Review of Remote Sensing Fundamentals

Allen Huang
Cooperative Institute for Meteorological Satellite Studies
Space Science & Engineering Center
University of Wisconsin-Madison, USA

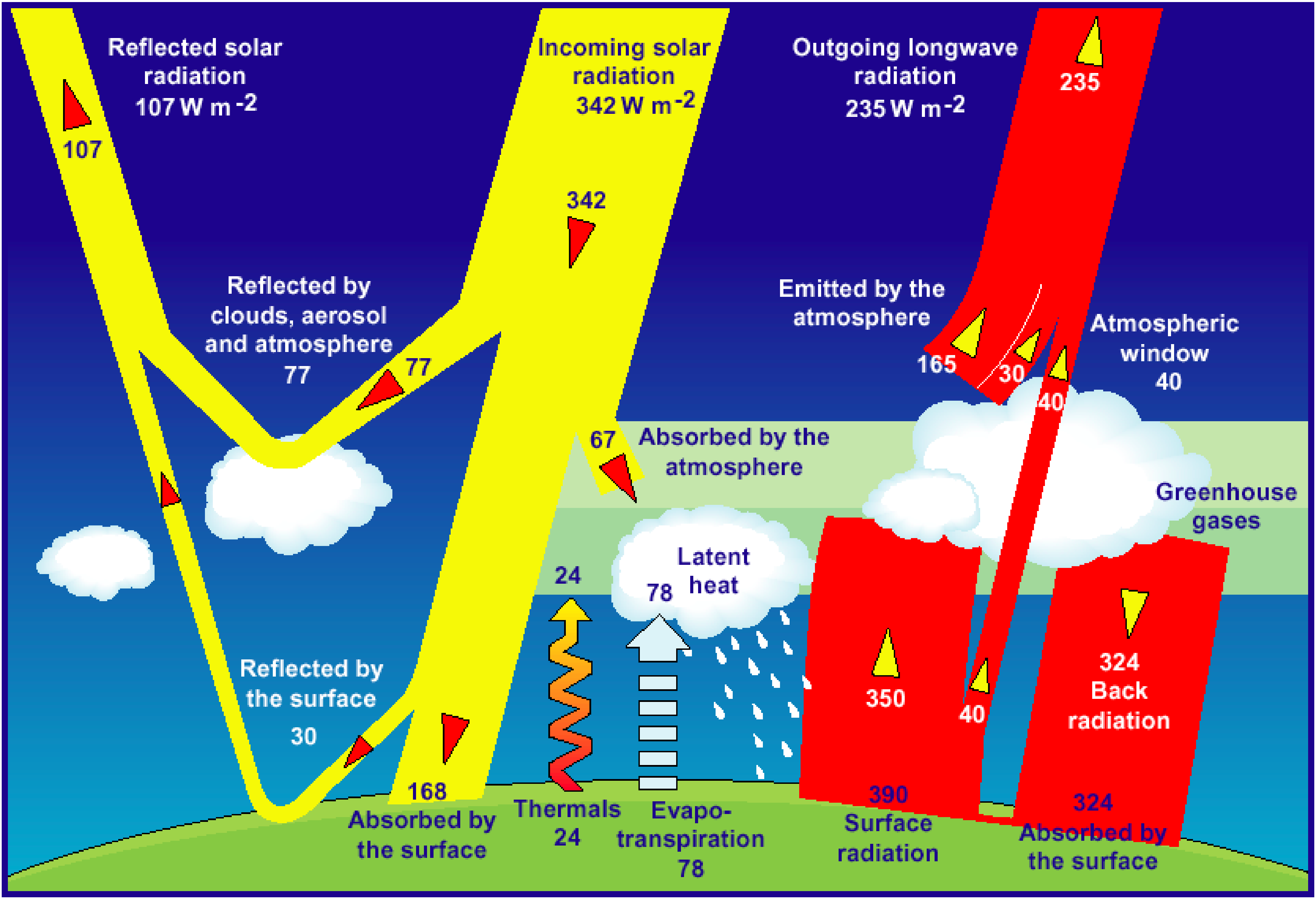
Topics:

- ❖ Visible & Infrared Measurement Principal
- ❖ Radiation and the Planck Function
- ❖ Infrared Radiative Transfer Equation

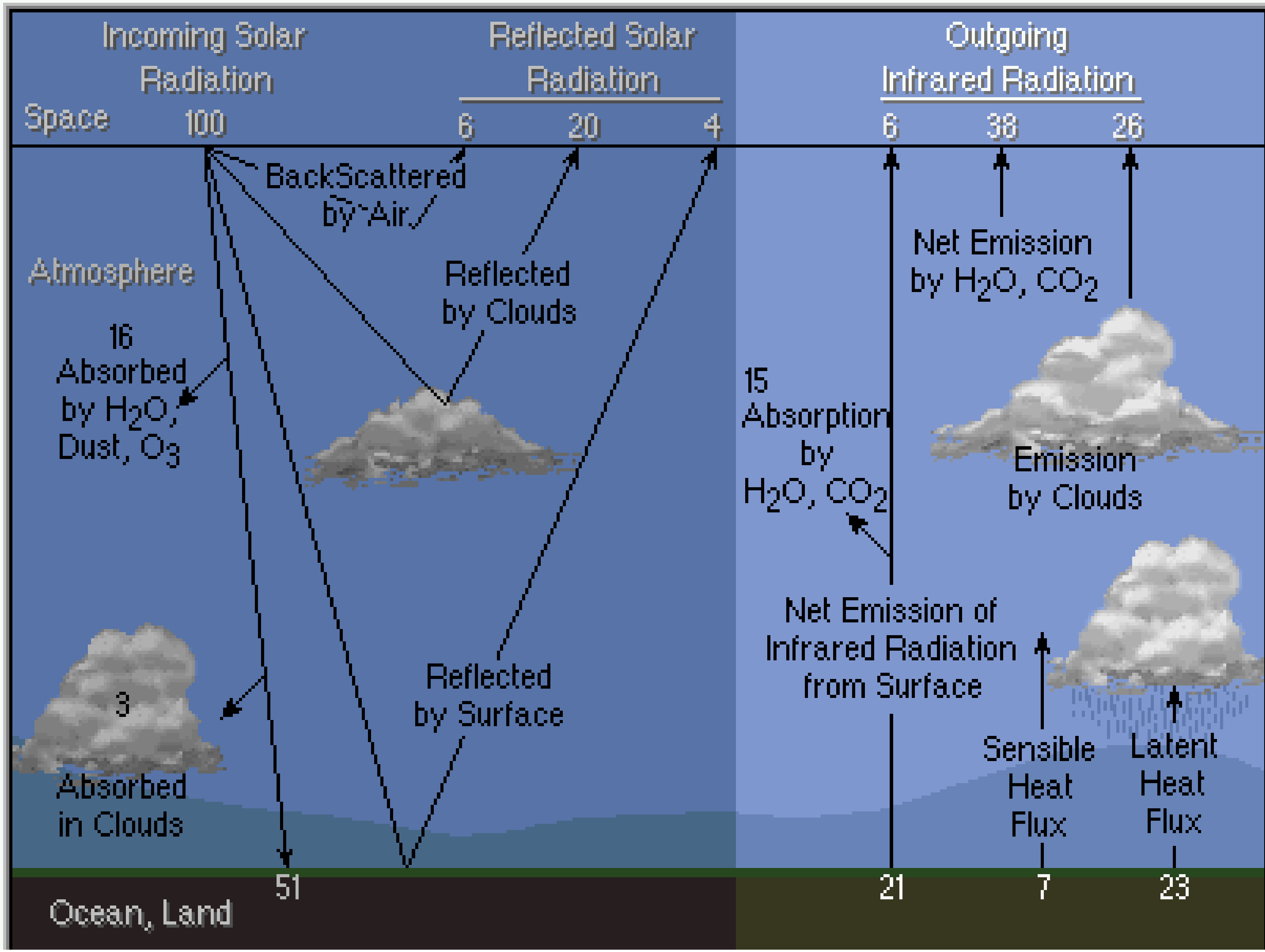
Selected Material Provided
by Bill Smith, Paul Menzel, Paolo Antonelli, Steve Miller & Gerald van der Grijn

MODIS direct broadcast data for enhanced forecasting
and real-time environmental decision making
IGARSS 2009 MODIS DB Short Course
7-10 July 2009, Cape Town, South Africa
http://www.igarss09.org/SC04.asp

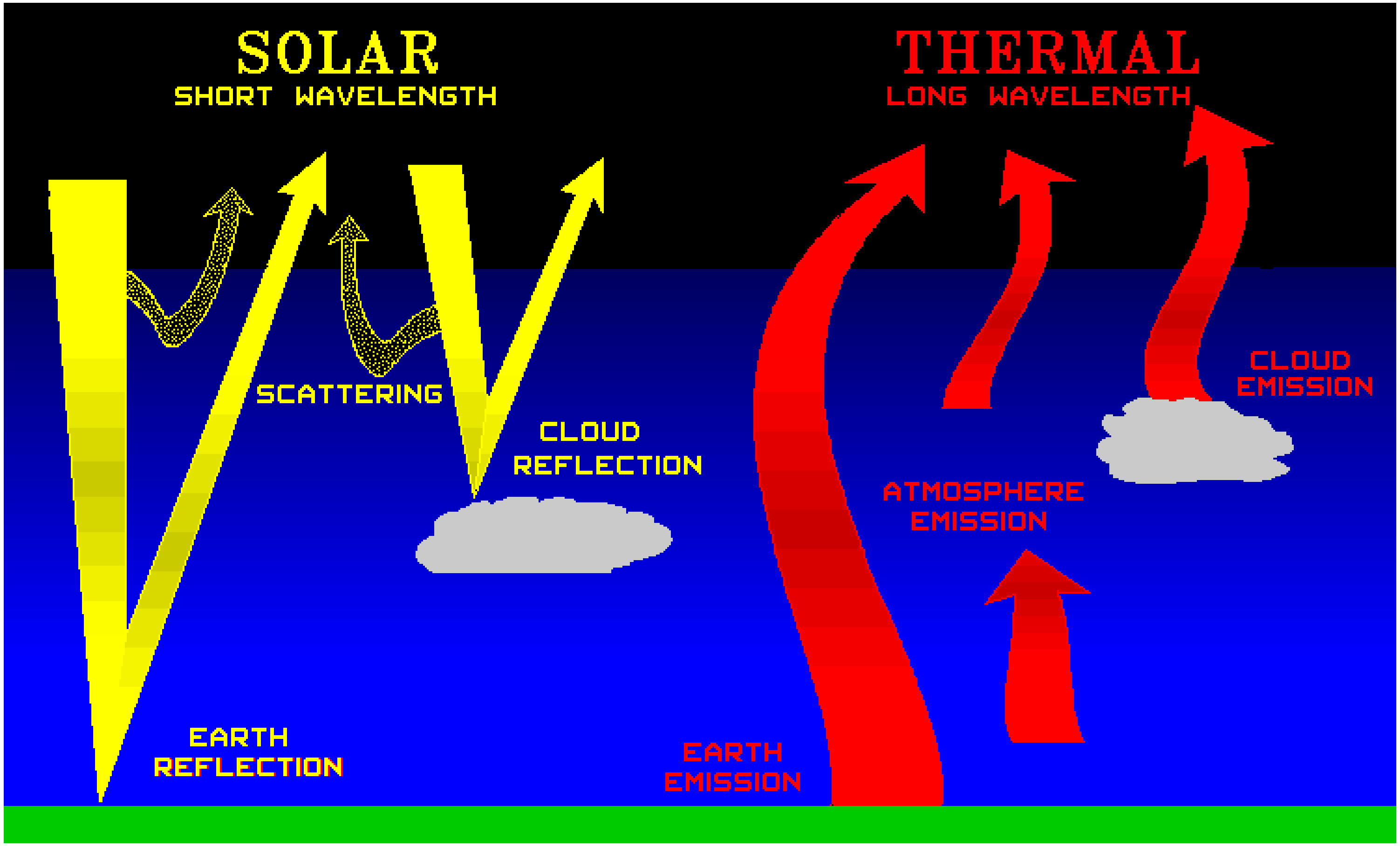
Earth System Energy Balance



Radiative Energy Balance



Remote Sensing of Natural Radiation



Visible & Near IR
(Reflective Bands)

Infrared (IR)
(Emissive Bands)

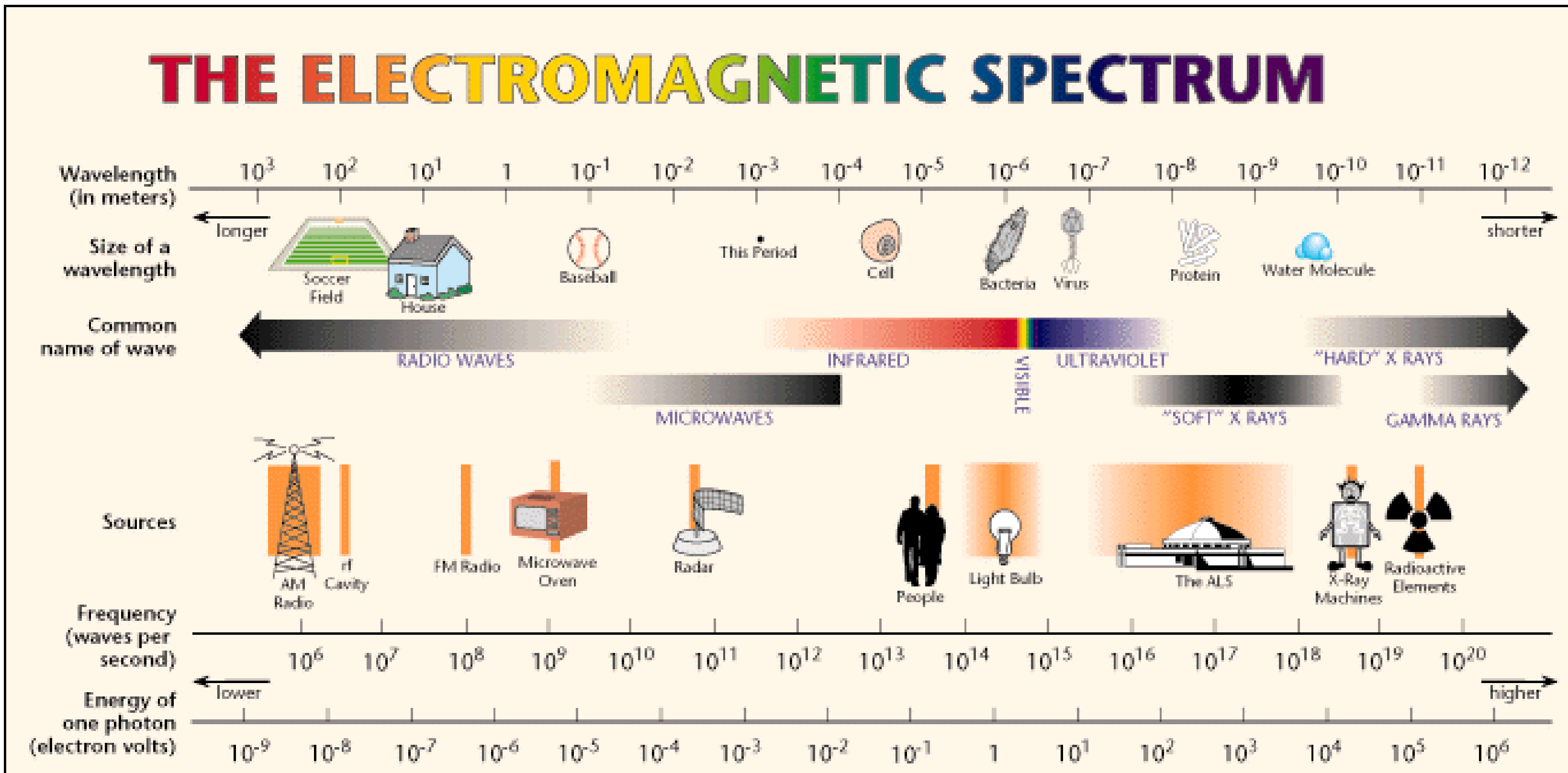
What do satellites actually measure ?

They measure TEMPERATURE, HUMIDITY, WIND, TRACE GASES, CLOUDS, AEROSOLS, OTHERS…, indirectly!

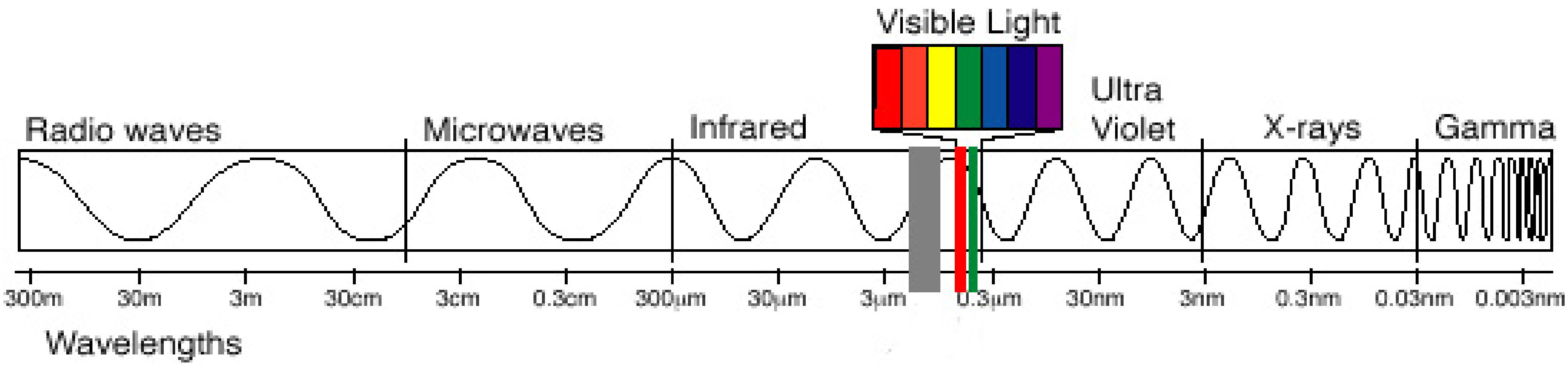
Instead, satellite observations are obtained using remote sensing techniques based on measurements of electromagnetic radiation

Electromagnetic Radiation

Every object with a temperature larger than 0 K emits electromagnetic radiation. Electromagnetic radiation therefore extends over a wide range of energies and wavelengths. The distribution of all radiant energies can be plotted in a chart known as the ***electromagnetic spectrum***.



The Electromagnetic (EM) Spectrum

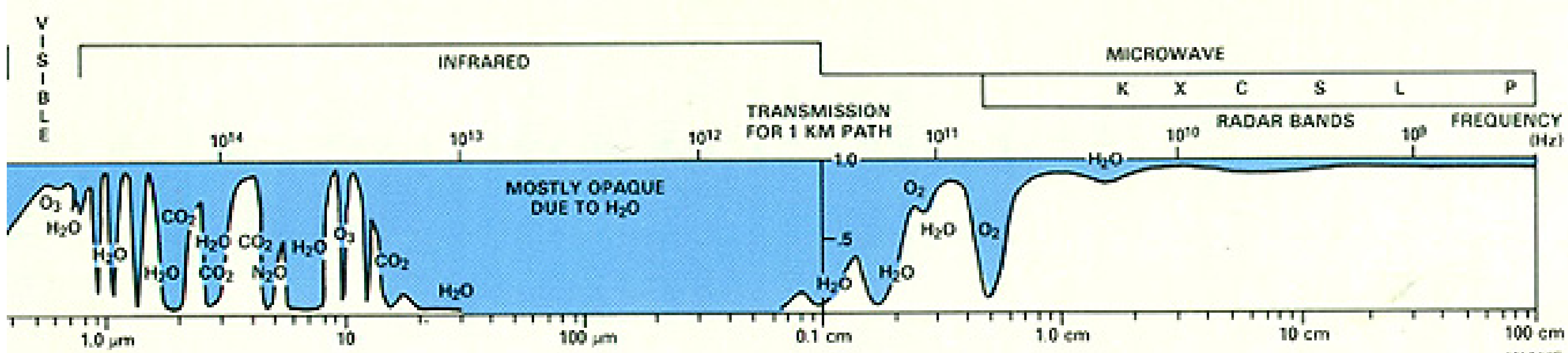


Remote sensing uses radiant energy that is reflected and emitted from Earth at various "wavelengths" of the electromagnetic spectrum

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

Electromagnetic Radiation

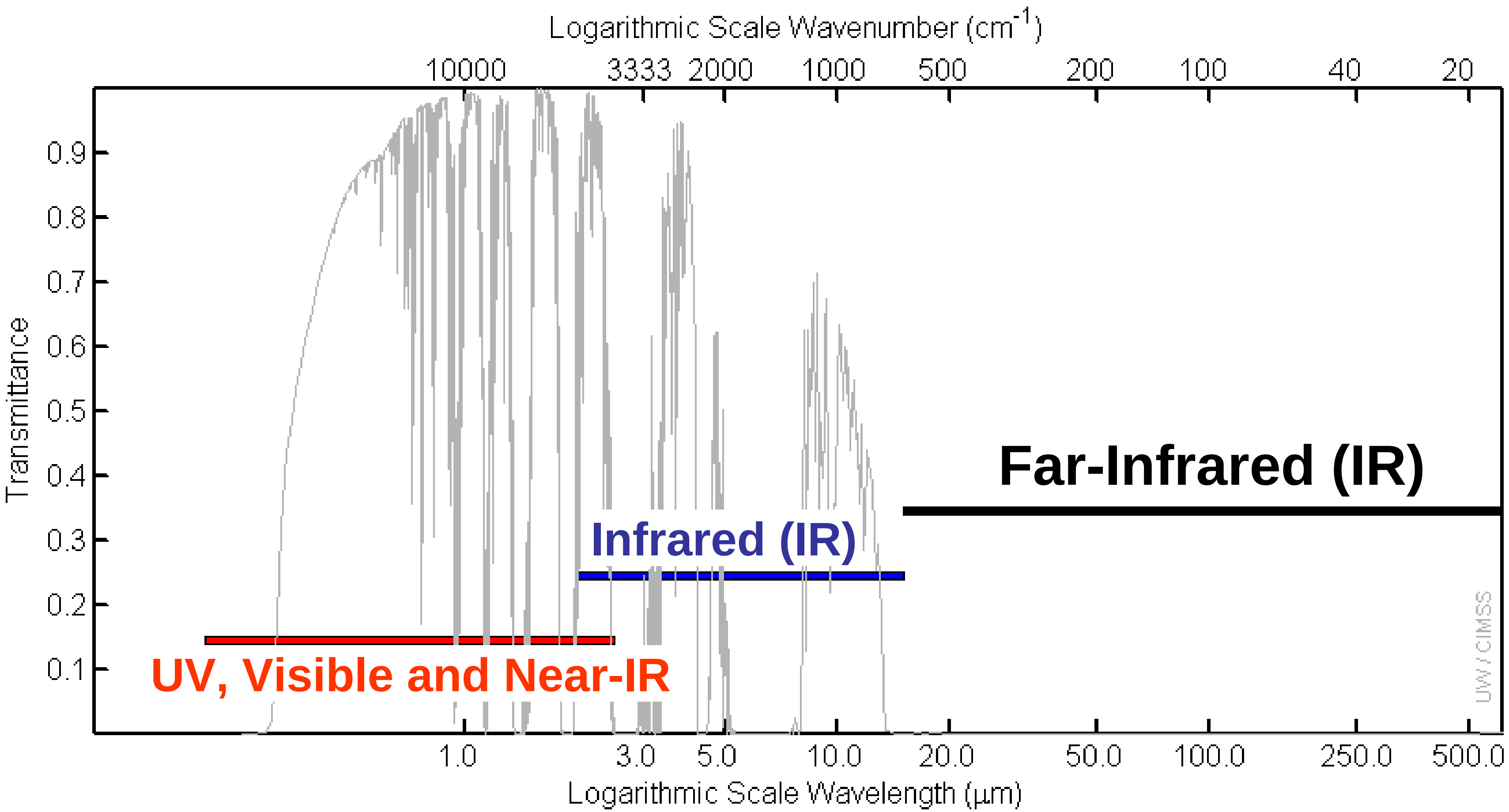
In the earth’s atmosphere, the radiation is partly to completely transmitted at some wavelengths; at others those photons are variably absorbed by interaction with air molecules.



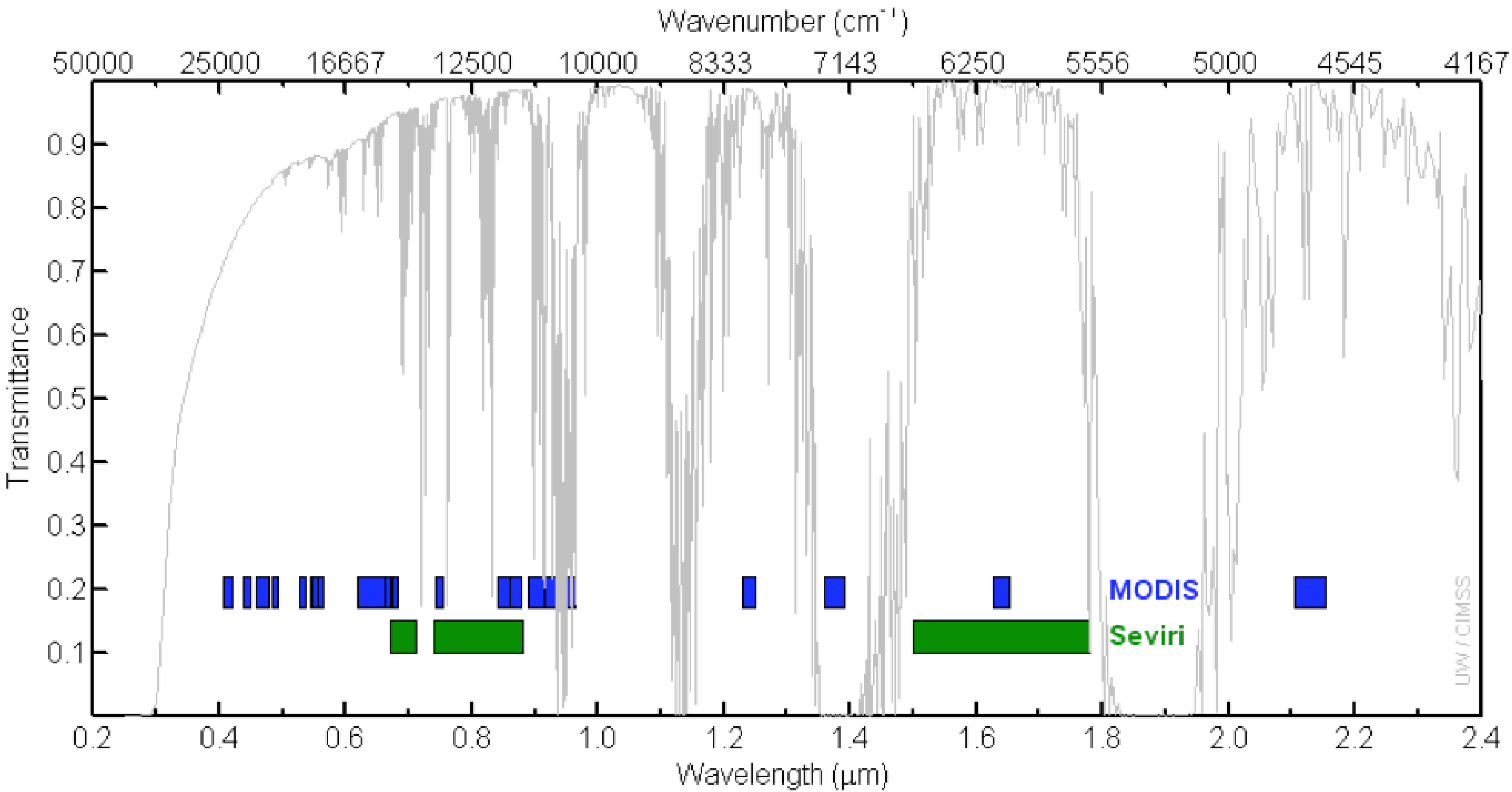
Blue zones mark minimal passage of incoming and/or outgoing radiation, whereas, white areas denote atmospheric windows in which the radiation doesn’t interact much with air molecules.

Most remote sensing instruments operate in one of these windows by making their measurements tuned to specific frequencies that pass through the atmosphere. Some sensors, especially those on meteorological satellites, directly measure absorption phenomena.

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



MODIS Visible and Near-infrared Bands



Visible →

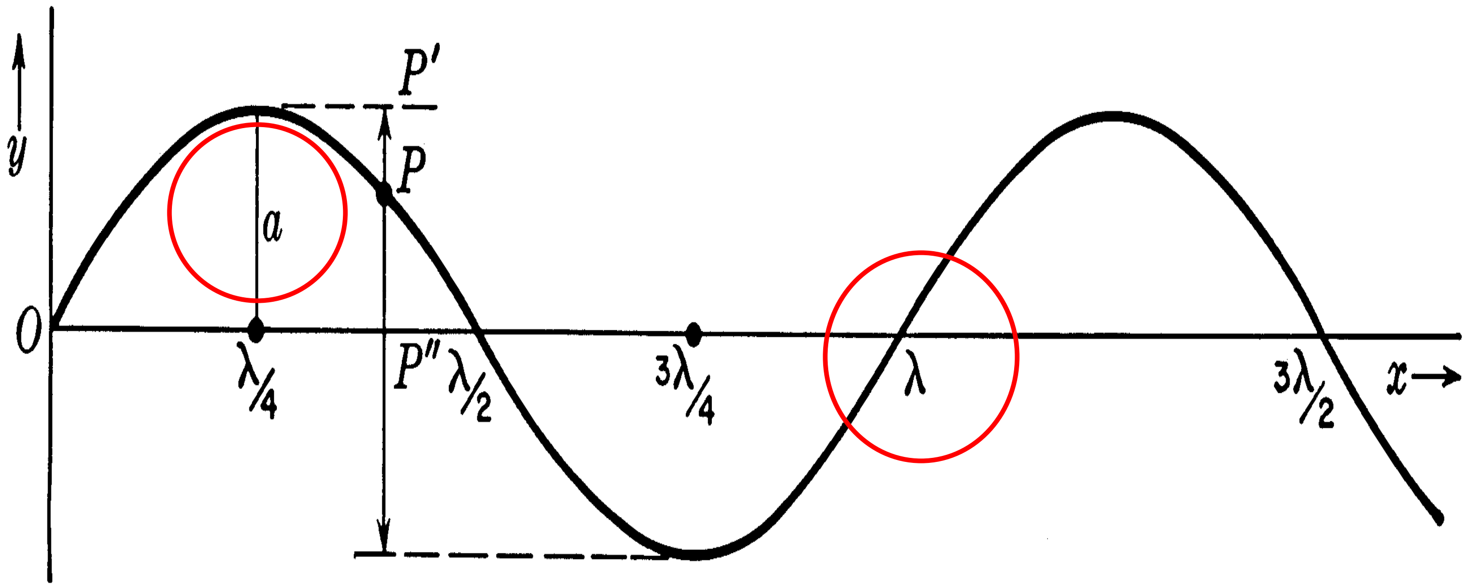
Near IR →

MODIS Reflected Solar Bands

Primary Use	Band	Bandwidth[1]	Spectral Radiance[2]	Required SNR[3]
Land/Cloud/Aerosols Boundaries	1	620 - 670	21.8	128
	2	841 - 876	24.7	201
Land/Cloud/Aerosols Properties	3	459 - 479	35.3	243
	4	545 - 565	29.0	228
	5	1230 - 1250	5.4	74
	6	1628 - 1652	7.3	275
	7	2105 - 2155	1.0	110
Ocean Color/ Phytoplankton/ Biogeochemistry	8	405 - 420	44.9	880
	9	438 - 448	41.9	838
	10	483 - 493	32.1	802
	11	526 - 536	27.9	754
	12	546 - 556	21.0	750
	13	662 - 672	9.5	910
	14	673 - 683	8.7	1087
	15	743 - 753	10.2	586
	16	862 - 877	6.2	516
Atmospheric Water Vapor	17	890 - 920	10.0	167
	18	931 - 941	3.6	57
	19	915 - 965	15.0	250

Units: Wavelength (μm) vs. Wavenumber) (cm^{-1})

wavelength λ (μm) : distance between peaks
wavenumber ν (cm^{-1}): number of waves per unit distance



$$\lambda = 1/\nu$$

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

$$\lambda\ (\mu m) = 10{,}000 / \nu\ (cm^{-1})$$

Radiation is characterized by wavelength λ and amplitude a

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)

Definitions of Radiation

QUANTITY	SYMBOL	UNITS
Energy	dQ	Joules
Flux	dQ/dt	Joules/sec = Watts
Irradiance	dQ/dt/dA	Watts/meter^2
Monochromatic Irradiance	dQ/dt/dA/dλ	W/m^2/micron
	or	
	dQ/dt/dA/dν	W/m^2/cm^{-1}
Radiance	dQ/dt/dA/dλ/dΩ	W/m^2/micron/ster
	or	
	dQ/dt/dA/dν/dΩ	W/m^2/cm^{-1}/ster

Radiation is governed by Planck's Law

In wavelength:

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

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:

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

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

$$B(\lambda,T) = c_1 / \lambda^5 / [e^{c_2/\lambda T} - 1] \quad (\text{mW/m}^2\text{/ster/cm})$$

Planck's Law

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 λ(max) = .2897/T

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

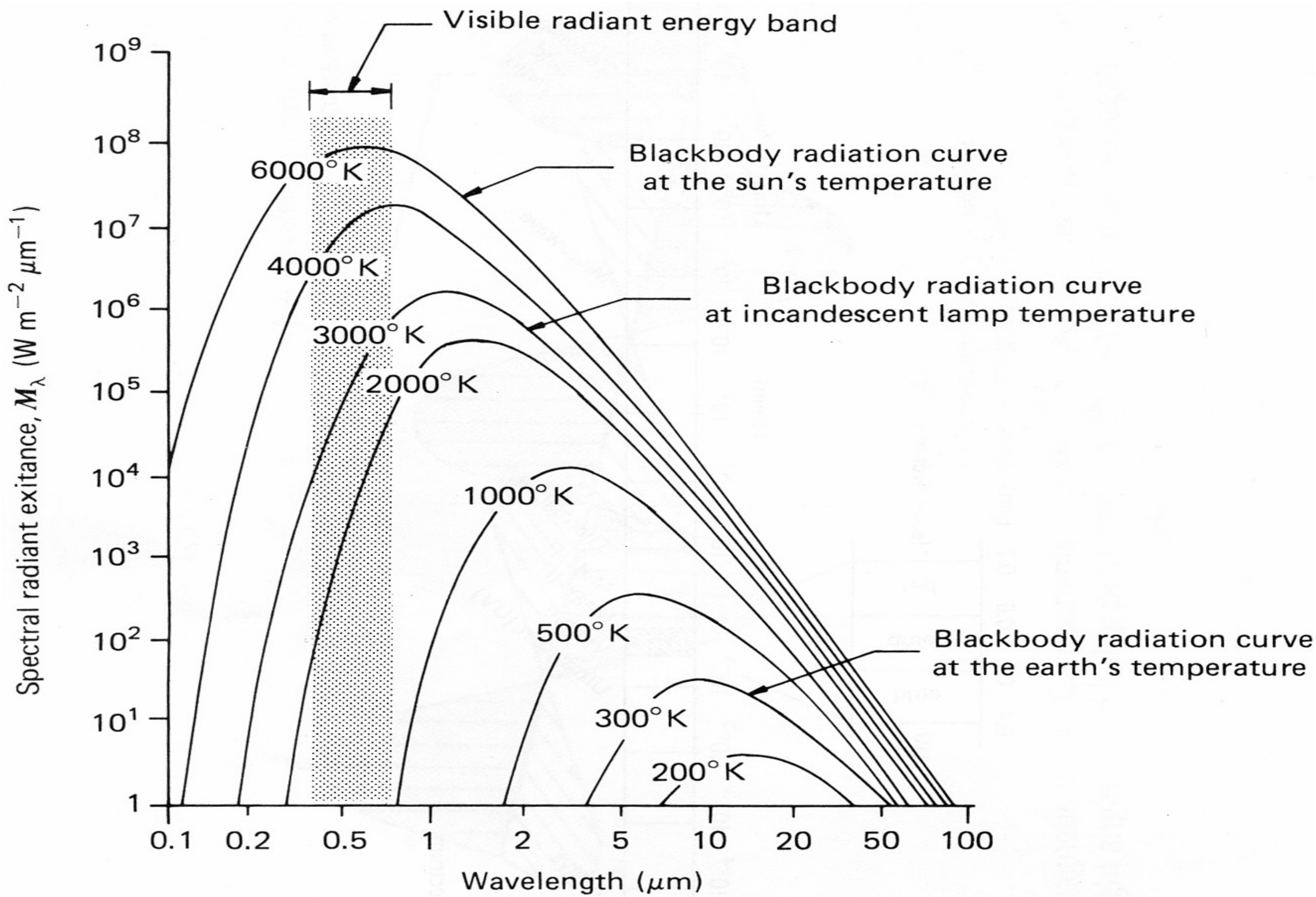
Stefan-Boltzmann Law $E = \pi \int_o^\infty B(\lambda,T)\, d\lambda = \sigma T^4$, where σ = 5.67 x 10-8 W/m2/deg4.

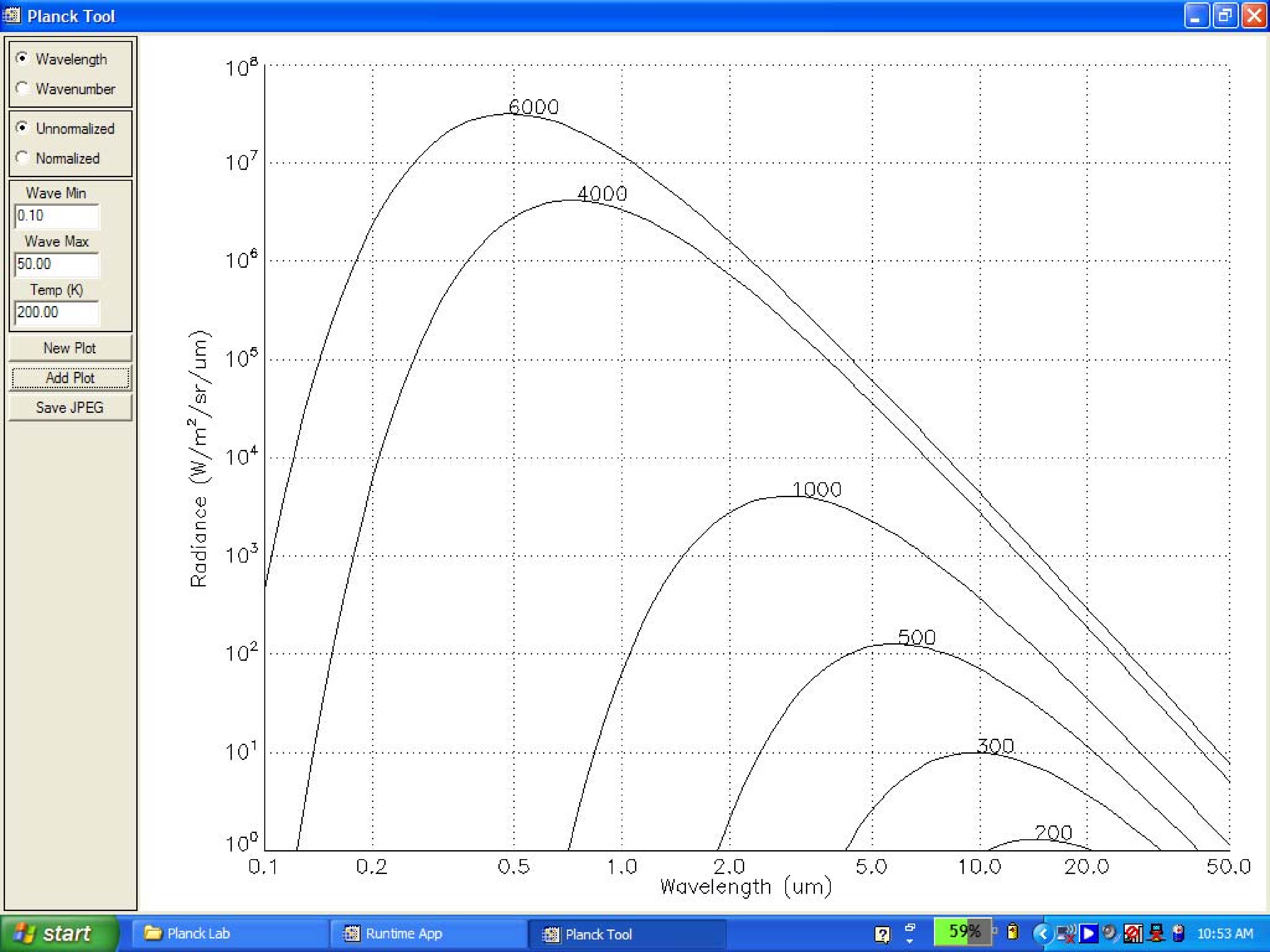
states that irradiance of a black body (area under Planck curve) is proportional to T^4 .

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
Radiance (W/m2/sr/um)
Wavelength (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
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 $B(\nu_{max},T) \sim T^{**}3$.

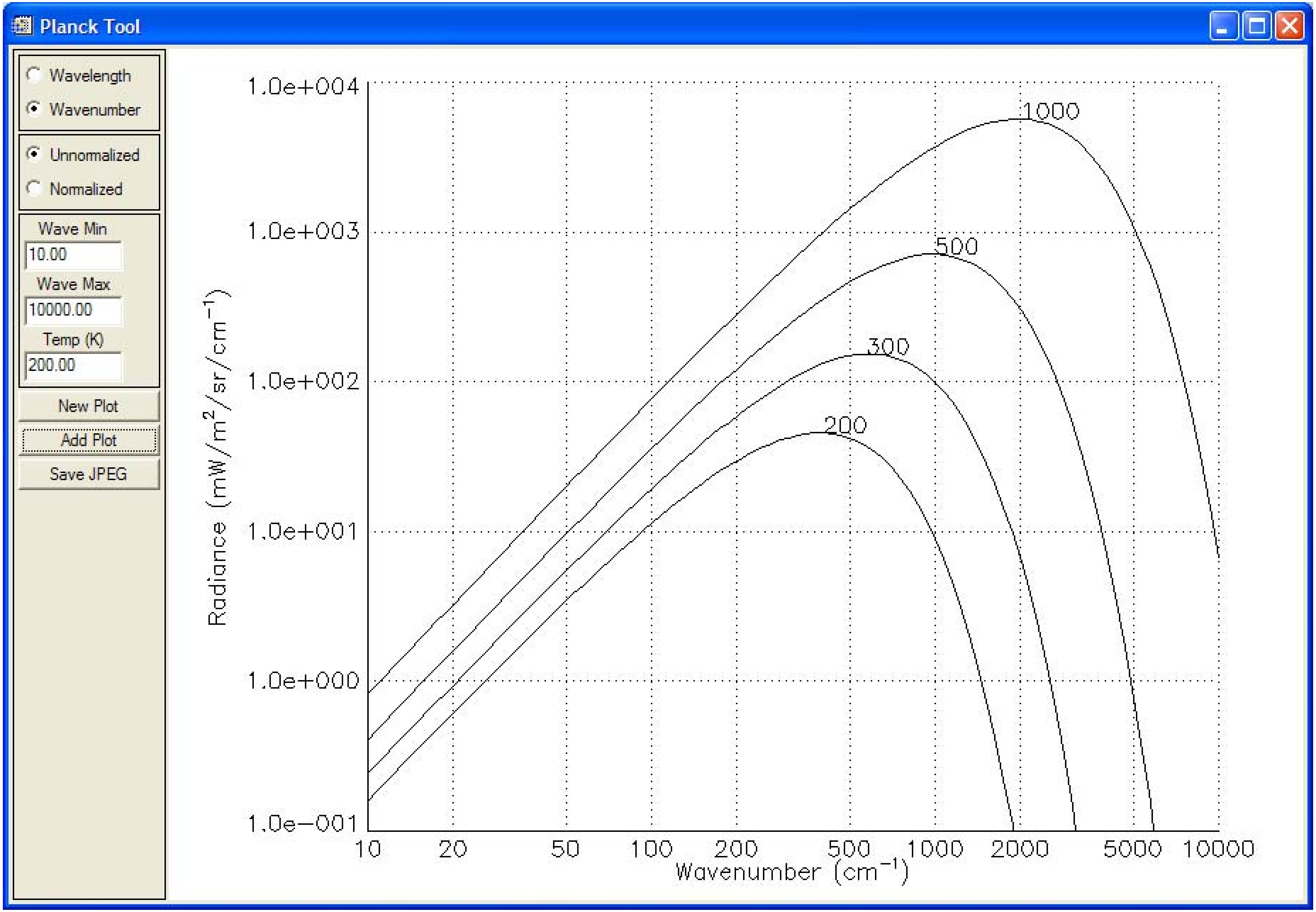
Stefan-Boltzmann Law $E = \pi \int_{o}^{\infty} B(\nu,T)\, d\nu = \sigma T^4$, where $\sigma = 5.67 \times 10\text{-}8\ W/m^2/deg^4$.

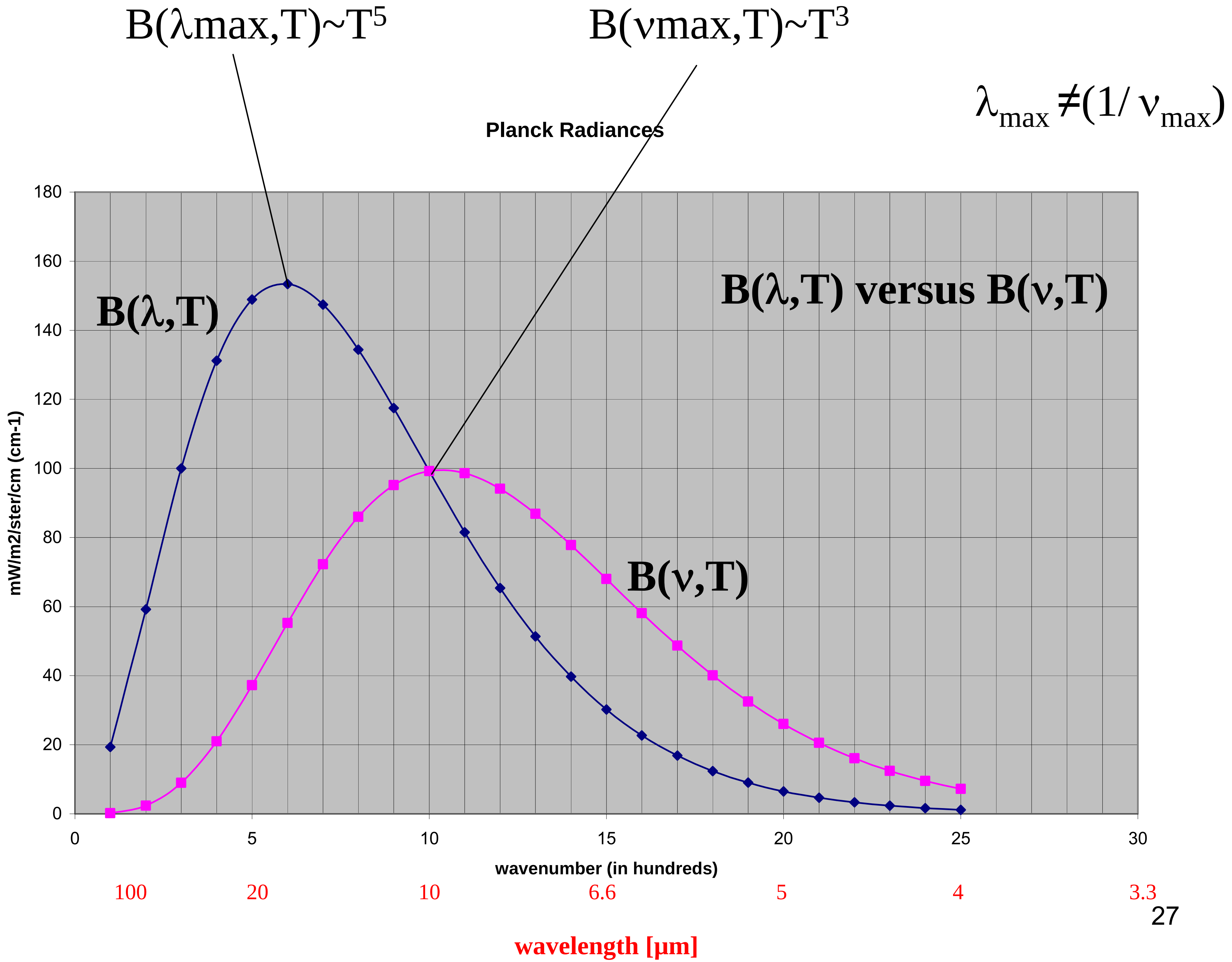
states that irradiance of a black body (area under Planck curve) is proportional to T^4 .

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

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

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

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

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) = 0.2897/T

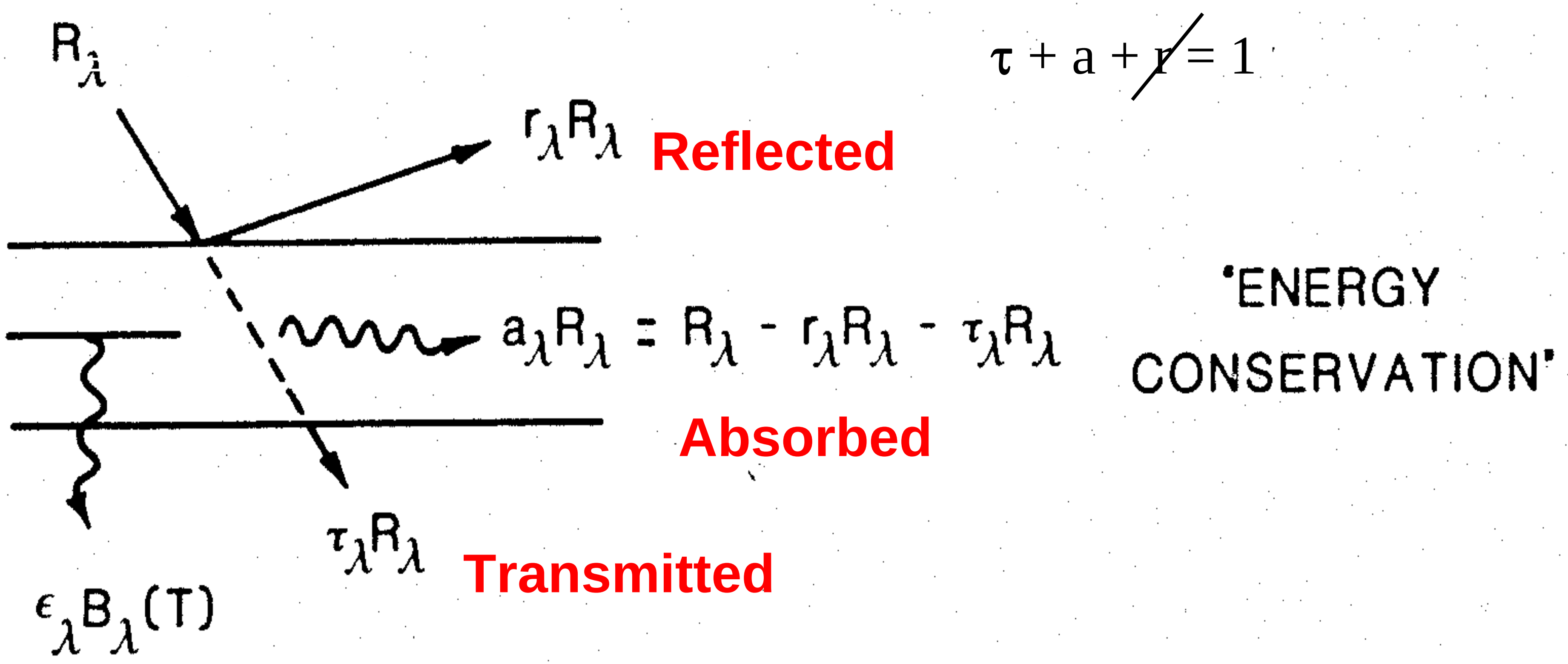
$B(\lambda_{max},T) \sim T^{**}5.$

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

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

Wavelength (μm) vs. Wavenumber (cm^{-1})

Energy conservation: $\tau + a + r = 1$



$$R_\lambda = (a_\lambda + r_\lambda + \tau_\lambda)\, R_\lambda$$

$$\tau + a + r = 1$$

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:

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

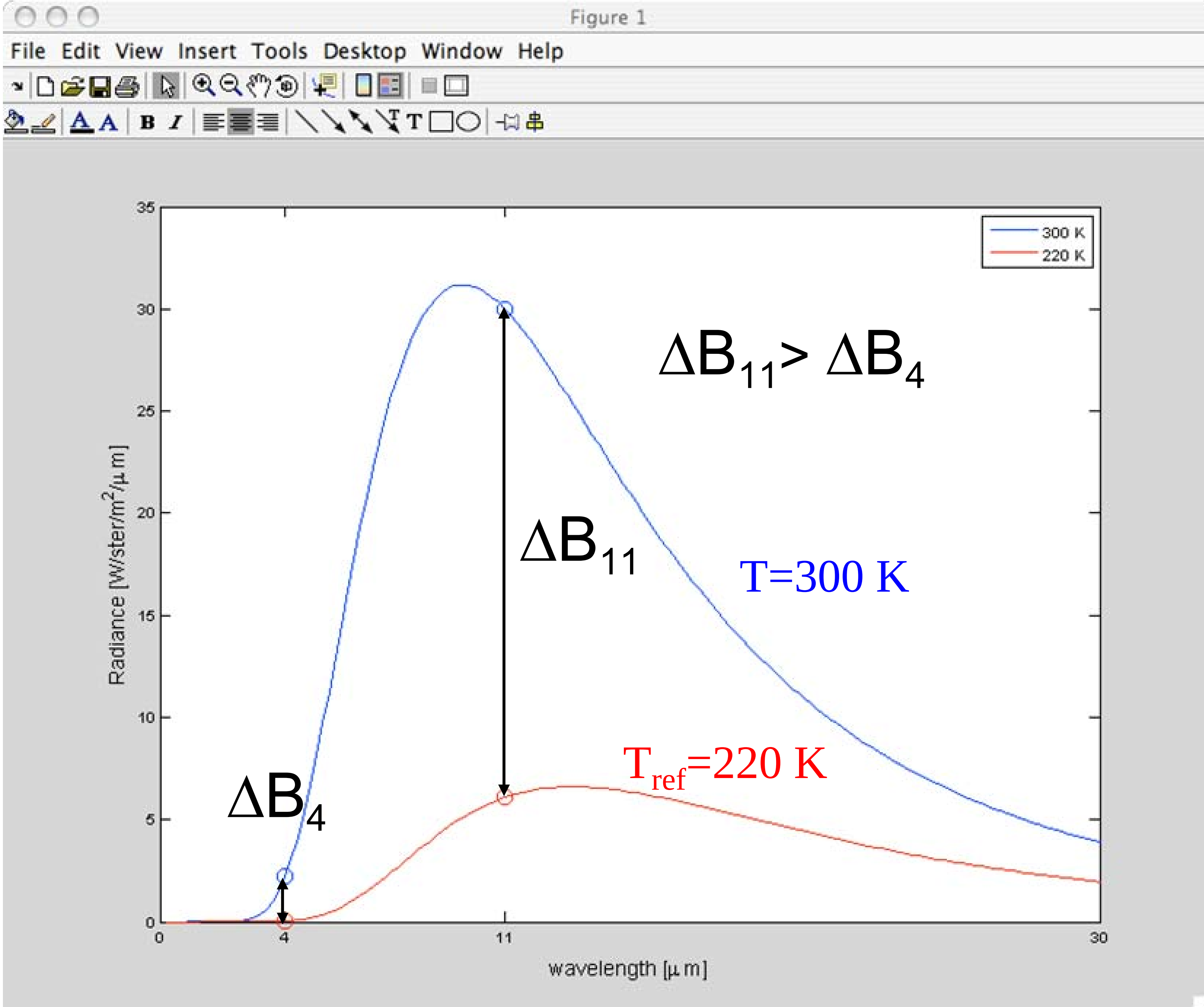


Figure 1
File Edit View Insert Tools Desktop Window Help
300 K
220 K
ΔB11> ΔB4
ΔB11
T=300 K
Tref=220 K
ΔB4
Radiance [W/ster/m2/µ m]
wavelength [µ m]
0
5
10
15
20
25
30
35
0
4
11
30
1

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

$$\Downarrow$$

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

$$\Downarrow$$

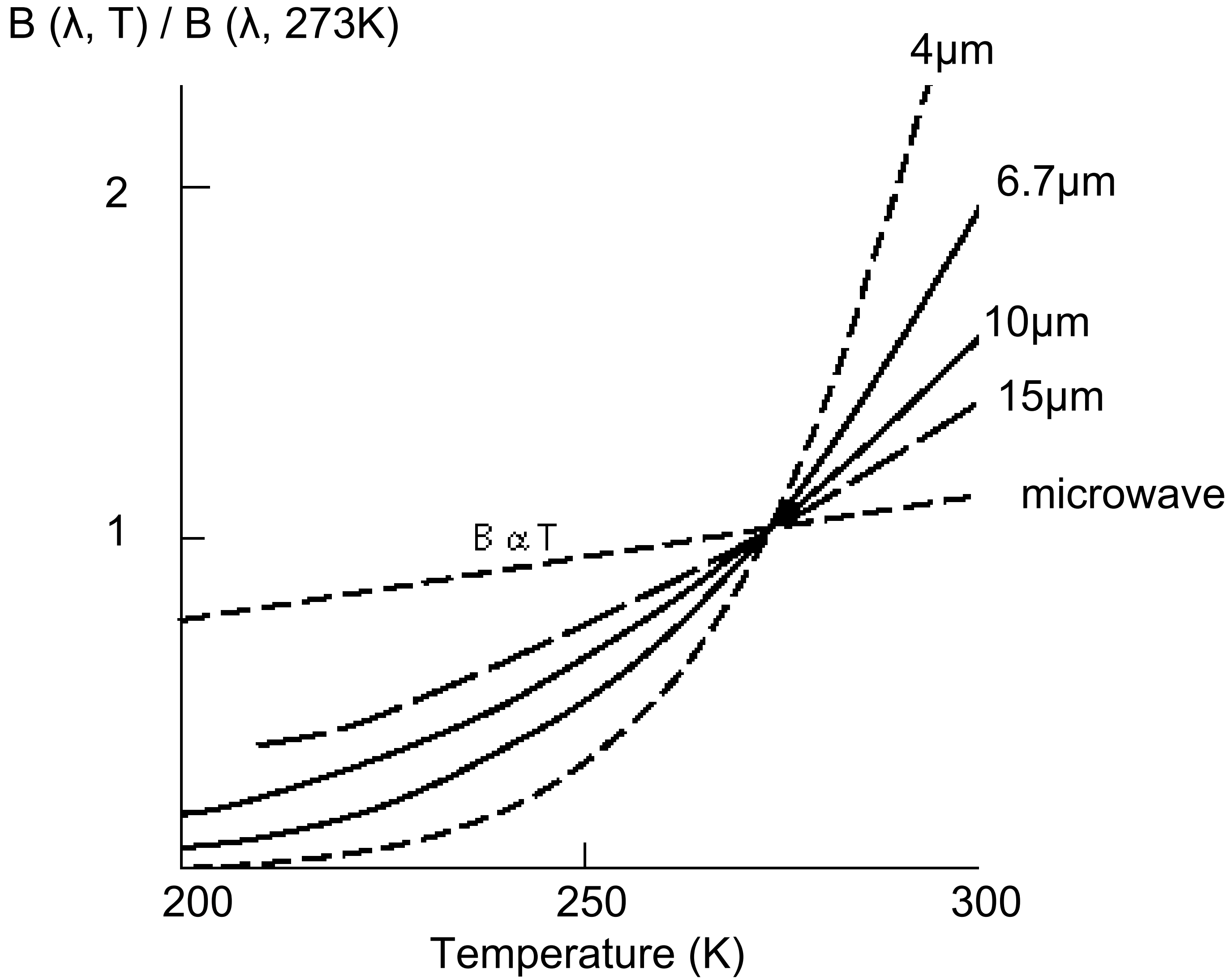
$$B \propto T^{\ \alpha}$$

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



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

$B(10\ um,273)= 6.1$

$B(10\ um,200)= 0.9 \rightarrow 0.15$

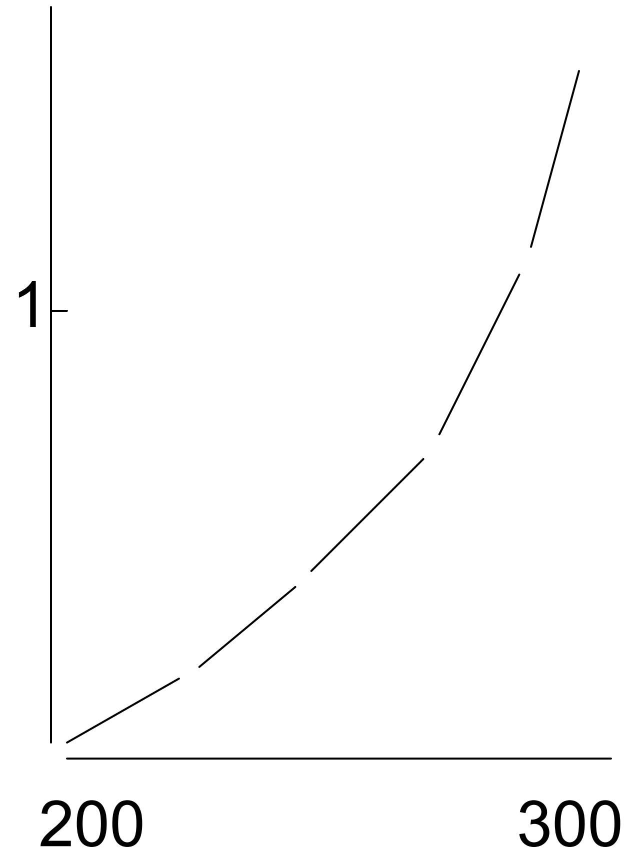
$B(10\ um,220)= 1.7 \rightarrow 0.28$

$B(10\ um,240)= 3.0 \rightarrow 0.49$

$B(10\ um,260)= 4.7 \rightarrow 0.77$

$B(10\ um,280)= 7.0 \rightarrow 1.15$

$B(10\ um,300)= 9.9 \rightarrow 1.62$



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

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

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

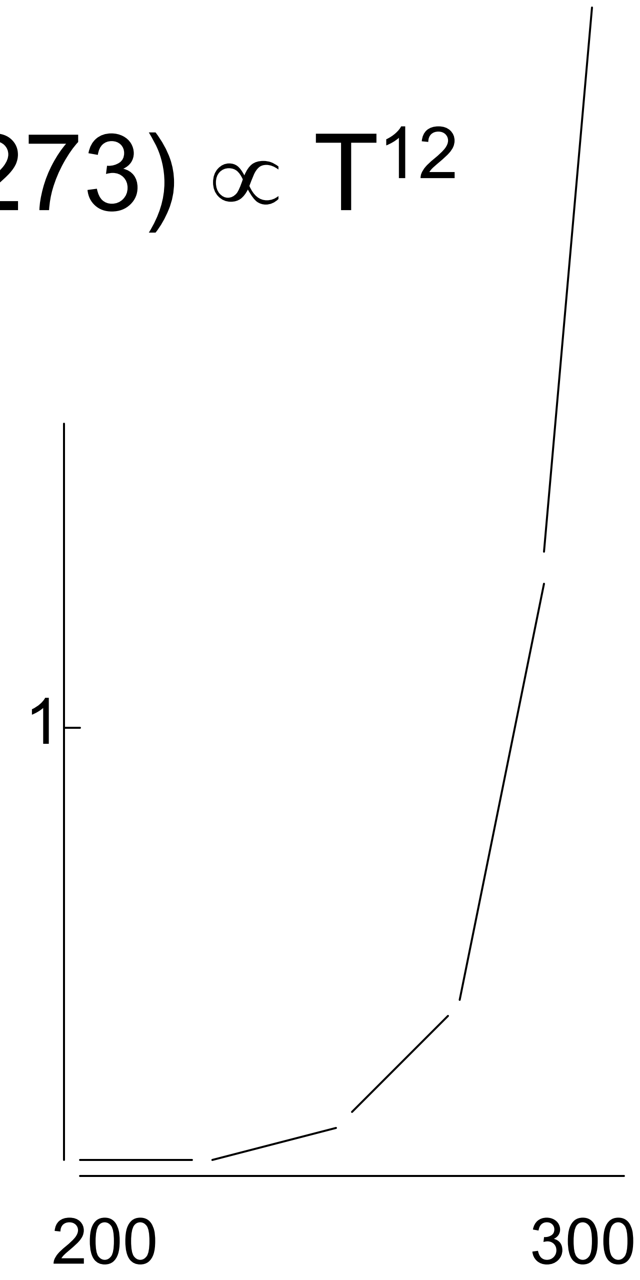
$B(4\ um,220) = 9.2 \times 10^{-3} \rightarrow 0.0$

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

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

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

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



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

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

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

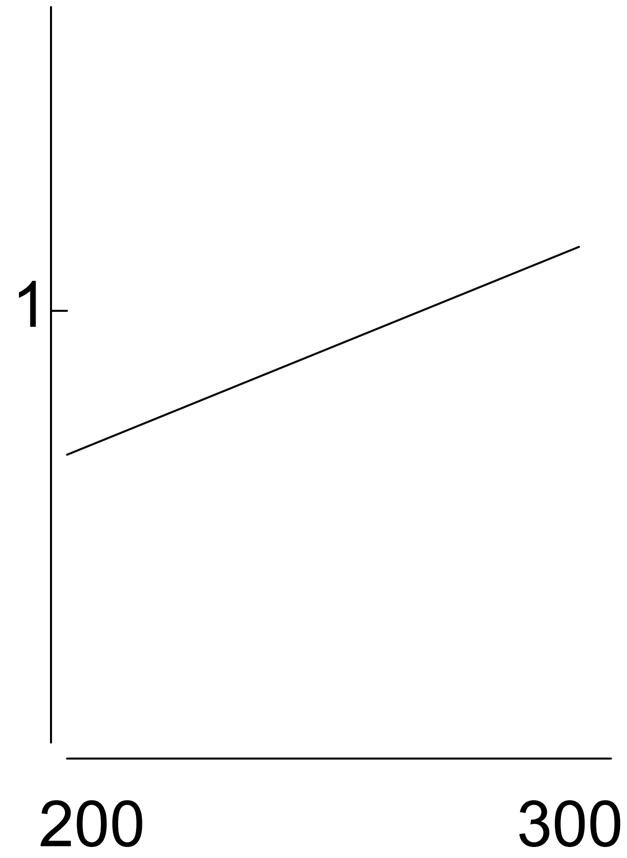
$B(0.3\ cm, 220) = 2.0 \rightarrow 0.78$

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

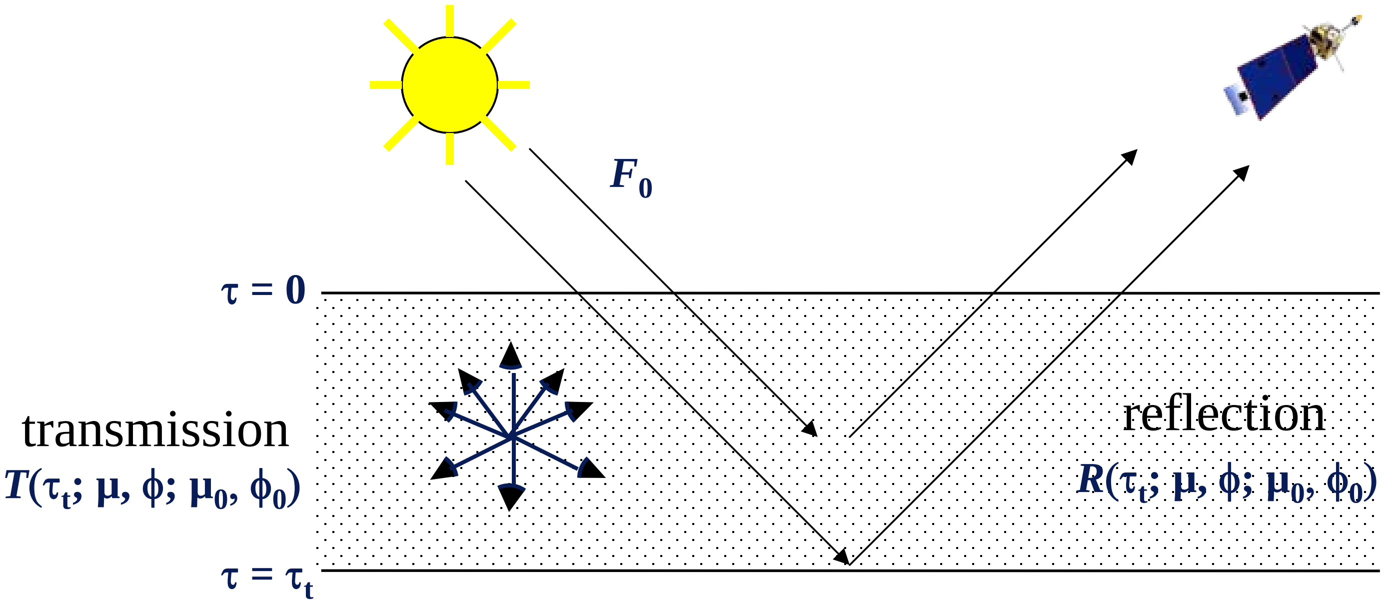
$B(0.3\ cm, 260) = 2.4 \rightarrow 0.94$

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

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



Reflection and Transmission of Plane-Parallel Layers



$$R(\tau_a, \omega_0; \mu, \mu_0, \phi) = \frac{\pi I(0, -\mu, \phi)}{\mu_0 F_0}$$

where

μ	=	absolute value of the cosine of the zenith angle $\lvert\cos\theta\rvert$
μ_0	=	cosine of the solar zenith angle $\cos\theta_0$
ϕ	=	relative azimuth angle between the direction of propagation of the emerging radiation and the incident solar direction

Visible: Reflective Bands

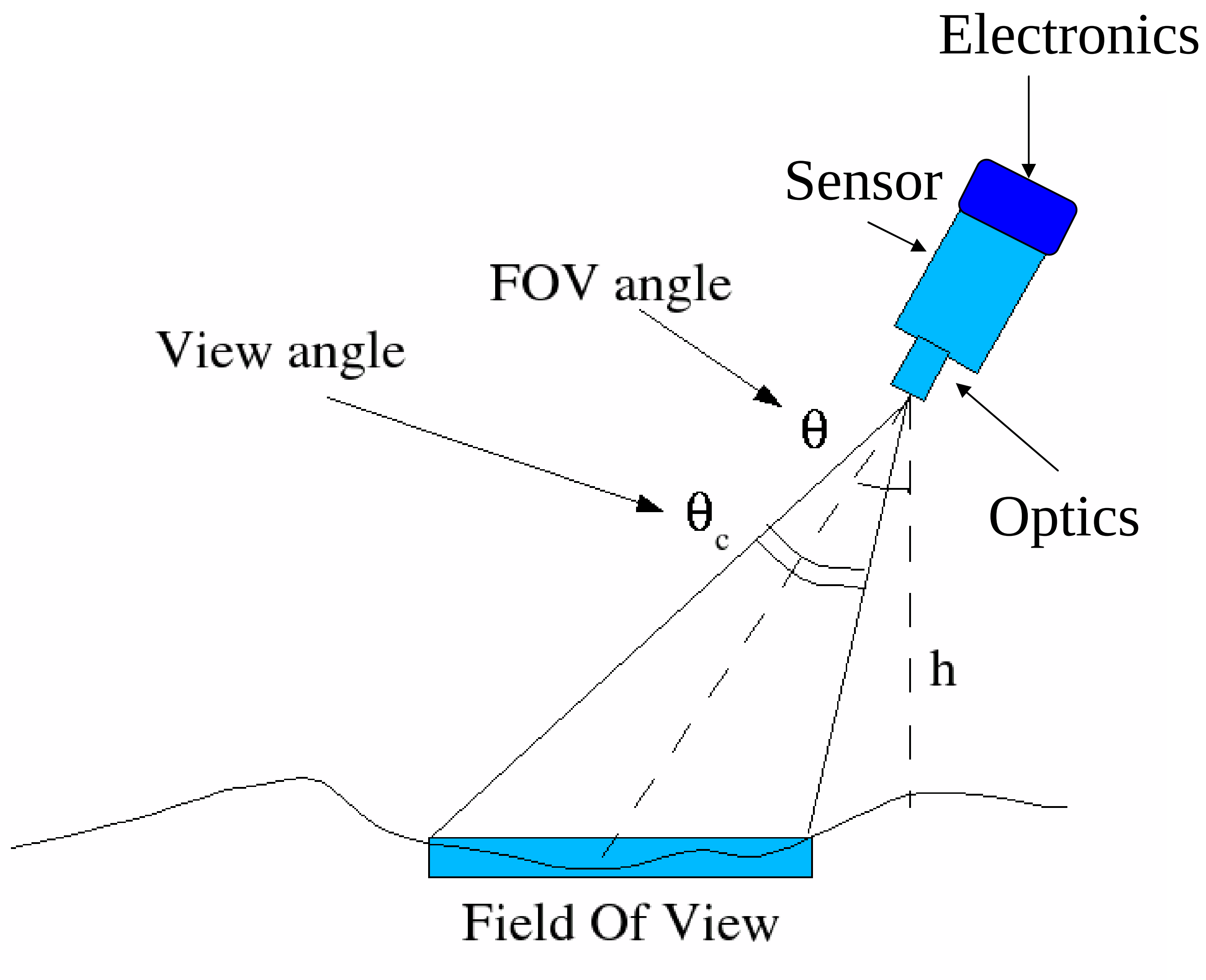
Used to observe solar energy reflected by the Earth system in the:

- 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

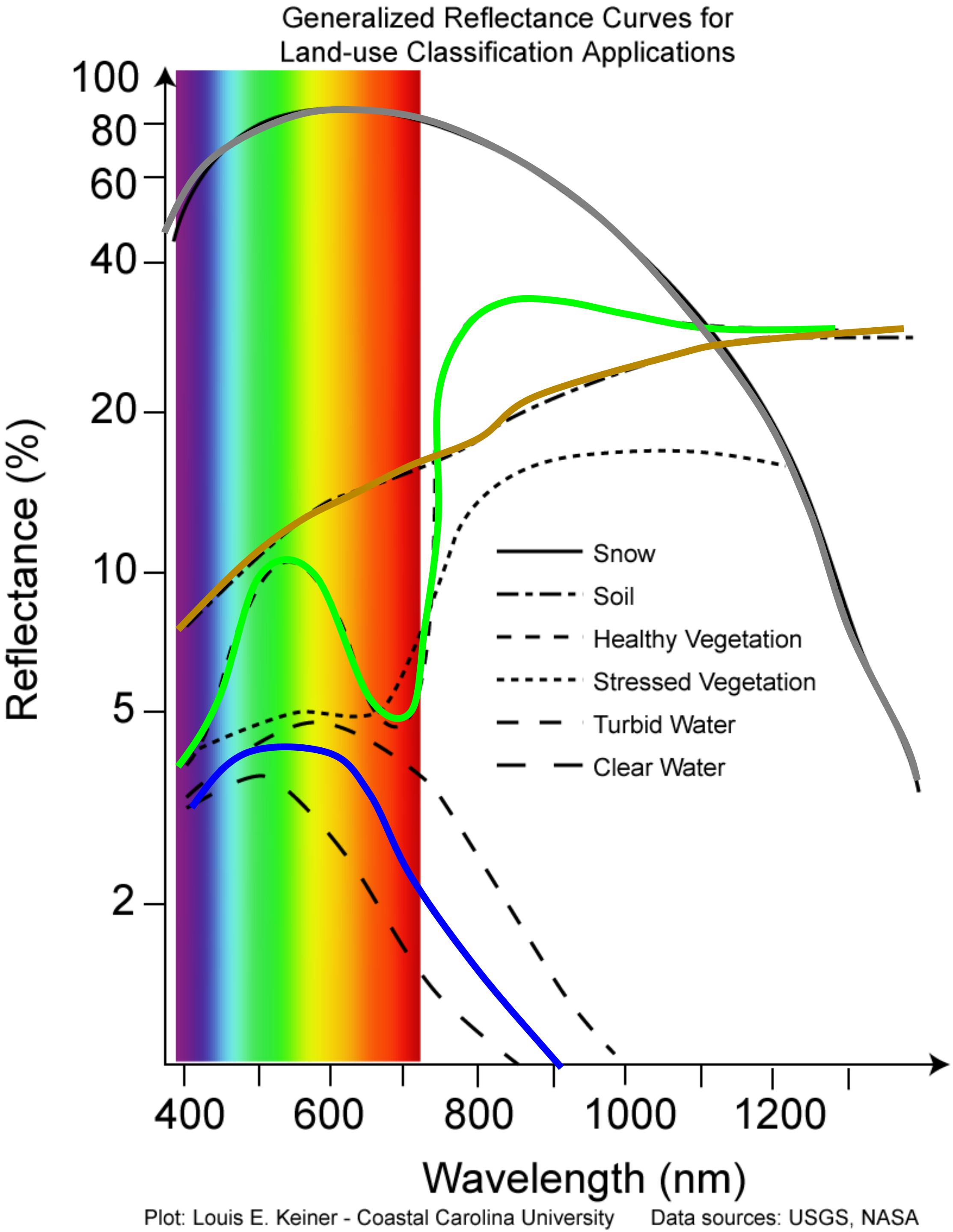
Only 1% is observed above 4 μm

Sensor Geometry



Reflectance

- To properly compare different reflective channels we need to convert observed radiance into a target physical property
- In the visible and near infrared this is done through the ratio of the observed radiance divided by the incoming energy at the top of the atmosphere
- The physical quantity is the Reflectance i.e. the fraction of solar energy reflected by the observed target



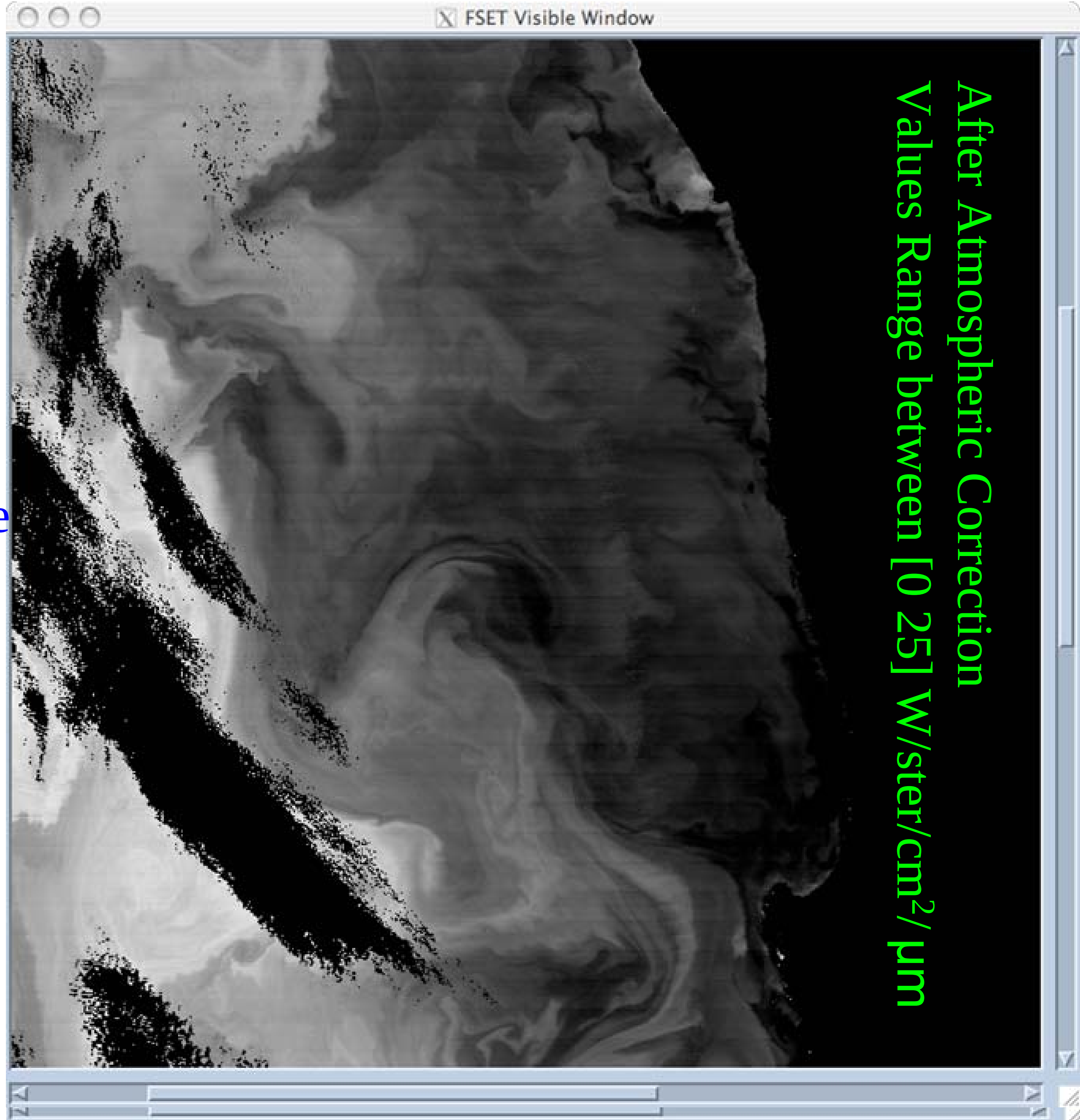
Soil

Vegetation

Snow

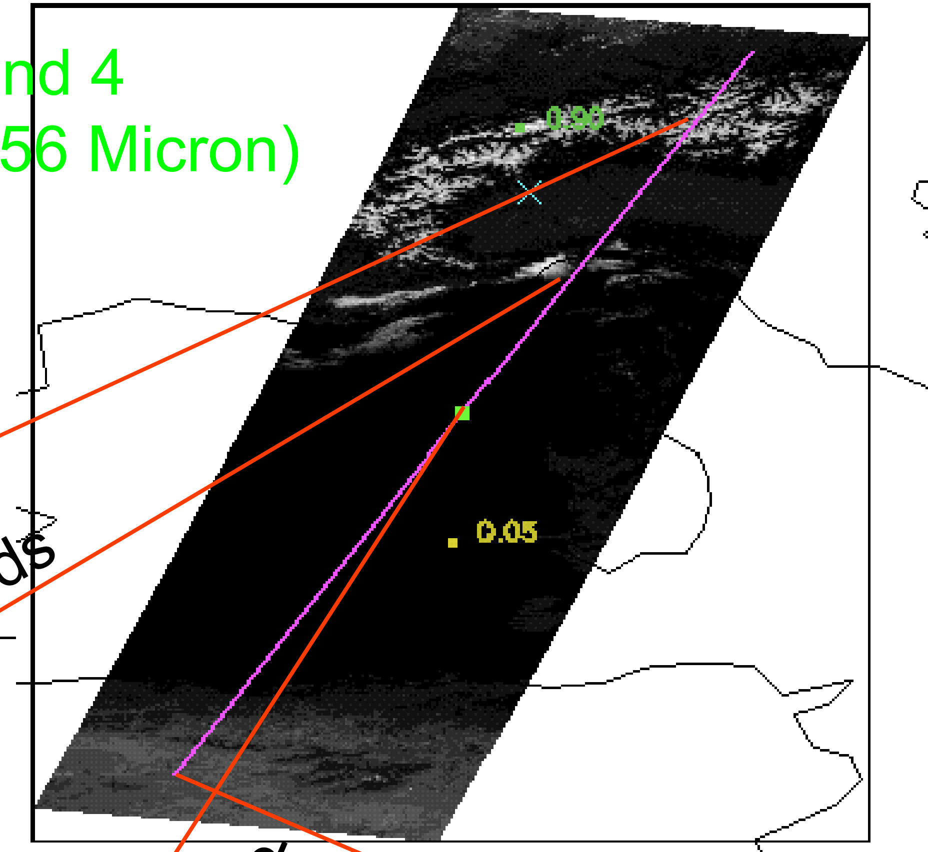
Ocean

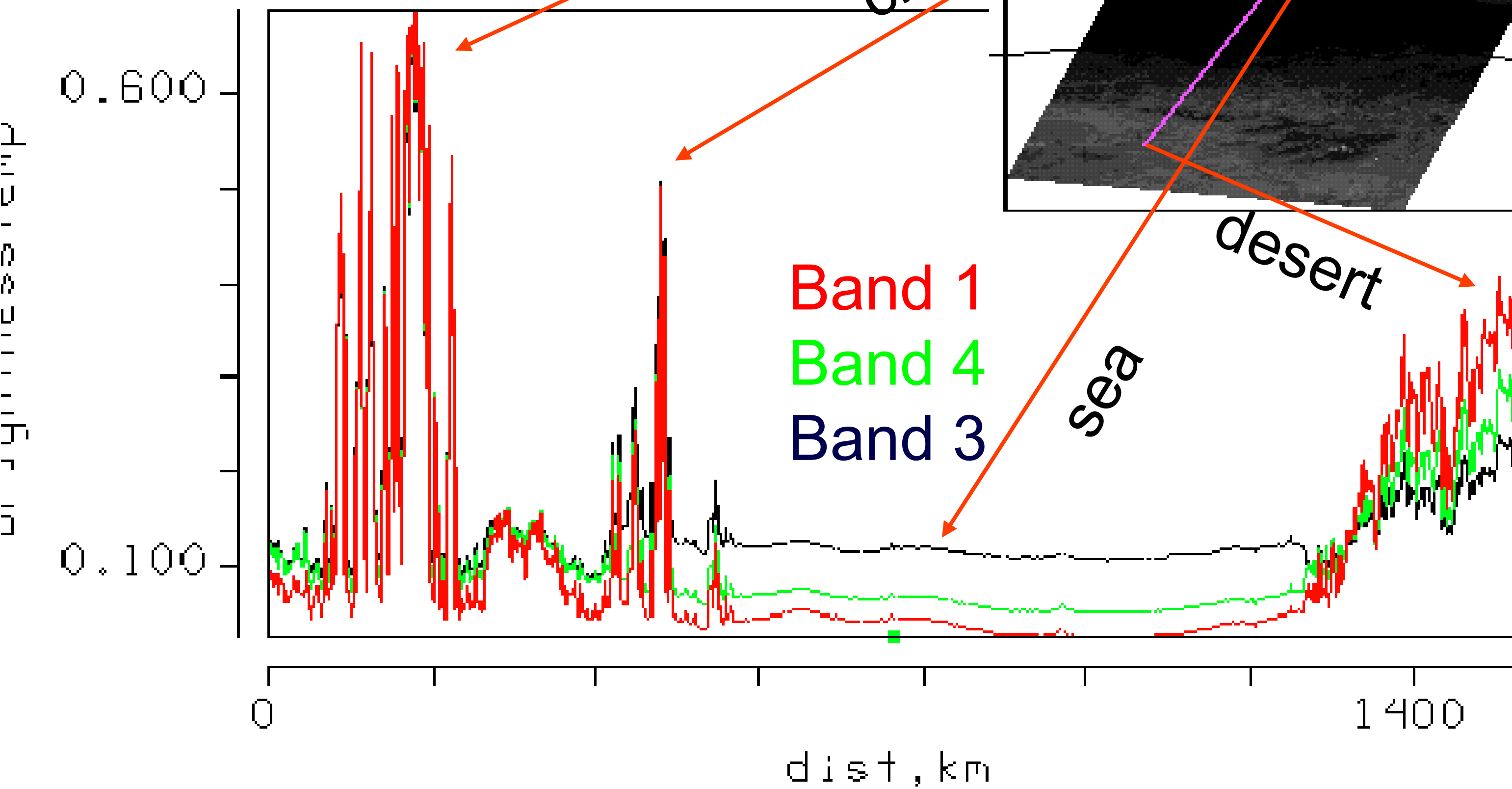
Radiance observed
In the Blue Band
At 0.41 μm

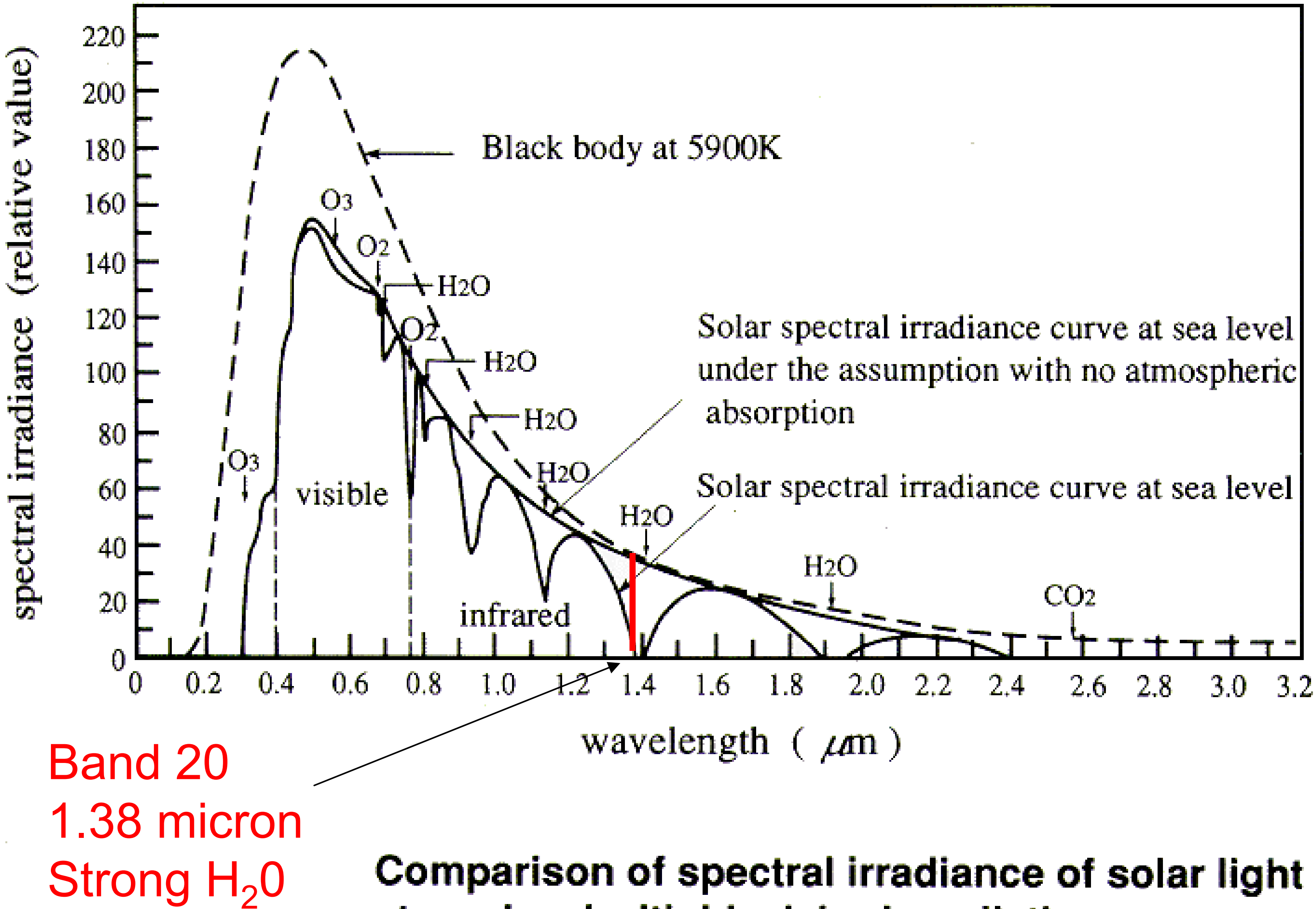


More than 75% of the
Observed energy
Over Ocean
In the blue bands
Is due to atmospheric
Scattering.
Less than 25% is due
to Water
Leaving Energy

Transects of Reflectance

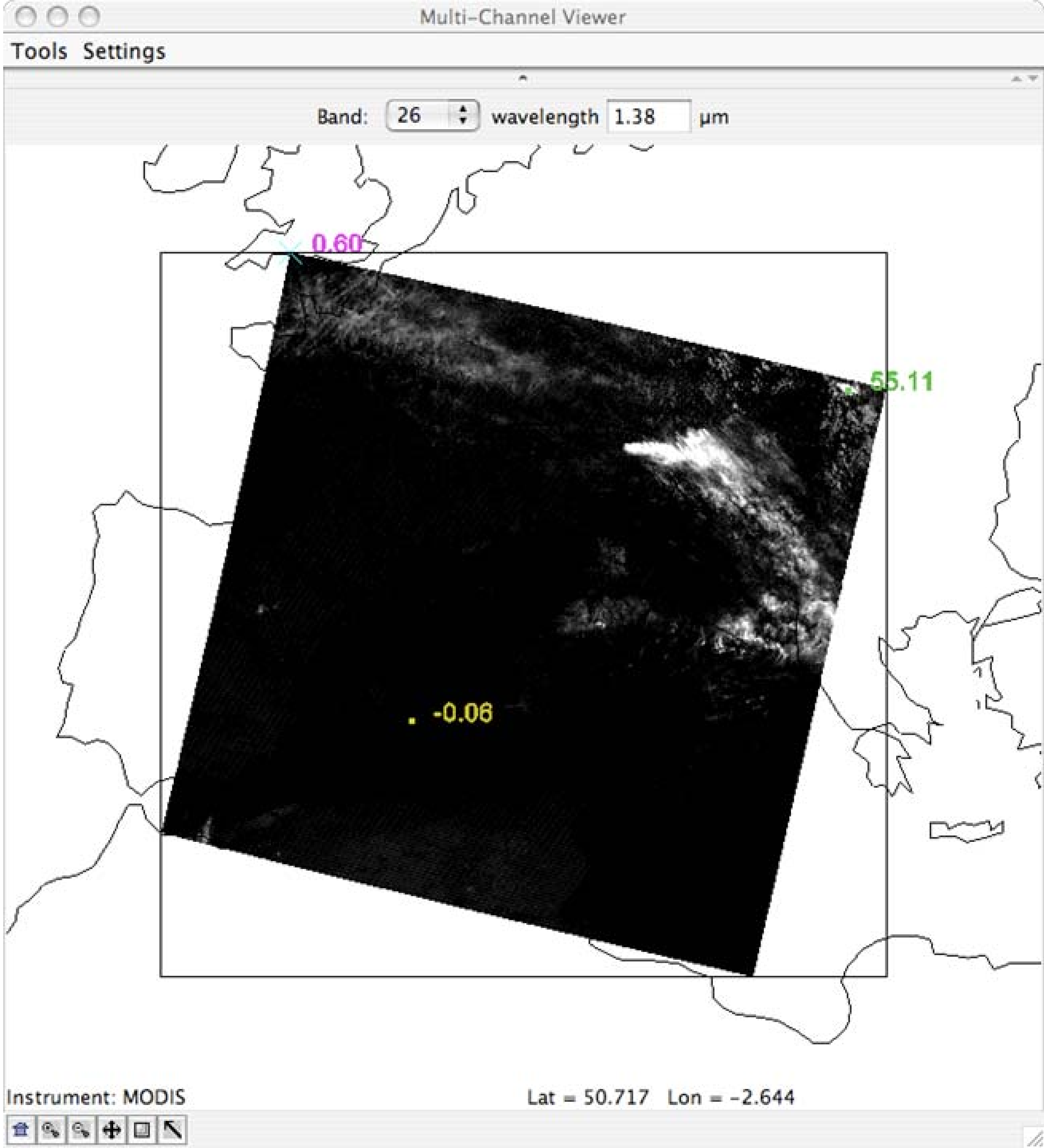


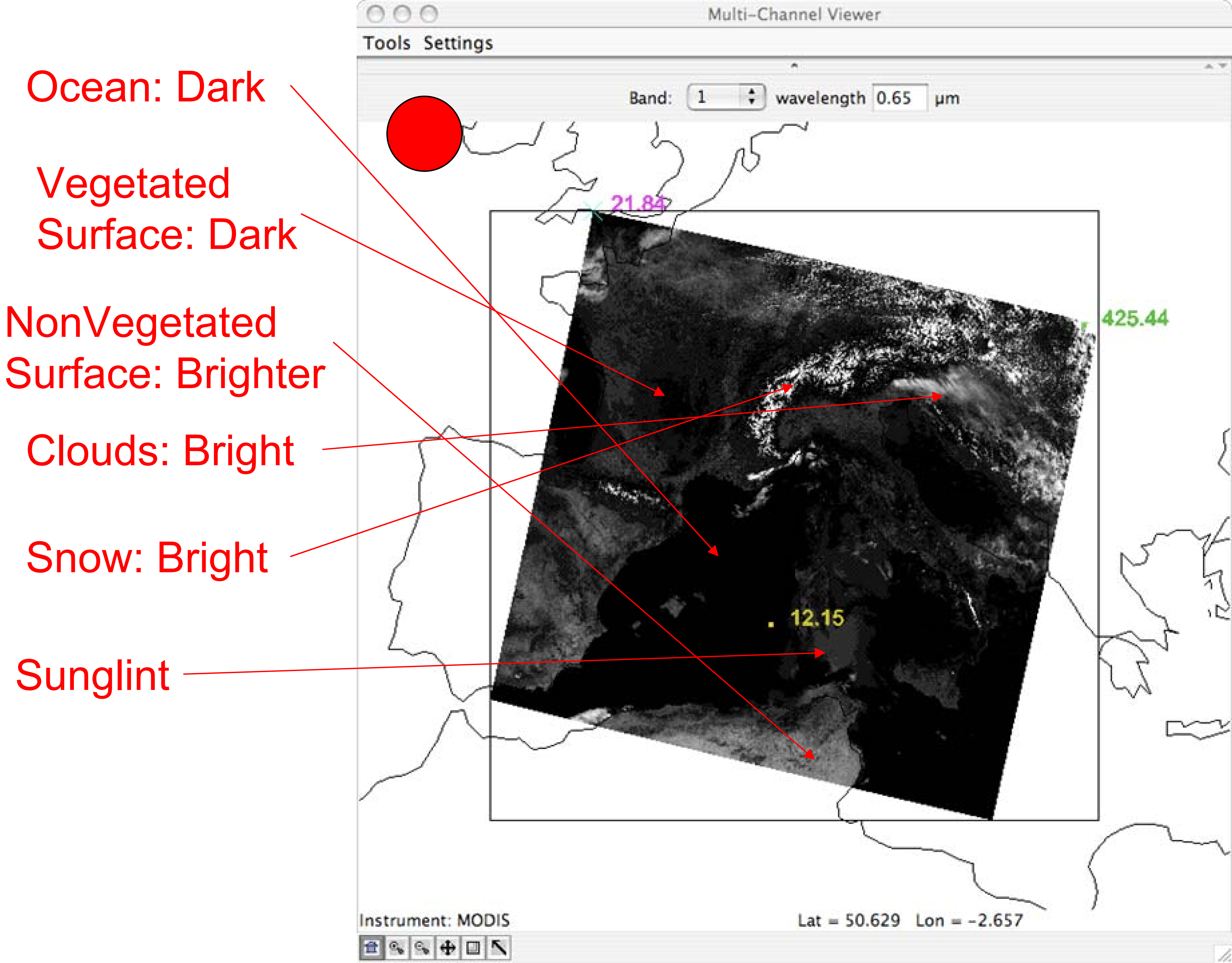




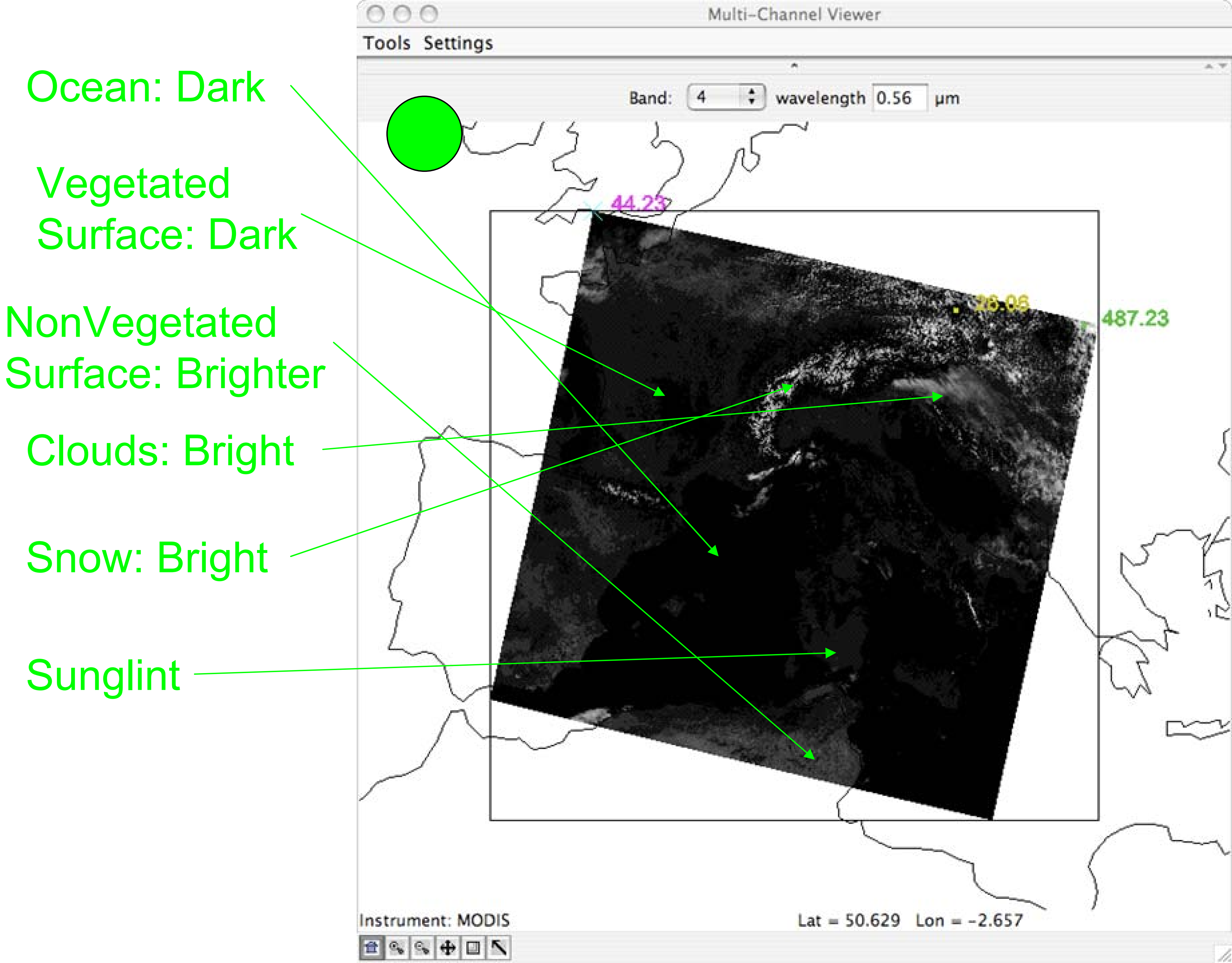
Comparison of spectral irradiance of solar light at sea level with black body radiation

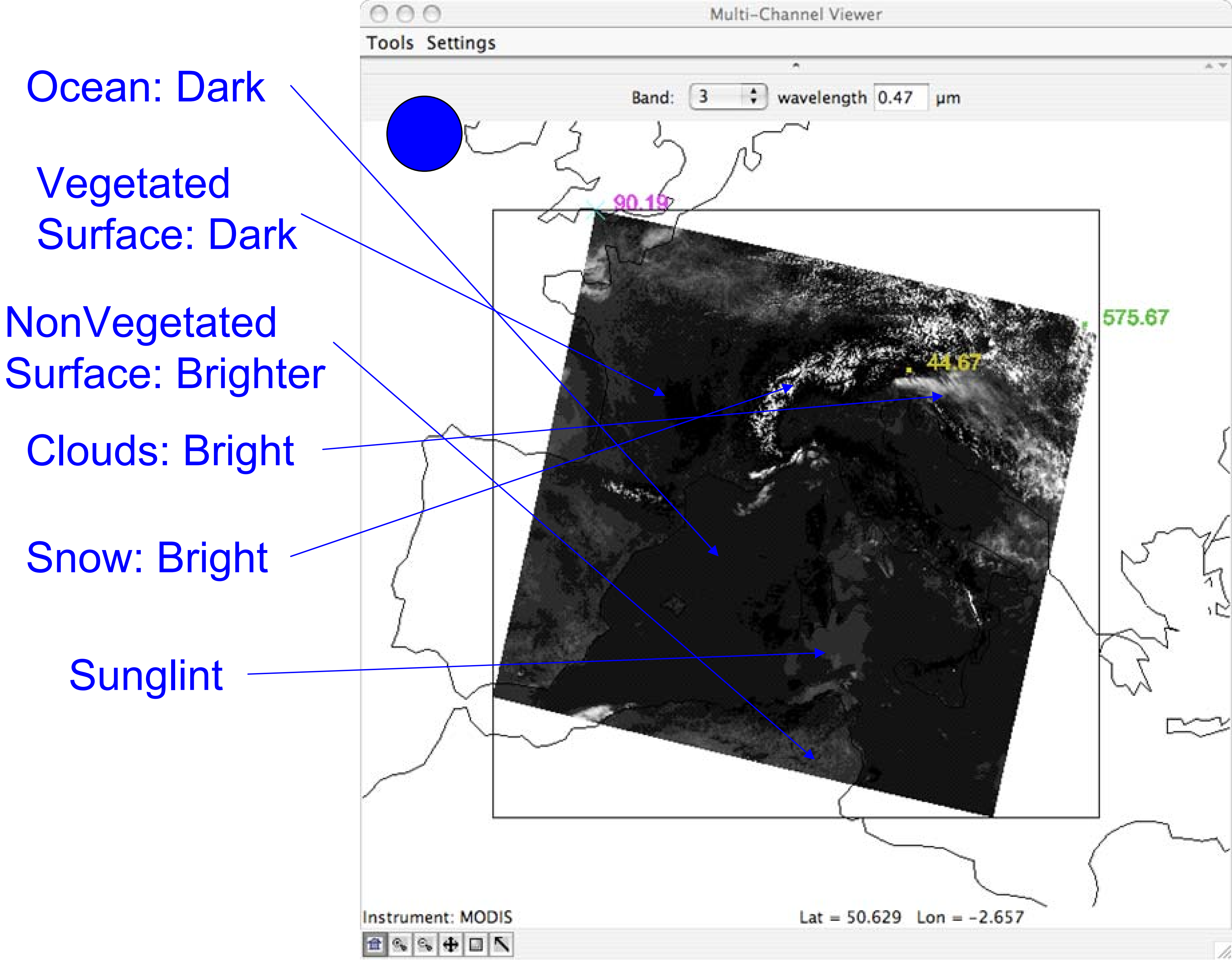
Only High Clouds Are Visible





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

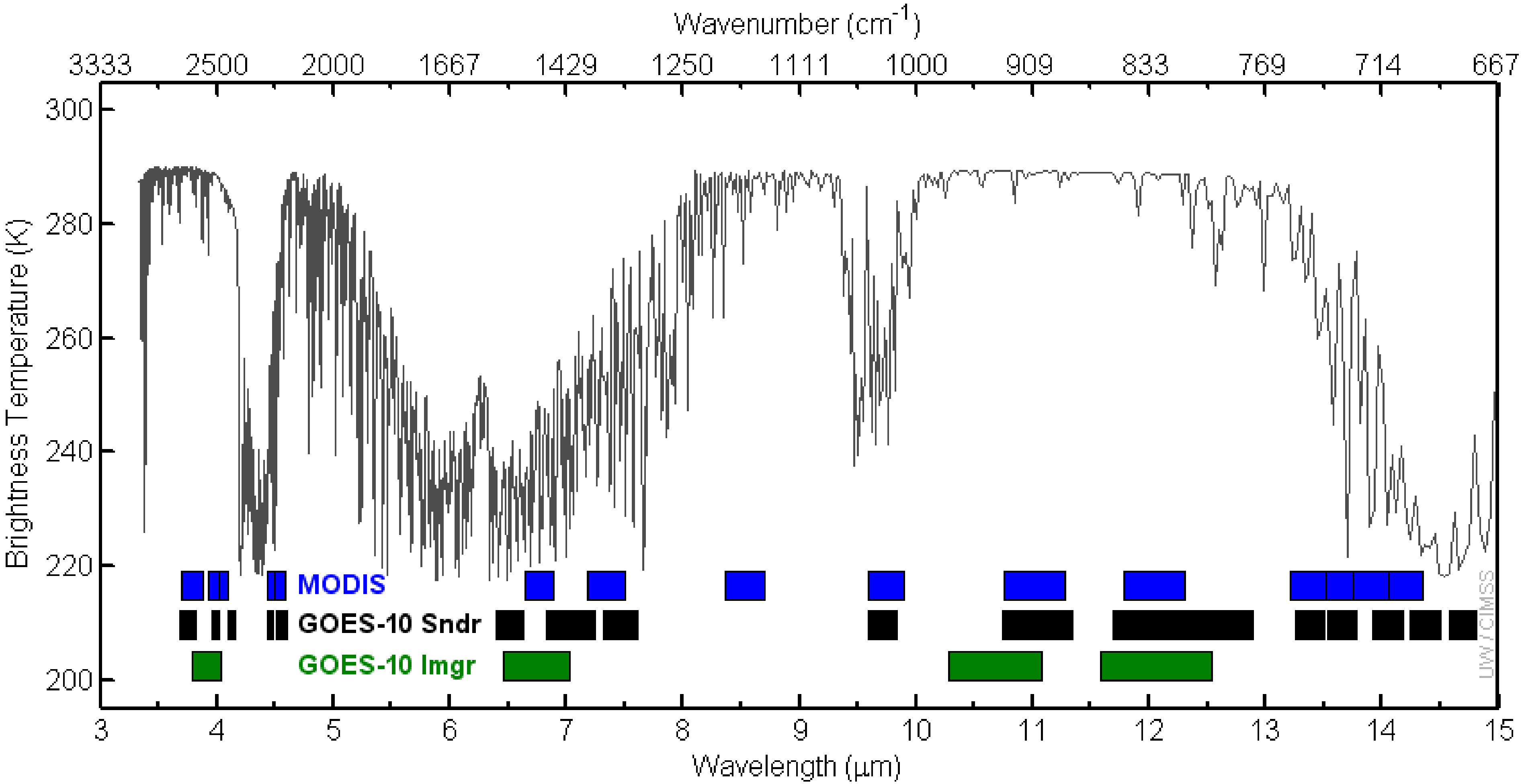

Ocean: Dark
Vegetated Surface: Dark
NonVegetated Surface: Brighter
Clouds: Bright
Snow: Bright
Sunglint
Multi-Channel Viewer
Tools Settings
Band: 4 wavelength 0.56 µm
44.23
28.06
487.23
Instrument: MODIS
Lat = 50.629 Lon = -2.657


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

MODIS Thermal Emissive Bands

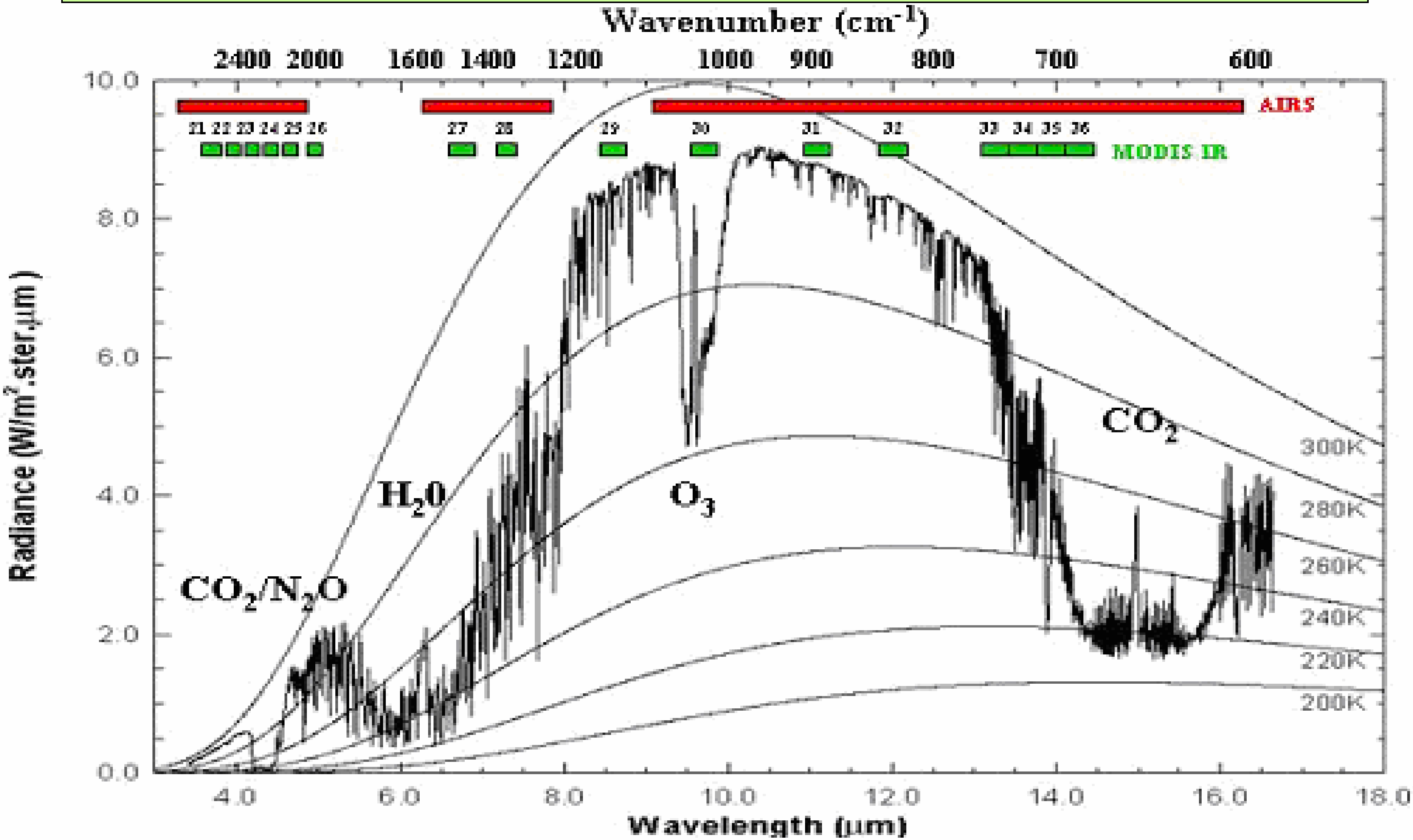
Primary Atmospheric Application	Band	Bandwidth[1]	$T_{typical}$ (K)	Radiance[2] at $T_{typical}$	NEΔT (K) Specification	NEΔT (K) Predicted
Surface Temperature	20	3.660-3.840	300	0.45	0.05	0.05
	22	3.929-3.989	300	0.67	0.07	0.05
	23	4.020-4.080	300	0.79	0.07	0.05
Temperature profile	24	4.433-4.498	250	0.17	0.25	0.15
	25	4.482-4.549	275	0.59	0.25	0.10
Moisture profile	27	6.535-6.895	240	1.16	0.25	0.05
	28	7.175-7.475	250	2.18	0.25	0.05
	29	8.400-8.700	300	9.58	0.05	0.05
Ozone	30	9.580-9.880	250	3.69	0.25	0.05
Surface Temperature	31	10.780-11.280	300	9.55	0.05	0.05
	32	11.770-12.270	300	8.94	0.05	0.05
Temperature profile	33	13.185-13.485	260	4.52	0.25	0.15
	34	13.485-13.785	250	3.76	0.25	0.20
	35	13.785-14.085	240	3.11	0.25	0.25
	36	14.085-14.385	220	2.08	0.35	0.35

MODIS Infrared Spectral Bands

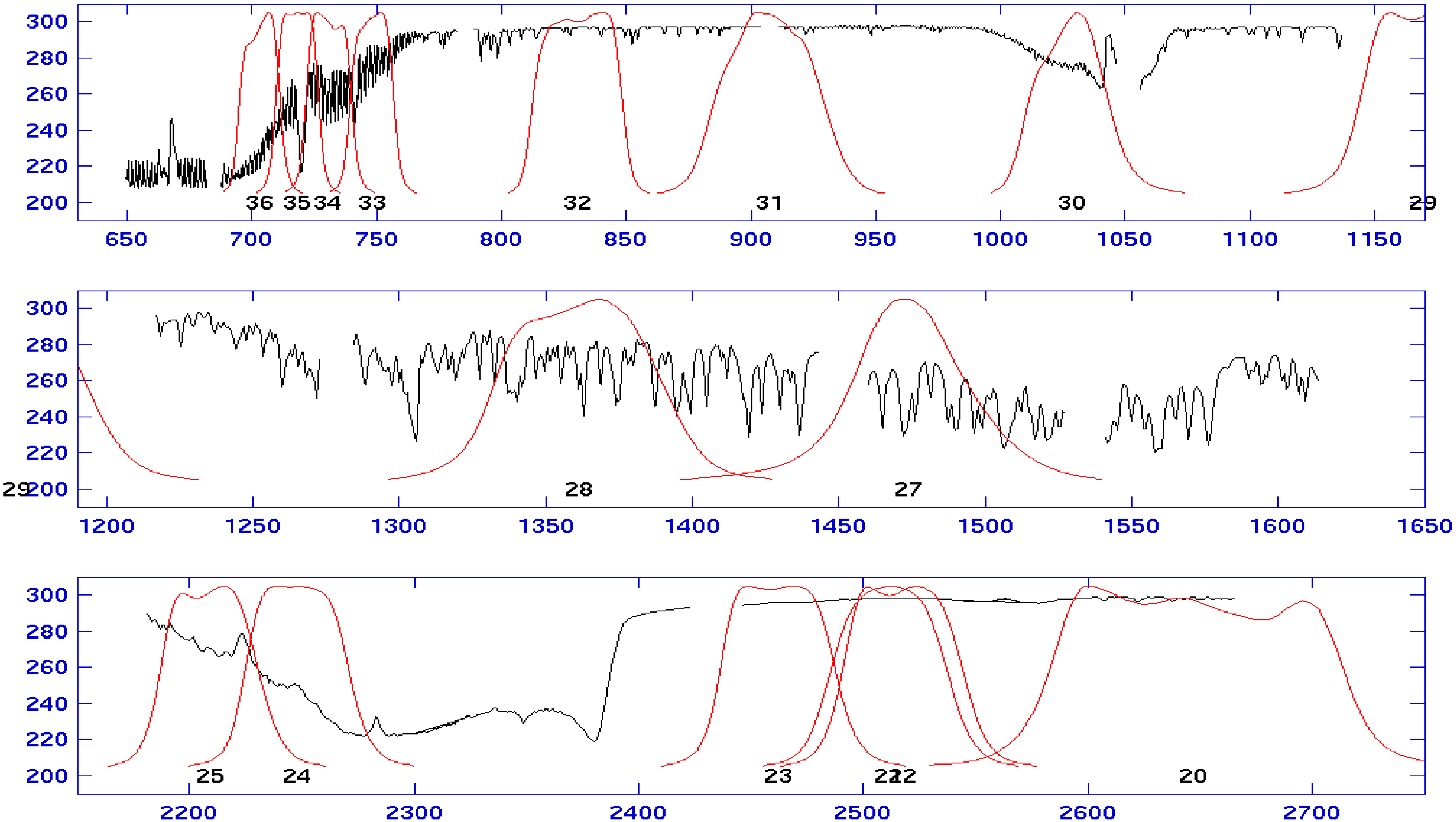


Short Wave IR → Long Wave IR

AIRS (Atmospheric Infrared Sounder) & MODIS – IR only



AIRS
(Atmospheric Infrared Sounder)
& MODIS

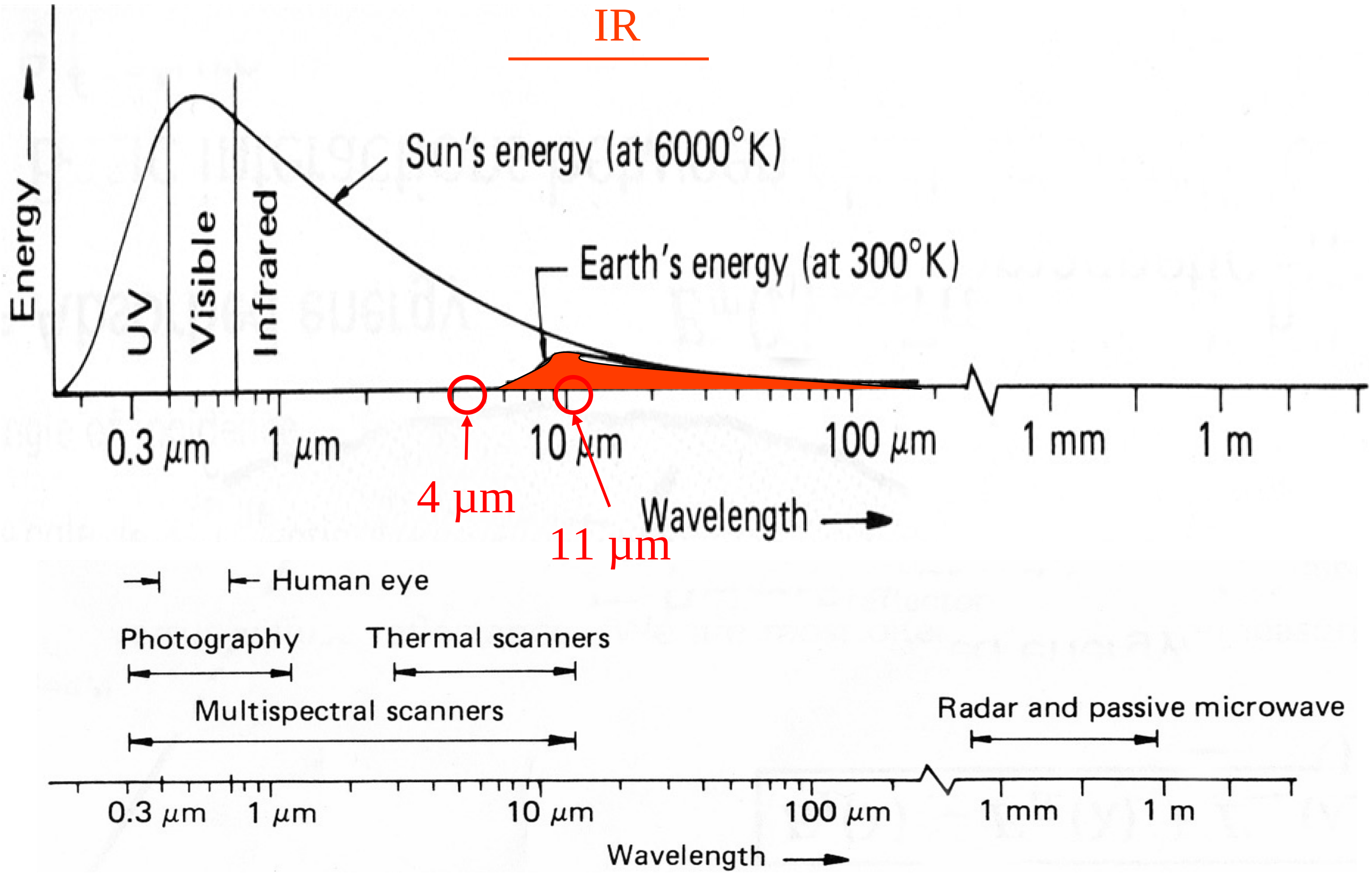


Emissive Bands

Used to observe terrestrial energy emitted by the Earth system in the IR between 4 and 15 μm

- About 99% of the energy observed in this range is emitted by the Earth
- Only 1% is observed below 4 μm
- At 4 μm the solar reflected energy can significantly affect the observations of the Earth emitted energy

Spectral Characteristics of Energy Sources and Sensing Systems



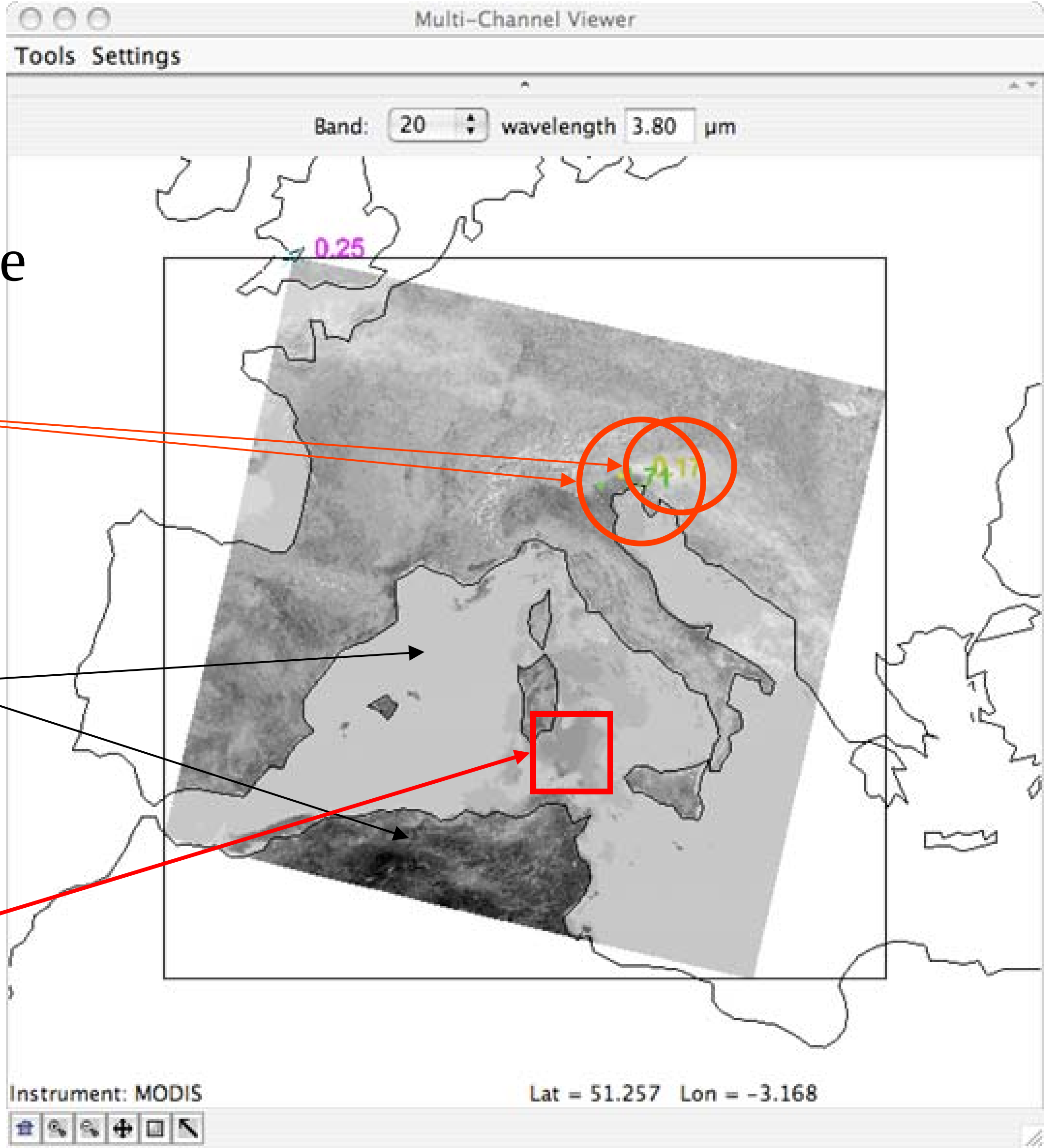
Observed Radiance at 4 micron

Window Channel:
- little atmospheric absorption
- surface features clearly visible

Range [0.2 1.7]

Values over land
Larger than over water

Reflected Solar everywhere
Stronger over Sunglint



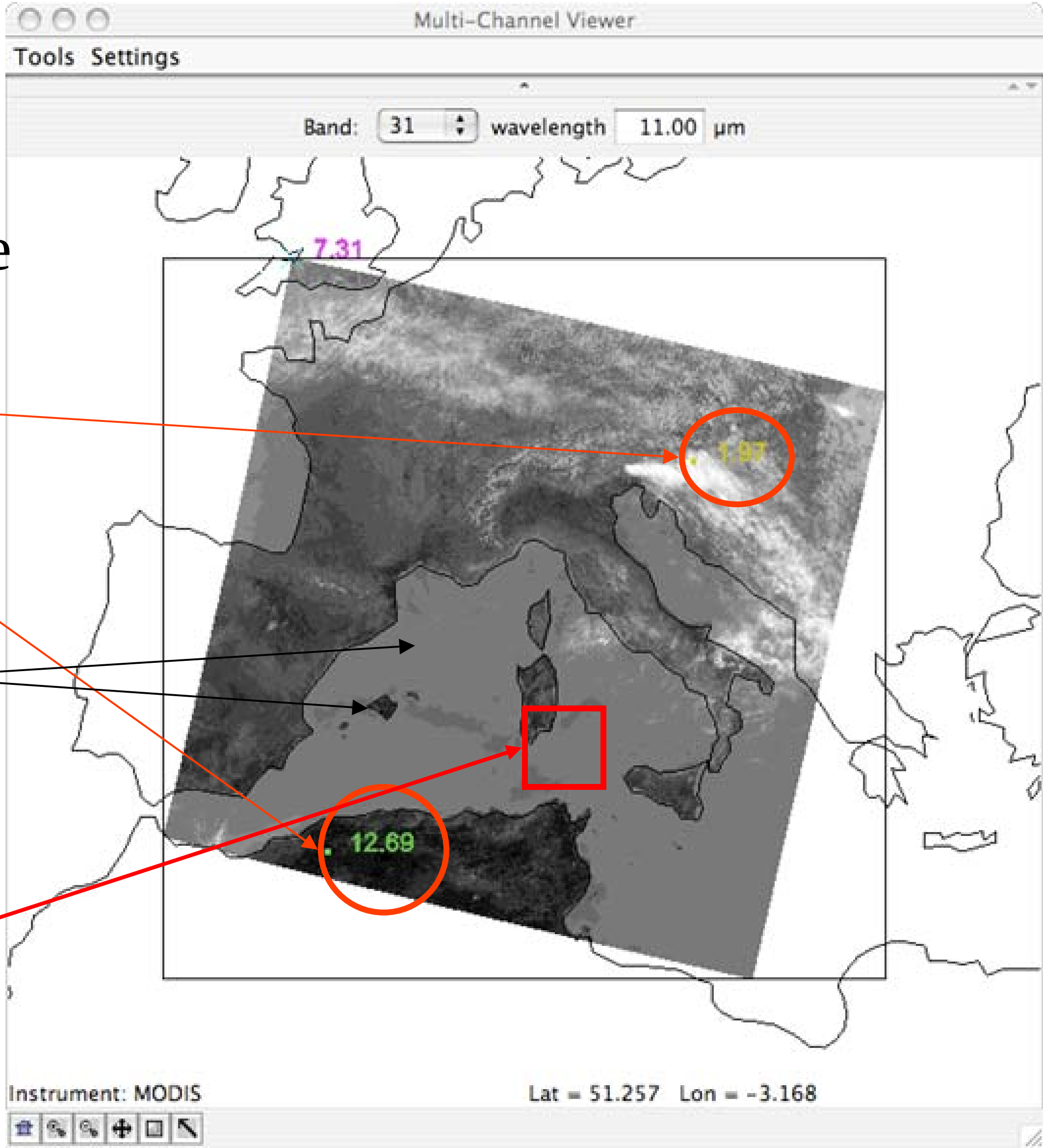
Observed Radiance at 11 micron

Window Channel:
•little atmospheric absorption
•surface features clearly visible

Range [2 13]

Values over land
Larger than over water

Undetectable Reflected Solar
Even over Sunglint



Brightness Temperature

- To properly compare different emissive channels we need to convert observed radiance into a target physical property

- In the Infrared this is done through the Planck function

- The physical quantity is the Brightness Temperature i.e. the Temperature of a black body emitting the observed radiance

Observed BT at 4 micron

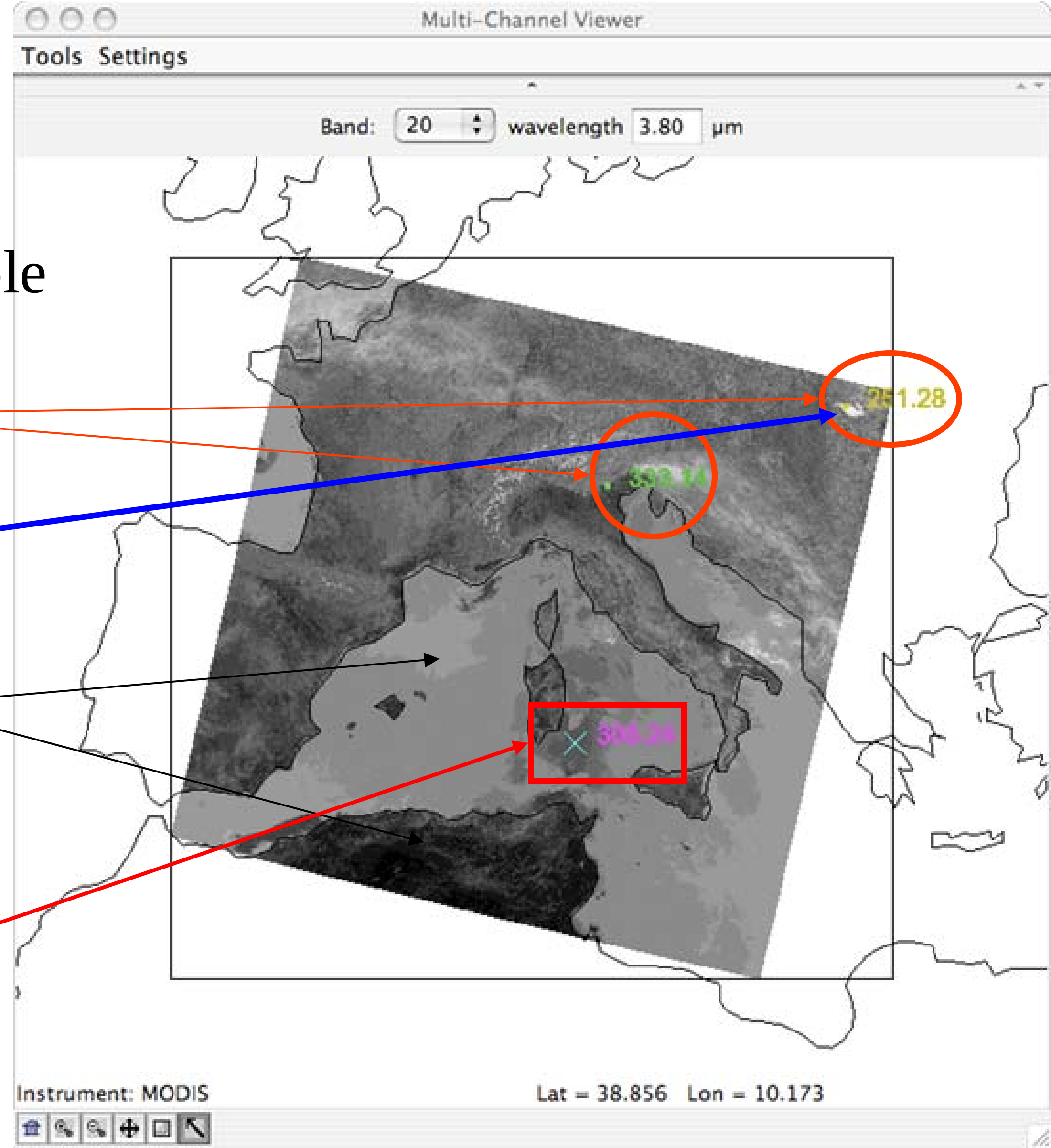
Window Channel:
- little atmospheric absorption
- surface features clearly visible

Range [250 335]

Clouds are cold

Values over land
Larger than over water

Reflected Solar everywhere
Stronger over Sunglint



Observed BT at 11 micron

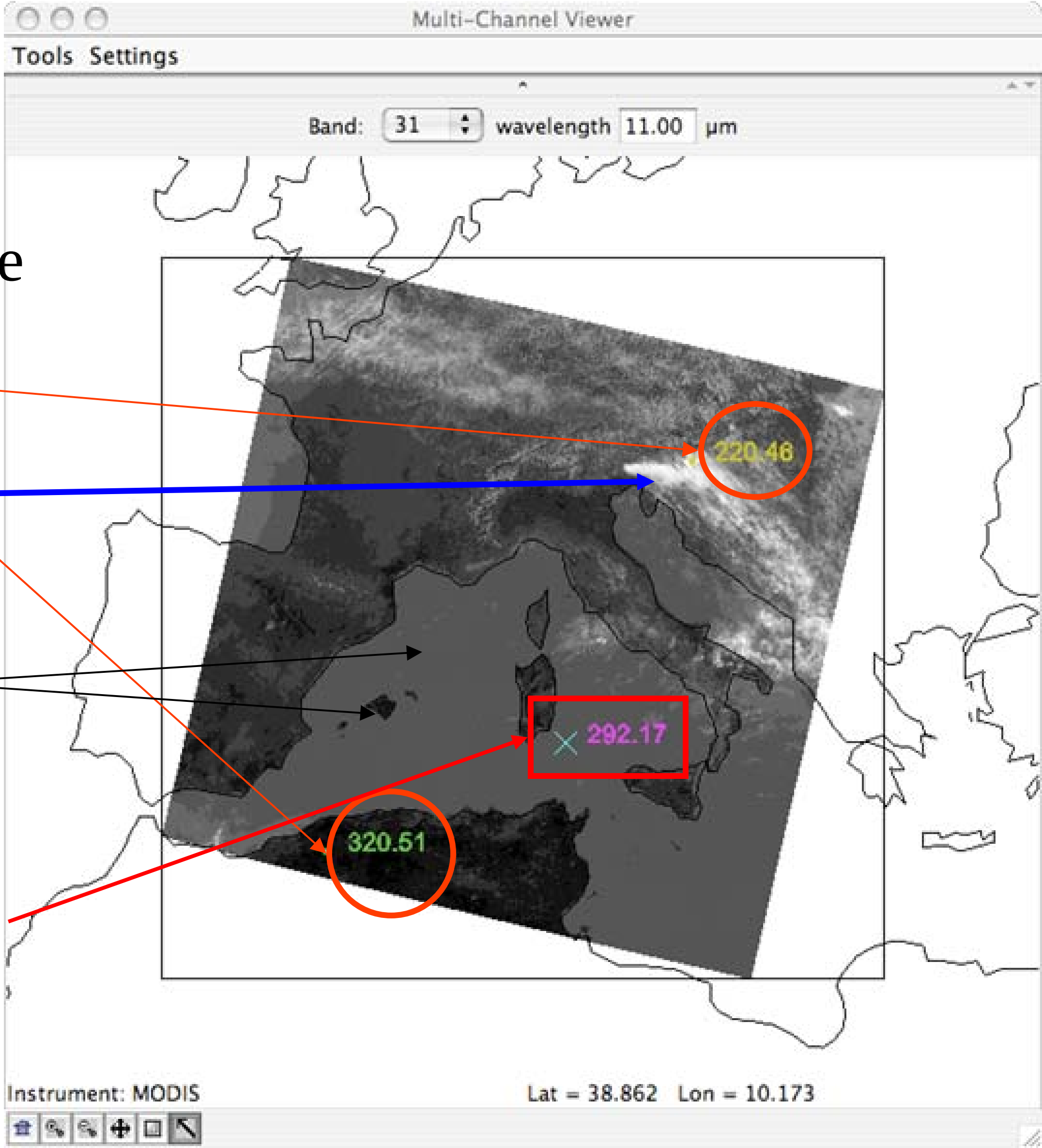
Window Channel:
- little atmospheric absorption
- surface features clearly visible

Range [220 320]

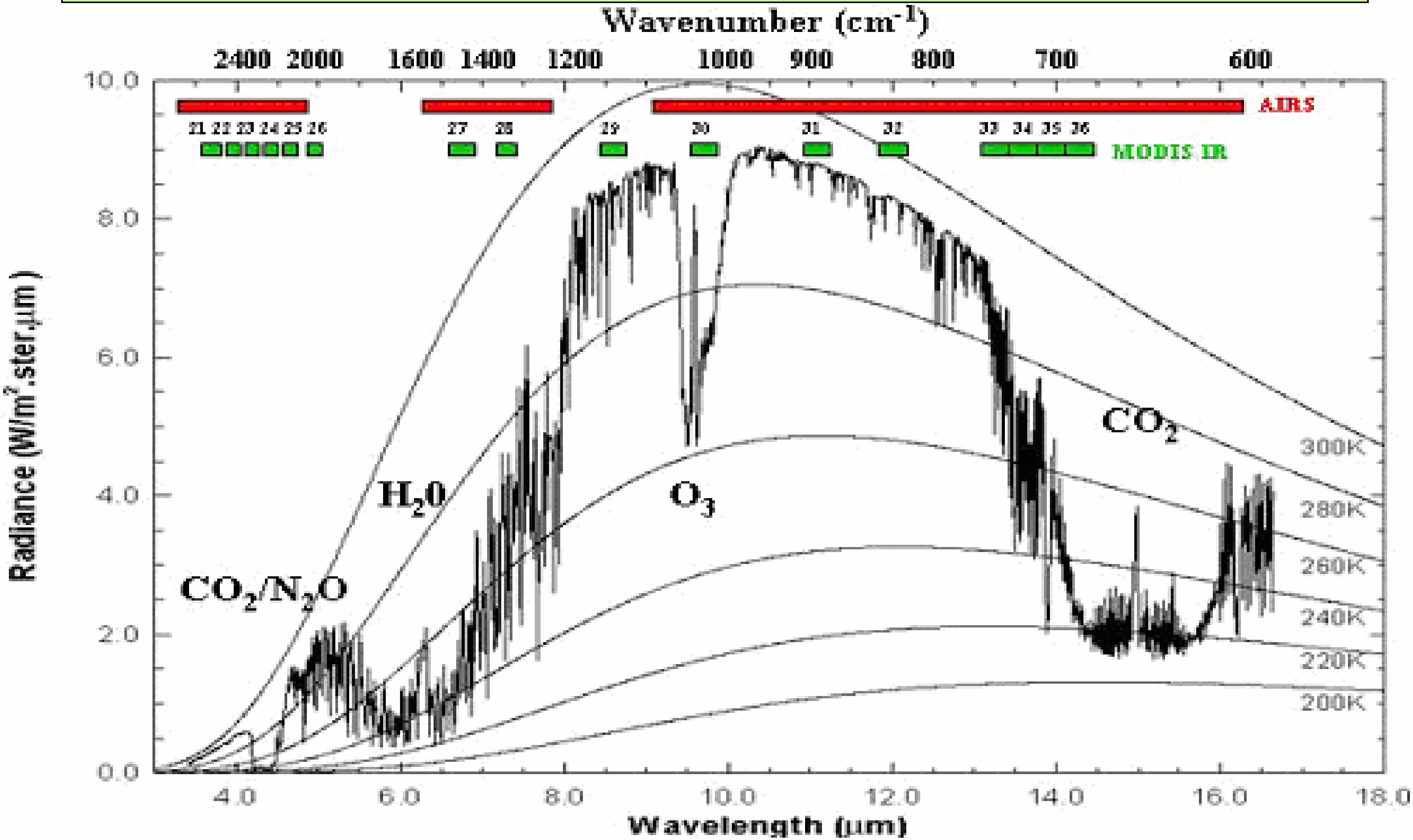
Clouds are cold

Values over land
Larger than over water

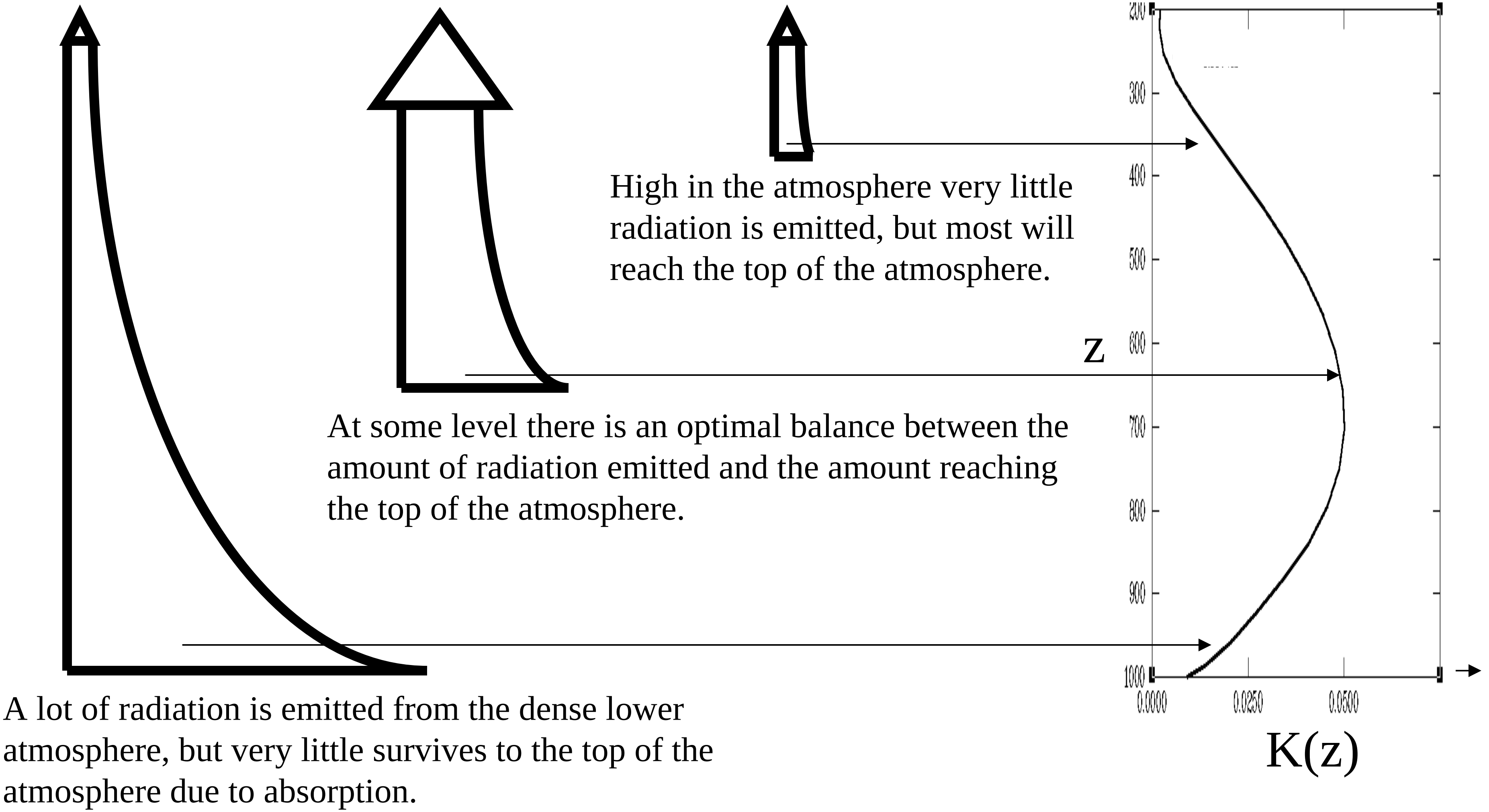
Undetectable Reflected Solar
Even over Sunglint



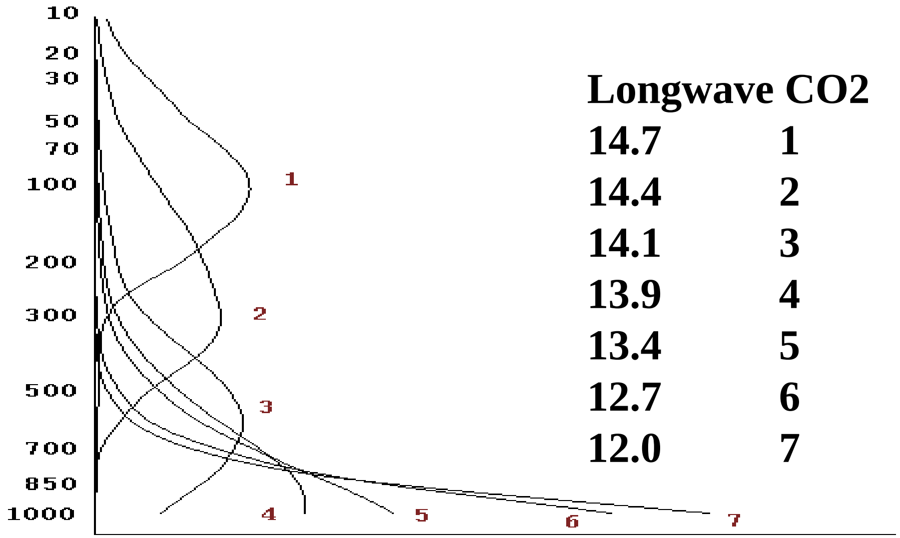
AIRS (Atmospheric Infrared Sounder) & MODIS – IR only



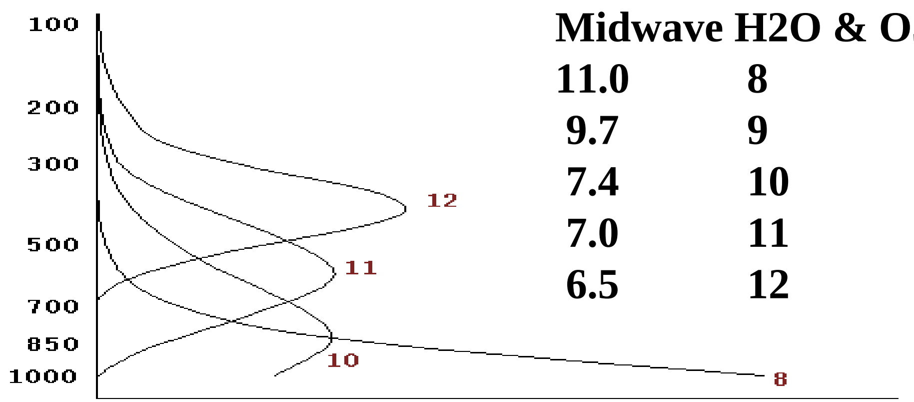
Real atmospheric weighting functions



Weighting Functions



Longwave CO2			
14.7	1	680	CO2, strat temp
14.4	2	696	CO2, strat temp
14.1	3	711	CO2, upper trop temp
13.9	4	733	CO2, mid trop temp
13.4	5	748	CO2, lower trop temp
12.7	6	790	H2O, lower trop moisture
12.0	7	832	H2O, dirty window



Midwave H2O & O3			
11.0	8	907	window
9.7	9	1030	O3, strat ozone
7.4	10	1345	H2O, lower mid trop moisture
7.0	11	1425	H2O, mid trop moisture
6.5	12	1535	H2O, upper trop moisture

Radiance measured by IR Sensor

RTE (no scattering) in LTE

$$R_\nu = \tau_{s\nu} \cdot \varepsilon_{s\nu} \cdot B_\nu(T_S)$$ ← Upwelling IR radiation from surface

$$+ \int_{p_s}^{0} B_\nu(T(p)) d\tau_\nu(p)$$ ← Upwelling IR radiation from atm. layers

$$- \tau_{s\nu} \cdot r_{s\nu} \cdot \int_{p_s}^{0} B_\nu(T(p)) d\tau_\nu^*(p)$$ ← Reflected downwelling IR radiation

$$+ R_\nu^{sun} \cdot \cos(\theta) \cdot \tau_{s\nu}^{sun}(p_s) \cdot r_\nu^{sun}$$ ← **Reflected solar radiation**

R…radiance, υ…wavenumber, *s*…surface, *p*…pressure, *sun*…solar,

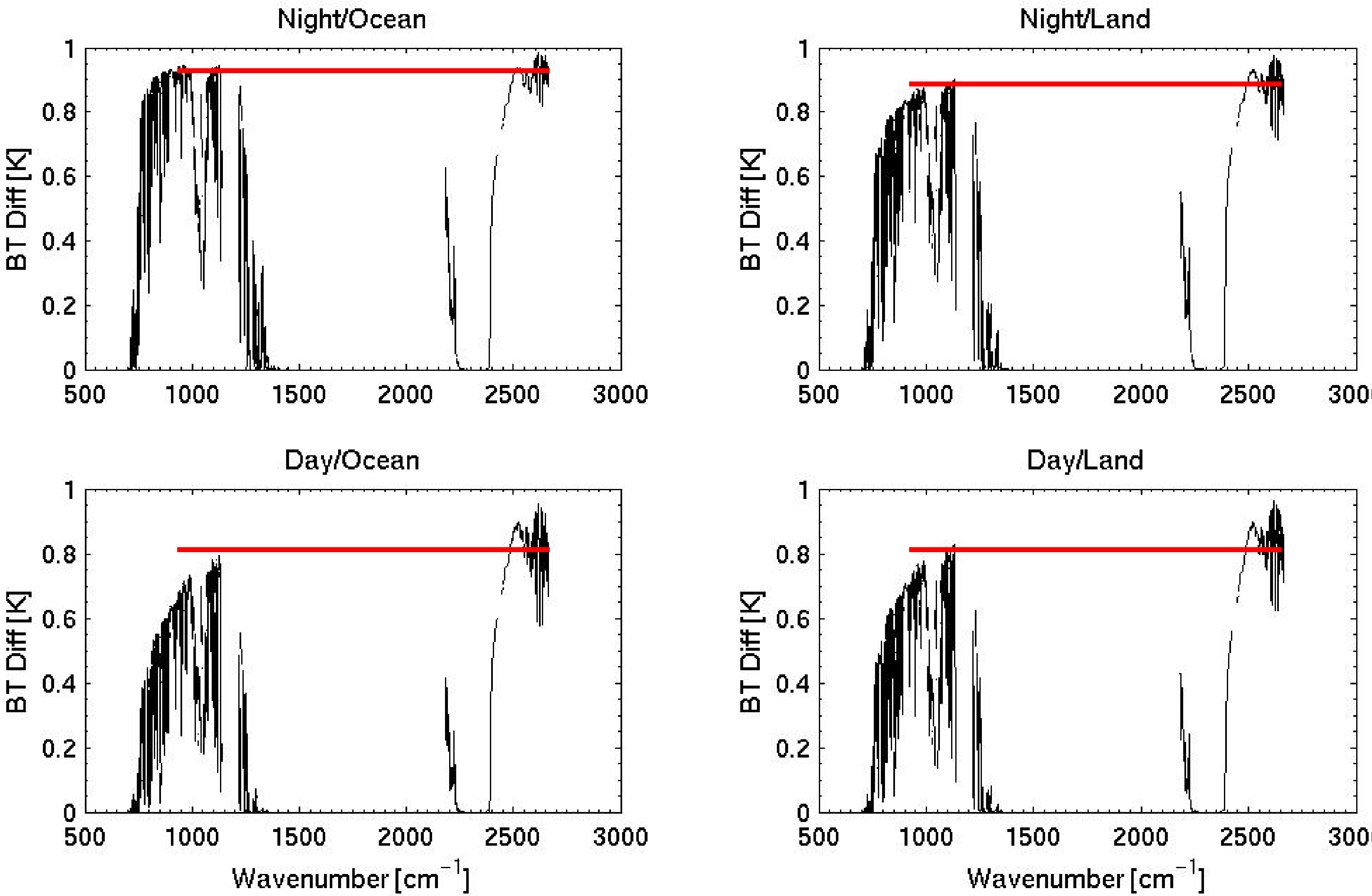
T…temperature, *B*…Planck function, ε …emissivity,

τ…level to space transmittance, θ...local solar zenith angle

r…reflectivity, with $r = (1- \varepsilon)/\pi$,

τ^*…level to surface (downwelling) transmittance [$\tau^* = \tau_\upsilon^2(p_s)/\ \tau_\upsilon(p)$]

Solar Effects (Day Vs. Night) on Infrared Measurements



Radiative Transfer Equation

Summary

Radiative Transfer Equation in Infrared:

models the propagation of terrestrial emitted energy through the atmosphere by

- absorption,
- scattering,
- emission and
- reflection

of gases, clouds, suspended particles, and surface.

The modeled radiances can be converted to brightness temperature and inverted to obtain atmospheric variables such as profile of temperature and water vapor profiles and clouds (height, fraction, optical thickness, size), aerosol/dust, surface temperature, and surface types etc…..

Summary

- Radiance is the Energy Flux (emitted and/or reflected by the Earth) which strikes the Detector Area at a given Spectral Wavelength (wavenumber) over a Solid Angle on the Earth;
- Reflectance is the fraction of solar energy reflected to space by the target;
- Given an observed radiance, the Brightness Temperature is the temperature, in Kelvin, of a blackbody that emits the observed radiance;
- Knowing the spectral reflective (Vis) and emissive (IR) properties (spectral signatures) of different targets it is possible to detect: clouds, cloud properties, vegetation, fires, ice and snow, ocean color, land and ocean surface temperature ……