ECE 333

Green Electric Energy

Lecture 15

The Solar Spectrum, Earth's Orbit, Altitude Angle of the Sun at Solar Noon

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Slides Courtesy of Prof. Tim O'Connell and George Gross

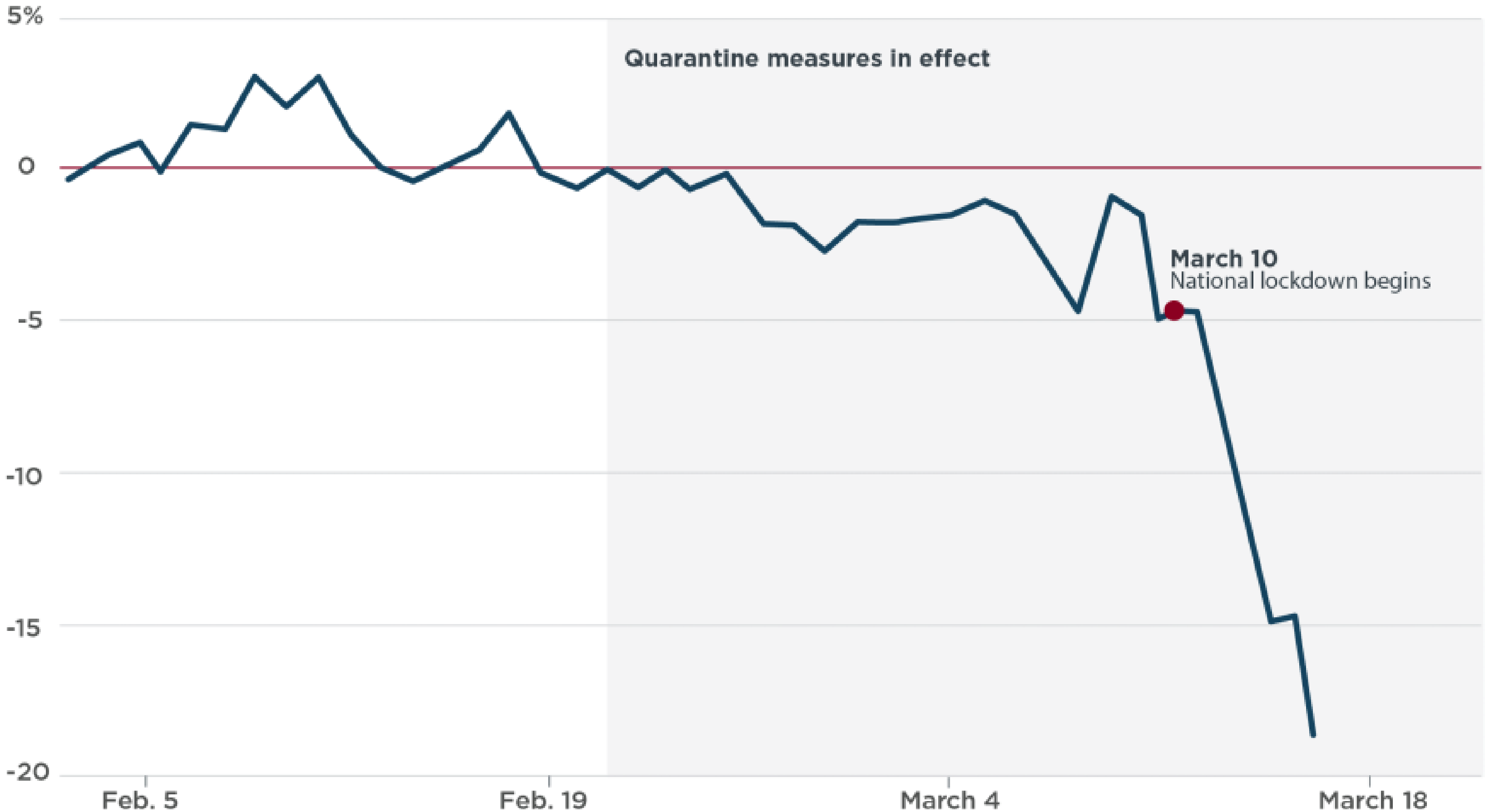
Announcements

- Announcements:
  - HW 7 is posted, due Thursday 4/2/20
  - Will discuss article in Lecture Wrap-up on Thursday
    - Optional, but opportunity for participation points
- Today
  - Exam 2 discussion
  - COVID and the grid
  - Begin Solar Energy!!!!
    - Reading: Masters sections 4.1-4.3

Exam 2 Discussion

- Date: April 9th
- Format: same as Exam 1
- Time: 24-hour window on April 9th
- Length: same as Exam 1
- Resources: Open book, open notes, open computer - You are welcome to use any resource ***except another person***.
- Bonus points: 5 bonus points on Exam 2 for attaching your ***<u>handwritten</u>*** note sheets for Exam 1 and 2 (8.5” x 11”, front and back)
  - Attach to the end of the test
- Submission: through Gradescope

COVID-19 and the Grid



"Is Plunging Power Demand Amid Coronavirus a Sign of Things to Come?"
https://epic.uchicago.edu/insights/is-plunging-power-demand-amid-coronavirus-a-sign-of-things-to-come/

Summary: Utilities are Well Prepared

- Taking precautions for operators
  - May require operators to live on-sight
- Decreased demand helps
- Bringing backup control rooms online
- Most utilities belong to at least one mutual assistance group
  - Informal network of electricity suppliers usually used for natural disasters like storms

"America's Electricity is Safe From the Coronavirus—for Now", Wired
https://www.wired.com/story/americas-electricity-is-safe-from-the-coronavirus-for-now/

The Solar Resource

- Before we can talk about solar power, we need to talk about the sun
- We can predict where the sun is at any time
- Need to know how much sunlight is available
- **Insolation** : *in*cident *sol*ar radi*ation*
- Want to determine the average daily insolation at a site
- Want to be able to choose effective locations and panel tilts of solar panels

The Sun and Blackbody Radiation

- The Sun
  - 1.4 million km in diameter
  - 3.8 x 10^{20} MW of radiated electromagnetic energy
- Definition: *Blackbody*
  - Both a *perfect emitter* and a *perfect absorber*
  - Perfect emitter – radiates more energy per unit of surface area than a real object of the same temperature
  - Perfect absorber – absorbs all radiation, none is reflected

Plank's Law

- Planck's Law – the wavelengths emitted by a blackbody depend on its temperature:

$$E_\lambda = \frac{3.74 \times 10^8}{\lambda^5 \left[\exp\left(\frac{14400}{\lambda T} \right) - 1 \right]} \qquad (4.1)$$

- λ = wavelength [μm]
- E_λ = emissive power per unit area of blackbody [W/(m²-μm)]
- T = absolute temperature (K)

288 K (Earth) Blackbody Spectrum

Earth as a blackbody:

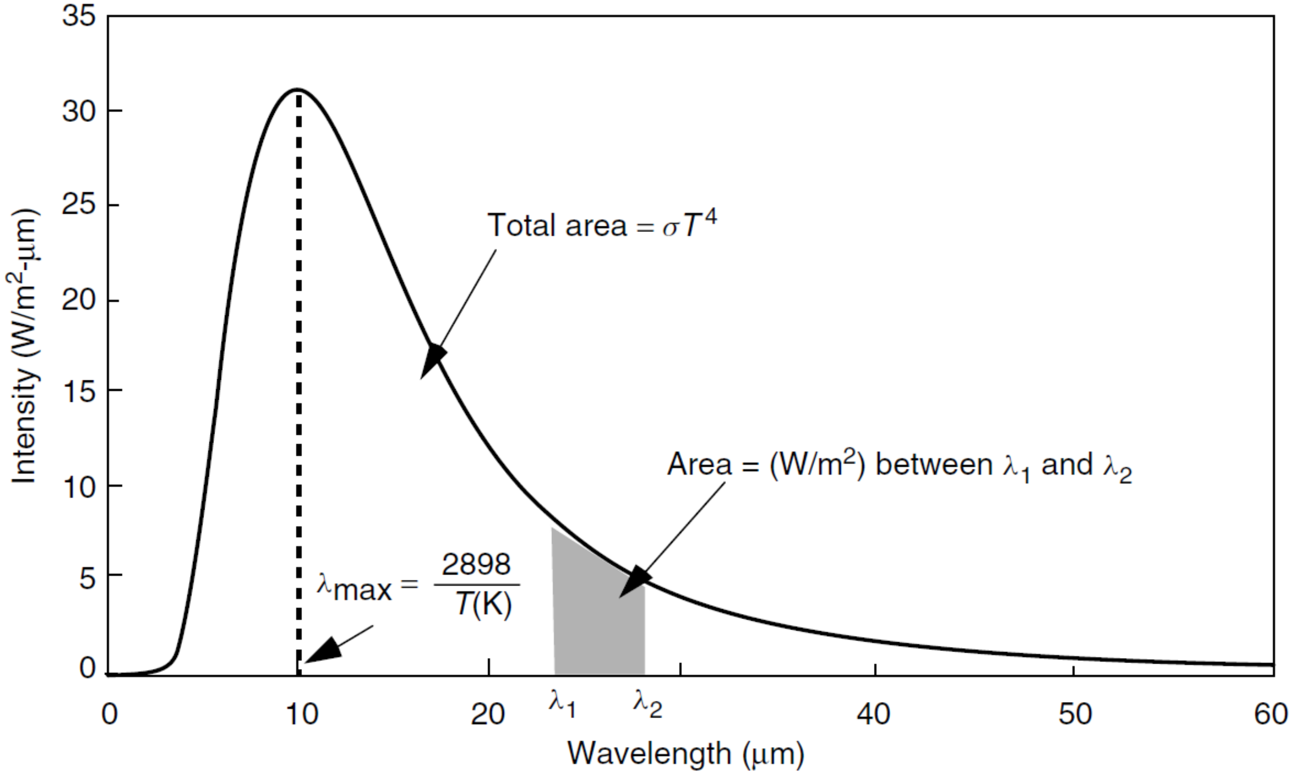
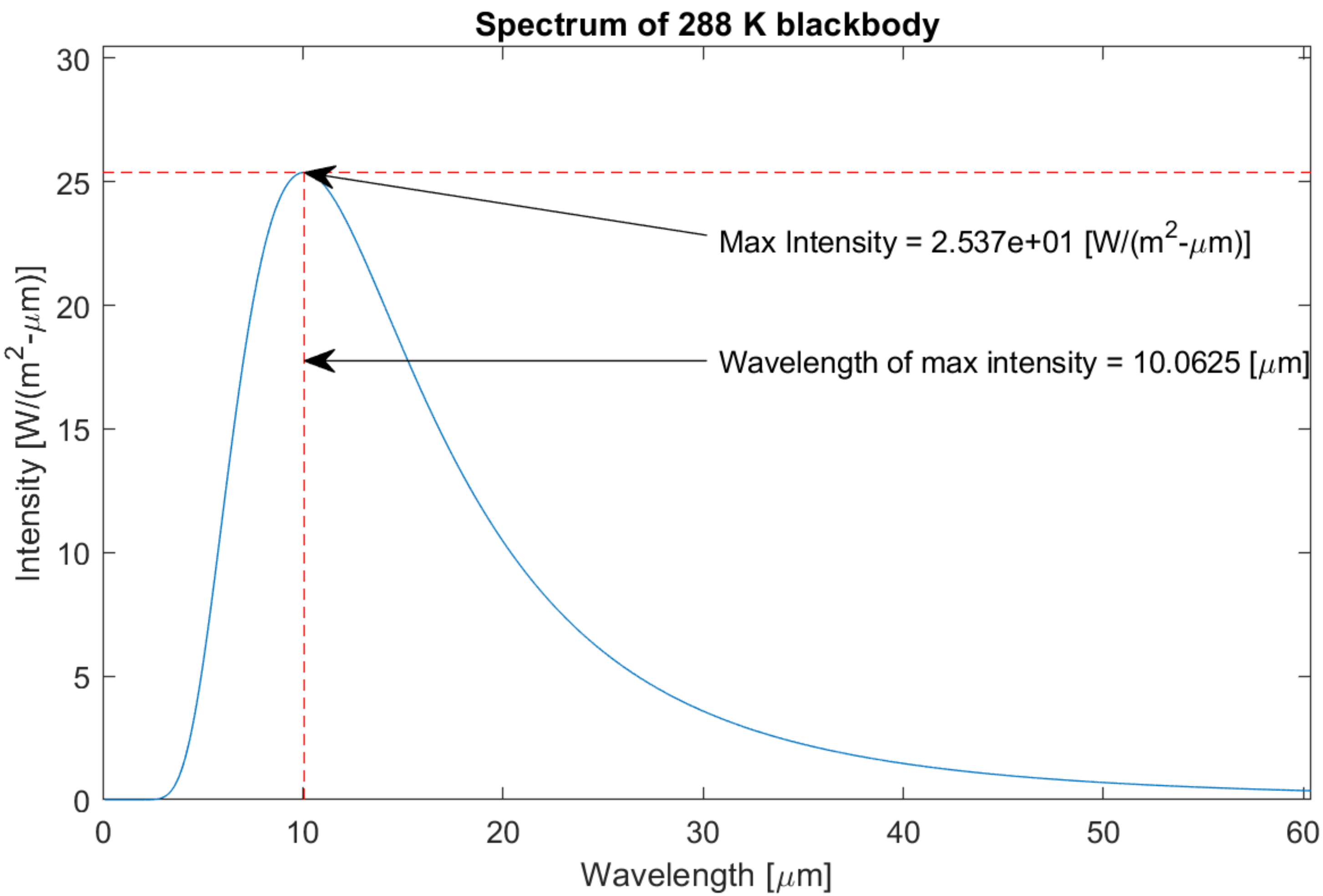


Figure 4.1 The spectral emissive power of a 288 K blackbody.

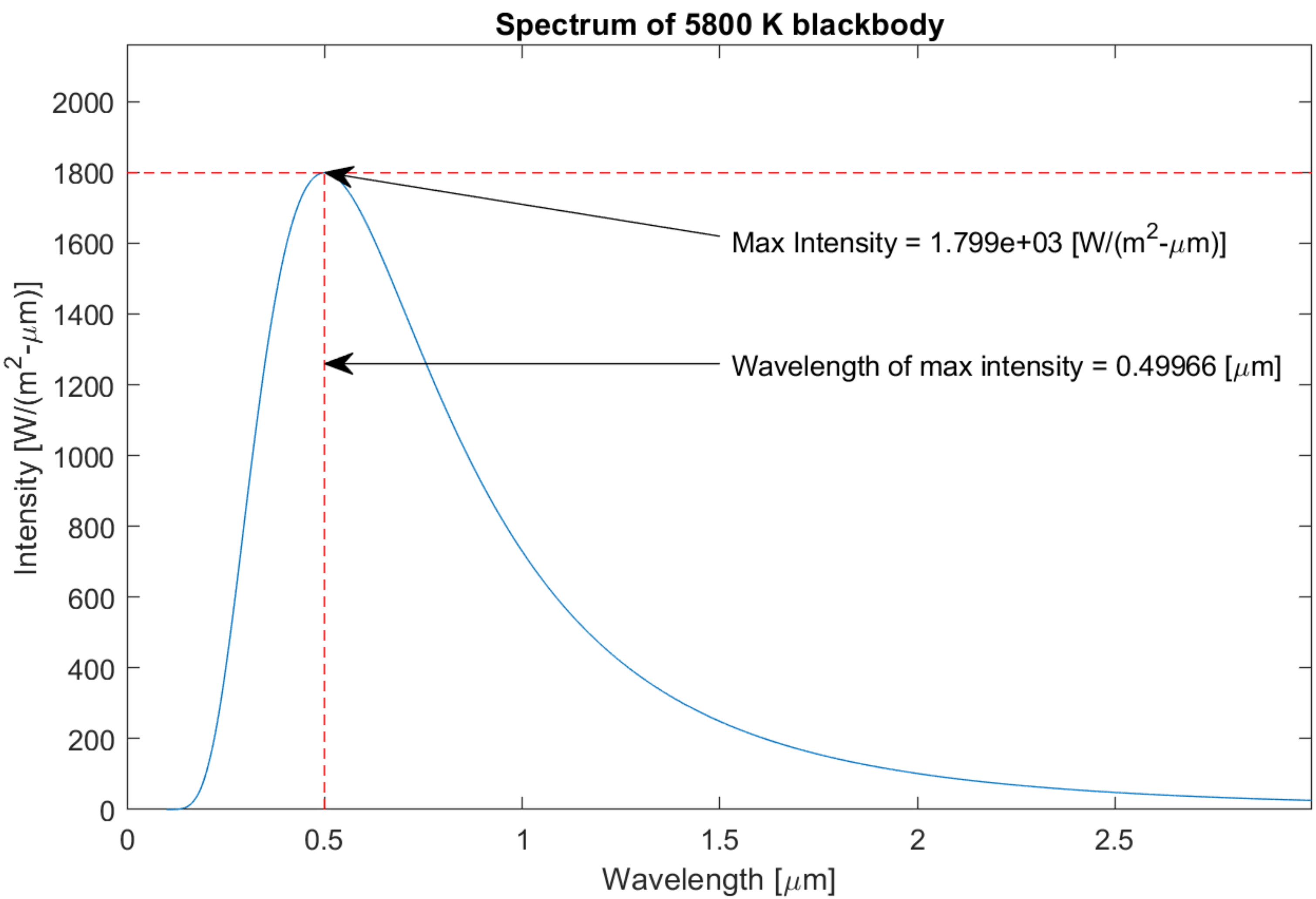
Area under curve is the total radiant power emitted per unit area

Matlab Script: *blackbody.m* – Earth

Book figure 4.1 for Earth spectrum is slightly wrong!

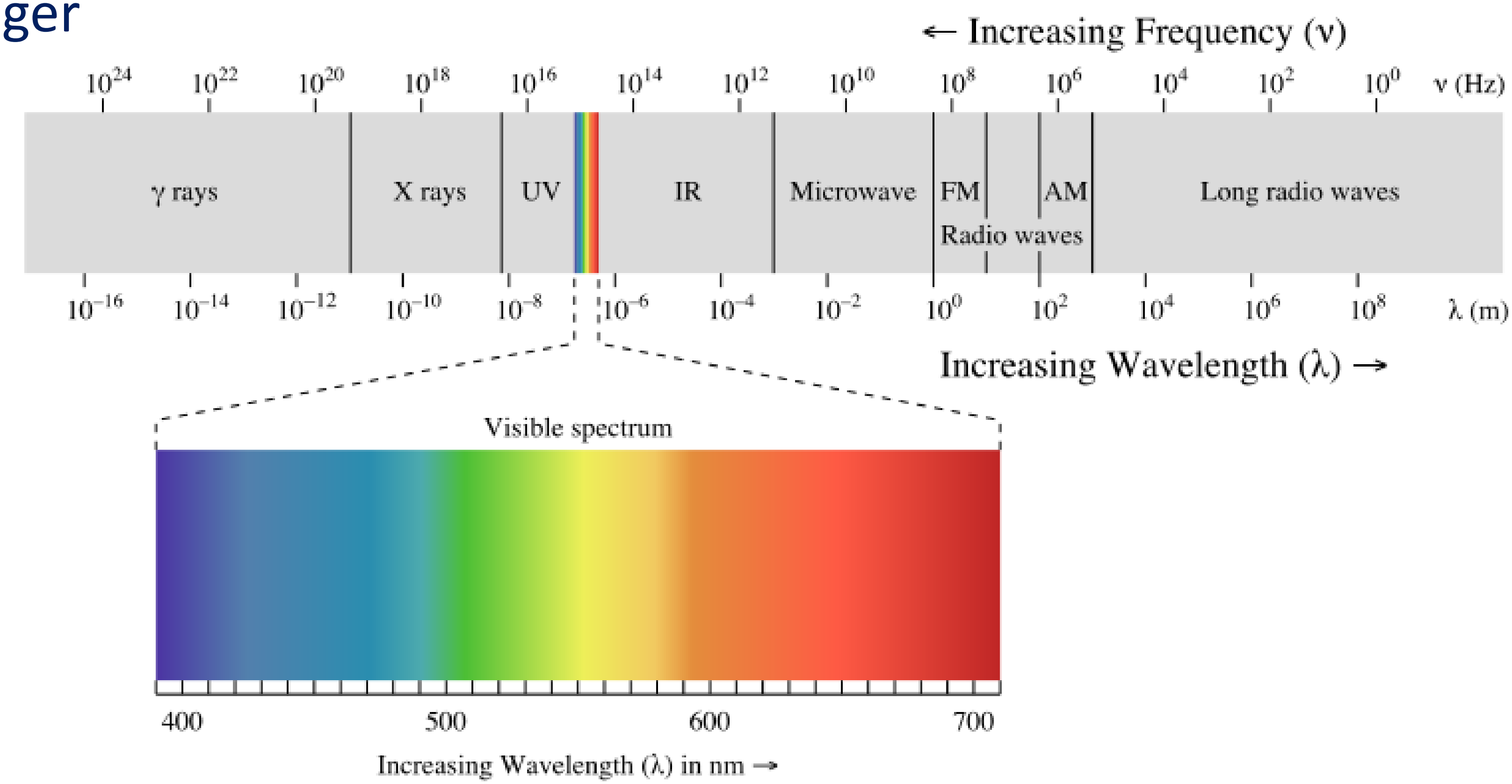


Matlab Script: *blackbody.m* – Sun



Electromagnetic Spectrum

Visible light has a wavelength of between 400 and 700 nm, with ultraviolet values immediately shorter, and infrared immediately longer



Source: en.wikipedia.org/wiki/Electromagnetic_radiation

Stefan-Boltzmann Law

- Total radiant power (W) emitted is given by the Stefan –Boltzman law of radiation:

$$E = A\sigma T^4 \qquad (4.2)$$

- E = total blackbody emission rate [W]
- σ = Stefan-Boltzmann constant = 5.67×10^{-8} [W/(m^2-K^4)]
- T = absolute temperature [K]
- A = surface area of blackbody [m^2]

$$\sigma T^4 = \int_0^\infty E_\lambda \, d\lambda \quad [W/m^2]$$

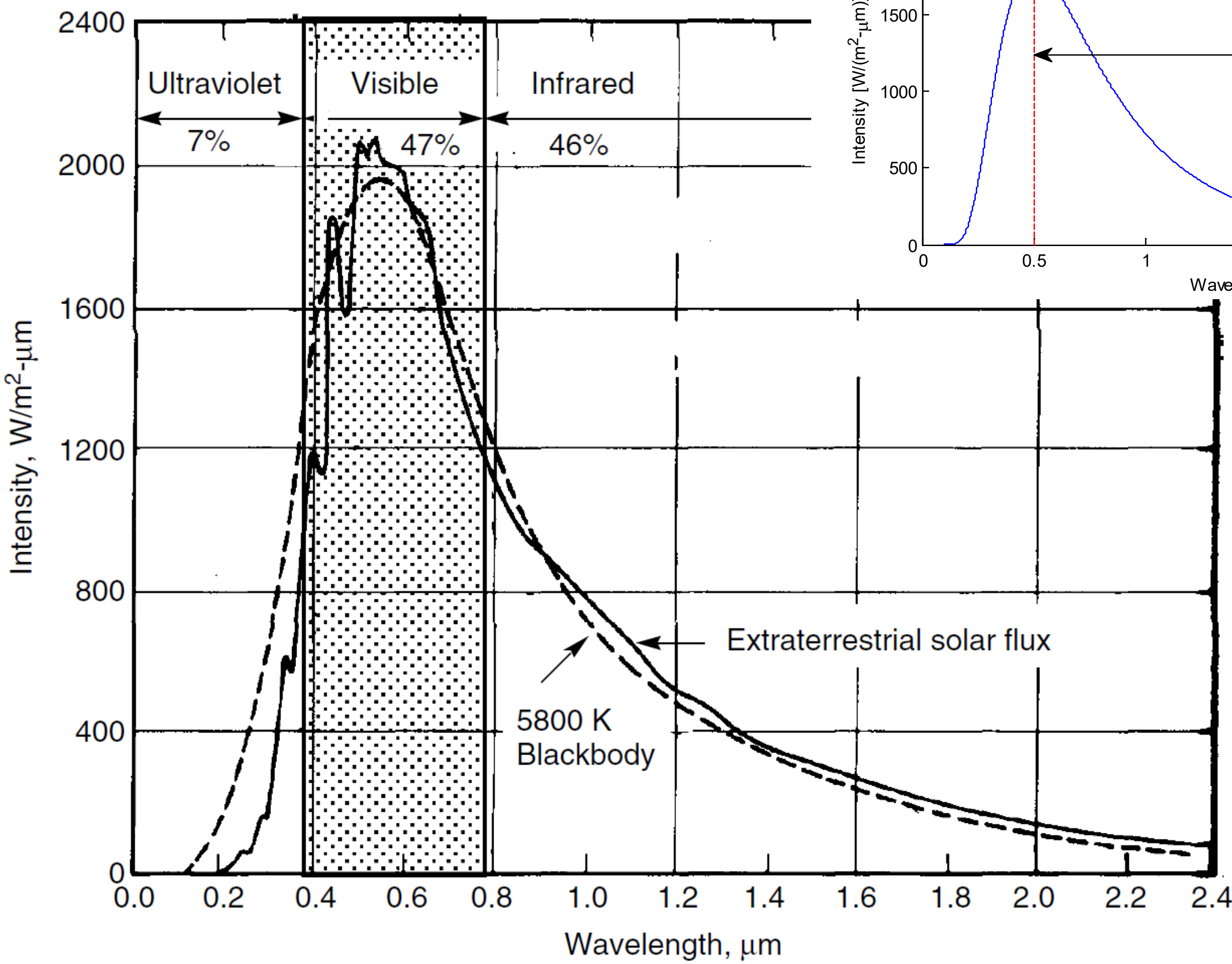
Wien's Displacement Rule

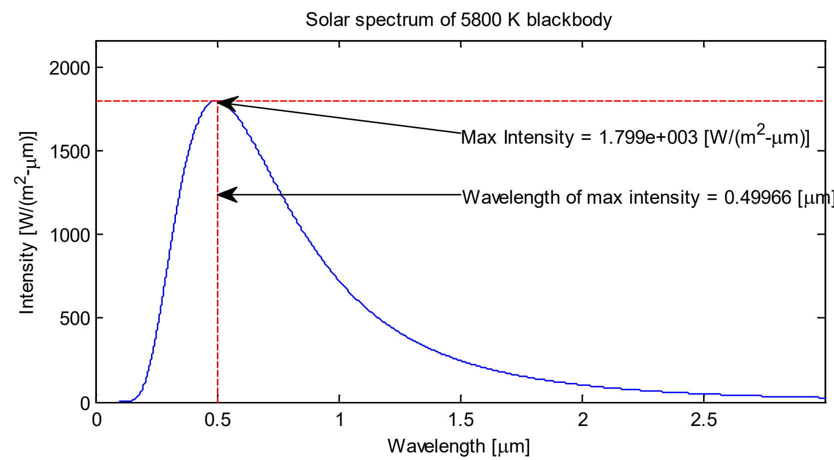
- The wavelength at which the emissive power per unit area reaches its maximum point

$$\lambda_{max} = \frac{2898}{T} \qquad (4.3)$$

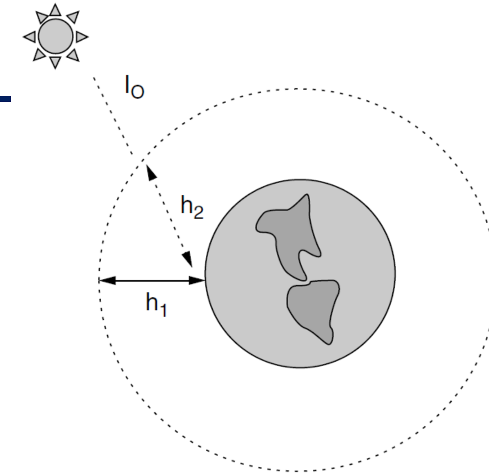
- T = absolute temperature [K]
- λ = wavelength [μm]
- λ_{max} =0.5 μm for the sun , T = 5800 K
- λ_{max} = 10.1 μm for the earth (as a blackbody), T = 288 K

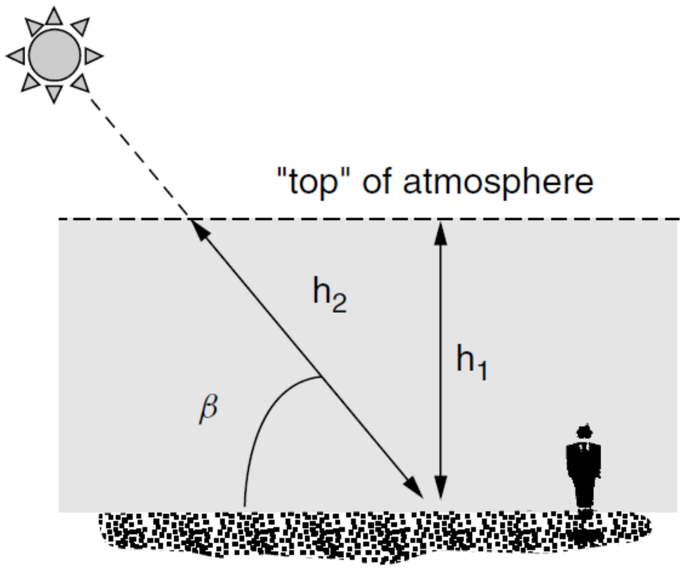
Extraterrestrial Solar Spectrum





Air Mass Ratio





$$\text{air mass ratio } m = \frac{h_2}{h_1} = \frac{1}{\sin\beta} \quad (4.4)$$

As sunlight passes through the atmosphere, less energy arrives at the earth's surface

$$h_2 = h_1 \quad \beta = 90^\circ$$

$$\beta = 41.2^\circ$$

Solar Spectrum on Earth's Surface

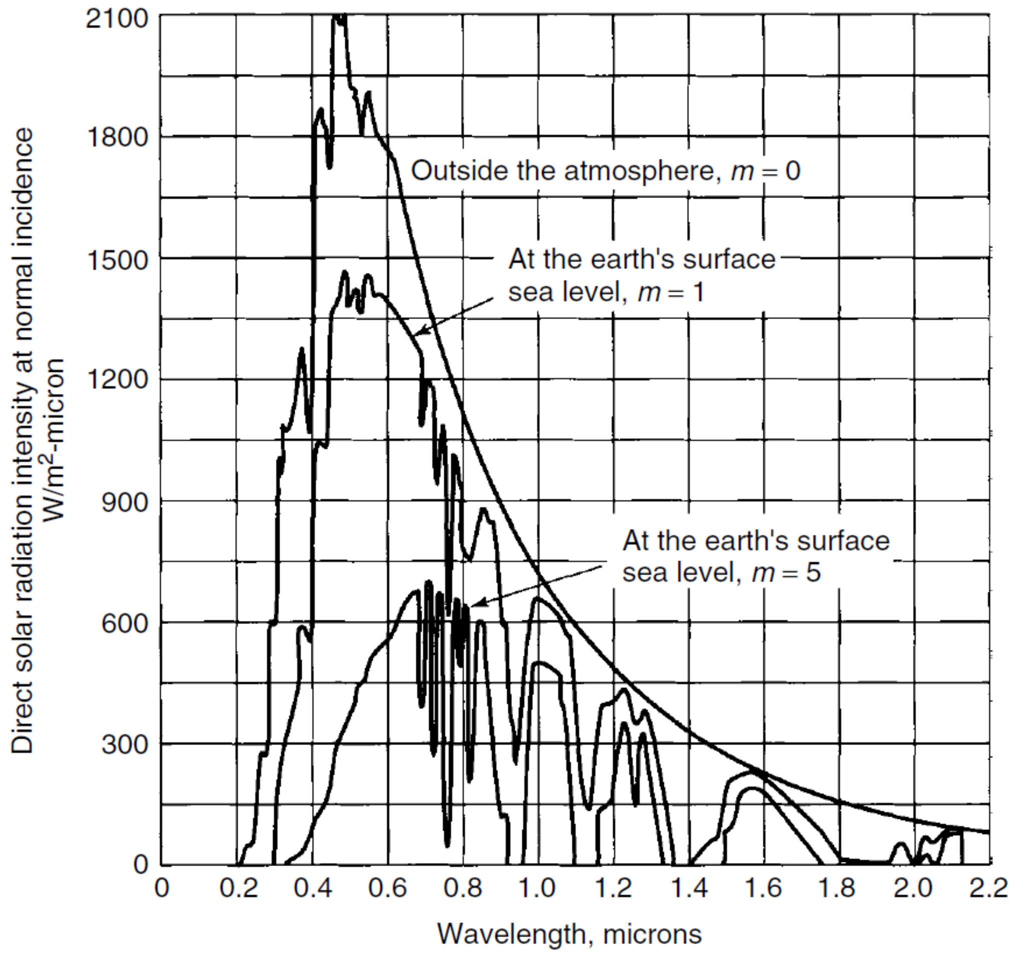


Figure 4.4 Solar spectrum for extraterrestrial ($m = 0$), for sun directly overhead ($m = 1$), and at the surface with the sun low in the sky, $m = 5$. From Kuen et al. (1998), based on *Trans. ASHRAE*, vol. 64 (1958), p. 50.

As the sun appears lower in the sky, *m* increases. Notice there is a large loss towards the blue end for higher *m*, which is why the sun appears reddish at sun rise and sun set.

4.2: The Earth's Orbit

- Orbit is elliptical (barely)
- One revolution every 365.25 days
- In one day, the earth rotates 360.99°
- Distance of the earth from the sun varies slightly over the year, but this is not responsible for seasons
  - Earth farthest from Sun in Northern Hemisphere summer!
  - For solar energy applications, we'll consider the characteristics of the earth's orbit to be <u>**unchanging**</u>

The Earth's Orbit

- n is the **day number**
- d is the distance from the Earth to the Sun

$$d = 1.5 \times 10^{8} \left\{ 1 + 0.017 \sin \left[\frac{360(n - 93)}{365} \right] \right\} \text{ km} \qquad \textbf{(4.5)}$$

TABLE 4.1 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	$n = 335$

The Earth's Orbit

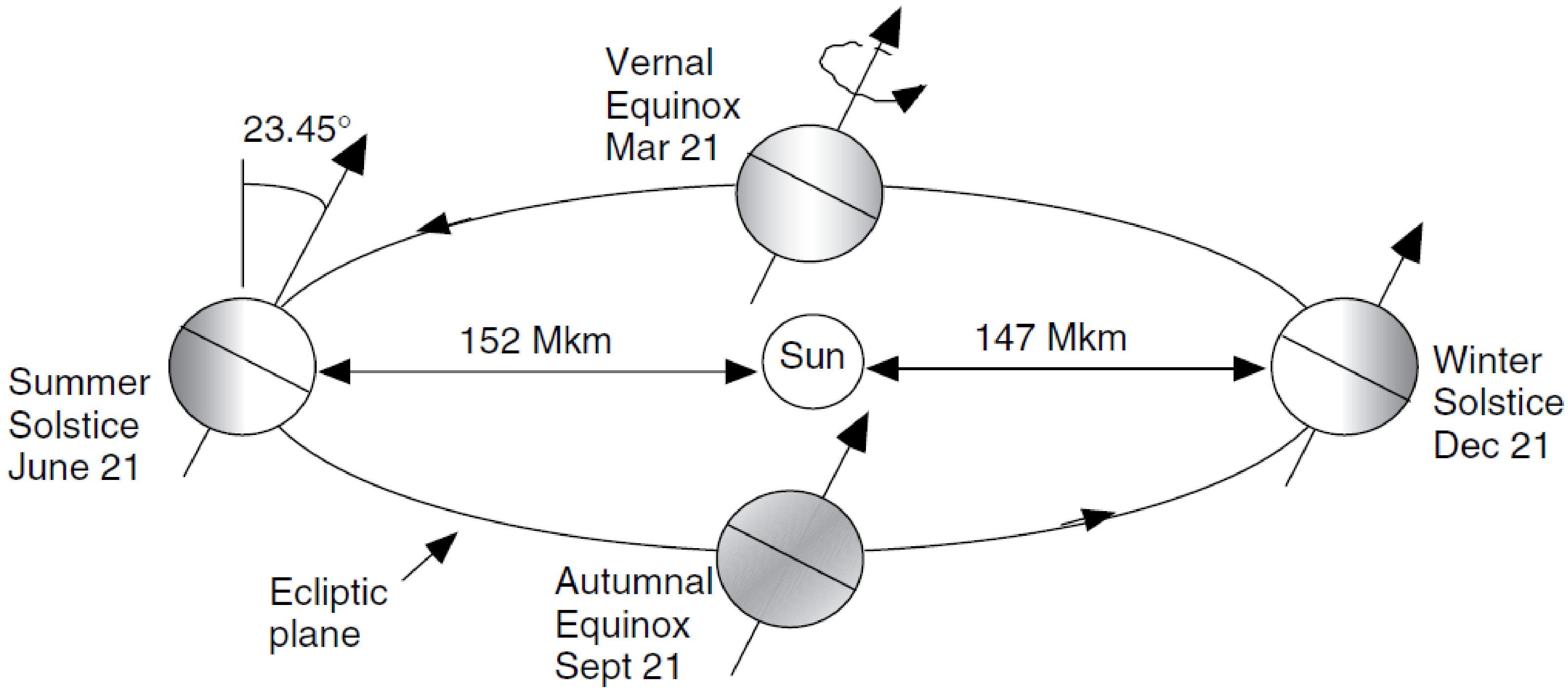
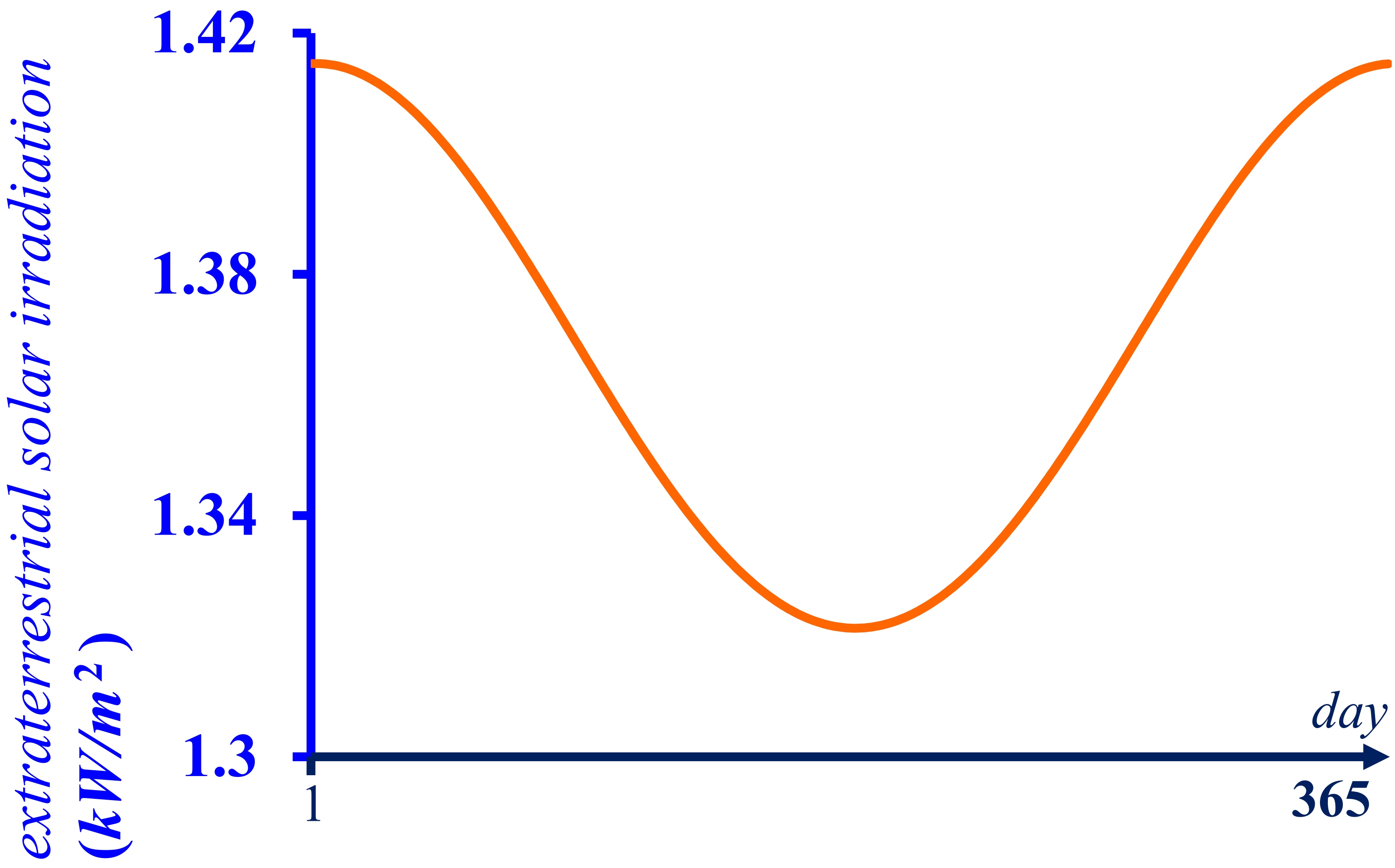


Figure 4.5 The tilt of the earth's spin axis with respect to the ecliptic plane is what causes our seasons. "Winter" and "summer" are designations for the solstices in the Northern Hemisphere.

Annual Extraterrestrial Solar Irradiation



Source: *http://solardat.uoregon.edu/SolarRadiationBasics.html/*

Extraterrestrial Solar Irradiation Over a Year

- The extraterrestrial solar irradiation variation over a day is negligibly small and so we assume that its value is constant as the earth rotates each day
- We use the **approximation** i_0 given by:

$$i_0\Big|_d$$

$$i_0\Big|_d = 1,367\left[1 + 0.034\cos\left(2\pi\frac{d}{365}\right)\right] \qquad d = 1,2,\ldots,365/366$$

W/m^2

Extraterrestrial Solar Irradiation

- We consider the approximation of extraterrestrial solar irradiation on January 1: $d = 1$

$$\left. i_0 \right|_1 = 1{,}367 \left[1 + 0.034 \cos\left(2\pi \frac{1}{365} \right) \right] = 1{,}413 \frac{W}{m^2}$$

- Now, for August 1, $d = 213$ and the extraterrestrial solar irradiation is approximately

$$\left. i_0 \right|_{213} = 1{,}367 \left[1 + 0.034 \cos\left(2\pi \frac{213}{365} \right) \right] = 1{,}326 \frac{W}{m^2}$$

Extraterrestrial Solar Irradiation

- We observe that in the Northern hemisphere, the extraterrestrial solar irradiation is **higher** on a cold winter day than on a hot summer day
- This phenomenon results from the fact that the sunlight enters into the atmosphere with different **incident angles**; these angles impact greatly the fraction of extraterrestrial solar irradiation **received** on the earth's surface at different times of the year
- As such, at a specified geographic location, we need to determine the ***solar position in the sky*** to evaluate the ***effective amount*** of solar irradiation at that location

4.3: Altitude Angle of the Sun at Solar Noon

- **Solar declination** δ – the angle formed between the plane of the equator and the line from the center of the sun to the center of the earth
- δ varies between +/- 23.45˚

The Sun's Position in the Sky

- Solar declination from an Earth-centric perspective
  - Note: solar declination varies over the year, not during the day

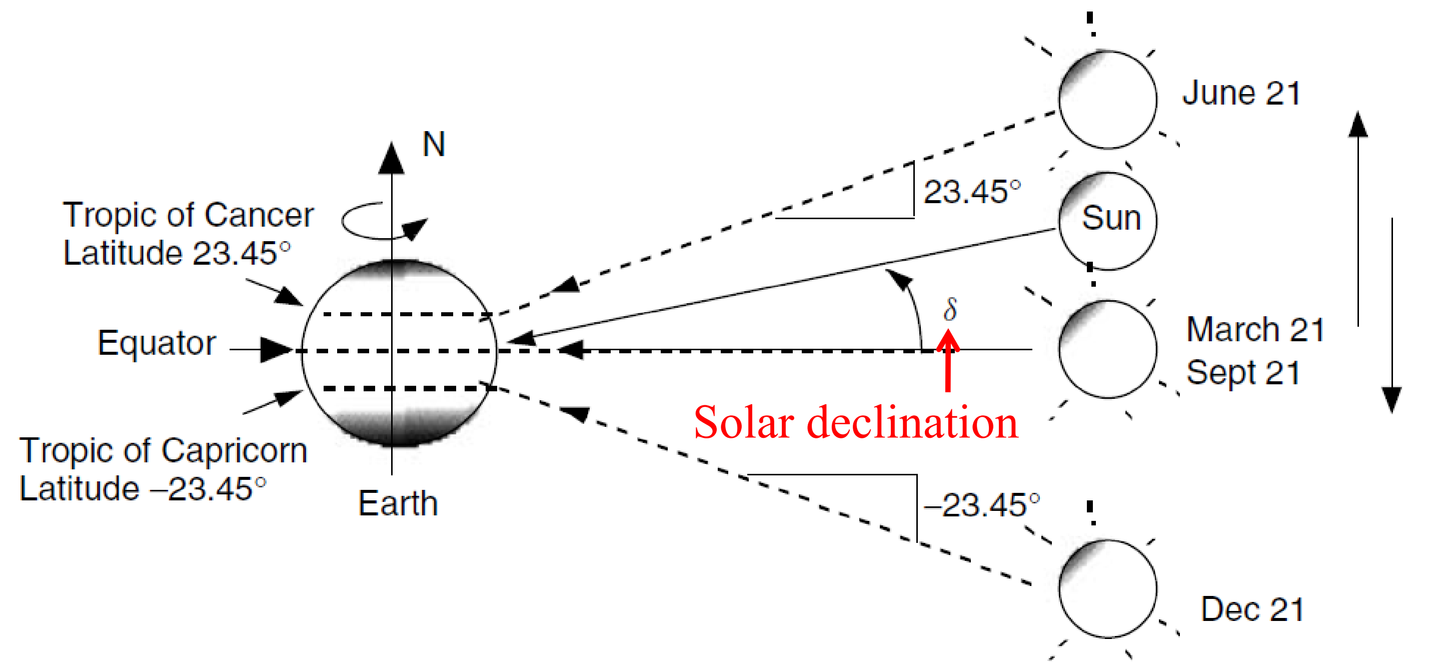


Figure 4.5 An alternative view with a fixed earth and a sun that moves up and down. The angle between the sun and the equator is called the solar declination δ.

4.3: Altitude Angle of the Sun at Solar Noon

- **Solar declination** δ – the angle formed between the plane of the equator and the line from the center of the sun to the center of the earth
- δ varies between +/- 23.45˚
- Assuming a sinusoidal relationship, a 365 day year, and n=81 is the Spring equinox, the approximation of δ for any day n can be found from

$$\delta = 23.45 \sin\left[\underbrace{\frac{360}{365}(n-81)}_{\text{degrees}}\right] \qquad (4.6)$$

Tropics and Poles

- **Tropics**: Sun is always directly overhead at least once per year
- **Polar regions** (above/below the Arctic/Antarctic circle): Have at least one 24-hour day and one 24-hour night per year

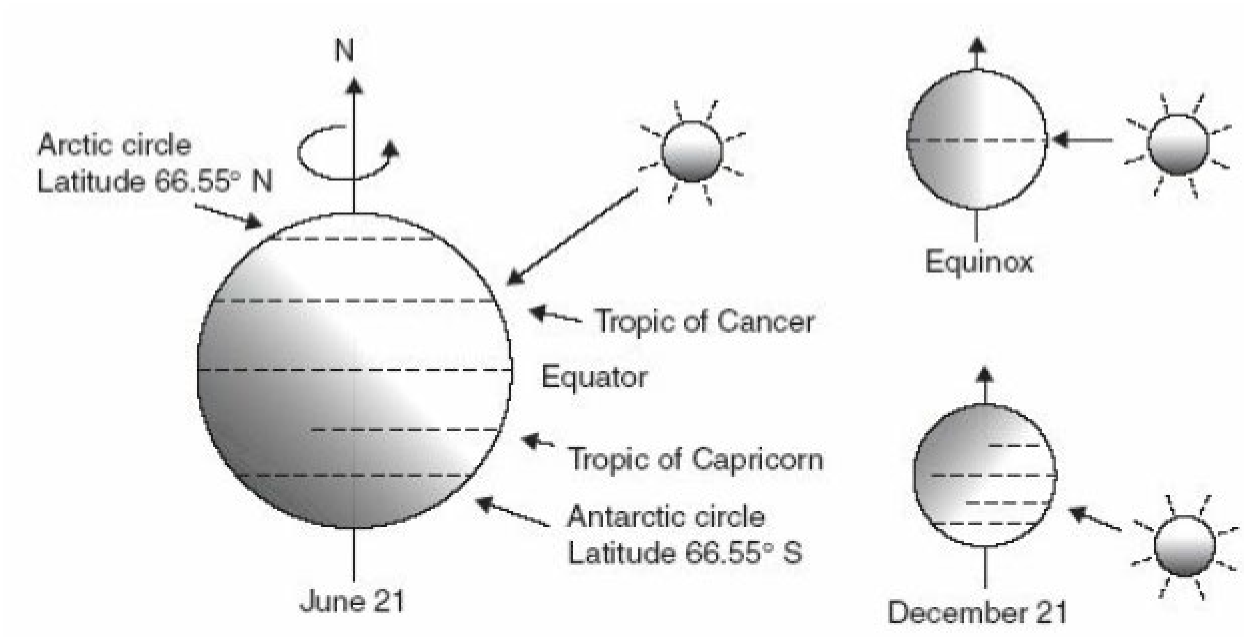


Figure 4.7: Defining Earth's key latitudes is easy with the simple version of the Earth-Sun system

Solar Noon and Collector Tilt

- **Solar noon** – sun is directly over the local line of longitude
- Rule of thumb for the Northern Hemisphere: a South-facing collector tilted at an angle equal to the local latitude

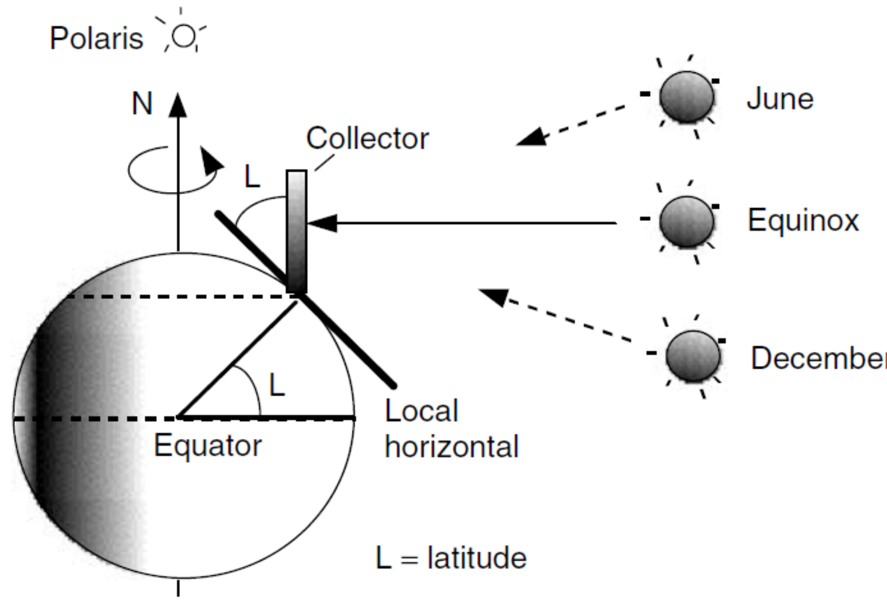


Figure 4.8 A south-facing collector tipped up to an angle equal to its latitude is perpendicular to the sun's rays at solar noon during the equinoxes.

- In this case, on an <u>equinox</u>, during solar noon, the sun's rays are perpendicular to the collector face

Altitude Angle β_N at Solar Noon

- Altitude angle at solar noon β_N – angle between the Sun and the local horizon

$$\beta_N = 90° - L + \delta \quad (4.7)$$

$0 \leq \beta_N \leq 90°$

$0 \leq L \leq 90°$

$-23.45° \leq \delta \leq 23.45°$

- Zenith – perpendicular axis at a site

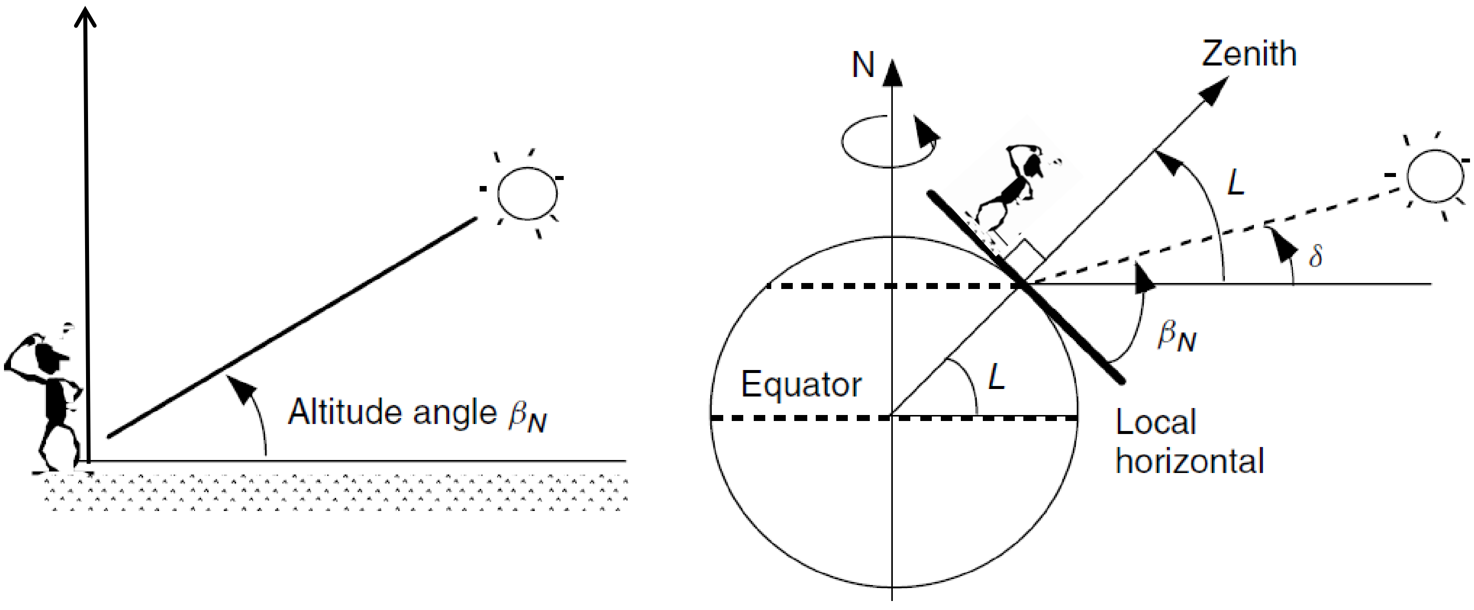


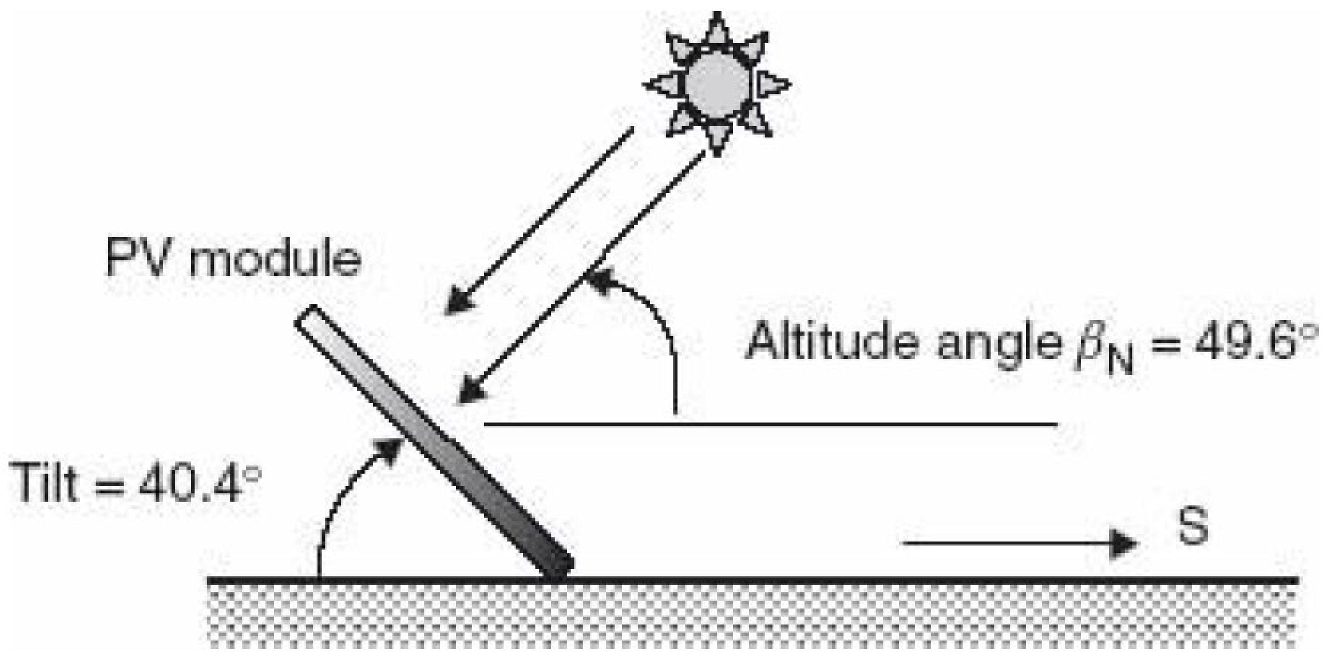
Figure 4.9 The altitude angle of the sun at solar noon.

Local Horizon: Be Careful!

- The *Local Horizon* is the direction (North or South) you would be looking at solar noon so that the Sun is in front of or directly above (not behind) you.
- Between the tropics, the local horizon changes from north to south during the year.
- In the northern hemisphere, the local horizon is always south; in the southern hemisphere, it's always north.
- In the tropics, $-23.45° \leq L \leq 23.45°$; **thus,** you have to adjust the sign of δ in Eqn. (4.7) depending on whether your local horizon is North or South.
  - For South local horizon (our local reference here in Illinois), use (4.7) as is
  - For North local horizon, flip the sign on δ

Tilt Angle of a Photovoltaic (PV) Module

- Rule of thumb: Tilt angle = $90° - \beta_N$
- Example 4.2, p. 196: Latitude = 32.1°, March 1st, Solar Noon



Wrap-up