Integrating the Solar Spectrum

PHYS 4400, Principles and Varieties of Solar Energy

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Pop Quiz

Note: quiz does not count toward grade…

Write down the approximate wavelengths associated with these colors:

1. Green
2. Blue-green
3. Yellow
4. Red
5. Orange
6. Deep blue
7. Ultraviolet
8. Near-infrared
9. Infrared

Comments on Quiz #1

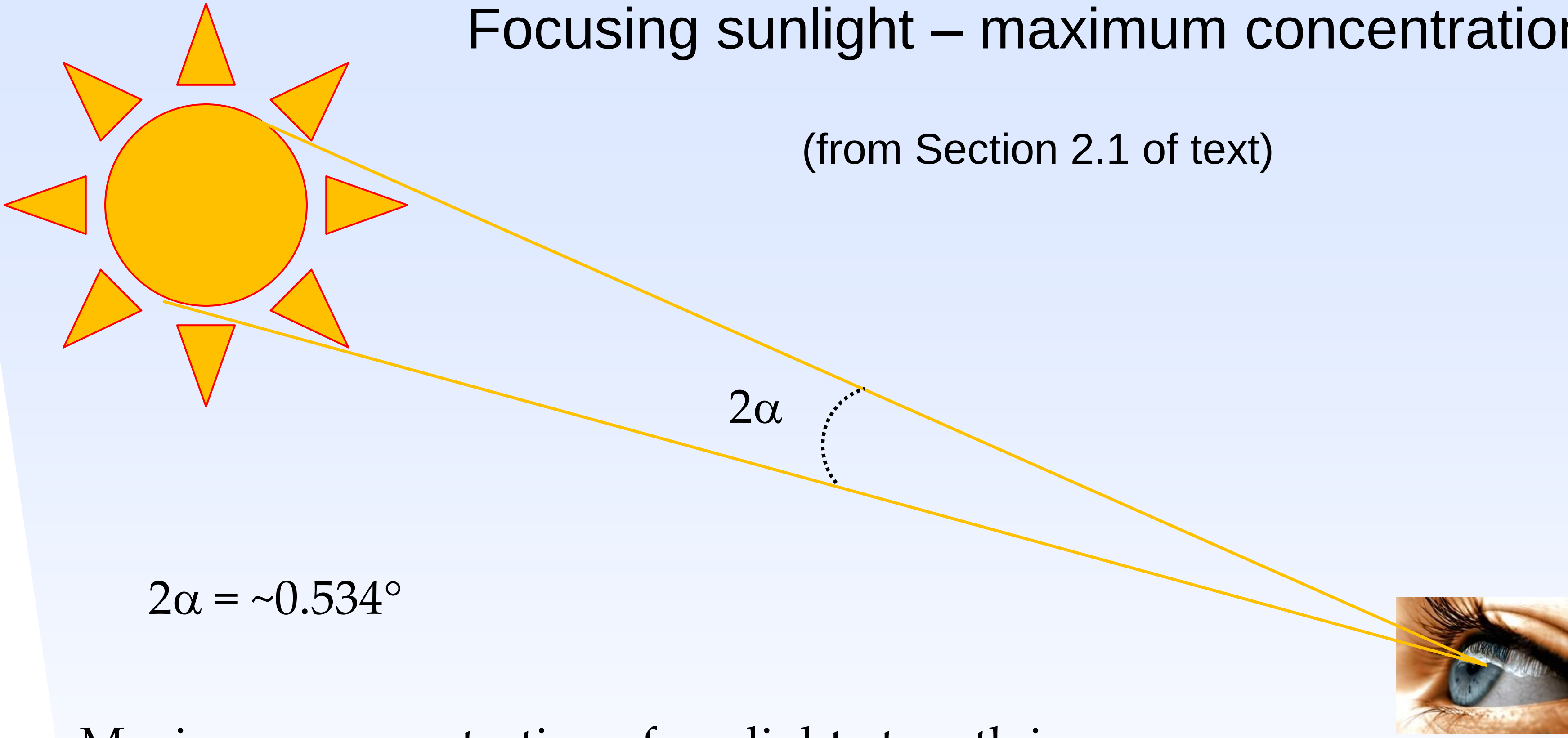
The quiz will cover topics covered up through the day before the quiz, including reading assignments, lectures, discussion, and homework. Expect ~ 15-20 True/false or multiple choice questions, and ~4-5 short answer problems.

Bring a calculator, pencil, and eraser for the quiz.

The quiz is closed book and closed notes.

Focusing sunlight – maximum concentration

(from Section 2.1 of text)



$2\alpha = \sim 0.534°$

Maximum concentration of sunlight at earth is approximated by $C_{max} = n^2 \cdot \sin^{-2}(\alpha)$ →

$C_{max} \cong 46{,}000$

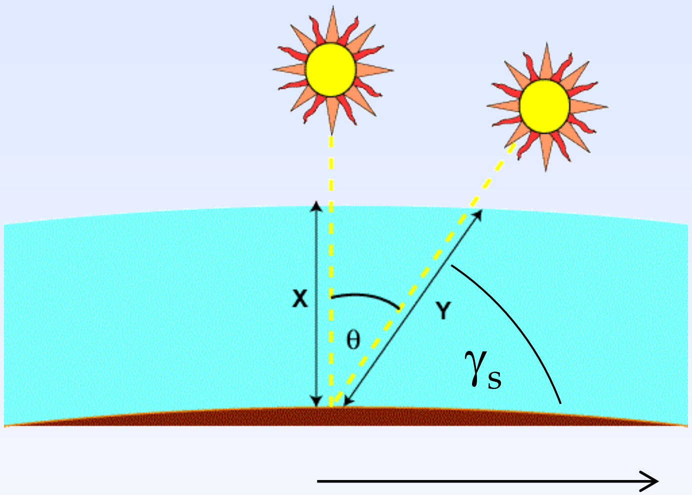
How do we calculate α ?

Air Mass – examples (Toledo, Ohio)

At 1 pm today (January 30), the sun will be at an elevation angle of γ_s = 30.5°.

$$AM = \frac{1}{\cos\theta}$$

$$AM = \csc(\gamma_s) = \frac{1}{\sin(\gamma_s)}$$



Therefore, on Jan. 30 at 1 pm, assuming clear weather: AM = 1.97.
How about June 21, at noon? In that case, γ_s = 70.3°, so that AM = 1.06.

What about the intensity (Direct, and Global) of the sunlight expected June 21?

$$I_D = 1353x0.7^{\left(AM^{0.678}\right)} = 933.6\ \mathrm{W\cdot m^{-2}}$$

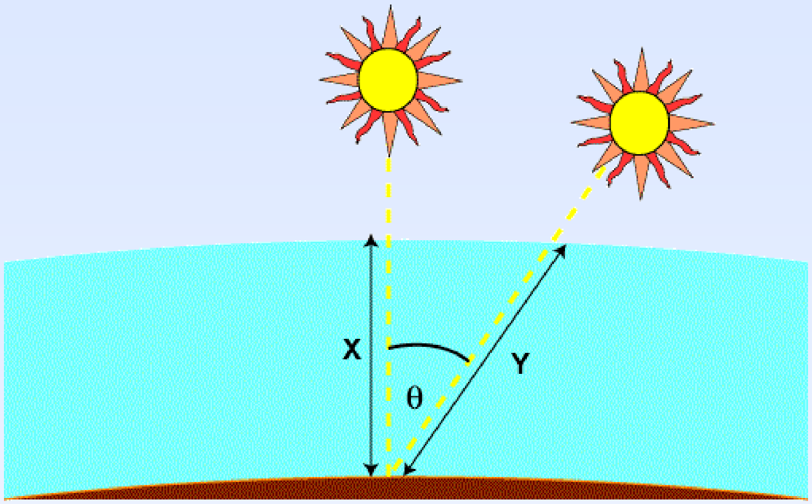
$$I_G = 1.1xI_D = 1{,}027\ \mathrm{W\cdot m^{-2}}$$

→ 1,022 W/m² on June 21

www.pveducation.org,
en.wikipedia.org/wiki/Air_mass_(solar_energy)
http://www.esrl.noaa.gov/gmd/grad/neubrew/SolarCalc.jsp

Air Mass (continued)

$$AM = \frac{1}{\cos\theta}$$



AM ≠ ∞ when θ = 90°

$$AM = \frac{1}{\cos\theta + 0.5057(96.07995 - \theta)^{-1.6364}}$$

In-class exercises:

- Calculate the intensity of sunlight in Toledo for January 29 at 1:00 pm using AM = 1.97.
- Calculate intensity again using the AM as calculated by the equation accounting for Earth's curvature.

Air Mass (continued)

In-class exercise:

- Calculate the intensity of sunlight for AM1.5.

$$AM = \frac{1}{\cos\theta + 0.5057(96.07995 - \theta)^{-1.6364}}$$

Solar intensity vs zenith angle z and airmass coefficient AM

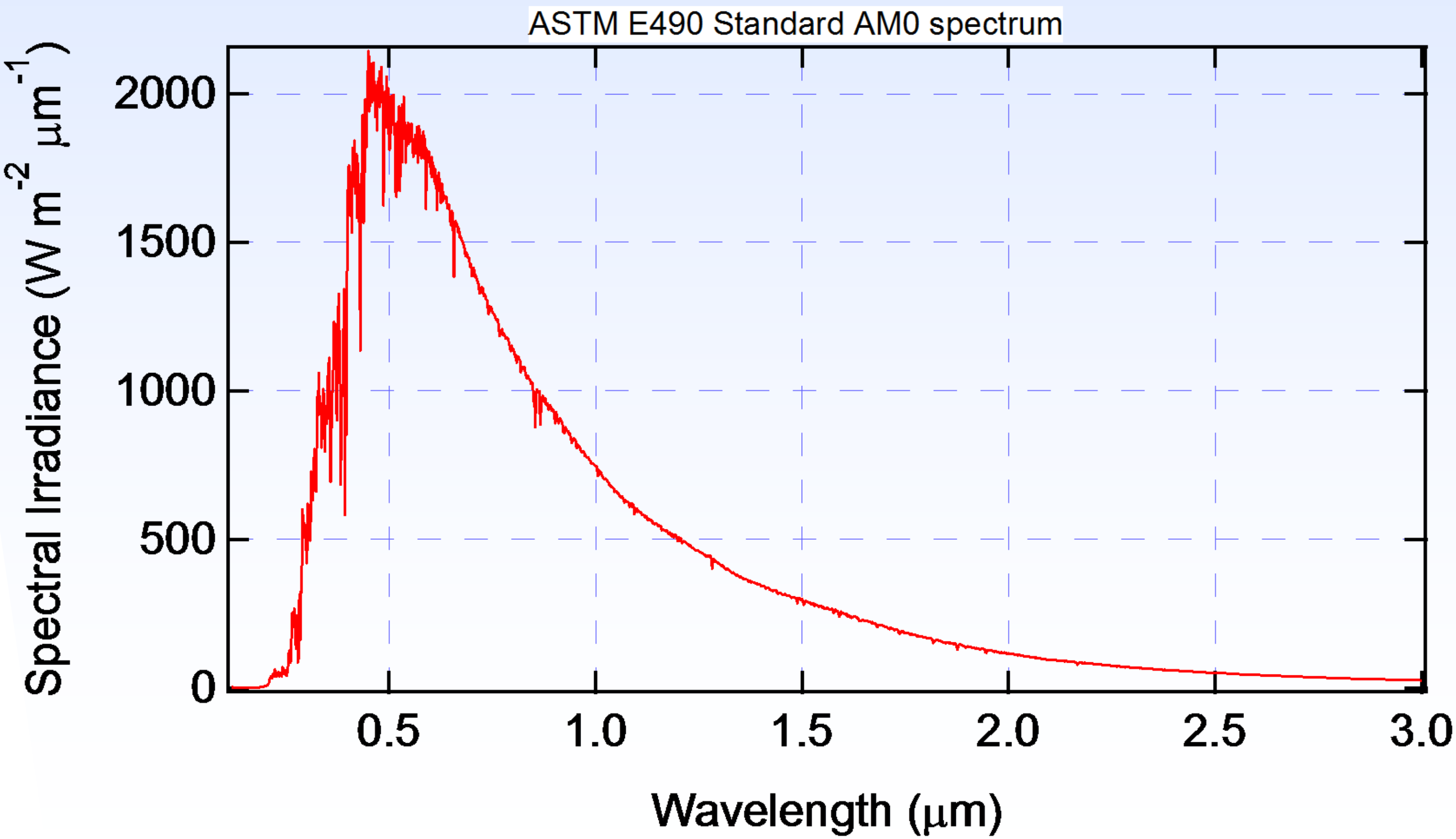
z	AM	range due to pollution[12]	formula (I.1)	ASTM G-173[11]
degree		W/m^2	W/m^2	W/m^2
-	0	1367[15]	1353	1347.9[16]
0°	1	840 .. 1130 = 990 ± 15%	1040	
23°	1.09	800 .. 1110 = 960 ± 16%[17]	1020	
30°	1.15	780 .. 1100 = 940 ± 17%	1010	
45°	1.41	710 .. 1060 = 880 ± 20%[17]	950	
48.2°	1.5	680 .. 1050 = 870 ± 21%[17]	930	1000.4[18]
60°	2	560 .. 970 = 770 ± 27%	840	
70°	2.9	430 .. 880 = 650 ± 34%[17]	710	
75°	3.8	330 .. 800 = 560 ± 41%[17]	620	
80°	5.6	200 .. 660 = 430 ± 53%	470	
85°	10	85 .. 480 = 280 ± 70%	270	
90°	38		20	

This illustrates that significant power is available at only a few degrees above the horizon.

AM0: the spectrum above Earth's atmosphere

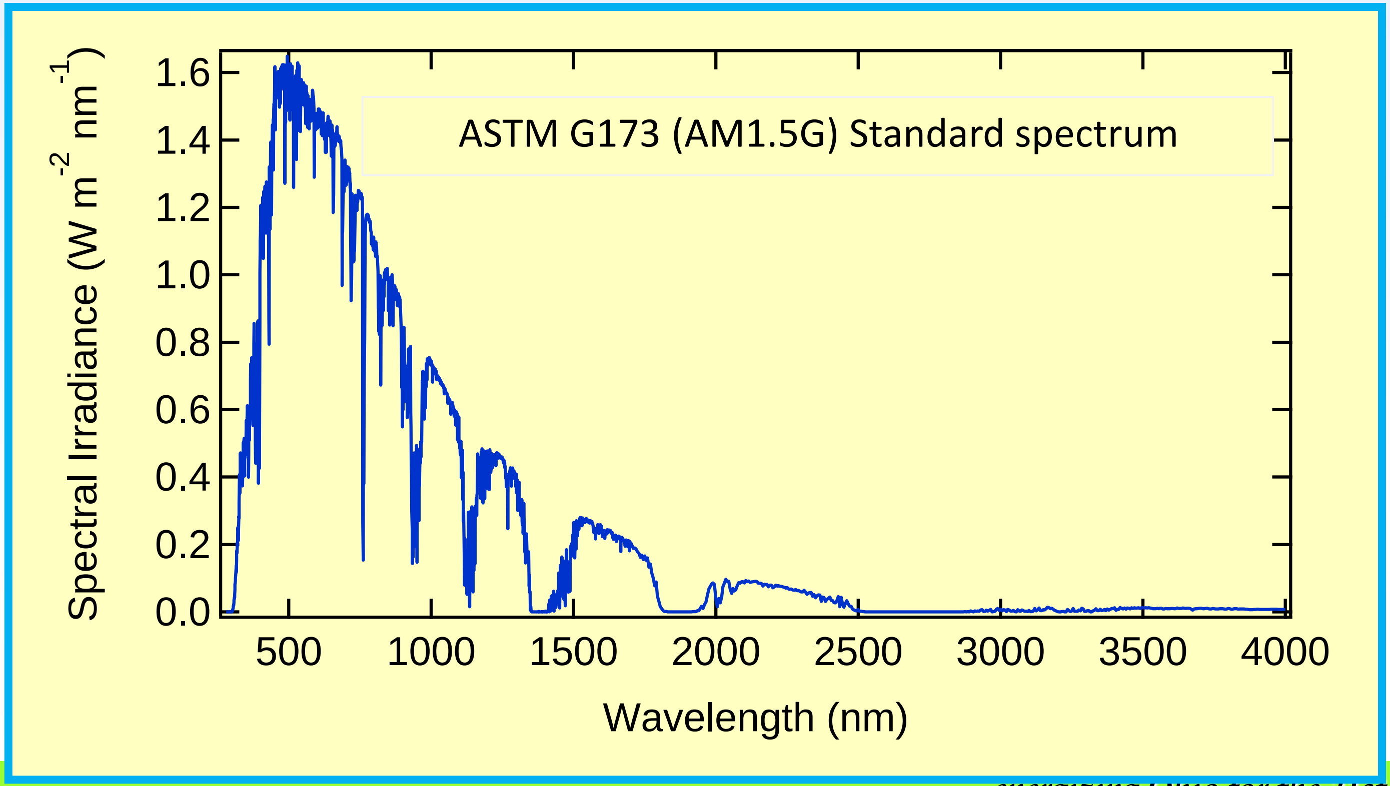
The AM0 spectrum applies to satellites and high-flying aircraft, which access the spectrum prior to any influence from Earth's atmosphere.

Integrated spectral irradiance = 1366 W/m^2.



AM1.5G: reference spectrum including direct and diffuse sunlight

- AM 1.5: From the equation provided for Air Mass, one calculates that cos θ = 0.667, so that θ = 48.2°. This represents the zenith angle, that it, the angle relative to the direction normal to Earth's surface.
- From the standard: "The receiving surface is defined in the standards as an inclined plane at 37 ° tilt toward the equator, facing the sun (i.e., the surface normal points to the sun, at an elevation of 41.81° above the horizon)." Note that 41.8° is the complement of 48.2°.
- Toledo latitude: 41.6639 ° N
- Integrating the energy within AM1.5G (ASTM G-173) yields 1000 W m^{-2}.



Standard Solar Reference Spectra

Where do these spectra come from (where can we get them)?

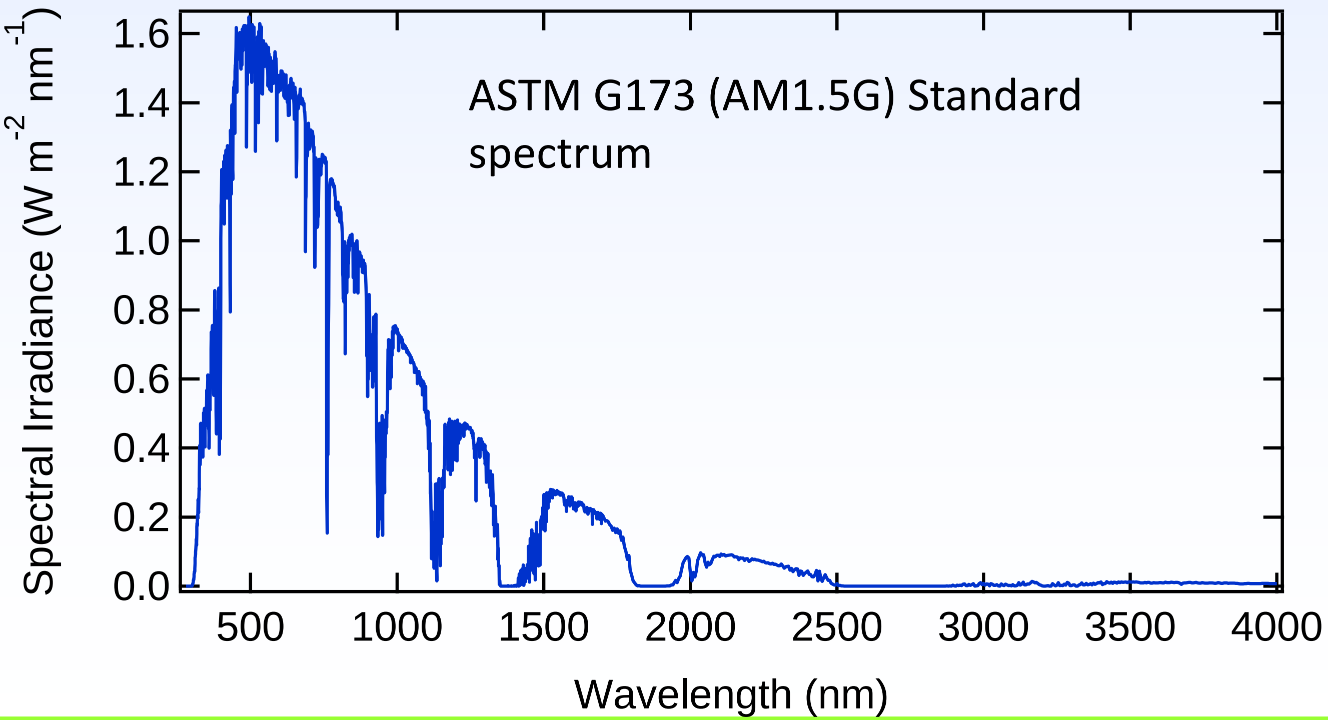
Start here: http://rredc.nrel.gov/solar/spectra/

The spectra most often referenced are the AM1.5G (technically referred to as the **ASTM G-173**) and the AM0 (technically known as the **ASTM E-490**).

What's in a square meter area of sunlight?

Assuming that the receiving area is normal to the incoming sunlight:

- Power, which when integrated with respect to time sums up to Energy. For example, 1,366 W/m^2 of sunlight, integrated for 1 hour, gives (1366 W/m^2)*(1 hr)*(3600 s/hr)*(1 J/s per W) = 4.92 x 10^6 J/m^2.
- Photons. A very large number of photons per second (as we will find). As a look ahead, each photon with energy above a semiconductor's bandgap can be absorbed, boosting an electron from the valence band to the conduction band and contributing an electron to the *photocurrent* of the PV cell.



Why does it matter what's in a square meter area of sunlight?

Photovoltaic solar cells respond differently depending on the energy of the incident photons.

Each photon absorbed within a PV cell generates one electron which can be collected as photocurrent.

Only those photons with energy greater than the bandgap energy of the semiconductor are absorbed; a semiconductor is typically transparent to photons of energy lower than the band gap energy.

http://pveducation.org/pvcdrom/pn-junction/band-gap

http://pveducation.org/pvcdrom/pn-junction/absorption-of-light

In-class exercises: integration of the solar spectra

How can we add up the power contained within the AM0 or AM1.5G spectra? *Answer: add up the values for the spectral irradiance – but we must do so carefully.*

If we have values for the Spectral Irradiance with each data point corresponding to a 1 nm spectral width (e.g., from 500 nm to 501 nm), the problem is simpler. However, upon examining the data contained in either of these spectra:

http://rredc.nrel.gov/solar/spectra/am0/E490_00a_AM0.xls

http://rredc.nrel.gov/solar/spectra/am1.5/ASTMG173/ASTMG173.xls

we find that the wavelength values start at 0.5 nm spacing, then move the 1 nm spacing, and ultimately go to 5 nm or larger spacing between points.

To properly integrate the spectrum, we can either break up the data into regions depending on the wavelength increment between data points, <u>or</u> we can interpolate the data to “fix it so that it is spaced by 1 nm for all wavelength regions.

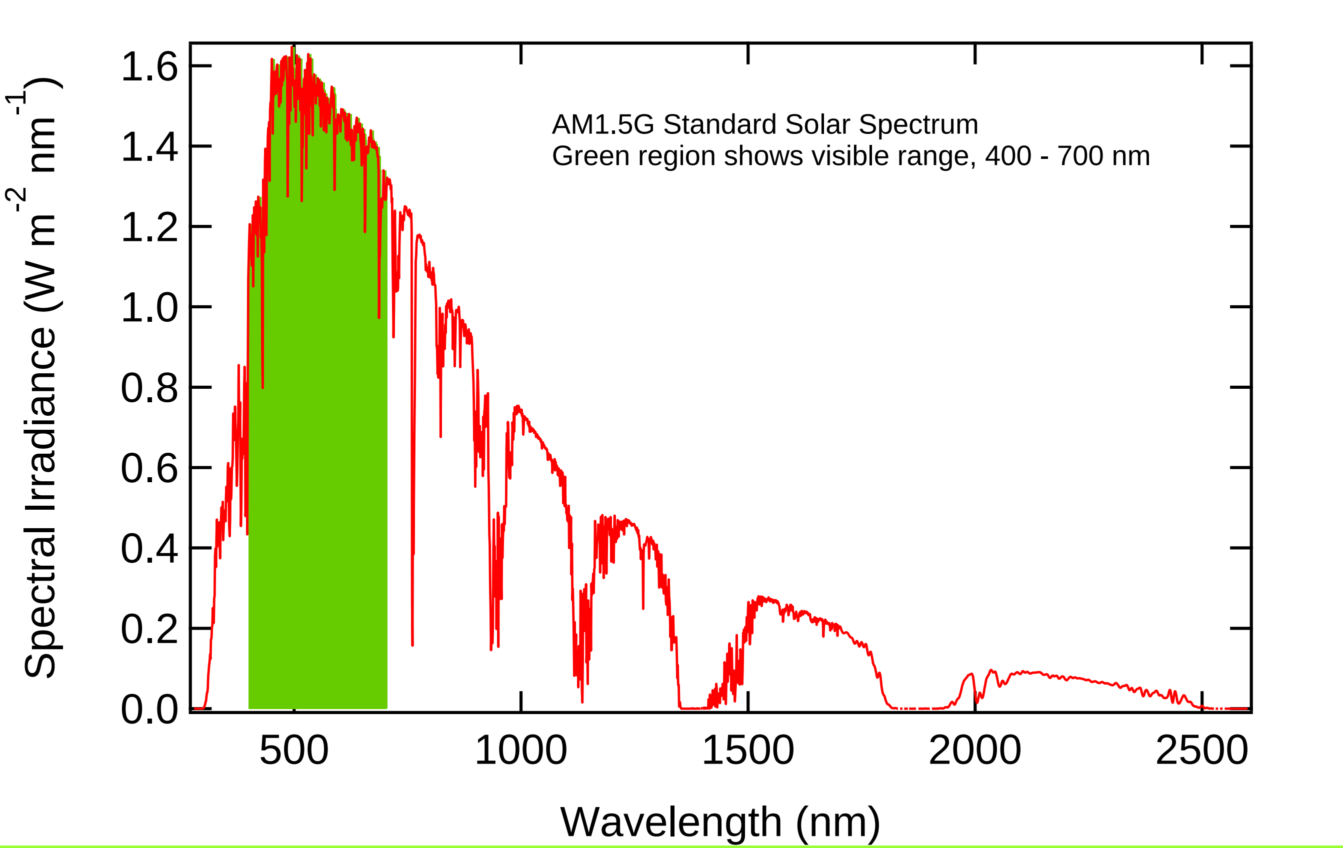
Let’s interpolate, after which we can simply add up the values, effectively multiplying each value by the 1 nm of spectral bandwidth to which it applies…

The interpolated data for AM0 and AM1.5G is provided on the course web site:

http://astro1.panet.utoledo.edu/~relling2/teach/4400.2014/spring2014_phys4400.html

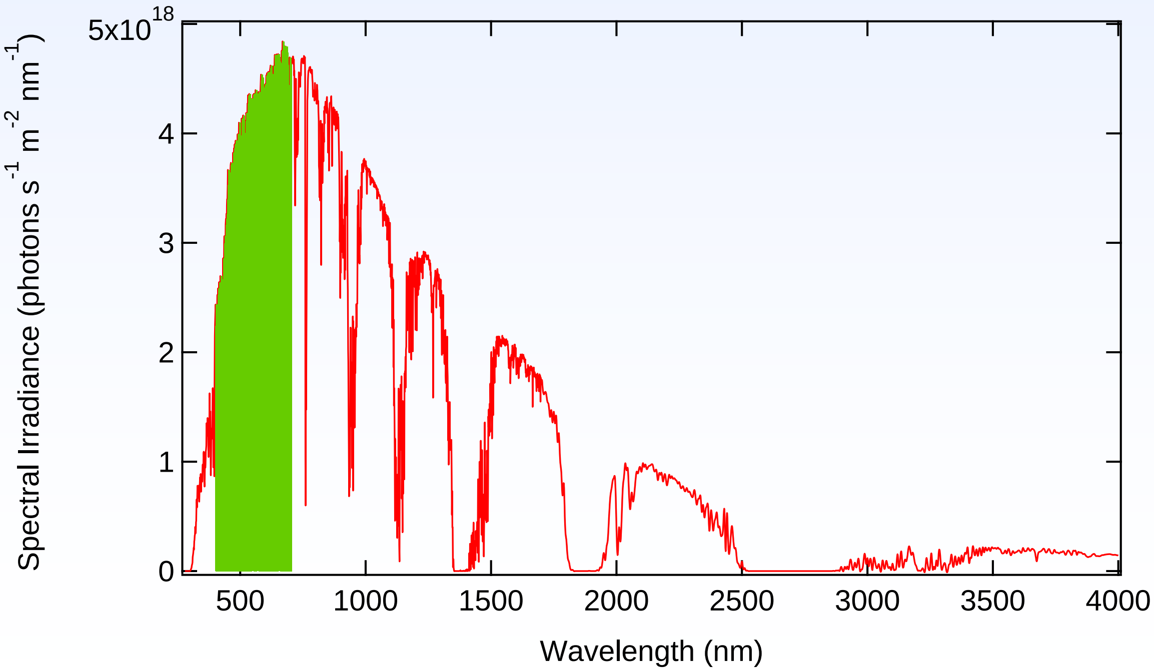
In-class exercise: integration of the AM1.5G solar spectrum

- How much power per unit area is contained within the AM1.5 spectrum? *This is much more easily answered using the interpolated spectra – summing from 400 nm to 700 nm yields 431.03 W m^{-2}.*
- What fraction of the total power of the AM1.5G spectrum falls within the visible range (400-700 nm)? *Summing the AM1.5G over the full range from 280 to 4000 nm gives 1000.36 W m^{-2}, so the fraction of power contained in the "visible" = 43.1 %.*

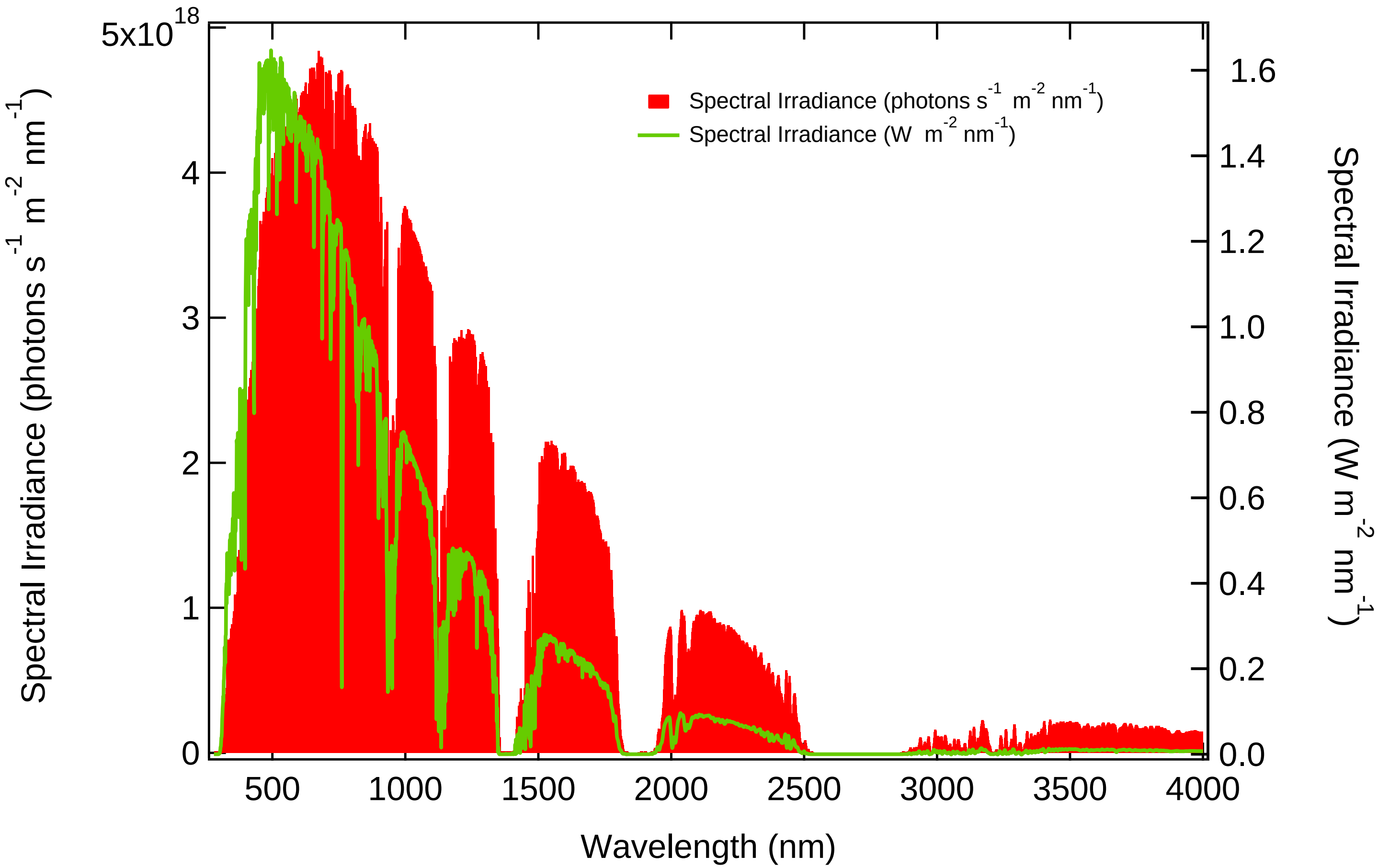


In-class exercises: integration of the solar spectra

- Conversion of spectral irradiance from (W m^{-2} nm^{-1}) to (photons s^{-1} m^{-2} nm^{-1}) is required to calculate photon flux within solar spectra.
- Accomplished by dividing the (W m^{-2} nm^{-1}) values by the photon energy, to convert W to photons/second…
- How many photons per second per unit area are incident within the visible portion of the AM1.5G spectrum? *For 400 nm to 700 nm range, we calculated 1.19 x 10^{21} photons s^{-1} m^{-2}.*
- What fraction of the total AM1.5G photons (from 280 to 4000 nm) lie in this visible range? W*e calculate a total irradiance of 4.30 x 10^{21} photons s^{-1} m^{-2}, so the fraction in the visible is 1.19/4.30 = 27.7 %.*



Comparing shape of spectra, W vs. photons/s



- What's going on here?