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Extra-terrestrial Solar Radiationand its Intensity Estimation

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
One of the earliest forms of energy under human use came is nothing but the solar energy extended from sun-bath to solar-drying. When it was thought to proceedscientifically in its application, because of being the input energy to operate a device designed, its estimation at the site became first and foremost importance. In the beginning, in the clear sky conditions at high altitudes, assuming free from climatic and weather effects, it was found that the intensity of solar radiation is changing: not only with the time of the day, day of the year, orientation and tilt of the surface under consideration at a chosen station but stations to stations too. To quantify these variations, the researchers throughout the globe, especially the United States and European Countries, attempted with great success to not only identify the factors responsible for variability noticed (in absence of atmosphere defined as extra-terrestrial region) but formulated also. These are understood in form of:due to the ellipticity of the earth's orbit, tilt of the spinning axis of the earth and temperature of the solar disc. In this communication, we have attempted to analyse the various theoretical factorsidentified, understood and formulatedin form of astronomical factors, geographical factors and geometrical factors which causes variation in the available solar radiation intensity on the earth's surface in absence of atmosphere.

Keywords: *Solar Radiation;Astronomicalfactors, Geographical factors,Geometrical factors.*

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I. Introduction

Solar energy received on earth's surface has many applications in the processes of nature itselfandin the devices and structures engineered by scientists and engineers. The natural applications are namely: hydrological cycle, photosynthesis, biological cycle in plants and animals etc. The engineered manmade applications are, namely, conversion of solar energy into heat, storage of heat and electrical energy generation, etc. The variability of solar radiation received on earth's surface is a boon for natural applications but constraint to the engineered applications. In case of engineered applications, we want to have optimum and steady radiation input available, but it is not possible because of two factors: firstly, the standard variable parameters associated with the generation at source, motion of receiver, geographical distribution of stations and the surface orientation and its tilt, and secondly, the earth's atmospheric composition, physical conditions and meteorological condition at the station. The second part involves the measurements by a network of closely spaced stations in form of spectral and total irradiance and the first part involves the theoretical formulation to quantify the various parameters in form of ellipticity of the earth's orbit, sun-earth angles, surface tilt and its orientation along with the spin of earth.

In this communication, we have attempted to go through the first part.The source of solar energy is the sun being an **active entity** full of dynamic process within its core plasma to outer corona connected in some processes and confined in many. The sun structure is divided into seven layers extending from central part core of it to the outermost part known as coronal layer. The photosphere is considered as the surface of the sun i.e., **solar disc** and only this has the sharply defined outer surface. The layers below this are the convective zone, radiative zone and core, while the layers outside it are the reversing layer, chromosphere and the coronal layer. The outer layers with respect to the solar disc (photosphere) are together called the **solar atmosphere**. The temperature of the solar disc is of the order of 6000Kwhich increases up to the order of 10^4K in chromosphere and further increases to 10^5K in coronal layer. Because of being at higher temperature of the solar atmosphere and its lower plasma density, it has minimal effect to the radiations emitted by the solar disc. It is these radiations at the temperature of the order of 6000K in which we are interested on earth to receive maximum for engineered solar energy applications. Assuming solar disc as a black body radiating at about 6000K, the spectral intensity distribution falls as: maximum intensity falls as 0.48μm of wavelength (λ) in the green portion, the 6.4

percent of the total energy is contained in Ultraviolet (UV) region ($\lambda < 0.38\mu m$); 48 percent is contained in the visible region ($0.38 < \lambda < 0.78\mu m$) and the remaining 45.6 percent falls in the Infra-Red (IR) region as shown in Fig.1[1].

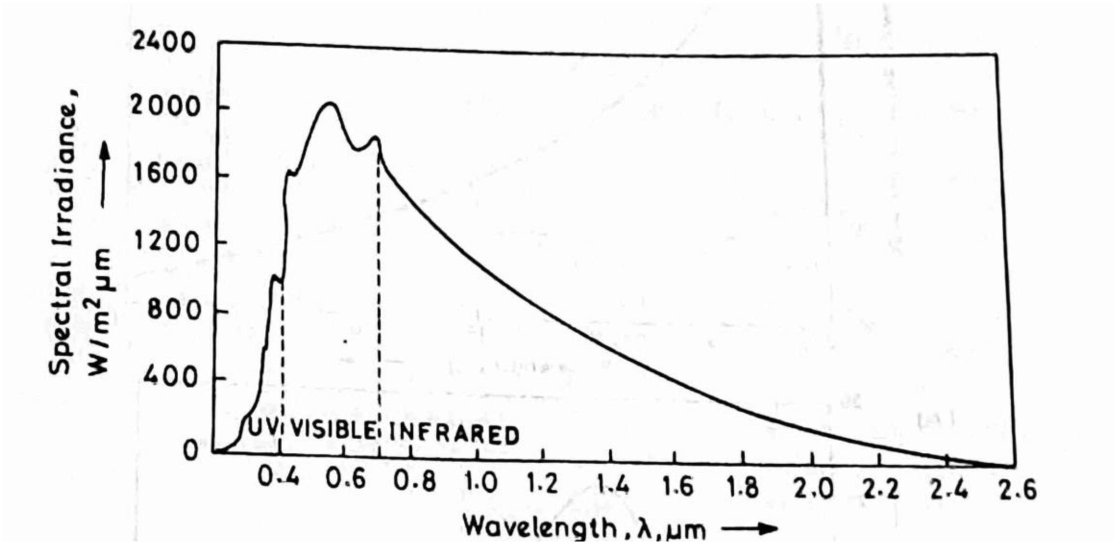

Fig.1: Spectral Solar Irradiance (Thekaekara, 1977)[1].

The radiations emitted by the solar atmosphere is mostly in Soft X-Rays (SXR), Hard X-Rays (HXR) and Gamma Rays (GR) which are actually die out in the earth's atmosphere by the time it reaches to the earth's surface along with harmful UV-radiations of solar disc. So, from engineered solar energy applications point of view, the radiation emitted by the solar disc for $\lambda > 0.38$ we are interested. Further for $\lambda > 2.5\mu m$, the intensity is so small that it contributes almost nil to any desired applications. So, the range of wavelength $0.38\mu m < \lambda < 2.5\mu m$, is of our consideration to estimate, record and utilize.

II. Radiation Emitted by the Sun

2.1 Source of Solar Radiation:

After the establishment of the fact that energy (E) is equal to the product of mass (m) and square of the speed of light (c) in vacuum as $E=mc^2$, the conversion of matter into energy, the **nuclear fusion reaction** in the core of the sun,is accepted as the source of solar energy and based on this the sun is termed as a continuous fusion reactor or thermal reactor, in which the most agreed reaction is,

$$4({}_1H^1) \longrightarrow {}_2He^4 + 26.7\text{Mev} \qquad (1)$$

In this nuclear reaction, four hydrogen nuclei fuses to form a single helium nucleus and releases energy due to **mass-defect**. This energy produced maintains the condition for the nuclear fusion reactions to sustain in form of thermal energy at a high temperature (10^6K). But being at temperature (T_s) it also radiates the energy outwards given by,

$$E = \epsilon.\sigma.(T_s)^4 \qquad (2)$$

where ϵ and σ are the **emissivity** of the radiating surface and ***Stefan-Boltzmann Constant*** respectively [1].

2.2 Temperature of the Solar Disc:

The radiated energy given by Equ. (1) comes into the radiative zone and convective zone where it is responsible for many dynamic processes in these two zones decided by their plasma density, thermal pressure and magnetic field pattern. These two zones are always in their dynamic equilibrium. The boundaries of core, radiative zone and convective zone are not sharply defined because of being in dynamic equilibrium in size, shape, density and temperature. The outer layer of convective zone is called the "surface of the sun" also known as photosphere and it is the photosphere only of which outer edge is sharply defined in form of its radiusand temperature where its temperature is of the order of 6000K.

2.3 Limits of Solar spectrum in Extra-terrestrial Region:

There are various methods to study the electromagnetic spectrum radiated out by the sun, the**direct methods** as: extrapolation from spectral measurements at various heights above sea level; by **indirect methods** as examining the state of the ozone layer and various layers of ionosphere and by direct radio reception from the sun. The radiated spectrum extends from fraction of an Angstrom to hundreds of meters [2-4]. The spectrum radiated by the solar disc, in the range of 2500A^o to 30,000A^o carries nearly 98 percent of the total emitted energy. The solar radiation outside this limit has its own importance but regarding solar energy application point of view, their intensity is much lower to explore.

The region of solar spectrum with which most of the solar energy applications are associated as photovoltaic, distillation, building heating and cooling, solar pond, solar collectors, solar drying etc., the sun may be regarded as a **heat radiator** by virtue of its temperature. It also converts absorbed radiation into heat. Treating it as a perfectly black body, the spectral curve of extra-terrestrial radiation of solar disc will be of the type as shown in the Fig.(2), [5].

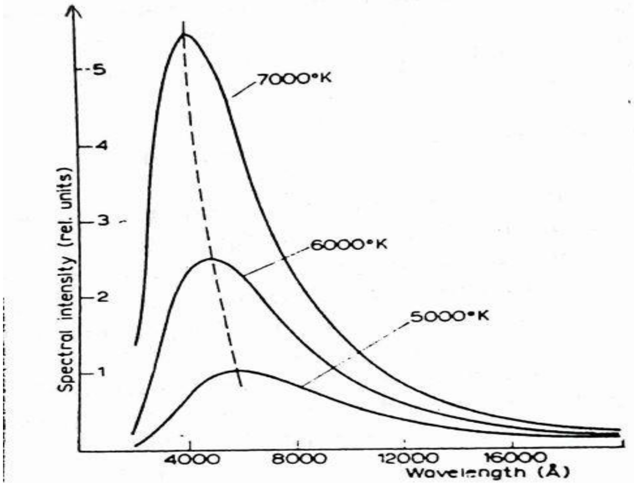

Fig.2: Spectral curves of Sun as a black body at T = 7000K, 6000K and 5000K

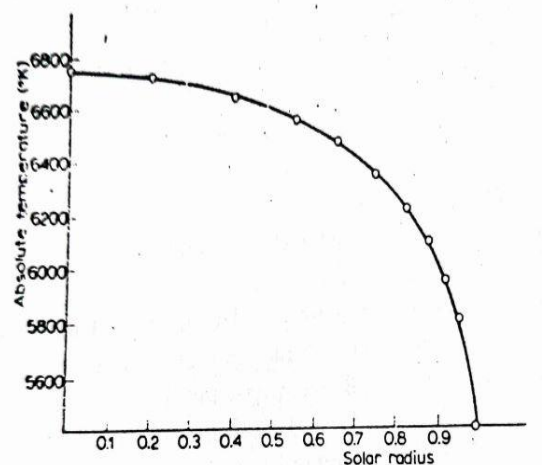

Fig.3: Variation of temperature across the solar disc.

Table 1: The extra-terrestrial solar irradiance, the WRC solar spectrum.

λ	$I_{sc,\lambda}$	$f_{o-\lambda}$	λ	$I_{sc,\lambda}$	$f_{o,\lambda}$	λ	$I_{sc,\lambda}$	$f_{o,\lambda}$
0.250	13.8	0.002	0.520	1820.9	0.243	0.880	965.7	0.621
0.275	224.5	0.005	0.530	1873.4	0.257	0.900	911.9	0.635
0.300	542.3	0.012	0.540	1873.3	0.271	0.920	846.8	0.648
0.325	778.4	0.023	0.550	1875.0	0.284	0.940	803.8	0.660
0.340	912.0	0.033	0.560	1841.1	0.298	0.960	768.5	0.671
0.350	983.0	0.040	0.570	1843.2	0.311	0.980	763.5	0.683
0.360	967.0	0.047	0.580	1844.6	0.325	1.000	756.5	0.694
0.370	1130.8	0.056	0.590	1782.2	0.338	1.050	668.6	0.720
0.380	1070.3	0.064	0.600	1765.4	0.351	1.100	591.1	0.743
0.390	1029.5	0.071	0.620	1716.4	0.377	1.200	505.6	0.783
0.400	1476.9	0.079	0.640	1693.6	0.40	1.300	429.5	0.817
0.410	1698.0	0.092	0.660	1545.7	0.424	1.400	354.7	0.846
0.420	1726.2	0.104	0.680	1492.7	0.447	1.500	296.6	0.870
0.430	1591.1	0.117	0.700	1416.6	0.468	1.600	241.7	0.890
0.440	1837.6	0.129	0.720	1351.3	0.488	1.800	169.0	0.921
0.450	1995.2	0.143	0.740	1292.4	0.507	2.000	100.7	0.941
0.460	2042.6	0.158	0.760	1236.1	0.526	2.500	49.5	0.968
0.470	1996.0	0.173	0.780	1188.7	0.544	3.000	25.5	0.981
0.480	2028.8	0.187	0.800	1133.3	0.561	3.500	14.3	0.988
0.490	1892.4	0.201	0.820	1089.0	0.577	4.000	7.8	0.992
0.500	1918.3	0.216	0.840	1035.2	0.593	5.000	2.7	0.996
0.510	1926.1	0.230	0.860	967.1	0.607	8.000	0.8	0.999

$I_{sc,\lambda}$ is the solar spectral irradiance in W/m² μm averaged over a small bandwidth centred at λ (in µm).
$f_{o,\lambda}$ is the fraction of the solar constant associated with wavelengths shorter than λ.

The average energy $I_{sc\lambda}$ over small band with $\lambda - \frac{d\lambda}{2}$ to $\lambda + \frac{d\lambda}{2}$ centred at wave length λ and the integrated fraction of energy $f_{o,}\ \lambda$ at wavelengths smaller than that for the standard curve of Fig.3 are indicted in Table-1, [7-9].

III. Factors affecting Solar Radiation Intensity in Extra-terrestrial Region/ Absence of Earth's Atmosphere

3.1 Astronomical Factors:

3.1.1 Ellipticity of the Earth's Orbit:

The first astronomical factor is the solar constant $I_{ON,}$for the solar spectrum between 0.30µm to 5.0µm. This is because the earth's orbit around the sun is elliptical not circular, due to which the distance between earth and sun is varying. It varies by 1.7% between minimum and maximum. The mean earth-sun distance is considered as one astronomical (AU) unit which is equal to 1.495×10^{11}m and the sun subtends an angle of 32′ on earth,[9].

Taking this mean earth-sun distance, the radiation received on earth outside its atmosphere is assumed as constant and formulated in terms of solar constant, I_{ON} which is nothing but the energy received from the solar disc per unit time, per unit cross-sectional area, perpendicular to the direction of propagation of the radiation at the mean earth-sun distance in absence of atmosphere. The value of I_{ON} is adopted by WRC as 1367 W/m^2 with an accuracy of the order of 1percent,[9].

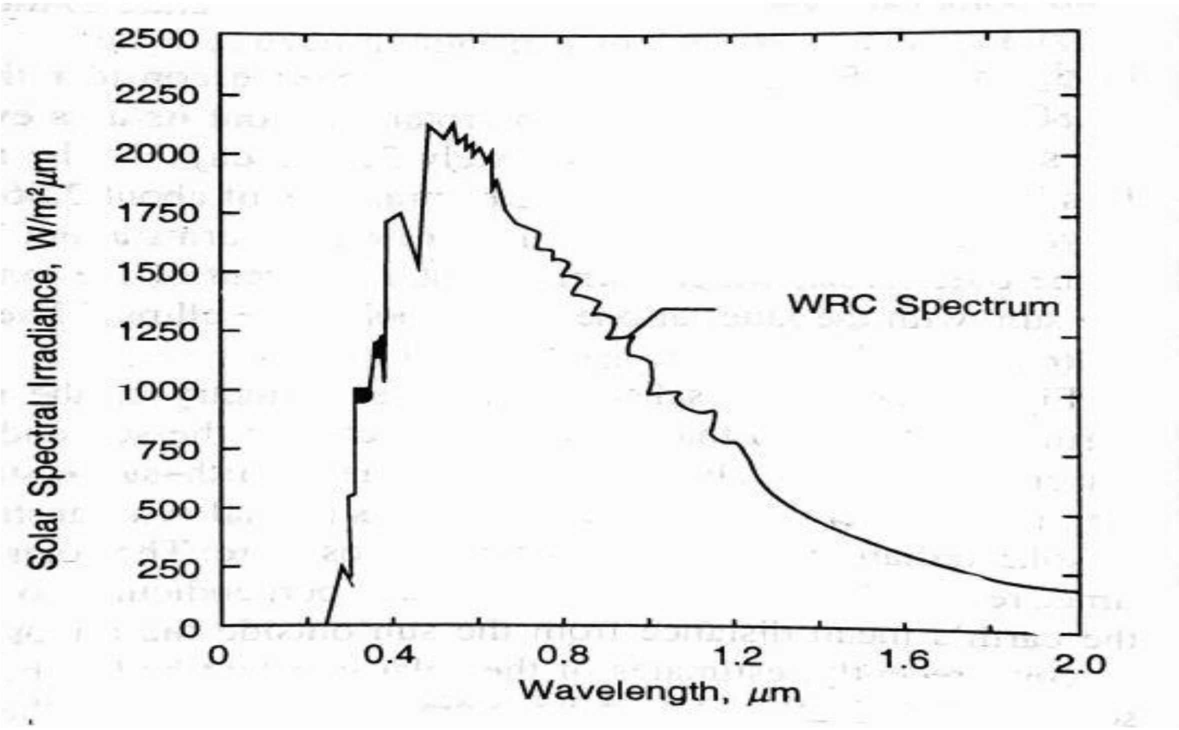

Fig.4: The WRC standard solar spectrum curve.

The concept of solar constant was introduced by **A. Pouillet in 1837** and the method for its determination was first given by **Langley in 1881**[5]. Assuming photo-spherical emission at steady rate, in its elliptical orbit, the extra-terrestrial radiation measured on a plane normal to the radiation on the n^{th} day of the year (n=1 for January 1^{st} and n=365 for December 31^{st}) in absence of earth's atmosphere is given by:

$$I_{EN} = I_{ON}\left[1.0 + 0.033\cos\left(\frac{360n}{365}\right)\right] \quad (2)$$

3.1.2 Tilt of the axis from its Rotational Plane:

In its orbit around the sun in its elliptical orbit, the earth spins and its axis of spin (polar axis) is not perpendicular to the orbital plane. It is tilted by 23.50^o with the normal to the plane.

The variability by this factor is measured in terms of declination angle δ which varies from 23.45^o on June 21^{st} to - 23.45^o on December 21^{st}, north or south of equatorial plane of the earth, respectively. On any n^{th} day of the year, it is given by (Cooper,1969):

$$\delta = 23.45 \cdot \sin\left[\frac{360}{365}(284 + n)\right] \quad (3)$$

Its variation with n is given in Fig.(5), [1]. It varies with the day of the year only.Physically, it represents the tilt of the earth's equatorial plane with its orbital plane around the sun on a particular day of the year. If earth's polar axis is not tilted, δ = 0 for any day of the year irrespective of the ellipticity of its orbit.

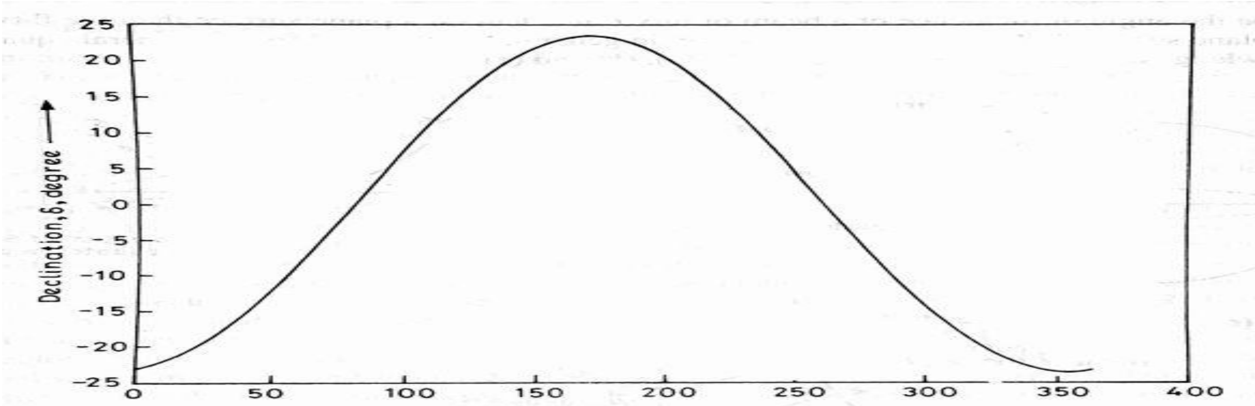

Fig.5: Variation of declination angle with the day of the year.

3.1.3 Spin of Earth:

This causes variation in the solar radiation intensity because of the fact that due to spin motion of earth about its axis, at a particular place may find the position of sun east or west of its meridian which governs that the sun's position is overhead or towards east (am) or towards west (pm). This variation is measured in terms of **sun-earth angles** as: Solar Time (ST), Equation of time; Solar altitude angle (α_s), Zenith angle (θz) and Solar Azimuth angle (γ_s). The solar time is different than the local time at a place.

The **Equation ofTime** (EOT) arises due to the variation in the length of the solar day time because with n, the day of the year, the earth's surface exposed to sun from sunrise to sunset is different due to tilt of the axis. It is expressed as:

$$EOT = 229.2[0.000075 + 0.001868\cos B - 0.032077\sin B - 0.014615\cos 2B - 0.04089\sin 2B] \quad (4)$$

where, $$B = [(n - 1) \cdot \left(\frac{360}{365}\right)] \quad (5)$$

The solar radiation available is finally decided by where is the sun at a time of measurement. Every station is associated with local time standardised with respect to a standard station longitude of the country known as **standard time**for the station under consideration. Therefore,

In general,

Solar Time (ST) = Local Time ±Longitude Correction + Ellipticity Correction

The longitude correction is measured in terms of difference of longitudes of the station and its standard zone longitude for that station and the ellipticity correction is measured in terms of EOT:

For the stations east of GMT:

Solar Time of a station=Standard Time (for the zone/country)
–[4(L_{std}– L_{loc}) East of GMT] + EOT (6)

For the stations west of GMT:

Solar Time of a station = Standard Time (for the zone/country)
+ [4(L_{std} – L_{loc}) west of GMT] + EOT (7)

Where L_{std} :Standard meridian(longitudein degree)of the zone/country.
L_{loc}: Local meridian (longitudein degree) of the station.
[4(L_{std} – L_{loc})] and EOT: are in the units of minute.

The solar time (ST) is used to determine the angular position of the sun east or west of the local meridian due to the spin of the earth about its axis which is measured in terms of hour angle (ω) given by:

$$\omega = (ST - 12).15^{o} \quad (8)$$

which is zero at solar noon (ST = 12), negative in the before solar noon hours and positive in after solar noon hours. This result is for a station in northern hemisphere and vice-versa in southern hemisphere. For a place in northern hemisphere its values are given in Table-2, [1].

Table 2: The values of hour angle with solar time of the day for a place in NorthernHemisphere.

Time of the day (hours)	6	7	8	9	10	11	12
Hour angle (degree)	−90	−75	−60	−45	−30	−15	0
Time of the day (hours)	12	13	14	15	16	17	18
Hour angle (degree)	0	+15	+30	+45	+60	+75	+90

The Zenith Angle (θ_z) is the angle between sun's ray and the normal to horizontal (horizon) plane at a station. At solar noon,$\theta_z= 0^o$and at the sunrise and sunset $\theta_z= 90^o$. The Solar Altitude Angle (α_s) is the angle made by sun's ray at a time for a given station with respect to the horizon of the station. So,we have: $\theta_z + \alpha_s = 90^o$
Hence, we find that the variability of solar radiation intensity without earth's atmosphere due to astronomical factors will be governed by: n, δ, ω,θ_z(orα_s)where δ vary with the day of the year and ω,θ_z (orα_s) vary with the time of the day for a given station.

3.2 Geographical Factors:

The geographical factors are: the variation of latitude (ϕ), longitude (L_{loc}). The height (h) above sea level is considered in presence of atmosphere. The effect of height of the place above sea level is expressed in terms of mean pressure P. The latitude (ϕ) and longitude (L_{loc}) are used to express the angle of incidence θ_z of sun's ray at a station at any local time of the n^{th} day of the year, as shown in Figs. (6) and (7) [10]. These factors are associated with a station and changes with the change of station.

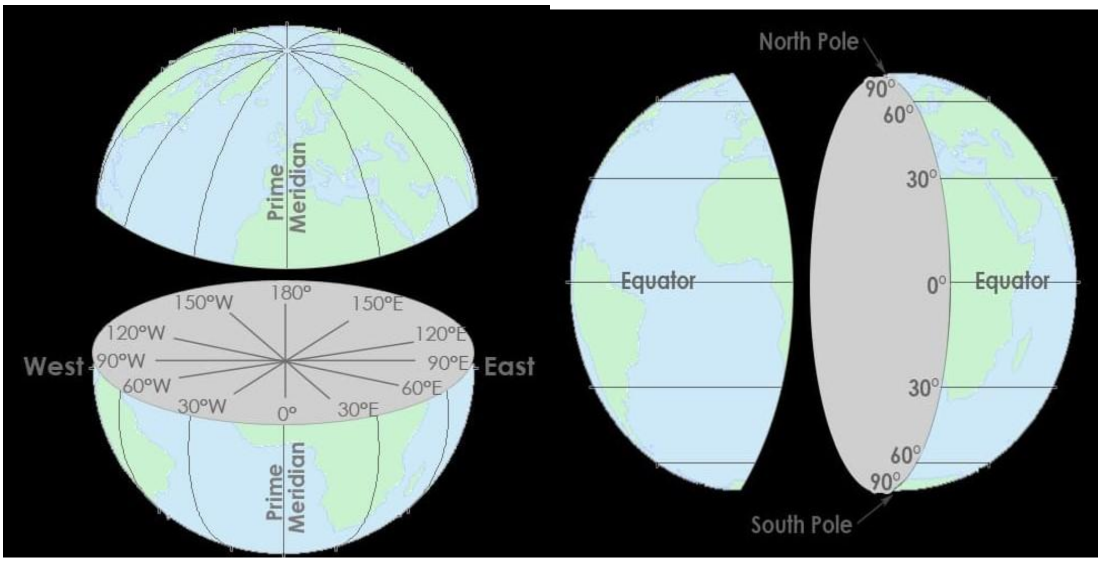

Fig.6: The longitude values and conventions for a given station on earth's surface.[10]. **Fig.7:** The latitude values and conventions for a given station on earth's surface.[10].

3.3 Geometrical factors:

At given station, these factors decide the orientation and tilt of the surface on which the solar radiation intensity is to be estimated at a given station at any time, for a particular day of the year. These parameters are associated with the surface of the station.

Surface Azimuth Angle (γ): is the angle in the horizontal plane made by the projection of outward normal of the surface in the horizontal plane with respect to south line at that station. The γ is negative if it is east of south direction and positive if it is west of south direction for northern hemisphere and vice-versa for southern hemisphere. It ranges from: $-180^o \leq \gamma \leq +180^o$ where $+180^o$ is same as -180^o which is due north. Sloped to east $\gamma = -90^o$, to west $\gamma = +90^o$, to south $\gamma = 0^o$. With respect to south if we rotate the tilt of surface with respect to vertical axis, clockwise rotation has range: $0 \leq\gamma \leq +180^o$ and anticlockwise rotation: $0 \geq \gamma \geq -180^o$ with respect to south facing reference. This angleγ is in the horizontal plane.

Sky Facing Surface

Surface Slope Angle(β):is the angle made by plane of the surface facing sky with horizontal at the station. It is in the vertical plane, north to south or south to north.

In sense of occurring ***north to south***,it is given by the range:$0 \leq \beta \leq 90^o$. For horizontal position $\beta = 0$. For $0 < \beta \leq 90^o$, the surface is facing towards south, east of south or west of south, decided by the γ. At$\beta = 90^o$:$\gamma = -90^o$represents **East Wall**, $\gamma = 0^o$ represents **South Wall** and $\gamma = +90^o$represents **West Wall.**So, for any orientation from south, east or west and tilt with horizontal we have: $0 \leq \beta \leq 90^o$ and $-90^o \leq \gamma \leq +90^o$.

In sense of occurring ***south to north***, β is still given by the range: $0 \leq \beta \leq 90^o$. For horizontal position $\beta = 0$. For $0 < \beta \leq 90^o$, the surface is facing towards north, east of north or west of north, decided by the γ. At $\beta = 90^o$:$\gamma = -90^o$ represents **East Wall**, $\gamma = \pm 180^o$ represents **North Wall** and $\gamma = +90^o$ represents **West Wall.**So, for any orientation from north, east or west and tilt with horizontal we have: $0 \leq \beta \leq 90^o$and $-90^o \geq \gamma \geq -180^o$ for any north – east orientations and $90^o \leq \gamma \leq +180^o$for any north – west orientations.

Earth Facing Surface

Surface Slope Angle (β): In either sense of tilt, north to south or south to north, when $90^o < \beta \leq 180^o$, it represents the earth facing surface for any orientation.In this situation, the solar radiation intensity calculated on a earth facing surface is totally the reflected radiation from the surrounding surfaces if the considered receiving surface is mounted at height above the ground.

At $\beta = 180^o$ again horizontal surface but it is now earth facing.

In general, a surface has two faces: top and bottom as sky facing and earth facing, respectively. For $-90^o \leq \gamma \leq 90^o$, the top face is towards southorientation extended from east to west via south when $0 < \beta \leq 90^o$ and the bottom face is earth facing extended from east to west via north. When $90^o < \beta < 180^o$, the top face starts becoming bottom and the bottom as top face, i.e.,$0<\beta < 90^o$,southfacing top face and earth facing bottom face and $90^o < \beta < 180^o$,north facing bottom face and earth facing top face.Since, the face to receive solar radiation, which is sky facing is well identified, γ and β, together completely parameterize the surface orientation,**east or west of south** and tilt,**south facing or north facing** with respect to horizontal respectively.

Now, taking into account the variability due to astronomical factors, geographical factors and geometrical factors, at a given station for a particular day at a given time on a considered surface in absence of earth's atmosphere on earth, the intensity of solar radiation will be estimated by the expression, reference [1]:

$$I_{EXT} = I_{EN} \,.\, \cos\theta_i \tag{8}$$

Where,

$$\cos\theta_i = [\{\cos\phi .\cos\beta + \sin\phi .\sin\beta .\cos\gamma\} .(\cos\delta .\cos\omega)] + [\{\sin\phi .\cos\beta - \cos\phi .\sin\beta .\cos\gamma\}] .\sin\delta + [\cos\delta .\sin\omega .\sin\beta .\sin\gamma] \tag{9}$$

where, I_{EN}, δ and ω are given by the Equs. (2), (3) and (6).

The number of daylights i.e., sunshine hours (N) can be calculated by knowing the hour angle spread between sunrise and sunset. Since at sunrise $\theta_z = 90^o$, $\theta_i = \theta_z$and $\beta = 0^o$for a horizontal surface, say, the sunrise hour angle isω_s ,then $\omega = -\omega_s$, then by Equ. (9) we get:

$$0 = \cos\phi .\cos\delta .\cos(-\omega_s) + \sin\phi .\sin\delta$$

Or

$$-\omega_s = \cos^{-1}[-\tan\phi .\tan\delta]$$

Similarly, the sunset hour angle will be:

$$+\omega_s = \cos^{-1}[-\tan\phi .\tan\delta]$$

Therefore, total angle between sunrise and sunset will be:

$$2\omega_s = 2\cos^{-1}[-\tan\phi .\tan\delta]$$

Since $15^o \equiv 1$ hr-duration, the number of daylights i.e., sunshine hours will be given by,

$$N = \frac{2}{15}\cos^{-1}[-\tan\phi .\tan\delta] \tag{10}$$

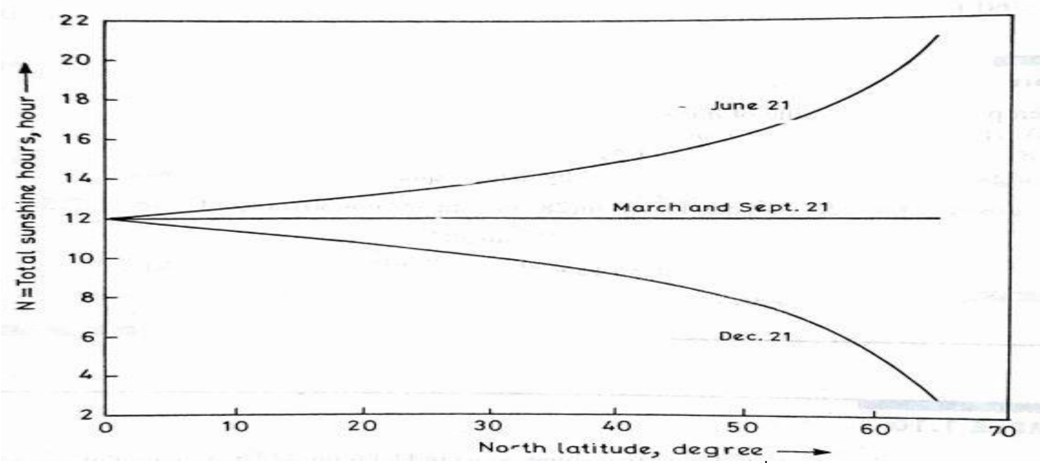

Fig.8: Variation of Daylight hours with latitude for different n[th] day of the year.

The variation of total number of daylights i.e., sunshine hours (N) with the day of the year (n) is given in the Fig.(8) [1].On March and September 21[st], N = 12hr, on June 21[st] it is maximum and on December 21[st] it is minimum at latitude more than 60^o.

IV. Conclusions:

i. Regarding solar energy applications used in practice, the solar energy intensity radiated by solar discis at constant rate and in the absence of earth's atmosphere it reaches to earth with the intensity I_{ON} (Watt/m^2) normal to the surface at a station known as solar constant.

ii. Because of orbital motion, spin motion and tilt of the spinning axis, the solar radiation intensity varies with the day of the year andtime of the day at a given station.

iii. At a given station, on a particular day, at a particular time it depends on the orientation and tilt of the surface under consideration.

iv. The station is characterised by longitude (L_{loc}, L_{std}), latitude (ϕ). The surface is characterised by the orientation as surface azimuth angle (γ) and tilt as surface slope angle (β). A particular day is characterised by n starting n = 1on 1[st] January and at a time the position of the sun with respect to the station is characterised in terms of declination angle (δ), hour angle (ω), solar time (ST), equation of time (EOT), solar altitude angle (α_s), solar azimuth angle (γ_s) and zenith angle (θ_z).

v. At a particular time, the angle of incidence (θ_i) is the angle subtended by the sun's ray with respect to the outward normal towards the sky to the surface receiving the solar radiation and the intensity of solar radiation in the extra-terrestrial region of earthi.e., on earth's surface in absence of atmosphere or on earth's surface without atmosphere can be obtained by Equ. (8).

vi. By knowing the angle subtended by the sun's rays at sunrise and sunset gives the number of sunshine hours (N) on a particular day of the year at a given station can be obtained by the Equ. (10).

V. Suggested work:

The variability factors governing the solar radiation due to atmosphere, climatic conditions and weather of the station should beanalysed andcompiled.

VI. Nomenclature:

HXR: Hard- X Rays
SXR: Soft X-Rays
EOT: Equation of time
WRC: World Radiation Centre
GR: Gamma Rays
ST: Solar Time
I_{ON}: Solar Constant
I_{EN}: Extra-terrestrial solar radiation normal to the surface
I_{EXT}: Solar radiation intensity on a given surface on a particular day outside earth's atmosphere / on the earth's surface in absence of atmosphere
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
α_s: Solar altitude angle
λ: Wavelength
ϵ: Emissivity of the radiating surface
σ: Stefan-Boltzmann Constant
$2\omega_s$: Total angle between sunrise and sunset on a particular day at a place
n: n^{th} day of the year, n=1 for January 1^{st}
N: Total no. of day light/sunshine hours on a particular day at a place

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