



# Solar Radiation

The objectives of this section are:

1. to review the properties of solar radiation;
2. to determine theoretical upper limit of solar radiation available at the earth's surface;
3. to determine the position of the sun in the sky and the beam radiation direction that is incident on surfaces of various orientations and shading.

Sources: Solar Engineering of Thermal Processes by Duffie & Beckman, John Wiley & Sons, 1991

<http://powerfromthesun.net/chapter3/Chapter3>

Reference: Principles of Solar Engineering, Goswami, Kreith and Kreider, Taylor & Francis, 2000

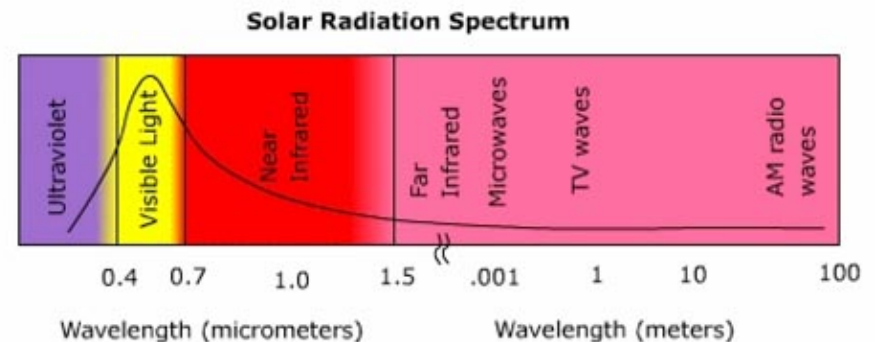
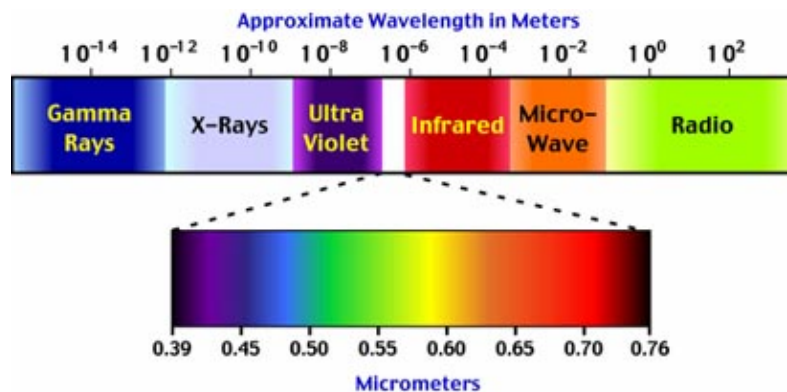




# Energy and Radiation\*

Radiation: The transfer of energy via electromagnetic waves that travel at the speed of light. The velocity of light in a vacuum is approximately  $3 \times 10^8$  m/s. The time it takes light from the sun to reach the Earth is 8 minutes and 20 seconds. Heat transfer by electromagnetic radiation can travel through empty space. Any body above the temperature of absolute zero ( $-273.15^\circ$  C) radiate energy to their surrounding environment.

The many different types of radiation is defined by its wavelength. The electromagnetic radiation can vary widely.

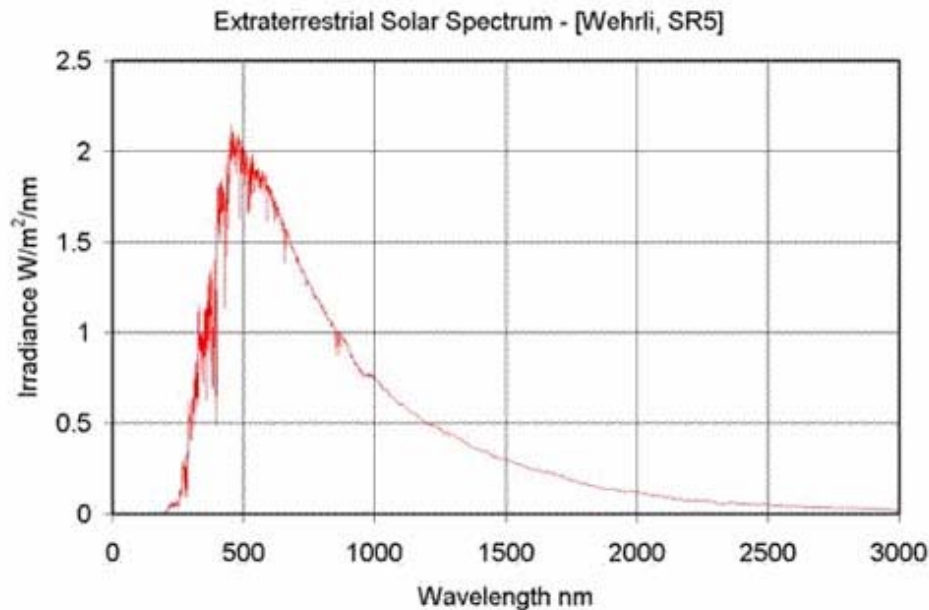


\*Source: [http://www.uwsp.edu/geo/faculty/ritter/geog101/textbook/energy/nature\\_of\\_electromagnetic\\_radiation.html](http://www.uwsp.edu/geo/faculty/ritter/geog101/textbook/energy/nature_of_electromagnetic_radiation.html)  
<http://www.physicalgeography.net>



# Sun Radiation Spectrum

Visible light has a wavelength of between 0.40 to 0.71 micrometers ( $\mu\text{m}$ ). The sun emits only a portion (44%) of its radiation in this range. Solar radiation spans a spectrum from approximately 0.1 to 4.0 micrometers. About 7% of the sun's emission is in 0.1 to 0.4 micrometers wavelength band (UV). About 48% of the sun's radiation falls in the region between 0.71 to 4.0 micrometers (near infrared : 0.71 to 1.5 micrometers; far infrared: 1.5 to 4.0 micrometers).



Solar radiation incident outside the earth's atmosphere is called extraterrestrial radiation. On average the **extraterrestrial irradiance is  $1367 \text{ W/m}^2$** . This value varies by  $\pm 3\%$  as the earth orbits the sun.

# Stephan-Boltzmann Law

The amount of electromagnetic radiation emitted by a body is directly related to its temperature. If the body is a perfect emitter (black body), the amount of radiation given off is proportional to the 4th power of its temperature as measured in degrees Kelvin. This natural phenomenon is described by the Stephan-Boltzmann law:

$$E = \sigma T^4$$

Where  $\sigma = 5.67 \times 10^{-8} \text{ Wm}^{-2}\text{k}^{-4}$  and T is in K

In general, good emitters of radiation are also good absorbers of radiation at specific wavelength bands. This is especially true of greenhouse gases. Some objects in nature have almost completely perfect abilities to absorb and emit radiation. We call these objects black bodies. The radiation characteristics of the sun and the Earth are very close to being black bodies.



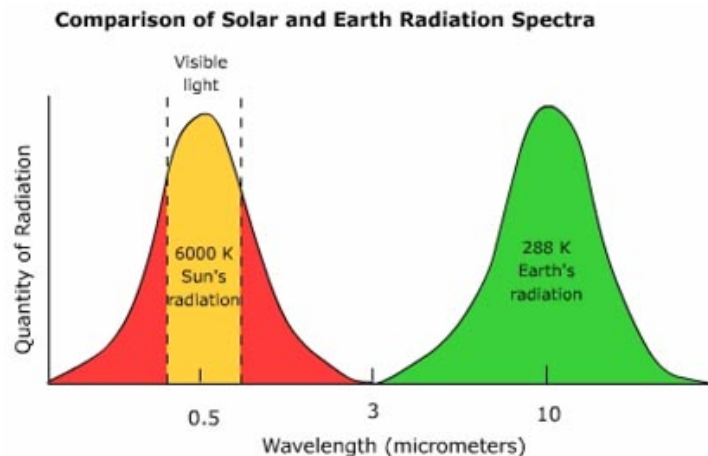
# Wien's Law

The wavelength of **maximum emission** of any body is inversely proportional to its absolute temperature. Thus, the higher the temperature, the shorter the wavelength of maximum emission. This phenomenon is often called Wien's law:

$$\lambda_{\max} = \frac{C}{T}$$

$$C = 2897$$

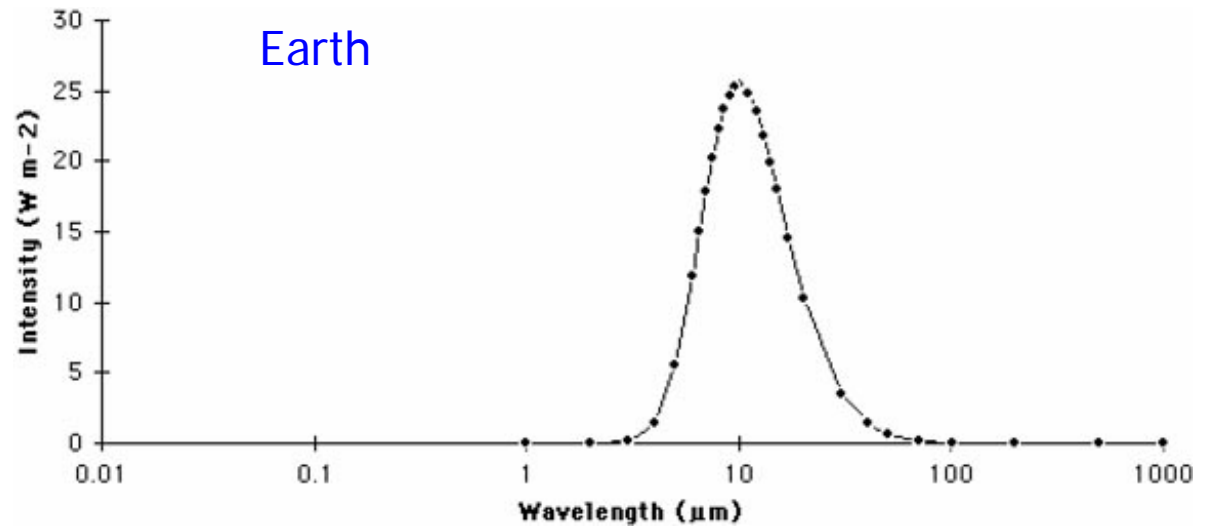
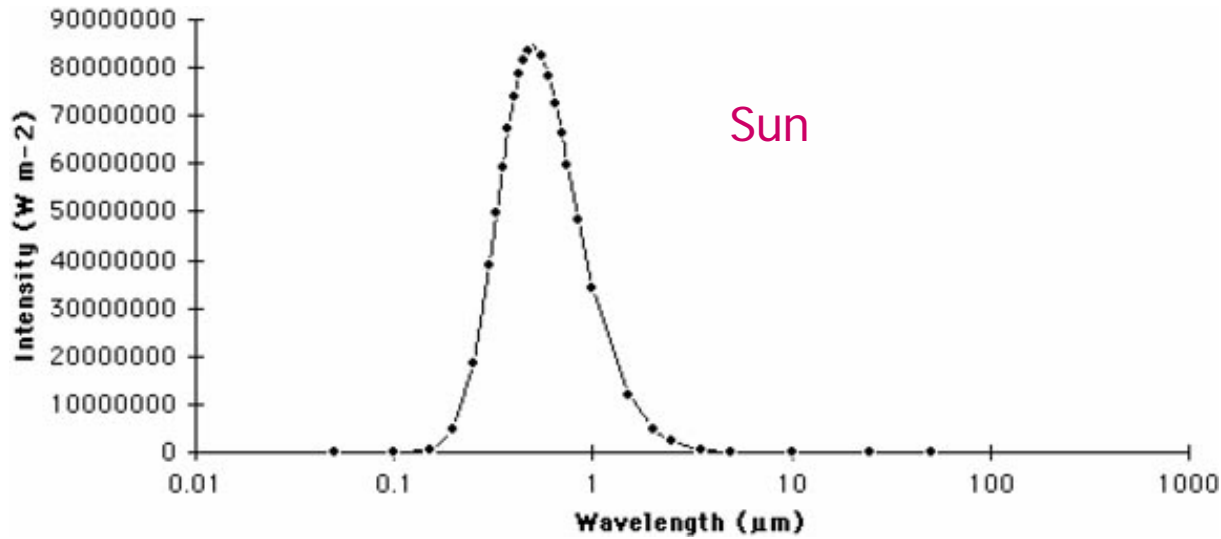
where T is in Kelvin. According to the above equation the wavelength of maximum emission for the sun (5800 K) is about 0.5  $\mu\text{m}$ , while the wavelength of maximum emission for the Earth (288 K) is approximately 10.0  $\mu\text{m}$ .



The gases of the atmosphere are relatively good absorbers of long wave radiation and thus absorb the energy emitted by the Earth's surface. The absorbed radiation is emitted downward toward the surface as **long wave atmospheric counter-radiation** keeping near surfaces temperatures warmer than they would be without this blanket of gases. This is known as the "greenhouse effect".



# Radiation Spectrum



# Inverse Square Law

The amount of radiation passing through a specific area is inversely proportional to the square of the distance of that area from the energy source. This phenomenon is called the inverse square law. Using this law we can model the effect that distance traveled has on the intensity of emitted radiation from a body like the sun.

$$Intensity = \frac{I}{d^2}$$

Where  $I$  is the intensity of radiation at one  $d$  and  $d$  is the distance traveled

Radiation from the Sun is lessened by the inverse square law as it reaches further and further away from the Sun. So the further away that a planet is from the Sun then the less radiation it receives. What happens to that radiation depends on whether the planet has an atmosphere, whether the atmosphere contains clouds and how the clouds, or the surface, reflect the radiation.

For planets with no atmosphere all the Sun's radiation will strike the surface. Some of this will be reflected away from the planet but the rest will be absorbed. The temperature of the surface will be raised until there is equilibrium between the energy radiated by the warm surface of the planet and the received solar radiation. For planets like Mercury, this results in a very hot surface where the Sun is shining (more than  $400^{\circ}\text{C}$ ) but very cold on the night side, where the radiation from the surface rapidly cools it to  $-180^{\circ}\text{C}$ .



# Extraterrestrial Radiation

The amount of solar radiant energy from outside the earth's atmosphere passing per unit time through unit surface area perpendicular to the sun's rays and at a distance of the mean radius of the terrestrial orbit is **1367 W/m<sup>2</sup>**. This value is referred to as **Solar Constant**.

The amount of extraterrestrial radiation reaching the earth is given by

$$I_o = 1367 \left( \frac{R_{av}}{R} \right)^2 \quad \text{W/m}^2$$

$R_{av}$  : the mean sun-earth distance

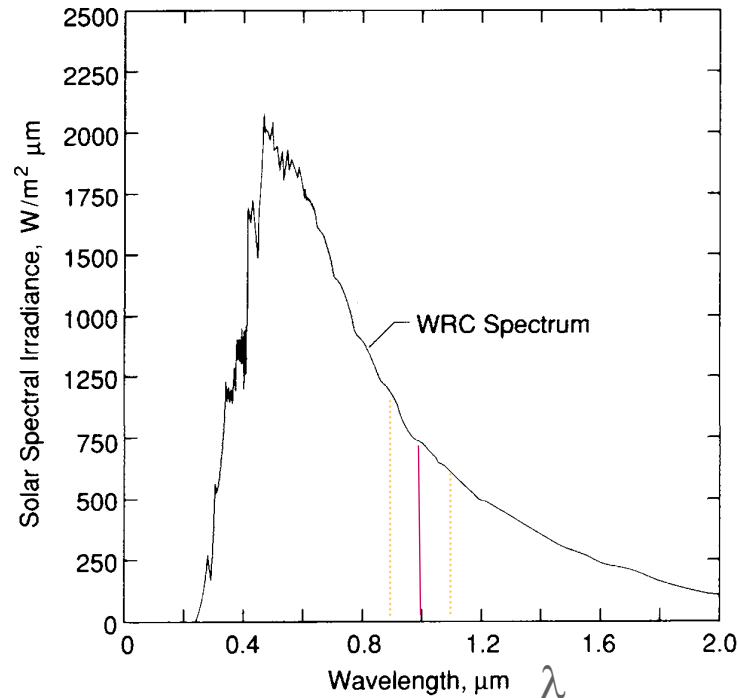
$R$ : the actual sun-earth distance on the day of the year

$$\begin{aligned} (R_{av} / R)^2 = & 1.00011 + 0.034221 * \cos (b) + 0.001280 * \sin (b) + 0.000719 * \cos (2b) \\ & + 0.000077 * \sin (2b) \end{aligned}$$

$b = 2\pi (d_n - 1) / 365$  radians and  $d_n$  is the day of the year



# Extraterrestrial Radiation Spectrum



$G_{SC,\lambda}$ : The average energy over small bandwidths centered at wavelength  $\lambda$ ;  
 $F_{0-\lambda}$ : The fraction of the total energy in the spectrum that is between wavelengths 0 and  $\lambda$ .

*The radiation that would be received in the absence of the atmosphere at mean-earth-sun distance (World Radiation Center (WRC) standard)*

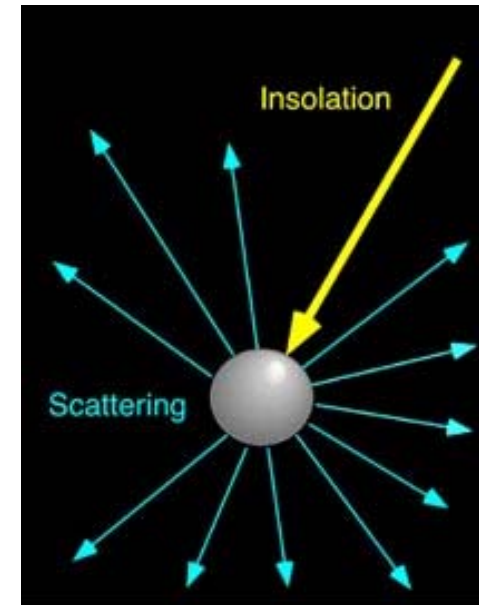


# Atmospheric Effects on Incoming Solar Radiation

The Earth is a planet with an atmosphere and is largely transparent to the incoming solar radiation. There are constituents in the atmosphere which prevent some kinds of radiation from reaching the surface, such as ozone which stops the ultraviolet. A fair proportion of the Earth is covered by clouds which reflect a lot of the Sun's radiation and thus affecting the surface temperature.

The process of scattering occurs when small particles and gas molecules diffuse part of the incoming solar radiation in random directions without any alteration to the  $\lambda$  of the electromagnetic energy. Scattering does, however, reduce the amount of incoming radiation reaching the Earth's surface. A significant proportion of scattered shortwave solar radiation is redirected back to space. **The amount of scattering that takes place is dependent on two factors:  $\lambda$  of the incoming radiation and the size of the scattering particle or gas molecule.** In the Earth's atmosphere, the presence of a large number of particles with a size of about  $0.5 \mu\text{m}$  results in shorter wavelengths being preferentially scattered. This factor also causes our sky to look blue because this color corresponds to those wavelengths that are best diffused. If scattering did not occur in our atmosphere the daylight sky would be black.

Intensity of solar radiation

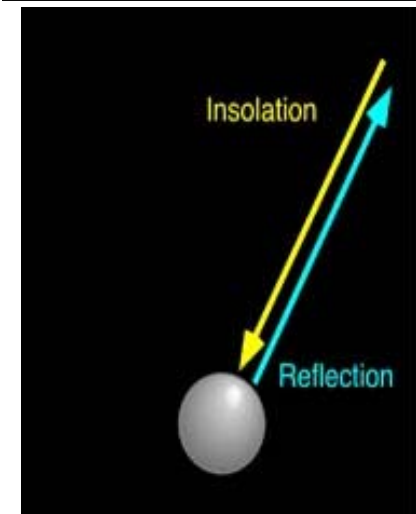
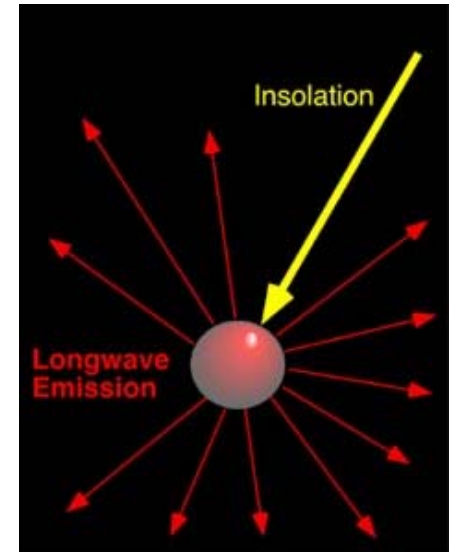




# Atmospheric Effects on Incoming Solar Radiation

If intercepted, some gases and particles in the atmosphere have the ability to absorb incoming insolation. **Absorption** is defined as a process in which solar radiation is retained by a substance and converted into heat. The creation of heat also causes the substance to emit its own radiation. In general, the absorption of solar radiation by substances in the Earth's atmosphere results in temperatures that get no higher than 1800° C. Bodies with temperatures at this level or lower would emit their radiation in the longwave band. Further, this emission of radiation is in all directions so a sizable proportion of this energy is lost to space.

The third process in the atmosphere that modifies incoming solar radiation is **reflection**. Reflection is a process where sunlight is redirected by 180° after it strikes an atmospheric particle. This redirection causes a 100 % loss of the insolation. Most of the reflection in our atmosphere occurs in clouds when light is intercepted by particles of liquid and frozen water. The reflectivity (albedo) of a cloud can range from 40 to 90 %.

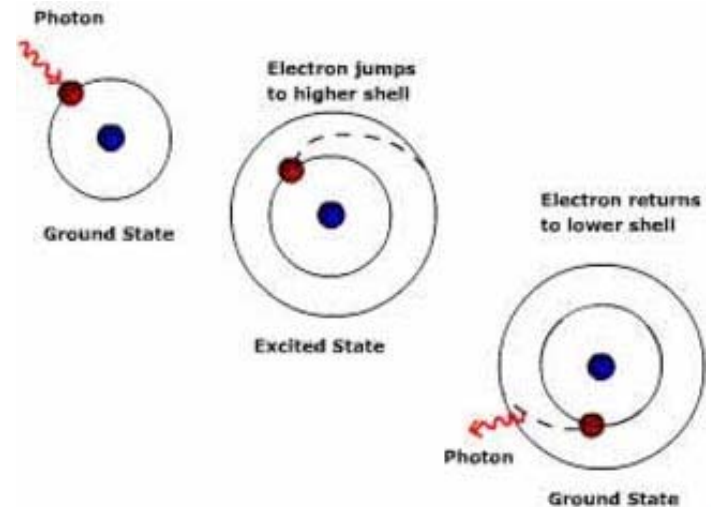


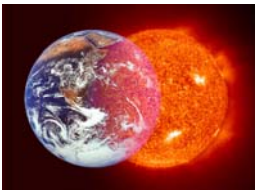


# Selective Absorption of the Atmosphere

At the smallest scale the electromagnetic radiation behaves as a particle, like when light is emitted by a single atom or molecule. When energy is given off there is a change in the orbital pattern of the electrons that surround the nucleus of an atom. As the orbit changes, a bundle of energy called a "**photon**" is released. However, **particles of light differ from particles of matter: they have no mass, occupy no space, and travel at the speed of light.** The amount of energy carried by a photon varies inversely with wavelength, the shorter the wavelength the more energetic is the photon. Normally, light is formed from a large number of photons, with the intensity related to the number of them.

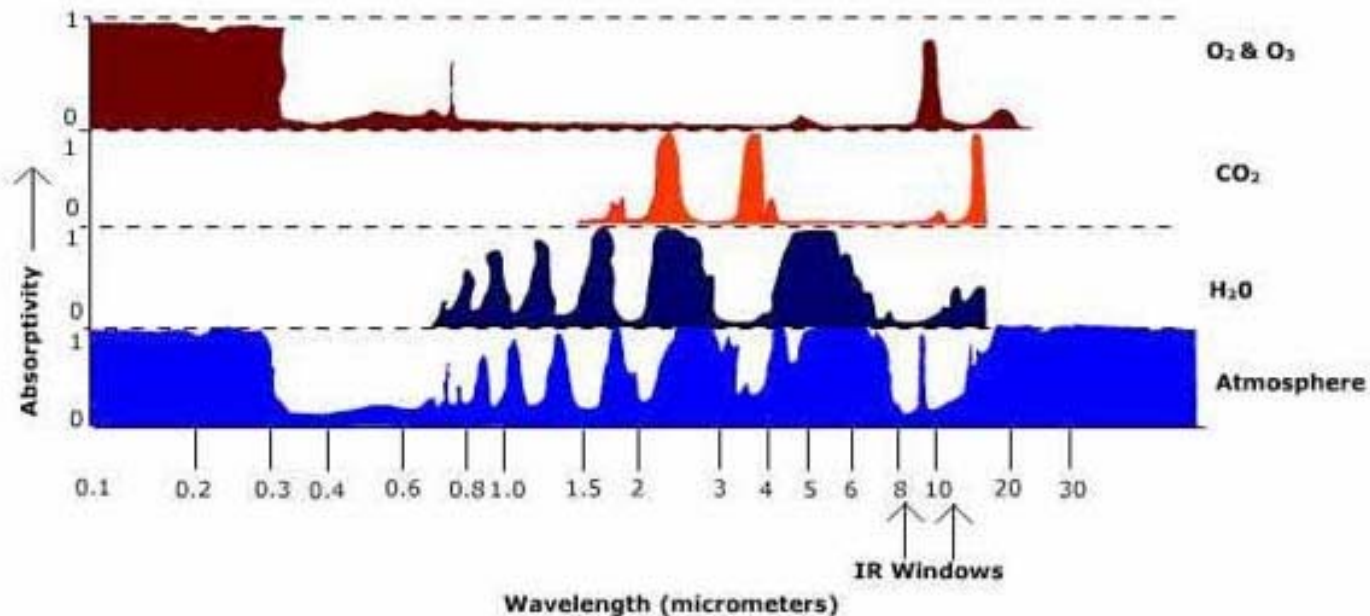
The gasses that comprise our atmosphere absorbs only particular wavelengths of light. Electrons orbit the nucleus of an atom at fixed orbital distances called orbital shells. The orbital shell for each atom is different and discrete. That is, for a given atom like hydrogen, its electrons can only orbit at particular distances and are different than those for atoms of other gases.





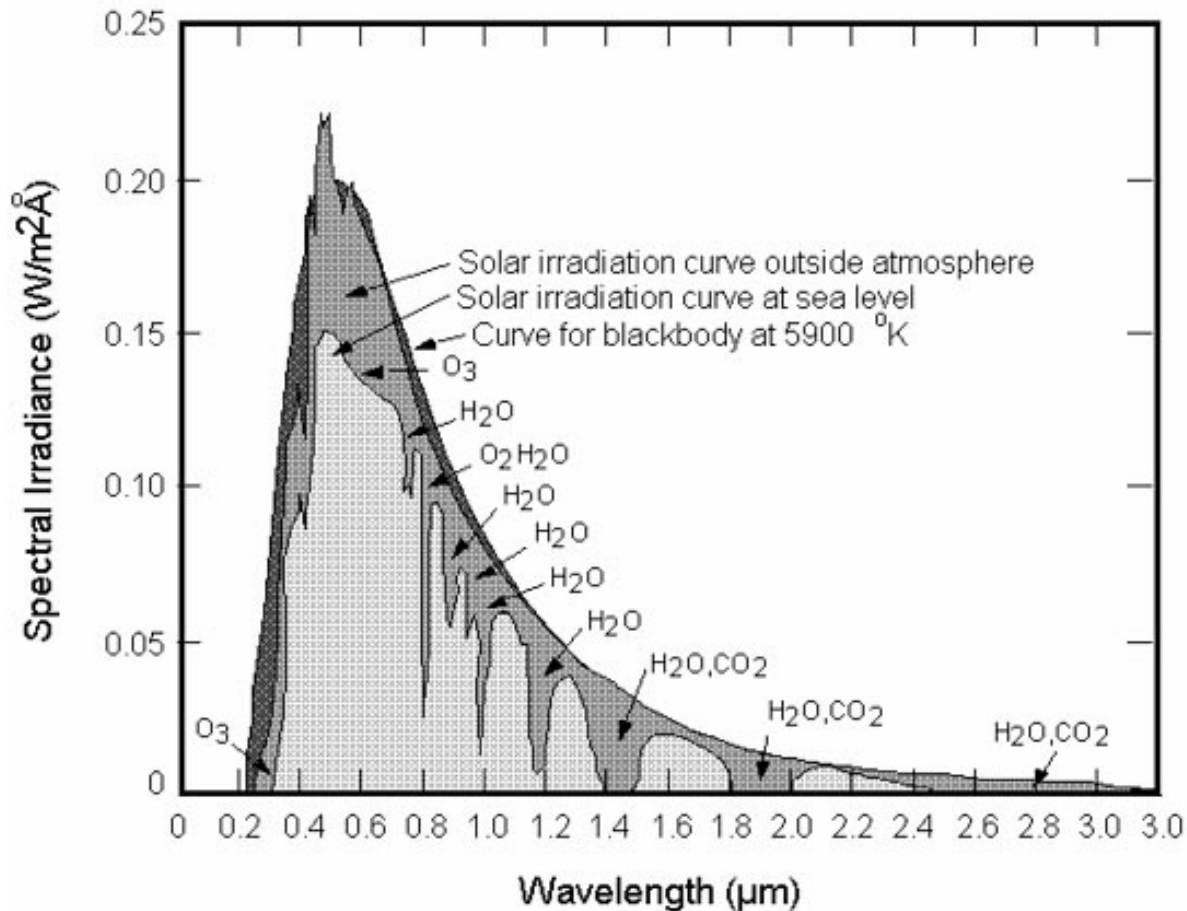
# Selective Absorption of the Atmosphere

The amount of energy carried by a photon depends on the wavelength. Thus the atoms that comprise a gas can only absorb, or emit, particular wavelengths of energy (i.e. photons of energy). We can see this selective absorption by examining Figure below. The graph shows very little absorption for atmosphere as a whole in the shortwave end of the spectrum, especially in the visible light band (the band of maximum emission for the Sun). The atmosphere absorbs far better in the long wave end of the electromagnetic spectrum which is the region of maximum emission (10 $\mu$ m) for the Earth.





# Solar Spectrum with Atmospheric Absorptions



Source: <http://www.csr.utexas.edu/projects/rs/hrs/pics/irradiance.gif>

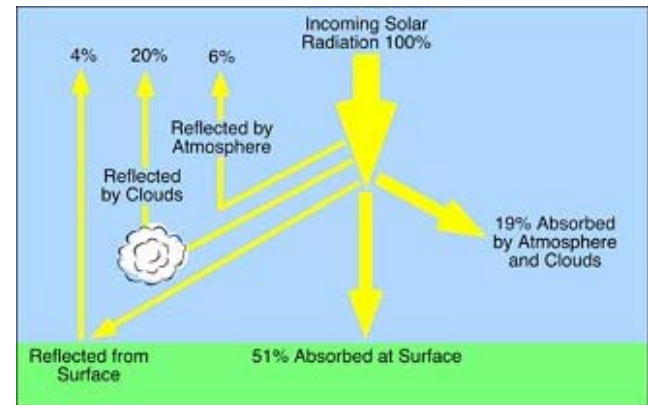
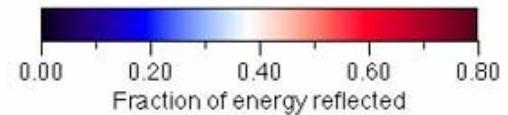
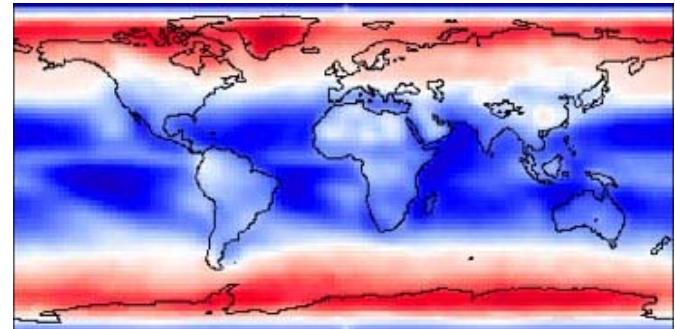


# Atmospheric Effects on Incoming Solar Radiation

Sunlight reaching the Earth's surface unmodified by any of the atmospheric processes is termed **direct solar radiation**. Solar radiation that reaches the Earth's surface after it was altered by the process of scattering is called **diffused solar radiation**. Not all of the direct and diffused radiation is available at the Earth's surface. Some of the radiation received at the Earth's surface is redirected back to space by reflection.

Of all the sunlight that passes through the atmosphere annually, only 51 % is available at the Earth's surface; to heat the Earth's surface and lower atmosphere, evaporate water, and run photosynthesis in plants. Of the other 49 %, 4 % is reflected back to space by the Earth's surface, 26 % is scattered or reflected to space by clouds and atmospheric particles, and 19 % is absorbed by atmospheric gases, particles, and clouds.

The spatial pattern of surface reflectivity as measured for the year 1987.



# Irradiance & Irradiation

**Irradiance** is given in  $W/m^2$  and is represented by the symbol  $G$ .

The rate at which radiant energy is incident on a surface per unit area of surface.

**Irradiation** is given in  $J/m^2$  and is the incident energy per unit area on a surface - determined by integration of irradiance over a specified time, usually an hour or a day.

**Insolation** is a term used to solar energy irradiation

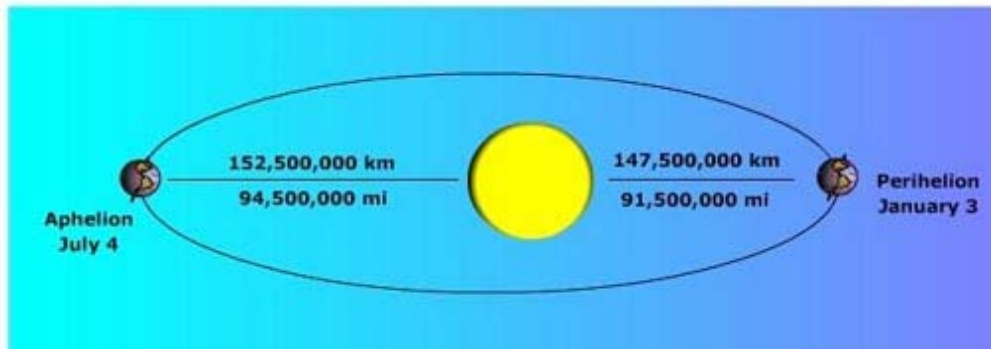
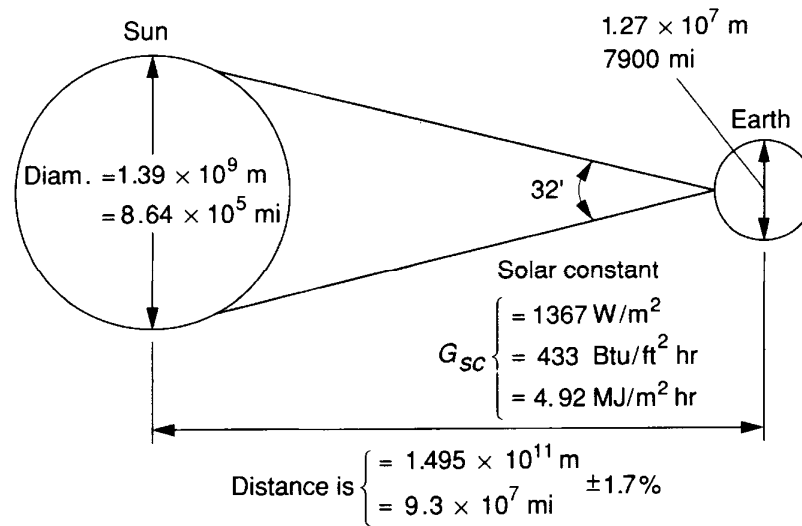
**Radiosity** is the rate at which radiant energy leaves a surface, per unit area, by combined emission, reflection and transmission.





# Sun-Earth Relationships

The solar constant,  $G_{SC}$  is the energy from the sun, per unit time, received on a unit area of surface perpendicular to the direction of propagation of the radiation, at mean earth-sun distance, outside of the atmosphere.



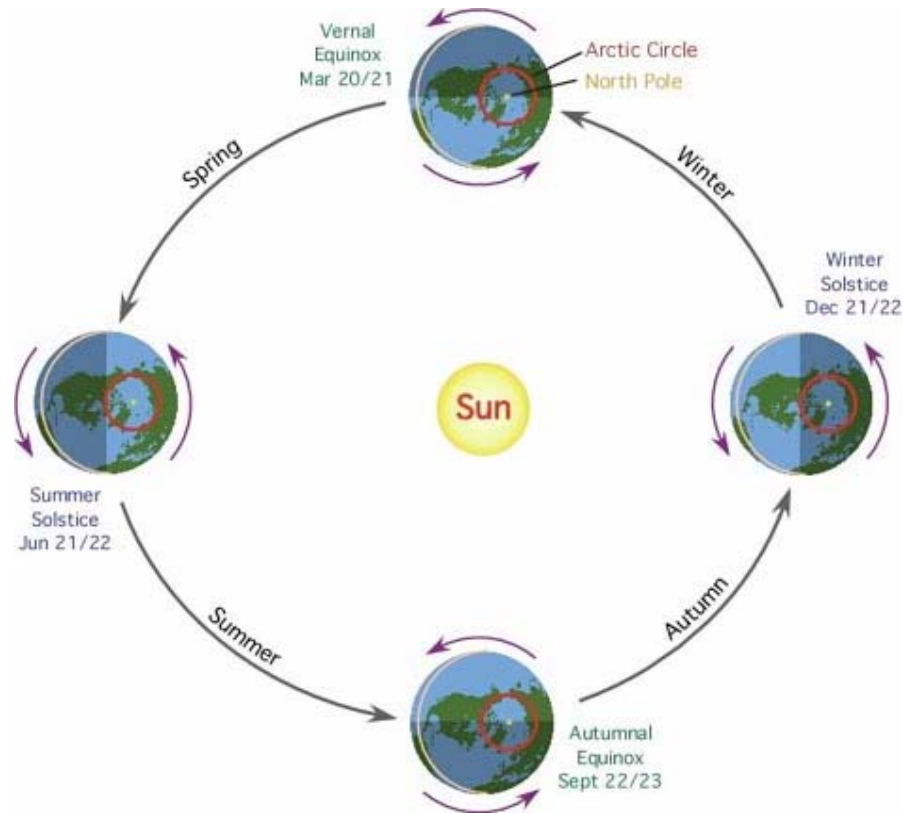
Earth's elliptic orbit

The elliptical path causes only small variations in the amount of solar radiation reaching the earth.





# Earth-Sun Relations

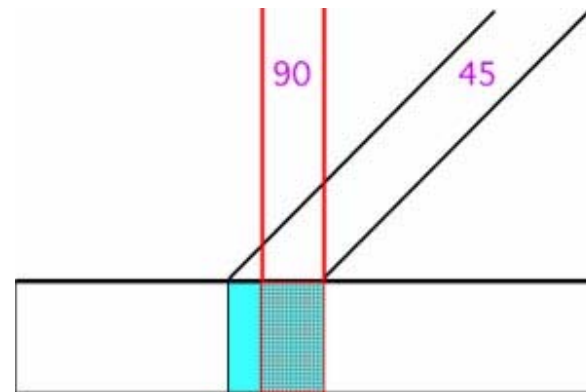
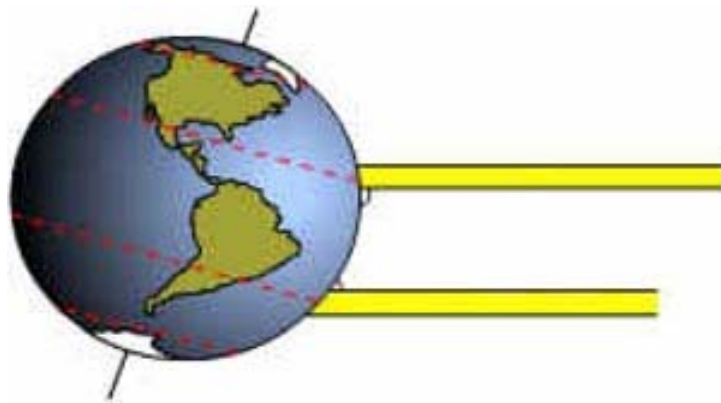


The earth itself rotates around the polar axis, which is inclined at approximately  $23.5^\circ$  from the normal to the elliptic plane of revolution of the earth around the sun.



# Sun-Earth Relationships

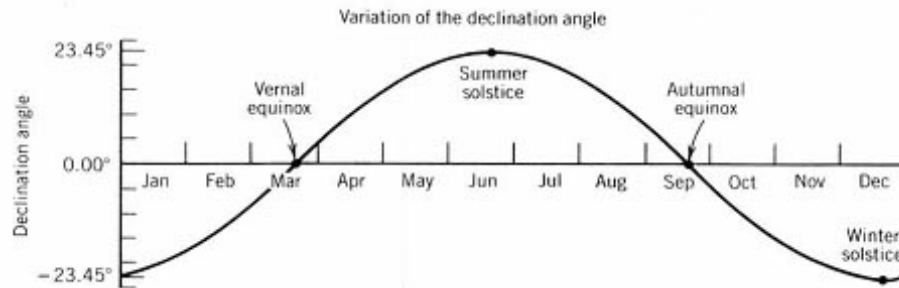
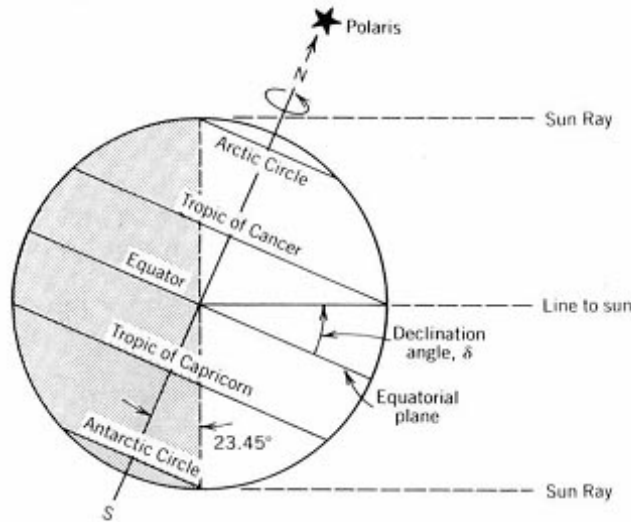
The Earth's axis is tilted  $23\frac{1}{2}$  degrees from being perpendicular to the plane of the ecliptic. The axis of rotation remains pointing in the same direction as it revolves around the Sun, pointing toward the star Polaris. The constant tilt and parallelism causes changes in the angle that a beam of light makes with respect to a point on Earth during the year, called the "**sun angle**". The most intense incoming solar radiation occurs where the sun's rays strike the Earth at the highest angle. As the sun angle decreases, the beam of light is spread over a larger area and decreases in intensity. During the summer months the Earth is inclined toward the Sun yielding high sun angles. During the winter, the Earth is oriented away from the Sun creating low sun angles.



Sun angle determines the intensity of energy.



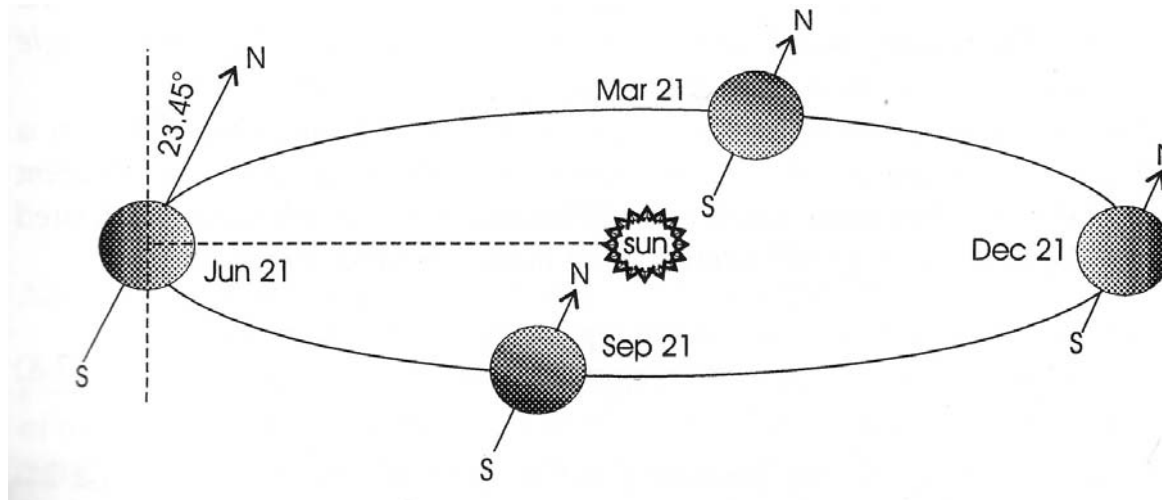
# Declination Angle



$$\delta = (0.006918 - 0.399912 \cos b + 0.070257 \sin b - 0.006758 \cos 2b + 0.000907 \sin 2b \\ + 0.002697 \cos 3b + 0.00148 \sin 3b) * (180/\pi)$$



# Orbit of the Earth Around the Sun

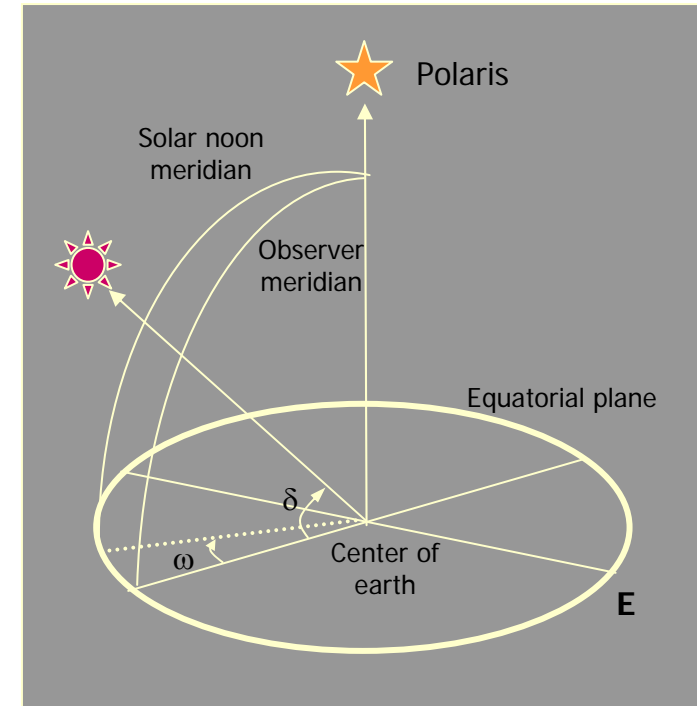
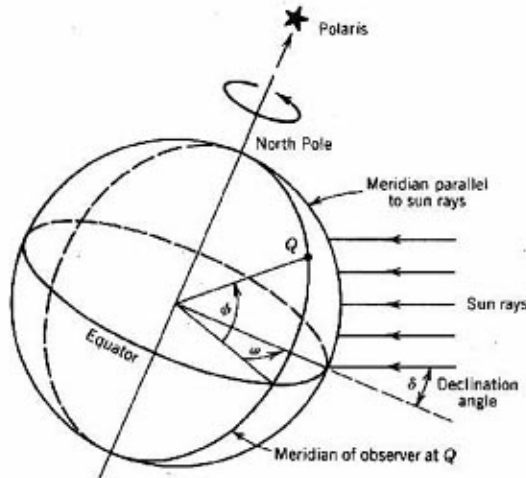


At about June 21, we observe that the noontime sun is at its highest point in the sky and the declination angle ( $\delta$ ) =  $+23.45^\circ$ . We call this condition *summer solstice* and it marks the beginning of Summer in the northern hemisphere. The *winter solstice* occurs on about December 22 - the northern hemisphere is tilted away from the sun. The noontime sun at its lowest point in the sky, i.e the declination angle ( $\delta$ ) =  $-23.45^\circ$ . In between, on about September 23 (autumnal equinox) and March 22 (vernal equinox), the line from the earth to the sun lies on the equatorial plane and  $\delta = 0^\circ$





# The Hour Angle ( $\omega$ )



This is the angle defined as the angle between the plane of the meridian containing the point of interest and the meridian that touches the earth -sun line. The hour angle is zero at solar noon. The hour angle increases by 15 degrees every hour. An expression for the hour angle is

$$\omega = 15(t_s - 12) \text{ (degrees)}$$

Where  $t_s$  is the solar time in hours. For example, when it is 3 hours after solar noon, the hour angle has a value of 45 degrees. When it is 2 hours and 20 minutes before solar noon, the hour angle is 325 degrees.

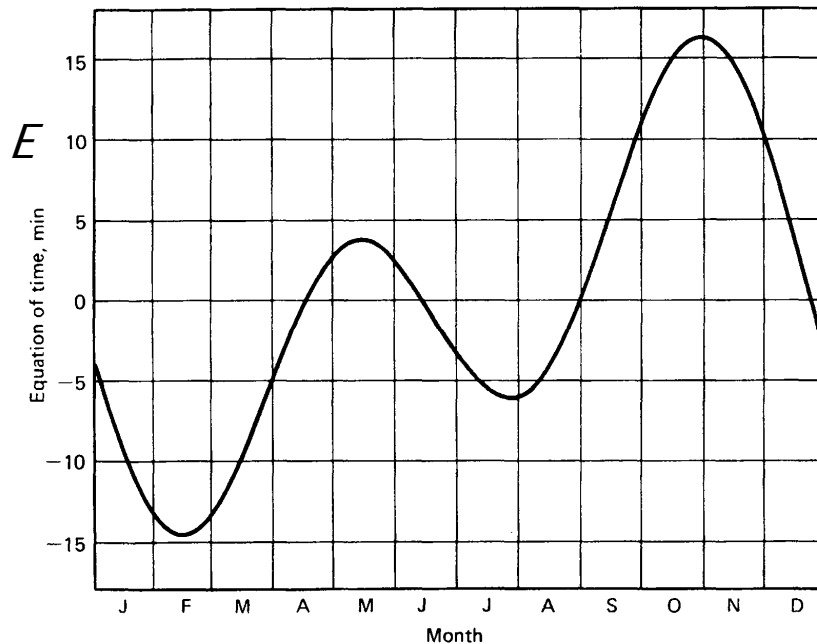


# Solar Time

Time based on the apparent angular motion of the sun across sky, with solar noon the time the sun crosses the meridian of the observer.

$$\text{Solar time} - \text{standard time} = 4(L_{st} - L_{loc}) + E$$

Where  $L_{st}$  is the standard meridian for local time zone.  $L_{loc}$  is the longitude of the location in question in degrees west. The time  $E$  is determined from the following figure.



**Tallahassee, FL**

Latitude: 30.438N

Longitude: 84.28W

Time zone: Eastern Daylight Saving

$$E = 229.2(0.000075 + 0.001868 \cos B - 0.032077 \sin B - 0.014615 \cos 2B - 0.04089 \sin 2B)$$

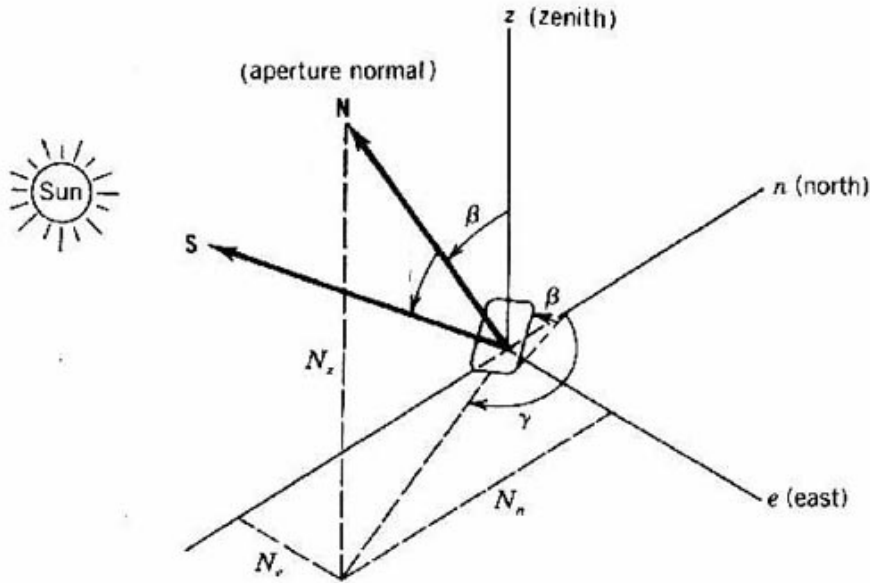
$$B = (n - 1) \frac{360}{365}$$

Where n is the day of the year





# Fixed Collector



$\theta$  = angle of incidence

$\beta$  = the slope of the collector surface measured from the horizontal position

$\gamma$ : the surface azimuth angle

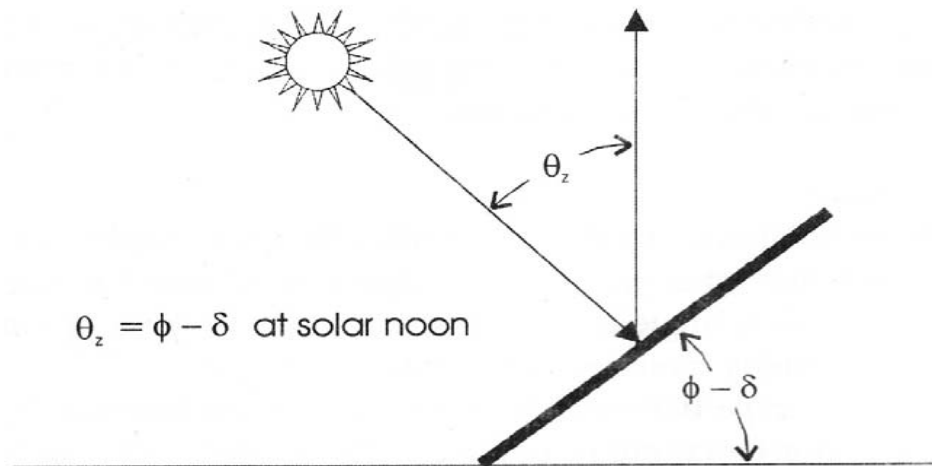
$$\cos \theta = (\sin \phi \cos \beta - \cos \phi \sin \beta \cos \gamma) \sin \delta + (\cos \phi \cos \beta + \sin \phi \sin \beta \cos \gamma) \cos \delta \cos \omega + \cos \delta \sin \beta \sin \gamma \sin \omega \dot{Z}$$

For Surfaces facing south

$$\cos \theta = \sin \alpha \cos \beta - \cos \alpha \sin \beta \cos \psi$$



# Mounting Angle of a Fixed Collector

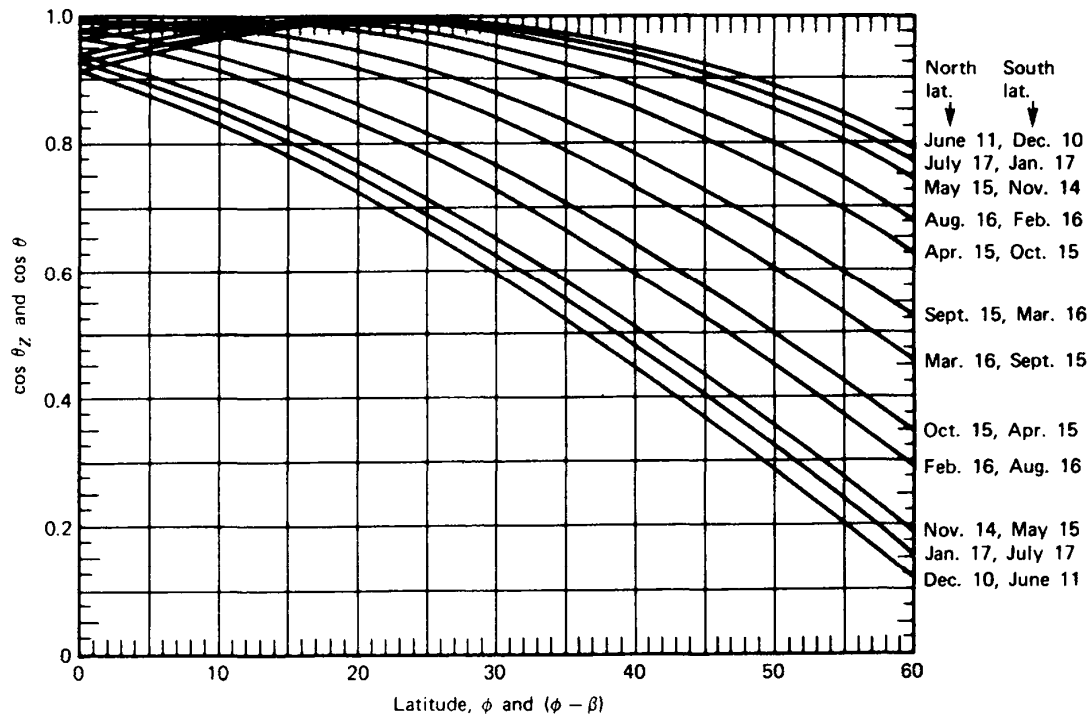


Optimizing the mounting angle of a fixed collector.



# Zenith Angle

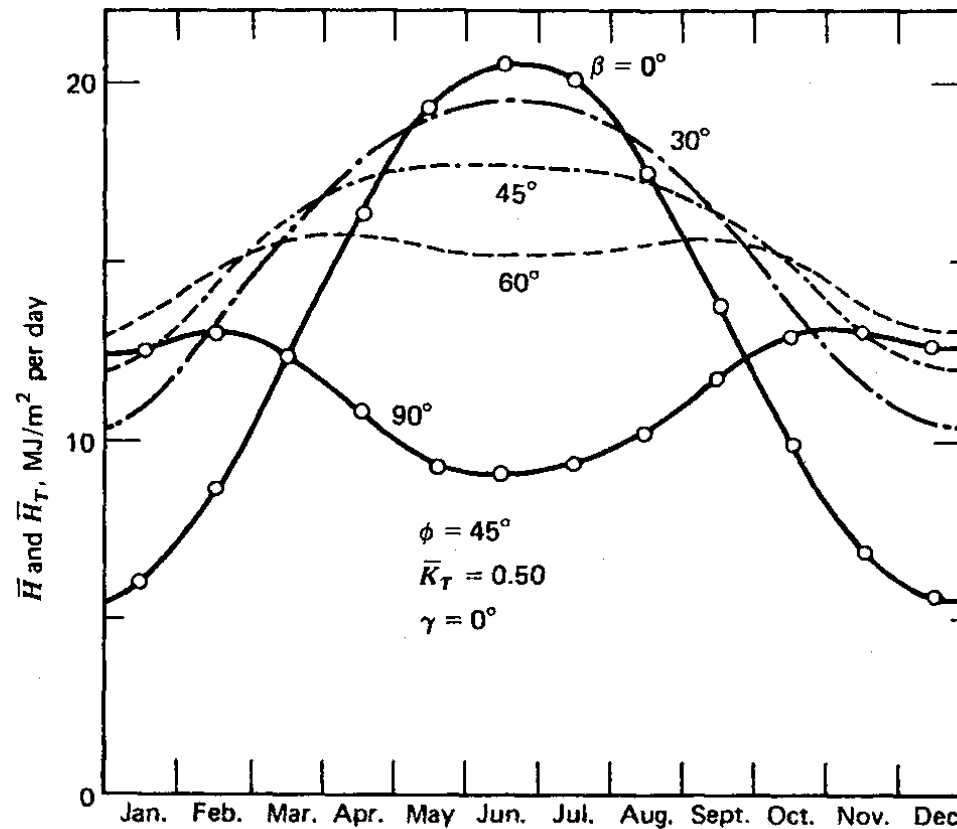
Determination of Zenith angle ( $\theta_z$ ) for tilted surfaces: The zenith angle for tilted surfaces is determined from Whillier's curves given below.



Cos  $\theta$  vs.  $(\phi - \beta)$  and  $\cos \theta_z$  vs.  $\phi$  for hours 11 to 12 and 12 to 1 for surfaces tilted toward the equator. The columns on the right show dates for the curves for north and south latitudes. In south latitudes, use  $|\phi|$ . Adapted from Whillier (1975).



# Inclination Effect



**Figure 2.21.1** Variation in estimated average daily radiation on surfaces of various slopes as a function of time of year for a latitude of  $45^\circ$ ,  $K_T$  of 0.50, surface azimuth angle of  $0^\circ$ , and a ground reflectance of 0.20.



# Algorithm

Ibrahim Reda & Amin Andreas, "Solar Position Algorithm for Solar Radiation Applications", NREL TP-560-34302, November 2005. <http://www.nrel.gov/docs/fy06osti/34302.pdf>





# Annual Global Irradiance

For clear sky condition

$$E_{global} = \left[ 650 \left( \sin \frac{4}{3\alpha} - 30 \right) + 325 \right] \times \left( 8 \times 10^{-5} \times h + 1 \right) \quad \text{W/m}^2$$

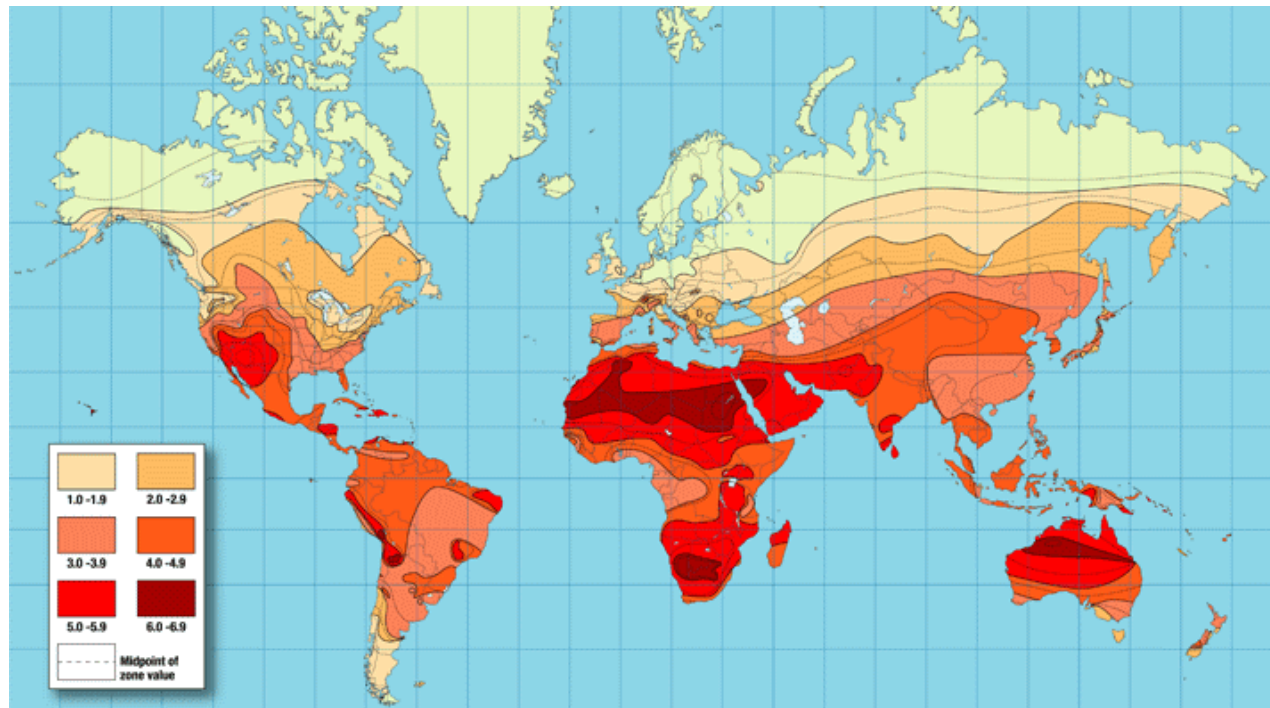
Where  $\alpha$  is the solar altitude in degrees and  $h$  is the geographic altitude in meters.

Source: Masato Oki & Hiroyuki Shiina, "Preliminary study on an estimation method for annual solar irradiance at various geological altitudes", Eighth International IBPSA Conference, Eindhoven, Netherlands, August 2003.





# Typical Daily Solar Insolation



Typical daily solar insolation on an optimally tilted surface during the worst month of the year around the world in  $\text{kWh/m}^2$

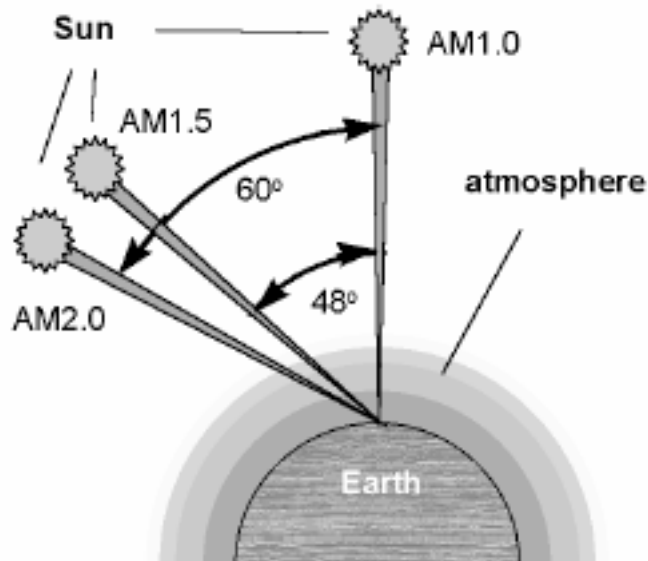
Commercially available data base: [www.meteotest.ch](http://www.meteotest.ch)

Other site: [wrdc-mgo.nrel.gov](http://wrdc-mgo.nrel.gov)





# Air Mass



The path length of the solar radiation through the Earth's atmosphere in units of Air Mass ( $AM$ ) increases with the angle from the zenith. The AM 1.5 spectrum is the preferred standard spectrum for solar cell efficiency measurements.

The easiest way to estimate the air mass in practice is to measure the length of the shadow  $s$  cast by a vertical structure of height  $h$  using

$$AM = \sqrt{1 + \left(\frac{s}{h}\right)^2}$$

**Air Mass  $AM$ :** The ratio of the mass of atmosphere through which beam radiation passes to the mass it would pass through if the sun were at zenith (directly overhead).

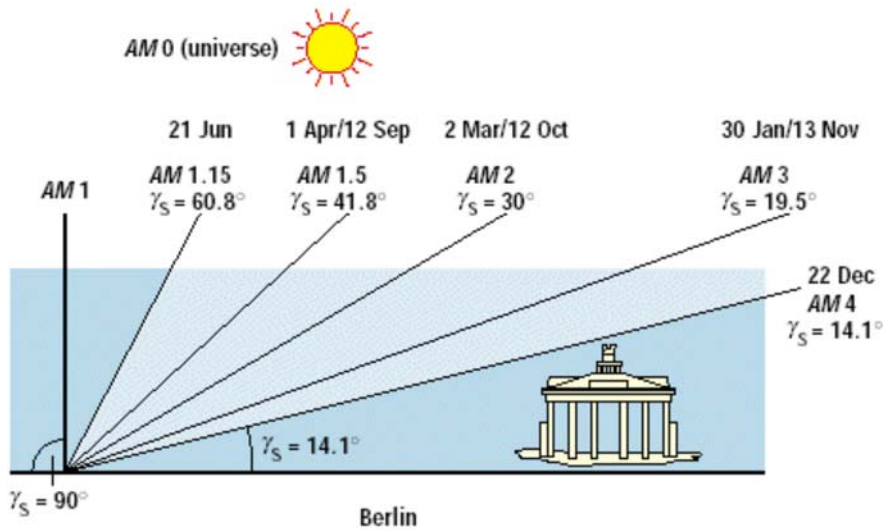
At sea level,  $AM = 1$  when the sun is at zenith;  $AM = 2$  for a zenith angle  $\theta_z$  of  $60^\circ$ .

For  $0 < \theta_z < 70^\circ$   $AM = 1/\cos \theta_z$

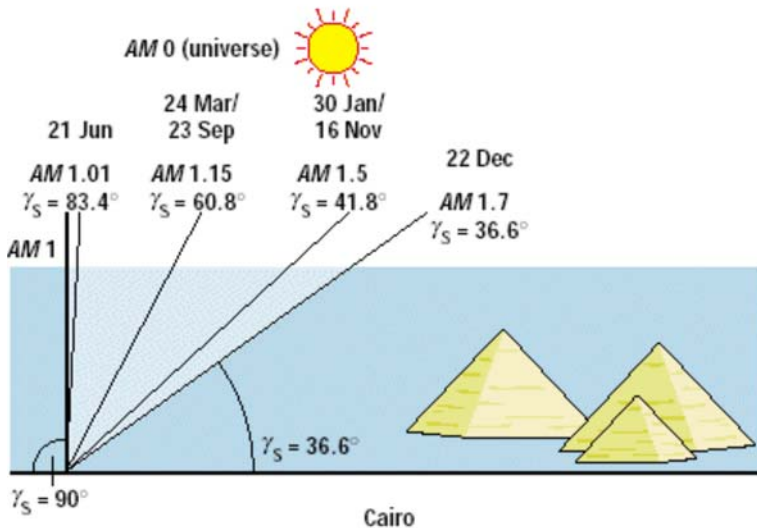


# Air Mass Variation

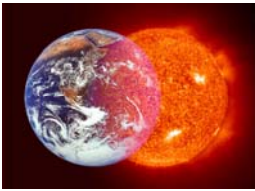
At the time during a day with highest sun elevation - solar noon



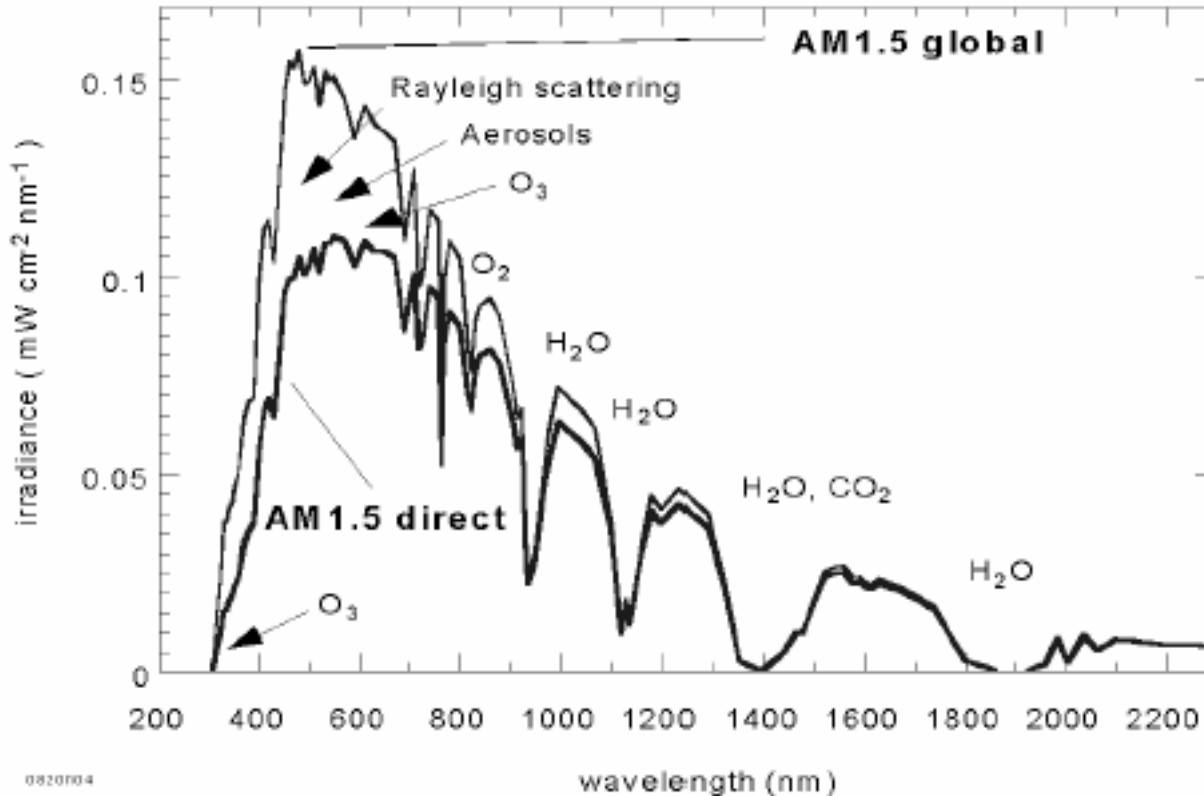
Berlin



Cairo



# Global Radiation



The global spectrum comprises the direct plus the diffused light.



# AM 1.5d Spectrum Energy Distribution

(eV) :	4.1	3.5	3.1	2.8	2.5	2.3	2.1	1.9	1.8	1.7	1.6	1.5	1.4	1.3	1.24	1.18	1.13	1.08	1.03	0.99	0.95	0.69	0.62	0.5
(nm) :	300	350	400	450	500	550	600	650	700	750	800	850	900	950	1000	1050	1100	1150	1200	1250	1300	1800	2000	2500
300	0	0.7	2.9	7.6	14	21	28	35	42	48	54	59	64	67	70	74	77	79	81	84	86	96	96	100
350		0	2.2	6.9	14	21	28	35	41	47	53	58	63	66	69	73	77	78	80	83	85	95	96	99
400			0	4.7	11	18	25	33	39	45	51	56	61	64	67	71	74	76	78	81	83	93	93	97
450				0	6.7	14	21	28	34	40	46	51	56	59	62	66	70	71	73	76	78	88	89	92
500					0	7.0	14	21	28	34	39	44	50	52	56	60	63	64	67	69	72	81	82	86
550						0	7.1	14	21	27	32	37	42	45	49	53	56	57	60	62	65	74	75	79
600							0	7.1	14	20	25	30	35	38	42	46	49	50	52	55	58	67	68	72
650								0	6.5	13	18	23	28	31	35	39	42	43	45	48	51	60	61	65
700									0	6.1	12	17	22	25	28	32	35	37	39	42	44	54	54	58
750										0	5.6	11	16	19	22	26	29	30	33	35	38	48	48	52
800											0	5.1	10	13	16	20	24	25	27	30	32	42	43	46
850												0	5.1	8.0	11	15	19	20	22	25	27	37	37	41
900													0	2.9	6.3	10	13	15	17	20	22	32	32	36
950														0	3.3	7.3	11	12	14	17	19	29	29	33
1000															0	3.9	7.2	8.4	11	13	16	26	26	30
1050																0	3.2	4.5	6.8	9.5	12	22	22	26
1100																	0	1.2	3.5	6.2	8.7	18	19	23
1150																		0	2.3	5.0	7.5	17	18	21
1200																			0	2.7	5.2	15	15	19
1250																				0	2.5	12	13	16
1300																					0	10	10	14
1800																						0	0.5	4.3
2000																							0	3.8
2500																								0

Silicon solar cells with a bandgap of 1.13ev can maximally absorb 77% of the terrestrial solar energy.

