UNIT-III

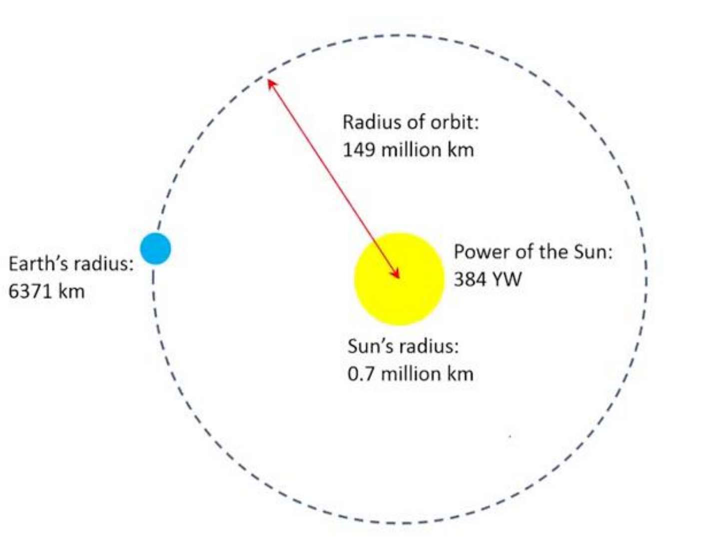
SOLAR RADIATION SPECTRA

Solar irradiance is the power per unit area received from the Sun in the form of electromagnetic radiation as reported in the wavelength range of the measuring instrument. The solar irradiance is measured in watt per square metre (W/m^2) in SI units. Solar irradiance is often integrated over a given time period in order to report the radiant energy emitted into the surrounding environment (joule per square metre, J/m^2) during that time period. This integrated solar irradiance is called solar irradiation, solar exposure, solar insolation, or insolation.

Surface of the Sun have 5500 °C .

Core of the Sun have several million °C

Sun gives out 384 Yotta Watts (yotta=10^{24}) i.e $384\times10^{24}=3.84\times10^{26}$ *watts*



the earth radius =6371Km

Radius of orbit=149 million Km= 149×10^6 KM =

$$\begin{aligned}&149 milli\\&149\times10^6\ Km\\&149\times10^6\times10^3\\&149\times10^9\ m\\&1.49\times10^{11}\ m\end{aligned}$$

Radius of sun= 0.7million Km=7000Km

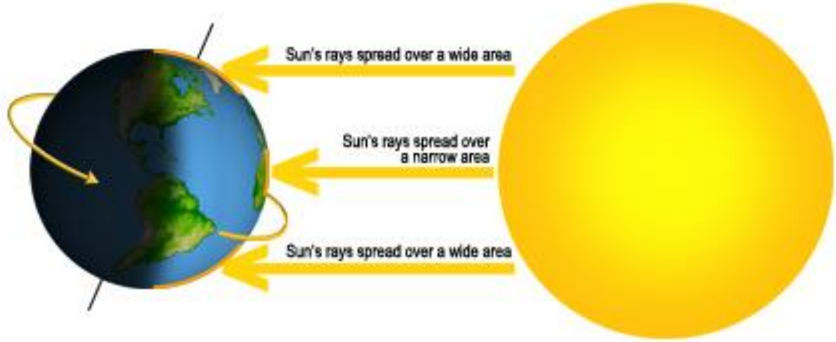
The intensity of sun at earth orbit is

$$= \frac{3.84 \times 10^{26}}{4.\pi \times \left(149 \times 10^{11}\right)^2} = 1377\ \mathrm{W/m^2} = \text{this is called solar constant}$$

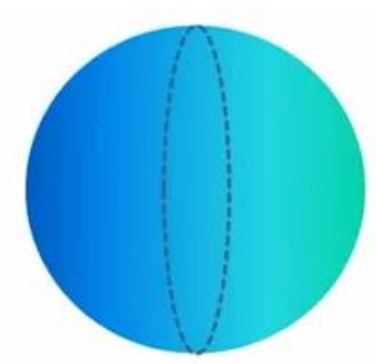
The earth orbit area $=4\pi r^2$ m^2 (here r= earth orbit radius)

1377 intensity was equally distributed through the earth orbit

Now we required sun intensity only on the earth. Here we should remember the sun rays falling on one side of the earth.



The area of the disc $=\pi r^2$ (here r=radius of the earth)



The earth received Power from the sun= intensity of sun at earth $\times$ The area of the disc

$$= \pi \times (6371 \times 10^3)^2 \times 1377$$
$$= 1.755 \times 10^{17}\ W\ or\ J/s$$

$$\text{Energy received from the sun in the year} = 1.755 \times 10^{17} * 60 * 60 * 24 * 365 = 5.5 \times 10^{24}\ \mathrm{J}$$

= 5.5 million Exa Joules

Solar irradiance is measured by satellites above Earth's atmosphere, and is then adjusted using the inverse square law to infer the magnitude of solar irradiance at one Astronomical Unit (AU) to evaluate the solar constant. The approximate average value cited, 1.3608 ± 0.0005 kW/m², which is 81.65 kJ/m² per minute, is equivalent to approximately 1.951 calories per minute per square centimeter, or 1.951 langleys per minute.

Solar output is nearly, but not quite, constant. Variations in total solar irradiance (TSI) were small and difficult to detect accurately with technology available before the satellite era (±2% in 1954). Total solar output is now measured as varying (over the last three 11-year sunspot cycles) by approximately 0.1%; see solar variation for details

The SI unit of irradiance is watt per square metre (W/m^2, which may also be written Wm^{-2}).

Solar Energy in Earth's Atmosphere

Layers of Earth's Atmosphere

You probably know that scientists think of our atmosphere as having several distinct layers with specific traits. Let's quickly review the structure of the atmosphere, since some aspects of that story are relevant to how and where solar energy gets absorbed.

Nearest ground level is the **troposphere**. It extends upward from the ground to an altitude of about 16 km (in the tropics, or 8 km near the poles). Most weather occurs, and most clouds are to be found, in this layer. Convection currents keep the gases in the troposphere well mixed. The troposphere is warmest near ground level, and cools gradually the higher up in it one goes.

Immediately above the troposphere lies the **stratosphere**. Some high-altitude clouds can be found in this layer. Temperatures actually increase with altitude as one moves upward through the stratosphere. Jet airliners fly in this layer, for it is far less turbulent than the underlying troposphere. The stratosphere extends upward from the top of the troposphere to an altitude of about 50 km. The ozone layer lies within the stratosphere.

Moving upward, the next layer is the **mesosphere**. By this point the atmosphere is very thin. Temperatures once again decline with increasing altitude (as was the case in the troposphere), falling as low as -100° C (-146° F) in the upper mesosphere. This layer is relatively poorly studied, for it is above the reach of most aircraft but below the altitude where satellites orbit. Most meteors burn up in the mesosphere. The top of the mesosphere lies about 80 to 85 km above Earth's surface.

Above the mesosphere lies the extremely tenuous thermosphere. This layer is so thin, in fact, that many satellites orbit within it. This region is one in which temperatures once again rise with increasing altitude, reaching as high as 2,500°C (4,500°F) in the daytime! Embedded within the thermosphere are several layers of the **ionosphere**; regions where ionized gas particles can reflect radio waves, a feature that people used to send messages beyond the line-of-sight range of the horizon before the advent of satellites. The thermosphere extends to somewhere between 500 and 1,000 km above the Earth's surface. Many of the atoms and molecules in the thermosphere (and above) have lost electrons, thus becoming electrically charged ions; so the motions of particles in the upper atmosphere are partially influenced by electrical currents and Earth's magnetic field.

Though not universally recognized as a layer of our atmosphere, some scientists consider the **exosphere** to be the outermost layer of Earth's atmosphere. Starting at the top of the thermosphere, this extremely tenuous layer gradually gives way to the vacuum of interplanetary space.

Solar EM Radiation Penetration into Earth's Atmosphere

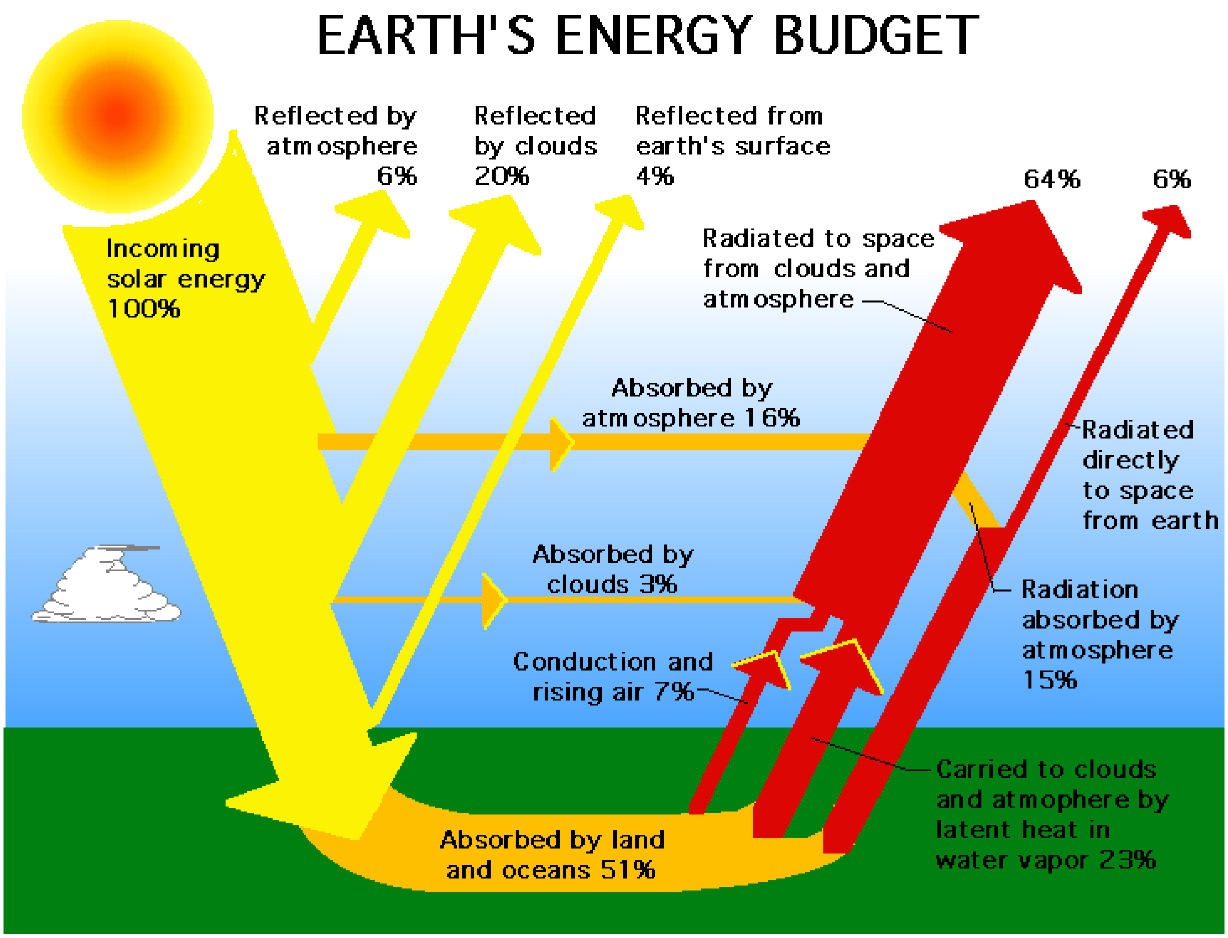
Let's now take a look at the electromagnetic radiation, of various wavelengths and energies, from the Sun as it penetrates into Earth's atmosphere. Recall that the Sun emits a broad range of frequencies, from high-energy X-rays and ultraviolet radiation, through visible light, on on down the spectrum to the lower energy infrared and radio waves. Different wavelengths of this solar radiation behave differently as they enter our atmosphere.

All of the high-energy X-rays are absorbed by our atmosphere well above our heads, which is very fortunate for us indeed! Likewise, most of the UV radiation (especially the highest energy, shortest wavelength regions of the UV spectrum) is blocked by the thermosphere, mesosphere, and stratosphere. The relatively low energy, long wavelength portion of the UV spectrum that does reach the ground forces us to wear sunglasses and slather ourselves with sunscreen to protect ourselves from sunburn and skin cancer.

A relatively narrow "window" of EM wavelengths around visible light reaches the ground. It includes some of the longer wavelength UV frequencies, some of the shorter wavelength IR frequencies, and all of the visble light region of the spectrum.

Most of the longer wavelength IR waves, and many of the shorter radio waves, are absorbed by the stratosphere before reaching the ground. There is a sizeable "radio window" of radio wave frequencies that also reach terra firma. The longest wavelength radio waves also fail to penetrate the atmosphere; many are absorbed or reflected by the ionosphere.

Recall how the temperature of the various layers of Earth's atmosphere rises and falls as one moves upward from the ground, in a seemingly haphazard fashion. First the temperature drops as we move upward through the troposphere; then it rises as we rise through the stratosphere; then it falls again through the mesosphere, only to rise again in the thermosphere. What's going on here? Near the Earth's surface, the sunlight that does reach the ground warms the Earth, which in turn warms the air immediately above it. So the troposphere is warmest next to the warm ground, and cooler higher up away from the warm ground. However, in the stratosphere, our friend the ozone layer is especially good at absorbing UV radiation; which shields us from most of these high-energy rays, and also heats this layer as the UV photons transfer their energy to the oxygen (ozone is an unusual type of oxygen molecule, O_3) molecules. And so it goes, throughout our upper atmosphere. The air varies in its chemical composition at different altitudes; and various chemical species absorb different wavelengths of EM radiation preferentially. Wherever there is the right combination of certain chemicals and an abundance of radiation of a type that those chemicals are good at absorbing, the atmosphere absorbes a lot of energy and its temperature rises. Remember how certain images of the Sun as certain specific wavelengths, especially in various narrow bands of the UV spectrum, provided us with "views" of very specific elements (such as helium or iron) in the Sun? Just as certain elements emit specific wavelengths of EM radiation, certain elements and compounds preferentially absorb certain specific wavelengths. In this sense, Earth's atmosphere is sort of the "flip side" of the Sun's atmosphere.



Absorption and scattering (reflection) by the atmosphere and clouds -- Absorption of solar radiation in the atmosphere occurs as radiant energy interacts with different atmospheric components. On average, about 15% of incoming solar radiation is absorbed by atmospheric molecules such as water vapor, oxygen and small particulates (aerosols). Certain wavelengths of infrared radiation are absorbed by carbon dioxide (CO_2) and water vapor (see Figure 2.03). The amount of energy absorbed varies significantly from one geographic location to another. Although the CO_2 concentration in the atmosphere is more or less uniform around the globe, atmospheric water vapor content can change dramatically from place to place due to oceanic, meteorological and biospheric effects. Typically, water vapor absorbs the greatest amount of solar radiation passing through the atmosphere, especially in the infrared region of the spectrum.

Scattering of solar radiation within the atmosphere also accounts for a reduction of energy reaching Earth. Atmospheric gas molecules and aerosols deflect solar radiation from its original path, scattering (reflecting) some radiation back into deep space and some toward Earth's surface. Clouds reflect much more incoming solar radiation than they absorb. The high albedo (the ratio of reflected energy to incoming energy) of clouds is a significant factor in the radiation balance, and so the distribution of clouds around the globe can have a large effect on climate. Cloud cover can be highly variable in space and time.

Combining together the percentages of incoming energy absorbed (18%) and scattered (26%) by the atmosphere plus clouds, the overall effect is that nearly half (18% + 26% = 44%) of the energy entering the atmosphere doesn't make it through to Earth's surface.

Energy Incident at Earth's Surface

Of the roughly 56% of the incoming solar radiation making it through the atmosphere to Earth's surface, about 6% gets reflected by the surface and 50% is absorbed at the surface. The fraction of the reflected solar radiation to the incident solar radiation defines "albedo." The larger the albedo, the more bright or reflective a surface or object; the smaller the albedo, the darker or more absorbing a surface. Although surface reflectance typically is small compared to what clouds reflect, its distribution (in both time and geographic location) around the globe affects the distribution of absorbed solar radiation. Surface reflectance of solar energy is also what many remote sensing instruments measure

EARTH-SUN ANGLES (SOLAR GEOMETRY)

The earth revolves around the sun every 365.25 days in an elliptical orbit, with a mean earth-sun distance of 1.496×10^{11} m (92.9×10^{6} miles) defined as one astronomical unit (1 AU). This plane of this orbit is called the *ecliptic plane.* The earth's orbit reaches a maximum distance from the sun, or *aphelion, of* 1.52×10^{11} m (94.4×10^{6} miles) on about the third day of July. The minimum earth-sun distance, *the perihelion,* occurs on about January 2nd, when the earth is 1.47×10^{11} m (91.3×10^{6} miles) from the sun. Figure 3.1 depicts these variations in relation to the Northern Hemisphere seasons.

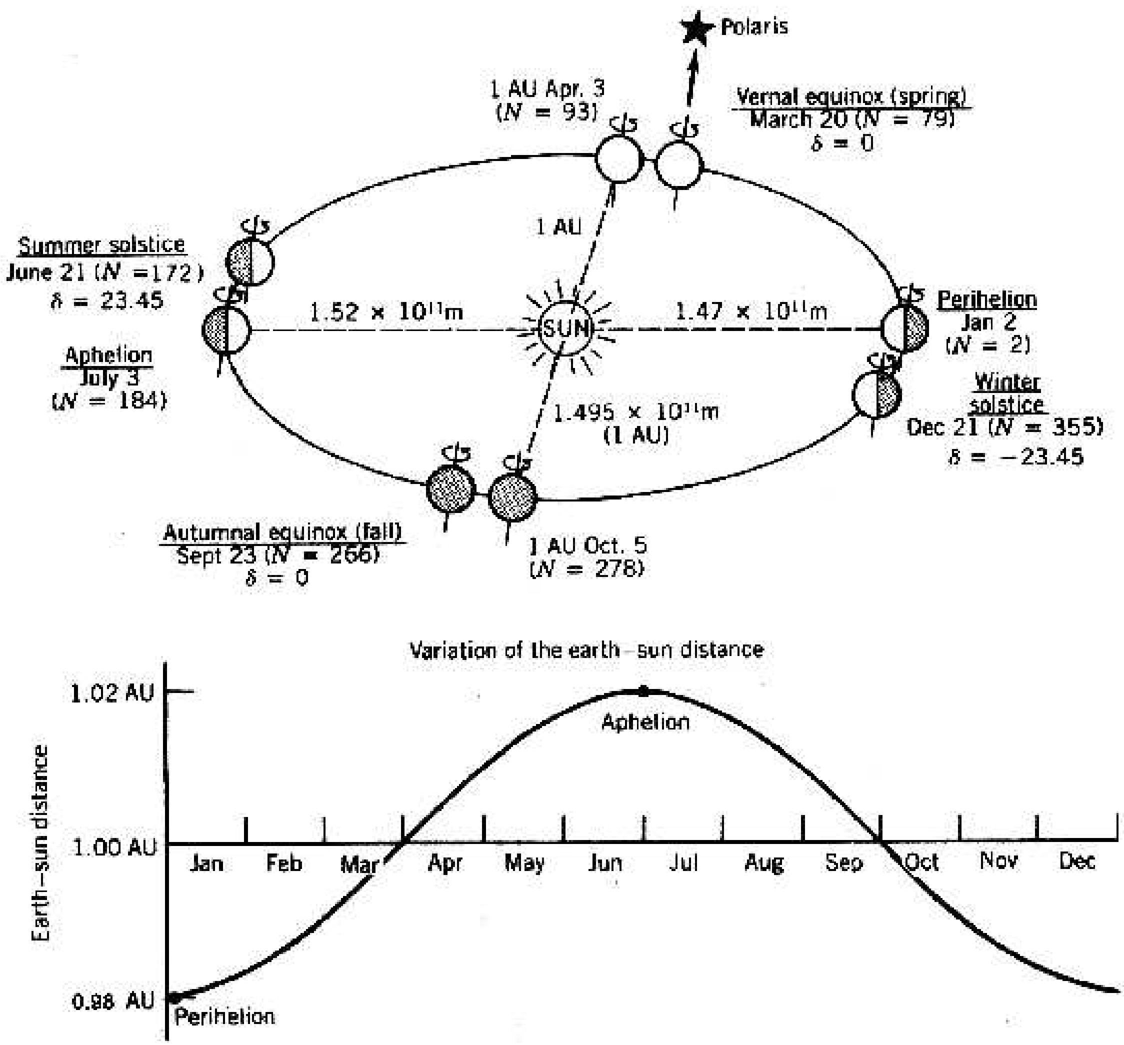
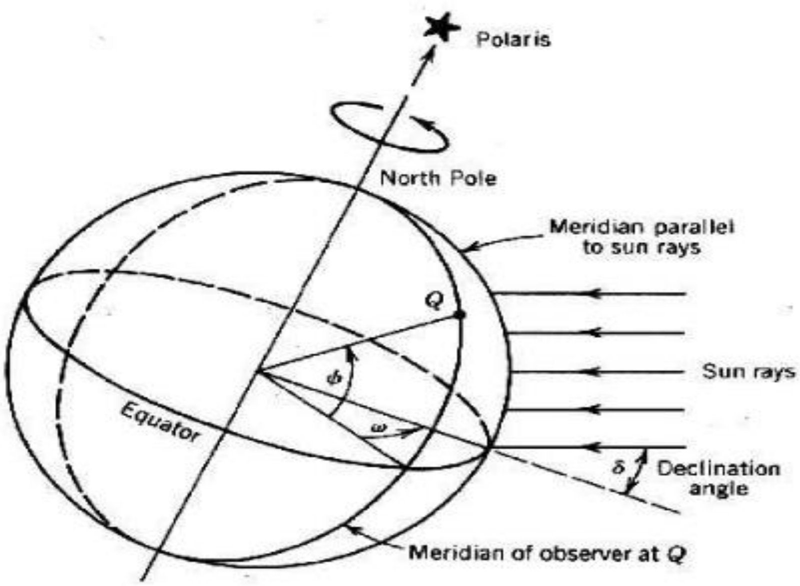


Figure 3.1 The ecliptic plane showing variations in the earth-sun distance and the equinoxes and solstices. The dates and day numbers shown are for 1981 and may vary by 1 or 2 days.

The Hour Angle

To describe the earth's rotation about its polar axis, we use the concept of the *hour angle (ω)*. As shown in Figure 3.3, the hour angle is the angular distance between the meridian of the observer and the meridian whose plane contains the sun. The hour angle is zero at *solar noon* (when the sun reaches its highest point in the sky). At this time the sun is said to be 'due south' (or 'due north', in the Southern Hemisphere) since the meridian plane of the observer contains the sun. The hour angle increases by 15 degrees every hour.



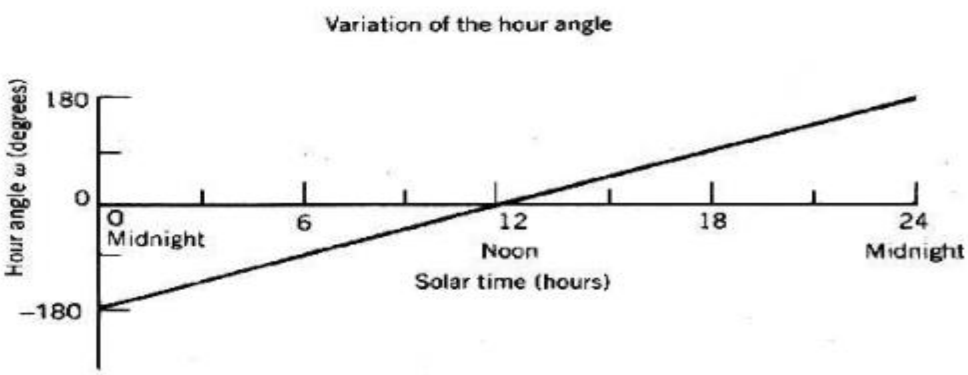
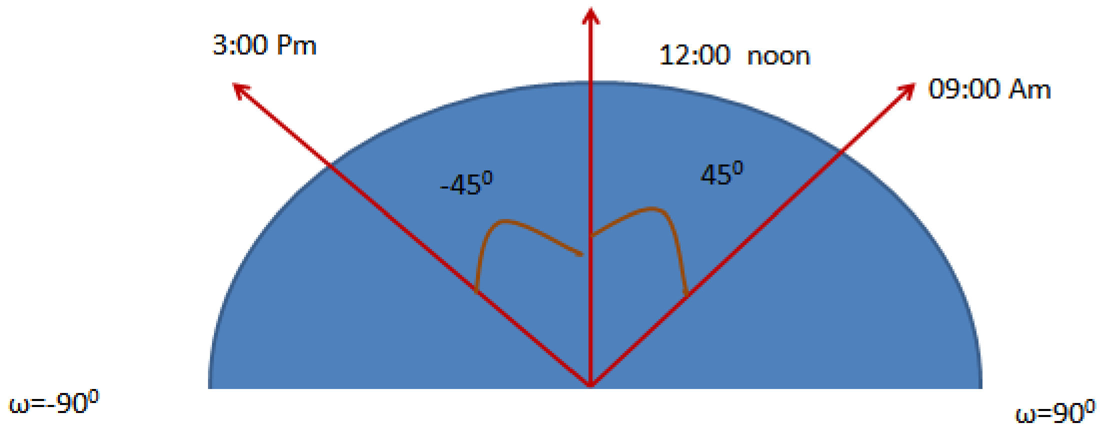


Figure 3.3 The hour angle (ω) This angle is defined as the angle between the meridian parallel to sun rays and the meridian containing the observer.

The *hour angle*, *H*, is the azimuth angle of the sun's rays caused by the earth's rotation, and *H* can be computed

$$\omega = \frac{\text{no.of minutes past midnight, AST} - 720\text{mins}}{4\,\text{min/deg}}$$

it is the angle representing the position of the sun with respective the clock hour with reference to sun's position at 12 Noon



Declination Angle

The plane that includes the earth 's equator is called the *equatorial plane.* If a line is drawn between the center of the earth and the sun, the angle between this line and the earth's equatorial plane is called the *declination angle* (δ), as depicted in Figure 3.5. At the time of year when the northern part of the earth's rotational axis is inclined toward the sun, the earth 's equatorial plane is inclined 23.45 degrees to the earth-sun line. At this time (about June 21), we observe that the noontime sun is at its highest point in the sky and the declination angle = +23.45 degrees. We call this condition the *summer solstice,* and it marks the beginning of summer in the Northern Hemisphere.

As the earth continues its yearly orbit about the sun, a point is reached about 3 months later where a line from the earth to the sun lies on the equatorial plane. At this point an observer on the equator would observe that the sun was directly overhead at noontime. This condition is called an *equinox* since anywhere on the earth, the time during which the sun is visible (daytime) is exactly 12 hours and the time when it is not visible (nighttime) is 12 hours. There are two such conditions during a year; the *autumnal equinox* on about September 23, marking the start of the fall; and the *vernal equinox* on about March 22, marking the beginning of spring. At the equinoxes, the declination angle (δ) is zero.

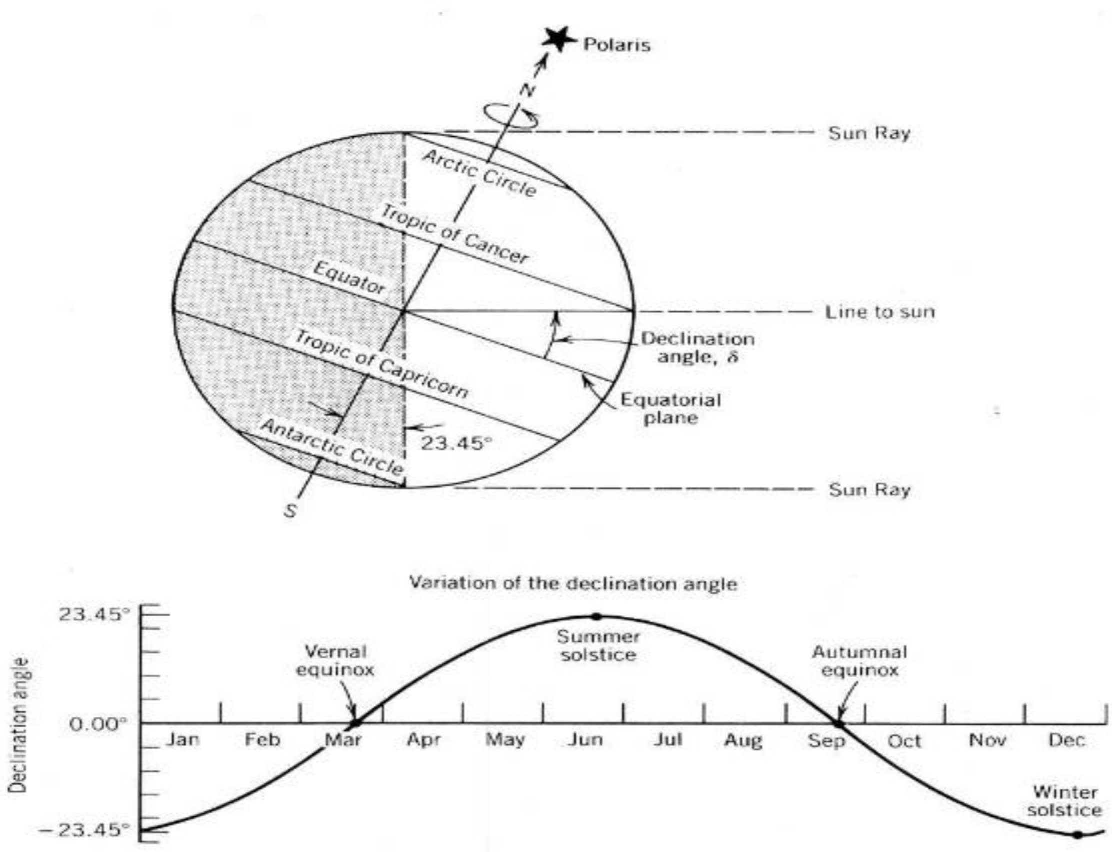


Figure 3.5 The declination angle (δ) The earth is shown in the summer solstice position when = +23.45 degrees. Note the definition of the tropics as the intersection of the earth-sun line with the surface of the earth at the solstices and the definition of the Arctic and Antarctic circles by extreme parallel sun rays.

The *winter solstice* occurs on about December 22 and marks the point where the equatorial plane is tilted relative to the earth-sun line such that the northern hemisphere is tilted away from the sun. We say that the noontime sun is at its "lowest point" in the sky, meaning that the declination angle is at its most negative value (i.e., δ = -23.45 degrees). By convention, winter declination angles are negative.

Accurate knowledge of the declination angle is important in navigation and astronomy. Very accurate values are published annually in tabulated form in an ephemeris; an example being (Anonymous, 198l). For most solar design purposes, however, an approximation accurate to within about 1 degree is adequate. One such approximation for the declination angle is

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

n= no.of days

Month	n for ith Day of Month	For Average Day of Month		
		Date	n	δ
January	i	17	17	−20.9
February	$31+i$	16	47	−13.0
March	$59+i$	16	75	−2.4
April	$90+i$	15	105	9.4
May	$120+i$	15	135	18.8
June	$151+i$	11	162	23.1
July	$181+i$	17	198	21.2
August	$212+i$	16	228	13.5
September	$243+i$	15	258	2.2
October	$273+i$	15	288	−9.6
November	$304+i$	14	318	−18.9
December	$334+i$	10	344	−23.0

Latitude Angle

The *latitude angle (φ)* is the angle between a line drawn from a point on the earth's surface to the center of the earth, and the earth's equatorial plane. The intersection of the equatorial plane with the surface of the earth forms the equator and is designated as 0 degrees latitude. The earth's axis of rotation intersects the earth's surface at 90 degrees latitude (North Pole) and -90 degrees latitude (South Pole). Any location on the surface of the earth then can be defined by the intersection of a longitude angle and a latitude angle.

Other latitude angles of interest are the Tropic of Cancer (+23.45 degrees latitude) and the Tropic of Capricorn (- 23.45 degrees latitude). These represent the maximum tilts of the north and south poles toward the sun. The other two latitudes of interest are the Arctic circle (66.55 degrees latitude) and Antarctic circle (-66.5 degrees latitude) representing the intersection of a perpendicular to the earth-sun line when the south and north poles are at their maximum tilts toward the sun. As will be seen below, the tropics represent the highest latitudes where the sun is directly overhead at solar noon, and the Arctic and Antarctic circles, the lowest latitudes where there are 24 hours of daylight or darkness. All of these events occur at either the summer or winter solstices.

$$\cos(\theta_z) = \sin(\phi) = \cos(L)\cos(\delta)\cos(\omega) + \sin(L)\sin(\delta)$$

L=latitude, ω= hour angle and δ=declination angle

Observer-Sun Angles

When we observe the sun from an arbitrary position on the earth, we are interested in defining the sun position relative to a coordinate system based at the point of observation, not at the center of the earth. The conventional earth-surface based coordinates are a vertical line (straight up) and a horizontal plane containing a north-south line and an east-west line. The position of the sun relative to these coordinates can be described by two angles; the *solar altitude angle* and the *solar zenith angle* defined below. Since the sun appears not as a point in the sky, but as a disc of finite size, all angles discussed in the following sections are measured to the center of that disc, that is, relative to the "central ray" from the sun.

Solar Altitude, Zenith, and Azimuth Angles

The solar altitude angle (α) is defined as the angle between the central ray from the sun, and a horizontal plane containing the observer, as shown in Figure 3.6. As an alternative, the sun's altitude may be described in terms of the *solar zenith* angle(θz) which is simply the complement of the solar altitude angle or

The other angle defining the position of the sun is the *solar azimuth angle (Υs or A).* It is the angle, measured clockwise on the horizontal plane, from the north-pointing coordinate axis to the projection of the sun's central ray.

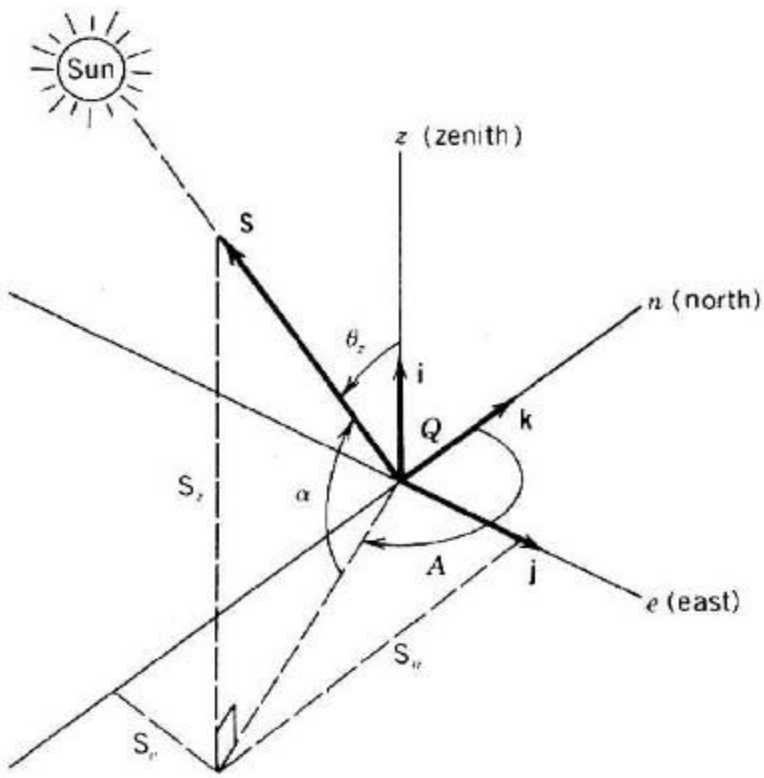


Figure 3.6 Earth surface coordinate system for observer at *Q* showing the solar azimuth angle *A*, the solar altitude angle (α) and the solar zenith angle(θz) for a central sun ray along direction vector ***S***. Also shown are unit vectors ***i***, ***j***, ***k*** along their respective axes.

There is a set of useful relationships among these angles. Equations relating the angle of incidence of beam radiation on a surface, *θ, to the other angles are*

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

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

$$\cos(\gamma_s) = \frac{\sin(\alpha)\sin(L) - \sin(\delta)}{\cos(\alpha)\cos(L)}$$

where γ_s is positive toward the west (afternoon), and negative toward the east (morning), and therefore, the sign of α_1 should match that of the hour angle.

Day length

Considering the earth to rotate 360° in 24 h, or 15°/h, the hour angle can be described as follows

$\omega_s = 15$ *per Hour*

Day length per hour = $t_d = \dfrac{2\omega_s}{15}$

i.e $= \dfrac{2}{15}\cos^{-1}(-\tan\phi\tan\delta)$

this is the day length is function of latitude angle ϕ and declination angle δ

The orbit of the Earth is an ellipse not a circle, hence the distance between the Earth and Sun varies over the year, leading to apparent solar irradiation values throughout the year approximated by

$$I_0 = I_{SC}\left[1 + 0.033\cos\left(\frac{N}{365}\times 360°\right)\right]$$

where the *solar constant, ISC* = 429.5 Btu/hr·ft² (1353 W/m²). The Earth's closest point (about 146 million km) to the sun is called the *perihelion* The Earth is tilted on its axis at an angle of 23.45°. As the Earth annually travels around the sun, the tilting manifests itself as our seasons of the year. The sun crosses the equator around March 21 (vernal equinox) and September 21 (autumnal equinox). The sun reaches its northernmost latitude about June 21 (summer solstice) and its southernmost latitude near December 21 (winter solstice).

The Earth is divided into latitudes (horizontal divisions) and longitudes (N-S divisions).

The equator is at a latitude of 0°; the north and south poles are at +90° and –90°, respectively; the Tropic of Cancer and Tropic of Capricorn are located at +23.45° and –23.45°, respectively. For longitudes, the global community has defined 0° as the prime meridian which is located at

Greenwich, England. The longitudes are described in terms of how many degrees they lie to the east or west of the prime meridian. A 24-hr day has 1440 mins, which when divided by 360°, means that it takes 4 mins to move each degree of longitude. The apparent solar time, *AST* (or local solar time) in the western longitudes is calculated from

$$AST = LST + (4\ \text{min/deg})(LSTM - Long) + ET$$

where

LST = Local standard time or clock time for that time zone (may need to adjust for daylight savings time, DST, that is $LST = DST - 1$ hr),

$Long$ = local longitude at the position of interest, and
$LSTM$ = local longitude of standard time meridian

$$LSTM = 15° \times \left(\frac{Long}{15°}\right)_{\text{round to integer}}$$

The difference between the true solar time and the mean solar time changes continuously day-today with an annual cycle. This quantity is known as the *equation of time*. The equation of time, *ET* in minutes, is approximated by

$$ET = 9.87\sin(2D) - 7.53\cos(D) - 1.5\sin(D)$$

$$\text{where} \quad D = 360°\,\frac{(N-81)}{365}$$

Example 1: Find the *AST* for 8:00 a.m. MST on July 21 in Phoenix, AZ, which is located at 112° W longitude and a northern latitude of 33.43°.

Solution: July 21 is the 202nd day of the year N=202

$$D = 360°\,\frac{(N-81)}{365} = 360°\,\frac{(202-81)}{365} = 119.3°$$

$$ET = 9.87\sin(2D) - 7.53\cos(D) - 1.5\sin(D)$$

$$= 9.87\sin(2 \times 119.3°) - 7.53\cos(119.3°) - 1.5\sin(119.3°) = -6.05\ \text{min}$$

$$LSTM = 15° \times \left(\frac{Long}{15°}\right)_{\text{round to integer}} = 15° \times \left(\frac{112°}{15°}\right)_{\text{round to integer}} = 15° \times 7 = 105°$$

$$\begin{aligned} AST &= LST + (4\text{ mins})(LSTM - Long) + ET \\ &= 8:00 + (4\text{ mins})(105° - 112°) + (-6.05\text{ min}) = 7:26\text{ a.m.} \end{aligned}$$