Solar Energy

Energy Resources and Utilization (ESL100)

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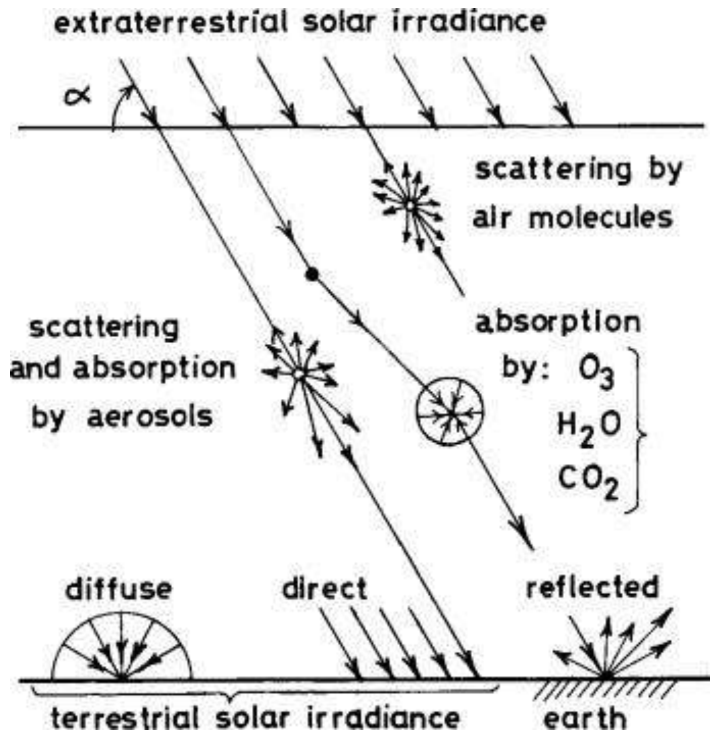
Basics

Air Mass (Path length of solar radiation through atmosphere assuming vertical path as unity)

- A part of sun's radiation travelling through the atmosphere and reaching the earth's atmosphere directly is defined as **direct/ beam radiation**.
- Major part of the radiation entering atmosphere is reflected back, absorbed or scattered within the atmosphere thus a part is re-radiated and finally reaches the earth's surface from all the directions. This is known as **diffused radiation**.

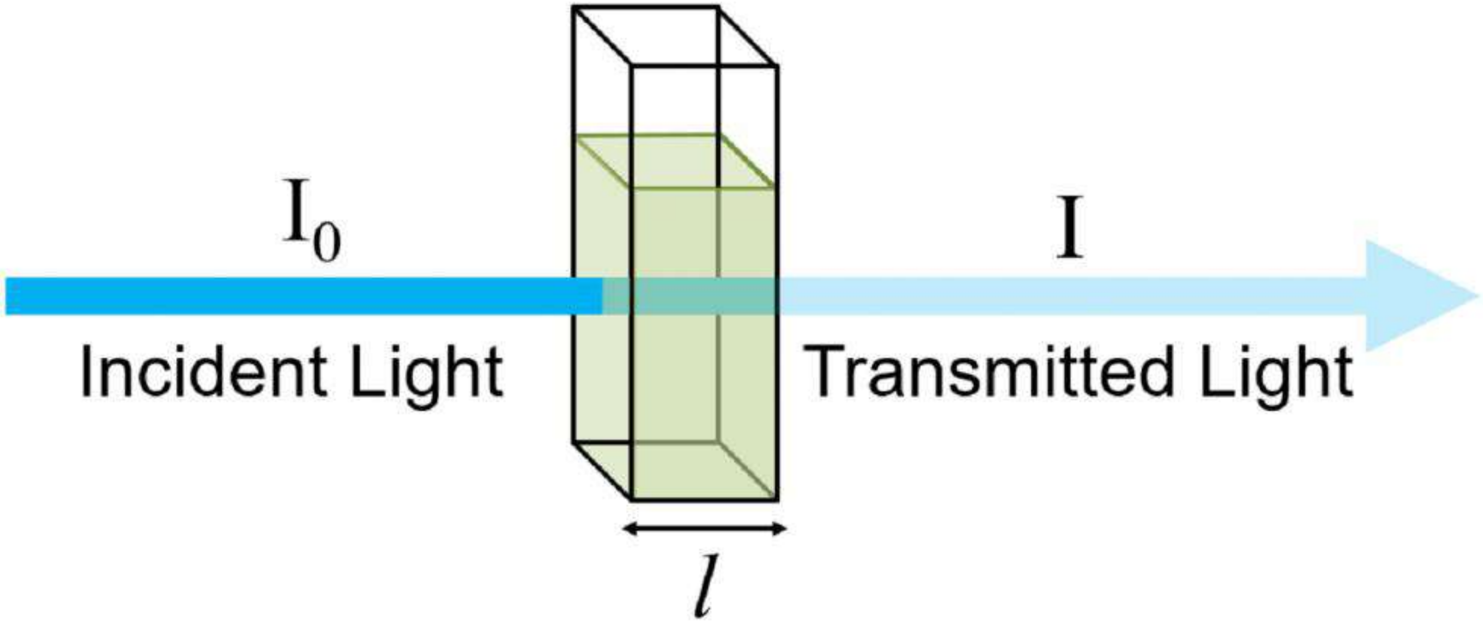
Albedo: *Earth reflects about 30 % of incoming solar radiation to extra-terrestrial region through earth's atmosphere.*

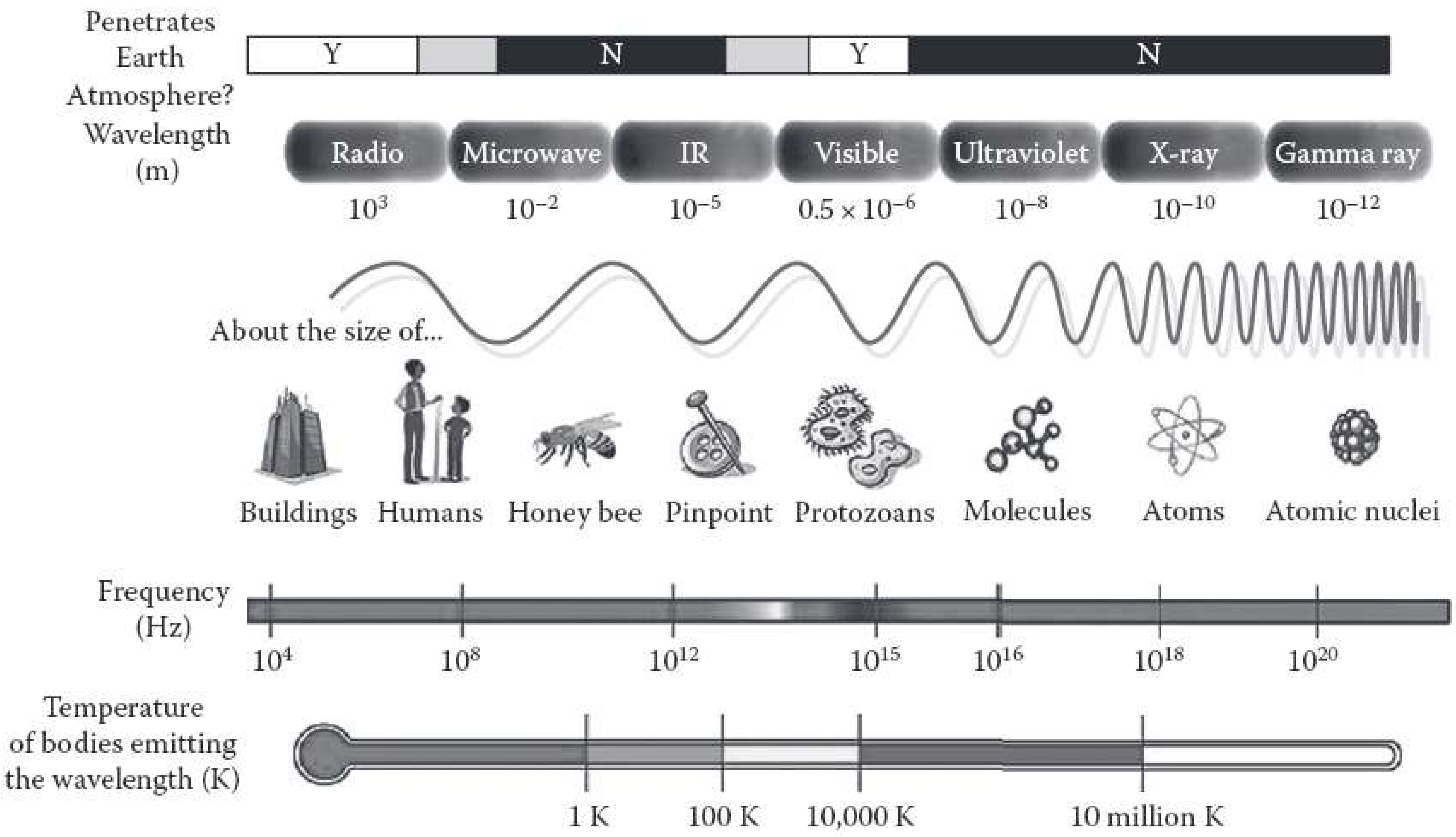


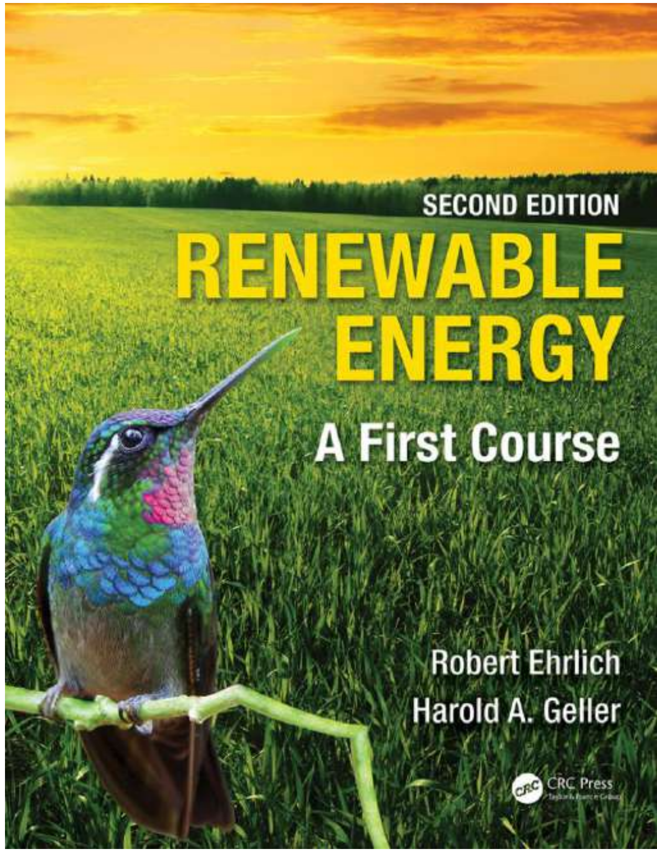
Extinction due to absorption and scattering
Beer Lambert's law

$$I = I_0 \exp(-kx)$$

Here x=l




Penetrates Earth Atmosphere?
Y
N
Y
N
Wavelength (m)
Radio
Microwave
IR
Visible
Ultraviolet
X-ray
Gamma ray
10^3
10^-2
10^-5
0.5 × 10^-6
10^-8
10^-10
10^-12
About the size of...
Buildings
Humans
Honey bee
Pinpoint
Protozoans
Molecules
Atoms
Atomic nuclei
Frequency (Hz)
10^4
10^8
10^12
10^15
10^16
10^18
10^20
Temperature of bodies emitting the wavelength (K)
1 K
100 K
10,000 K
10 million K


SECOND EDITION
RENEWABLE ENERGY
A First Course
Robert Ehrlich
Harold A. Geller
CRC Press

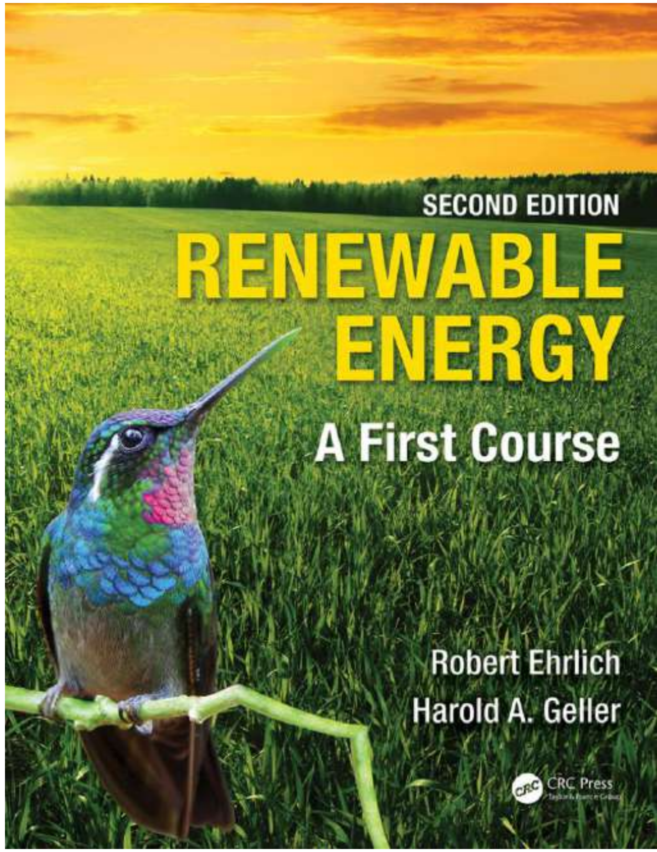
$$q = \frac{P}{A} = \varepsilon\sigma T^4,$$

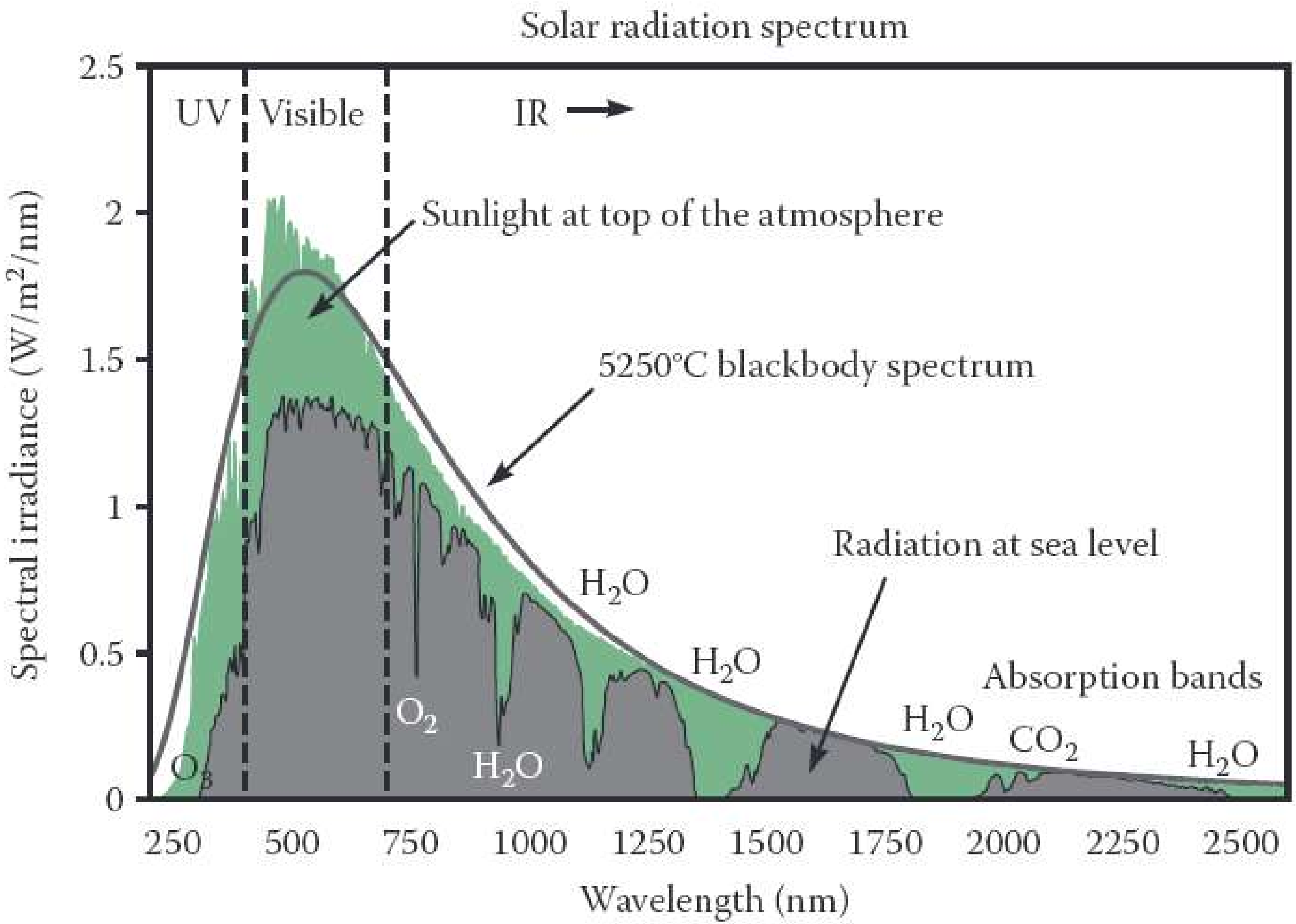
$$\sigma = 5.67 \times 10^{-8}\ \mathrm{W/m^2\ K^4}.$$

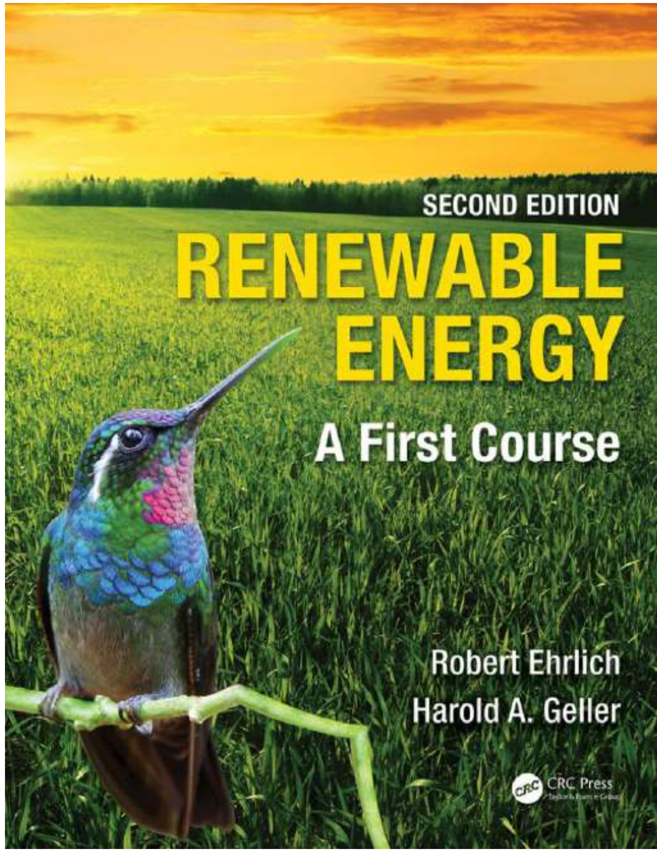
Wien's law:

$$\lambda_{\max} = \frac{0.002898\ \mathrm{m\,K}}{T}$$

Wavelength at which emissive energy is maximum







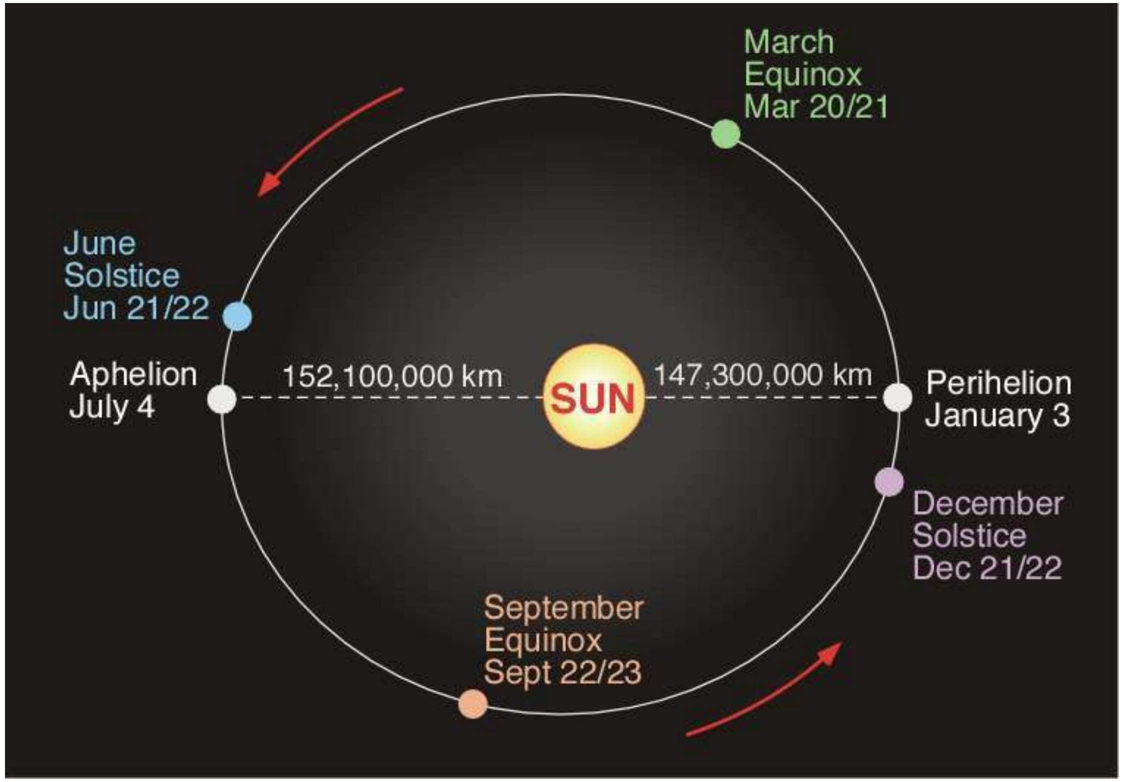
Solar spectra at sea level (gray shading) and the top of the atmosphere (light green shading) and the spectrum for a 5260°C or ~ 5600 K blackbody

Sun: The Primary power source for all

The energy that reaches the Earth from 20 days of sunshine is equal to the energy stored in all of Earth's reserves of fossil fuels like, coal, petroleum, and natural gas!!

<u>Sun-Earth Geometry:</u>

- Mean Sun-Earth distance: 149,500,000 km
- Earth's diameter: 12710 km
- Sun's dia: 1392400 km
- Solar surface temperature: 5600 K



• Tilt of the Earth's Axis

The ecliptic plane can be defined as a two-dimensional flat surface that geometrically intersects the Earth's orbital path around the Sun.

On this plane, the Earth's axis is not at right angles to this surface, but inclined at an angle of about 23.45° from the perpendicular.

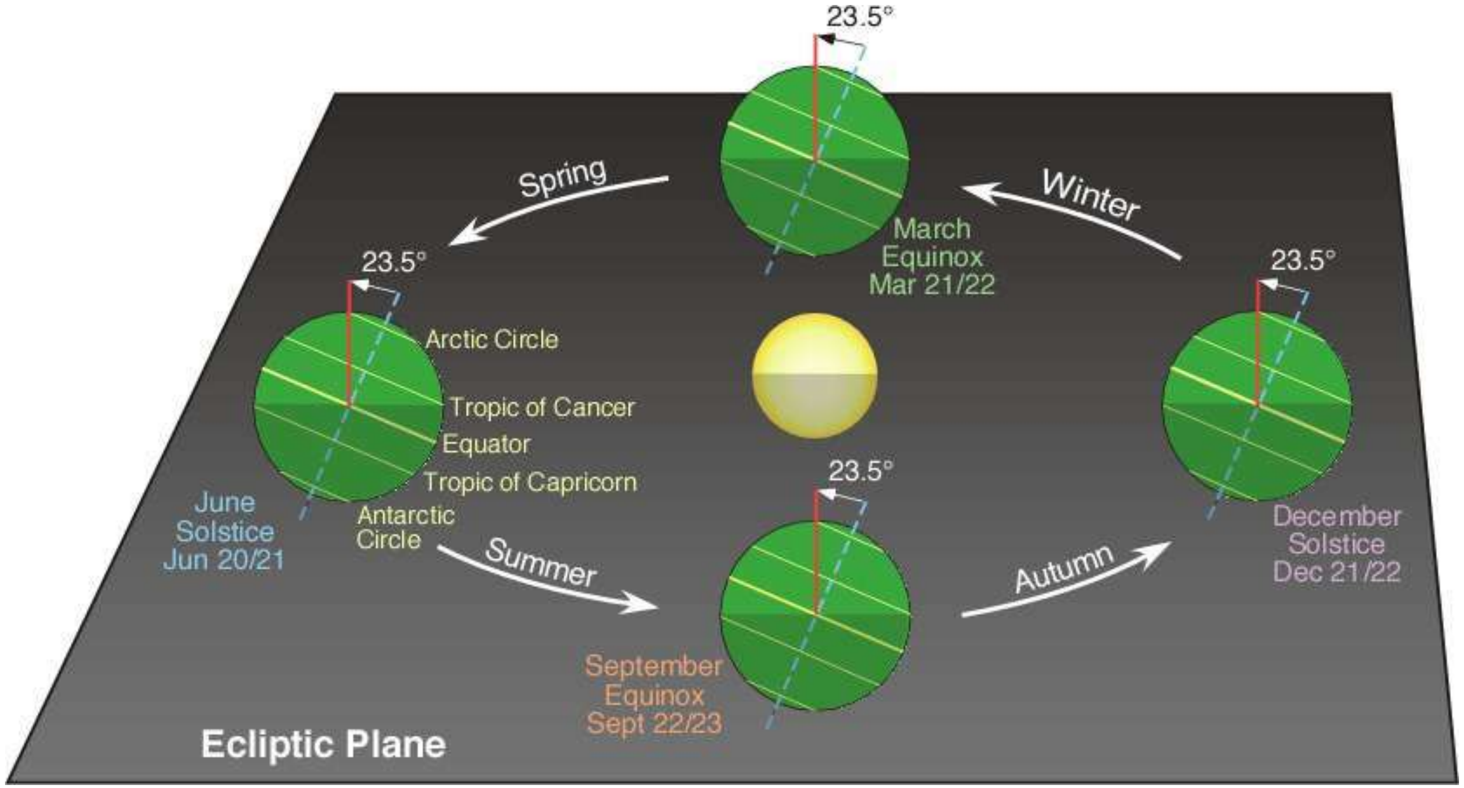
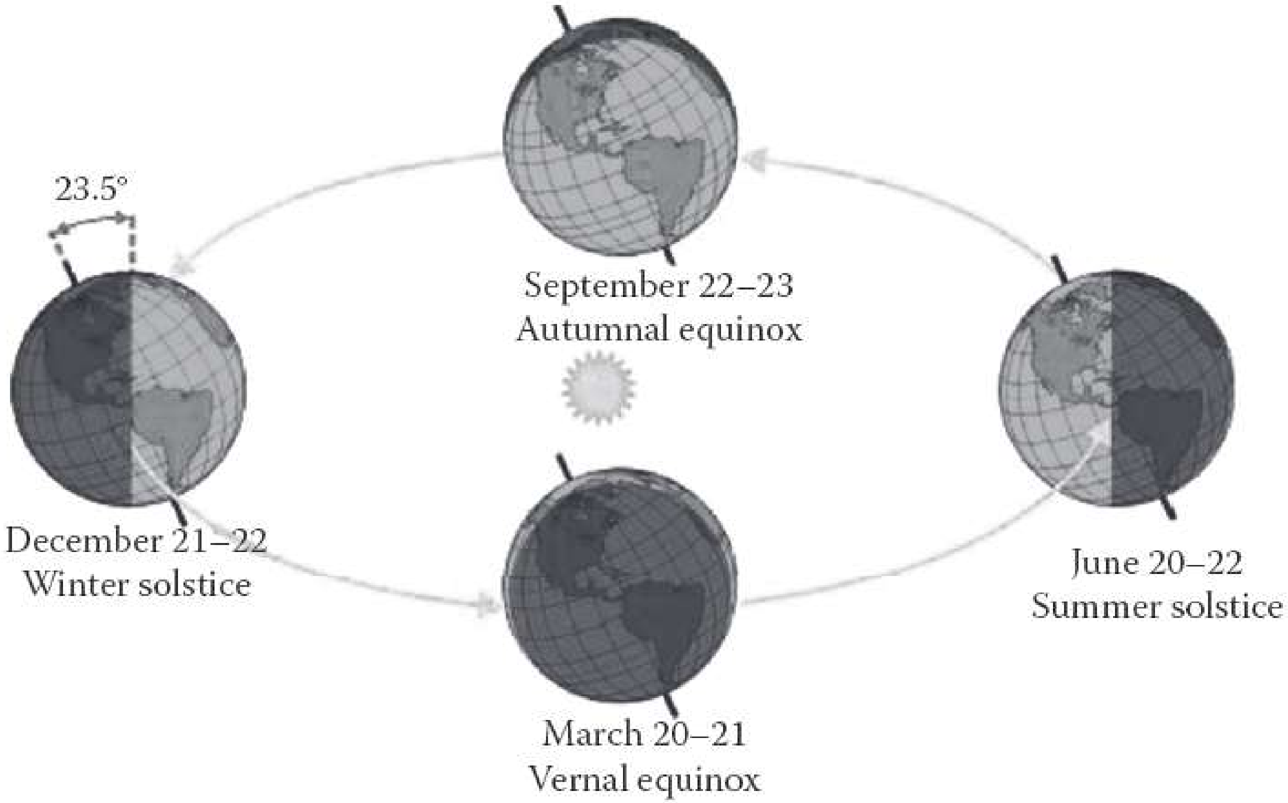
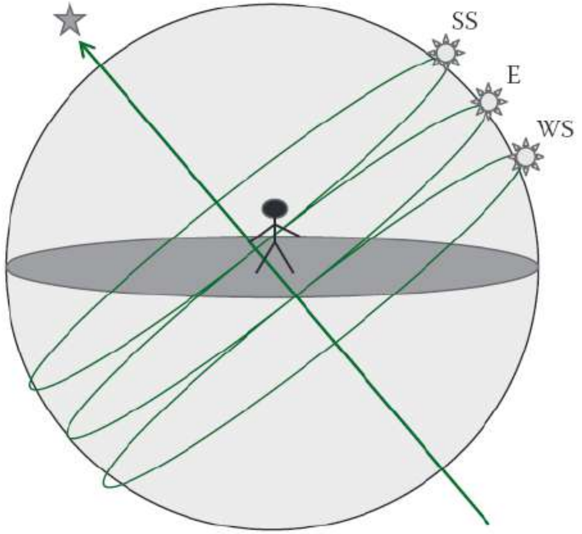
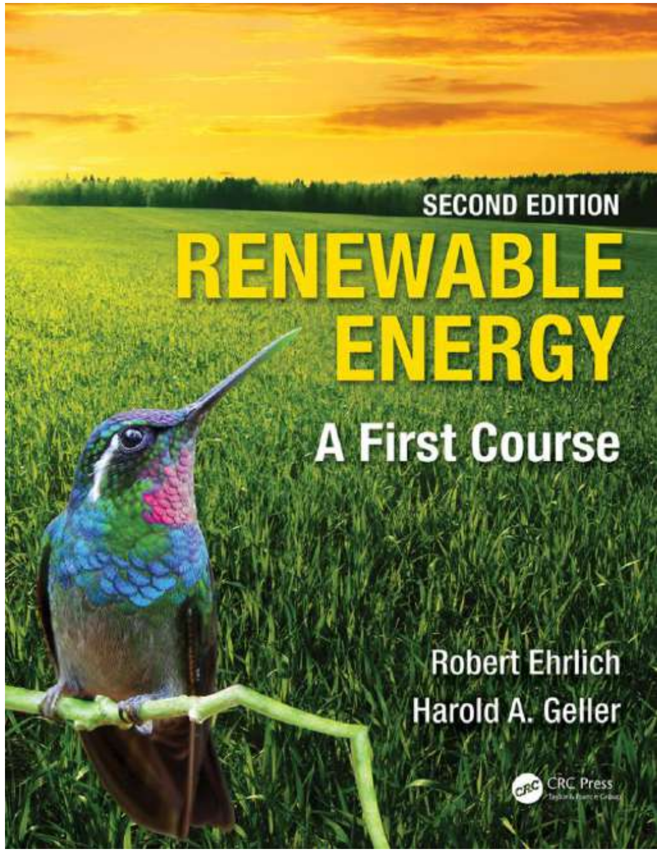


Figure shows a side view of the Earth in its orbit about the Sun on four important dates: June solstice, September equinox, December solstice, and March equinox.







Apparent motion of the sun as seen by an observer on Earth

Two worth noting events !! ☺

- <u>The Equinox (Spring & Autumnal)(20 March & 22 September):</u>

1. There are only two times of the year when the Earth's axis is tilted neither toward nor away from the sun, resulting in a "nearly" equal amount of daylight and darkness at all latitudes. These events are referred to as Equinoxes.
2. The word equinox is derived from two Latin words - *aequus* (equal) and *nox* (night). At the equator, the sun is directly overhead at noon on these two equinoxes.

- <u>The Solstice (Summer & Winter)(21 June & 21 December):</u>

1. The summer solstice occurs at the moment the earth's tilt toward from the sun is at a maximum. Therefore, on the day of the summer solstice, the sun appears at its highest elevation with a noontime position that changes very little for several days before and after the summer solstice.

- <u>Solar constant :</u>
- The amount of solar energy received per unit time per unit area at the mean distance of the earth from the sun on a surface normal to the sun is called the solar constant Isc.
- This quantity is difficult to measure from the surface of the earth because of the effect of the atmosphere.
- When the sun is closest to the earth, on December 21 the solar heat on the outer edge of the earth's atmosphere is about 1400 W/m^2 and when the sun is farthest away on June 21 is about 1310 W/m^2.
- Solar constant in SI: ~ 1367 W/m^2

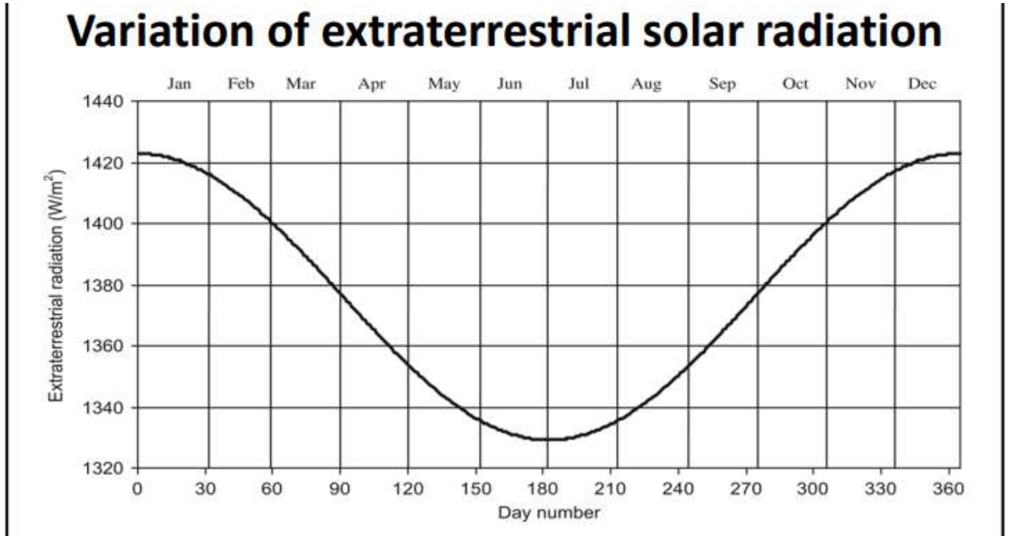
➢Variation of extraterrestrial radiation

- Throughout the year the solar heat Ion varies between these limits as indicated in figure in the range of 3% and can be calculated by:

$$Ion = Isc\ [\ 1+0.033\ \cos(360\ N / 365]$$

- Where: Ion = extraterrestrial radiation measured on the plane normal to the radiation on the Nth day of the year (W/m^2); and Isc = solar constant, (W/m^2).

- The latest value of Isc as obtained from recent satellite data and adopted by the World Radiation Center, is 1367 W/m^2 with an estimated error of 1%.



SUN-EARTH ANGLES

Latitude (ϕ):

- Angle made by the radial line, joining the given location to the center of the earth, with it's projection on the equatorial plane.
- Northern hemisphere: +ve
- Southern Hemisphere: –ve

Source: Solar Energy: Fundamentals, Design, Modelling and Applications, G. N. Tiwari

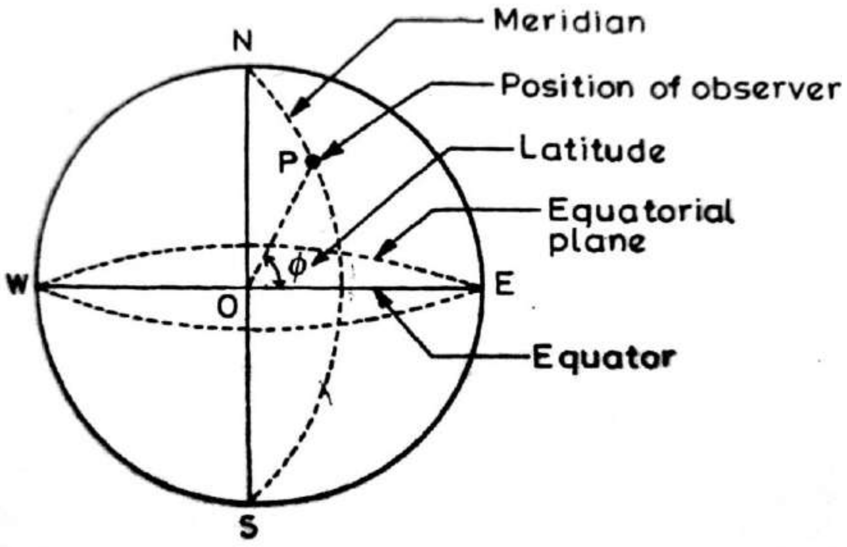


Figure: Latitude of a place

Attribute	Name of Corresponding Angle	Definition of Angle
Location	Latitude (ϕ) (angle between the earth's equatorial plane and a line from the centre of the earth to the site/ location)	Angular location of the place (site) north (+ ve) or south (- ve) of equator

SUN-EARTH ANGLES

Day of the year	Declination (δ) δ = 23.45° sin [{360 (284 + n)}/365] [Maximum value: 23.45° Minimum value: (-) 23.45°]	Angular position of the sun at solar noon with respect to plane of the equator (+ ve , north of equator)

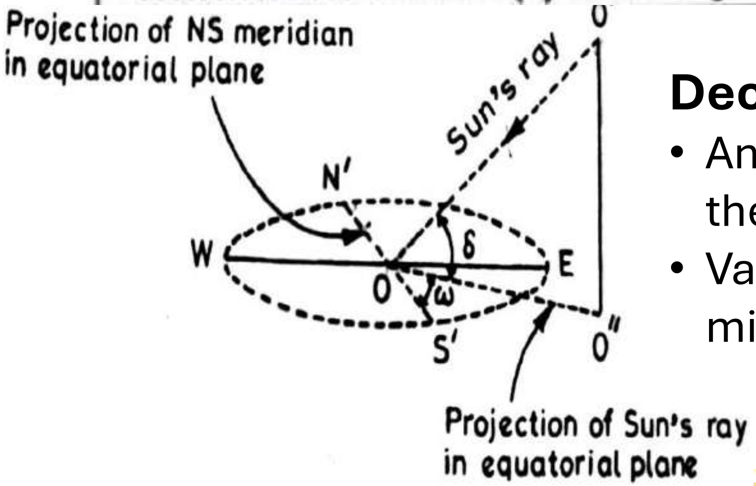


Figure: Declination angle

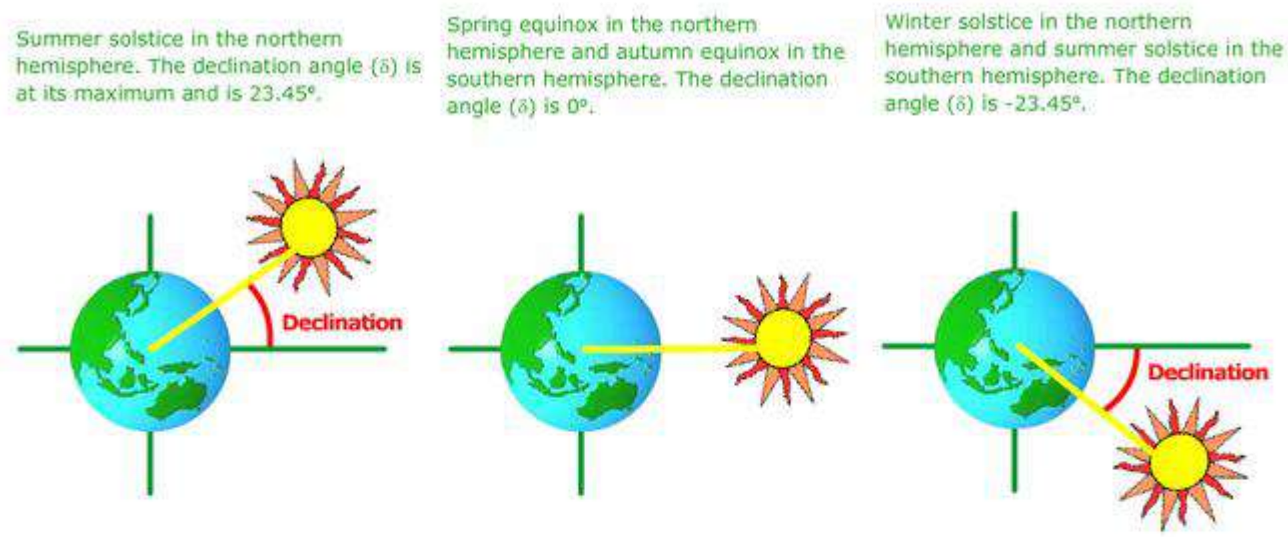
Declination Angle (δ):

- Angle between the line joining the centers of the sun and the earth and its projection on the equatorial plane.
- Varies from a maximum value of 23.45° on June 21 to a minimum value of -23.45° on December 21.

$$\text{Solar declination angle } (\delta) = 23.45 \times \sin \frac{(284+n)\times 360}{365}$$

Source: Solar Energy: Fundamentals, Design, Modelling and Applications, G. N. Tiwari

https://www.pveducation.org/pvcdrom/properties-of-sunlight/declination-angle



Declination (δ)

$\delta = 23.45^\circ \sin [\{360 (284 + n)\}/365]$

[Maximum value: 23.45°

Minimum value: (-) 23.45°]

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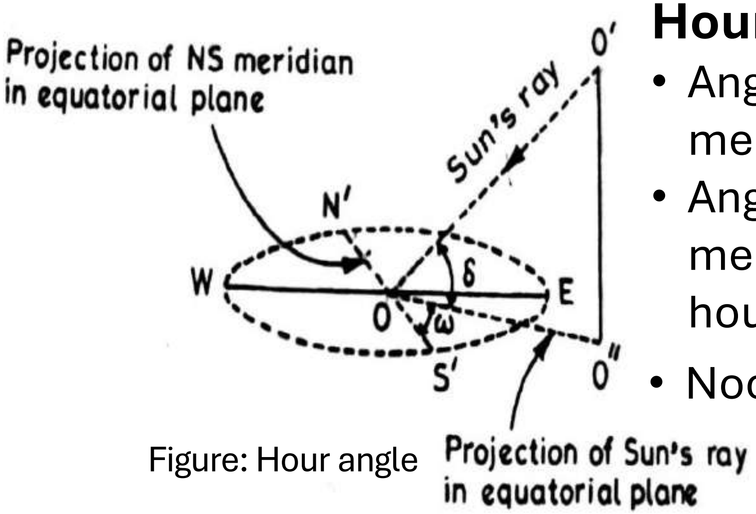


Figure: Hour angle

Hour Angle (ω):

- Angle through which the earth must be rotated to bring the meridian of the plane directly under the sun.
- Angular displacement of the sun east or west of the local meridian, due to rotation of the earth on its axis at 15° per hour.
- Noon: 0; Morning: -ve; Afternoon: +ve

$$\text{Solar hour angle } (\omega) = (ST - 12) \times 15$$

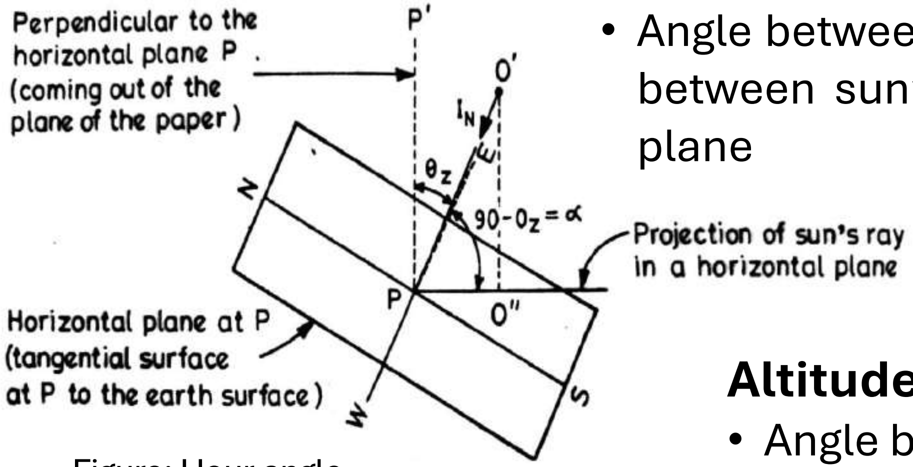


Figure: Hour angle

Zenith Angle (θ_z):

- Angle between the vertical and the line to the sun, i.e., angle between sun's ray and perpendicular line to the horizontal plane

$$\cos\theta_z = \cos\emptyset \times \cos\delta \times \cos\omega + \sin\emptyset \times \sin\delta$$

Altitude Angle (α):

- Angle between sun rays and a horizontal plane

$$\alpha = 90 - \theta_z$$

Source: Solar Energy: Fundamentals, Design, Modelling and Applications, G. N. Tiwari

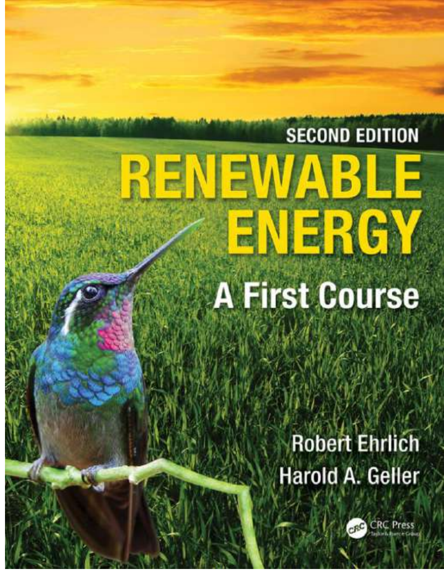
Time of Day	Hour Angle (ω) [(-) ve in the morning and (+) ve in the afternoon]	Angular displacement of the sun, east or west of the local meridian due to rotation of earth on its axis (at 15° an hour)

Hour Angle = (15) x (Number of Hours from Solar Noon);Solar Noon: The time when the sun is just above the local meridian (longitude)- Thus, the value of hour angle at solar noon would be zero; Solar Day: It is the interval of time from the moment the sun crosses the local meridian to the next time it crosses the same meridian- Essentially it is the period between two successive solar noons at a place.

The hour angle is based on **SOLAR TIME** and not the **LOCAL (standard/clock) TIME** -Need to convert LOCAL/STANDARD time to SOLAR time prior to the determination of hour angle

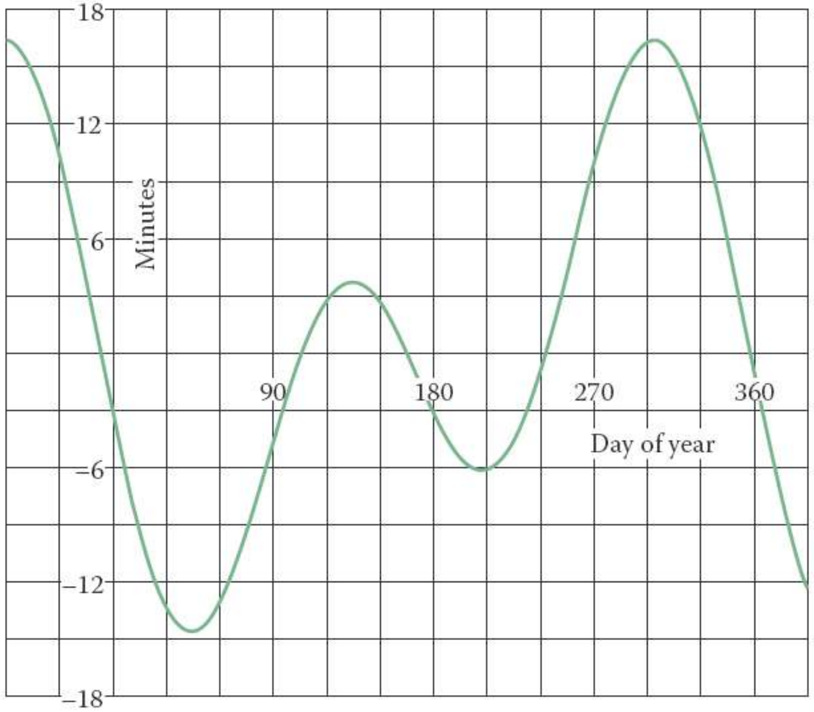
The Solar Noon could be different from the Standard Noon as indicated by the clocks as the standard times of a time zone are based on the Solar Noon at a specific location - Need to correct the standard time as defined by a clock for the difference in the longitudes of the location of interest and the standard time location.

Unfortunately, the local time you measure on clocks is not exactly the same as solar time based on the apparent motion of the sun for two reasons. The first reason is the presence of time zones, so you need to correct the solar time based on how far you are in longitude from the western edge of your time zone, i.e., $(\psi - \psi_{zone})$. The second correction is based on something with the poetic name: the *equation of time* ω_{Eq}. The rotation of the Earth from one noon to the next takes exactly 24 h on average, but there are small variations due to the fact that the sun advances in the sky at a nonuniform rate each day due to the changes in the speed of the Earth in its elliptical orbit around the sun. These small variations are depicted in Figure 9.7, which is a plot of the equation of time.



Taking both corrections to solar time into account (the time zone and equation of time), we may write Equation 9.10 for the hour angle in degrees:

$$\omega = 15°/\text{h}\,(t_{\text{solar}} - 12\,\text{h} + \omega_{\text{Eq}}) + (\psi - \psi_{\text{zone}}). \tag{9.10}$$



Since the rate of rotation of earth on its axis is not uniform during the year (thus changing the length of the day and also the time of Solar Noon) a correction **EQUATION OF TIME** is used for the same.

Solar Time = Standard Time + Longitude Correction + Equation of Time

Solar altitude angle (α_s):

- Angle between sun ray and its projection in a horizontal plane.

$$\alpha = \alpha_s$$

Slope (β):

- Angle between the plane surface, under consideration, and the horizontal.
- +ve for surface sloping towards south
- -ve for the surfaces sloping towards north.

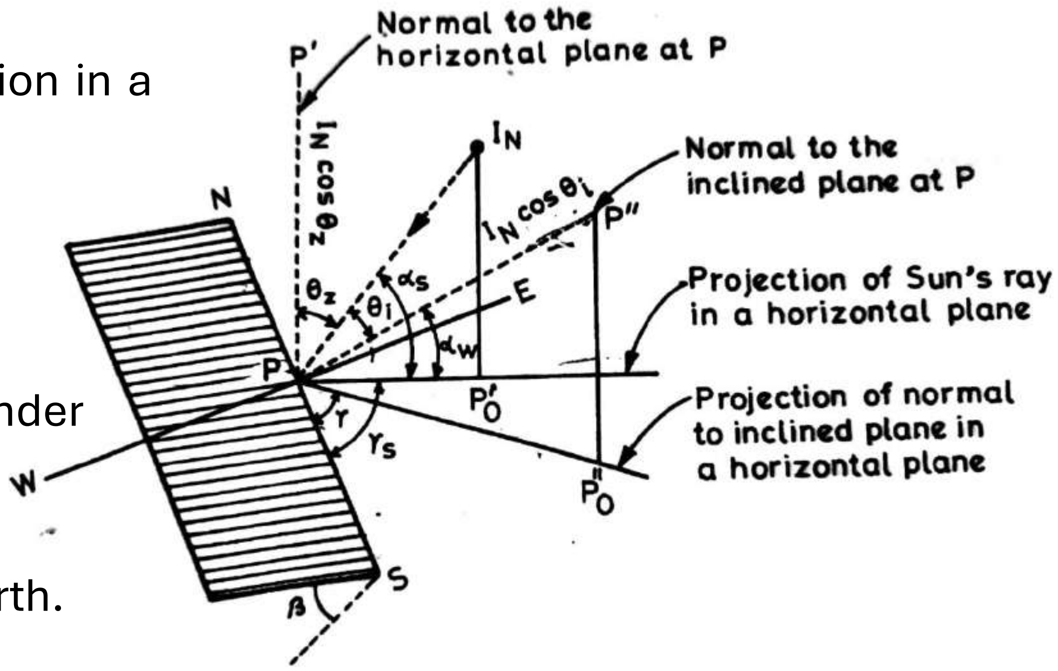


Figure: Solar altitude angle, Slope and Surface azimuth angle

Surface azimuth angle (Y):

- Angle in the horizontal plane, between the line due south and the projection of the normal to the surface (inclined plane) on the horizontal plane.
- By convention, for northern hemisphere: -ve if projection is east of south and +ve if west of south (vice-versa for southern hemisphere).

Source: Solar Energy: Fundamentals, Design, Modelling and Applications, G. N. Tiwari

SUN-EARTH ANGLES

Solar azimuth angle (γ_s):

- Angle in a horizontal plane, between the line due south and the projection of beam radiation on the horizontal plane.
- By convention, for northern hemisphere: -ve if projection is east of south and +ve if west of south (vice-versa for southern hemisphere).

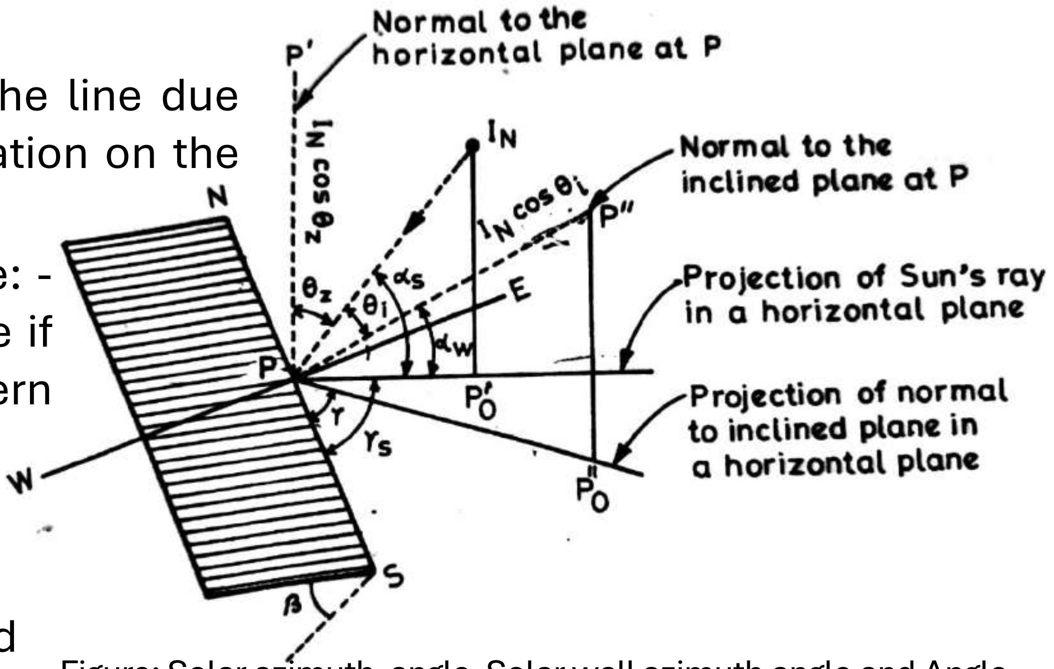


Figure: Solar azimuth angle, Solar wall azimuth angle and Angle of incidence

Solar wall azimuth angle (α_ω):

- Angle between normal to the inclined plane and projection of sun's ray in a horizontal plane

Angle of incidence (θ_i):

- Angle between beam radiation on a surface and the normal to that surface, expressed as:

$$cos\theta_i = (\cos\emptyset\cos\beta + \sin\emptyset\sin\beta\cos\gamma)\cos\delta\cos\omega + \cos\delta\sin\omega\sin\beta\sin\gamma + \sin\delta\,(\sin\emptyset\cos\beta - \cos\emptyset\sin\beta\cos\gamma)$$

Source: Solar Energy: Fundamentals, Design, Modelling and Applications, G. N. Tiwari

Useful Links

- https://www.nrel.gov/grid/solar-resource/spectra-am1.5.html
- https://pvpmc.sandia.gov/modeling-guide/1-weather-design-inputs/irradiance-insolation/spectral-content/am-1-5-standard-spectrum/

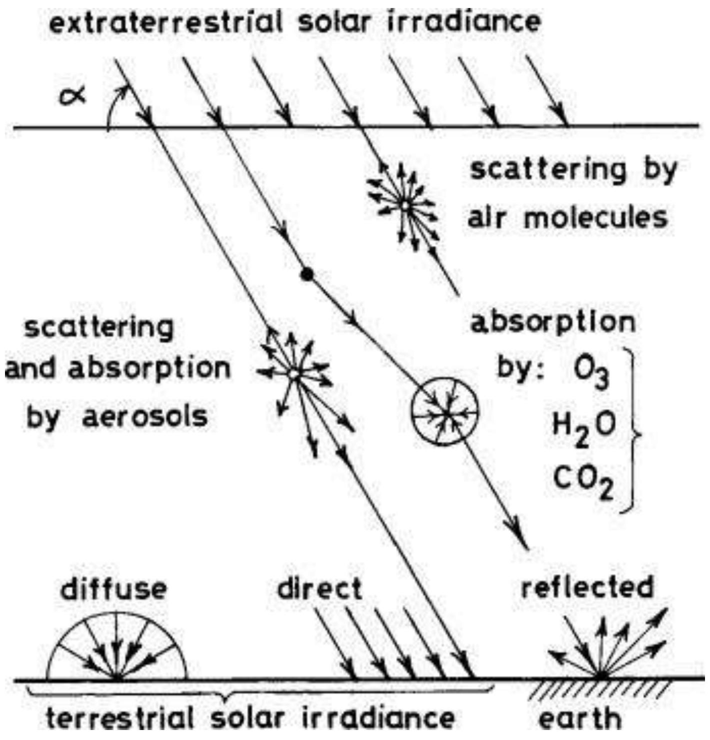
Acknowledgement

- Prof. T C Kandpal
- Prof. Dibakar Rakshit
- Prof. K Ravi Kumar

Basics

1. How can we measure Solar radiation?
    a. Pyranometer (Global)
    b. Pyrheliometer (Beam)

- Air Mass (Path length of solar radiation through atmosphere assuming vertical path as unity)
- A part of sun's radiation travelling through the atmosphere and reaching the earth's atmosphere directly is defined as direct/ beam radiation.
- Major part of the radiation entering atmosphere is reflected back, absorbed or scattered within the atmosphere thus a part is re-radiated and finally reaches the earth's surface from all the directions. This is known as diffused radiation.



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