Part A

Unit – II:

Solar Radiation: *Extra-Terrestrial radiation, spectral distribution of extra terrestrial radiation, solar constant, solar radiation at the earth's surface, beam, diffuse and global radiation, solar radiation data.*

Measurement of Solar Radiation: *Pyrometer, shading ring pyrheliometer, sunshine recorder, schematic diagrams and principle of working.*

Solar Radiation Geometry: *Flux on a plane surface, latitude, declination angle, surface azimuth angle, hour angle, zenith angle, and solar altitude angle, expression for angle between the incident beam and the normal to a plane surface (No derivation) local apparent time. Apparent motion of sun, day length, numerical examples.*

Solar Energy – General Aspects:

Sun and Earth Sun

- It is a sphere of very hot gases and its largest members of the solar system.
- The diameter of the sun is 1.39×10^6 km
- The distance between the sun and earth is 1.496×10^8 km, it subtends an angle of only 32 minutes (0.53°) at the earth's surface.
- Sun completes one rotation in four weeks when observed from the earth. But the equator of the sun takes 27 days and Polar Regions takes about 30 days for each rotation.
- The effective black body of the sun is 5773 K.
- The heat generation is mainly due to various kinds of fusion reactions but most of the energy is released in which hydrogen (i.e. four protons) combine to form helium, the fusion reaction is as follows.

$$4({}_1H^1) \rightarrow {}_2H^4_e + 26.3\ \text{MeV}$$

This energy is produced in the interior of the solar sphere and transmitted out by the radiation into the system.

Net energy radiated is given by the equation, $E = s\sigma T^4$

Where s = Emissivity of the surface, σ = Stefan's Boltzmann constant and T_c = Effective black body surface temperature of the sun.

Earth

- It is almost round in shape and has diameter if 1.27 x 10^4 km.
- Its real shape is a sphere flattened at the poles and bulged in the plan normal to the poles.
- The earth's inner core is solid mass made of iron and nickel and the next outer core is melted state or iron and nickel. The outer most portions are made of rocks.
- The existence of the blue green algae indicates beginning of photosynthesis at least 3 x 10^9 years ago. As a result of photosynthesis, the level of O_2 and O_3 increased. In the atmosphere which block the ultra violet (UV) solar radiation coming from the sun. Half of the earth is lit by the sun at a time. It reflects one-third of the sunlight that falls on it is known as earth's albedo.
- The length of days and nights keep changing because the earth is spinning about its axis which is inclined at an angle of 23.5°.

Figure 2.1 Sun and Earth in the solar system.

The amount of solar energy available on the earth's surface is 3.7 x 10^{20} MW, Out of which only 10^{17} Watts hits the atmosphere, and where as solar power available at the earth surface is 10^{16} watts, but for civilization the total power required is 10^{13} Watts. The atmospheric constituents affect the solar

radiation by two processes called absorption and scattering. The energy radiated by the sun as electromagnetic waves of which 99 percent have wave lengths in the range of 0.2 to 0.4 μm. Solar energy reaching the top of the earth's atmosphere consists of about 8% UV radiation (short wave length, less than 0.39 μm), 46% percent visible light (0.39 μm to 0.78 μm) and remaining 46% infrared radiation (long wave length, more than 0.78 μm).

Figure 2.2 (a) Elliptical orbit of Earth's revaluation (b) Inclination of Earth's axis

The earth revolves around the sun in an elliptical orbit as shown in Figure 2.2 (a). The earth is closest to the sun on 21st March and 23rd September. The earth is farthest from the sun on 21st June and 22nd December. Therefore the intensity of solar radiation outside the earth's atmosphere reduces with distance and is dependent on the distance between earth and the sun. In fact, the intensity of solar radiation reaching outside the earth's atmosphere varies with the square of the distance between the centers of the earth and the sun. This is the reason why earth received 7% more radiation on 21st March and 23rd September compared to 21st June and 22nd December. The intensity of solar radiation keeps on attenuating as earth propagates away from the surface of the sun, but the content of wavelengths in the radiation spectrum does not change.

The earth is tilted about 23.45° with respect to the earth's orbit around the sun as shown in Figure 2.2 (b). Owing to this tilting of earth's axis, the northern hemisphere of the earth points towards the sun in the month of June and its points away from the sun in the month of December. However, earth's axis remains perpendicular to the imaginary line drawn from the earth to the sun during the months of September and March. The sun earth's distance varies during earth's rotation around the sun, there by varying the solar energy reaching its surface during revolution, which brings about sensational

changes. The northern hemisphere has summer when the earth is tilting forwards the sun and winter when the earth is tilting away from the sun. In the months of September and March, both the hemispheres are at the same distance from the sun and receive equal sun shine. During the summer, the sun is higher in the sky, while the sun is lower in the sky during winter for the northern hemisphere.

Solar Radiation:

Extraterrestrial solar radiation: The intensity of sun's radiation outside the earth's atmosphere is called '*extraterrestrial*' radiation.

Extraterrestrial radiation is a measure of solar radiation that would be received in the absence of atmosphere.

Terrestrial radiation: The radiation received in the earth's atmosphere is called '*terrestrial radiation*' and is nearly 70% of extraterrestrial radiation.

[When radiation passes through the earth's atmosphere, it is subjected to the mechanism of atmospheric absorption and scattering depending on atmospheric conditions. Earth's atmosphere contains various constituents, suspended dust and solid particles, such as air molecules, oxygen, nitrogen, carbon dioxide, carbon monoxide, ozone, water vapor and dust. Therefore solar radiation or intensity of radiation is depleted during its passage through the atmosphere. The solar radiation that reaches the earth's surface after passing the earth's atmosphere is called terrestrial radiation. The propagation of solar radiation through the earth's atmosphere is shown in Figure 2.3]

Figure 2.3 Solar Radiation

Spectral distribution of extraterrestrial radiation: light rays radiated from the sun are in the form of electromagnetic waves in infrared, visible ultraviolet frequency bands. The frequency spectrum of solar light is a graph of wave length against power density, shown in Figure 2.4

Figure 2.4 Spectral Distribution of Extraterrestrial Solar Radiation

The solar spectrum has three basic levels:

1. "*Infrared band*" with wave lengths too long for response by human eye frequency range: 40x010^{14} to 7.5 x 10^{10} Hz, wave lengths between 0.75 µm & 1.95 µm with an energy of 618 W/m^2. It constitutes 46% of solar radiation.
2. "*Visible band*" The solar radiation contains 46% visible light (band) with a frequency range: 6 x 10^{16} to 7.69 x 10^{14} Hz, with the wave length between 0.39 µm & 0.78 µm, with an energy of 640 W/m^2.

"*Ultraviolet band*" The solar radiation contains only 8% of UV light with a Frequency range of 6 x 10^{16} to 7.5 x 10^{10} Hz, with the wave length between 0.005 µm & 0.39 µm, with energy of 95 W/m^2.

[Note: 1µm = 10^{-6} m, (µ - Micro)]

Irradiance: It is the rate at which the radiant energy is incidenting on a unit surface area. It is the measure of power density of sunlight falling per unit area and time. It is measured in W/m^2. Heat energy is measured in Joules and while Watt or Joules per second is a measure of Power.

Irradiation: It is a solar energy per unit surface area which is striking a body over a specified time. Hence it is integration of solar illumination or irradiance over specified time (usually an hour or kilowatt a day). It is measured in kilowatt-hour or kilowatt day per square meter. For example, if irradiance is 20 kW/m^2 for 5 hours, irradiance is 20 x 5 = 100 kW-hr/m^2.

Beam/Direct Radiation (I_b): Solar radiation received on the surface of the earth without change in direction is known as beam/direct radiation.

Diffuse/Sky Radiation (I_d): The solar radiation received from the sun after its direction has been changed by reflection and scattering by atmosphere is known as diffuse/sky radiation.

Total/Global Radiation (I_T/I_g): The sum of beam and diffuse radiation intercepted at the surface of earth per unit area of location is known as total/global radiation, it is also known as '*insolation*'.

Air mass (m): Air mass is the ratio of the path length through the atmosphere which the solar beam actually traverses up to earth's surface to the vertical path length through the atmosphere. As shown in Figure 2.5

Mathematicaly $Air\ mass(m)=\frac{path\ lenght\ travelled\ by\ beam\ radiation}{vertical\ path\ length\ of\ the\ atmosphere}=\frac{AC}{AB}$

$$\therefore Air\ mass(m)=cosec\ \alpha\ or\ sec\ \theta_z$$

Figure 2.5 Concept of Air mass

Solar Constant (I_{sc}): It is defined as the energy received from the sun per unit time on a unit surface area perpendicular to the direction of propagation of solar radiation at the top of earth's atmosphere when the earth is at its mean distance from the sun. The value of solar constant is taken as 1.353 kW/m^2. (The standard value of solar constant based on the experimental measurements is 1.376 kW/m^2 with accuracy of ±1.5%)

Solar Radiation at the earth's surface:

Solar radiation received at the earth's surface is an attenuated form because it is subjected to the mechanisms of absorption and scattering as it passes through the atmosphere (Figure 2.3). Absorption occurs primarily because of the presence of ozone and water vapor in the atmosphere, and to a lesser extent due to other gases (like CO, CO_2, NO_2, O_2, CH_4, O_3) Particulate Matter and dust particles. It results in increase in internal energy of the atmosphere. On the other hand, scattering occurs due to all gaseous molecules as well as particulate matter in the atmosphere. The scattered radiation is redistributed in all directions, some going back into the space and some reaching the earth's surface.

The atmosphere at any location on the earth's surface is often classified into two broad types an atmosphere without clouds and atmosphere with

clouds. In the former case, the sky is cloudless everywhere, while in the later, the sky is partly or fully covered by clouds. The mechanisms of absorption and scattering are similar in both types of atmosphere. However it is obvious that less attenuation takes place in a cloudless sky. Consequently maximum radiation is received on the earth's surface under the conditions of cloudless sky.

In general the intensity of diffuse radiation coming from various directions in the sky is not uniform. The diffuse radiation is therefore said to be anisotropic in nature. However in many situations, the intensity from all directions tends to be reasonably uniform. It is then modeled as being perfectly uniform as is said to be isotropic in nature.

Extensive studies have been made on mechanisms of absorption and scattering, and on the determination of attenuation coefficients for various substances. Nevertheless, it is in general not possible to predict, to a reasonable degree of accuracy, the variation with time of the beam and diffuse radiation with might be expected at a specified location on the earth's surface.

***Depletion of Solar radiation*:**

The earth's atmosphere contains various gaseous constituents, suspended dust and other minute solid and liquid particulate matter. These are air molecules, ozone, oxygen, nitrogen, carbon dioxide, carbon monoxide, water vapor, dust, and water droplets. Therefore solar radiation is depleted during its passage through the atmosphere. Different molecules to different things as explained below

- ***Absorption***: Selective absorption of various wavelengths occurs by different molecules. The absorbed radiation increases the energy of the absorbing molecules, thus raising their temperatures.
  (a) Nitrogen, molecular oxygen and other atmospheric gases absorb the X-rays and extreme ultraviolet radiations.
  (b) Ozone absorbs a significant amount of ultraviolet radiation in the range ($\lambda < 0.38\ \mu m$).
  (c) Water vapor (H_2O) and carbon dioxide absorb almost completely the infrared radiation in the range ($\lambda > 2.3\ \mu m$) and deplete to some extent the near infrared radiation below this range.
  (d) Dust particles and air molecules also absorb a part of solar radiant energy, irrespective of wavelength.

- ***Scattering***: Scattering by dust particles and air molecules (or gaseous particles of different sizes) involves redistribution of incident energy. A part of the scattered radiation is lost (reflected back) to space and the remaining

is directed downwards to the earth's surface from different directions as diffuse radiation. It is the scattered sunlight that makes the sky blue. Without the atmosphere and its ability to scatter sunlight, the sky would appear black as it does on the moon.

Solar Radiation Data

Most radiation data is measured for horizontal surfaces. A typical daily record of the global and diffuse radiation flux measured on a clear day is shown in Figure 2.6. It is seen that a fairly, smooth variation with the maximum occurring around noon is obtained on a clear day. In contrast, an irregular variation with many peaks and valleys may be obtained on a cloudy day. We will use the symbols I_g and I_d to represent the instantaneous values of the global and diffuse flux plotted in Figure 2.6 and express these quantities in W/m^2. Since solar radiation fluxes do not normally change rapidly with time, we will use the same symbols I_g and I_d to represent hourly values also. These quantities expressed in $kW\text{-}h/m^2\text{-}h$ or $kJ/m^2\text{-}h$. The shaded area below the graphs represent global and diffuse flux incident over a whole day. We will use the symbols H_g and H_d to represent these qualities and express them in $kW\text{-}h/m^2\text{-}day$ of $kJ/m^2\text{-}day$.

Solar radiation flux is some times reported in langleys per hour per day (1 langley = 1 cal/cm^2 = 1.163×10^{-2} kWh/m^2). The 'langley' has been adopted in honor of Samuel Langley who made the first measurement of the spectral distribution of the sun.

A solar designer primarily interested in average values for a location. The averaging is usually done over all days of a month and indicated by a bar over the symbol. Tabulations showing the hourly variation of global and diffuse radiation(I_g and I_d), the amount received per day ($\bar{H}_g$ and $\bar{H}_d$) and sunshine hours per day ($\bar{S}$) are available for many locations in India. The table 2.1 to 2.4 shows the data for two locations of India i.e. New Delhi and Mumbai.

Figure 2.6 Daily Variation of Global and Diffuse radiation data measured on a horizontal surface (a) Clear sky (b) cloudy sky

Location: New Delhi (28°35’ N, 77°12’ E)

	$\bar{I}_g$														$\bar{H}_g$	$\bar{S}$
	6	7	8	9	10	11	12	13	14	15	16	17	18	19	kWh/m² -day	h
J	0.000	0.004	0.096	0.271	0.433	0.556	0.618	0.615	0.552	0.430	0.268	0.099	0.005	0.000	3.987	7.6
F	0.000	0.020	0.163	0.364	0.540	0.670	0.727	0.728	0.659	0.534	0.358	0.165	0.021	0.000	5.001	9.0
M	0.001	0.066	0.260	0.475	0.655	0.781	0.845	0.844	0.769	0.635	0.458	0.249	0.064	0.001	6.138	8.2
A	0.010	0.130	0.339	0.554	0.727	0.848	0.910	0.903	0.833	0.699	0.523	0.318	0.122	0.010	6.935	8.6
M	0.030	0.177	0.383	0.581	0.746	0.865	0.925	0.920	0.844	0.719	0.547	0.352	0.158	0.027	7.287	8.0
J	0.036	0.164	0.339	0.510	0.657	0.757	0.809	0.813	0.750	0.639	0.483	0.318	0.159	0.036	6.544	5.9
J	0.026	0.130	0.275	0.425	0.549	0.640	0.672	0.671	0.606	0.518	0.412	0.273	0.141	0.032	5.334	5.8
A	0.012	0.101	0.243	0.392	0.512	0.607	0.640	0.659	0.595	0.510	0.392	0.255	0.107	0.013	5.053	5.6
S	0.003	0.079	0.248	0.431	0.587	0.698	0.757	0.747	0.689	0.571	0.417	0.244	0.074	0.003	5.602	7.0
O	0.000	0.036	0.202	0.406	0.581	0.701	0.764	0.758	0.692	0.569	0.391	0.191	0.033	0.000	5.355	8.8
N	0.000	0.009	0.128	0.319	0.495	0.620	0.685	0.680	0.613	0.490	0.315	0.125	0.010	0.000	4.523	9.2
D	0.000	0.003	0.085	0.259	0.425	0.543	0.605	0.605	0.538	0.418	0.255	0.086	0.003	0.000	3.843	8.0

Table 2.1 Monthly average hourly global radiation $\bar{I}_g$, daily global radiation $\bar{H}_g$ and sunshine hours $\bar{S}$

N.B. Time indicated is LAT. Value of I_g given for a particular time corresponds to the radiation (in kWh/m²-h) incident on a horizontal surface during the one hour preceding the time. Multiply by 3600 to obtain an hourly value (in kJ/m²-h)

Location: New Delhi (28°35’ N, 77°12’ E)

	$\bar{I}_d$														$\bar{H}_d$
	6	7	8	9	10	11	12	13	14	15	16	17	18	19	kWh/m² -day
J	0.000	0.003	0.051	0.103	0.140	0.160	0.174	0.172	0.162	0.137	0.100	0.051	0.003	0.000	1.240
F	0.000	0.013	0.076	0.126	0.159	0.183	0.191	0.190	0.180	0.160	0.125	0.075	0.013	0.000	1.474
M	0.001	0.043	0.113	0.159	0.189	0.210	0.222	0.226	0.215	0.197	0.163	0.113	0.041	0.001	1.861
A	0.009	0.083	0.153	0.202	0.236	0.262	0.274	0.279	0.274	0.250	0.212	0.156	0.079	0.008	2.473
M	0.027	0.114	0.190	0.244	0.279	0.303	0.315	0.318	0.308	0.286	0.247	0.189	0.107	0.022	2.922
J	0.033	0.124	0.215	0.286	0.342	0.382	0.399	0.299	0.377	0.340	0.279	0.203	0.114	0.028	3.540
J	0.023	0.096	0.178	0.257	0.316	0.358	0.372	0.365	0.333	0.291	0.241	0.174	0.101	0.023	3.135
A	0.009	0.074	0.153	0.224	0.277	0.317	0.334	0.331	0.302	0.265	0.210	0.149	0.075	0.010	2.727
S	0.002	0.053	0.123	0.178	0.222	0.256	0.269	0.263	0.248	0.217	0.167	0.118	0.048	0.002	2.152
O	0.000	0.026	0.087	0.128	0.154	0.169	0.179	0.177	0.169	0.154	0.126	0.083	0.021	0.001	1.465
N	0.000	0.007	0.057	0.099	0.122	0.137	0.145	0.146	0.142	0.124	0.099	0.055	0.006	0.000	1.141
D	0.000	0.002	0.045	0.092	0.123	0.144	0.155	0.156	0.147	0.125	0.092	0.043	0.002	0.000	1.117

Table 2.2 Monthly average hourly diffuse radiation $\bar{I}_d$, daily global radiation $\bar{H}_d$

N.B. Time indicated is LAT. Value of I_g given for a particular time corresponds to the radiation (in kWh/m²-h) incident on a horizontal surface during the one hour preceding the time. Multiply by 3600 to obtain an hourly value (in kJ/m²-h)

Location: Mumbai (19°07’ N, 72°51’ E)

	$\bar{I}_g$														$\bar{H}_g$	$\bar{S}$
	6	7	8	9	10	11	12	13	14	15	16	17	18	19	kWh/m² -day	h
J	0.000	0.018	0.154	0.358	0.528	0.660	0.735	0.746	0.685	0.560	0.383	0.175	0.022	0.000	5.031	9.3
F	0.000	0.032	0.198	0.407	0.599	0.737	0.823	0.835	0.769	0.644	0.456	0.230	0.042	0.000	5.755	9.7
M	0.001	0.062	0.252	0.465	0.654	0.801	0.888	0.901	0.832	0.704	0.513	0.281	0.072	0.001	6.448	9.5
A	0.004	0.095	0.288	0.492	0.695	0.845	0.937	0.955	0.893	0.759	0.563	0.333	0.113	0.005	6.991	9.6
M	0.012	0.124	0.294	0.489	0.710	0.864	0.952	0.962	0.899	0.768	0.578	0.360	0.150	0.017	7.262	9.3
J	0.011	0.093	0.217	0.364	0.508	0.605	0.666	0.678	0.638	0.548	0.412	0.253	0.108	0.015	5.177	5.6
J	0.007	0.069	0.168	0.286	0.399	0.498	0.541	0.555	0.515	0.433	0.325	0.199	0.082	0.009	4.061	2.4
A	0.003	0.057	0.162	0.290	0.407	0.478	0.554	0.540	0.493	0.410	0.293	0.176	0.066	0.005	3.976	2.4
S	0.001	0.051	0.184	0.329	0.466	0.576	0.650	0.693	0.669	0.571	0.401	0.222	0.068	0.002	4.878	5.2
O	0.000	0.038	0.195	0.382	0.550	0.663	0.749	0.773	0.733	0.616	0.429	0.222	0.050	0.001	5.443	8.2
N	0.000	0.022	0.166	0.367	0.547	0.669	0.731	0.741	0.741	0.545	0.371	0.174	0.024	0.000	5.074	8.9
D	0.000	0.013	0.142	0.342	0.517	0.647	0.717	0.719	0.719	0.524	0.353	0.155	0.017	0.000	4.794	8.9

Table 2.3 Monthly average hourly global radiation $\bar{I}_g$, daily global radiation $\bar{H}_g$ and sunshine hours $\bar{S}$

N.B. Time indicated is LAT. Value of I_g given for a particular time corresponds to the radiation (in kWh/m²-h) incident on a horizontal surface during the one hour preceding the time. Multiply by 3600 to obtain an hourly value (in kJ/m²-h)

Location: New Delhi (28°35' N, 77°12' E)

	$\bar{I}_d$														$\bar{H}_d$
	6	7	8	9	10	11	12	13	14	15	16	17	18	19	kWh/m² -day
J	0.000	0.010	0.064	0.104	0.133	0.155	0.164	0.161	0.150	0.133	0.107	0.070	0.012	0.000	1.279
F	0.000	0.020	0.083	0.127	0.161	0.178	0.184	0.177	0.161	0.143	0.121	0.083	0.023	0.000	1.467
M	0.001	0.041	0.109	0.162	0.192	0.209	0.207	0.202	0.189	0.172	0.146	0.104	0.040	0.000	1.776
A	0.002	0.067	0.145	0.203	0.237	0.254	0.252	0.242	0.222	0.201	0.174	0.130	0.062	0.002	2.187
M	0.009	0.087	0.172	0.234	0.268	0.280	0.281	0.273	0.259	0.236	0.199	0.153	0.086	0.011	2.508
J	0.010	0.076	0.164	0.243	0.304	0.339	0.367	0.359	0.336	0.301	0.244	0.166	0.079	0.011	2.969
J	0.008	0.059	0.147	0.234	0.309	0.373	0.396	0.404	0.368	0.316	0.244	0.160	0.067	0.008	3.065
A	0.001	0.048	0.145	0.249	0.333	0.377	0.432	0.414	0.380	0.327	0.233	0.143	0.060	0.002	3.156
S	0.001	0.045	0.144	0.227	0.288	0.345	0.366	0.359	0.339	0.296	0.224	0.139	0.049	0.001	2.860
O	0.000	0.025	0.115	0.167	0.207	0.232	0.244	0.249	0.220	0.190	0.147	0.096	0.031	0.000	1.982
N	0.000	0.012	0.067	0.101	0.124	0.142	0.148	0.144	0.142	0.128	0.103	0.065	0.012	0.000	1.193
D	0.000	0.009	0.061	0.092	0.113	0.129	0.137	0.139	0.133	0.119	0.098	0.061	0.010	0.000	1.106

Table 2.4 Monthly average hourly diffuse radiation $\bar{I}_d$, daily global radiation $\bar{H}_d$

N.B. Time indicated is LAT. Value of I_g given for a particular time corresponds to the radiation (in kWh/m²-h) incident on a horizontal surface during the one hour preceding the time. Multiply by 3600 to obtain an hourly value (in kJ/m²-h)

Instruments for measuring Solar Radiation and Sunshine

The instruments used for measurement will now be described. The solar radiation flux is usually measured with the help of pyranometer or pyrheliometer.

Pyranometer:

A pyranometer is an instrument which measures either global or diffuse radiation falling on a horizontal surface. A sketch of one type of pyranometer as installed for the measurement of global radiation is shown in Figure 2.7. Basically pyranometer consists of a black surface which heats up when exposed to solar radiation. Its temperature increases until the rate of heat gain by solar radiation is equal to the rate of heat loss by conduction, convection and re-radiation. The hot junctions of a thermopile are attached to the black surface, while the cold junctions are located under a guard plate so that they do not receive radiation directly. As a result emf is generated, recorded or integrated over a period of time and is a measure of global radiation.

Figure 2.7 Pyranometer for measuring global Radiation

(1) Black surface, (2) Glass domes, (3) Guard plate, (4) Leveling screws, (5) Mounting plate, (6) Bolts, (7) Platform

The pyranometer shown in Figure 2.7 is used commonly in India. It has a hot junction arranged in the form of horizontal disc of diameter 25 mm and coated with a special black lacquer having a very high absorptivity in the solar wavelength region. The disc is placed on the large diameter guard plate which may be horizontal or slopping. Two concentrating hemispheres, 30 mm and 50 mm in diameter respectively, made of optical glass having excellent transmission characteristics, are used to protect the disc surface from the weather. An accuracy of about ±2% can be obtained with the instrument.

Shading Ring Pyranometer:

The pyranometer can also be used for the measurement of diffuse radiation. This is done by mounting it at the centre of a semicircular shading ring. The shading ring is fixed in such a way that its plane is parallel to the plane of the path of the sun's daily movement across the sky and its shades the thermopile element and two glass domes of the pyranometer at all times from Direct sunshine. Consequently, the pyranometer measures only the Diffuse radiation received from the sky.

Figure 2.8 shading ring for measurement of diffuse radiation

The construction of one type of shading ring is as shown in Figure 2.8. ABCD is a horizontal rectangular frame 35 cm X 80 cm with its long sides in east-west direction. To the side AB and CD of the frame are provided two angle-iron arms, EF and GH, 70 cm long with slots along their length, carrying sliders, SS on which is mounted the semicircular shading ring R. The arms are pivoted about a horizontal axis which passes through the centre of the rectangular frame and can be adjusted at an angle to the horizontal equal to the latitude of the station. The movement of the ring up and down the arms allows for changes in the sun's declination. The shading ring is of aluminum, 50 mm broad and is bent to a radius of 450 mm. the inner surface of the ring is painted dull black. To the bottom of the frame ABCD is fixed a thick metal plate P with a circular slot so that the frame, when fixed on a masonry platform with nuts and bolts, can be adjusted in its proper position by rotation about

vertical axis. To the top of the frame is fitted another thick metal plate p' on which the pyranometer is mounted.

Pyrheliometer:

A pyrheliometer is an instrument which measures beam radiation falling on a surface normal to the sun's rays. In contrast to a pyranometer, the black absorber plate (with the hot junctions of thermopile attached to it) is located at the base of a collimating tube as shown in Figure 2.9. The tube is aligned with the direction of the sun's rays with the help of two-axis tracking mechanism and the alignment indicator. Thus the black plate receives only beam radiation & a small amount of diffuse radiation falling with in acceptance angle of the instrument.

Figure 2.9 Pyrheliometer for measuring beam radiation

(1) Tube blackened on inside surface, (2) Baffle, (3) Alignment indicator, (4) Black absorber plate, (5) Thermopile junctions, (6) two-axis tracking mechanism

Sunshine recorder:

The duration of bright sunshine in a day is measured by means of a sunshine recorder as shown in Figure 2.10. The sun's rays are focused by a glass sphere to a point on a card strip held in a grove in a spherical bowl mounted concentrically with the sphere. Whenever there is a bright sunshine, the image formed is intense enough to burn a spot on the card strip. Through the day as the sun moves across the sky, the

Figure 2.10 Sunshine recorder

image moves along the strip. Thus, a burnt trace whose length is proportional to the duration of sunshine is obtained on the strip.

Solar Radiation Geometry

Latitude (Angle of Latitude), (Ø): The latitude of a location on the earth's surface is the angle made by the radial line joining the specified location to the centre of the earth with the projection of this line on the equatorial plane as shown in the Figure 2.11. The latitude is positive for northern hemisphere and negative for southern hemisphere.

Figure 2.11 Latitude

Declination angle, (δ): It is the angle made by the line joining the centers of the sun and earth with the equatorial plane as shown in Figure 2.12. The angle of declination varies when earth revolves around the sun. It has a maximum value of 23.45° when the earth achieves a position in its orbit corresponding to 21st June and has a minimum value of -23.45° when the earth is in orbital position corresponding to 21st December. The angle of declination is taken positive when it is measured above the equatorial plane in the northern hemisphere. The angle of declination is given by the equation

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

Where '*n*' is the number of days from January 1.

Figure 2.12 Declination angle

Hour angle, (ω): The hour angle at any instant is the angle through which the earth has to turn to bring the meridian of the observer directly in line with sun ray's. It is an angular measure of time. It is the angle in degree traced by the sun in one hour with reference to the twelve noon of the location. The convection of measuring it is that noon-based calculated local apparent time (LAT) is positive in afternoon and negative in forenoon as shown in Figure 2.13. The earth completes one rotation (360°) in 24 hours. Hence one hour corresponds to 15° of earth's rotation. As at solar noon the sun rays in line with local meridian or longitude, the hour angle at that instant is zero. The hour angle is given by the equation

Figure 2.13 Hour angle

$$\omega = [\text{Solar time-12}] * 15°$$

Inclination or Altitude angle, (α): The angle between the sun's ray and its projection on a horizontal surface is known as the inclination angle, as shown in the Figure 2.14

Zenith angle, (θ_Z): It is an angle between sun's ray and the perpendicular to the horizontal plane as shown in Figure 2.14

Solar Azimuth angle, (γ_s): It is the angle on a horizontal plane, between the line due south and the projection of the sun's ray on the horizontal plane. It is taken as positive when measured from south towards west.

Surface Azimuth angle, (γ): It is the angle in the horizontal plane, between the line due south and the horizontal projection of the normal to the inclined plane surface (flat plate collector) as shown in Figure 2.14. It is taken as positive when measured from south towards west.

Slope or Tilt angle, (β): It is the angle between the inclined plane surface (flat plate collector) and the horizontal plane as shown in Figure 2.14. It is taken to be positive for the surface sloping towards south.

Angle of incidence, (θ): The angle of incidence for any surface is defined as the angle formed between the direction of the sun ray and the line normal to the surface as shown in Figure 2.14.

Figure 2.14 Solar radiation geometry

General equation for cos θ

$$\cos\theta = [\sin Ø\ (\sin\delta\cos\beta + \cos\delta\cos\gamma\cos\omega\sin\beta) + \cos Ø\ (\cos\delta\cos\omega\cos\beta - \sin\delta\cos\gamma\sin\beta) + \cos\delta\sin\gamma\sin\omega\sin\beta]$$

Where,

θ	:	Angle of incidence
Ø	:	Angle of latitude
δ	:	Angle of declination
γ	:	Surface azimuth angle
β	:	Tilt angle

1. *For a vertical surface: $\beta = 90°$:*

$$\cos\theta = \sin\emptyset \cos\delta \cos\gamma \cos\omega - \cos\emptyset \sin\delta \cos\gamma + \cos\delta \sin\gamma \sin\omega$$

Note: ($\sin 90° = 1$, $\cos 90° = 0$)

2. *For a horizontal surface: $\beta = 0°$: $\theta = \theta_Z$ (Zenith angle)*

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

Note: ($\sin 0° = 0$, $\cos 0° = 1$)

Also,

$$\cos\theta = \cos\theta_z = \sin\alpha \left(\text{since } \theta_z = \frac{\pi}{2} - \alpha\right)$$

3. *Surface facing south: $\gamma = 0°$:*

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

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

4. *Vertical surface facing south: $\beta = 90°$, $\gamma = 0°$:*

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

The angle of incidence can also be expressed in terms of θ_Z *(Zenith angle)* as:

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

$$\cos\gamma_s = \left(\frac{\cos\theta_Z \sin\emptyset - \sin\delta}{\sin\theta_Z - \cos\emptyset}\right)$$

Latitude and longitude

Latitude: On a globe of the earth, line of latitude is circle of different sizes. The largest one is at the circle of equator (circle at equator with centre at earth's centre) whose latitude is taken as zero. The circles at the poles have latitude of 90° North and 90° South (or -90°) where these circles shrink to a point, there are 180 circles of which 90 in each hemisphere specify the latitude of various points on earth's surface as shown in Figure 2.15 (a). Each degree of latitude is about 111 km apart. Latitude lines run horizontally and these lines are parallel.

Longitude: On the globe, vertical lines of constant longitude (meridians) extend from pole to pole similar to the segment boundaries on a peeled orange. Every meridian has to cross the equator and equator is a circle, like any circle, it has 360° of divisions. Hence, the longitude of a point is marked a value of that division where its meridian meets the equator circle. The meridian passing through the Royal Astronomical observatory at Greenwich, UK has been chosen as zero latitude. The meridian passing through this location is called prime meridian. This prime meridian or longitude is considered zero longitude and there are 180 longitude lines or degree as cast (+180°) and 180° at west (-180°) of Greenwich. The longitude lines meet at poles and these have wide separation at equator about (111 km). The longitudinal lines are shown in Figure 2.15 (b). Solar noon is the time when the sun is at the longitude of place.

Apparent motion of the sun

To an observer on the earth, on any given day, the sun rises in the east, moves in a tilted plane in the angle of [90° - Ø] with the horizontal, and finally sets in the west. Thus, the apparent plane in which the sun moves intersects the horizontal plane in a line positioning east-west. However because of the declination angle this E-W line of intersection does not coincide with E-W passing through the observer O. for a location in the northern hemisphere, this line is to the south in winter (declination negative, 21st December with an angle of -23.45°) to the north in summer (declination positive, 21st June with an

angle of 23.45°) and coincides with the E–W line passing through the observer on two equinox days i.e. 21st March & 21 September (declination iszero).

Figure 2.15 Apparent motion of the sun

Local Apparent Time (LAT)

The time used for calculating the hour angle ω is the local apparent time. This can be obtained from the standard time observed on a clock by applying two corrections. The first correction arises because of the difference between the longitude of a location and the meridian on which the standard time is based. The correction has magnitude of 4 minutes for every degree difference in longitude. The second correction called the equation of time correction due to fact that earth's orbit and rate of rotation are subjected to small variations. This correction is based in experimental observations and is plotted in Figure 2.15.

Figure 2.16 Equation of time correction

Thus, LAT = standard time ± 4 (standard time longitude – longitude of location) + (equation of time correction)

The equation of time correction (in minutes) can also be calculated from following empirical relation

$E = 229.18\ (0.000075 + 0.001868 \cos B - 0.032077 \sin B - 0.014165 \cos 2B - 0.04089 \sin 2B)$

Sunrise, sunset & Day length

Horizontal surface: The hour angle corresponding to sunrise or sunset (ω_s) on a horizontal surface is given by

$$\cos \omega_s = -\tan \phi \tan \delta, \therefore \omega_s = \cos^{-1}(-\tan \phi \tan \delta) \quad \text{in degree}$$

If an above equation yields a positive value then it is sunrise, if it yields negative value then it is sunset, then corresponding day length is given by the equation

$$L_d = \frac{2}{15}\omega_s = \cos^{-1}(-\tan \phi \tan \delta) \quad \text{in hours}$$

Inclined surface facing due south:

$$\omega_{st} = \cos^{-1}(-\tan(\phi - \beta)\tan\delta)$$

$$|\omega_{st}| = \min[|\cos^{-1}(-\tan\phi\tan\delta)|, |\cos^{-1}(-\tan(\phi - \beta)\tan\delta|]$$

Inclined surface facing due north:

$$\omega_{st} = \cos^{-1}(-\tan(\phi + \beta)\tan\delta)$$

$$|\omega_{st}| = \min[|\cos^{-1}(-\tan\phi\tan\delta)|, |\cos^{-1}(-\tan(\phi + \beta)\tan\delta|]$$

Estimation of average solar radiation

Angstrom's equation for average global radiation:

The expression for the average radiation on a horizontal surface in terms of constants *a* and *b* and observed values of average length of solar days, as suggested by angstrom is given by

$$\frac{H_g}{H_c} = a + b\left(\frac{L_a}{L_m}\right)$$

Where H_g = Monthly average of daily global radiation on a horizontal surface at the location in (kJ/m^2 day)

H_c = Monthly average of the daily global radiation on the same horizontal surface at the same location but on clear sky day (kJ/m^2 day)

a, b = Constants determined from various cities in the world by measurements

L_a = Average length of solar day for a particular month calculated or observed (in hours)

L_m = Length of the longest solar day in the month (in hours)

Modified Angstrom's equation

The modified Angstrom's equation is written by replacing H_c by H_o in the above equation.

$$\frac{H_g}{H_o} = a + b\left(\frac{L_a}{L_m}\right)$$

Where H_o = Monthly average of the daily extraterrestrial radiation, which would fall on a horizontal surface at the location under consideration (in kJ/m^2 day)

The expression for H_o is given by

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

Where,

n = Number of days in the year
I_{sc} = *Solar Constant*
$\emptyset$ = Angle of latitude for location
δ = Angle of declination of equatorial plane
ω = hour angle for local apparent time

The integral $\int dt$ in above equation is in terms of hours. It can be changed to an angle of $\int d\theta$ in radians.

Now,

$$1\ hour = 15^\circ = \frac{15\pi}{180} rad.$$

$$\therefore dt = \frac{180}{15\pi} d\omega = \frac{12}{\pi} d\omega$$

Inserting the value of dt in the H_o equation and integrating between sun rise ($-\omega_s$) to ($+\omega_s$) for a total day light period we get

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

By solving the integral we get

$$H_o = \frac{24}{\pi} I_{sc} \left[\left\{1 + 0.033 \cos\left(\frac{360n}{365}\right)\right\} (\omega_s \sin \emptyset \sin \delta + \cos \emptyset \cos \delta \sin \omega_s)\right] \text{kJ/m}^2 \text{ day}$$

The value of H_o can be calculated for a clear sky day on a flat surface location.

Hence the value of H_g (daily global radiation-monthly average) for a horizontal surface at the location is then calculated by using the values of H_o, a,b in the modified Angstrom's equation

H_o can be obtained from charts or can be calculated by following empirical relation

$$H_o = \frac{24}{\pi} I_{sc} \left[\left\{ 1 + 0.033 cos \left(\frac{360}{365} n \right) \right\} \left(\cos \emptyset \cos \delta \cos \omega_s + \frac{2\pi \omega_s}{360} \sin \emptyset \sin \delta \right) \right]$$

Sl No	*City*	*a*	*b*	*Mean percentage error*
01	Ahmedabad	0.28	0.48	3.0
02	Bangalore	0.18	0.64	3.9
03	Bhavangar	0.28	0.47	2.8
04	Chennai	0.30	0.44	3.5
05	Goa	0.30	0.48	2.1
06	Jodhpur	0.33	0.46	2.0
07	Kodaikanal	0.32	0.55	2.9
08	Kolkata	0.28	0.42	1.3
09	Mangalore	0.27	0.43	4.2
10	Minicoy	0.26	0.39	1.4
11	Nagpur	0.27	0.50	1.6
12	New Delhi	0.25	0.57	3.0
13	Pune	0.31	0.43	1.9
14	Shilong	0.22	0.57	3.0
15	Srinagar	0.35	0.40	4.7
16	Thiruvananthapuraam	0.37	0.39	2.5
17	Vishakhapatanam	0.28	0.47	1.2

Table 2.5 constants for a and b for Indian cities

Example 2.1: Determine the sunset hour angle and day length at allocation of latitude of 32° on March 30.

Given data, *Ø = 32°, day of the year = March 30*.

Solution,

The total number of days up to March 30 is i.e. n = 31 + 28 + 30 = 89
Jan Feb Mar

The declination angle is given by the equation,

$$\delta = 23.45 \sin \left[\frac{360}{365} (284+n) \right] = 23.45 \sin \left[\frac{360}{365} (284+89) \right] = \mathbf{3.22°}$$

Hour angle is calculated by the equation,

$$\omega_s = \cos^{-1}(-\tan \emptyset \tan \delta) = \cos^{-1}(-\tan 32° \tan 3.22°) = \mathbf{92.01°}$$

Day length is given by the equation,

$$L_d = \frac{2}{15}\omega_s = \frac{2}{15}92.01 = 12.268 \text{ hours} = \mathbf{12^h16'08''}$$

Example 2.2: Determine the day length in hours at New Delhi (latitude = 28.6°) on June 28 in a leap year.

Given data, *Ø = 28.6°, day of the leap year = June 28.*

Solution,

The total number of days up to June 28 is i.e.

n = 31 + 29 + 31 + 30 + 31 + 28 = 180 days

Jan Feb Mar Apr May Jun

The declination angle is given by the equation,

$$\delta = 23.45 \sin\left[\frac{360}{365}(284+n)\right] = 23.45 \sin\left[\frac{360}{365}(284+180)\right] = \mathbf{23.24°}$$

Hour angle is calculated by the equation,

$$\omega_s = \cos^{-1}(-\tan \emptyset \tan \delta) = \cos^{-1}(-\tan 28.6° \tan 23.24°) = \mathbf{103.54°}$$

Day length is given by the equation,

$$L_d = \frac{2}{15}\omega_s = \frac{2}{15}10.54 = 13.8 \text{ hours} = \mathbf{12^h48'}$$

Example 2.3: Calculate the Local Apparent Time (LAT) and declination at a location latitude 24°20' N, longitude 77°21' E at 12:30 IST on July 24. Equation of time correction is (-1' 06")