Solar Radiation

- Outline
  - Properties of radiation: Summary of equations, terms, concepts
  - Solar Spectrum
  - Terrestrial Solar Radiation: Effects of atmosphere, angular dependence of radiation, variation of solar radiation
  - Calculation of Solar Radiation:
    - Estimate of intensity of solar radiation
    - Angular Dependence
      - Solar Noon calculations
      - Time-based calculations
  - Solar Radiation Data Sets

Caution: **Watch your units!!!** Make sure you pay attention to radians, degrees. Also pay attention to details - which hemisphere, difference between solar noon and local time, etc.

Solar Radiation

- Goals
  - Calculate power density, photon flux, photon energy, photon wavelength & relationships between them.
  - Calculate properties of arbitrary light source given its spectral irradiance
  - Calculate properties of black body radiation: Max temperature, total power.
  - Convert local time to solar time
  - Determine angles of incident sunlight, both at solar noon and as a function of time.
  - Determine light normal to a surface, at solar noon and at an arbitrary time

Properties of Radiation

Summary of equations & concepts:

- Wave/energy relationship:

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

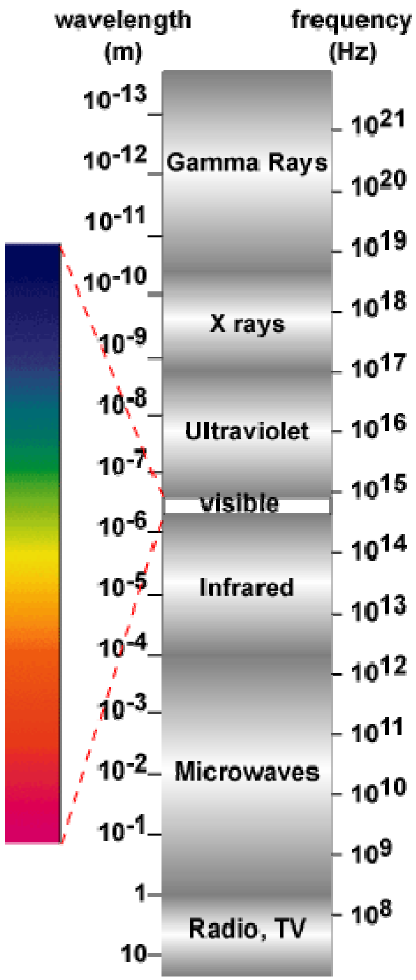
- Common units of energy: electron-V (eV)

  1 eV = 1.602×10^{-19} J

- Power density (H, W/m²) and monochromatic photon flux (Φ, photons/sec·m²):
  - **Power** density (in W/m²) is photon flux (# photons/m²·sec) multiplied by energy per photon.

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

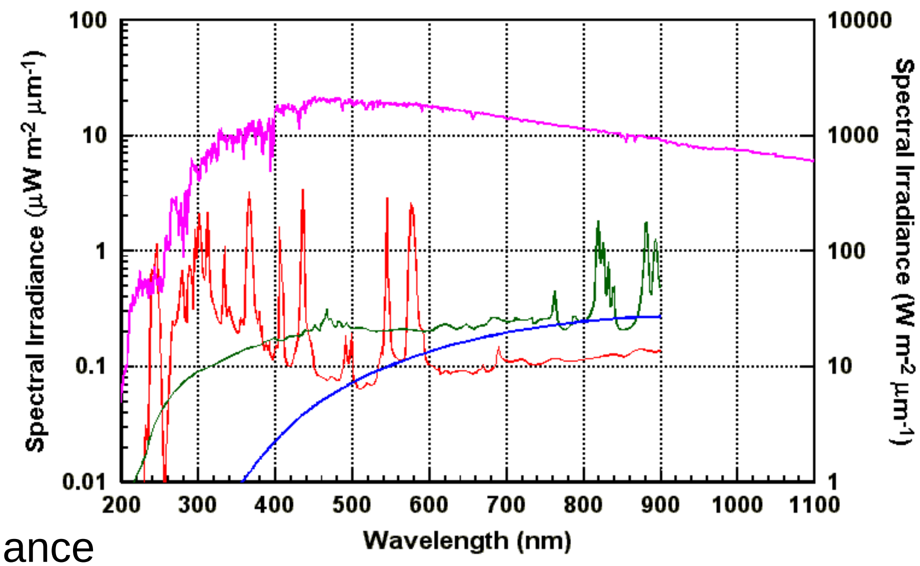
Electromagnetic Spectrum



Spectral Irradiance

- Spectral irradiance, F, is standard way to specify the properties of a light source
- Gives the power density at a particular wavelength.
- Units are $\frac{W}{m^2}\frac{1}{\mu m}$. The W/m² refers to the power density at a given wavelength, the μm refers to the wavelength at which the power density is specified.

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).



$$H\left(\frac{W}{m^2}\right) = \int_0^\infty F(\lambda)d\lambda$$ continuous spectral irradiance

$$= \sum_{i=1}^{N} F_i(\lambda)\Delta\lambda$$ Discrete spectral irradiance, N is # points in F(λ)

Black Body Radiation

- Blackbody: emits based on its temperature; absorbs all light incident on it.
- Spectral Irradiance for black body:
  - Depend on temperature of blackbody source
  - ↑T -» ↑ power density, shifts spectrum more to blue

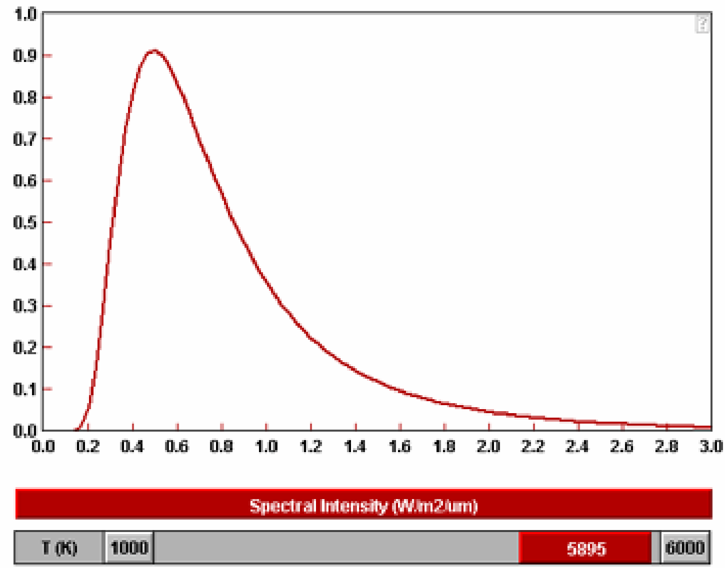
$$F(\lambda) = \frac{2\pi hc^2}{\lambda^5\left(\exp\left(\frac{hc}{k\lambda T}\right) - 1\right)}$$

- Power density for blackbody:

$$H = \sigma T^4$$

- Wavelength at peak spectral irradiance:

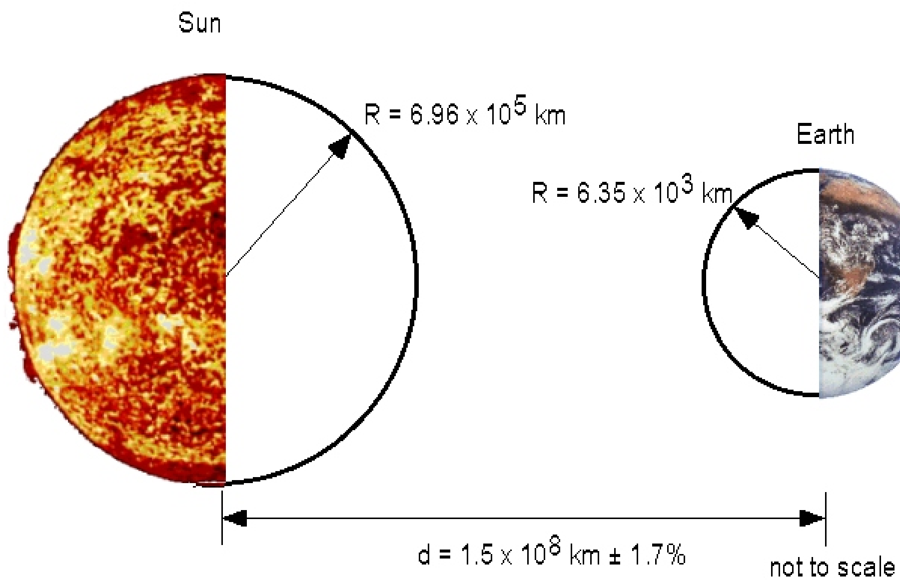
$$\lambda_p(\mu m) = \frac{2900}{T}$$



Solar Radiation

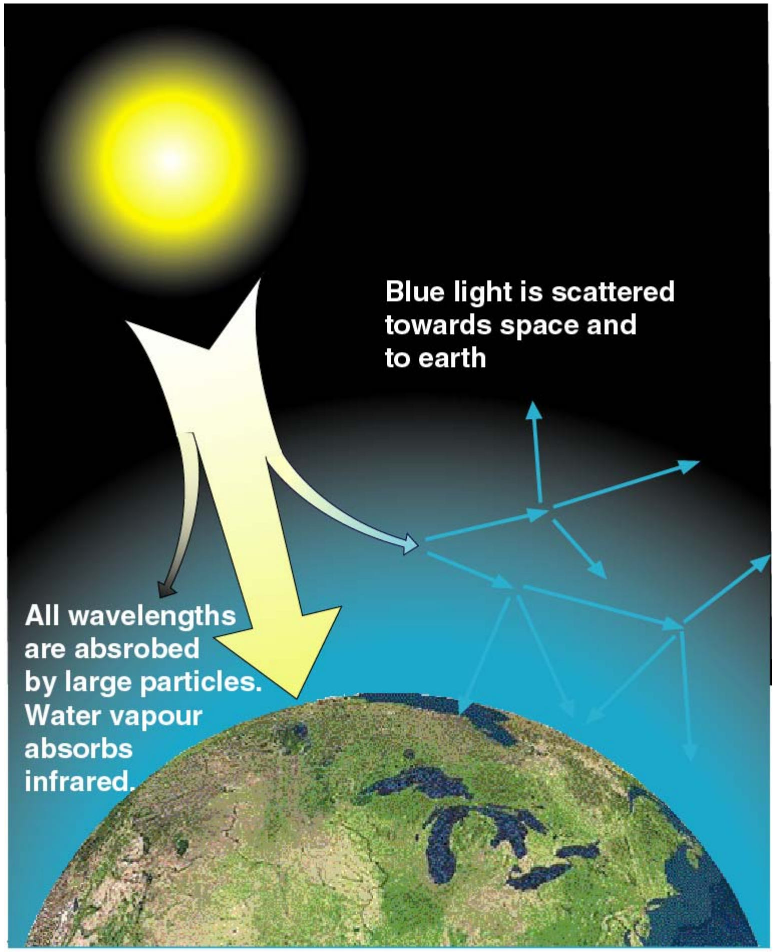
- Sun approximates a black body at ~6000K, radiating with a power density of $H_{sun} \approx 73 MW/m^2$.
- Total power emitted is $4\pi R^2_{sun}$, where the radius of the sun, $R_{sun} = 6.96 \times 10^5$ km.
- Power density at a distance D from sun if given by:

$$H\left(\frac{W}{m^2}\right) = \frac{R_{sun}^2}{D^2} \times H_{sun}$$



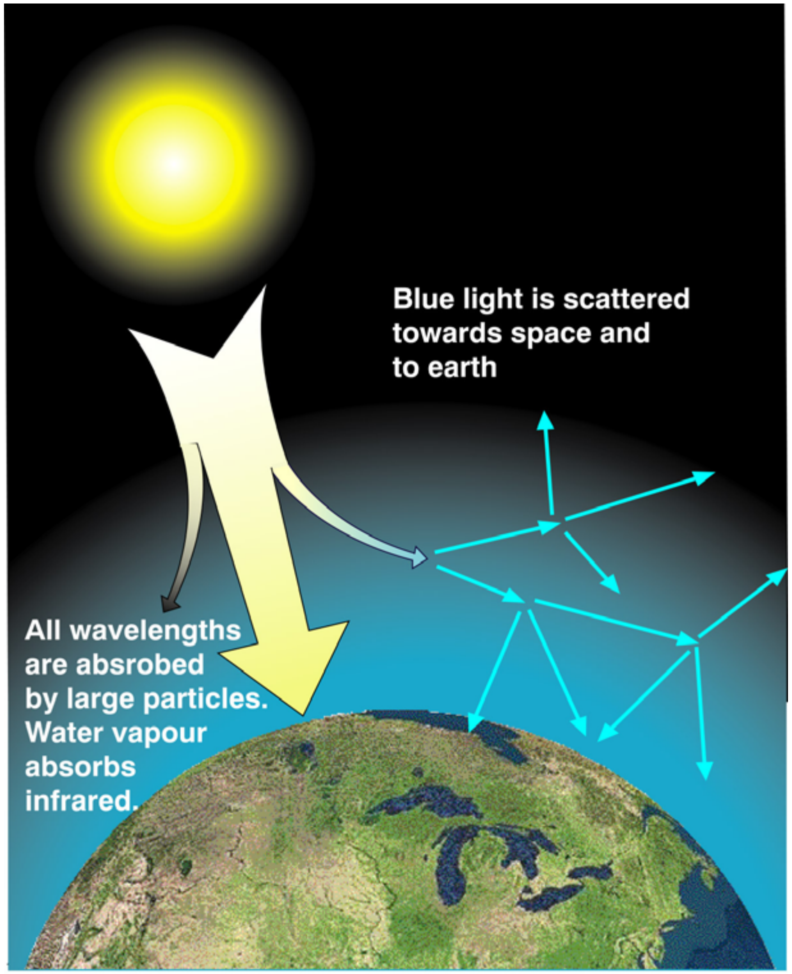
Terrestrial Radiation

- Earth's atmosphere has several impacts on radiation:
  - Scattering of ~10% of light causes this light to hit earth's surface at a wide range of angles and coming from anywhere in the sky. It is most effective for higher energy photons.
    - Direct light is the light from the sun which reaches the earth without scattering.
    - Diffuse light is scattered by the atmosphere.
  - Absorption in the atmosphere changes both the power density and the spectral distribution of terrestrial solar spectrum.
    - Ozone absorbs at high photon energies.
    - Water vapor, CO_2, absorb in infra-red.
  - Clouds, other local variation in atmosphere introduce variability (both locally and temporally) into terrestrial solar radiation.



Atmospheric Effects

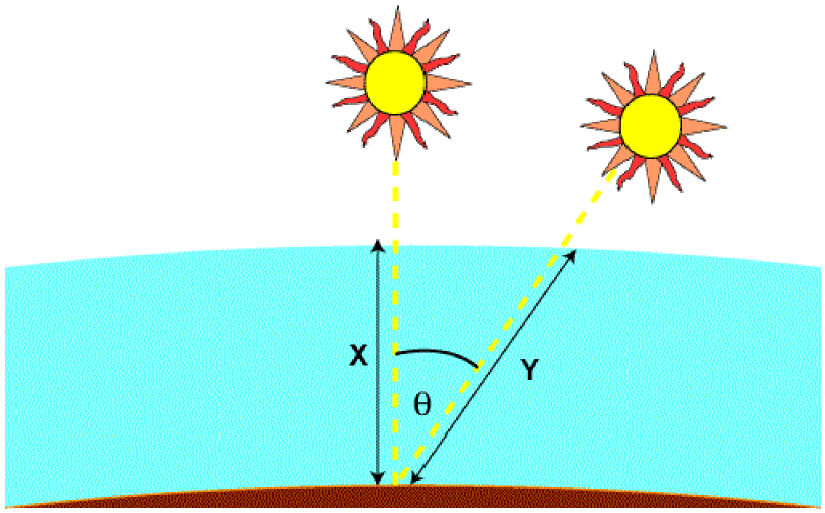
- Atmosphere has several different effects: scattering, absorption, reflection
  - Scattering
    - Primarily blue light is scattered – changes the spectrum that reaches Earth.
    - Scattering changes the direction from which light appears to come.
    - Two components of solar radiation – direct and indirect light.
    - Indirect light ~ 10% of total.
    - Indirect light cannot be concentrated.



Terrestrial Radiation

- Since the impact of the atmosphere on the terrestrial solar radiation is substantially determined by the path length of the light through the atmosphere, the terrestrial solar radiation is characterized by the Air Mass.
- Air Mass (AM) is defined as:

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



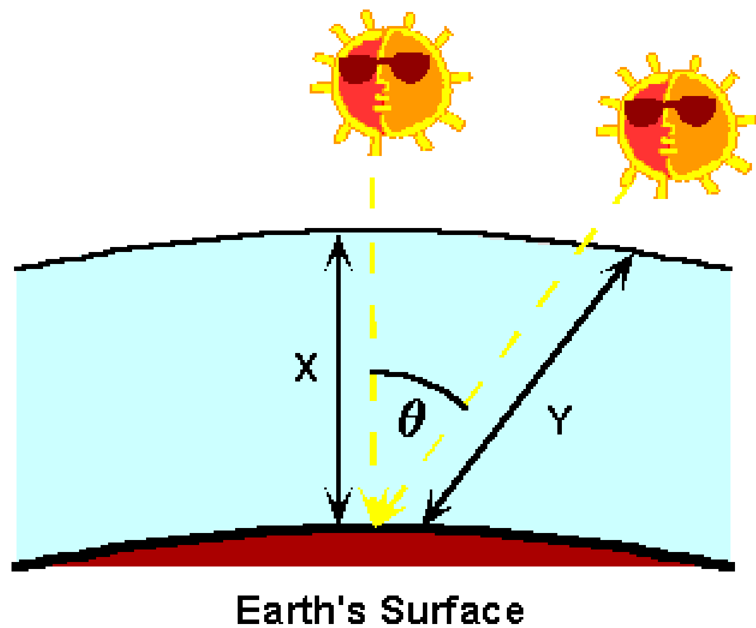
- Because of the variability in terrestrial radiation, a standard terrestrial solar spectrum is defined, called AM1.5G. (G stands for global, or the direct + diffuse radiation).
- The standard AM1.5G spectrum consists of a standard spectral irradiance for terrestrial solar radiation.
- The solar radiation outside the Earth's atmosphere is called AM0.

Air Mass

- Absorption in incident light is approximated by concept of Air Mass.
- Air mass depends on the path length that the sun makes through the atmosphere.

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

- Power density in space called AM0.
- Standard conditions AM1.5
- Direct and indirect radiative power can be approximated from AM value.



$$I_D = 1.353 \times \left(0.7^{AM}\right)^{0.678}$$

$$I_G = 1.1 \times I_D$$

I_D is direct irradiance, I_G is global irradiance (direct + indirect (diffuse)).

Angular Dependence

- The angle between the sun and the Earth's surface is continually changing because of the rotation of the Earth about the sun and the rotation of the Earth on its axis.
- Determining the angle between the sunlight and a surface is critical in finding the usable since only the component of the incident sunlight which is normal to a surface can be used by the surface.
- The position of the sun is specified by three angles:
  - Declination angle
  - Elevation angle
  - Azimuth angle
- When calculating solar angles, more convenient to express the day of the year (d) as the number of degrees which the earth has rotated around the sun – denoted by Ω.
  - Generally the day of the year is referenced from the Spring Equinox (d = 81).
  - In one year, the earth moves 360°, so moves 360°/365 in one day.

$$\Omega = \frac{360^\circ}{365}(d - 81)$$

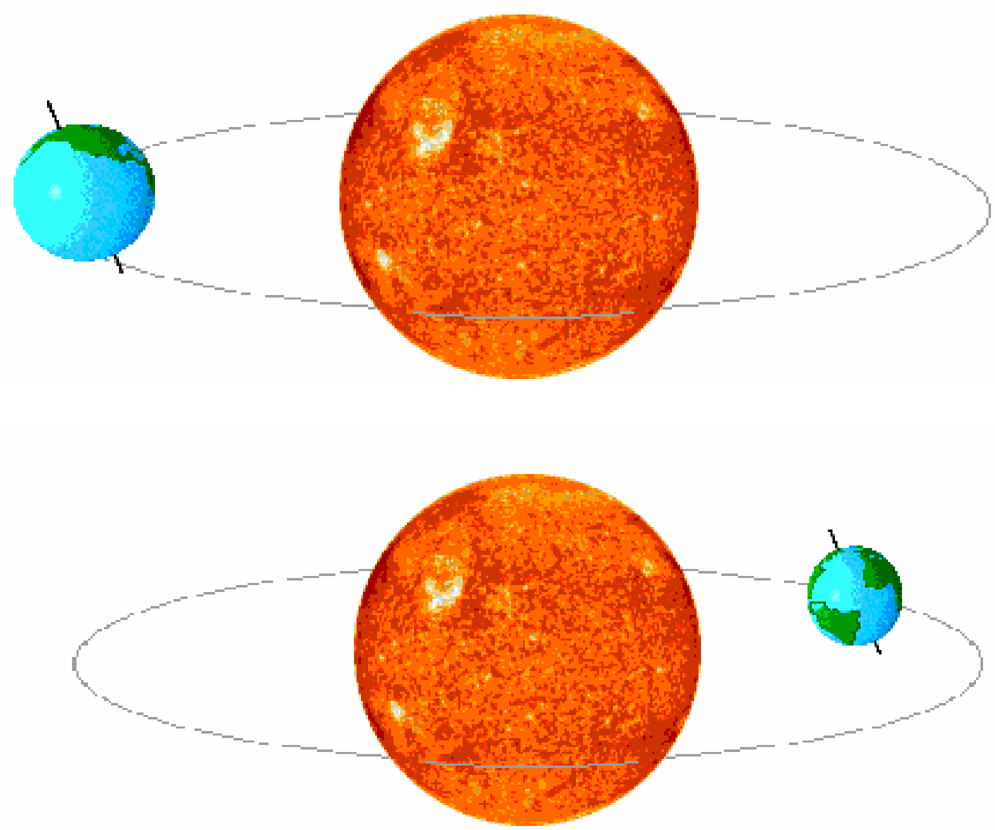
For daily variation

$$\Omega = \frac{360^\circ}{365}\left(d - 81 + \frac{hour - 12}{24}\right)$$

For hourly variation, where hour is the hour of the day.

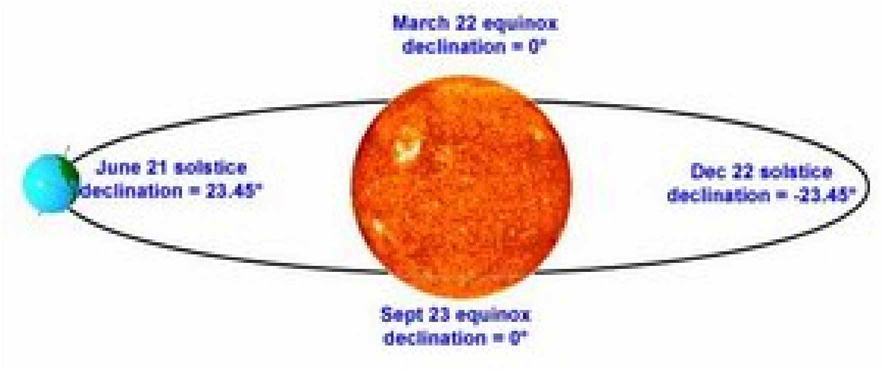
Rotation of Earth

- Angular dependence has a daily and seasonal component.
- Seasonal component
- Tilt of the Earth's axis and rotation around the sun causes a variation in the angle at which the sun strikes the Earth
- Declination angle represents this tilt
- Maximum value of the declination angle is the tilt of the earth's a axis (23.45°)

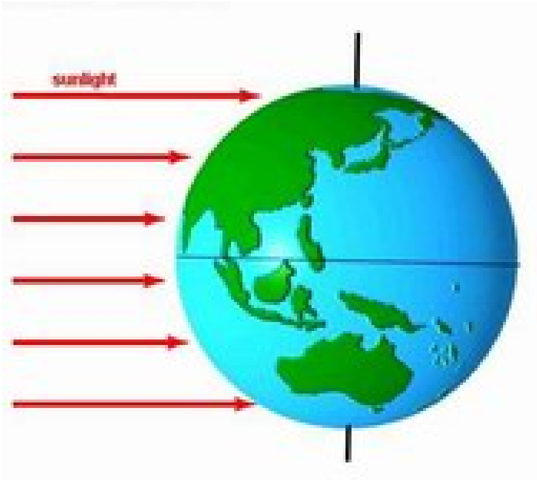


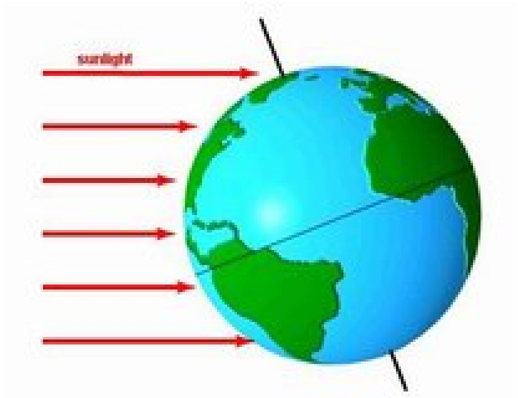
Solar Radiation

- Declination angle: angle between the sun the earth



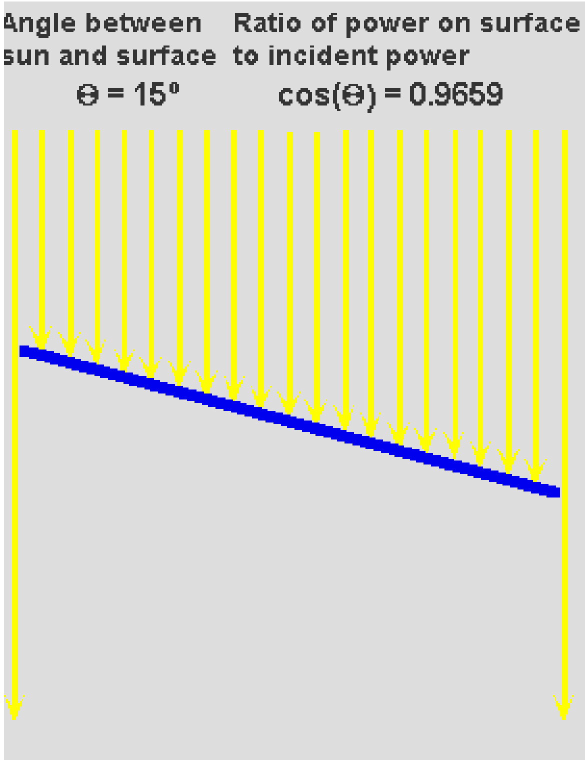
- The declination angle, which is the same everywhere on earth at a given time, and changes with seasons.

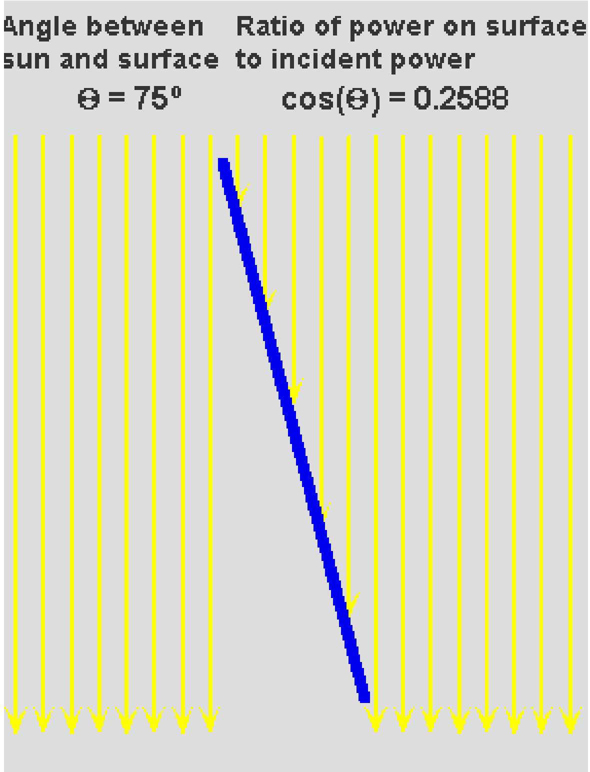




Rotation of Earth

- Rotation of the Earth changes the angle at which the sun strikes the Earth and also through AM the power density of sunlight on the Earth's surface.





Rotation of Earth

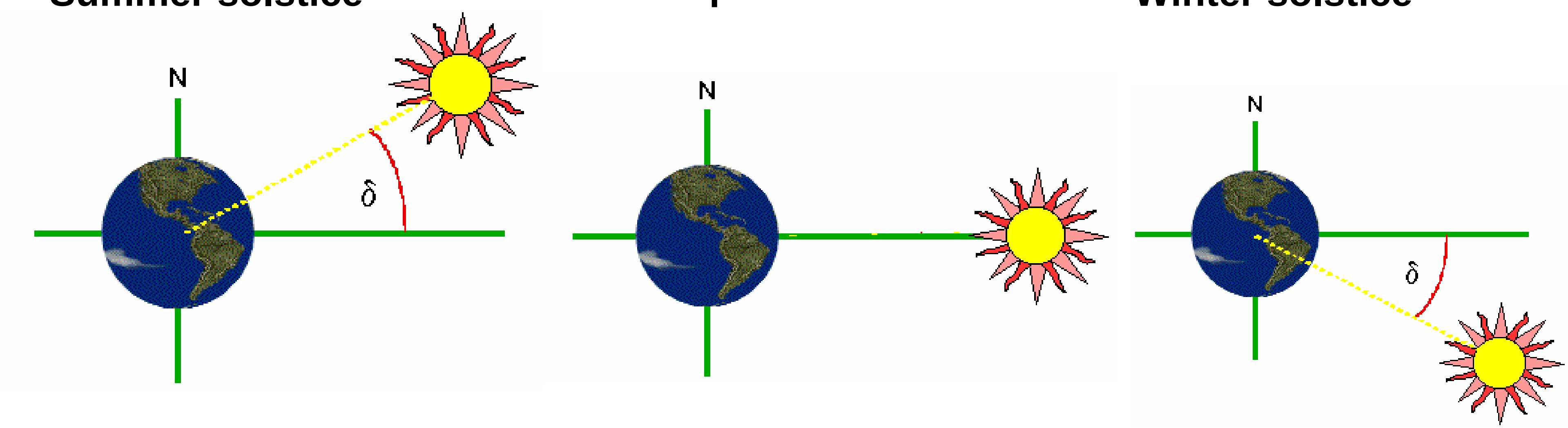
- Declination angle
  - The declination angle, denoted by δ, varies seasonally due to the tilt of the Earth on its axis of rotation and the rotation of the Earth around the sun.
  - Maximum and minimum occur at summer and winter solstice
  - Declination angel is 0 at equinoxes.

$$\delta = \sin^{-1}\left[\sin(23.45°)\sin\Omega\right] \approx 23.45°\sin\Omega$$

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

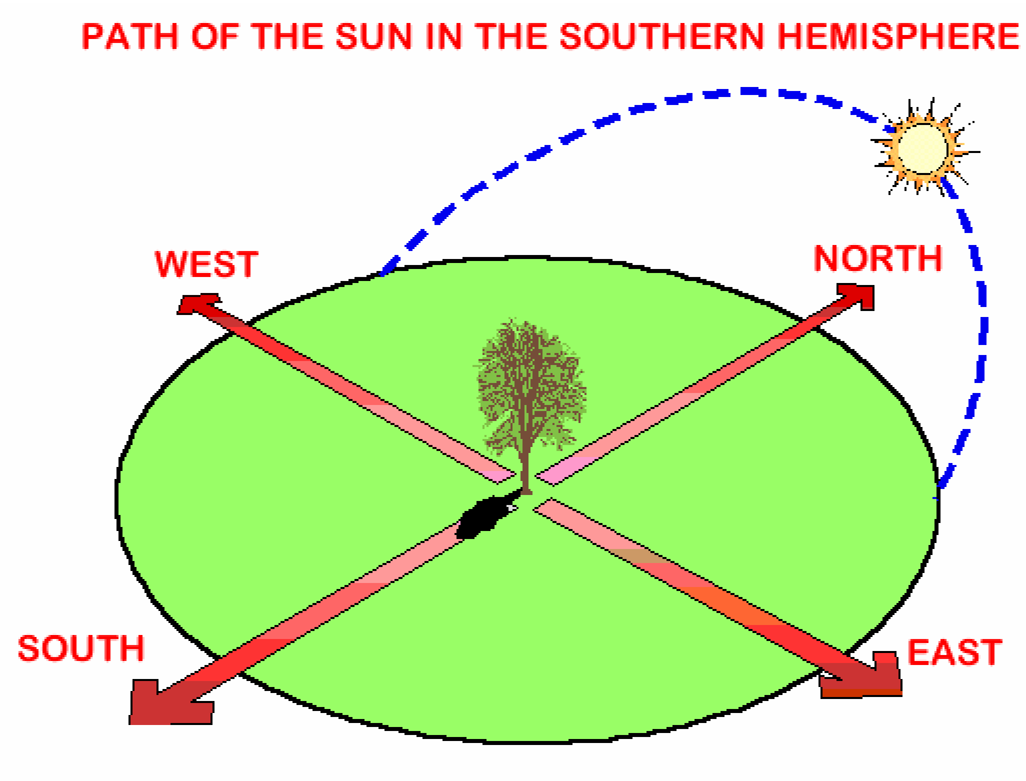
d is the number of day of the year.

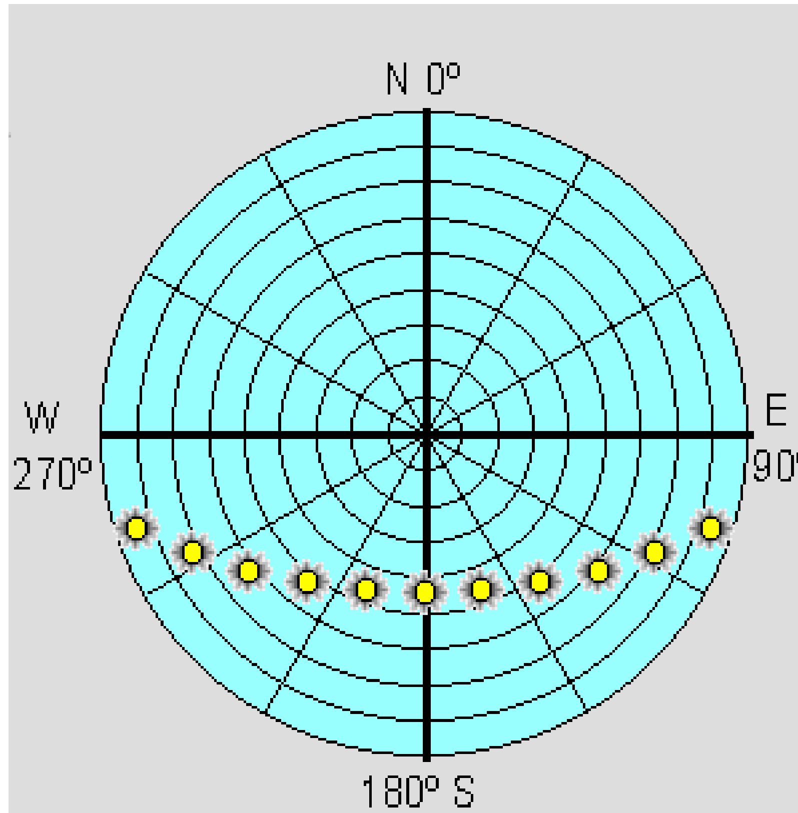
Summer solstice **Equinox** **Winter solstice**



Path of sun

- Net path of sun throughout the day calculated based on azimuth and altitude angle.
- Represent on polar plots or elevation angle plots.

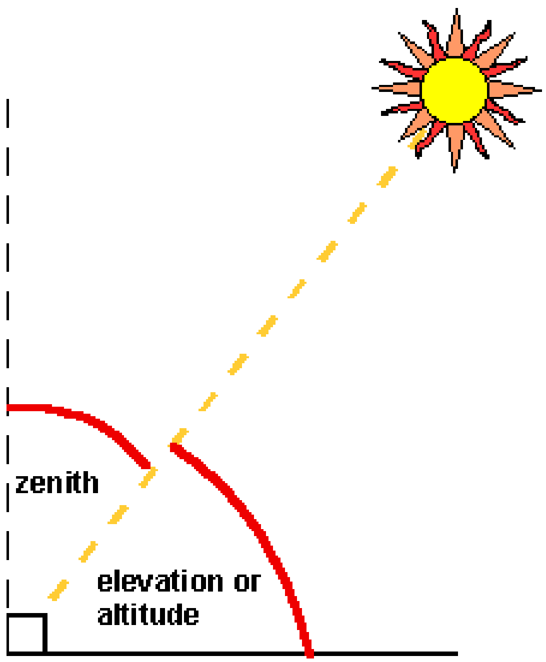


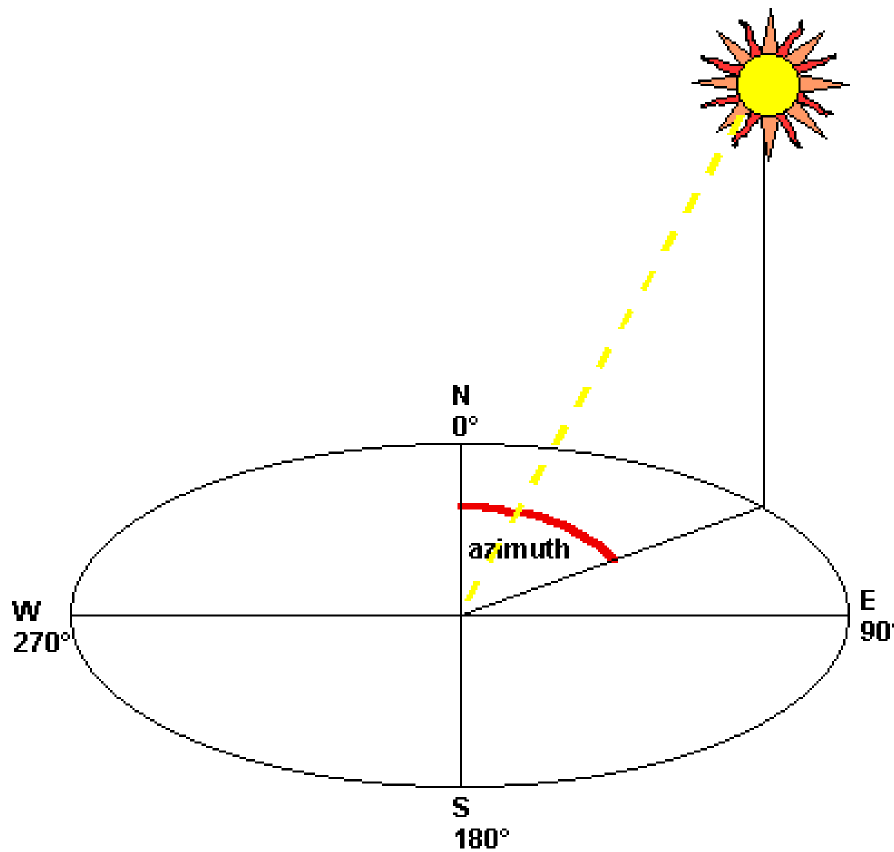


Atlanta, Feb 19th

Azimuth and elevation

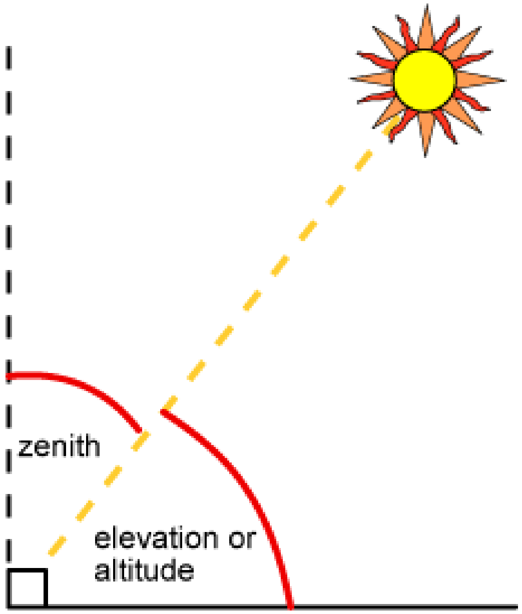
- Daily and seasonal angular dependence at a particular location given by azimuth and elevation (or zenith or altitude) angle.
- Both elevation and azimuth vary through the day.
- Maximum and minimum value depend on latitude and season.
- Azimuth is due East/West at sunrise/sunset on equinoxes.





Elevation Angle

- The elevation angle (used interchangeably with altitude angle) is the angular height of the sun in the sky measured from the horizontal.
  - Note: both altitude and elevation are also used to describe the height in meters above sea level – this is NOT the same parameter.
- Zenith angle is measured from vertical rather than horizontal.
- The elevation angle varies throughout the day – it is 0° at sunrise and achieves its maximum value at solar noon.
- The elevation angle at solar noon is largest at Summer Solstice (where it equals latitude plus maximum declination (23.45°)) and lowest at Winter Solstice, (where it equals latitude minus maximum declination (23.45°)) .
- For most many latitudes (greater than 23°), the sun is never directly overhead.



Elevation angle

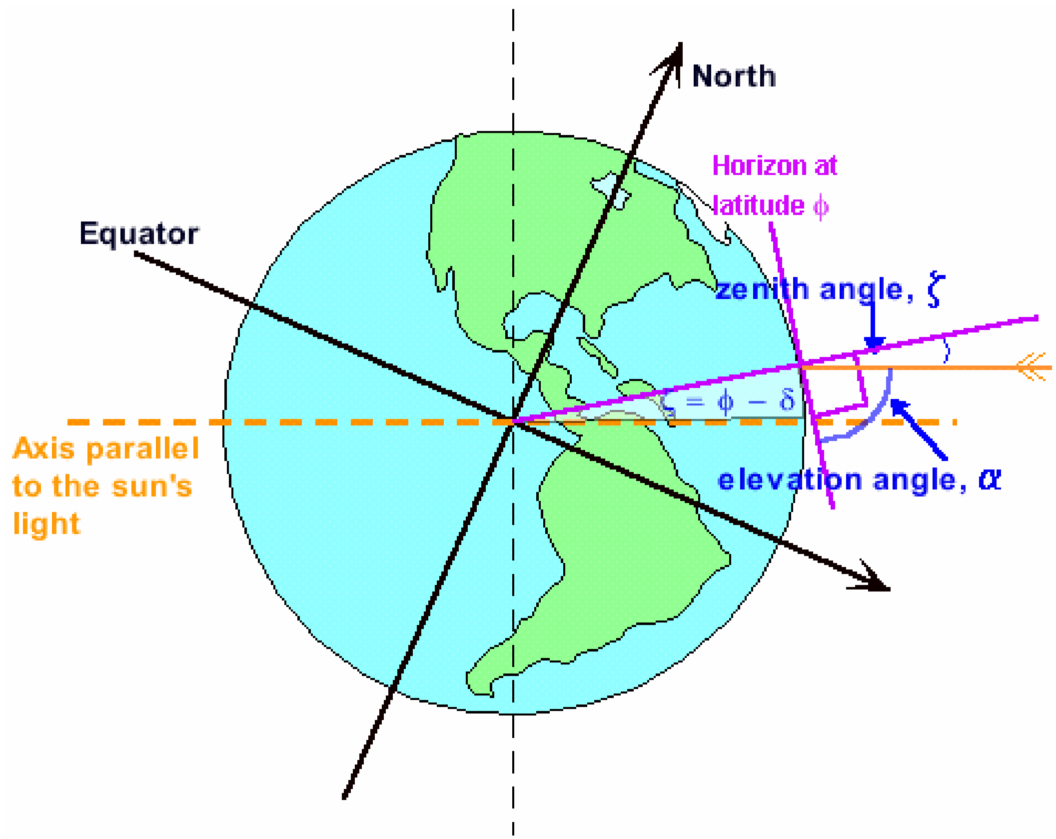
- Maximum and minimum elevation depend on latitude and season.
- Maximum altitude angle can be found from declination and latitude.

$$\alpha = 90^{\circ} + \phi - \delta$$

δ is the declination angle at a particular day of the year

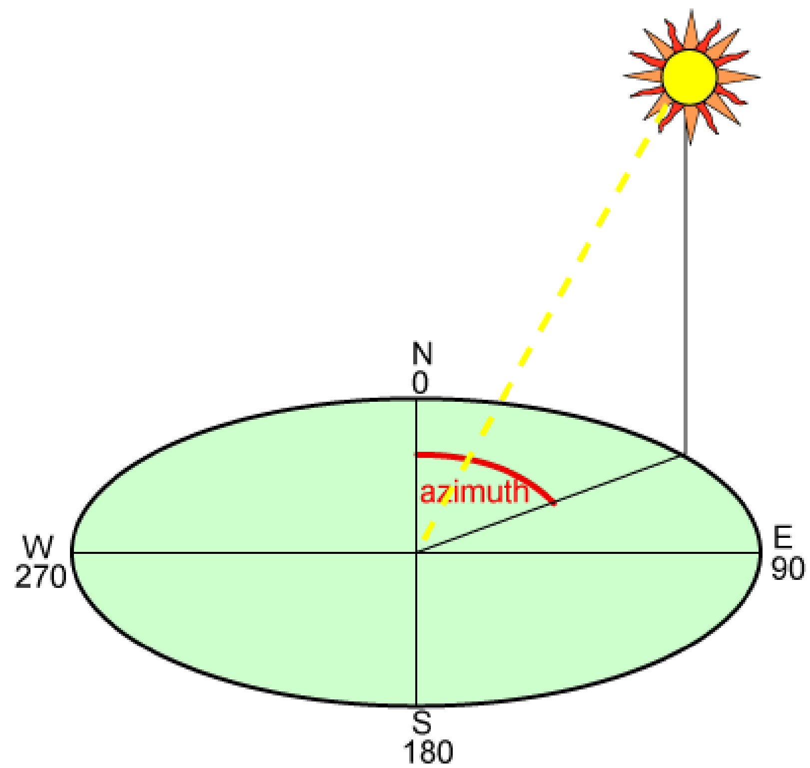
ϕ Is the latitude angle

α Is the altitude angle.



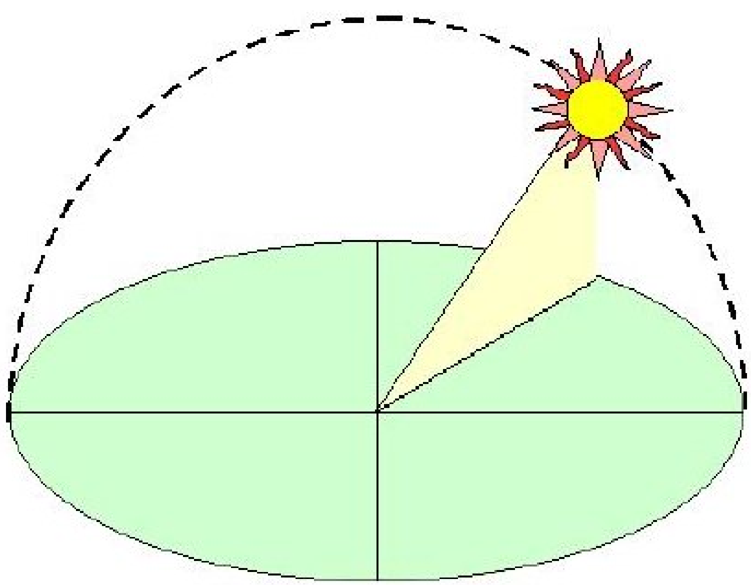
Azimuth Angle

- 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.
- 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

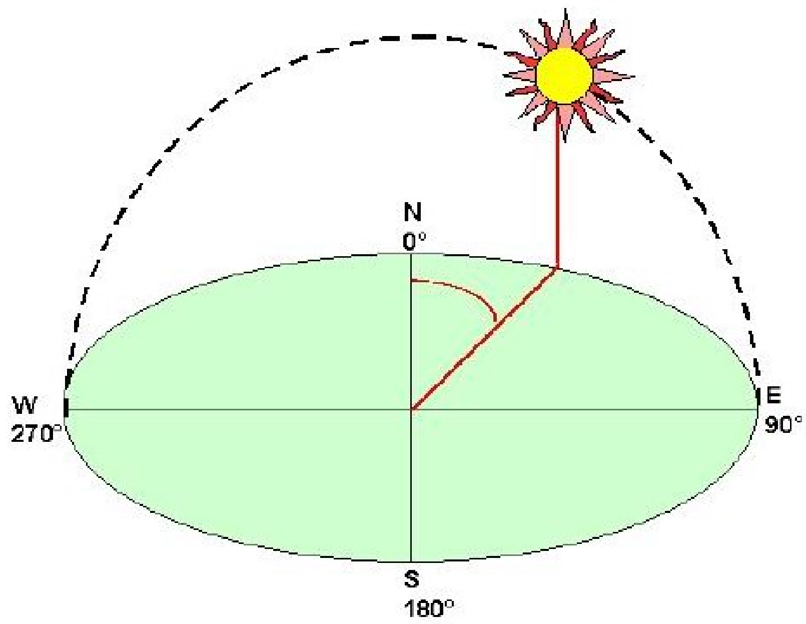


Solar Radiation

- For hourly calculations, we also need to calculate the azimuth and elevation (also called altitude or zenith (90 – elevation)) angles throughout each day.



Altitude or elevation angle



Azimuth angle

$$\sin\alpha = \sin\phi \sin\delta + \cos\phi \cos\delta \cos(hra)$$

$$\cos\Theta = \frac{\cos\phi \sin\delta - \sin\phi \cos\delta \cos(hra)}{\cos\alpha}$$

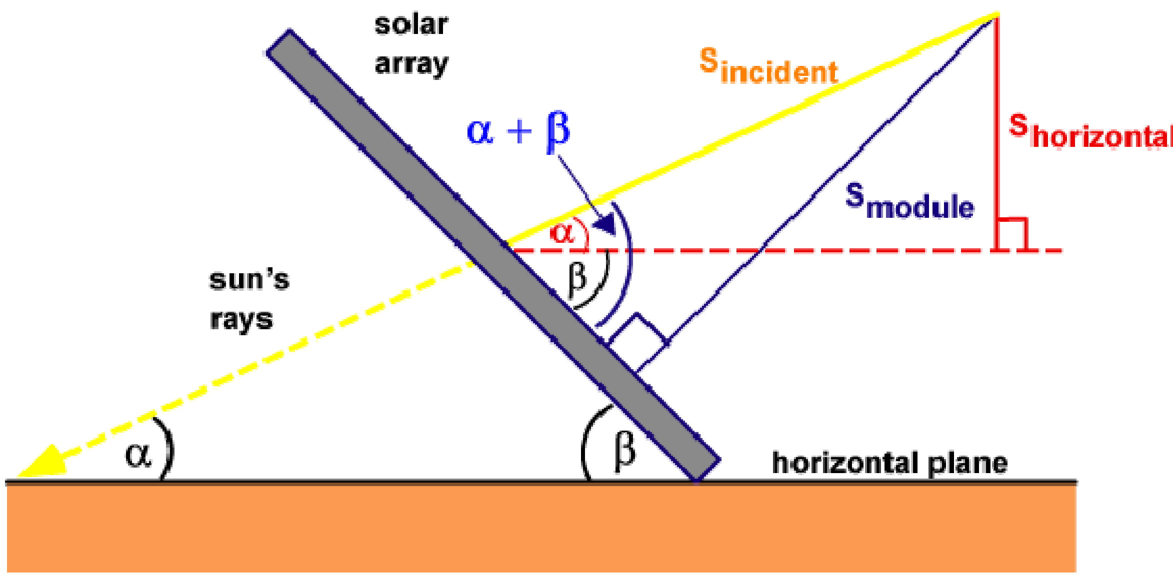
Power on a tilted surface

- The amount of solar radiation incident on a tilted module surface is the component of the incident solar radiation which is perpendicular to the module surface.
- In solar radiation data sets, the sunlight is often specified as the component normal to a horizontal surface ($S_{horizontal}$)

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

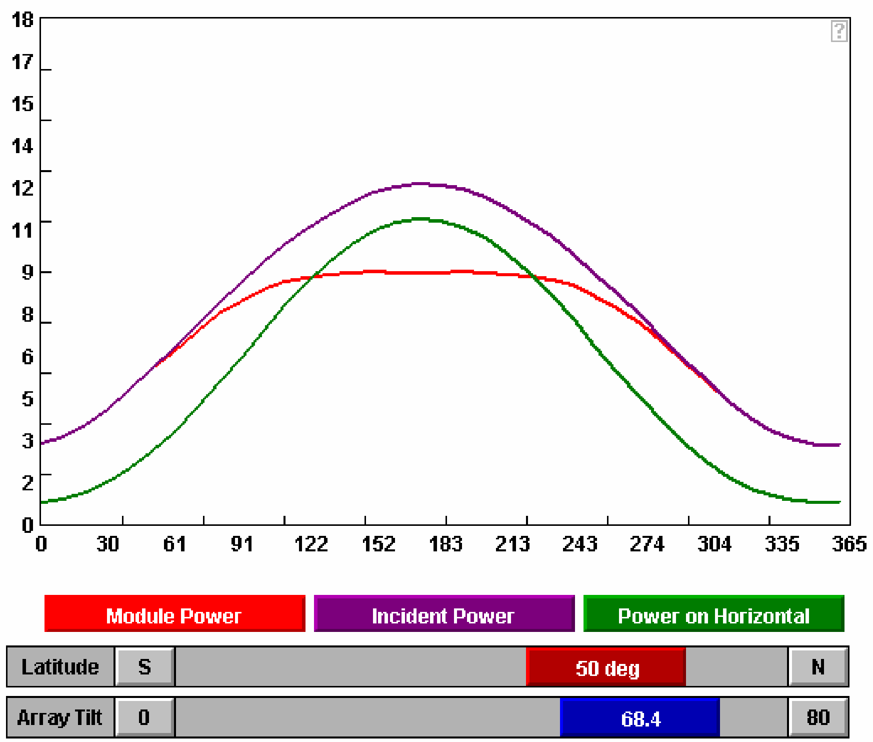
$$S_{module} = S_{incident}\sin(\alpha+\beta)$$

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



Effect of Module Tilt

- Maximum power into a module occurs when the surface is normal to the incident sunlight, but since the angle of the sun is continually changing, a module with fixed tilt captures only a fraction of the total power over a year.
- Optimum often to set module tilt = latitude, but usually get equal amounts of sunlight in summer and winter.
- For maximum power: module tilt = Latitude - 15°
- For more uniform production of power:
  module tilt = Latitude + 15°



Hourly Sun Calculations

- Hourly sun position calculations
  - To perform system analysis on an hourly level and to use TMY data, need to calculate (1) the sun's position (declination, azimuth, elevation) for each hour of the day and (2) the normal component of the solar radiation on a tilted surface.
  - There are numerous equations for declination, varying in what non-idealities they take into account.
  - The accuracy of the calculations depends on the use to which they will be put – flat plate PV systems are generally not oriented very accurately.
  - The accuracy required for positioning tracking increases as the level of concentration increases.
- Notes on angular calculations and accuracy
  - As the sun crosses the sky, its variation from one position to another is described in degrees of arc. Subsets of degrees are minutes, and then seconds, with 1 º = 60 minutes and 1 minute = 60 sec.
  - For solar energy calculations, need accuracy of calculations to ~ 3 minutes, much less for flat plate systems. Generally do not need the corrections on the order of seconds needed in astronomical calculations.
  - Convert from degrees to radians

$$\deg \frac{\pi}{180} = \text{rad}$$

Solar Radiation

- Hourly calculations for solar radiation
  - Need to (1) convert from local time to solar time and (2) convert time-based inputs (time of day) into angles.
- Solar time and local time
  - The solar calculations use solar time, in which the sun is at its highest spot in the horizon at solar noon.
  - Two basic corrections for local time and solar time: (1) Time zones and (2) Equation of time.
- Time Zones
  - Time zones introduced to make coordination of activities easier.
  - There are 24 time zones, each 15º apart.
  - Each time zone had its own meridian (LSTM for local solar time meridian), and at the meridian the local time is also solar time (ignoring non-idealities).
  - The Prime Meridian is the meridian from which time and other astronomical features are defined, which is located in Greenwich, England.

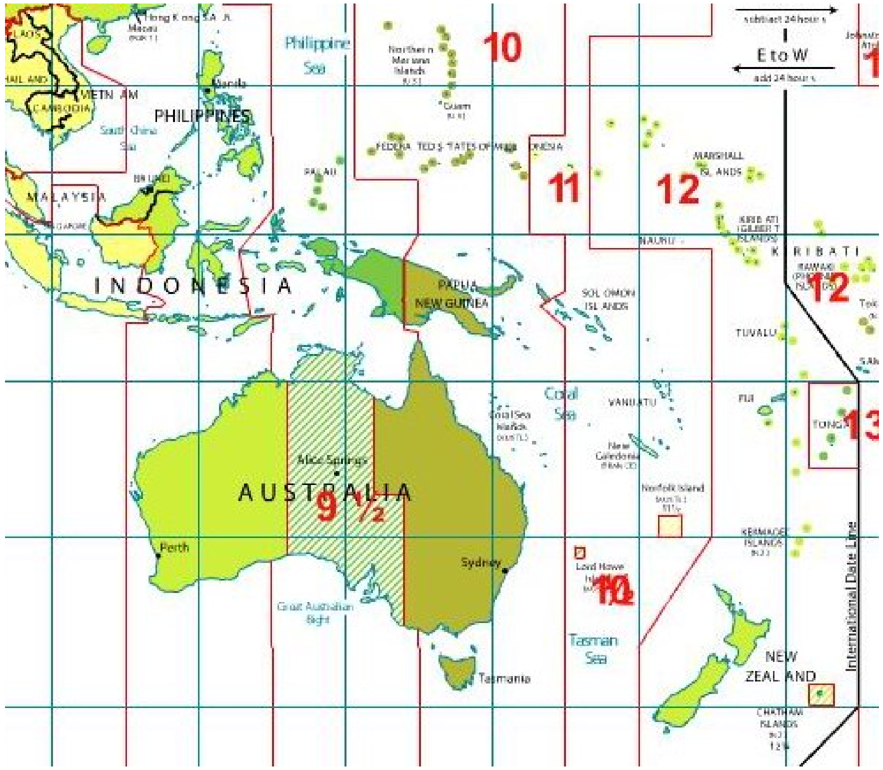
Solar Radiation

- Time Zones
  - Ideally, a time zone spans 7½º on either side of the meridian, but often substantially different due to political boundaries.

$$LSTM = 15^{\circ} \times \Delta T_{UTC}$$

  - Need to determine how many minutes need to be added/ subtracted to account for the difference between the LSTM and the longitude of a particular location.
  - The earth rotates 1º every 4 minutes, so time correction (TC) in minutes to account for location within a time zone is:

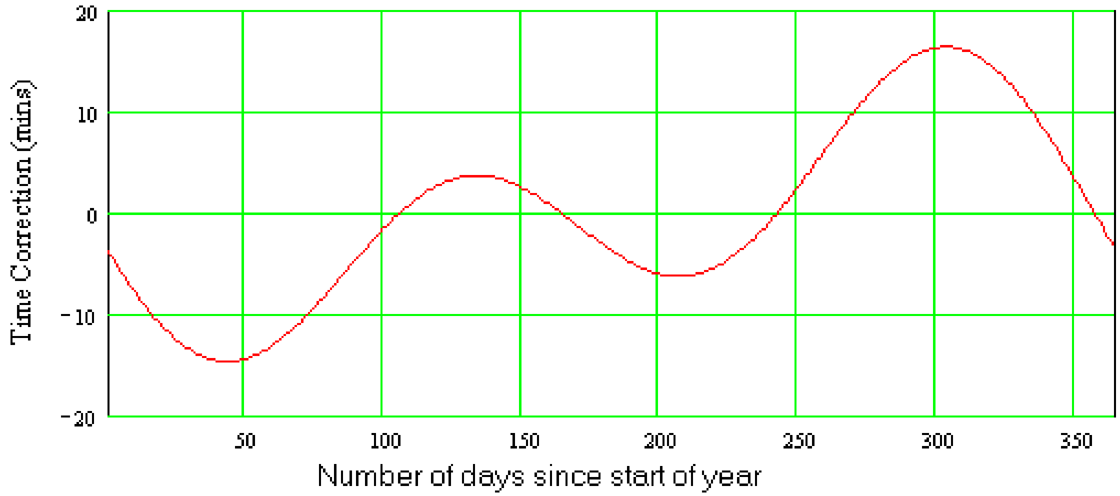
$$TC_1 = 4\left(LSTM - Longitude\right)$$



Blue = LSTM, red = time zone boundaries

Solar Radiation

- Equation of time
  - Accounts for variations in solar time due to variations in orbit of earth around the sun.



$$EoT = 9.87\sin 2\Omega - 7.53\cos\Omega - 1.5\sin\Omega$$

$$\Omega = \frac{360}{365}\left(NDY - 81 + \frac{hour - 12}{24}\right)$$

Solar Radiation

- Total time correction
  - Total time correction is the sum of the Equation of Time and the time correction for longitude.

$$\text{Local Solar Time} = \text{Local Time(minutes)} + \text{TC}_1 + EOT$$

- Hour Angle
  - Final part of the time part of the solar radiation calculations is to convert the solar time to an angle
  - One day has 24 hours, and the earth rotes 360º in this time, so the earth rotates 15º every hour.
  - The hour angle is 0 at solar noon, negative in the morning, positive in the afternoon.

$$HRA = 15^\circ (LST - 12)$$

Solar Radiation

- Equations and models for declination:
  - If the Earth's orbit is assumed circular, then:

$$\delta \approx \varepsilon \sin \Omega$$

Holds for small values of ε, ε = 23.45º

$$\Omega = \frac{2\pi}{365}\left(NDY - 81\right)$$

NDY is number of the day of the year, and "81" is the day of the year when the equinox occurs (which is defined from UTC, where it occurs on day "80")

  - Earth's orbit around the sun is elliptical, not circular.
  - The earth processes, and therefore the tilt of the Earth is not constant.
  - Parallax error: the angle are determined from the center of the earth, not its surface.
  - Other smaller errors:
    - The sun appears to be in a different position in the sky due to refraction of light in the atmosphere – only significant at higher latitudes.
    - Difficulties in defining the position of the sun in the sky due to the size of the sun's disc (which is 0.27 º).

Solar Radiation

- More complicated model of declination:
  - Including some of these factors (elliptical orbit, procession) gives:

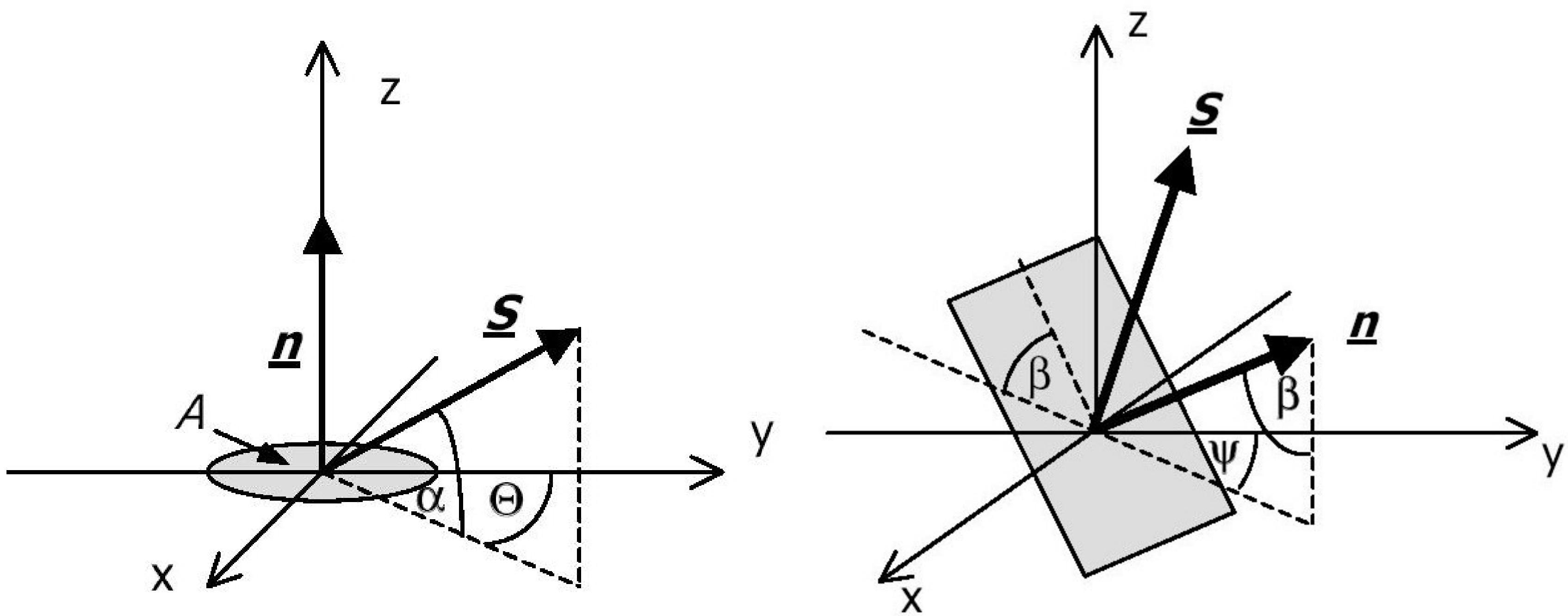
$$\delta = 0.006918 - 0.399912\cos\Omega + 0.070257\sin\Omega$$
$$- 0.0006758\cos 2\Omega + 0.000907\sin 2\Omega$$
$$- 0.002697\cos 3\Omega + 0.00148\sin 3\Omega$$

  - Where (in radians)

$$\Omega = \frac{2\pi}{365}\left(NDY - 1 + \frac{hour - 12}{24} \right)$$

Solar Radiation

- Normal component of solar radiation on an tilted surface, tilted both north-south (variation in azimuth) and elevation of surface.



From A. Sproul, ANZES Conference, 2002

$$S_{\text{module}} = S_{\text{incident}}\left[\cos\alpha \sin\beta \cos(\psi - \Theta) + \sin\alpha \cos\beta\right]$$

Solar Radiation

- Solar Radiation and location dependent parameters
  - General parameters
    - Ambient temperature
    - Average wind speed
    - Presence of a microclimate
  - Solar Radiation:
    - Full description of solar radiation involves measurements of direct and diffuse radiation several times an hour for a statistically significant time period (usually at least 10 years).
    - This level of data is expensive to obtain, or exists only for limited locations, and due to its volume also inherently requires a computer program to analyze and use.
    - Full data sets used for statistical processing of data – used in worst-month type calculations to determine relationship between availability and battery size.
    - Reduced data sets include monthly averages and TMY

Solar Radiation

- Typical Metrological Year (TMY)
  - TMY data maintains the variability in the solar resource, while reducing multiple year's worth of data to a single year.
  - TMY solar radiation data determined by averaging the solar radiation for each month of the year over multiple years.
  - The monthly data averaged over the entire data set is compared to the average solar radiation for that month from every year. The month in a particular year with the average closest to the average over the entire data set becomes the data used for that month.
  - TMY data consists of global and direct (and in some sets diffuse) radiation measurements every hour of the day. The angle at which the global and direct radiation measurements are taken must be verified in the specification of data, as there is more than a single TMY standard (TMY2 also exists).
  - Global generally measured on a horizontal surface.

Solar Radiation

- Typical Metrological Year (TMY)
  - TMY data generally needs to be processed by computer to extract information.
  - Sample from TMY2 data:

```
24229 PORTLAND            OR  -8 N 45 36 W 122 36    12
 7201010100000000000?00000?00000?00000?00000?00000?00000?010A710A70050A70039A7093A71031A7000B8000A70016A700213A70999999009011F8068F8000A703E7
 7201010200000000000?00000?00000?00000?00000?00000?00000?010B810B80048B80038E7093B81032B8190B8005B89999?099999?00999999999011F8068F8000A703E7
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```

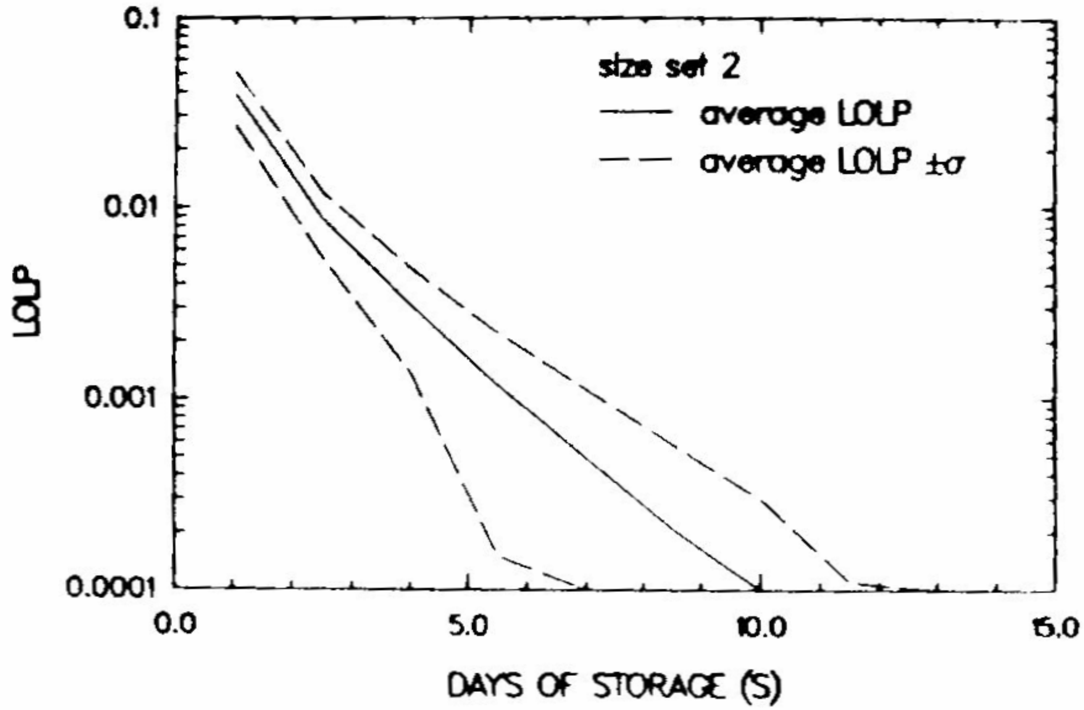
  - Each file contains 8670 lines of data.
  - Instructions for use of data are included in the description of most formats.
  - TMY data also includes more information than solar radiation, including temperature, wind speed and direction, cloud conditions, and other atmospheric conditions

Solar Radiation

- Statistical analysis of radiation provides an indication of the amount of storage needed.
- Common statistical analysis s to analyze the probability of having a given number of “cloudy” or less that 50% radiation days in a row.
  - Example: probability of having 5 cloudy days in a row is 3%: This means that if the battery is sized for 5 days, then the availability should be 97%.
  - This is an approximation:
    - Assumes that array will recharge battery to a full level before another cloudy period comes (tends to underestimate battery size needed).
    - Ignores the power available to the array during the cloudy days (tends to underestimate the power available).
  - Some monthly-average climate data also includes probability of a given number of < 50% days in a row

Solar Radiation

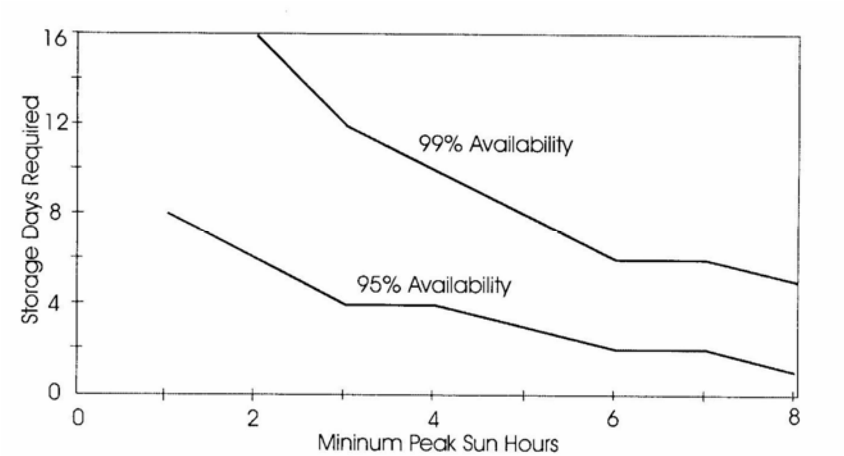
- Statistical analysis of solar radiation allows analysis of system performance as a function of availability.



  – Shows how for a given array size, the availability and its standard deviation varies with storage.

Solar Radiation

- Statistical approach can work for a range of locations, as appearance of cloudy says in not random, but is correlated with deviation from average expected for that latitude.
- Means that many locations will behave relatively similarly on a statistical analysis.



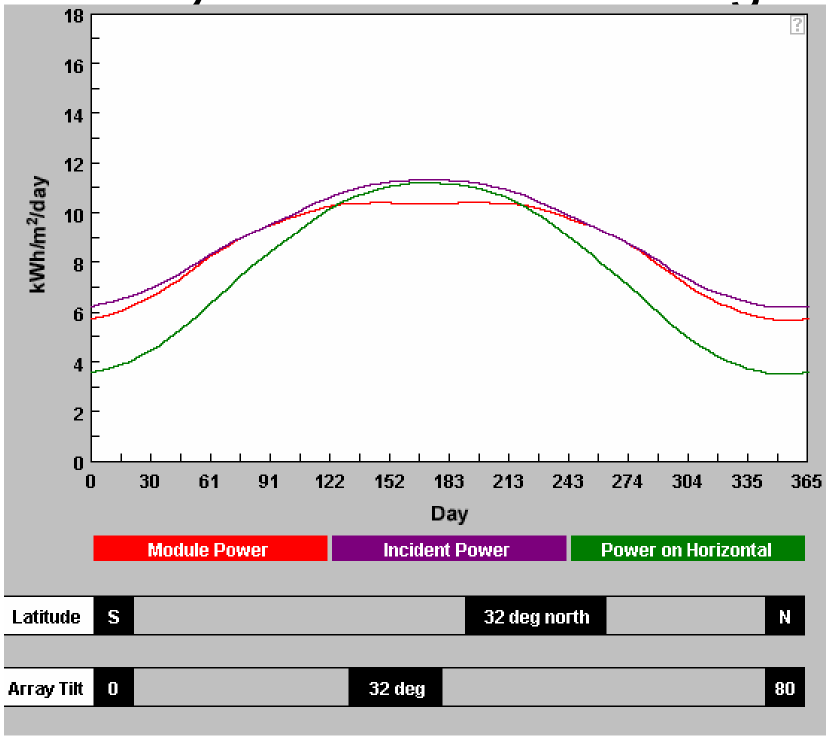
- Locations with distinct weather patterns (ie weather patterns which consistently have cloud cover probabilities not well correlated to their averages) cannot use generalized graphs, but need to be calculated based on their location.
  – Example: Monsoon climates with high averages and high distinct rainfall patterns.

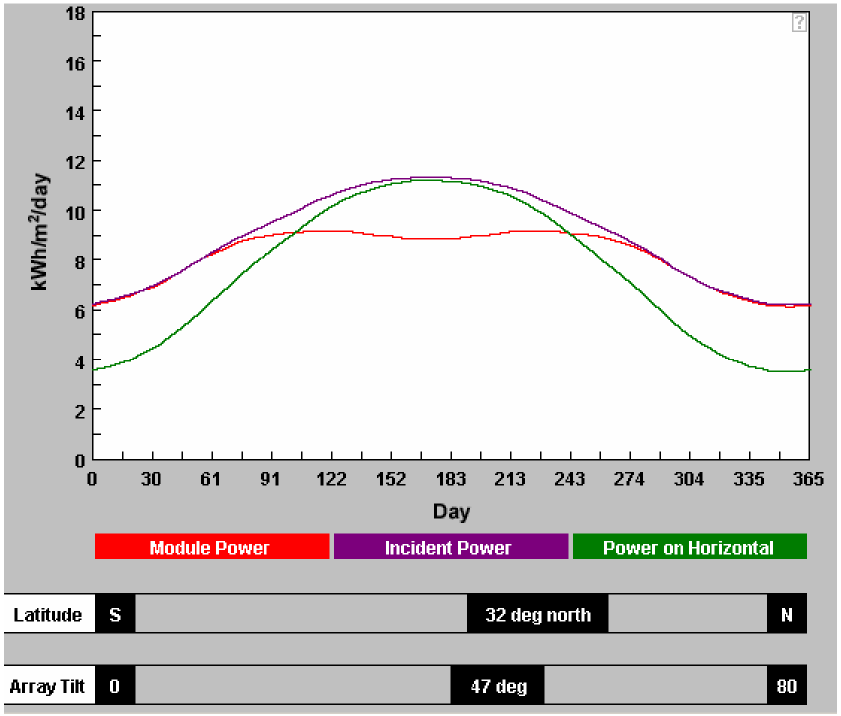
Solar Resource

- Previously, calculated average insolation at the Earth's surface as ~240 W/m^2.
- Several features change the spectrum, power density and duration (and therefore net energy) at a given location.
  - Atmospheric effects:
    - Scattering
    - Absorption
  - Rotation of the Earth about the sun
    - Daily and seasonal variations change power density
    - Seasonal variations change duration
  - Local weather conditions
    - Cloud cover
  - Microclimates
    - Small scale, local changes in insolation or weather patterns.

Power on a tilted surface.

- The tilt of a surface will determine the power from that surface throughout the year.
- Array angle = latitude gives maximum overall power in ideal location
- Array = latitude + 15 deg often used as optimized summer



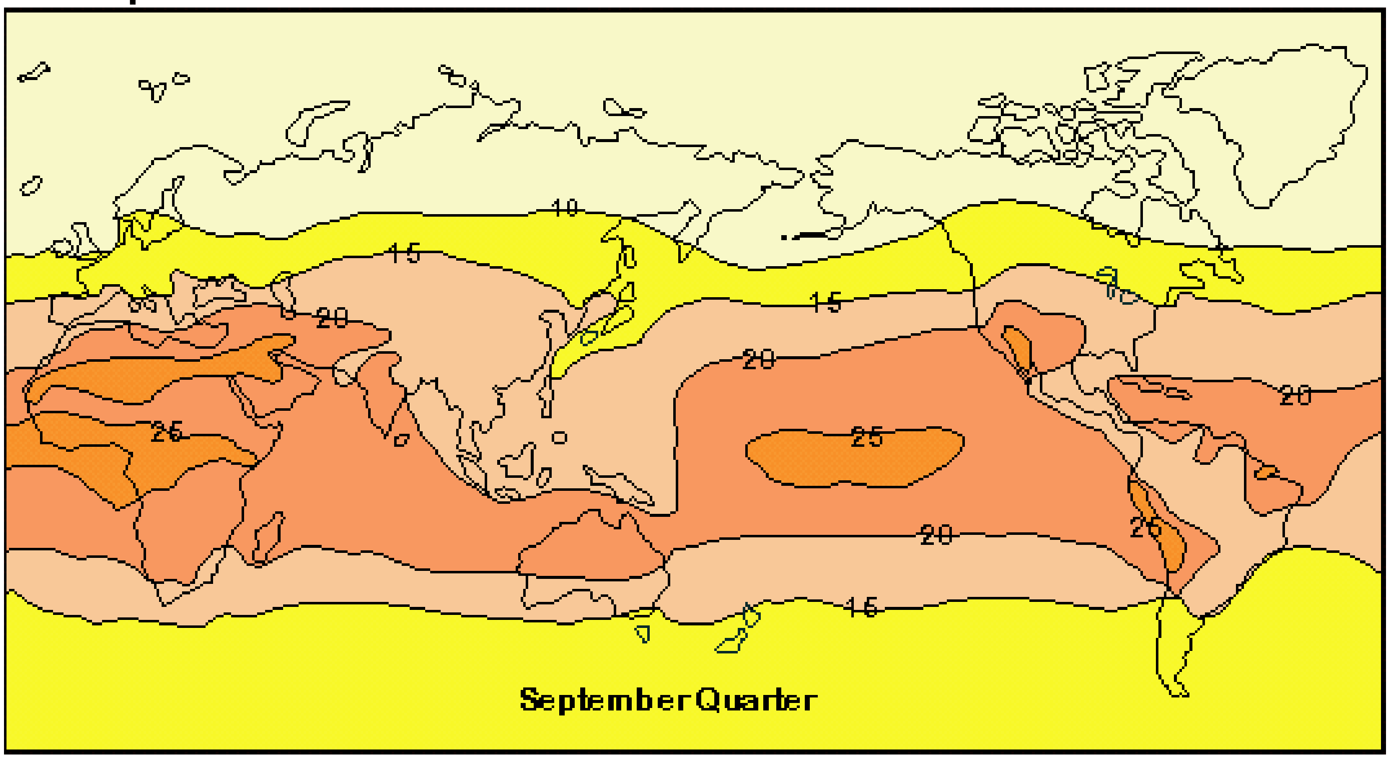


Measured solar radiation

- Actual solar radiation varies from ideal due to effects of local weather.
- Goal is to determine: (1) Total expected power during year; (2) Variation throughout the year.
- Typical Metrological Year (TMY) data
  - Measures radiation (and several other parameters such as temperature) at hour intervals for multiple years.
  - Calculates average for each month, and then picks the month with the average value closest to the average.
  - Keeps realistic day-to-day variation of solar radiation.
  - Used for simulation of systems.
  - Requires long measurement history.

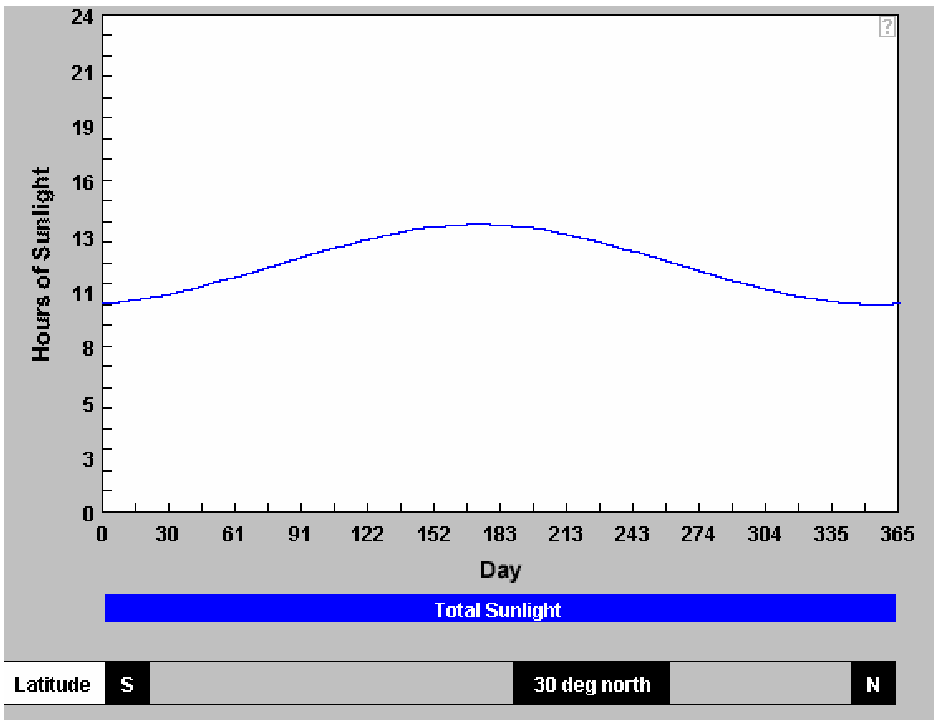
Measured solar radiation

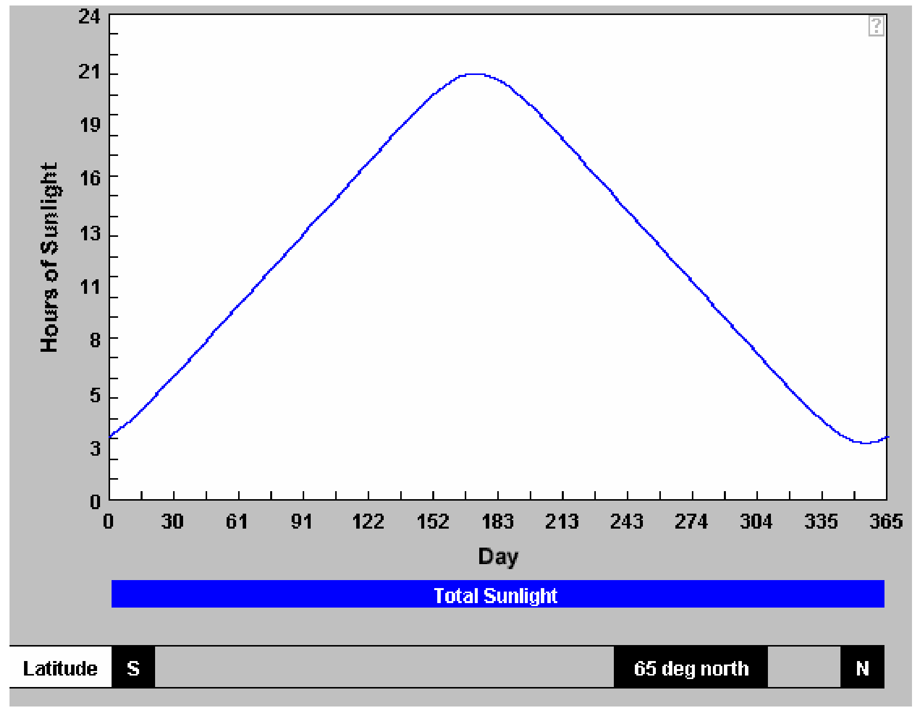
- Average solar radiation per month:
  - Gives average power density per day in a particular month for a particular angle (usually either horizontal or tile=latitude).
- Contour plots for solar radiation



Variation in solar radiation

- Variation due to (1) Variations in length of day and transmission through atmosphere and (2) Variation in local climate (ie cloud cover).
- Equatorial regions have more uniform solar radiation
- Cloud cover can be measured by probability of # sunny days in a row





Examples:

- Wavelength of light with wavelength 1000 nm?

- 1 x 10^{17} photons/s on 1 cm^2. Energy of photons is 2 eV. What is power density?