ME 476
Solar Energy

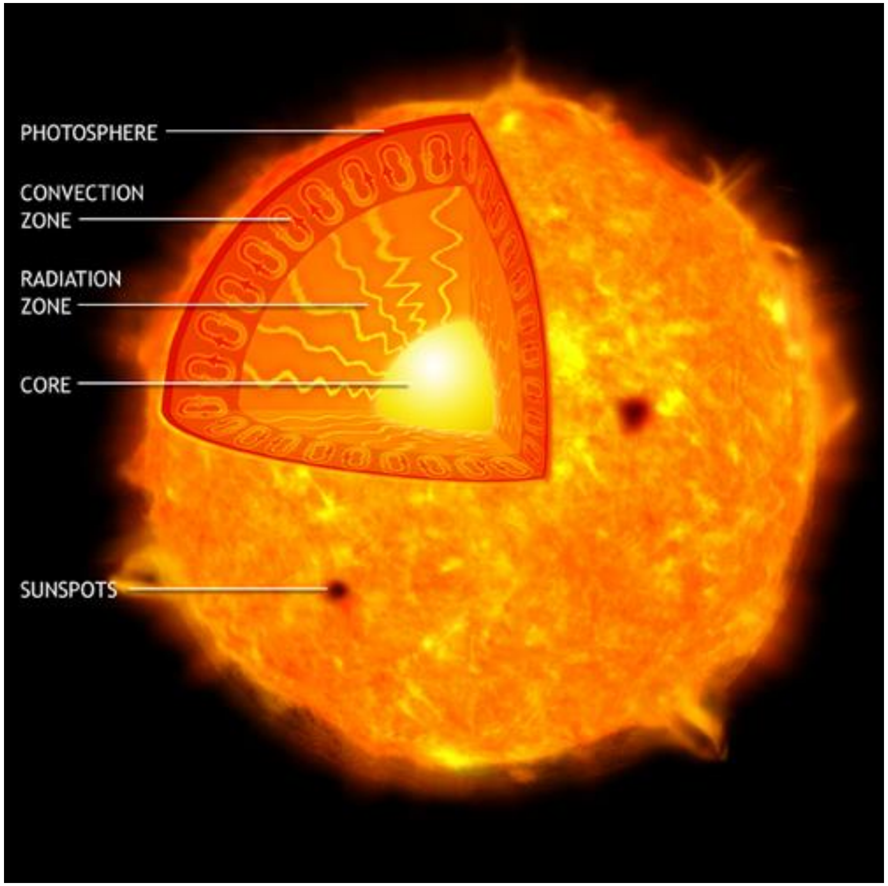
UNIT THREE
SOLAR RADIATION

Unit Outline

- What is the sun?
- Radiation from the sun
- Factors affecting solar radiation
  - **Atmospheric effects**
  - **Solar radiation intensity**
  - **Air mass**
  - **Seasonal variations**
- Calculating time
- Solar angles
- Solar irradiation on surfaces

What is the Sun?

- The sun is a gaseous body composed mostly of hydrogen and some helium.
- The huge gravitational force causes intense pressure and temperature at the core.
- These conditions initiate nuclear fusion reactions.
- The sun fuses hydrogen into helium at its core and the resulting energy radiates outward.
- Energy is convected to the photosphere



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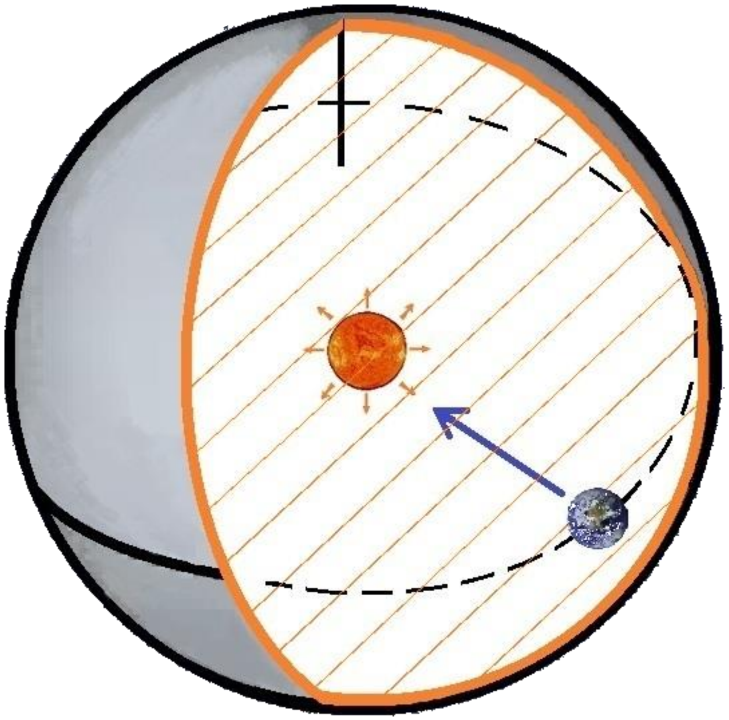
Radiation from the Sun

- The surface of the photosphere is at about 5777 K.
- Once the energy reaches the surface of the photosphere, it escapes to space by radiation.
- The sun is considered a blackbody.
- It radiates diffusely (uniformly) in all directions.
- All the energy leaving the sun's surface will reach a sphere containing earth.

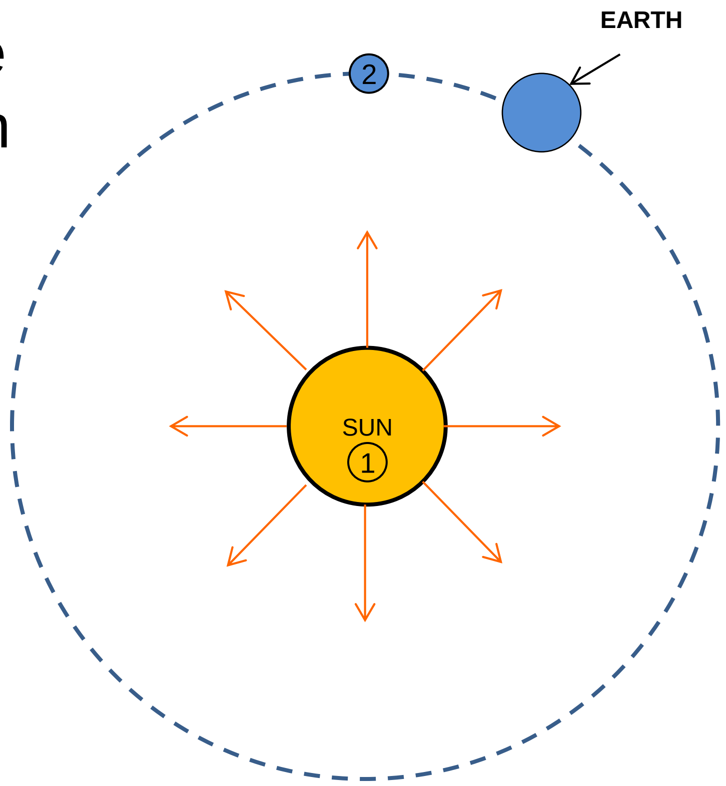


Radiation from the Sun

- The net radiation heat transfer between the sun's surface (1) and the surface of the sphere containing earth (2) is given by:

$$\dot{Q}_{1\rightarrow 2} = A_1 F_{1\rightarrow 2}\,\sigma(T_1^4 - T_2^4)$$

- $F_{1\rightarrow 2} = 1$
- $A_1 = 4\,\pi\,r_1^{\,2}$, where r_1 is the radius of the sun (6.955×10^8 m)
- T_2 is negligible
- The total rate of heat transfer leaving the sun's surface and reaching Surface 2 is: 3.84×10^{26} W.

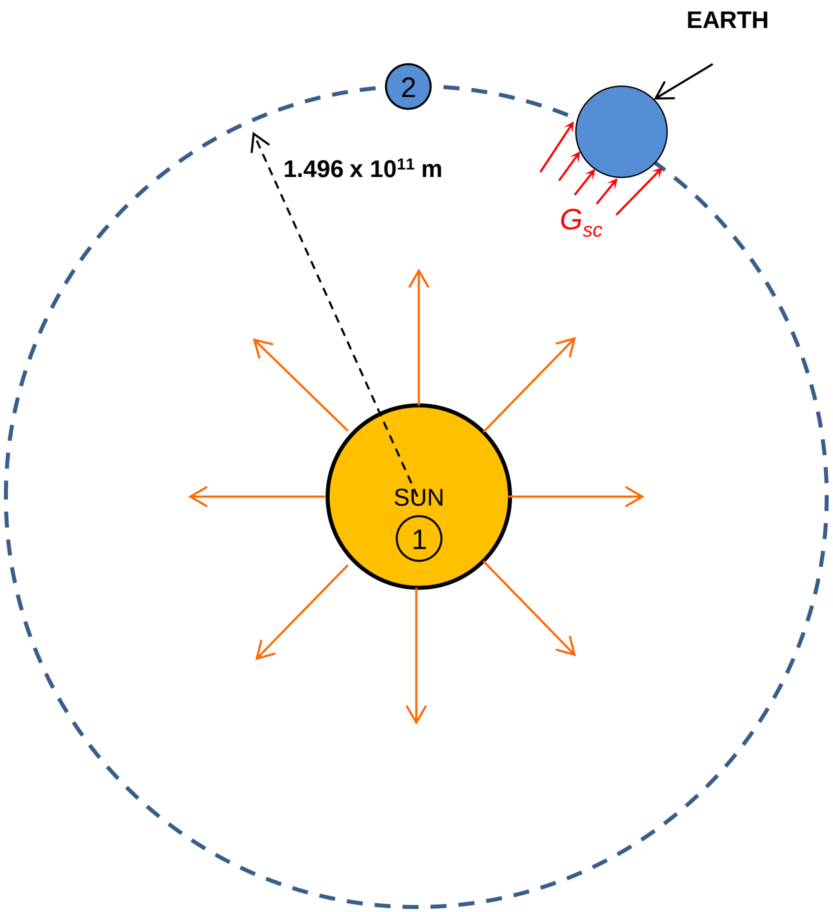


Solar Constant

- The average distance between the sun and earth is 1.496 x 10^{11} m.
- This distance is called an ***astronomical unit*** (AU).
- The irradiance (G_{sc}) incident on Surface 2 (including earth) will be:

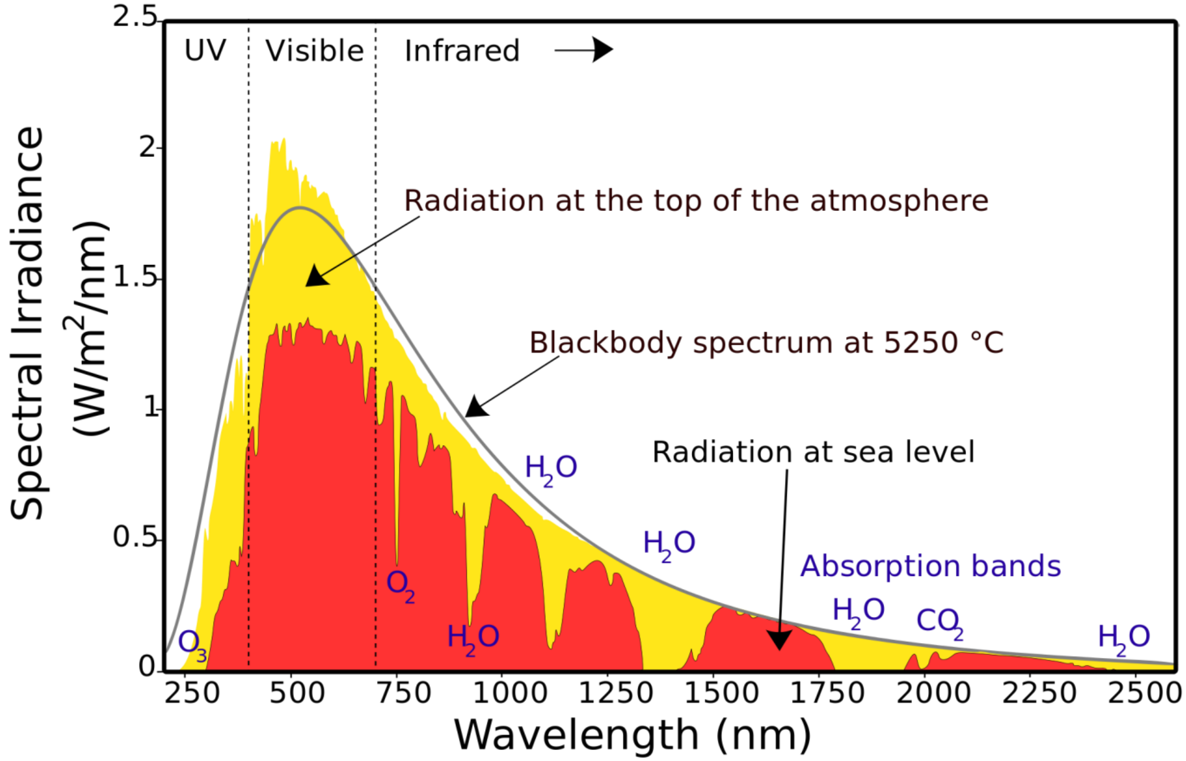
$$G_{sc} = \frac{\dot{Q}_{1\rightarrow 2}}{A_2} = \frac{\dot{Q}_{1\rightarrow 2}}{4\pi {r_2}^2}$$

- The value of G_{sc} is 1367 W/m^2.
- This value is called the ***Solar Constant.***



Solar Radiation Spectrum

- The solar radiation spectrum closely matches the spectrum of a blackbody (but only at the top of the atmosphere).
- Once solar radiation penetrates the atmosphere, the spectrum is affected by the presence of gases.
- For example, ozone (O_3) greatly reduces ultraviolet radiation.



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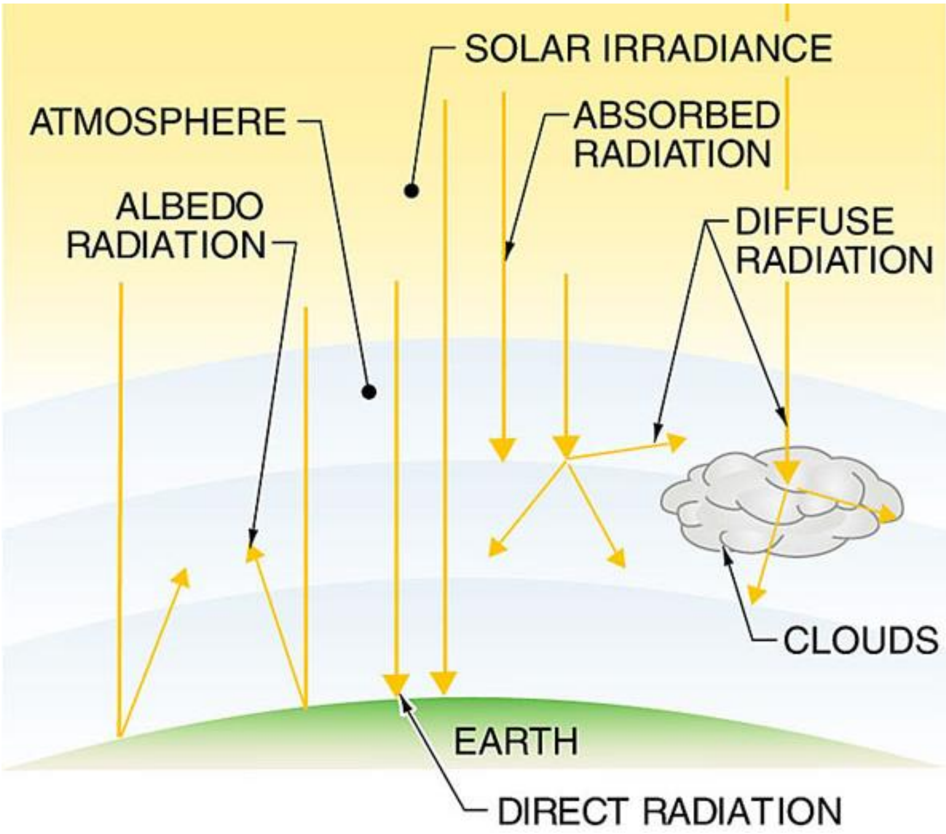
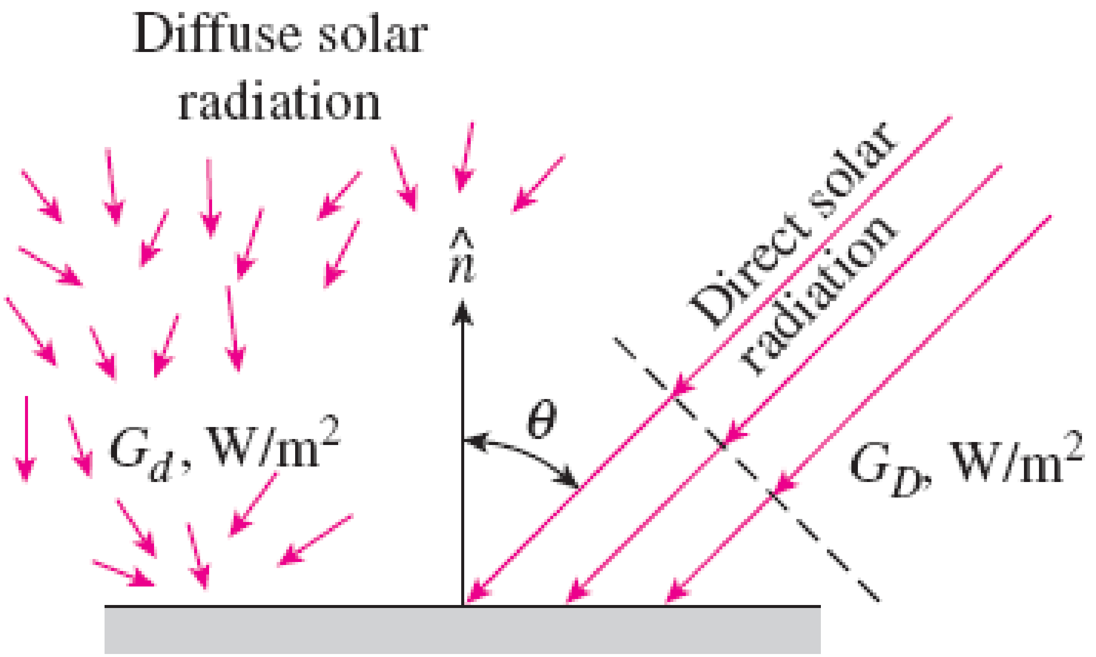
Atmospheric Effects

- The solar irradiance reaching the earth’s surface is affected by:
  - **Suspended particles (e.g. dust)**
  - **Gases in the atmosphere**
  - **Clouds**
- These substances can:
  - **Absorb solar radiation**
  - **Reflect solar radiation**
  - **Scatter solar radiation**



Atmospheric Effects

- Solar radiation not affected by these substances reaches the earth's surface as ***direct radiation***.
- Remaining radiation reaching the surface is ***diffuse radiation***.
- Total of direct and diffuse radiation is called ***global radiation***.



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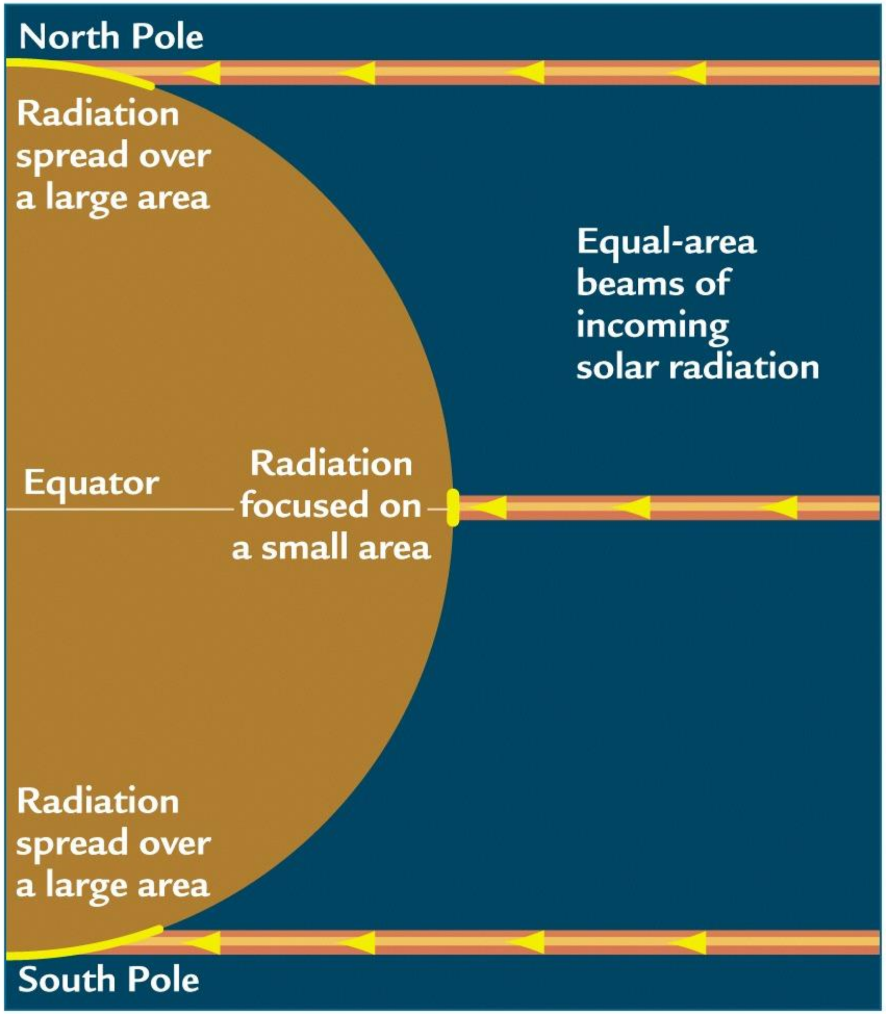
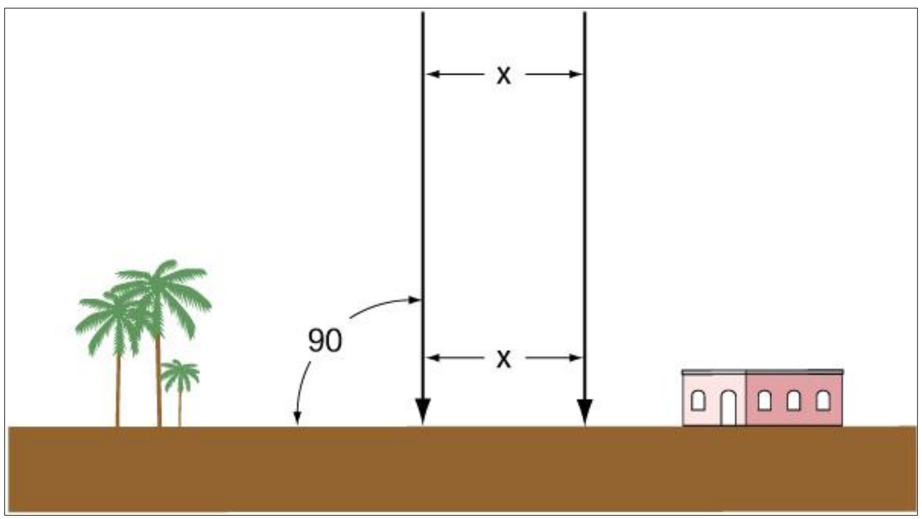
Solar Radiation Intensity

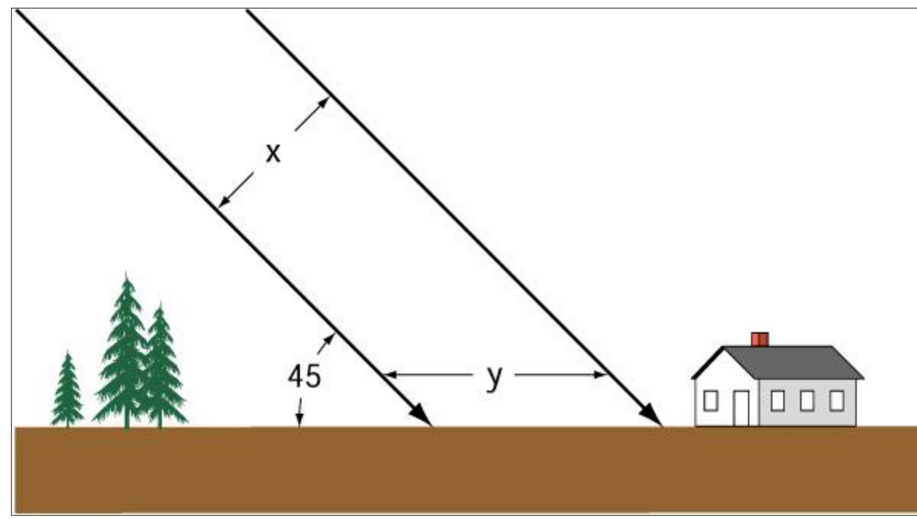
- Solar irradiance (*G*) incident on the earth's surface in the normal direction is focused on a small area.
- If the same (*G*) is incident at a different angle, it will be spread over a larger area.
- This means that the solar intensity in the normal direction is highest.
- Solar intensity at high **latitudes** is lower.



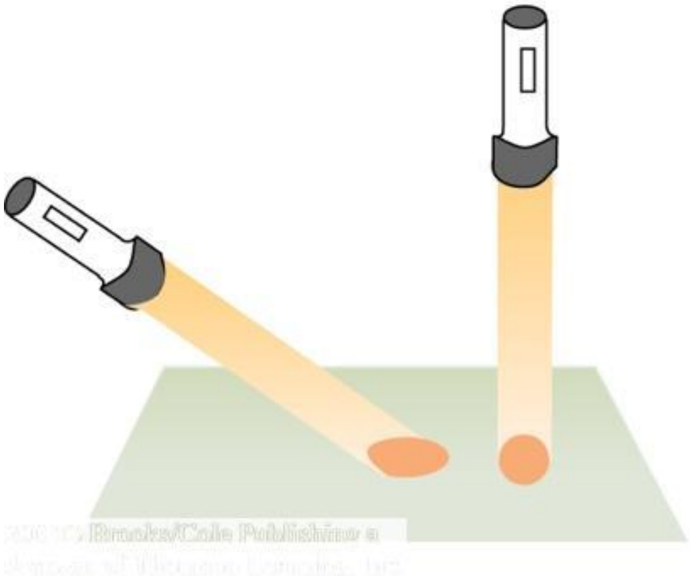
Solar Radiation Intensity

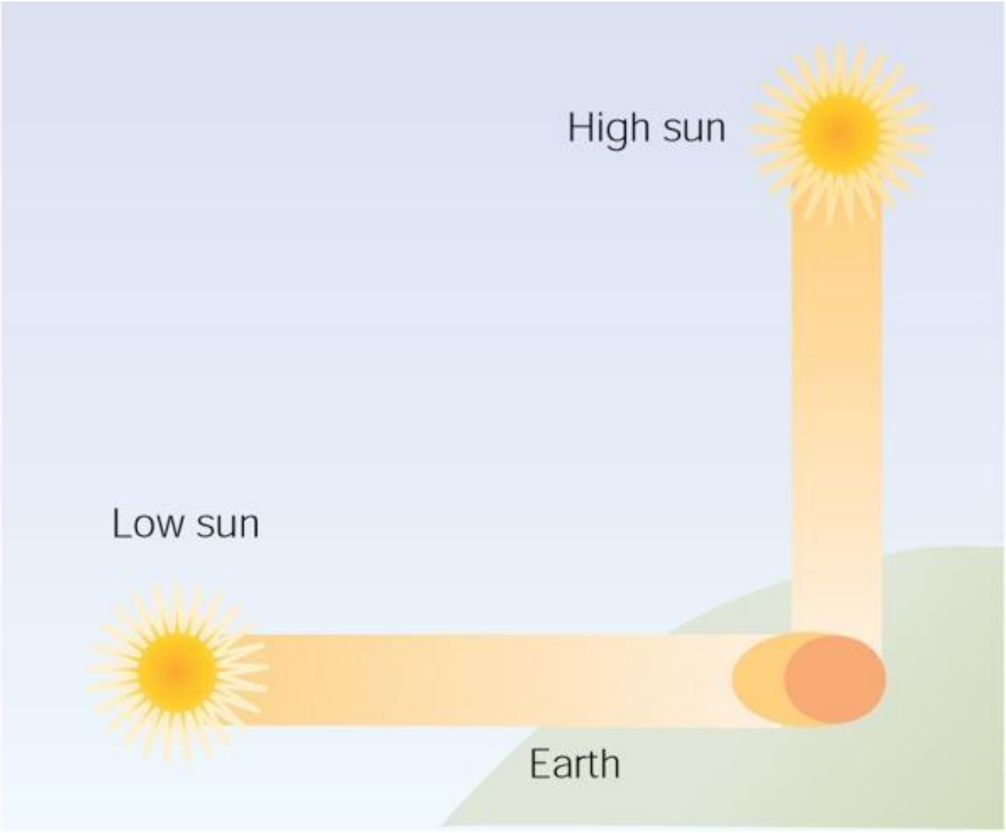
- This also means that solar intensity is higher in the middle of the day (e.g. at noon) than in the early morning or late afternoon.





Solar Radiation Intensity





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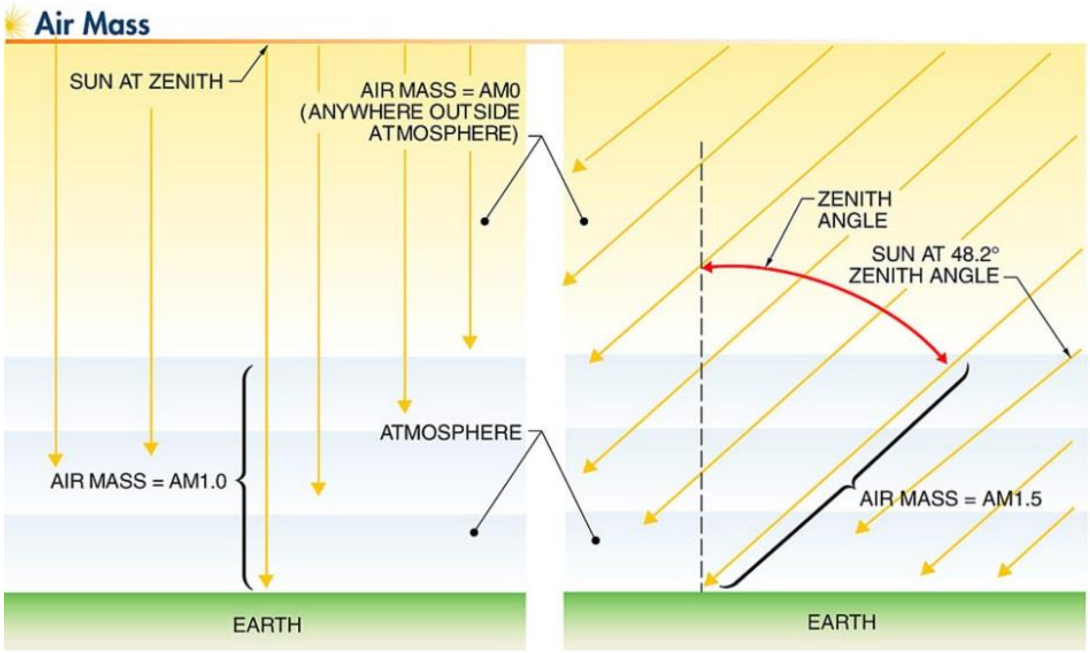
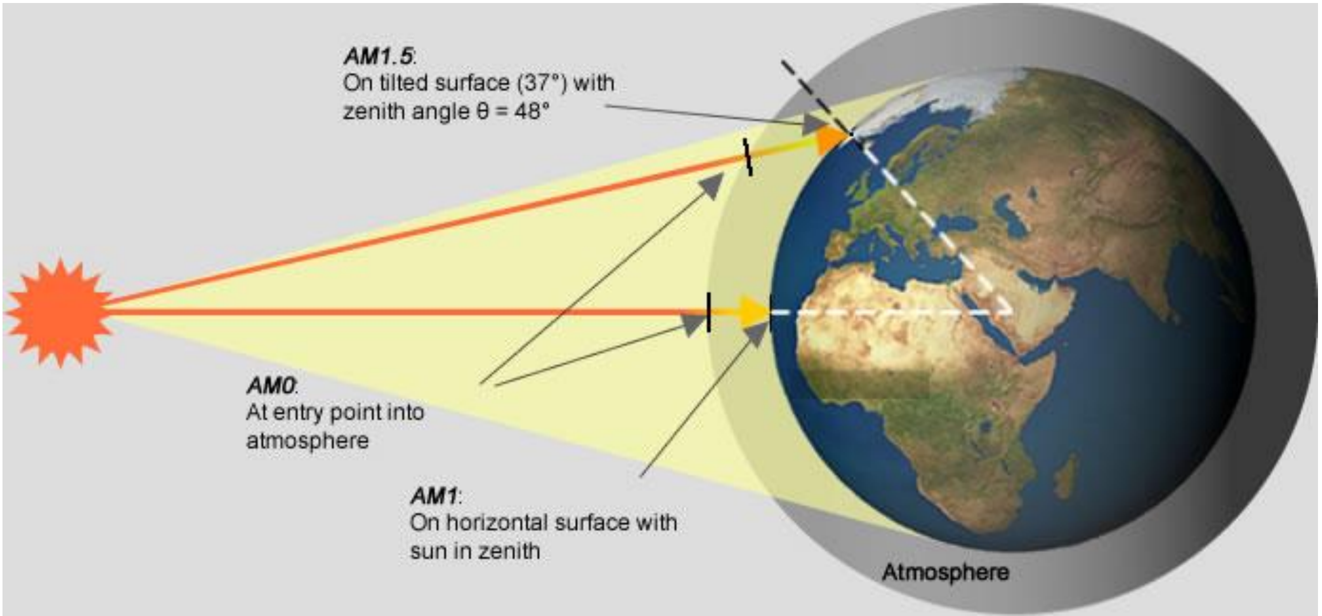
Air Mass

- The amount of solar radiation interacting with the atmosphere depends on how much atmosphere it passes through.
- When the sun is directly overhead (at ***zenith***), the amount of atmosphere that the sun's rays pass through is at a minimum.
- As the sun approaches the horizon, the sun's rays must pass through a greater amount of atmosphere.
- This phenomenon is characterized by the ***air mass.***



Air Mass

- The larger the air mass, the more solar radiation will be absorbed (or reflected) by the atmosphere
- This reduces the quantity of solar irradiance reaching the earth's surface.
- The larger air mass also changes its wavelength composition
- This is the reason for the change in the sun's color in early morning and late afternoon.



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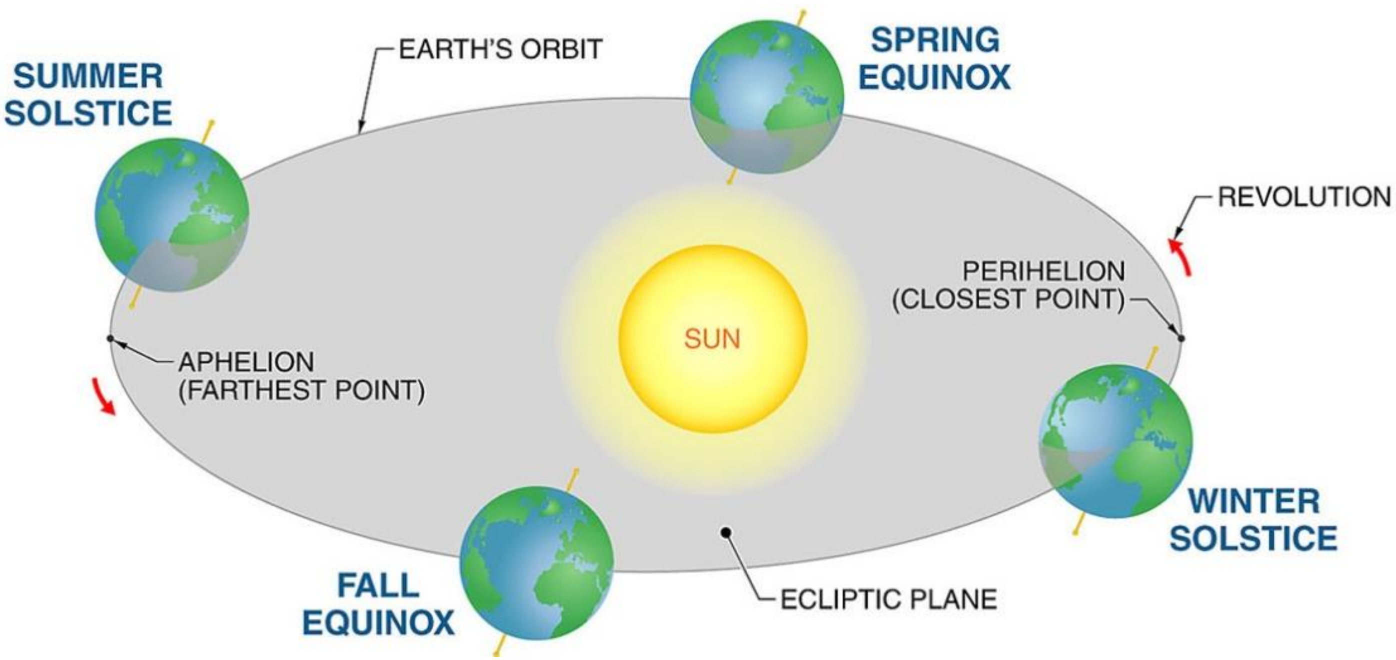
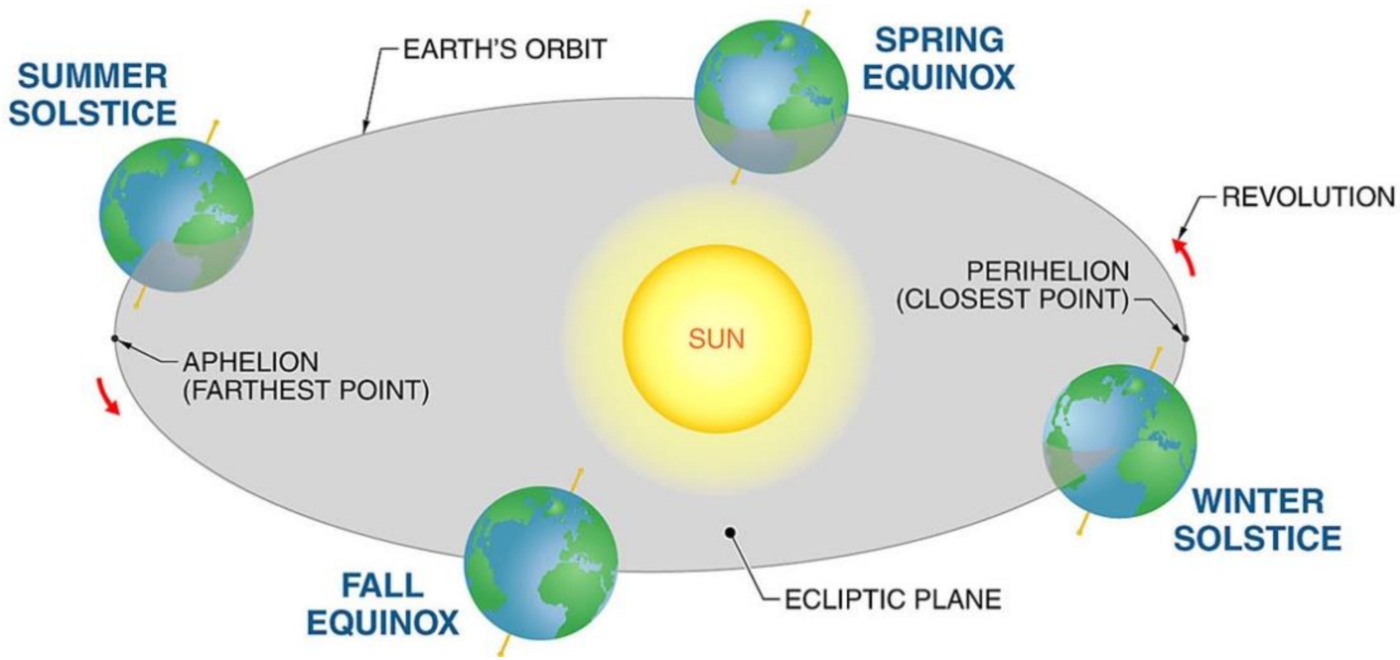
Seasonal Variation of Solar Radiation

- The earth rotates around the sun in an elliptical orbit.
- The plane formed by the earth's rotation around the sun is called the ***ecliptic plane***.
- The earth's axis is tilted by 23.5° to the ecliptic plane.
- Because of this tilt, the lengths of day and night vary throughout the year.



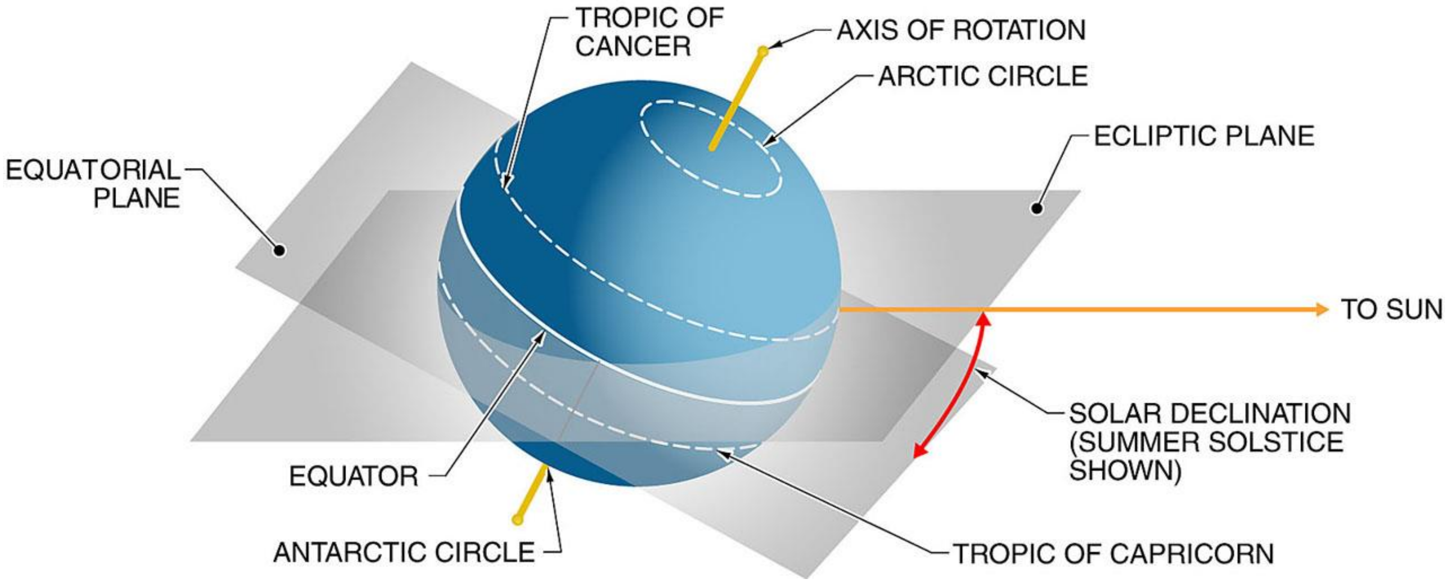
Seasonal Variation of Solar Radiation

- The point at which the day is shortest in the northern hemisphere is called ***winter solstice***.
- The point at which the day is longest in the northern hemisphere is called ***summer solstice***.
- The two points at which day and night have equal lengths are called the ***spring equinox*** and ***fall equinox***.



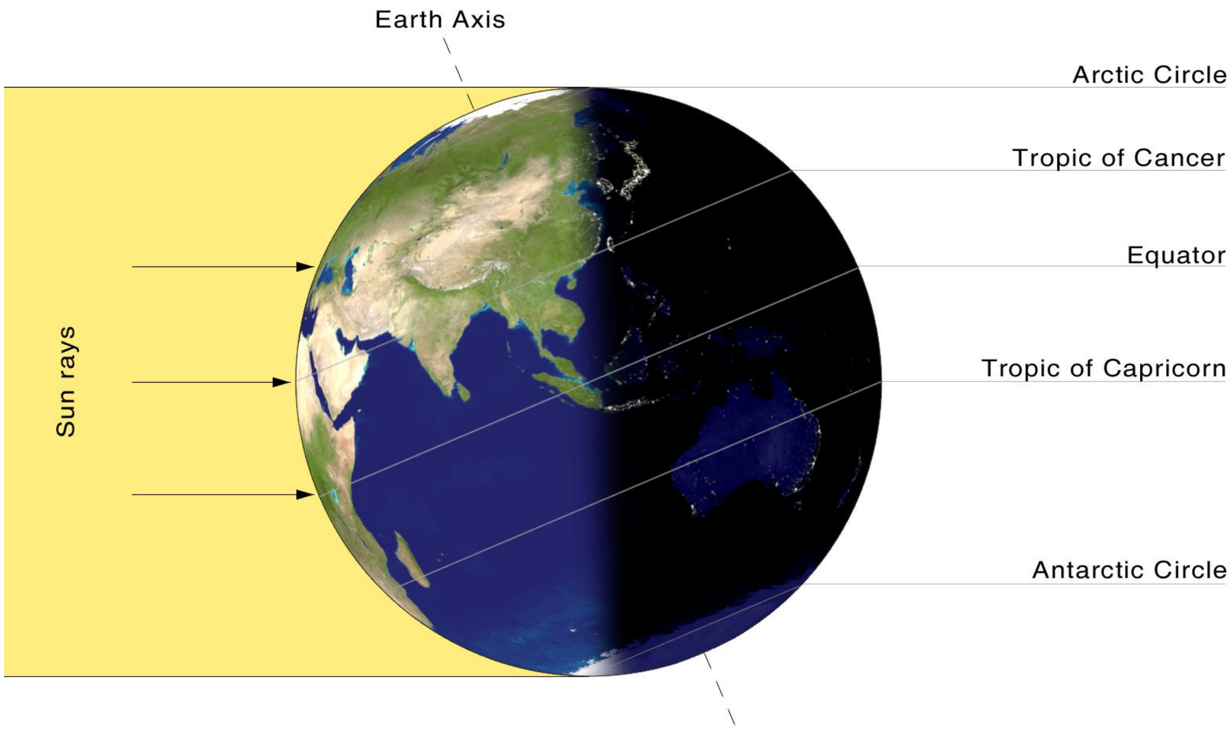
Sun’s Declination

- The ***equatorial plane*** is the surface cutting through the earth’s equator.
- ***Solar declination*** is the angle between the equatorial plane and the rays of the sun.
- The angle of solar declination changes continuously as Earth orbits the sun, ranging from –23.5° to +23.5° (positive when the northern hemisphere is tilted toward the sun).



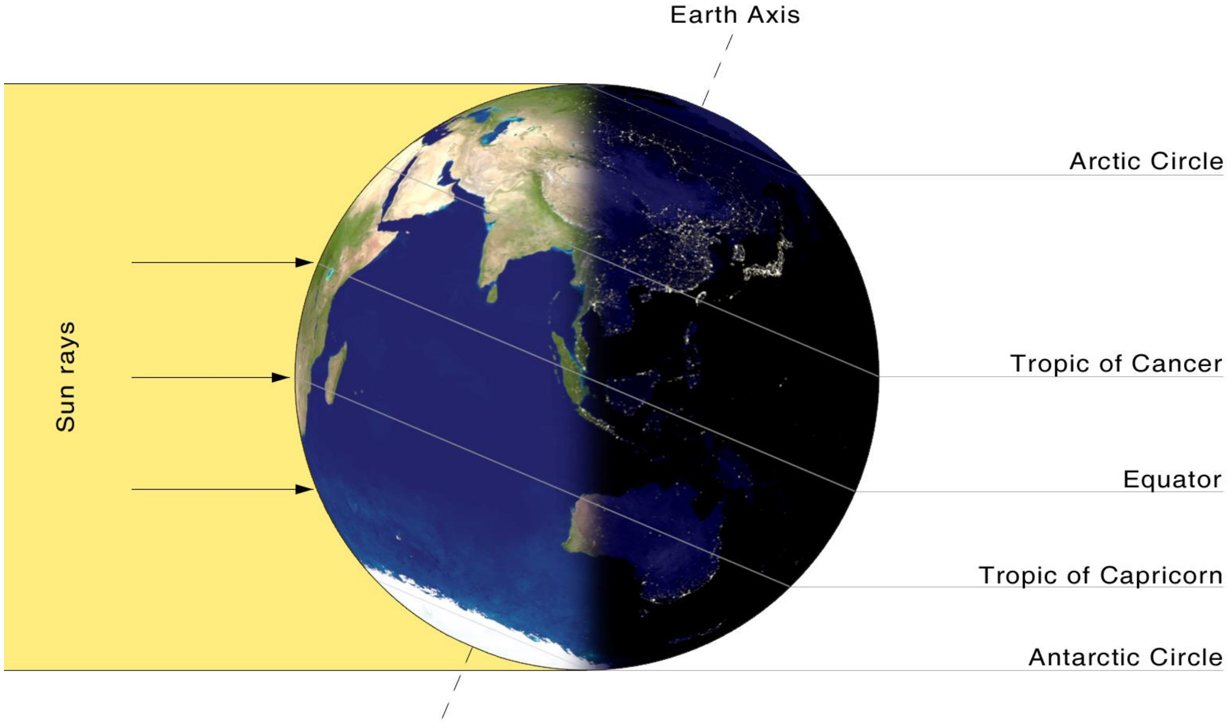
Summer Solstice

- At summer solstice, the sun's rays are perpendicular to the tropic of cancer.
- Daytime is longest in the northern hemisphere.
- Daytime is shortest in the southern hemisphere.



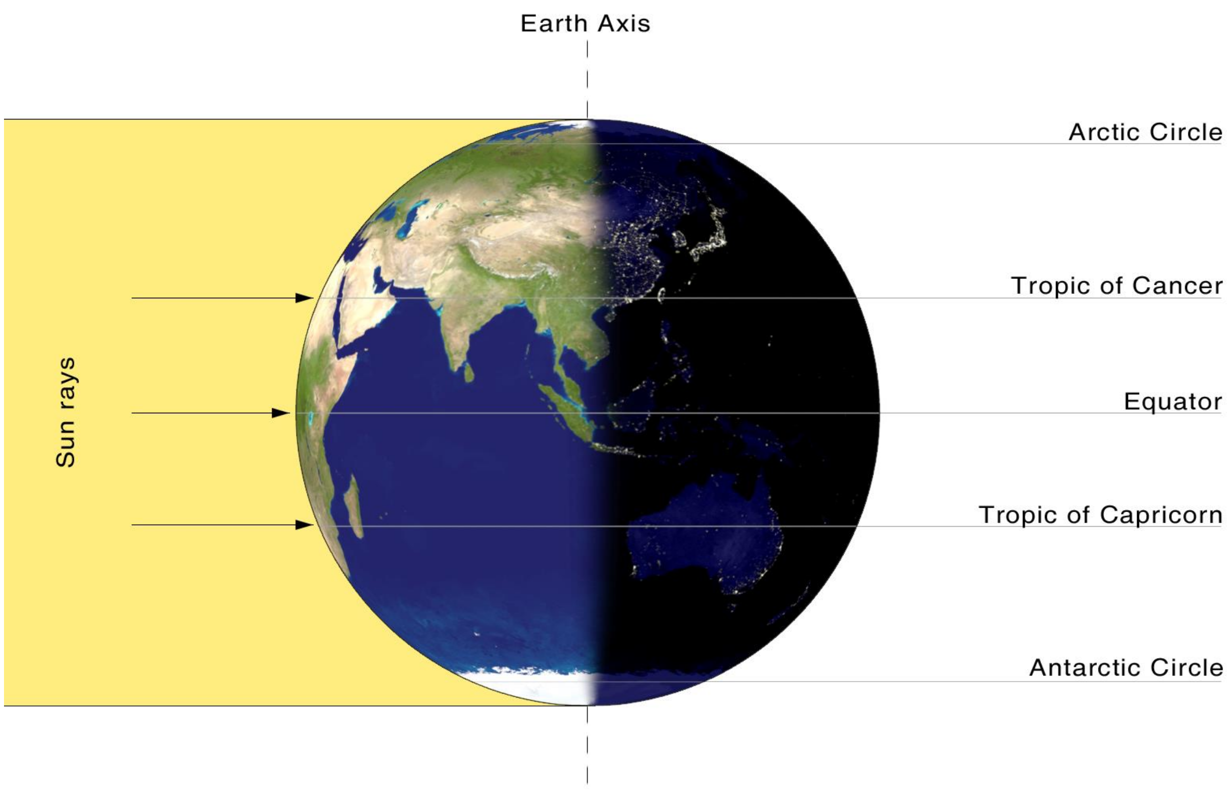
Winter Solstice

- At winter solstice, the sun's rays are perpendicular to the tropic of capricorn.
- Daytime is shortest in the northern hemisphere.
- Daytime is longest in the southern hemisphere.



Spring and Fall Equinoxes

- At spring and fall equinoxes, the sun's rays are perpendicular to the equator.
- Day and night have equal lengths.



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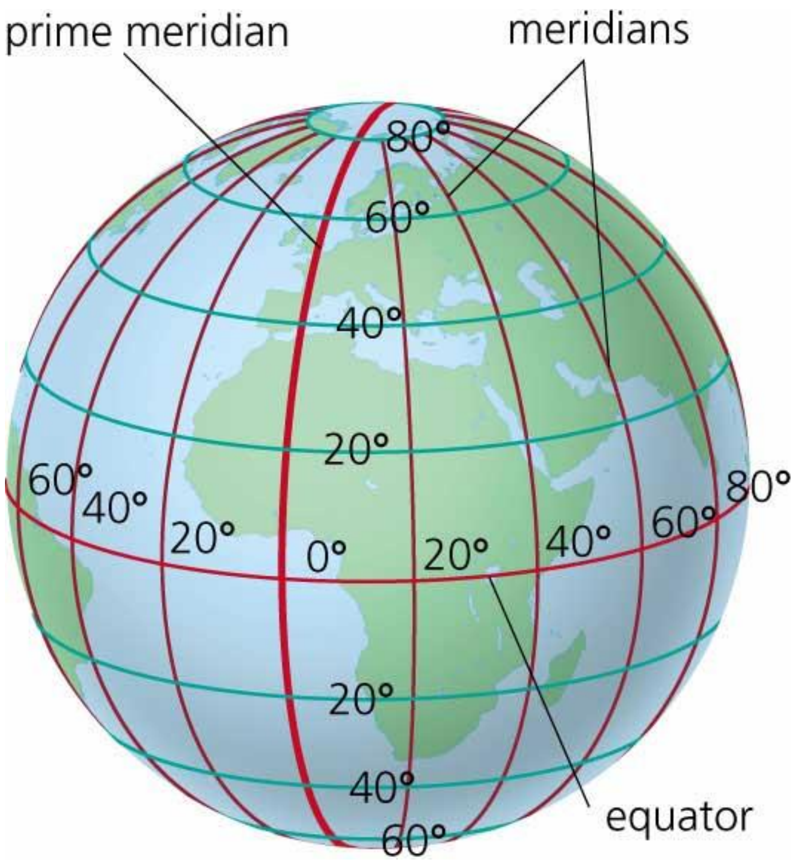
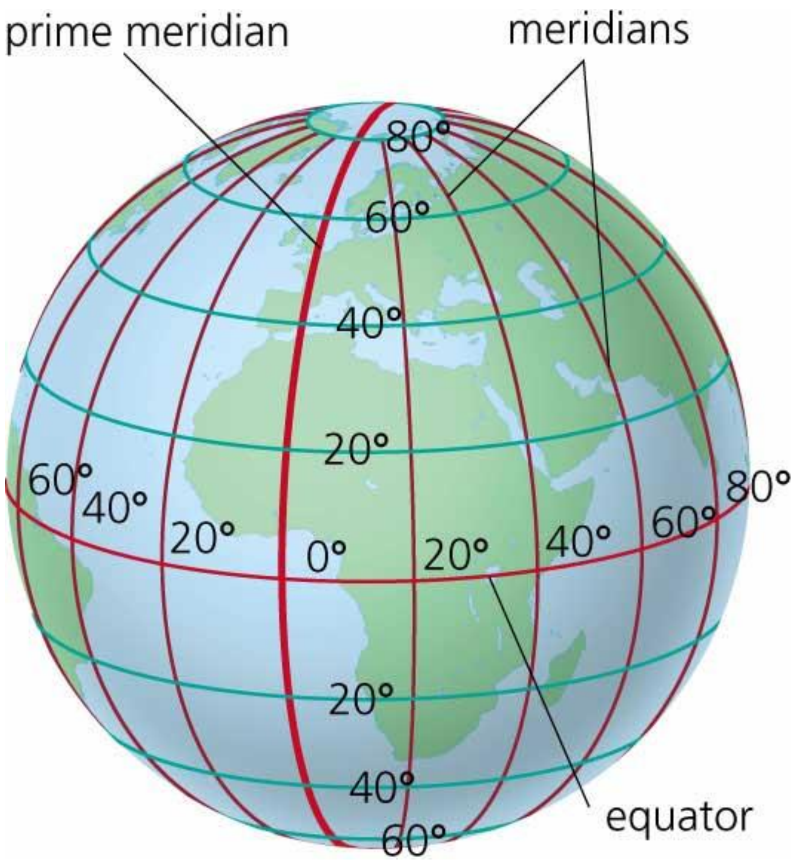
Lines of Longitude

- ***Lines of longitude*** start at the north pole and end at the south pole.
- Lines of longitude are also called ***meridians***.
- There are 360 meridians, one for each degree.
- The meridian passing through Greenwich is called the prime meridian, and it is given the value of 0°.
- Riyadh is approximately 46° east of the prime meridian.



Lines of Longitude

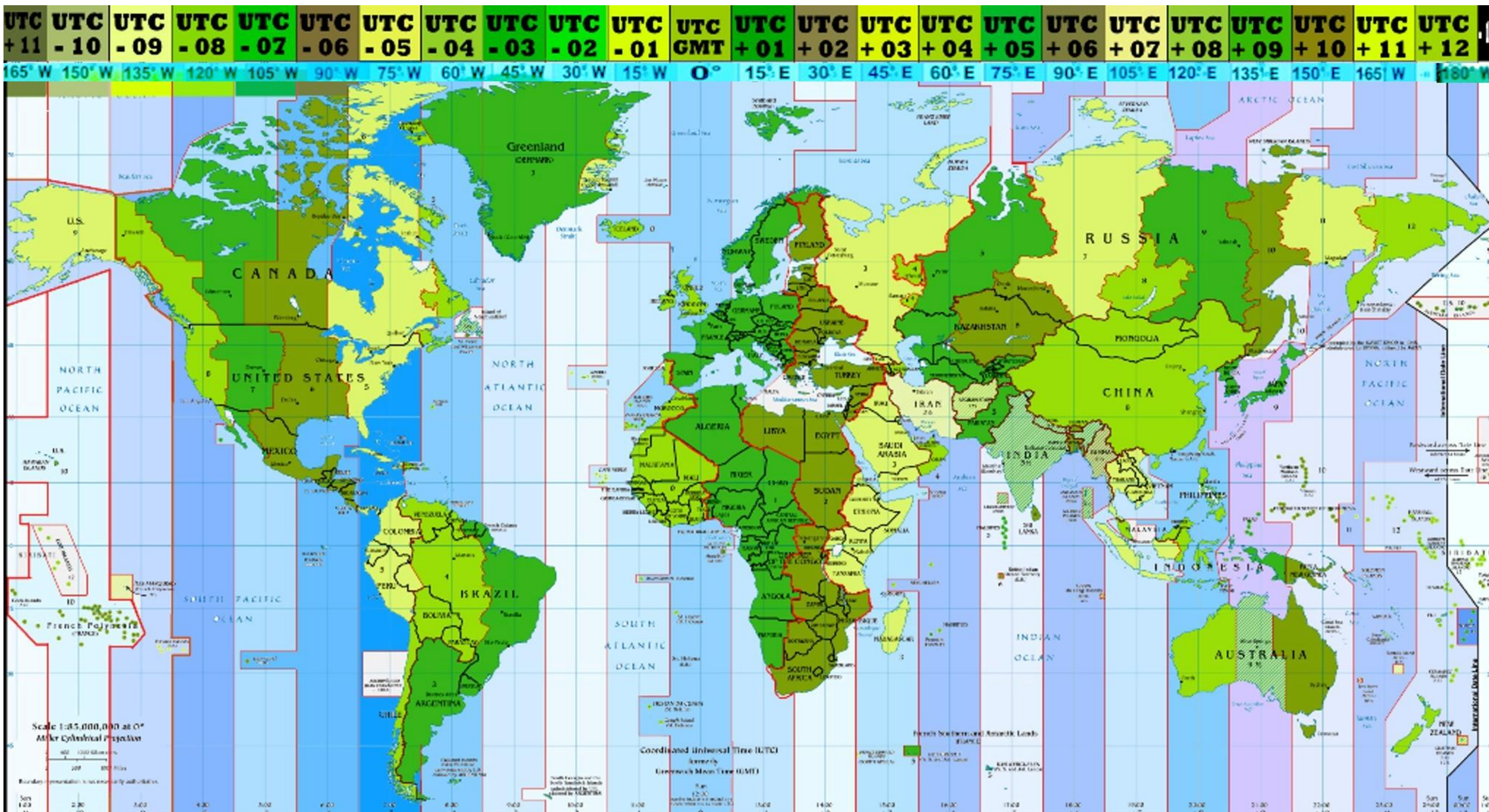
- As the earth turns once around its axis, it passes through 360 meridians.
- Moving from one meridian to the next takes 4 minutes.
- 15 degrees of longitude correspond to 1 hour.
- **Example**: If the time in Greenwich is 10:00, the time in a city 30° east will be 12:00, and the time in a city 45° west will be 7:00.



What about the time in locations between?

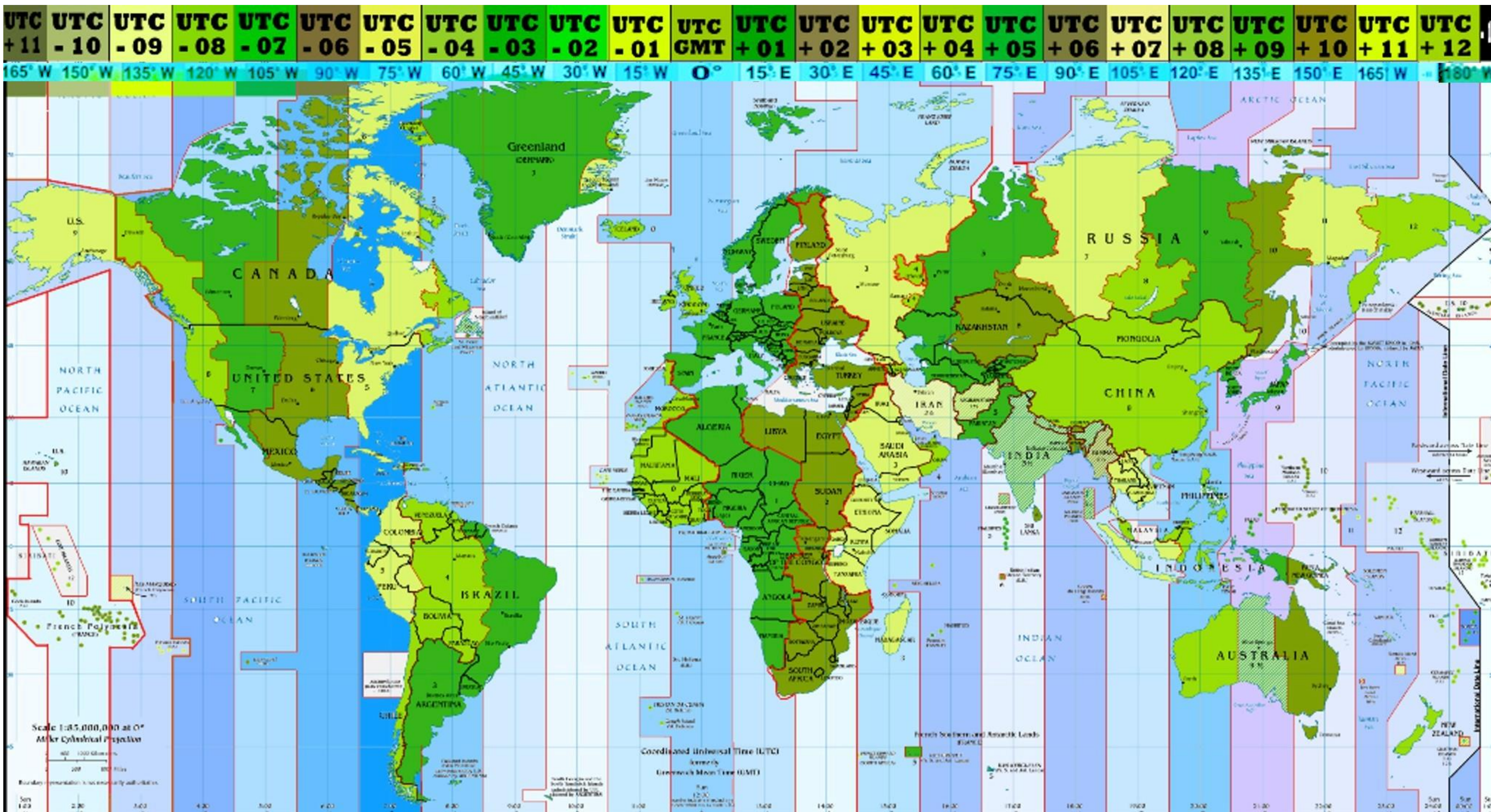
Standard Time

- To simplify calculation of time and avoid an infinite number of times throughout the world, Standard Time was introduced
- Clocks are usually set for the same reading throughout a zone covering approximately 15° of longitude



Standard Time

- The time at the center of the zone is called ***standard time***
- Zones are 15° apart



Solar Time

- Solar time is the time used in calculating the sun's position.
- Solar time does not coincide with standard time.
- In solar time, 12:00 always represents the time when the sun is exactly halfway through the sky.
- This time is called ***solar noon***.
- The time of Dhuhr Athan is solar noon.

Solar Time

- It is necessary to convert standard time to solar time by applying two corrections
  1. Constant correction for the difference in longitude between the observer's meridian (longitude) and the meridian on which the local standard time is based
  2. Equation of time, which takes into account the changes in the earth's rate of rotation

Conversion from Standard Time to Solar Time

- Local solar time at a given location is denoted by LST

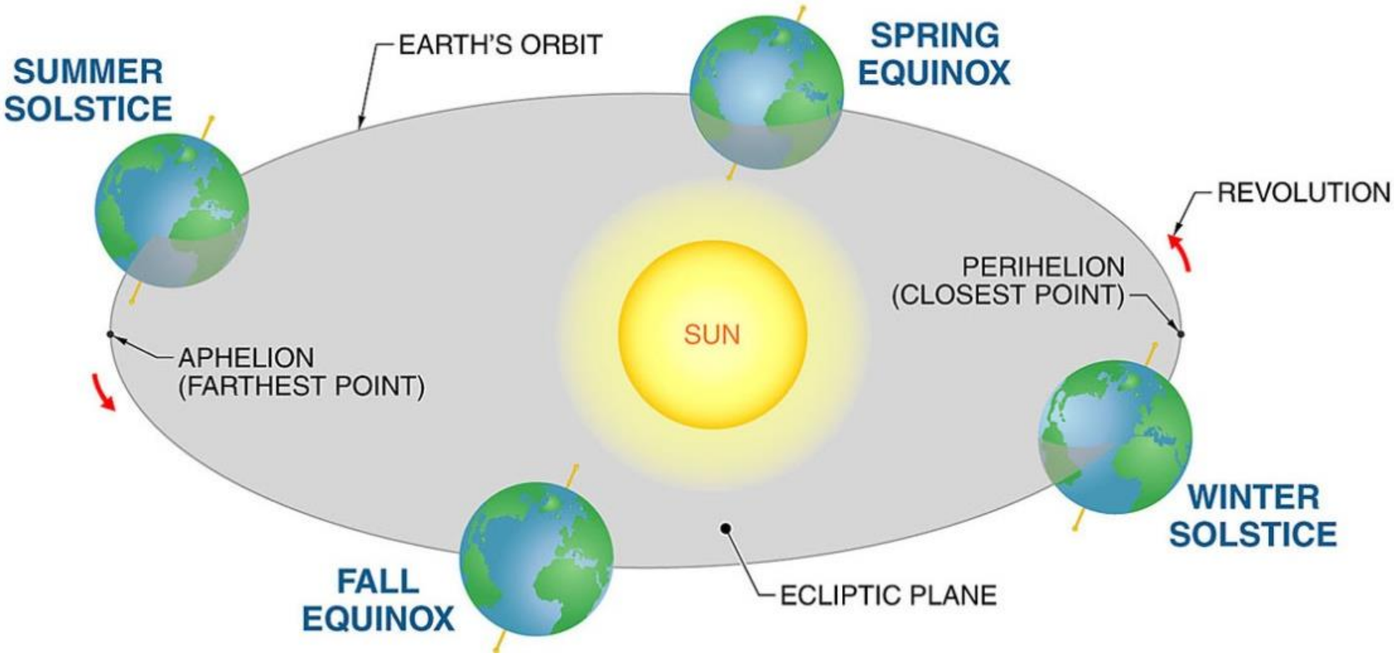
$$\text{LST} = \text{Local Standard Time} - \underbrace{(L_L - L_S)(4 \text{ min/deg W})}_{\text{Correction for Longitude}} + \underbrace{EOT}_{\text{Correction for Rate of Earth Rotation}}$$

Where:

- L_L is the longitude at the given location
- L_S is the longitude at the standard meridian for the time zone
- deg W means moving in the western hemisphere
  - **If a location is in the eastern hemisphere, (4) becomes (-4)**
- EOT is called the Equation of Time

Equation of Time

- Earth moves in an elliptical (not circular) orbit around the sun, moving faster near Perihilion than at Aphelion.
- This affects solar time.
- The correction used to account for this phenomenon is called Equation of Time (EOT)



Equation of Time

- EOT can be found from:

$$EOT = 229.2\,(0.000075 + 0.001868\cos N - 0.032077\sin N - 0.014615\cos 2N - 0.04089\sin 2N)$$

Where:

$$N = (n - 1)(360/365)$$

n is the day of the year

Equation of Time

EOT for the 21st of each month:

	Equation of Time, min	Declination, degrees	A, $\frac{\text{Btu}}{\text{hr-ft}^2}$	A, $\frac{\text{W}}{\text{m}^2}$	B, Dimensionless	C, Dimensionless
Jan	–11.2	–20.2	381.0	1202	0.141	0.103
Feb	–13.9	–10.8	376.2	1187	0.142	0.104
Mar	–7.5	0.0	368.9	1164	0.149	0.109
Apr	1.1	11.6	358.2	1130	0.164	0.120
May	3.3	20.0	350.6	1106	0.177	0.130
June	–1.4	23.45	346.1	1092	0.185	0.137
July	–6.2	20.6	346.4	1093	0.186	0.138
Aug	–2.4	12.3	350.9	1107	0.182	0.134
Sep	7.5	0.0	360.1	1136	0.165	0.121
Oct	15.4	–10.5	369.6	1166	0.152	0.111
Nov	13.8	–19.8	377.2	1190	0.142	0.106
Dec	1.6	–23.45	381.6	1204	0.141	0.103

Time Calculation Examples

- If the local standard time in Makkah is 9:45am on February 21st, calculate the solar time:

SOLUTION

- L_S is 45° east
- L_L for Makkah is 39.8° east
- Correction for longitude: (39.8 – 45) x (-4) = 20.8 min
- EOT = -13.9 min (from table or equation)

$\rightarrow$ LST = 9:45 – (20.8 min) – 13.9 min ≈ 9:10

$$\text{LST} = \text{Local Standard Time} - \underbrace{(L_L - L_S)(4\ \text{min/deg W})}_{\text{Correction for Longitude}} + \underbrace{EOT}_{\text{Correction for Rate of Earth Rotation}}$$

Correction for Longitude

Correction for Rate of Earth Rotation

Time Calculation Examples

- What is the time of Dhuhr Athan in Riyadh on February 21st?

SOLUTION

- L_S is 45° east, and L_L for Riyadh is 46.7° east
- Correction for longitude: (46.7 – 45) x (-4) = -6.8 min
- EOT = -13.9 min (from table or equation)
- LST at Dhuhr Athan is solar noon, which is always 12:00

→ 12:00 = Local Standard Time – (-6.8 min) – 13.9 min

→ Local Standard Time = 12:00 + 13.9 – 6.8 ≈ 12:07

$$\text{LST} = \text{Local Standard Time} - (L_L - L_S)(4\ \text{min/deg W}) + EOT$$

Correction for Longitude

Correction for Rate of Earth Rotation

Time Calculation Examples

- If the local standard time in Atlanta, Georgia is 3:00pm on November 21st, calculate the solar time:

SOLUTION

- L_S is 75° west
- L_L for Atlanta is 84.4° west
- Correction for longitude: (84.4 – 75) x (4) = 37.6 min
- EOT = 13.8 min (from table or equation)

$\rightarrow$ LST = 15:00 – (37.6 min) + 13.8 min ≈ 14:36

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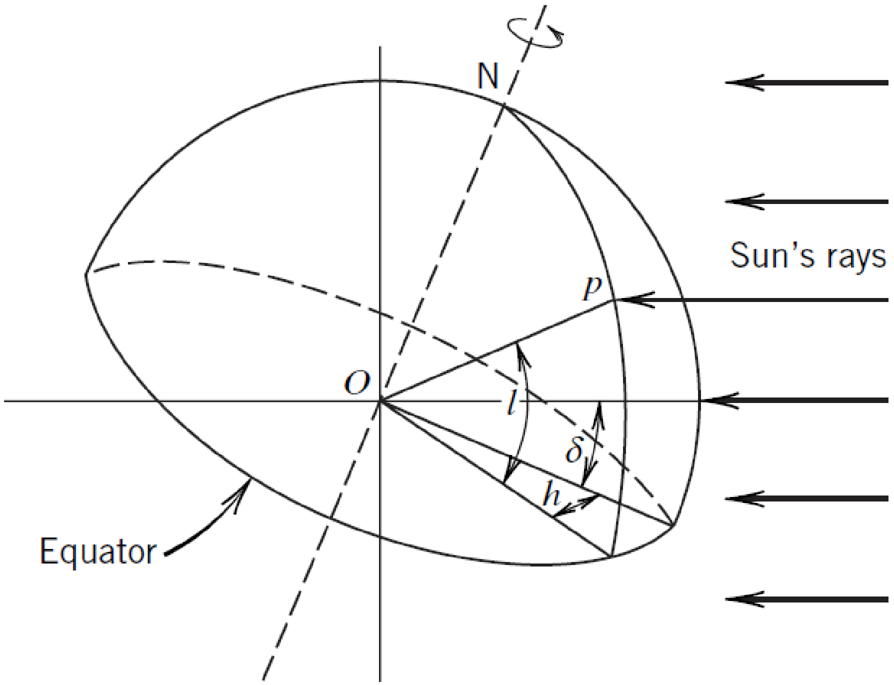
Solar Angles

- The location of the sun is determined by:
  - **Location on earth**
  - **Day of the year**
  - **Time of the day**
- It is convenient to describe these three quantities by angles:
- Location on earth is determined by latitude (*l*)
- Day of the year is determined by declination angle (δ)
- Time of the day is determined through solar time by the hour angle (*h*)



Declination Angle

- The declination angle can be determined as follows:

$$\delta = 0.3963723 - 22.9132745\cos N + 4.0254304\sin N - 0.3872050\cos 2N + 0.05196728\sin 2N - 0.1545267\cos 3N + 0.08479777\sin 3N$$

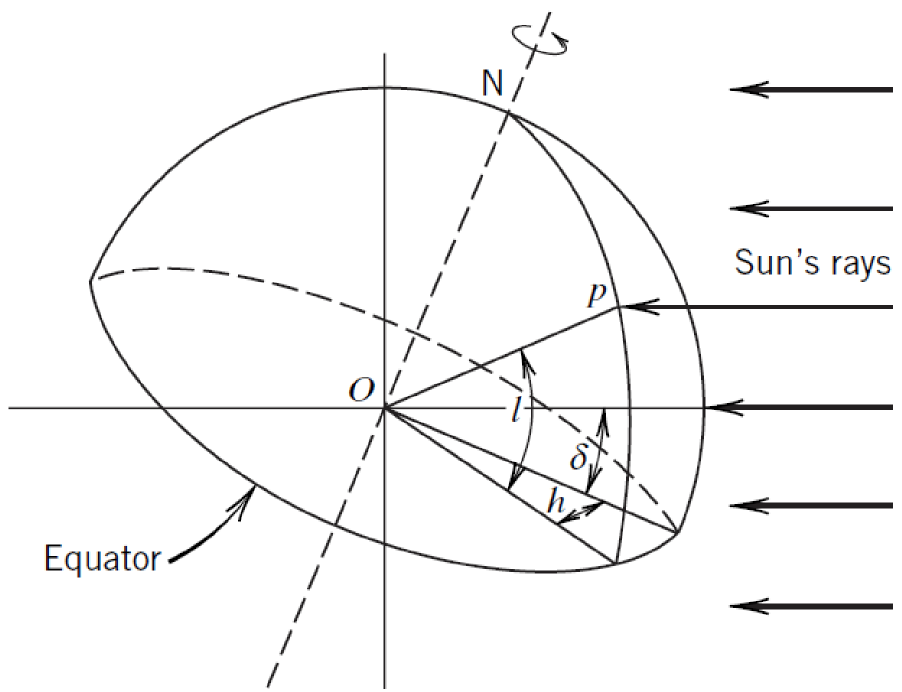
Where:

$$N = (n - 1)(360/365)$$

n is the day of the year

Hour Angle

- The *hour angle h* is the angle between the projection of *P* on the equatorial plane and the projection on that plane of a line from the center of the sun to the center of earth.
- 15° of hour angle corresponds to one hour of time.



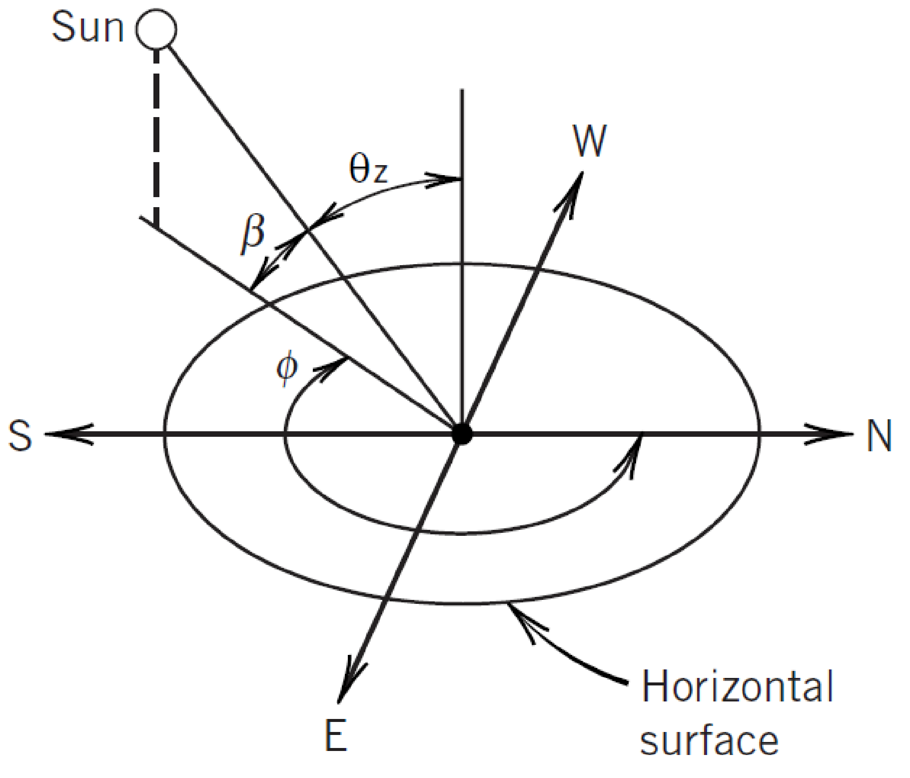
Hour Angle

- The hour angle is set to zero at local solar noon
- The hour angle is considered negative in the morning and positive in the afternoon.
- The maximum value of hour angle is at sunset
- The minimum value of hour angle is at sunrise
- The magnitude of hour angle at sunrise and sunset on a given day are identical.
- The hour angle is calculated by:

$$h = (\text{LST} - 12{:}00) \times 15°/\text{hour}$$

Determining Sun's Location in the Sky

- The sun's location in the sky can be determined from the following information:
  - **Latitute (*l*)**
  - **Declination angle (δ)**
  - **Hour angle (*h*)**
- The most convenient way to describe the sun's location in the sky is by using two angles:
- Solar ***elevation (or altitude) angle*** (β)
- Solar ***azimuth angle*** (ϕ)



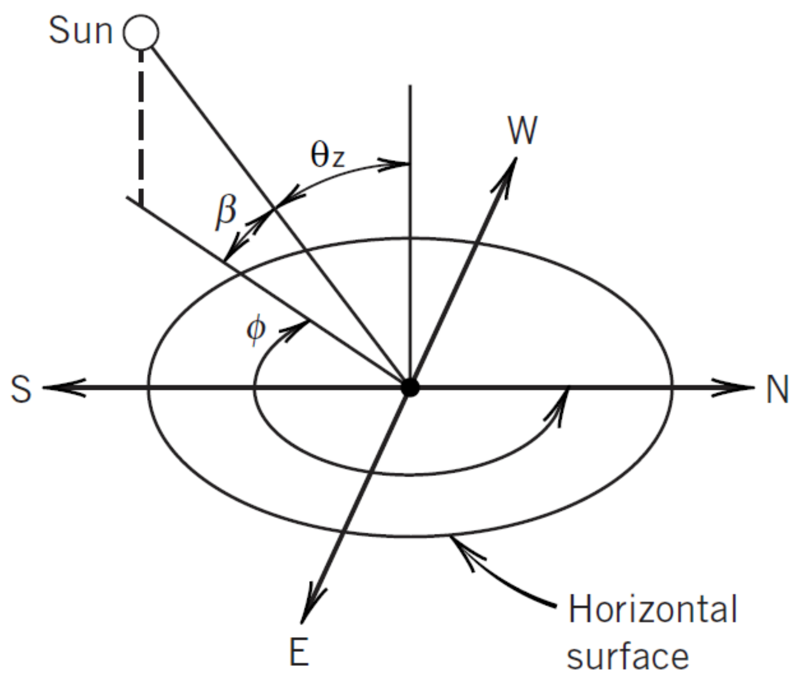
Solar Elevation Angle

- The ***solar elevation angle*** is the angle between the sun's ray and the projection of that ray on a horizontal surface
- At sunrise and sunset, the solar elevation angle is 0°.
- It can be found from:

$$\sin\beta = \cos l \cos h \cos\delta + \sin l \sin\delta$$

- The daily maximum elevation angle occurs at noon (β_{noon}).
- It is given by:

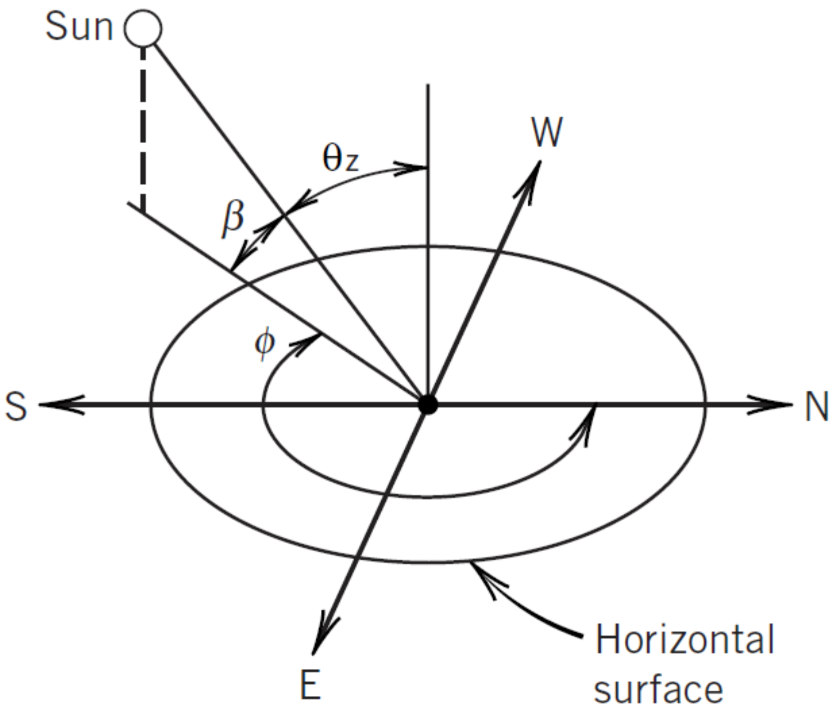
$$\beta_{noon} = 90 - |l - \delta| \text{ degrees}$$



Sun's Zenith Angle

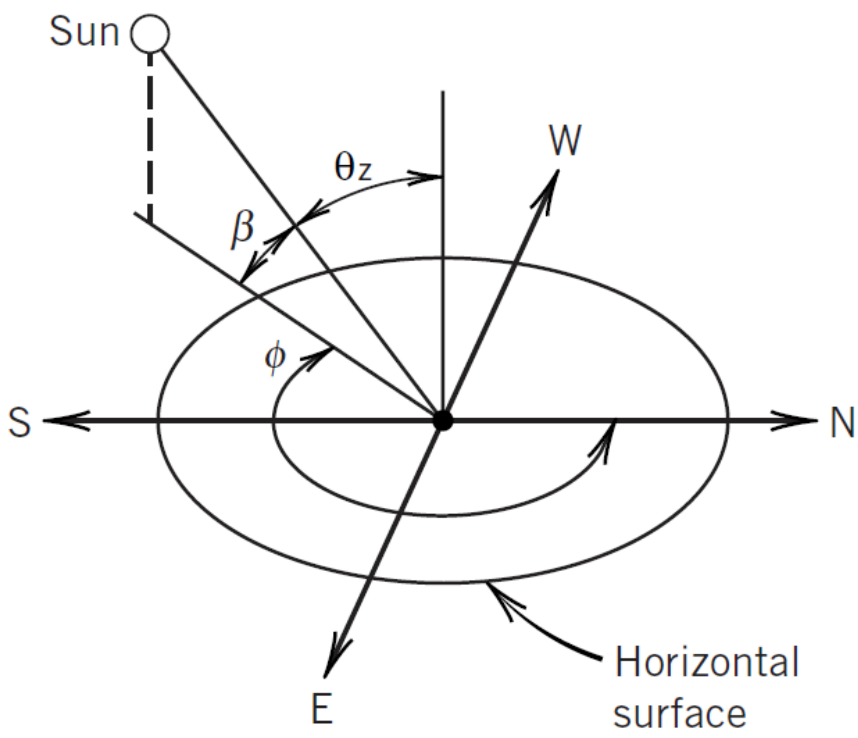
- The sun's ***zenith angle*** (β_Z) is the angle between the sun's rays and a perpendicular to the horizontal plane at point *P*.

$$\beta + \theta_Z = 90 \text{ degrees}$$



Solar Azimuth Angle

- The ***solar azimuth angle*** (ϕ) is the angle in the horizontal plane measured, in the clockwise direction, between north and the projection of the sun's rays on the horizontal plane.
- The solar azimuth angle can be found from:



$$\cos\phi = \frac{\sin\delta\cos l - \cos\delta\sin l\cos h}{\cos\beta}$$

Example

For Riyadh on February 21st, calculate sunset time (in standard time).

SOLUTION

At sunset, the elevation angle β = **0°**
Latitude of Riyadh: l = **24.6°**
Declination angle on February 21st: δ = **-10.8°**

$$\sin\beta = \cos l \cos h \cos\delta + \sin l \sin\delta$$

sin (0) = cos (24.6) x cos (h) x cos (-10.8) + sin (24.6) x sin (-10.8)
→ *h* = 85°

h = (LST – 12:00) x 15°/hour
→ LST = 17:40

$$\text{LST} = \text{Local Standard Time} - (L_L - L_S)(4 \text{ min/deg W}) + EOT$$

Local Standard Time = 17:40 + (46.7 – 45)x(-4) + 13.9
→ **Local Standard Time ≈ 17:47**

Example

For Riyadh on February 21st, calculate the azimuth angle at sunset

SOLUTION

The solar azimuth angle is given by:

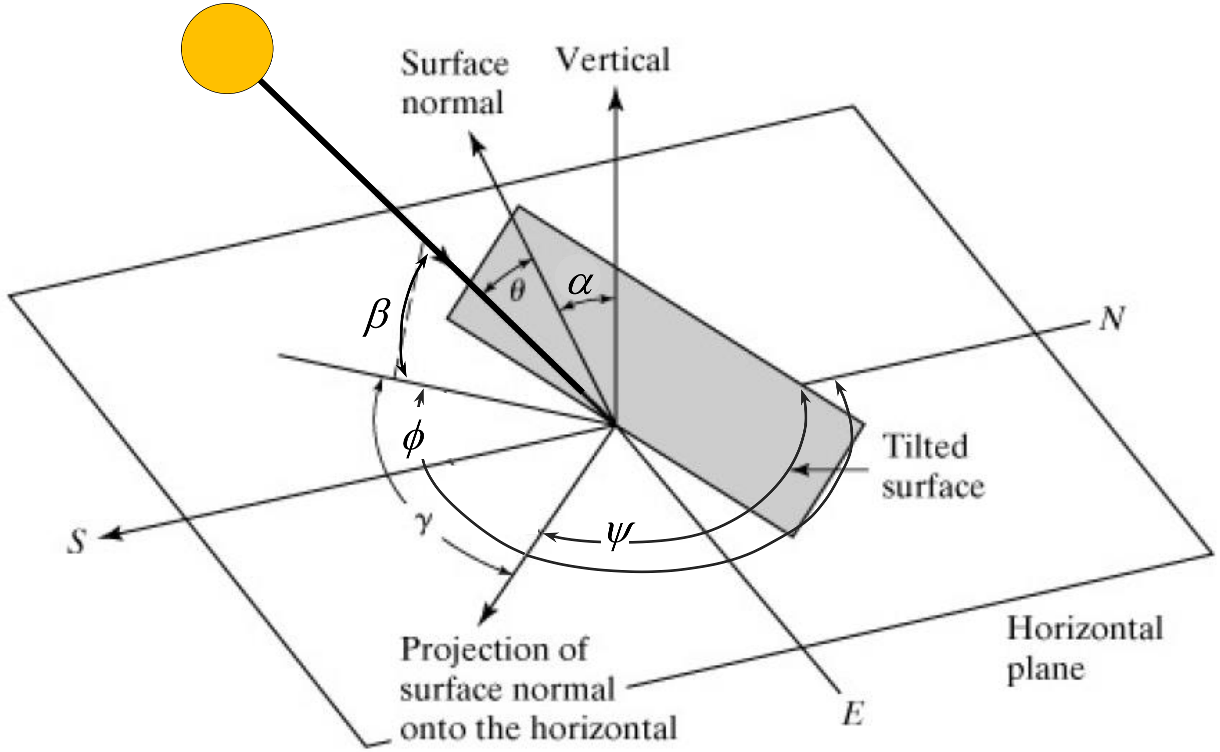
$$\cos\phi = \frac{\sin\delta\cos l - \cos\delta\sin l\cos h}{\cos\beta}$$

At sunset, the elevation angle β = **0°**
Latitude of Riyadh: l = **24.6°**
Declination angle on February 21st: δ = **-10.8°**
Hour angel (found from previous example): h = **85°**

cos (ϕ) = sin (-10.8) x cos (24.6) – cos (-10.8) x sin (24.6) x cos (85)
→ cos (ϕ) = -0.206 (second quadrant)
→ ϕ = 101.9° OR 258.1°
The first solution represents sunrise, and the second represents sunset.
→ **ϕ = 258.1°**

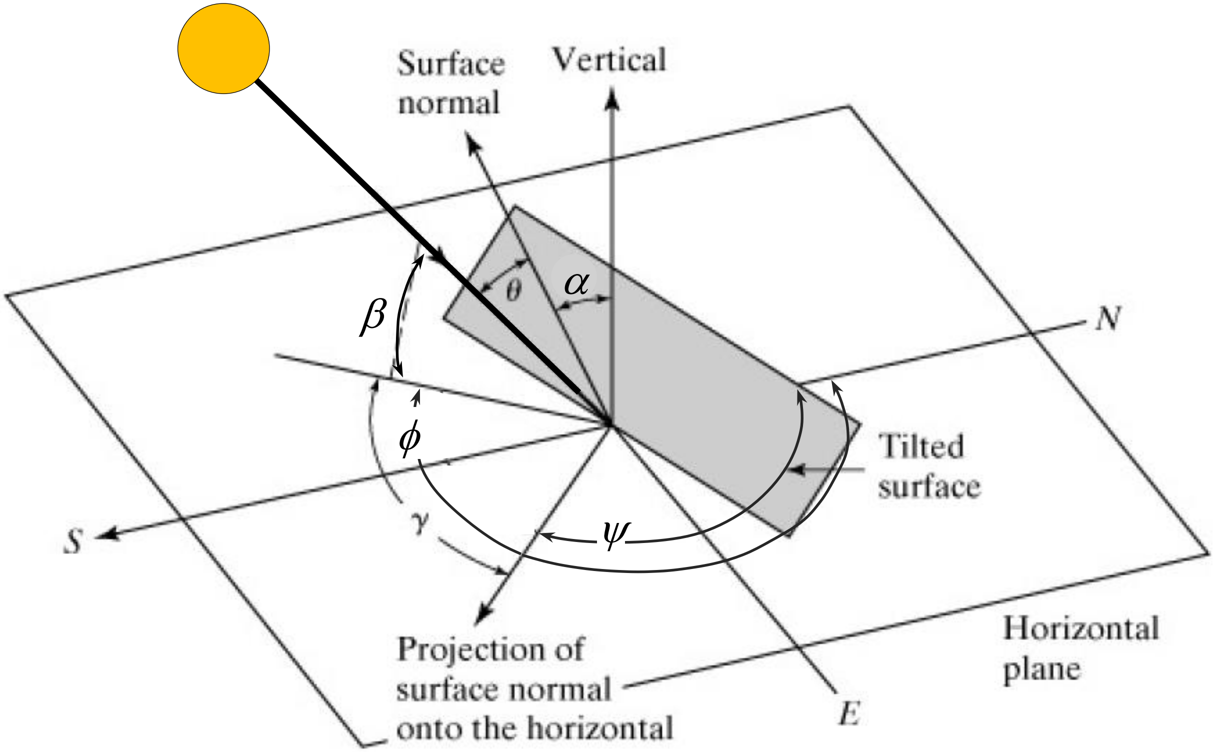
Angles for Non-Horizontal Surfaces

- The ***angle of incidence*** (θ) is the angle between the sun's rays and the normal to the surface.
- The ***tilt angle*** (α) is the angle between the normal to the surface and the normal to the horizontal surface



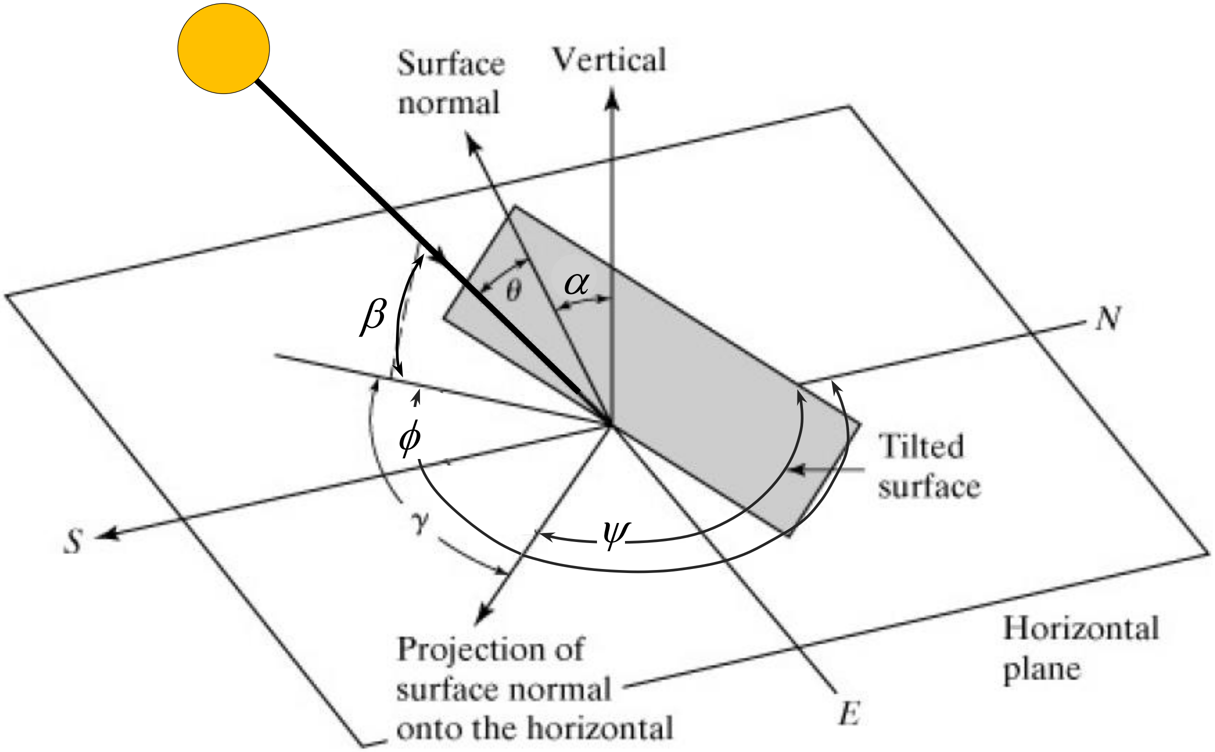
Angles for Non-Horizontal Surfaces

- The ***surface solar azimuth angle*** (γ) is the angle measured in the horizontal plane between the projection of the sun's rays on that plane and the projection of a normal to the surface



Angles for Non-Horizontal Surfaces

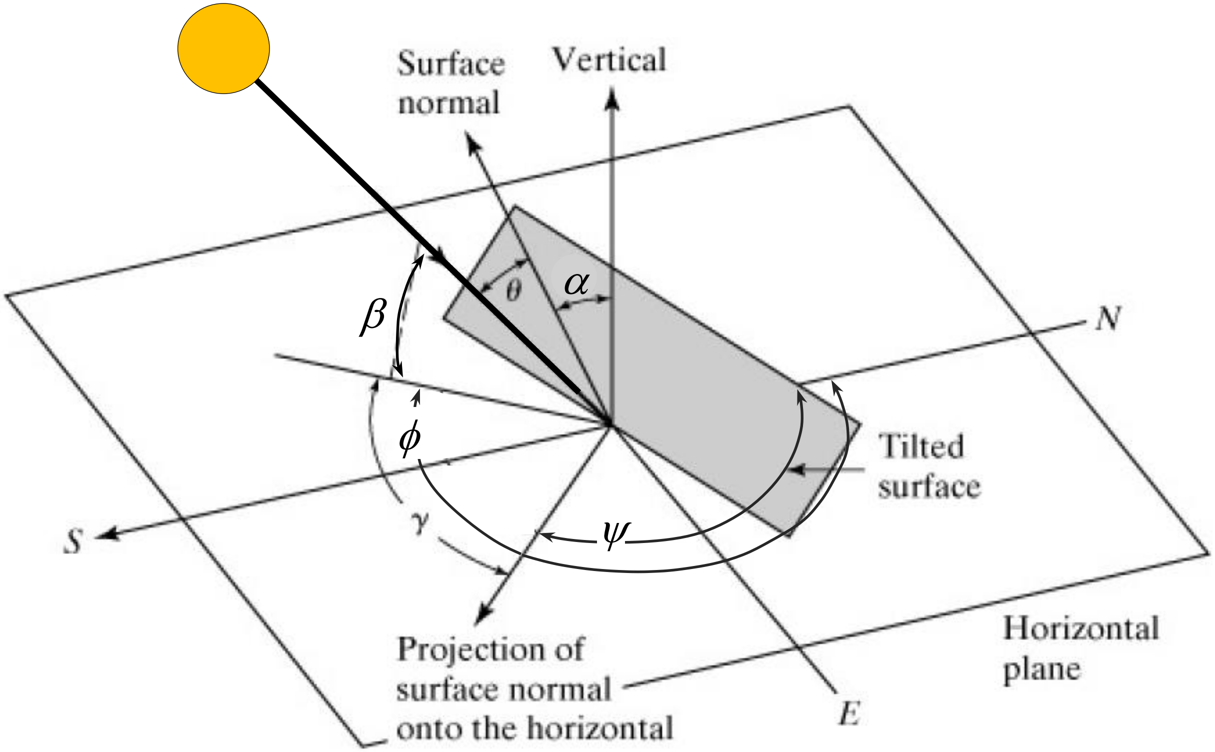
- The ***surface azimuth angle*** (ψ) is the angle in the horizontal plane measured, in the clockwise direction, between north and the projection of the normal to the surface.



Non-Horizontal Surface Angles Relations

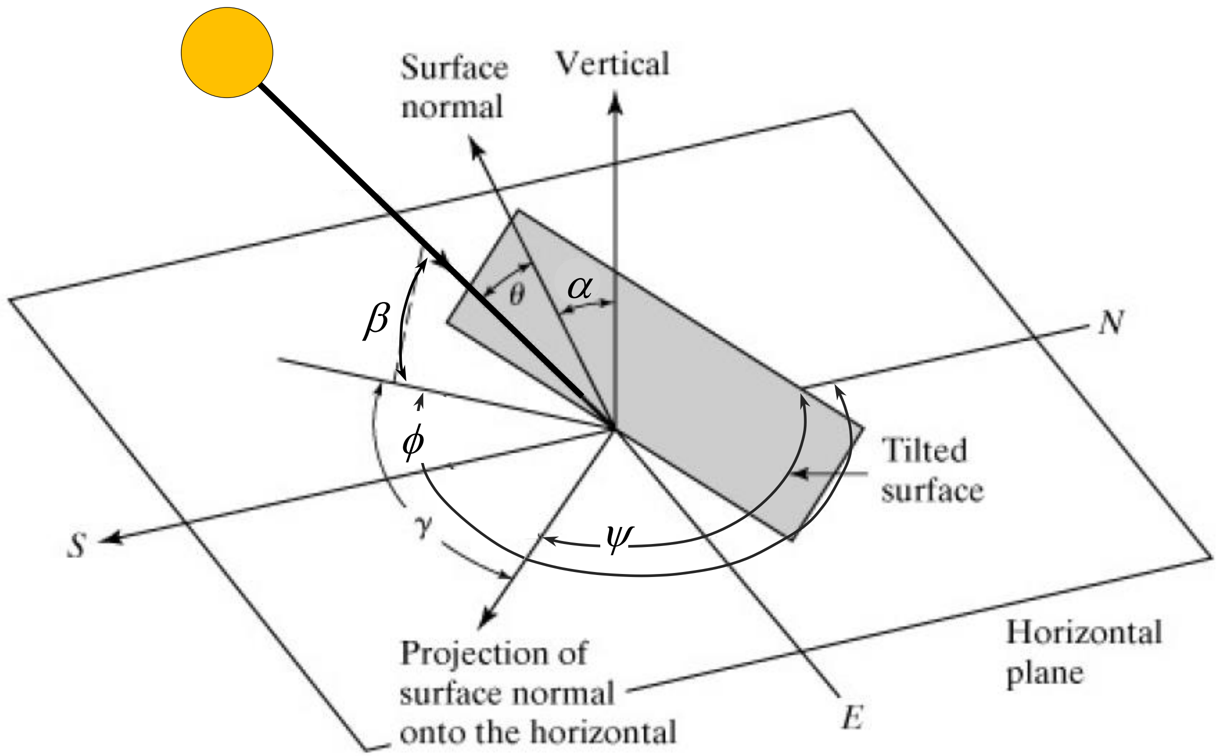
$$\gamma = |\phi - \psi|$$

$$\cos\theta = \cos\beta\cos\gamma\sin\alpha + \sin\beta\cos\alpha$$



Special Case: Horizontal Surface

- If the surface is horizontal, $\alpha = 0$
  - ✓ $\theta = \theta_Z$ (zenith angle)
  - ✓ The angles: ψ *and* γ are undefined.



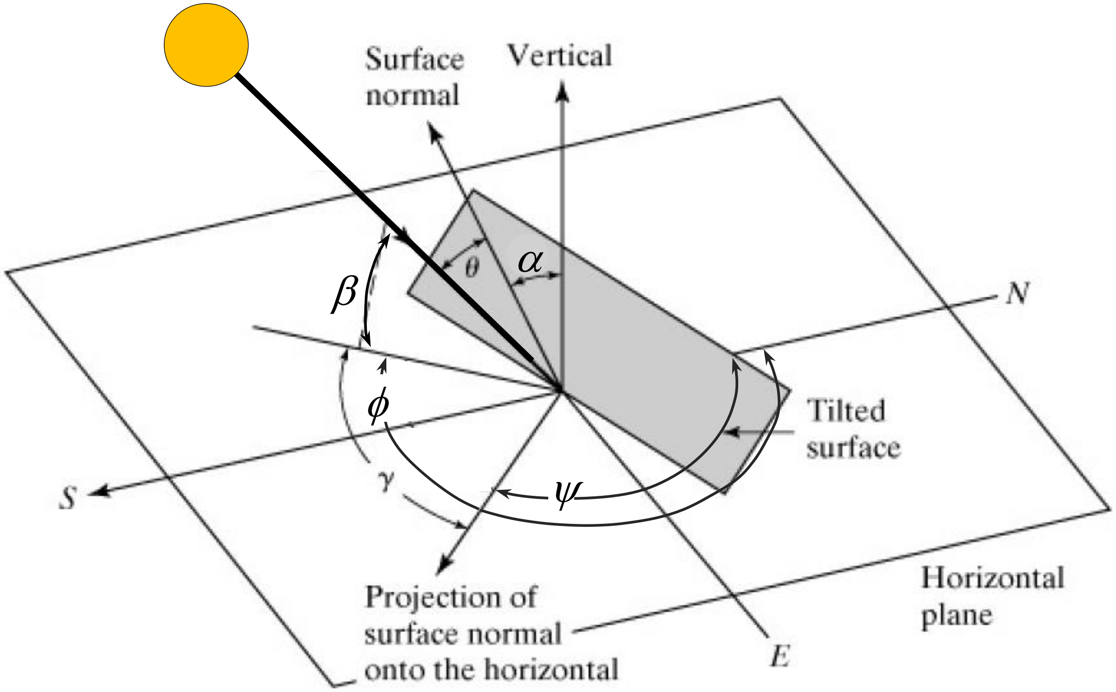
Summary of Solar Angle Relations

h = (LST – 12:00) x 15°/hour

$$\sin\beta = \cos l \cos h \cos\delta + \sin l \sin\delta$$

$$\cos\phi = \frac{\sin\delta\cos l - \cos\delta\sin l\cos h}{\cos\beta}$$

$$\beta + \theta_Z = 90 \text{ degrees}$$



Summary of Surface Angle Relations

$$\gamma = |\phi - \psi|$$

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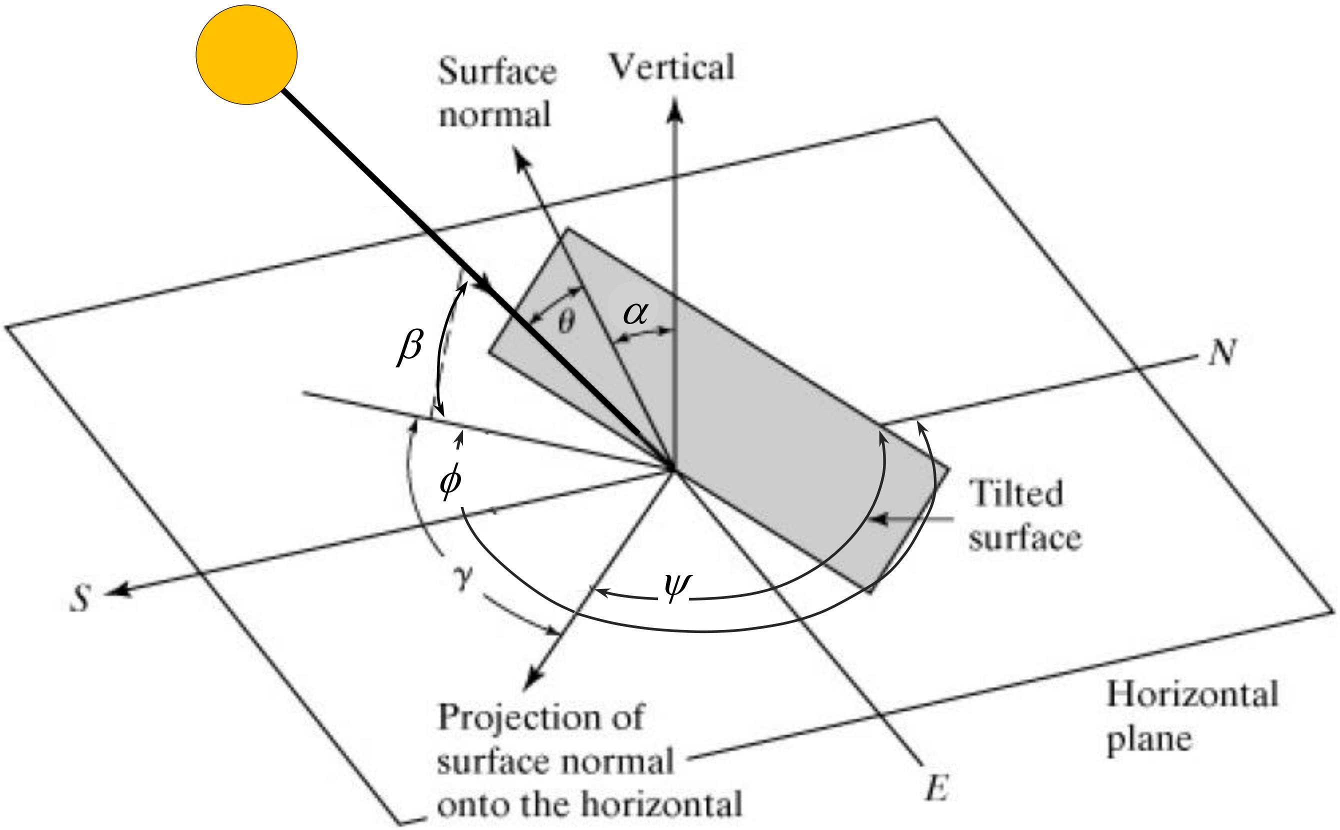

Example

- A flat plate solar collector is placed on a roof in the city of Dubai. The collector is tilted by 30° to the south. For May 21st at 14:00 (local standard time), calculate the angle of incidence (θ).

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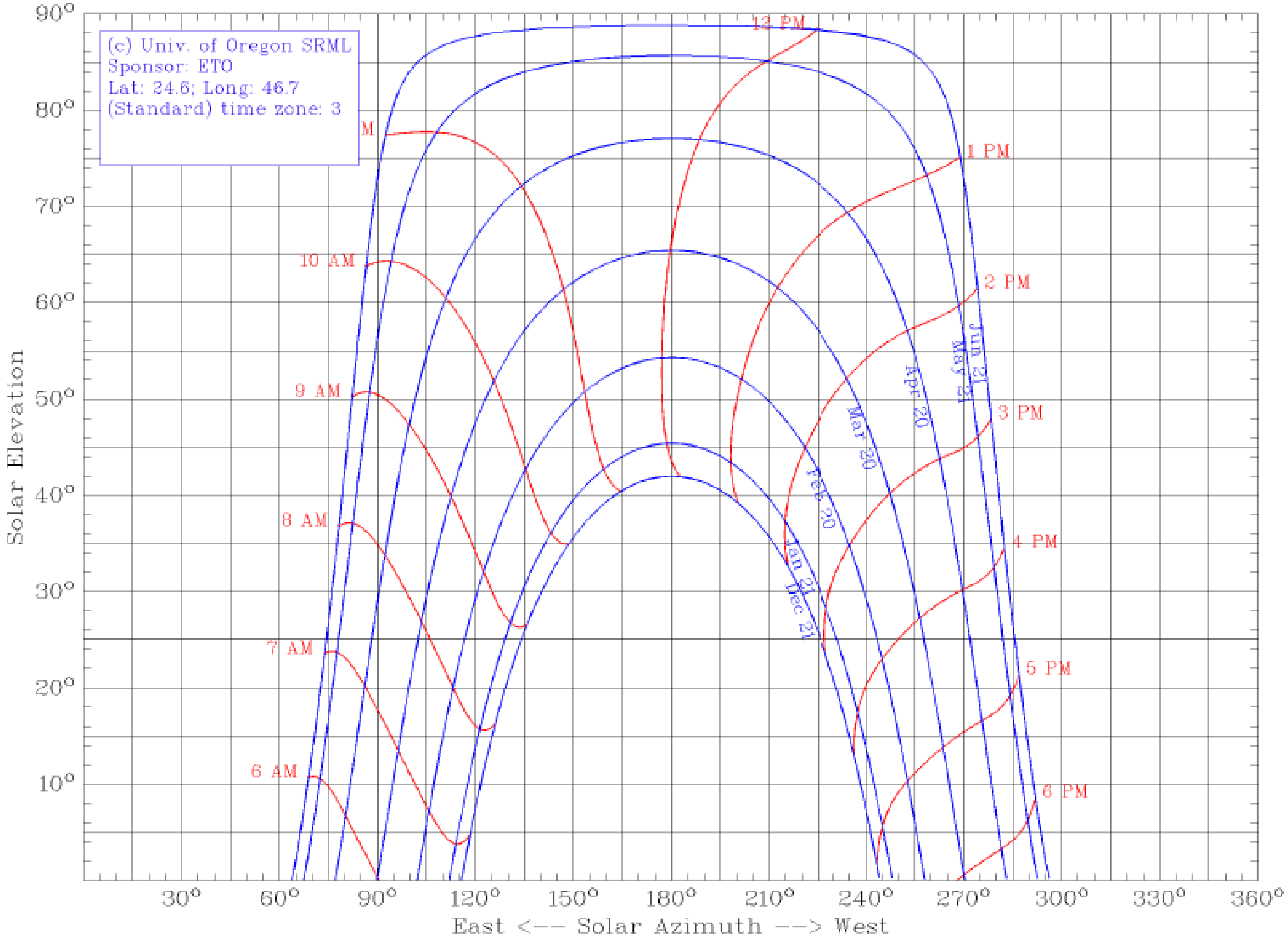
A flat plate solar collector is placed on a roof in the city of Dubai. The collector is tilted by 30° to the south. For May 21st at 14:00 (local standard time), calculate the angle of incidence (θ).

GIVEN

- For Dubai:
  - **Latitude (*l*) = 25.2° North**
  - **Longitude (L_L) = 55.3° East**
  - **Standard Meridian (L_S) = 60°**
- For May 21st:
  - **EOT = 3.3 min**
  - **δ = 20°**
- Tilt Angle: **α = 30°**
- The collector is facing south: surface azimuth angle **ψ = 180°**

Sun Chart

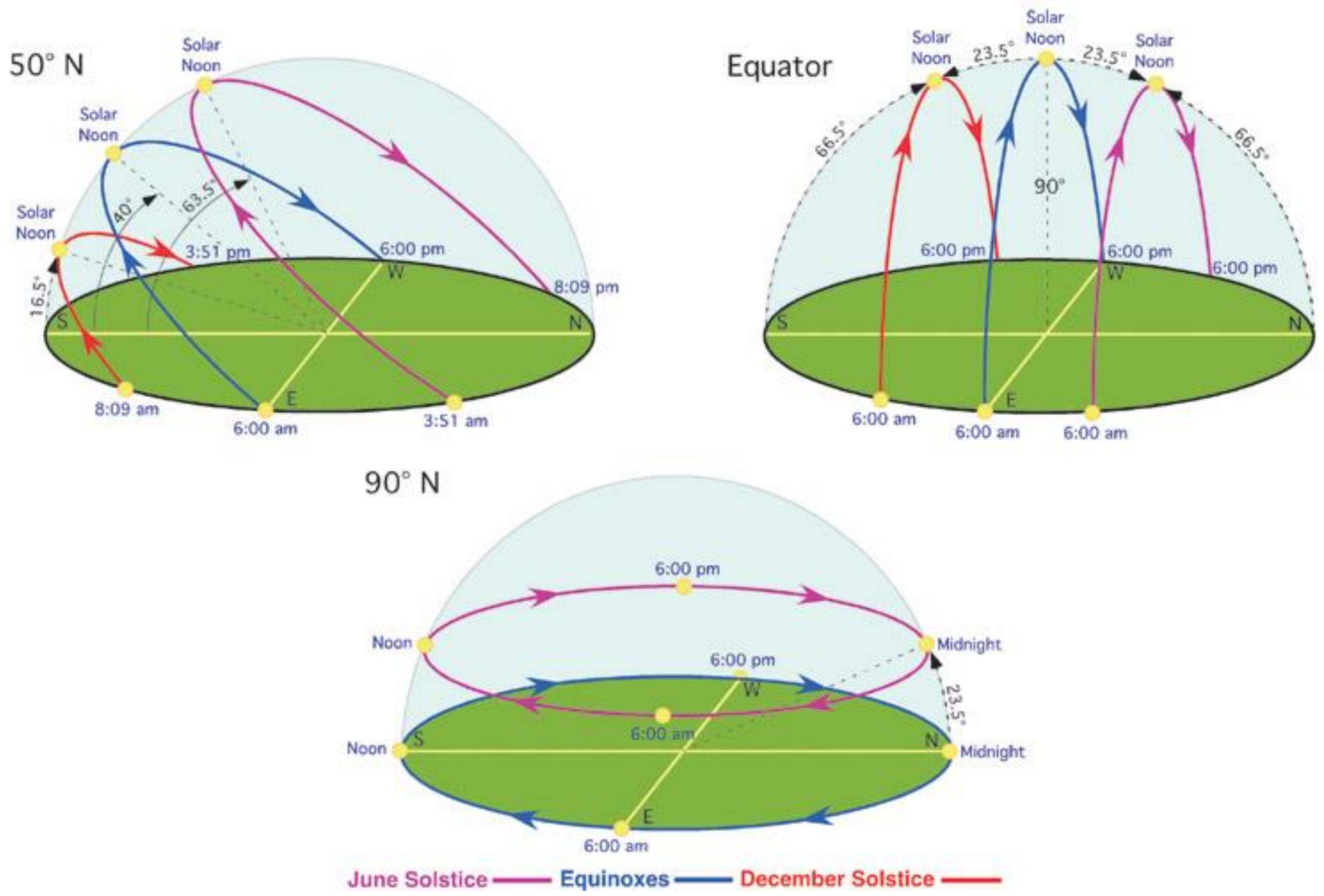
The Sun Chart shows the changes in of the solar elevation and azimuth angles for representatives days of the year.



http://solardat.uoregon.edu/SunChartProgram.html

Sun Path

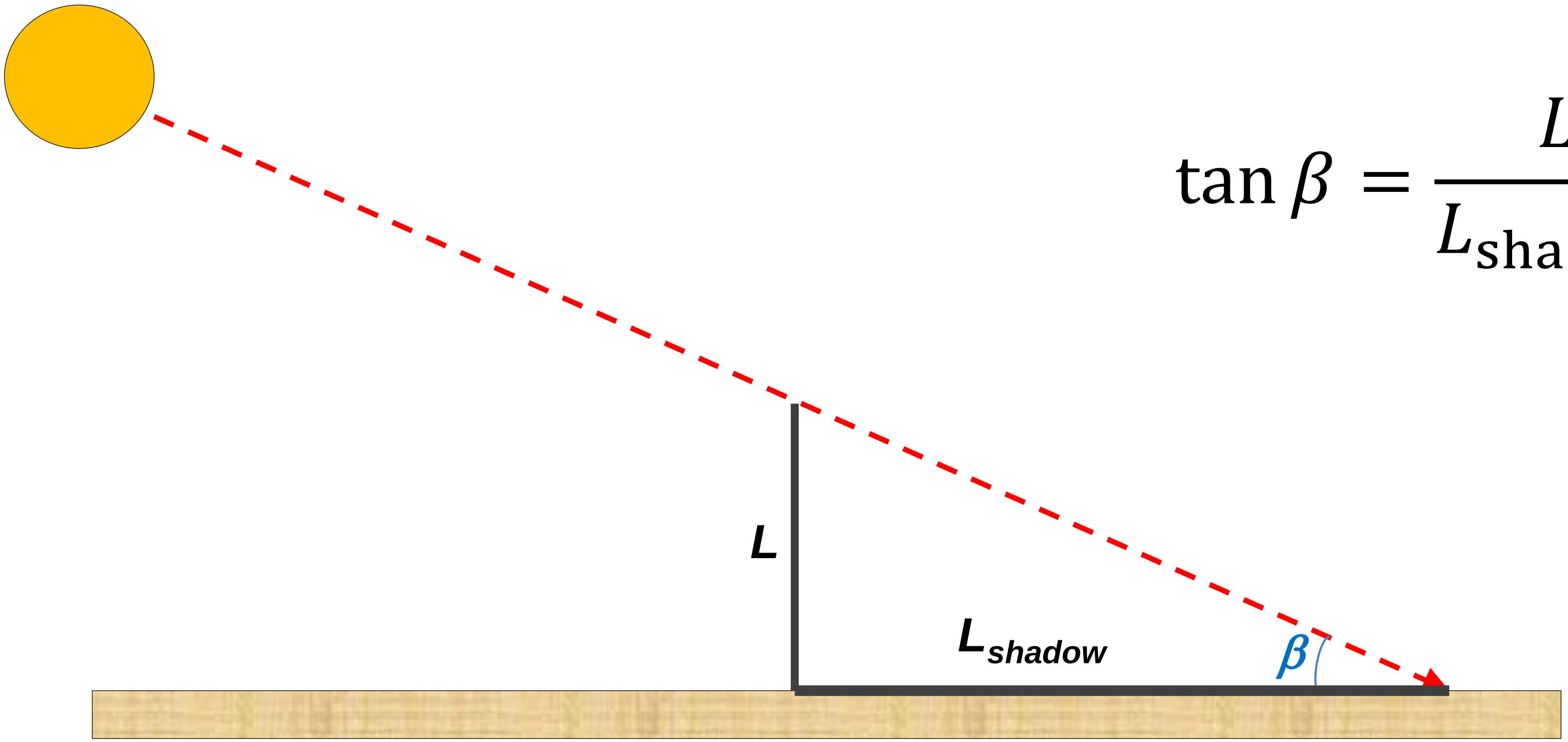
- A sun chart can be viewed in three-dimensions.
- The result is usually referred to as the Sun Path.



Experiment

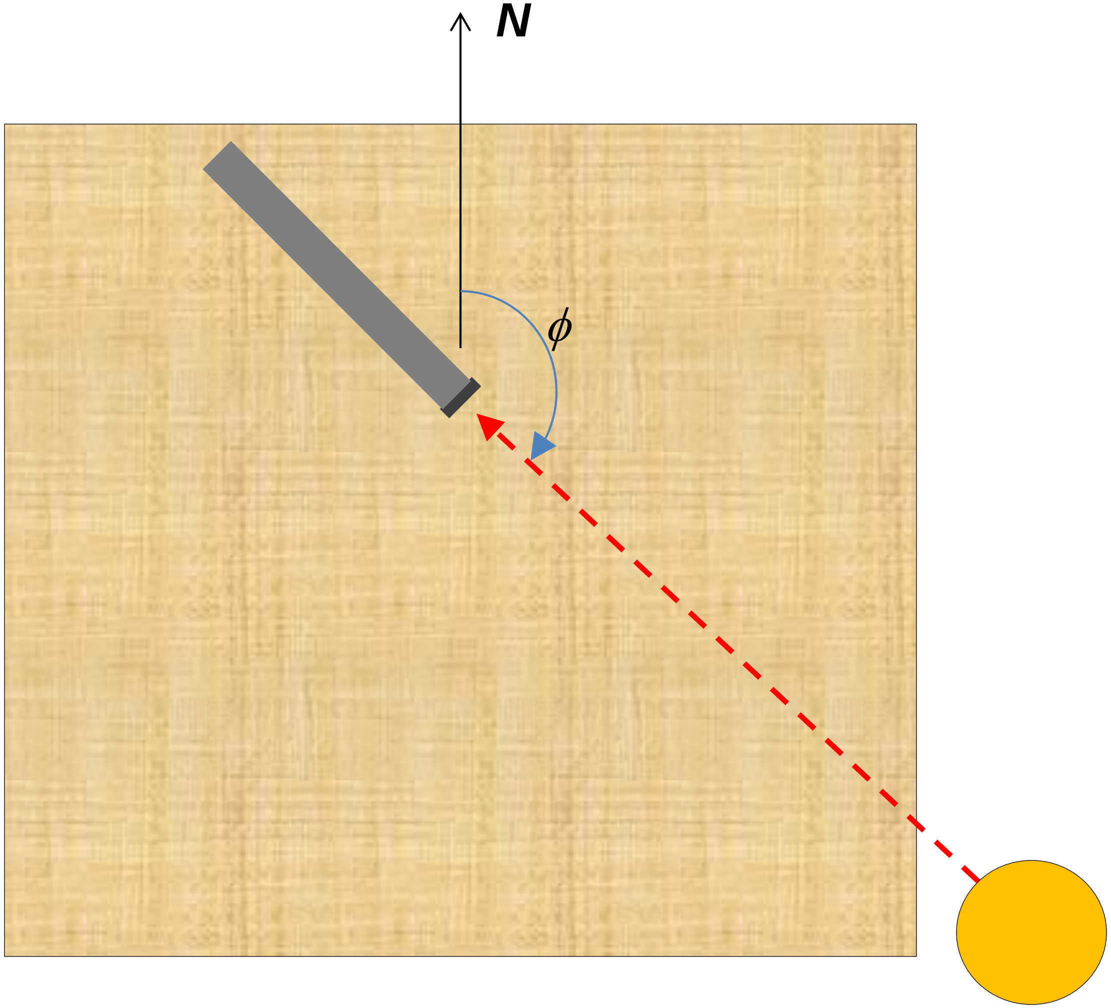
- The solar elevation and azimuth angles will be measured on March 2nd at 9:45am on the roof of the ME Department.
- The elevation angle can be measured by measuring the length of the shade of an object.

$$\tan\beta = \frac{L}{L_{\mathrm{shadow}}}$$



Experiment

- The solar azimuth angle (ϕ) can be measured by a protractor



Experiment

- At 9:45am on March 2nd , the following can be shown:

$$\text{LST} = \text{Local Standard Time} - (L_L - L_S)(4 \text{ min/deg W}) + EOT$$

LST = 9:45 – (46.7 – 45) x (-4) – 12.19
→ LST = 9:39.6 am (or 9.66)

h = (LST – 12:00) x 15°/hour
→ ***h* = -35.1°**

Latitude of Riyadh: l = **24.7°**
Declination angle on February 21st: δ = **-7.21°**

$$\sin\beta = \cos l \cos h \cos\delta + \sin l \sin\delta$$

→ β **= 43.2°**

$$\cos\phi = \frac{\sin\delta \cos l - \cos\delta \sin l \cos h}{\cos\beta}$$

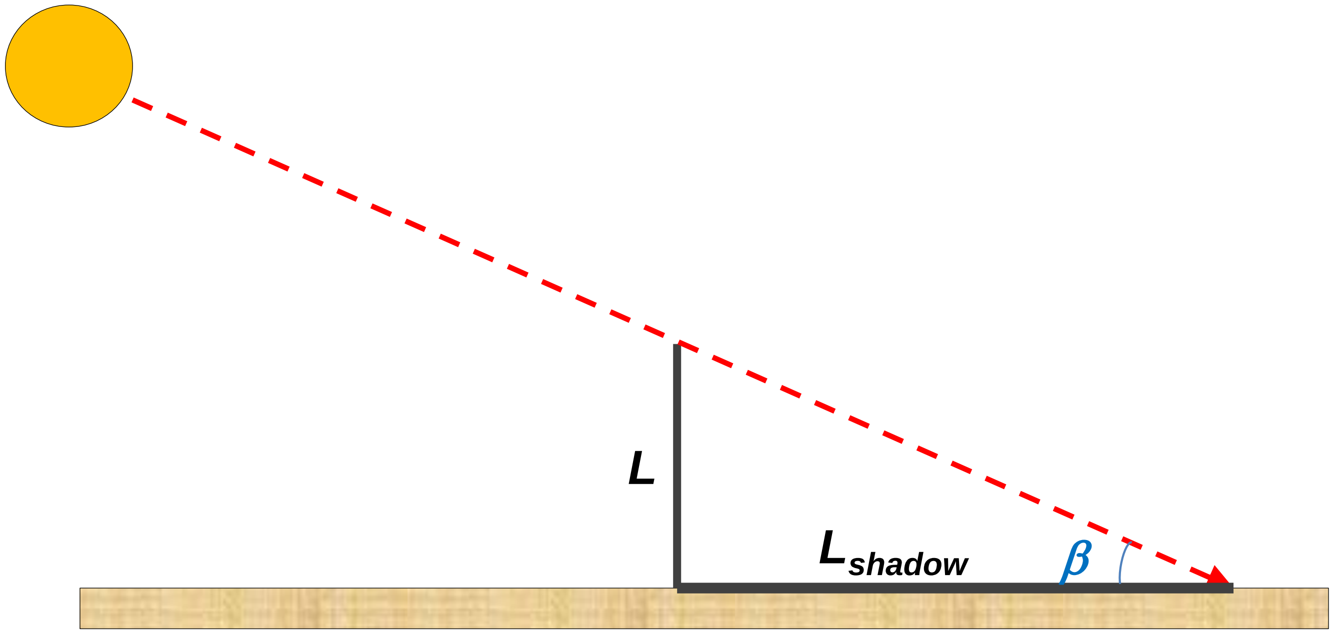
→ ϕ **= 128.5°**

Experiment

- We will use a ruler that has a length L = 1.05 m long.

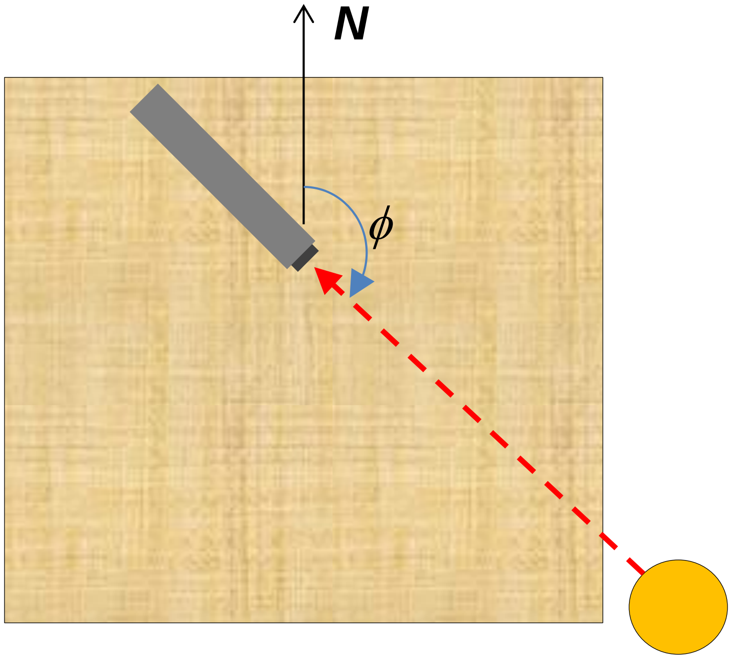
$$\tan 43.2 = \frac{1.05}{L_{\text{shadow}}}$$

- The length of the shadow should be L_{shadow} = 1.12 m.



Experiment

- The solar azimuth angle (ϕ) can be measured by a protractor
- The protractor will measure the angle between north and the shadow. We'll call this angle (K)
- $\phi = 180° - K$
- Since ϕ is 128.5°, the protractor should measure an angle of 51.5° (or ~ 52°).



Unit Outline

- What is the sun?
- Radiation from the sun
- Factors affecting solar radiation
  - **Atmospheric effects**
  - **Solar radiation intensity**
  - **Air mass**
  - **Seasonal variations**
- Calculating time
- Solar angles
- Solar irradiation on surfaces

Solar Irradiation on Surfaces

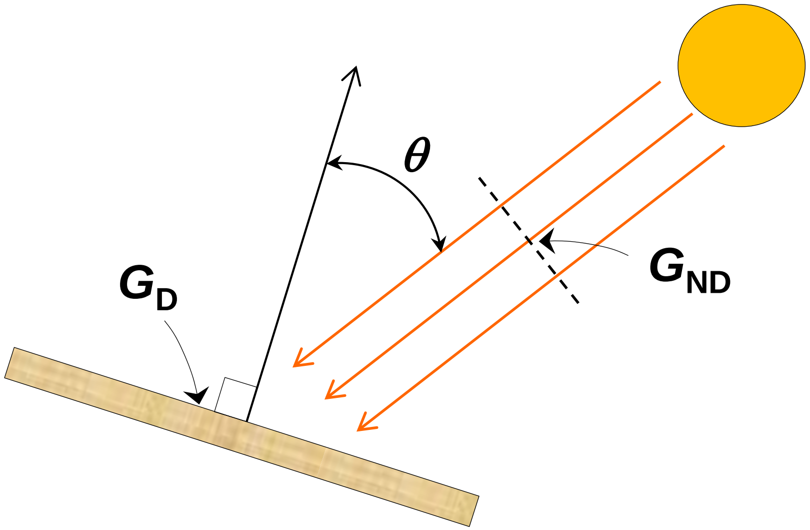
- A surface can be irradiated by the following three sources:
  - Direct irradiation (G_D).
  - Diffuse irradiation ($G_{d\theta}$).
  - Irradiation reflected from the ground (G_R).
- The total irradiation on a surface is, therefore:

$$G_t = G_D + G_{d\theta} + G_R$$

- To model the performance of a solar collector, it is necessary to have accurate information about each of the three components.

Determination of Direct Irradiation (G_D)

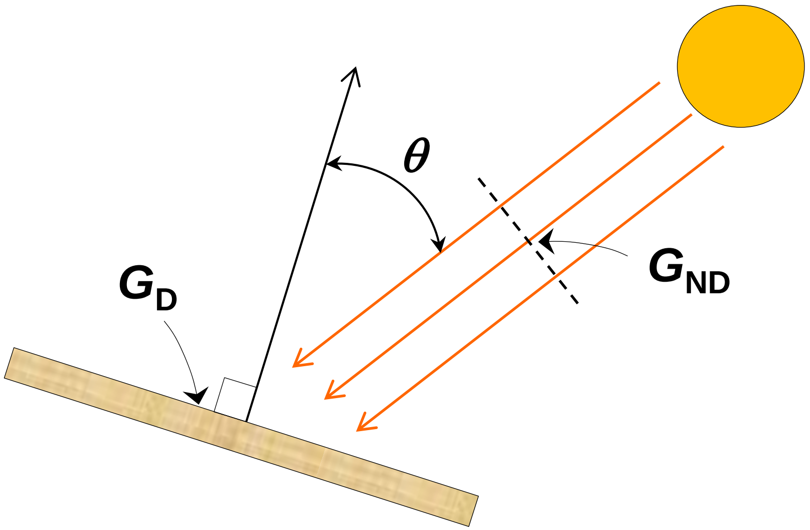
- Direct irradiation on a surface of any orientation can be deduced from the direct irradiation on a surface normal to the sun's rays.
- The direct irradiation on a surface normal to the sun's rays is usually called ***direct normal irradiance*** (DNI).
- Direct normal irradiance is denoted by (G_{ND}).



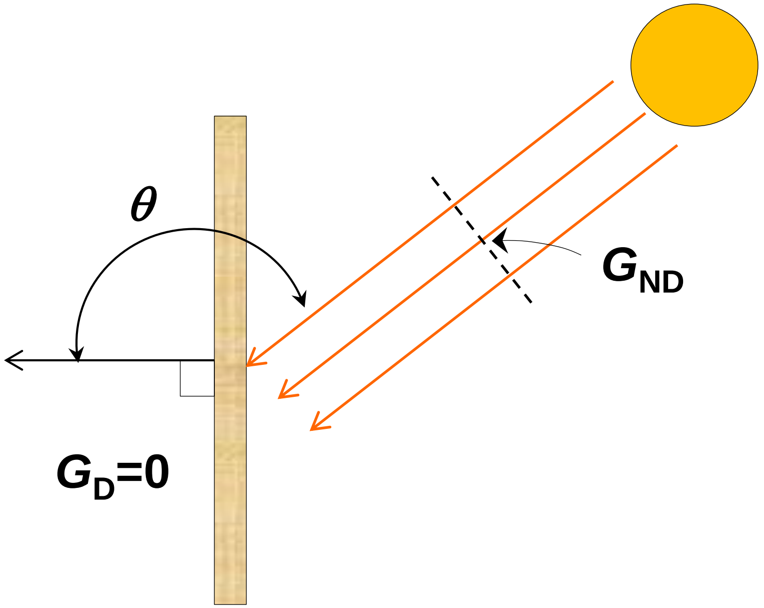
Determination of Direct Irradiation (G_D)

- The general relationship between G_{ND} and G_D is:

$$G_D = G_{ND} \cos \theta$$



- If the angle of incidence (θ) is larger than 90°, the surface is not receiving direct sunlight.
- In this case, $G_D = 0$.

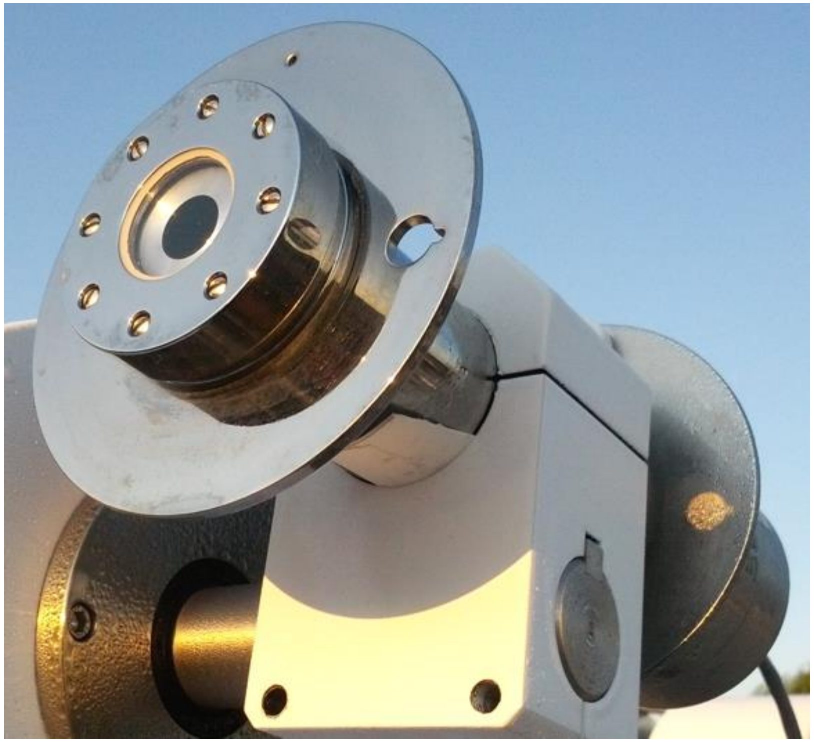


Determination of Direct Normal Irradiance (G_{ND})

- Direct normal irradiance (G_{ND}) can either be measured or estimated
- Measurements provide accurate, real-time data for a specific location.
    - **Requires a well-maintained measurement station.**
- Estimation of G_{ND} is more convenient, but it is not as accurate as actual measurements.
- The most common method for measuring G_{ND} is by using a ***pyrheliometer***.
- The most common method to estimate G_{ND} is the ***ASHRAE Clear Sky Model***.

Pyrheliometer

- A pyrheliometer measures direct normal irradiance.
- Sunlight enters the instrument through a window and is directed onto a sensor.
- The sensor converts heat to an electrical signal.
- The signal voltage is converted via a formula to measure watts per square meter.
- To keep the sunlight normal to the window at all times, a solar tracking system is used.



ASHRAE Clear Sky Model

- This model estimates the direct normal irradiance (G_{ND}) on a clear day, i.e. no clouds, dust, or pollution.

$$G_{ND} = \frac{A}{\exp(B/\sin\beta)}$$

where,

- A: apparent solar irradiation at air mass equal to zero (in W/m^2)
- B: atmospheric extinction coefficient
- β : solar elevation (altitude) angle

ASHRAE Clear Sky Model

$$G_{ND} = \frac{A}{\exp(B/\sin\beta)}$$

- *A* and *B* can be found from the table below on the 21st day of every month.

	Equation of Time, min	Declination, degrees	A, $\frac{\text{Btu}}{\text{hr-ft}^2}$	A, $\frac{\text{W}}{\text{m}^2}$	B, Dimensionless	C, Dimensionless
Jan	–11.2	–20.2	381.0	1202	0.141	0.103
Feb	–13.9	–10.8	376.2	1187	0.142	0.104
Mar	–7.5	0.0	368.9	1164	0.149	0.109
Apr	1.1	11.6	358.2	1130	0.164	0.120
May	3.3	20.0	350.6	1106	0.177	0.130
June	–1.4	23.45	346.1	1092	0.185	0.137
July	–6.2	20.6	346.4	1093	0.186	0.138
Aug	–2.4	12.3	350.9	1107	0.182	0.134
Sep	7.5	0.0	360.1	1136	0.165	0.121
Oct	15.4	–10.5	369.6	1166	0.152	0.111
Nov	13.8	–19.8	377.2	1190	0.142	0.106
Dec	1.6	–23.45	381.6	1204	0.141	0.103

ASHRAE Clear Sky Model

- Actual direct normal irradiance (G_{ND}) may differ from the ASHRAE Clear Sky Model due to local atmospheric conditions.

Monthly adjustment factors for the ASHRAE clear-sky model based on solar measurements in Riyadh averaged over the years 1996–2000

	Month											
	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
ϕ	0.825	0.766	0.843	0.879	0.907	0.978	0.965	0.962	0.949	0.928	0.852	0.880

- Al-Sanea, S. A., Zedan, M. F., & Al-Ajlan, S. A. (2004). Adjustment factors for the ASHRAE clear-sky model based on solar-radiation measurements in Riyadh. *Applied energy*, *79*(2), 215-237.

- For this reason, actual measurements are more reliable.

Determination of Diffuse Irradiation ($G_{d\theta}$)

- Diffuse irradiation ($G_{d\theta}$) on a surface of any orientation can be deduced from the diffuse irradiation on a horizontal surface (G_d).

$$G_{d\theta} = G_d \, F_{sur\text{-}sky}$$

where, $F_{sur\text{-}sky}$ is the view factor of the surface with respect to the sky.

- $F_{sur\text{-}sky}$ is given by:

$$F_{sur-sky} = \frac{1 + \cos\alpha}{2}$$

where α is the tilt angle.

Diffuse Irradiation on Horizontal Surface (G_d)

- Diffuse irradiation on a horizontal surface (G_d) can be either measured or estimated.
- The most common method for measuring G_d is by using a ***pyranometer***.
- The most common method to estimate G_d is by applying a factor to G_{ND} from the **ASHRAE Clear Sky Model**.

Pyranometer

- A pyranometer measures total irradiance on a plane.
- Its method of operation is similar to a pyrheliometer, but it does not track the sun.
- Usually, a pyranometer is mounted horizontally.
- It is also usually mounted high above the ground to avoid reflected irradiation.

Pyranometer

- For a pyranometer mounted horizontally and high above the ground:

$$G_t = G_D + G_d + \cancel{G_R}^{\,0} \quad \Rightarrow \quad G_t = G_{ND} \cos\theta + G_d$$

- Since the pyranometer is mounted horizontally, θ is the same as the zenith angle (θ_Z).
- Substituting and rearranging:

$$G_d = G_t - G_{ND} \cos\theta_Z$$

- By using a pyrheliometer to obtain G_{ND} and a pyranometer to obtain G_t, G_d can be found.

G_d from ASHRAE Clear Sky Model

- Diffuse irradiation on a horizontal surface (G_d) can be estimated using the ASHRAE Clear Sky Model.

  $G_d = C\ G_{ND}$

  where C can be found from the table below.

	Equation of Time, min	Declination, degrees	A, $\frac{\text{Btu}}{\text{hr-ft}^2}$	A, $\frac{\text{W}}{\text{m}^2}$	B, Dimensionless	C, Dimensionless
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Determination of Reflected Irradiation (G_R)

- The amount of irradiation a surface receives due to reflection from the ground (G_R) is given by:

  $G_R = G_{tH}\, \rho_g\, F_{sur\text{-}g}$

- where,
  - $\boldsymbol{G_{tH}}$: total irradiation the ground receives from the sun.
  - $\boldsymbol{\rho_g}$: reflectance of the ground.
  - $\boldsymbol{F_{sur\text{-}g}}$: view factor of the surface with respect to the ground.

- $F_{sur\text{-}g}$ can be found from:

$$F_{\mathrm{sur-g}} = \frac{1 - \cos\alpha}{2}$$

Example

A flat plate solar collector is placed on a roof in the city of Dubai. The collector is tilted by 30° to the south. For May 21st at 14:00 (local standard time), calculate the total irradiation on this collector. Assume the ground reflectivity to be 0.6.

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GIVEN

- For Dubai:
  - **Latitude (*l*) = 25.2° North**
  - **Longitude (L_L) = 55.3° East**
  - **Standard Meridian (L_S) = 60°**
- For May 21st:
  - **EOT = 3.3 min**
  - **δ = 20°**
- Tilt Angle: α **= 30°**
- The collector is facing south: surface azimuth angle ψ **= 180°**
- Ground reflectivity: ρ **= 0.6**

$G_t = G_D + G_{d\theta} + G_R$

$G_D = G_{ND} \cos\theta$

ASHRAE Clear Sky Model: $G_{ND} = \dfrac{A}{\exp(B/\sin\beta)}$

$G_{d\theta} = G_d\, F_{sur\text{-}sky}$

$$F_{\text{sur}-\text{sky}} = \frac{1 + \cos\alpha}{2}$$

$G_d = C\, G_{ND}$

$G_R = G_{tH}\, \rho_g\, F_{sur\text{-}g}$

$$F_{\text{sur}-\text{g}} = \frac{1 - \cos\alpha}{2}$$

Solar Radiation Measurement Station at KSU

- The station is located on the roof of the ME Department.
- It has been collecting data every minutes for more than a year.

OLD DATA

http://rredc.nrel.gov/solar/new_data/Saudi_Arabia/

NEW DATA

https://rratlas.kacare.gov.sa/RRMMPublicPortal/