Remote Sensing Fundamentals
Part I:
Radiation and the Planck Function

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We all are “remote sensors”

- Ears
- Eyes
- Brain

Human Optical Detection System

- continuous wave 10 ^26 Watts
- Matched to wavelength 0.5 um
- Sensitivity ~10 photons
- Servo-controlled (angle and aperture)
- 2d array ~ 10^5 elements
- Stereo and color
- Parallel connected to adaptive computer
- Detector weight ~20 g
- “Computer” weight ~1 kg

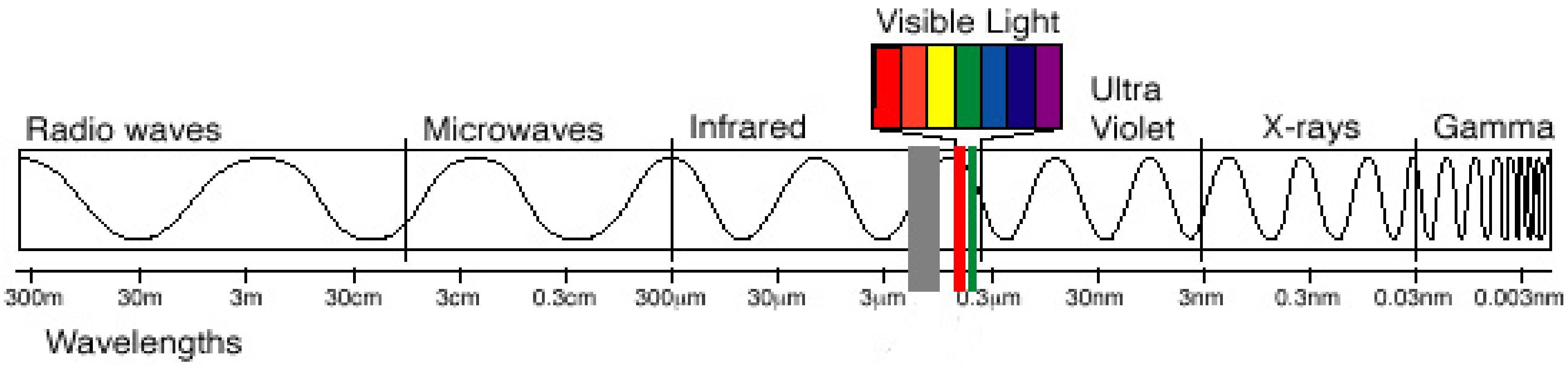
Adapted from T. S Moss, Infrared Phys., 16, 29 1976

All satellite remote sensing systems involve the measurement of electromagnetic radiation.

Electromagnetic radiation has the properties of both waves and discrete particles, although the two are never manifest simultaneously.

Electromagnetic radiation is usually quantified according to its wave-like properties; for many applications it considered to be a continuous train of sinusoidal shapes.

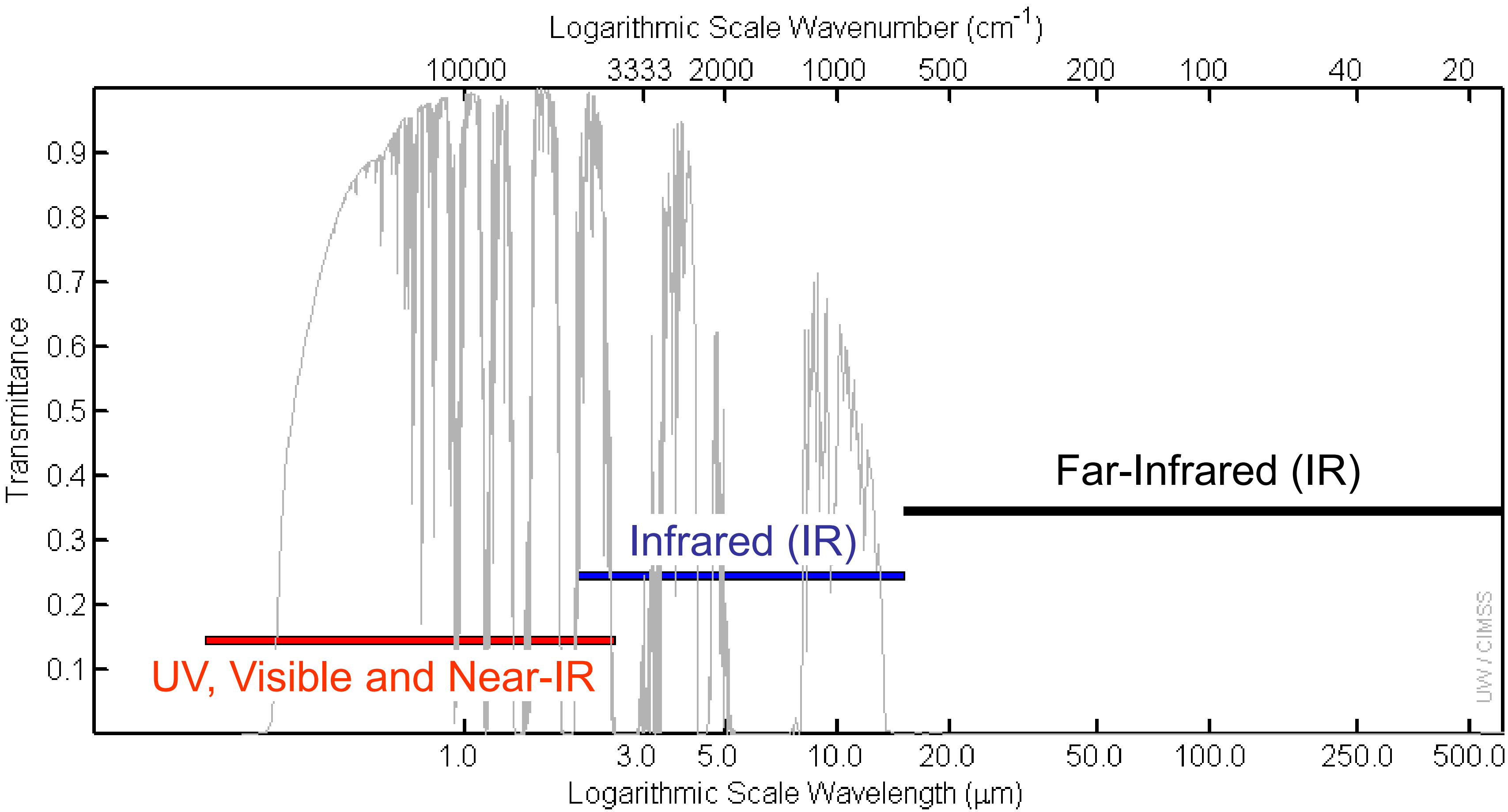
The Electromagnetic Spectrum



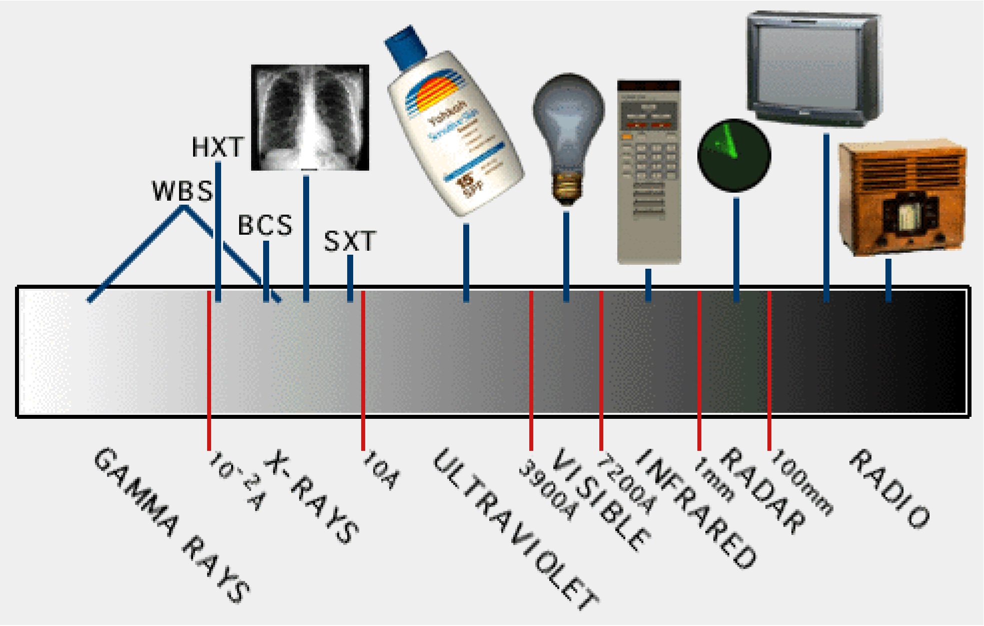
Remote sensing uses radiant energy that is reflected and emitted from Earth at various "wavelengths" of the electromagnetic spectrum

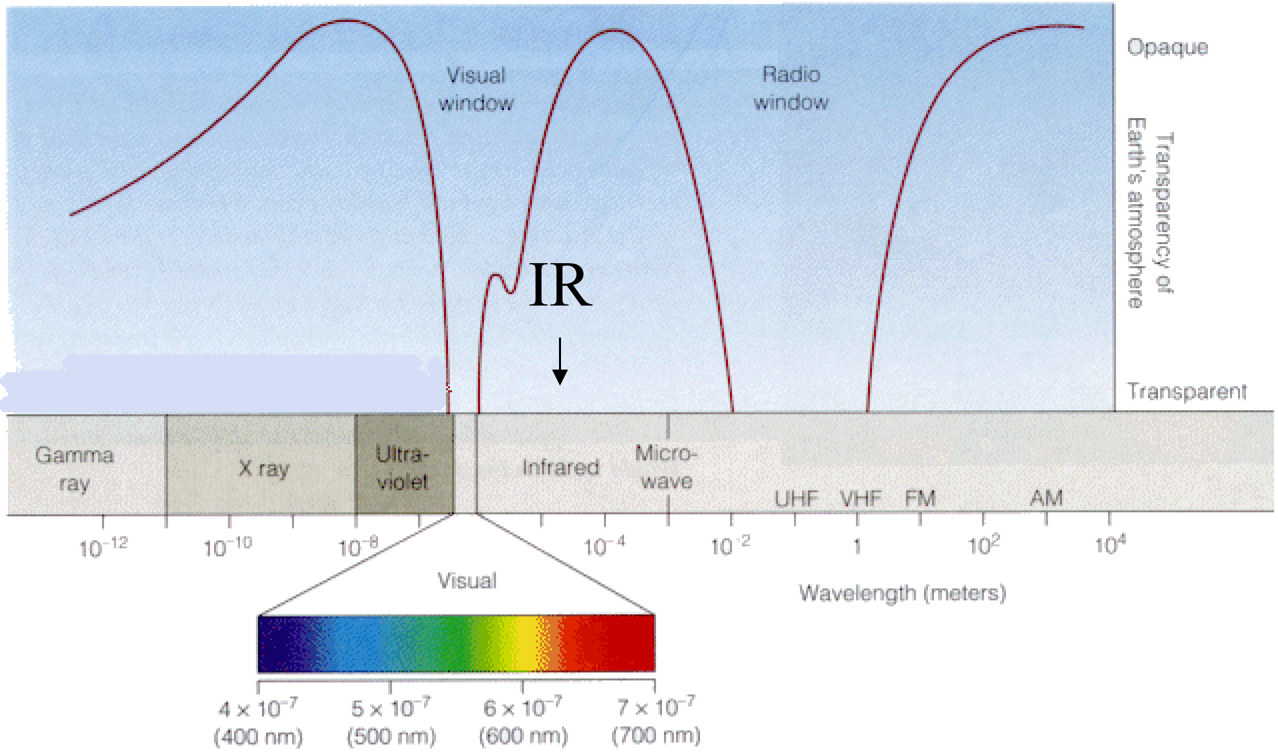
Our eyes are sensitive to the visible portion of the EM spectrum

UV, Visible and Near-IR and IR and Far-IR

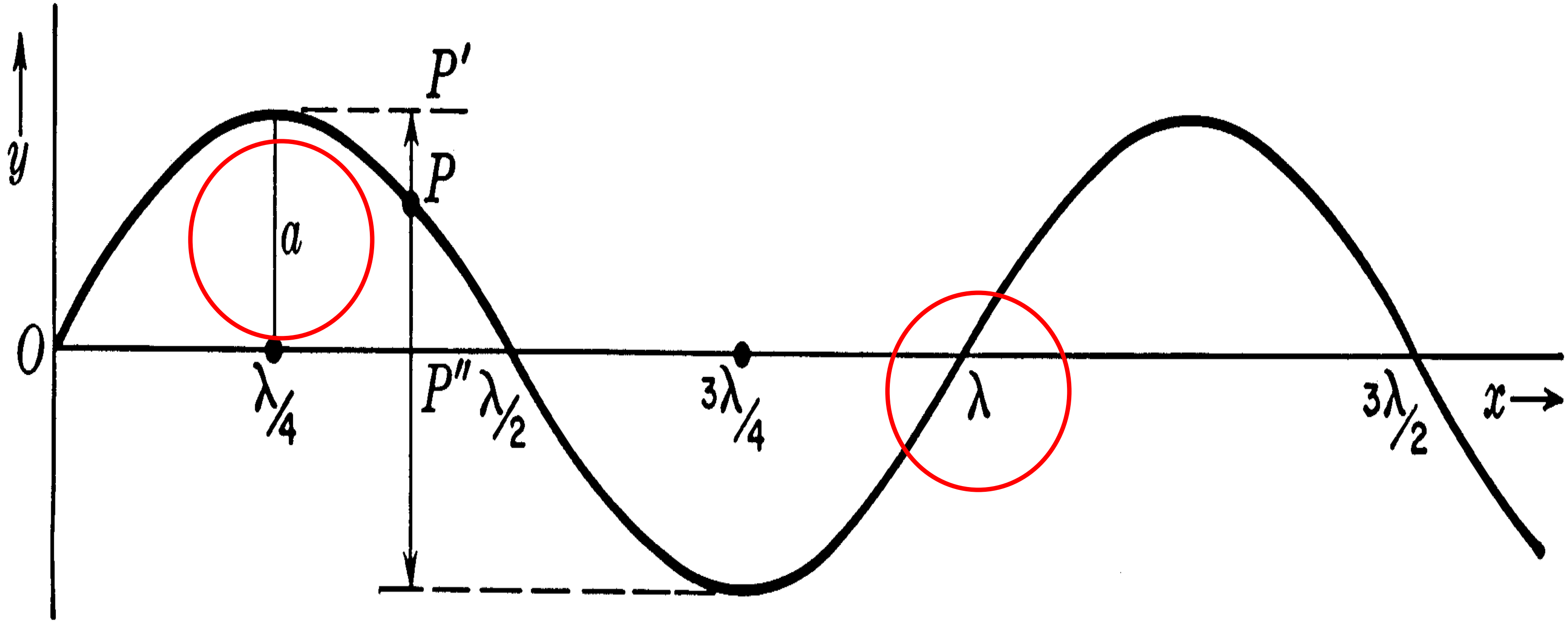


Electromagnetic Spectrum





wavelength λ : distance between peaks (μm)



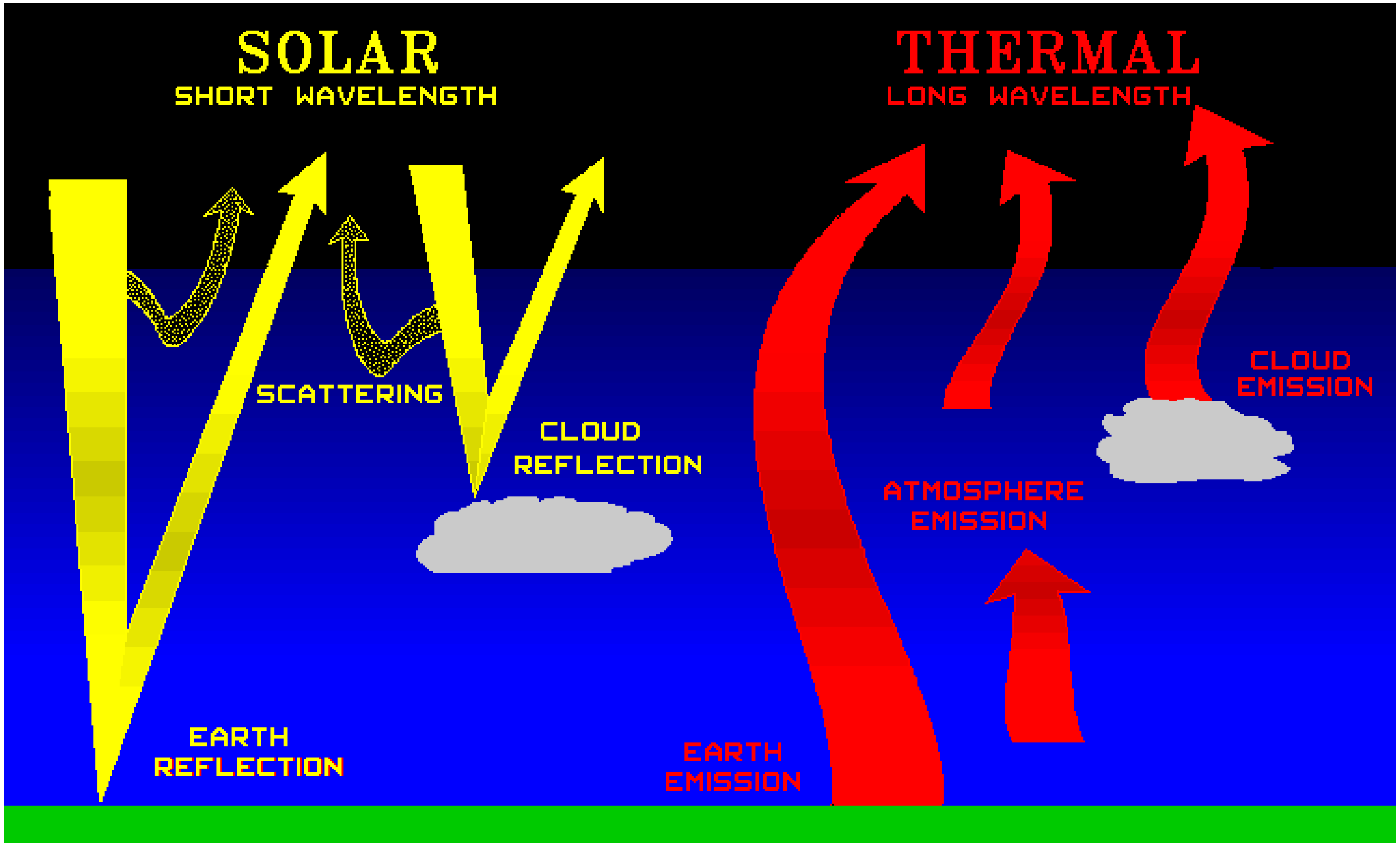
wavenumber ν : number of waves per unit distance (cm)

$$\lambda = 1/\nu$$

$$d\lambda = -1/\nu^2\, d\nu$$

Radiation is characterized by wavelength λ and amplitude a

Visible (Reflective Bands) | Infrared (Emissive Bands)



Terminology of radiant energy

Energy from the Earth Atmosphere

over time is

Flux

which strikes the detector area

Irradiance

at a given wavelength interval

Monochromatic Irradiance

over a solid angle on the Earth

Radiance observed by satellite radiometer

is described by

The Planck function

can be inverted to

Brightness temperature

Terminology of radiant energy

Energy (Joules) from the Earth Atmosphere

over time is

Flux (Joules/sec or W)

which strikes the detector area

Irradiance (W/m^2)

at a given wavelength interval

Monochromatic Irradiance (W/m2/micrometer)

over a solid angle on the Earth

Radiance (W/m2/micromenter/ster) observed by satellite radiometer

is described by

The Planck function

can be inverted to

Brightness temperature (K)

Radiation from the Sun

The rate of energy transfer by electromagnetic radiation is called the radiant flux, which has units of energy per unit time. It is denoted by

$$F = dQ / dt$$

and is measured in joules per second or watts. For example, the radiant flux from the sun is about 3.90 x 10**26 W.

The radiant flux per unit area is called the irradiance (or radiant flux density in some texts). It is denoted by

$$E = dQ / dt / dA$$

and is measured in watts per square metre. The irradiance of electromagnetic radiation passing through the outermost limits of the visible disk of the sun (which has an approximate radius of 7 x 10**8 m) is given by

$$E\ (\text{sun sfc}) = \frac{3.90 \times 10^{26}}{4\pi\ (7 \times 10^{8})^{2}} = 6.34 \times 10^{7}\ \text{W m}^{-2}\ .$$

The solar irradiance arriving at the earth can be calculated by realizing that the flux is a constant, therefore

$$E\ (\text{earth sfc}) \times 4\pi R_{es}^2 = E\ (\text{sun sfc}) \times 4\pi R_s^2,$$

where R_{es} is the mean earth to sun distance (roughly 1.5×10^{11} m) and R_s is the solar radius. This yields

$$E\ (\text{earth sfc}) = 6.34 \times 10^7\ (7 \times 10^8 / 1.5 \times 10^{11})^2 = 1380\ \text{W m}^{-2}.$$

The irradiance per unit wavelength interval at wavelength λ is called the monochromatic irradiance,

$$E_\lambda = dQ / dt / dA / d\lambda\ ,$$

and has the units of watts per square metre per micrometer. With this definition, the irradiance is readily seen to be

$$E = \int_o^\infty E_\lambda\, d\lambda\ .$$

In general, the irradiance upon an element of surface area may consist of contributions which come from an infinity of different directions. It is sometimes necessary to identify the part of the irradiance that is coming from directions within some specified infinitesimal arc of solid angle $d\Omega$. The irradiance per unit solid angle is called the radiance,

$$I = dQ / dt / dA / d\lambda / d\Omega,$$

and is expressed in watts per square metre per micrometer per steradian. This quantity is often also referred to as intensity and denoted by the letter B (when referring to the Planck function).

If the zenith angle, θ, is the angle between the direction of the radiation and the normal to the surface, then the component of the radiance normal to the surface is then given by $I \cos\theta$. The irradiance represents the combined effects of the normal component of the radiation coming from the whole hemisphere; that is,

$$E = \int_{\Omega} I \cos\theta \, d\Omega \qquad \text{where in spherical coordinates } d\Omega = \sin\theta \, d\theta \, d\varphi \, .$$

Radiation whose radiance is independent of direction is called isotropic radiation. In this case, the integration over $d\Omega$ can be readily shown to be equal to π so that

$$E = \pi I \, .$$

Radiation is governed by Planck's Law

In wavelength:

$$B(\lambda,T) = c_1 / \{ \lambda^5 [e^{c2/\lambda T} - 1] \} \quad (\text{mW/m}^2\text{/ster/cm})$$

where λ = wavelength (cm)

T = temperature of emitting surface (deg K)

c_1 = 1.191044 x 10-8 (W/m^2/ster/cm^{-4})

c_2 = 1.438769 (cm deg K)

In wavenumber:

$$B(\nu,T) = c_1 \nu^3 / [e^{c2\nu/T} - 1] \quad (\text{mW/m}^2\text{/ster/cm}^{-1})$$

where ν = # wavelengths in one centimeter (cm-1)

T = temperature of emitting surface (deg K)

c_1 = 1.191044 x 10-5 (mW/m^2/ster/cm^{-4})

c_2 = 1.438769 (cm deg K)

Brightness temperature is uniquely related to radiance for a given wavelength by the Planck function.

Using wavelengths

Planck's Law $B(\lambda,T) = c_1 / \lambda^5 / [e^{c_2/\lambda T} - 1]$ $(mW/m^2/ster/cm)$

where λ = wavelengths in cm

T = temperature of emitting surface (deg K)

c_1 = 1.191044 x 10-5 $(mW/m^2/ster/cm^{-4})$

c_2 = 1.438769 (cm deg K)

Wien's Law $dB(\lambda_{max},T) / d\lambda = 0$ where $\lambda(max) = .2897/T$

indicates peak of Planck function curve shifts to shorter wavelengths (greater wavenumbers) with temperature increase. Note $B(\lambda_{max},T) \sim T^5$.

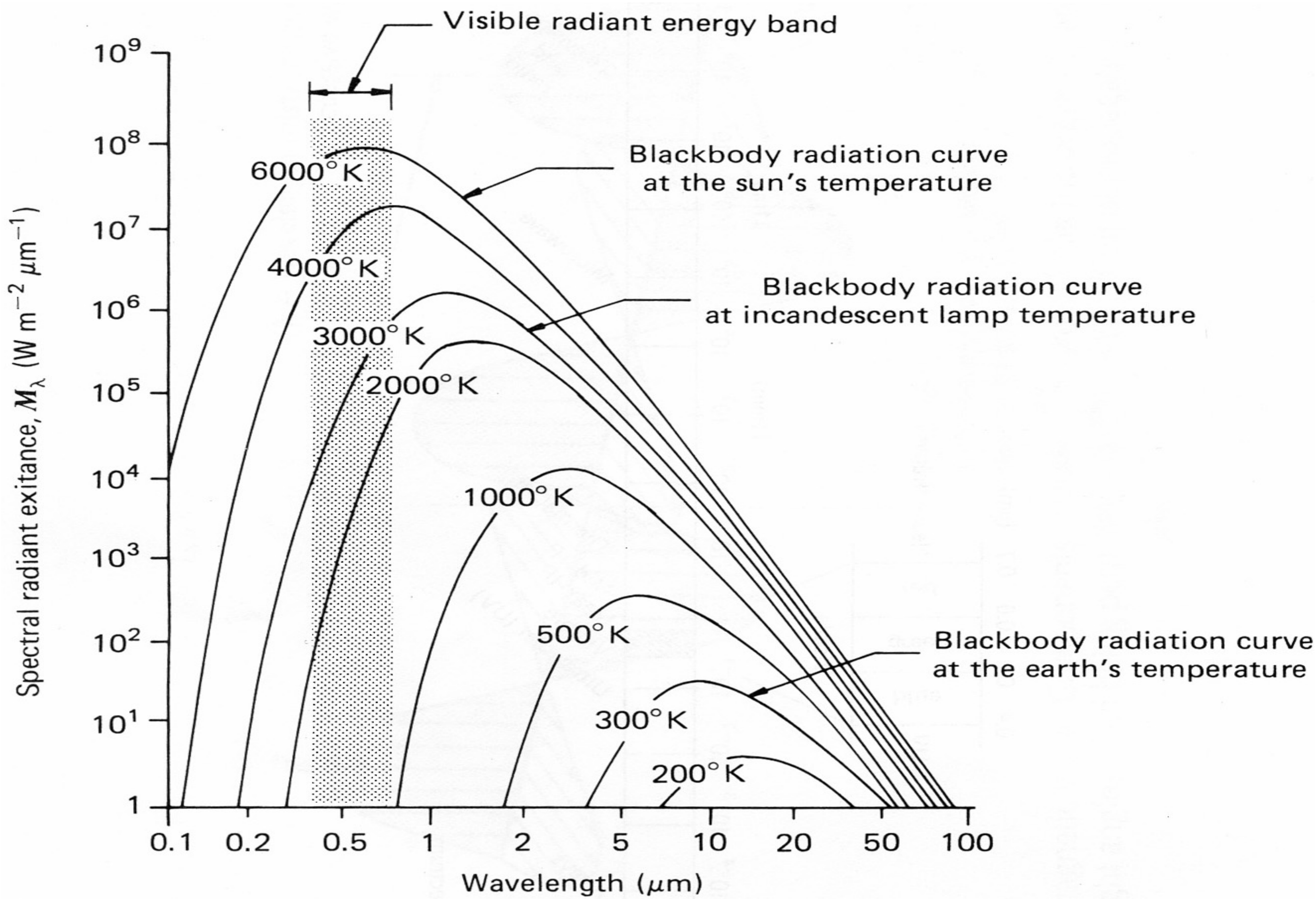
Stefan-Boltzmann Law $E = \pi \int_o^\infty B(\lambda,T)\, d\lambda = \sigma T^4$, where σ = 5.67 x 10-8 W/m2/deg4.

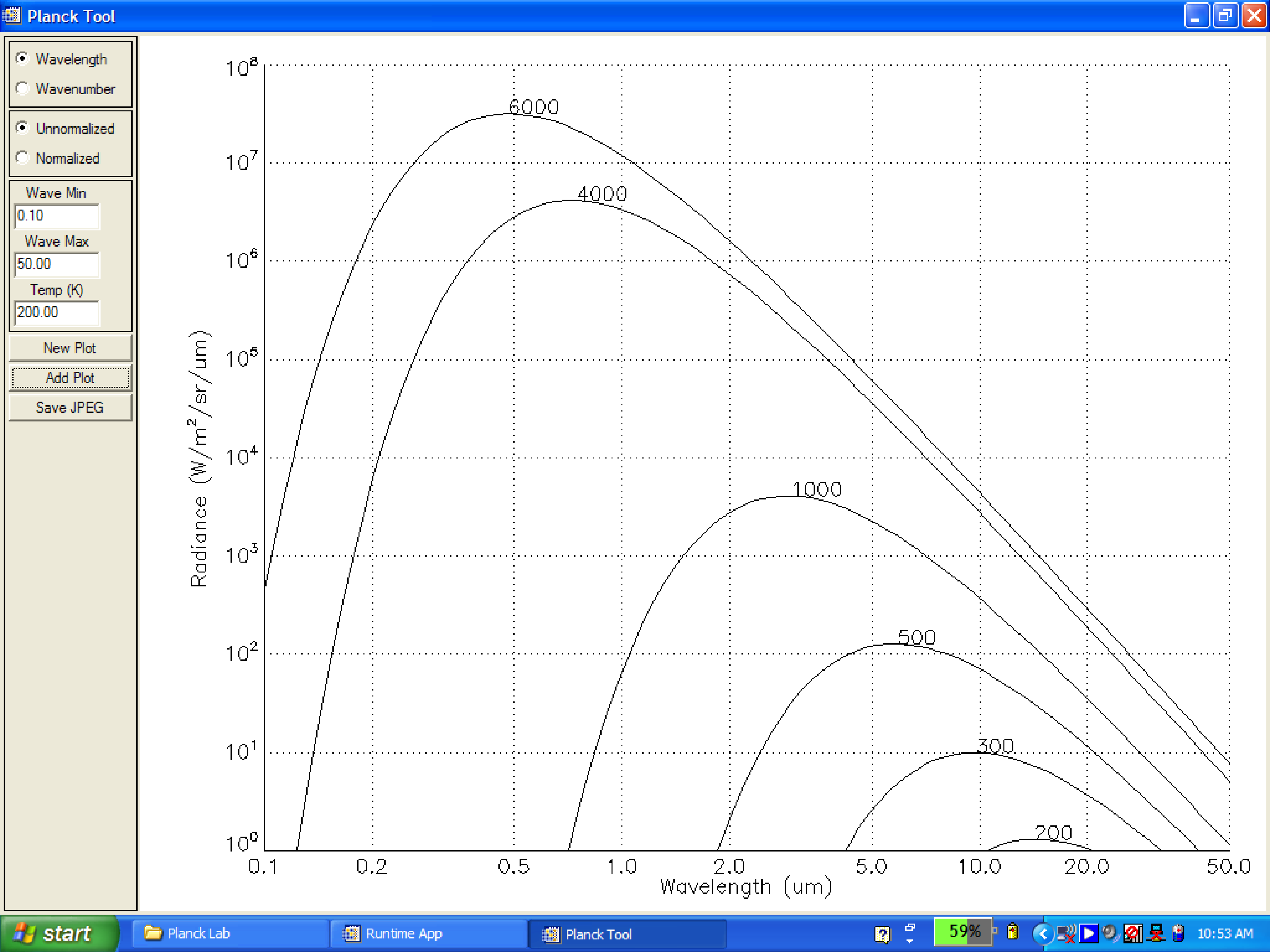
states that irradiance of a black body (area under Planck curve) is proportional to T^4 .

Brightness Temperature

$$T = c_2 / [\lambda \ln(\frac{c_1}{\lambda^5 B_\lambda} + 1)]$$ is determined by inverting Planck function

Spectral Distribution of Energy Radiated from Blackbodies at Various Temperatures




Planck Tool
Wavelength
Wavenumber
Unnormalized
Normalized
Wave Min
0.10
Wave Max
50.00
Temp (K)
200.00
New Plot
Add Plot
Save JPEG
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0
Radiance (W/m^2/sr/um)
6000
4000
1000
500
300
200
0.1
0.2
0.5
1.0
2.0
5.0
10.0
20.0
50.0
Wavelength (um)
start
Planck Lab
Runtime App
Planck Tool
59%
10:53 AM

Using wavenumbers

Wien's Law $dB(\nu_{max},T) / dT = 0$ where $\nu(max) = 1.95T$
indicates peak of Planck function curve shifts to shorter wavelengths (greater wavenumbers) with temperature increase. Note $B(\nu_{max},T) \sim T^{**}3$.

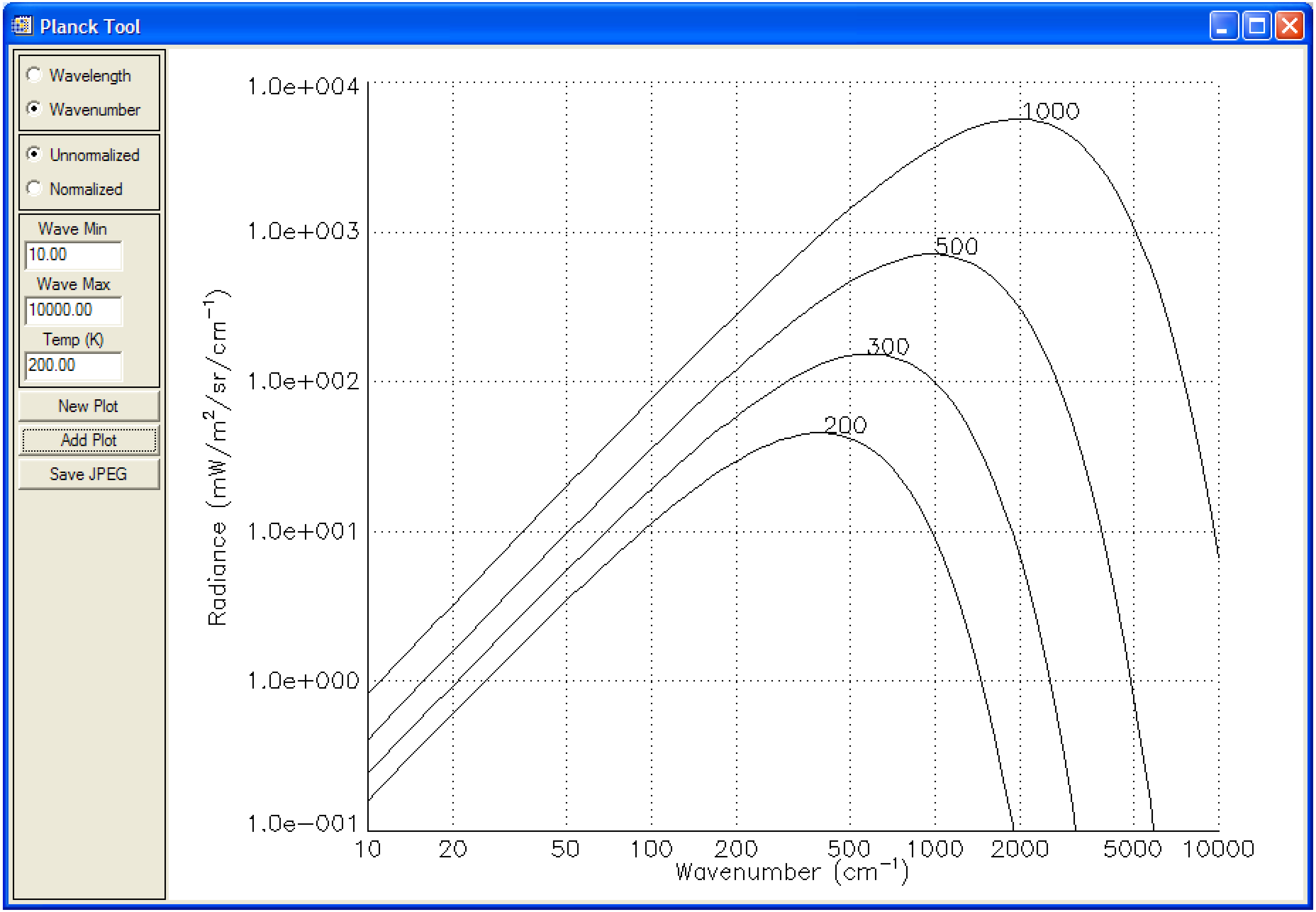
Stefan-Boltzmann Law $E = \pi \int_{o}^{\infty} B(\nu,T)\, d\nu = \sigma T^4$, where $\sigma = 5.67 \times 10\text{-}8\ W/m^2/deg^4$.

states that irradiance of a black body (area under Planck curve) is proportional to T^4 .

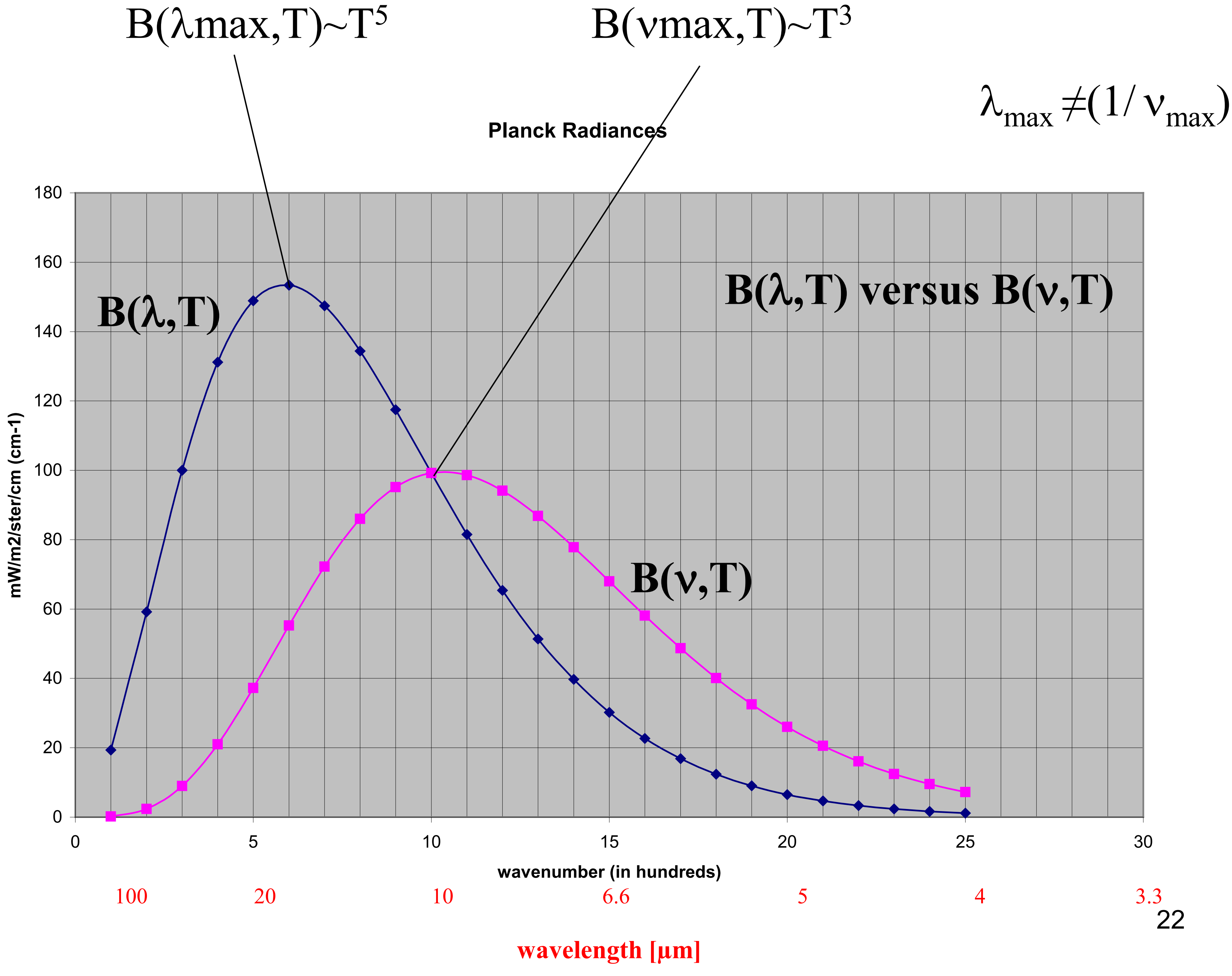
Brightness Temperature

$$T = c_2\nu/[\ln(\frac{c_1\nu^3}{B_\nu} + 1)]$$ is determined by inverting Planck function

Brightness temperature is uniquely related to radiance for a given wavelength by the Planck function.



Planck Tool
Wavelength
Wavenumber
Unnormalized
Normalized
Wave Min
10.00
Wave Max
10000.00
Temp (K)
200.00
New Plot
Add Plot
Save JPEG
1.0e+004
1.0e+003
1.0e+002
1.0e+001
1.0e+000
1.0e−001
Radiance (mW/m2/sr/cm−1)
1000
500
300
200
10
20
50
100
200
500
1000
2000
5000
10000
Wavenumber (cm−1)


B(λmax,T)~T5
B(νmax,T)~T3
λmax ≠(1/ νmax)
Planck Radiances
B(λ,T) versus B(ν,T)
B(λ,T)
B(ν,T)
mW/m2/ster/cm (cm-1)
180
160
140
120
100
80
60
40
20
0
0
5
10
15
20
25
30
wavenumber (in hundreds)
100
20
10
6.6
5
4
3.3
wavelength [µm]

Using wavenumbers

$$B(\nu,T) = c_1\nu^3 / [e^{c_2\nu/T} - 1]$$

$(mW/m^2/ster/cm^{-1})$

ν(max in cm-1) = 1.95T

$B(\nu_{max},T) \sim T^{**}3.$

$$E = \pi \int_0^\infty B(\nu,T)\, d\nu = \sigma T^4,$$

$$T = c_2\nu/[\ln(\frac{c_1\nu^3}{B_\nu} + 1)]$$

Using wavelengths

$$B(\lambda,T) = c_1 / \{ \lambda^5 [e^{c_2/\lambda T} - 1] \}$$

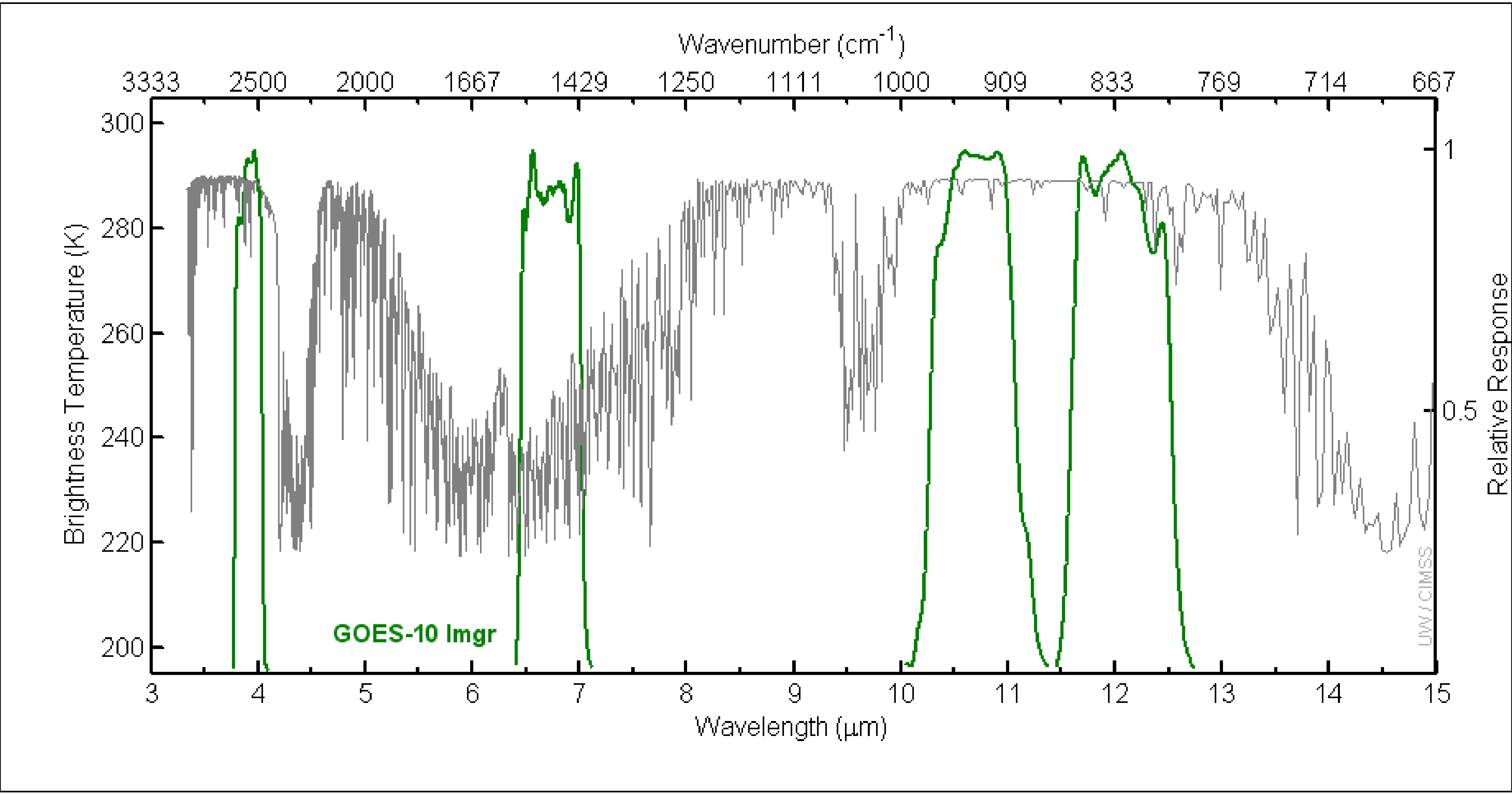
$(mW/m^2/ster/\mu m)$

λ(max in cm)T = 0.2897

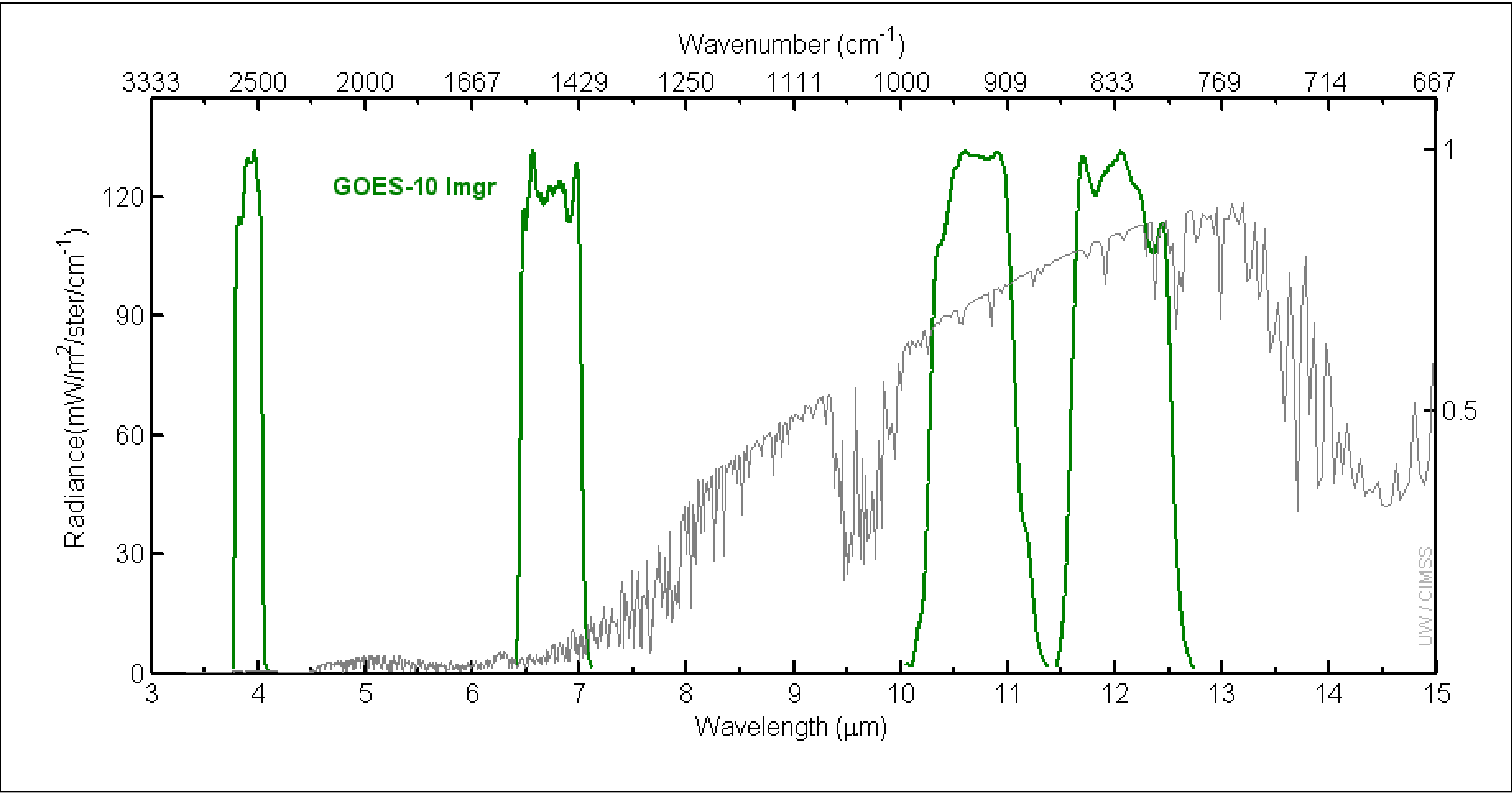
$B(\lambda_{max},T) \sim T^{**}5.$

$$E = \pi \int_0^\infty B(\lambda,T)\, d\lambda = \sigma T^4,$$

$$T = c_2/[\lambda \ln(\frac{c_1}{\lambda^5 B_\lambda} + 1)]$$



Wavenumber (cm-1)
3333
2500
2000
1667
1429
1250
1111
1000
909
833
769
714
667
300
280
260
240
220
200
Brightness Temperature (K)
1
0.5
Relative Response
GOES-10 Imgr
UW / CIMSS
3
4
5
6
7
8
9
10
11
12
13
14
15
Wavelength (µm)



Wavenumber (cm-1)
3333
2500
2000
1667
1429
1250
1111
1000
909
833
769
714
667
GOES-10 Imgr
Radiance(mW/m2/ster/cm-1)
120
90
60
30
0
1
0.5
UW / CIMSS
3
4
5
6
7
8
9
10
11
12
13
14
15
Wavelength (µm)

Temperature sensitivity

$$dB/B = \alpha \, dT/T$$

The Temperature Sensitivity α is the percentage change in radiance corresponding to a percentage change in temperature

Substituting the Planck Expression, the equation can be solved in α:

$$\alpha = c_2 \nu / T$$

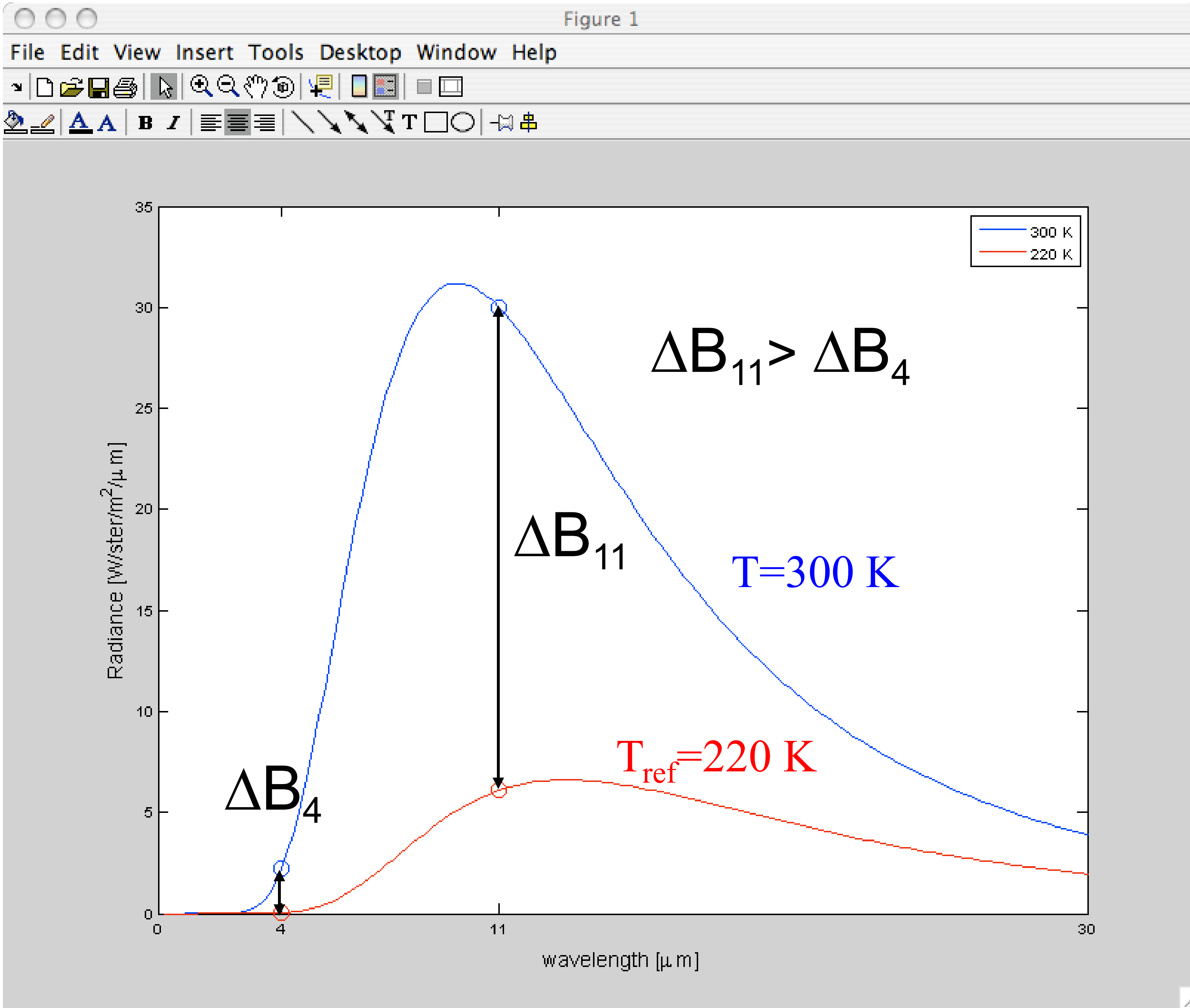


Figure 1
File Edit View Insert Tools Desktop Window Help
300 K
220 K
ΔB11> ΔB4
ΔB11
ΔB4
T=300 K
Tref=220 K
Radiance [W/ster/m2/µm]
wavelength [µm]
0
5
10
15
20
25
30
35
0
4
11
30

7

(Approximation of) B as function of α and T

$\Delta B/B = \alpha \, \Delta T/T$

Integrating the Temperature Sensitivity Equation Between T_{ref} and T (B_{ref} and B):

$B = B_{ref}(T/T_{ref})^{\alpha}$

Where $\alpha = c_2 \nu / T_{ref}$ (in wavenumber space)

$$B = B_{ref} (T/T_{ref})^{\alpha}$$

$$\Downarrow$$

$$B = (B_{ref} / T_{ref}^{\alpha})\ T^{\alpha}$$

$$\Downarrow$$

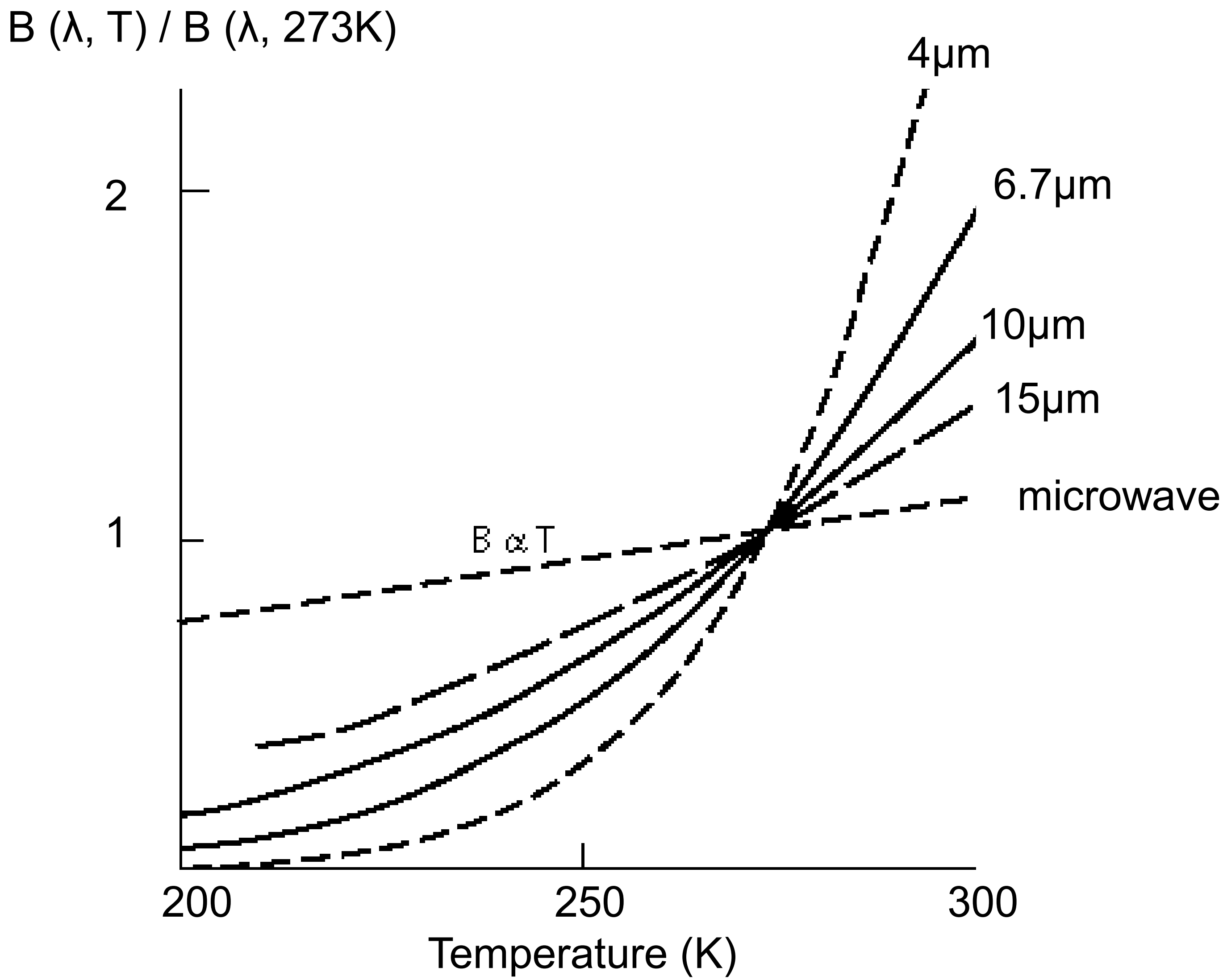
$$B \propto T^{\alpha}$$

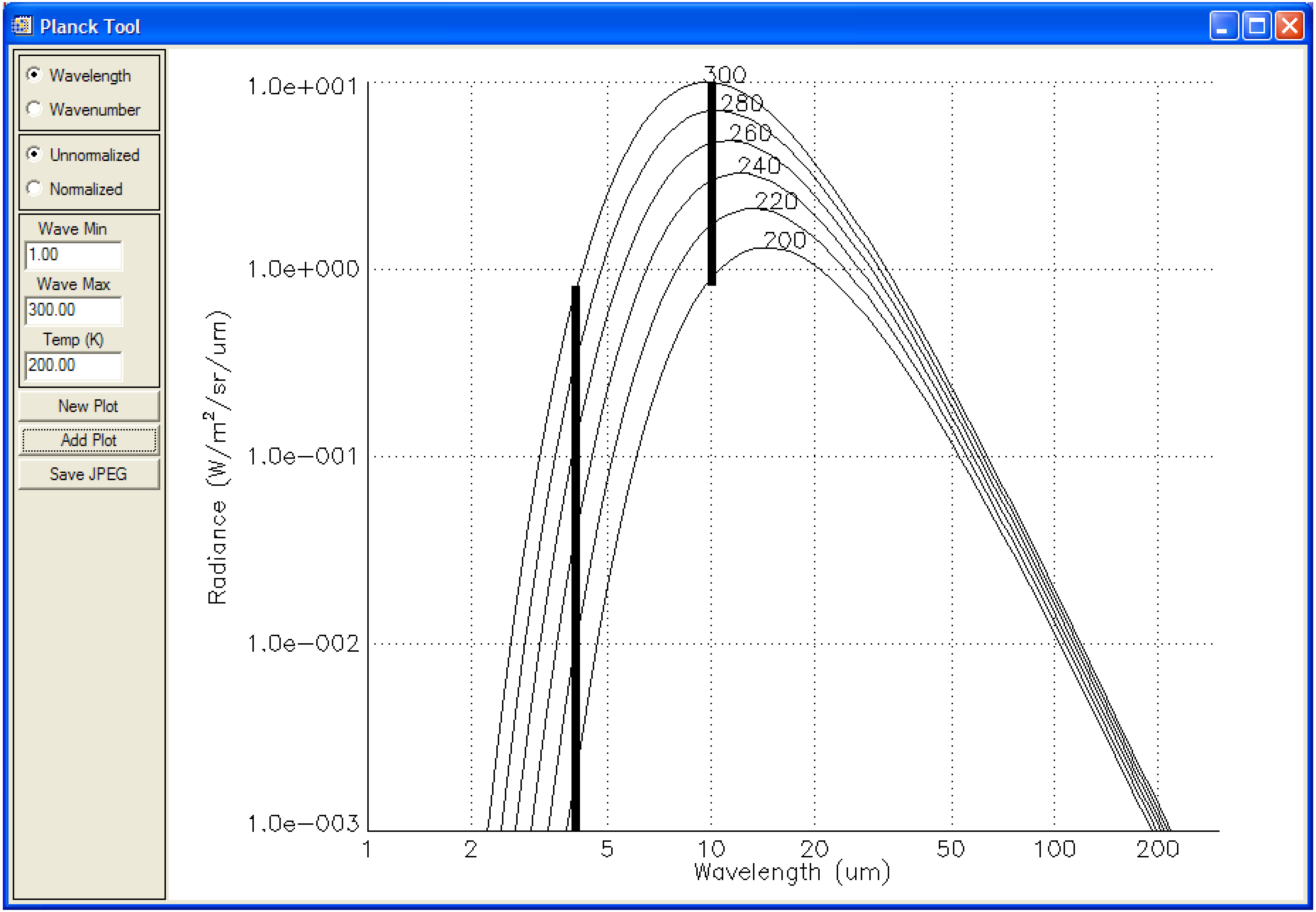
The temperature sensitivity indicates the power to which the Planck radiance depends on temperature, since B proportional to T^{α} satisfies the equation. For infrared wavelengths,

$\alpha = c_2\nu/T = c_2/\lambda T.$

Wavenumber	Typical Scene Temperature	Temperature Sensitivity
900	300	4.32
2500	300	11.99

Temperature Sensitivity of B(λ,T) for typical earth scene temperatures




Planck Tool
Wavelength
Wavenumber
Unnormalized
Normalized
Wave Min
1.00
Wave Max
300.00
Temp (K)
200.00
New Plot
Add Plot
Save JPEG
300
280
260
240
220
200
1.0e+001
1.0e+000
1.0e−001
1.0e−002
1.0e−003
Radiance (W/m2/sr/um)
1
2
5
10
20
50
100
200
Wavelength (um)

$B(10\ um,T) / B(10\ um,273) \propto T^4$

B(10 um,273)= 6.1

B(10 um,200)= 0.9 → 0.15

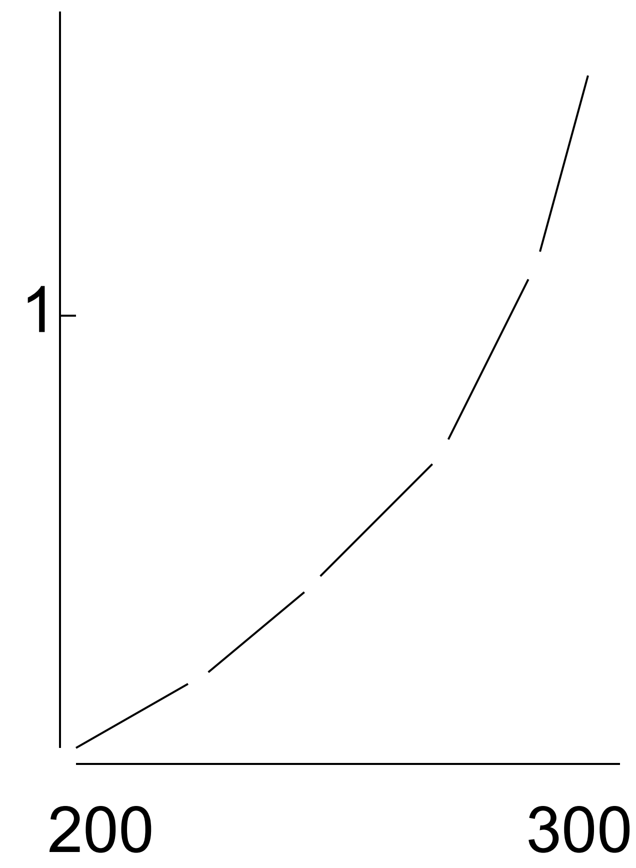
B(10 um,220)= 1.7 → 0.28

B(10 um,240)= 3.0 → 0.49

B(10 um,260)= 4.7 → 0.77

B(10 um,280)= 7.0 → 1.15

B(10 um,300)= 9.9 → 1.62



$B(4\ um,T) / B(4\ um,273) \propto T^{12}$

$B(4\ um,273) = 2.2 \times 10^{-1}$

$B(4\ um,200) = 1.8 \times 10^{-3} \rightarrow 0.0$

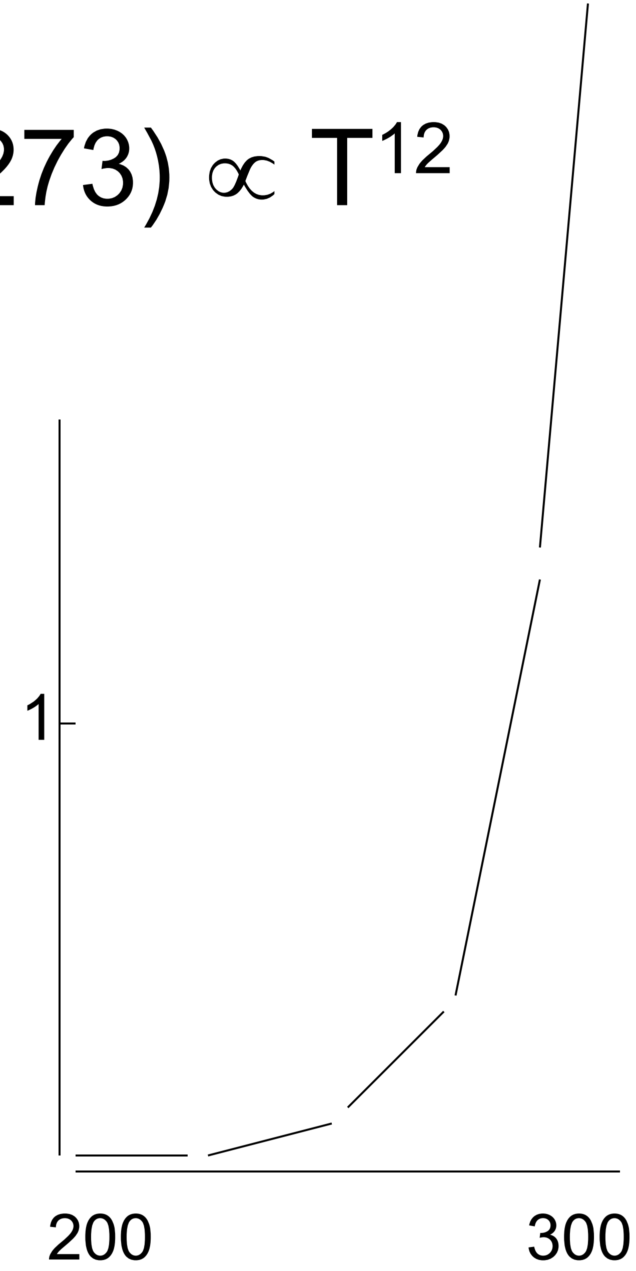
$B(4\ um,220) = 9.2 \times 10^{-3} \rightarrow 0.0$

$B(4\ um,240) = 3.6 \times 10^{-2} \rightarrow 0.2$

$B(4\ um,260) = 1.1 \times 10^{-1} \rightarrow 0.5$

$B(4\ um,280) = 3.0 \times 10^{-1} \rightarrow 1.4$

$B(4\ um,300) = 7.2 \times 10^{-1} \rightarrow 3.3$



$B(0.3\ \text{cm}, T) / B(0.3\ \text{cm}, 273) \propto T$

$B(0.3\ \text{cm}, 273) = 2.55 \times 10^{-4}$

$B(0.3\ \text{cm}, 200) = 1.8 \rightarrow 0.7$

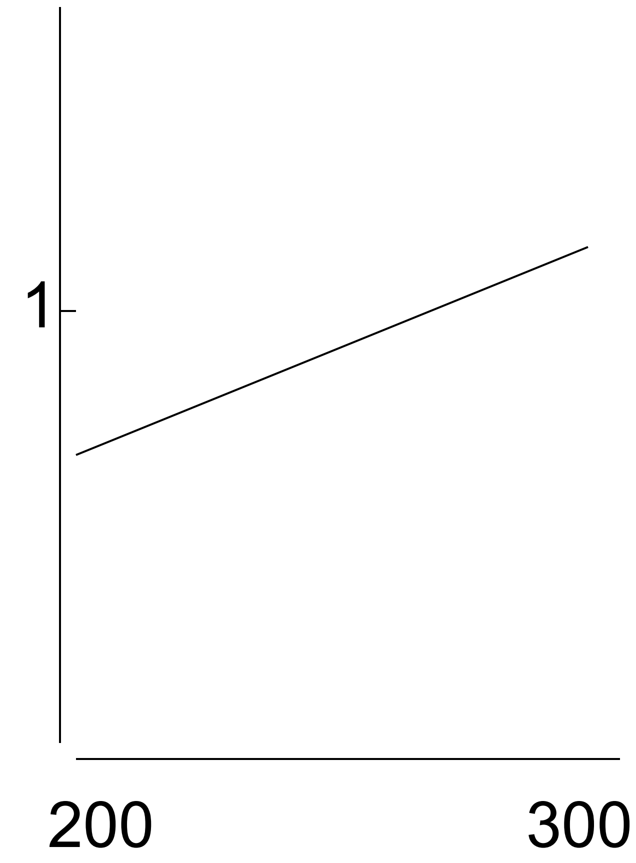
$B(0.3\ \text{cm}, 220) = 2.0 \rightarrow 0.78$

$B(0.3\ \text{cm}, 240) = 2.2 \rightarrow 0.86$

$B(0.3\ \text{cm}, 260) = 2.4 \rightarrow 0.94$

$B(0.3\ \text{cm}, 280) = 2.6 \rightarrow 1.02$

$B(0.3\ \text{cm}, 300) = 2.8 \rightarrow 1.1$



Radiation is governed by Planck's Law

$$B(\lambda,T) = c_1 / \{ \lambda^5 [e^{c_2/\lambda T} - 1] \}$$

In microwave region $c_2/\lambda T << 1$ so that

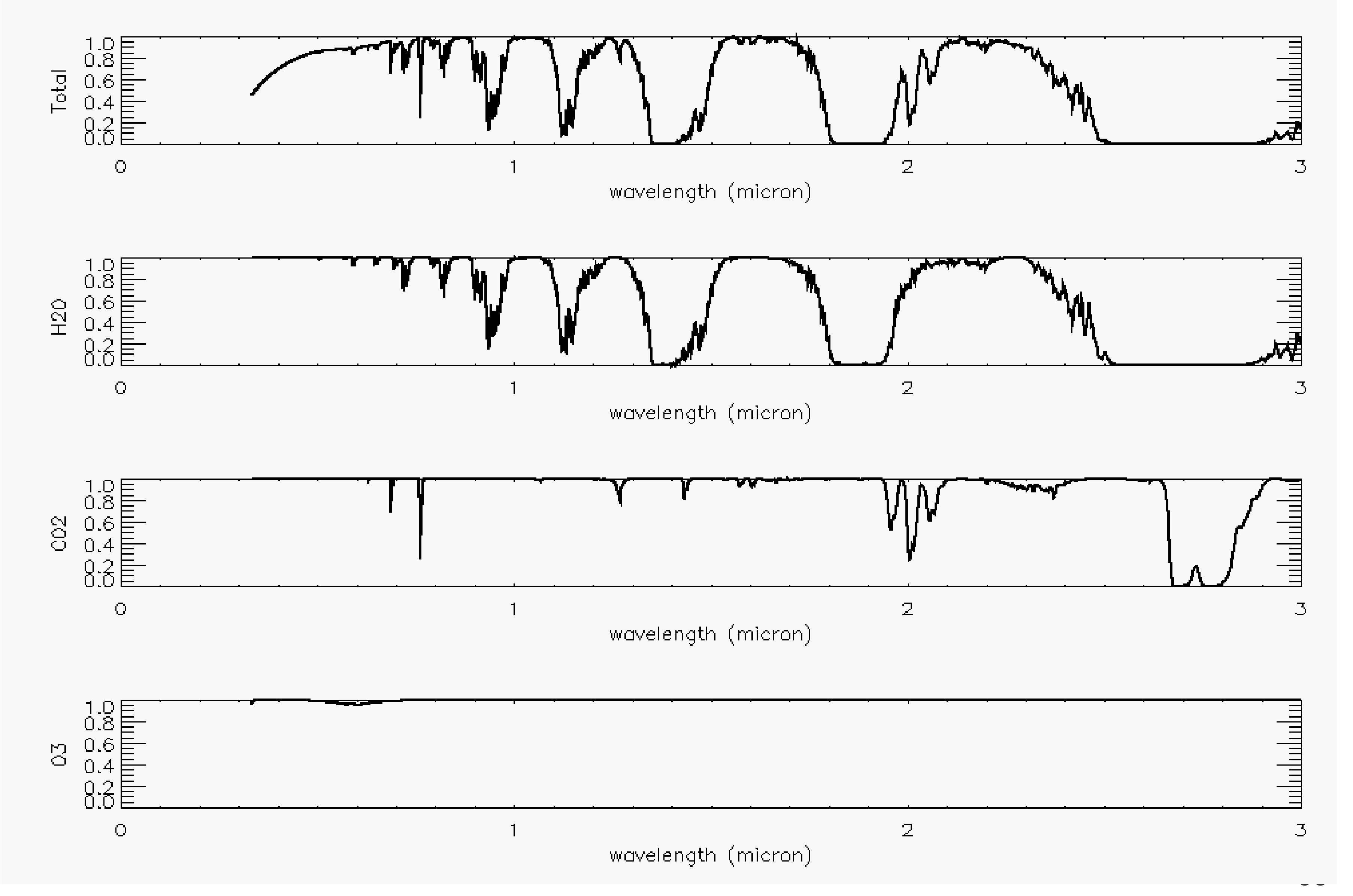
$$e^{c_2/\lambda T} = 1 + c_2/\lambda T + \text{second order}$$

And classical Rayleigh Jeans radiation equation emerges

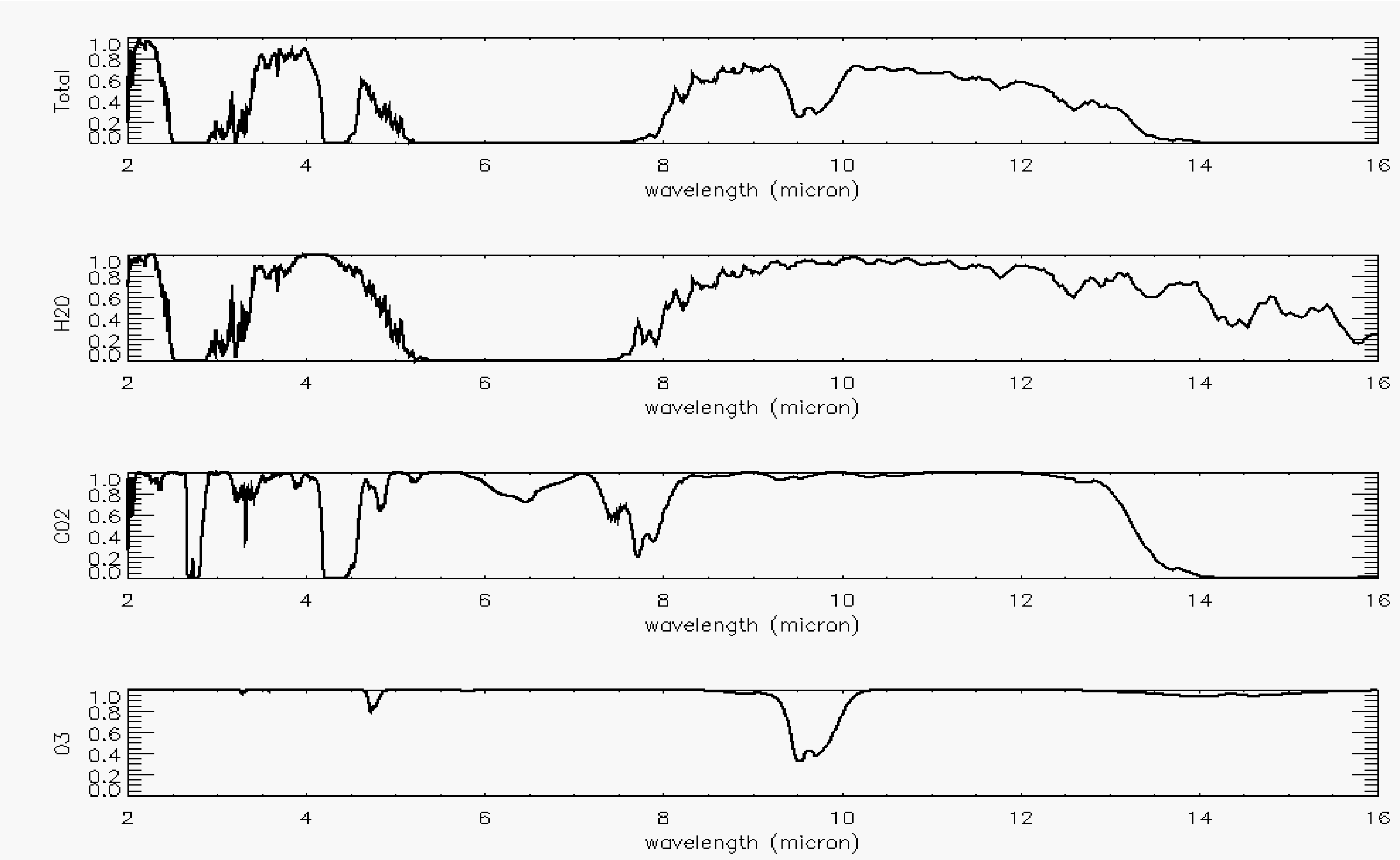
$$B_\lambda(T) \approx [c_1 / c_2] [T / \lambda^4]$$

Radiance is linear function of brightness temperature.

UV – NEAR IR Atmospheric Transmission Spectra (0.5 – 3 microns)

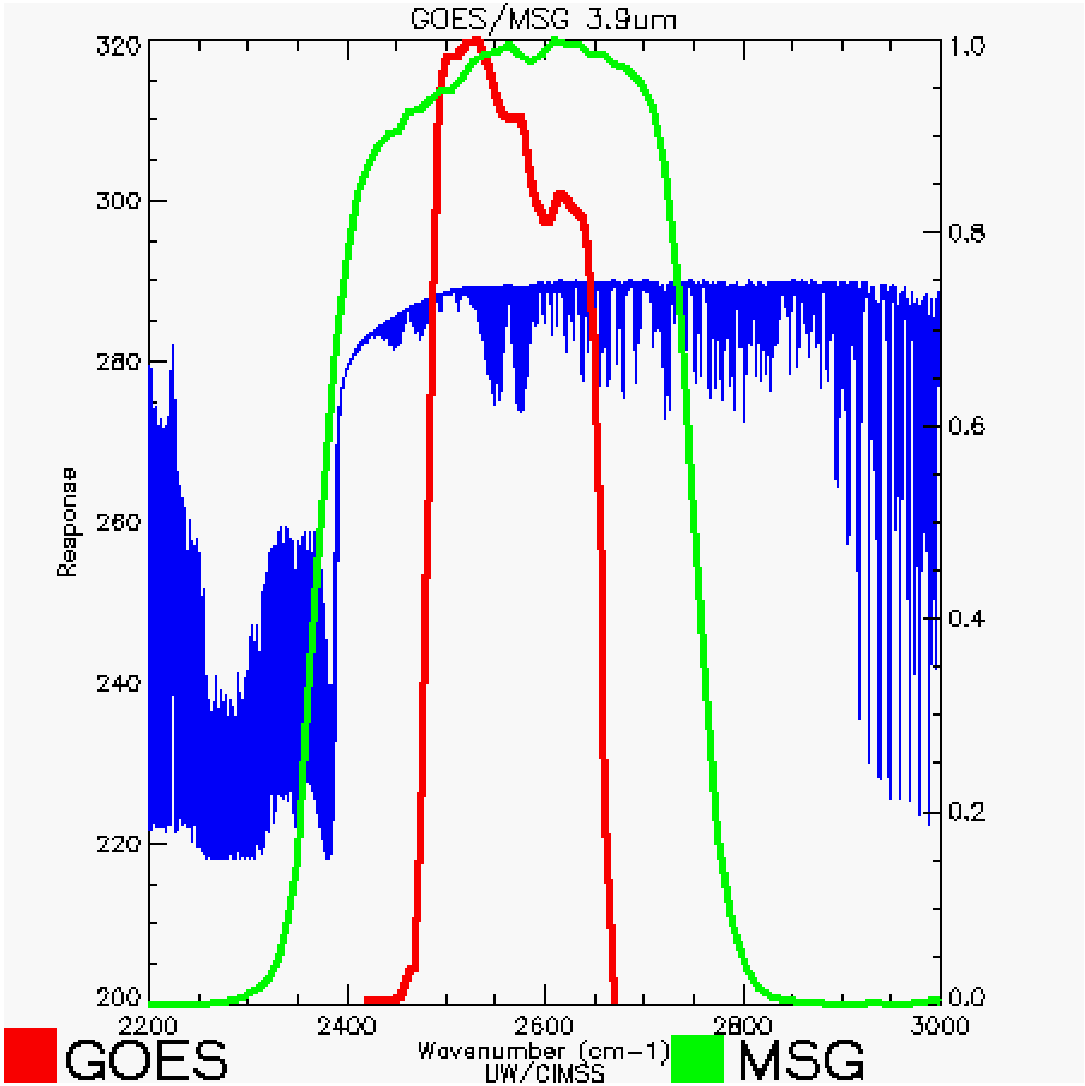


Near-IR – FAR IR Atmospheric Transmission Spectra (2 – 15 microns)

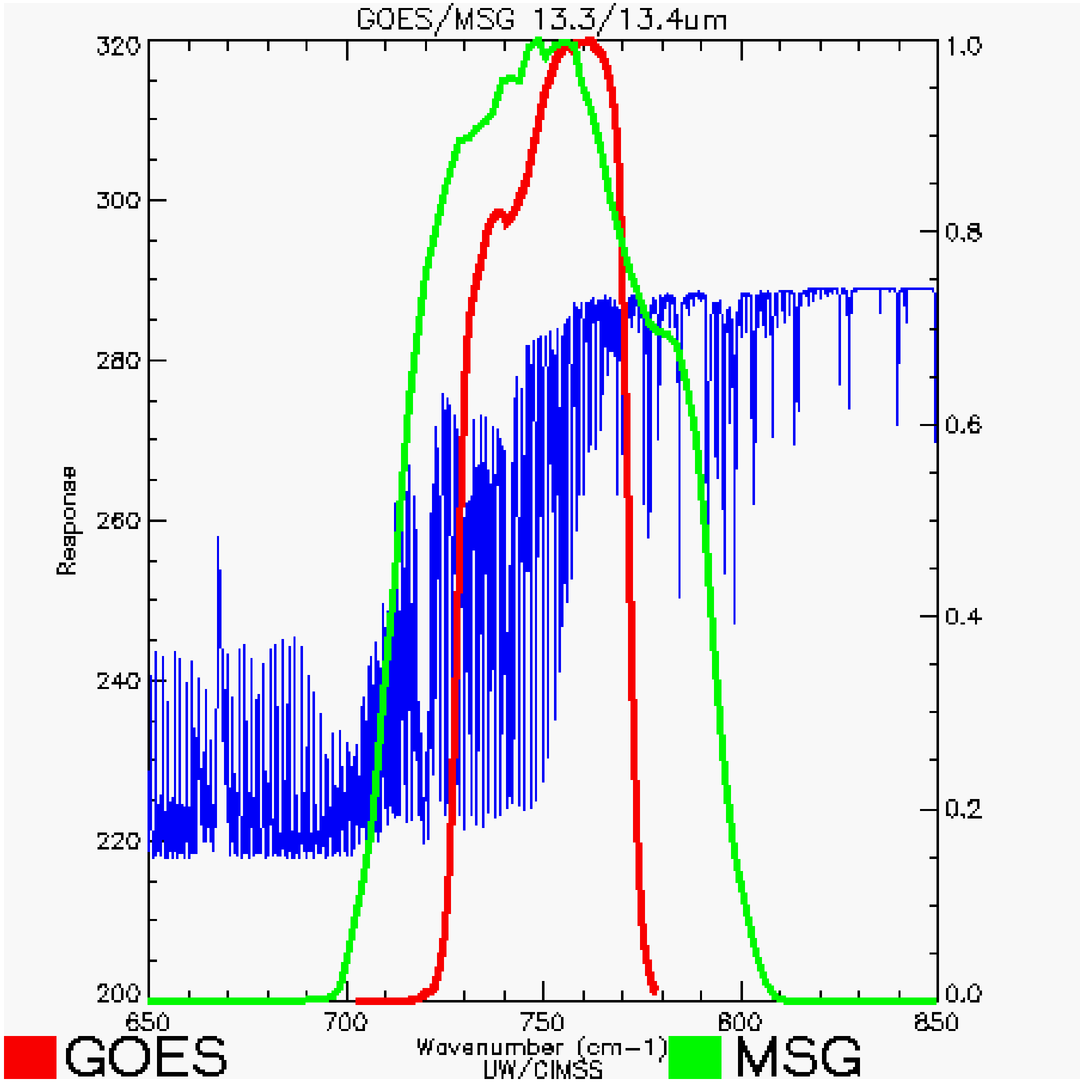


Radiance to Brightness Temperatures

Via Planck function, but need to take into account the spectral width of the given band.

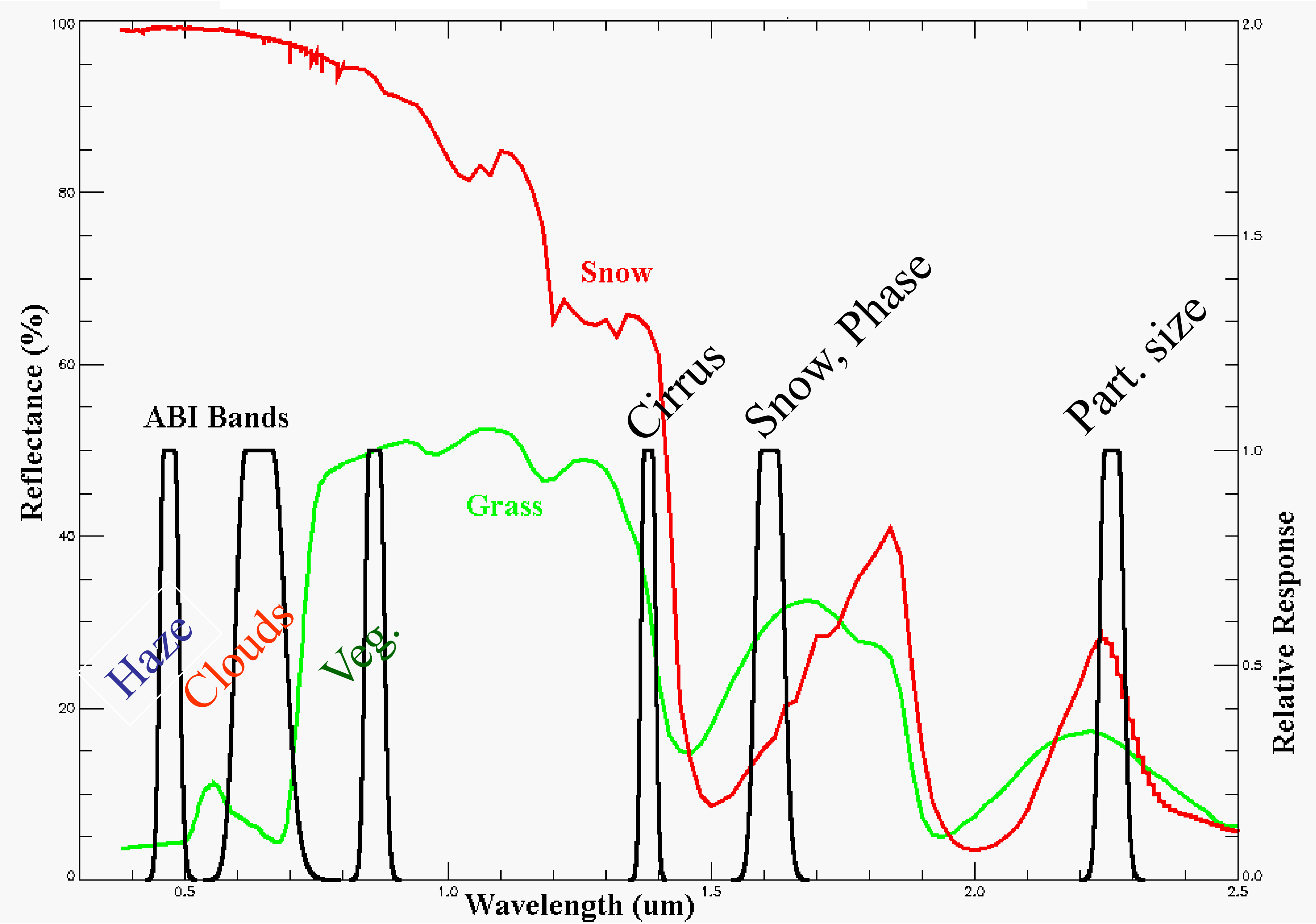


Above: GOES-12 and MSG 3.9um SRF and night-time spectra.
GOES-12 BT: 288.278K MSG BT: 284.487 **GOES-MSG: 3.791K**



Above: GOES-12 and MSG 13.3/13.4um SRF and spectra.
GOES-12 BT: 270.438K MSG BT: 268.564K GOES-MSG: 1.874K

Visible and near-IR channels on the ABI



GOES-10 Imager and Sounder have one visible band near 0.6 um

Reflectance Ratio Test Basis

Based on our knowledge of reflectance spectra, we can predict:

R2/R1 = 1.0 for cloud (if you can't see the surface underneath)

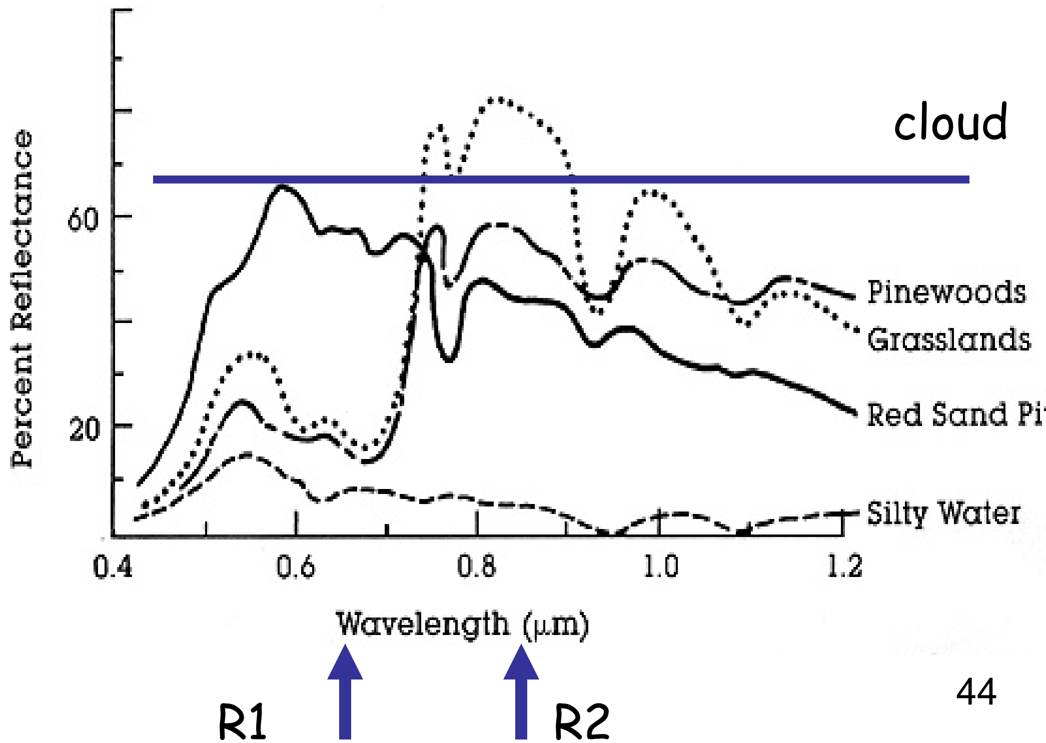
R2/R1 > 1.0 for vegetation (look at pinewoods spectra)

R2/R1 << 1.0 for water

R2/R1 about 1 for desert

Glint is a big limiting factor To this test over oceans.

Also, smoke or dust can look Like cloud in R2/R1.



Visible: Reflective Bands

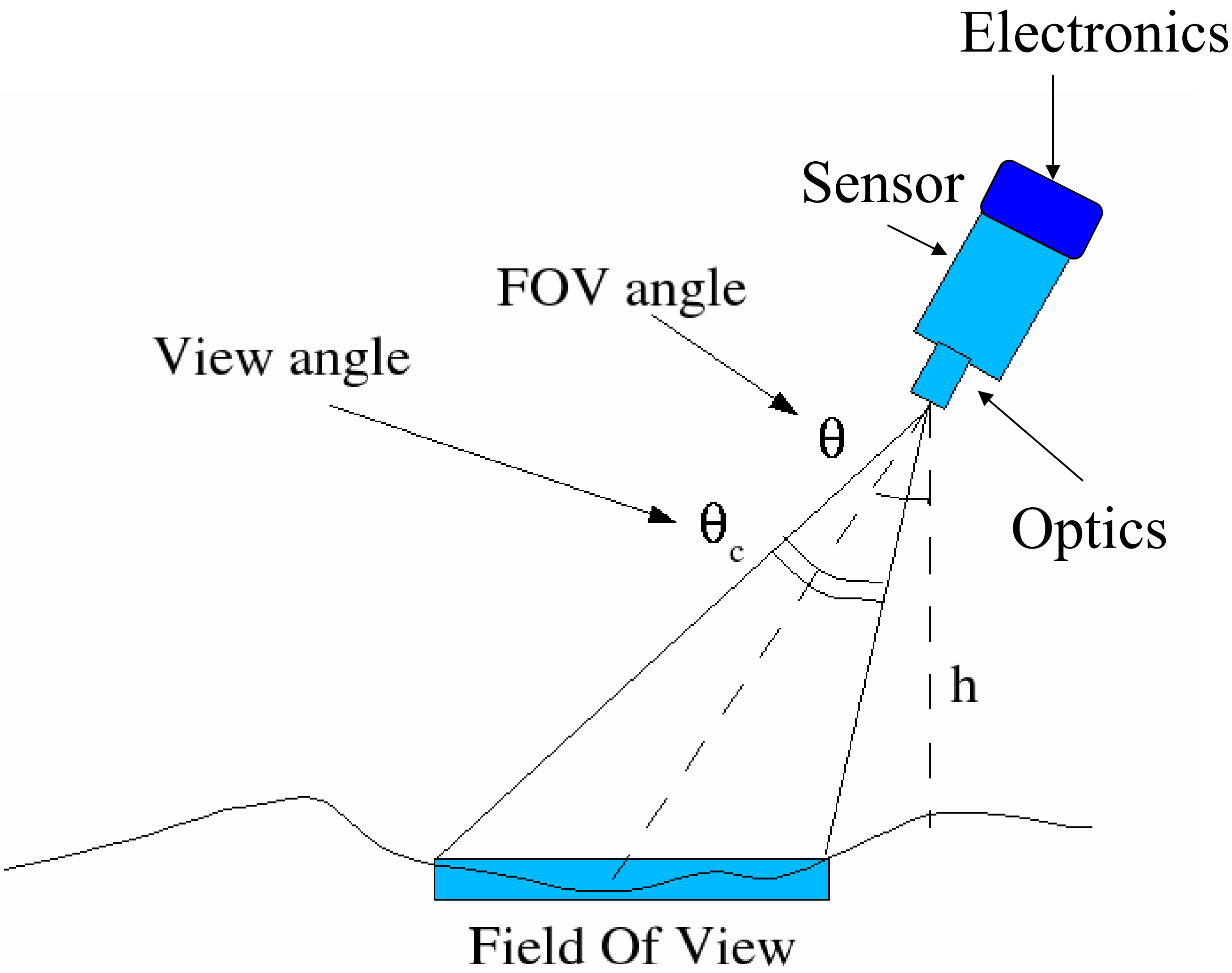
Used to observe solar energy reflected by the Earth system in the:

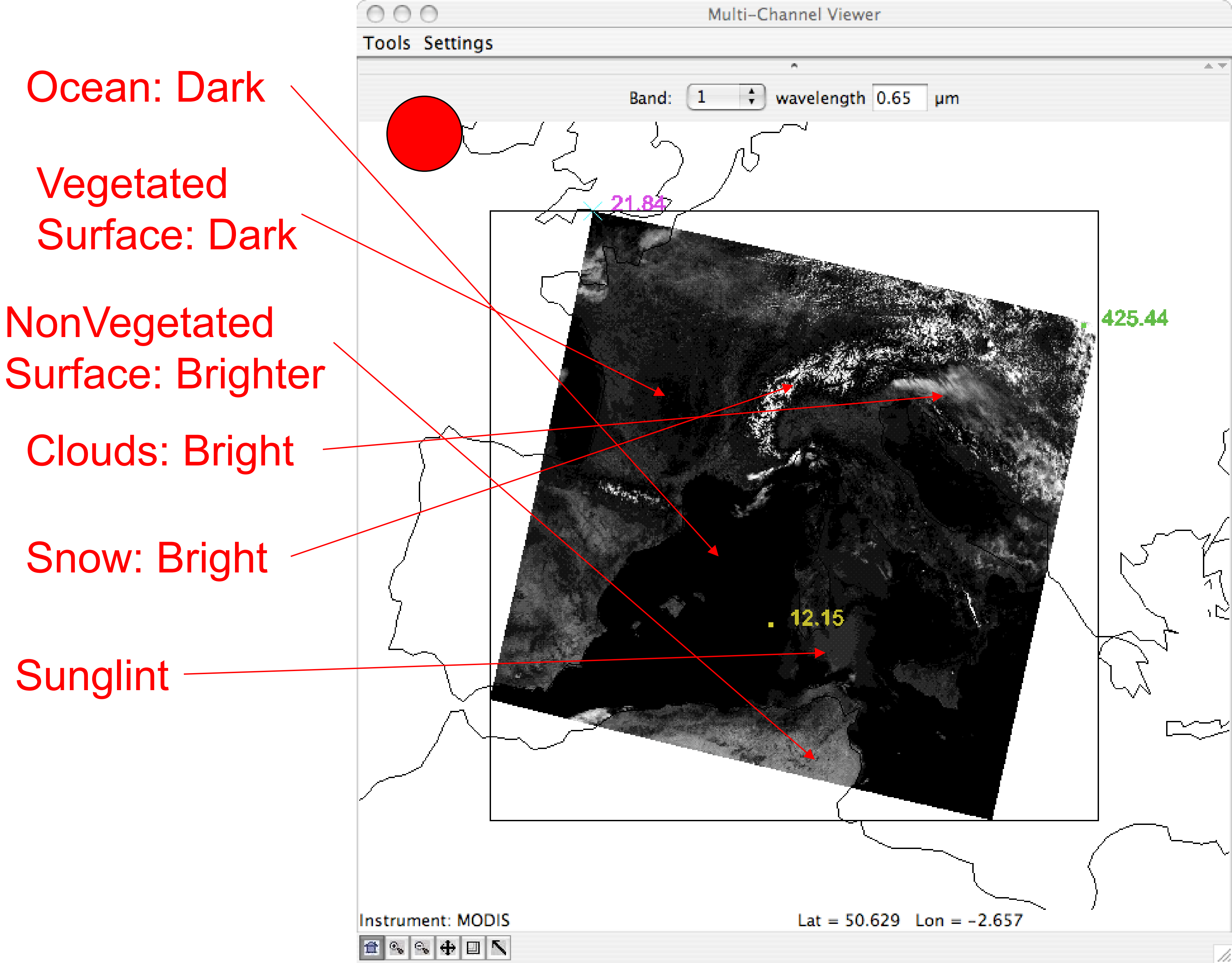
- Visible between 0.4 and 0.7 µm
- NIR between 0.7 and 3 µm

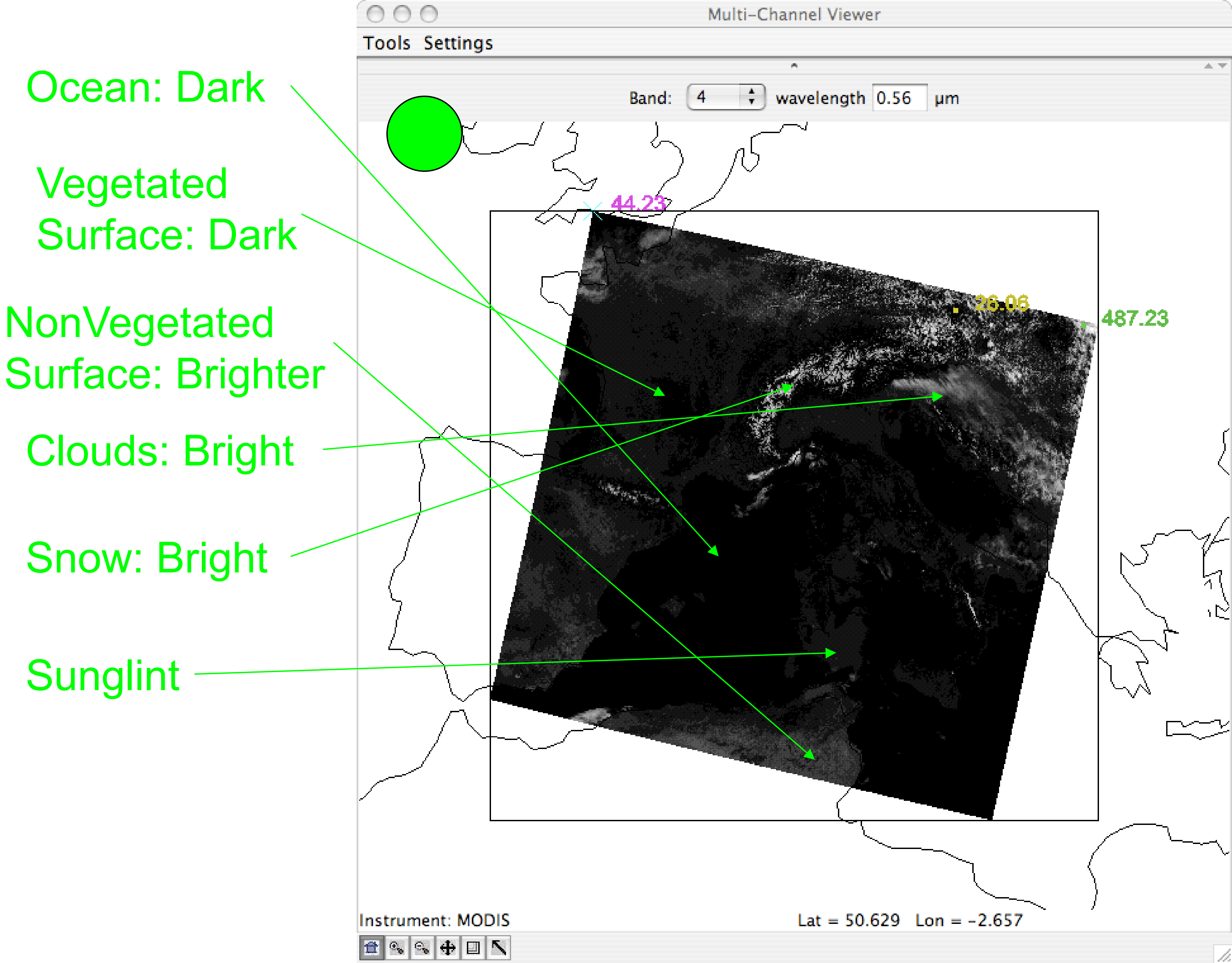
About 99% of the energy observed between 0 and 4 µm is solar reflected energy

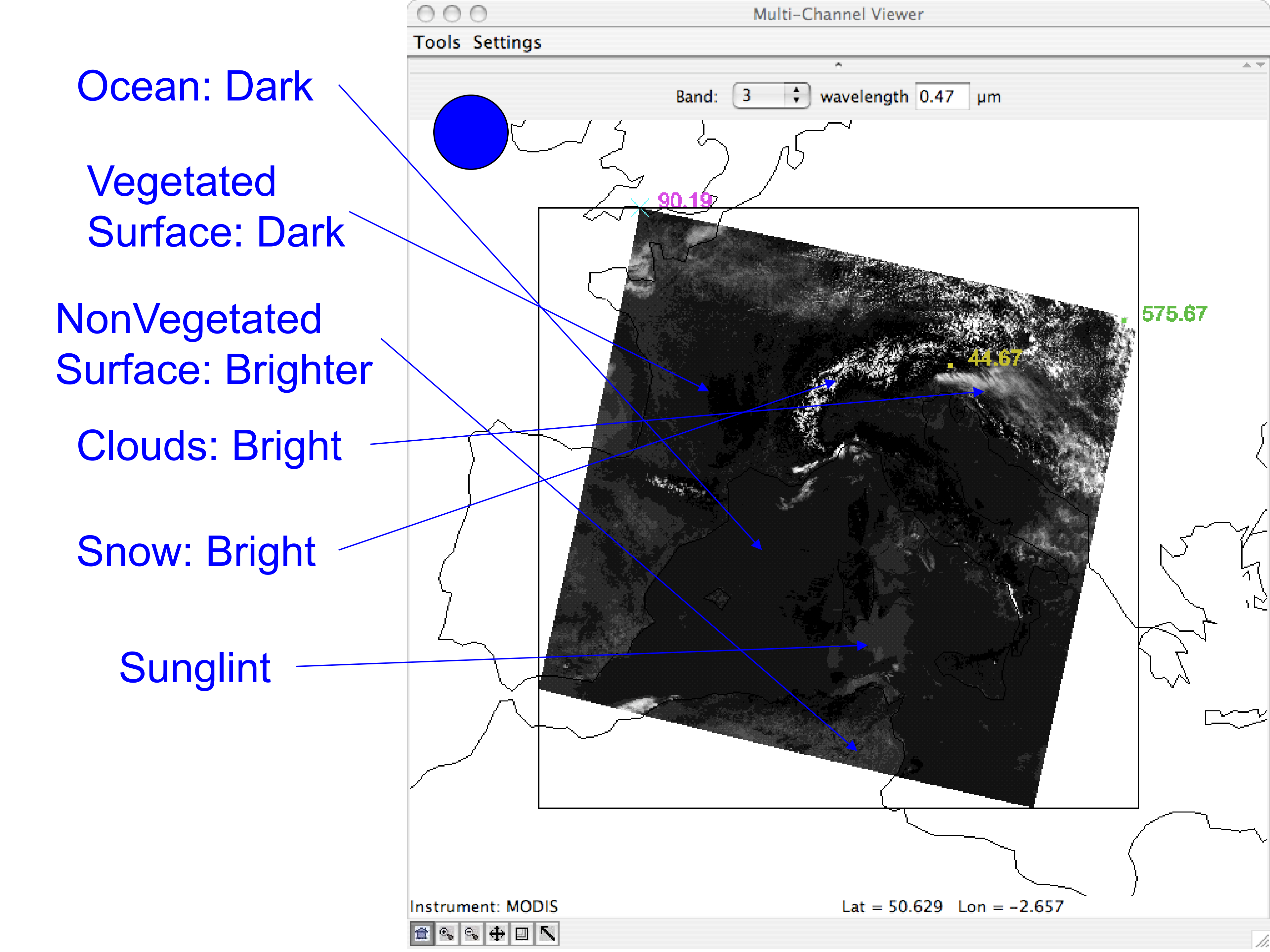
Only 1% is observed above 4 µm

Sensor Geometry




Ocean: Dark
Vegetated Surface: Dark
NonVegetated Surface: Brighter
Clouds: Bright
Snow: Bright
Sunglint
Multi-Channel Viewer
Tools Settings
Band: 1 wavelength 0.65 µm
21.84
425.44
12.15
Instrument: MODIS
Lat = 50.629 Lon = -2.657


Ocean: Dark
Vegetated Surface: Dark
NonVegetated Surface: Brighter
Clouds: Bright
Snow: Bright
Sunglint
Multi-Channel Viewer
Tools Settings
Band: 4 wavelength 0.56 µm
44.23
26.06
487.23
Instrument: MODIS
Lat = 50.629 Lon = -2.657


Ocean: Dark
Vegetated Surface: Dark
NonVegetated Surface: Brighter
Clouds: Bright
Snow: Bright
Sunglint
Multi-Channel Viewer
Tools Settings
Band: 3 wavelength 0.47 µm
90.19
575.67
44.67
Instrument: MODIS
Lat = 50.629 Lon = -2.657

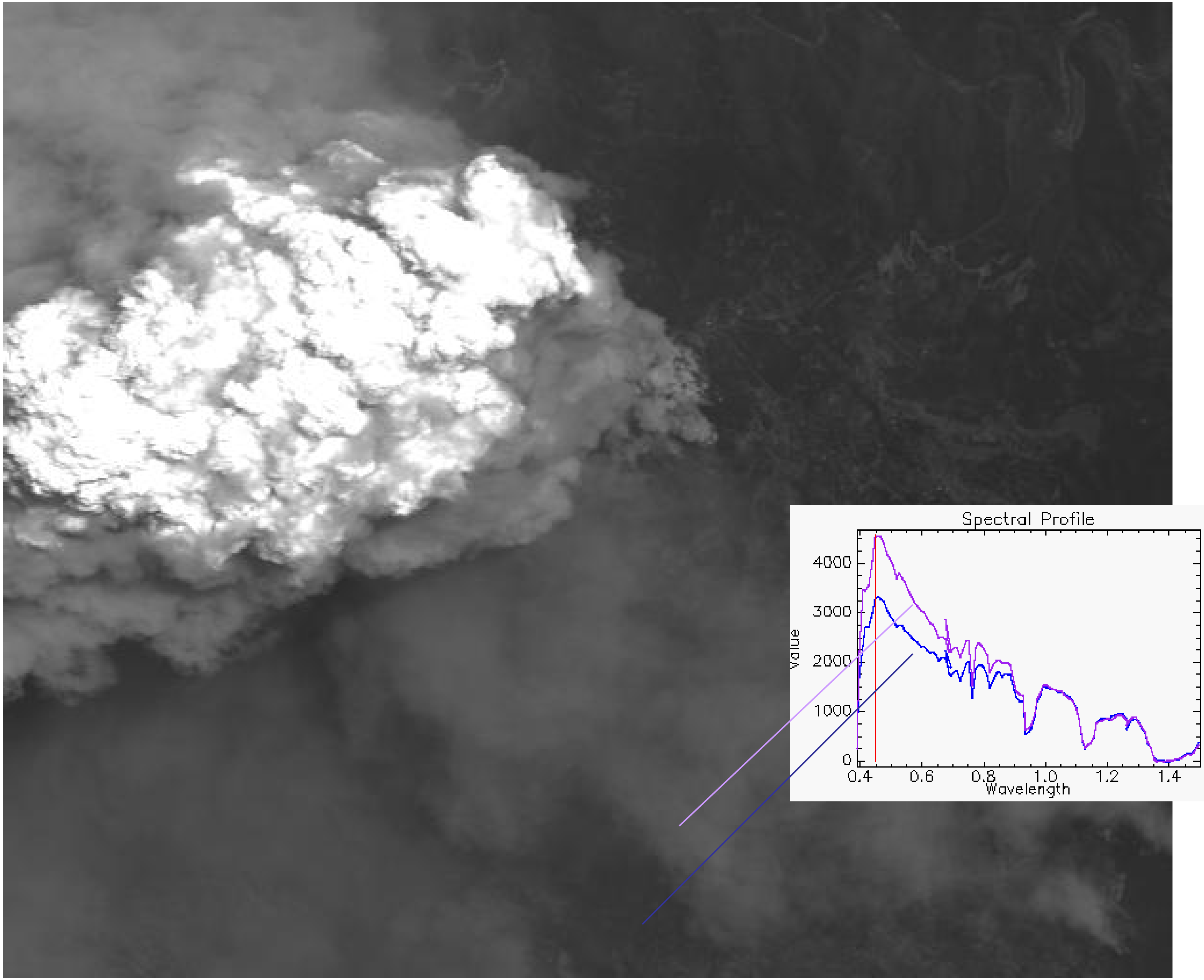
Linden_shadow_1.581_1.640um

Shadow

Linden_vegetation_0.831_0.889

Linden_0.577_0.696_um

Linden_haze_0.439_0.498um



Smoke

Bit Depth and Value Range

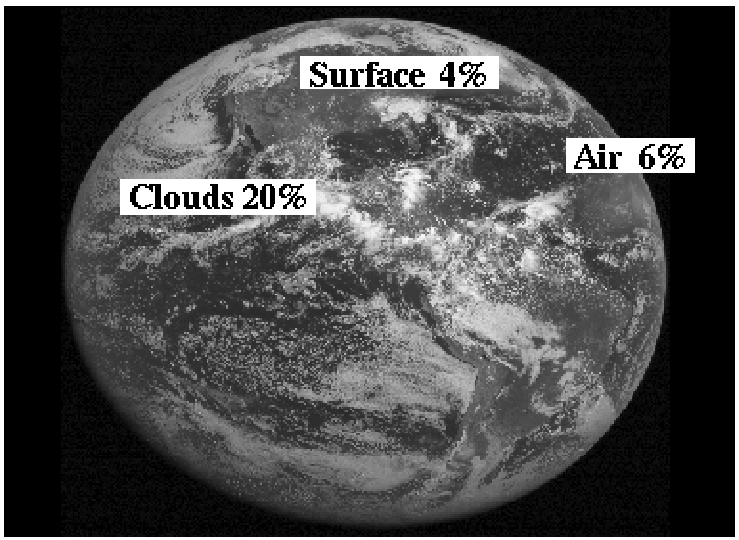
- With 12 bits 2^{12} integer numbers can be represented
  - Given ΔR, the range of radiances we want to observe, the smallest observable variation is $\Delta R / 2^{12}$
  - Given dR smallest observable variation, the range of observable radiances is $dR * 2^{12}$
  - If too small of the range is used, then the quantification error range is larger. If the range is too large, then there is more possbility for 'saturation'.

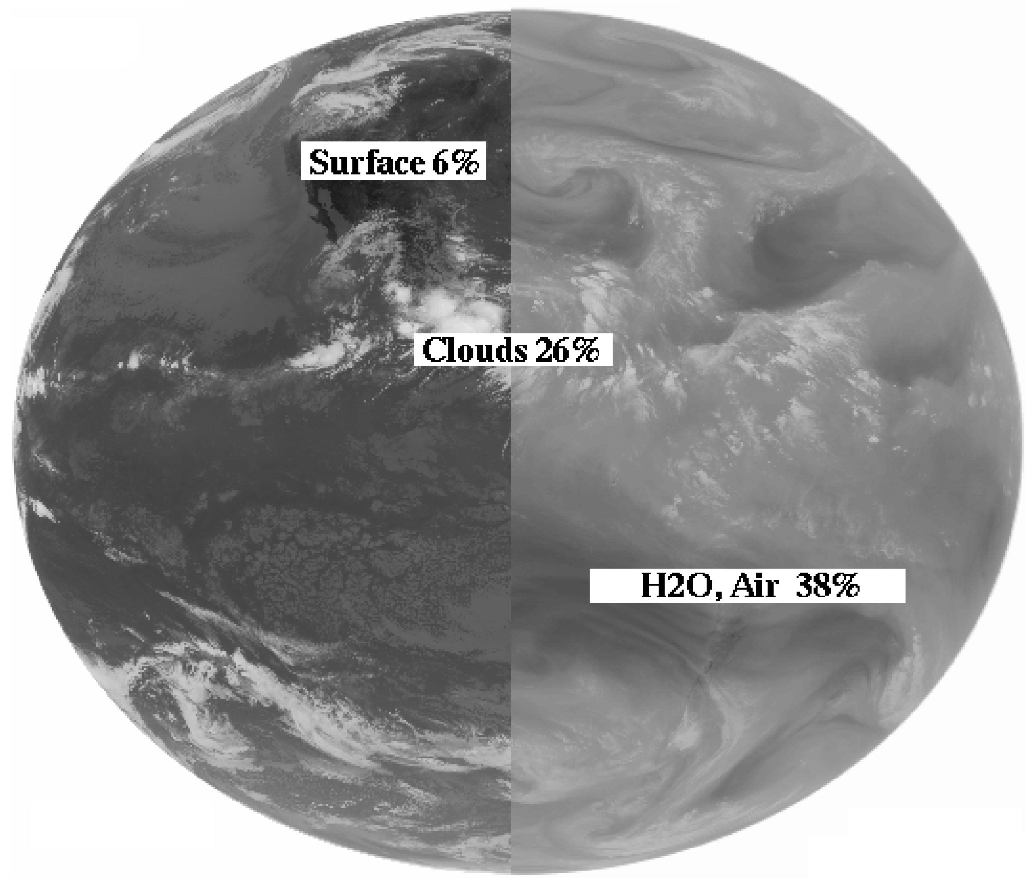
GOES-10 Imager is 10-bit, while the GOES-10 sounder in 13-bit. MODIS data is 12-bit.

Global Mean Energy Balance

Global Mean Energy Balance

Top of the Atmosphere





Reflected Solar Radiation (30%)

Outgoing Infrared Radiation (70%)

NOAA/NESDIS/ORA/ARAD/ASPT