Chapter Two
Solar Radiation and its Measurements

2.1. Solar Radiation

The sun is a spherical source of about 1.39 million km diameter, at an average distance of 149.6 million km from earth. Radiation from the sun sustains life on earth and determines the climate. The solar radiation can be divided into two types, extraterrestrial and terrestrial.

2.1.1. Extraterrestrial Solar Radiation

Extraterrestrial solar radiation (H) is the solar radiation which falls on a surface normal to the rays of the sun outside the atmosphere of the earth. A typical spectral distribution of extraterrestrial radiation is shown in Figure 2-1. The curve rises sharply with the wavelength and reaches the maximum value of 2074 W/m^2-µm at a wavelength of 0.48 µm. It then decreases asymptotically to zero.

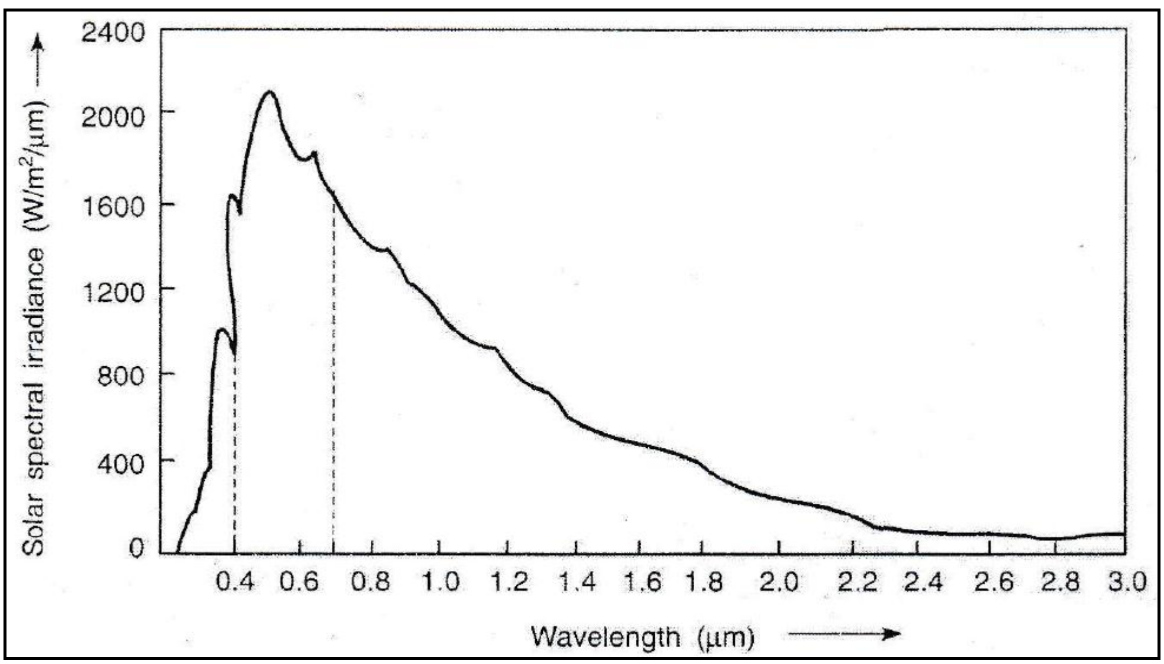

Figure (2-1): Spectral distribution of extraterrestrial radiation.

This extraterrestrial solar radiation at the mean earth sun distance, D_o, is called the **solar constant, H_o**. Using the value obtained by measurements from NASA, the solar constant is said to be 1353 W/m^2. Thus, the extraterrestrial solar radiation, H, can be calculated by using the following equation :

$$H = H_0\left(1 + 0.034 Cos\left(\frac{360.d_n}{365.25}\right)\right) \quad (2\text{-}1)$$

Where d_n is the day's number from year which can be estimated from table 2-1 (where i is day number from month). A plot for estimating the extraterrestrial solar radiation as a function of the time of year is shown in figure 2-2.

Table (2-1) The value of nth day of year.

month	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
d_n	i	31+i	59+i	90+i	120+i	151+i	181+i	212+i	243+i	273+i	304+i	334+i

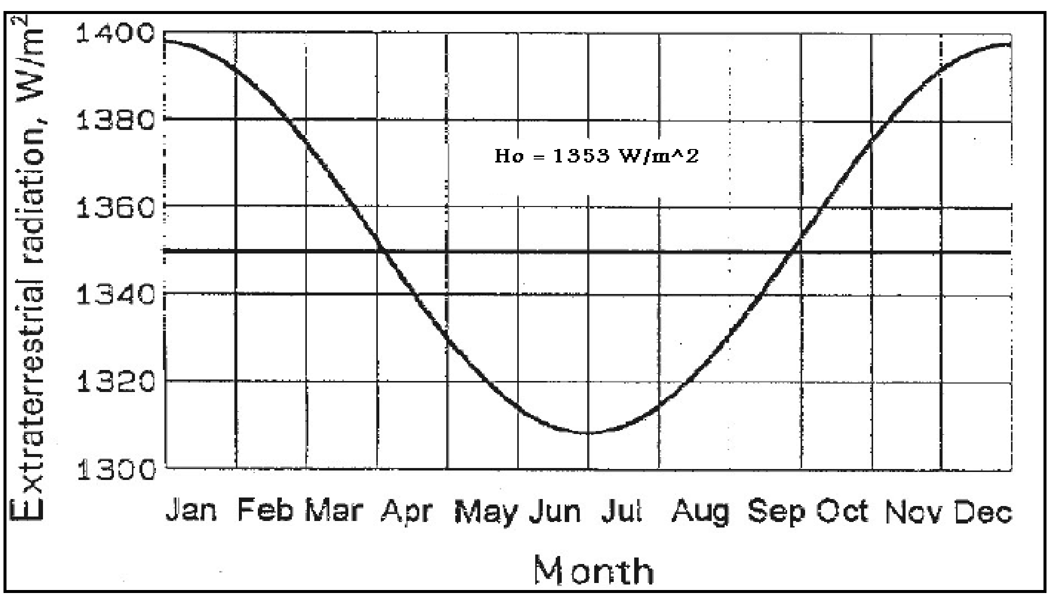

Figure (2-2) The variation of extraterrestrial radiation with time of year .

2.1.2. Terrestrial Solar Radiation

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. Short wave ultraviolet rays are absorbed by ozone and long wave infrared rays are absorbed by CO_2 and water vapours. Scattering is due to air molecules, dust particles and water droplet that cause attenuation of radiation as detailed in Figure 2-3. Minimum attenuation takes place in a clear sky when the earth's surface receives maximum radiation.

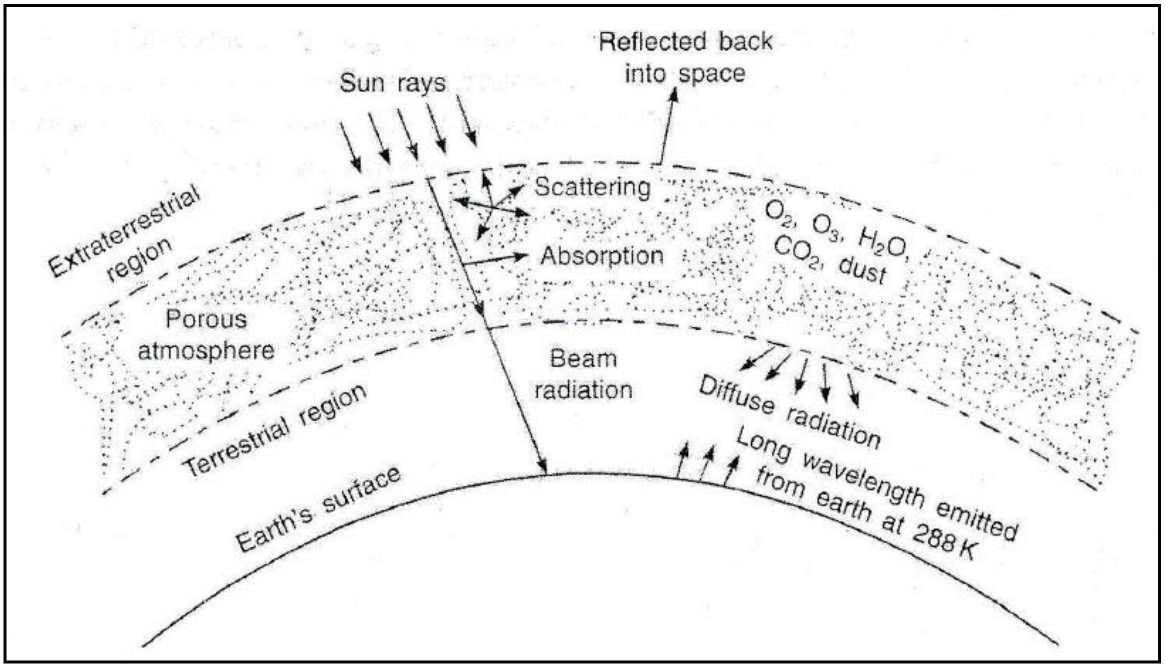

Figure (2-3): Solar radiation atmospheric mechanisms.

Beam radiation (H_b): Solar radiation received on the earth's surface without change in direction.

Diffuse radiation (H_d): The radiation received on a terrestrial surface (scattered by aerosols and dust) from all parts of the sky dome.

Total radiation (H_t): The sum of beam and diffuse radiations (H_b + H_d). 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 (H_g).**

Irradiance (W/m^2): The rate of incident energy per unit area of a surface.

Albedo: The solar radiation that reflects from the earth's surface.

Sun at zenith: It is the position of the sun directly overhead.

Air mass (AM): It is the ratio of the path length of beam radiation through the atmosphere to the path length if the sun were at zenith (which equal to $1/\cos(Z_s)$, where Z_s is **solar zenith angle** and represented in figure 2-4). At sea level AM = 1, when the sun is at zenith or directly overhead.

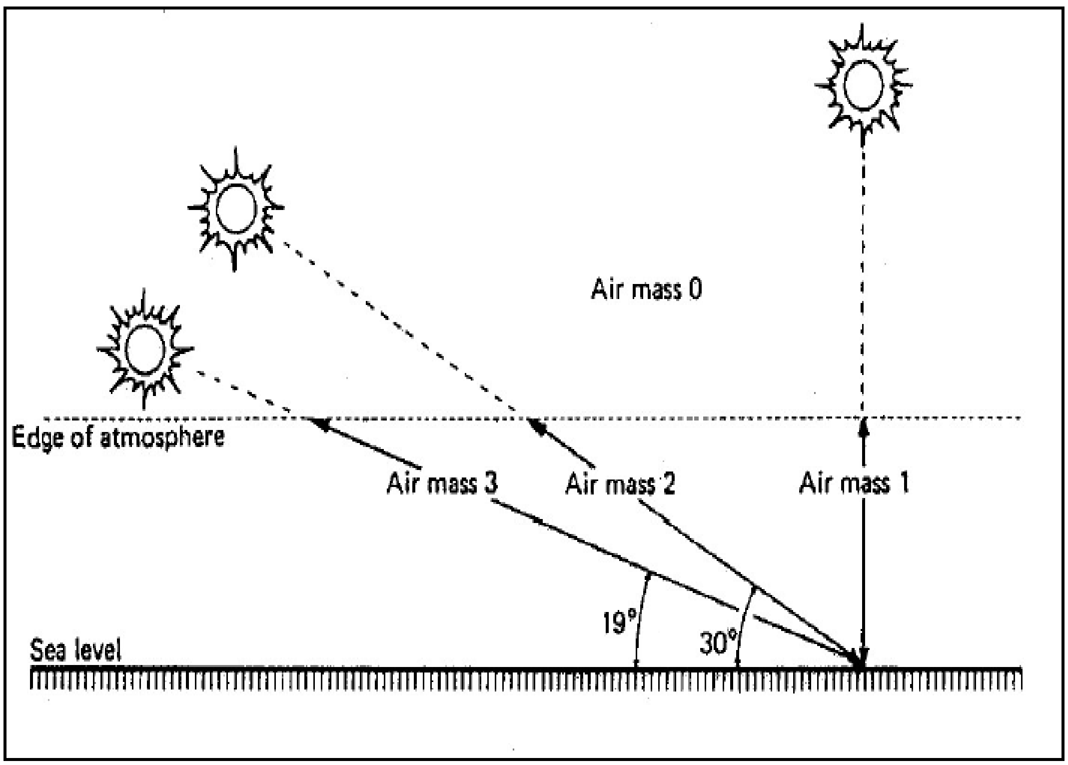

Figure (2-2) Path length of solar radiation through the atmosphere for ($20° \leq A \leq 90°$) .

Hottel's clear-day model beam solar irradiance is based on atmospheric transmittance calculations as follows:

$$H_{b,N} = H\,(A_o + A_1 EXP(-k\,AM)) \qquad (2\text{-}2)$$

Where A_o, A1 and k are a "clear" and an "urban haze" atmosphere coefficients, as a function of location altitude. For the clear 23-km visibility haze model, the three constants are given by:

$$A_o = 0.4 - 0.0075(6-A_L)^2 \quad (2\text{-}3)$$

$$A_1 = 0.55 + 0.005(6.5-A_L)^2 \quad (2\text{-}4)$$

$$k = 0.26 + 0.02(2.5-A_L)^2 \quad (2\text{-}5)$$

Where A_L is the local elevation in kilometers. For the urban 5-km visibility haze model, the parameters are given by:

$$A_o = 0.25 - 0.006(6- A_L)^2 \quad (2\text{-}6)$$

$$A_1 = 0.76+ 0.001(6.5- A_L)^2 \quad (2\text{-}7)$$

$$k = 0.25 + 0.08(2.5- A_L)^2 \quad (2\text{-}8)$$

The diffuse solar irradiance on a horizontal surface may be calculated by using the following equation:

$$H_{d,h} = H \cos(Z_s) \, [0.27 - 0.3(A_o+A_1 \, EXP(-k \, AM))] \quad (2\text{-}9)$$

The total instantaneous solar radiation on a horizontal surface, H_h, is the sum of the beam radiation, $H_{b,h}$, and the sky diffuse radiation, $H_{d,h}$, and also denoted as the global solar radiation on a horizontal surface which is represented in the following equation:

$$H_h = H_{b,h} + H_{d,h} = H_{b,N} \cos(Z_S) + CH_{b,N} \quad (2\text{-}10)$$

Where C sky diffuse factor

But the instantaneous total radiation at normal incidence is given by:

$$Ht = H_{b,N} + CH_{b,N} \quad (2\text{-}11)$$

The spectral distribution of solar radiation as a function of wavelength can be listed in table 2-2. It can be seen from this table that the solar radiation contains about 47% of visible range and this ratio decrease by dust effect especially for Iraq environment.

Table (2-2) The spectral distribution of solar radiation.

Range	Wavelength (nm)	Percentage %	Specific Radiation W/m^2
UV	0-380	7	95
Visible	380-780	47	640
IR	780-3000	46	618

Figure 2-3 illustrates measurements of the direct and diffuse spectral irradiance at two different times of the day, at solar noon and late afternoon. From this figure, it can be seen that the spectral distribution of direct irradiance changes significantly over the day, while the spectral distribution of diffuse irradiance remains nominally the same. For completely diffuse irradiance, module performance does not depend on solar angle of incidence, therefore, under very overcast conditions; the short circuit current does not change as the module is pointed in different conditions.

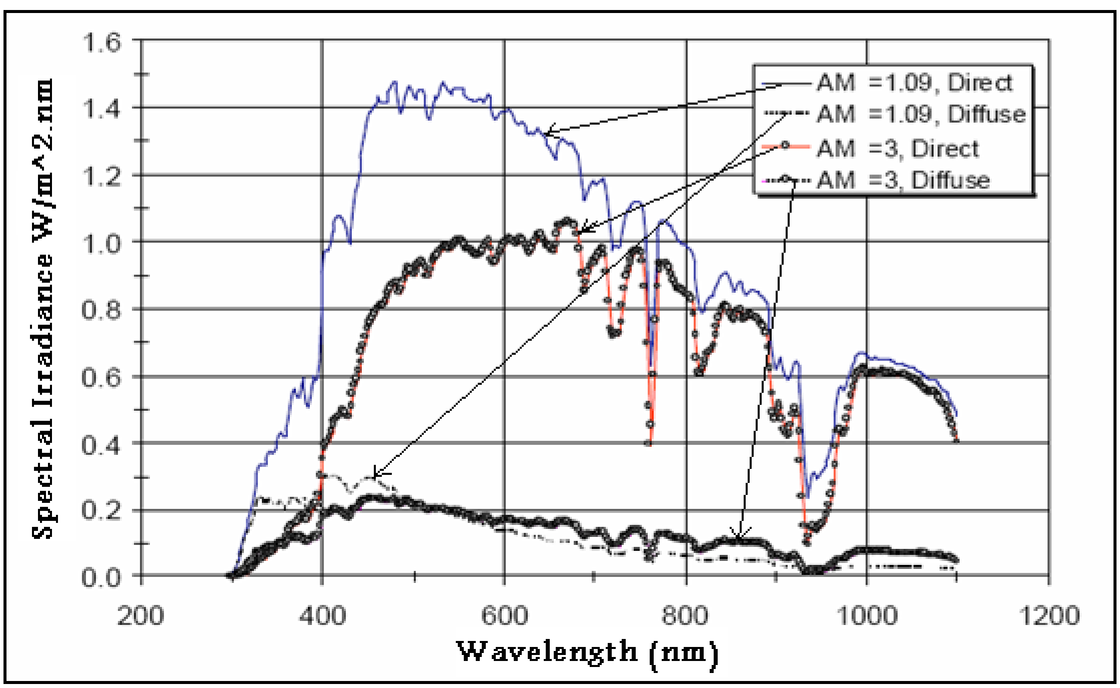

Figure (2-3) Direct and diffuse solar spectral irradiance at solar noon with air mass (AM. 1.09) and at later afternoon (AM. 3)

2.1.3. Atmospheric Extinction of Solar Radiation

Solar radiation received at the surface of the earth is subject to variations due to change in the extraterrestrial radiation caused by interaction of the radiation with air molecules, water (vapor and droplets) and dust (scattering and absorption). Figure 2-4 explains the solar radiation out the atmosphere and beyond entire the earth's atmosphere. The degree to which scattering occurs is a function of number of particles through which the solar radiation must pass, and of the size of the particles relative to λ, the wavelength of the radiation.

- Air molecules are very small relative to the wavelength of the solar radiation, and scattering occurs in accordance with the theory of Rayleigh (i.e, the scattering coefficient varies with λ^{-4}). Rayleigh scattering is significant only at short wavelengths smaller than 0.6 µm.
- Dust scattering due to particles that are much larger than air molecules and that vary in size and concentration from location to location according to height and from time to time; the scattering coefficient varying approximately as $\lambda^{-0.75}$ (Mie scattering).
- Water vapor scattering depends on the amount of perceptible water (the amount of water vapor in the air column above the observer), and scattering coefficient varies as λ^{-2}. The effects of scattering by dust and water is Subjected to Angstrom's turbidity equation which can be written as:

$$\tau_{a,\lambda} = \exp(-B\lambda^{-\alpha} AM) \qquad (2\text{-}12)$$

Where $\tau_{a,\lambda}$ is the atmospheric transmittance of solar radiation, B is the Angstrom turbidity coefficient varies from 0 to 0.4 for very clean to very turbid atmosphere respectively, α is a coefficient depends on the size distribution of the aerosols (a value of 1.3 is commonly used) and λ is the wavelength of solar radiation in micrometers. B and α will vary with time as atmospheric conditions change.

- Absorption of radiation is due to ozone in the ultraviolet (short wave radiation below 0.29µm) and to water vapor and carbon dioxide in the infrared bands. Water vapor absorbs strongly in bands centered at 1.0, 1.4, and 1.8µm. beyond 2.5 µm, the transmission of the atmosphere is very low due to absorption by H_2O and CO_2. The effect of Rayleigh scattering by air molecules and absorption by O_3, H_2O and CO_2 on the spectral distribution of beam irradiance are shown in figure 2-5.

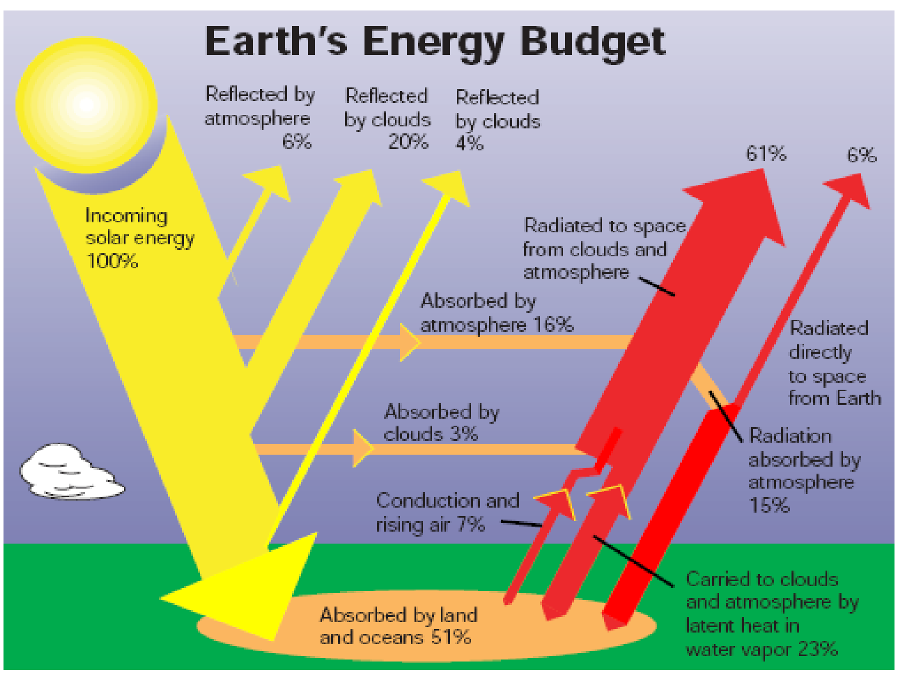

Figure (2-4) Earth gains energy through solar radiation and losses energy through thermal infrared radiation lost to space.

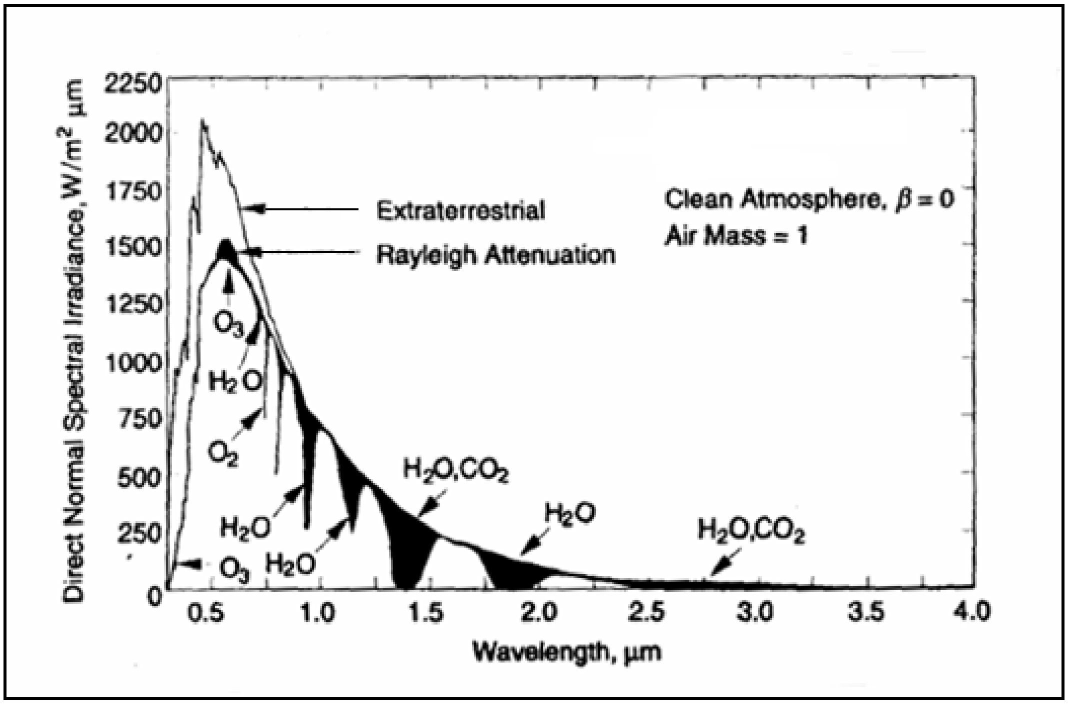

Figure (2-5) Effect of Rayleigh scattering and atmospheric absorption on the spectral distribution of beam irradiance.

2.2. Fundamental of Solar Radiation

In order to track the sun throughout the day for every day of the year, there are geometric relationships for the position of the collector with respect to the time that need to be known.

2.2.1. Sun Earth Geometrical Relationship

The earth makes one rotation about its axes every 24 hours and completes a rotation around the sun in approximately 365 days. The path of the earth takes around the sun is located slightly off center, thus making the earth closest to sun at the winter solstice (perihelion at 21-Dec.), at 1.47 $\times 10^{11}$m, and furthest from the sun at the summer solstice (Aphelion at 21-June), at a distance of 1.52$\times 10^{11}$m. The axis of rotation of the earth is tilted at an angle of 23.45° with respect to the orbital plane, as shown in figure 2-6.

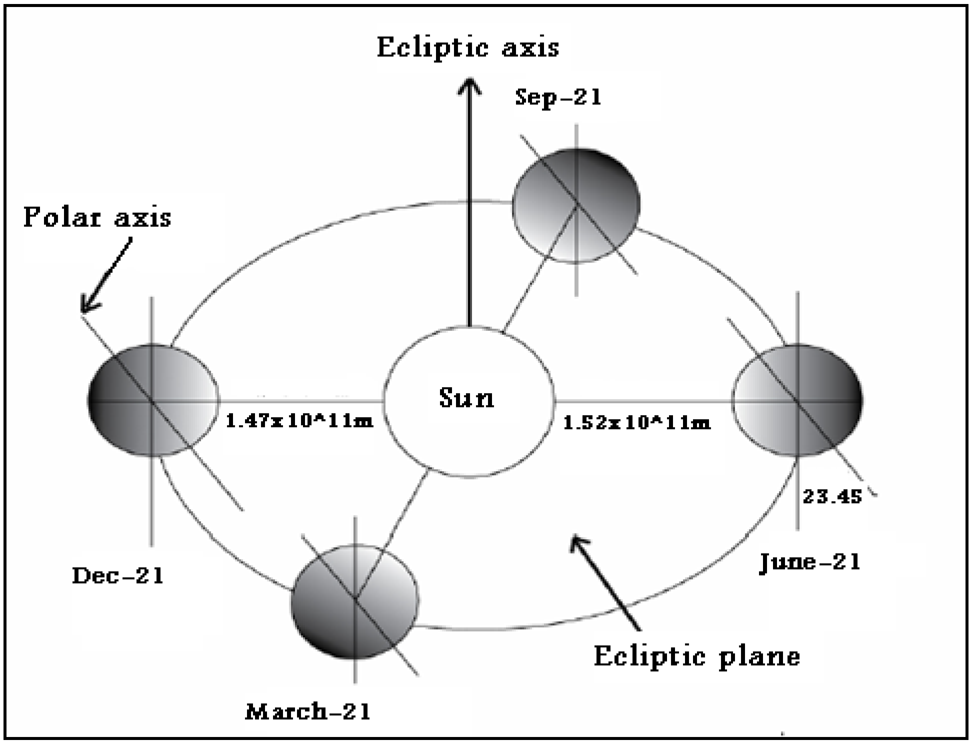

Figure (2-6) Motion of the earth around the sun.

2.2.2. Solar Angles

The angle of declination, δ_s **,** is the angle between The earth's equator and the line connected between the center of the earth and the sun as shown in figure 2-7.

The declination angle varies between -23.45° on December 21 to +23.45° on June 21. The angle of declination, δ_S, is estimated by use of the following equation:

$$\delta_s = 23.45^{o} \sin\left(360 \frac{284 + d_n}{365}\right) \quad (2\text{-}13)$$

where d_n is the day number during the year with the first of January set as $d_n = 1$, and d_n can be conveniently obtained with the help of table 2-1.

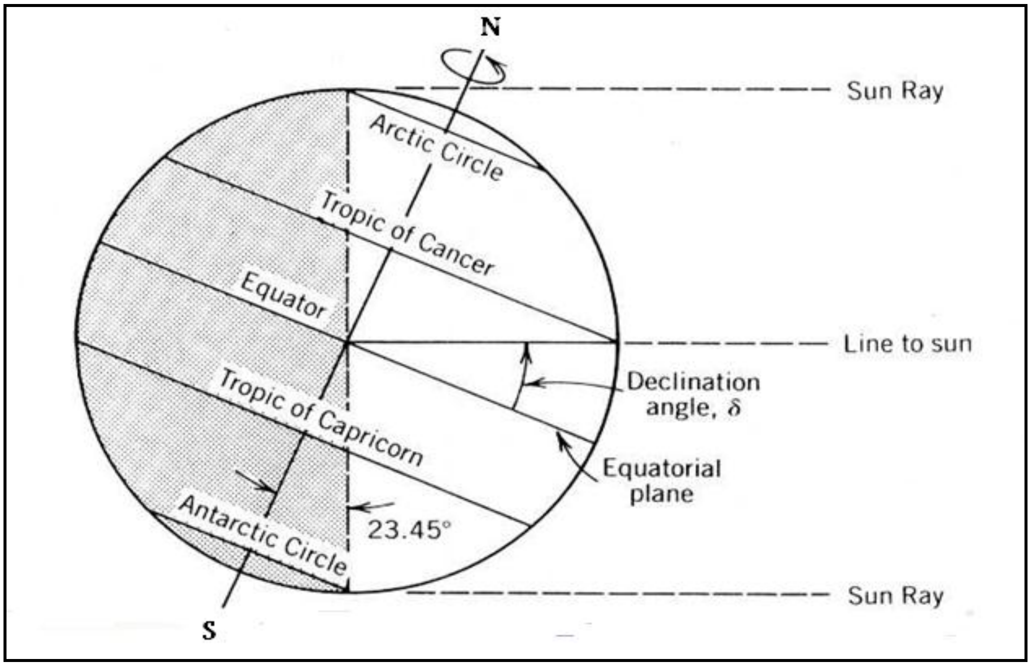

Figure (2-7) The declination angle (shown in the summer solstice position where δ_S = +23.45°).

The **altitude angle, A**, is the angle between a line collinear with the sun's rays and the horizontal, and can be calculated by use of the following equation:

$$\sin(A)=\cos Z_s = \sin(L)\sin(\delta_s) + \cos(L)\cos(\delta_s)\cos(h_s) \qquad (2\text{-}14)$$

Where L is the latitude of site, δ_S is the declination angle of sun and h_s is the hour angle.

zenith angle, Zs, is the angle between the site to the sun line and the vertical at site which is found by subtracting the altitude angle from ninety degrees as in the following equation :

$$Z_s = 90 - A \qquad (2\text{-}15)$$

The solar azimuth angle, AZs, is the angle between a south line and the projection of the site to the sun line on the horizontal plane. For the azimuth angle, the sign convention used is positive if west of south and negative if east of south. The azimuth angle is found by using the following equation:

$$\cos(AZs) = \frac{\sin(A)\sin(L) - \sin(\delta_S)}{\cos(A)\cos(L)} \qquad (2\text{-}16)$$

The hour angle is the angular distance between the meridian of the observer and the meridian whose plane contains the sun. It becomes zero at solar noon and increases 15° every hour. An expression to calculate the hour angle from solar time is:

$$h_s = 15\,(T_{sol.} - 12) \quad \text{(degree)} \qquad (2\text{-}17)$$

Where $T_{sol.}$ is the solar time in hours. The values of the hour angle east due south (morning) are negative; and the values west of due south (afternoon) are positive.

The latitude angle, L, is defined as the angle between the line from the center of the earth to the site of interest and the equatorial plane; and can be found on an atlas or by use of Global positioning system. The latitude of Baghdad is about 33°.

2.3. Solar module Orientation

There are two angles specified for the solar module which determine the orientation of the module with respect to the sun. The first angle is called **tilt angle of module denoted by (T_m)**: is defined as the angle between the module surface and the horizontal plane. The second angle is

the module azimuth angle: is defined as the angle between the projection normal to the module surface and the south which denoted by (AZ_m). Most solar modules mounted in a fixed position which its projection facing the equator. As the direction of the sun with respect to the module changes throughout the day the effective area or aperture of the module will change. Thus, very little sunlight reaches the active surface of the module. As the sun goes higher in the sky, the module intercepts more sunlight until maximum aperture. When the sun's angle is large with respect to the module, not only is the aperture small but the loss due to reflectance from the module surface increases.

The solar angle of incidence on a module: is the angle between the solar radiation and the normal to the module surface which can be calculated using the following equation. (see figure 2-8):

$$AOI = \cos^{-1}\left[\cos(Tm)\cos(Zs) + \sin(Tm)\sin(Zs)\cos(AZs - AZm)\right] \qquad (2\text{-}18)$$

Where AOI is the solar incidence angle, T_m is the tilt angle of module, Zs is the zenith angle of sun, AZ_m is the azimuth angle of module (0°: South, 90°: East) and AZ_S is the azimuth angle of sun (0°: South, 90°: East).

beam solar irradiance for tilted fixed surfaces is given by:

$$H_{b,t} = H_{b,N} \cdot \cos(AOI)$$

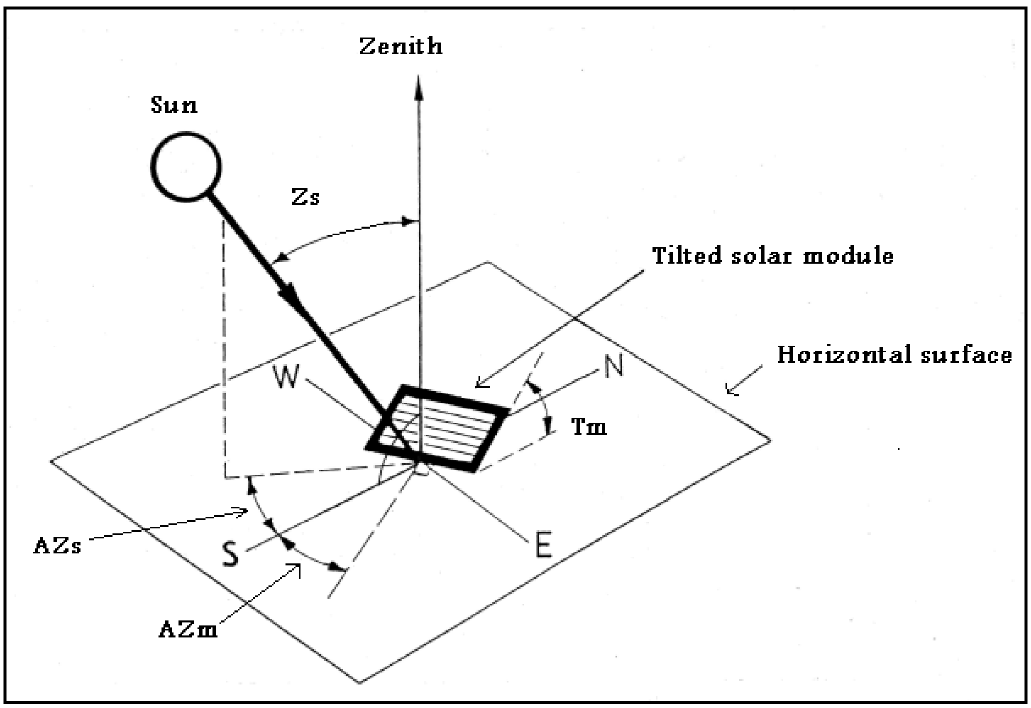

Figure (2-8) Solar System Angles.

2.3. Solar Radiation Measurements

Pyranometer

The pyranometer is an instrument measures global or diffuse radiation on horizontal surface. It covers total hemispherical solar radiation with a view angle of 2π steradians It can measure diffuse sky radiation by providing a shading ring or disk to shad beam radiation.

Pyrheliometer

pyrheliorneter is an instrument which measures beam radiation on a surface normal to the sun.

Homework

Q1) calculate the beam solar radiation at normal incidence ($H_{b,N}$) for Baghdad at 11:00AM in 15-June (d_n=166) when solar constant 1353 W/m^2, visibility 23km and latitude of Baghdad is 33^o.

Q2) calculate the beam solar radiation for tilted fixed surface due south (AZ_m=0) for Baghdad at 10:00AM in 15-May (d_n=135) when $H_{b,N}$=500 W/m^2 and T_m=60^o, L=33^o.