosphere is composed of O_2, N_2 and CO_2 we call mixed gases in which we have Rayleigh scattering only, as for thisbecause size of molecules <λ of the radiation. This extinction is measured in terms of air-mass (m)which is defined as:

$$m = \left(\frac{\text{actual path length traversed by solar beam in atmosphere}}{\text{verticle depth of atmosphere}}\right) \text{ at a place.}$$

It is given by, $$m = [\{(\frac{Re}{H}) \cdot \cos\theta_z\}^2 + 2\left(\frac{Re}{H}\right) + 1]^{1/2} - \left(\frac{Re}{H}\right) \cdot \cos\theta_z \quad (7)$$

Assuming earth's atmosphere as homogenous and spherical. According to observation,
H = 7991 km and R_e = 6370 km and we find that;
$m = \sec\theta_z$ ($\theta_z < 70^o$)
m = 0, outside the atmosphere. At a station, within the atmosphere, it is more in the morning and evening and less in the solar noon. According to ***Bouguer-Lambert Law***, the attenuation of beam in a medium is exponential and decided by the path length in terms of optical air- mass (m) and the total attenuation coefficient (k) given by,

$$I_{BN} = I_{EN} \cdot \exp(-k \cdot m) \quad (8)$$

But, when molecule or particle size > or of the order of λ, the wavelength of radiation, which is case for water-vapour, larger aerosol particles, water crystals etc., there is Mie Scattering.In terms of individual transmittances, we express Equ. (8) in form of:

$$I_{BN} = I_{EN} \cdot [\tau_r \cdot \tau_m \cdot \tau_g \cdot \tau_o \cdot \tau_w] \quad (9)$$

and $f_b = \tau_r \cdot \tau_m \cdot \tau_g \cdot \tau_o \cdot \tau_w$

It is this, the factor f_b demands to develop models theoretical or experimental to estimate I_{BN} at a particular station. [4], [5], [6].

3.2 Meteorological Factors:

These factors, due to which there is an attenuation in the incident extra-terrestrial radiation, are: the effect of cloudiness of the sky and the effect of the albedo of the ground. These factors are studied under: ***the atmosphere with clouds***. The presence of clouds partly or overcast days or in the case of dominance of aerosols as hazy days, the I_{EN}, in part, reaches the ground in form of diffuse radiation which is defined as: the downward radiation received on the horizontal surface from a solid angle of 2π, with the exception of the solid angle subtended by the solar disc. In the variability of the overcast or hazy conditions, there are challenges to estimate the factor f_d in Equ. (6). When the sky is completely overcast by clouds uniformly or hazy uniformly, the diffuse irradiance is ***isotropic diffuse radiation*** and in case of partly cloudy or non-uniform cloudiness it is called ***anisotropic diffuse radiation***. Global radiation isthe sum total of direct and diffuse radiation. It is the global radiation measurement and diffuse radiation measurement are easy to proceed and indirectly from these measurements we estimate the beam radiation averaged hourly, monthly or annual respectively ([4], [7], [8]).

IV. Analysis of the Variability Factors:

The theoretical variability factors as sun-earth angles, revolution and rotation of earth, tilt of spinning axis of earth and orientation and tilt of the surface are completely parameterised. But, the variability in the terrestrial region under the categories of cloudless sky conditions and cloud sky conditions, there are two basic ways in which the geographical distribution of solar irradiance can be studied, should be applied. In this, one of them involves the measurement of global and diffuse radiations by a network of closely spaced stations equipped with high resolving instruments and the other is based on the use of physical formulae and constants identified. In practice, a combination of both the methods are used in formulation of models to estimate the solar irradiance. For transmittance (f_b) evaluation the formulated models are Lacis and Hamsen [10]. Davies et al. [11] and Bird and Hulstrom [12]. There are Meteorological Radiation Models (MRM) and Cloud Radiation Model (CRM) to estimate the solar radiation for various sky conditions extending from clear sky to overcast sky. These are given in Fig. (2) to Fig. (5).

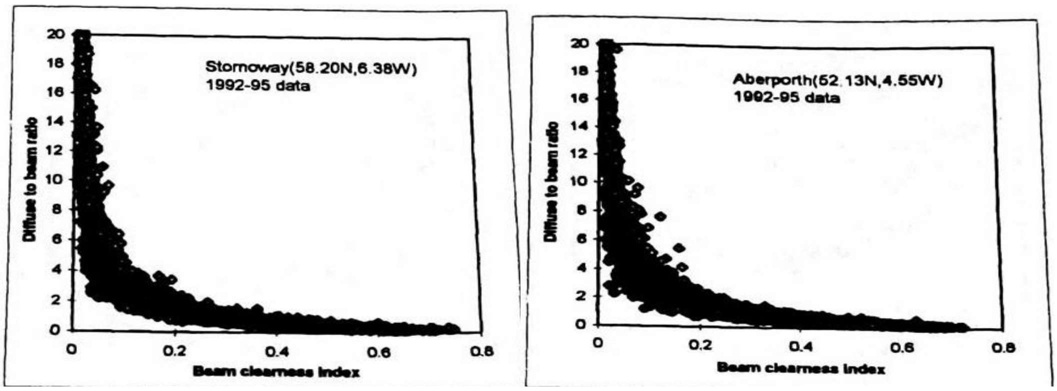

Fig.2: Correlation between hourly diffuse and beam radiation for non-overcast conditions of sky with sunshine fraction greater than zero. [14]

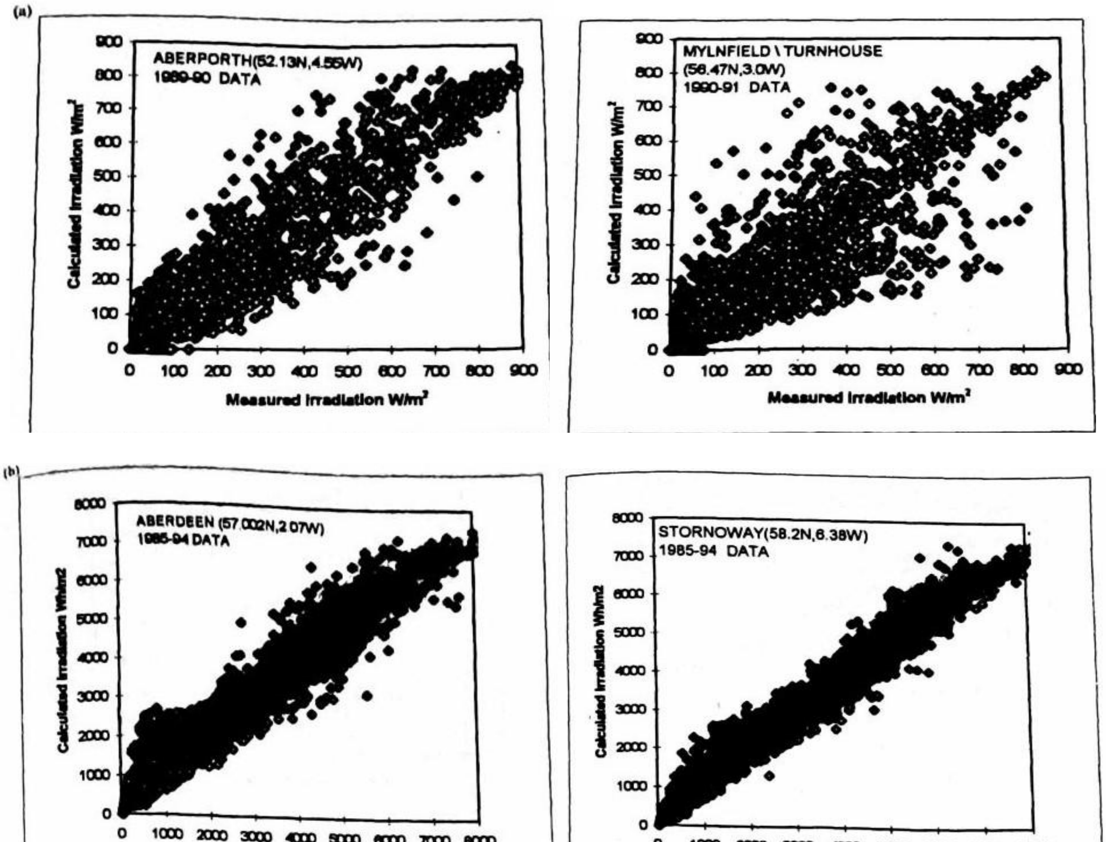

Fig.3(a) & (b): Estimation of proposedall-sky model for hourly global radiation.[14]

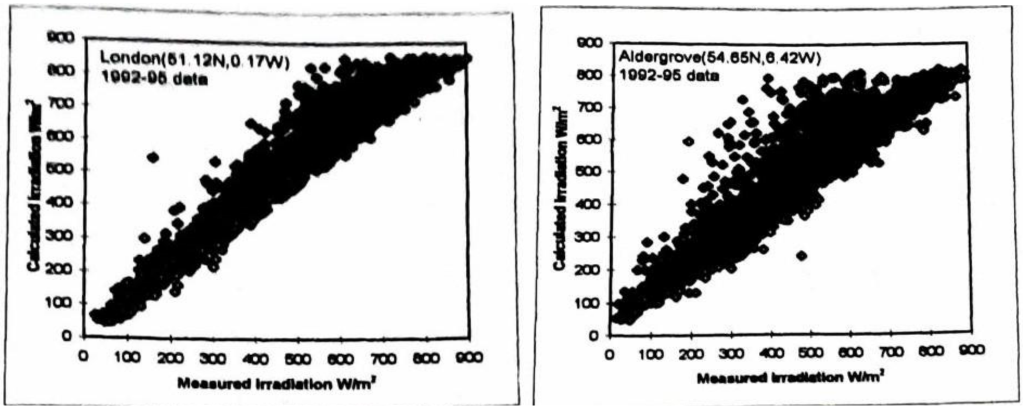

Fig.4: Estimation of proposed all-sky model for daily global radiation.[14]

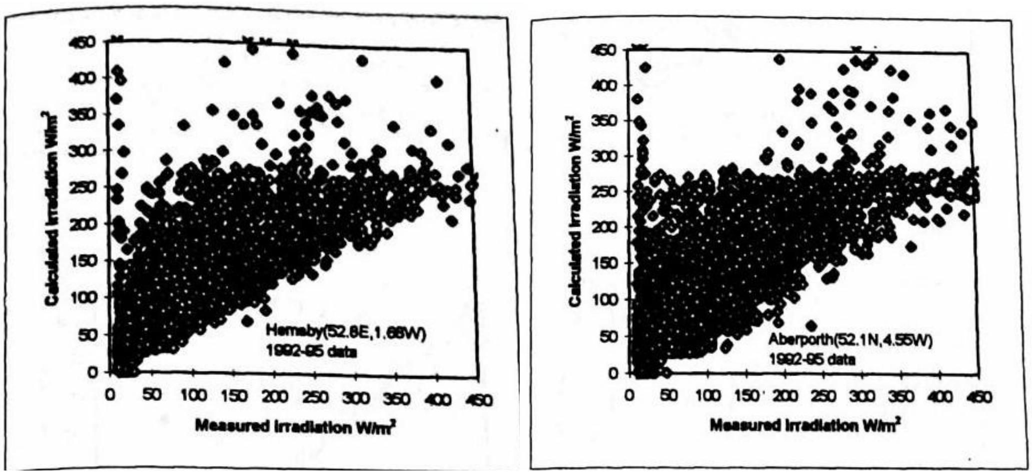

Fig.5: Estimation of proposed overcast sky model with sunshine fraction equal tozero. [14]

The accuracy estimation of M.R.M model at an hourly radiation (0-200W/m^2) and daily radiation (0-1300W/m^2) is estimated in terms of Mean Bias Error (MBE) and Root Mean Square Error (RMSE) in percentage, as given in Tables – (1) and (2).It is given in detail in [14] and [15].

	1985–86		1987–88		1989–90		1991–92		1993–94	
Location	MBE	RMSE	MBE	RMSE	MBE	RMSE	MBE	RMSE	MBE	RMSE
Camborne	30	60	38	61	25	53	31	63	41	79
London*	41	73	42	65	35	60	33	50	36	58
Bracknell	26	54	32	62	27	49	32	59	32	60
Aberporth	28	61	19	44	17	38	21	44	18	45
Finningley†	27	58	28	52	20	42	28	58	30	61
Aldergrove	16	46	45	74	29	60	21	38	18	44
Mylnfield*	65	91	31	71	32	70	24	62	28	66
Aberdeen	24	58	27	62	18	48	22	57	25	55
Stornoway	6	27	14	41	13	39	11	39	15	44

*Period considered = 1984–93.
†Period considered = 1986–95.

Table 1: Accuracy estimation of MRM at an hourly radiation (0-200W/m^2) and daily radiation (0-1300 W/m^2) in terms of MBE and RMSE (in percentage). [14]

Location	1985–86		1987–88		1989–90		1991–92		1993–94	
	MBE	RMSE	MBE	RMSE	MBE	RMSE	MBE	RMSE	MBE	RMSE
Camborne	9	30	12	31	9	28	8	32	9	35
London*	17	26	19	31	15	25	13	23	13	29
Bracknell	10	24	10	21	9	21	12	26	12	24
Aberporth	3	18	7	18	0	17	6	19	6	18
Hemsby	3	49	15	53	10	53	—	—	14	51
Finningley†	9	21	9	20	9	21	10	21	9	17
Aldergrove	6	20	9	25	8	19	7	15	8	20
Mylnfield*	21	35	15	45	7	33	6	30	3	24
Aberdeen	9	22	9	21	5	19	5	21	11	21
Stornoway	0	16	3	18	12	23	4	18	9	20

*Period considered = 1984–93.
†Period considered = 1986–95.

Table 2: Accuracy estimation of MRM at an hourly radiation (200-400W/m^2) and daily radiation (1300-2600 W/m^2) in terms of MBE and RMSE (in percentage). [14]

V. Conclusions:

i. For radiation on horizontal and inclined surfaces, more close recording stations network should be prepared taking care of variability of radiation in 250-300km range and based on the data collected the model should be prepared.

ii. At a station, maximum solar radiation is received under clear sky conditions which is required for most of the solar devices because they operate when the radiation is maximum or at least above a certain threshold level. Consequently, for the clear sky conditions, theradiation measurement is important for many devices especially thephotovoltaic.

iii. The high level of solar radiation can create serious problems in agriculture and architecture along with green house applications. So, from devising the control devices and utilization of solar radiation under clear sky conditions, its measurement is of utmost importance.

iv. The measurement ofsolar radiationunder clear sky conditions is also important to assess and devise the solar systems for cooling and heating of a building based on its use as an office building or residential building in solar architecture.

VI. Nomenclature:

UV: Ultra Violet
IR: Infra-Red
I_{ON}:Solar Constant
I_{EN}: Extra-terrestrial solar radiation normal to the surface
I_S: Total solar radiation on an inclined surface.
θ_i: Angle of incidence
θ_z: Zenith angle
ϕ: Latitude angle of the place
β: Surface slope angle
γ: Surface azimuth angle
ω: Hour angle
δ: Declination angle
n: n^{th} day of the year, n=1 for January1^{st}
α: Angstrom turbidity coefficient
EOT: Equation of time
NTP: Normal Temperature and pressure
R_e: Radius of the earth
H: Average thickness of the atmosphere
k: Total attenuation coefficient/extinction coefficient/optical thickness
m: Optical air- mass

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