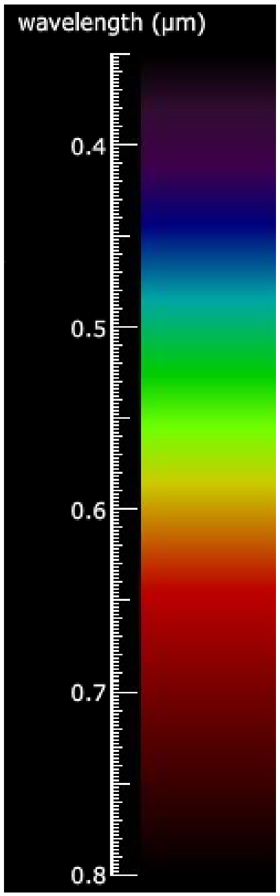
Lecture 2: The Nature of Light

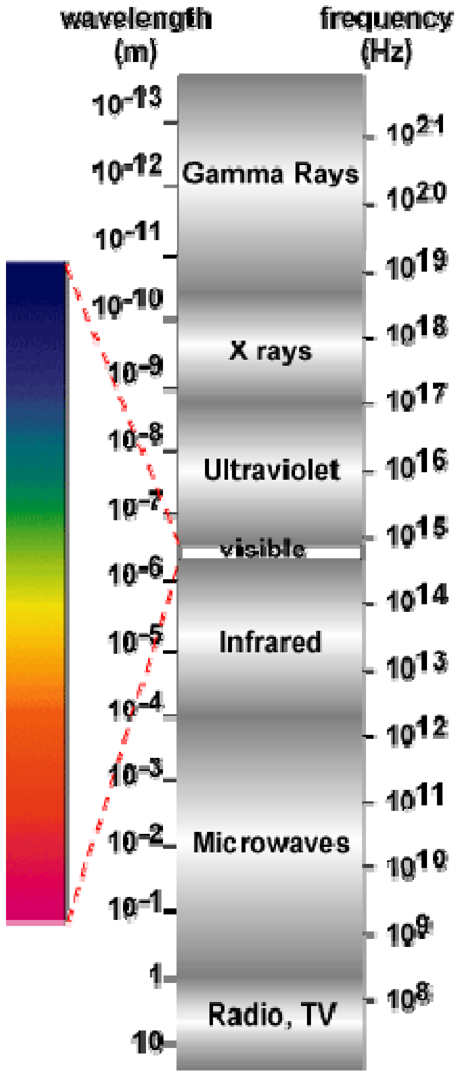
Reading Assignment – Chapter 2 of PVCDROM

Dr. Alan Doolittle*

*Most of the figures and text are from the online text for this class, PVCDROM.PVEDUCATION.org. Original references are given therein.

The Nature of Light





$$E = \frac{hc}{\lambda}$$

$$E = \frac{1.24}{\lambda(\mu m)}$$

The photon flux is defined as the number of photons per second per unit area:

$$\Phi = \frac{\#\ of\ photons}{\sec m^2}$$

power density in units of W/m²,

$$H\left(\frac{W}{m^2}\right) = \Phi \times \frac{hc}{\lambda}(J) = q\Phi\frac{1.24}{\lambda(\mu m)}$$

The Nature of Light

The spectral irradiance can be determined from the photon flux by converting the photon flux at a given wavelength to W/m^2 as shown in the section on Photon Flux. The result is then divided by the given wavelength, as shown in the equation below.

$$F = \left(\frac{W}{m^2 \mu m}\right) = q\Phi \frac{1.24}{\lambda^2 (\mu m)} = q\Phi \frac{E^2(eV)}{1.24}$$

where:
F is the spectral irradiance in $Wm^{-2}\mu m^{-1}$;
Φ is the photon flux in # photons $m^{-2}sec^{-1}$;
E and λ are the energy and wavelength of the photon in eV and μm respectively; and
q, h and c are constants.

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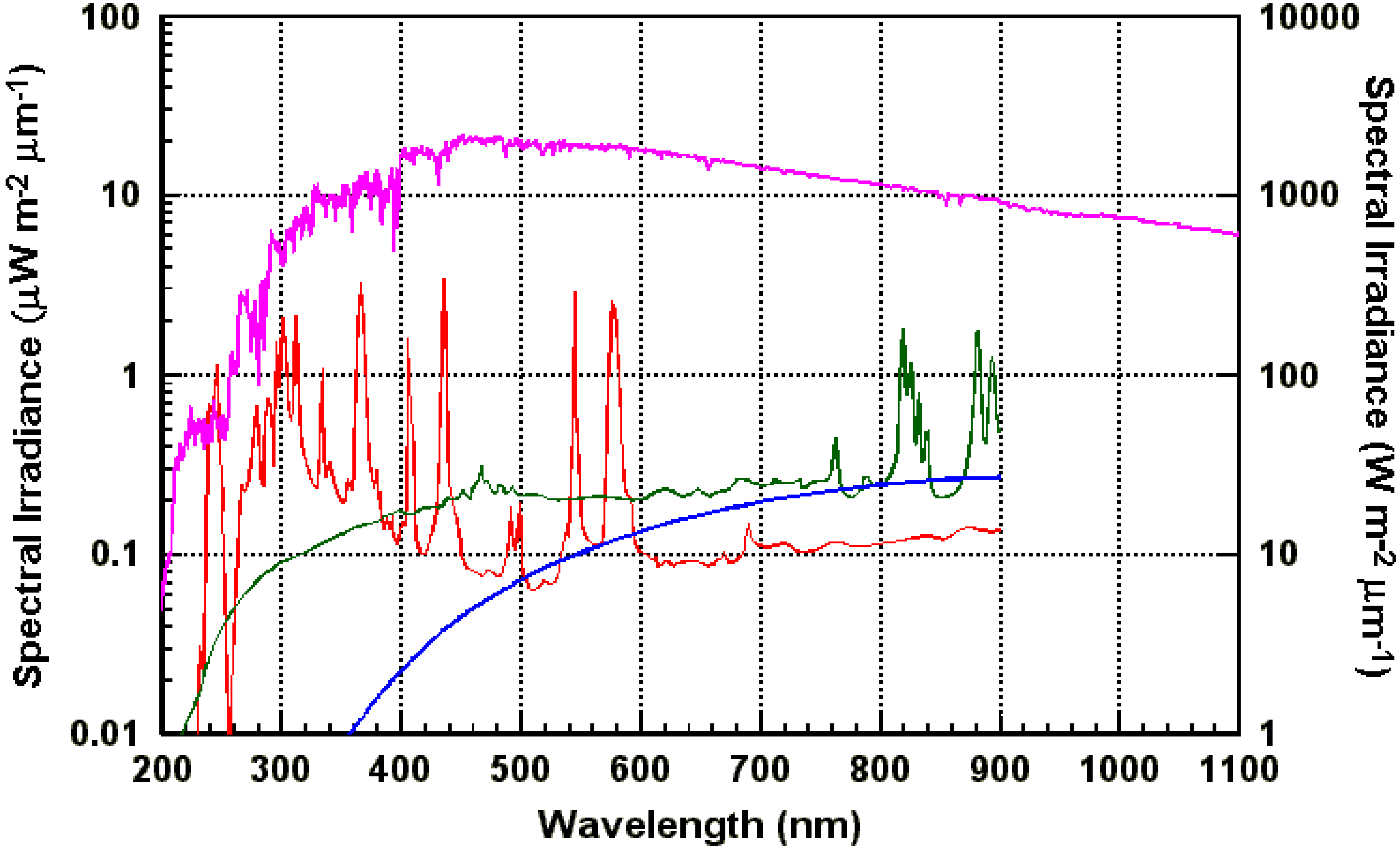
Modified Xenon lamps with decreased IR content are often used to simulate the solar spectrum. One popular method of removing some IR is to use a “Dichroic filter”.



The spectral irradiance of xenon (green), halogen (blue) and mercury (red) light bulbs (left axis) are compared to the spectral irradiance from the sun (purple, which corresponds to the right axis).

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The total power density emitted from a light source can be calculated by integrating the spectral irradiance over all wavelengths or energies of interest. However, a closed form equation for the spectral irradiance for a light source often does not exist. Instead the measured spectral irradiance must be multiplied by a wavelength range over which it was measured, and then calculated over all wavelengths. The following equation can be used to calculate the total power density emitted from a light source.

$$H = \int_0^\infty F(\lambda)d\lambda = \sum_{i=0}^{\infty} F(\lambda)\Delta\lambda$$

where:
H is the total power density emitted from the light source in W m^{-2};
F(l) is the spectral irradiance in units of $Wm^{-2}\mu m^{-1}$; and
$d\lambda$ or $\Delta\lambda$ is the wavelength.

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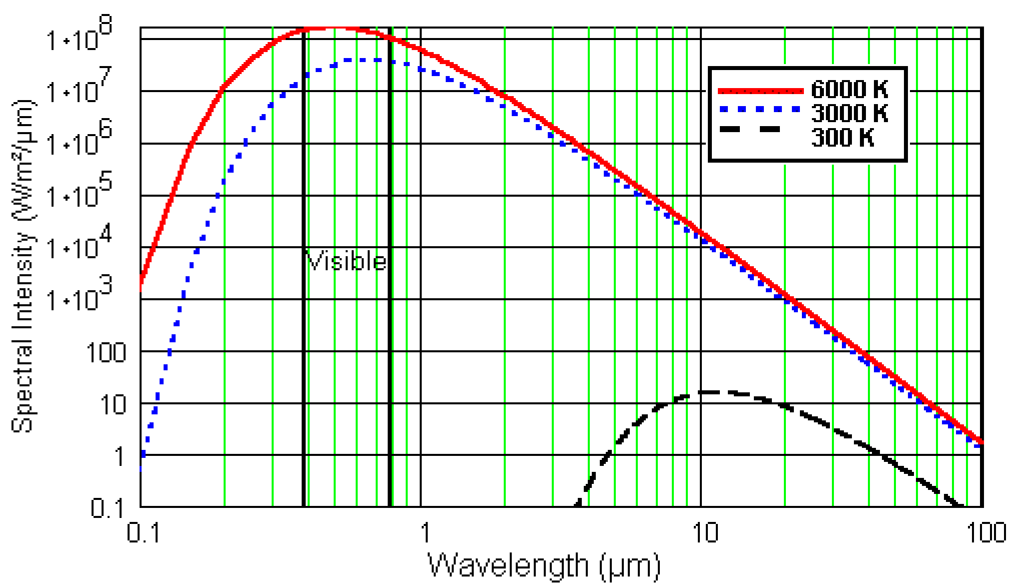
Blackbody Radiation

$$F(\lambda) = \frac{2\pi h c^2}{\lambda^5\left(\exp\left(\frac{hc}{k\lambda T}\right) - 1\right)}$$

where:
l is the wavelength of light (µm);
T is the temperature of the blackbody (K);
F is the spectral irradiance in $Wm^{-2}\mu m^{-1}$; and
h,c and k are constants.

$$H = \sigma T^4$$



$$\lambda_p(\mu m) = \frac{2900}{T}$$

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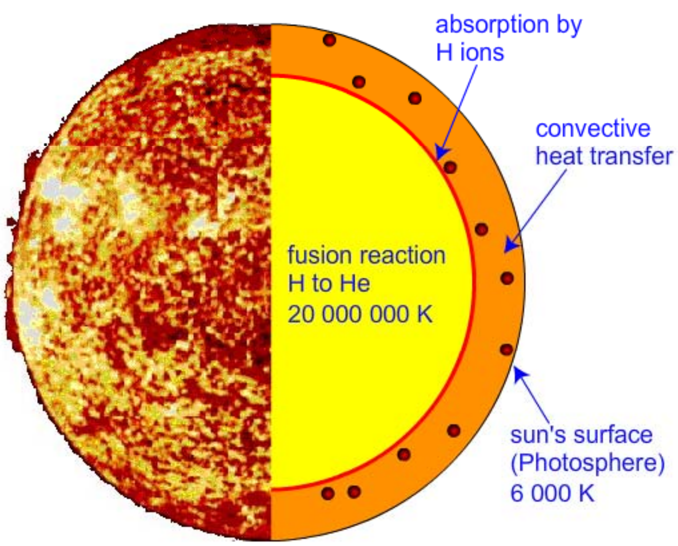
The sun's internal temperature is ~20 million degrees kelvin due to nuclear fusion reactions.
The inner radiation is strongly absorbed by a layer of hydrogen atoms closer to the sun's surface. The surface of the sun, called the photosphere, is at a temperature of 5762 ± 50 K and closely approximates a blackbody radiator.

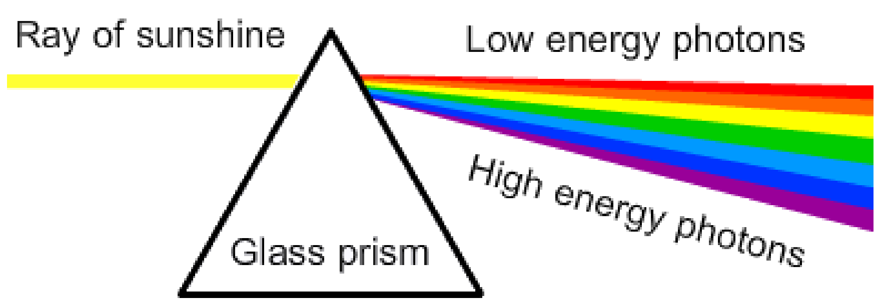
Power density leaving each surface element of the sun, H = 62499432.6 W/m^2

The total power emitted by the sun is 9.5×10^{25} W.

The light is composed of many wavelengths

Different wavelengths show up as different colors, but not all the wavelengths can be seen since some are "invisible" to the human eye.





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At a distant point,

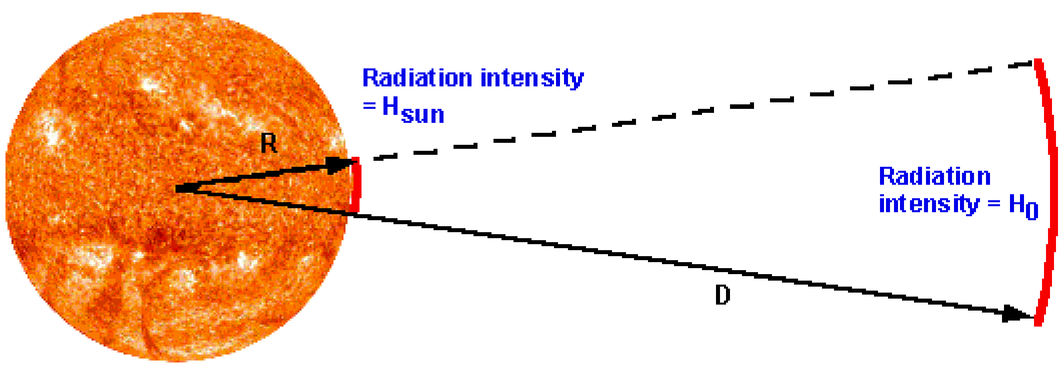
$$H_0 = \frac{R_{sun}^2}{D^2} H_{sun}$$

where:

H_{sun} is the power density at the sun's surface (in W/m^2) as determined by Stefan-Boltzmann's blackbody equation;

R_{sun} is the radius of the sun in meters as shown in the figure below; and

D is the distance from the sun in meters as shown in the figure below.



$$\frac{H}{H_{constant}} = 1 + 0.033 \cos\left(\frac{360(n-2)}{365}\right)$$

where:

H is the radiant power density outside the Earth's atmosphere (in W/m^2);

$H_{constant}$ is the value of the solar constant, **<u>1.353 kW/m^2</u>**; and

n is the day of the year.

These variations are typically small and for photovoltaic applications the solar irradiance can be considered constant. The value of the solar constant and its spectrum have been defined as a standard value called air mass zero (AM0) and takes a value of 1.353 kW/m^2.

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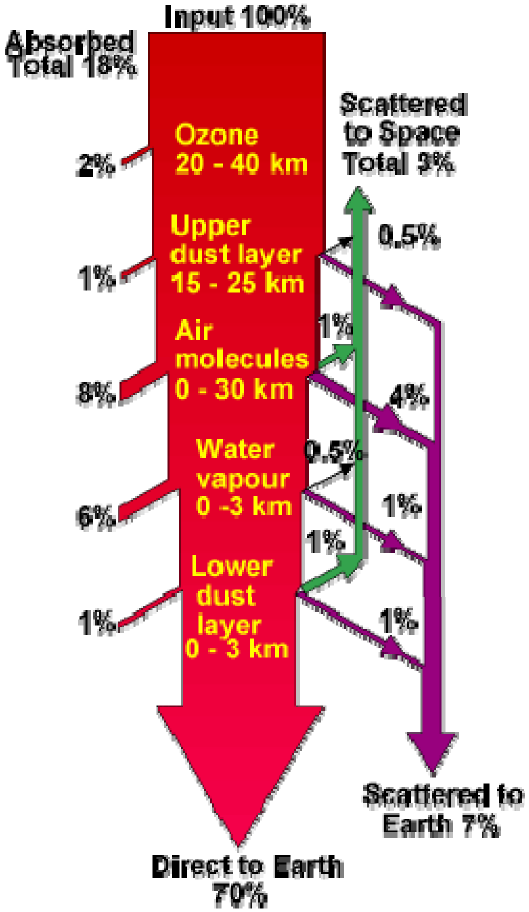
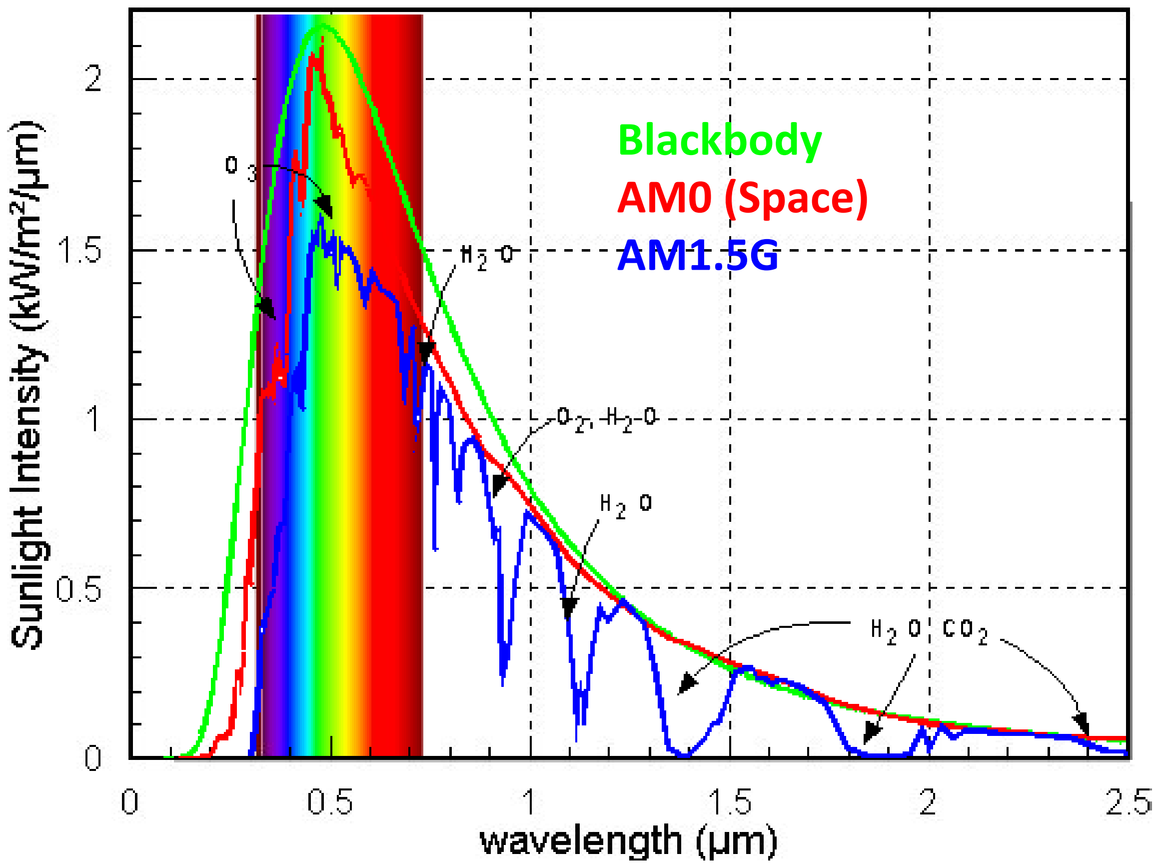
AM0 (Space)





The direct spectra is important in “concentrator solar cells where the optical acceptance angle is small.

The global spectra is important for “flat plate” solar cells where the optical acceptance angle is higher

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Different spectra are described by its "Air Mass"

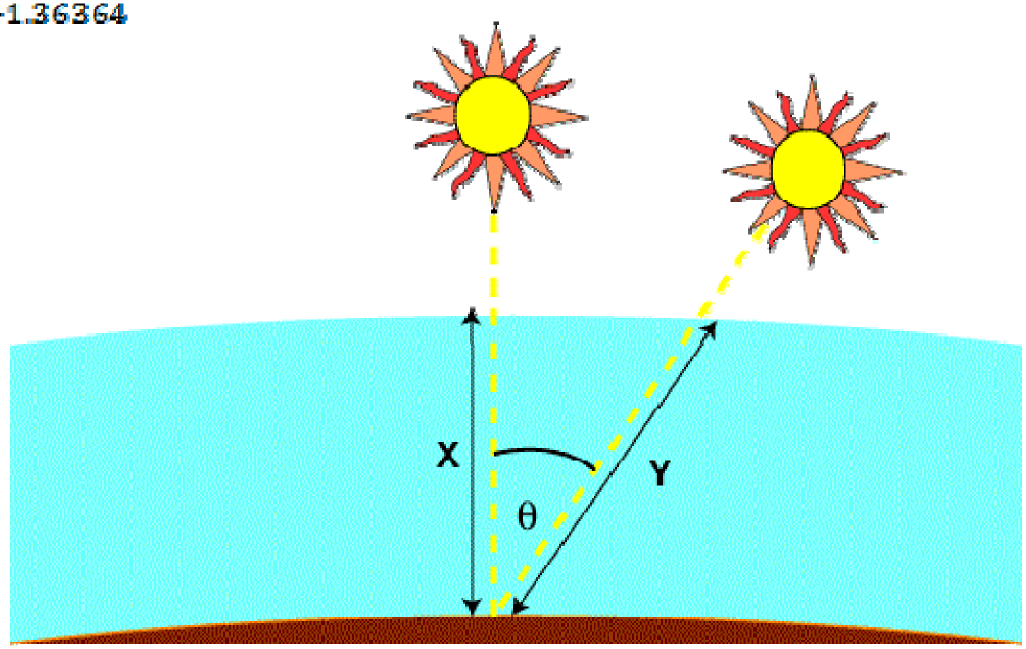
The Air Mass is the path length which light takes through the atmosphere normalized to the shortest possible path length (that is, when the sun is directly overhead). The Air Mass quantifies the reduction in the power of light as it passes through the atmosphere and is absorbed by air and dust. The Air Mass is defined as:

$$AM = \frac{1}{\cos\theta + 0.50572(96.07995-\theta)^{-1.36364}}$$

or more simply,

$$AM = \frac{1}{\cos(\theta)}$$

where θ is the angle from the vertical (zenith angle). When the sun is directly overhead, the Air Mass is 1.



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The standard spectrum at the Earth's surface is called AM1.5G, (the G stands for global and includes both direct and diffuse radiation) or AM1.5D (which includes direct radiation only).

The intensity of AM1.5D radiation can be approximated by reducing the AM0 spectrum by 28% (18% due to absorption and 10% to scattering).

The global spectrum is 10% higher than the direct spectrum.

Rounding off for convenience:
These calculations give approximately 970 W/m^2 for AM1.5G. However, the standard AM1.5G spectrum has been normalized to give 1kW/m^2 due to the convenience of the round number and the fact that there are inherently variations in incident solar radiation.

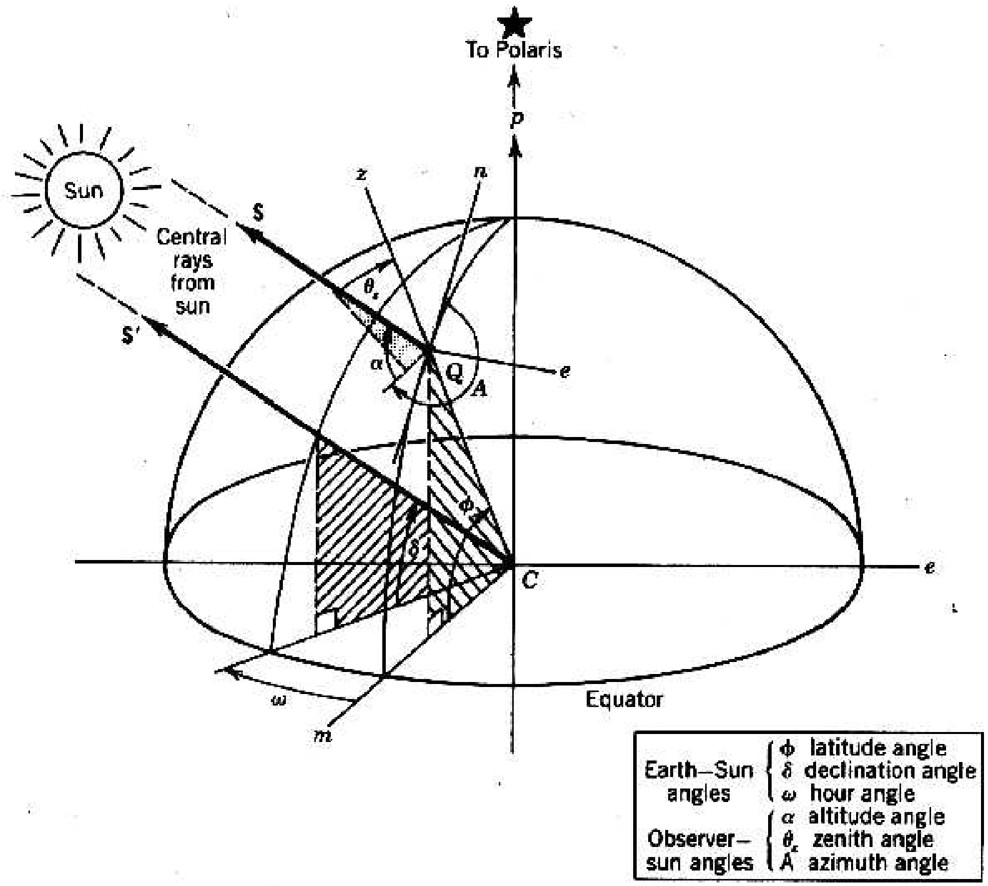
$$I_D = 1.353 \cdot \left[(1 - ah)0.7^{\left(AM^{0.678}\right)} + ah\right]$$

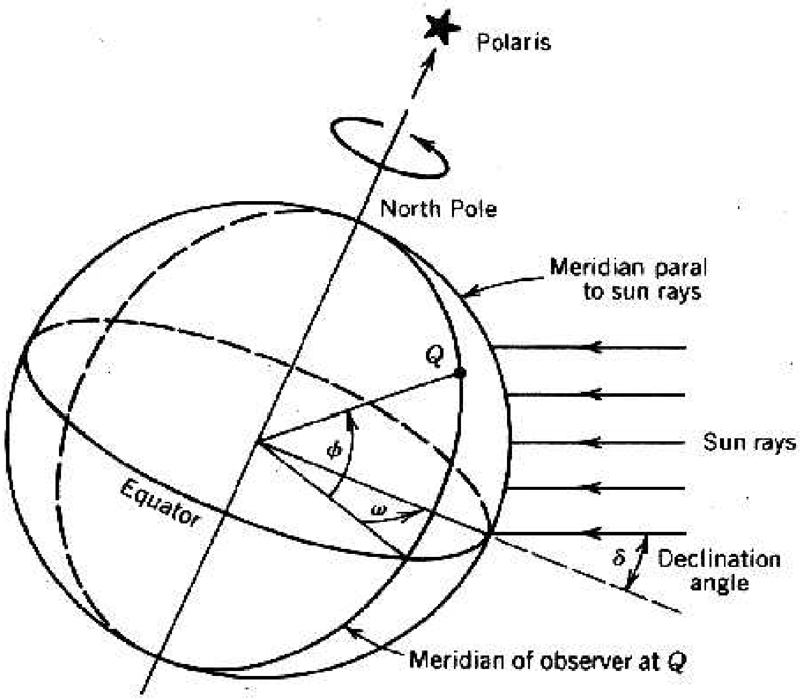
where a = 0.14 and h is the location height above sea level in kilometers

$$I_G = 1.1 \cdot I_D$$

The Nature of Sunlight

Relative orientation of the earth to sun and definition of symbols.





δ is the declination angle

ϕ or φ is the latitude angle (it is positive for Northern Hemisphere locations and negative for Southern Hemisphere).

αis the maximum elevation/altitude angle

The Nature of Sunlight – Solar Time

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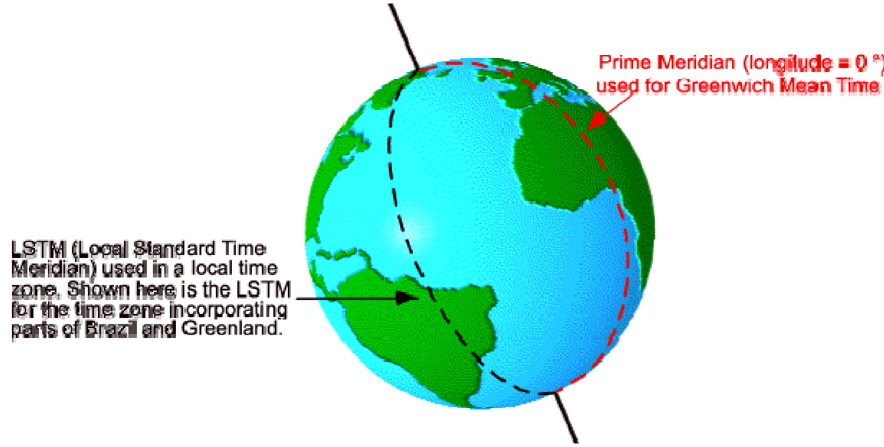
$$LSTM = 15° \cdot \Delta T_{GMT}$$

where ΔT_{GMT} is the difference of the Local Time (LT) from Greenwich Mean Time (GMT) in hours. 15°= 360°/24 hours.



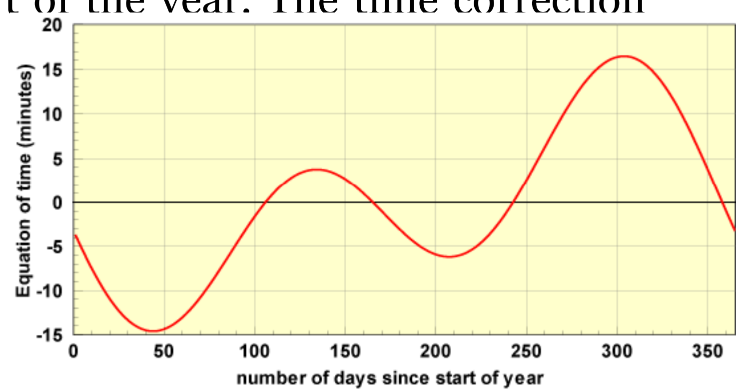
The equation of time (EoT) (in minutes) is an empirical equation that corrects for the eccentricity of the Earth's orbit and the Earth's axial tilt.

$$EoT = 9.87\sin(2B) - 7.53\cos(B) - 1.5\sin(B)$$

where

$$B = \frac{360}{365}(d - 81)$$

in degrees and d is the number of days since the start of the year. The time correction EoT is plotted in the figure below.



The Nature of Sunlight – Solar Time

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Time Correction Factor (TC)

The net Time Correction Factor (in minutes) accounts for the variation of the Local Solar Time (LST) within a given time zone due to the longitude variations within the time zone and also incorporates the EoT above.

$$TC = 4(LSTM - Longitude) + EoT$$

The factor of 4 minutes comes from the fact that the Earth rotates 1° every 4 minutes.

Local Solar Time (LST)

The Local Solar Time (LST) can be found by using the previous two corrections to adjust the local time (LT).

$$LST = LT + \frac{TC}{60}$$

Hour Angle (HRA)

The Hour Angle converts the local solar time (LST) into the number of degrees which the sun moves across the sky. By definition, the Hour Angle is 0° at solar noon. Since the Earth rotates 15° per hour, each hour away from solar noon corresponds to an angular motion of the sun in the sky of 15°. In the morning the hour angle is negative, in the afternoon the hour angle is positive.

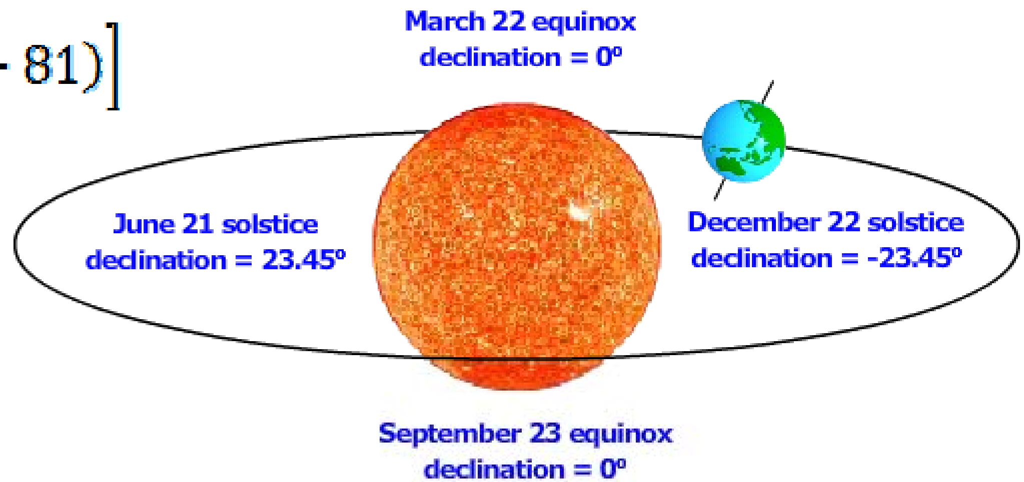
$$HRA = 15°(LST - 12)$$

The Nature of Sunlight – Declination

Declination angle is:

$$\delta = 23.45^\circ \sin\left[\frac{360}{365}(d-81)\right]$$

Where d is the number of days since the start of the year.



Animation showing how the tilt angle changes from the summer solstice in the northern hemisphere (or winter in the southern hemisphere) to the northern hemisphere winter solstice (summer in the south).

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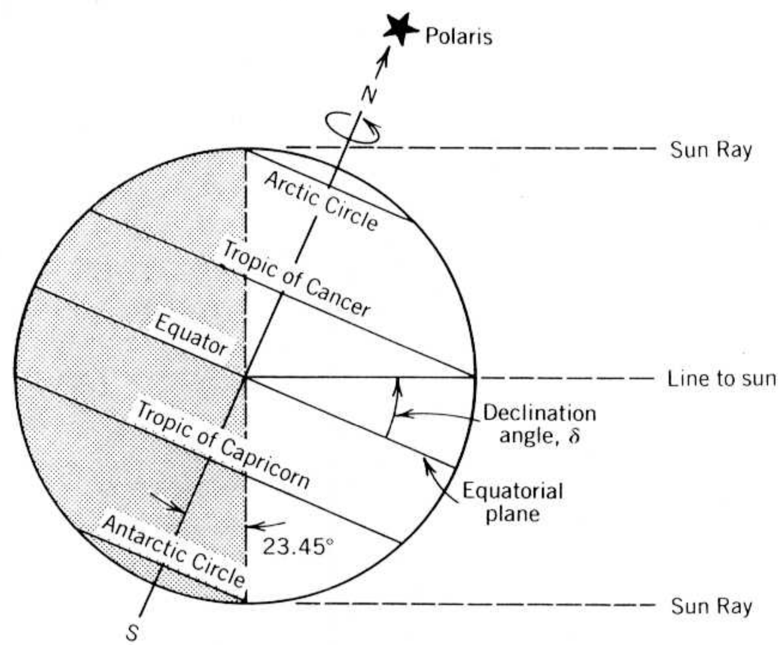
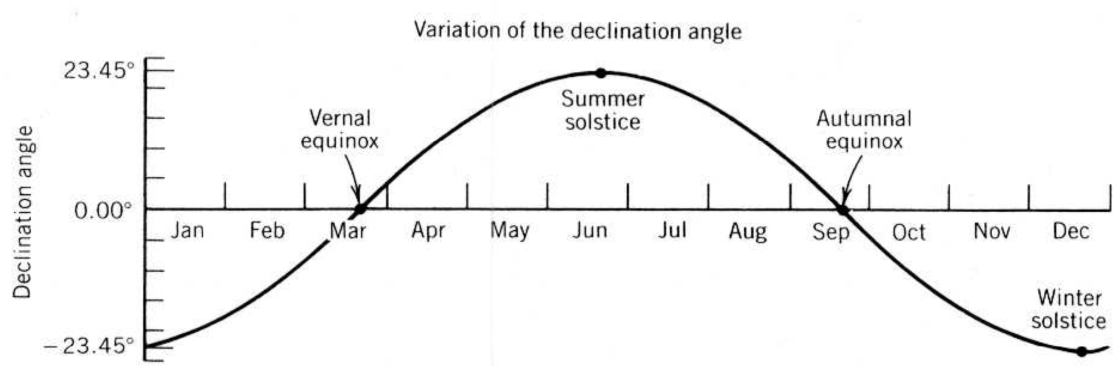




The Nature of Sunlight – Elevation

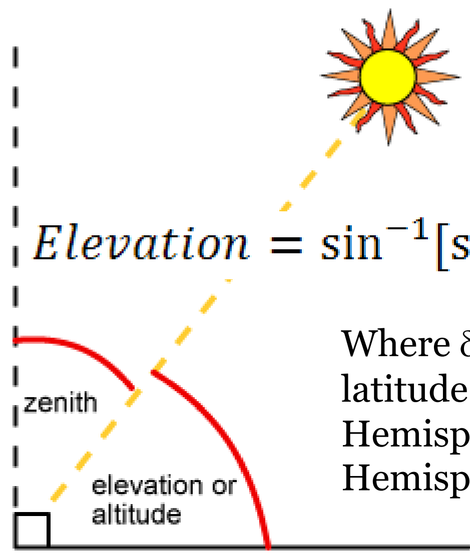
The elevation angle (used interchangeably with altitude angle) is the angular height of the sun in the sky measured from the horizontal. Confusingly, both altitude and elevation are also used to describe the height in meters above sea level. The elevation is 0° at sunrise and 90° when the sun is directly overhead (which occurs for example at the equator on the spring and fall equinoxes). The zenith angle is similar to the elevation angle but it is measured from the vertical rather than from the horizontal, thus making the zenith angle = 90° - elevation.

The peak elevation angle at solar noon is

$$\alpha = 90 - \phi + \delta$$

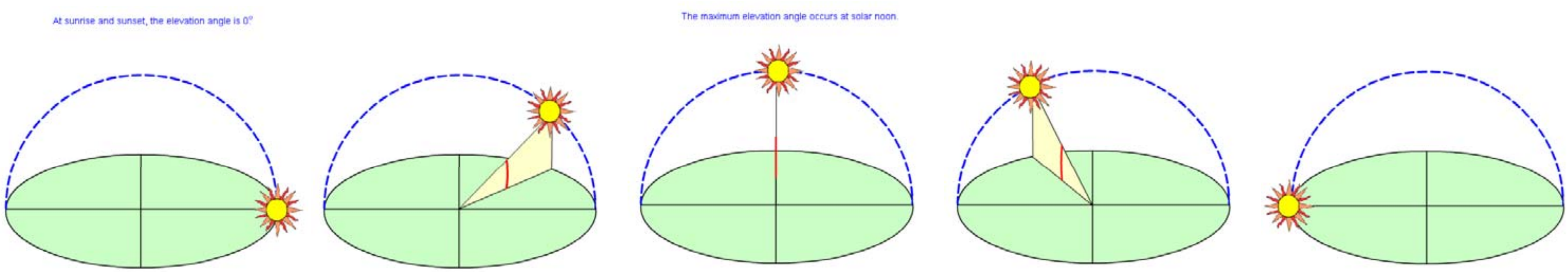
$$Sunrise = 12 - \frac{1}{15^0}\cos^{-1}\left(\frac{-\sin\varphi\sin\delta}{\cos\varphi\cos\delta}\right) - \frac{TC}{60}$$

$$Sunset = 12 + \frac{1}{15^0}\cos^{-1}\left(\frac{\sin\varphi\sin\delta}{\cos\varphi\cos\delta}\right) - \frac{TC}{60}$$



$$Elevation = \sin^{-1}[\sin\delta\sin\varphi + \cos\delta\cos\varphi\cos(HRA)]$$

Where δ is the declination angle and ϕ or φ is the latitude angle (it is positive for Northern Hemisphere locations and negative for Southern Hemisphere).



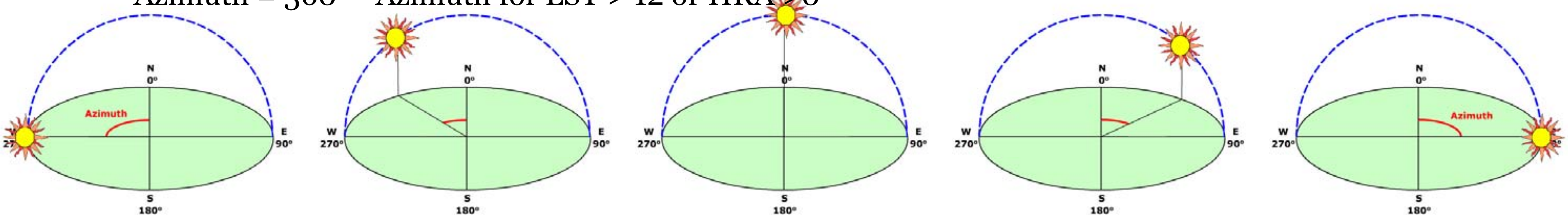
The Nature of Sunlight – Azimuthal Variations

The azimuth angle is the compass direction from which the sunlight is coming. At solar noon, the sun is always directly south in the northern hemisphere and directly north in the southern hemisphere. The azimuth angle varies throughout the day as shown in the animation below. At the equinoxes, the sun rises directly east and sets directly west regardless of the latitude, thus making the azimuth angles 90° at sunrise and 270° at sunset. In general however, the azimuth angle varies with the latitude and time of year and the full equations to calculate the sun's position throughout the day are given on the following page.

$$Azimuth = \cos^{-1}\left[\frac{\sin\delta\cos\phi - \cos\delta\sin\phi\cos(HRA)}{\cos\alpha}\right]$$

Where δ is the declination angle and ϕ is the latitude angle (it is positive for Northern Hemisphere locations and negative for Southern Hemisphere).

The above equation only gives the correct azimuth in the solar morning so that:
Azimuth = Azimuth, for LST <12 or HRA < 0
and
Azimuth = 360° - Azimuth for LST > 12 or HRA >0



The Nature of Sunlight – Parameters for Atlanta

Standard time zone: UTC/GMT -5 hours
Latitude: 33° 46‘ North
Longitude: 84° 25‘ West

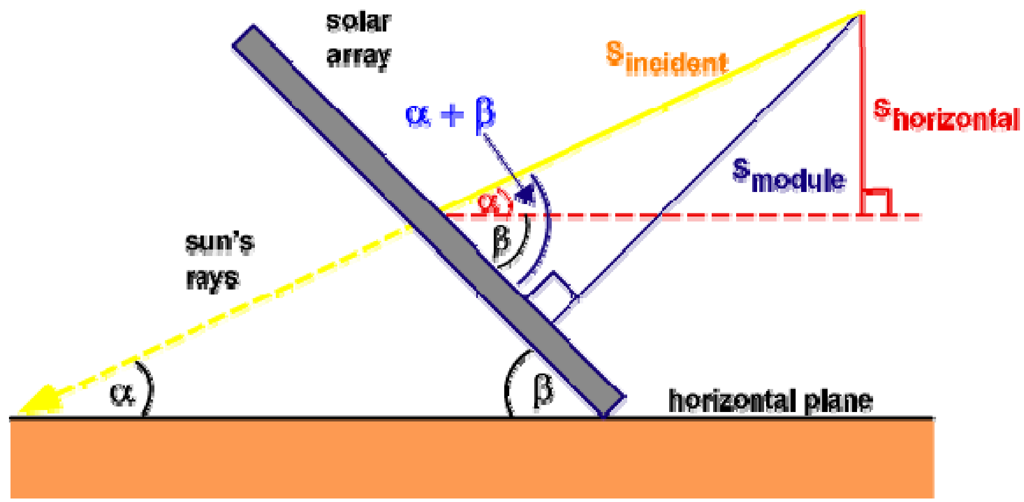
The Nature of Sunlight – Effect of Plate Angle

The equations relating S_{module}, S_{horiz} and $S_{incident}$ are:

$$S_{horizontal} = S_{incident} \sin\alpha$$

$$S_{module} = S_{incident} \sin(\alpha + \beta)$$

$$S_{module} = \frac{S_{horizontal} \sin(\alpha + \beta)}{\sin\alpha}$$



where
α is the elevation angle; and
β is the tilt angle of the module measured from the horizontal.
The elevation angle has been previously given as:

$$\alpha = 90 - \phi + \delta$$

where ϕ is the latitude; and
δ is the declination angle

The Nature of Sunlight – Peak Hour Estimation

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Peak Sun Hours

The average daily solar insolation in units of kWh/m^2 per day is sometimes referred to as "peak sun hours". The term "peak sun hours" refers to the solar insolation which a particular location would receive if the sun were shining at its maximum value for a certain number of hours. Since the peak solar radiation is 1 kW/m^2, the number of peak sun hours is numerically identical to the average daily solar insolation. For example, a location that receives 8 kWh/m^2 per day can be said to have received 8 hours of sun per day at 1 kW/m^2. Being able to calculate the peak sun hours is useful because PV modules are often rated at an input rating of 1kW/m^2.