PEME5308

NON-CONVENTIONAL ENERGY SOURCES

Module:1 Section:3

(Solar Energy)

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Solar Radiation

- Intensity of solar radiation incident on a surface is important in the design of solar collectors, photovoltaic cells, solar heating and cooling systems, and thermal management of building.
- This effect depends on both the location of the sun in the sky and ***the clearness of the atmosphere*** as well as on the **nature and orientation of the building**.
- We need to know

  - *Characteristics of sun's energy* outside the earth's atmosphere, its intensity and its spectral distribution

  - *Variation with sun's location in the sky* during the day and with seasons for various locations on the earth's surface.

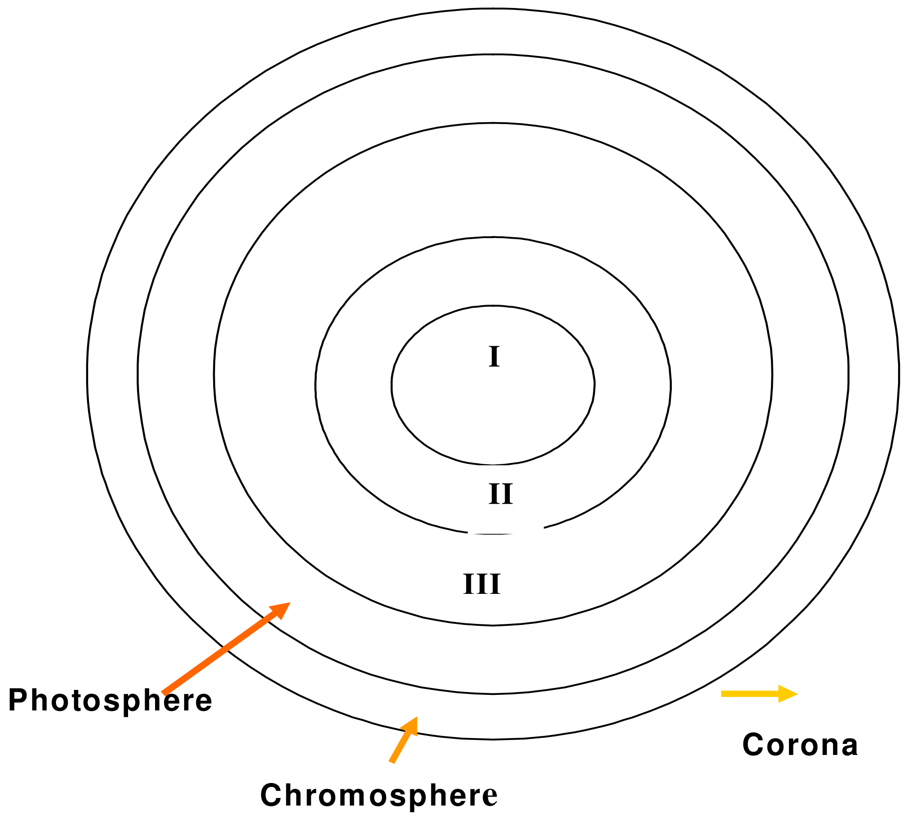
Solar Radiation

The sun's structure and characteristics determine the nature of the energy it radiates into space.

Energy is released due to continuous fusion reaction with interior at a temperature of the order of million degrees.

Radiation is based on sun's outer surface temperature of 5777 K.

Solar Geometry



Solar Geometry

The Sun: Major Characteristics

- A sphere of hot gaseous matter
- Diameter, $D_s = 1.39\times10^6$ km (Earth diameter, $D_E = 1.27\times10^4$ km)
- Rotates about its axes (not as a rigid body)
- Takes 27 earth days at its equator and 30 days at polar regions.
- The sun has an *effective black body temperature of 5777 K*

  i.e. It is the temperature of a blackbody radiating the same amount of energy as does the sun.

- **Mean earth-sun distance: L** = 1.496×10^8 km

The Structure of Sun

Central Region: (Region – I)

Energy is generated due to fusion Reaction of gases – transforms hydrogen into helium.

- 90% of energy is generated within the core range of 0 – 0.23 R
- The temperature in the central region is in million degrees.
- The temperature drops to 130,000 K with in a range of 0.7R

Convection Region (Region – III)

- 0.7R to R where convection process involves
- The temperature drops to 5,000 K

Photosphere:

Upper layer of the convective zone

- Composed of strongly ionized gas
- Essentially opaque
- Able to absorb and emit continuous spectrum of radiation
- Source of the most solar radiation

Chromosphere (10,000km)

Further outer gaseous layer with temperature somewhat higher tan the Photosphere.

Corona

Still further outer layer

- extremity of sun.
- Consists of Rarified gases.
- Temperature as high as 1000,000 K

Thermal Radiation

Thermal radiation is the intermediate portion (0.1 ~ 100μm) of the electromagnetic radiation emitted by a substance as a result of its temperature.

Thermal radiation heat transfer involves transmission and exchange of electromagnetic waves or photon particles as a result of temperature difference.

Planck's Spectral Distribution of Black Body Emissive Power

The thermal radiation emitted by a black substance covers a range of wavelength (λ), referred as spectral distribution and given as

$$E_{\lambda,b} = \frac{C_1}{\lambda^5\left[e^{(C_2/\lambda T)} - 1\right]}$$

$$C_1 = 2\pi\pi h_0^2 = 3.742\times10^8\,W.\mu m^4/m^2$$

$$C_2 = hc_0/k = 1.439\times10^4\,\mu m.K$$

$$h = \text{Planck's constant} = 6.626\times10^{-24}\,J.s$$

$$k = \text{Boltzmann constant} = 1.381\times10^{-23}\,J/K$$

Black Body Emissive Power

The total black body emissive power is obtained by integrating the spectral emissive power over the entire range of wavelengths and derived as

$$\mathbf{E_b} = \int_0^{\infty} \mathbf{E_{\lambda,b}} = \frac{\mathbf{C_1}}{\lambda^5 \left[e^{(C_2/\lambda T)} - 1 \right]} d\lambda \qquad E_b = \sigma T^4$$

Where σ = Stefan-Boltzman constant

= $5.6697 \times 10^{-8} W/m^2.K^4$

Extraterrestrial Radiation

Solar radiation that would be received in the absence of earth atmosphere.

Extraterrestrial solar radiation exhibit a spectral distribution over a ranger of wavelength: 0.1- 2.5 μm

- Includes ultraviolet, visible and infrared

Solar Constant I_{sc}

Solar Constant = Solar radiation intensity upon a surface normal to sun ray and at outer atmosphere (when the earth is at its mean distance from the sun).

$$I_{SC} = 1367 W/m^2$$

Variation of Extraterrestrial Radiation

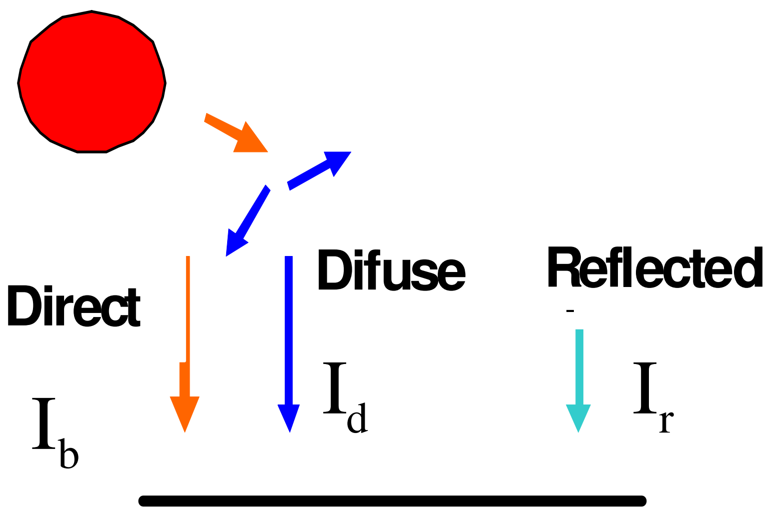
Solar radiation varies with the day of the year as the sun-earth distance varies.

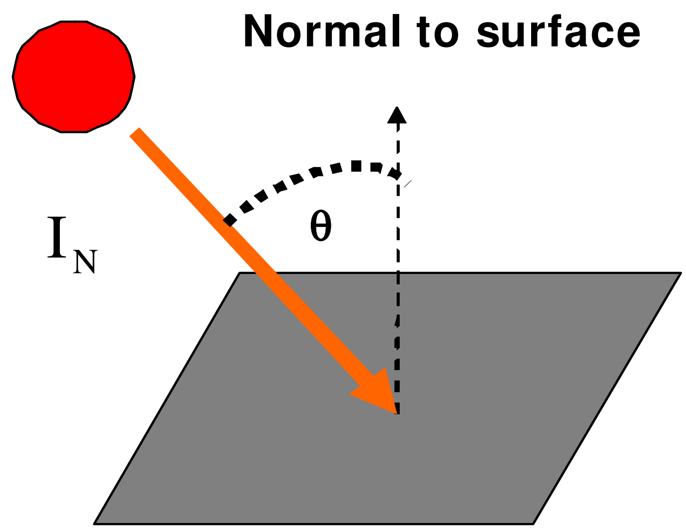
An empirical fit of the measured radiation data

$$I'_{sc} = I_{sc}\left(1 + 0.033\ \cos\ \frac{360n}{365}\right)$$ n = day of the year

Since cosine function varies from +1 to -1,
the extra terestrial radiation flux varies by ±3.3%

Solar Radiation on Earth's Surface





Total or global radiation on a surface

$$I_g = I_b + I_d + I_r$$

$$I_\theta = I_N \cos\theta$$

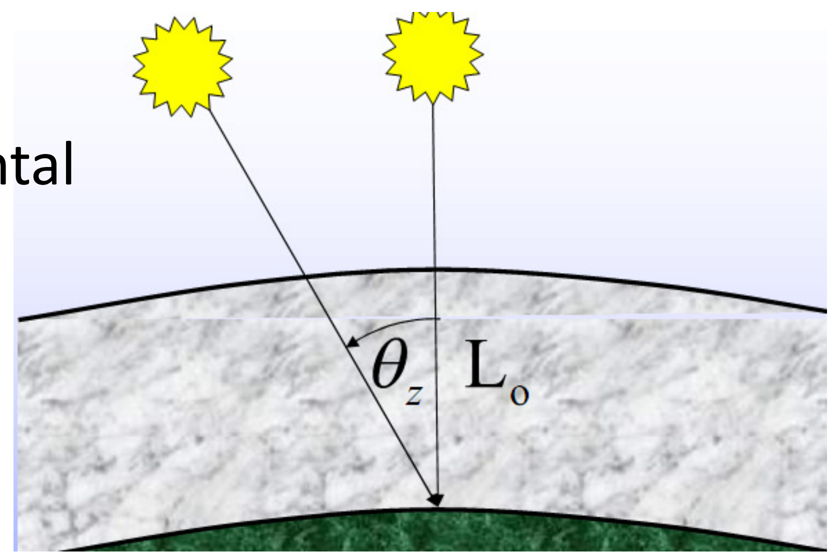
Orientation of a surface on earth with respect sun or normal to sun's ray can be determined in terms basic Earth-Sun angles.

Air mass

Used as a measure of the distance travelled by beam radiation through atmosphere before it reaches a location on the earth's surface

Defined as the ratio of the mass of the atmospheric through which beam Radiation passes to the mass it would pass through if the sun is directly overhead (i.e. at zenith)

Zenith angle is the angle made by Sun's rays with the normal to a horizontal surafce



$$\text{Air mass, AM} = \frac{L_0 / \cos\theta_z}{L_0} = \frac{1}{\cos\theta_z} = \sec\theta_z$$

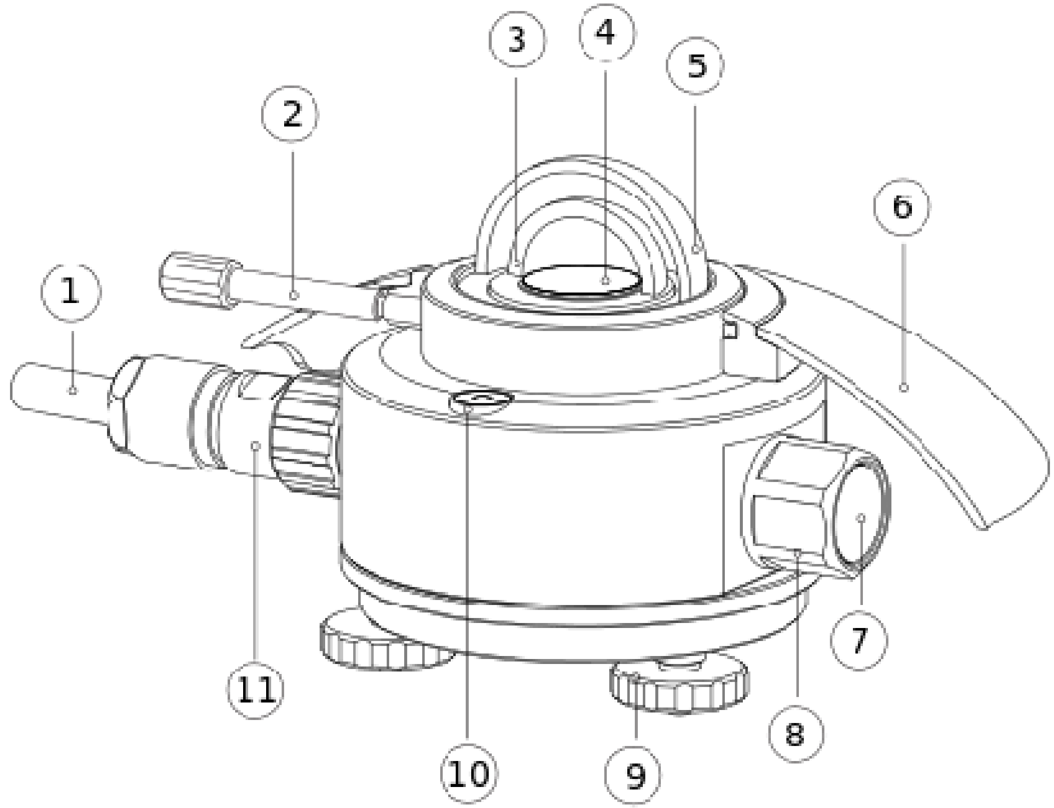
AM0 corresponds to extraterrestrial radiation

AM1

Measurement of solar radiation

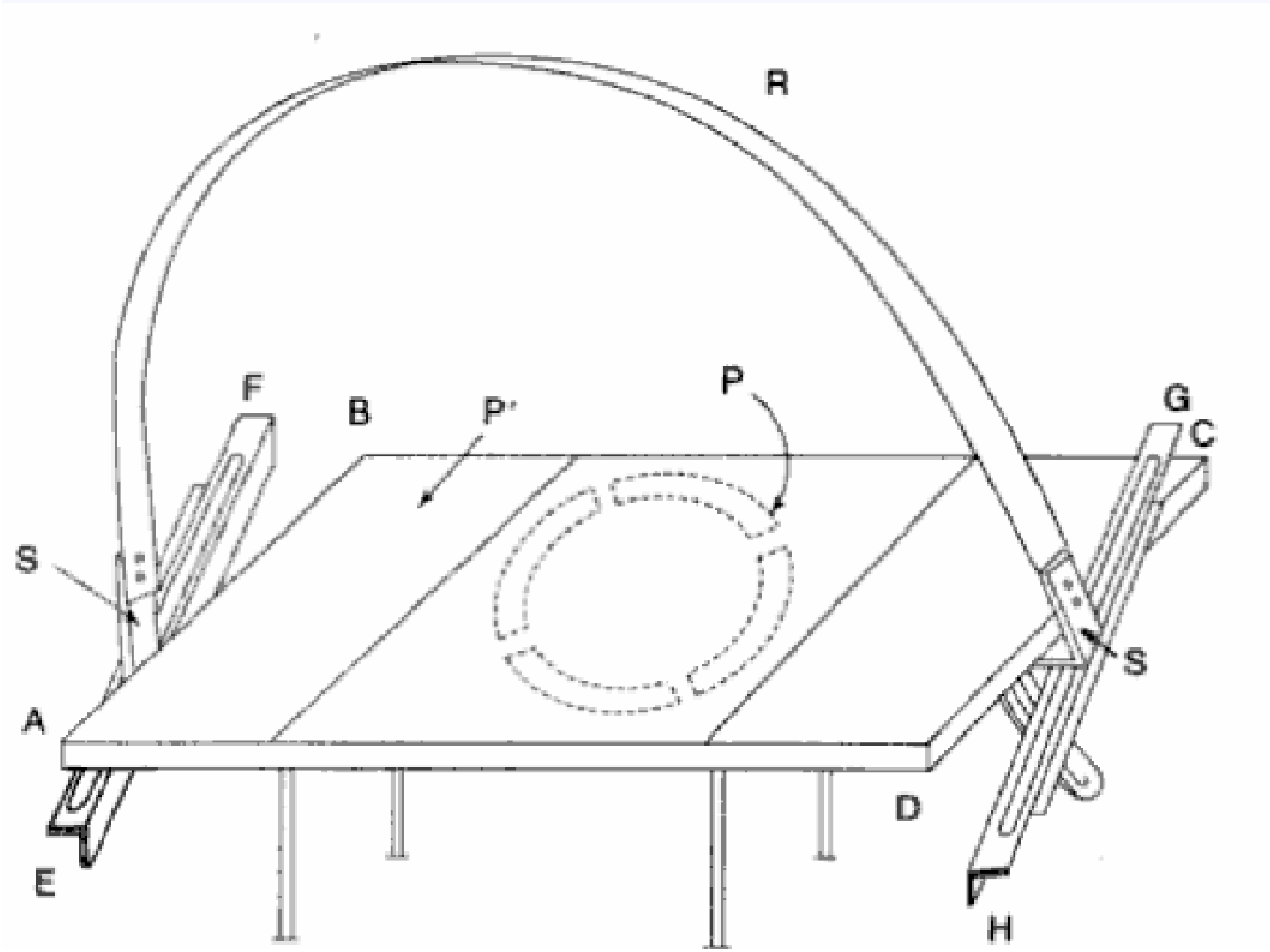
Pyranometer

Measurement of solar radiation



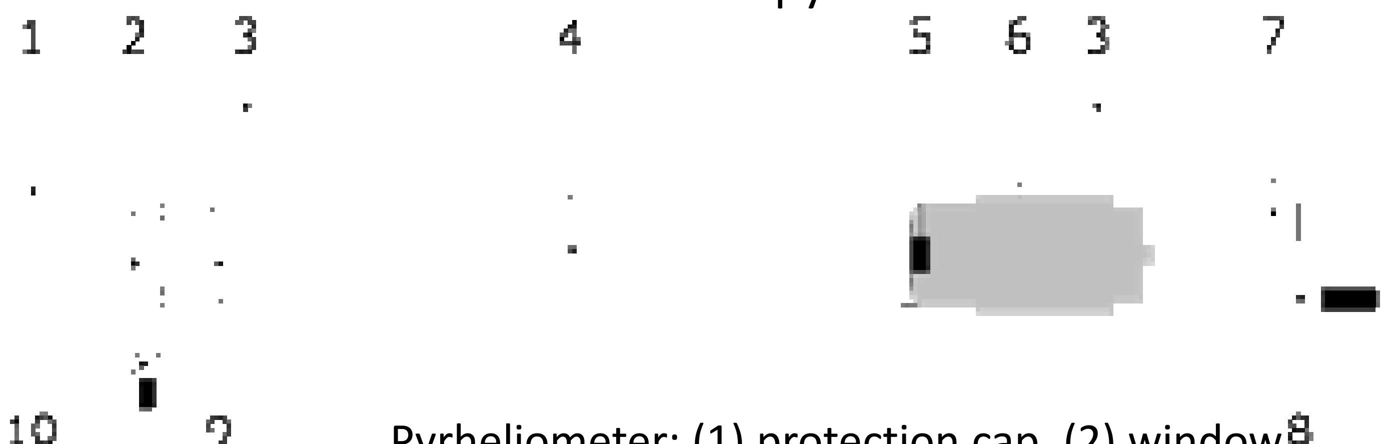
(1) cable, (3) glass inner dome, (4) thermopile sensor, (5) glass outer dome, (7) humidity indicator with desiccant, (11) connector.

Measurement of solar radiation



Pyranometer shade ring

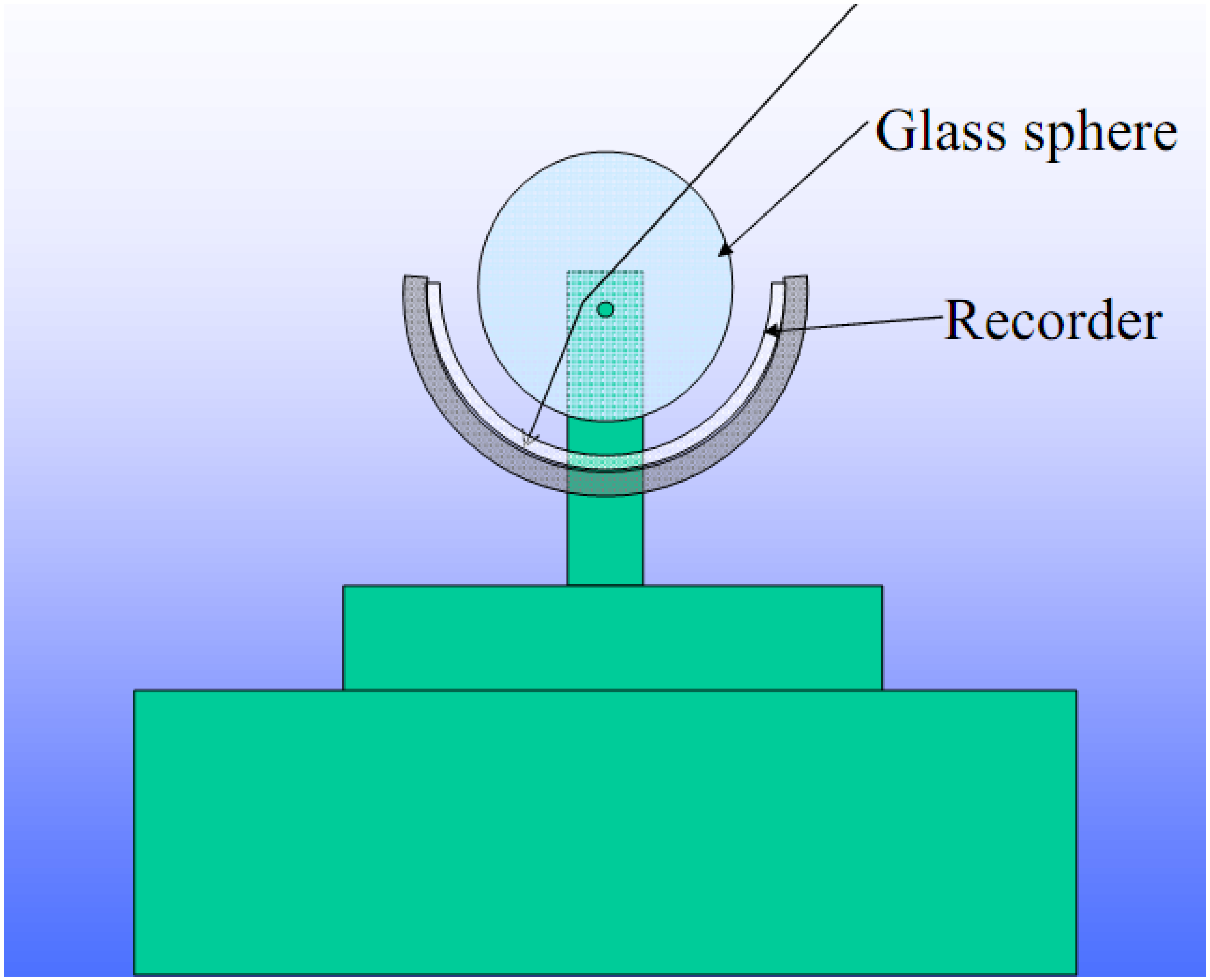
A **pyrheliometer** is an instrument for measurement of direct beam solar irradiance.
Sunlight enters the instrument through a window and is directed onto a thermopile which converts heat to an electrical signal that can be recorded. The signal voltage is converted via a formula to measure watts per square metre.It is used with a solar tracking system to keep the instrument aimed at the sun. A pyrheliometer is often used in the same setup with a pyranometer.



Pyrheliometer: (1) protection cap, (2) window with heater, (3) sight, (5) sensor, (7) humidity indicator, (10) cable for heater

Measurement of solar radiation

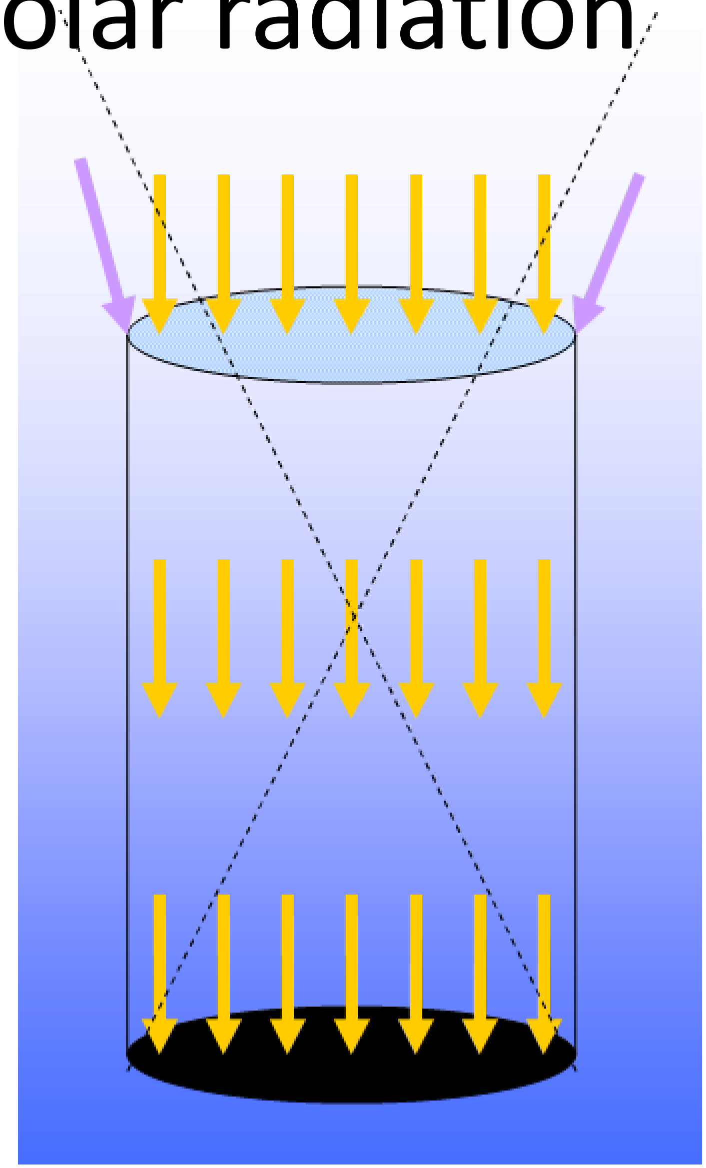
Sun shine recorder



Measurement of solar radiation

Pyrheliometer

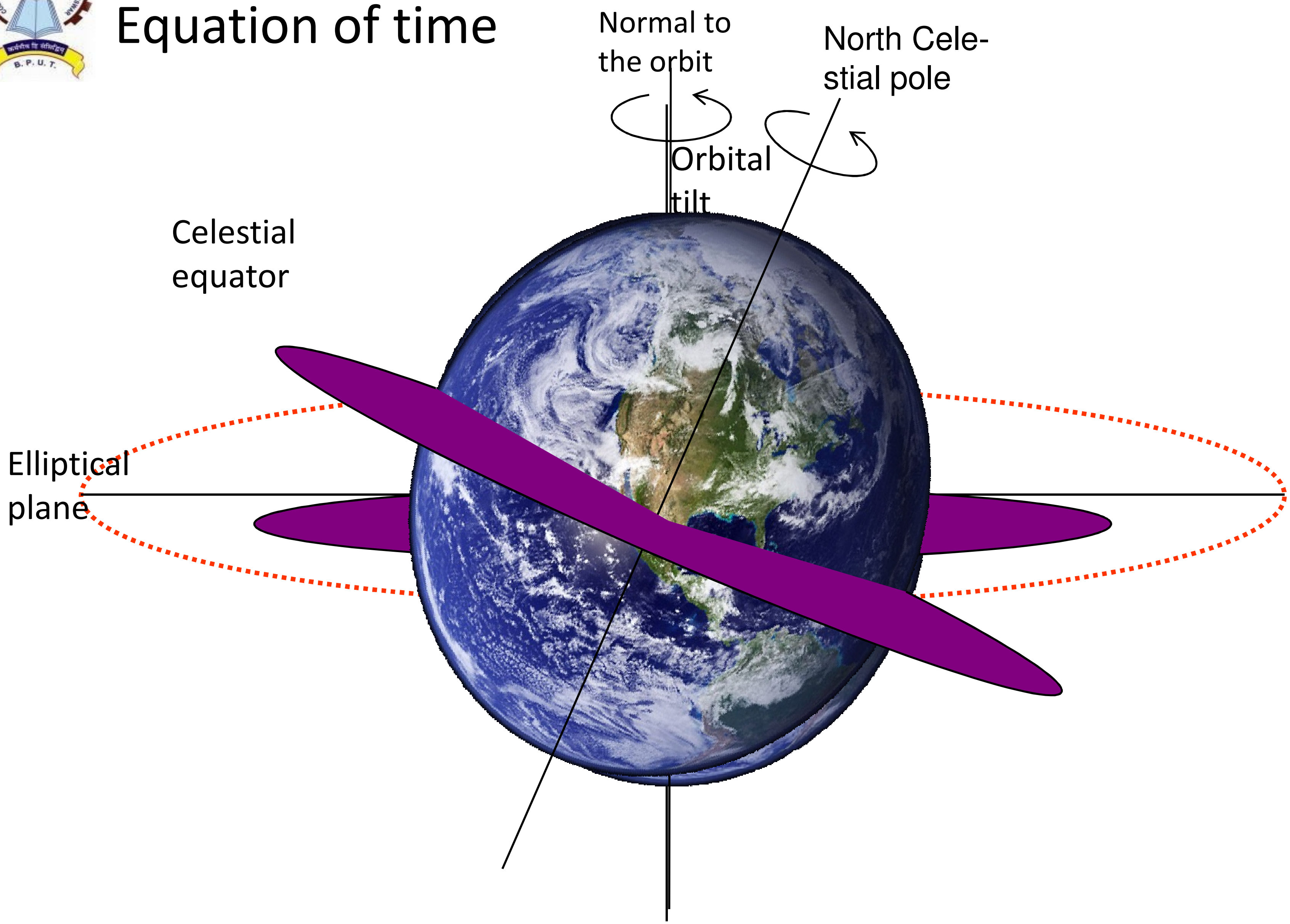
It measures only beam or direct radiation with a small aperture



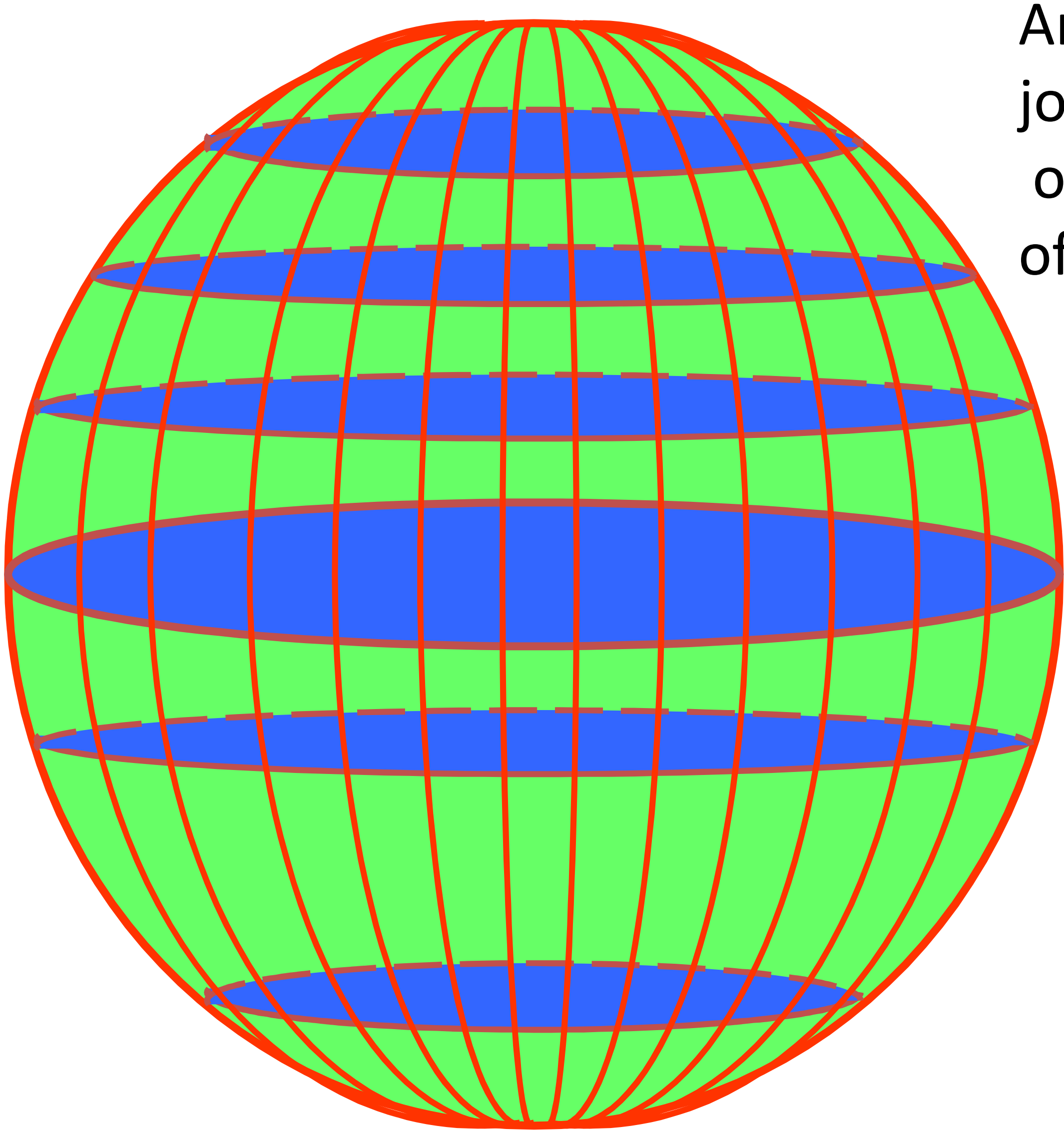
Basic Definitions

1. Radiation = Propagation of electromagnetic energy through free space.
2. Irradiance = Flow (Flux) Intensity of radiant energy (Units W m^{-2})
3. Insolation = Solar irradiance striking Earth.
4. Declination = Latitude at which the Sun strikes overhead
5. Terrestrial Radiation = Infrared radiation emitted by the Earth.
6. Albedo = Fraction of radiation that is reflected by an object
7. Zenith Angle = Angle (of Sun, etc.) from top of sky.
8. Equinoxes = Days when day = night = 12 hours over all Earth.
9. Solstices = Days of extreme declination $\approx$ Dec21 and June 21.
10. Aphelion = Day when Earth is furthest from Sun $\approx$ July 4.
11. Perihelion = Day when Earth is closest to Sun $\approx$ Jan 3.

Equation of time

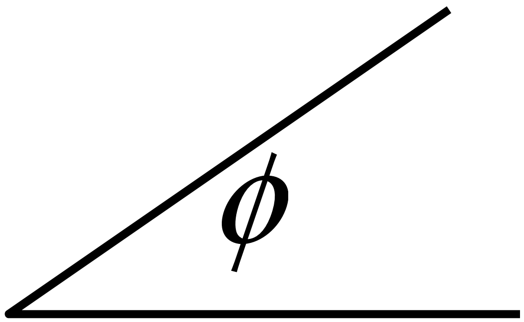


Geographical coordinates



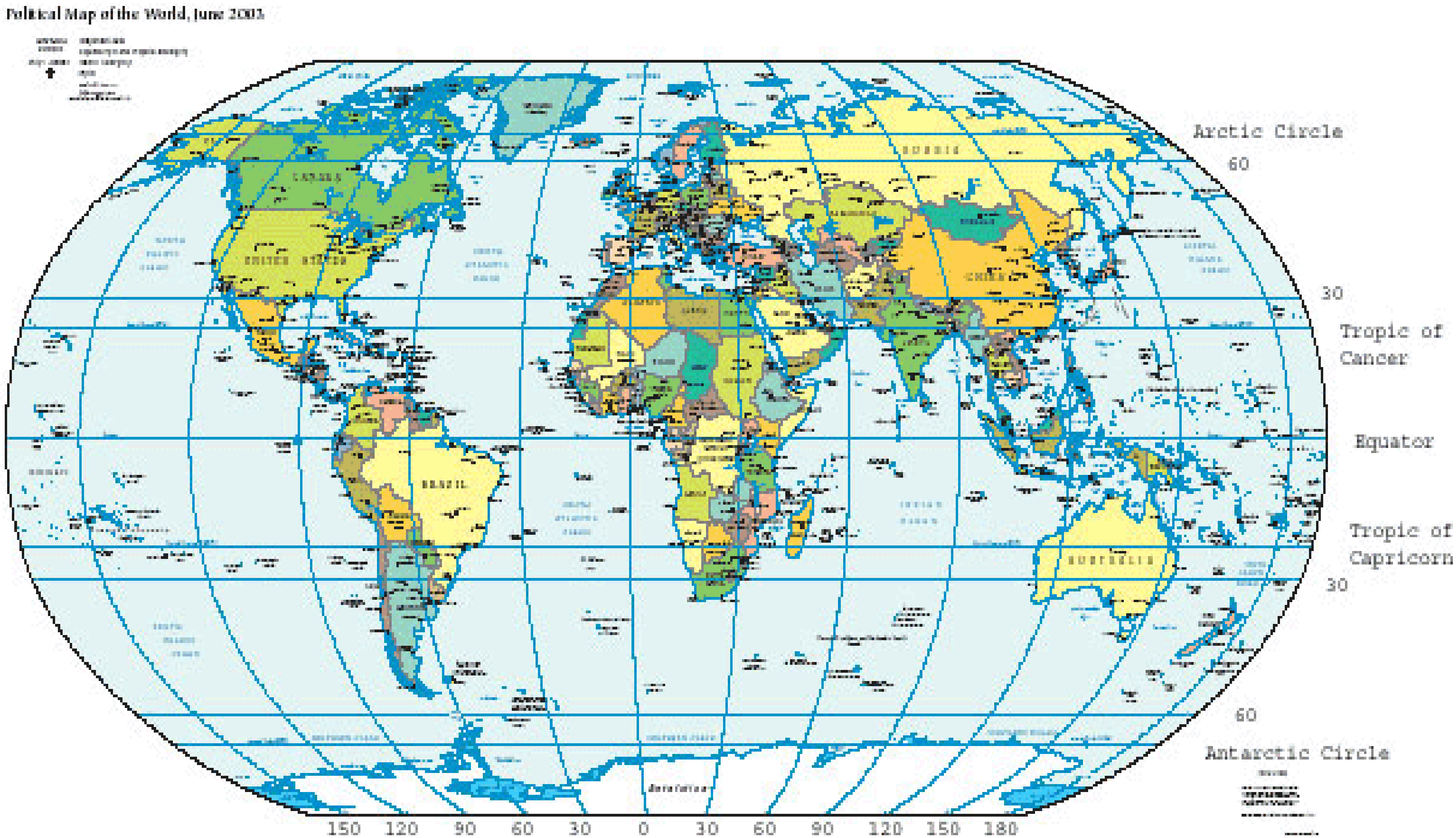
Angle made by the radial line joining the location to the centre of the earth with Projection of the line on the equilateral plane

vary from -90° (south) to +90° (north)

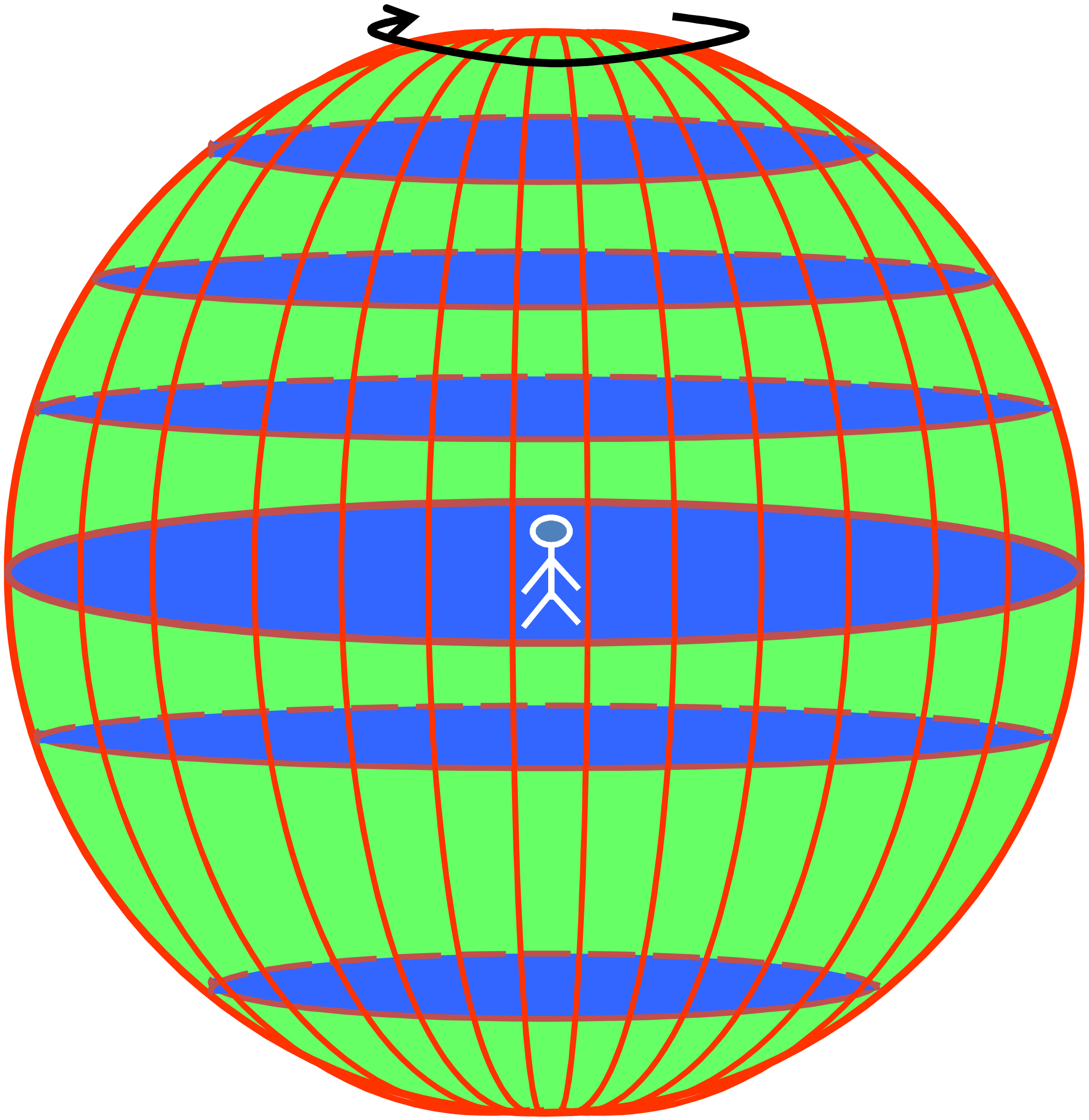


$\phi : Latitude$

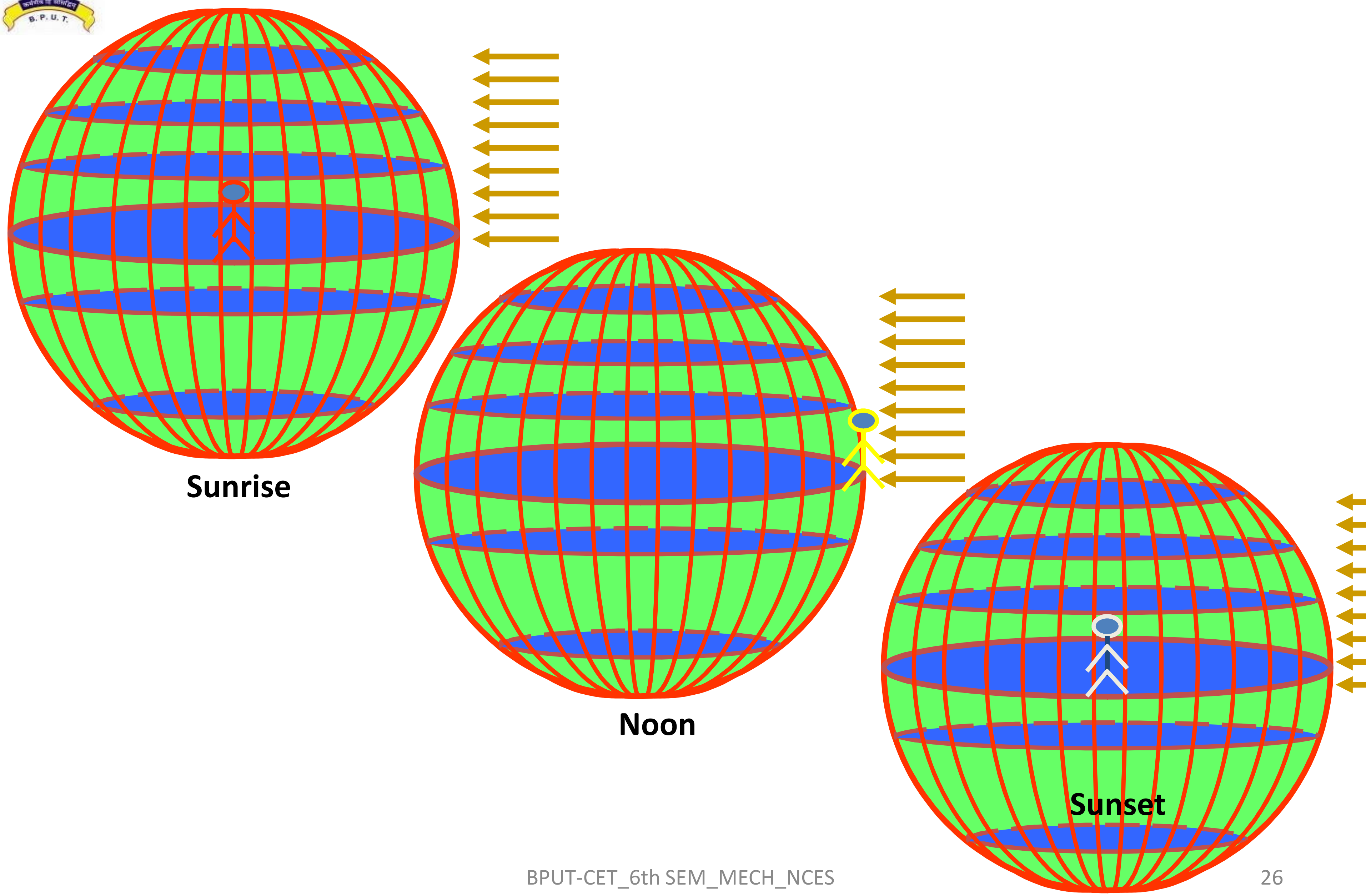
Geographical coordinates



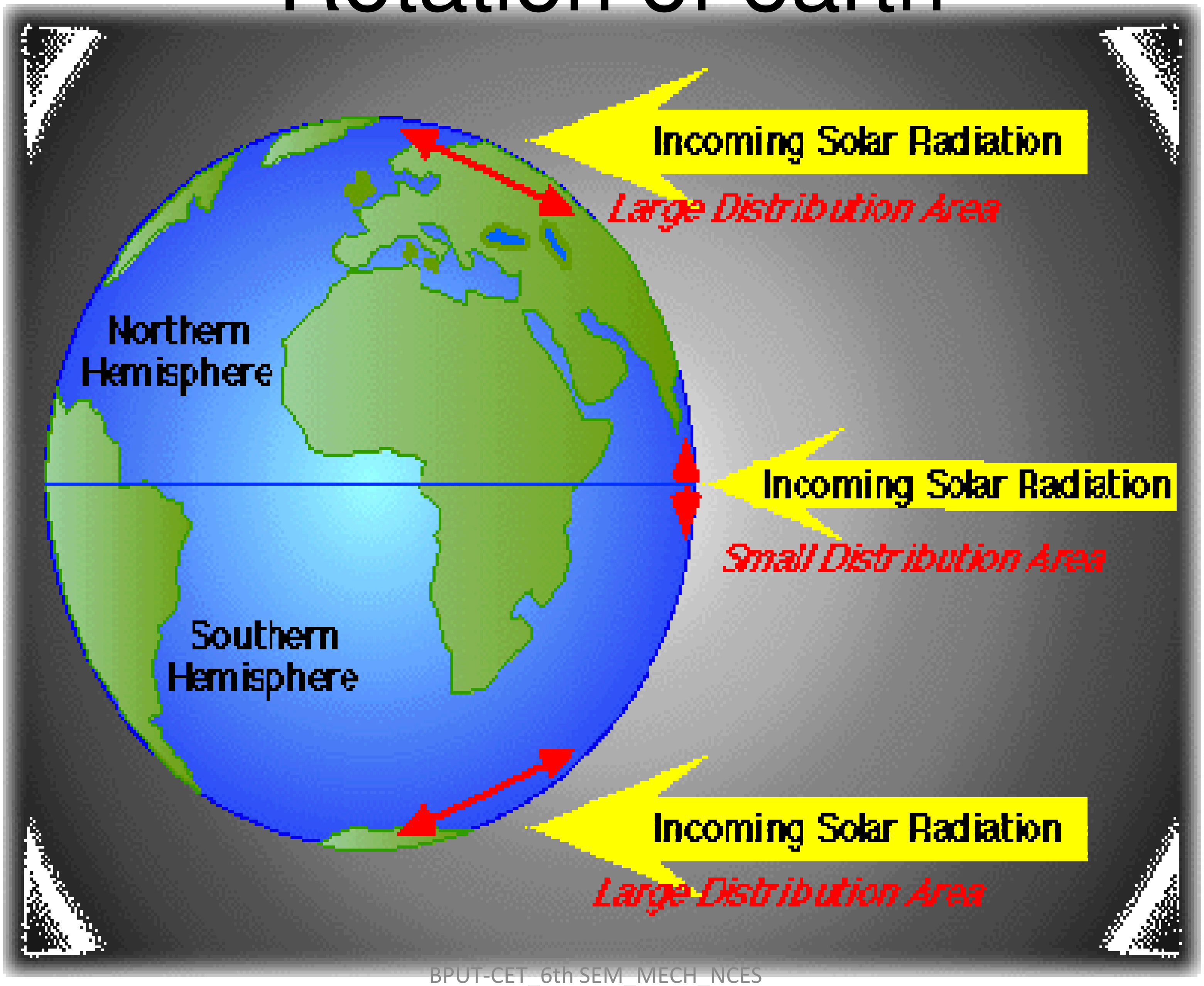
Rotation of earth



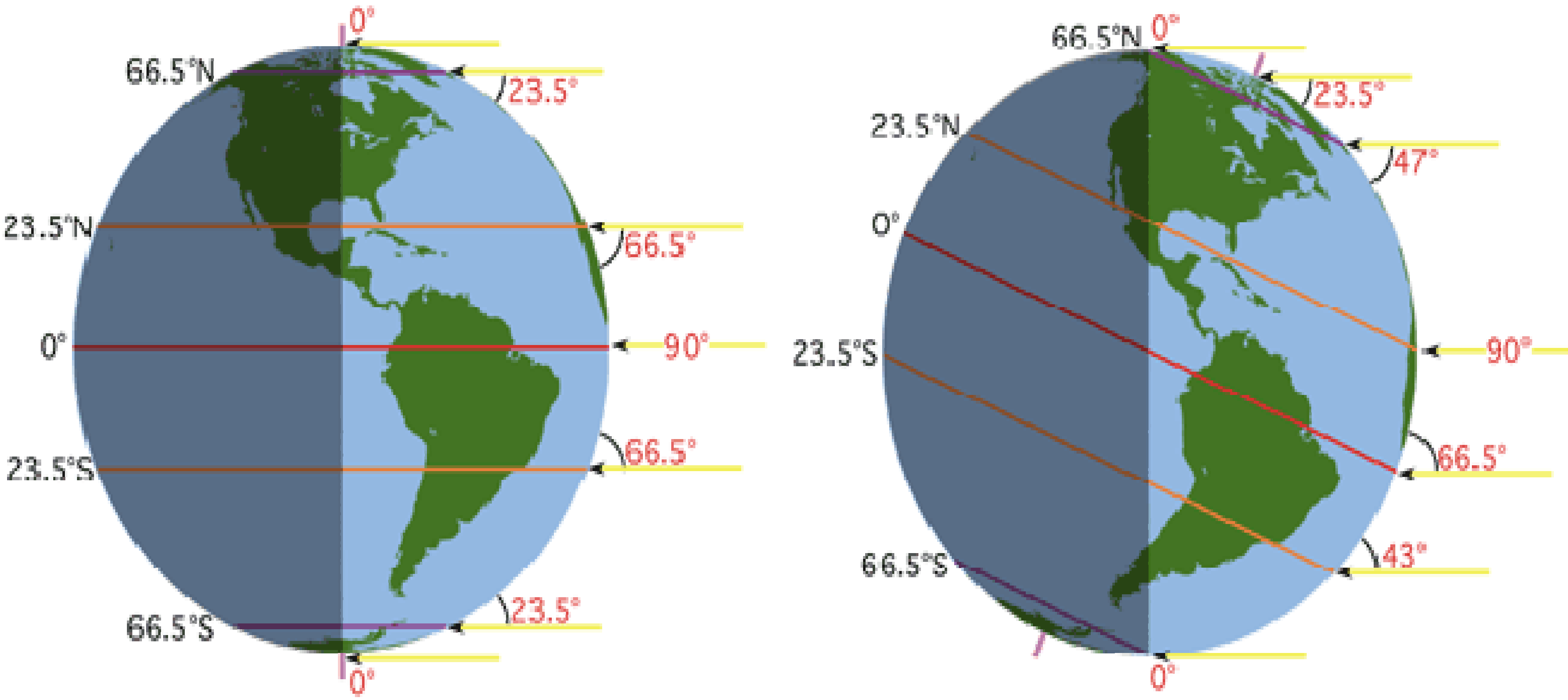
Rotation of earth



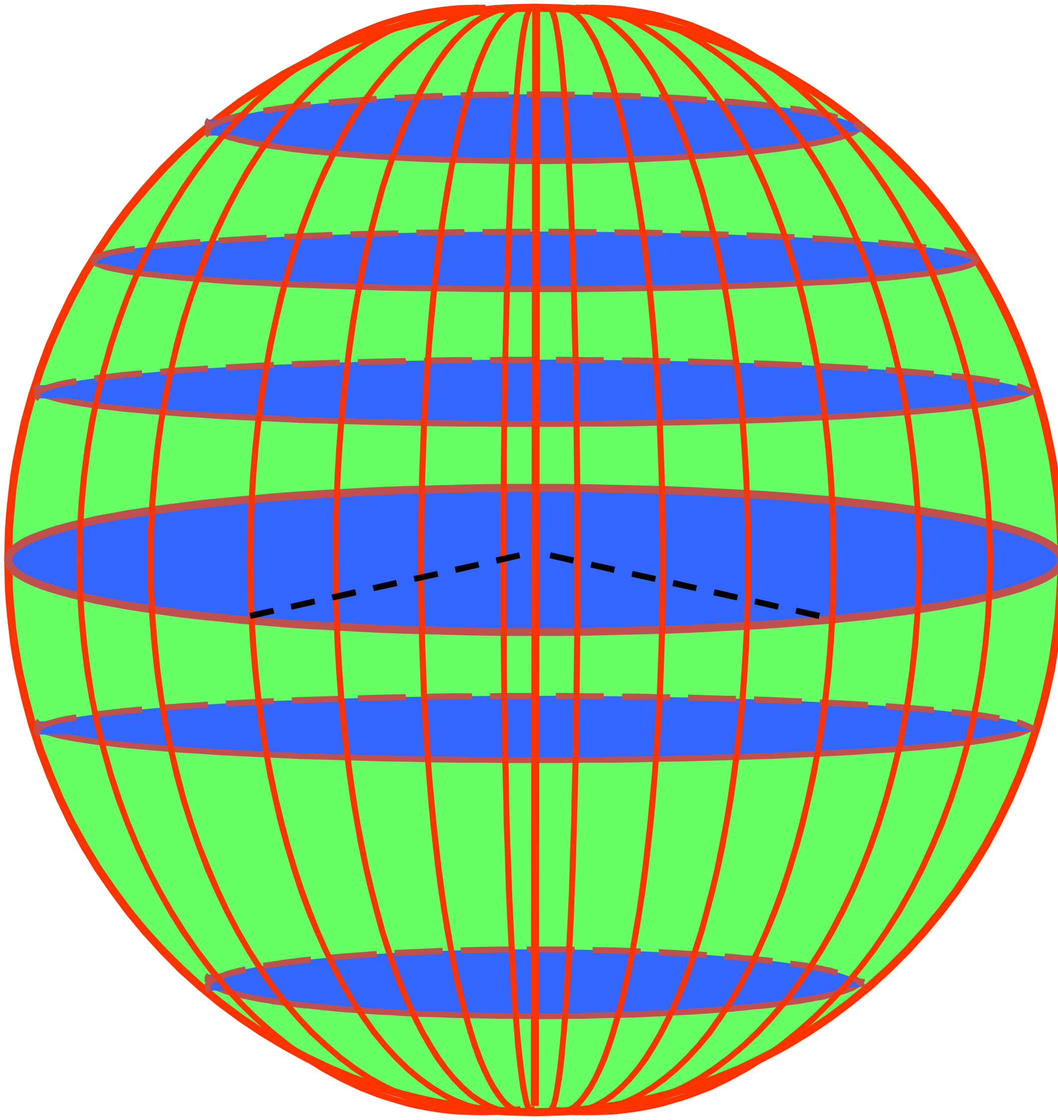
Rotation of earth



Latitude angle



Geographical coordinates



ψ

-ve **+ve**

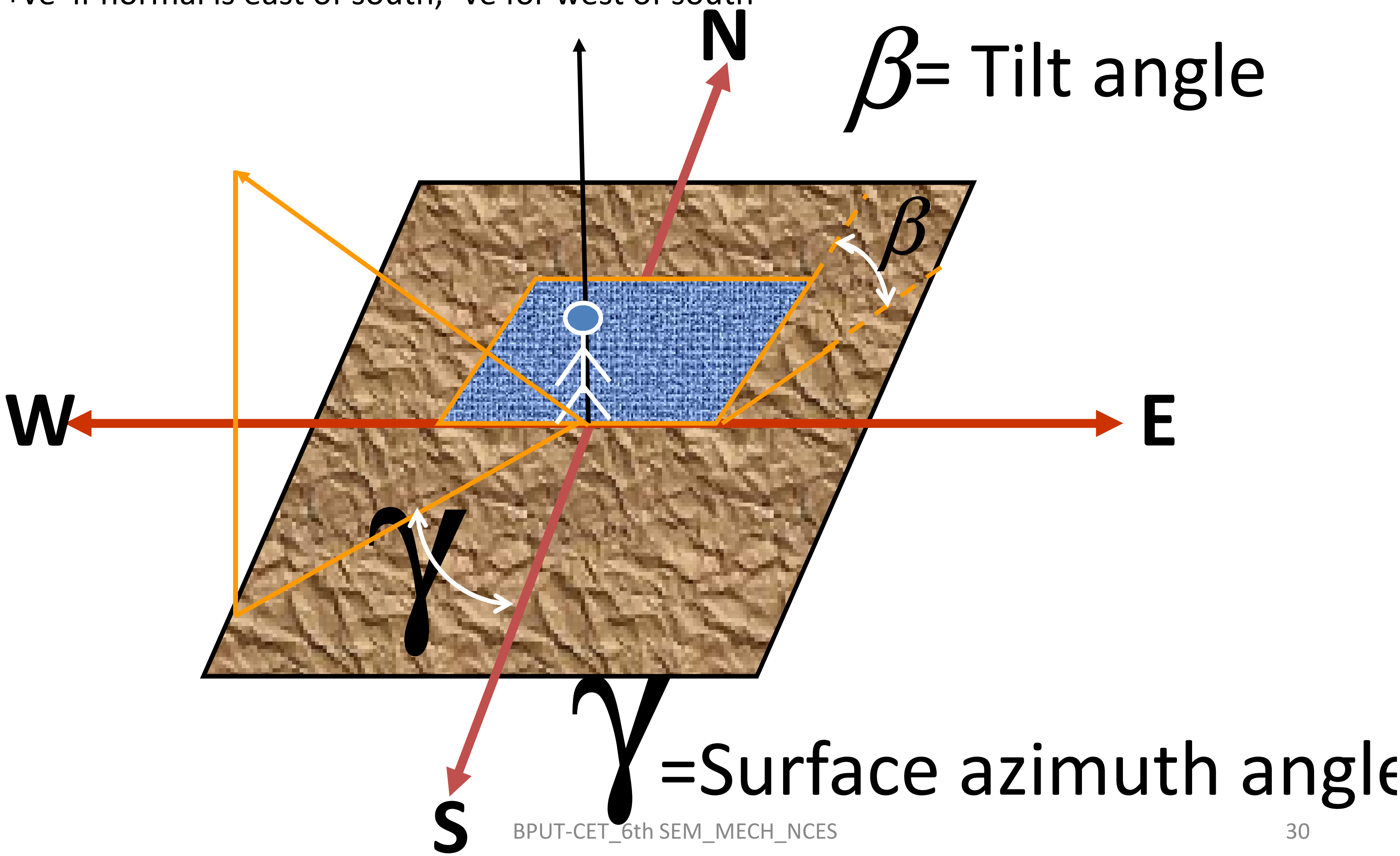
ψ: Longitude angle

Surface azimuth angle, is the angle made in the horizontal plane between the horizontal l

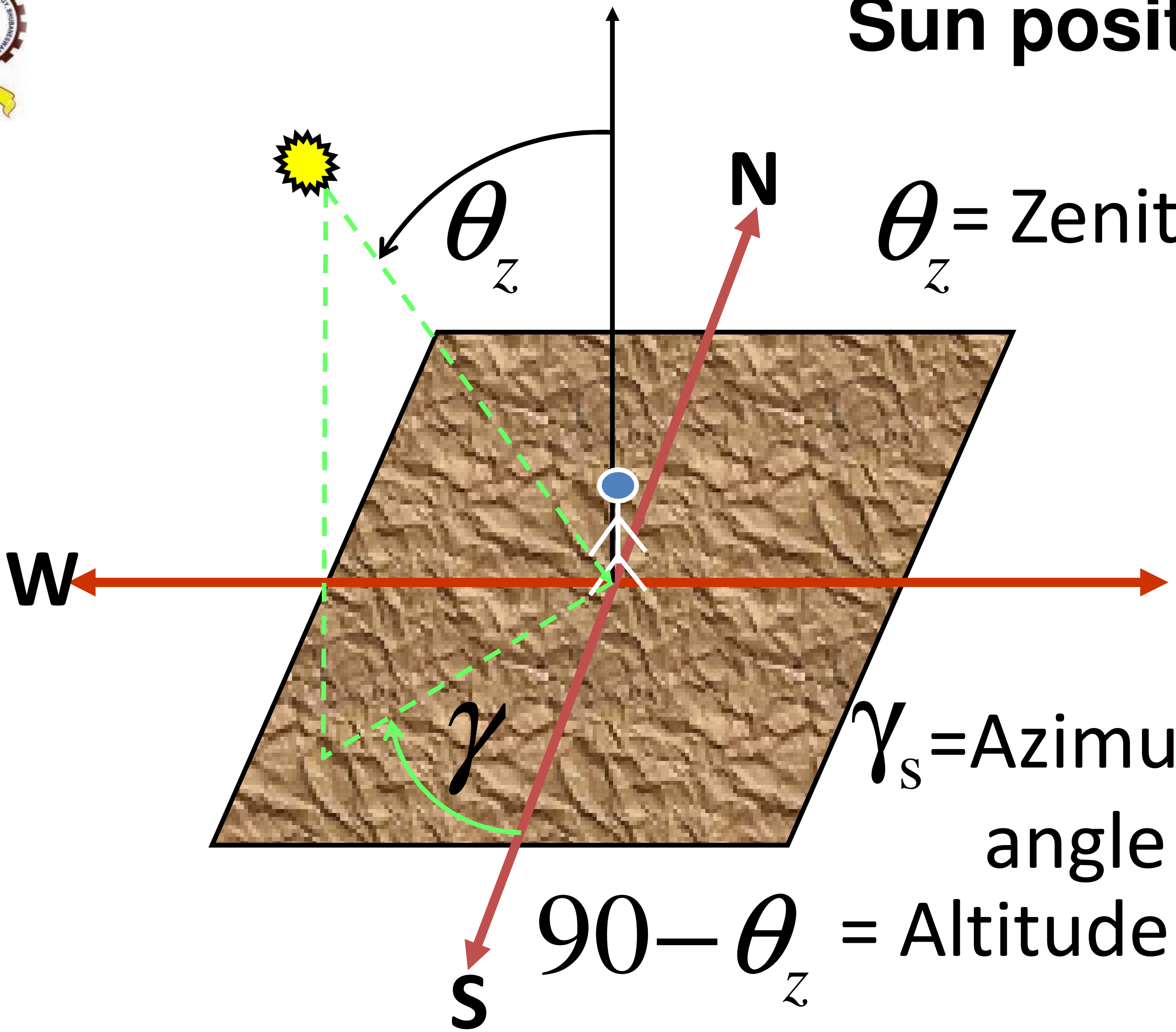
Slope,β is the angle made by the plane surface with the horizontal. It can vary from 0-180°

due south and the projection of the normal to the surface on the horizontal plane.

+ve if normal is east of south, -ve for west of south



Sun positions

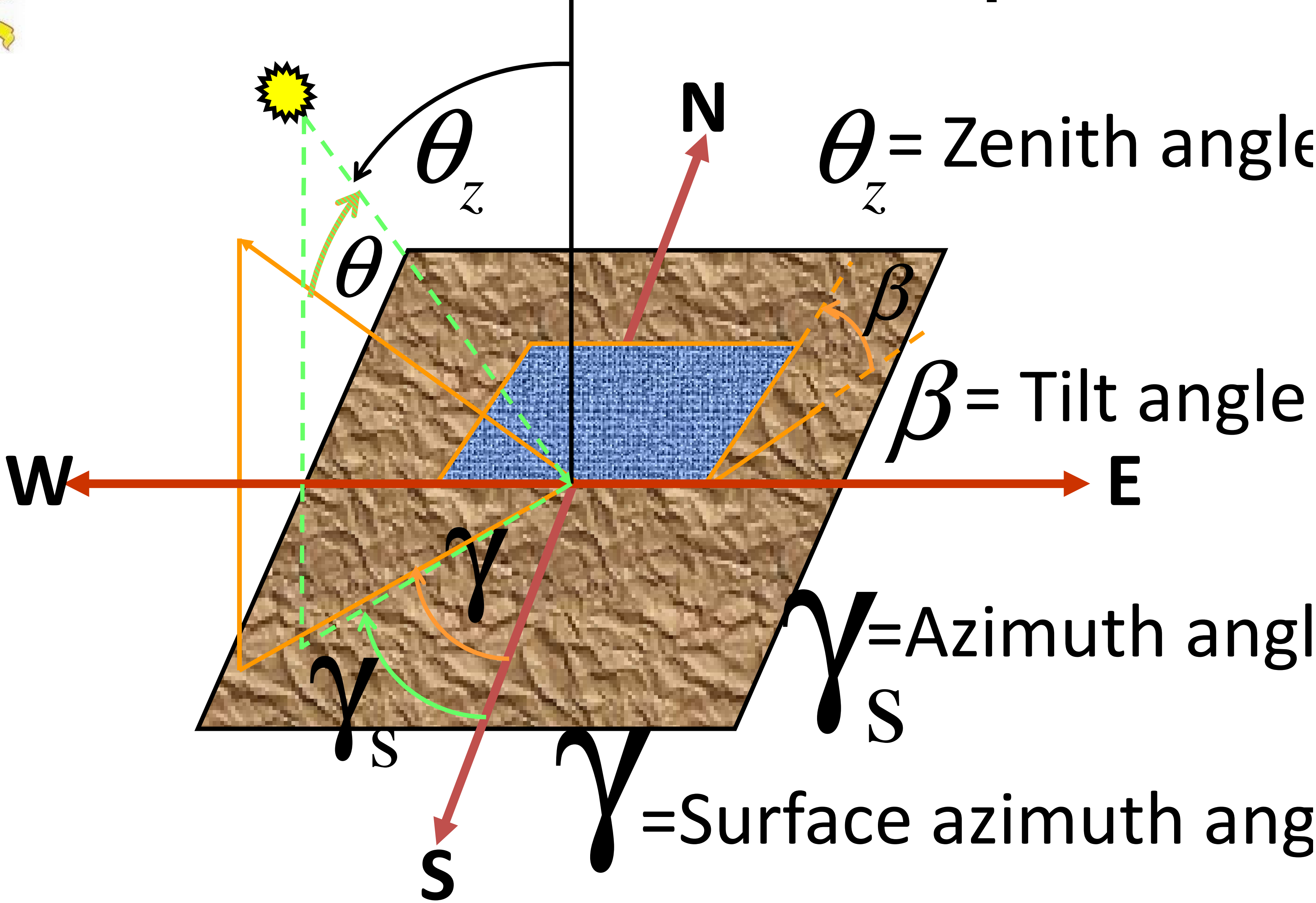


θ_z = Zenith angle

γ_s =Azimuth angle

$90-\theta_z$ = Altitude angle

Sun positions



SOLAR ANGLES

θ_z **= Zenith Angle** = Angle between sun's ray and a line perpendicular to the horizontal plane at P.

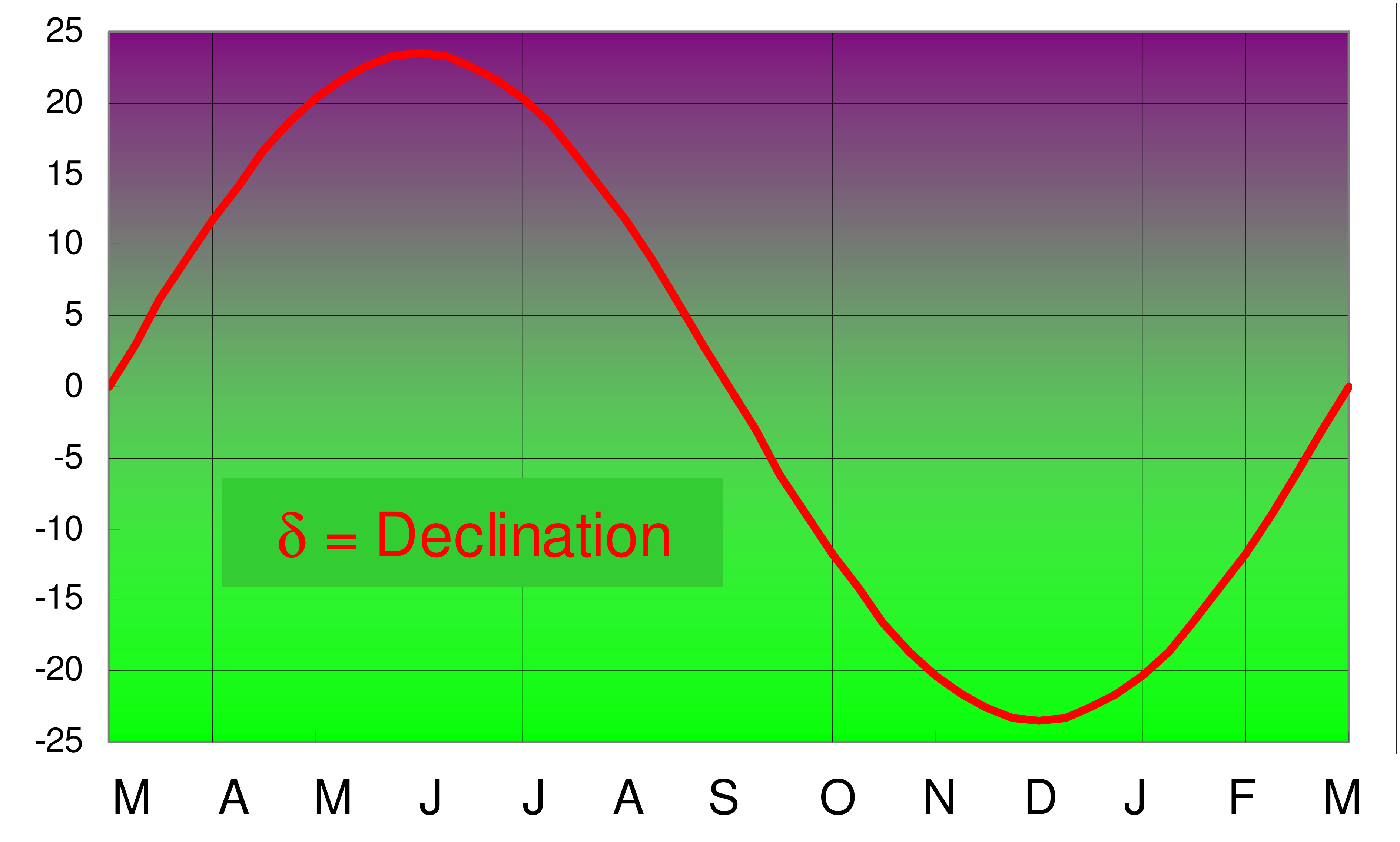
α_a= **Altitude Angle** = Angle in vertical plane between the sun's rays and projection of the sun's ray on a horizontal plane.

It follows $\theta_z + \alpha_a = \pi/2$

ϕ

γ_s = Azimuth angle = Angle measured from south to the horizontal projection of the sun's ray.

Declination (δ)



Hour Angle: (ω_s)

Hour Angle is an angular measure of time and is equivalent to 15° per hour. It varies from -180° to 180°.

- At the solar room, the hour angle (h) is zero,

Morning: negative and Afternoon: positive

- The hour angle expresses the time of the day with respect to solar noon.
- One hour time is represented by 360/24 or 15 degrees of hour angle

-

Angle between tilted surface & sun ray

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

Vertical surface, $\beta = 90^o$

$$\cos\theta = \sin\phi\cos\delta\cos\gamma\cos\omega$$
$$+\cos\phi\sin\delta\cos\gamma + \cos\delta\sin\omega\sin\gamma$$

Horizontal surface, $\beta = 0^o$ / Zenith angle θ_z

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

Angle between tilted surface & sun ray

Zenith angle(θz) is given by

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

Azimuth angle (γ) is given by

$$\cos\gamma = \frac{\sin\phi\cos\delta\cos\omega - \cos\phi\sin\delta}{\sin\theta_z}$$

Sun rise, sunset and daylength

Sunrise and sunset hour angle is given by

$$\omega_s = -\cos^{-1}(\tan\phi \tan\delta)$$

Time difference between noon sunrise or sunset (hour)

$$h_{ss/sr} = \frac{1}{15}\left[-\cos^{-1}(\tan\phi \tan\delta)\right]$$

Day length

$$S_{\max} = \frac{2}{15}\left[-\cos^{-1}(\tan\phi \tan\delta)\right]$$

Local Apparent Time

Solar time: Time corresponding to the position of sun i.e., based on hour angle ω_s

Standard time: Time corresponding to the position of sun at a reference place known as standard longitude for a country ψ_{std}.

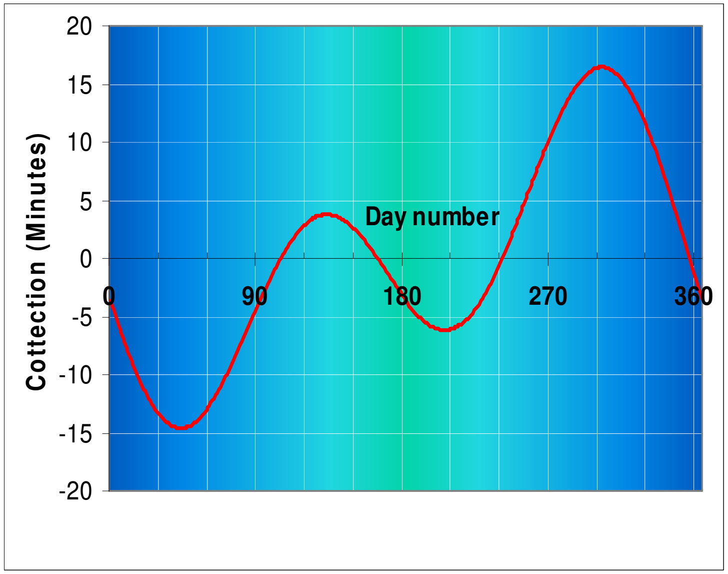
At standard longitude:

Solar time/LAT=Standard time ±4(standard time longitude-longitude of loaction)+equation of time (E_t)

First correction: Due to difference between the longitude of a location and a meridian on which the standard time is based

Local Apparent Time

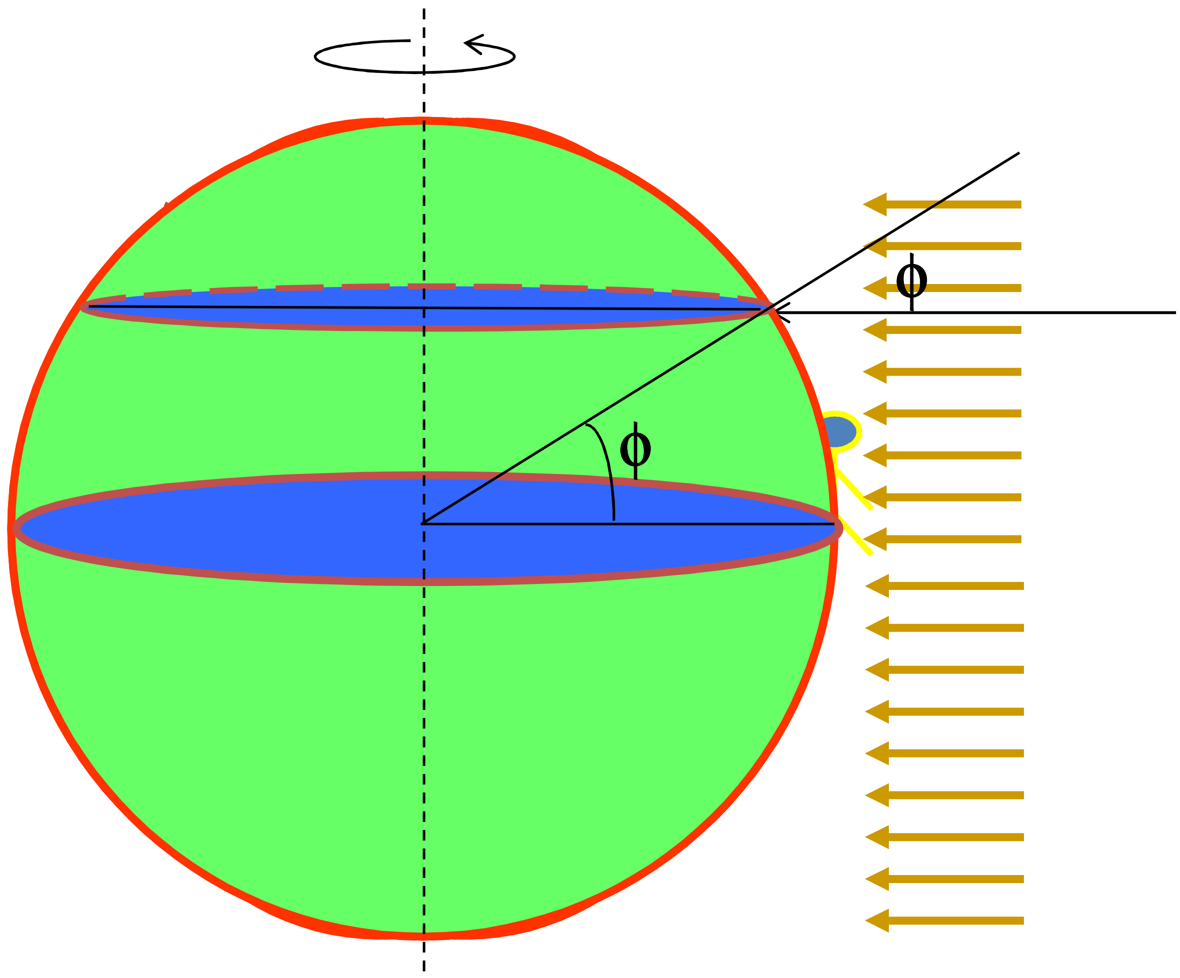
Second correction: Equation of time Correction is due to the fact that eath's orbit and rate of rotation are subject To small variation



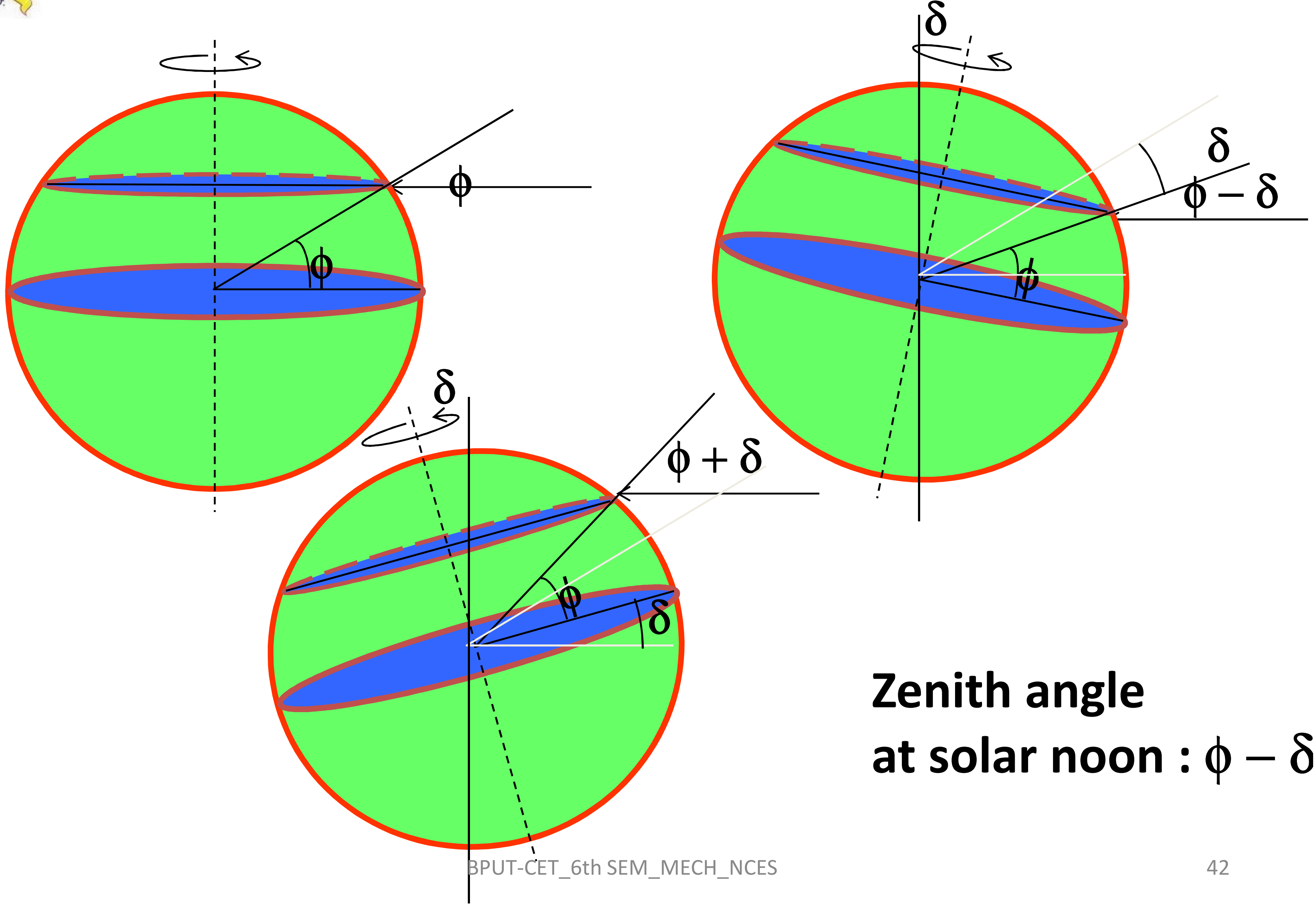
$$E_t = 229.18(0.000075 + 0.001868\cos B - 0.032077\sin B - 0.014615\cos 2B - 0.04089\sin 2B) \text{ in min}$$

$$B = \frac{360}{364}(n-1), \text{n is the day of the year}$$

Solar radiation on horizontal surface



Solar radiation on horizontal surface



Zenith angle
at solar noon : $\phi - \delta$

Solar radiation data

Most radiation data is measured horizontal surfaces

I_g and I_d represents instantaneous values of the global and diffuse flux

Since solar radiation do not normally change rapidly with time, the same can be used for hourly values also.
Units : kWh/m2-h or kJ/m2-h

H_g and H_d represent global and diffuse radiation for whole day

$\overline{I}_g, \overline{I}_d$ are monthly average hourly global and diffuse heat flux

$\overline{H}_g, \overline{H}_d$ are monthly average daily global and diffuse heat flux

Empirical equations for predicting the availability of solar radiation

The measurement of solar radiation over a period of time at a place is the best approach for estimating average radiation at a place.

If this is not possible, data from nearby locations having similar geography and climate can be used.

When both are not possible, one can use empirical correlations linking The values of radiation(global or diffuse) with meteorological parameters like sunshine hours, cloud cover and precipitation.

Sometimes hourly data may be needed for some specifc purpose which Is not found from measured data

Monthly average daily global radiation

$$\frac{\overline{H}_g}{\overline{H}_c} = a + b\left(\frac{\overline{S}}{\overline{S}_{max}}\right)$$

where

$\overline{H}_g$ = monthly average of the daily global radiation on a horizontal surface at a location (kJ/m^2-day)

$\overline{H}_c$ = monthly average of the daily global radiation on a horizontal surface at the same location on a clear day (kJ/m^2-day)

$\overline{S}$ = monthly average of the sun shine hours per day at a location (h)

$\overline{S}_{max}$ = monthly average of the maximum possible sun shine hours per day at the location (h)

a,b = constants obtained by fitting data

$\overline{H}_c$ is replaced by $\overline{H}_o$ due to difficulties in deciding what constitutes a clear sky where $\overline{H}_o$ is called monthly average of the daily extraterrestrial radiation.

Hence

$$\frac{\overline{H}_g}{\overline{H}_o} = a + b\left(\frac{\overline{S}}{\overline{S}_{max}}\right)$$

Monthly average daily global radiation

$\overline{H}_o$ is the mean of the value H_o for each day of the month.

H_o is obtained by integrating over the day length as follows

$$H_o = I_{sc}\left(1 + 0.033\cos\frac{360n}{365}\right)\int(\sin\phi\sin\delta + \cos\phi\cos\delta\cos\omega)dt$$

$$\text{Now}, t = \frac{180\omega}{15\pi}$$

where t is in hours and ω is in radians.

$$\text{Hence, } dt = \frac{180}{15\pi}d\omega$$

$$H_o = \frac{12}{\pi}I_{sc}\left(1 + 0.033\cos\frac{360n}{365}\right)\int_{-\omega_s}^{\omega_s}(\sin\phi\sin\delta + \cos\phi\cos\delta\cos\omega)dt$$

$$= \frac{24}{\pi}I_{sc}\left(1 + 0.033\cos\frac{360n}{365}\right)(\omega_s\sin\phi\sin\delta + \cos\phi\cos\delta\sin\omega_s)$$

$\overline{H}_o$ is determined the particular day in each month on which extraterrestrial radiation is nearly equal to the monthly mean value.

the dates on which $\overline{H}_o = H_o$ are as follows

Jan 17, Feb 16, Mar 16, Apr 15, May 15, Jun 11, Jul 17, Aug 16, Sept 15, Oct 15, Nov 14, Dec 10. Dates are almost middle of the month.

Hourly global, beam and diffuse radiation Under cloudless skies

$$I_g = I_b + I_d$$

where

$I_g =$ hourly global radiation

$I_b =$ hourly beam radiation

$I_d =$ hourly diffuse radiation

Now, $I_b = I_{bn} \cos\theta_z$

where

$I_{bn} =$ beam radiation in the direction of the rays

$\theta_z =$ angle of incidence on a horizontal surface, i.e. the zenith angle

Solar radiation on tilted surfaces

Beam radiation

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

while for a horizontal surface

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

Hence,

$$r_b = \frac{\cos\theta}{\cos\theta_z} = \frac{\sin\delta\sin(\phi-\beta) + \cos\delta\cos\omega\cos(\phi-\beta)}{\sin\phi\sin\delta + \cos\phi\cos\delta\cos\omega}$$

Beam radiation

The ratio of the beam radiation flux falling on a tilted surface to that falling surface is called the tilt factor for beam radiation. It is denoted by the symbol 'r_b'

For the case of a tilted surface facing south(i.e. $\gamma=0^0$)

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

while for a horizontal surface

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

Hence,

$$r_b = \frac{\cos\theta}{\cos\theta_z} = \frac{\sin\delta\sin(\phi-\beta) + \cos\delta\cos\omega\cos(\phi-\beta)}{\sin\phi\sin\delta + \cos\phi\cos\delta\cos\omega}$$

Diffuse radiation

The tilt factor 'r_d 'for a diffuse radiation is ratio of the diffuse radiation flux falling on the tilted surface to that falling on a horizontal surface. the value of tilt factor depends on the distribution of diffuse radiation over the sky and on the portion of the sky dome seen by the tilted surface.

$$r_d = (1+\cos\beta)/2$$

$(1+\cos\beta)/2$ is radiation shape factor for a tilted surface w.r.t the sky

Reflected radiation

Since $(1+\cos\beta)/2$ is the radiation shape factor for a tilted surface w.r.t the sky, it follows that $(1-\cos\beta)/2$ is the radiation shape factor w.r.t. the surrounding ground.

reflectivity is ρ

the tilt factor for reflected radiation is

$$r_r = \rho(1-\cos\beta)/2$$

Flux on tilted surface

$$I_T = I_b r_b + I_d r_d + (I_b + I_d) r_r$$

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