Sunlight and its Properties II

EE 446/646

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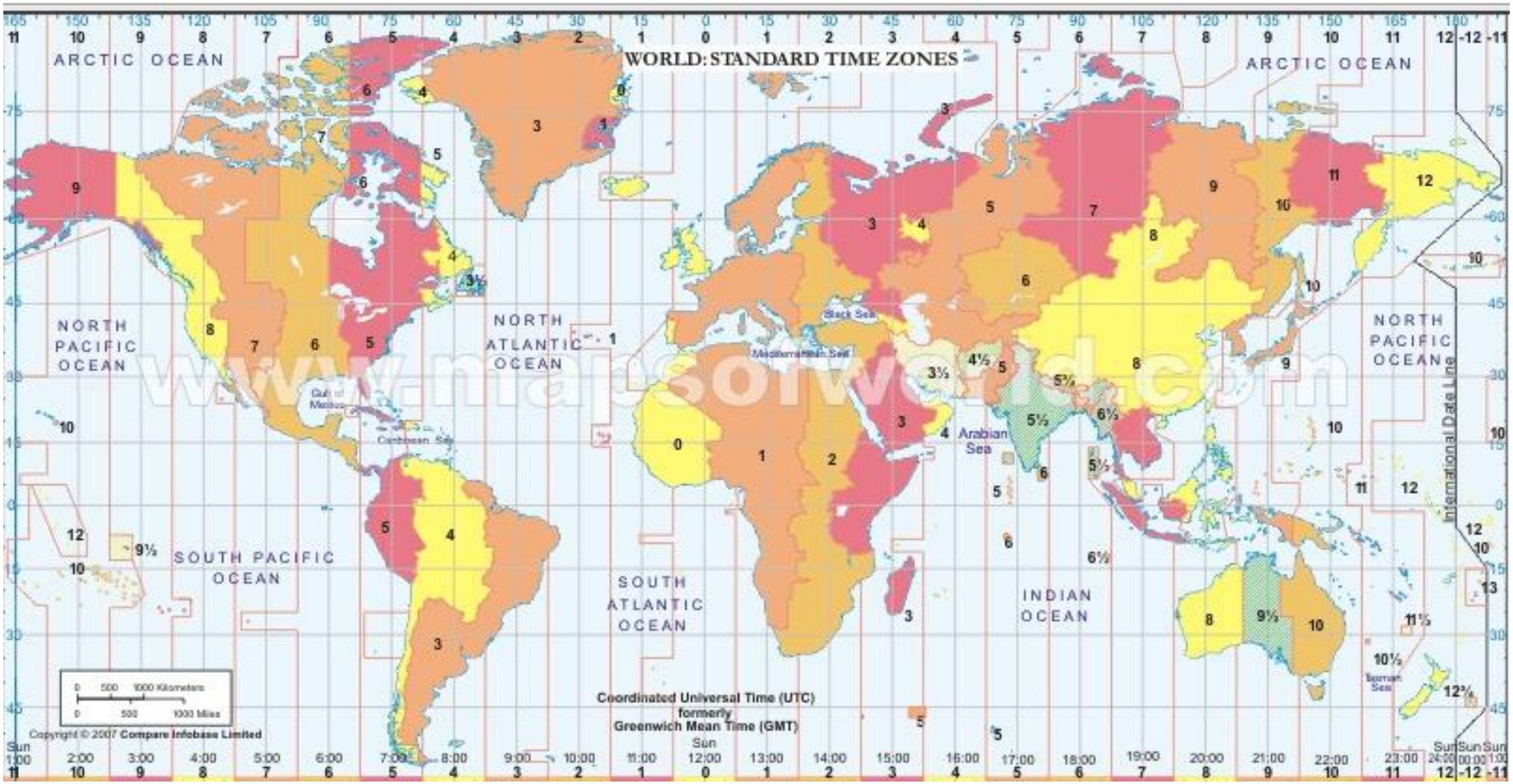
Solar Time (ST) and Civil (clock) Time (CT)

- There are two adjustments that need to be made in order to convert ST to CT:
  - **The first is the Longitude adjustment** (the world is divided into 24 1-hour time zones, each spanning 15^o of longitude)
    - All clocks within a time zone are set to the same 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, UK at 0^o longitude)
    - The longitude correction between local clock time and solar time is the time it takes for the sun to travel between the local time meridian and the observer's line of longitude (4 minutes/degree)
      - Example 1: San Francisco, CA (longitude 122^o) will have solar noon 8 minutes after the sun crosses the 120^o local time meridian.
      - Example 2: Las Vegas , NV (longitude 115^o) will have solar noon 20 minutes before the sun crosses the 120^o local time meridian.
      - Example 3: Fresno, CA (longitude 120^o) will have solar noon when the sun crosses the 120^o local time meridian.

Time Zones



WORLD: STANDARD TIME ZONES
ARCTIC OCEAN
NORTH PACIFIC OCEAN
NORTH ATLANTIC OCEAN
SOUTH PACIFIC OCEAN
SOUTH ATLANTIC OCEAN
INDIAN OCEAN
Arabian Sea
Black Sea
Mediterranean Sea
Gulf of Mexico
Caribbean Sea
International Date Line
Coordinated Universal Time (UTC) formerly Greenwich Mean Time (GMT)
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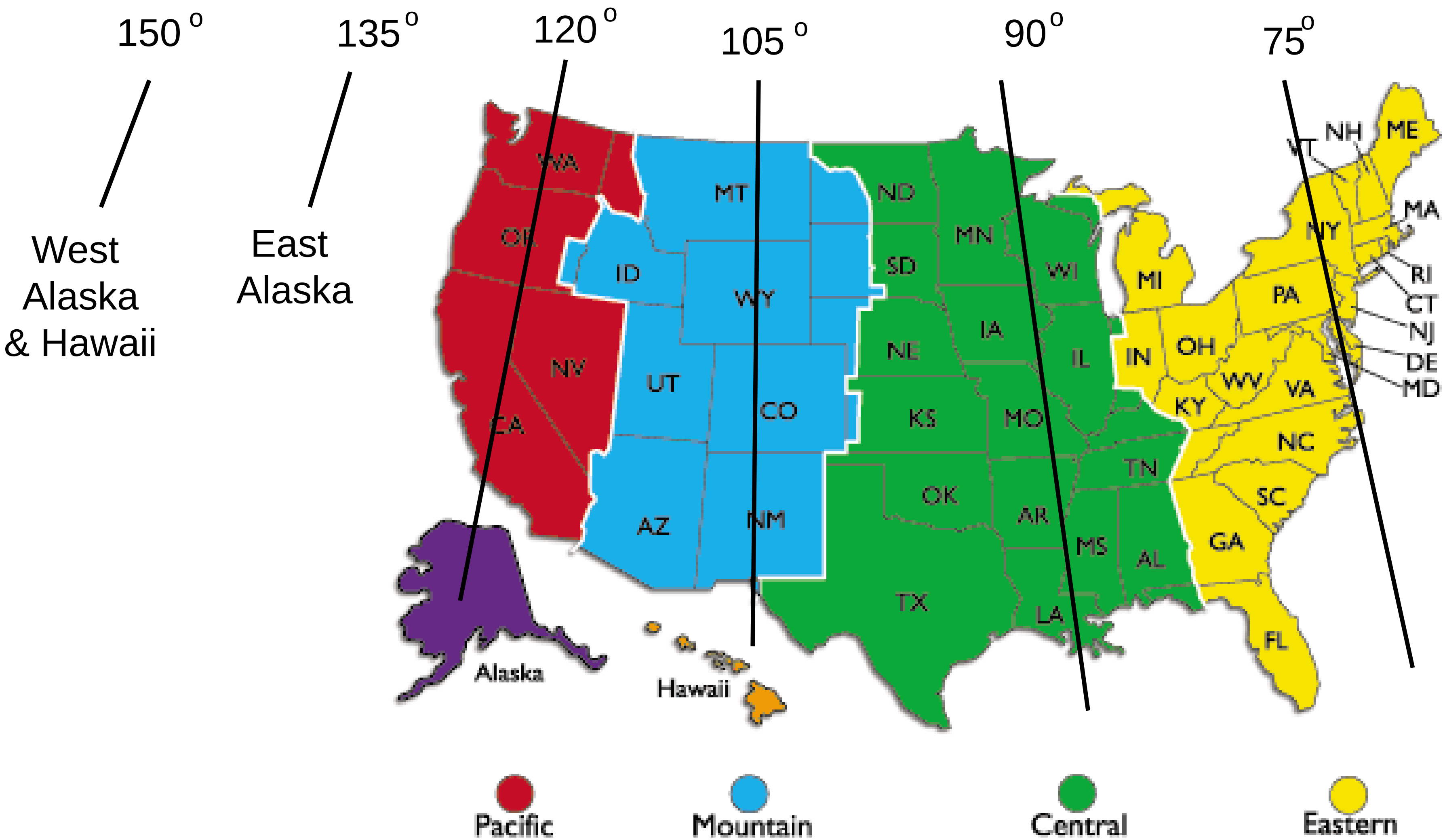
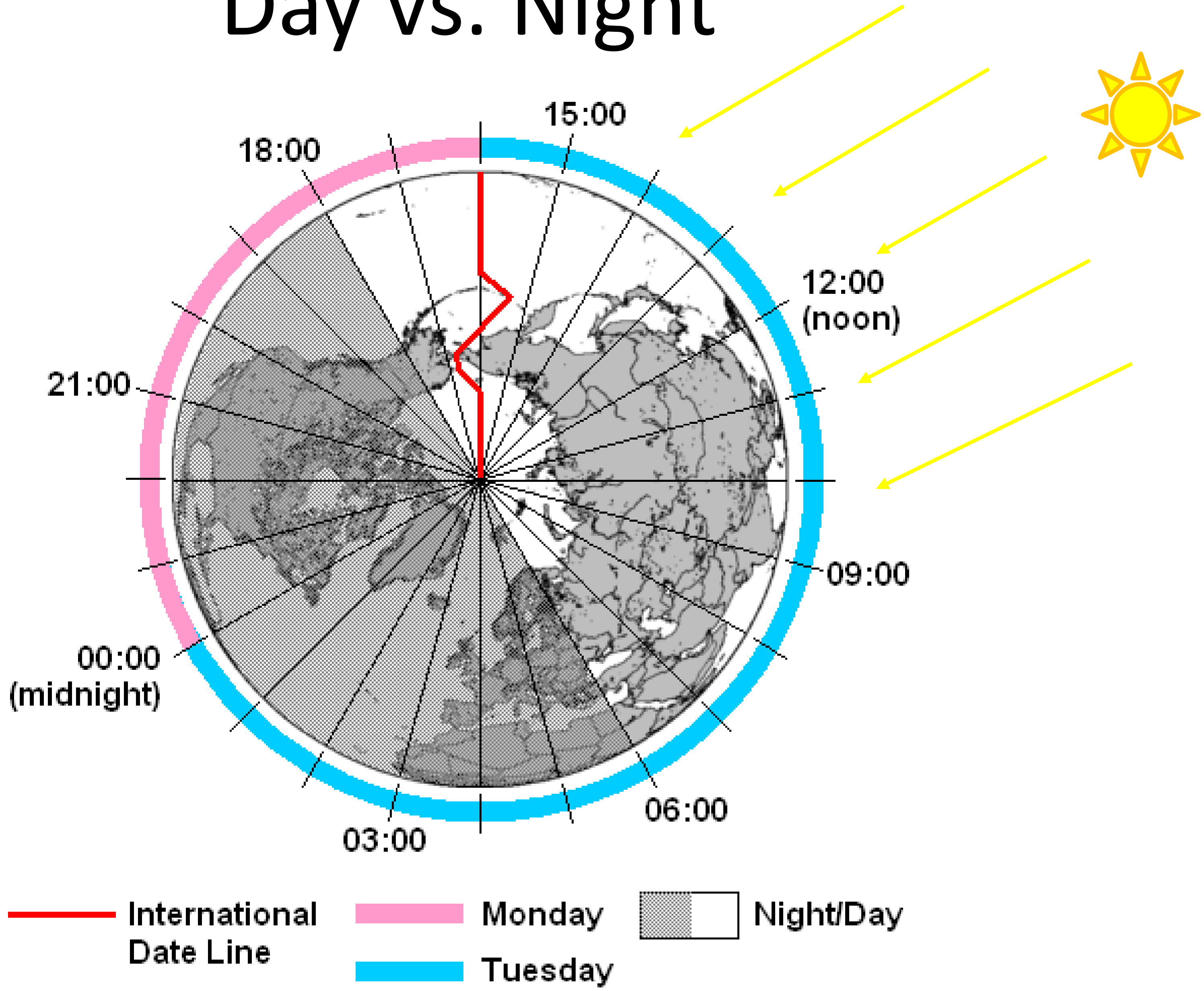
US Time Zones with Local Time Meridian



Day vs. Night


15:00
18:00
12:00
(noon)
21:00
09:00
00:00
(midnight)
06:00
03:00
International
Date Line
Monday
Tuesday
Night/Day

Solar Time (ST) and Civil (clock) Time (CT)

- There are two adjustments that need to be made to ST in order to convert to CT:
  - **The second is a fudge factor** that takes into account the uneven way in which the earth moves around the sun
    - This is a 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.
    - The difference between a 24-hour day and a solar day changes according to the following *Equation of Time* (where E is in minutes) :

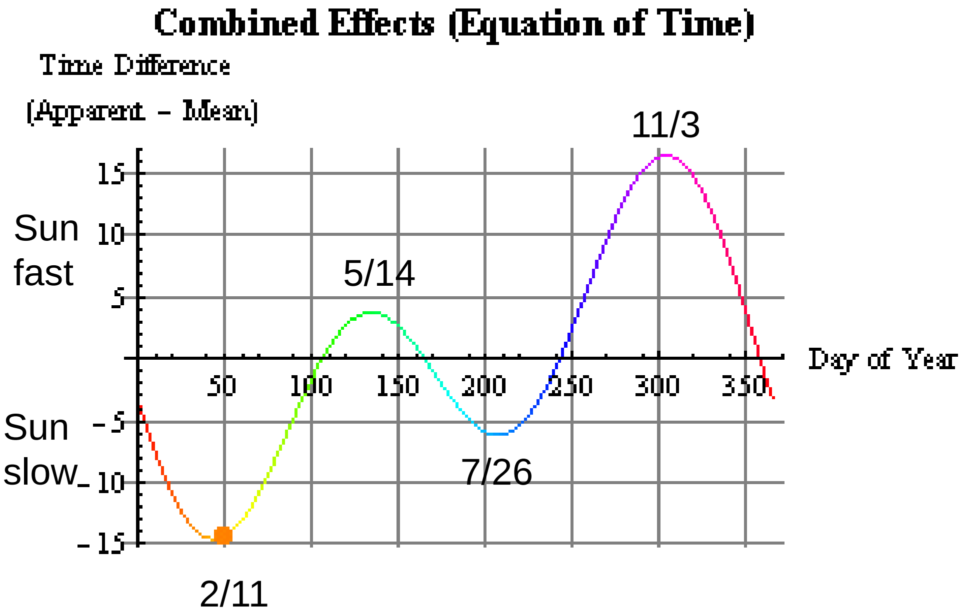
$$E = 9.87\sin(2B) - 7.53\cos B - 1.5\sin B$$

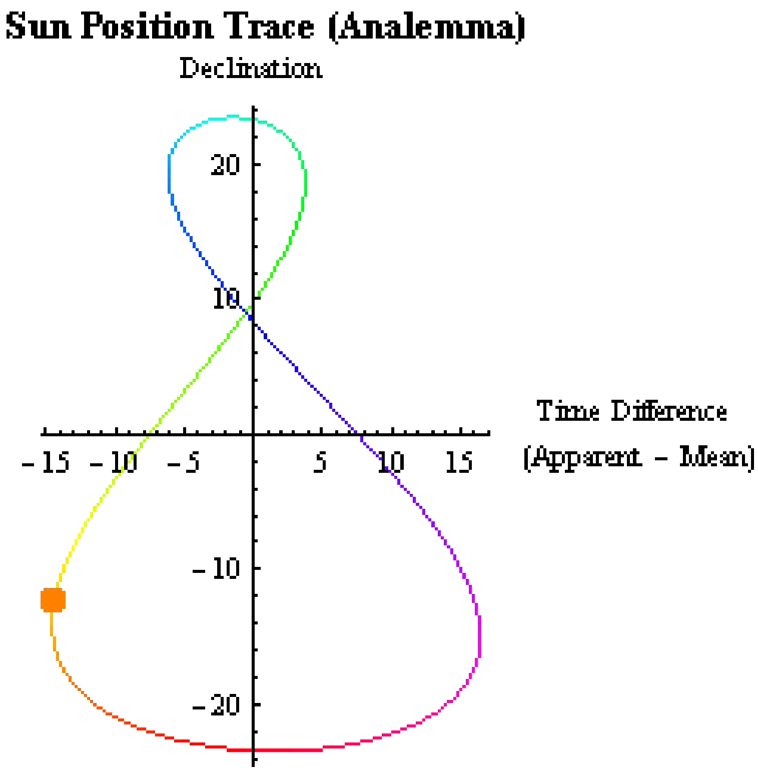
where

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

Equation of Time and Analemma

- **Equation of Time**: Plot of the difference between clock time and solar time at solar noon over a 1-year period.
- **Analemma:** Plot the position of the sun declination angle as a function of equation of time.



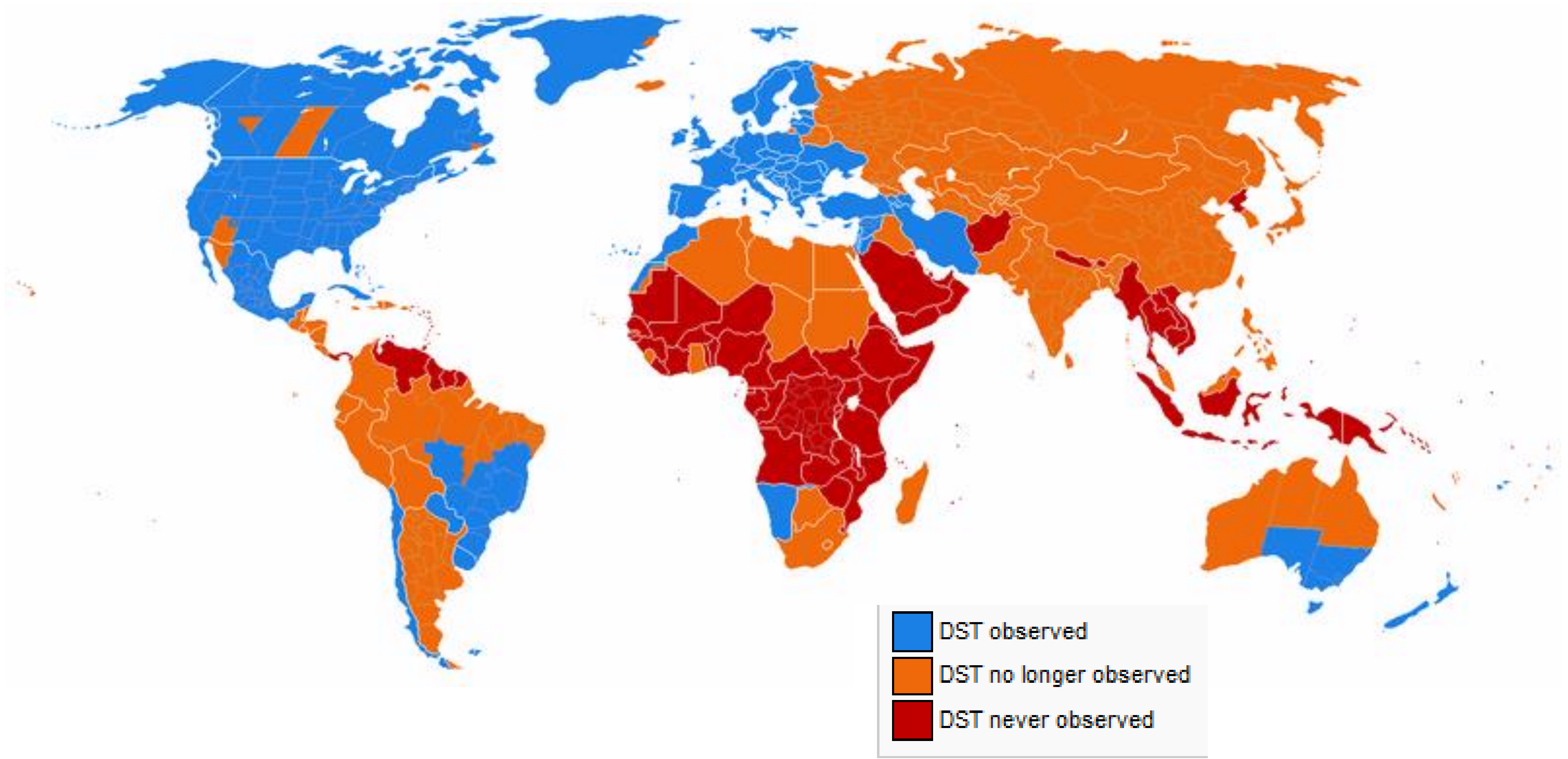


Final Relationship between ST and CT

ST = CT+4x(Local Time Meridian – Local Longitude) + E

- Finally, when daylight savings Time is in effect (34 weeks between early March and early November), one hour must be added to the local CT (except in AZ)
- **Example:** Find Eastern Daylight Time for solar noon (ST = 12:00) in Boston (longitude: 71.1^o west) on July 1st. Answer:
  - n=182
  - B = 99.89^o
  - E = -3.5 min
  - The Local Time Meridian: 75^o
  - Longitude adjustment: 4(75-71.1)=15.6 min
  - CT = 12:00 – 15.6 – (-3.5) = 12:00 - 12.1 = 11:48 am (EST)
  - Add daylight savings: solar noon will occur at 12:48 pm (EDT)

Countries Practicing Daylight Savings Time



Sunrise and Sunset Revisited

- The sun's hour angle at sunrise can be determined by setting the altitude angle to zero:

$$H = \cos^{-1}\{-\tan\delta \tan L\}$$

- This hour angle is the converted to solar time of sunrise

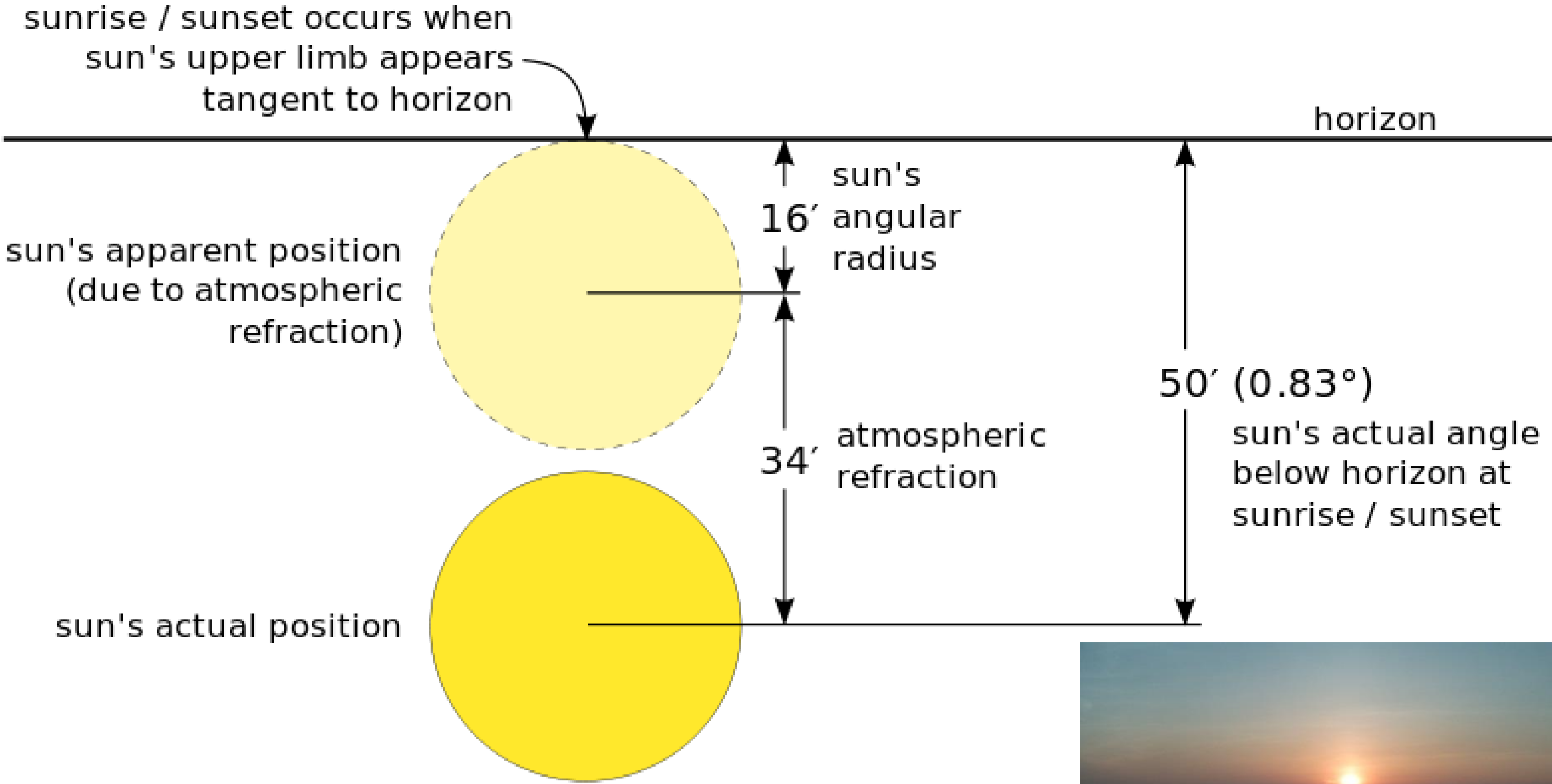
$$ST = 12 - (H/15)$$

- Finally, ST is converted to CT:

CT = ST - 4x(Local Time Meridian – Local Longitude) - E

- Sunrise and sunset times are different due to two factors:
  1) Atmospheric refraction – this bends the sun rays and make them appear to rise 2.4 min earlier (for sunrise) and later (for sunset).
  2) The weather service defines sunrise and sunset when the top of the sun first appears at the horizon (while ours is based on the sun's center crossing the horizon).

Sunrise and Sunset Revisited

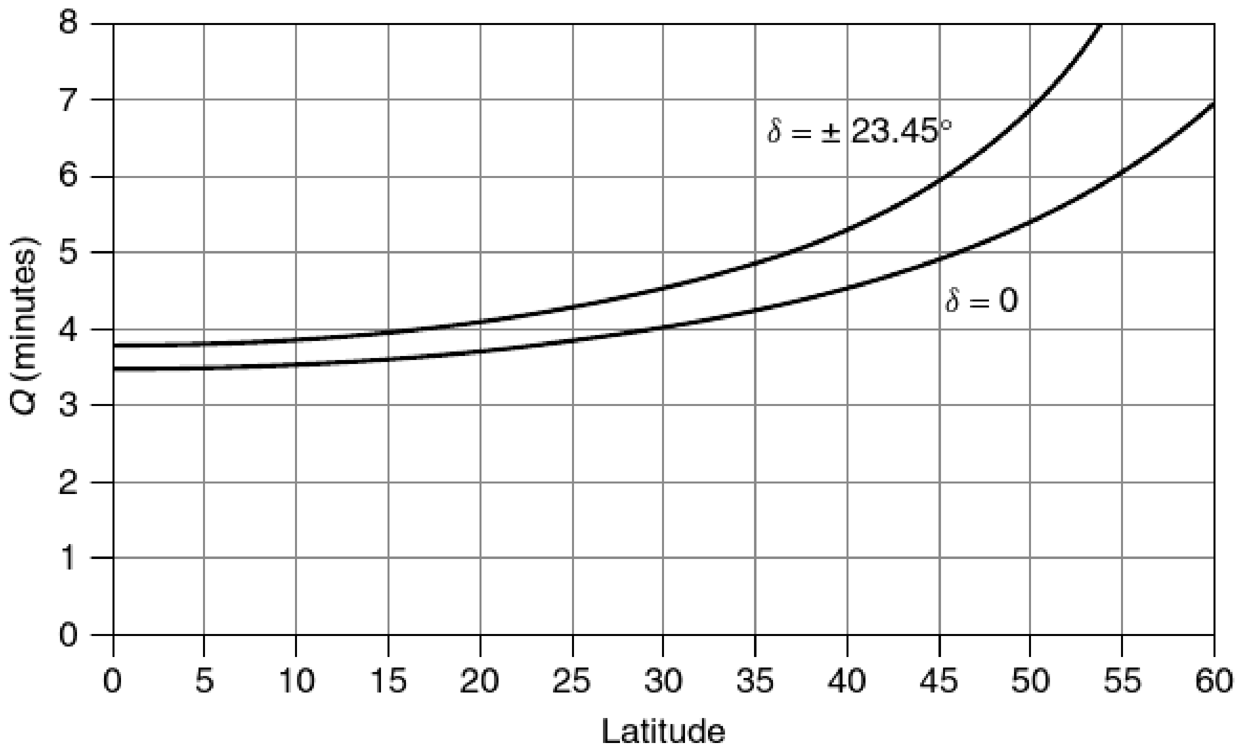


Sunrise Revisited

- Adjustment factor that should be subtracted for sunrise

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

- Finally, **CT = ST - 4x(LTM – Local Longitude) - E - Q**
- Q should be added when calculating sunset.

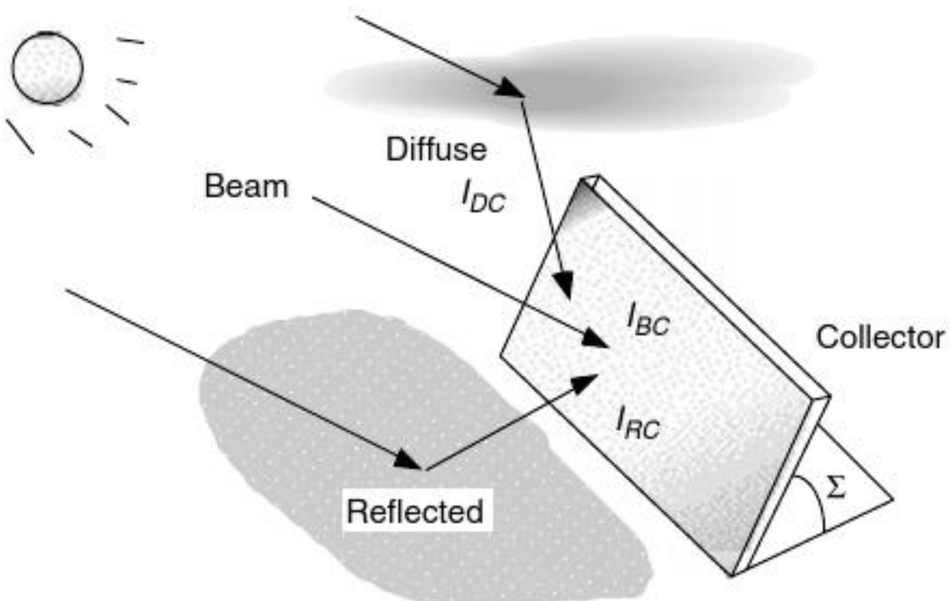


Sunrise and Sunset Revisited

- Example: Find the time at which sunrise will occur in Boston (longitude: 71.1^o west) on July 1st:
- Answer:
  - Declination angle: δ = 23.1 deg
  - Longitude: L = 71.1 deg
  - Hour angle at sunrise: H = 112.86 deg
  - Solar Time: ST = 4:28.6 am
  - Equation of Time: E = -3.5 min
  - The Local Time Meridian: 75^o
  - Longitude adjustment: 4(75-71.1)=15.6 min
  - Adjustment factor: Q = 5.5 min
  - CT = 4:28.6 – 15.6min – (-3.5min) - 5.5min = 4:11 am (EST)
  - Add daylight savings: sunrise will occur at 5:11 am (EDT)
  - Sunset will occur at 8:25pm

Decomposition of solar flux striking a collector

- ***Direct-beam radiation*** is sunlight that reaches the earth's surface without scattering.
- ***Diffuse radiation:*** scattered sunlight (i.e., what makes the sky blue) responsible for the light entering the north-facing windows.
- ***Reflected radiation (albedo):*** sunlight that is reflected from the ground and other nearby structures.
- ***Global radiation :*** the sum of the all three components above.



Direct beam radiation

- Day-to-day variation of extra-terrestrial solar insolation (due to change in sun-to-earth distance).

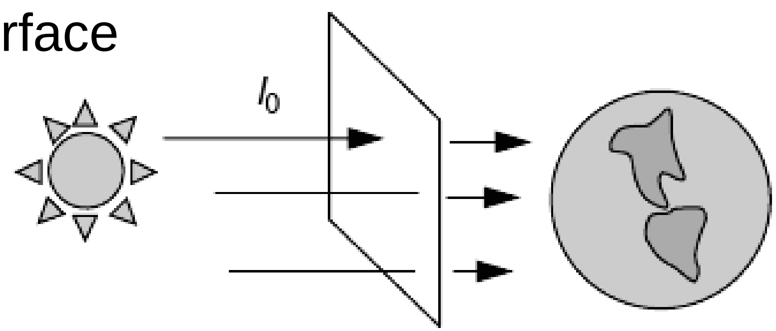
$$I_0 = \mathrm{SC} \cdot \left[1 + 0.034 \cos\left(\frac{360n}{365}\right)\right] \qquad (\mathrm{W/m^2})$$

where the solar constant SC = 1.377 kW/m^2.

- The attenuation of incoming radiation is a function of distance travelled through the atmosphere. An exponential model is often used for this

$$I_B = Ae^{-km}$$

where
I_B: beam portion reaching the earth surface
A: apparent extra-terrestrial flux
k: optical depth
m: air mass ratio (defined earlier)



Close fit of optical depth and apparent extra-terrestrial flux

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

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

Air mass ratio:

approximate expression: $m \approx 1/\sin\beta$

Accurate expression: $m = \sqrt{(708\sin\beta)^2 + 1417} - 708\sin\beta$

TABLE 7.6 Optical Depth k, Apparent Extraterrestrial Flux A, and the Sky Diffuse Factor C for the 21st Day of Each Month

Month:	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
A (W/m^2):	1230	1215	1186	1136	1104	1088	1085	1107	1151	1192	1221	1233
k:	0.142	0.144	0.156	0.180	0.196	0.205	0.207	0.201	0.177	0.160	0.149	0.142
C:	0.058	0.060	0.071	0.097	0.121	0.134	0.136	0.122	0.092	0.073	0.063	0.057

Source: ASHRAE (1993).

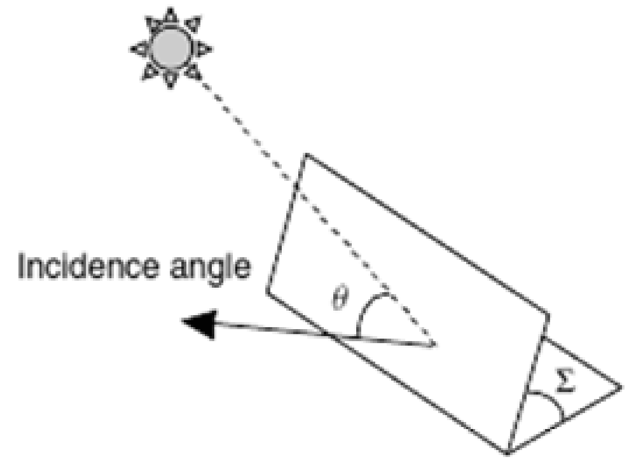
Example

- Determine the direct-beam radiation at solar noon in Las Vegas (L = 36 deg.) on January 21.
- Answer:
  - A = 1,230 W/m^2
  - K = 0.142
  - Declination Angle δ= -20.1 deg
  - Altitude angle at solar noon β = 33.9 deg
  - air mass ratio m = 1.793
  - Clear sky beam radiation: I_B = 953 W/m^2.

Beam striking a collector surface

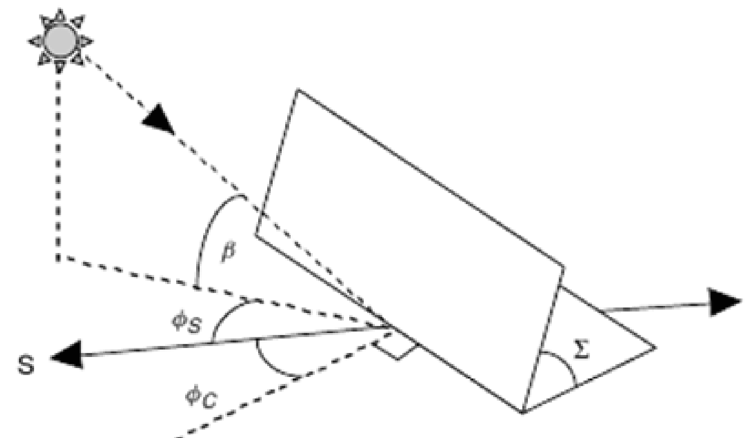
- **Incidence angle θ:** angle between a normal to the collector face and the incoming solar beam.

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



- The incidence angle depends on the sun angles (altitude and azimuth) and collector angles (azimuth and tilt)

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



- Special case of horizontal surface:

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

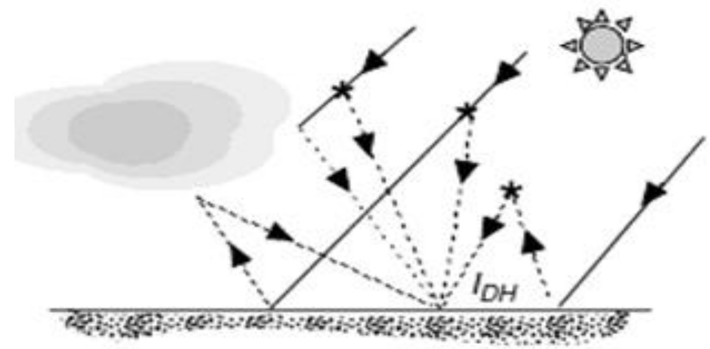
Example

- Determine the beam radiation at solar noon in Las Vegas (L = 36 deg.) on January 21, on a collector that faces 25 towards the southwest and tilted by 15 degrees.
- Answer (refer to previous example)
  - Altitude angle at solar noon $\beta = 33.9^o$
  - Clear sky beam radiation: $I_B = 953\ W/m^2$.
  - sun azimuth = 0^o
  - Collector azimuth = -25^o
  - Collector tilt= 15^o
  - $\text{Cos}\theta = \cos(33.9)*\cos(0-(-25))*\sin(15)+\sin(33.9)*\cos(15) =.733$
  - Beam radiation on the collector =953x.733 = 684 W/m^2.

Diffuse Radiation

- This is difficult to estimate accurately.
- Model that is often used: diffuse radiation on a horizontal surface is proportional to the direct beam radiation all day.

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

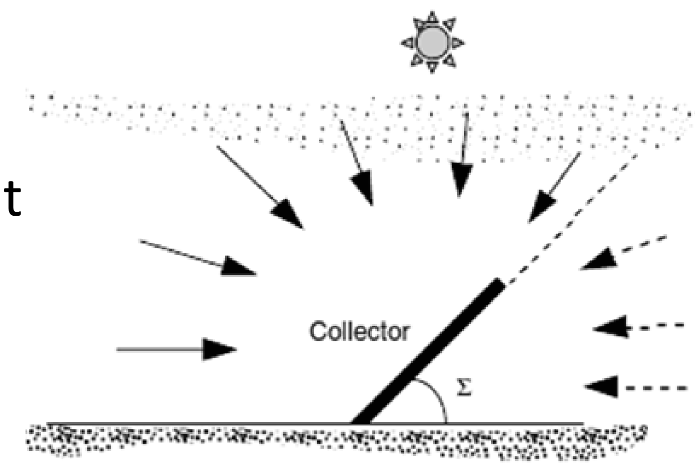


where C is the sky diffuse factor that varies daily as follows:

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

- The diffuse light received by a collector that is tilted at an angle is approximated by

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



Reflected Radiation

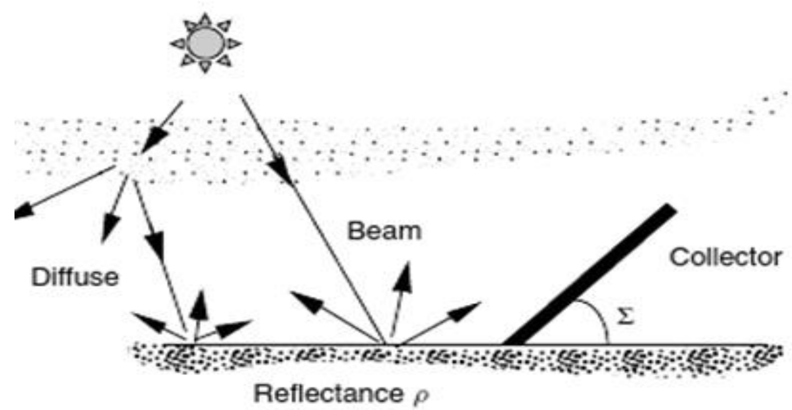
- This is also hard to estimate accurately.
- Estimates of ground reflectance ρ range from 0.8 for fresh snow to 0.1 for gravel. Ordinary ground or grass assume a reflectance of 0.2.

- The reflected radiation received by a collector can be estimated by

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

or

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



Total (Global) Radiation Striking a Collector

Global radiation is the sum of the three components (direct ration, diffuse radiation, and reflected radiation):

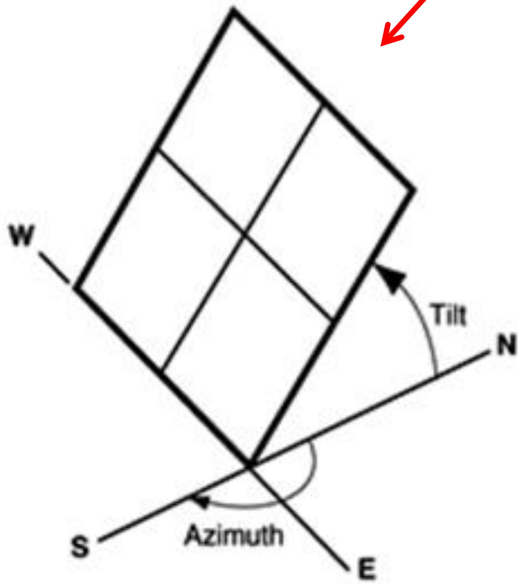
$$I_C = I_{BC} + I_{DC} + I_{RC}$$

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

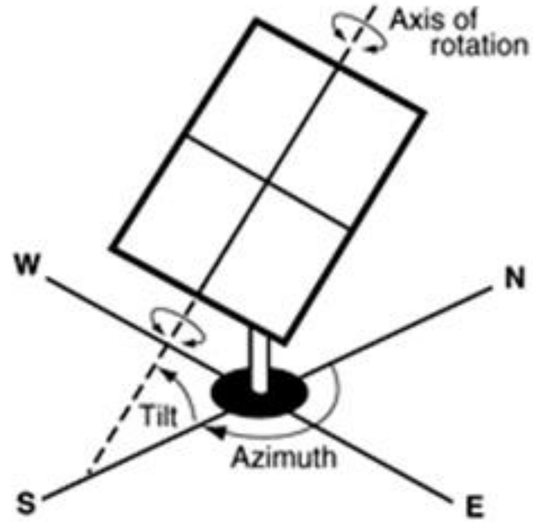
Capturing Sunlight - Types of PV Arrays

So far we looked at solar irradiance striking a fixed collector.

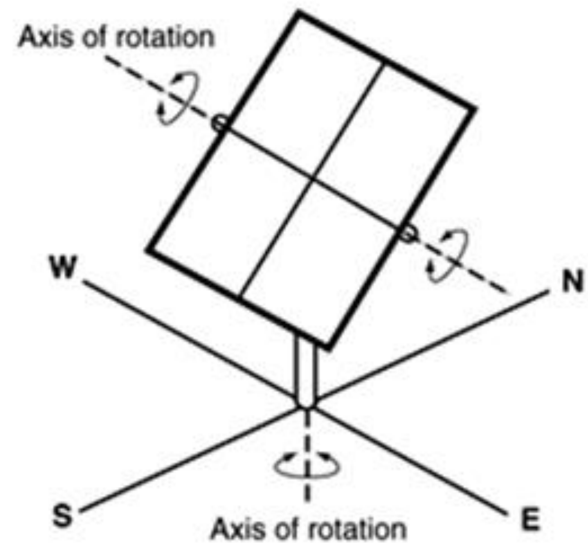
Now we consider solar irradiance striking tacking collectors.



PV array facing south at fixed tilt.



One axis tracking PV array with axis oriented south.



Two-axis tracking PV array

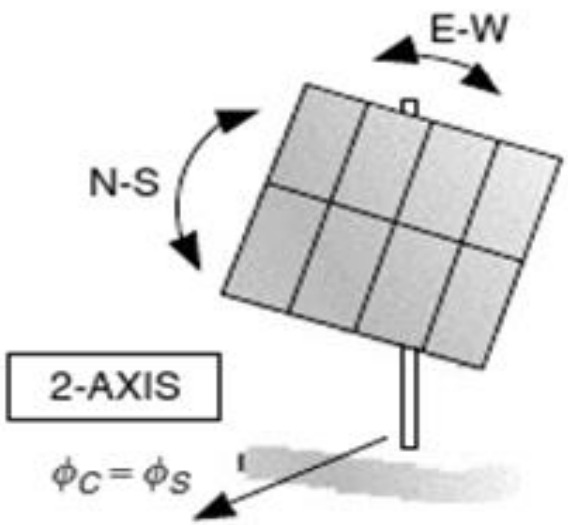
Two-Axis Tracking

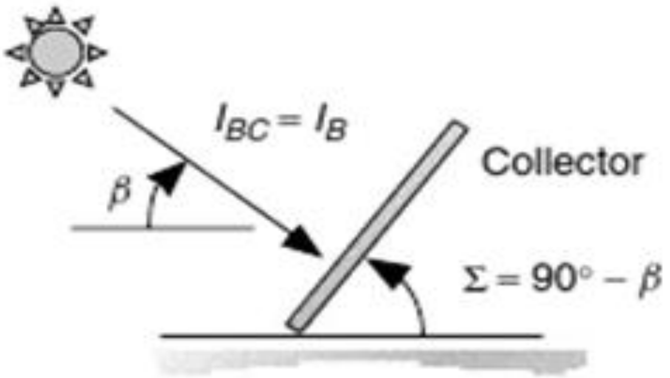
Two-Axis Tracking:

$$I_{BC} = I_B$$

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

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





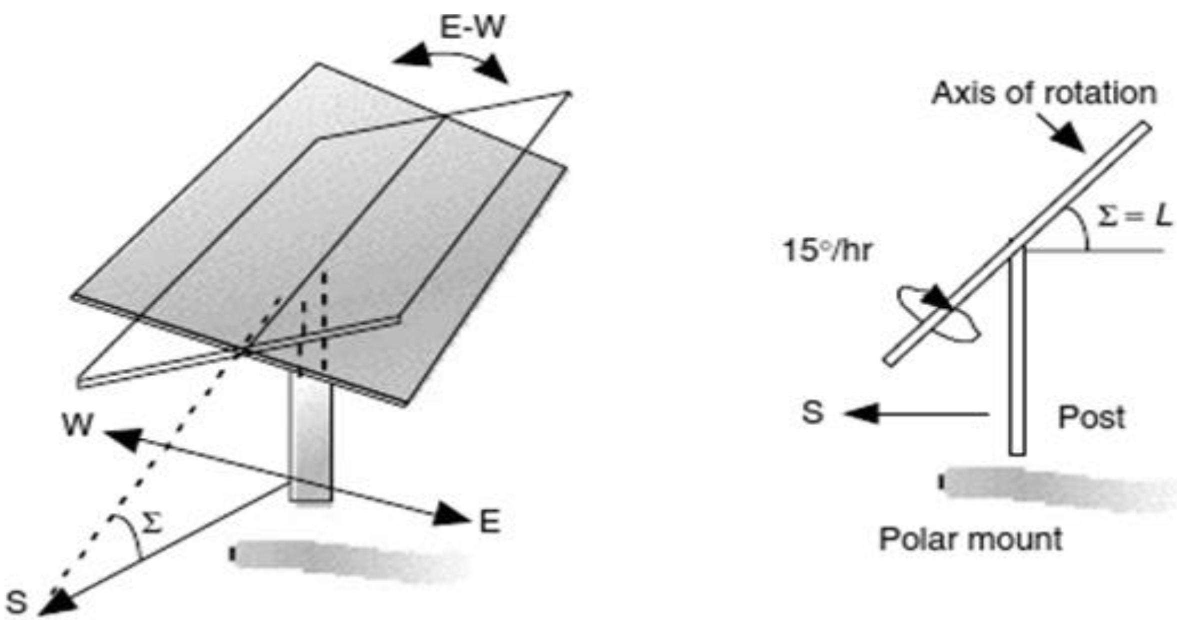
4 Types of Single-Axis Tracking: Rotation about a polar axis (i.e., polar mount: *Σ = L)* is most popular

One-Axis, Polar Mount:

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

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

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



Example

- Calculate the clear-sky insolation on both a two-axis tracking mount and single-axis polar mount(locate at 40^o latitude) at solar noon on the summer solstice. Ignore ground reflectance.
- Answer:
  - Declination angle δ =23.45^o
  - Sun altitude angle at solar noon β = 73.45^o
  - Air Mass ratio m =1.043
  - From Table 7.6, A = 1088 (W/m^2) and k =0.205

	Two-Axis Tracker	Single-Axis Pole Mount
Direct beam rad. (W/m^2)	879	806
Diffuse rad. (W/m^2)	115	104
Total radiation (W/m^2)	**994**	**910**