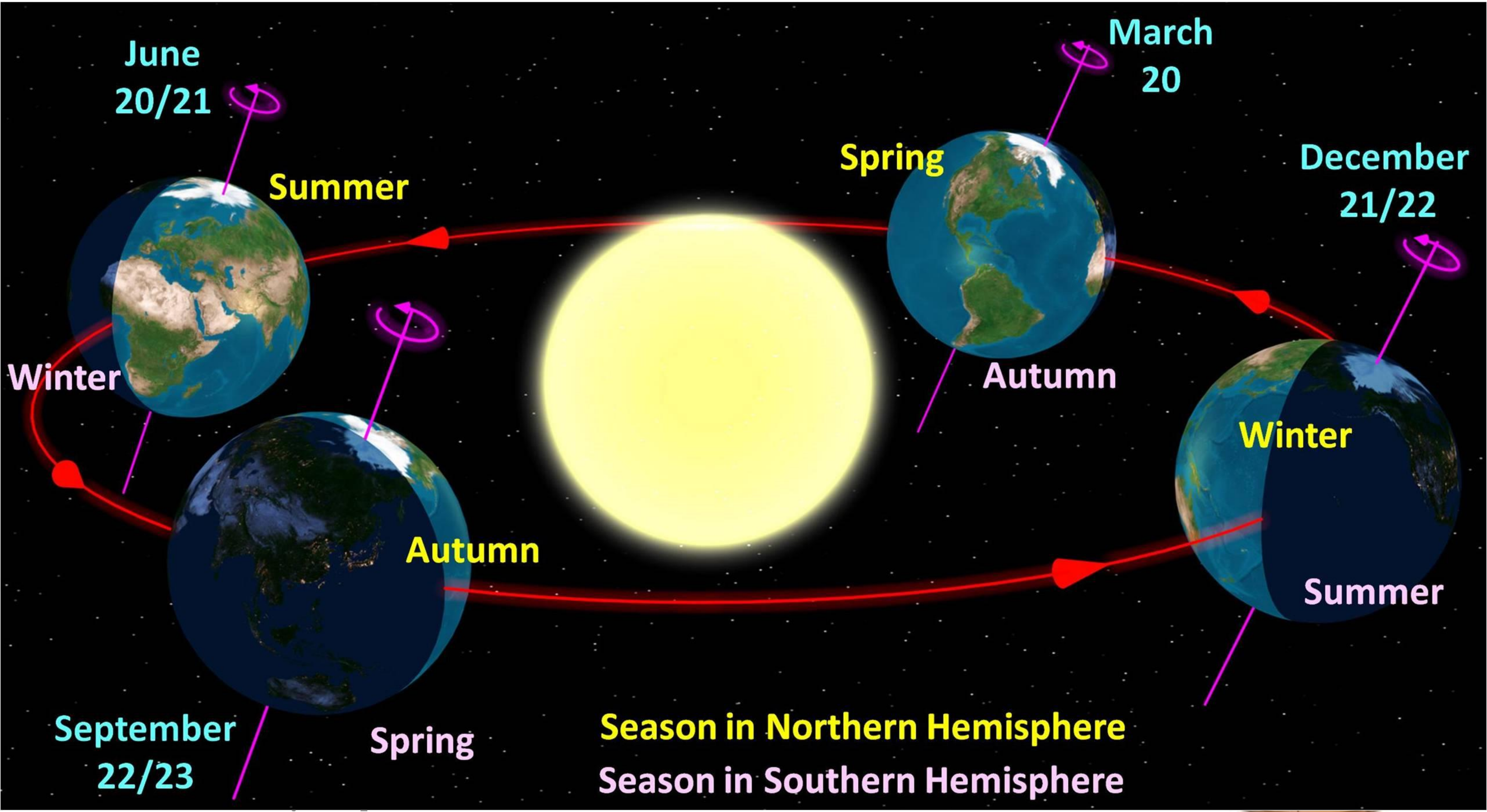
SOLAR ENERGY

General Aspects


June
20/21
Summer
Winter
March
20
Spring
Autumn
December
21/22
Winter
Summer
Autumn
September
22/23
Spring
Season in Northern Hemisphere
Season in Southern Hemisphere

Nature of the solar resource Earth is tilted 23.45°

On the winter solstice (December 21)

1. The north pole has its maximum angle of inclination away from the sun
2. Everywhere above 66.55°N (90 - 23.45) is in darkness for 24 hours,
3. Everywhere above 66.55°S is in sunlight for 24 hours
4. the sun passes directly overhead over the tropic of Capricorn (23.45°S)

On the equinox (March 22 & September 22)

1. Both poles are equidistant
2. the day is exactly 12 hours long
3. the sun passes directly overhead over the equator
4. The sun tracks a straight line across the sky

On the summer solstice (June 22)

1. The reverse of the winter solstice

1. The fusion reaction is as follows: $4({}_1H^1) \rightarrow {}_2He^4 + 26.3\ \text{MeV}$
2. This energy is produced in the interior of the solar sphere and transmitted out by the radiation into system.

   Net energy radiated, $E = \varepsilon\sigma T_s^4$

   where ε = Emissivity of surface, $\sigma = 5.670374419x10^{-8}\,\frac{W}{m^2 K^4}$, and T_s = Effective black body surface temperature of sun.

3. The earth's inner core is a solid mass made of iron and nickel and the next outer core is melted state of iron and nickel.
4. The outermost portion is made of rocks.
5. Half the earth is lit by the sunlight at a time. It reflects one-third of the sunlight that falls on it, is known as earth's albedo.
6. The amount of the suns energy that reaches the earth (before entering the atmosphere)
7. The average value of irradiance per year is called the solar constant (G_{sc}) and is equivalent to 1353, 1367 or 1373 W/m2 depending on who you believe
   1. 1353 (±1.5%) from Thekaekara (1976) – derived from measurements at very high atmosphere and used by NASA
   2. 1367 (±1%) Adopted by the World Radiation Centre
   3. 1373 (±1-2%) from Frohlich (1978) - derived from satellite data

Global irradiance is actually made up of two components.

(*i*) *"Direct beam radiation" from the sun* and

(*ii*) *"Diffuse radiation" from the sky* (radiation that has been *scattered* by the atmosphere).

- The amount of radiation received varies throughout the day as the *path of solar radiation* through the atmosphere *lengthens* and *shortens*. For the same reason, seasonal and *lattitudal variations* can cause the total solar energy received (known as **insolation or solar irradiation**) to range from an average of 2 MJ/m^2/day (or 0.55 kWh/m^2/day) in a northern winter to an average of 20 MJ/m^2/day (or 5.55 kWh/m^2/day) in the tropical regions of the world.

— The *diffuse energy* may amount to only 15–20 percent of global irradiance on a clear day and 100 percent on a *cloudy day*.

Solar radiation is the energy radiated by the sun.

1. The radiated energy received on earth surface is called Solar irradiation.
2. Solar radiation received on a flat horizontal surface on earth is called Solar insolation.

The solar radiation is of the following two types:

1. Extraterrestrial solar radiation
2. Terrestrial solar radiation

1. **Extraterrestrial solar radiation:**

The intensity of sun's radiation outside the earth's atmosphere is called "extraterrestrial" and has no diffuse components.

Extraterrestrial radiation is the measure of solar radiation that would be received in the absence of atmosphere.

2. **Terrestrial solar radiation:**

The radiation received on the earth surface is called "terrestrial radiation" and is nearly 70% of extraterrestrial radiation.

Terms used in solar radiations:

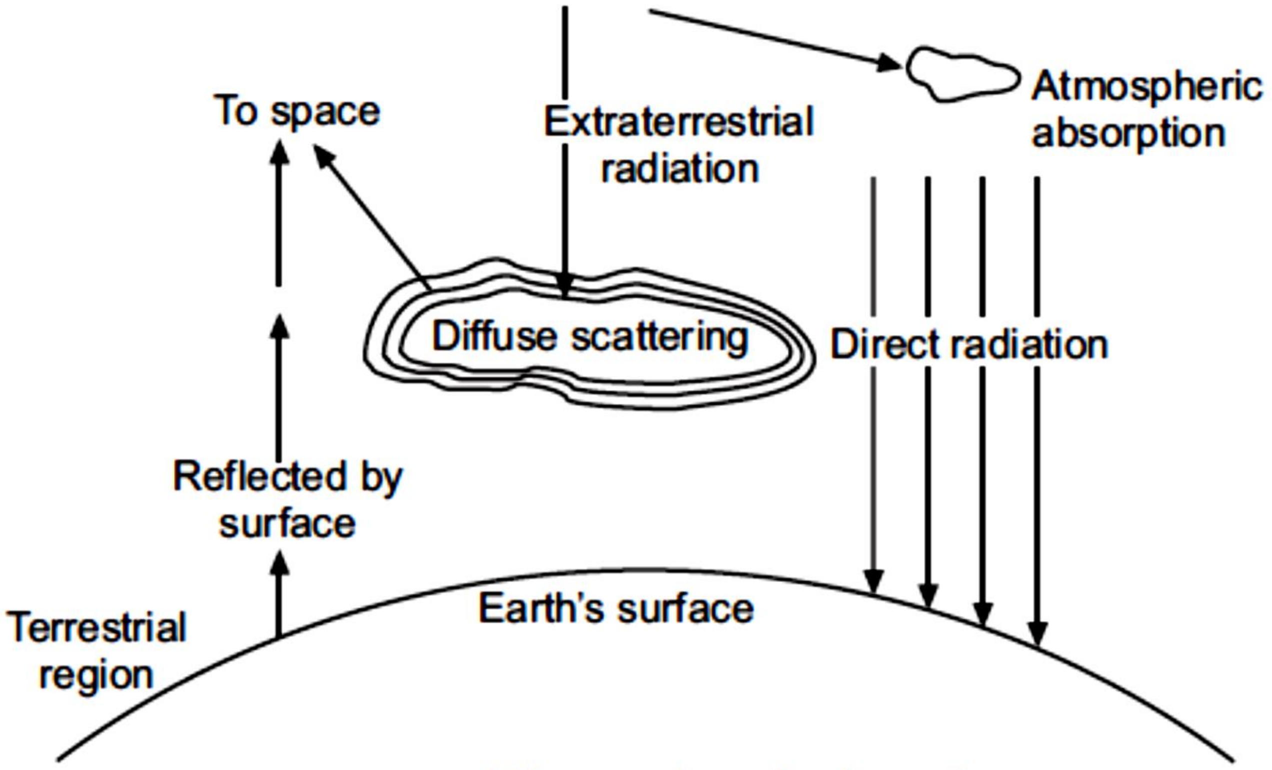


Fig. 2.2. Direct, diffuse and total solar radiations.

Beam (or direct) radiation (I_b): Solar radiation received on the surface of earth without change in directions is known as “beam or direct radiation”.

Diffuse radiation (I_d): The solar radiation received from the sun after its direction has been changed by reflection and scattering by atmosphere is known as “diffuse radiation”.

Total radiation (I_T): The sum of beam and diffuse radiations intercepted at the surface of earth per unit area of location is known as “total radiation”. It is also known as “Insolation”.

Mathematically: $$I_T = I_b + I_d$$

Airmass (ma): It is the path length of radiation through the atmosphere, considering the vertical path at level as unity.

1. $m_a = 1$, when sun is at zenith (i.e., directly above head).
2. $m_a = 2$, when zenith angle (θz) is 60°.
3. $m_a = \sec \theta z$, when $m_a > 3$
4. $m_a = 0$ just above the earth’s atmosphere

“Reasons for variation in solar radiations reaching the earth than received on the outside of the atmosphere”

1. As solar radiations pass through the earth's atmosphere the shortwave 'ultraviolet rays' are 'absorbed' by ozone in atmosphere and the long wave infrared waves' are 'absorbed' by carbon dioxide and moisture in the atmosphere.
2. A portion of radiations is 'scattered' by the components of atmosphere such as water vapor and dust.
3. A portion of this scattered radiation always reaches the earth's surface as 'diffuse radiation'.
4. Thus radiations finally received at the earth's surface consists partly of beam radiation and partly of diffuse radiation.

$$G_{on} = G_{sc}\left(1 + 0.033\cos\frac{360n}{365}\right)$$

Where:

G_{on} = Irradiance

G_{sc} = Solar constant

n = Day number (number of days since 1_{st} January)

Note: cosine is for degrees

The “solar constant” (I_{sc}) is the energy from the sun received on a unit area perpendicular to solar rays at the mean distance from the sun (1.5×10^8 km) outside the atmosphere.

Solar constant is characterized by the following:

(i) It is constant and not affected by daily, seasonal, atmospheric condition, clarity of atmosphere etc.

(ii) It is on a unit area on imaginary spherical surface around earth’s atmosphere for mean distance between the sun and the earth.

(iii) It is on surface normal to sun’s rays. Sun rays are practically parallel (beam radiation).

(iv) It has a measured value of “1353 W/m^2”.

$$\text{Isc in terms of kJ/m}^2\text{. hour} = \frac{1353 \times 3600}{1000} = 4870.8 \text{ kJ/m}^2 \text{ hour}$$

The value of solar constant remains constant throughout the year.

However, this value changes with location because earth-sun distance changes seasonally with time.

The extraterrestrial relation observed on different days is known as apparent extraterrestrial solar irradiance and can be calculated on any of the year using the following relation:

$$I_0 = I_{sc}\left[1 + 0.033\cos\left(\frac{360\,(n-2)}{365}\right)\right]$$

$$I_0 \simeq I_{sc}\left[1 + 0.033\cos\left(\frac{360\,n}{365}\right)\right]$$

where,

I_0 = Apparent extraterrestrial solar irradiance (W/m^2),

n = Number of days of the year counting January 1 as the first day of the year, and

I_{sc} = Solar constant = 1353 W/m^2.

(The standard value of the solar constant based on experimental measurements is 1367 W/m^2 with accuracy of ±1.5%).

According above Equation, the apparent solar irradiance will be maximum during December last or first weak of January as the earth's center is nearest to the sun during these days.

Clarity Index:

The ratio of radiation received on earth's horizontal surface over a given period to radiation on equal surface area beyond earth's atmosphere in direction perpendicular to the beam is called "Clarity index".

It depends upon the clarity of atmosphere for passage of solar beam radiation. Clarity index can be between 0.1 to 0.7.

Concentration ratio:

It is the ratio of solar power per unit area of the concentrator surface (kW/m^2) to power per unit area on the line focus or point focus (kW/m^2).

The various angles which are useful for conversion of beam radiation on the arbitrary surface are:

1. **Latitude angle (ϕ):**

The 'latitude of a place' is the angle subtended by the radial line joining the place to the centre of the earth, with the projection of the line on the equatorial plane.

The latitude is taken as positive for any location towards the 'northern hemisphere' and negative towards the 'southern hemisphere' i.e., the latitude(s) at equator is 0^0 while at north and south poles are + 90° and – 90° respectively.

2. **Declination angle (d):**

It is the angle made by the line joining the centres of the sun and the earth with its projection on the equatorial plane.

This angle varies from a maximum value of +23.5° on June 21 to minimum of –23.5° on December 21.

The declination (in degrees) for any day may be calculated from the approximate equation of "Cooper".

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

3. H**our angle (ω):**

It is angle through which the earth must be rotated to bring the meridian of the plane directly under the sun.

In other words, it is the angular displacement of the sun, east or west of the local meridian, due to rotation of the earth on its axis at an angle of 15° per hour.

It is measured from noon based on the local solar time (LST) or local apparent time (LAT), being positive in the morning and negative in the afternoon.

It is the angle measured in the earth's equilateral plane, between the projection OP and the projection of a line from the center of the sun to the center of the earth.

At solar noon w being zero and each hour angle equating 15° of longitude with "morning positive" and "afternoon negative" (e.g. w = + 15° for 11.00 and ω = – 37.5° for 14.30), hour angle can be expressed as : $\omega = 15\,(12 - LST)$

Altitude angle (α) or solar altitude:

It is a vertical angle between the projection of the sun rays on the horizontal plane and direction of the sunrays, passing through the point.

Zenith angle (θ_z): It is a vertical angle between sun's rays and a line perpendicular to the horizontal plane through the point.

Mathematically,

$$\theta_z = \frac{\pi}{2} - \alpha$$

Solar azimuth angle (γ_s):

It *is the polar angle (in degrees) along the horizontal east or west of north.*

Or

It is a horizontal angle measured from north to the horizontal projection of the sun's rays. This angle is *positive* when measured *west wise.*

The following expressions hold good for angles θ_z and γ_s in terms of *basic angles* ϕ, δ and ω:

$$\cos \theta_z = \cos \phi \cos \omega \cos \delta + \sin \phi \sin \delta$$

$$\cos \gamma_s = \sec \alpha (\cos \phi \sin \delta - \cos \delta \sin \phi \cos \omega)$$

and,

$$\sin \gamma_s = \sec \alpha \cos \delta \sin \omega$$

Surface azimuth angle (γ):

It is the angle of deviation of the normal to the surface from the local meridian, the zero point being south, east positive and west negative.

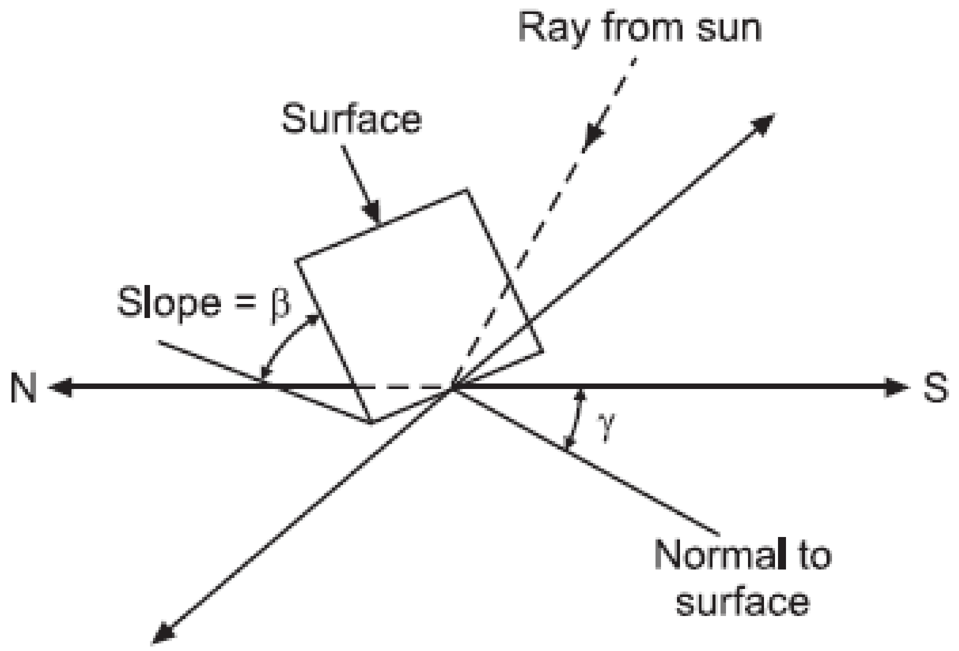
Slope or tilt angle (β):

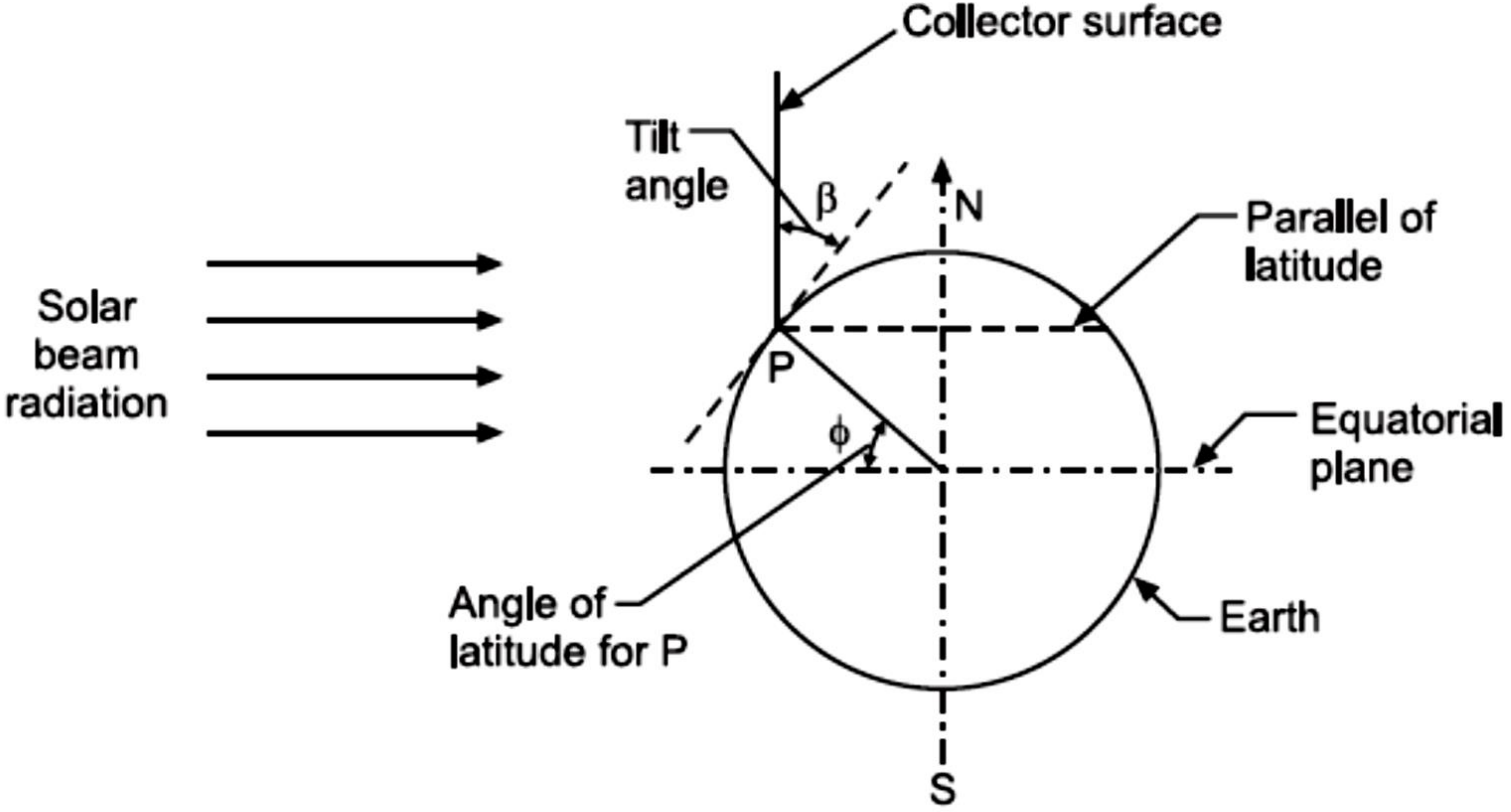
It is the angle made by the plane surface with the horizontal.

It is taken to be positive for surfaces sloping towards the south and negative for surfaces sloping towards north.

Incident angle (θ):

It is the angle being measured between beam of rays and normal to the plane.




Collector surface
Tilt angle
β
N
Parallel of latitude
Solar beam radiation
P
ϕ
Equatorial plane
Angle of latitude for P
Earth
S

Calculations of cos θ for any hour and any 'location':

The angle of incident θ is the *most significant parameter*. The power collected by the collector surface is *less* than the power available from the sun rays by *factor cos*θ as shown in Fig. 2.7. The angle of incident θ depends on the *position of sun* in the sky.

General equation for cos θ:

$$\begin{aligned}\cos\theta = {} & [\sin\phi\,(\sin\delta\cos\beta + \cos\delta\cos\gamma\cos\omega\sin\beta) \\ & + \cos\phi\,(\cos\delta\cos\omega\cos\beta - \sin\delta\cos\gamma\sin\beta) \\ & + \cos\delta\sin\gamma\sin\omega\sin\beta]\end{aligned} \qquad \text{...(2.8)}$$

where,

θ = Angle of incidence,

ϕ = Angle of latitude,

δ = Angle of declination,

γ = Angle of surface azimuth, and

β = Tilt angle (angle of slope).

1. For a **vertical surface; $\beta = 90°$:**

$$\therefore \quad \cos\theta = \sin\phi\cos\delta\cos\gamma\cos\omega - \cos\phi\sin\delta\cos\gamma + \cos\delta\sin\gamma\sin\omega \quad ...(2.9)$$

$(\because \sin 90° = 1 \text{ and } \cos 90° = 0)$

2. For a **Horizontal surface; $\beta = 0°$; $\theta = \theta_z$** (*zenith angle*) :

$$\therefore \quad \cos\theta\ (= \cos\theta_z) = \sin\phi\sin\delta + \cos\phi\cos\delta\cos\omega. \quad ...(2.10)$$

$(\because \cos 0° = 1, \sin 0° = 0)$

Also,

$$\cos\theta = \cos\theta_z = \sin\alpha \left(\because \theta_z = \frac{\pi}{2} - \alpha\right) \quad ...(2.10(a))$$

3. **Surface facing south, $\gamma = 0$:**

$$\cos\theta = \sin\phi\,(\sin\delta\cos\beta + \cos\delta\cos\omega\sin\omega) + \cos\phi\,(\cos\delta\cos\omega\cos\beta - \sin\delta\sin\beta)$$

$$\therefore \quad \cos\theta = \sin\delta\sin(\phi - \beta) + \cos\delta\cos\omega\cos(\phi - \beta) \quad ...(2.11)$$

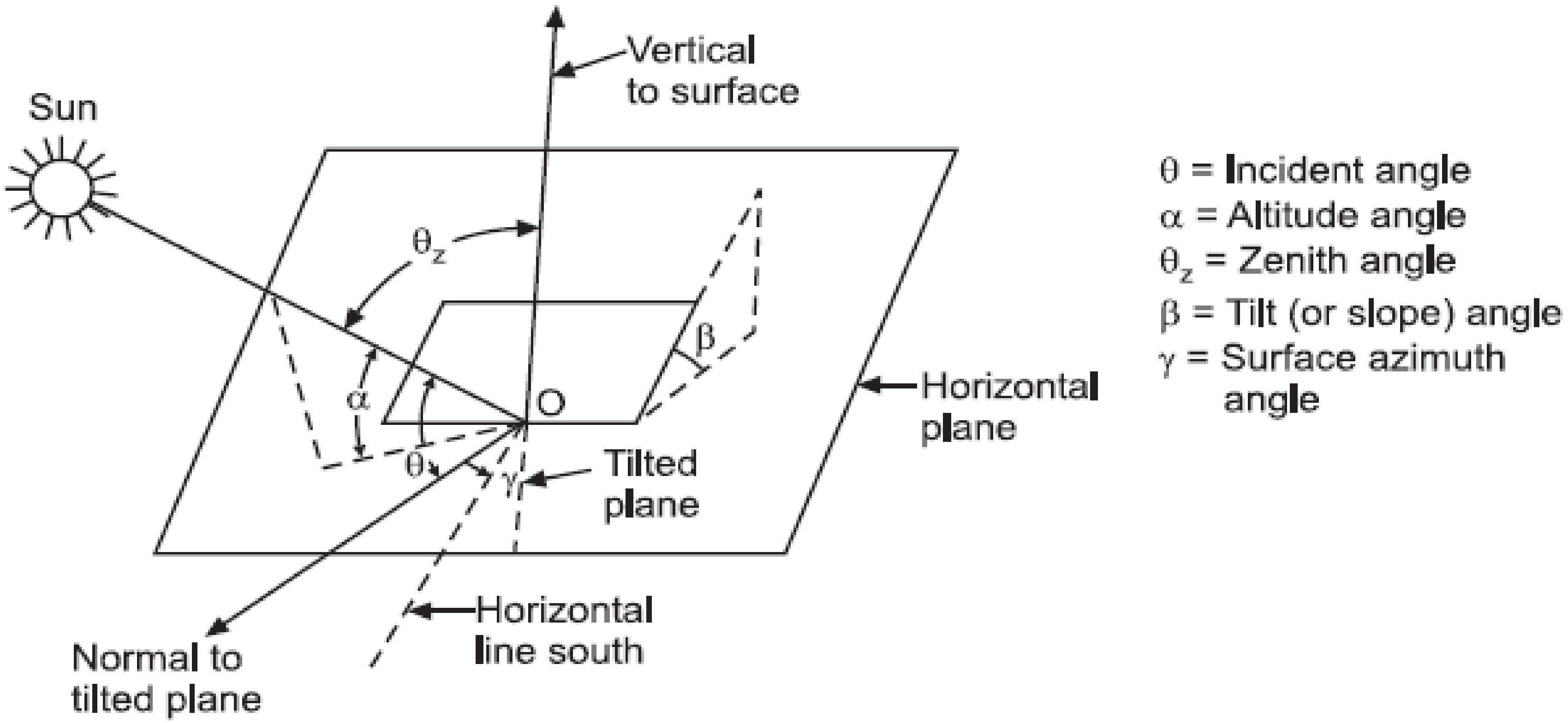
4. Vertical surface facing south, $\beta = 90°$, $\gamma = 0$:

$$\cos\theta = \sin\phi\cos\delta\cos\omega - \cos\phi\sin\delta$$

The *angle of incidence* θ *can also be expressed in terms of* θ_z *(zenith angle) as:*

$$\cos\theta = \cos\theta_z\cos\beta + \sin\theta_z\sin\beta\cos(\gamma_s - \gamma)$$

$$\cos\gamma_s = \frac{(\cos\theta_z\sin\phi - \sin\delta)}{\sin\theta_z - \cos\phi}$$



Solar Day-Length, Sunrise and Sunset:

We make the following observations:

1. During ‘winter’ the sun rises late and sets early, the day length is shorter.
2. During ‘summer’ sun rises early, sets late and day length is longer.
3. With the increase of the angle of latitude (from equator to north pole) the difference in day length between summer and winter becomes more and more prominent.

The ‘sunrise hour’ ‘sunset hour’ and ‘day-length’ depend upon latitude of the location and season and day in the year.

The expressions are derived as follows:

For a horizontal surface on the ground Eqn. (Earlier slide) is written as

$$\cos\theta = \sin\phi \sin\delta + \cos\phi \cos\delta \cos\omega_s$$

(For sunrise and sun set the hour angle is designated as ω_s,

The hour angle ω varies during the day.

At sunrise, as the sun light is parallel to the ground surface, therefore, angle of incidence $\theta = 90°$, $\cos\theta = 0$

Inserting this value in

$$\cos\theta = \cos\theta_z \cos\beta + \sin\theta_z \sin\beta \cos(\gamma_s - \gamma)$$

$$\cos 90° = \sin\phi \sin\delta + \cos\phi \cos\delta \cos\omega_s$$

or, $$\sin\phi \sin\delta = -\cos\phi \cos\delta \cos\omega_s$$

or, $$\cos\omega_s = -\frac{\sin\phi \sin\delta}{\cos\phi \cos\delta}$$

$$= -\tan\phi \tan\delta$$

i.e., $$\omega_s = \cos^{-1}(-\tan\phi \tan\delta)$$

Day-length (t_{day}) in hours:

$$\text{Total day-length} = \omega_s + \omega_s$$
$$= 2\,\omega_s$$
$$= 2\cos^{-1}(-\tan\phi\tan\delta)$$

Since 15° of the hour angle is equivalent to 1 hour, hence $2\cos^{-1}(-\tan\phi\tan\delta)°$ corresponds to $\left[\dfrac{2\cos^{-1}(-\tan\phi\tan\delta)}{15}\right]$ hours.

$$\therefore \textit{Day-length (in hours)},\ t_{day} = \frac{2}{15}\left[\cos^{-1}(-\tan\phi\tan\delta)\right] \text{ hours}$$

Thus, the length of the day (t_{day}) is a *function of latitude and solar declination.*

The angle hour at sunrise or sunset on an '*inclined surface*' (ω_{si}) will be *lesser* than the value obtained by Eqn. $\cos\theta = \sin\phi\sin\delta + \cos\phi\cos\delta\cos\omega_s$, if the corresponding angle of incidence (q) comes out to be more than 90°. Thus for an *inclined surface facing south*, substituting θ = 90° in Eqn. $\cos\theta = \sin\delta\sin(\phi-\beta) + \cos\delta\cos\omega\cos(\phi-\beta)$ we get:

$$\omega_{si} = \cos^{-1}[-\tan(\phi-\beta)\tan\delta]$$

The corresponding day-length (in hours) is then given as:

$$t_{day} = \frac{2}{15}\cos^{-1}[-\tan(\phi-\beta)\tan\delta]$$

1. Determine the sunset hour angle and day-length at a location latitude of 32° on March 30.
2. Determine the day-length in hours at Delhi (latitude = 28.6°) on June 28 in a leap year.
3. Calculate Local Apparent Time (LAT) and declination at a location latitude 24° 20’ N, longitude 77°30’E at 12.30 IST on July 24. Equation of time correction = – (1’ 06”).