BMM4753 RENEWABLE ENERGY RESOURCES

Chapter 2. Solar Thermal Energy

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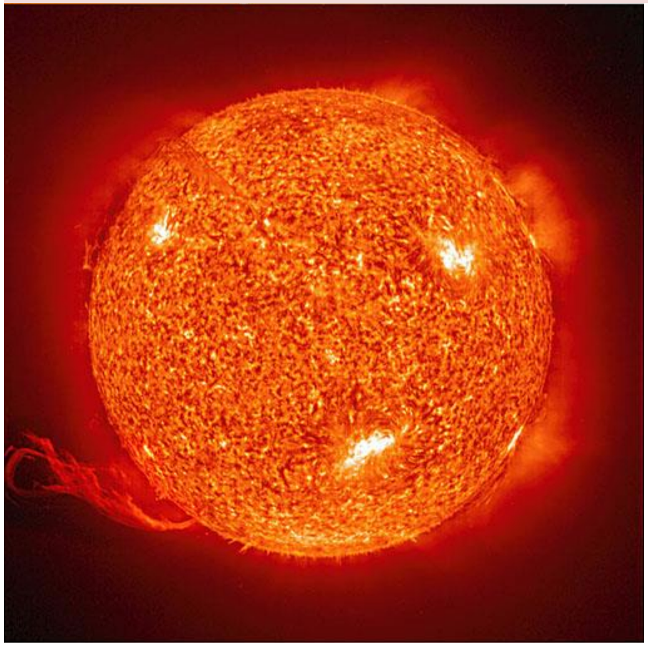
Summary

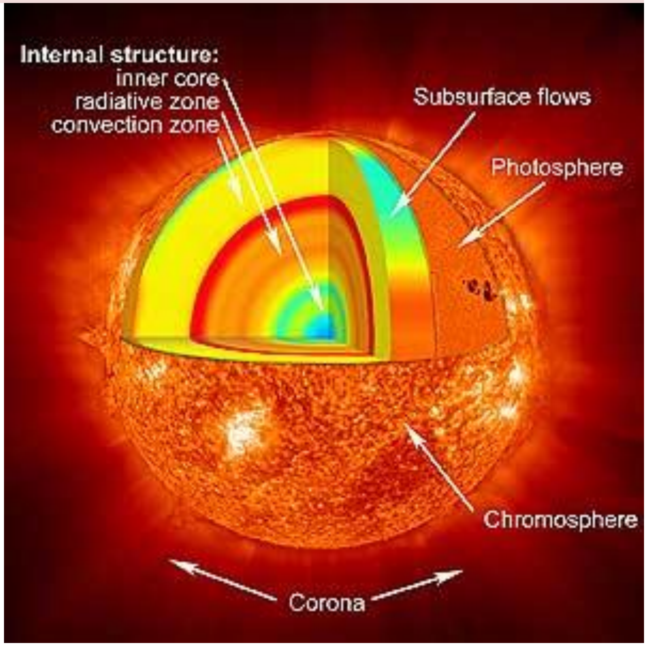
2.1 Introduction

Sun is hydrodynamic sphere body of hot gaseous matter; swirl, flow under gravity and magnetic spewing enormous quantities of energy releases from nuclear fusion. Solar radiations pass through the earth's atmosphere and are subjected to scattering and atmospheric absorption. A part of scattered radiation is reflected back into space. Solar radiation varies in intensity at different locations on the earth, which revolves elliptically around the sun. For the calculation of solar radiation, the position on the earth's surface with regard to sun's rays can be located. Short wave ultraviolet rays are absorbed by ozone and long wave infrared rays are absorbed by CO_2 and water vapors. Scattering is due to air molecules, dust particles and water droplets that cause attenuation of radiation. Minimum attenuation takes place in a clear sky when the earth's surface receives maximum radiation. Solar constant, is the energy from the sun received on a unit area perpendicular to solar rays at the mean distance from the sun outside the atmosphere, at 1367 W/m^2 or 4.921 MJ/m^2/h.

2.1 Introduction

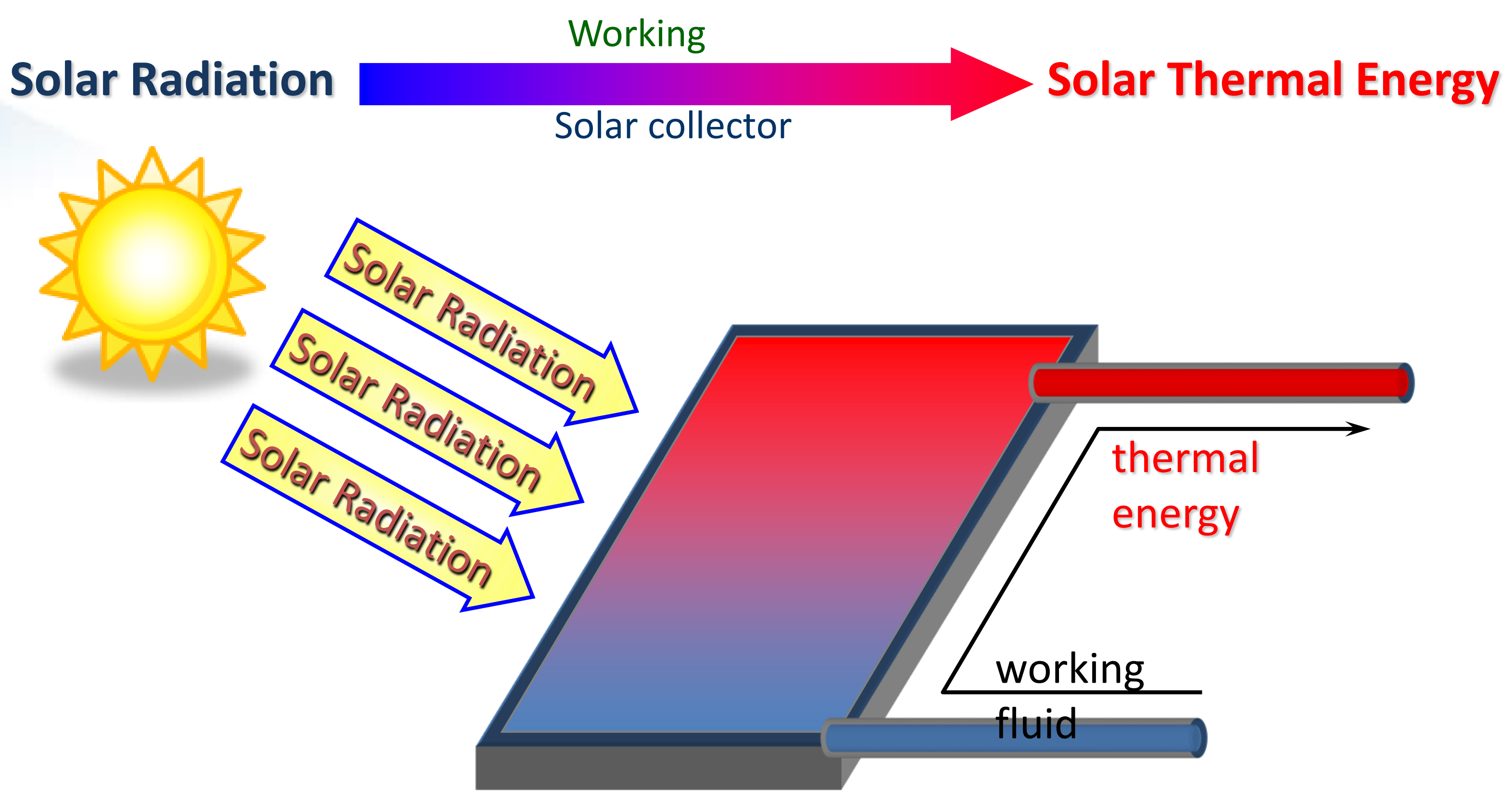


Diameter
1,390,000km
Distance
150,000,000km
Consist
H He O C Ne Fe
Surface 5,500°C
Photosphere 6,000°C
Core 15,000,000°C



Solar radiation, energy from the sun is in the form of electromagnetic waves
Photosphere, turbulent with a roiling surface, sunspots, giant flares 6,000°C
Chromosphere, above the photosphere; flares from hot gas like filaments
Corona, outer part of the Sun's atmosphere; immense clouds of glowing gas

2.2 How to Use Solar Thermal Energy



2.2 How to Use Solar Thermal Energy

2.3 Solar radiation component – Solar constant

Energy radiated from the sun is electromagnetic waves reaching the planet earth in three spectral regions,

i. ultraviolet 6.4% ($\lambda < 0.38\ \mu$m),

ii. visible 48% ($0.38\ \mu\text{m} < \lambda < 0.78\ \mu$m)

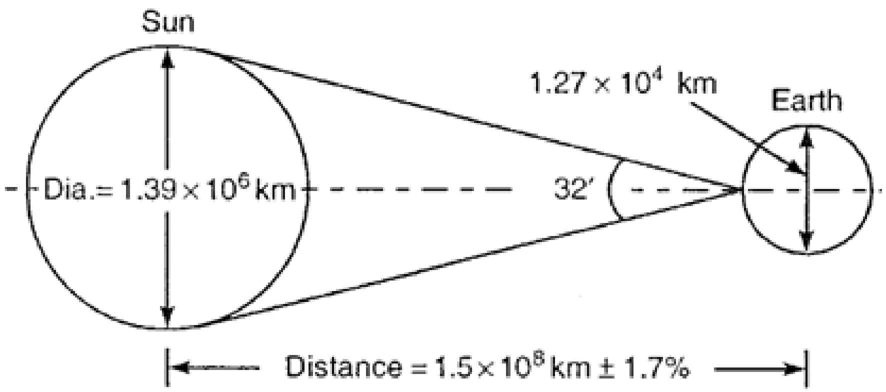
iii. infrared 45.6% ($\lambda > 0.78\ \mu$m) of total energy.

Due to the enormous distance between the sun and the earth (1.495×10^8 km) the beam radiation received is almost parallel from the sun on the earth.

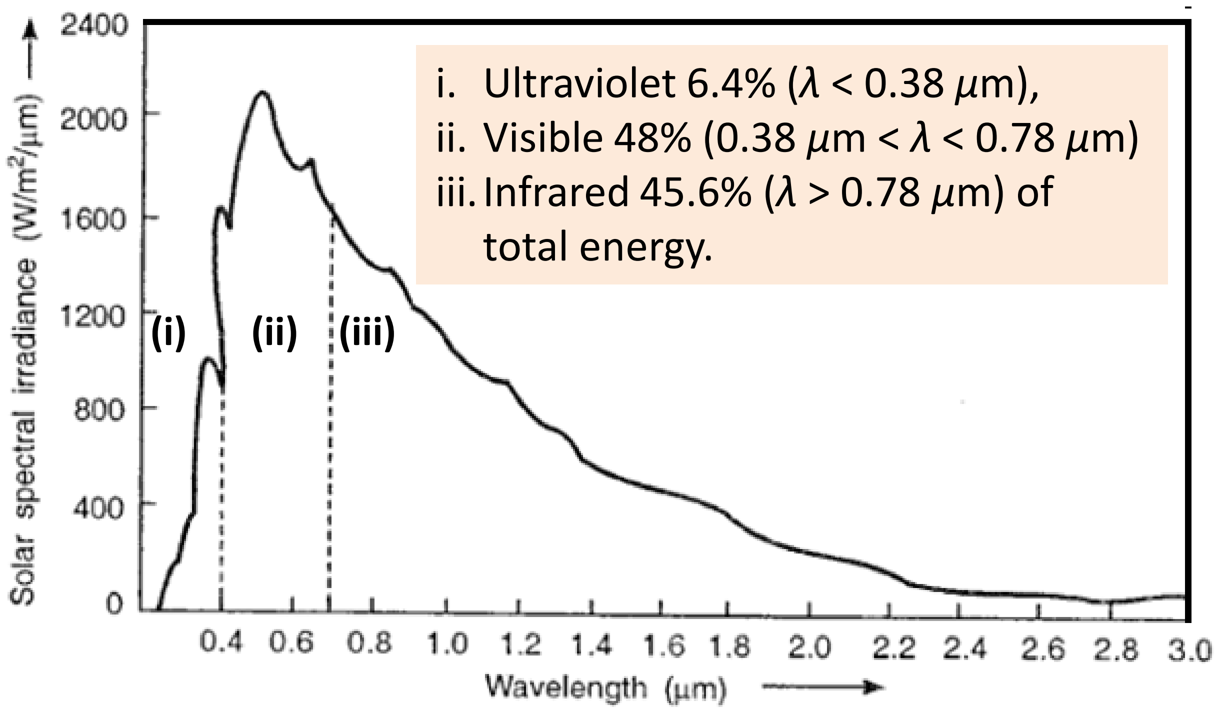
The solar constant, *Isc*

Energy from the sun on a unit area perpendicular to solar rays at the mean distance from the sun outside the atmosphere.

1,367 W/m^2 = 4.921 MJ/m^2/h.



2.3 Solar radiation component – Spectral Extraterrestrial Radiation



Extraterrestrial radiation: solar radiation in the absence of atmosphere

- ❑ Rises sharply with wavelength and reaches maximum value of 2,074 W/m^2/μm at a wavelength of 0.48 μm and decreases asymptotically to zero
- ❑ 99% of the sun's radiation is obtained up to a wavelength of 4 μm

2.3 Solar radiation component – Spectral Extraterrestrial Radiation

- The distance between the sun and the earth varies due to the elliptical motion of the earth.
- Accordingly, the extraterrestrial flux also varies, which can be calculated (on any day) by the equation,

$$I_n = I_{sc}\left[1 + 0.33\cos\frac{360n}{365}\right]\ \text{W/m}^2$$

  where *n* is the day of the year counted from the first day of January.
- Solar radiation reaching the earth is essentially equivalent to blackbody radiation.
- Using the **Stefan-Boltzmann law**, the equivalent blackbody temperature is 5,779 K for a solar constant of 1,367 W/m^2.

2.3 Solar radiation component – Spectral Extraterrestrial Radiation

Stephan-Boltzmann Law

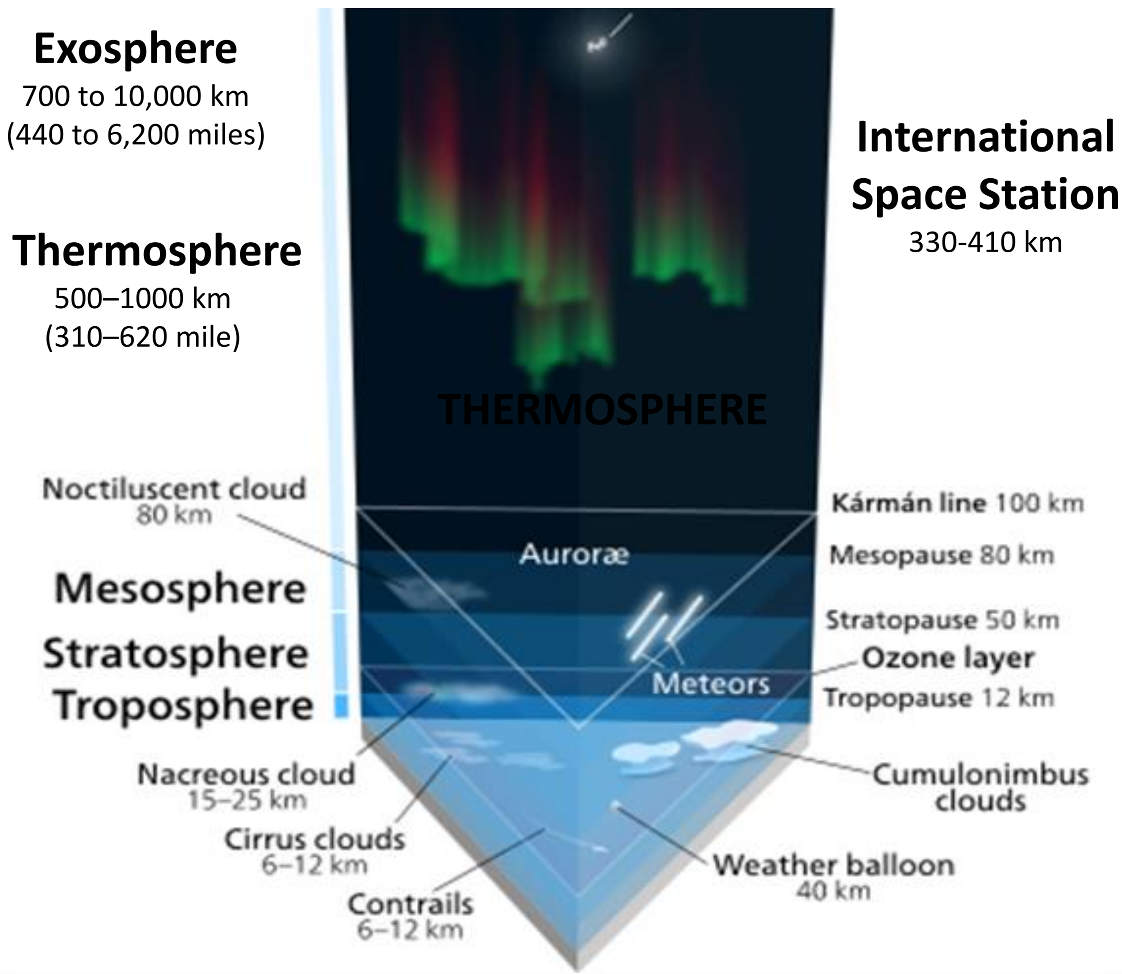
The amount of electromagnetic radiation emitted by a body is directly related to its temperature. If the body is a perfect emitter (black body), the amount of radiation given off is proportional to the 4th power of its temperature (*K*) given by the Stephan-Boltzmann law: -

$$E = \sigma T^4 \quad W/m^2$$

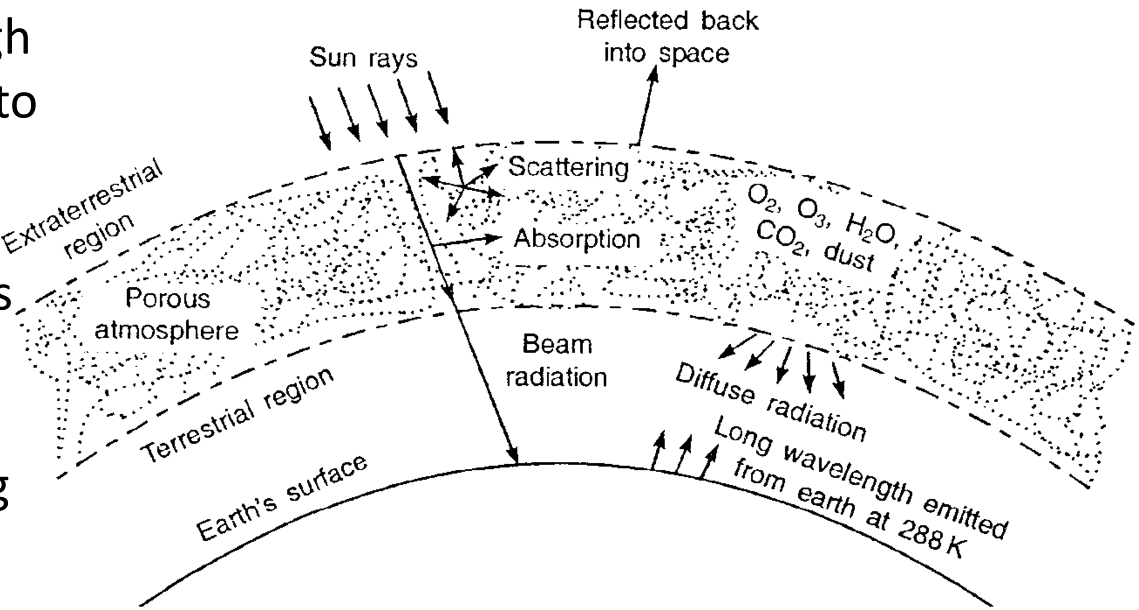
where, Stephan-Boltzmann constant σ= 5.67 x 10^{-8} W/m^2K^4 , and *T* is in *K*.

- Good emitters of radiation are also good absorbers of radiation
- Especially true of greenhouse gases
- Black bodies are perfect absorb/emit radiation
- Radiation characteristics of Sun and Earth are close to black bodies.

2.3 Solar radiation component – Atmosphere of earth



2.3 Solar radiation component – Terrestrial Solar Radiation



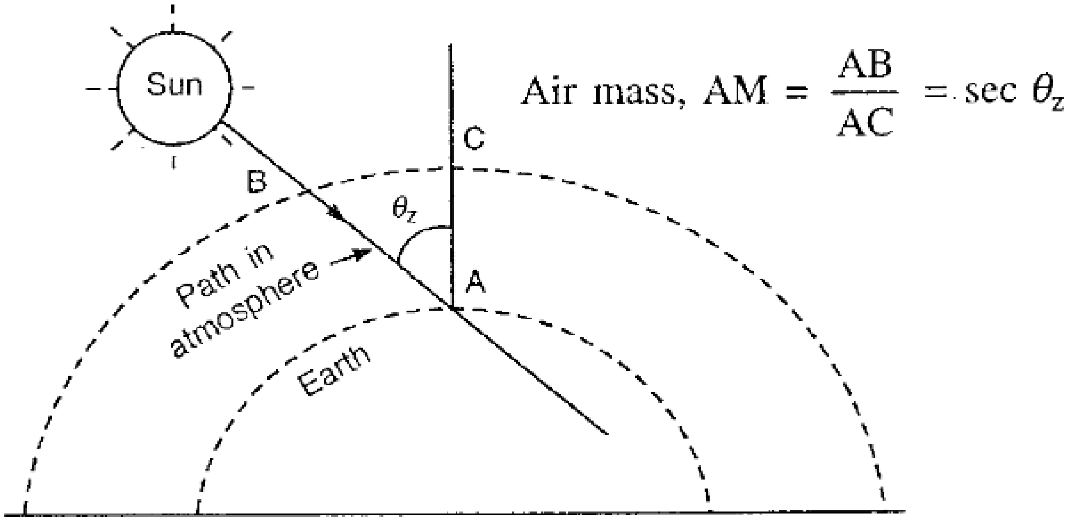
- Solar radiations pass through atmosphere and subjected to scattering and atmospheric absorption
- Part of scattered radiation is reflected back into space.
- Short wave ultraviolet rays absorbed by ozone and long wave infrared rays are absorbed by CO_2 and water vapors.
- Scattering is due to air molecules, dust particles and water droplets that cause attenuation of radiation
- Minimum attenuation takes place in a clear sky when the earth's surface receives maximum radiation.

2.3 Solar radiation component – Terrestrial Solar Radiation

- **Beam radiation *(h):*** Solar radiation received on the earth's surface without change In direction, is called *beam* or *direct radiation.*
- **Diffuse radiation *(I_d):*** The radiation received on a terrestrial surface (scattered by aerosols and dust) from all parts of the sky dome, is known as *diffuse radiation.*
- **Total radiation *(IT):*** The sum of beam and diffuse radiations (lb + I_d) is referred to as total radiation. When measured at a location on the earth's surface, it is called *solar insolation* at the place. When measured on a horizontal surface, it is called *global radiation* (lg).
- **Sun at zenith:** It is the position of the sun directly overhead.
- **Irradiance (W/m^2):** The rate of incident energy per unit area of a surface is termed *irradiance.*
- **Albedo:** The earth reflects back nearly 30% of the total solar radiant energy to the space by reflection from clouds, by scattering and by reflection at the earth's surface. This is called the *albedo* of the earth's atmosphere system.

2.3 Solar radiation component – Terrestrial Solar Radiation

- **Air mass (AM):** The ratio of the path length of beam radiation through the atmosphere, to the path length if the sun were at zenith. At sea level AM = 1, when the sun is at zenith or directly overhead; AM = 2 when the angle subtended by zenith and line of sight of the sun is 60°; AM = 0 just above the earth's atmosphere. Air mass at zenith angle Θ_Z is given by



Sun rays passing through atmosphere.

In winter, the sun is low and the air mass is higher and vice versa during summer.

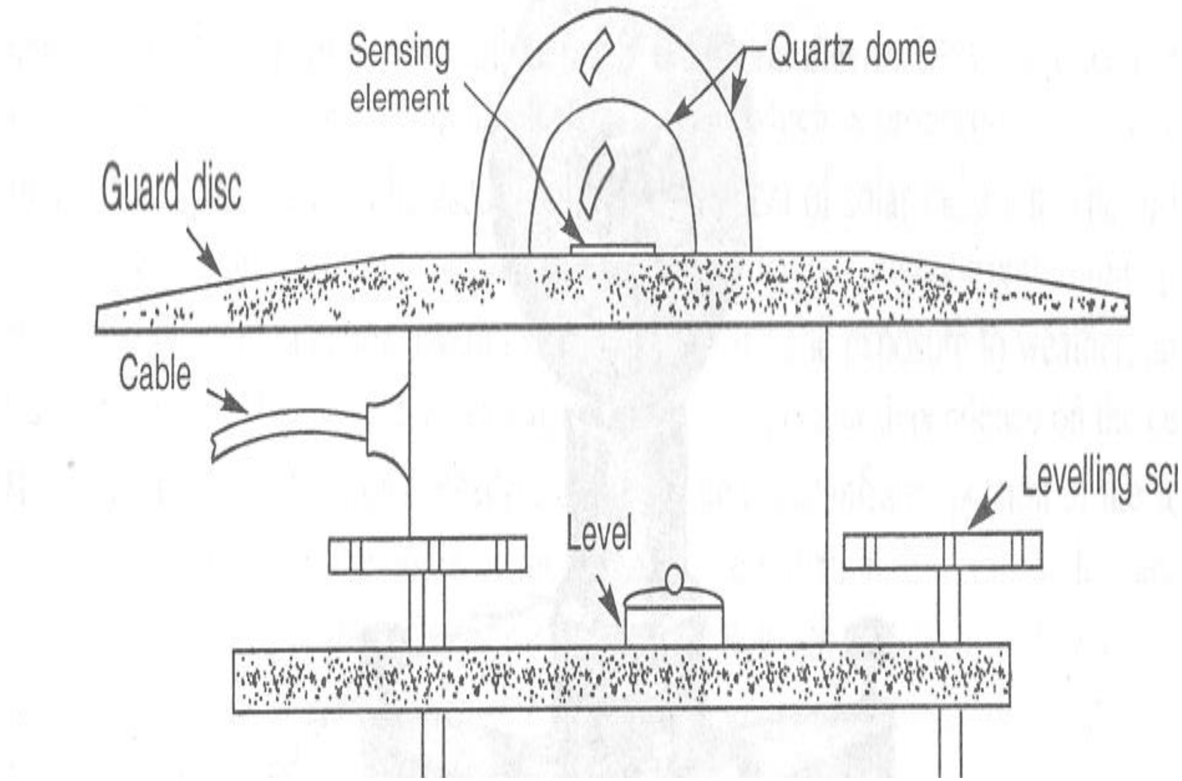
2.4 Instruments to Measure Insolation (Solar Radiation)

Pyranometers

Pyranometers measures total global solar irradiance from the whole sky.

Diffuse solar irradiance measured by adding a shadowing device to a pyranometers, which blocks the direct component of total irradiance.

2.4 Instruments to Measure Insolation (Solar Radiation)



Crossed-section of Pyranometers

2.4 Instruments to Measure Insolation (Solar Radiation)

Pyranometer

i. It measures global or diffuse radiation on a horizontal surface and covers total hemispherical solar radiation with a view angle of 2π steradians.
ii. It was designed by the Eppley laboratories, USA and operates on the principle of thermopile.
iii. It consists of a black surface which heats up when exposed to solar radiation. Its temperature rises until the rate of heat gain from solar radiation equals the heat loss by conduction, convection and radiation. On the black surface the hot junctions of a thermopile are attached, while the cold junctions are placed in a position such that they do not receive the radiation. An electrical output voltage (0 to 10 mV range) generated by the temperature difference between the black and white surfaces indicates the intensity of solar radiation. The output can be obtained on a strip chart or on a digital printout over a period of time. This is a measure of global radiation.

2.4 Instruments to Measure Insolation (Solar Radiation)

Pyranometer

iv. It can also measure diffuse sky radiation by providing a shading ring or disc to shade the direct sun rays.

v. The shading ring is provided with an arrangement such that its plane is parallel to the plane of the sun's path across the sky. Consequently, it shades the thermopile element at all times from direct sunshine and the pyranometer measures only the diffuse radiation obtained from the sky. A continuous record can be obtained either on an electronic chart or on an integrated digital printout system. As the shading ring blocks a certain amount of diffuse sky radiation besides direct radiation, a correction factor is applied to the measured value.

2.4 Instruments to Measure Insolation (Solar Radiation)

Pyrheliometer

Pyrheliometer measures direct component of solar irradiance, which is important when installing concentrating collectors.

Handheld pyranometers

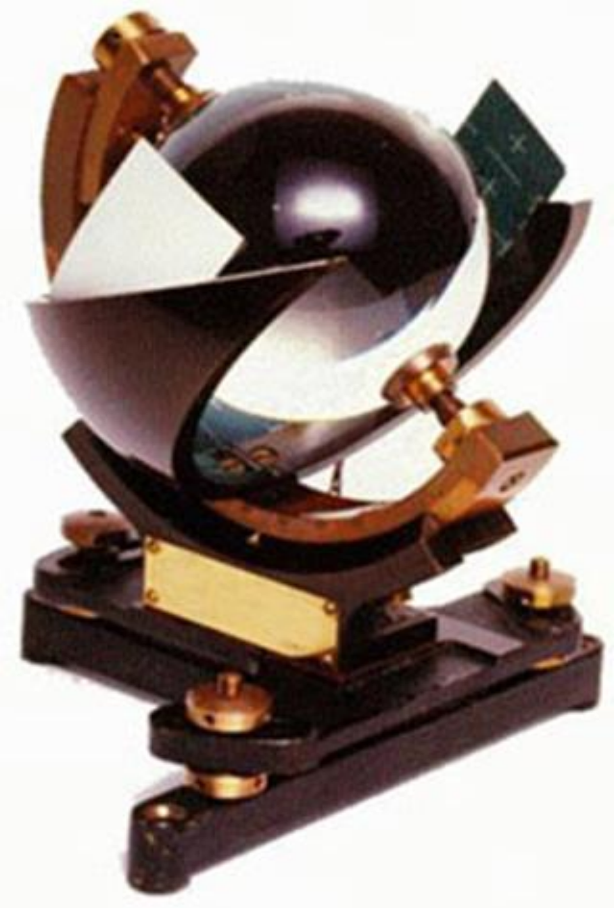
Handheld pyranometers use less precise sensors, suitable for field measurements.

2.4 Instruments to Measure Insolation (Solar Radiation)

Pyrheliometer

An instrument which measures beam radiation on a surface normal to the sun's rays. The sensor is a thermopile and its disc is located at the base of a tube whose axis is aligned in the direction of the sun's rays. Thus, diffuse radiation is blocked from the sensor surface. The pyrheliometer designed by Eppley Laboratories, USA, consists of bismuth silver thermopile, with 15 temperature-compensated junctions connected in series. It is mounted at the end of a cylindrical tube, with a series of diaphragms (the aperture is limited to an angle of 5.42°). The instrument is mounted on a motor-driven heliostat which is adjusted every week to cover changes in the sun's declination. The output of the pyreheliometer can either be recorded on a strip chart recorder or integrated over a suitable time period. The pyrheliometer readings give data for atmospheric turbidity and provide a clearness index.

2.4 Instruments to Measure Insolation (Solar Radiation)



Sunshine Recorder

This instrument is used to measure the duration, in hours of bright sunshine during the course of the day

The duration in hours of bright sunshine in a day is measured by a sunshine recorder. It consists of a glass sphere installed in a section of spherical metal bowl, having grooves for holding a recorder card strip. The glass sphere is adjusted to focus sun rays to a point on the card strip. On a bright sunshine day, the focused image burns a trace on the card. Through the day the sun moves across the sky, the image moves along the strip. The length of the image is a direct measure of the duration of bright sunshine.

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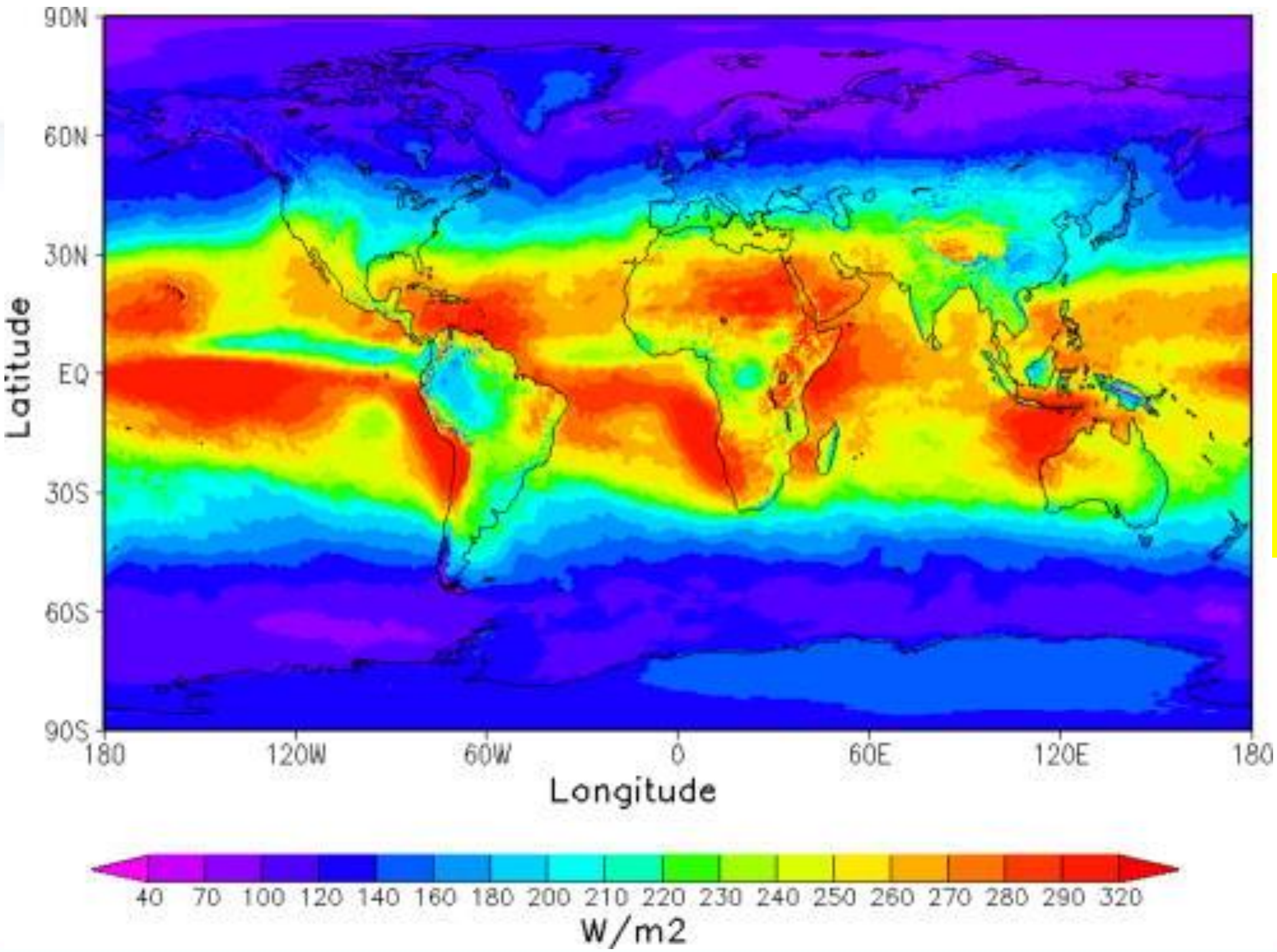
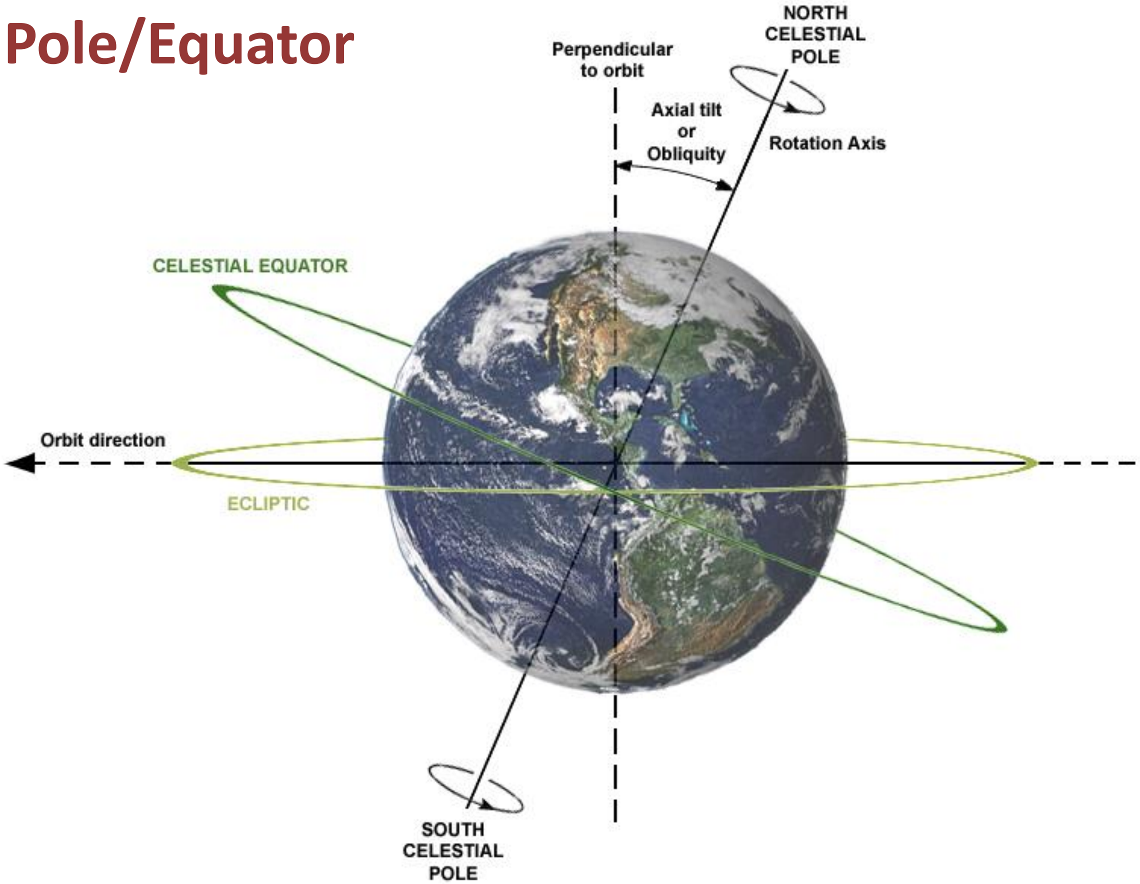
2.4 Instruments to Measure Insolation (Solar Radiation)



Annual global mean downward solar radiation distribution at the surface

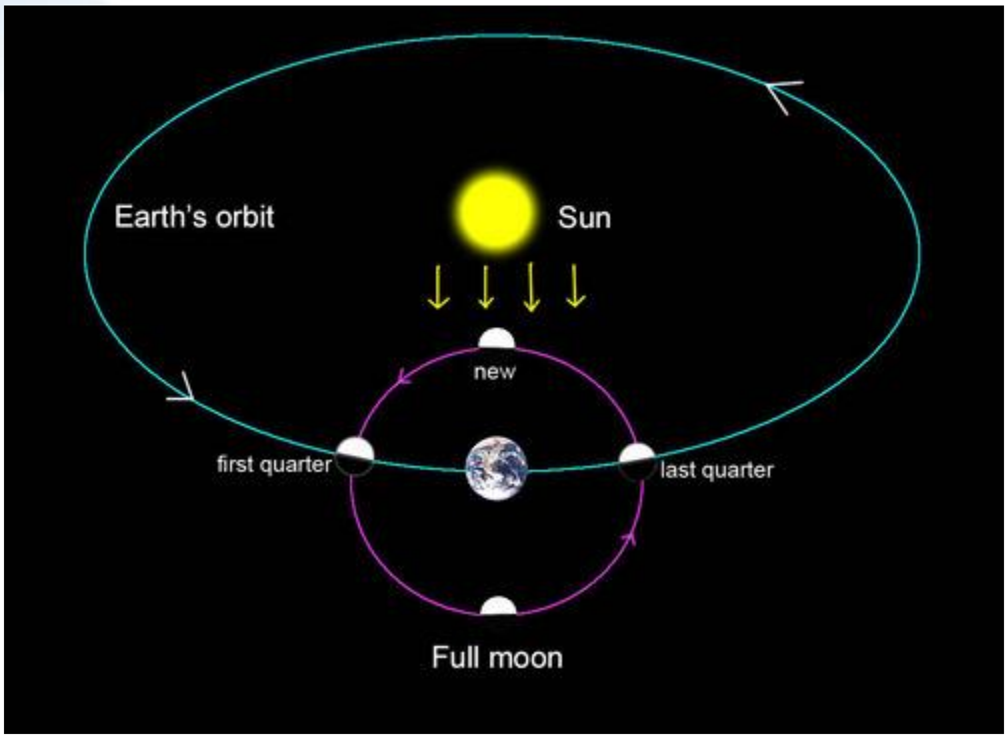
2.5 Sun – Earth Relationships

Celestial Pole/Equator



2.5 Sun – Earth Relationships

Earth's Orbit

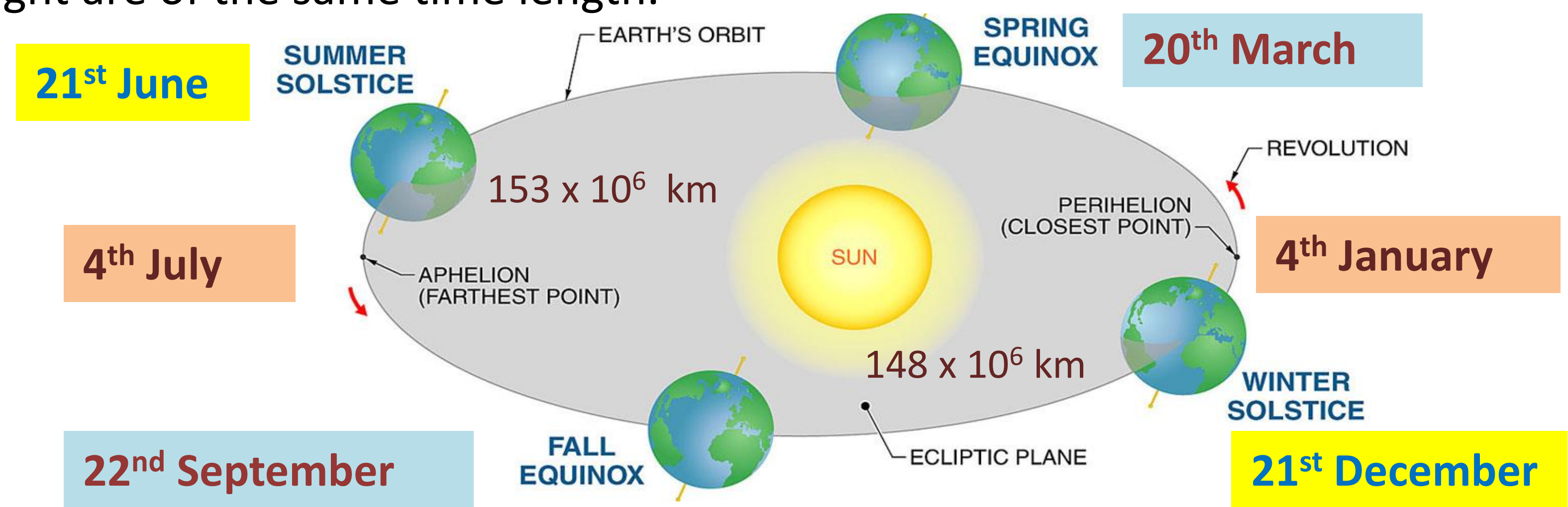


- Diameter of Earth 12,700 km, moves around the Sun in an orbit
- Diameter of the Sun 1,390,000 km and distance 153 – 148 x 10^6 km from Earth.
- Moon moves around the Earth, together moves around the Sun
- Diameter of the Moon, 3,475 km is just about 1/4 that of the Earth.
- Moon is 384,470 km from Earth, distance of 30 times Earth diameters.

2.5 Sun – Earth Relationships

Elliptical Plane/Orbit

- Earth makes a slightly elliptical orbit around the sun in one year
- The ecliptic plane is formed by Earth's elliptical orbit around the sun
- Perihelion is the point in Earth's orbit when it is closest to the sun, 4th Jan
- Aphelion is the point in Earth's orbit when it is farthest from the sun, 4th July
- Equinox is either of the two times when sun crosses the Equator in which day and night are of the same time length.

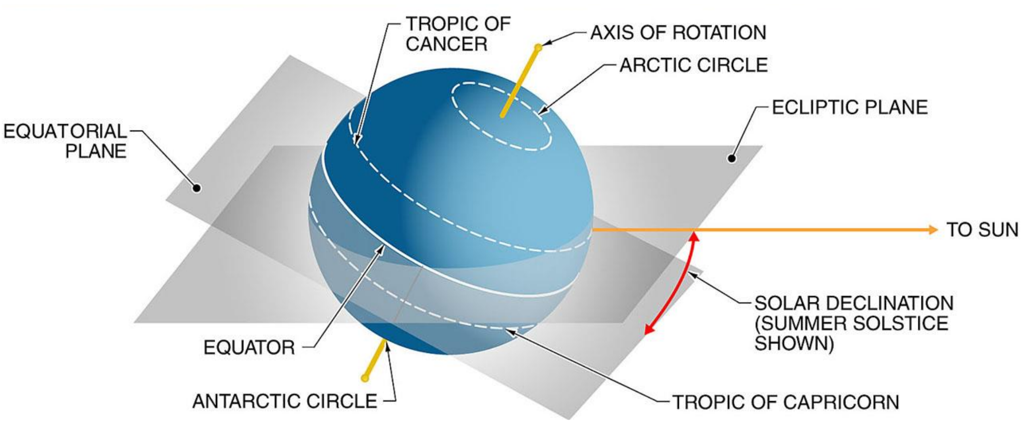


2.5 Sun – Earth Relationships

Solar Declination

- Solar declination is the angle between the equatorial plane and the rays of the sun
- As earth revolves around the sun, the orientation produces a varying solar declination
- Solar declination changes as earth orbits the sun, –23.5° to +23.5°

- Positive in Northern Hemisphere tilted toward the sun.
- Angle between the ecliptic and equatorial planes does not change, but as viewed from the sun at different times of the year, the equatorial plane appears to change in orientation

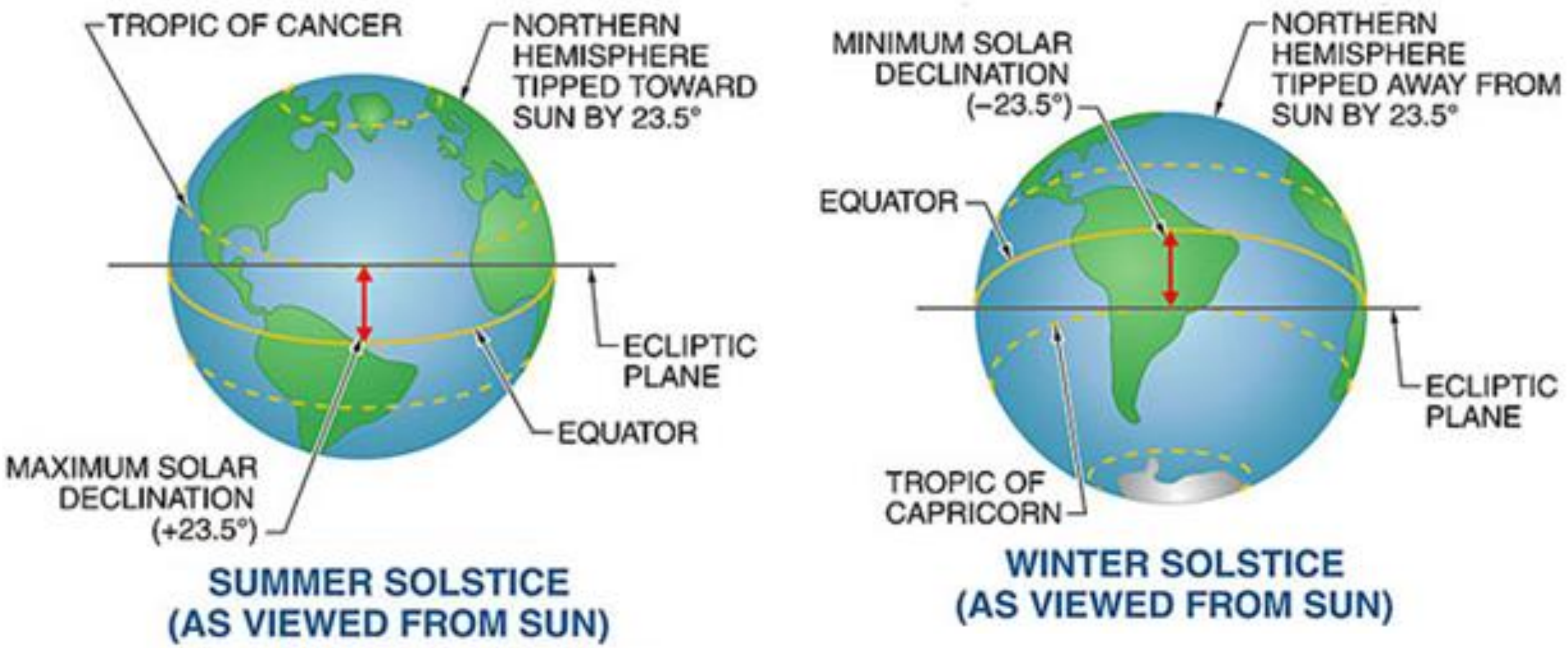


  - Dip below the ecliptic plane (summer in the Northern Hemisphere),
  - Become edge-on (fall),
  - Tip above the ecliptic (winter), and
  - Return to edge-on (spring)

2.5 Sun – Earth Relationships

Solstices

- Summer solstice when the Northern Hemisphere tip towards the sun
- Winter solstice when the Northern Hemisphere tip away from the sun.



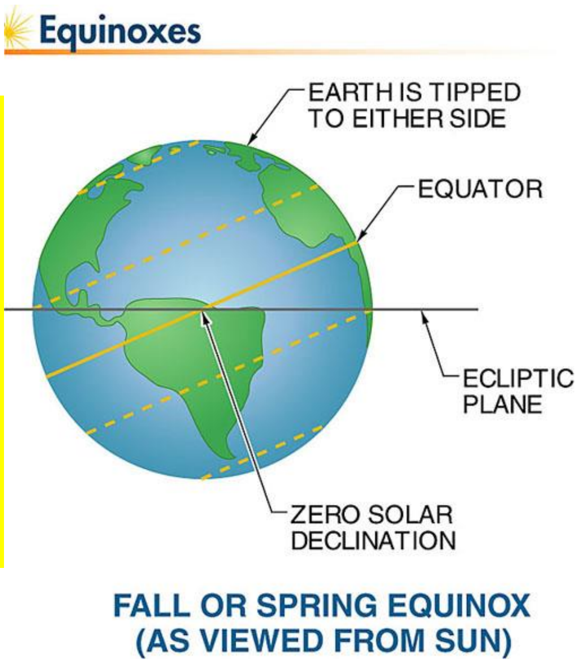
2.5 Sun – Earth Relationships

Equinox

Fall equinox and spring equinox occurs when the sun is directly in line with the equator

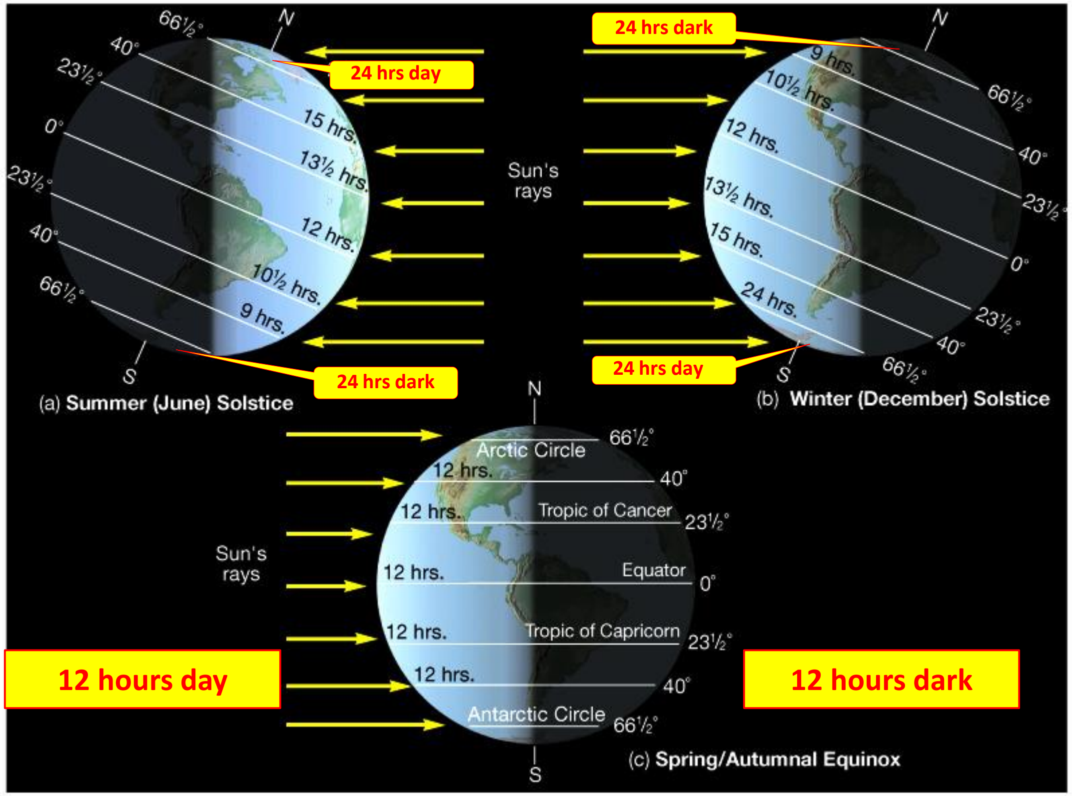
Spring equinox = March 21
Fall equinox = September 23
Sun is at zenith at noon, equator
Everywhere on Earth

- Length of day/night = 12 hrs
- Sun rises sets due east
- Sun sets due west.



2.5 Sun – Earth Relationships

Length of Day/Night

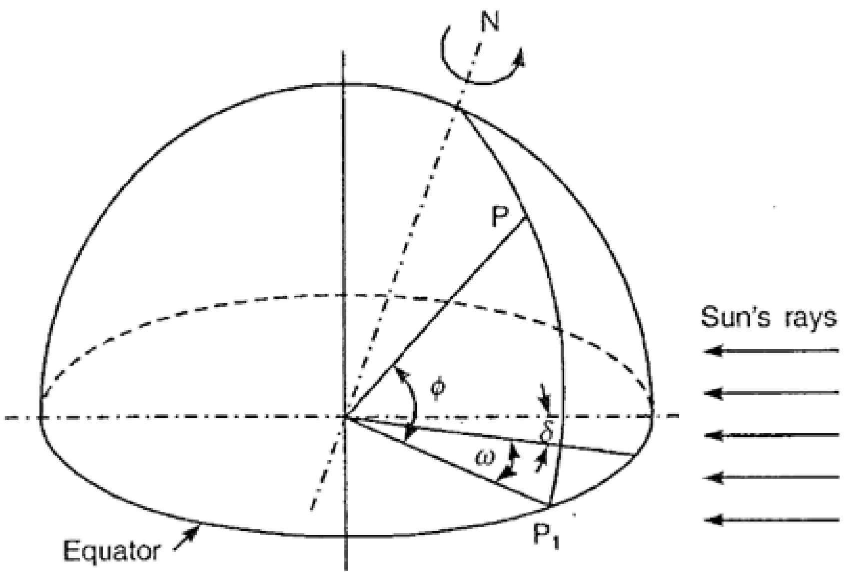


Lighter Mode – Four Seasons in Malaysia

2.6 Solar Radiation Geometry

Sun Position

Solar radiation varies in intensity at different locations on the earth, which revolves elliptically around the sun



Latitude ϕ, hour angle ω and sun's declination δ.

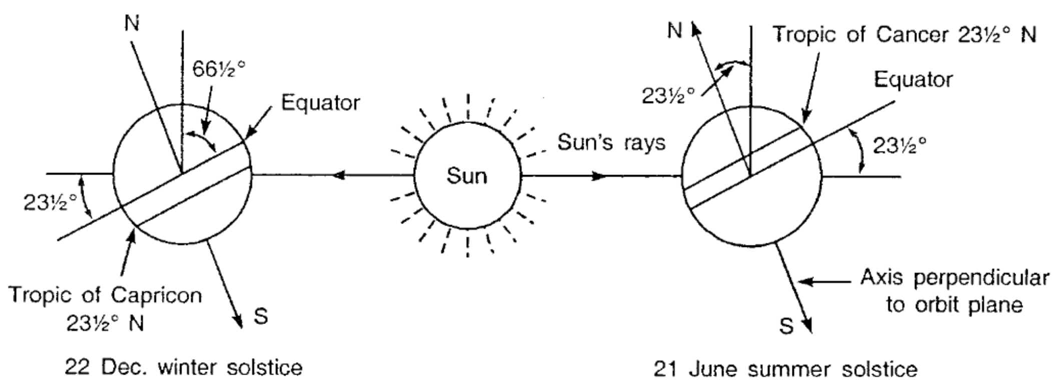
Solar radiation for point P on the earth's surface can be calculated if its position with regard to sun's rays is known

- latitude Φ
- hour angle ω
- sun's declination δ.

2.6 Solar Radiation Geometry

Latitude (Φ) 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. Conventionally, the latitude for northern hemisphere is positive.

Declination (δ) is the angle subtended by a line joining the centres of the earth and the sun with its projection on the earth's equatorial plane. Declination occurs as the axis of the earth is inclined to the plane of its orbit at an angle 66.5°



Tropics and northern hemisphere.

2.6 Solar Radiation Geometry

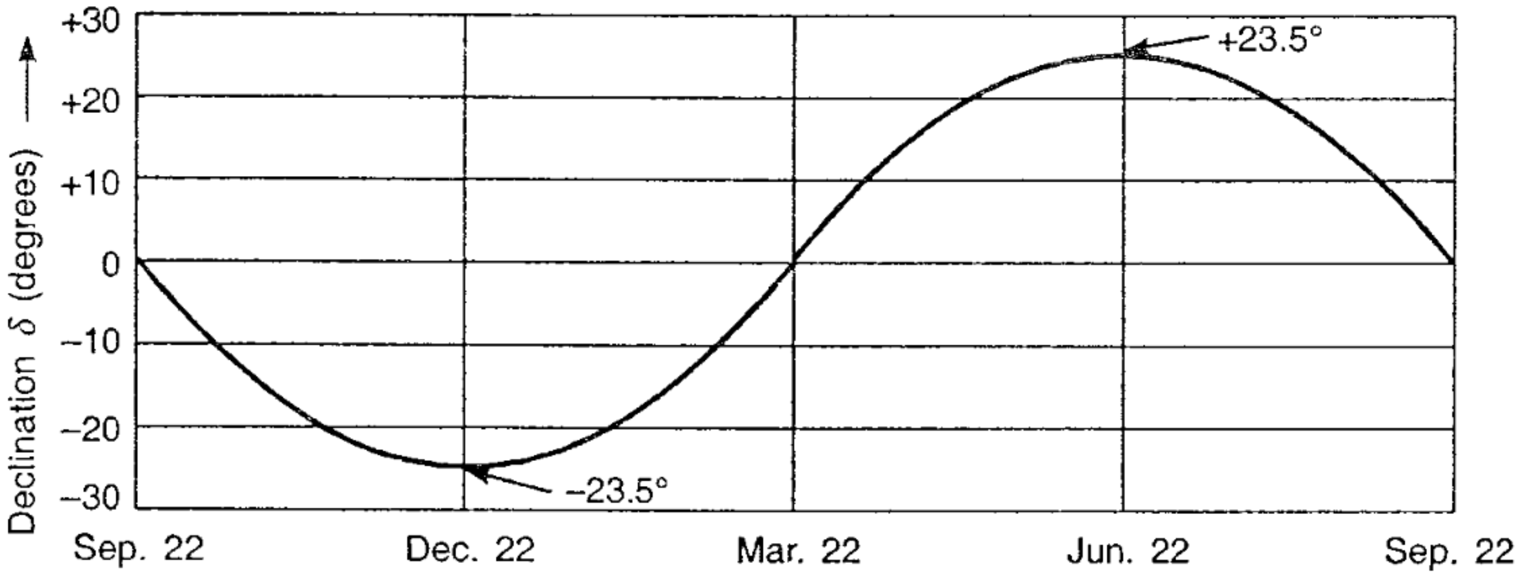
- The declination angle (δ) changes from a maximum value of +23.45° on June 21 to a minimum of -23.45° on December 22.
- The declination is zero on two equinox days, i.e. March 22 (Fall) and September 22 (Spring).
- The angle of declination may be calculated as suggested by Cooper (1969)

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

where *n* is the total number of days counted from first January till the date of calculation.

For June 21, 2004, n = 31 + 29 + 31 + 30 + 31 + 21 = 173

2.6 Solar Radiation Geometry



Spring equinox | Winter equinox | Fall equinox | Summer equinox | Spring equinox

Time of the year ⟶

2.6 Solar Radiation Geometry

Hour angle (ω) is the angle through which the earth must rotate to bring the meridian of the point directly under the sun.

- It is the angular measure of time at the rate of 15° per hour.
- Hour angle is measured from noon, based on local apparent time being positive in the afternoon and negative in the forenoon

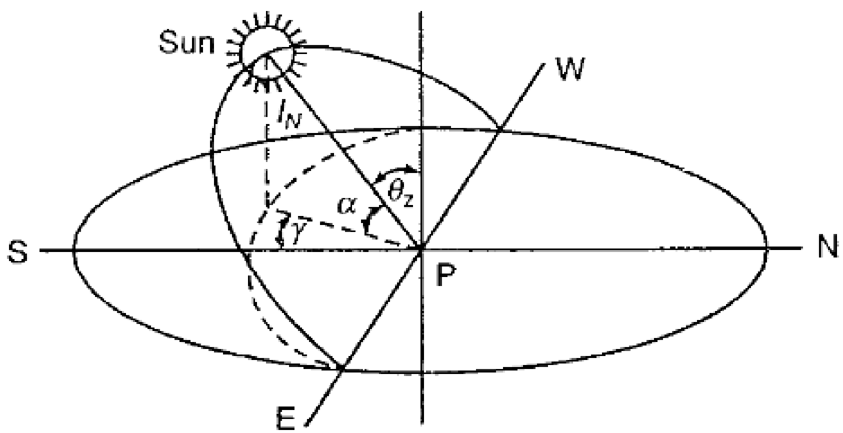
Altitude angle (α) is a vertical angle between the direction of sun rays (passing through the point) and its projection on the horizontal plane.

Zenith angle (θ_z) is the vertical angle between the sun's rays and the line perpendicular to the horizontal plane through the point. It is the complimentary angle of the sun's altitude angle. Thus, $\theta_Z + \alpha = \frac{\pi}{2}$

2.6 Solar Radiation Geometry

Surface azimuth angle (γ) is an angle subtended in the horizontal plane of the normal to the surface on the horizontal plane. By convention the angle is taken,

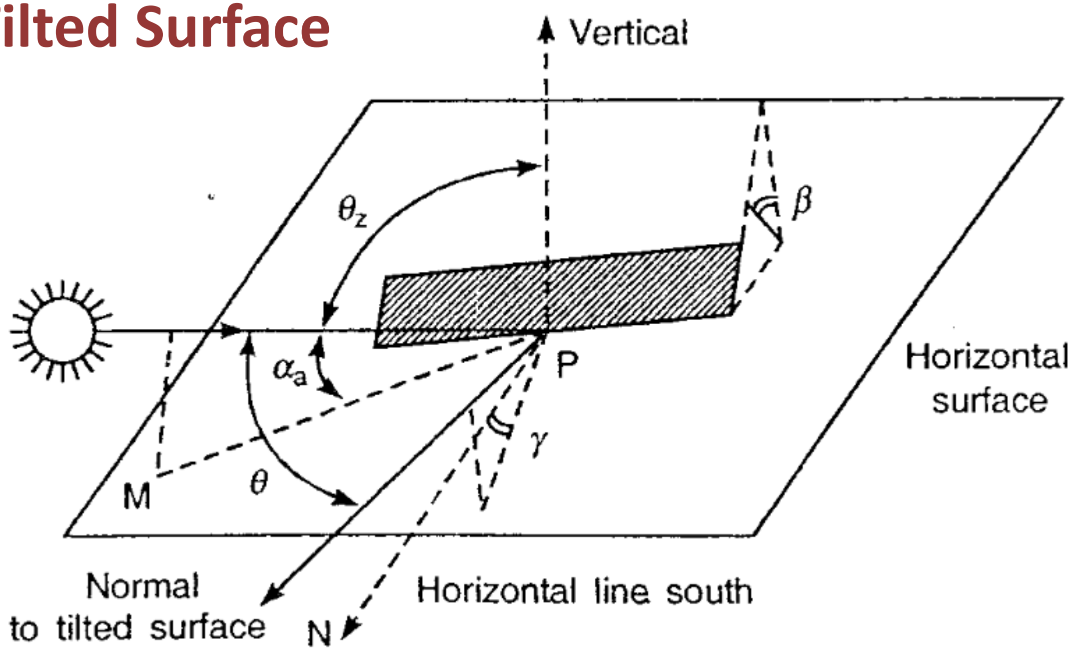
- positive if the normal is west of south
- negative when east of south in northern hemisphere
- vice versa for southern hemisphere.



Sun's zenith, altitude and azimuth angles (northern hemisphere)

2.6 Solar Radiation Geometry

Tilted Surface



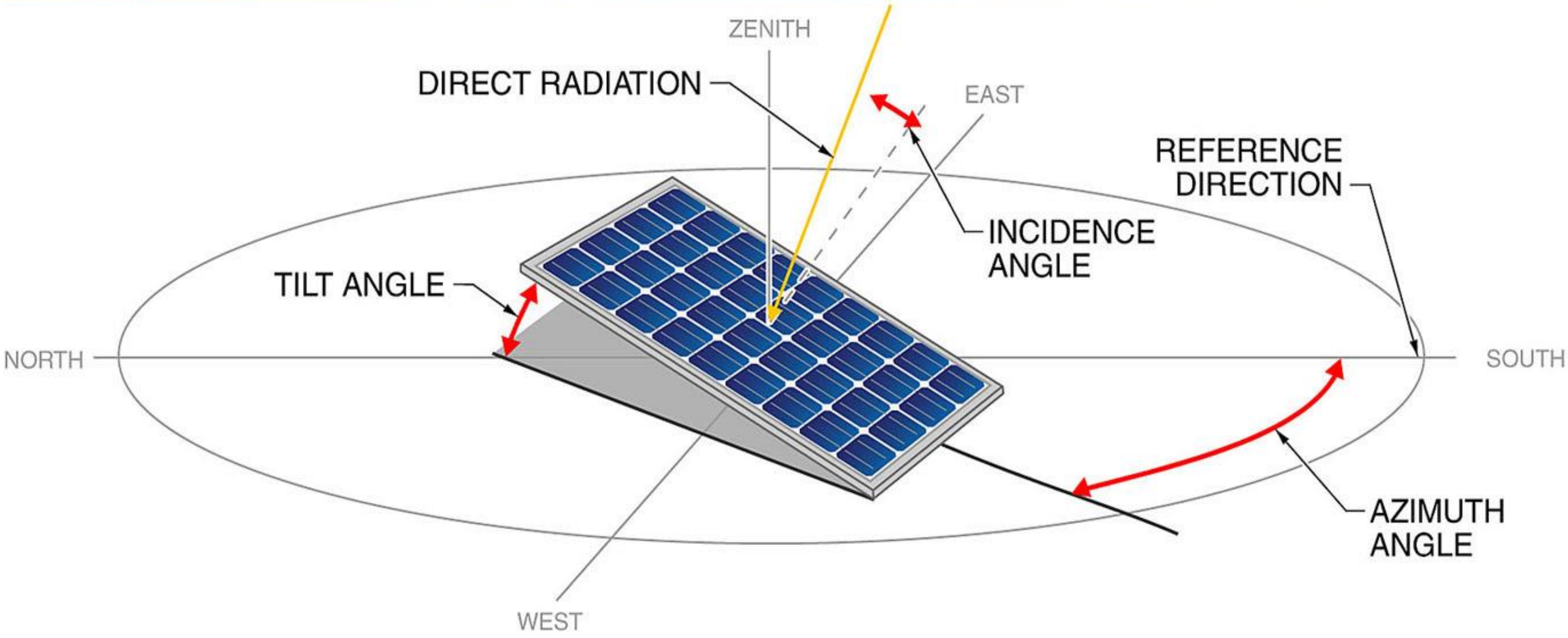
θ = angle of incidence
θ_z = zenith angle
α_a = solar altitude angle
β = slope
γ = surface azimuth angle

Slope (β) is an angle made by the plane surface with the horizontal surface. The angle is taken:-

- ❑ positive for a surface sloping towards south (+S)
- ❑ negative for a surface sloping north (-N)

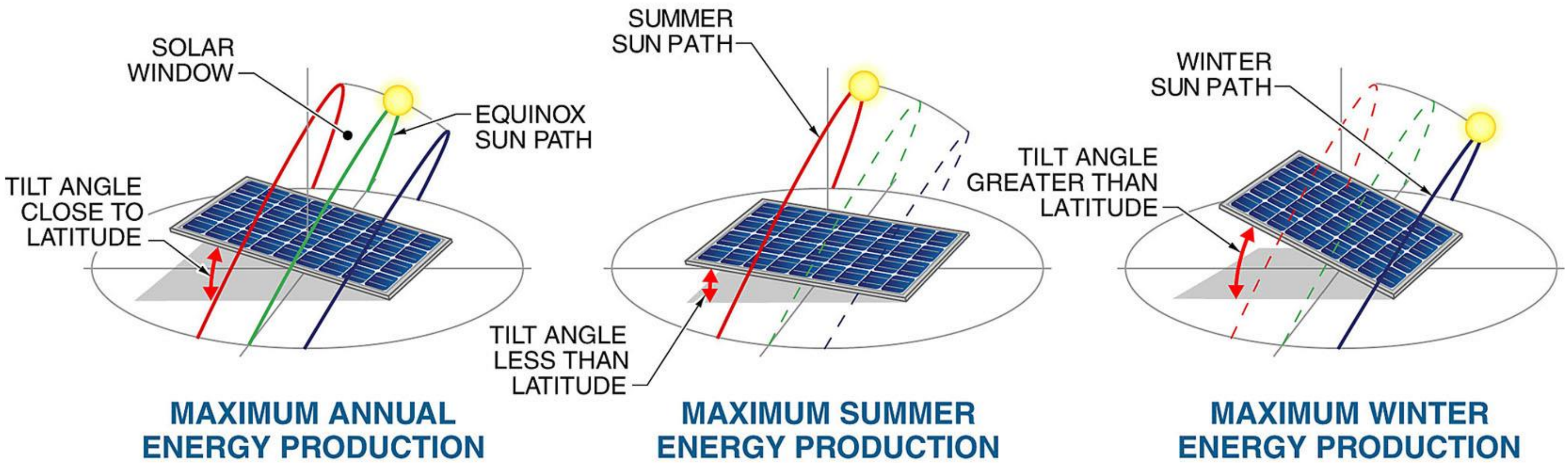
2.6 Solar Radiation Geometry

Array orientation of azimuth/tilt angles



2.6 Solar Radiation Geometry

Optimum Tilt Angle



Energy production at certain times of the year can be optimized by adjusting the array tilt angle.

2.6 Solar Radiation Geometry

Calculation of Cos Θ

The beam energy falling on a surface having any orientation, the incident beam flux I_b is multiplied by cos Θ, where Θ is the angle between the incident beam and the normal to the tilted surface. The angle Θ depends on the position of sun in the sky.

A general equation showing the relation of angles is

$$\boxed{\begin{aligned}\cos\Theta = {} & \sin\Phi\,(\sin\delta\cos\beta + \cos\delta\cos\gamma\cos\omega\sin\beta) \\ & + \cos\Phi\,(\cos\delta\cos\omega\cos\beta - \sin\delta\cos\gamma\sin\beta) \\ & + \cos\delta\sin\gamma\sin\omega\sin\beta\end{aligned}}$$

i) For vertical surface, $\beta = 90^o$

$$\cos\Theta = \sin\Phi\cos\delta\cos\gamma\cos\omega - \cos\Phi\sin\delta\cos\gamma + \cos\delta\sin\gamma\sin\omega$$

2.6 Solar Radiation Geometry

Calculation of Cos θ

ii) For horizontal surface, $\beta = 0^o$; θ = zenith angle θ_z

$$\cos\theta = \sin\Phi \sin\delta + \cos\Phi \cos\delta \cos\omega$$

iii) For northern hemisphere, winter south facing sun $\gamma = 0^o$

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

iv) For vertical surface facing due south , $\beta = 90^o$, $\gamma = 0^o$

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

Solar Azimuth Angle (γ_s)

An angle in the horizontal plane between the line due south and projection of beam radiation on the horizontal plane. Conventionally, the solar azimuth angle is considered positive if the projection of the sun beam is west of south and negative if east of south in northern hemisphere.

2.6 Solar Radiation Geometry

Sunrise, Sunset and Length of Day

The times of sunrise and sunset and the duration of the day length depend upon the latitude of the location and the month in the year. At sunrise and sunset, the sunlight is parallel to the ground surface with a zenith angle of 90°. The hour angle pertaining to sunrise or sunset (w_s) is obtained from case (ii)

$$\cos \omega_s = -\tan \Phi \tan \delta$$

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

- value of hour angle corresponding to sunrise is positive
- value of hour angle corresponding to sunset is negative

The total angle between sunrise and sunset is given by

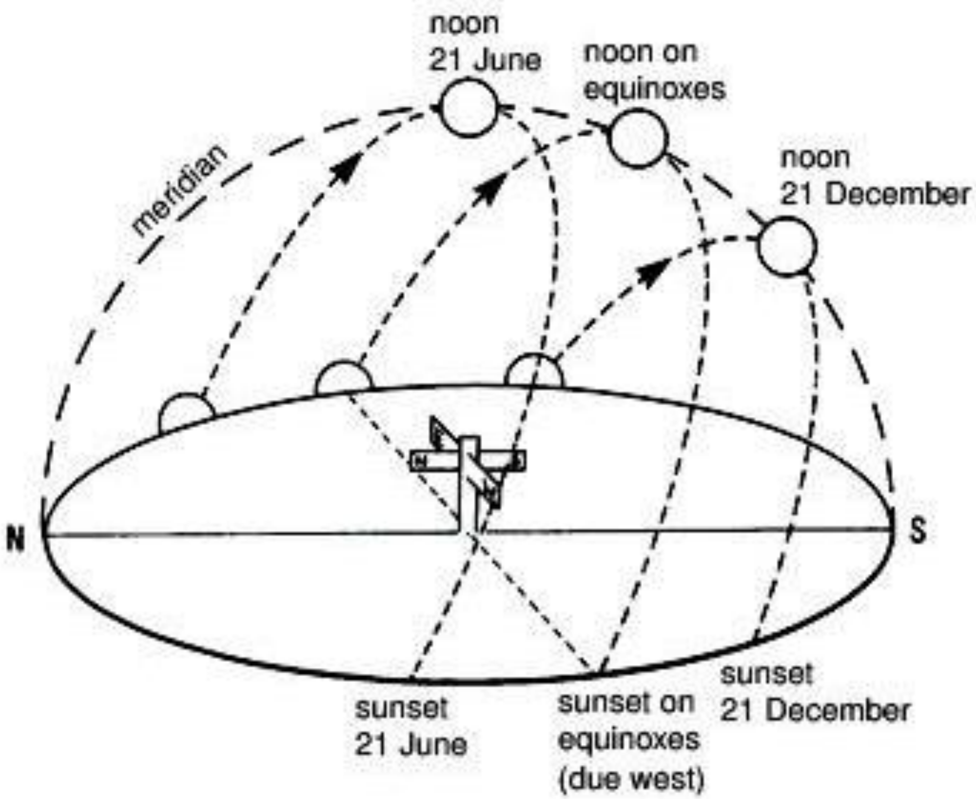
$$2\omega_s = 2\cos^{-1}(-\tan \Phi \tan \delta)$$

Since 15° of hour angle corresponds to one hour,
the corresponding day length (T_d) in hours is given by

$$T_d = \frac{2}{15}\cos^{-1}(-\tan \Phi \tan \delta)$$

2.6 Solar Radiation Geometry

Sunrise, Sunset and Length of Day



Sun in the northern hemisphere

2.6 Solar Radiation Geometry

Local Apparent Time (LAT)

It is the time used for calculating the hour angle ω is and not the same as the 'local clock time'. It can be obtained from the local time observed on a clock by applying two corrections:-

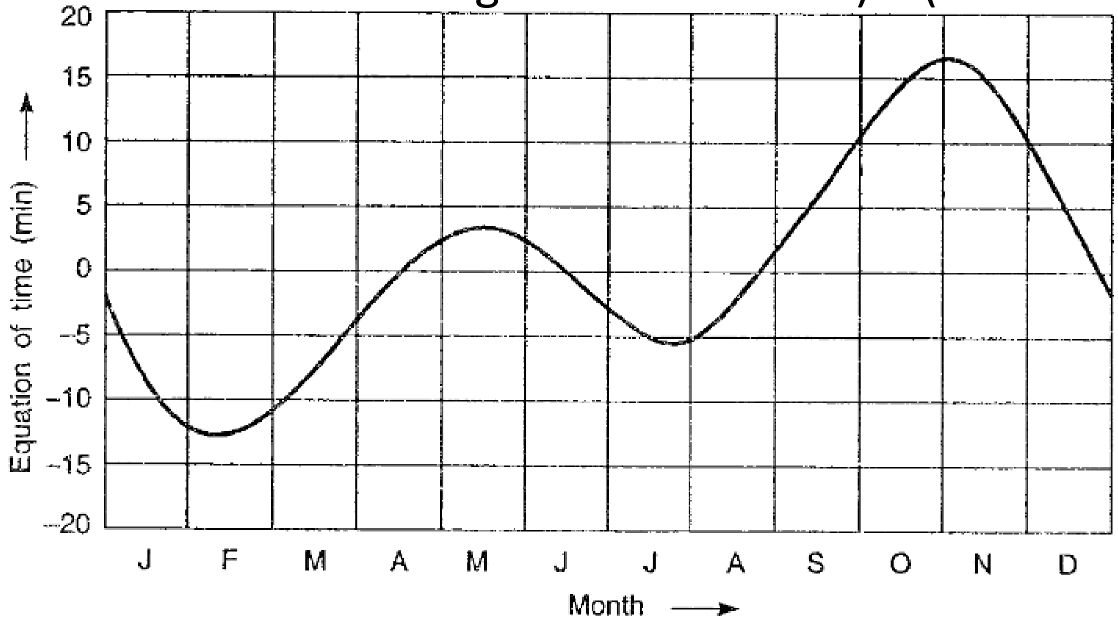
i. correction arises due to the difference between the longitude of a location and the meridian on which the standard time is determined. This correction has a magnitude of4 minutes for each degree difference in longitude.
ii. correction known as the 'equation of time correction' which is required due to the fact that the earth's orbit and the rate of rotation are subject to certain fluctuations.

This correction is applied by results of experimental observations as plotted in Figure

2.6 Solar Radiation Geometry

Local Apparent Time (LAT)

Local apparent time (LAT) = Standard time ± 4 (Standard time longitude - Longitude of location) + (Time correction)



Graph for the ‘equation of time correction’

2.6 Solar Radiation Geometry

Local Apparent Time (LAT)

Example:

Determine the local apparent time corresponding to 13:30 1ST on July 1, at Delhi (28°35' N, 77°12' E). The 'equation of time correction' on July 1 -4 minutes. In India, the standard time is based on 82°30' E.

Solution

$LAT =$ 13.50 h - 4 [(82.50) - (77.2)] min + (-4 min)

= 13.50 h - 4 (82.50 - 77.2) min - 4 min

= 13.50 h - 21.20 min - 4 min

= 13.50 h - 25.20 min

= 13.50 h - 0.42 h

= 13.08 h

= **13 h 4 min 48 s**

2.7 Estimation of Solar Radiation

Solar Radiation Availability

Dates When Day Value is Equal to Monthly Average Value

Month	Jan	Feb	Mar	Apr	May	June
Date	17	16	16	15	15	11

Month	July	Aug	Sep	Oct	Nov	Dec
Date	17	16	15	15	14	10

2.7 Estimation of Solar Radiation

The measurement of solar radiation at every location is not feasible and engineers have developed empirical equations by utilizing the meteorological data like the number of sunshine hours, the day length and the number of clear days. For accurate calculations, the hourly, the daily and the monthly time scales are used. Angstrom (1924) suggested a linear equation to determine the amount of sunshine at a given location.

$$H_g = H_c \left\{ a + b \left[\frac{D_L}{D_{max}} \right] \right\}$$

H_g = monthly average of daily global radiation on a horizontal surface at a given location, in MJ/m^2/day

H_c = monthly average of daily global radiation on a horizontal surface at the same location on a clear sky day, in MJ/m^2/day

D_L = monthly average measured solar day length, in hours

D_{max}= monthly average of longest day length, in hours

a, b = constants for the location

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2.7 Estimation of Solar Radiation – Malaysian Climate Profile

Location	Latitude φ	Longitude ψ	Angstrom Constants a	b
Alor Setar	6°07′00"N	100°22′00"E	0.31	0.40
Bandaraya Melaka	2°11′20″N	102°23′04″E	0.28	0.28
Ipoh	4°36′00"N	101°04′00"E	0.32	0.25
Johor Bharu	1°29′00"N	103°44′00"E	0.17	0.60
Kangar	6°26′00"N	100°12′00"E	0.31	0.40
Kota Bharu	6°08′00"N	102°15′00"E	0.20	0.47
Kota Kinabalu	5°58′17″N	116°05′42″E	0.31	0.40
Kuala Lumpur	3°08′51″N	101°41′36″E	0.27	0.35
Kuala Terengganu	5°20′00"N	103°09′00"E	0.32	0.25
Kuantan	3°49′00"N	103°20′00"E	0.27	0.35
Kuching	1°33′36″N	110°20′42″E	0.28	0.28
Pekan	3° 30′00"N	103°25′00"E	0.27	0.35
Pulau Pinang	5°24′00"N	100°14′00"E	0.31	0.40
Putrajaya	2°55′00″N	101°40′00"E	0.32	0.25
Seremban	2°43'00"N	101°57′00"E	0.28	0.28
Shah Alam	3°05′00"N	101°32′00"E	0.32	0.25
Wilayah Labuan	5°19′13″N	115°12′40″E	0.31	0.40

2.7 Estimation of Solar Radiation – Malaysian Climate Profile

City	Climate	Max./min. temperature, rainfall, and sunshine duration											
		1	2	3	4	5	6	7	8	9	10	11	12
Kuala Lumpur	Max.	32°C	33	33	33	33	32	32	32	32	32	31	31
	Min.	22°C	22	23	23	23	23	23	23	23	23	23	23
	Rain	159 mm	154	223	276	182	120	120	133	173	258	263	223
	Sun	6 hr	7	7	7	7	6	6	6	5	5	5	5
Malacca	Max.	32°C	33	33	32	32	31	31	31	31	31	31	31
	Min.	22°C	23	23	23	23	23	23	23	23	23	23	23
	Rain	90 mm	104	147	184	166	172	181	178	206	216	237	142
	Sun	7 hr	7	7	7	7	6	7	6	6	6	5	5
Penang	Max.	32°C	32	32	32	31	31	31	31	31	31	31	31
	Min.	23°C	23	24	24	24	24	23	23	23	23	23	23
	Rain	70 mm	93	141	214	240	170	208	235	341	380	246	107
	Sun	8 hr	8	8	7	7	7	7	6	5	5	6	7
Kota Bahru	Max.	29°C	30	31	32	33	32	32	32	32	31	29	29
	Min.	22°C	23	23	24	24	24	23	23	23	23	23	23
	Rain	163 mm	60	99	81	114	132	157	168	195	286	651	603
	Sun	7 hr	8	9	9	8	7	7	7	7	6	5	5
Kuala Terengganu	Max.	28°C	29	30	31	32	32	31	31	31	30	29	26
	Min.	22°C	23	23	23	24	23	23	23	23	23	23	23
	Rain	174 mm	99	109	101	103	108	110	141	184	266	643	559
	Sun	7 hr	7	8	8	8	7	7	7	6	6	5	4
Pekan / Kuantan	Max.	29°C	31	32	33	33	33	32	32	32	32	30	29

2.7 Estimation of Solar Radiation

Solar radiation incident on a surface has three components.

i. Beam solar radiation
ii. Diffuse solar radiation
iii. Reflected solar radiation from ground and surroundings.

- Maximum solar energy if flat plate collectors always face the sun using a sun tracking equipment.
- Solar thermal radiation collecting appliances are tilted at an angle to the horizontal.
- Measuring instruments generally measure the values of solar radiation falling on a horizontal surface.
- Mathematical analysis is necessary to convert the values measured on horizontal surfaces to the corresponding values obtainable on the inclined surfaces.

2.7 Estimation of Solar Radiation

Beam radiation

Inclined surface faces south obtain maximum solar radiation even in winter, i.e. $\gamma = 0°$. Therefore,

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

In horizontal surface $(\theta = \theta_Z)$, therefore

$$\cos\theta_Z = \sin\emptyset\sin\delta + \cos\emptyset\cos\delta\cos\omega$$

Ratio of beam radiation falling on an inclined surface to that falling on a horizontal surface is termed *tilt factor for beam radiation* R_b

$$R_b = \frac{\cos\theta}{\cos\theta_Z} = \frac{\sin\delta\sin(\emptyset-\beta) + \cos\delta\cos\omega\cos(\emptyset-\beta)}{\sin\emptyset\sin\delta + \cos\emptyset\cos\delta\cos\omega}$$

Other equations for R_b can be derived complying to conditions $\gamma \neq 0°$.

2.7 Estimation of Solar Radiation

Diffuse radiation

The ratio of diffuse radiation falling on a tilted surface with a slope β to horizontal surface is known ***tilt factor for diffuse radiation*** R_d given by

$$R_{\mathrm{d}} = \frac{1 + \cos\beta}{2}$$

where $(1 + \cos \beta)/2$ is the ***radiation shape factor*** for an inclined surface with reference to the sky.

2.7 Estimation of Solar Radiation

Reflected radiation

$(1 + \cos \beta)/2$ = radiation shape factor for inclined surface with respect to sky
$(1 - \cos \beta)/2$ = radiation shape factor for inclined surface with respect to surroundings

Beam and diffuse radiation after reflection from the ground is diffuse and isotropic with reflectivity is ρ, the ***tilt factor for reflected radiation*** is given by

$$R_{\mathrm{r}} = \frac{\rho(1-\cos\beta)}{2}$$

2.7 Estimation of Solar Radiation

Total radiation

The total radiation flux falling on an inclined surface at any instant is given by

$$I_{\mathrm{T}} = I_{\mathrm{b}}R_{\mathrm{b}} + I_{\mathrm{d}}R_{\mathrm{d}} + (I_{\mathrm{b}} + I_{\mathrm{d}})R_{\mathrm{r}}$$

Dividing the above equation by $\boldsymbol{I_g}$, we get the ratio of solar flux reaching on an inclined surface at any instant to that on a horizontal surface.

$$\frac{I_{\mathrm{T}}}{I_{\mathrm{g}}} = \left(1 - \frac{I_{\mathrm{d}}}{I_{\mathrm{g}}}\right)R_{\mathrm{b}} + \frac{I_{\mathrm{d}}}{I_{\mathrm{g}}}R_{\mathrm{d}} + R_{\mathrm{r}} \qquad (\because I_{\mathrm{g}} = I_{\mathrm{b}} + I_{\mathrm{d}})$$

Diffuse reflectivity, ρ = 0.2 for concrete surface or grass
ρ = 0.7 for snow cover

2.7 Estimation of Solar Radiation

Total radiation

- The monthly average of daily radiation reaching a tilted surface is required in dealing with liquid flat-plate collectors and in other applications.
- Liu and Jordan suggested that the **ratio of the daily radiation** falling on an inclined surface (H_T) to the daily global radiation on an horizontal surface (Hg) can be represented by

$$\frac{H_{\mathrm{T}}}{H_{\mathrm{g}}} = \left(1 - \frac{H_{\mathrm{d}}}{H_{\mathrm{g}}}\right) R_{\mathrm{b}} + \frac{H_{\mathrm{d}}}{H_{\mathrm{g}}} R_{\mathrm{d}} + R_{\mathrm{r}}$$

2.7 Estimation of Solar Radiation

Total radiation

For a surface facing south (γ = 0°), Liu and Jordan proposed

$$R_{\mathrm{b}} = \frac{\omega_{\mathrm{si}} \sin\delta \sin(\emptyset - \beta) + \cos\delta \sin\omega_{\mathrm{si}} \cos(\emptyset - \beta)}{\omega_{\mathrm{sh}} \sin\emptyset \sin\delta + \cos\emptyset \cos\delta \sin\omega_{\mathrm{sh}}}$$

$$R_{\mathrm{r}} = \frac{\rho(1 - \cos\beta)}{2}$$

$$R_{\mathrm{d}} = \frac{1 + \cos\beta}{2}$$

Where ω_{si} and ω_{sh} are sunrise and sunset hour angle (in radians) for inclined surface and horizontal surface respectively.

Problem 2.1: Monthly average hourly solar flux H_T

Compute the monthly average hourly solar flux received on a flat-plate collector located at a place in Pekan (03°30' N, 103°25' E) facing due south (γ = 0°) and inclined with a slope of 12° on 16th day of October 2012.

Given data:

H_g = 4.076 kWh/m²-day

H_d = 2.954 kWh/m²-day

Ground reflectivity, $\rho = 0.2$, $\omega = 7.5°$

Liu and Jordan (1960) suggested that the *ratio of the daily radiation* falling on an inclined surface (H_T) to the daily global radiation on an horizontal surface (H_g) be represented by the expression

$$\frac{H_T}{H_g} = \left(1 - \frac{H_d}{H_g}\right)R_b + \frac{H_d}{H_g}R_d + R_r$$

Solution 2.1: Monthly average hourly solar flux H_T

Monthly average hourly solar flux

For given data: $H_g = 4.076$ kWh/m²-day
$H_d = 2.954$ kWh/m²-day
Ground reflectivity, $\rho = 0.2$, $\omega = 7.5°$

The angle of declination may be calculated as suggested by Cooper (1969)

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

where n is the total number of days counted from first January on 16/10/2012

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	*n*
31	28	31	30	31	30	31	31	30	16	**289**

Hence,

$$\delta = 23.45 sin\left[\frac{360}{365}(284+289)\right] = -9.97°$$

Solution 2.1: Monthly average hourly solar flux H_T

Ratio of beam radiation falling on an inclined surface to that falling on a horizontal surface is termed *tilt factor for beam radiation* R_b

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

$$= \frac{\sin(-9.97^\circ)\sin(3.5-12)+\cos(-9.97^\circ)\cos 7.5\cos(3.5-12)}{\sin 3.5\sin(-9.97^\circ)+\cos 3.5\cos(-9.97^\circ)\cos 7.5} = 1.028$$

The ratio of diffuse radiation falling on a tilted surface with a slope β to horizontal surface is known *Tilt Factor For Diffuse Radiation* R_d given by

$$R_d = \frac{1+\cos\beta}{2} = \frac{1+\cos 12^\circ}{2} = 0.989$$

Beam and diffuse radiation after reflection from the ground is diffuse and isotropic with reflectivity is ρ, the *Tilt Factor For Reflected Radiation* is given by

$$R_r = \frac{0.2(1-\cos 12^\circ)}{2} = 0.0022$$

Solution 2.1: Monthly average hourly solar flux H_T

Liu and Jordan suggested that the Ratio Of The Daily Radiation falling on an inclined surface (H_T) to the daily global radiation on an horizontal surface (Hg) can be represented by

$$\frac{H_T}{H_g} = \left(1 - \frac{H_d}{H_g}\right) R_b + \frac{H_d}{H_g} R_d + R_r$$

$$= \left(1 - \frac{2.954}{4.076}\right) 1.028 + \left(\frac{2.954}{4.076}\right) 0.989 + 0.0022 = 1.002$$

The monthly average of daily radiation reaching on a inclined surface (H_T) tilted flat-plate collector surface is given

$$H_T = 1.002 \times H_g = 1.002 \times 4.076 = 4.084 \frac{\text{kWh}}{\text{m}^2} \text{day}$$

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