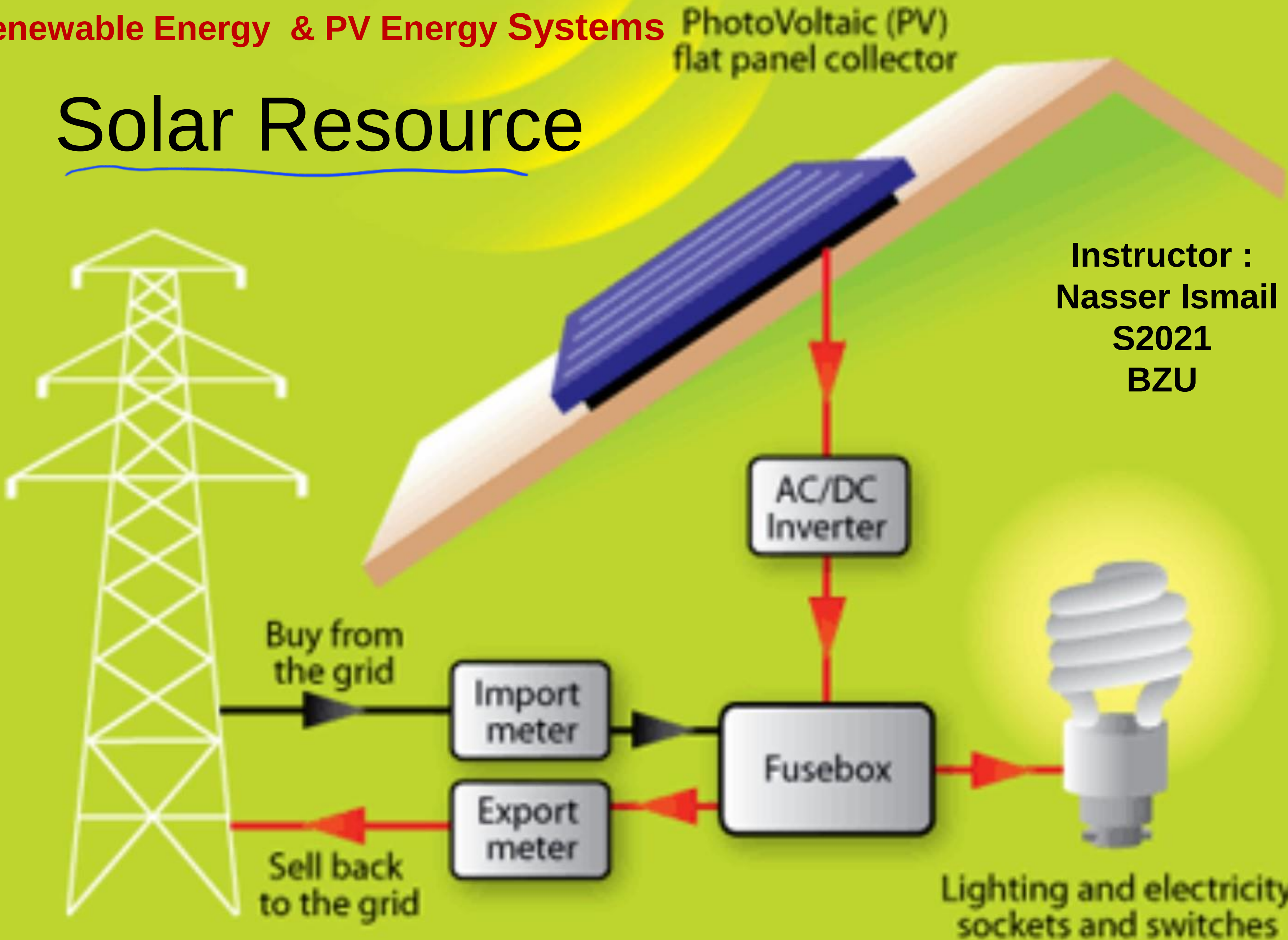
ENEE5307

Renewable Energy & PV Energy Systems

Solar Resource



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S2021

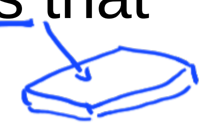
BZU

THE SOLAR RESOURCE

- To design and analyze solar systems, we need to know how much sunlight is available.
- A fairly straightforward, though complicated-looking, set of equations can be used to predict where the sun is in the sky at any time of day for any location on earth, as well as the solar intensity **(or insolation: incident solar Radiation) on a clear day.**

العزل

- To determine average daily ***insolation*** (**not insulation**) under the combination of clear and cloudy conditions that exist at any site we need to start with long-term measurements of sunlight hitting a horizontal surface.



- Another set of equations can then be used to estimate the insolation on collector surfaces that are not flat on the ground.

THE SOLAR SPECTRUM

- The source of insolation is, of course, the sun—that gigantic, 1.4 million kilometer diameter, thermonuclear furnace fusing hydrogen atoms into helium.
- Every object emits radiant energy in an amount that is a function of its temperature.
- The usual way to describe how much radiation an object emits is to compare it to a theoretical abstraction called a *blackbody*.
- **A blackbody is defined to be** a perfect emitter as well as a perfect absorber.
- As a perfect emitter, it radiates more energy per unit of surface area than any real object at the same temperature.

Planck's law

- As a perfect absorber, it absorbs all radiation that impinges upon it; that is, none is reflected and none is transmitted through it.
- The wavelengths emitted by a blackbody depend on its temperature as described by *Planck's law*:

$$E_\lambda = \frac{3.74 \times 10^8}{\lambda^5 \left[\exp\left(\frac{14{,}400}{\lambda T} \right) - 1 \right]}$$

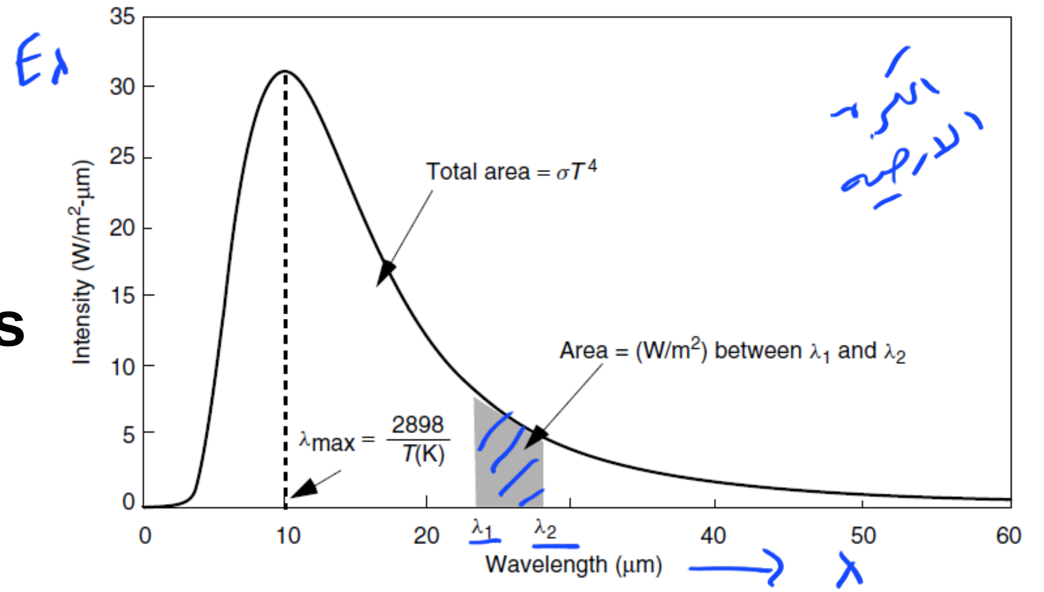
288

- where
- E_λ is the emissive power per unit area of a blackbody (W/m^2)
- T - is the absolute temperature of the body (K),
- λ - is the wavelength (μm).
- Modeling the earth itself as a 288 K (15◦C) blackbody results in the emission spectrum plotted in next figure.

$$E_\lambda = \frac{3.74 \times 10^8}{\lambda^5 \left[\exp\left(\frac{14{,}400}{\lambda T} \right) - 1 \right]}$$

- **The area under Planck's curve between any two wavelengths is the power emitted between those wavelengths, so the total area under the curve is the total radiant power emitted.**
- That total is conveniently expressed by the *Stefan–Boltzmann law of radiation*:

$$E = A\sigma T^4$$



The spectral emissive power of a 288 K blackbody

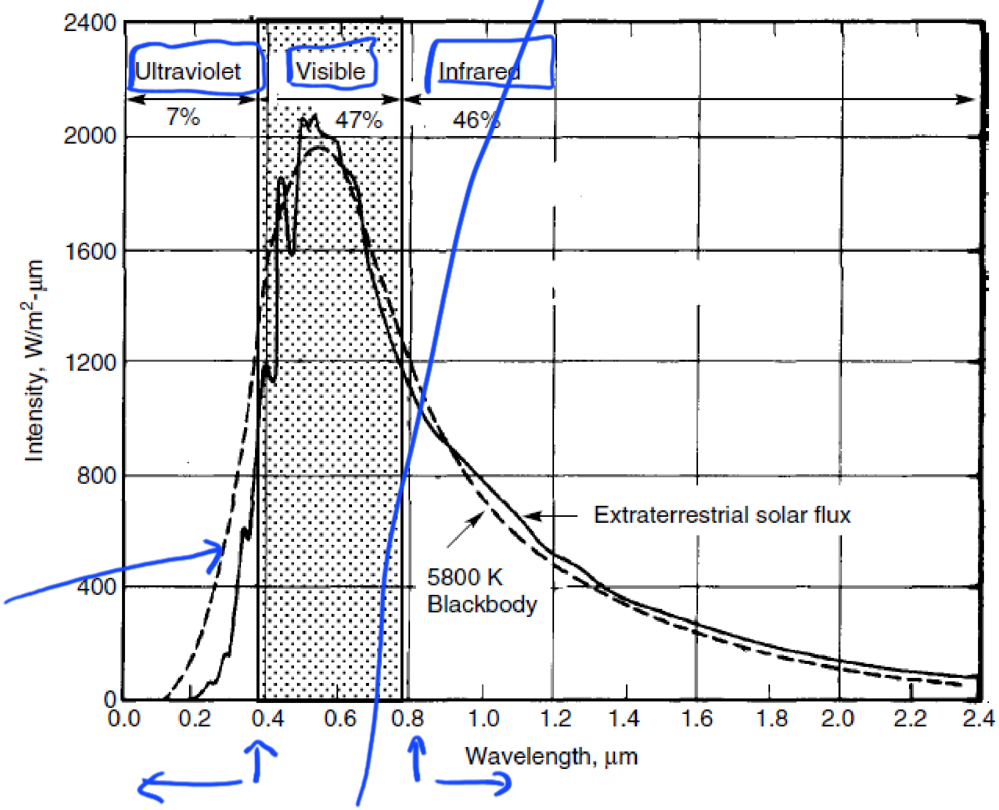
Where
E - is the total blackbody emission rate (W),
σ - is the Stefan–Boltzmann constant = 5.67 × 10^−8 W/m^2-K^4,
T - is the absolute temperature of the blackbody (K),
and A - is the surface area of the blackbody (m^2).

Solar Spectrum

atmosphere

Earth

- Sun's surface has a spectral distribution that closely matches that predicted by Planck's law for a 5800 K blackbody.
- The total area under the blackbody curve has been scaled to equal 1.37 kW/m^2, which is the solar insolation just outside the earth's atmosphere.

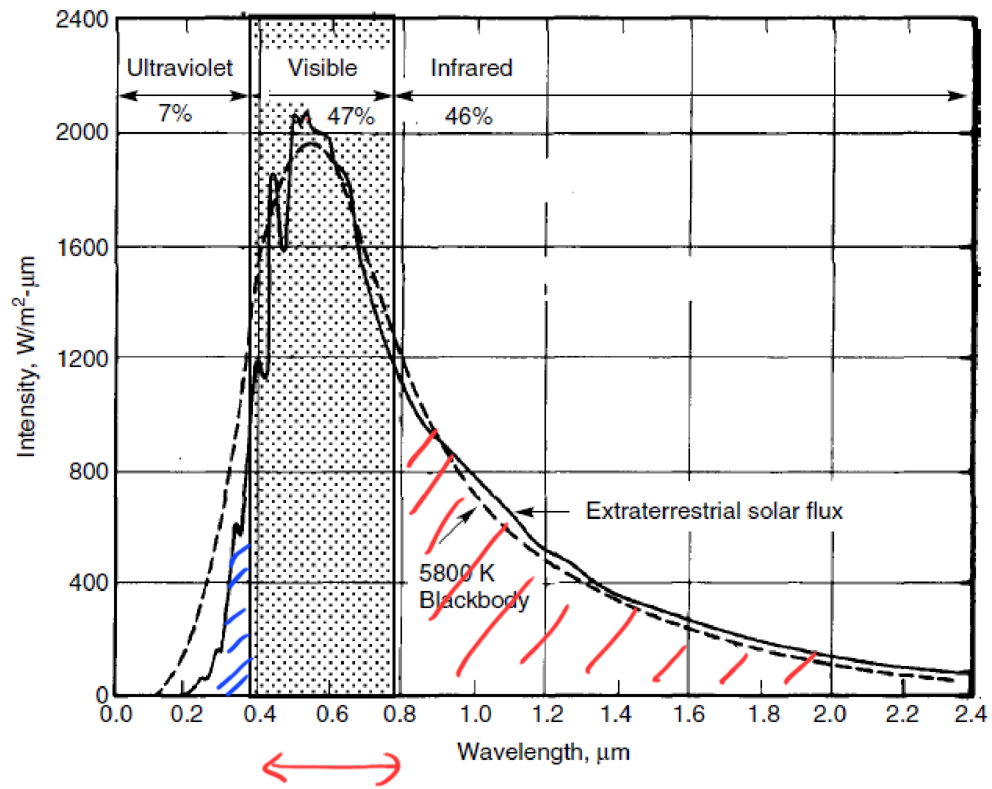


The extraterrestrial solar spectrum compared with a 5800 K blackbody

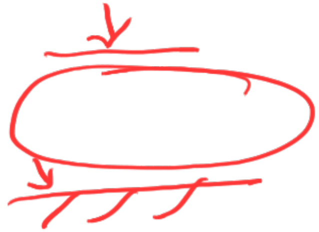
Solar Spectrum

- Also shown are the areas under the actual solar spectrum that corresponds to wavelengths within the:
  - **ultraviolet UV (7%),**
  - **visible (47%), and**
  - **infrared IR (46%)**

  portions of the spectrum.
- The visible spectrum, which lies between the UV and IR, ranges from **0.38 μm (violet) to 0.78 μm (red).**



Air Mass Ratio



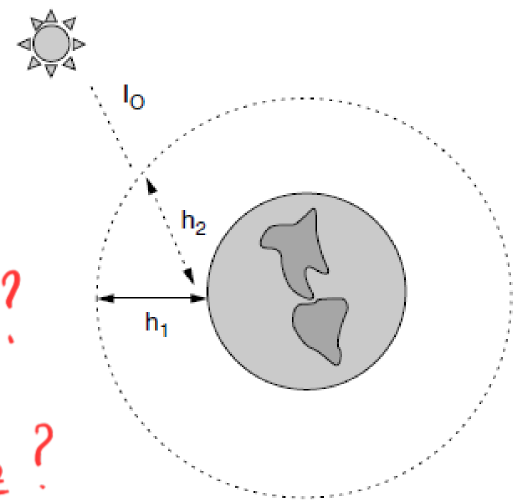
- As solar radiation makes its way toward the earth's surface, some of it is absorbed by various constituents in the atmosphere, giving the terrestrial spectrum an irregular, bumpy shape.
- The terrestrial spectrum also depends on how much atmosphere the radiation has to pass through to reach the surface.
- The length of the path $\mathbf{h_2}$ taken by the sun's rays as they pass through the atmosphere, divided by the minimum possible path length $\mathbf{h_1}$, which occurs when the sun is directly overhead, is called the *air mass ratio*, *m*.

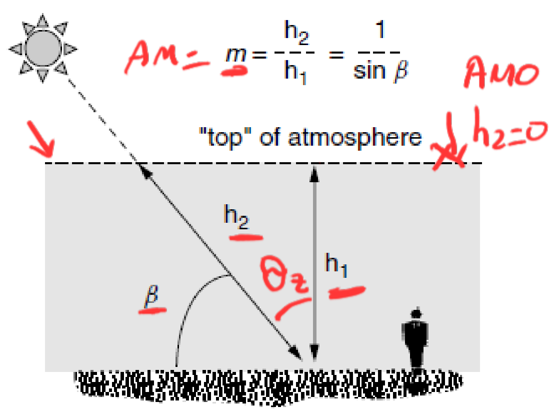
- **h1** = path length through the atmosphere with the sun directly overhead,
- **h2** = path length through the atmosphere to reach a spot on the surface,
- ***β* = the altitude angle of the sun (see Figure)**
- Thus, an air mass ratio of 1 (designated "AM1") means that the sun is directly overhead.
- By convention, AM0 means no atmosphere; that is, it is the extraterrestrial solar spectrum.
- Often, an air mass ratio of 1.5 is assumed for an average solar spectrum at the earth's surface.

Air mass ratio $$m = \frac{h_2}{h_1} = \frac{1}{\sin\beta}$$?

AM

θ_z ?

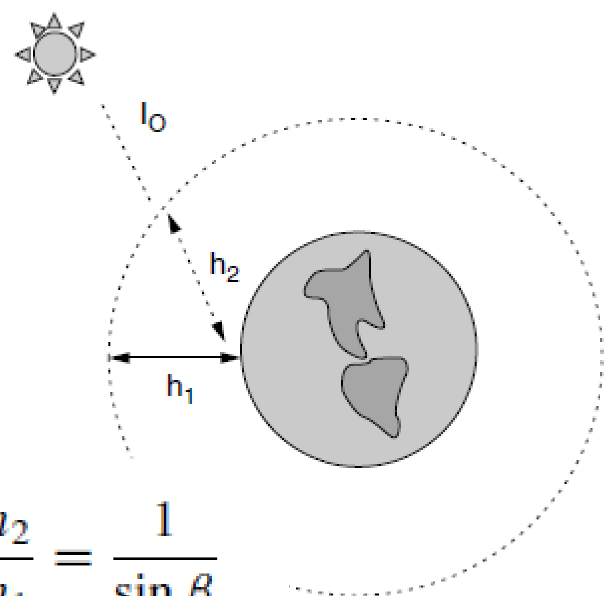


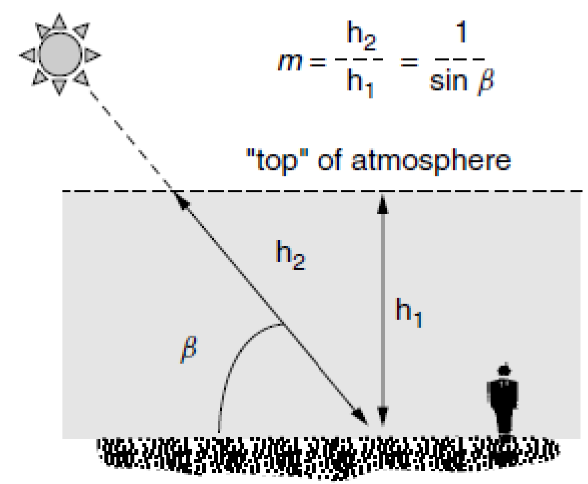


- With AM1.5:
  - ➢ 2% of the incoming solar energy is in the UV portion of the spectrum,
  - ➢ 54% is in the visible,
  - ➢ and 44% is in the infrared.

$m = AM$

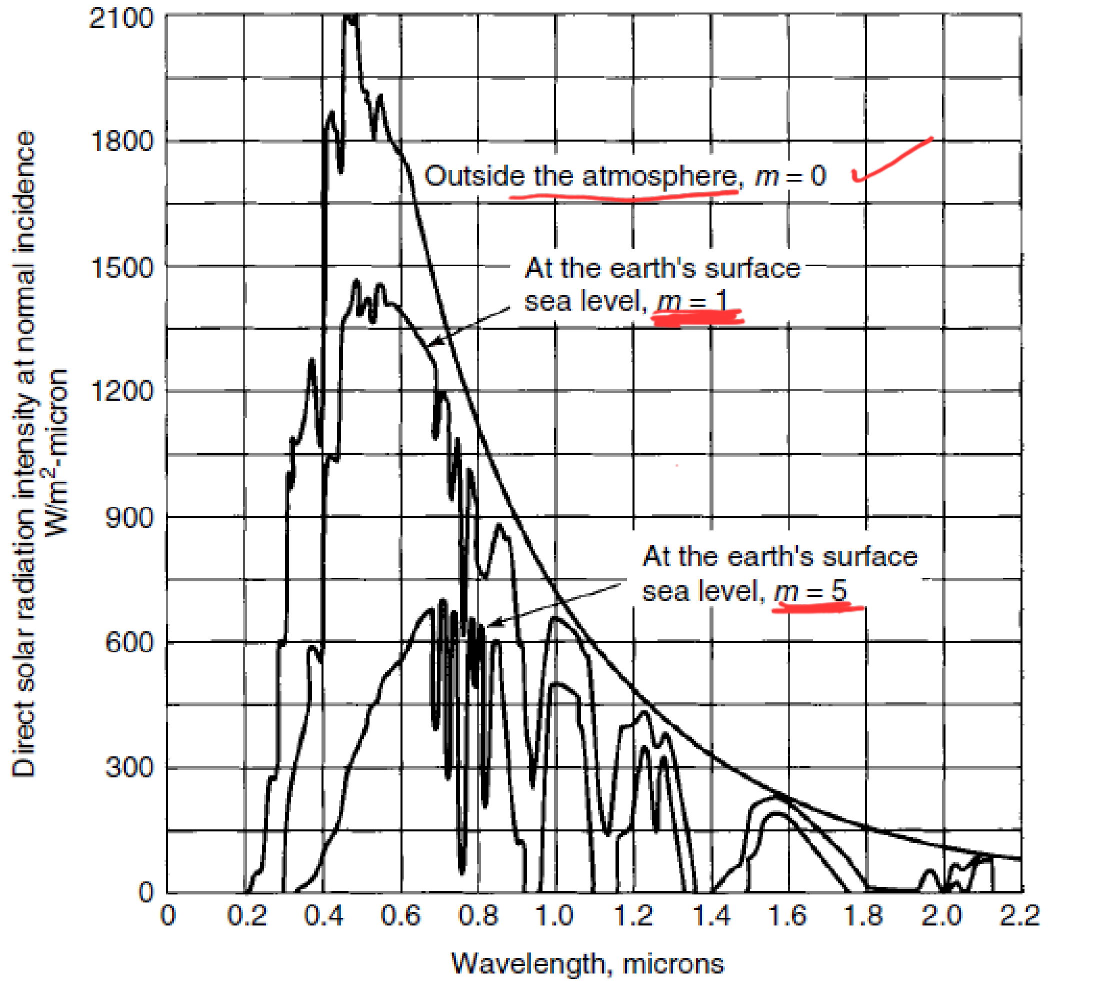
- **The air mass ratio *m* is a measure of the amount of atmosphere the sun's rays must pass through to reach the earth's surface.**
- **For the sun directly overhead and at sea level, *m* = 1.**





Air mass ratio $m = \dfrac{h_2}{h_1} = \dfrac{1}{\sin\beta}$

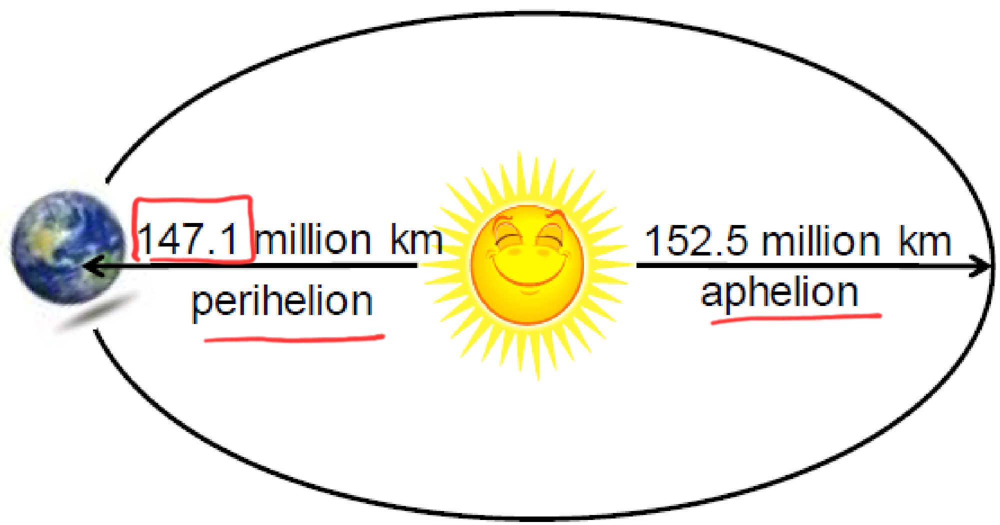
- The impact of the atmosphere on incoming solar radiation for various air mass ratios is shown in Figure
- As sunlight passes through more atmosphere, less energy arrives at the earth's surface and the spectrum shifts some toward longer wavelengths.



Solar spectrum for extraterrestrial *(m* = 0*)*, for sun directly overhead *(m* = 1*)*, and at the surface with the sun low in the sky, *m* = 5.

THE EARTH’S ORBIT

- The earth revolves around the sun in an elliptical orbit, making one revolution every 365.25 days.
- Perihelion is the point in orbit when it is closest to the sun (~ Jan 3rd)
- Aphelion is the farthest point (~ july 4th)



THE EARTH'S ORBIT

- This variation in distance is described by the following relationship:

$$d = 1.5 \times 10^8 \left\{ 1 + 0.017 \sin \left[\underbrace{\frac{360(n - 93)}{365}}_{\text{degrees}} \right] \right\} \text{ km}$$

- **where n is the *day number*, with January 1 as day 1 and December 31 being day number 365.**
- ***It should be noted in all equations developed here involving trigonometric functions use angles measured <u>in degrees, not radians.</u>***

- Each day, as the earth rotates about its own axis, it also moves along the ellipse.
- ***Amount of solar radiation at a particular location is a direct result of earths orbit and tilt***

Ecliptic & Equatorial planes

- The ecliptic plane: plane of Earth's orbit around the sun
- Equatorial plane : plane containing Earths equator and extending outward into space
- Because of earths tilt, angle between these planes is 23.5 deg and remains constant as earth rotates around the sun
- This angle is what causes seasonal variations in earth's climate
- As earth rotates around the sun, the Northern Hemisphere tilts away from the sun during winter and toward the sun during summer, and the opposite happens for the southern parts and thus opposite seasons

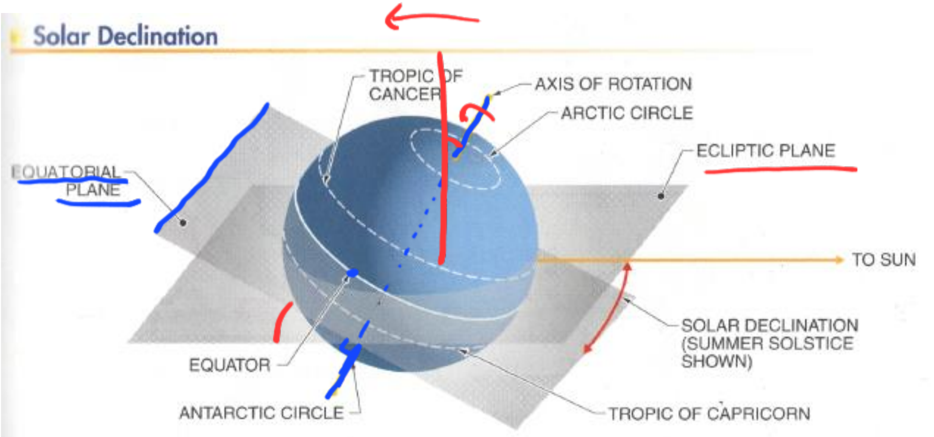


Figure 2-19. *The equatorial plane is tipped 23.5° from the ecliptic plane. As Earth revolves around the sun, this orientation produces a varying solar declination.*

Solar Declination Angle

- Solar declination angle is the angle between the equatorial plane and the rays of sun
- The angle of solar declination changes continuously as earth orbits the sun from -23.45 to +23.45 deg (positive when northern hemisphere is tilted toward the sun)
- The angle between ecliptic and equatorial planes doesn't change, but as viewed from the sun at different times of the year, the equatorial plane appear to change in orientation
- It appears to dip below the ecliptic plane (summer in northern hemisphere), become on-edge(fall), dip above (winter), again on edge (Spring)

- The dates when min , max and zero declination occur are used to mark the beginning of seasons

$-23.5 < \delta < +23.5$

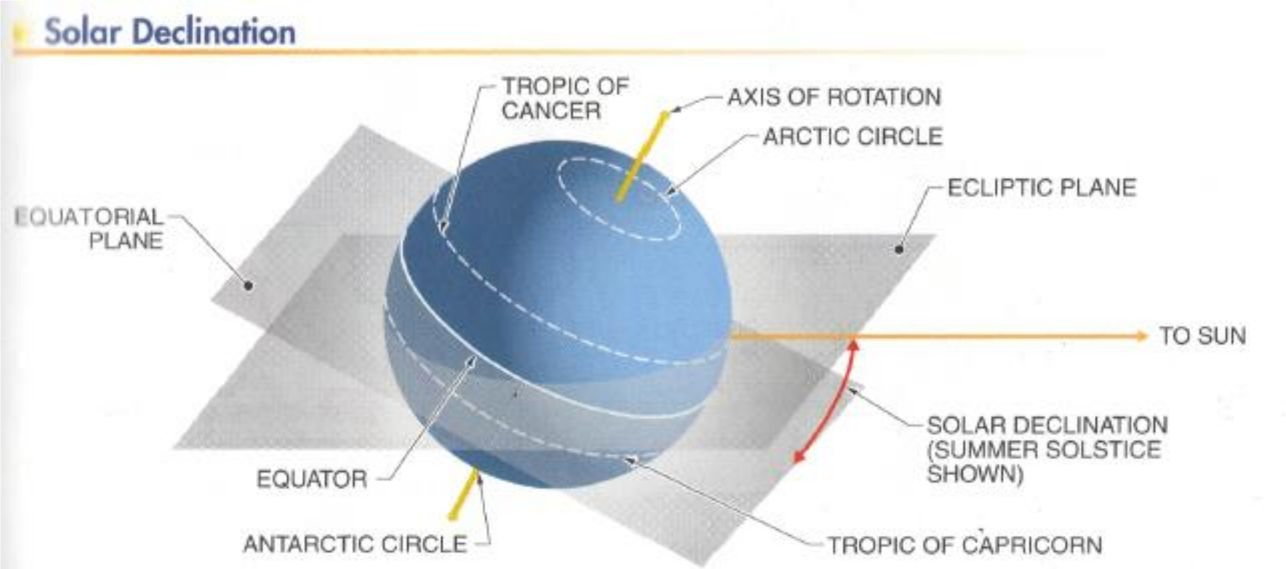


Figure 2-19. *The equatorial plane is tipped 23.5° from the ecliptic plane. As Earth revolves around the sun, this orientation produces a varying solar declination.*

- The earth’s spin axis is currently tilted 23.45◦ with respect to the ecliptic plane and that tilt is, of course, what causes our seasons.

اذار   بداية الربيع   بداية الخريف ايلول

- On March 21 and September 21, a line from the center of the sun to the center of the earth passes through the equator and everywhere on earth we have 12 hours of daytime and 12 hours of night, hence the term *equinox* (equal day and night).

اعتدال

بداية الشتاء

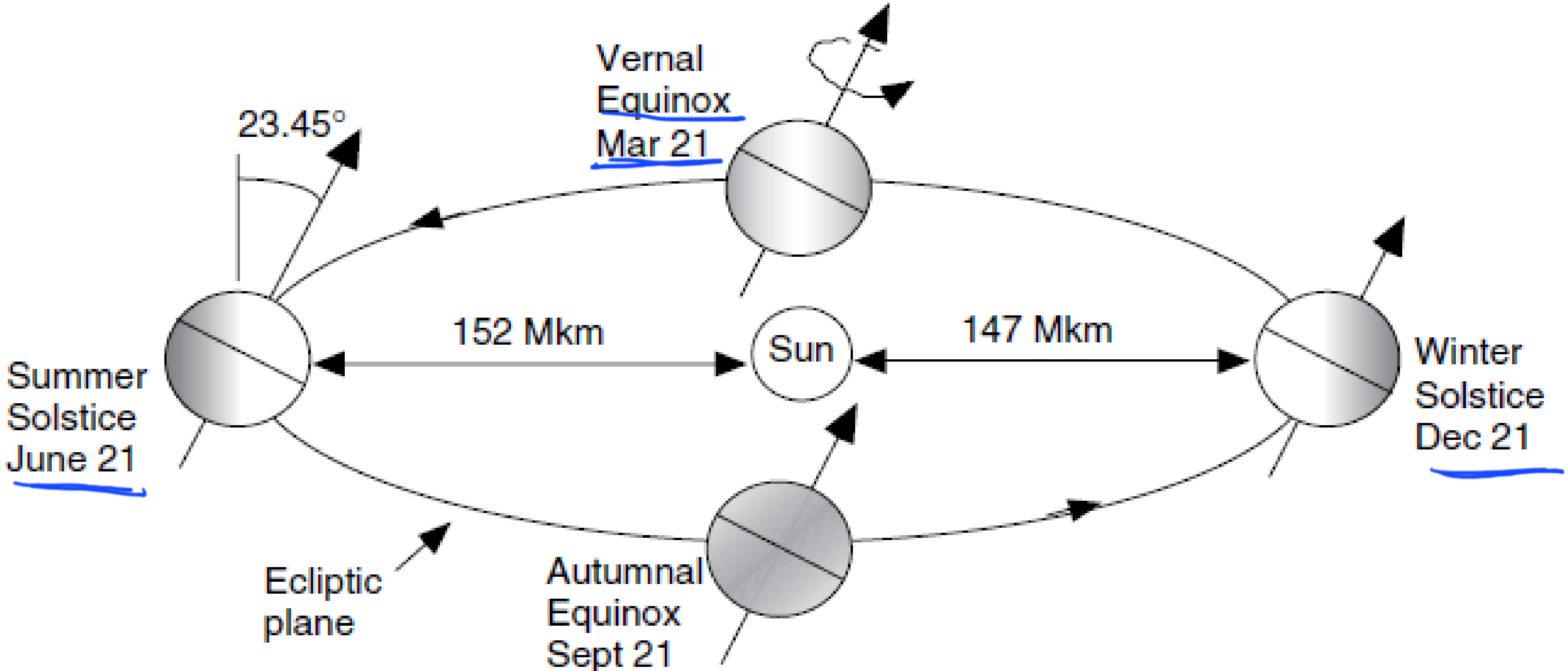
- On December 21, the winter *solstice* in the Northern Hemisphere, the inclination of the North Pole reaches its highest angle away from the sun (23.45◦), while on June 21 the opposite occurs. التقارب

بداية الصيف

TABLE 7.1 Day Numbers for the First Day of Each Month

January	$n = 1$	July	$n = 182$
February	$n = 32$	August	$n = 213$
March	$n = 60$	September	$n = 244$
April	$n = 91$	October	$n = 274$
May	$n = 121$	November	$n = 305$
June	$n = 152$	December	$n = 335$

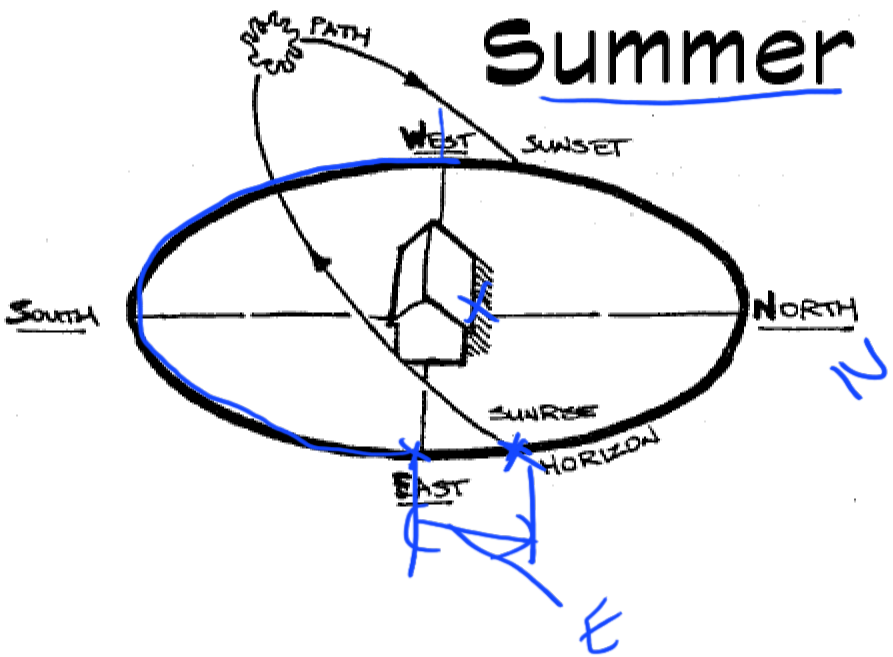
- By the way, for convenience we are using the twenty-first day of the month for the solstices and equinoxes even though the actual days vary slightly from year to year.

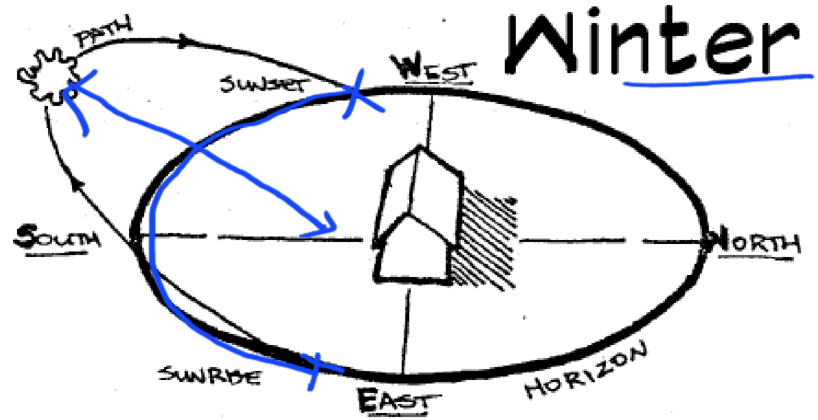


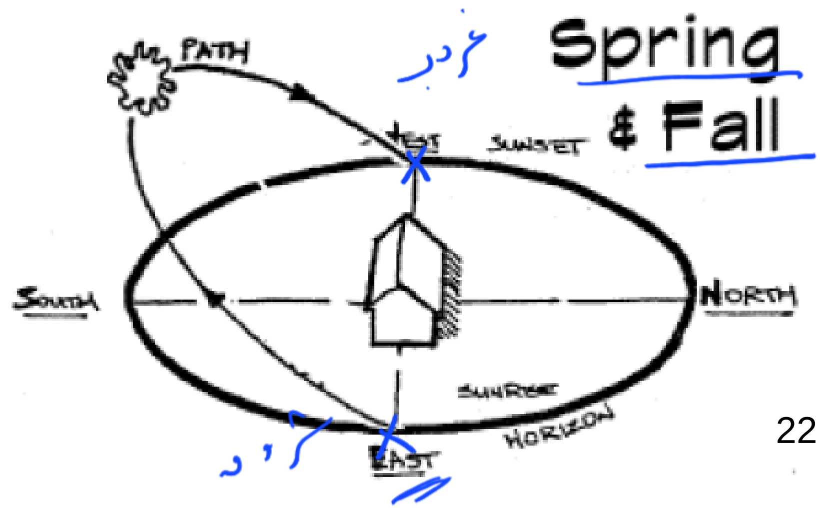
*

The tilt of the earth's spin axis with respect to the ecliptic plane is what causes our seasons. "Winter" and "summer" are designations for the solstices in the Northern part

Sun Angles and Solar window

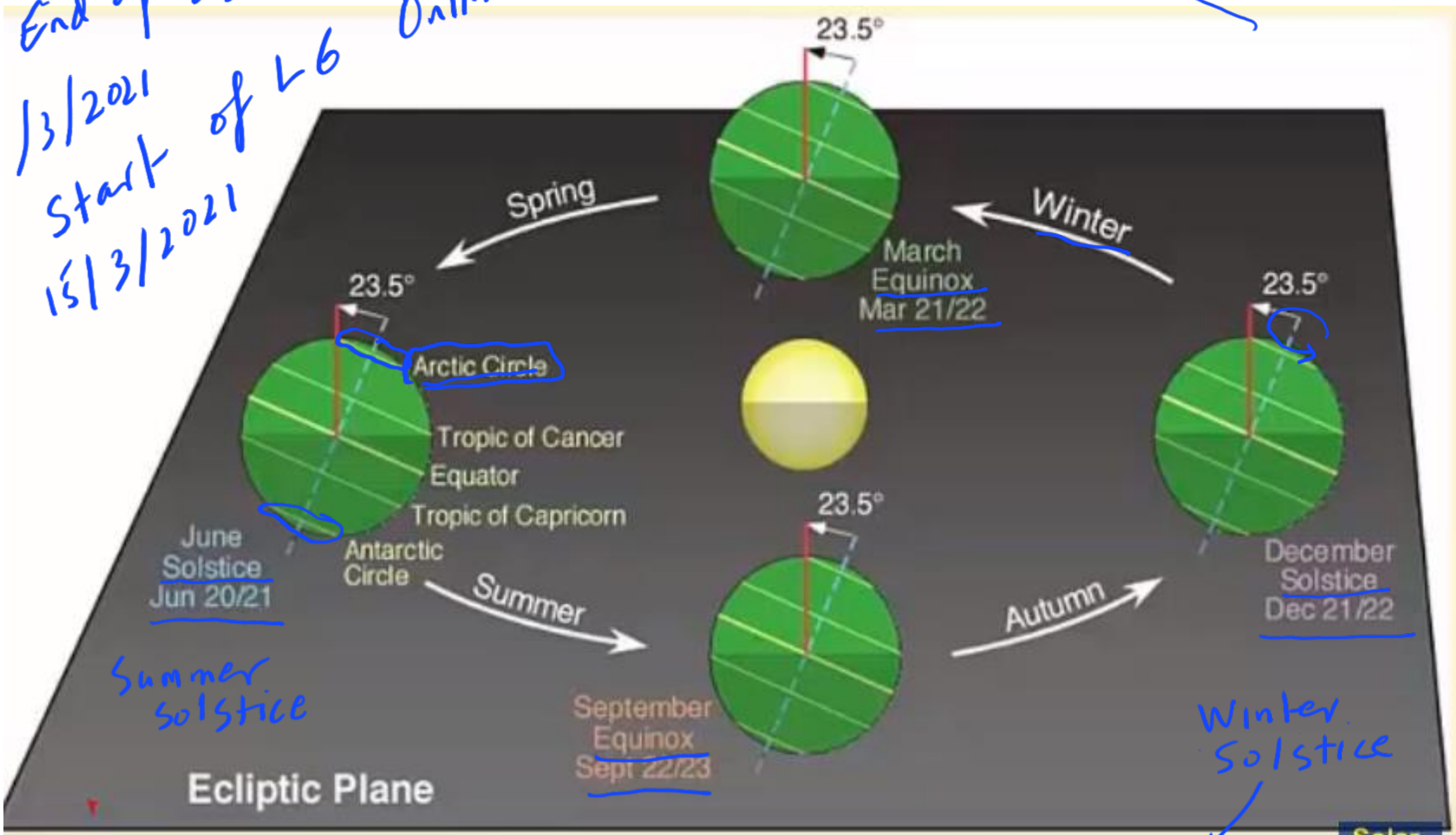







Axis of the earth

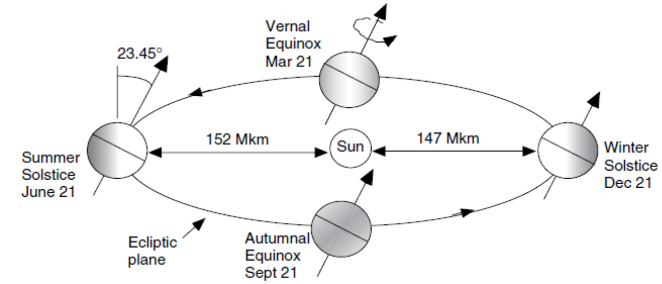
End of L5
10/3/2021
Start of L6 Online
15/3/2021



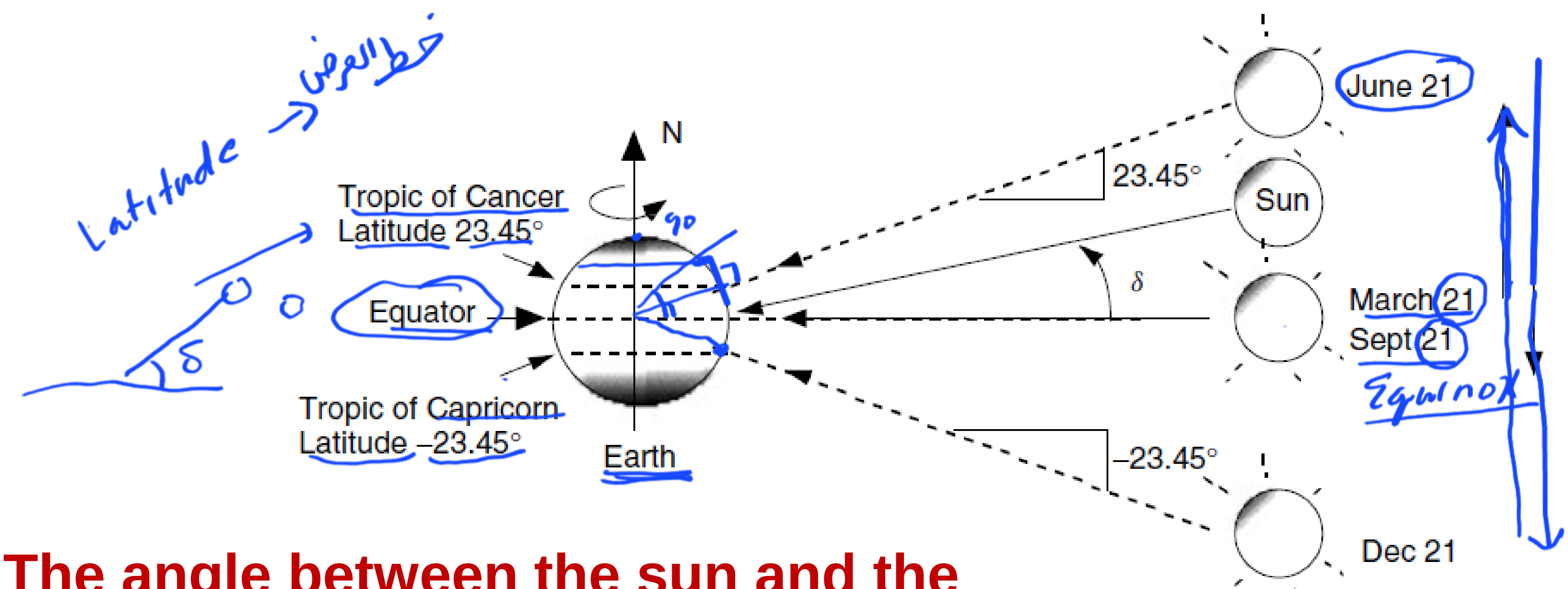
ALTITUDE ANGLE OF THE SUN AT SOLAR NOON

- We all know that the sun rises in the east and sets in the west and reaches its highest point sometime in the middle of the day.
- In many situations, **it is quite useful to be able to predict exactly where in the sky the sun will be at any time, at any location on any day of the year**.
- *In the context of photovoltaics, we can, for example, use knowledge of solar angles to help pick the best tilt angle for our modules to expose them to the greatest insolation.*

- This figure is difficult to use when trying to determine various solar angles as seen from the earth.



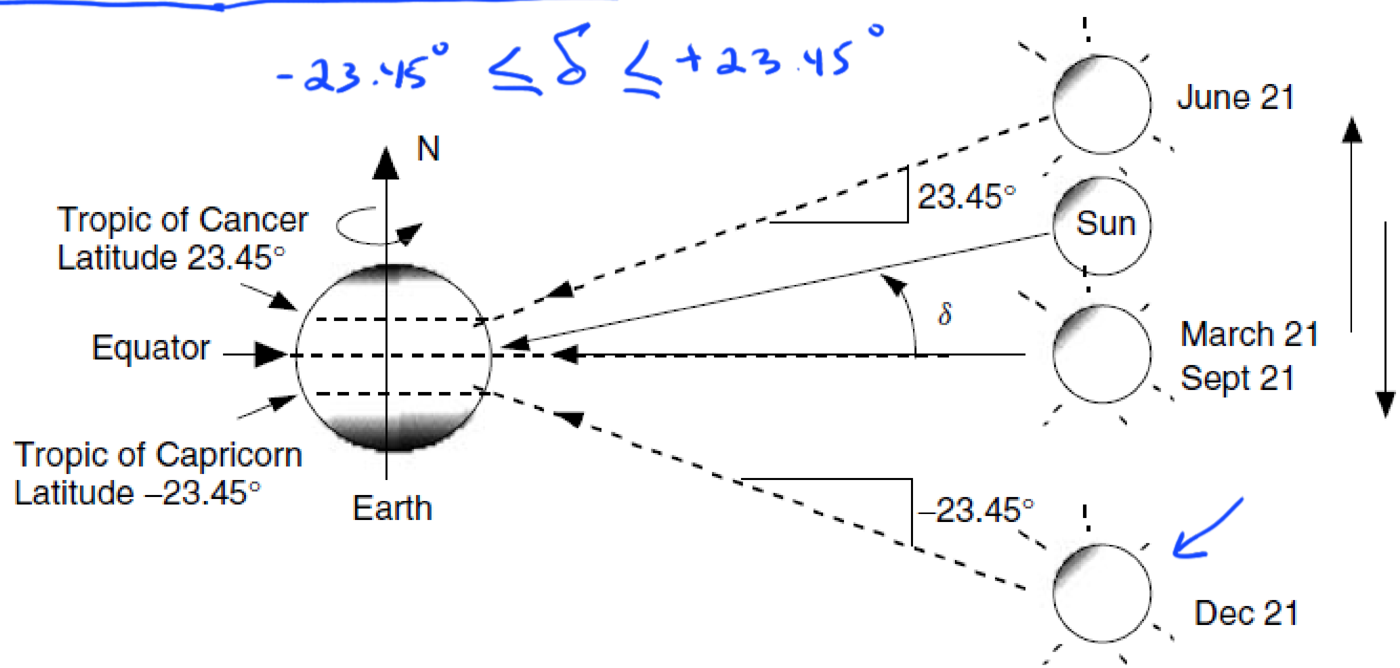
- An alternative (and ancient!) perspective is shown next in which the earth is fixed, spinning around its north–south axis; the sun sits somewhere out in space, slowly moving up and down as the seasons progress.



The angle between the sun and the equator is called the solar declination *δ*.

- On June 21 (the summer solstice) the sun reaches its highest point, and a ray drawn at that time from the center of the sun to the center of the earth makes an angle of 23.45° with the earth's equator.
- On that day, the sun is directly over the Tropic of Cancer at latitude 23.45°.
- At the two equinoxes, the sun is directly over the equator.
- On December 21 the sun is 23.45° below the equator, which defines the latitude known as the Tropic of Capricorn.

$$-23.45^\circ \leq \delta \leq +23.45^\circ$$



- The solar declination angle , δ varies between the extremes of ± 23.45°, and a simple sinusoidal relationship that assumes a 365-day year and which puts the spring equinox on day $n = 81$ provides a very good approximation.

1/1 → n = 1 → table
21/3 → n = 81

- Exact values of declination, which vary slightly from year to year, can be found in the annual publication *The American Ephemeris and Nautical Almanac*.

*

$$\boxed{\delta = 23.45 \sin\left[\frac{360}{365}(n-81)\right]}$$

TABLE 7.2 Solar Declination δ for the 21st Day of Each Month (degrees)

	21	21	21	21	21	21	21	21	21	21	21	21
Month:	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sept	Oct	Nov	Dec
δ:	−20.1	−11.2	0.0	11.6	20.1	23.4	20.4	11.8	0.0	−11.8	−20.4	−23.4

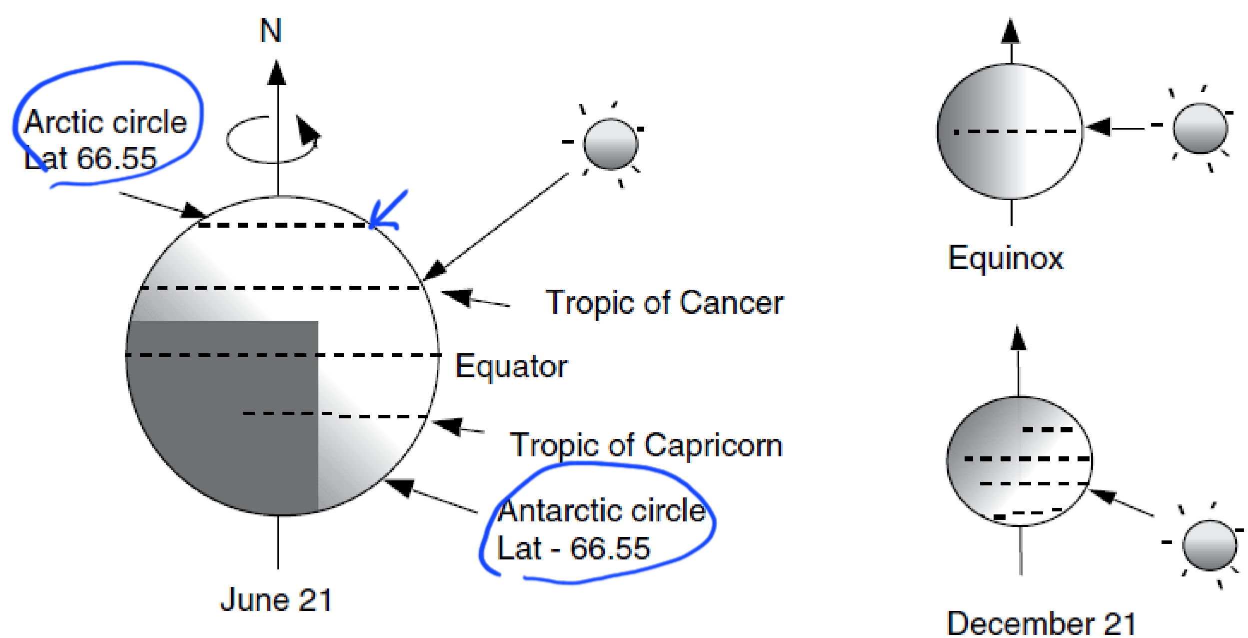
* must remember 1) 2) max 3) 4) min

21/June in the Northern part

- During the summer solstice all of the earth’s surface above latitude 66.55◦ (90◦ − 23.45◦) have 24 hours of daylight,

الغسق الجوني   الليالي البيضاء

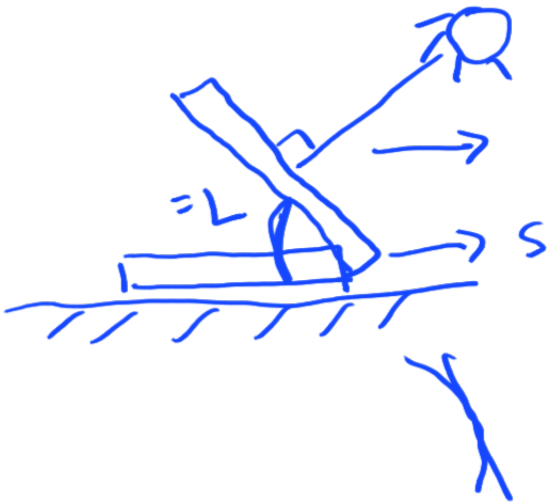
- While in the Southern Hemisphere below latitude 66.55◦ it is continuously dark.
- Those latitudes, of course, correspond to the Arctic and Antarctic Circles.

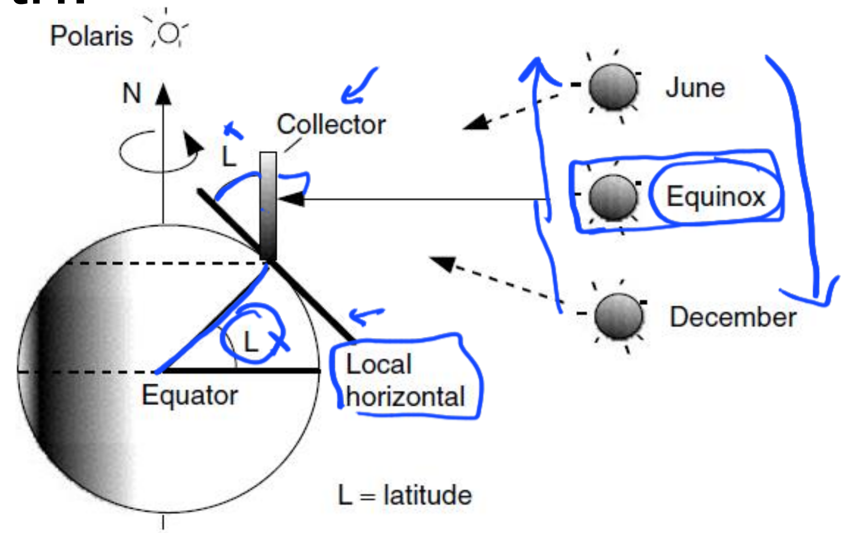


- Figure below shows a south-facing collector on the earth's surface that is tipped up (tilted) at an angle equal to the local latitude, L.

خط العرض الاردن $31.5°$ N

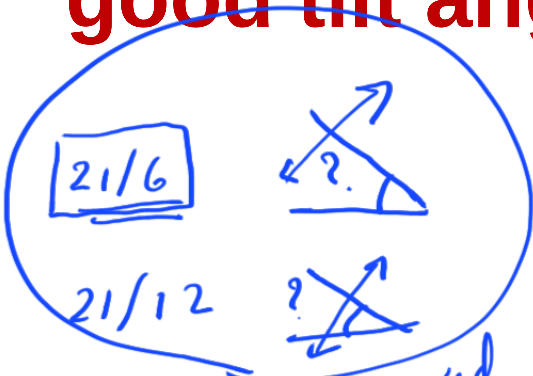
- As can be seen, with this tilt angle the collector is parallel to the axis of the earth.



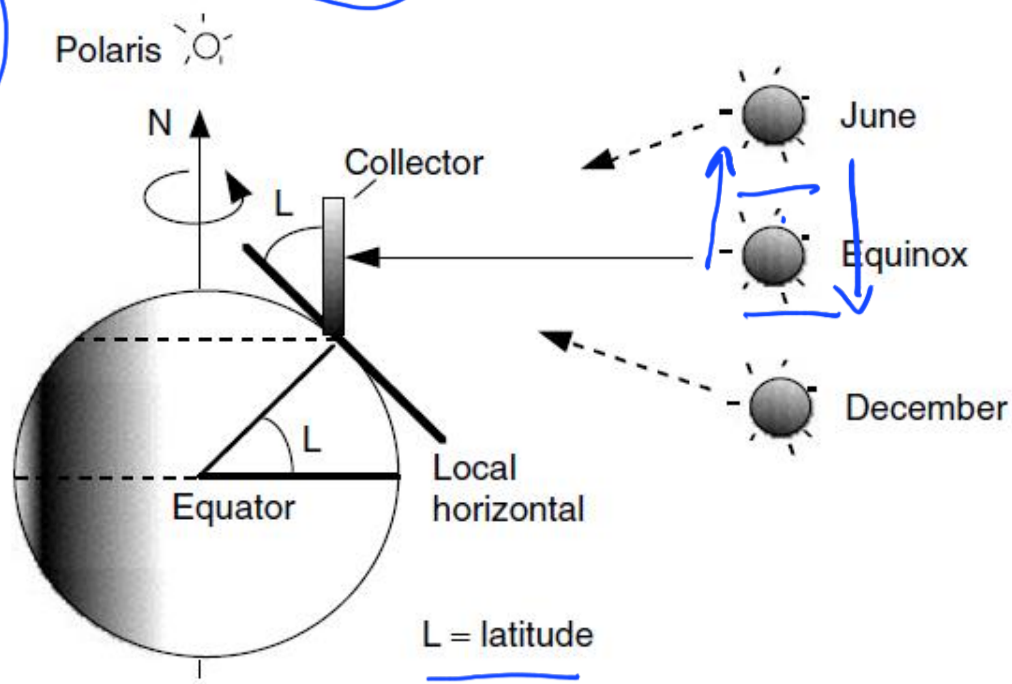


- During an equinox, at *solar noon*, when the sun is directly over the local meridian (line of longitude), the sun's rays will strike the collector at the best possible angle; that is, they are perpendicular to the collector face.

- **At other times of the year the sun is a little high or a little low for normal incidence, but on the average it would seem to be a good tilt angle.**



to be answered later



Solar Noon

- Solar noon is an important reference point for almost all solar calculations.

23.45°

- In the Northern Hemisphere, at latitudes above the Tropic of Cancer, solar noon occurs when the sun is due south of the observer.
- South of the Tropic of Capricorn, in New Zealand for example, it is when the sun is due north.
- And in the tropics, the sun may be either due north, due south, or directly overhead at solar noon.

Solar Noon *(very important)*

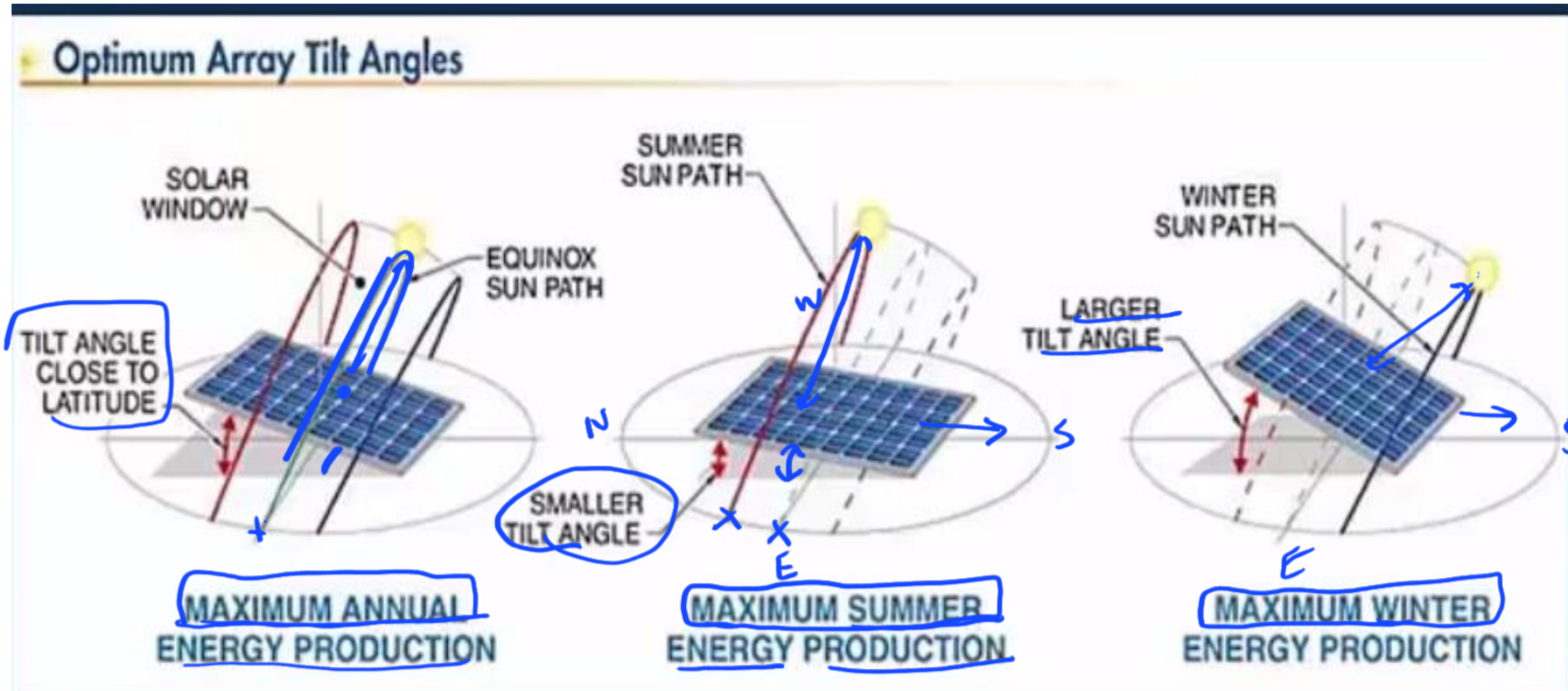
- 1) On the average, facing a collector toward the equator (for most of us in the Northern Hemisphere, this means facing it south)

tilt = L

- 2) and tilting it up at an angle equal to the local latitude is a good rule-of-thumb for average annual performance.
- Of course, if you want to emphasize winter collection, ***you might want a slightly higher angle, and vice versa for increased summer efficiency.***

الشتاء tilt > L

الصيف tilt < L

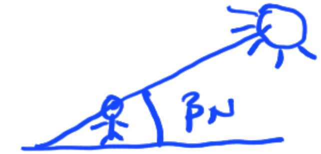


1) tilt = L

2) tilt < latitude = L

3) tilt > L

local Latitude
خط العرض

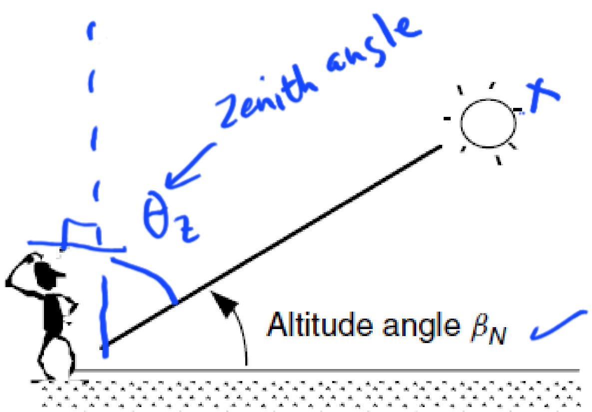


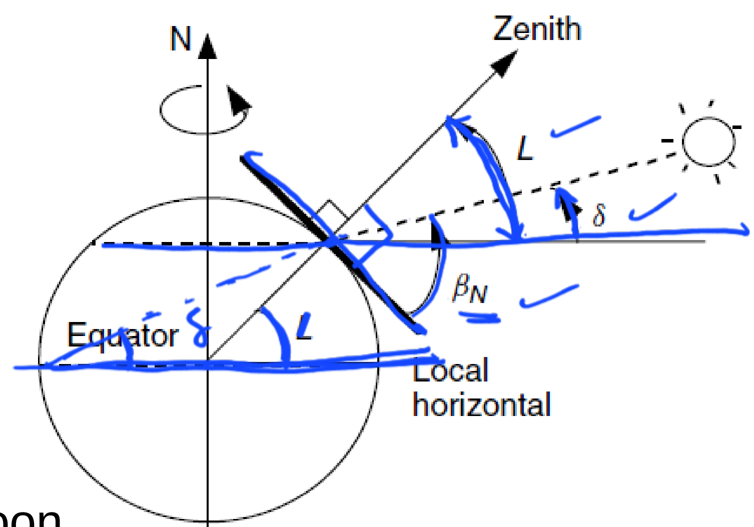
Altitude Angle β_N

- The *altitude angle* β_N is the angle between the sun and the local horizon directly beneath the sun. From Fig. we can write down the following relationship by inspection:

$$\boxed{\beta_N = 90^\circ - L + \delta}$$

- where L is the latitude of the site.
- **Notice in the figure the term *zenith* is introduced, which refers to an axis drawn directly overhead at a site.**





The altitude angle of the sun at solar noon

Tilt Angle of a PV Module

- Find the optimum tilt angle for a south-facing photovoltaic module in Tucson (latitude 32.1°) at solar noon on March 1. → 21/3 march $\delta = 0$
- ***Solution.*** March 1 is the sixtieth day of the year so the solar declination is

n=60

1/1 … 31/1

n: 1 … 31

$$\delta = 23.45 \sin\left[\frac{360}{365}(n - 81)\right] = 23.45^\circ \sin\left[\frac{360}{365}(60 - 81)^\circ\right] = -8.3^\circ$$

-21.8

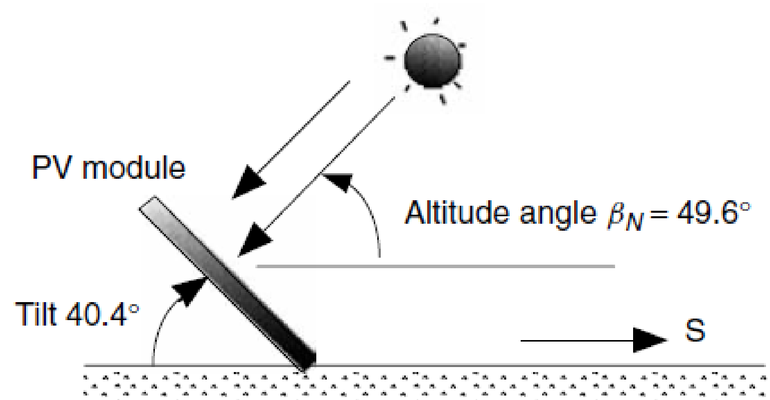
- The altitude angle of the sun equal to

$$\boxed{\beta N = 90^\circ - L + \delta} = 90 - 32.1 - 8.3 = 49.6^\circ$$

0 58

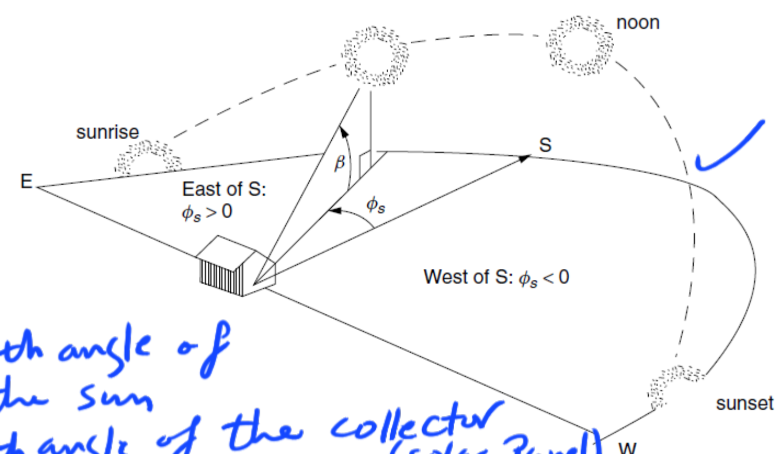
- The tilt angle that would make the sun's rays perpendicular to the module at noon would therefore be

$$\boxed{\text{Tilt} = 90 - \beta N} = 90 - 49.6 = 40.4$$



SOLAR POSITION AT ANY TIME OF DAY

- The location of the sun at any time of day can be described in terms of its ***altitude angle β*** and its ***azimuth angle*** of the sun ***φ_s*** as shown
- The subscript *s* in the azimuth angle helps us remember that this is the azimuth angle of the sun.
- Later, we will introduce another azimuth angle for the solar collector and a different subscript *c* will be used.
- ***By convention, the azimuth angle is positive in the morning with the sun in the east and negative in the afternoon with the sun in the west.***

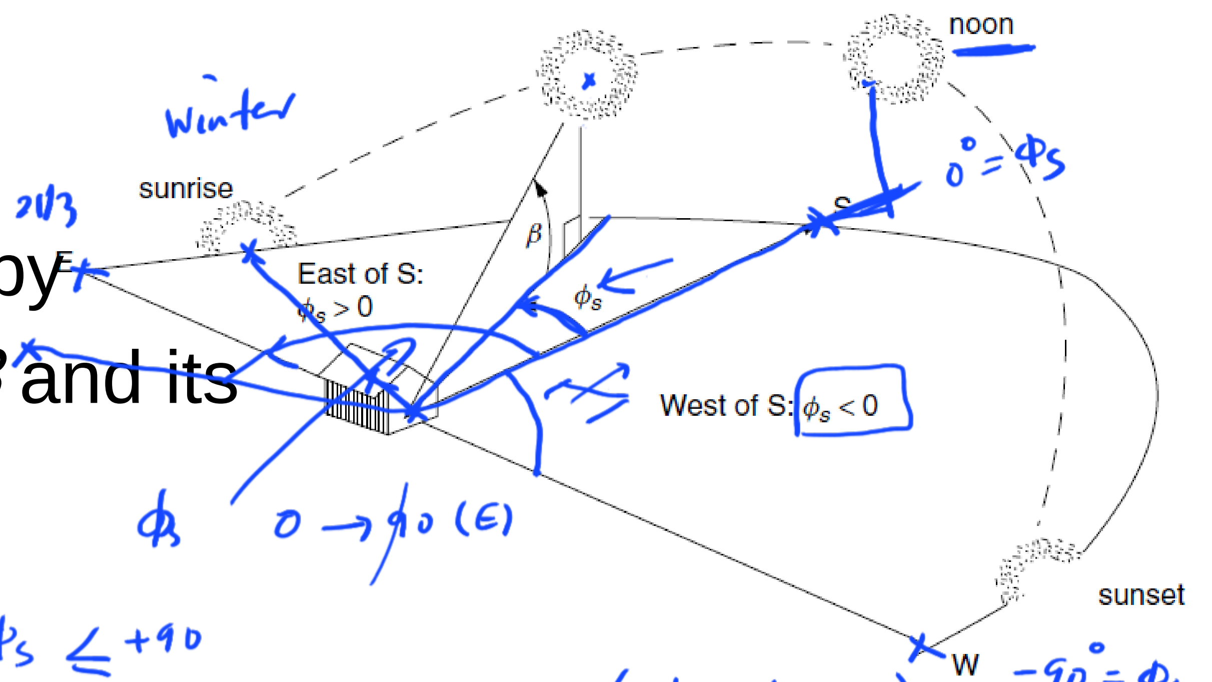


$\Phi_s \rightarrow$ Azimuth angle of the sun

$\Phi_c \rightarrow$ Azimuth angle of the collector (solar Panel)

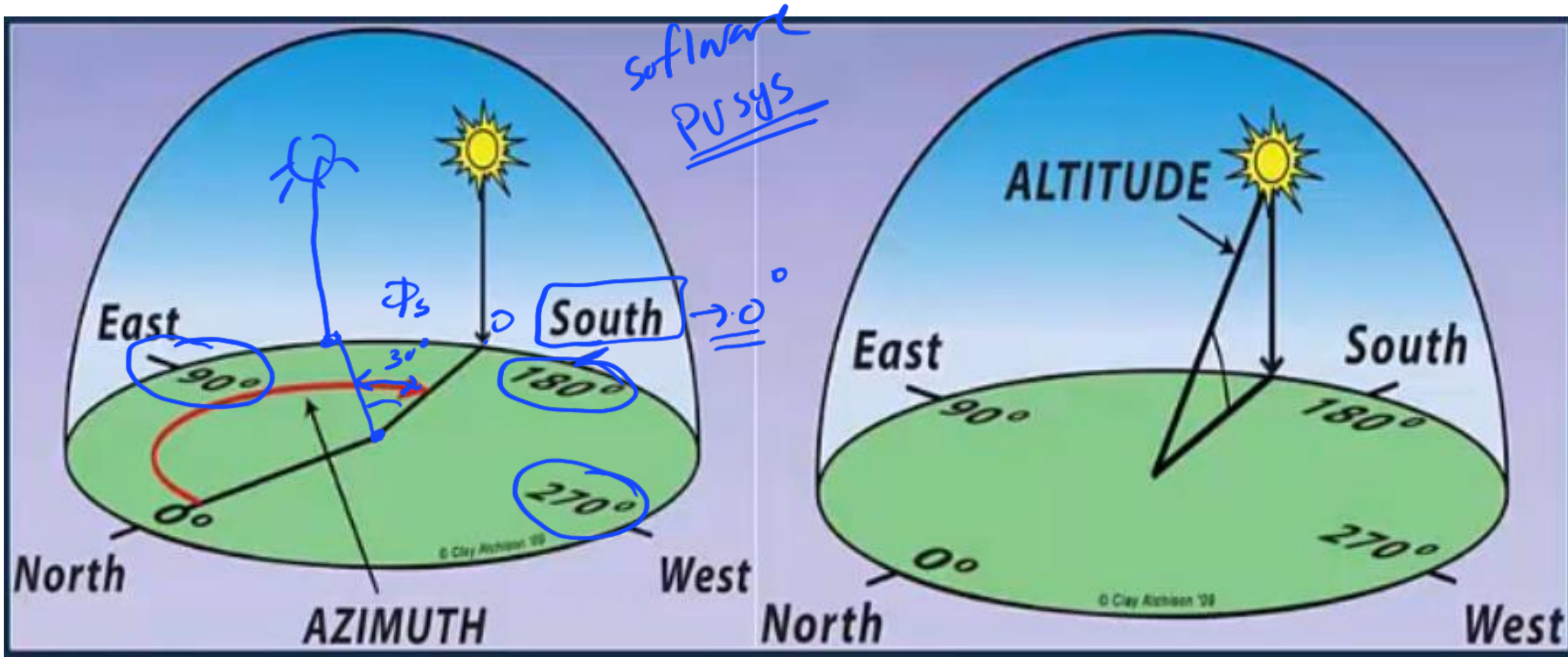
SOLAR POSITION AT ANY TIME OF DAY

- Notice that the azimuth angle shown in Figure uses true south as its reference, and this will be the assumption in this course unless otherwise stated.
- For solar work in the Southern Hemisphere, azimuth angles are measured relative to north.
- The sun's position can be described by its altitude angle β and its azimuth angle φ_s.



21/3 → $-90 \leq \phi_s \leq +90$

$\frac{180^\circ}{15} = 12$ hour of sun (day length)



End of L6 15/3/2021

Start of L7 Online 17/3/2021

Azimuth and Altitude angles of the sun

- The azimuth and altitude angles of the sun depend on the latitude, day number, and, most importantly, the time of day.
- For now, we will express time as the number of hours before or after solar noon.
- Thus, for example, 11 A.M. *solar time* is one hour before the sun crosses your local meridian
- Later we will learn how to make the adjustment between solar time and local clock time.
- The following two equations (next slide) allow us to compute the altitude and azimuth angles of the sun.

Hour Angle

$\frac{1440}{360} = 4$ min

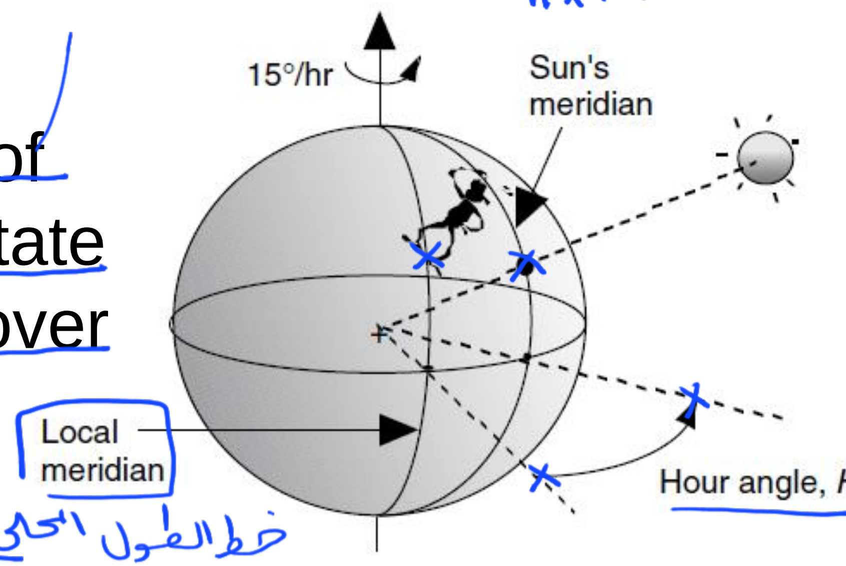
360 line

24 h

$24 \times 60 = 1440$ Min

h × min

- Notice that time in these equations is expressed by a quantity called the *hour angle*, *H*.
- The hour angle is the number of degrees that the earth must rotate before the sun will be directly over your local meridian (line of longitude). خطوط الطول
- As shown in Figure, at any instant, the sun is directly over a particular line of longitude, called the sun's meridian.



خط الطول المحلي

latitude

solar declination angle

altitude angle

$$\sin\beta = \cos L \cos\delta \cos H + \sin L \sin\delta$$

Hour angle

Azimuth angle of the sun

$$\sin\phi_S = \frac{\cos\delta \sin H}{\cos\beta}$$

Hour Angle

- The difference between the local meridian and the sun's meridian is the hour angle, with positive values occurring in the morning before the sun crosses the local meridian.
- * Considering the earth to rotate 360° in 24 h, or 15°/h, the hour angle can be described as follows:

12:00

$$\text{Hour angle } H = \left(\frac{15^\circ}{\text{hour}}\right) \times (\text{hours before solar noon})$$

$H = \frac{15^\circ}{h} \times 1h = +15^\circ$

- Thus, the hour angle H at $\boxed{\text{11:00 A.M}}$. solar time would be $+15^\circ$ (the earth needs to rotate another 15°, or 1 hour, before it is solar noon).

14:00

$H = \frac{15^\circ}{h} \times (-2h) = -30^\circ$

- In the afternoon, the hour angle is negative, so, for example, at $\boxed{\text{2:00 P.M}}$. solar time H would be -30°.

Hour Angle

- There is a slight complication associated with finding the azimuth angle of the sun from

$$\sin\beta = \cos L \cos\delta \cos H + \sin L \sin\delta$$

$$\sin\phi_S = \frac{\cos\delta \sin H}{\cos\beta}$$

ϕ_s ?

- During spring and summer in the early morning and late afternoon, the magnitude of the sun's azimuth is liable to be more than 90◦ away from south (that never happens in the fall and winter).

- Since the inverse of a sine is ambiguous, $\boxed{\sin x = \sin(180 - x)}$, we need a test to determine whether to conclude the azimuth is greater than or less than 90◦ away from south.
- Such a test is

$$\text{if} \quad \boxed{\cos H \ge \frac{\tan\delta}{\tan L},} \qquad \text{then } |\phi_S| \le 90^\circ; \qquad \text{otherwise } |\phi_S| > 90^\circ$$

Example : where is the sun?

Find the altitude β angle and azimuth angle for the sun ϕ_s at 3:00 P.M. solar time in Istanbul, Turkey (latitude ~40◦) on the summer solstice. (June 21st)

- **Solution:** Since it is the solstice we know, without computing, that the solar declination $\boxed{\delta \text{ is } 23.45^\circ}$.
- Since 3:00 P.M. is three hours after solar noon, we obtain

$$H = \left(\frac{15^\circ}{\text{h}}\right) \cdot (\text{hours before solar noon}) = \frac{15^\circ}{\text{h}} \cdot (-3\ \text{h}) = -45^\circ$$

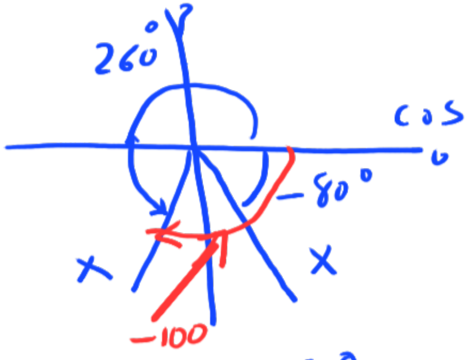
- The altitude angle β

$$\sin\beta = \cos L \cos\delta \cos H + \sin L \sin\delta$$

$$= \cos 40^\circ \cos 23.45^\circ \cos(-45^\circ) + \sin 40^\circ \sin 23.45^\circ = 0.7527$$

$$\beta = \sin^{-1}(0.7527) = 48.8^\circ$$

Sin $= 180-(-80)$



- the sine of the azimuth angle is

$$\sin\phi_S = \frac{\cos\delta \sin H}{\cos\beta}$$

$$= \frac{\cos 23.45^\circ \cdot \sin(-45^\circ)}{\cos 48.8^\circ} = -0.9848$$

$\rightarrow -80$

- But the arcsine is ambiguous and two possibilities exist:

$$\phi_S = \sin^{-1}(-0.9848) = -80^\circ$$

$$\text{or} \quad \phi_S = 180 - (-80) = 260^\circ$$

- To decide which of these two options is correct

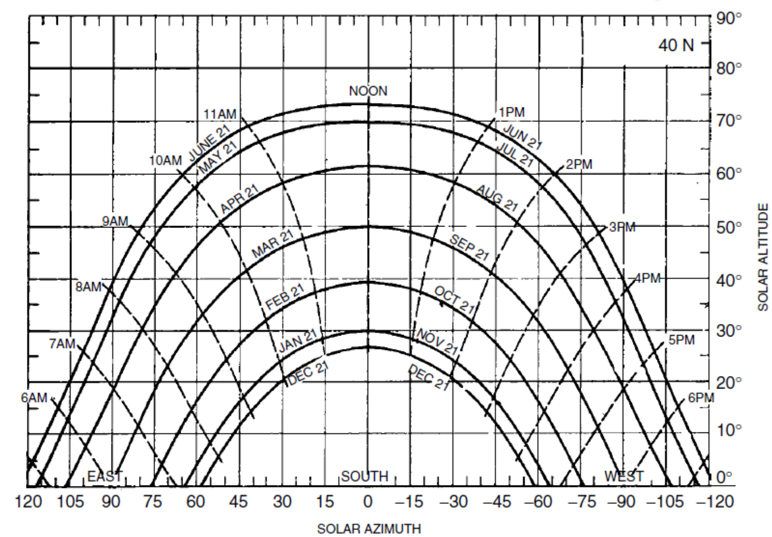
$$\cos H = \cos(-45^\circ) = 0.707 \qquad \text{and} \qquad \boxed{\frac{\tan\delta}{\tan L}} = \frac{\tan 23.45^\circ}{\tan 40^\circ} = 0.517$$

Since $\boxed{\cos H \geq \dfrac{\tan\delta}{\tan L}}$ we conclude that the azimuth angle is

$$\phi_S = -80^\circ \qquad (80^\circ \text{west of south})$$

- Solar altitude and azimuth angles for a given latitude can be conveniently portrayed in graphical form, (sun path diagram) in which solar altitude and azimuth angles for 40◦ latitude is shown
- Similar sun path diagrams for other latitudes are available.
- As can be seen, in the spring and summer the sun rises and sets slightly to the north and our need for the azimuth test

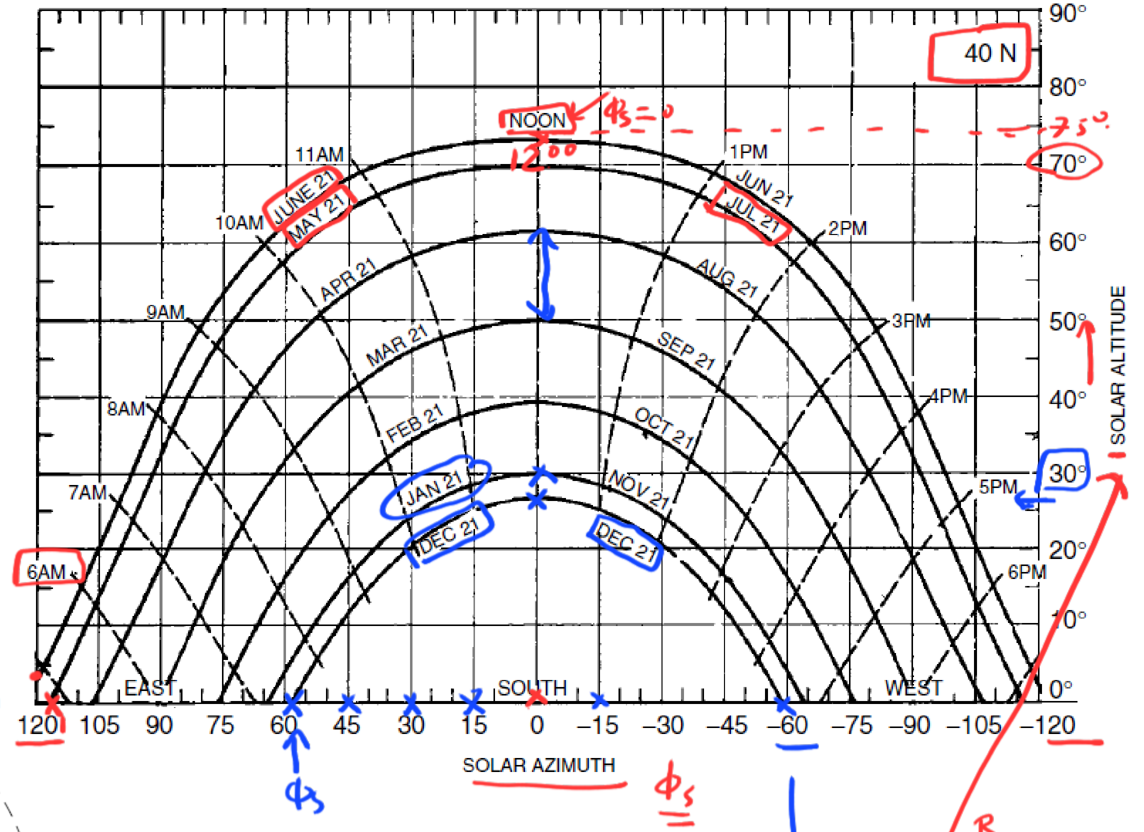
given previously is apparent;



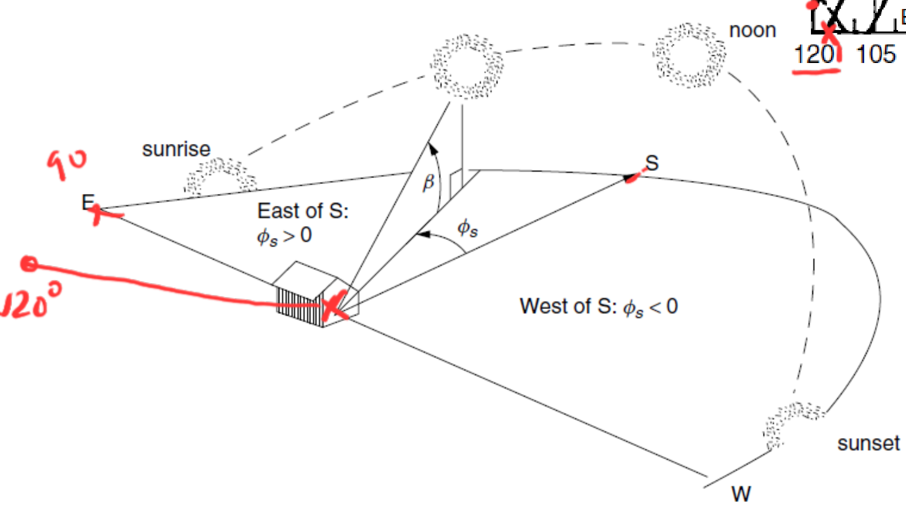
- at the equinoxes, it rises and sets precisely due east and due west (everywhere on the planet);
- during the fall and winter the azimuth angle of the sun is never greater than 90°.

Sun-path Diagram

time of the Day

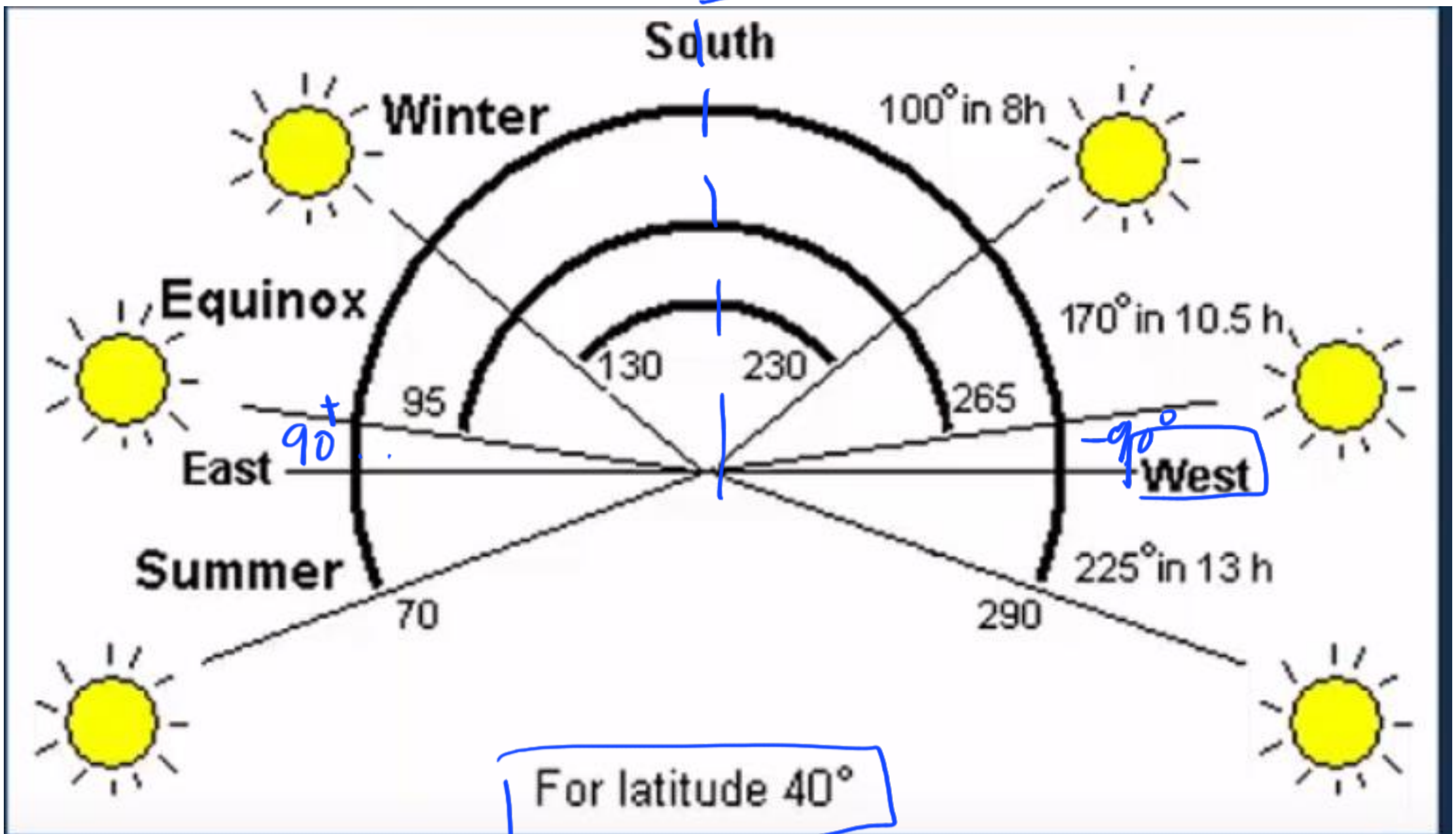


طول النهار



0°

X
180° → PVsys



South
Winter
100° in 8h
Equinox
170° in 10.5 h
130
230
95
265
90°
-90°
East
West
Summer
225° in 13 h
70
290
For latitude 40°

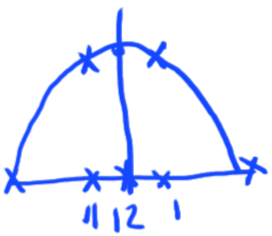
SUN PATH DIAGRAMS FOR SHADING ANALYSIS

will not be covered for Now

- Sun Path Diagrams also have a very practical application in the field when trying to predict shading patterns at a site—a very important consideration for photovoltaics, which are very shadow sensitive.
- The concept is simple. What is needed is a sketch of the azimuth and altitude angles for trees, buildings, and other obstructions along the southerly horizon that can be drawn on top of a sun path diagram.
- Sections of the sun path diagram that are covered by the obstructions indicate periods of time when the sun will be behind the obstruction and the site will be shaded.
- There are several site assessment products available on the market that make the superposition of obstructions onto a sun path diagram pretty quick and easy to obtain.

- Table below shows an example of the hour-by-hour insolation available on a clear day in January at 40° latitude for south-facing collectors with fixed tilt angle, or for collectors mounted on 1-axis or 2-axis tracking systems.
- The equations that were used to compute this table will be presented later,

TABLE 7.3 Clear Sky Beam Plus Diffuse Insolation at 40° Latitude in January for South-Facing Collectors with Fixed Tilt Angle and for Tracking Mounts (hourly W/m^2 and daily kWh/m^2-day)[a]



Solar Time	Tracking		Tilt Angles				Latitude 40°		
	One-Axis	Two-Axis	0	20	30	40	50	60	90
			January 21					(W/m^2)	
7, 5	0	0	0	0	0	0	0	0	0
8, 4	439	462	87	169	204	232	254	269	266
9, 3	744	784	260	424	489	540	575	593	544
10, 2	857	903	397	609	689	749	788	803	708
11, 1	905	954	485	722	811	876	915	927	801
12	919	968	515	761	852	919	958	968	832
kWh/d:	6.81	7.17	2.97	4.61	5.24	5.71	6.02	6.15	5.47

Winter

will be visited again

SOLAR TIME AND CIVIL (CLOCK) TIME

$CT \xrightarrow{\text{تحويل}} ST$

- For most solar work it is common to deal exclusively in solar time (ST), where everything is measured relative to solar noon (when the sun is on our line of longitude).
- There are occasions, however, when local time, called civil time or clock time (CT), is needed.
- There are two adjustments that must be made in order to connect local clock time and solar time.

360

4/min

- ***The first is a longitude adjustment*** that has to do with the way in which regions of the world are divided into time zones.
- ***The second is a little factor*** that needs to be thrown in to account for the uneven way in which the earth moves around the sun.

SOLAR TIME AND CIVIL (CLOCK) TIME

- Obviously, it just wouldn't work for each of us to set our watches to show noon when the sun is on our own line of longitude.
- Since the earth rotates 15◦ per hour (4 minutes per degree), for every degree of longitude between one location and another, clocks showing solar time would have to differ by 4 minutes.
- To deal with these longitude complications, the earth is nominally divided into 24 1-hour time zones, with each time zone ideally spanning 15◦ of longitude.

Local Time

- Each time zone is defined by a *Local Time Meridian* located, ideally, in the middle of the zone, with the origin of this time system passing through Greenwich, England, at 0° longitude.
- The longitude correction between local clock time and solar time is based on the time it takes for the sun to travel between the local time meridian and the observer's line of longitude.
- If it is solar noon on the local time meridian, it will be solar noon 4 minutes later for every degree that the observer is west of that meridian.

- For example, San Francisco, at longitude 122°, will have solar noon 8 minutes after the sun crosses the 120° Local Time Meridian for the Pacific Time Zone.

Equation of Time

- The second adjustment between solar time and local clock time is the result of the earth's elliptical orbit, which causes the length of a *solar day* (solar noon to solar noon) to vary throughout the year.
- As the earth moves through its orbit , the difference between a 24-hour day and a solar day changes following an expression known as the *Equation of Time*, *E*:

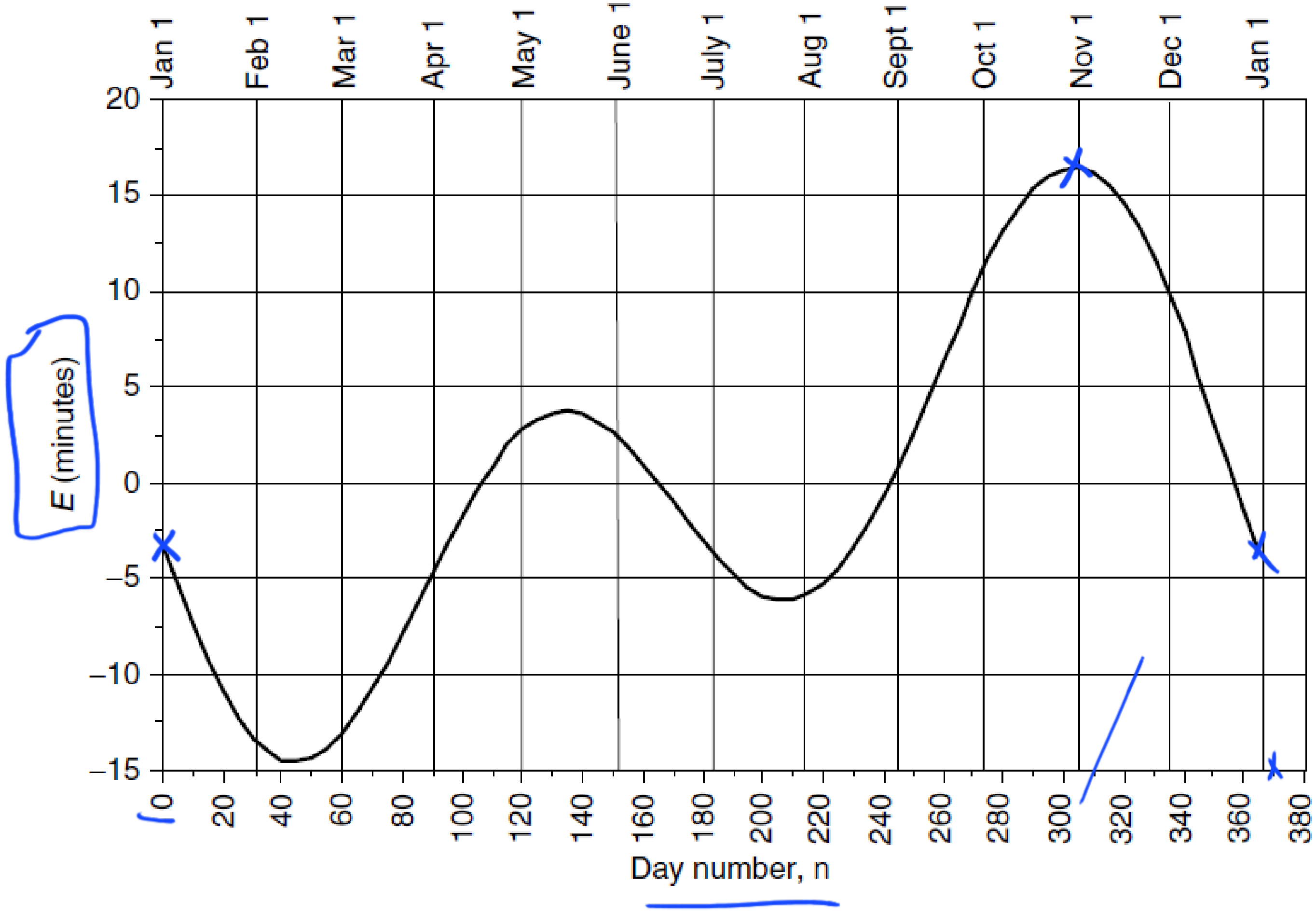
$$\boxed{E = 9.87 \sin 2B - 7.53 \cos B - 1.5 \sin B} \qquad \text{(minutes)}$$

where

$$B = \frac{360}{364}(n - 81) \qquad \text{(degrees)}$$

day number

Equation of Time



The Equation of Time adjusts for the earth's tilt angle and noncircular orbit.

- Putting together the longitude correction and the Equation of Time gives us the final relationship between local standard clock time (CT) and solar time (ST).

$$\text{Solar Time (ST)} = \text{Clock Time (CT)} + \frac{4\ \text{min}}{\text{degree}}(\text{Local Time Meridian} - \text{Local longitude})^{\circ} + E(\text{min}) \quad ($$

- When Daylight Savings Time is in effect, one hour must be added to the local clock time ("Spring ahead, Fall back").

SUNRISE AND SUNSET

$\beta \leftarrow$ altitude angle ?

- A sun path diagram, can be used to locate the azimuth angles and approximate times of sunrise and sunset.
- A more careful estimate of sunrise/sunset can be found
- At sunrise and sunset, $\boxed{\text{the altitude angle } \beta \text{ is zero,}}$ so we can write

$$\sin\beta = \cos L \cos\delta \cos H + \sin L \sin\delta = \underline{0}$$

H_{SS}?

H_{SR}?

$$\cos H = -\frac{\sin L \sin\delta}{\cos L \cos\delta} = -\underline{\tan L \tan\delta}$$

- Solving for the hour angle at sunrise, *HSR*, gives

$$H_{SR} = \cos^{-1}(-\underline{\tan L \tan\delta}) \qquad (+ \text{ for } \underline{\text{sunrise}})$$

- Notice that since the inverse cosine allows for both positive and negative values, we need to use our sign convention, which requires the positive value to be used for sunrise (and the negative for sunset).
- Since the earth rotates 15◦/h, the hour angle can be converted to time of sunrise or sunset using:

degrees

$$\text{Sunrise(geometric)} = 12{:}00 - \frac{H_{SR}}{15^\circ/h}$$

- Another correction factor which is subtracted from sunrise and added to sunset

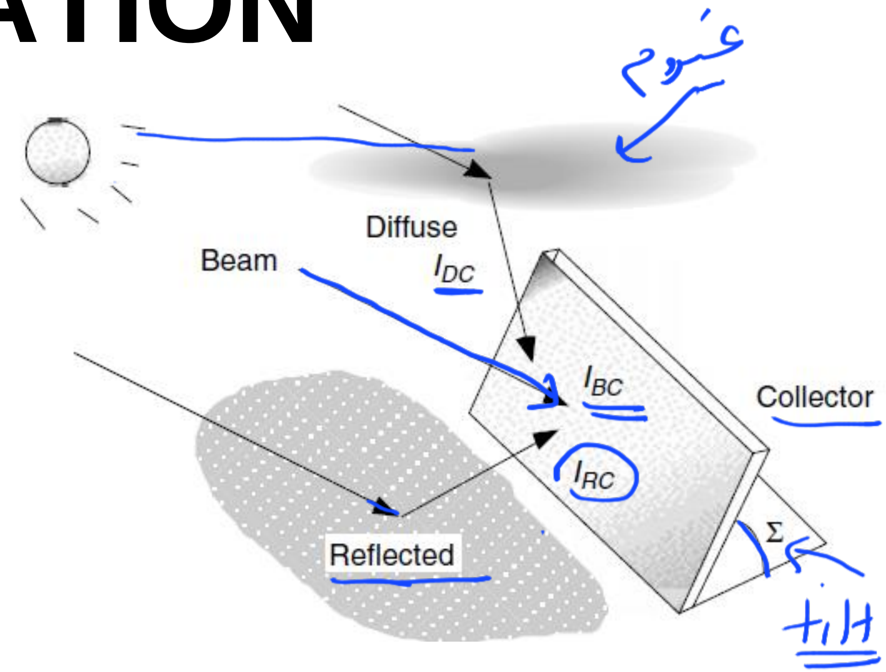
$$Q = \frac{3.467}{\cos L \cos \delta \sin H_{SR}} \qquad (min)$$

Assignment / mini Project
(calculation)

CLEAR SKY DIRECT-BEAM RADIATION

CLEAR SKY DIRECT-BEAM RADIATION

- Solar flux striking a collector (I_C) will be a combination of :
  - *Direct-beam* radiation that passes in a straight line through the atmosphere to the receiver (I_{BC}),
  - *Diffuse* radiation that has been scattered by molecules and aerosols in the atmosphere (I_{DC}), and
  - *Reflected* radiation that has bounced off the ground or other surface in front of the collector (I_{RC})

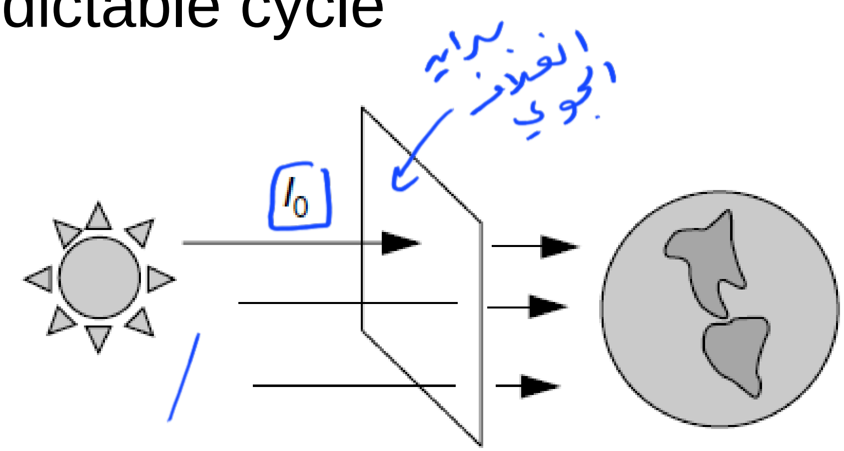


Solar collectors that focus sunlight usually operate on just the beam portion of the incoming radiation since those rays are the only ones that arrive from a consistent direction

- Most photovoltaic systems, however, don't use focusing devices, so all three components—beam, diffuse, and reflected—can contribute to energy collected.
- ***The goal of this discussion is to be able to estimate the rate at which just the beam portion of solar radiation passes through the atmosphere and arrives at the earth's surface on a clear day.***
- Later, the diffuse and reflected radiation will be added to the clear day model.
- And finally, procedures will be presented that will enable more realistic average insolation calculations for specific locations based on empirically derived data for certain given sites.

Extraterrestrial (ET) solar insolation, I_0

- The starting point for a clear sky radiation calculation is with an estimate of the extraterrestrial (ET) solar insolation, I_0, that passes perpendicularly through an imaginary surface just outside of the earth's atmosphere as shown below
- This insolation depends on the distance between the earth and the sun, which varies with the time of year. It also depends on the intensity of the sun, which rises and falls with a fairly predictable cycle



- One expression that is used to describe the day-to-day variation in extraterrestrial solar insolation is the following:

day #

$$I_0 = \mathrm{SC} \cdot \left[1 + 0.034 \cos\left(\frac{360n}{365}\right)\right] \qquad (\mathrm{W/m^2})$$

1377 W/m²

  - ➢ SC is the solar constant and =1.377 kW/m^2
  - ➢ n is day number
- As the beam passes through the atmosphere, a good portion of it is absorbed by various gases in the atmosphere, or scattered by air molecules or particulate matter

- In fact, over a year's time, less than half of the radiation that hits the top of the atmosphere reaches the earth's surface as direct beam.
- On a clear day, however, with the sun high in the sky, beam radiation at the surface can exceed 70% of the extraterrestrial flux.

I_0

- Attenuation of incoming radiation is a function of the distance that the beam has to travel through the atmosphere, which is easily calculable, as well as factors such as dust, air pollution, atmospheric water vapor, and clouds, which are not so easy to account for

- A commonly used model treats attenuation as an exponential decay function:

$$I_B = Ae^{-km}$$ am = m air mass

  - where I_B is the beam portion of the radiation reaching the earth's surface (normal to the rays),
  - A is an "apparent" extraterrestrial flux,
  - and k is a dimensionless factor called the *optical depth*
- The air mass ratio m was introduced earlier as:

Air mass ratio $\boxed{m = \dfrac{1}{\sin\beta}}$

- where β is the altitude angle of the sun.

$$A = 1160 + 75 \sin\left[\frac{360}{365}(n - 275)\right] \quad (\mathrm{W/m^2})$$

$$k = 0.174 + 0.035 \sin\left[\frac{360}{365}(n - 100)\right]$$

where again n is the day number.

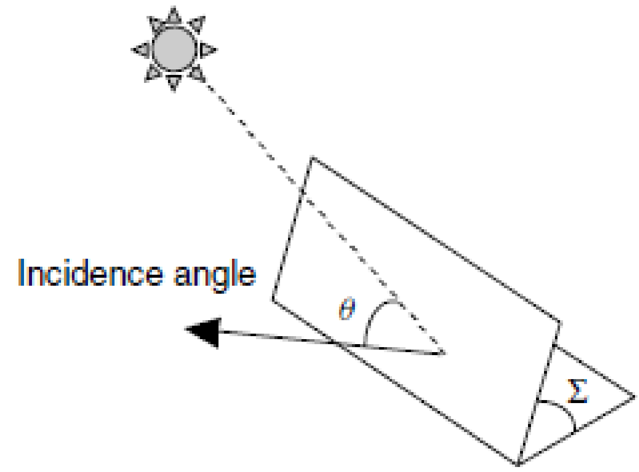
TOTAL CLEAR SKY INSOLATION ON A COLLECTING SURFACE

- Reasonably accurate estimates of the clear sky, direct beam insolation are easy enough to work out and the geometry needed to determine how much of that will strike a collector surface is straightforward.
- It is not so easy to account for the diffuse and reflected insolation but since that energy bonus is a relatively small fraction of the total, even crude models are usually acceptable.

Direct-Beam Radiation

- The translation of direct-beam radiation I_B (normal to the rays) into beam insolation striking a collector face I_{BC} is a simple function of the angle of incidence θ between a line drawn normal to the collector face and the incoming beam radiation
- It is given by:

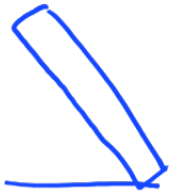
$$I_{BC} = I_B \cos\theta$$



Beam insolation on a horizontal surface I_{BH}

- For the special case of beam insolation on a horizontal surface I_{BH}

$$I_{BH} = I_B \cos(\overbrace{90^\circ - \beta}^{\theta}) = I_B \sin\beta$$



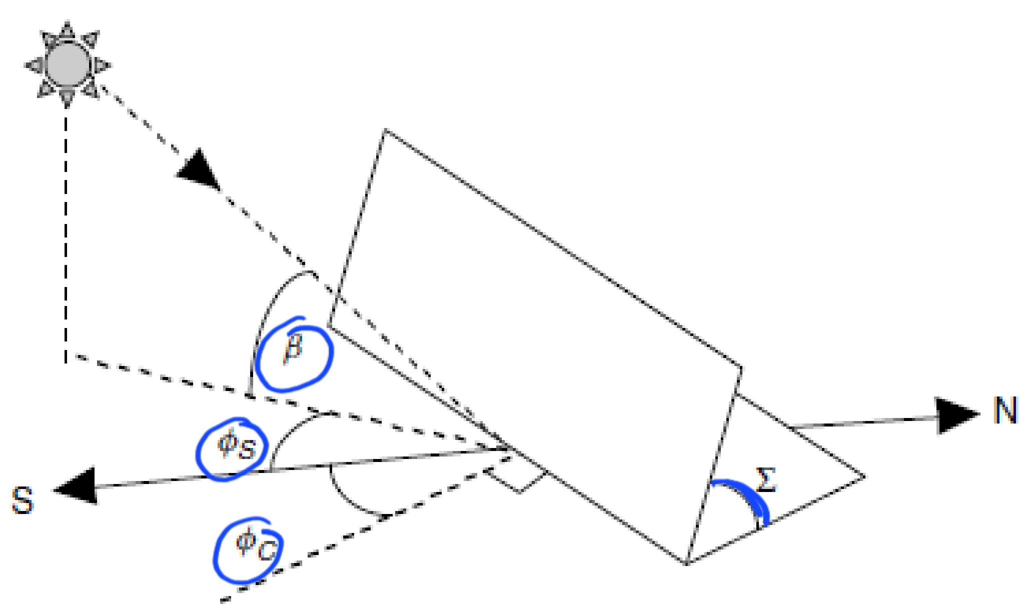
- The angle of incidence θ will be a function of the collector orientation and the altitude and azimuth angles of the sun at any particular time

- The solar collector is tipped up at an angle Σ and faces in a direction described by its azimuth angle φ_C ← fixed. ← not fixed (tracking) (measured relative to due south, *with positive values in the southeast direction and negative values in the southwest*).

ϕ_s

- The incidence angle is given by

$$\cos\theta = \cos\beta\cos(\phi_S - \phi_C)\sin\Sigma + \sin\beta\cos\Sigma$$



Diffuse Radiation

- The diffuse radiation on a collector is much more difficult to estimate accurately than it is for the beam.
- Consider the variety of components that make up diffuse radiation as shown earlier
- Incoming radiation can be scattered from atmospheric particles and moisture, and it can be reflected by clouds.
- Some is reflected from the surface back into the sky and scattered again back to the ground.
- The simplest models of diffuse radiation assume it arrives at a site with equal intensity from all directions; that is, the sky is considered to be *isotropic*.
- Obviously, on hazy or overcast days the sky is considerably brighter in the vicinity of the sun, and measurements show a similar phenomenon on clear days as well, but these complications are often ignored.

Diffuse Radiation

- Diffuse radiation can be scattered by atmospheric particles and moisture or reflected from clouds. Multiple scatterings are possible.

Horizontal collector

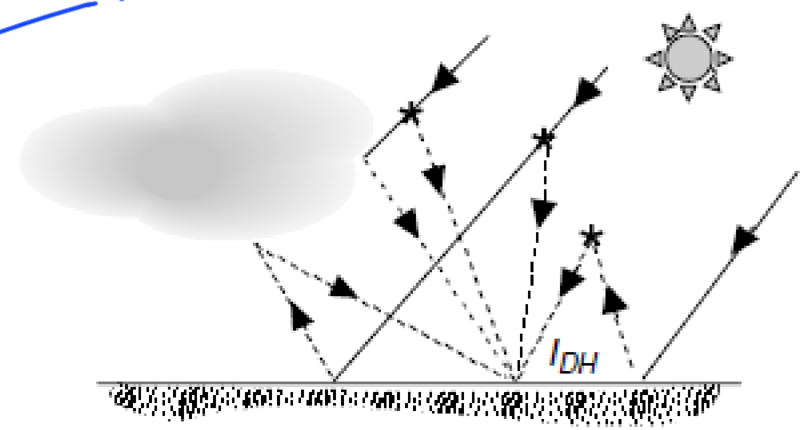
Known

*

$$I_{DH} = C\, I_B$$

- where C is a sky diffuse factor.
- Monthly values of C are given in Tables, and a convenient approximation is as follows:

$$C = 0.095 + 0.04 \sin\left[\frac{360}{365}(n - 100)\right]$$

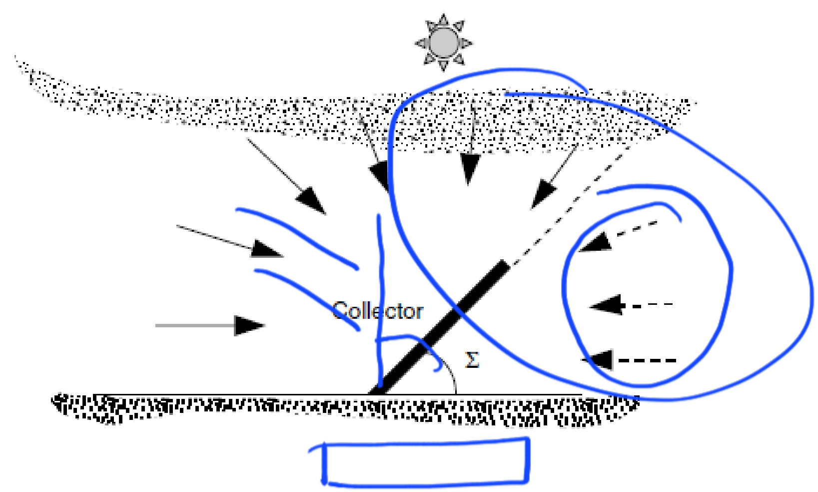


On a day with clear skies previous equation typically predicts that about 15% of the total horizontal insolation on a clear day will be diffuse.

- The following expression for diffuse radiation on the collector, I_{DC}, is used when the diffuse radiation is idealized in this way:

$$I_{DC} = I_{DH}\left(\frac{1+\cos\Sigma}{2}\right) = C\, I_B\left(\frac{1+\cos\Sigma}{2}\right)$$

Diffuse radiation on a collector assumed to be proportional to the fraction of the sky that the collector "sees".



Reflected Radiation

- The final component of insolation striking a collector results from radiation that is reflected by surfaces in front of the panel.
- This reflection can provide a considerable boost in performance, as for example on a bright day with snow or water in front of the collector, or it can be so modest that it might as well be ignored.
- The assumptions needed to model reflected radiation are considerable, and the resulting estimates are very rough indeed.
- The simplest model assumes a large horizontal area in front of the collector, with a reflectance ρ that is diffuse, and it bounces the reflected radiation in equal intensity in all directions, as shown in Fig. 4.24. Clearly this is a very gross assumption, especially if the surface is smooth and bright.

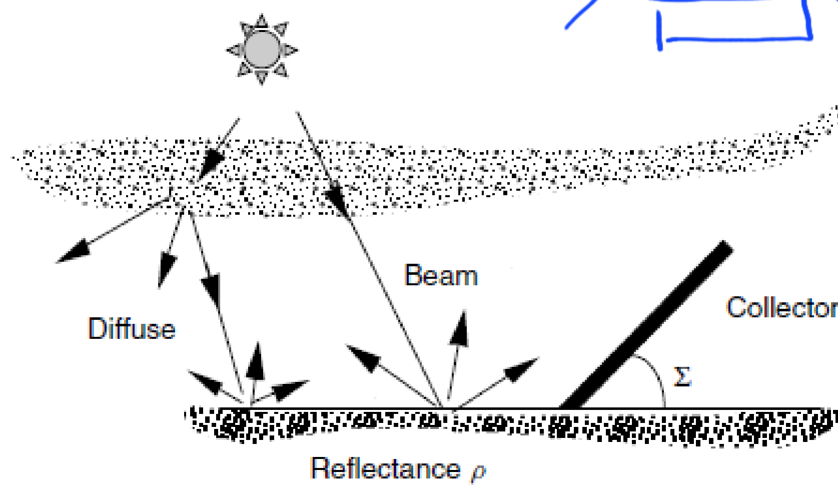
- The amount reflected can be modeled as the product of the total horizontal radiation (beam I_{BH} , plus diffuse I_{DH}) times the ground reflectance ρ.
- The fraction of that ground-reflected energy that will be intercepted by the collector depends on the slope of the panel , resulting in the following expression for reflected radiation striking the collector I_{RC}:

$$I_{RC} = \rho(I_{BH} + I_{DH})\left(\frac{1-\cos\Sigma}{2}\right)$$

- For a horizontal collector ($\Sigma = 0$), $I_{RC}=0$;

- for a vertical panel, it predicts

that the panel "sees" half of the reflected radiation, which also is appropriate for the model.



$$\ast \longrightarrow I_{RC} = \rho I_B(\sin\beta + C)\left(\frac{1-\cos\Sigma}{2}\right)$$

Total Radiation

- Combining the equations for the three components of radiation, direct beam, diffuse and reflected gives the following for total rate at which radiation strikes a collector on a clear day:

ليس للحفظ

$$\boxed{I_C = I_{BC} + I_{DC} + I_{RC}}$$

$$I_C = Ae^{-km}\left[\cos\beta\cos(\phi_S - \phi_C)\sin\Sigma + \sin\beta\cos\Sigma + C\left(\frac{1+\cos\Sigma}{2}\right)\right.$$

$$\left.+\rho(\sin\beta + C)\left(\frac{1-\cos\Sigma}{2}\right)\right]$$

- This a convenient summary, which can be handy when setting up a spreadsheet or other computerized calculation of clear sky insolation.

End of L7

show the next on Wednesday until here 17/3/2021

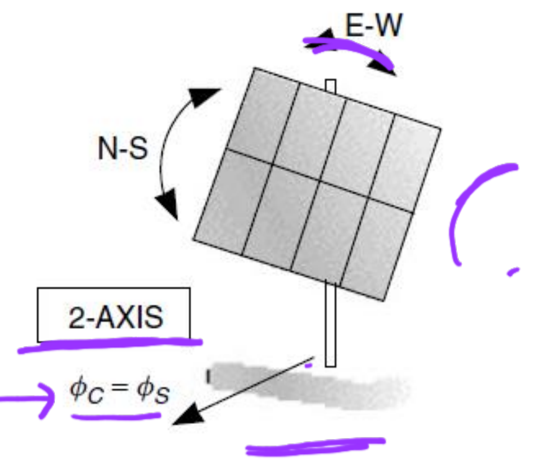
Wednesday 24/3 لحد هنا

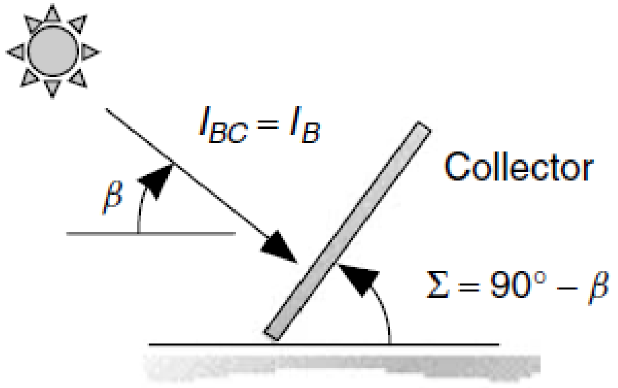
L8 online 22/3/2021

Mechanical Tracking Systems

- Thus far, the assumption has been that the collector is permanently attached to a surface that doesn't move.
- In many circumstances, however, racks that allow the collector to track the movement of the sun across the sky are quite cost effective.
- Trackers are described as being either ***two-axis*** *trackers*, which track the sun both in **azimuth and altitude** angles so the collectors are always pointing directly at the sun, or ***single-axis trackers***, which track only one angle or the other.

1)



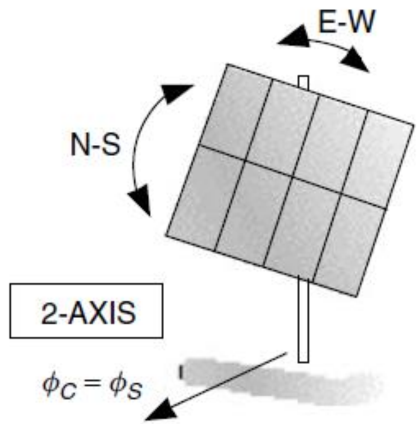


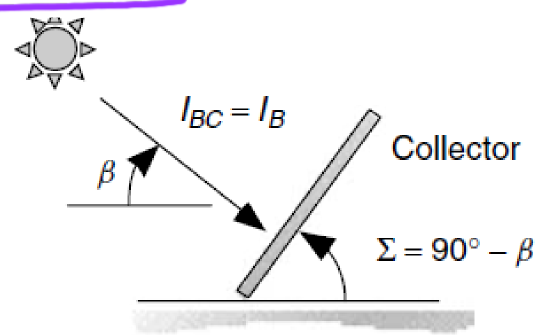
- Calculating the beam plus diffuse insolation on **a two-axis tracker** is quite straightforward:
- The beam radiation on the collector is the full insolation I_B normal to the rays calculated earlier.
- The diffuse and reflected radiation were found earlier with a collector tilt angle equal to the complement of the solar altitude angle, that is, $90^\circ - \beta$.

$$\boxed{I_{BC} = I_B}$$

$$I_{DC} = C I_B \left[\frac{1 + \cos(90^\circ - \beta)}{2}\right]$$

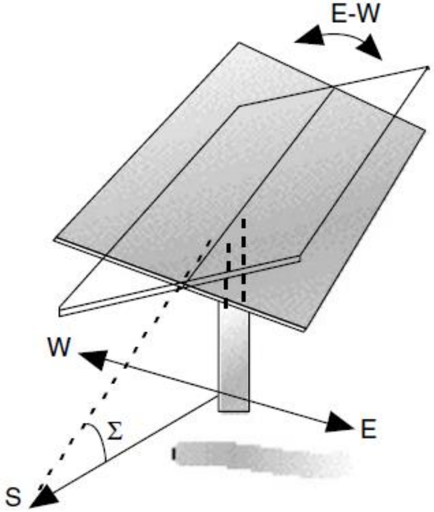
$$I_{RC} = \rho (I_{BH} + I_{DH}) \left[\frac{1 - \cos(90^\circ - \beta)}{2}\right]$$

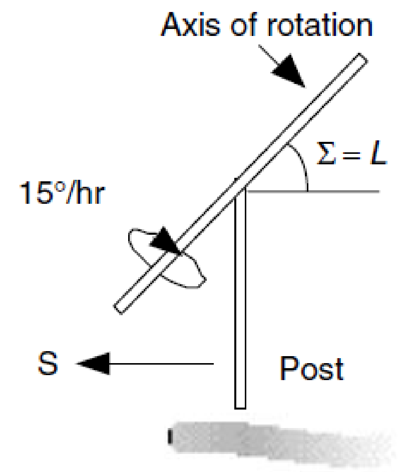




Single-axis tracking

- **Single-axis tracking for photovoltaics** is almost always done with a mount having a manually adjustable tilt angle along a north-south axis, and a tracking mechanism that rotates the collector array from east-to-west,
- When the tilt angle of the mount is set equal to the local latitude (called a *polar mount*), not only is that an optimum angle for annual collection, but the collector geometry and resulting insolation are fairly easy to evaluate as well.





Polar mount

- The beam, diffuse, and reflected radiation on a polar mount, **one-axis tracker are given by:**

$$I_{BC} = I_B \cos \delta$$

$$I_{DC} = C I_B \left[\frac{1 + \cos(90^\circ - \beta + \delta)}{2} \right]$$

$$I_{RC} = \rho (I_{BH} + I_{DH}) \left[\frac{1 - \cos(90^\circ - \beta + \delta)}{2} \right]$$

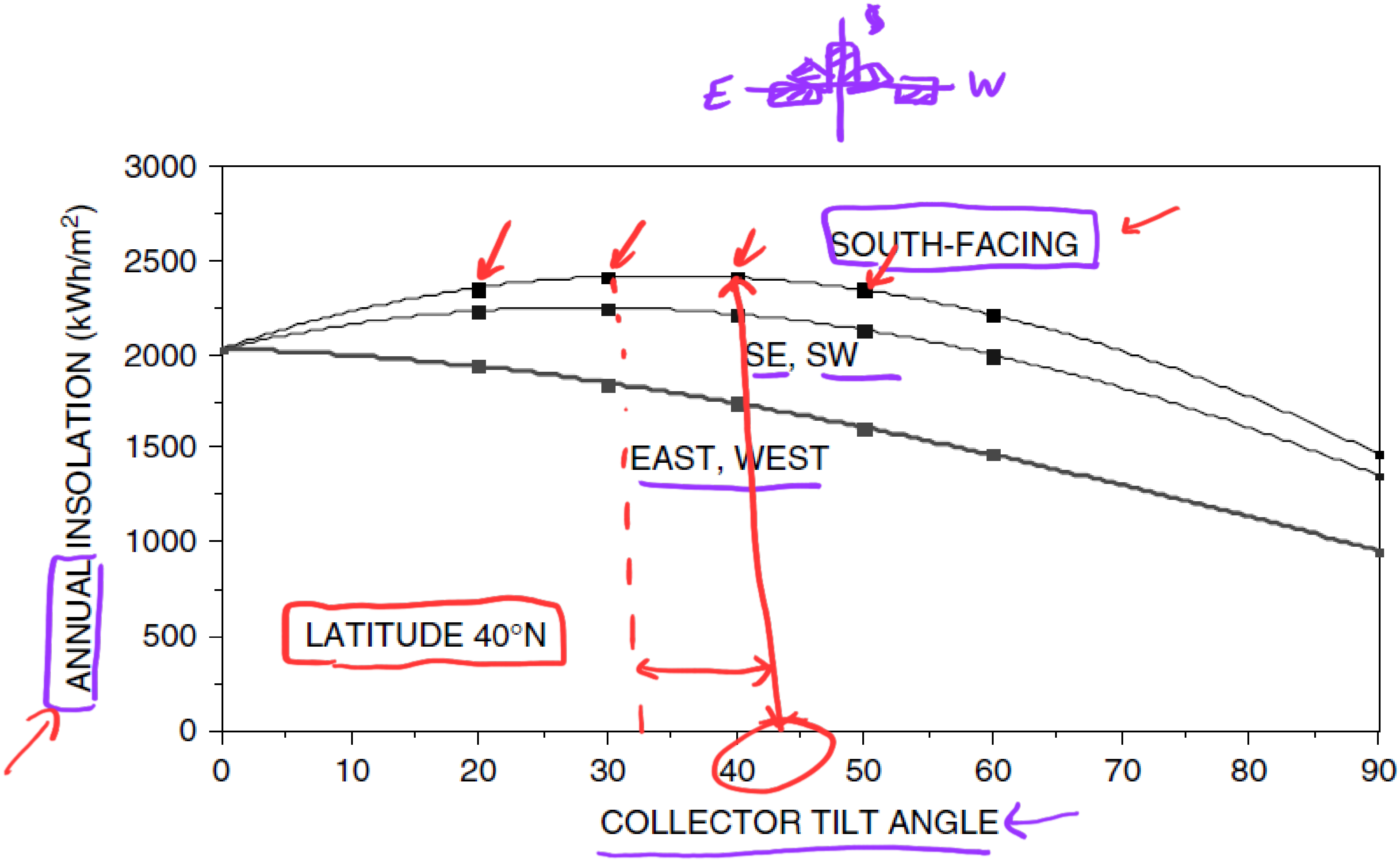
- To assist in keeping this whole set of clear-sky insolation relationships straight, a helpful summary of nomenclature and equations is **provided in the main reference**
- And, obviously, working with these equations is tedious until they have been put onto a spreadsheet. Excel Matlab
- Or, for most purposes it is sufficient to look up values in a table and, if necessary, do some interpolation
- There are tables of hour-by-hour clear-sky insolation for various tilt angles and latitudes, an example of which is given here in Table 7.7

TABLE 7.7 Hour-by-Hour Clear-Sky Insolation in June for Latitude 40°

Solar Time	Tracking		Tilt Angles, Latitude 40°						
	One-Axis	Two-Axis	0	20	30	40	50	60	90
			June 21					(W/m^2)	
6, 6	471	524 ×2	188	128	93	57	53	48	32
7, 5	668	742 ×2	386	330	289	240	185	126	45
8, 4	772	855 ×2	572	538	498	445	380	305	51
9, 3	835	921 ×2	731	722	686	632	560	473	147
10, 2	875	961 ×2	853	865	834	780	703	607	233
11, 1	898	982 ×2	929	956	928	874	795	693	288
12	906	989 ×1	955	987	960	906	826	723	308
kWh/d:	9.94	10.96	8.27	8.06	7.62	6.96	6.18	5.23	1.90

Note: Similar tables for other months and latitudes are given in Appendix C

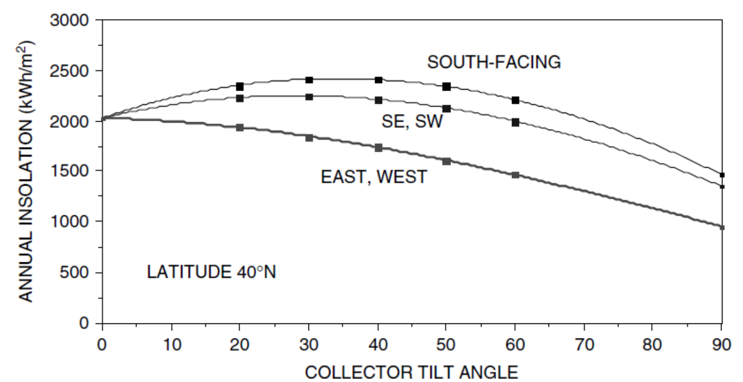
From “Renewable and efficient electric power systems » G. Masters



Annual insolation, assuming all clear days, for collectors with varying azimuth and tilt angles. Annual amounts vary only slightly over quite a range of collector tilt and azimuth angles.

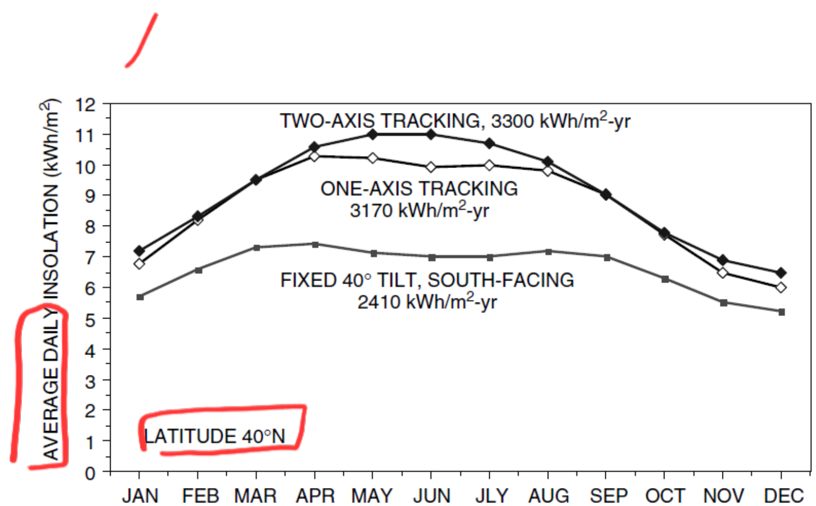
- While Fig. 7.28 seems to suggest that orientation isn’t critical, remember that it has been plotted for annual insolation without regard to monthly distribution.
- For a grid-connected photovoltaic system, for example, this may be a valid way to consider orientation.
- Deficits in the winter are automatically offset by purchased utility power, and any extra electricity generated during the summer can simply go back onto the grid.
- For a stand-alone PV system, however, where batteries or a generator provide back-up power, it is quite important to try to smooth out the month-to-month energy delivered to minimize the size of the back-up system needed in those low-yield months.

Fig. .29.



- A graph of monthly insolation, instead of the annual plots, shows dramatic variations in the pattern of monthly solar energy for different tilt angles.
- Such a plot for three different tilt angles at latitude 40◦, each having nearly the same annual insolation, is shown
- As shown, a collector at the modest tilt angle of 20◦ would do well in the summer, but deliver very little in the winter, so it wouldn't be a very good angle for a stand-alone PV system.
- At 40◦ or 60◦, the distribution of radiation is more uniform and would be more appropriate for such systems.

Fig. .29.



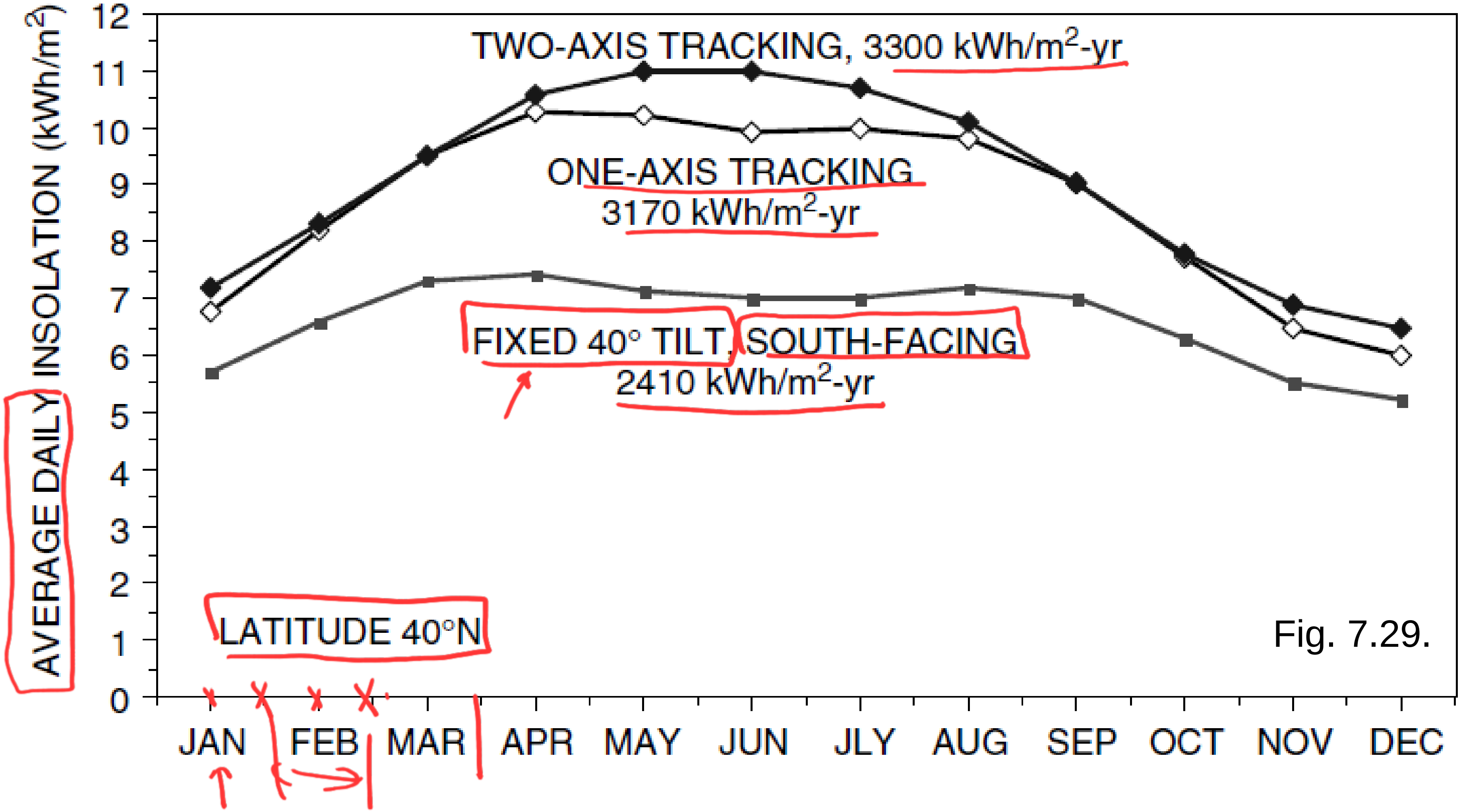


Fig. 7.29.

Clear sky insolation on a fixed panel compared with a one-axis, polar mount tracker and a two-axis tracker.

- In Fig. 7.30, monthly insolation for a south-facing panel at a fixed tilt angle equal to its latitude is compared with a one-axis polar mount tracker and also a two-axis tracker. The performance boost caused by tracking is apparent: Both trackers are exposed to about one-third more radiation than the fixed collector.
- Notice, however, that the two-axis tracker is only a few percent better than the single-axis version, with almost all of this improvement occurring in the spring and summer months

Clear sky insolation on a fixed panel compared with a one-axis, polar mount tracker and a two-axis tracker

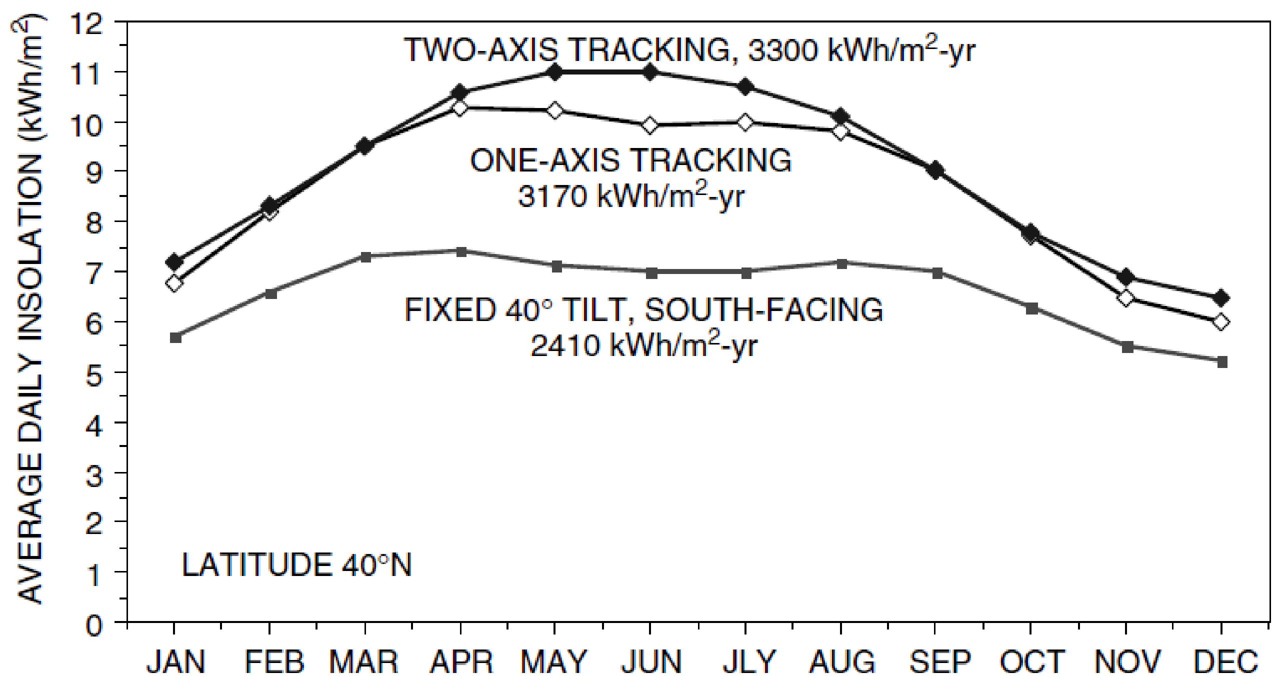


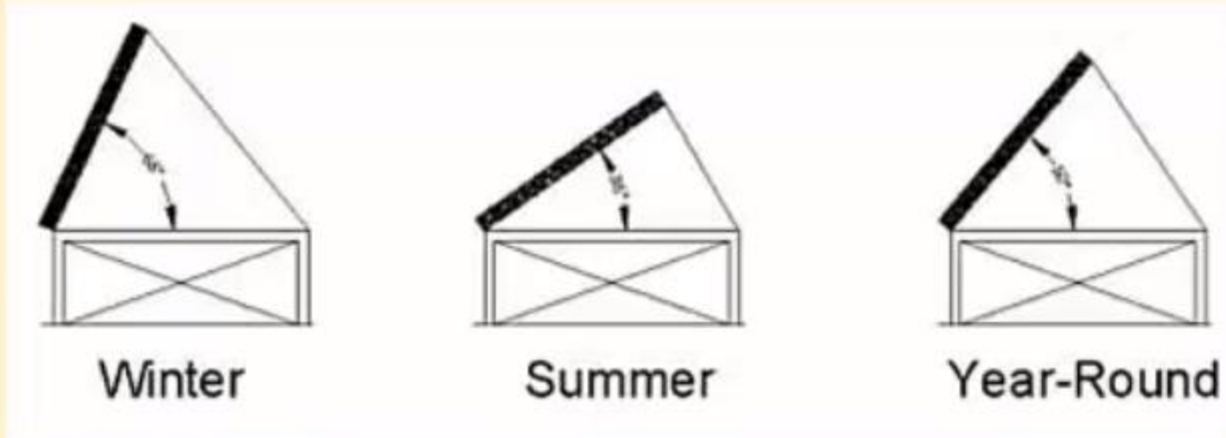
TABLE 7.8 Daily and Annual Clear-Sky Insolation (Beam plus Diffuse) for Various Fixed-Orientation Collectors, Along with one- and Two-Axis Trackers

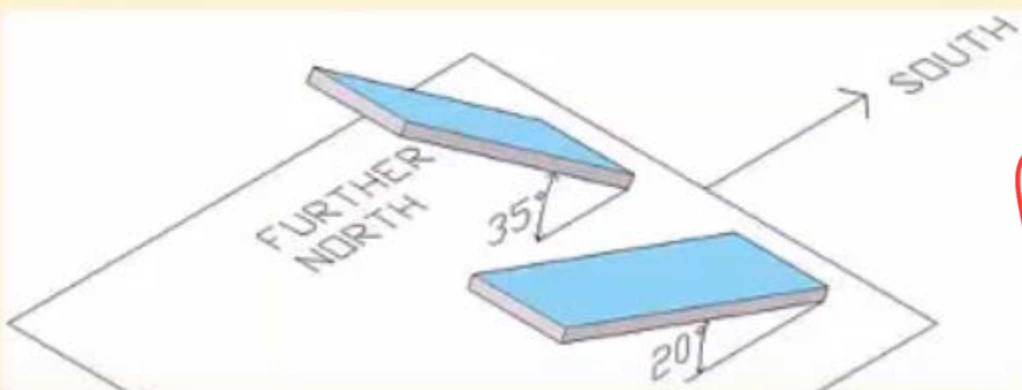
→ 32°N

Daily Clear-Sky Insolation (kWh/m^2) Latitude 40°N																					
Azim:		S						SE/SW						E, W						Tracking	
Tilt:	0	20	30	40	50	60	90	20	30	40	50	60	90	20	30	40	50	60	90	One-Axis	Two-Axis
Jan	3.0	4.6	5.2	5.7	6.0	6.2	5.5	4.1	4.5	4.7	4.9	4.9	4.0	2.9	2.8	2.7	2.6	2.4	1.7	6.8	7.2
Feb	4.2	5.8	6.3	6.6	6.8	6.7	5.4	5.3	5.6	5.7	5.7	5.5	4.2	4.1	3.9	3.7	3.5	3.3	2.2	8.2	8.3
Mar	5.8	6.9	7.2	7.3	7.1	6.8	4.7	6.5	6.6	6.6	6.4	6.0	4.1	5.5	5.3	5.0	4.6	4.3	2.8	9.5	9.5
Apr	7.2	7.7	7.7	7.4	6.9	6.2	3.3	7.5	7.4	7.1	6.6	6.1	3.7	6.9	6.6	6.2	5.7	5.2	3.3	10.3	10.6
May	8.1	8.0	7.7	7.1	6.4	5.5	2.3	8.0	7.6	7.2	6.5	5.8	3.2	7.7	7.3	6.8	6.2	5.5	3.5	10.2	11.0
Jun	8.3	8.1	7.6	7.0	6.2	5.2	1.9	8.0	7.6	7.1	6.4	5.6	3.0	7.8	7.4	6.9	6.3	5.6	3.4	9.9	11.0
July	8.0	7.9	7.6	7.0	6.3	5.5	2.2	7.9	7.5	7.1	6.4	5.7	3.2	7.6	7.2	6.7	6.1	5.5	3.4	10.0	10.7
Aug	7.1	7.5	7.5	7.2	6.7	6.0	3.2	7.3	7.2	6.9	6.5	5.9	3.6	6.7	6.4	6.0	5.5	5.0	3.2	9.8	10.1
Sept	5.6	6.7	6.9	7.0	6.9	6.5	4.5	6.3	6.4	6.3	6.1	5.8	4.0	5.4	5.2	4.9	4.5	4.1	2.7	9.0	9.0
Oct	4.1	5.5	6.0	6.3	6.4	6.4	5.1	5.0	5.3	5.4	5.4	5.2	4.0	3.9	3.7	3.6	3.3	3.1	2.1	7.7	7.8
Nov	2.9	4.5	5.1	5.5	5.8	5.9	5.3	3.9	4.3	4.6	4.7	4.7	3.9	2.8	2.7	2.6	2.5	2.3	1.6	6.5	6.9
Dec	2.5	4.1	4.7	5.2	5.5	5.7	5.2	3.6	3.9	4.2	4.4	4.4	3.8	2.4	2.3	2.2	2.1	2.0	1.4	6.0	6.5
Total	2029	2352	2415	2410	2342	2208	1471	2231	2249	2216	2130	1997	1357	1938	1848	1738	1612	1467	960	3167	3305

Tables for other latitudes are in Appendix D

Max performance is achieved when panels are perpendicular to the sun's rays





Year round tilt = latitude

Winter + 15 lat.

Summer – 15 lat.

→ tilt = latitude + 15°

→ tilt = latitude − 15

Method # 1:
Quick and Easy (But Less Effective)

- Take your latitude and add 15 degrees for the winter, or subtract 15 degrees for the summer.
- For example: if your latitude is 40 degrees, the angle you want to tilt your panels in the winter is: 40 + 15 = 55 degrees.
- In the summer, it would be: 40 - 15 = 25 degrees

Method # 2(a): The Better Way (Winter)

- In the winter months, when there's less sun, take your latitude, multiply it by 0.9, and then add 29 degrees.
- For example: if your latitude is 40 degrees, the angle you want to tilt your panels in the winter is: (40 * 0.9) + 29 = 65 degrees.
- This is about 10 degrees steeper than the "quick and easy" way! It's also more effective, because you want your panels to be directly facing the sun at mid-day during those short winter days.

Method # 2(b): The Better Way (Summer)

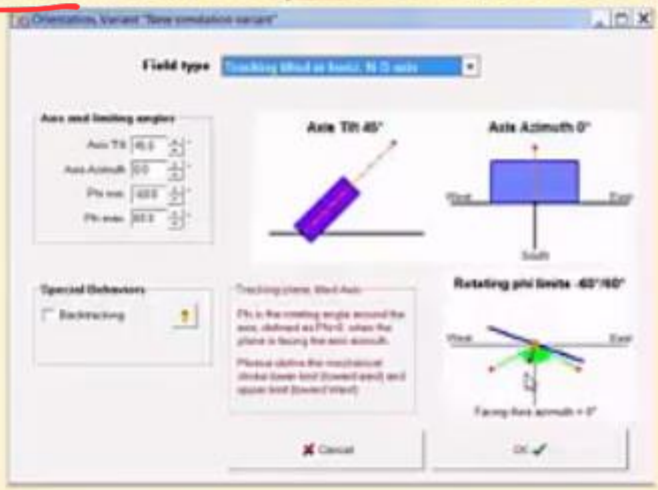
- Take your latitude, multiply it by 0.9, and subtract 23.5 degrees.
- For example: if your latitude is 40 degrees, your panels should be tilted at: (40 * 0.9) - 23.5 = 12.5 degrees.

Method # 2(c):
The Better Way (Spring & Fall)

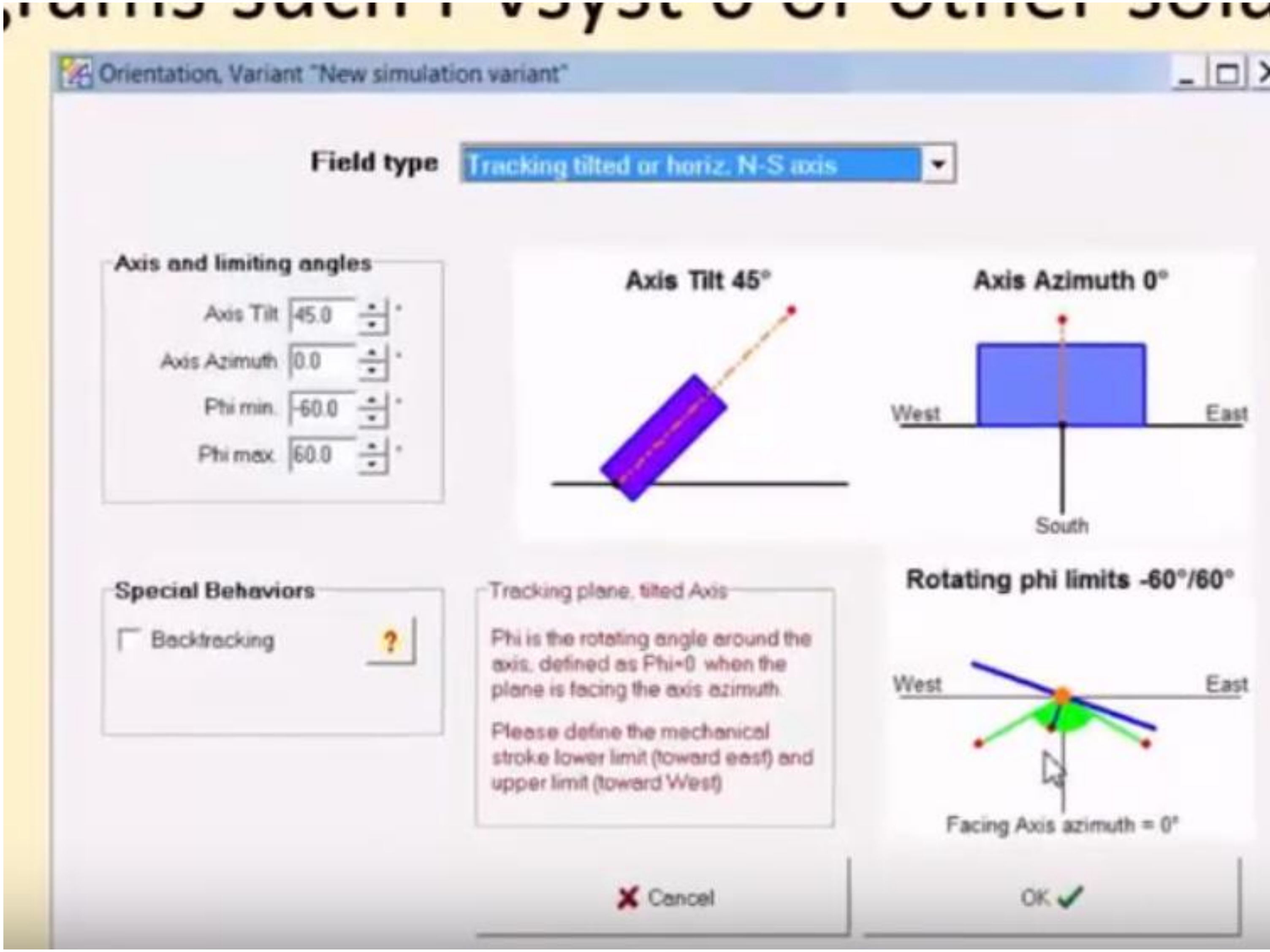
- **Method 2(c): The Better Way (Spring & Fall)**
- Take your latitude and subtract 2.5 degrees.
- For example: if your latitude is 40 degrees, the best tilt for your panels in the spring & fall is: 40 - 2.5 = 37.5 degrees.

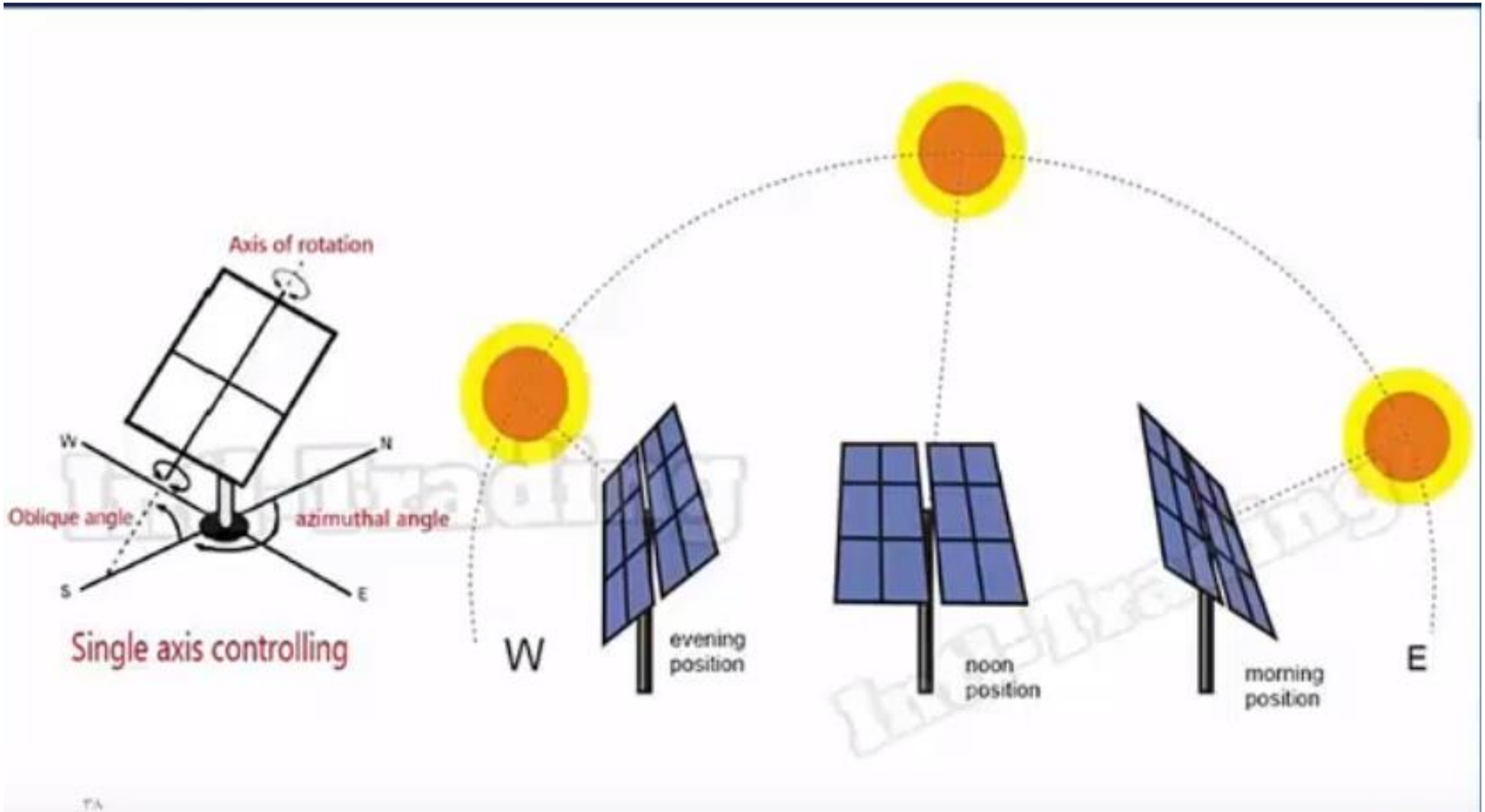
Choosing the Right Tilt

- Using simulation programs such PVsyst 6 or other solar PV software.



- Making local measurements for a test case


Orientation, Variant "New simulation variant"
Field type
Tracking tilted or horiz. N-S axis
Axis and limiting angles
Axis Tilt 45.0 °
Axis Azimuth 0.0 °
Phi min. -60.0 °
Phi max. 60.0 °
Axis Tilt 45°
Axis Azimuth 0°
West
East
South
Special Behaviors
Backtracking
?
Tracking plane, tilted Axis
Phi is the rotating angle around the axis, defined as Phi=0 when the plane is facing the axis azimuth.
Please define the mechanical stroke lower limit (toward east) and upper limit (toward West)
Rotating phi limits -60°/60°
West
East
Facing Axis azimuth = 0°
Cancel
OK


Axis of rotation
W
N
Oblique angle
azimuthal angle
S
E
Single axis controlling
W
evening
position
noon
position
morning
position
E

Using PV syst program

د. محمد ابو الطيب

- Using Pvsyst lect21 https://www.youtube.com/watch?v=bsxwTNZV8bk

PVWatts ?

- User needs lect22

https://www.youtube.com/watch?v=_G2Ll202vm8

- Lect23

https://www.youtube.com/watch?v=u3OZbXGH9AM

- Lect24

https://www.youtube.com/watch?v=oy9QUGd8x0Y

- Lect 25

https://www.youtube.com/watch?v=7tS2vPWHW8w

- Off grid design lect20

https://www.youtube.com/watch?v=bkbZtAUE8GM