The Florida Advanced Technological Education (FLATE) Center wishes to make available, for educational and non-commercial purposes only, materials relevant to the "EST1830 Introduction to Alternative/Renewable Energy" course comprised of images, texts, facilitator's notes, and other demonstration materials.

This instructional resource forms part of FLATE's outreach efforts to facilitate a connection between students and teachers throughout the State of Florida. We trust that these activities and materials will add value to your teaching and/or presentations.

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Introduction to Alternative and Renewable Energy

EST1830

3. Energy Production

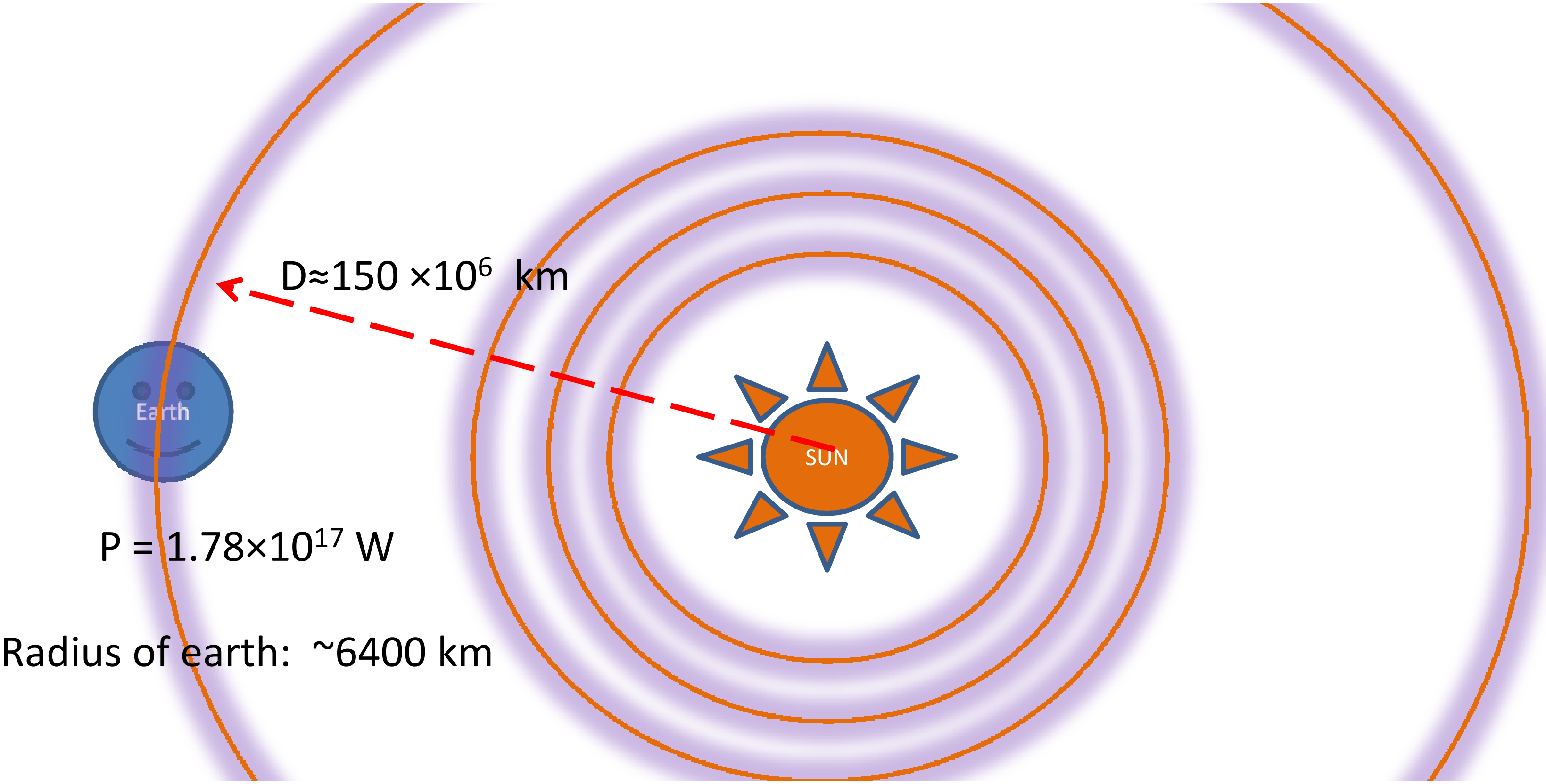
3.1 Renewable Energy Technologies

3.1.1 Solar Energy

3. Energy Production

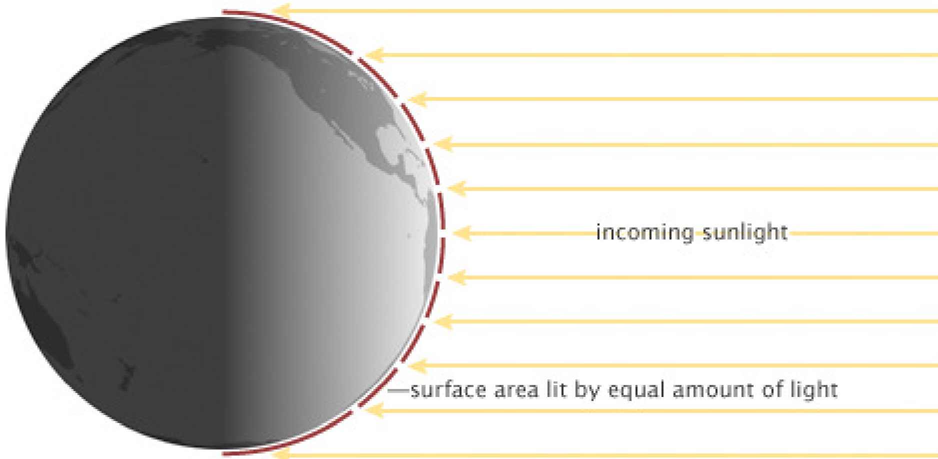
- 3.1.1 Solar Energy
  - 3.1.1a Sun's Position
  - 3.1.1b Sun Path
  - 3.1.1c Irradiation
  - 3.1.1d Air Mass
  - 3.1.1e Irradiance on Plate
- 3.1.1.1 Photovoltaics
- 3.1.1.2 Solar Thermal
  - 3.1.1.2a Low Temperature Collectors
  - 3.1.1.2b Medium Temperature Collectors
  - 3.1.1.2c High Temperature Collectors

3.1.1 Solar Irradiance



From section 2.14, we found that the earth receives about $P = 1.78\times10^{17}$ W at the outer atmosphere. If we further assume that the earth reflects 30% of incident solar radiation (insolation), then 70% of power is $P=1.25\times10^{17}$ W at the upper atmosphere.

3.1.1 Solar Irradiance



http://earthobservatory.nasa.gov/Features/EnergyBalance/page2.php

On the daylight side, only the point directly under the Sun receives full-intensity solar radiation. From the equator to the poles, the Sun' rays meet Earth at smaller and smaller angles, and the light gets spread over larger and larger surface areas (red lines). (NASA illustration by Robert Simmon.)

(1) The total solar irradiance (P) is the maximum possible power that the Sun can deliver to Earth's average distance from the Sun. But as the earth rotates this power is distributed across the entire surface area ($4 \cdot \pi \cdot R_E^2$). Only half the Earth is ever lit by the Sun at one time, which **halves** the total solar irradiance.

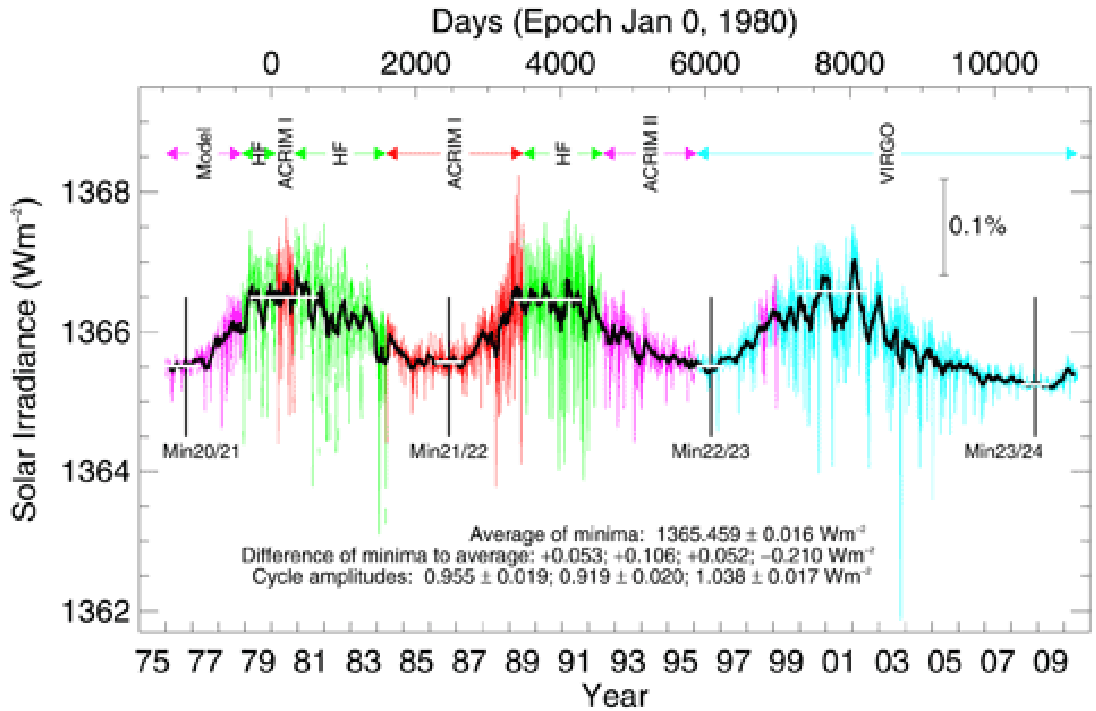
(2) Total solar irradiance is the maximum power the Sun can deliver to a surface that is perpendicular to the path of incoming light. Because the Earth is approximated as a sphere, only areas near the equator at midday come close to being perpendicular to the path of incoming light. Everywhere else, the light comes in at an angle. The progressive decrease in the angle of solar illumination with increasing latitude reduces the average solar irradiance by an **additional one-half.**

So, **$P = 3.13 \times 10^{16}$ W** shining on the earth

3.1.1 Solar Irradiance

- $P=3.13 \times 10^{16}$ W is equal to 31300 TW of average solar power hitting the earth's surface over a year.
  - This is about 2.74×10^{17} kW-h per year
- Remember
  - US consumes ~ 3.5 TW of energy per year
  - World ~ 15 TW each year
  - But, energy consumption is more than just electricity

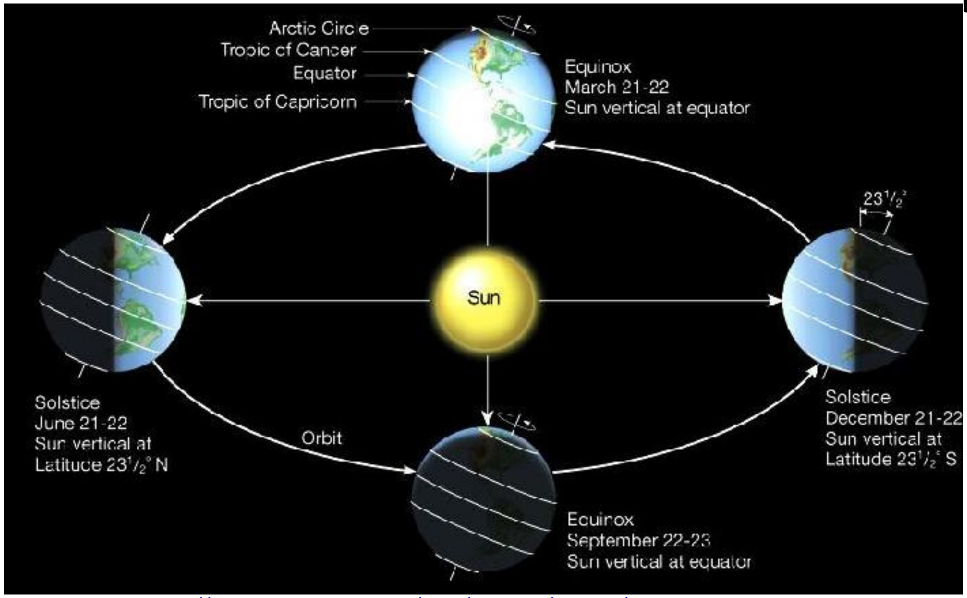
3.1.1 Solar Irradiance Cycle



Sun has an 11-year cycle driven by dark sunspots and bright faculae.

Current Solar Constant: **1366 W/m²**

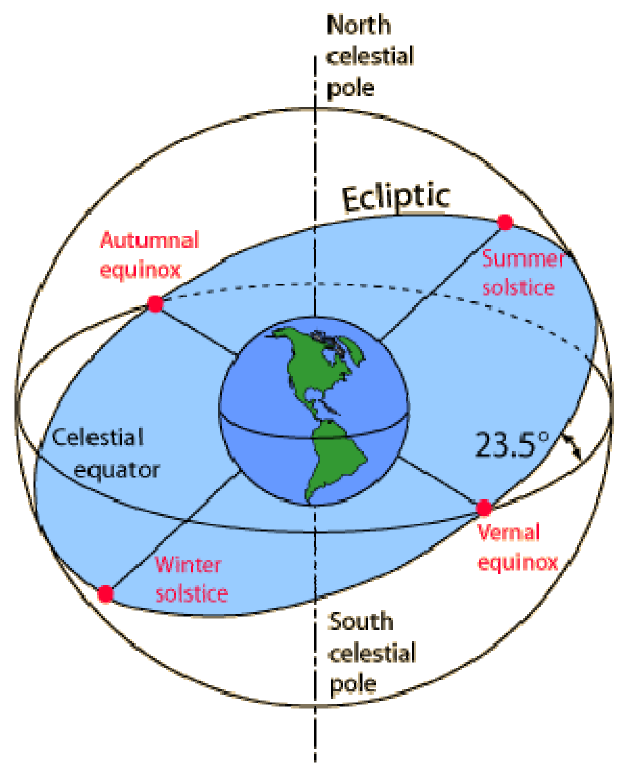
3.1.1a Ecliptic



http://www.astro.virginia.edu/class/oconnell/astr121/guide04.html

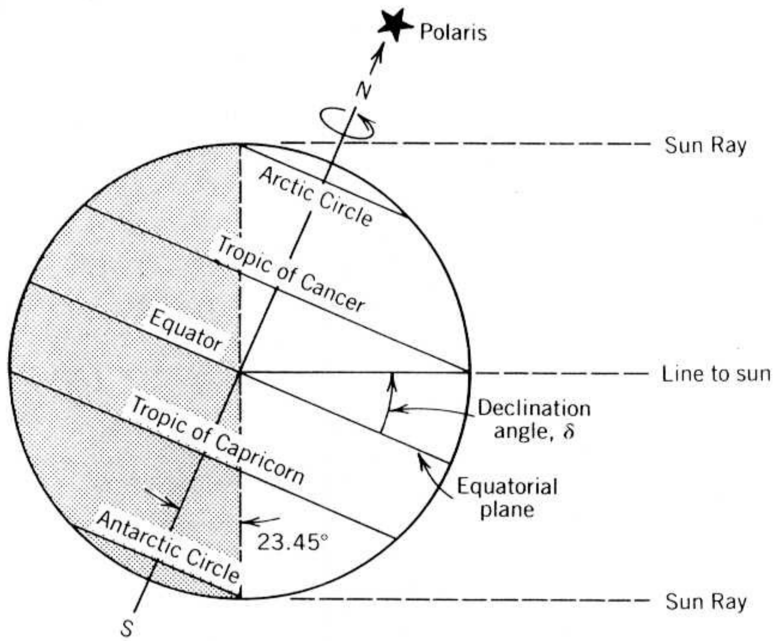
Earth's Orbit around sun

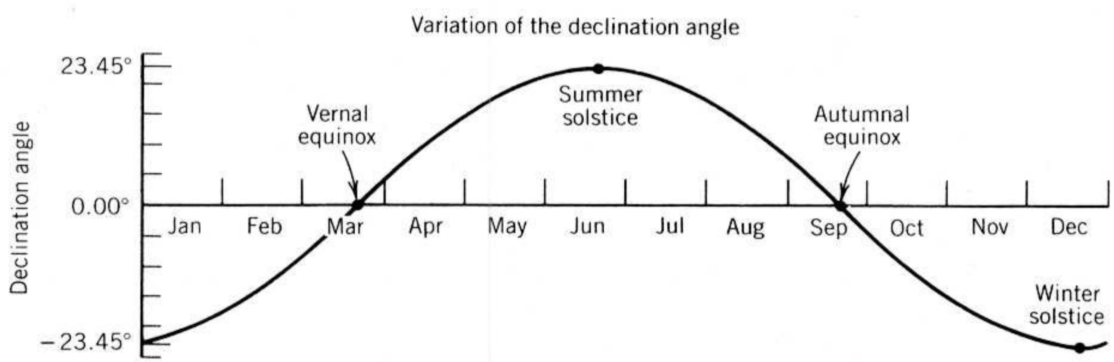
- From Earth's perspective, sun appears to revolve around the earth. Ancient geocentric view.
- Ecliptic
  - The apparent path of the Sun's motion on the celestial sphere as seen from Earth is called the ecliptic.
  - The ecliptic plane is tilted 23.5° with respect to the plane of the celestial equator since the Earth's spin axis is tilted 23.5° with respect to its orbit around the sun.



http://hyperphysics.phy-astr.gsu.edu/hbase/eclip.html

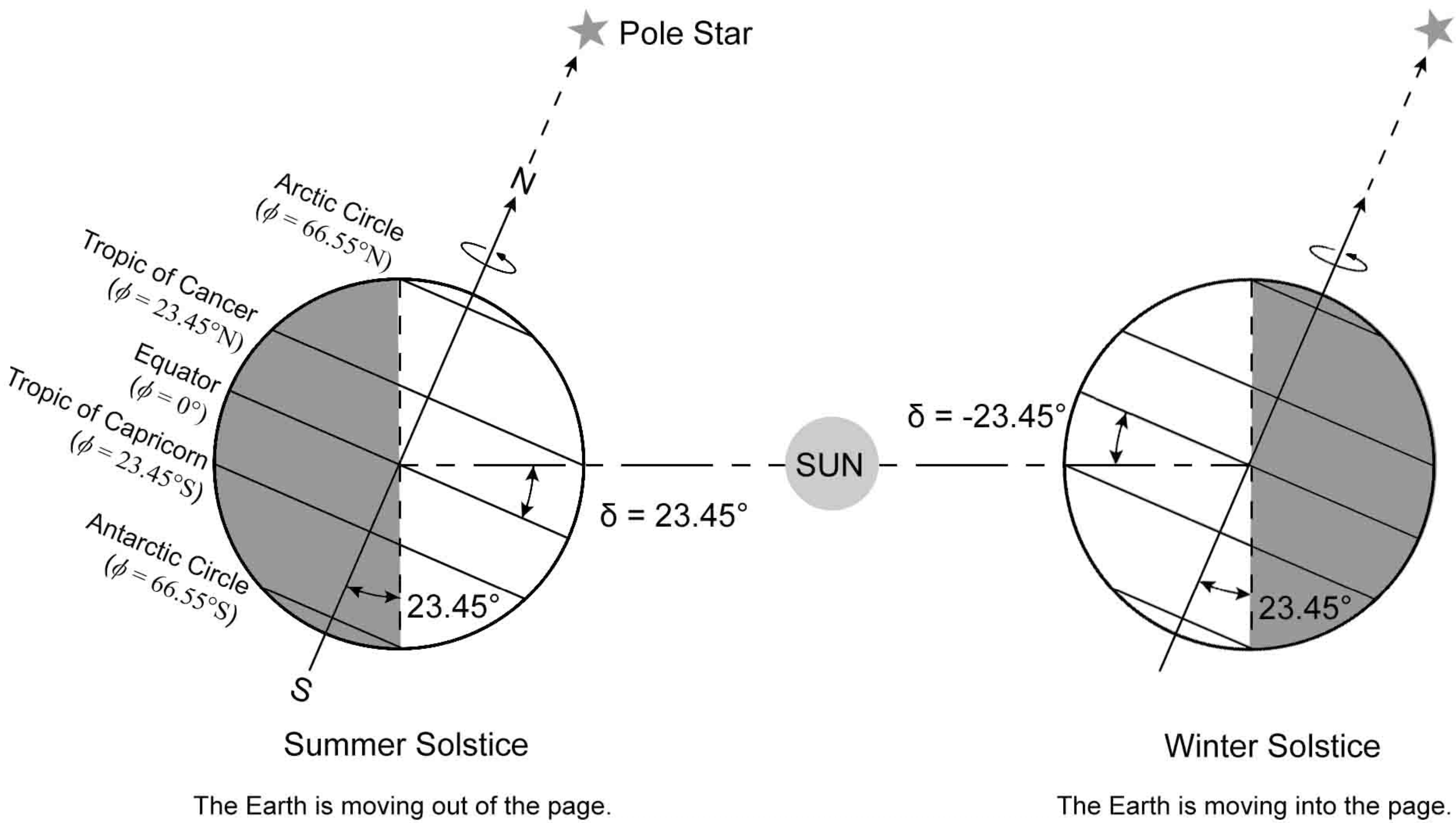
3.1.1a Seasonal Declination Change



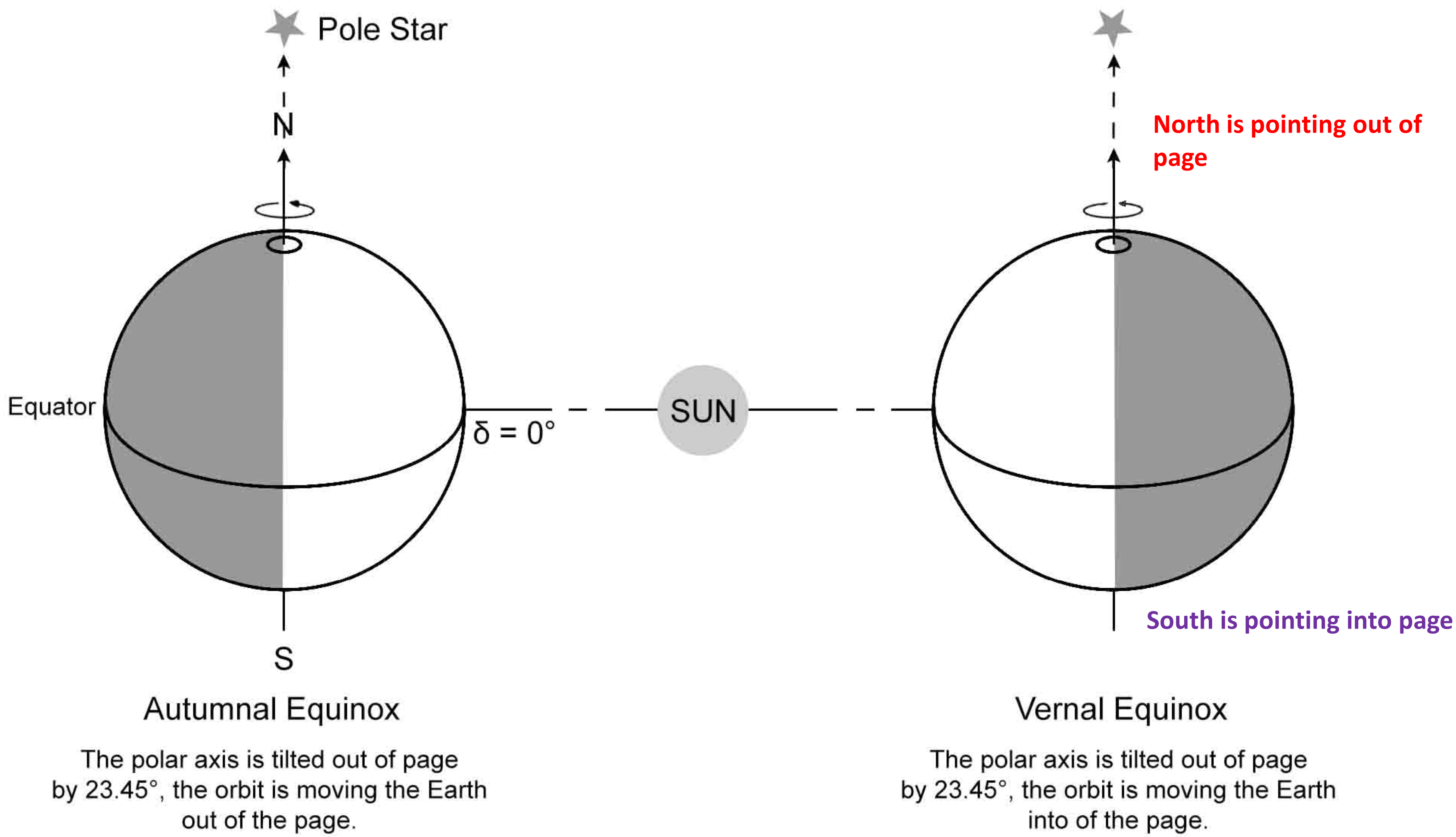


http://www.powerfromthesun.net/chapter3/Chapter3Word.htm

3.1.1a Earth's Orbit

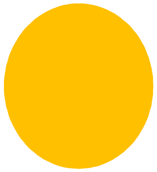


3.1.1a Earth's Orbit



http://www.itacanet.org/eng/elec/solar/source.htm

3.1.1a Vernal Equinox at Chichen Itza



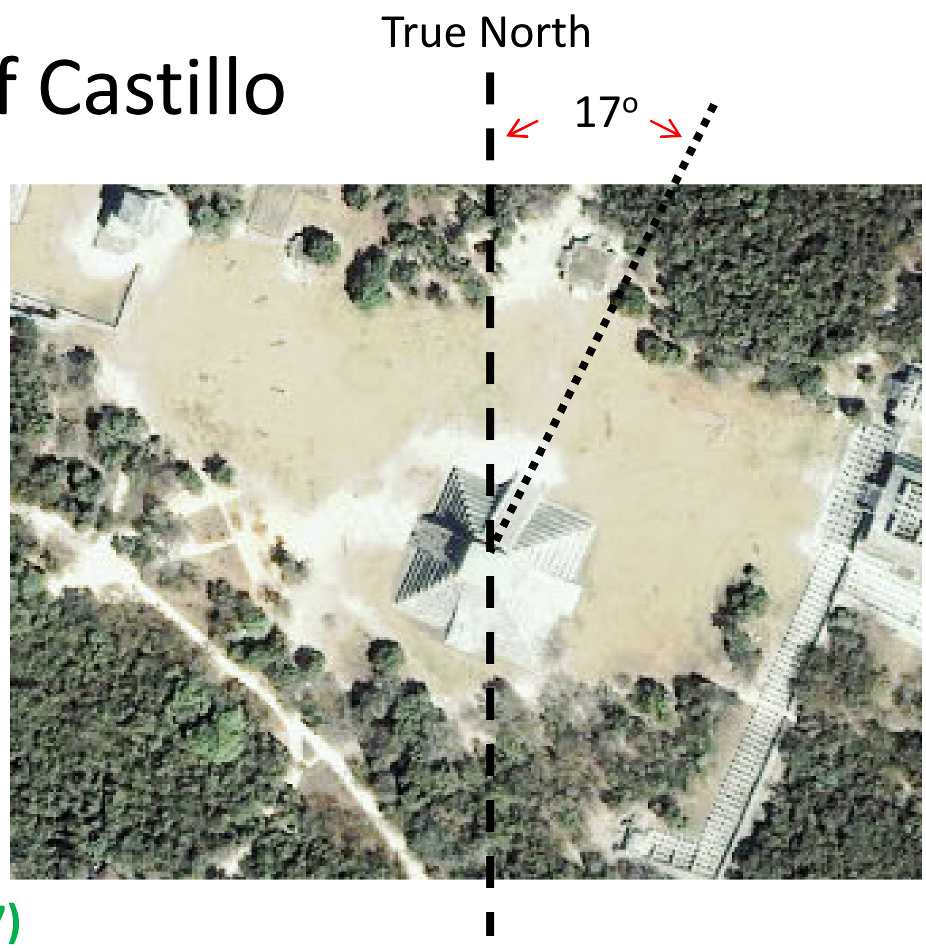
Location:
20º 40´ 01 N (20.6667)
88º 34´09 W (-88.6)

- Vernal Equinox: March 21
- Between 3:30-5:50pm local time
- Built around 800AD
- **Structure oriented about 17 degrees east of true north to get the effect.**

http://www.world-mysteries.com/chichen_kukulcan.htm

3.1.1a Vernal Equinox at Chichen Itza

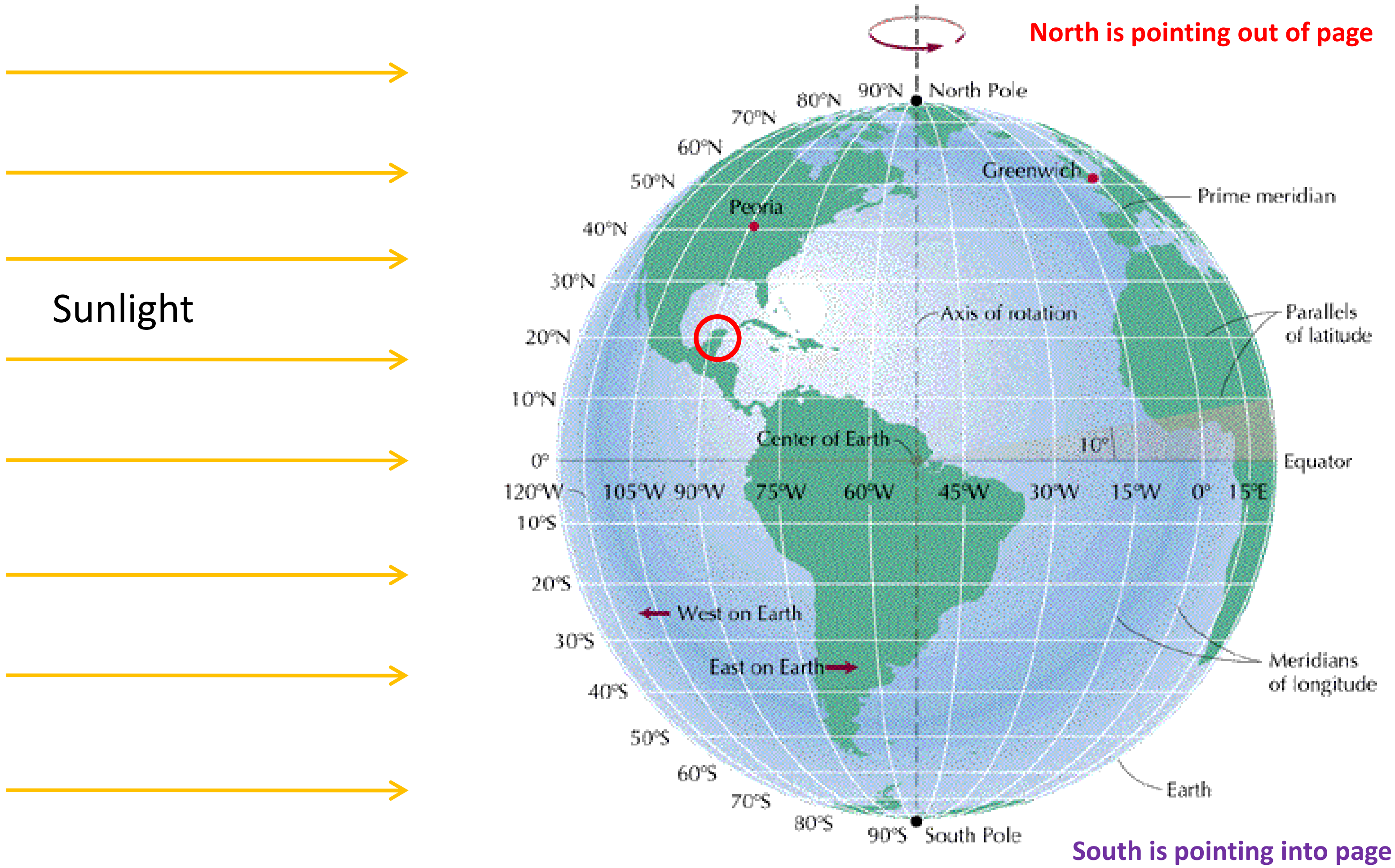
Top View of Castillo



Location:
20º 40´ 01 N (20.6667)
88º 34´09 W (-88.6)

http://www.satimagingcorp.com/galleryimages/IK_Chichen_Itza_Mexico_05-MAR-2001_copyrighted.jpg

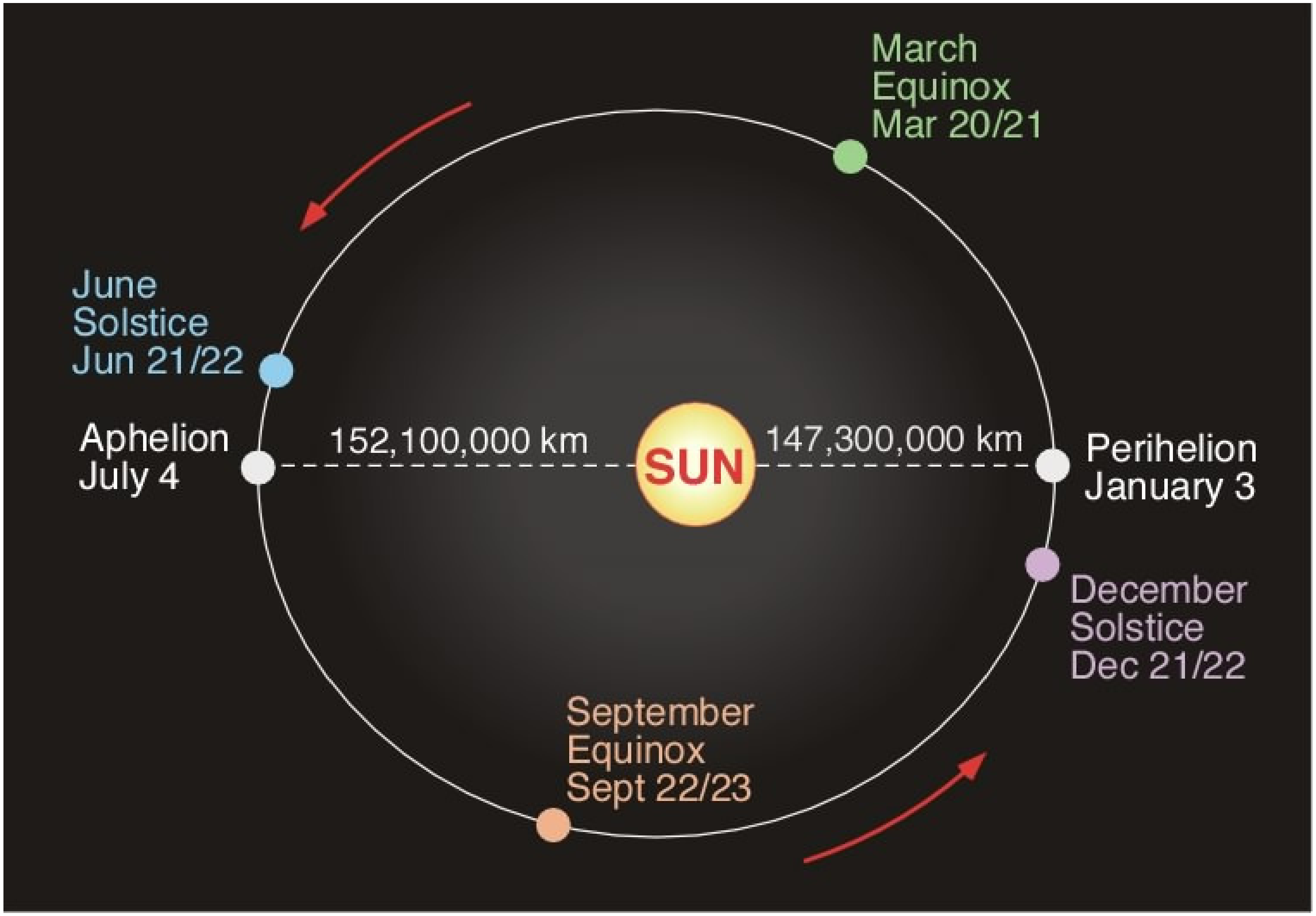
3.1.1a Vernal Equinox at Chichen Itza



Earth position relative to the sun at Vernal Equinox: March 21

http://www.montgomerycollege.edu/Departments/planet/M_AS102/coordinates/LatitudeLongitudeEarth.html

3.1.1a Elliptical Orbit



http://www.physicalgeography.net/fundamentals/6h.html

3.1.1a Solar Irradiance

- Solar Irradiance (Incident Solar Radiation→ Insolation)
- Solar Constant: **1366 W/m^2**
  - Measured in terms of Power per unit area
  - "Constant" is really a yearly average.
  - Because, earth's orbit around sun is elliptical
    - Aphelion (point in orbit when earth is the farthest away from sun): 152×10^6 km around July 4.
    - Perihelion (point in orbit when earth is closest to the sun): 147×10^6 km around January 3.
    - So earth is closest to sun during Florida winter, but farthest away from sun during the summer.
    - Does not take into account sun's 11-year cycle.
- The intensity of solar radiation falling on earth changes according to season

3.1.1a Orbit Ellipticity of Planets

Solar Irradiance at the Planets			
Planet	Solar Irradiance, W*m^{-2}		
	Mean	Perihelion	Aphelion
Mercury	9116.4	14447.5	6271.1
Venus	2611.0	2646.4	2575.7
Earth	**1366.1**	1412.5	1321.7
Mars	588.6	715.9	491.7
Jupiter	50.5	55.7	45.9
Saturn	15.04	16.76	13.53
Uranus	3.72	4.11	3.37
Neptune	1.510	1.515	1.507
134340Pluto*	0.878	1.571	0.560

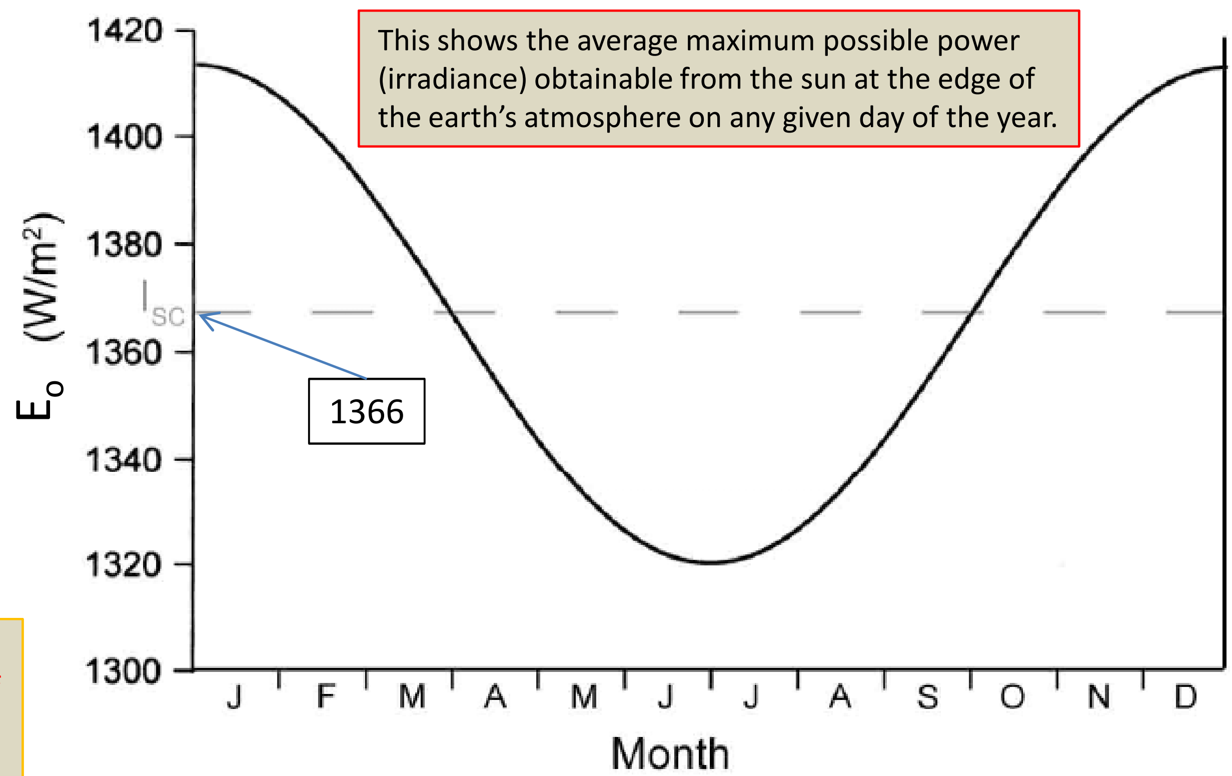
*Dwarf Planet

http://rredc.nrel.gov/solar/spectra/am0/ASTM2000.html

3.1.1a Solar Irradiance

Solar Irradiance can be estimated for each day of the year using this empirical relation. n=day of the year: Jan 1=1; Jan 2=2….Dec 31=365….and I_{sc} is the solar constant.

$$E_o = SC\left[1 + 0.034\cos\left(2\pi \frac{n-3}{365.25}\right)\right]$$

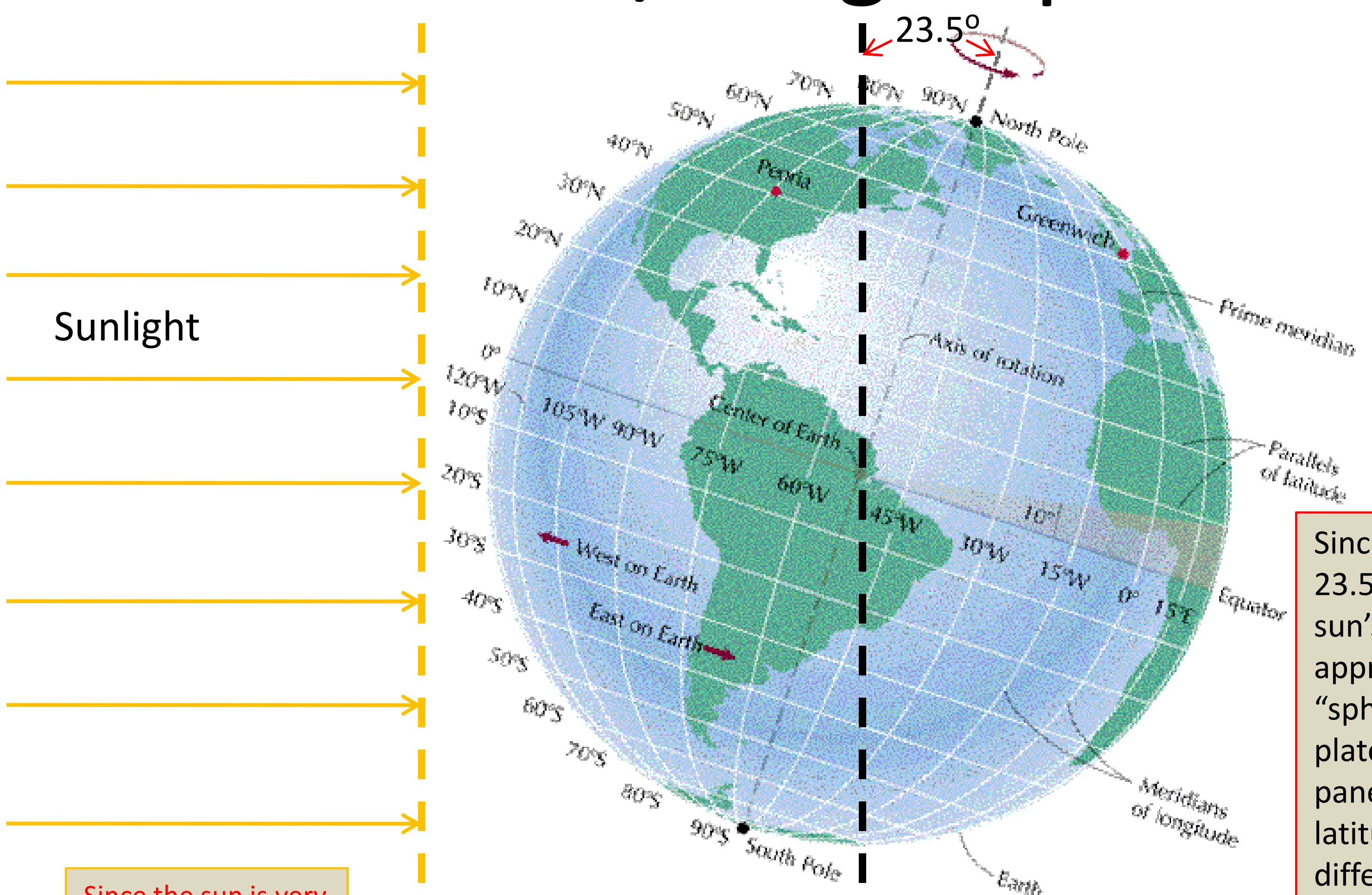


The solar irradiance (E_o) at any given day of the year is the average for the entire earth on that given day.

3.1.1a Irradiation

- BUT…we are not as interested in the overall solar irradiance when putting up a fixed plate solar panel….we are more interested in **irradiation** on a fixed plate. (more about this later)
- A general analysis concludes that the energy available from sunlight on any fixed plate solar panel on earth depends on
  - ☑ Time of year: Summer, Fall, Winter, Spring
  - ☑ Location: Latitude/Longitude
  - ☑ Time of Day

3.1.1b Lat/Long Dependence



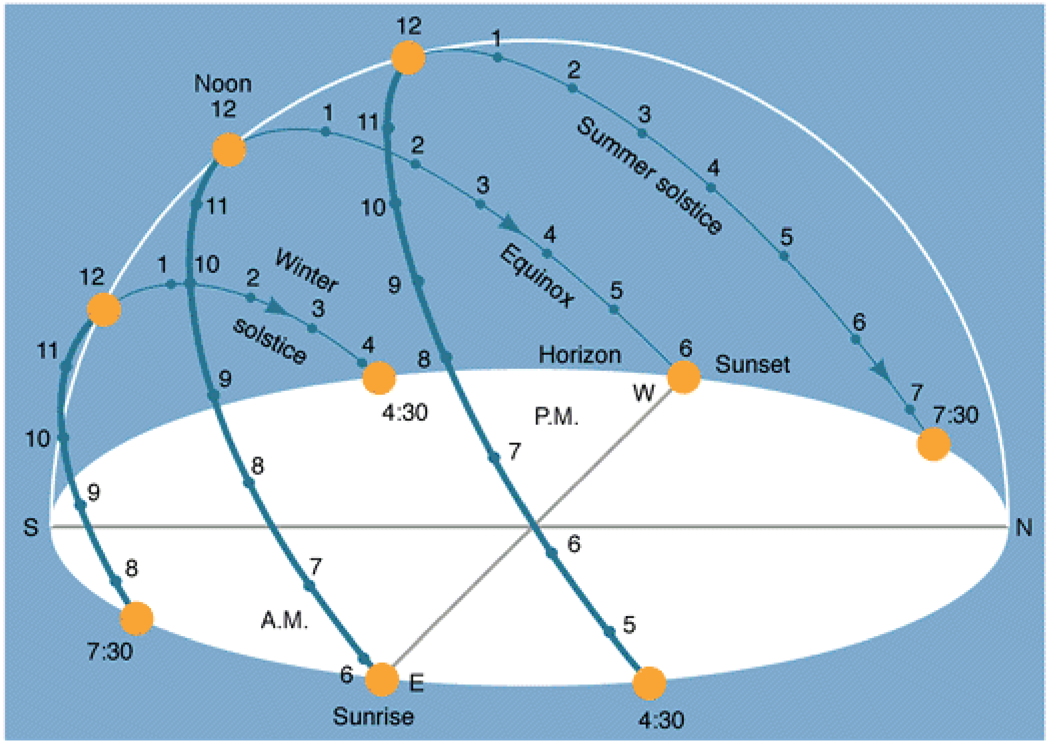
Since the earth is tilted 23.5° with respect to the sun's rays and is approximated as "spherical", fixed flat plates (such as solar panels) at different latitudes must be tilted at different angles to keep them perpendicular to the sun's rays at noon time.

Since the sun is very far away, we can assume that sun rays reaching earth are nearly parallel.

http://www.montgomerycollege.edu/Departments/planet/M_AS102/coordinates/LatitudeLongitudeEarth.html

3.1.1b Sun Path

Sun Path during winter solstice, equinox, and summer solstice

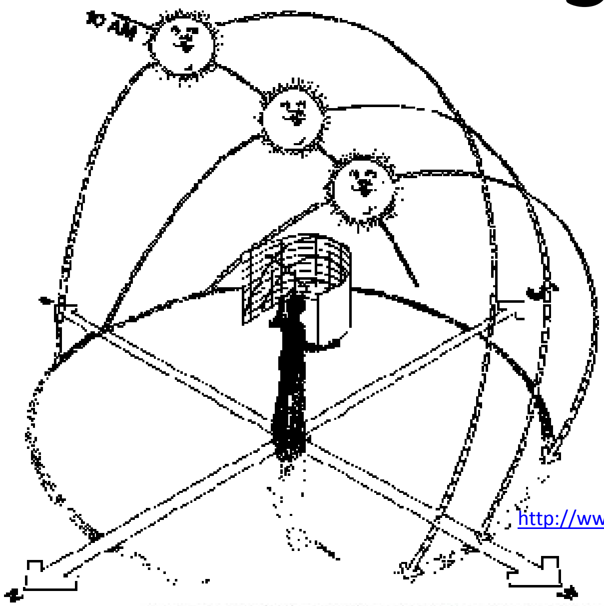


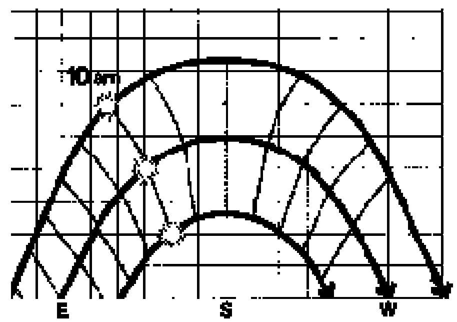
(1) From the earth's perspective we will see the sun tracing a path from east to west according to the time of **day**.

(2) We will also see a variation in the sun's angular position relative to the earth's horizon depending on time of **year**.

- A geocentric viewpoint helps us to locate our fixed solar panels and tilt them to the best angle possible so that the sun's rays hit them at a perpendicular angle (90°).
- For fixed panels, the maximum energy output can be achieved when their surfaces are perpendicular to the sun at solar noon.
- Solar noon is the point in time when the sun is at its daily zenith (may or may not be 12 o'clock).

3.1.1b Sun Path





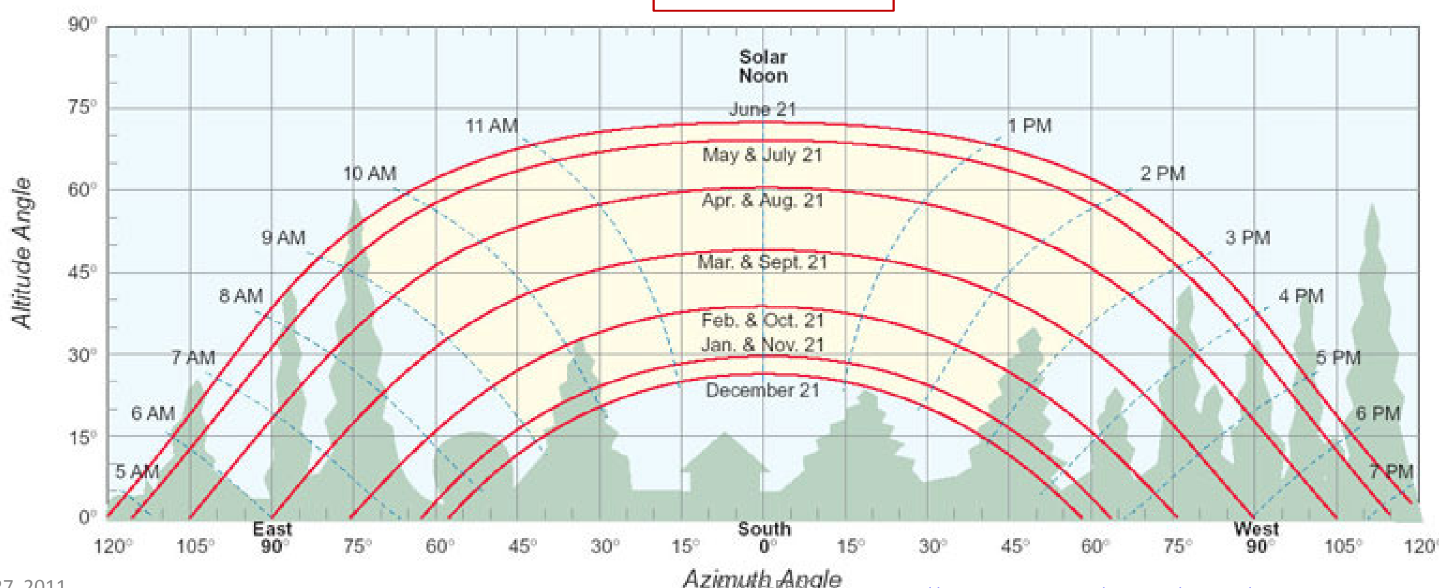
http://www.usc.edu/dept/architecture/mbs/tools/vrsolar/Help/solar_concepts.html

(1) From the earth's perspective we will see the sun tracing a path from east to west according to the time of **day**. The sun's position is located by the Azimuth Angle (A_z) relative to true North.

(2) We will also see a variation in the sun's angular position relative to the earth's **horizon** depending on time of **year**. That angular position is called the Altitude Angle (α).

Peoria, IL

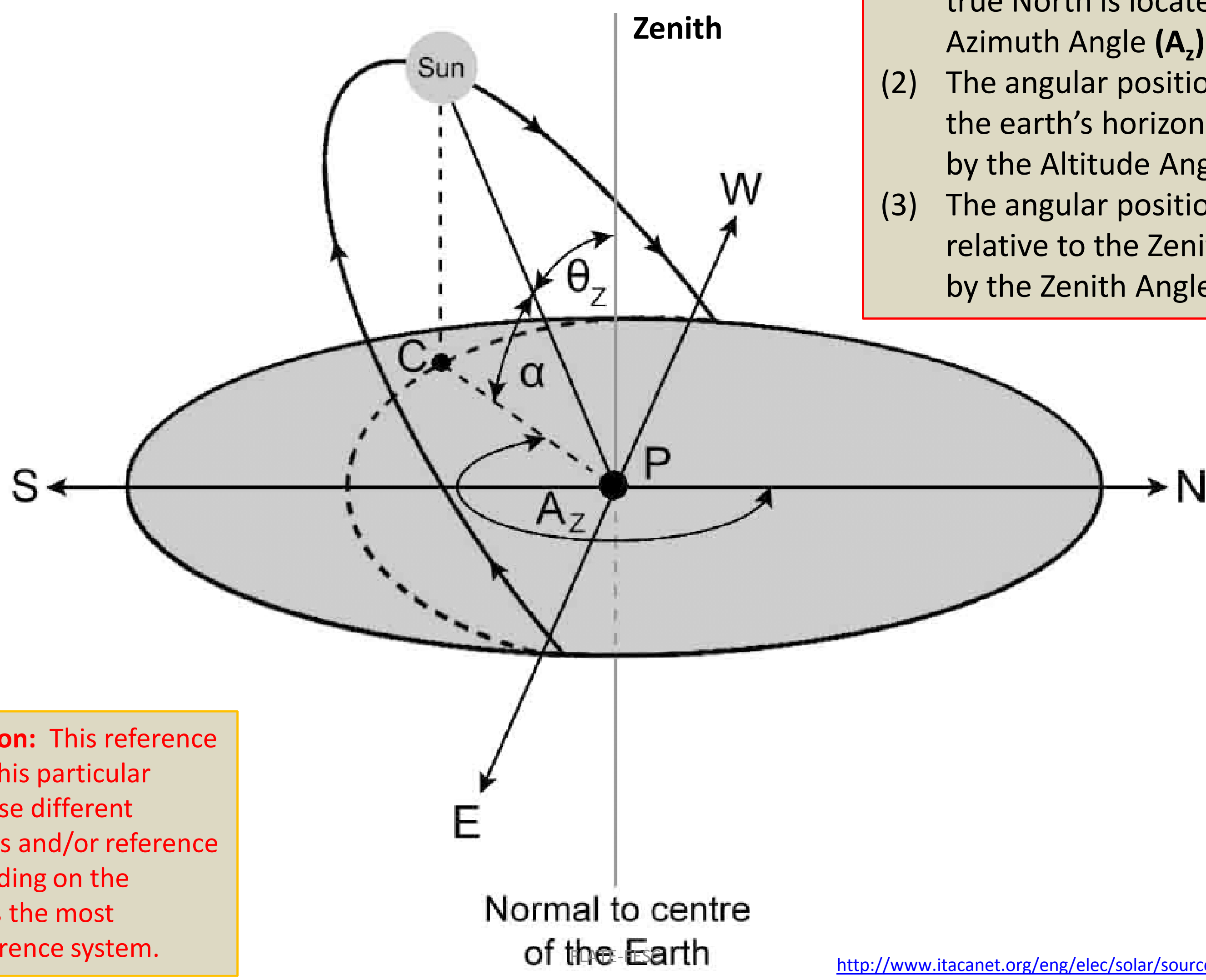
Sun Path Chart for 40° North Latitude



To use this chart for southern latitudes, reverse horizontal axis (east/west & AM/PM)

http://www.oksolar.com/abctech/images/solar_path_large.jpg

3.1.1b Sun Path

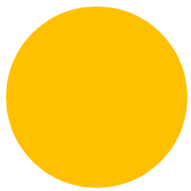


(1) The sun's position relative to true North is located by the Azimuth Angle **(A_z)**.
(2) The angular position relative to the earth's horizon is located by the Altitude Angle **(α)**.
(3) The angular position of the sun relative to the Zenith is located by the Zenith Angle **(θ_z)**.

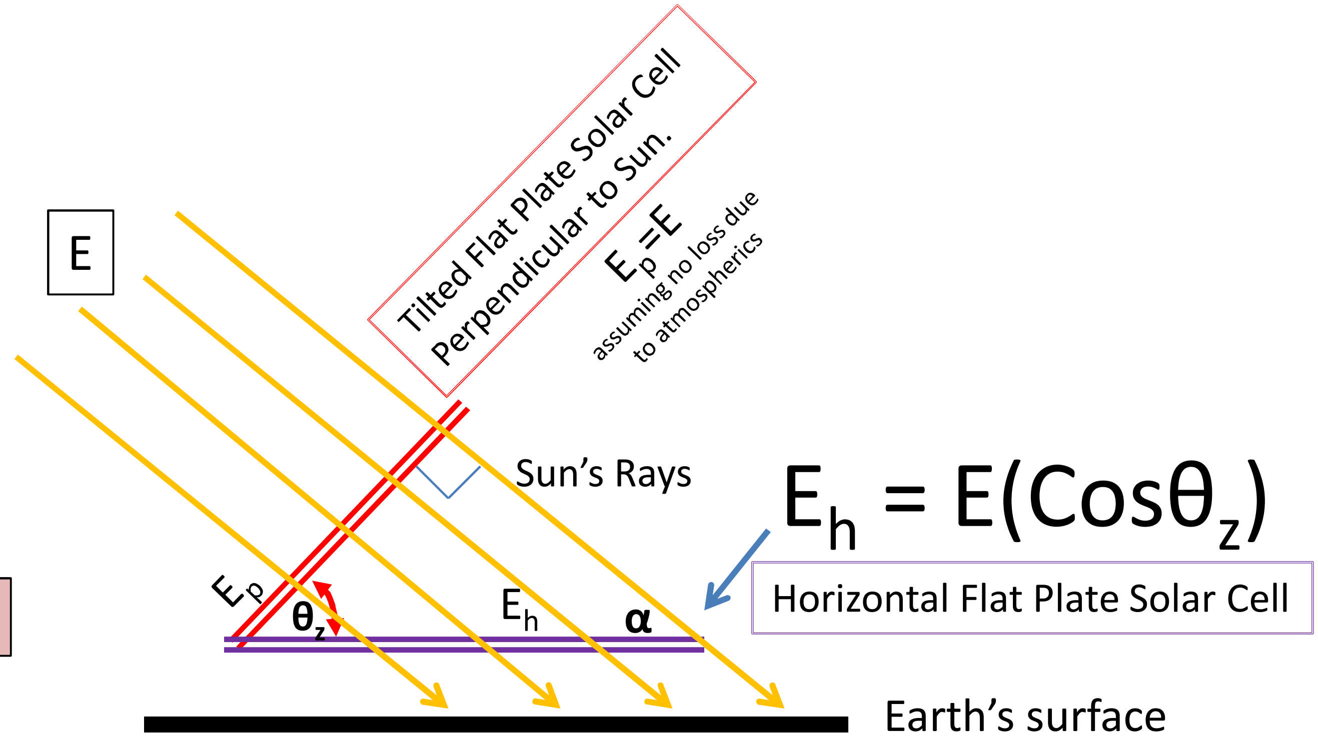
Word of caution: This reference system is for this particular class. Some use different variable names and/or reference frames depending on the author. This is the most prevalent reference system.

http://www.itacanet.org/eng/elec/solar/source.htm

3.1.1b The "Cosine Effect"



Let E=the solar irradiance from the sun.



Zenith Angle **(θ_z)**.

(1) The plate perpendicular to the sun is exposed to a straight "hit" by the sun's rays.

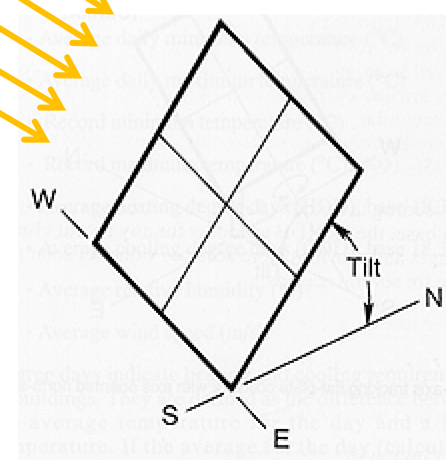
(2) But, the horizontal plate get's the sun's rays at an angle equal to the Zenith Angle **(θ_z)**.

(3) So over time (ie. a day), the plate perpendicular to the sun's rays yields higher energy output than the horizontal plate because $\mathbf{E_p \geq E_h}$

3.1.1b Sun Path

- For fixed panels, the maximum energy output can be achieved when their surfaces are perpendicular to the sun at solar noon.

- The panels must be tilted to the best angle possible.
- But, that depends on the time of year and location on earth.
- NREL suggests that they be tilted at an angle equal to the site's latitude.

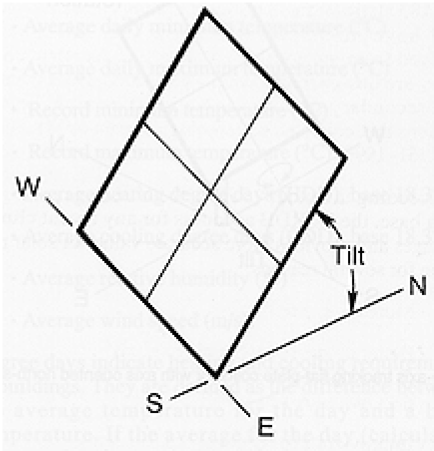


Flat-plate collector facing south at fixed tilt

<u>NREL: To optimize performance</u>

- ○ Winter: collector should be tilted 15º > than latitude
- ○ Summer: collector should be tilted 15º < than latitude

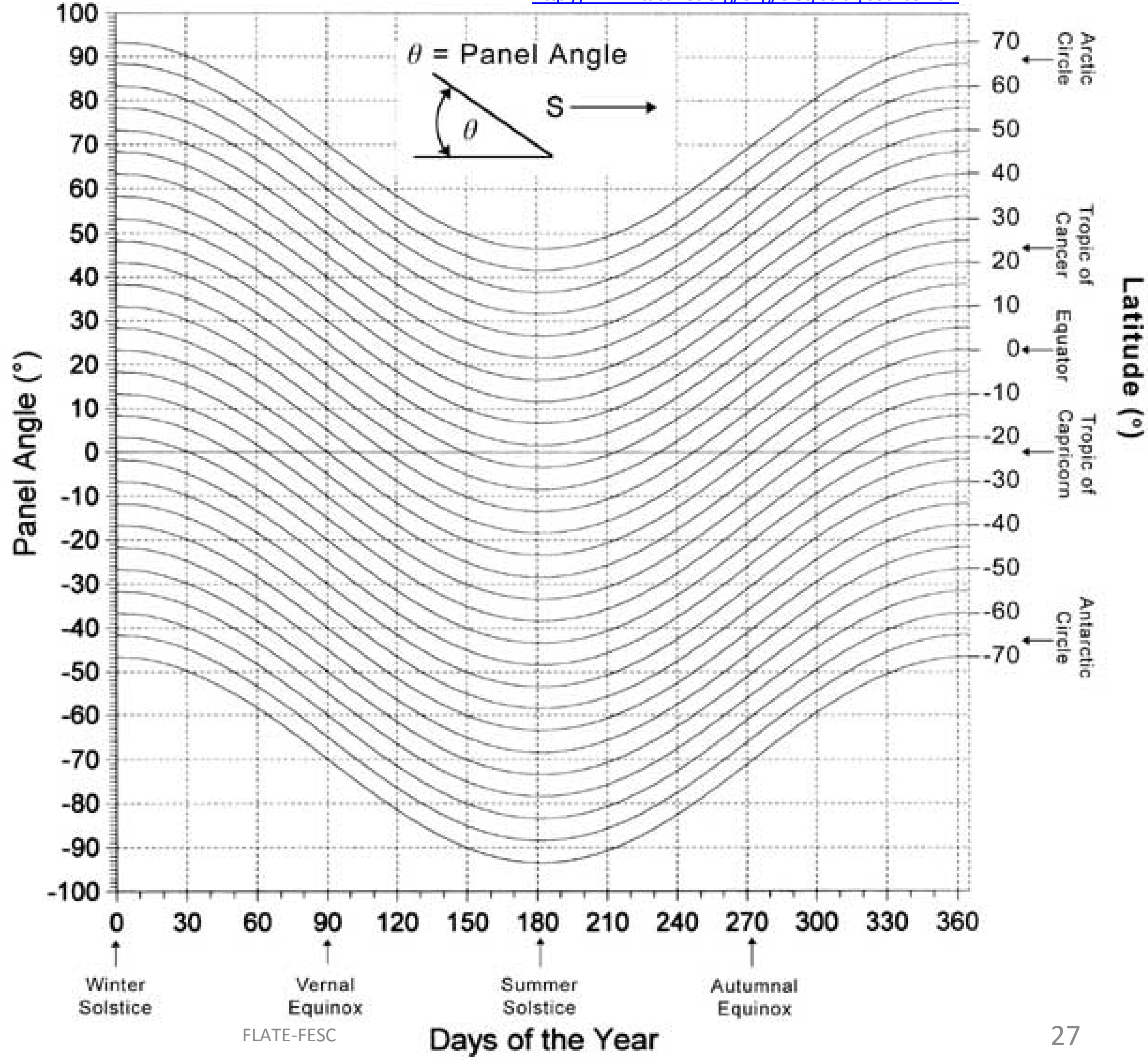
3.1.1b Fixed Solar Panel Angles



Flat-plate collector facing south at fixed tilt

Find the latitude of your site on the y-axis (right hand side), then follow the line that corresponds most closely to your site and using the numbered days on the x-axis read the panel angle off the y-axis on the left hand side.

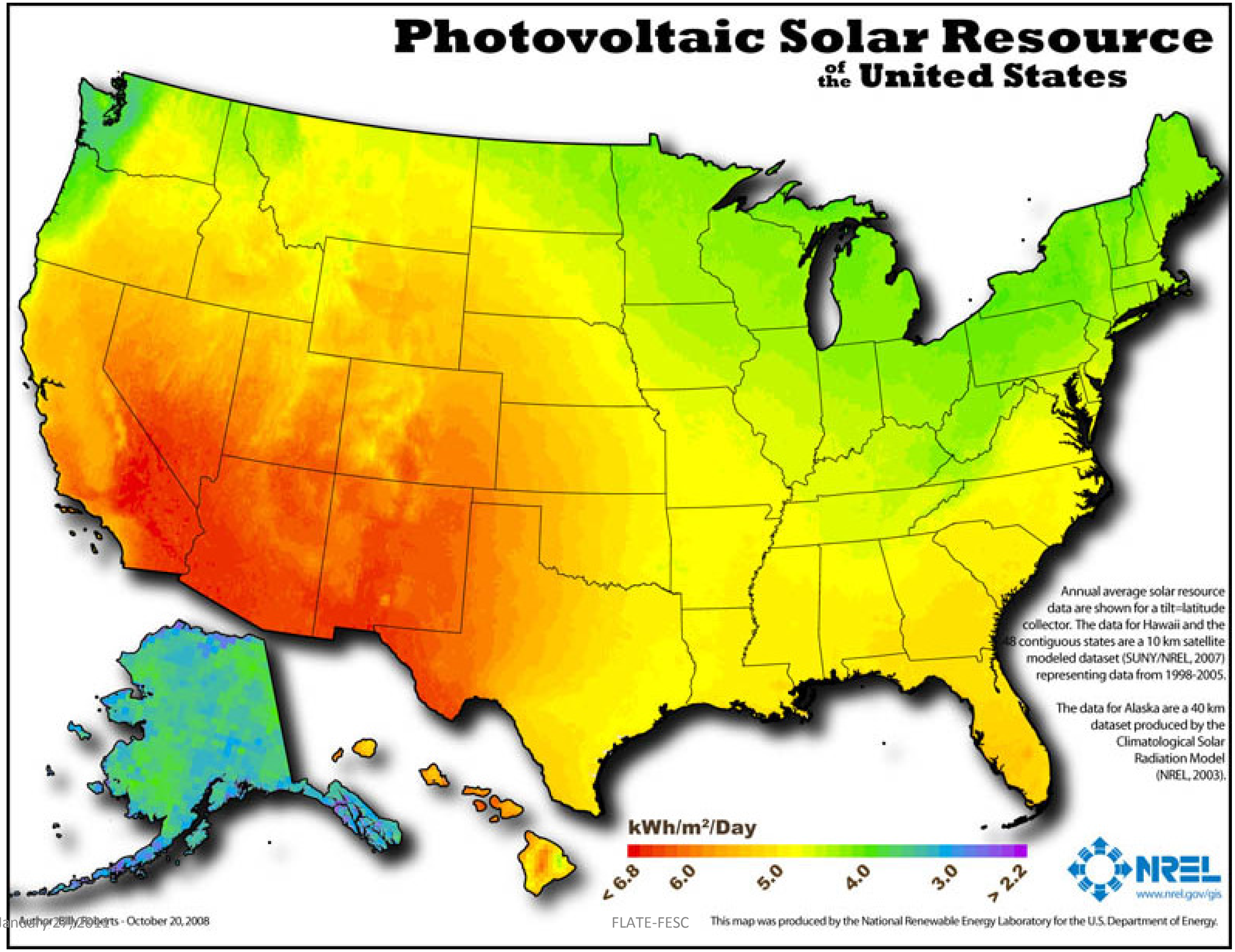
http://www.itacanet.org/eng/elec/solar/source.htm



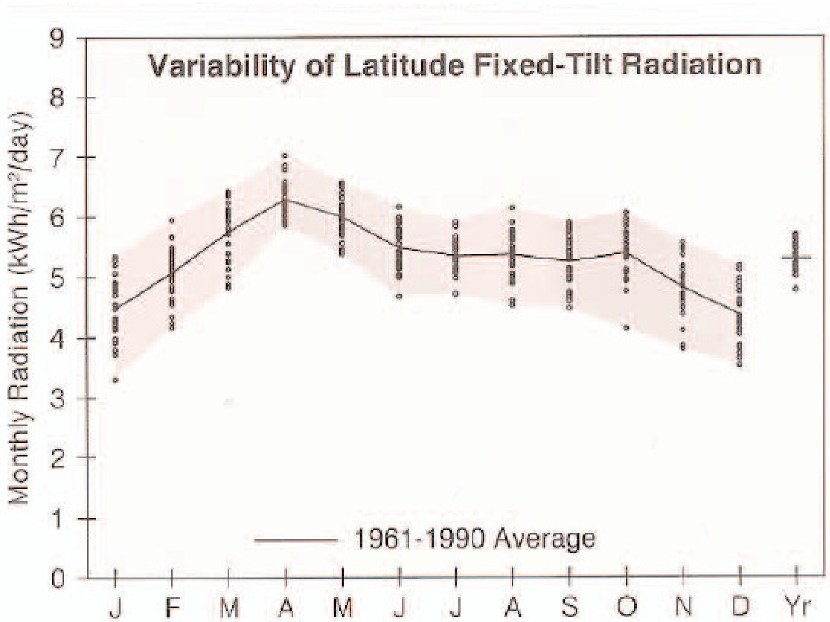
3.1.1c Irradiation

- Irradiation is not the same as Irradiance…sorry about the names.
  - Irradiation is measured in units of energy per unit area (J/m^2) or (kWh/m^2) as opposed to Irradiance which is measured in power per unit area (W/m^2).
  - Think of solar irradiance as the power given off by the sun and irradiation as the energy (or radiation) from the sun to which a solar panel is exposed over a period of time (one day for example).
  - Irradiation is usually represented by the symbol *H*, whereas irradiance is represented by *E*

3.1.1c Irradiation



3.1.1c Irradiation Data



Tampa, FL

WBAN NO. 12842

LATITUDE: 27.97° N
LONGITUDE: 82.53° W
ELEVATION: 3 meters
MEAN PRESSURE: 1018 millibars

STATION TYPE: Secondary

http://rredc.nrel.gov/solar/pubs/redbook/PDFs/FL.PDF

Solar Radiation for Flat-Plate Collectors Facing South at a Fixed Tilt (kWh/m²/day), Uncertainty ±9%

Tilt (°)		Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
0	Average	3.2	4.0	5.1	6.2	6.4	6.1	5.8	5.5	4.9	4.4	3.6	3.1	4.9
	Min/Max	2.6/3.7	3.4/4.5	4.3/5.6	5.8/6.8	5.7/7.1	5.1/6.9	5.1/6.4	4.6/6.3	4.3/5.4	3.6/4.9	3.0/4.0	2.7/3.5	4.5/5.2
Latitude -15	Average	3.9	4.6	5.5	6.4	6.4	5.9	5.7	5.5	5.2	5.0	4.2	3.8	5.2
	Min/Max	3.0/4.6	3.8/5.3	4.7/6.1	5.9/7.1	5.7/7.0	5.0/6.7	5.0/6.3	4.7/6.3	4.5/5.8	4.0/5.6	3.4/4.8	3.1/4.4	4.7/5.5
Latitude	Average	4.5	5.1	5.8	6.3	6.0	5.5	5.3	5.4	5.2	5.4	4.8	4.4	5.3
	Min/Max	3.3/5.3	4.2/5.9	4.8/6.4	5.9/7.0	5.4/6.6	4.7/6.2	4.7/5.9	4.5/6.2	4.5/5.9	4.1/6.1	3.8/5.6	3.5/5.2	4.8/5.7
Latitude +15	Average	4.8	5.3	5.7	5.9	5.3	4.8	4.7	4.9	5.0	5.5	5.1	4.7	5.1
	Min/Max	3.5/5.8	4.3/6.2	4.7/6.4	5.4/6.5	4.8/5.8	4.1/5.3	4.2/5.2	4.2/5.6	4.3/5.7	4.1/6.2	4.0/6.0	3.7/5.7	4.6/5.5
90	Average	4.0	4.0	3.5	2.8	2.0	1.7	1.8	2.2	2.9	3.9	4.2	4.1	3.1
	Min/Max	2.8/5.0	3.2/4.8	3.0/4.0	2.6/3.0	1.9/2.1	1.6/1.8	1.7/1.9	2.0/2.4	2.4/3.2	2.8/4.4	3.1/5.0	3.1/5.0	2.7/3.3

3.1.1c Irradiation

- A general analysis concludes that the energy available from sunlight on any fixed plate solar panel on earth depends on
  - ☑ Time of year: Summer, Fall, Winter, Spring
  - ☑ Location: Latitude/Longitude
  - ☑ Time of Day

But it also depends on,

  - ☑ Atmospheric Absorption

3.1.1.d Air Mass

Not all of the sun's rays reach earth….recall our discussion on atmospheric absorption.

How much energy does light lose in traveling from the edge of the atmosphere to the surface of the Earth?

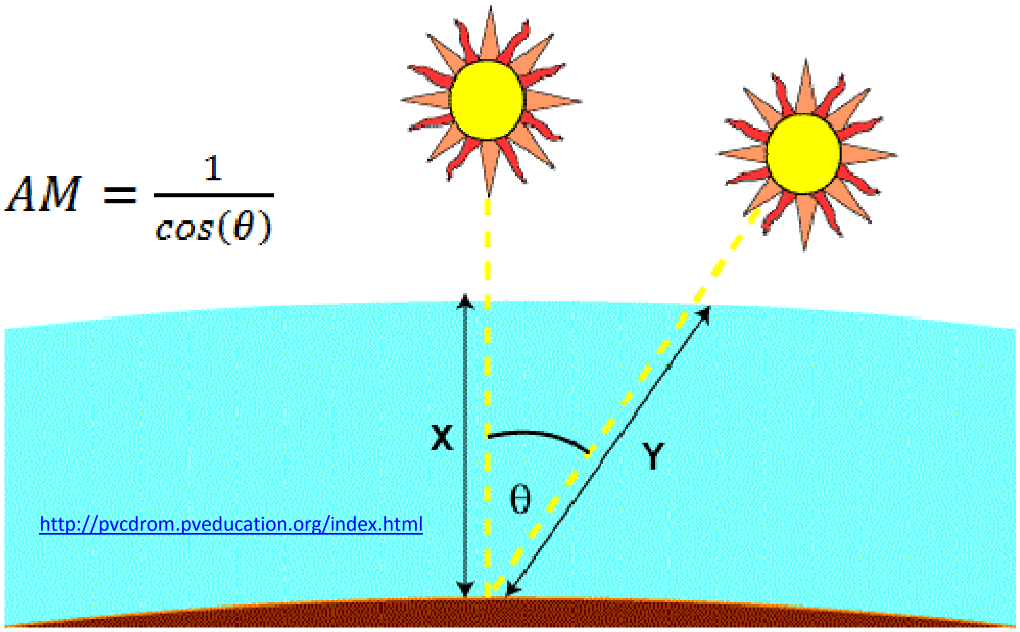
Air mass (AM) is the term used to describe the relative path length that the sun's rays have to traverse through the atmosphere before reaching the ground. An AM=1 condition occurs when the sun is directly overhead at a sea-level site; air mass values of 10 or greater occur near sunrise and sunset.

http://www1.eere.energy.gov/solar/pv_cell_light.html

3.1.1.d Air Mass

Assuming a flat horizon. That is, not taking the curvature of the earth into account.

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



This energy loss depends on the thickness of the atmosphere that the sun's energy must pass through. The radiation that reaches sea level at high noon in a clear sky is 1000 W/m^2 and is described as "air mass 1" (or AM1) radiation. As the sun moves lower in the sky, the light passes through a greater thickness (or longer path) of air, losing more energy. Because the sun is overhead for only a short time, the air mass is normally greater than one—that is, the available energy is less than 1000 W/m^2. http://www1.eere.energy.gov/solar/pv_cell_light.html

3.1.1.d Air Mass

The standard spectrum of sunlight at the Earth's surface

✓AM1.5G (where G stands for "global" and includes both direct and diffuse radiation)
✓AM1.5D (which includes direct radiation only).

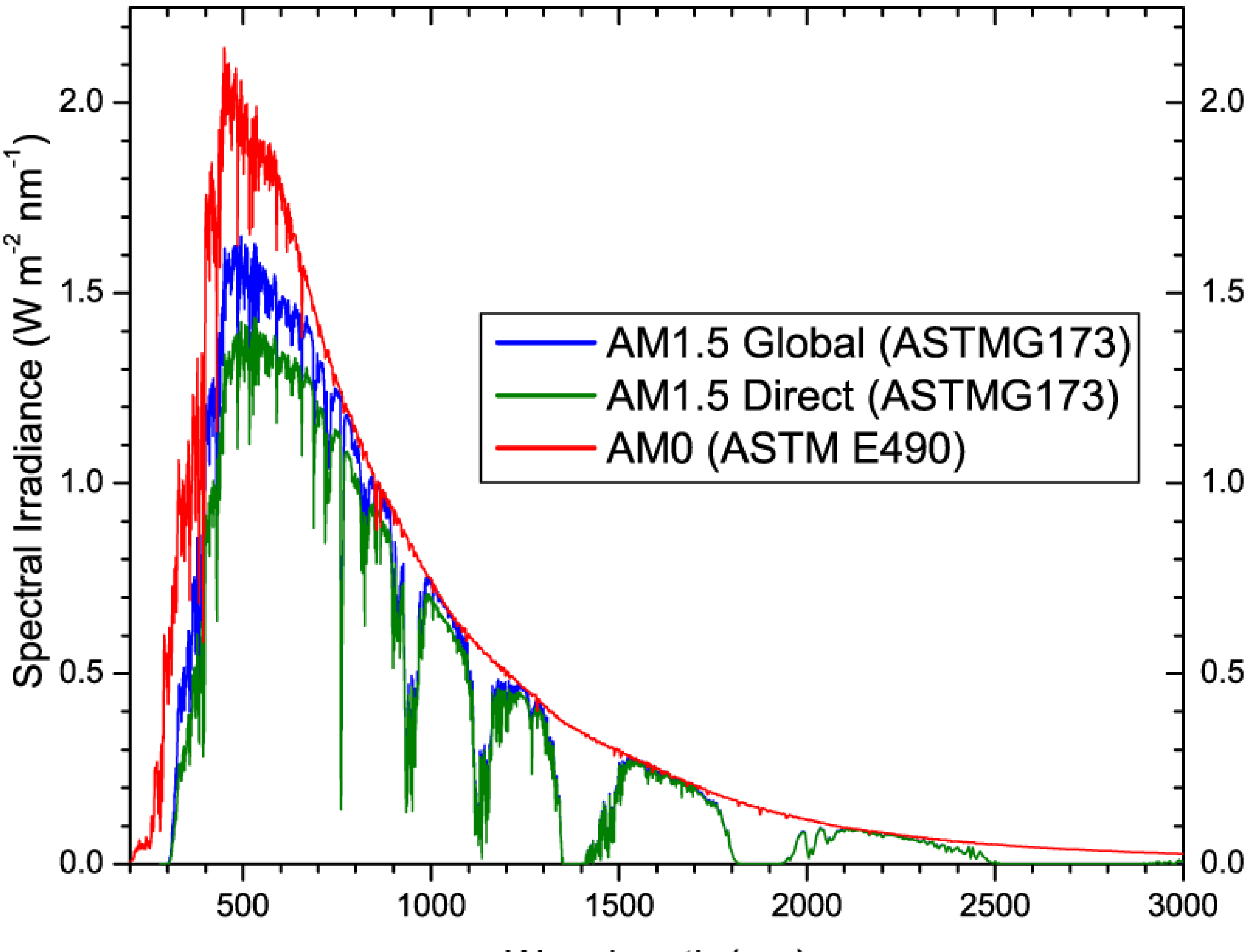
The number "1.5" indicates that the length of the path of light through the atmosphere is 1.5 times that of the shorter path when the sun is directly overhead.

✓AM0 is the standard spectrum outside the Earth's atmosphere where no light has yet passed through the atmosphere.

- AM0 is typically used to predict the expected performance of PV cells in space.
- The intensity of AM1.5D radiation is approximated by reducing the AM0 spectrum by 28%, where 18% is absorbed and 10% is scattered.
- The global spectrum is 10% greater than the direct spectrum.
- These calculations give about 970 W/m^2 for AM1.5G. However, the standard AM1.5G spectrum is "normalized" to give 1000 W/m^2, because of inherent variations in incident solar radiation.

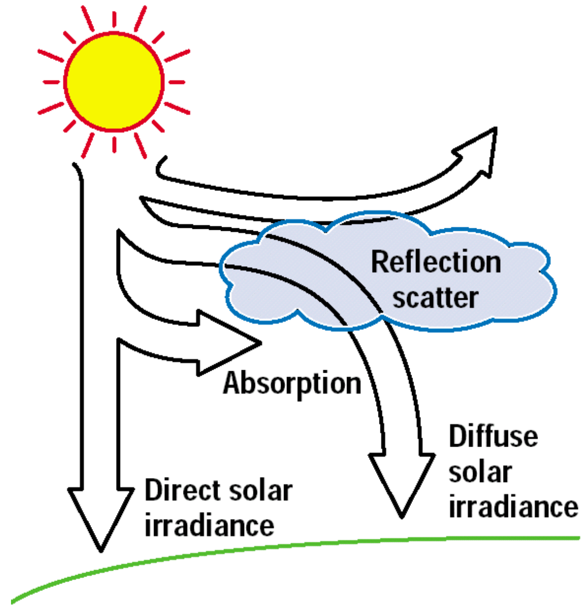
http://www1.eere.energy.gov/solar/pv_cell_light.html

3.1.1.d Air Mass



http://pvcdrom.pveducation.org/APPEND/Am1_5.htm

3.1.1e Irradiance on Plates



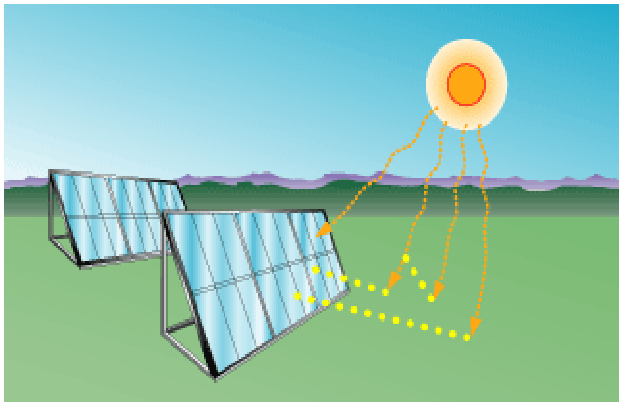
❑Direct light consists of radiation that comes straight from the sun
❑Diffuse light is sunlight that is reflected off clouds, the ground, or other objects. It obviously takes a longer path than a direct light ray to reach a module.
❑Global sunlight is composed of direct-normal and diffuse components of sunlight.
❑Additionally, diffuse and direct-normal sunlight generally have different energy spectra or distributions of color.

Volker Quaschning - Understanding Renewable Energy Systems - Earthscan, London, 2005

3.1.1e Irradiance on Plates

What is the total irradiation on a solar plate?

http://www1.eere.energy.gov/solar/pv_cell_light.html



Flat-plate collectors, which typically contain a large number of solar cells mounted on a rigid, flat surface, can make use of both direct sunlight and the diffuse sunlight reflected from clouds, the ground, and nearby objects.

✓The global irradiance on a horizontal surface on Earth consists of the direct irradiance E_{dir} and diffuse irradiance E_{dif}.

✓On a tilted plane, there is another irradiance component: E_{ref}, which is the component that is reflected from the ground.

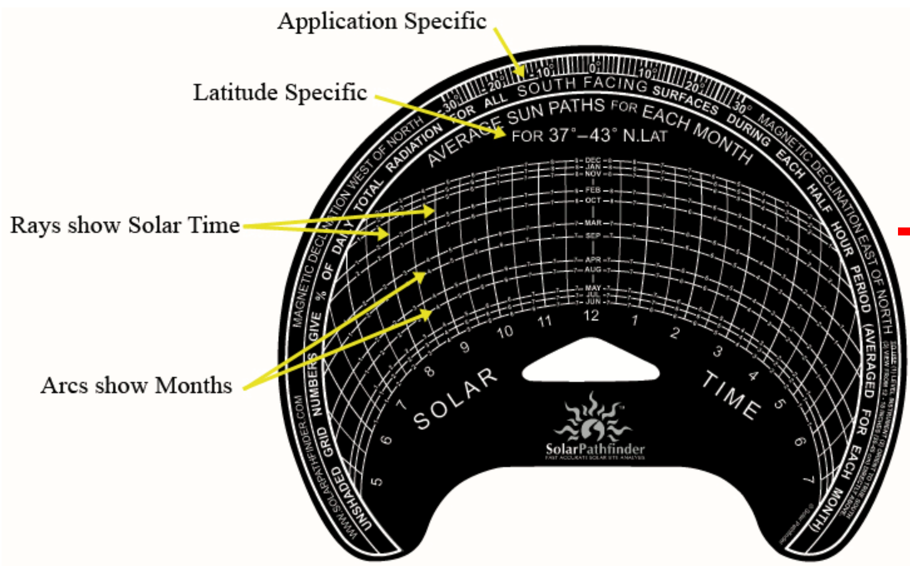
✓Hence, the irradiance E_{tilt} on a tilted plane consists of three components: $E_{tilt} = E_{dir} + E_{dif} + E_{ref}$.

Volker Quaschning - Understanding Renewable Energy Systems - Earthscan, London, 2005

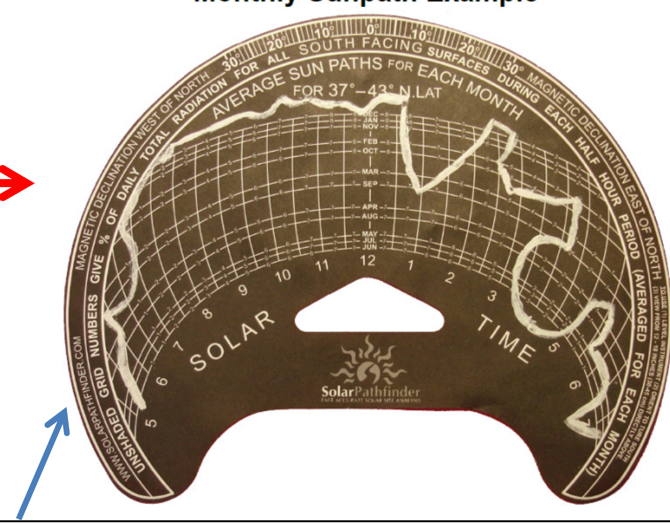
3.1.1e Shading Losses

- One important thing to consider is how much shading will fall onto the solar panels. Either rooftop or mounted.
- Shading will degrade desired energy output from solar panels.
- Instruments are available that can help determine shading losses.

http://www.solarpathfinder.com/products



Monthly Sunpath Example



To find the site percent, add the numbers in the unshaded part of the sunpath arc. The site tracing shown here has 64% solar available for January, found by adding 2 + 3 + 4 + 5 + 6 + 7 + 7 +8 + 8 + 8 + 6 = 64%. This shows that only 64% of the potential available radiation is reaching this particular location during January. 36% of the potential available radiation is blocked out in the middle of the winter.

3.1.1 Solar Energy

- A general analysis concludes that the energy available from sunlight on any fixed plate solar panel on earth depends on
  - ☑ Time of year: Summer, Fall, Winter, Spring
    - Altitude Angle **(α)**
    - Zenith Angle **(θ_z)**.
  - ☑ Location: Latitude/Longitude
  - ☑ Time of Day
    - Azimuth Angle **(A_z)**
  - ☑ Atmospheric Absorption
    - Air mass. More specifically, the energy spectra falling onto the photovoltaic plate (this will be discussed in the next section)