ENGR-3000:
Renewable Energy, Technology, and Resource Economics

Introduction to Solar Power: The Solar Resource

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6 June 2019
Ísafjörður, Iceland

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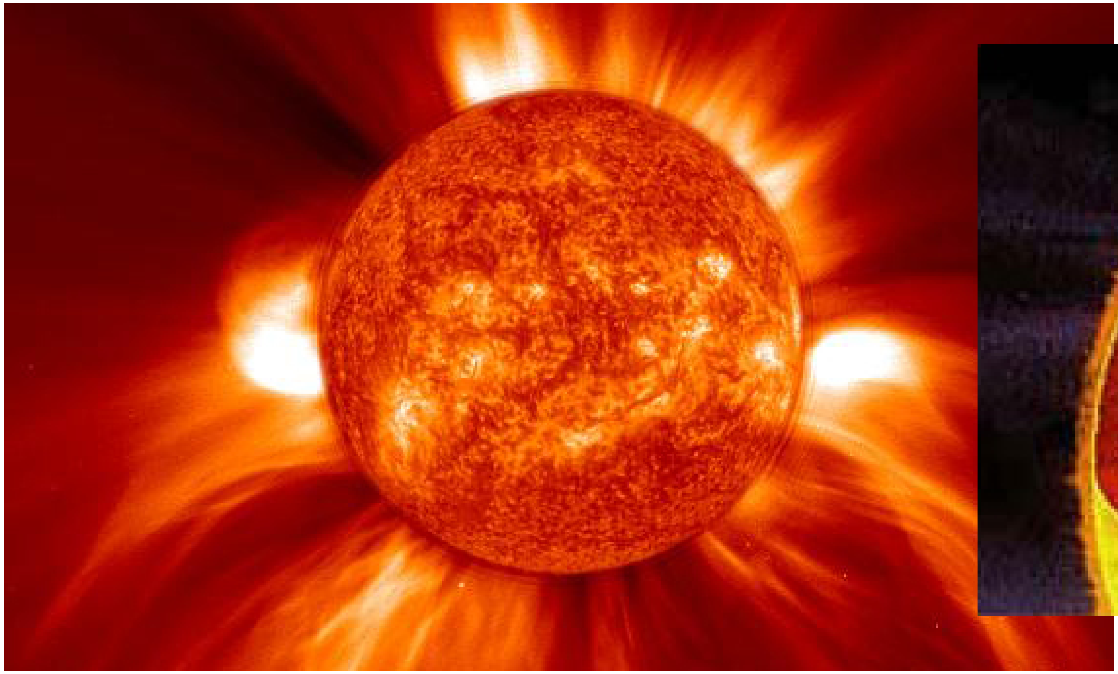
An Introduction to Solar Power: Outline

- Solar Energy Output:
  - How do we characterize solar energy?
- Earth's Energy Budget:
  - What happens to the sum's energy once it gets here?
- The Orbit and Orientation of the Earth in Space:
  - How does the earth move around the sun?
- Sun Paths:
  - How does the sun move through our sky?
- Quantifying the Sun's Useable Energy:
  - How do we measure the sun's energy
  - Where is the data stored?

Solar Energy: Origins

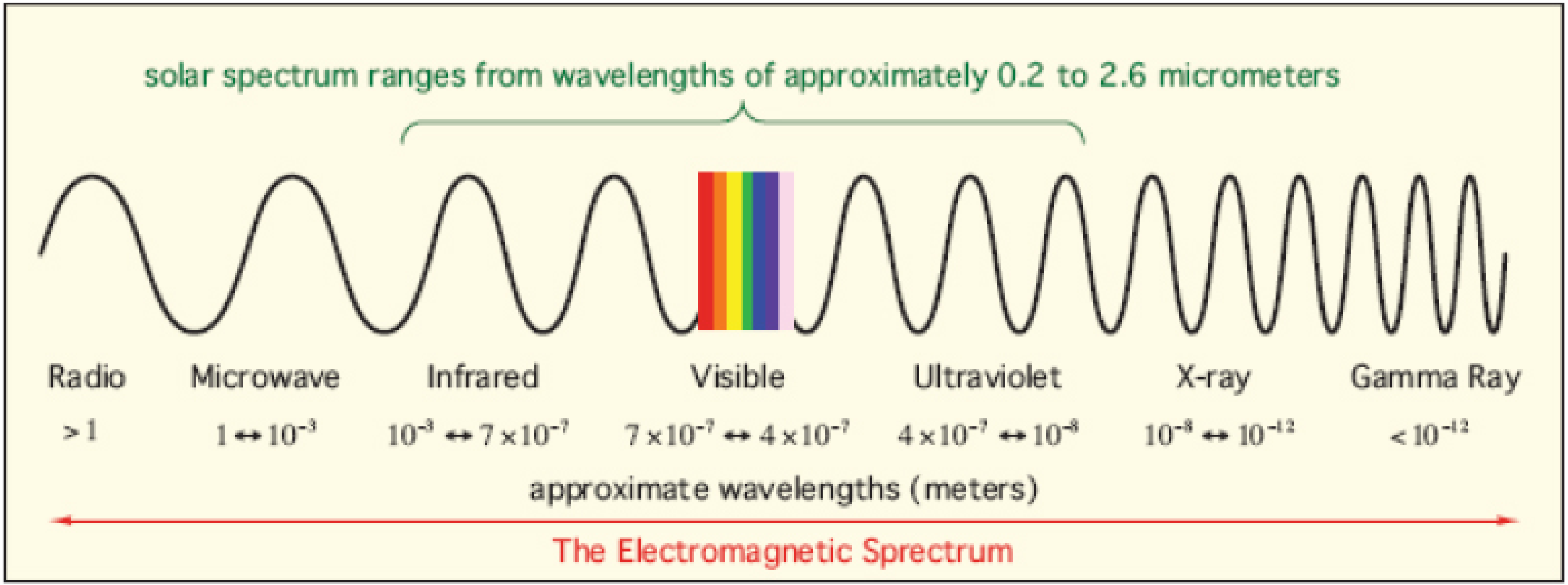
- Solar Energy originates deep within the sun, the product of nuclear fusion.
- Total solar radiation output ≅ 3.8×10^{20} MW
- This energy reaches the surface of the sun through radiation and convection
- The energy travels from the surface of the sun outward through radiation



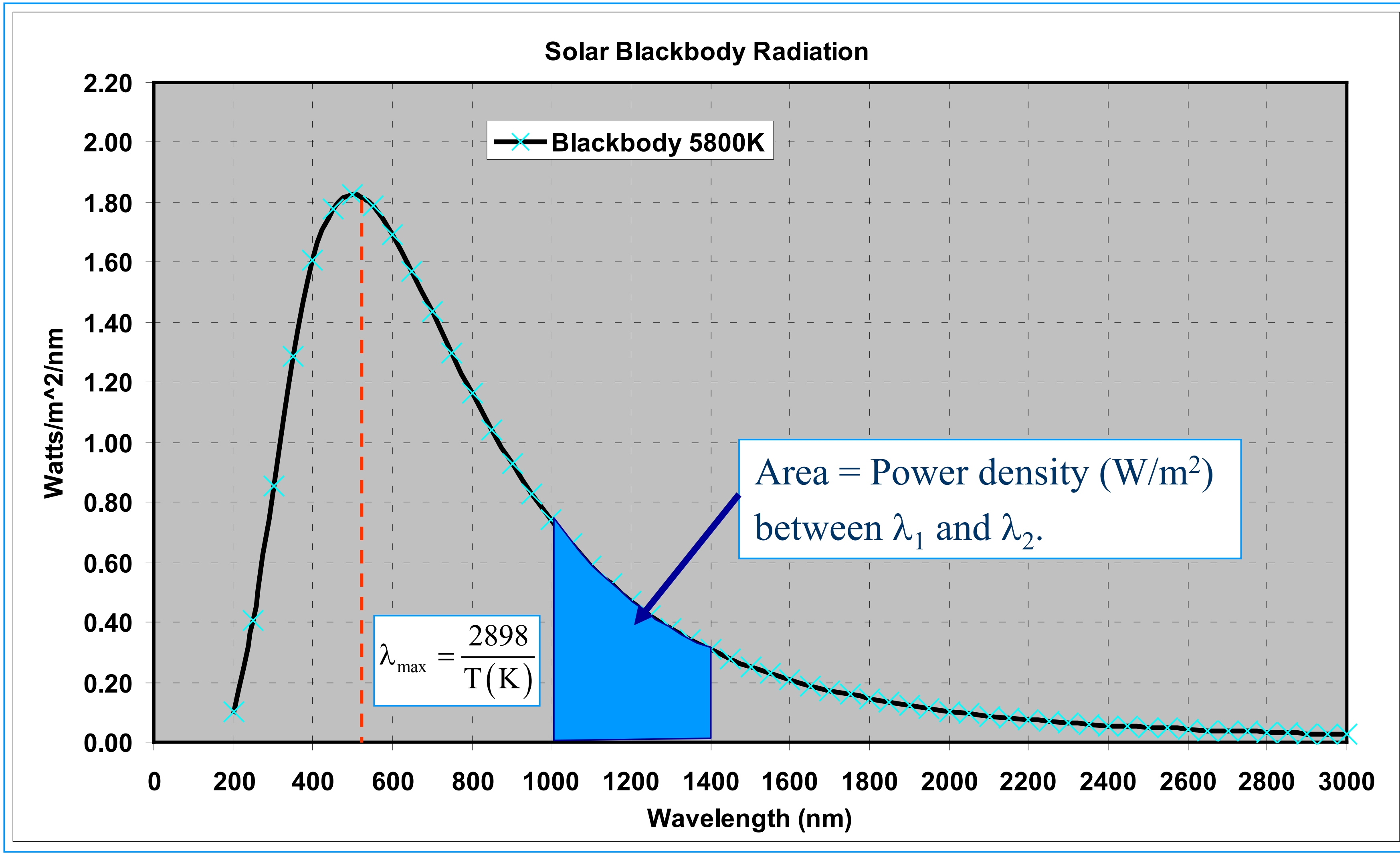
www.suntrek.org

The Solar Spectrum

- The sun's radiant energy is distributed across the entire electromagnetic spectrum:



Blackbody Radiation



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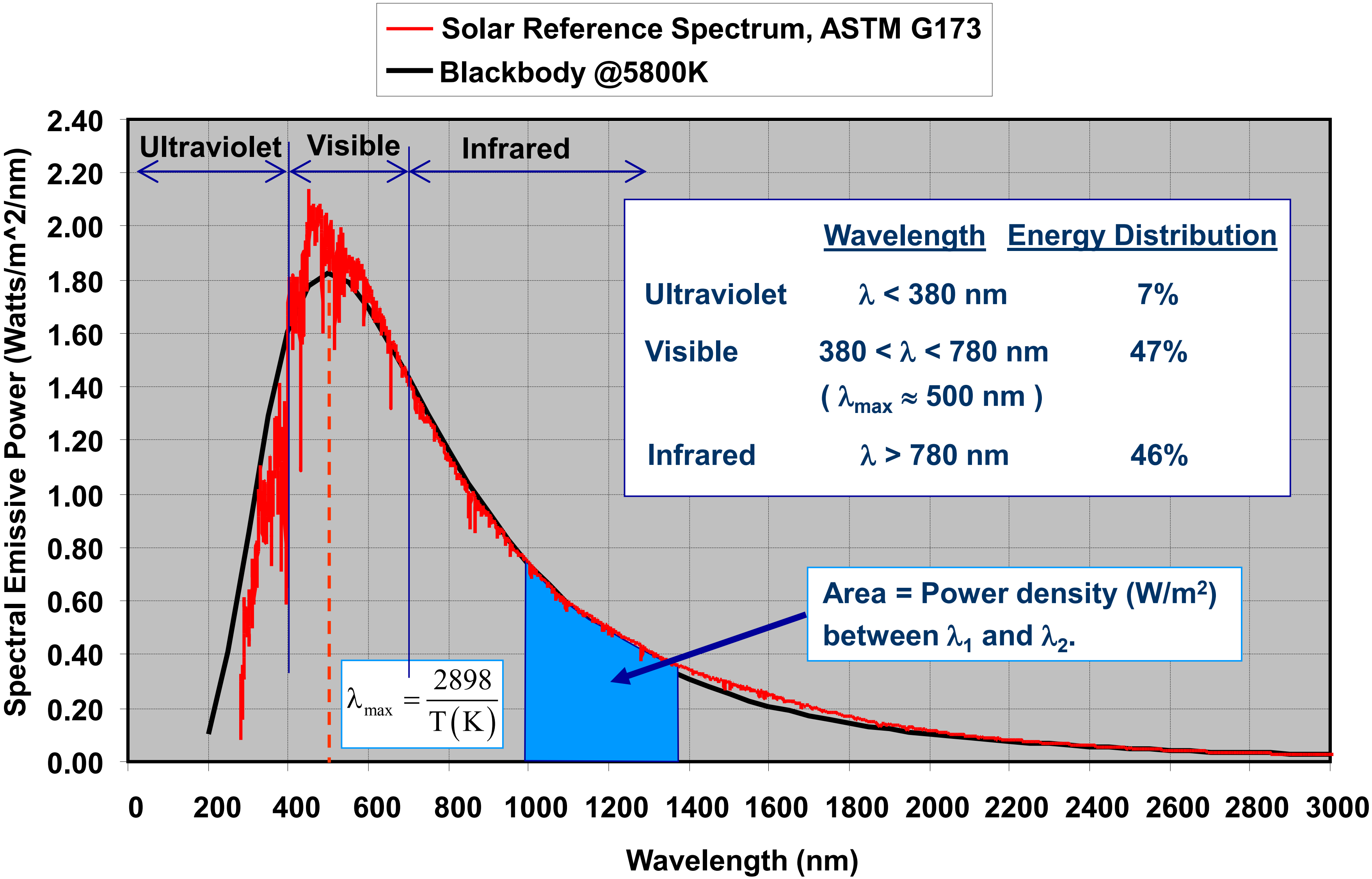
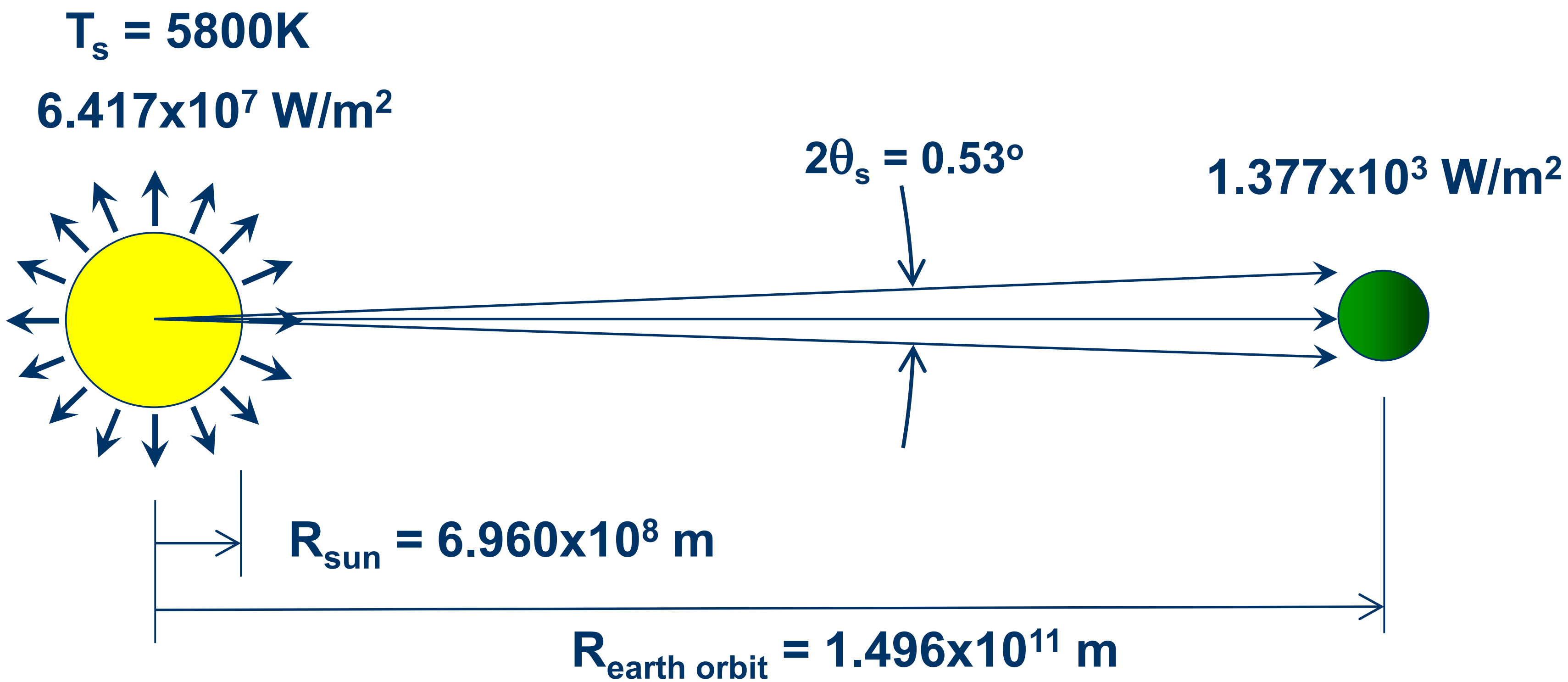
The Solar Spectrum



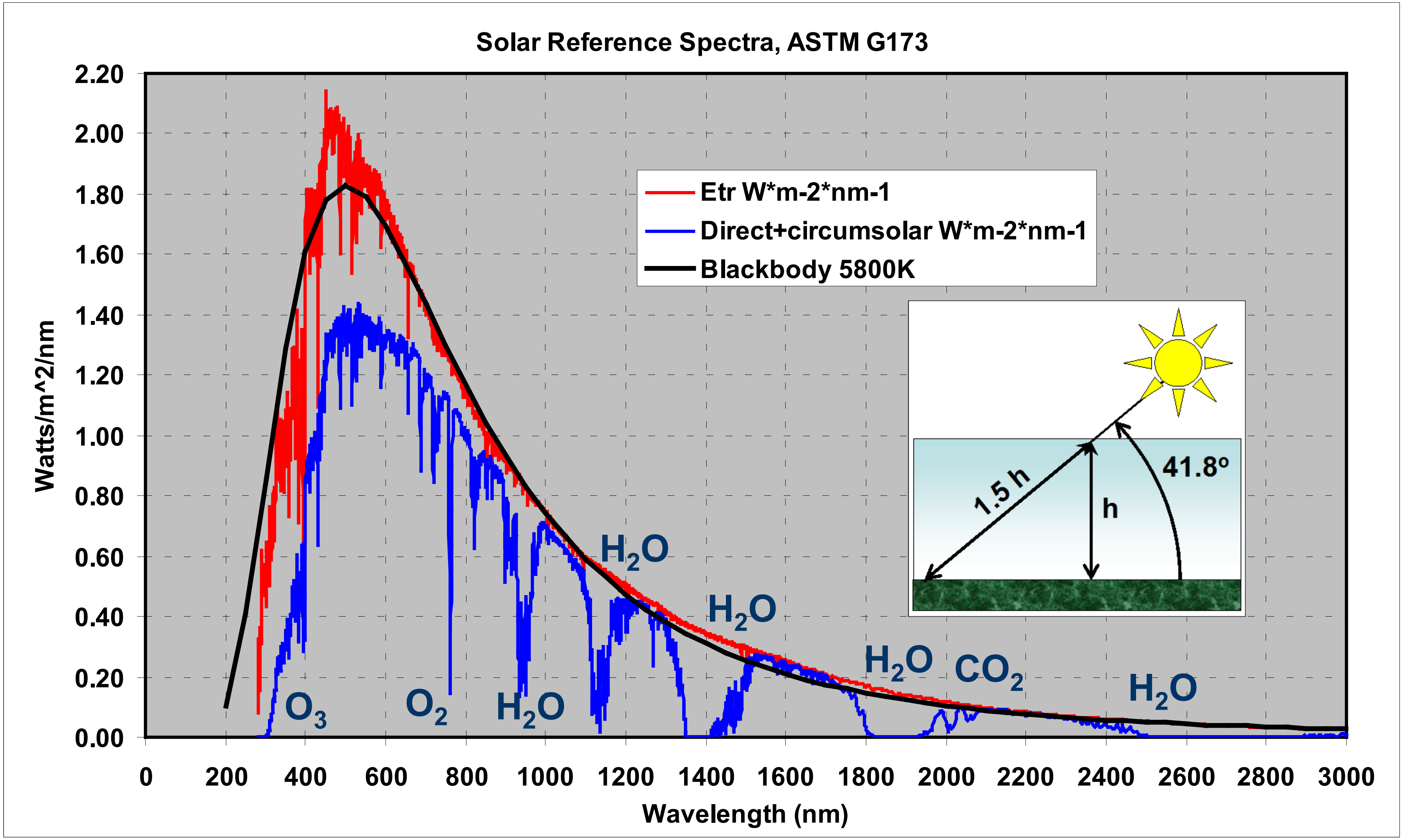
	Wavelength	Energy Distribution
Ultraviolet	$\lambda < 380$ nm	7%
Visible	$380 < \lambda < 780$ nm ($\lambda_{max} \approx 500$ nm)	47%
Infrared	$\lambda > 780$ nm	46%

Solar Energy Output and Insolation

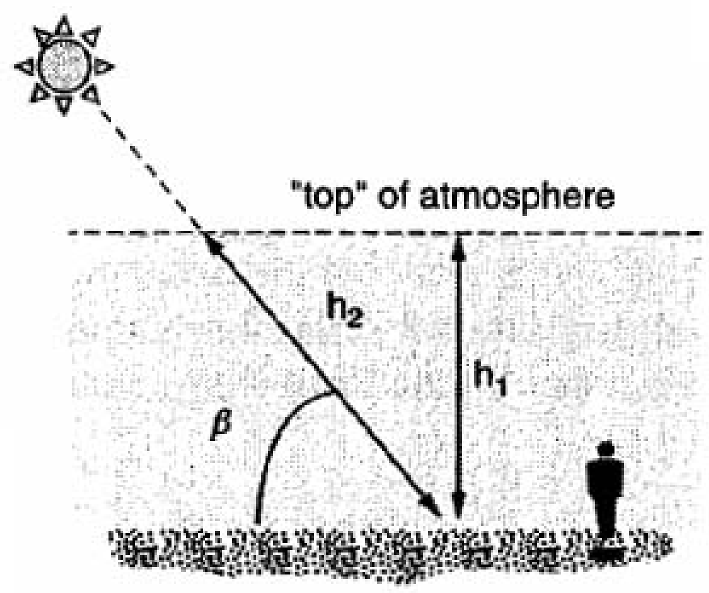
- Insolation: The amount of solar energy striking the earth



Solar Spectrum ASTM G173-03



Air Mass Ratio

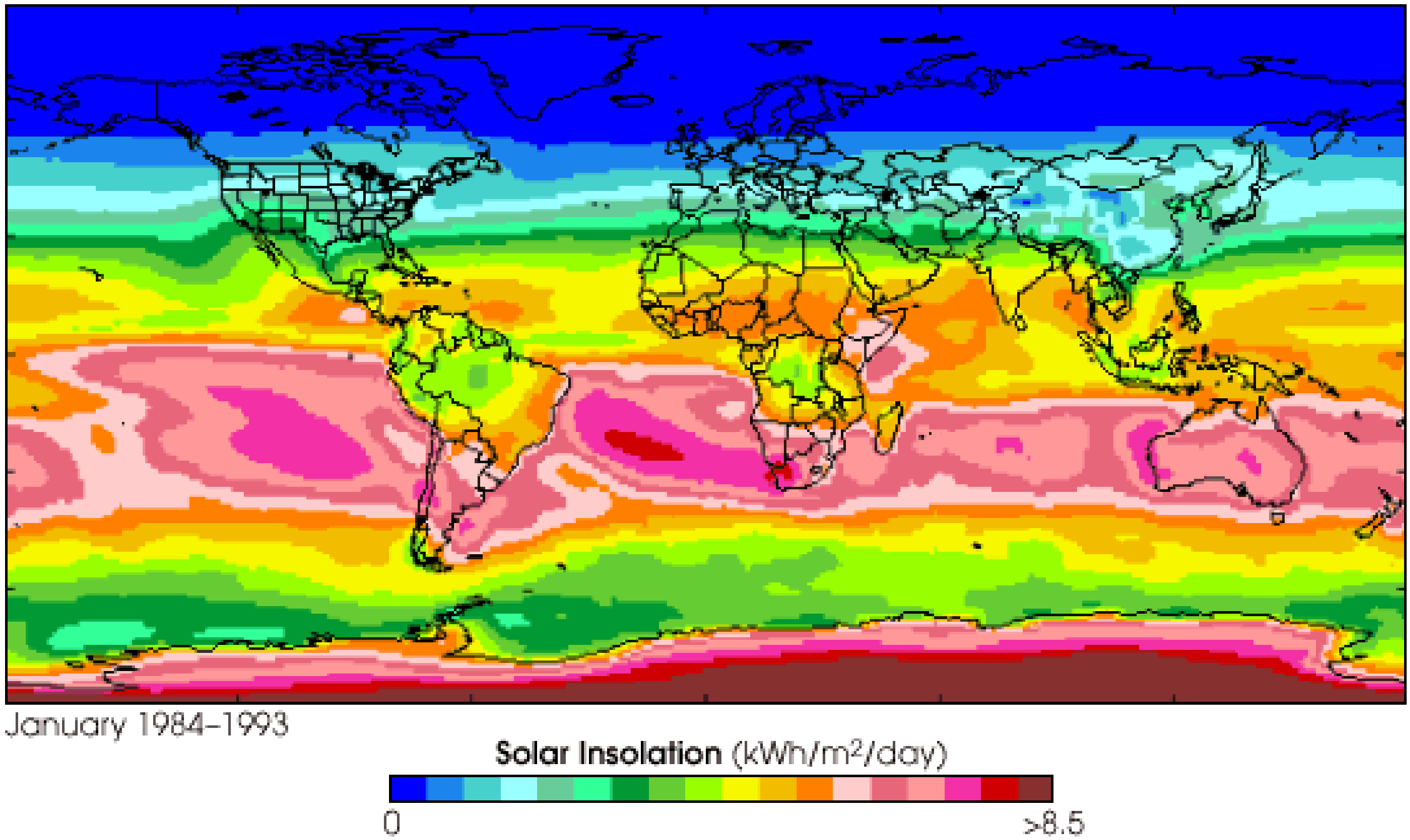


$$\text{air mass ratio } m = \frac{h_2}{h_1} = \frac{1}{\sin\beta}$$

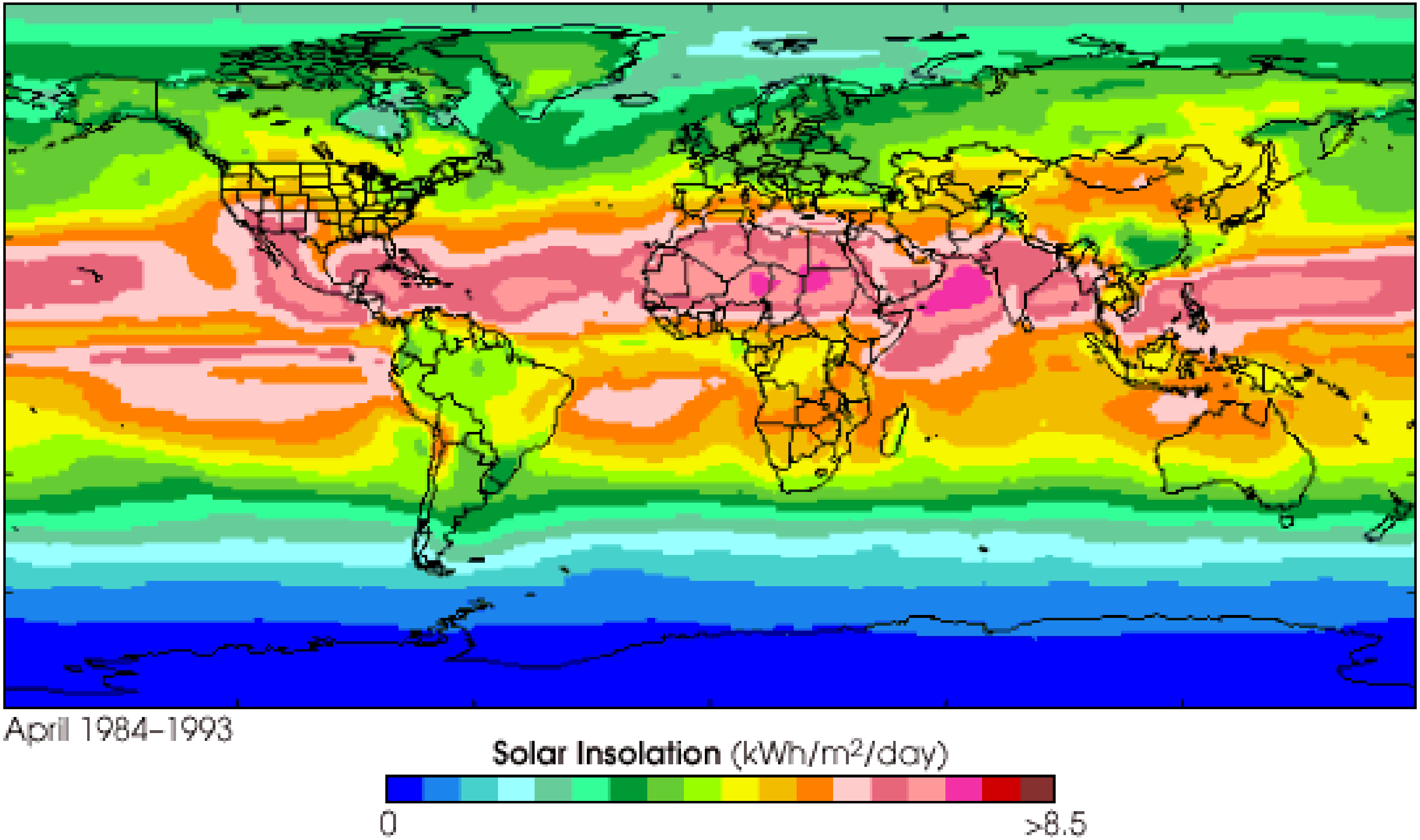
- Air mass ratio of 1 (“AM1”) means sun is directly overhead
- AM0 means no atmosphere
- AM1.5 is assumed average at the earth’s surface

➢ **Generally, at ground level, use a maximum solar irradiance G_0 = 1000W/m^2.**

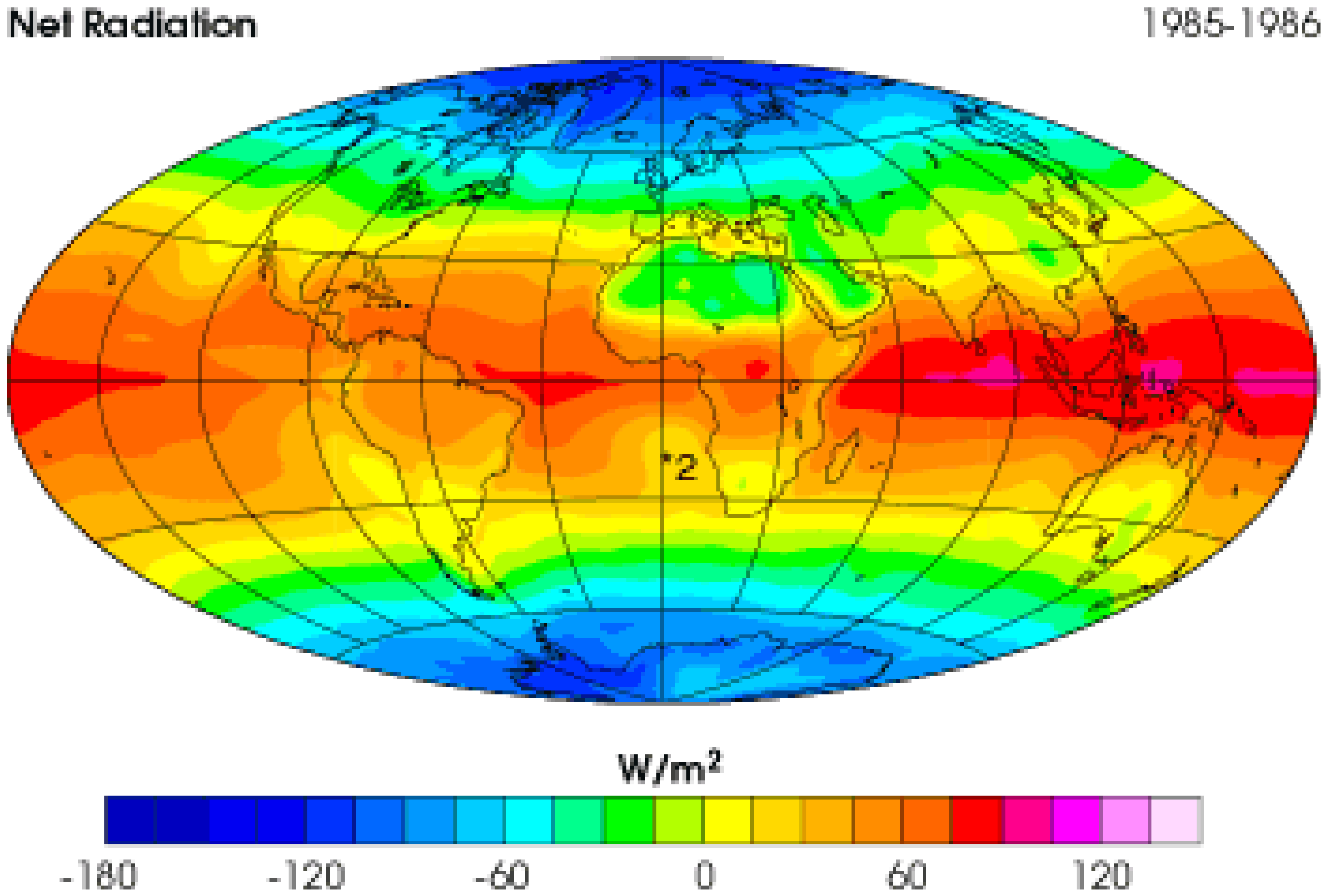
Solar Insolation – January



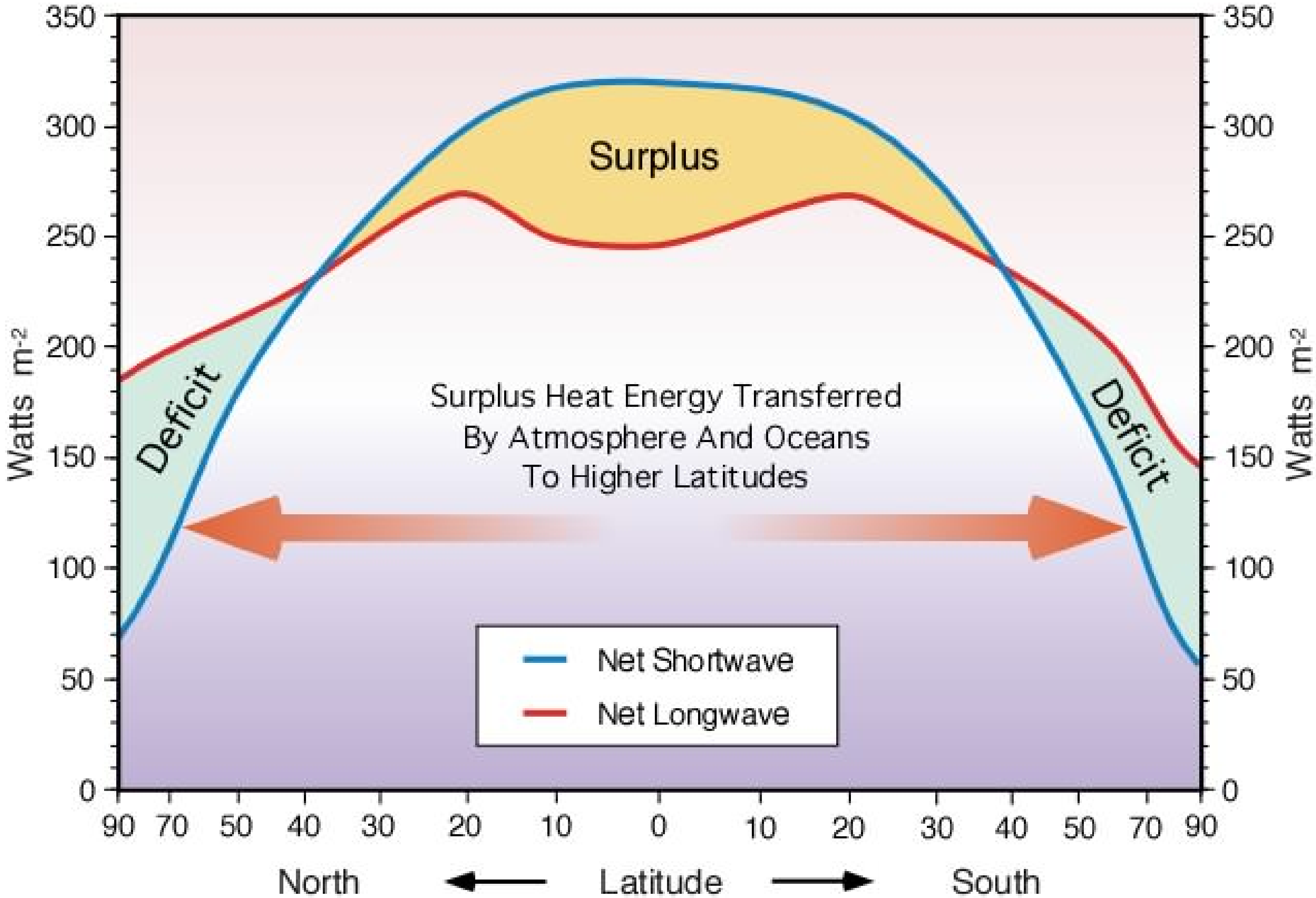
Solar Insolation – April



Net Radiation

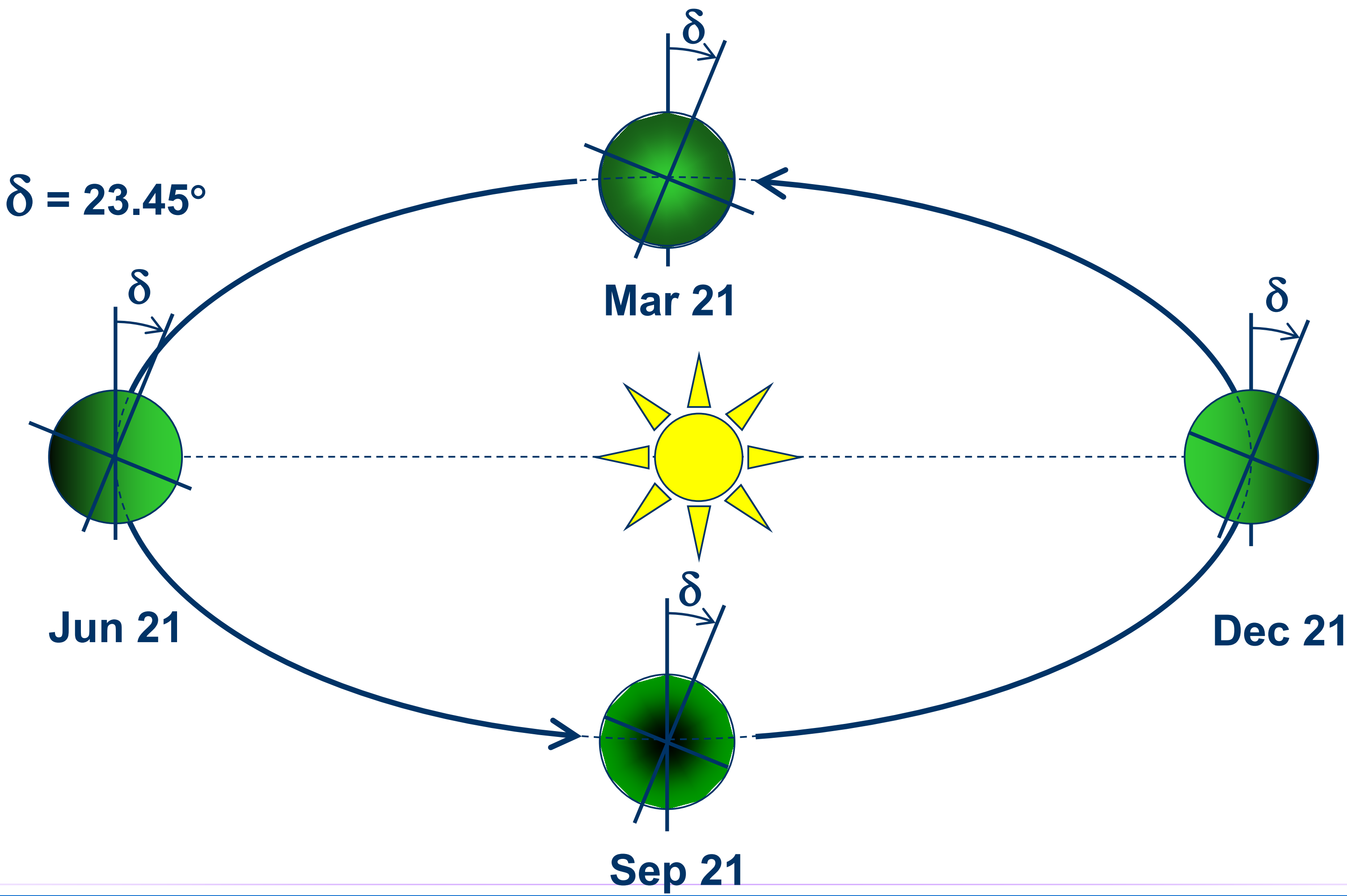


Radiation Balance

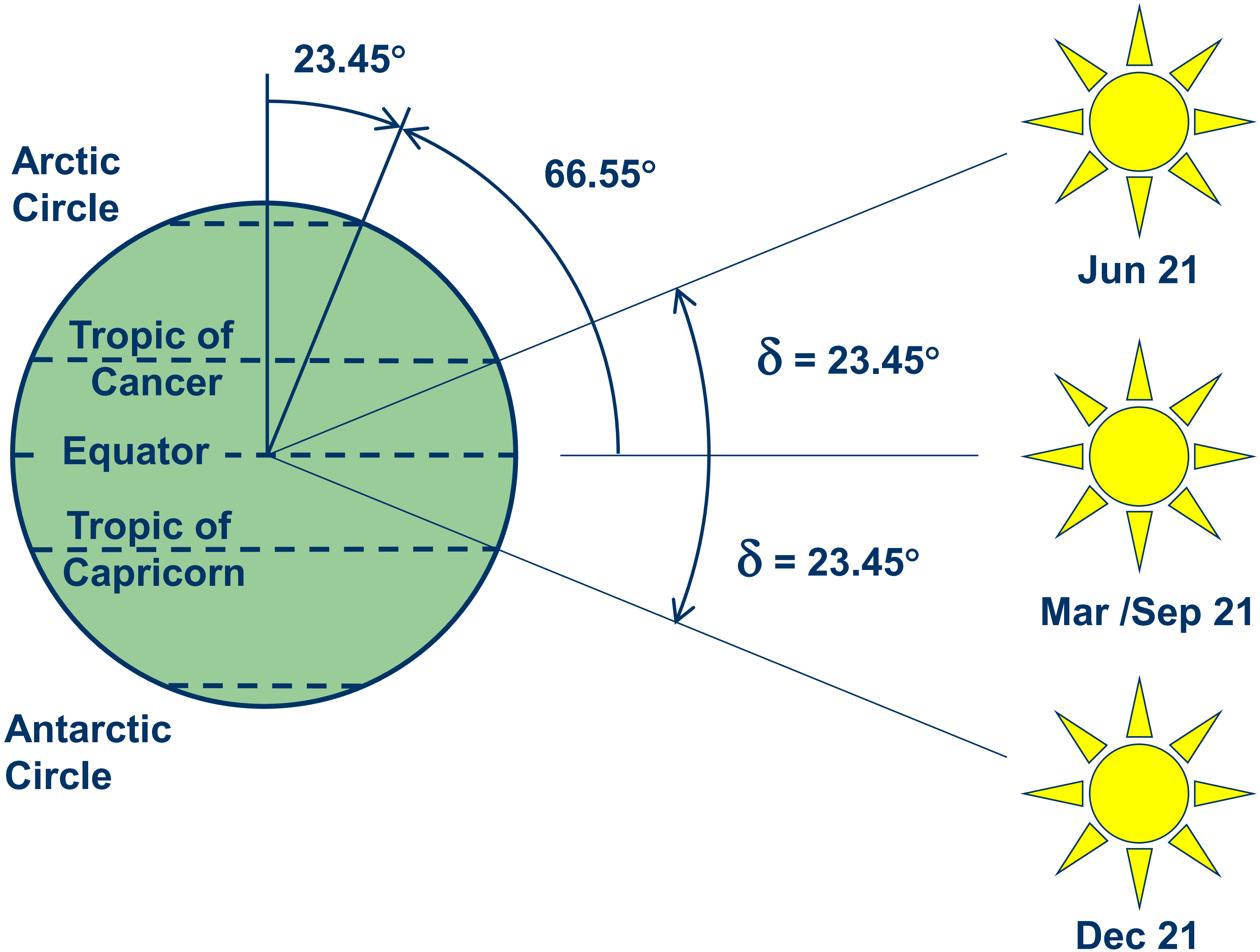


Earths Orbit and Declination

- R (distance to sun) varies from 147×10^6 km on Jan. 2 to 152×10^6 km on July 3 (closer in winter, further in summer)



Solar Declination



The Earth's Orbit

- One revolution every 365.25 days

- n = day number (Jan. 1 is day 1)

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	$n = 335$

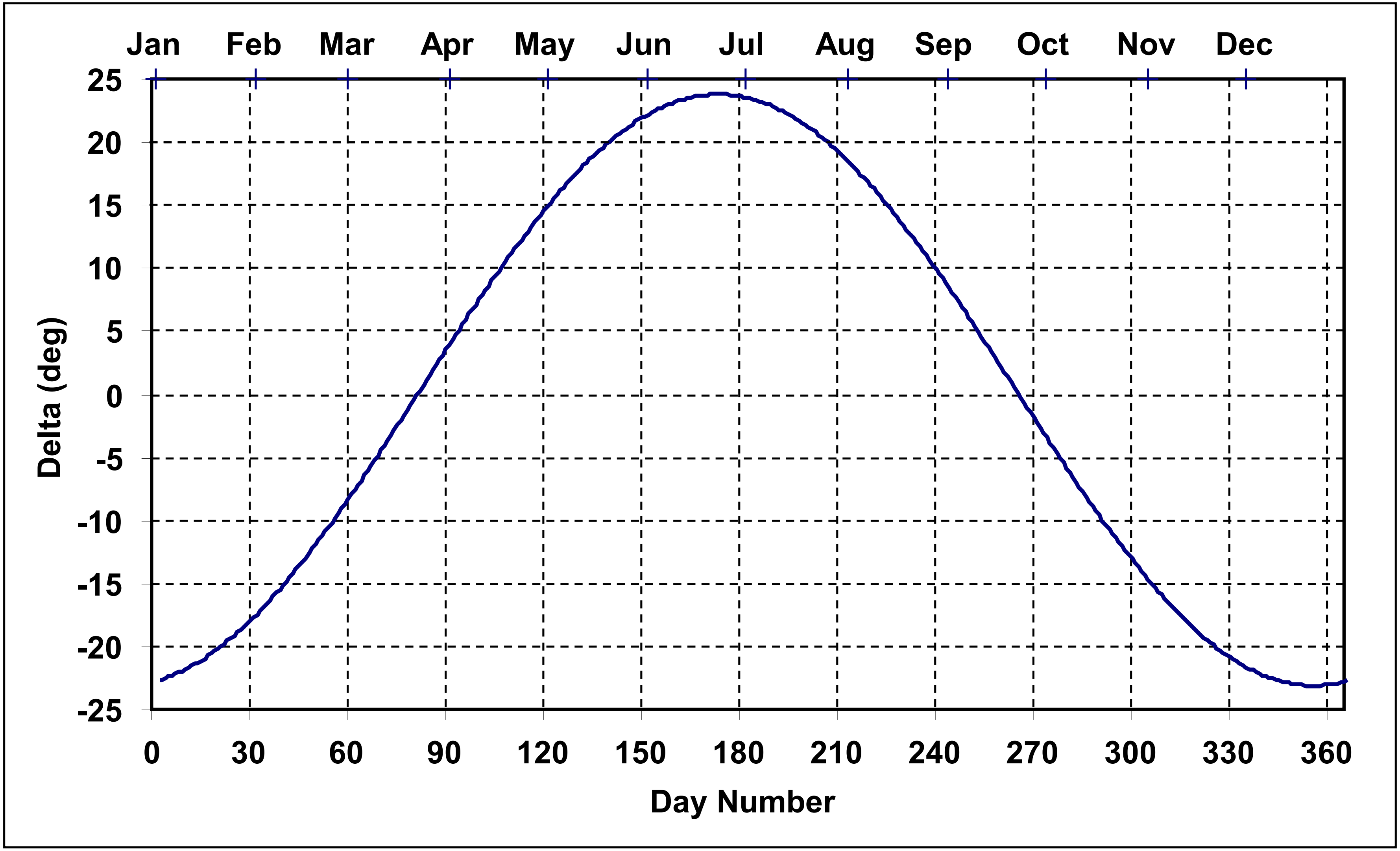
G.M. Masters, Renewable and Efficient Electric Power Systems, Wiley 2004

Solar Declination

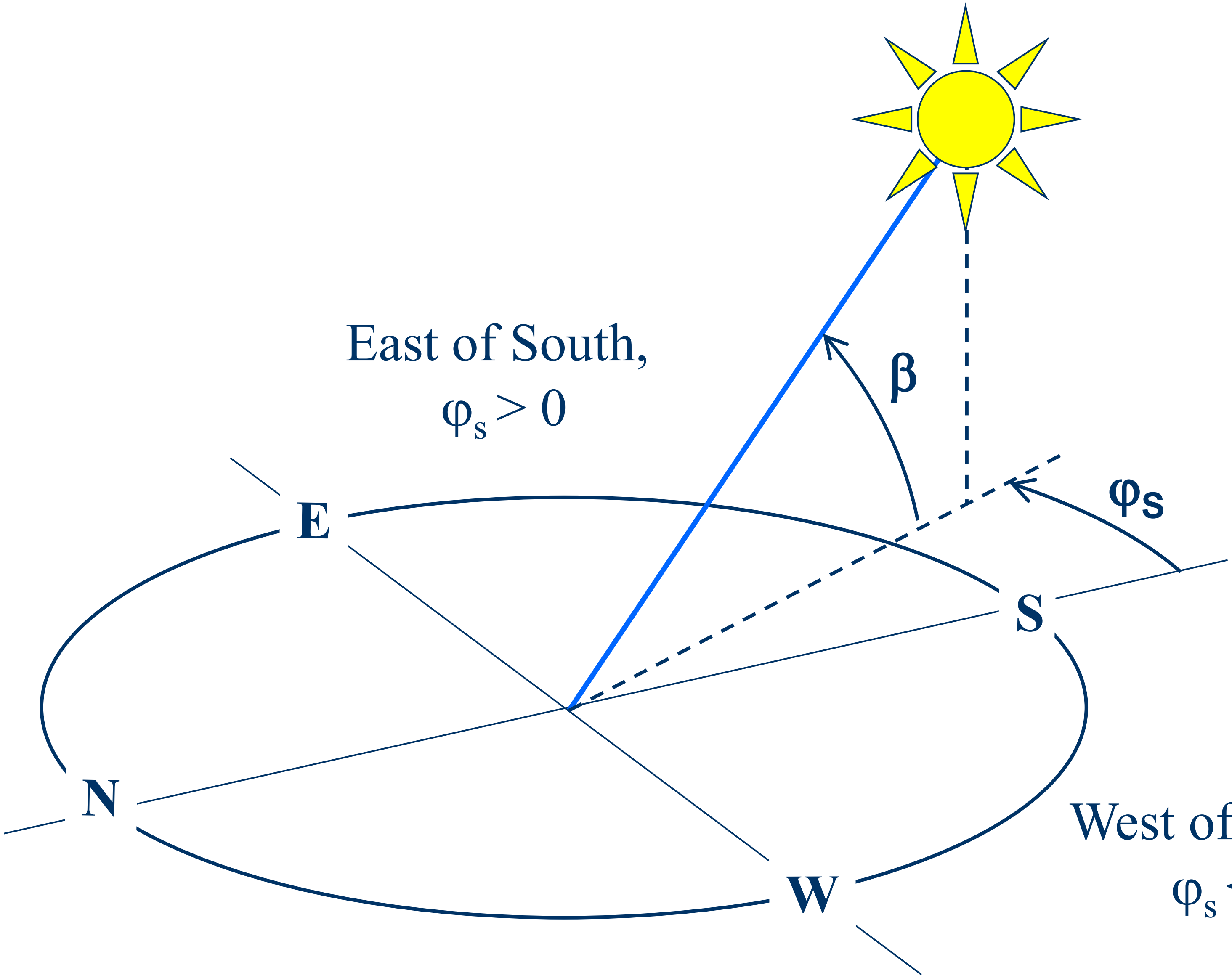
- Solar declination δ – the angle formed between the plane of the equator and the line from the center of the sun to the center of the earth
- δ varies between +/– 23.45°
- Assuming a sinusoidal relationship, a 365 day year, and n = 81 is the spring equinox, the approximation of δ for any day n can be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

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

Solar Declination



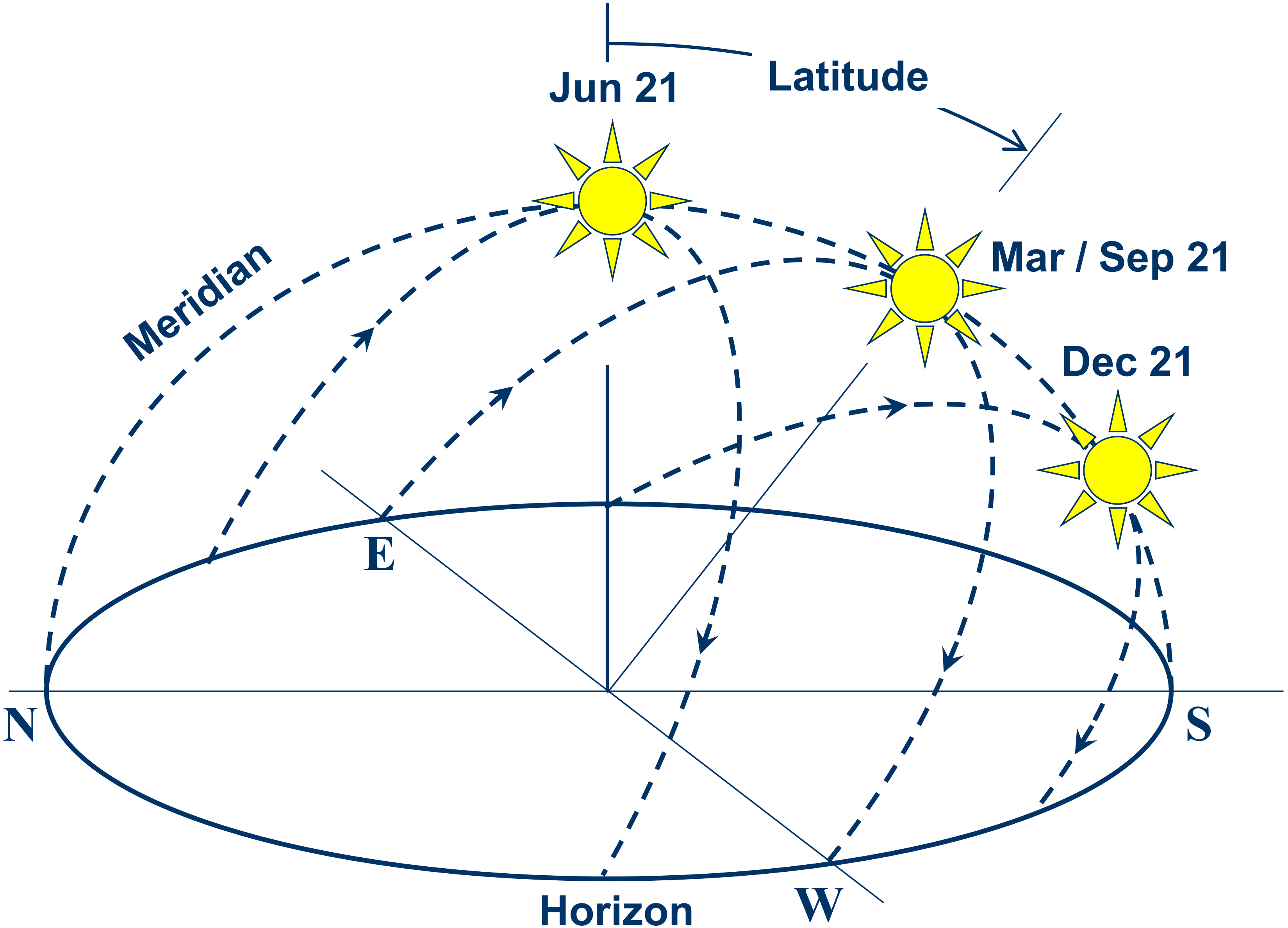
Sun Position: Altitude and Azimuth Angles



Solar Position at Any Time of Day

- Described in terms of altitude angle β and azimuth angle of the sun ϕ_S
- β and ϕ_S depend on latitude, day number, and time of day
- Azimuth angle (ϕ_S) convention
  - positive in the morning when sun is in the east
  - negative in the evening when sun is in the west
  - reference in the Northern Hemisphere (for us) is true south
- Hours are referenced to solar noon

Sun Paths: Annual Variation

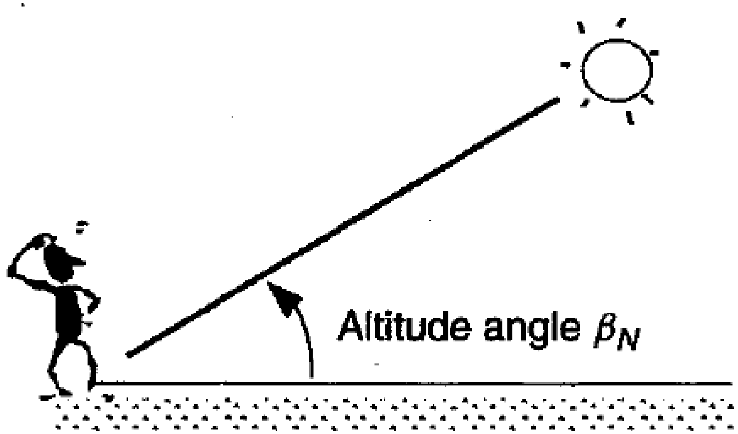


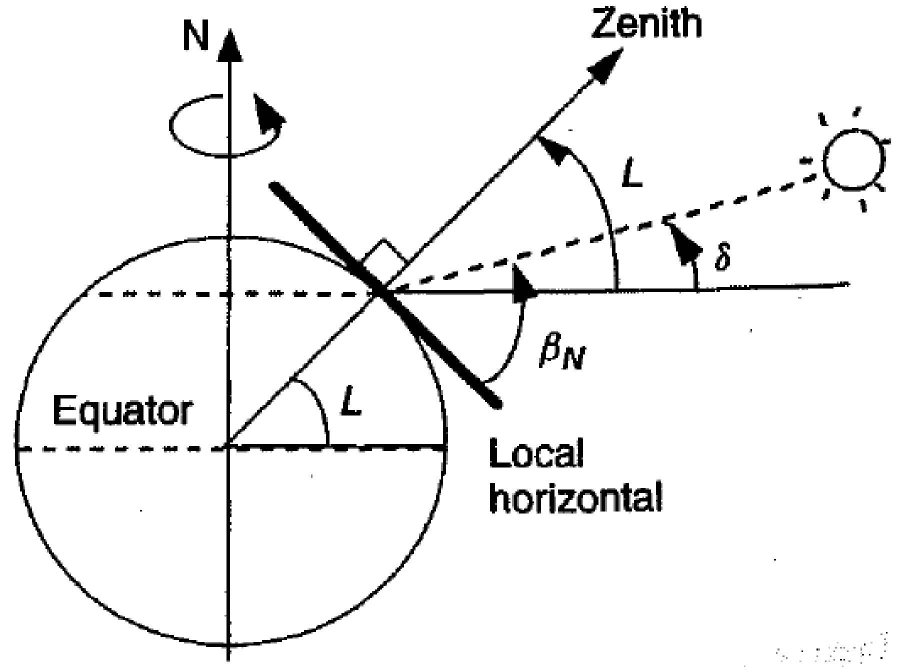
Altitude Angle β_N at Solar Noon

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

$$\beta_N = 90° - L + \delta$$

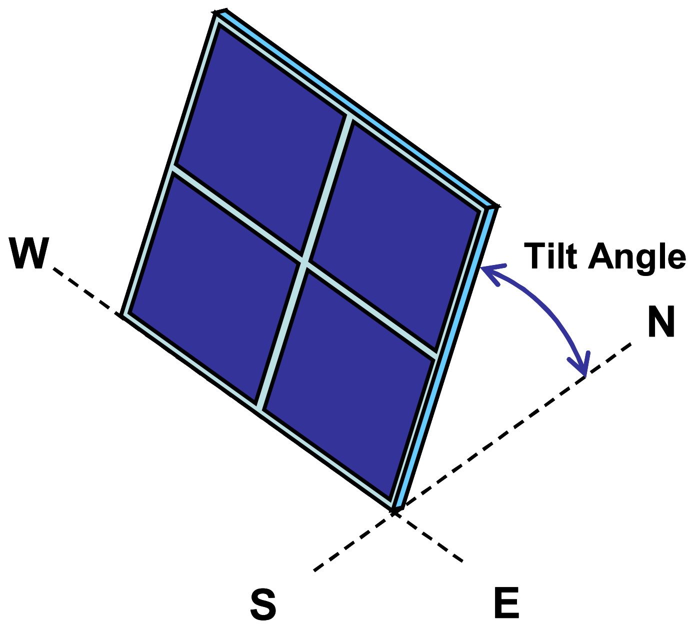
- Zenith – perpendicular axis at a site

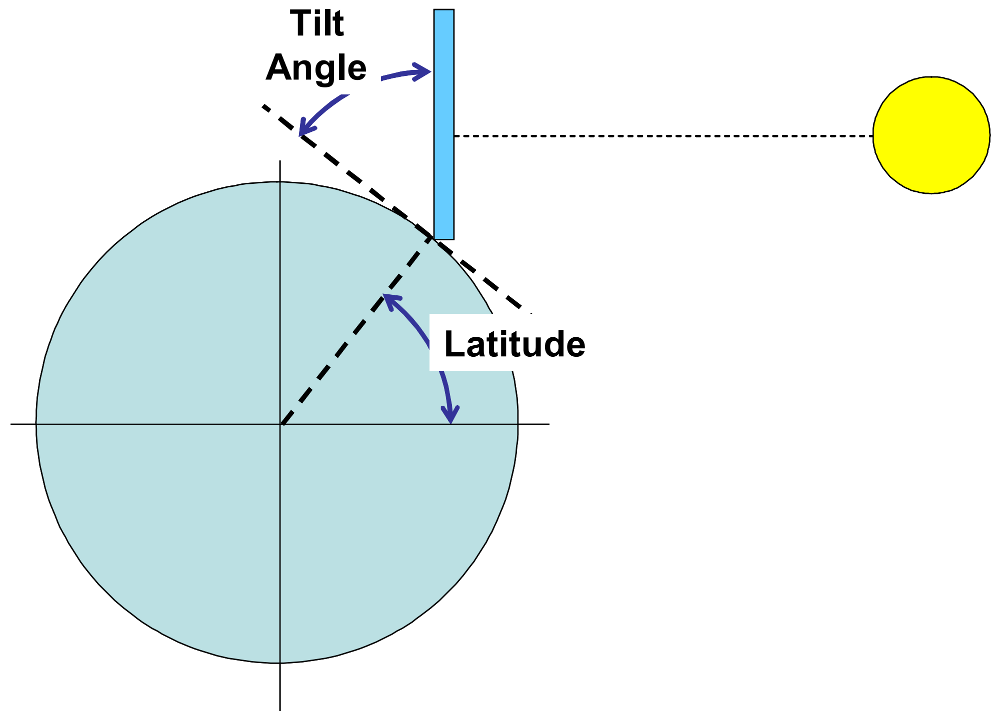




Flat Plate Collectors

- Tilt = Latitude: optimal for year-round use
- Tilt = Latitude + 15°: optimal for winter use
- Tilt = Latitude - 15°: optimal for summer use

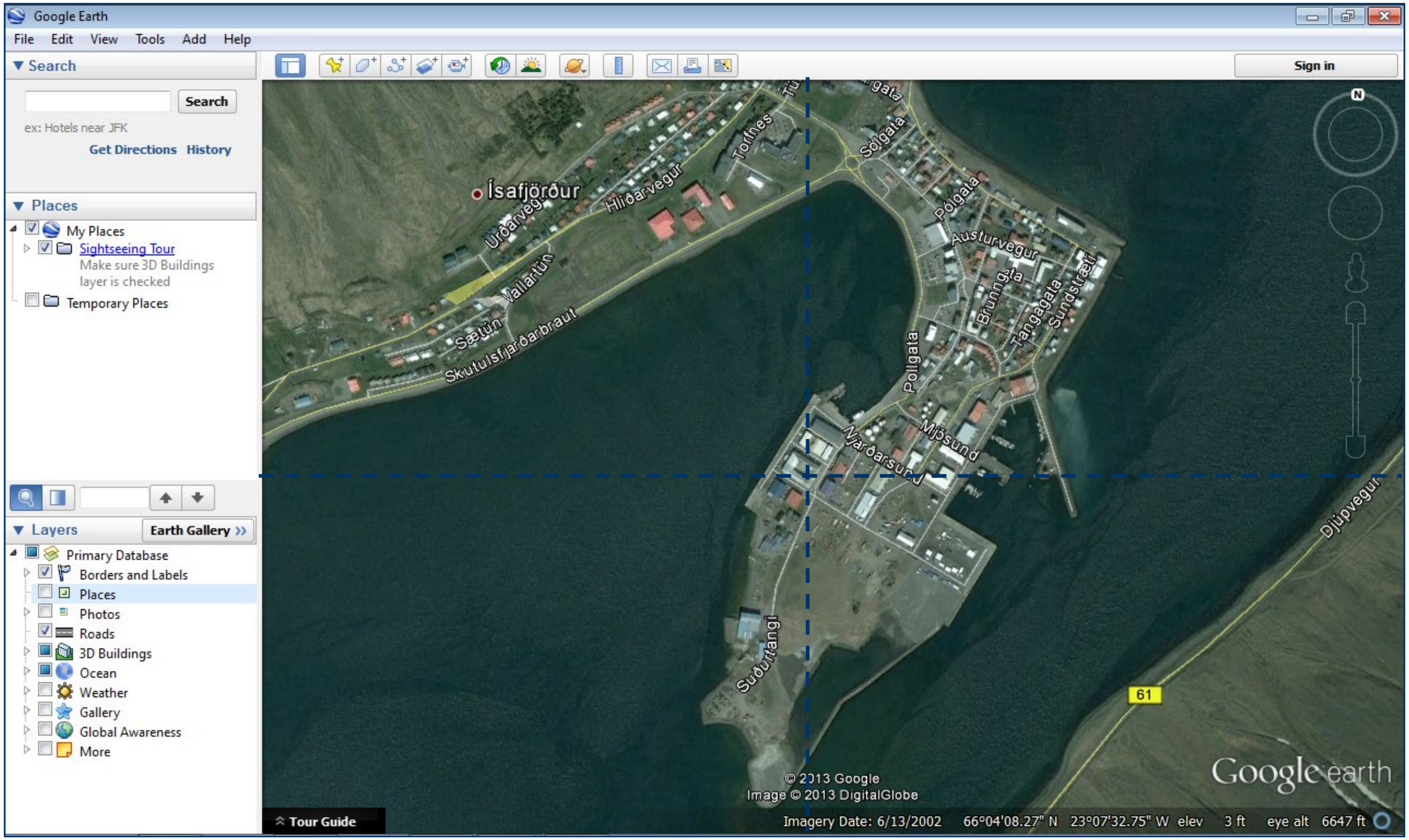




Determining Location: Latitude and Longitude

- Using Google Earth:

Ísafjörður: 66°04’08.40” N; 23°07’33.13”W



Example – Tilt of a Flat Plate Collector

- Find the optimum tilt angle for a south-facing PV module located at in Tucson (latitude 32.1°) at solar noon on March 1
- From Table 7.1, March 1 is day n = 60
- The solar declination δ is

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

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

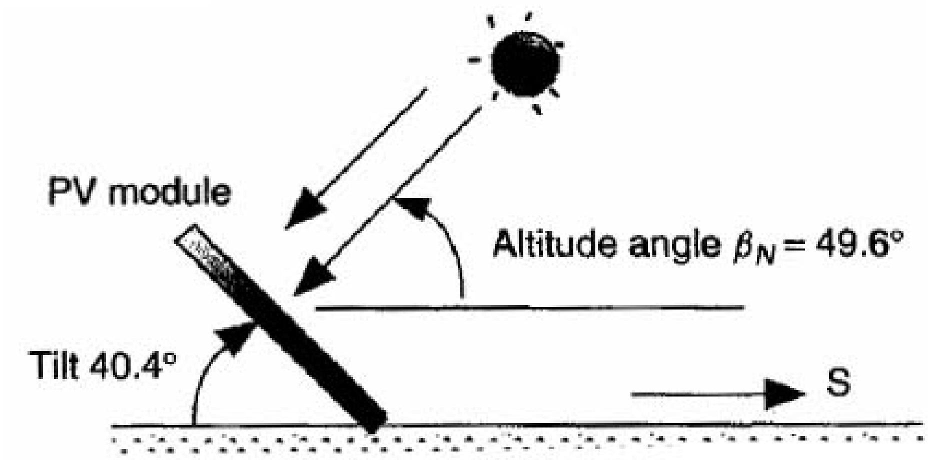
Example, Cont'd – Tilt of a Flat Plate Collector

- The altitude angle is

$$\beta_N = 90° - L + \delta \ = 90° - 32.1° - 8.3° = 49.6°$$

- To make the sun's rays perpendicular to the panel, we need to tilt the panel by

$$\text{tilt} = 90° - \beta_N \ = 40.4°$$



Exercise: Optimum Tilt of a Flat Plate Collector

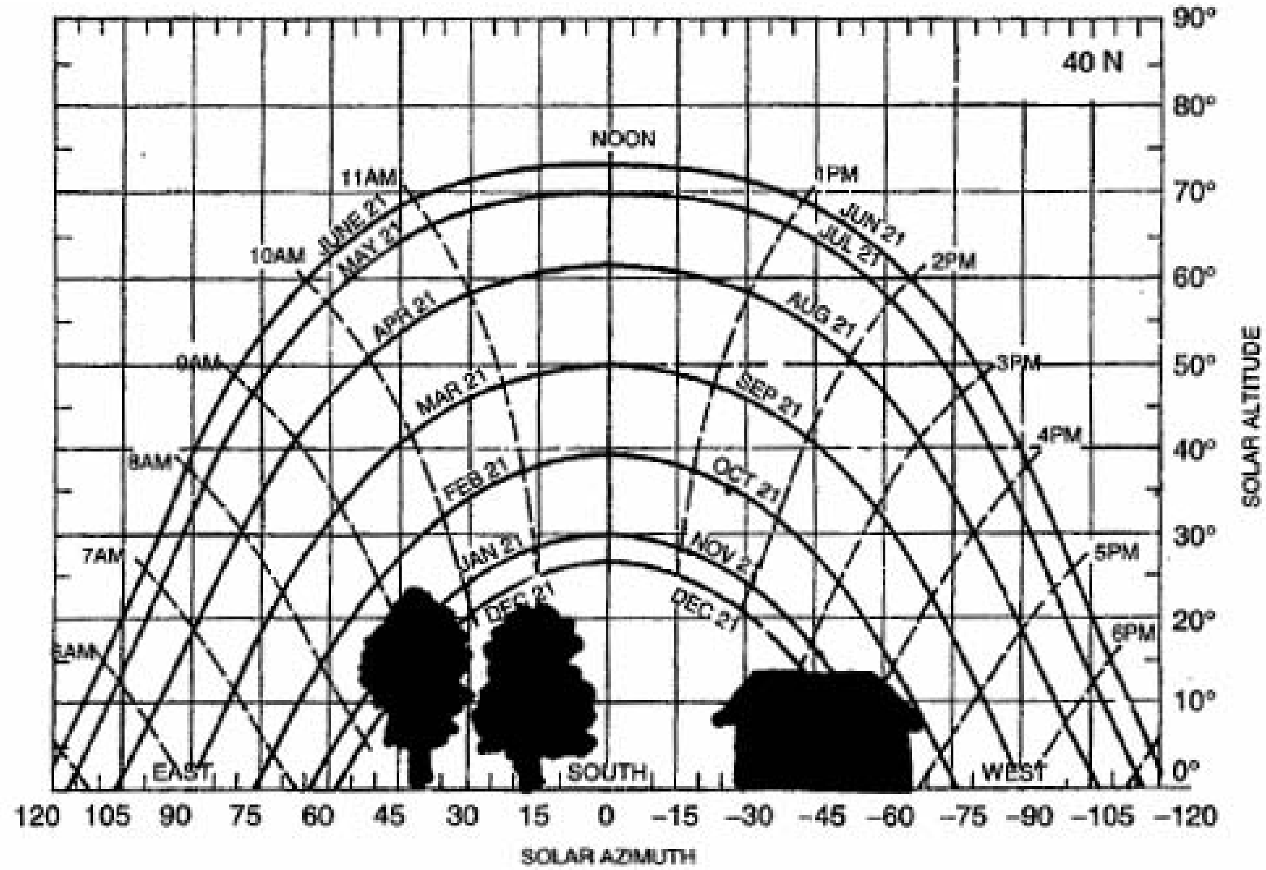
- Find the optimum tilt angle for a south-facing PV module located at your home town at solar noon on October 15 (day 288)

Sun Path Diagrams for Shading Analysis

- The knowing the location, day, and time, the position of the sun can be calculated.
- This can also help determine what sites will be in the shade at any time
- Sketch the azimuth and altitude angles of trees, buildings, and other obstructions
- Sections of the sun path diagram that are covered indicate times when the site will be in the shade

Sun Path Diagram for Shading Analysis

- Trees to the southeast, small building to the southwest
- Can estimate the amount of energy lost to shading



G.M. Masters, Renewable and Efficient Electric Power Systems, Wiley 2004

Shade Analysis Tools

- Suneye digital camera plus software analysis tools
- Solar Pathfinder hemispherical mirror

www.solmetric.com

www.solarpathfinder.com

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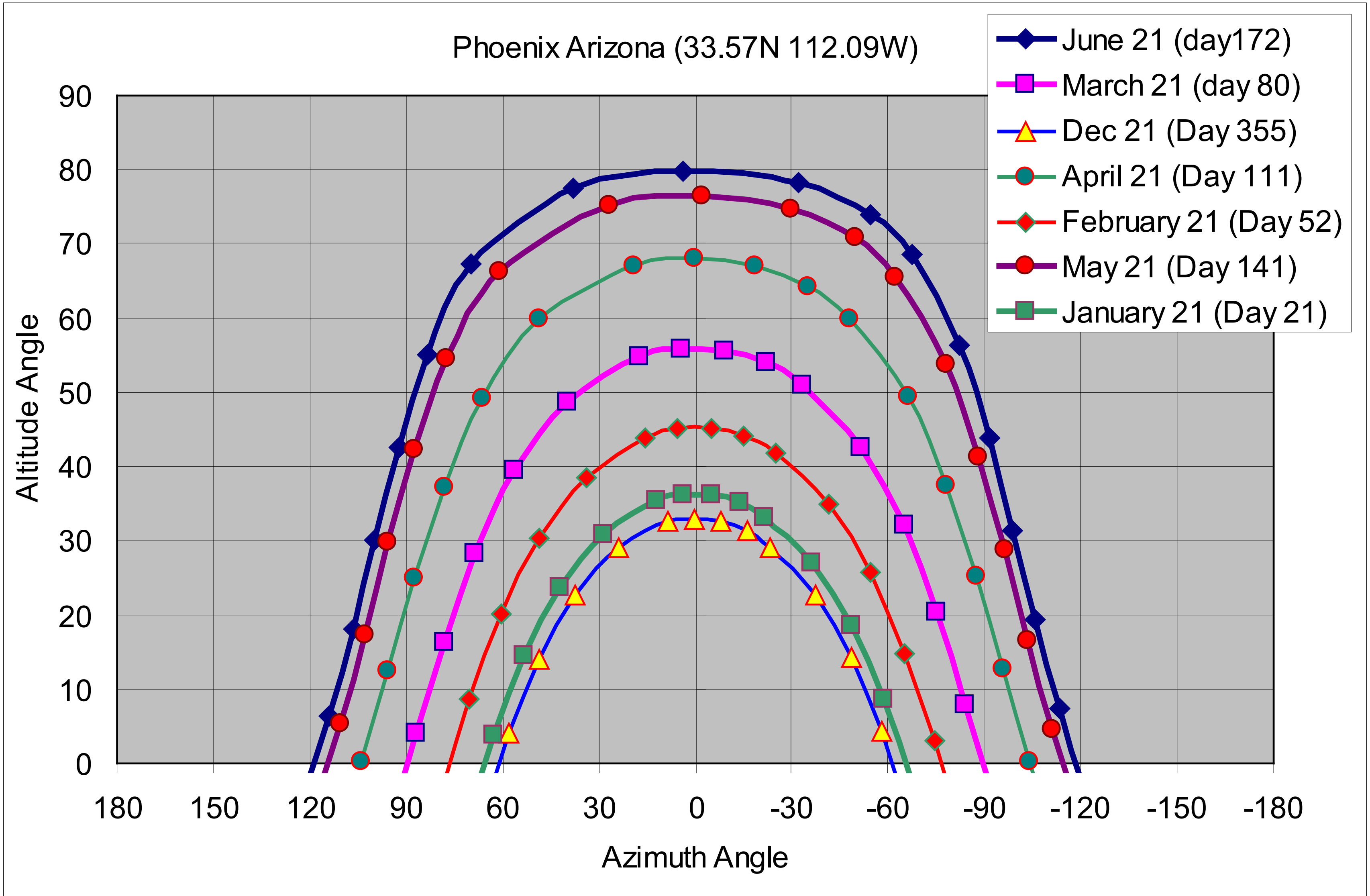
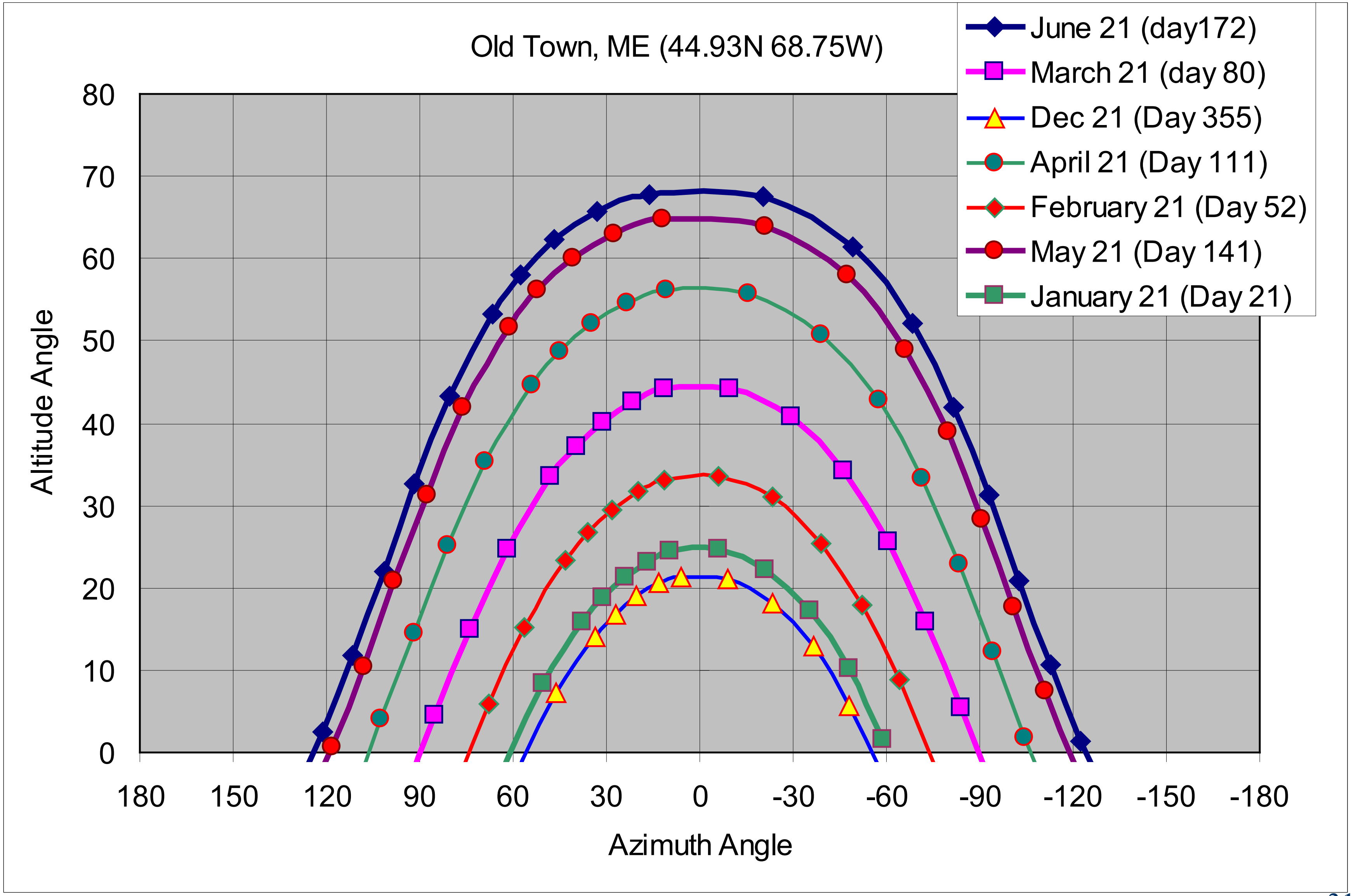
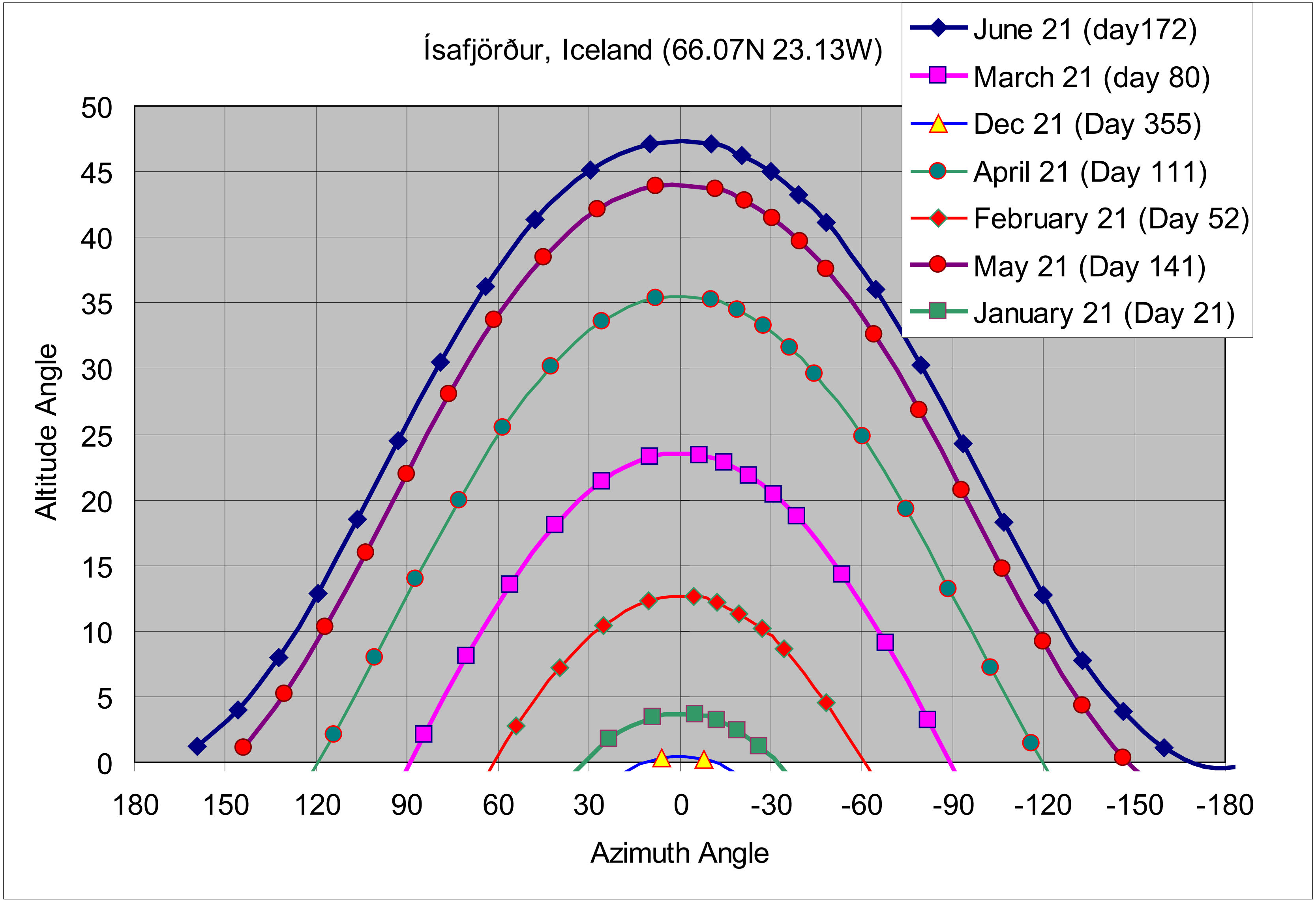
Sun Path Diagram: Phoenix AZ



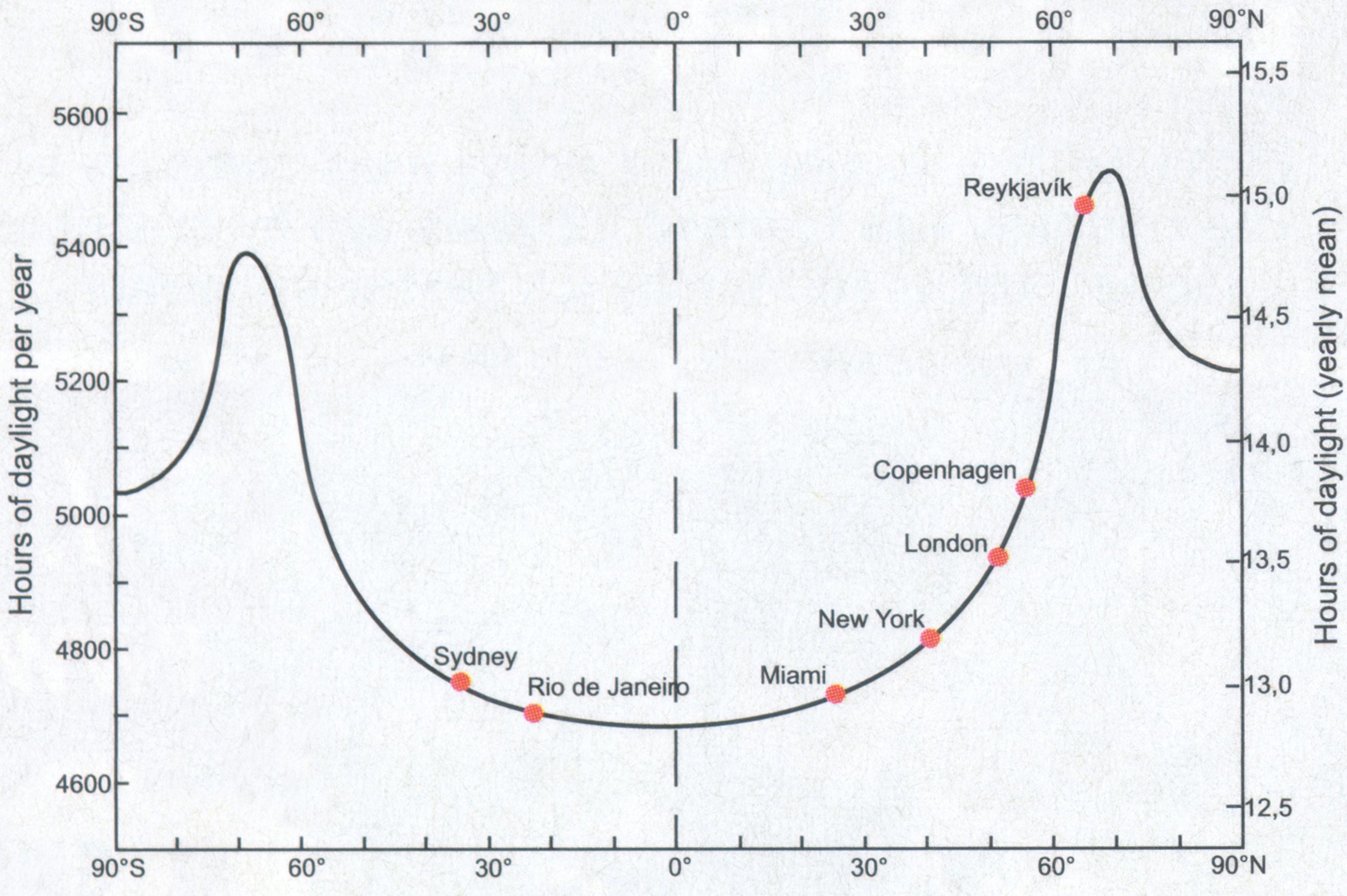
Sun Path Diagram: Old Town, ME



Sun Path Diagram: Ísafjörður, Iceland



Daylight by Latitude



Hours of daylight at different latitutes north and south

North of the Arctic Circle

- A Day in Northern Scandinavia . . .

Clear Sky Direct-Beam Radiation

- Direct beam radiation I_{BC} – passes in a straight line through the atmosphere to the receiver
- Diffuse radiation I_{DC} – scattered by molecules in the atmosphere
- Reflected radiation I_{RC} – bounced off a surface near the reflector

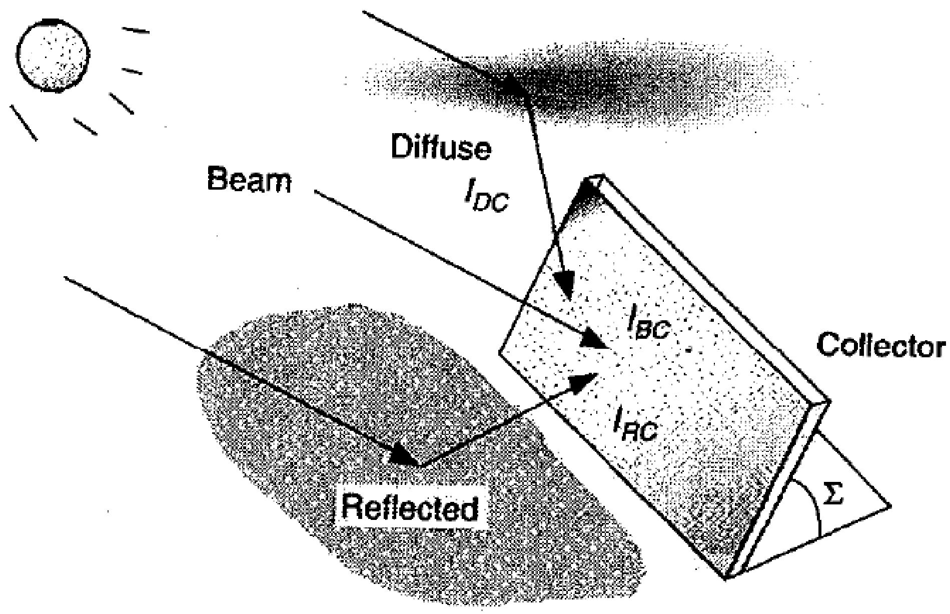
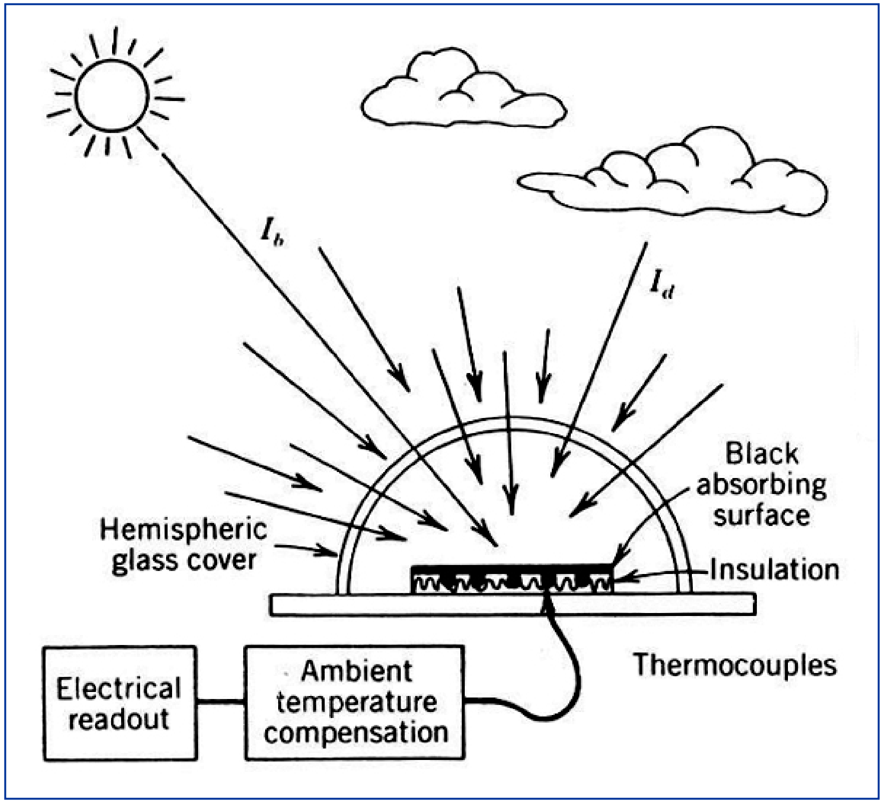


Figure 7.18

Measuring Solar Irradience

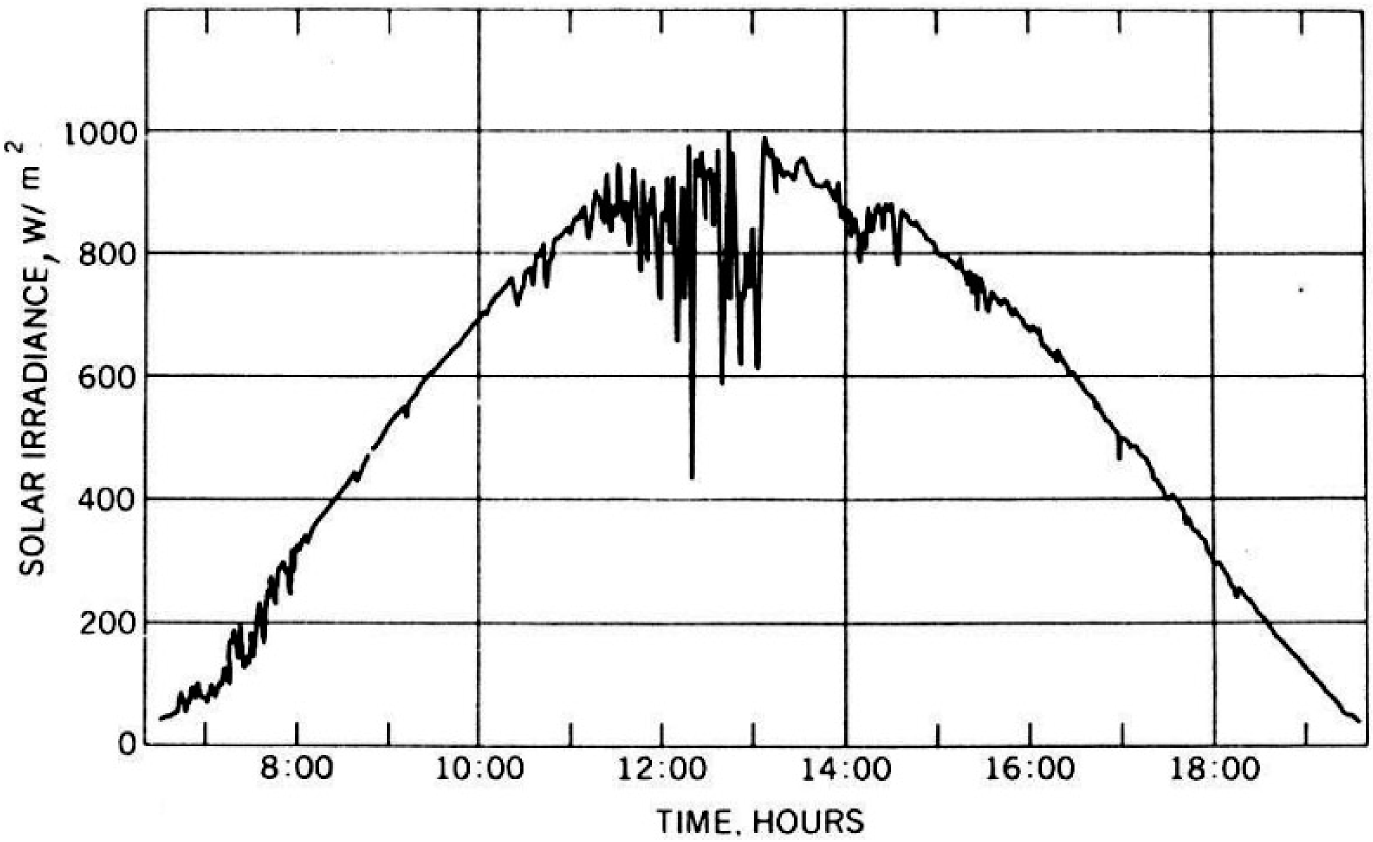
- Pyranometer
  - I_b = direct beam irradience
  - I_d= diffuse irradience



www.novalynx.com

Solar Irradience, Mostly Clear Day

- Greenbelt, MD, USA (39ºN, 77ºW)

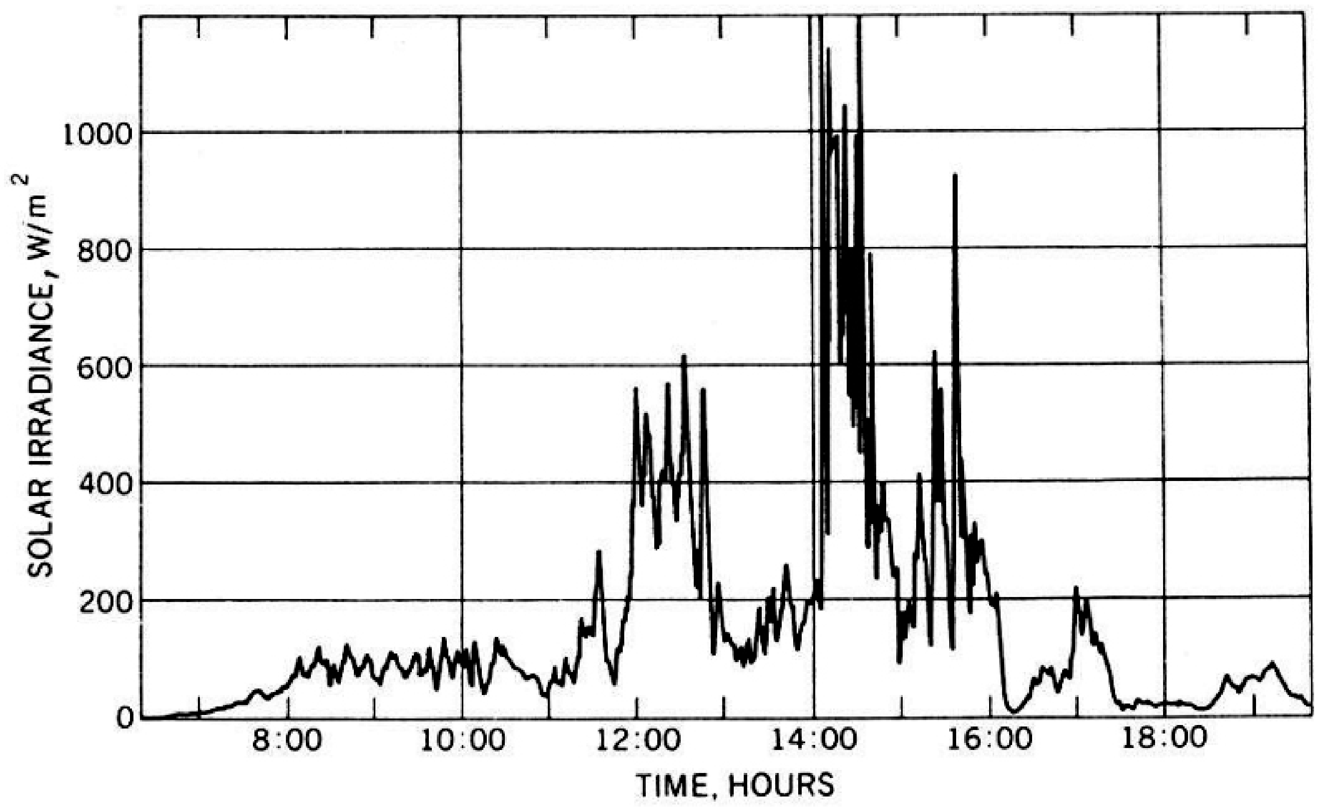


- Solar Insolation (area under curve) = 7.53 kWh/m²/day

www.powerfromthesun.net

Solar Irradience, Mostly Cloudy Day

- Greenbelt, MD, USA (39°N, 77°W)

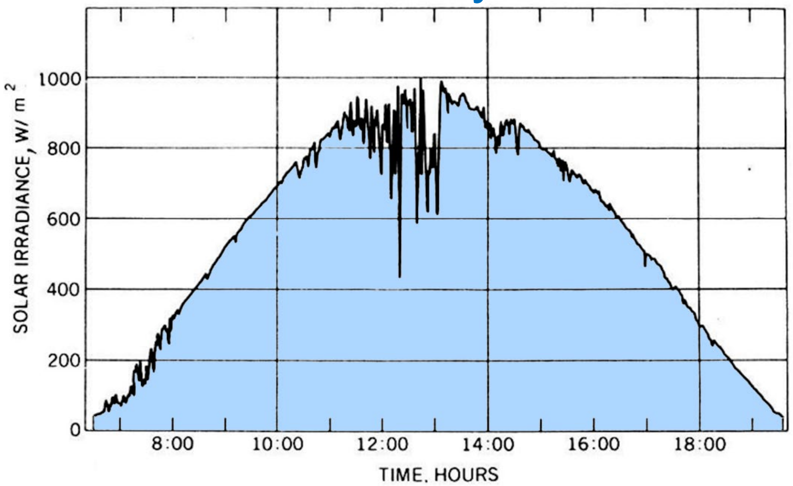


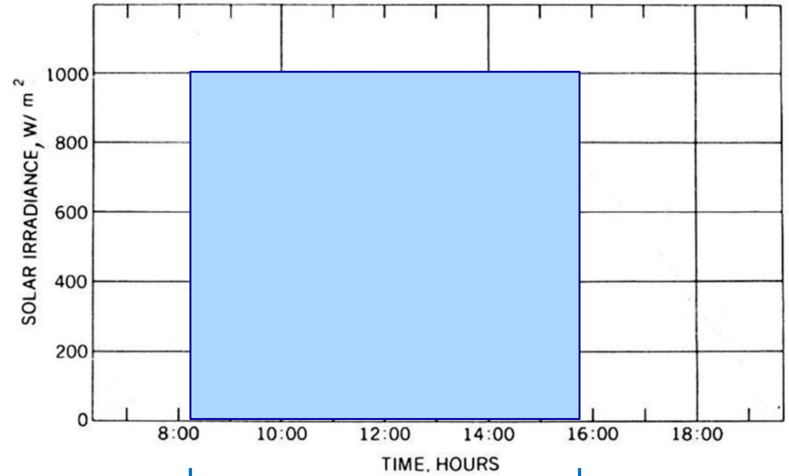
- Solar Insolation (area under curve) = 2.03 kWh/m^2/day

www.powerfromthesun.net

Solar Insolation and Irradience

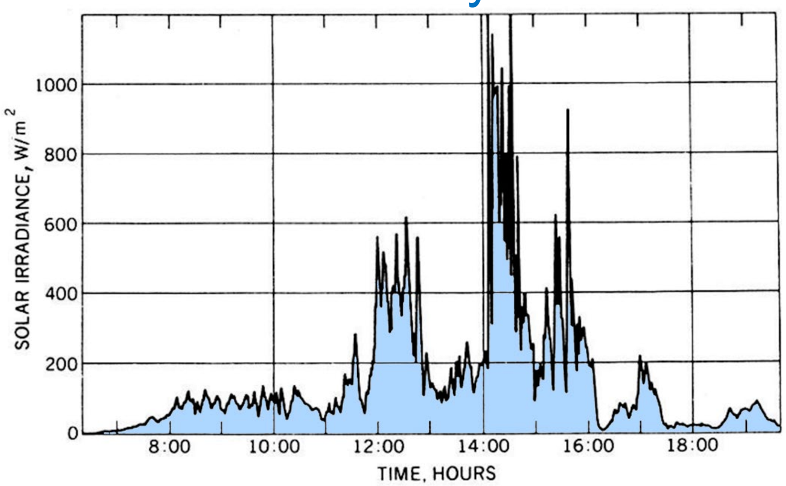
7.53 kWh/m^2/day

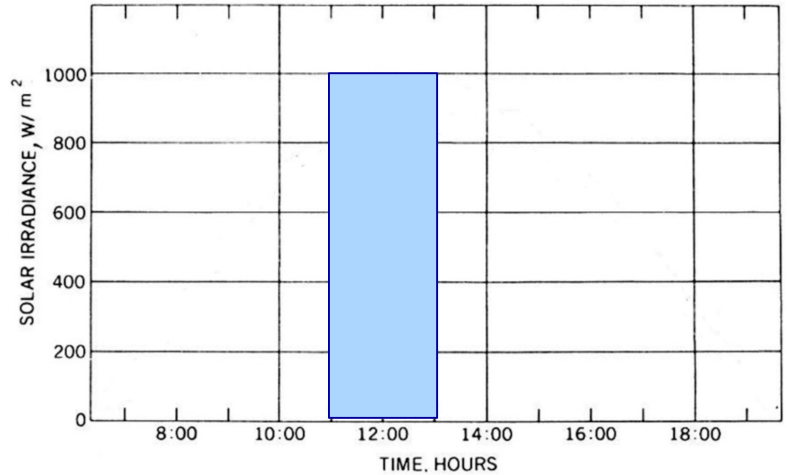




7.53 h

2.03 kWh/m^2/day





2.03 h

Solar Radiation and Data Manual for Flat Plate and Concentrating Solar Collectors: Phoenix AZ

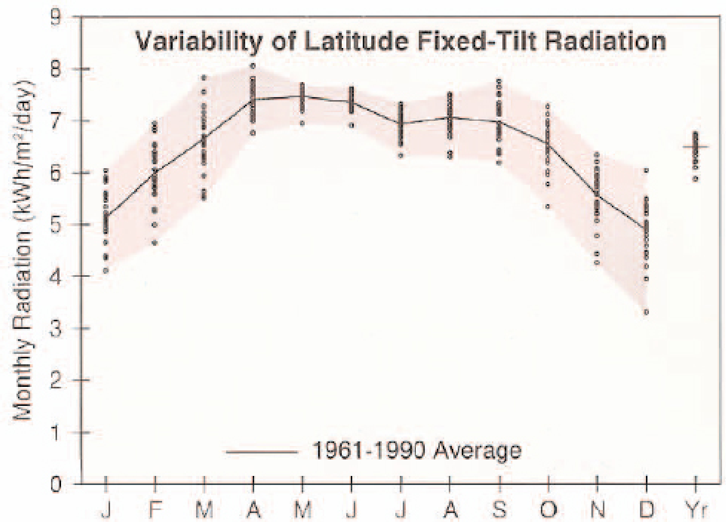
- http://rredc.nrel.gov/solar/pubs/redbook/

Phoenix, AZ

WBAN NO. 23183

LATITUDE: 33.43° N
LONGITUDE: 112.02° W
ELEVATION: 339 meters
MEAN PRESSURE: 974 millibars

STATION TYPE: Primary



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

Tilt (°)		Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
0	Average	3.2	4.3	5.5	7.1	8.0	8.4	7.6	7.1	6.1	4.9	3.6	3.0	5.7
	Min/Max	2.8/3.7	3.5/4.8	4.7/6.4	6.4/7.8	7.5/8.3	7.8/8.7	6.9/8.1	6.3/7.5	5.4/6.7	4.2/5.3	3.0/4.0	2.2/3.5	5.3/5.9
Latitude -15	Average	4.4	5.4	6.4	7.5	8.0	8.1	7.5	7.3	6.8	6.0	4.9	4.2	6.4
	Min/Max	3.6/5.1	4.3/6.2	5.3/7.4	6.8/8.2	7.4/8.2	7.6/8.4	6.8/8.0	6.5/7.8	6.1/7.6	5.0/6.6	3.8/5.5	2.9/5.1	5.8/6.6
Latitude	Average	5.1	6.0	6.7	7.4	7.5	7.3	6.9	7.1	7.0	6.5	5.6	4.9	6.5
	Min/Max	4.1/6.0	4.7/6.9	5.5/7.8	6.8/8.1	6.9/7.7	6.9/7.6	6.3/7.3	6.3/7.5	6.2/7.8	5.3/7.3	4.3/6.3	3.3/6.0	5.9/6.7
Latitude +15	Average	5.5	6.2	6.6	6.9	6.6	6.3	6.0	6.4	6.7	6.7	5.9	5.3	6.3
	Min/Max	4.4/6.6	4.8/7.3	5.4/7.8	6.2/7.5	6.1/6.8	5.9/6.5	5.5/6.3	5.7/6.8	5.9/7.5	5.4/7.4	4.4/6.8	3.5/6.7	5.6/6.5
90	Average	4.9	5.0	4.5	3.7	2.7	2.3	2.4	3.1	4.2	5.1	5.1	4.8	4.0
	Min/Max	3.8/5.9	3.8/5.9	3.7/5.3	3.3/3.9	2.6/2.8	2.1/2.4	2.2/2.5	2.8/3.3	3.7/4.6	4.1/5.7	3.7/6.0	3.1/6.2	3.5/4.2

Solar Radiation and Data Manual for Flat Plate and Concentrating Solar Collectors: Caribou, ME

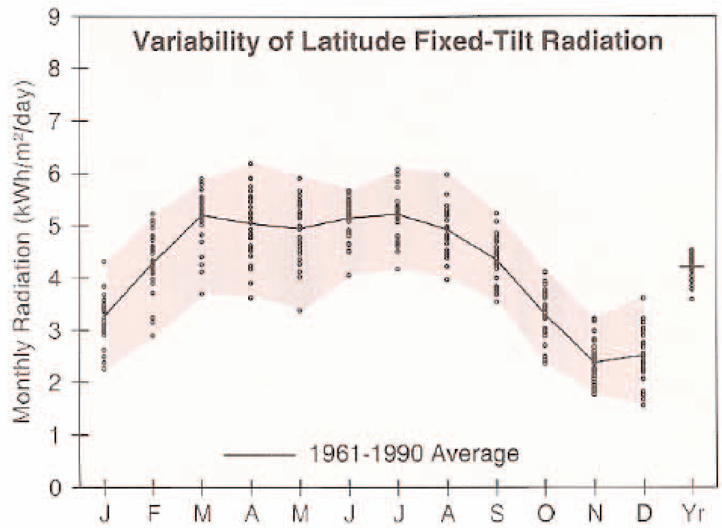
- http://rredc.nrel.gov/solar/pubs/redbook/

Caribou, ME

WBAN NO. 14607

LATITUDE: 46.87° N
LONGITUDE: 68.02° W
ELEVATION: 190 meters
MEAN PRESSURE: 991 millibars

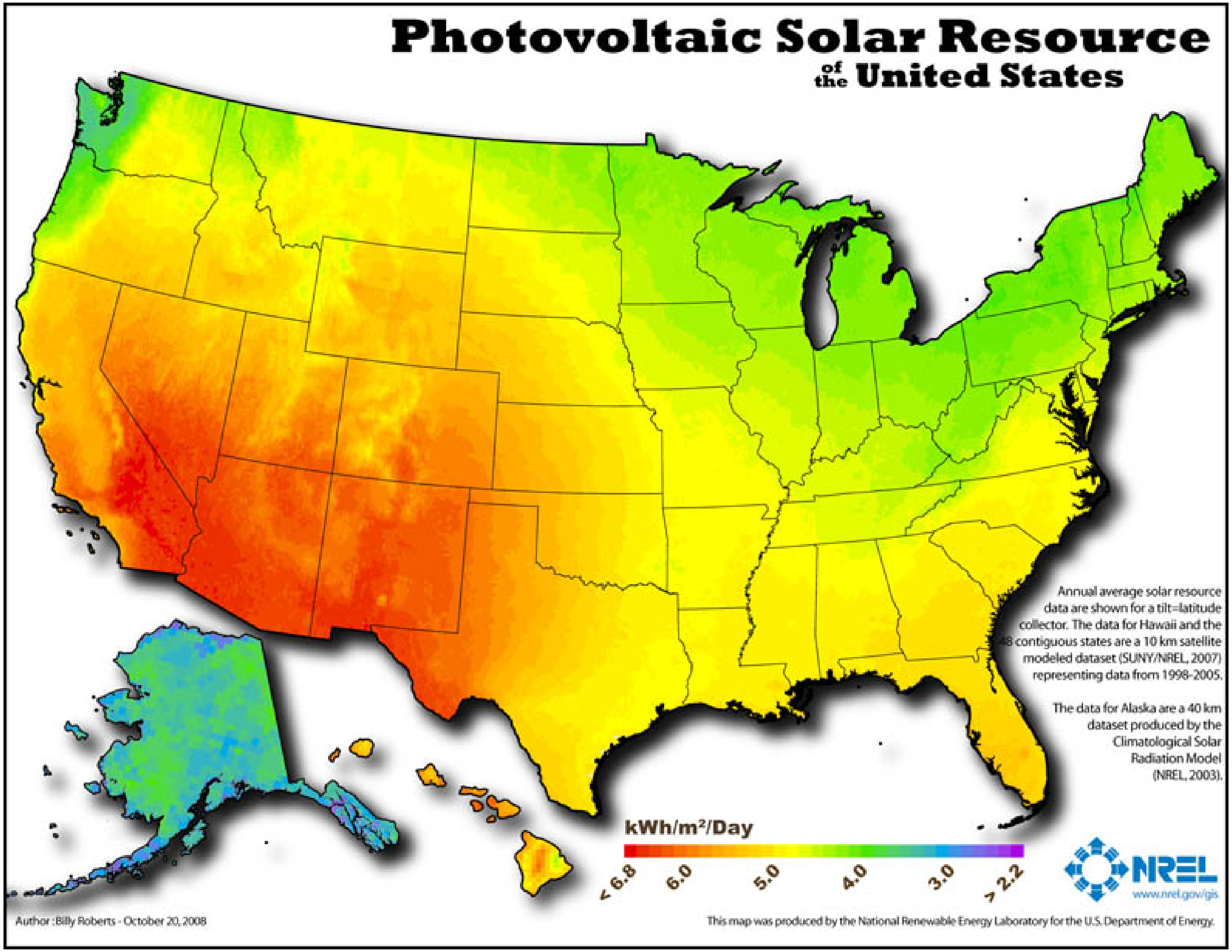
STATION TYPE: Primary



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

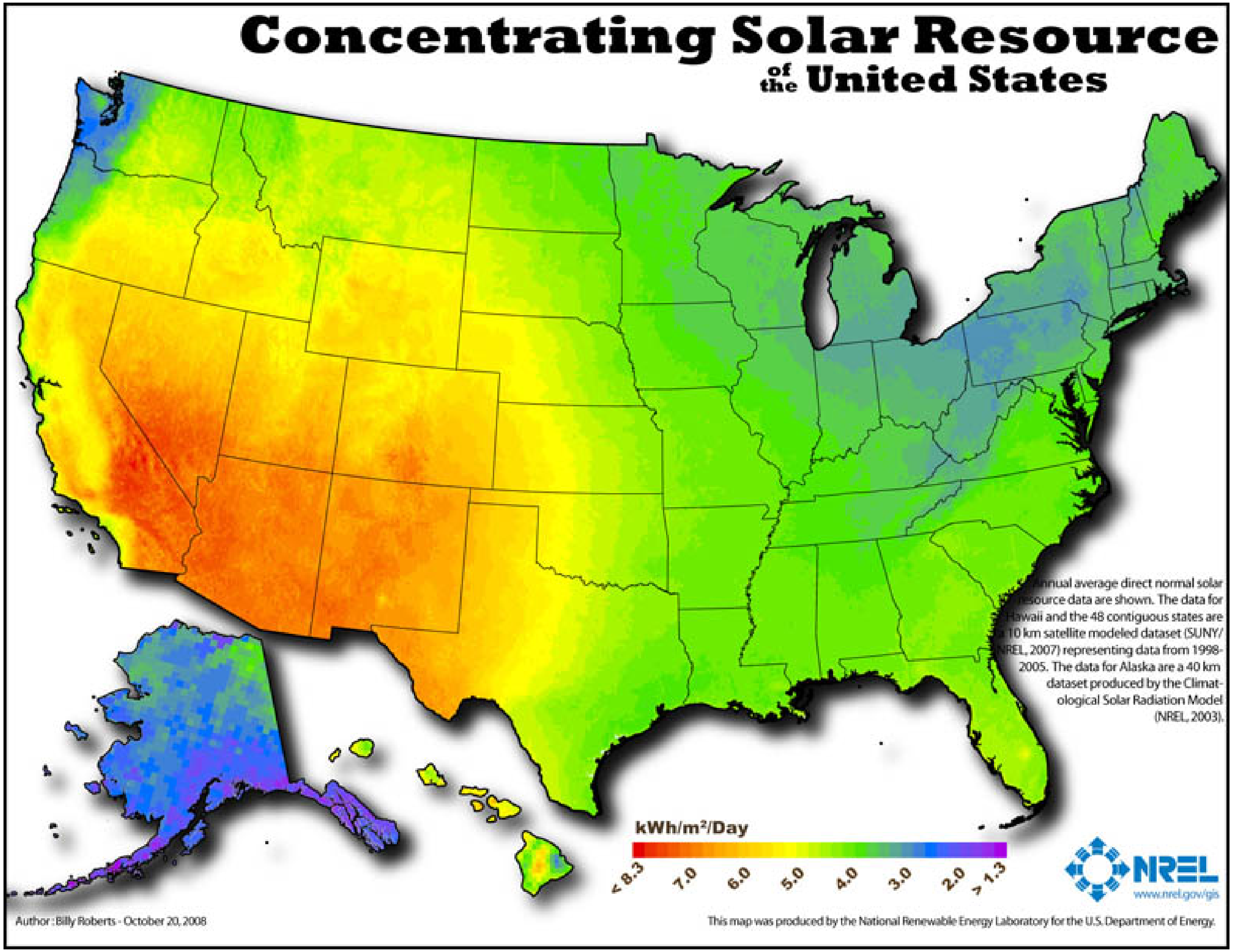
Tilt (°)		Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
0	Average	1.6	2.6	3.8	4.6	5.2	5.7	5.6	4.8	3.6	2.3	1.4	1.2	3.6
	Min/Max	1.3/1.8	1.9/2.9	3.0/4.3	3.5/5.4	3.6/6.2	4.7/6.4	4.6/6.5	4.0/5.7	3.1/4.2	1.8/2.7	1.1/1.7	0.9/1.5	3.1/3.7
Latitude -15	Average	2.9	3.9	5.0	5.1	5.3	5.6	5.6	5.2	4.3	3.1	2.2	2.2	4.2
	Min/Max	2.0/3.7	2.7/4.7	3.6/5.6	3.8/6.2	3.6/6.3	4.4/6.2	4.5/6.6	4.2/6.2	3.6/5.2	2.3/3.9	1.6/2.9	1.4/3.1	3.6/4.5
Latitude	Average	3.3	4.3	5.2	5.0	4.9	5.1	5.2	4.9	4.3	3.3	2.4	2.5	4.2
	Min/Max	2.3/4.3	2.9/5.2	3.7/5.9	3.6/6.2	3.4/5.9	4.1/5.7	4.2/6.1	4.0/6.0	3.5/5.2	2.4/4.1	1.8/3.2	1.6/3.6	3.6/4.5
Latitude +15	Average	3.5	4.5	5.2	4.7	4.4	4.5	4.6	4.5	4.1	3.3	2.5	2.7	4.0
	Min/Max	2.4/4.7	3.0/5.5	3.6/5.9	3.3/5.9	3.0/5.2	3.5/4.9	3.6/5.3	3.6/5.4	3.3/5.0	2.3/4.2	1.8/3.4	1.6/3.9	3.4/4.3
90	Average	3.4	4.2	4.6	3.7	2.9	2.8	2.9	3.0	3.2	2.8	2.3	2.7	3.2
	Min/Max	2.3/4.7	2.8/5.2	3.1/5.3	2.4/4.8	2.0/3.4	2.3/3.0	2.3/3.2	2.5/3.7	2.5/3.8	2.0/3.6	1.6/3.2	1.5/3.9	2.6/3.5

U.S. Solar Resource Maps: PV



www.nrel.gov/gis/solar.html

U.S. Solar Resource Maps: CSP



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Solar Insolation in USA, Spain, and Germany