Remote Sensing Fundamentals Part II: Radiation and Weighting Functions

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

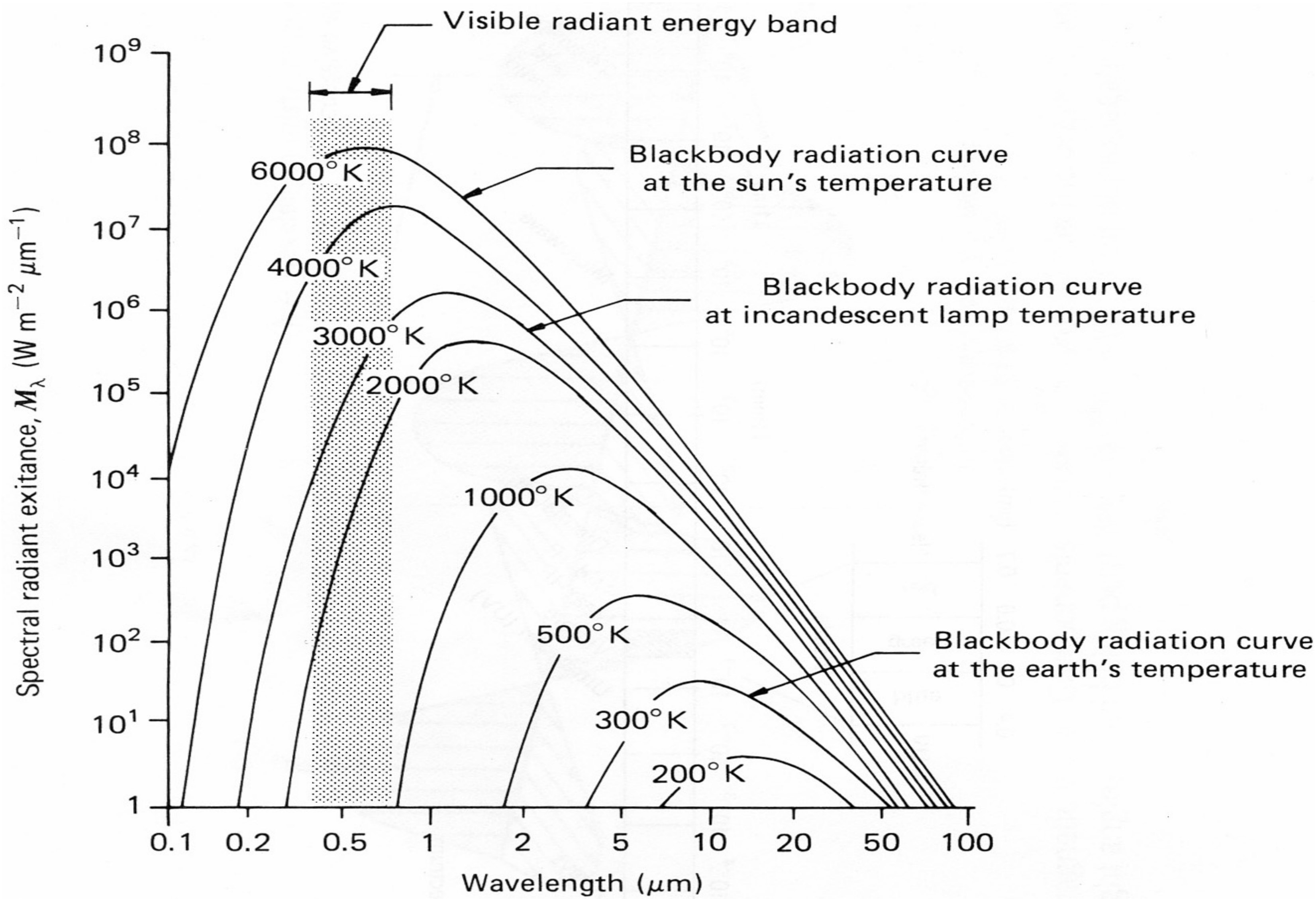
Stefan-Boltzmann Law $E = \pi \int_o^\infty B(\lambda,T)\, d\lambda = \sigma T^4$, where σ = 5.67 x 10-8 W/m2/deg4.

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

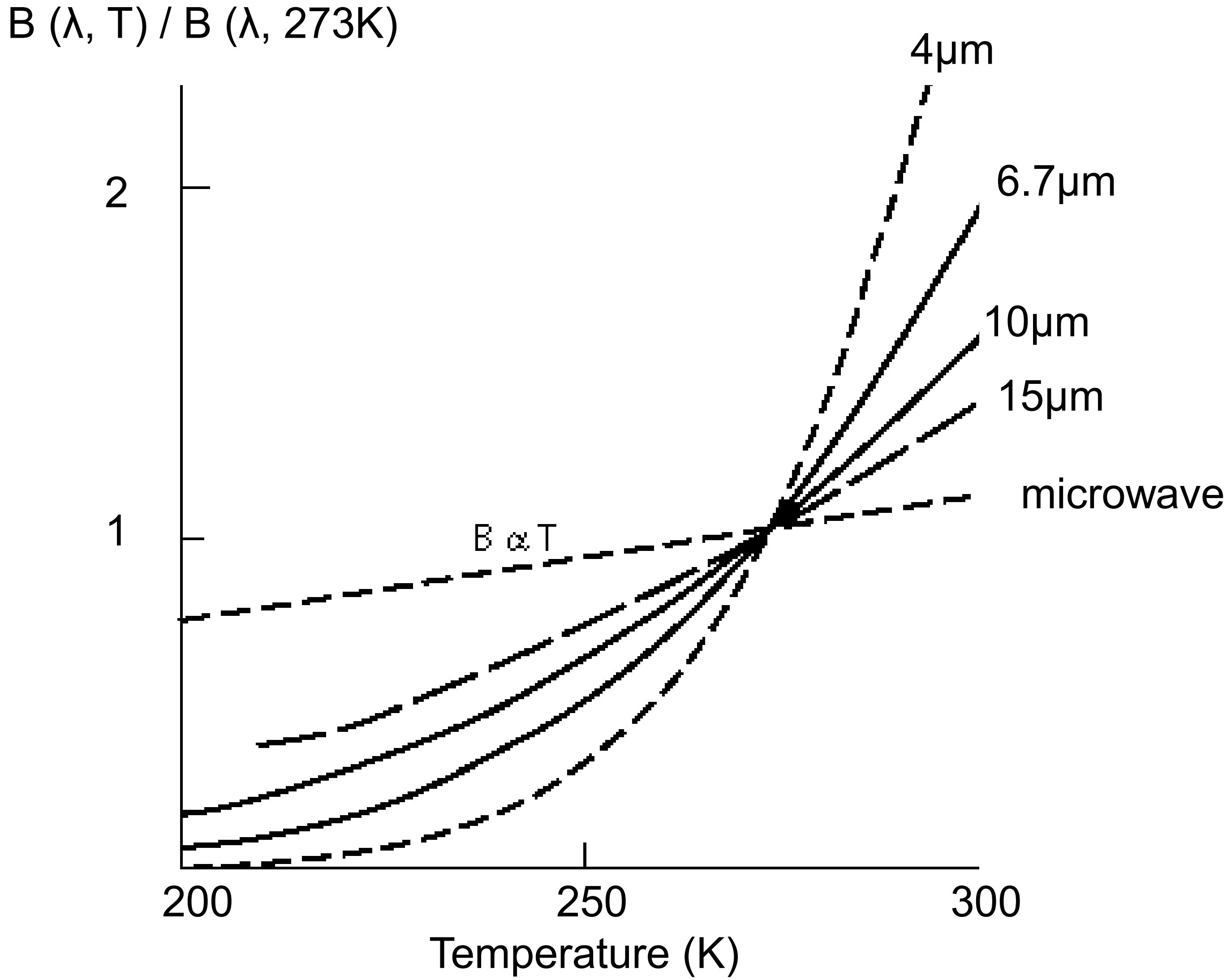
Brightness Temperature

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

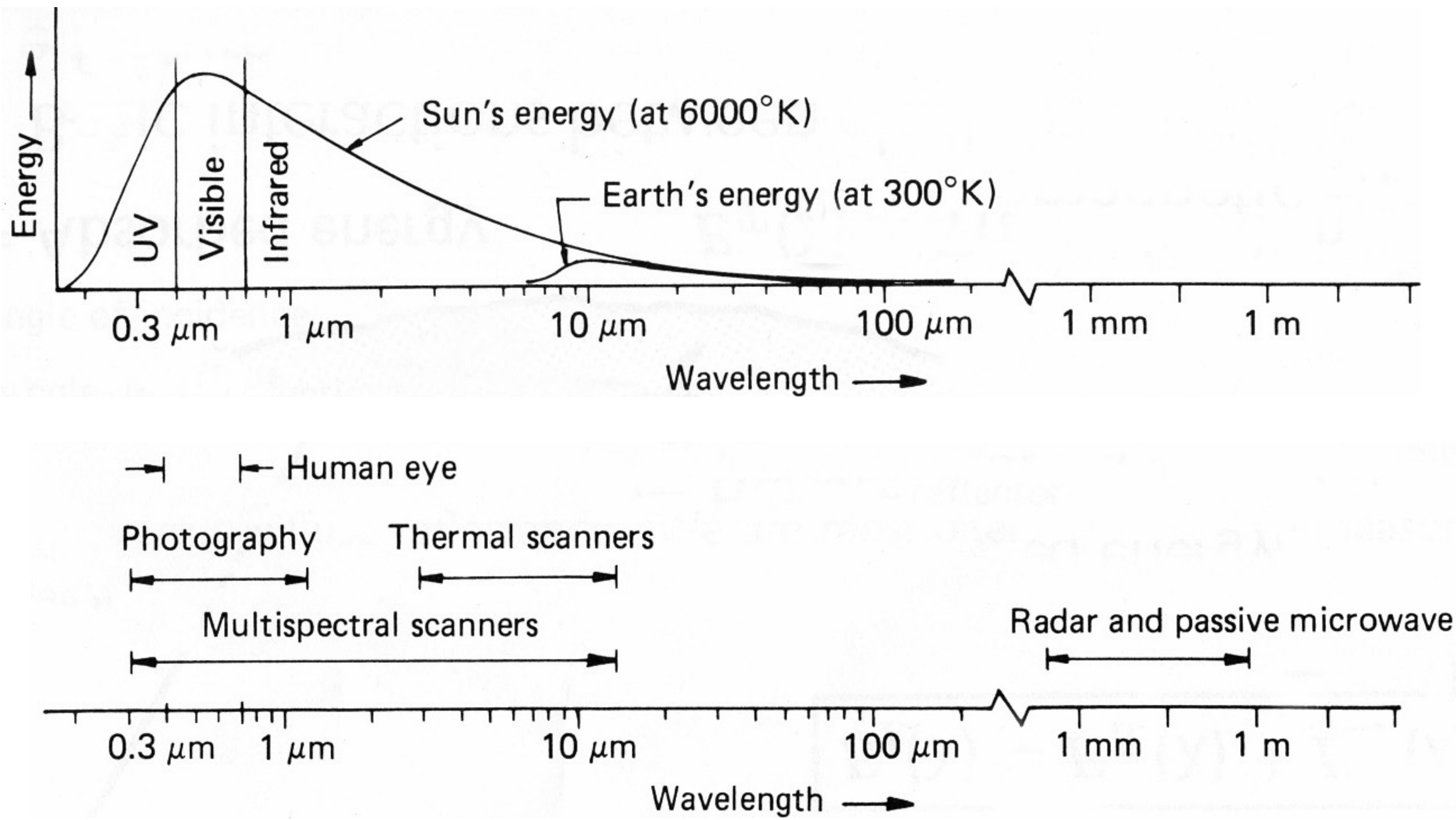
Spectral Distribution of Energy Radiated from Blackbodies at Various Temperatures



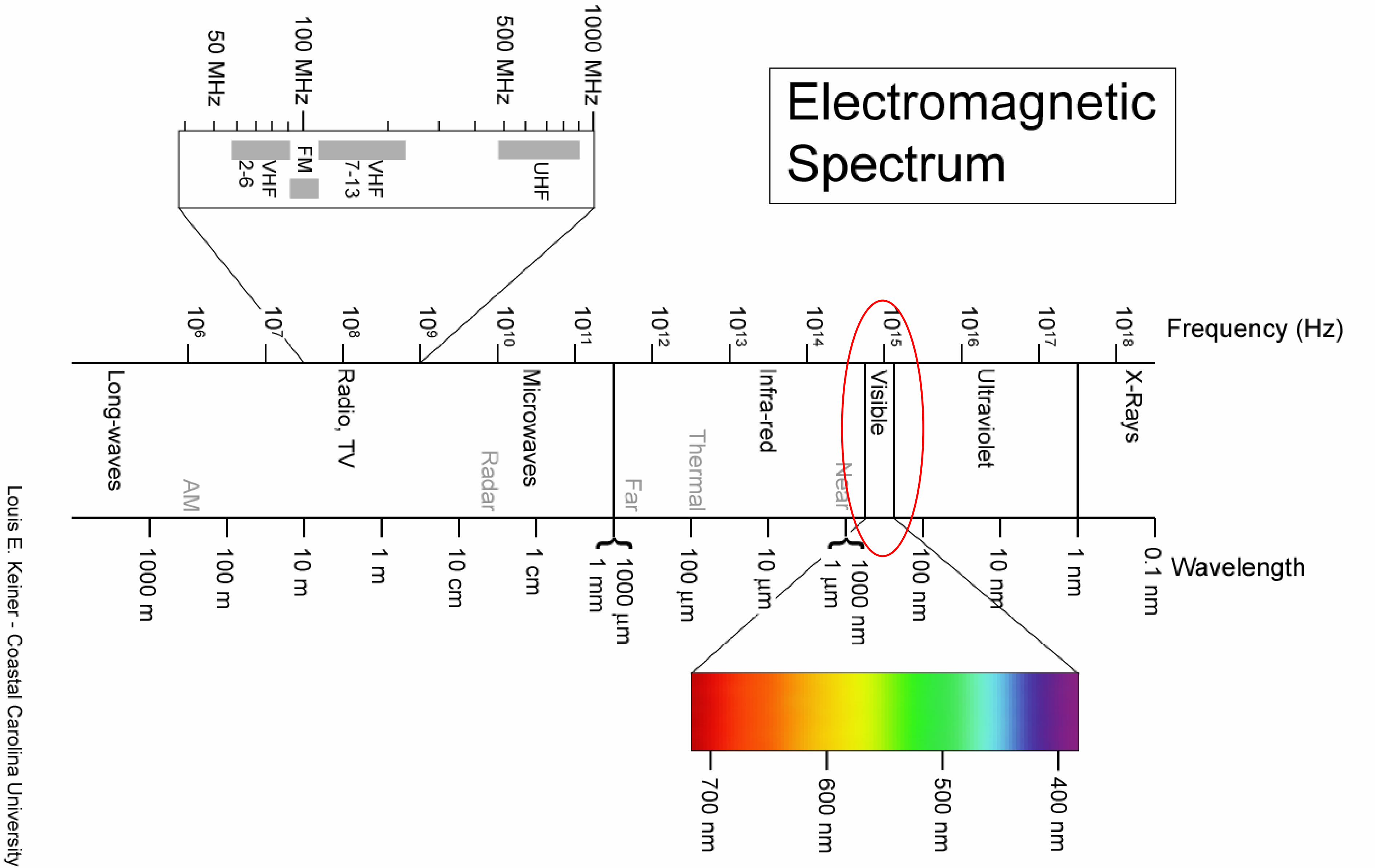
Temperature Sensitivity of B(λ,T) for typical earth scene temperatures

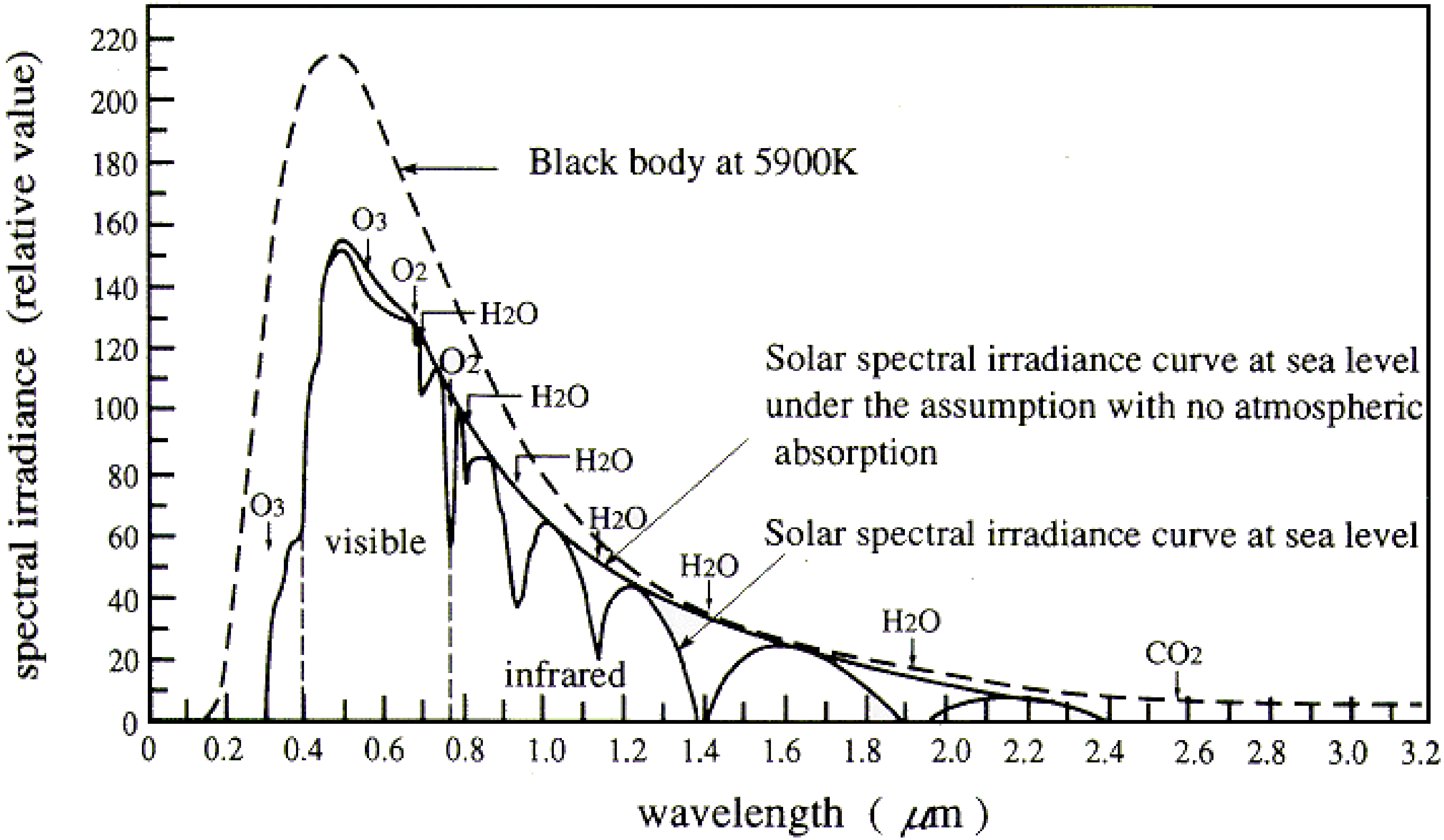


Spectral Characteristics of Energy Sources and Sensing Systems



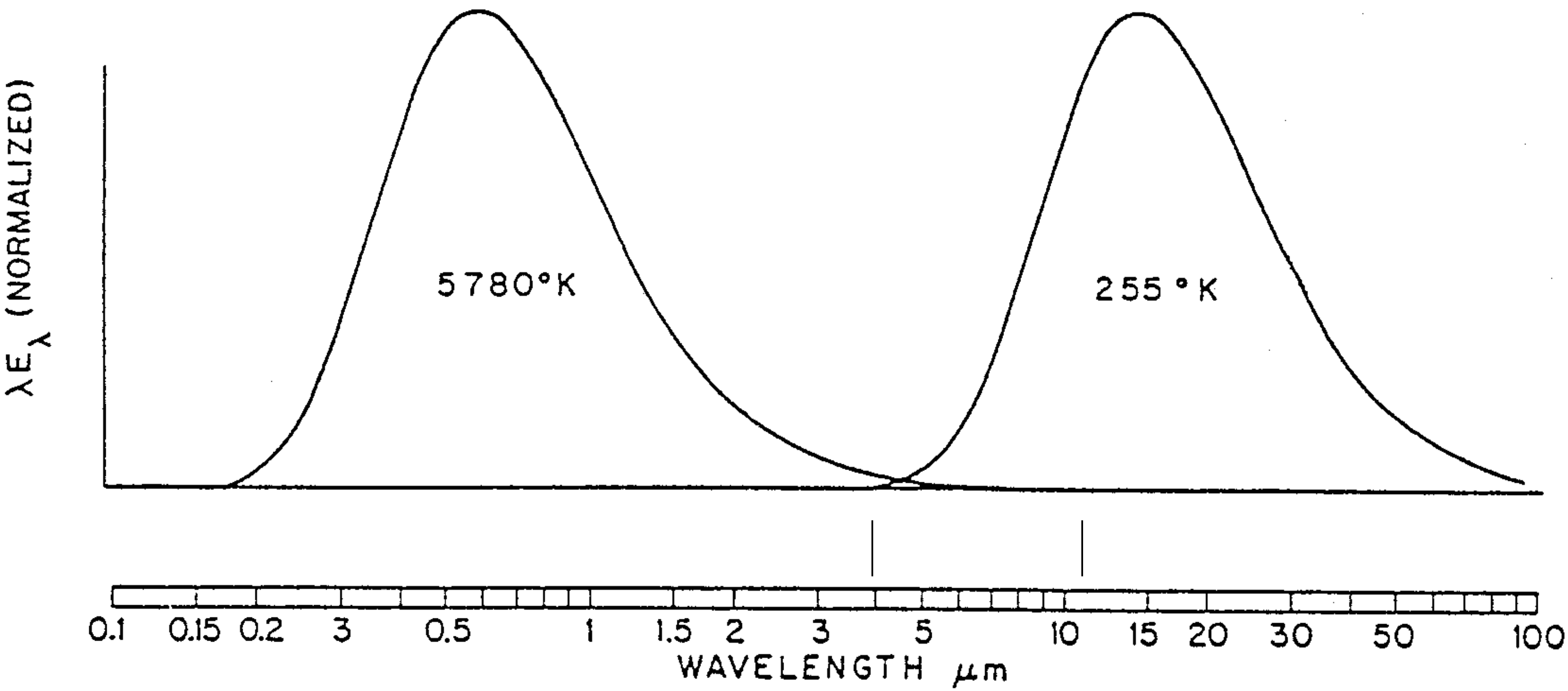
Electromagnetic Spectrum



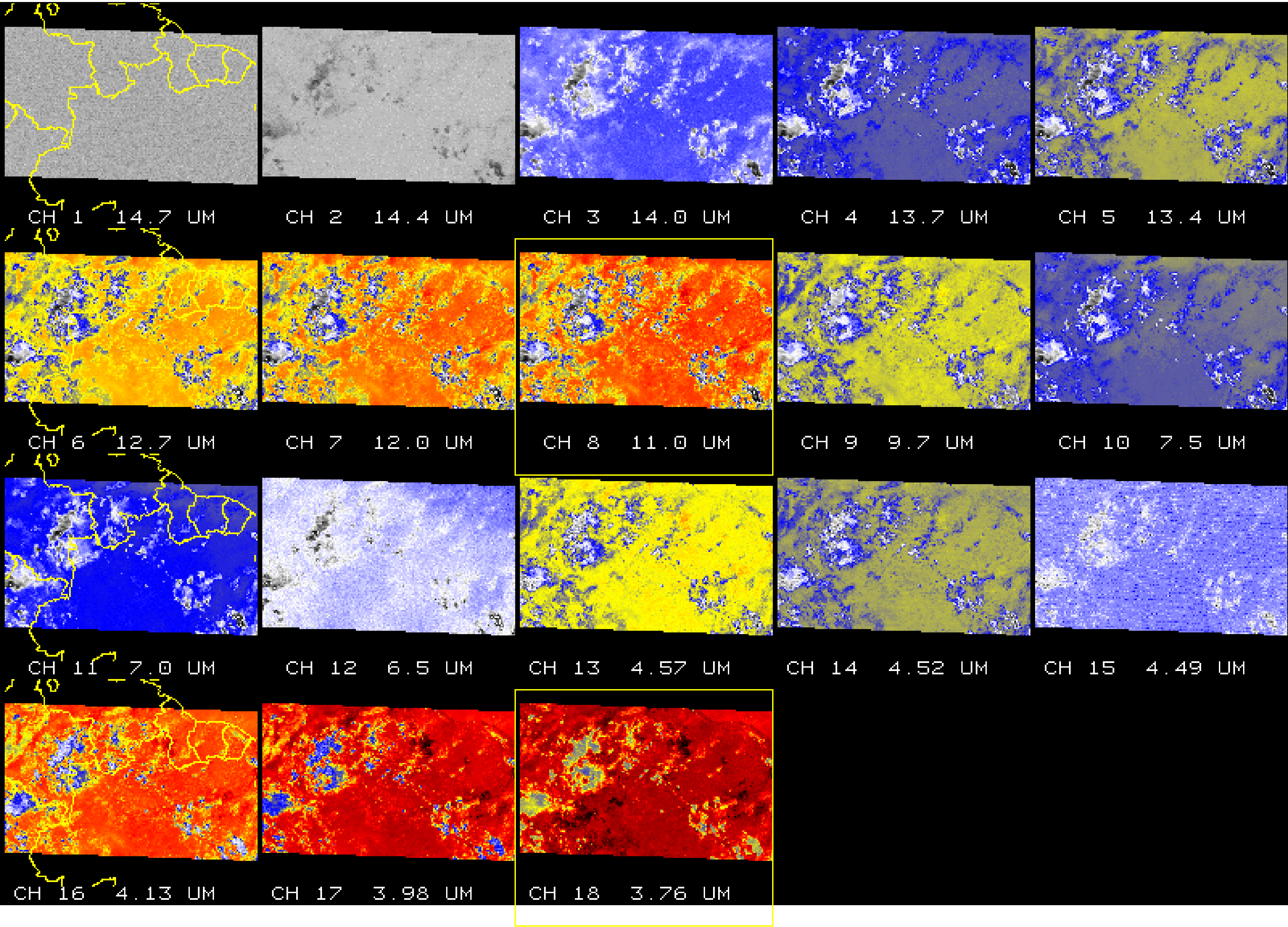


Comparison of spectral irradiance of solar light at sea level with black body radiation

Black body Spectra



<u>Normalized</u> black body spectra representative of the sun (left) and earth (right), plotted on a logarithmic wavelength scale. The ordinate is multiplied by wavelength so that the area under the curves is proportional to irradiance.



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CH 2 14.4 UM
CH 3 14.0 UM
CH 4 13.7 UM
CH 5 13.4 UM
CH 6 12.7 UM
CH 7 12.0 UM
CH 8 11.0 UM
CH 9 9.7 UM
CH 10 7.5 UM
CH 11 7.0 UM
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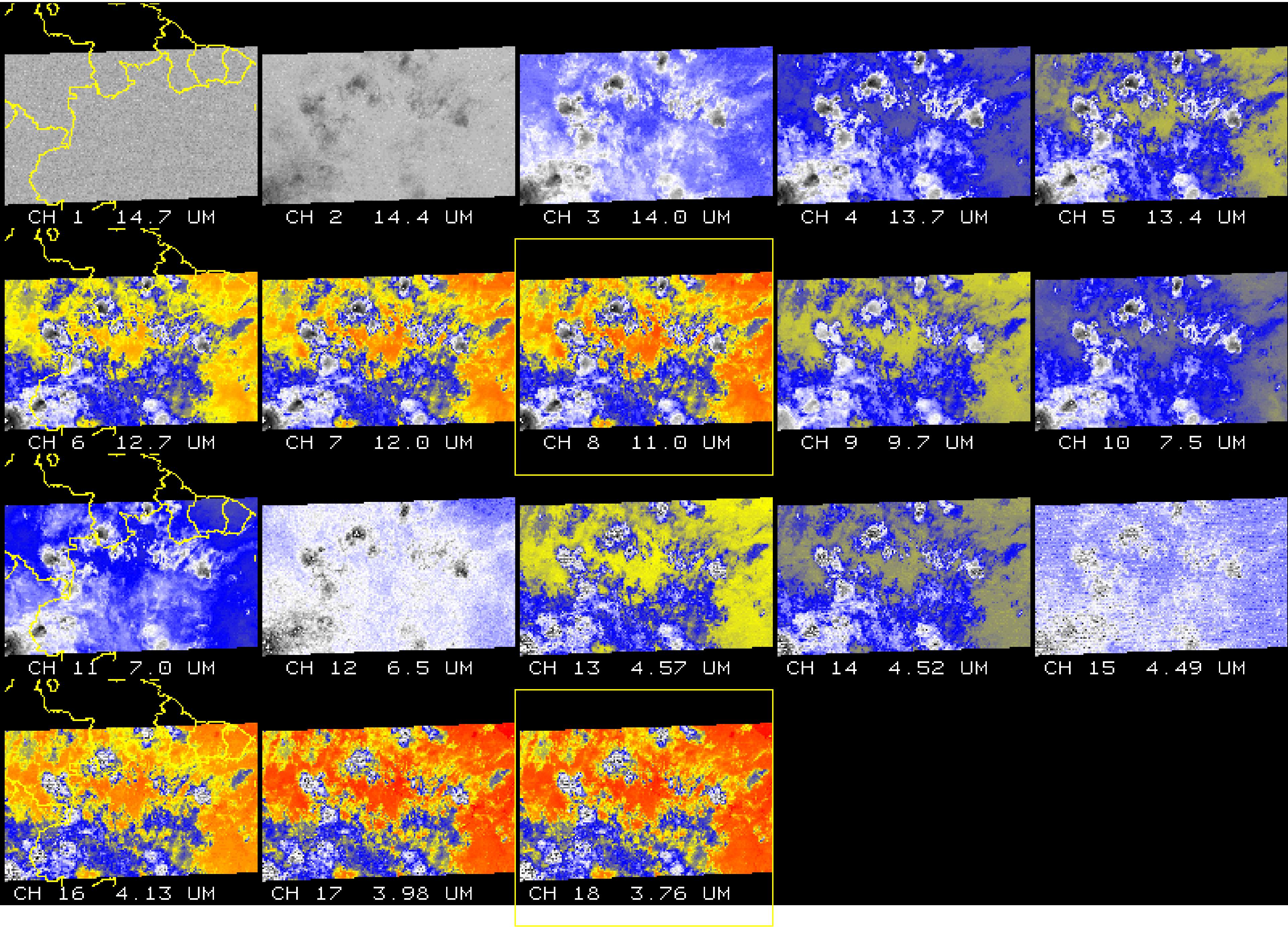
CH 14 4.52 UM
CH 15 4.49 UM
CH 16 4.13 UM
CH 17 3.98 UM
CH 18 3.76 UM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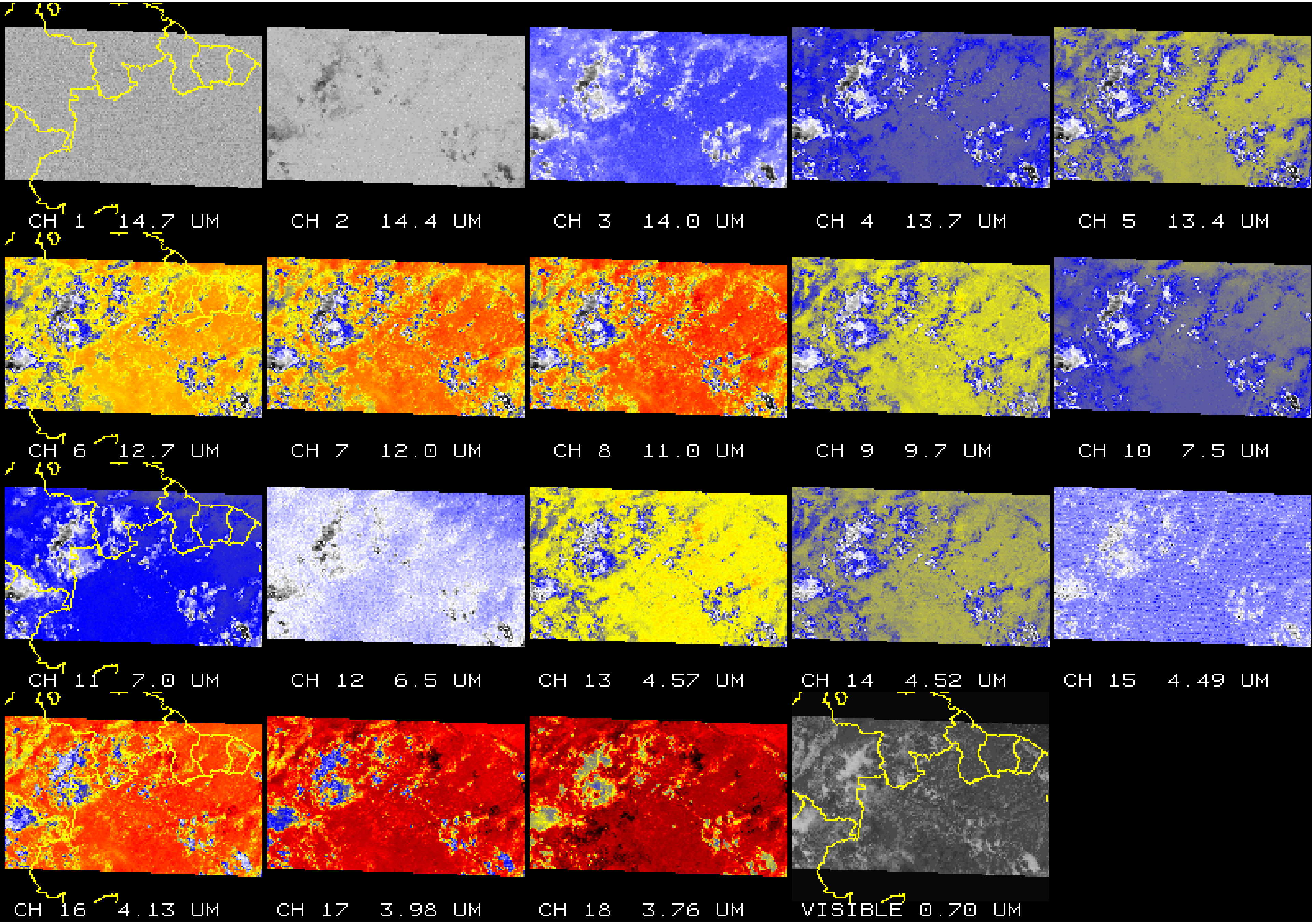
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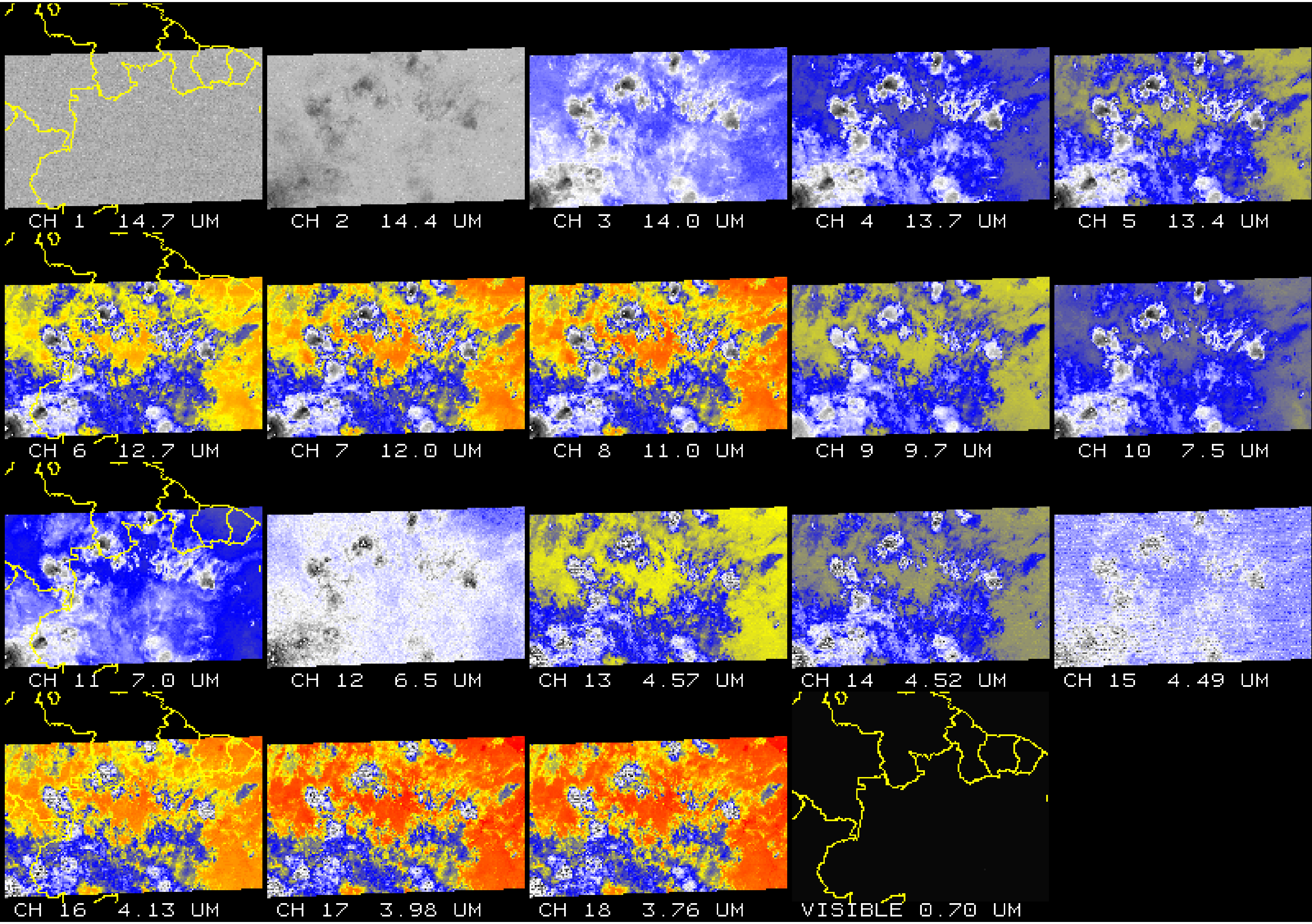
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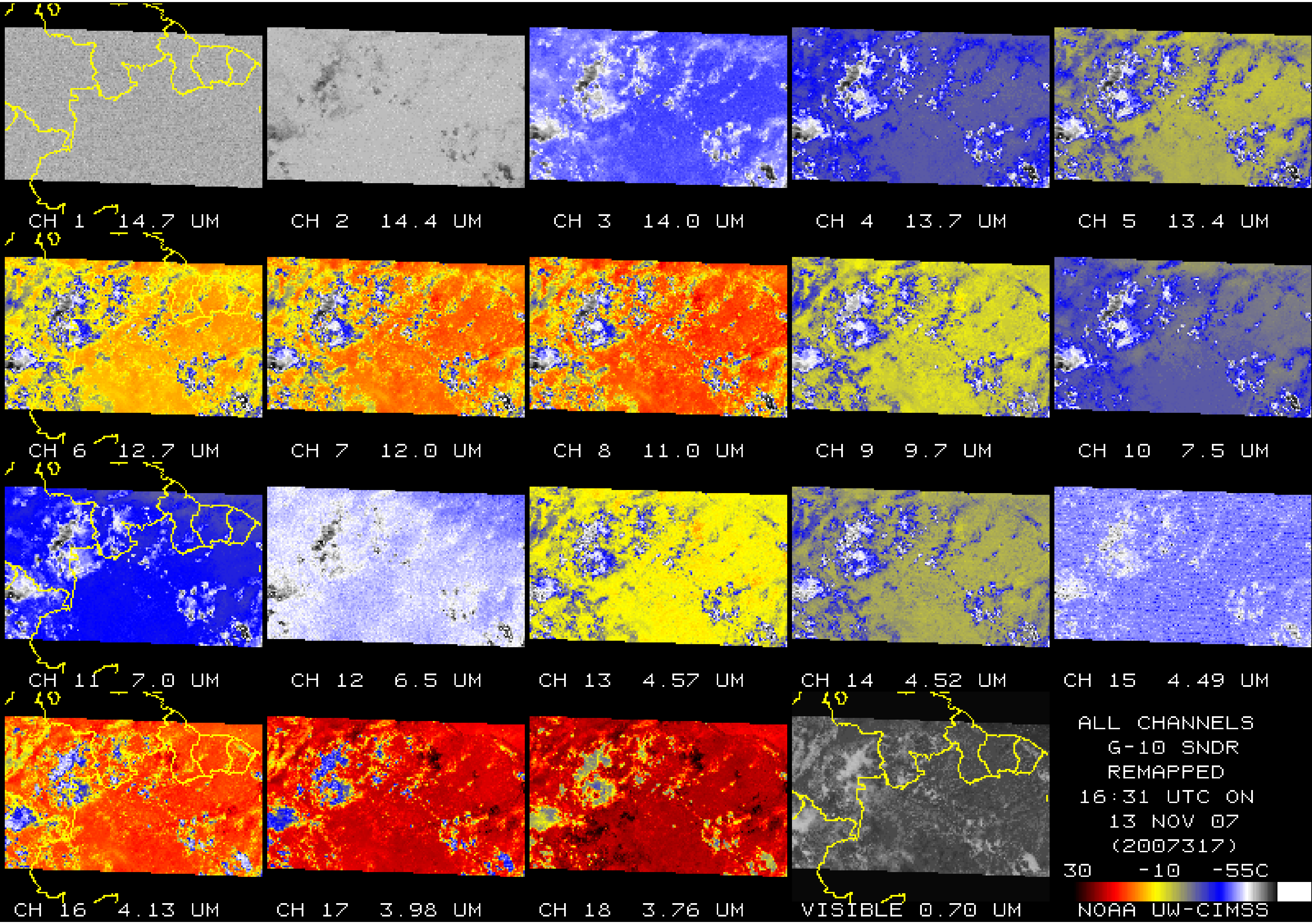
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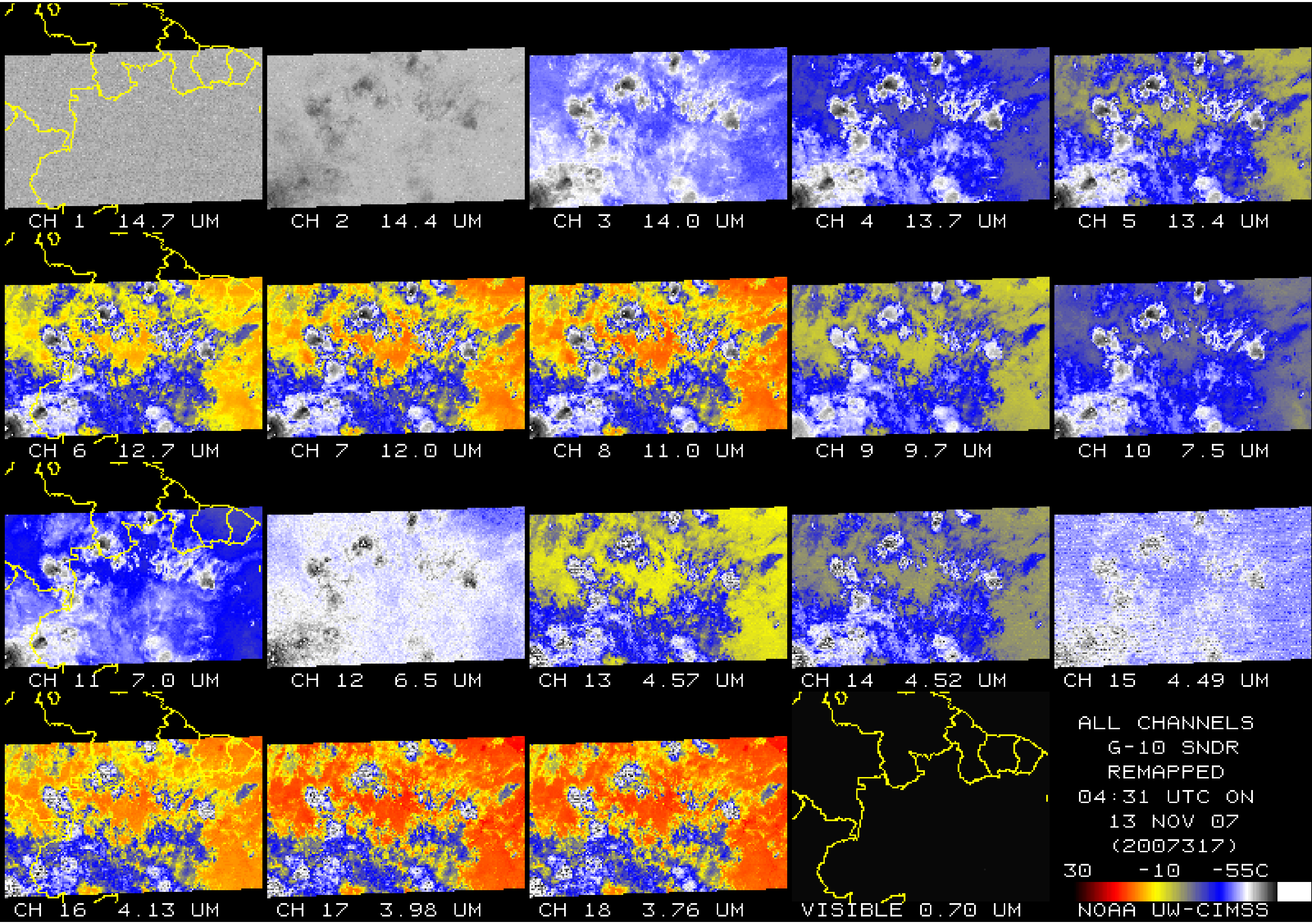
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Emission, Absorption

Blackbody radiation B_λ represents the upper limit to the amount of radiation that a real substance may emit at a given temperature for a given wavelength.

Emissivity ε_λ is defined as the fraction of emitted radiation R_λ to Blackbody radiation,

$$\varepsilon_\lambda = R_\lambda / B_\lambda \, .$$

In a medium at thermal equilibrium, what is absorbed is emitted (what goes in comes out) so

$$a_\lambda = \varepsilon_\lambda \, .$$

Thus, materials which are strong absorbers at a given wavelength are also strong emitters at that wavelength; similarly weak absorbers are weak emitters.

Transmittance

Transmission through an absorbing medium for a given wavelength is governed by the number of intervening absorbing molecules (path length u) and their absorbing power (k_λ) at that wavelength. Beer's law indicates that transmittance decays exponentially with increasing path length

$$\tau_\lambda (z \rightarrow \infty) = e^{- k_\lambda u (z)}$$

where the path length is given by $u(z) = \int_z^\infty \rho \, dz$.

$k_\lambda u$ is a measure of the cumulative depletion that the beam of radiation has experienced as a result of its passage through the layer and is often called the optical depth σ_λ.

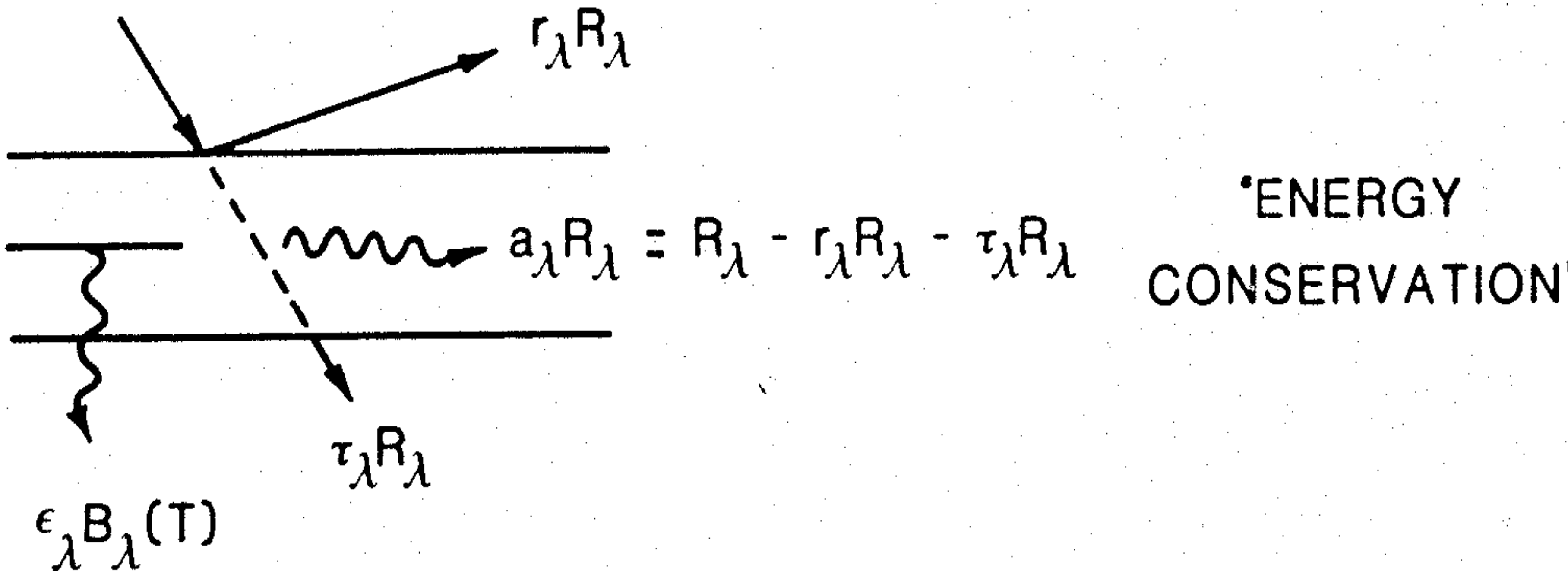
Realizing that the hydrostatic equation implies $g \rho \, dz = - q \, dp$

where q is the mixing ratio and ρ is the density of the atmosphere, then

$$u(p) = \int_o^p q \, g^{-1} \, dp \qquad \text{and} \qquad \tau_\lambda (p \rightarrow o) = e^{- k_\lambda u (p)}$$

Energy conservation

$\tau + a + \cancel{r} = 1$



$$\boldsymbol{\tau} + a + r = 1$$

Emission, Absorption, Reflection, and Scattering

If a_λ, r_λ, and τ_λ represent the fractional absorption, reflectance, and transmittance, respectively, then conservation of energy says

$$a_\lambda + r_\lambda + \tau_\lambda = 1 \quad .$$

For a blackbody $a_\lambda = 1$, it follows that $r_\lambda = 0$ and $\tau_\lambda = 0$ for blackbody radiation. Also, for a perfect window $\tau_\lambda = 1$, $a_\lambda = 0$ and $r_\lambda = 0$. For any opaque surface $\tau_\lambda = 0$, so radiation is either absorbed or reflected $a_\lambda + r_\lambda = 1$.

At any wavelength, strong reflectors are weak absorbers (i.e., snow at visible wavelengths), and weak reflectors are strong absorbers (i.e., asphalt at visible wavelengths).

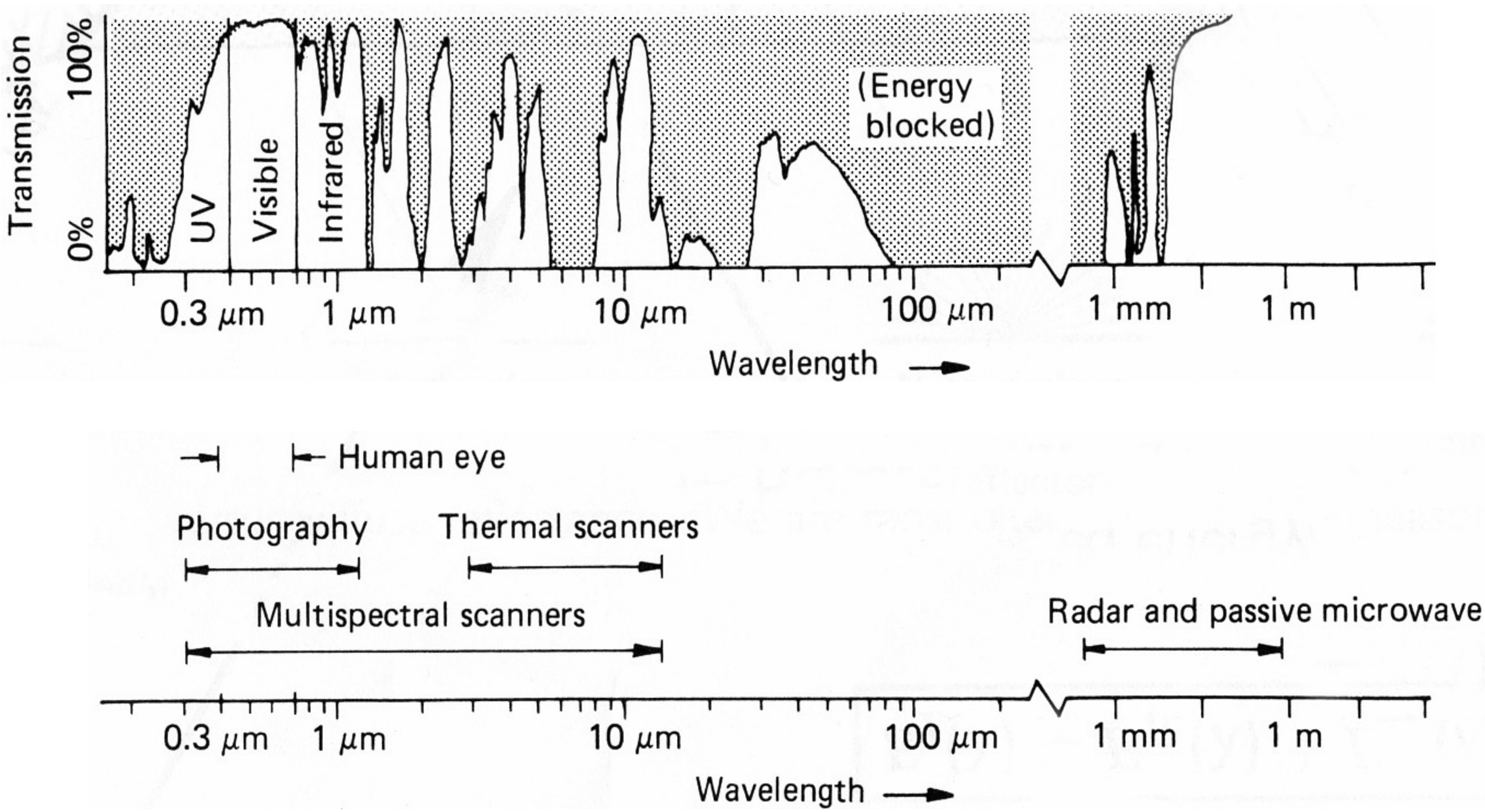
Radiative Transfer Equation

The radiance leaving the earth-atmosphere system sensed by a satellite borne radiometer is the sum of radiation emissions from the earth-surface and each atmospheric level that are transmitted to the top of the atmosphere. Considering the earth's surface to be a blackbody emitter (emissivity equal to unity), the upwelling radiance intensity, I_λ, for a cloudless atmosphere is given by the expression

$$I_\lambda = \varepsilon_\lambda^{sfc} B_\lambda(T_{sfc})\, \tau_\lambda(sfc - top) + \sum_{layers} \varepsilon_\lambda^{layer} B_\lambda(T_{layer})\, \tau_\lambda(layer - top)$$

where the first term is the surface contribution and the second term is the atmospheric contribution to the radiance to space.

Spectral Characteristics of Atmospheric Transmission and Sensing Systems

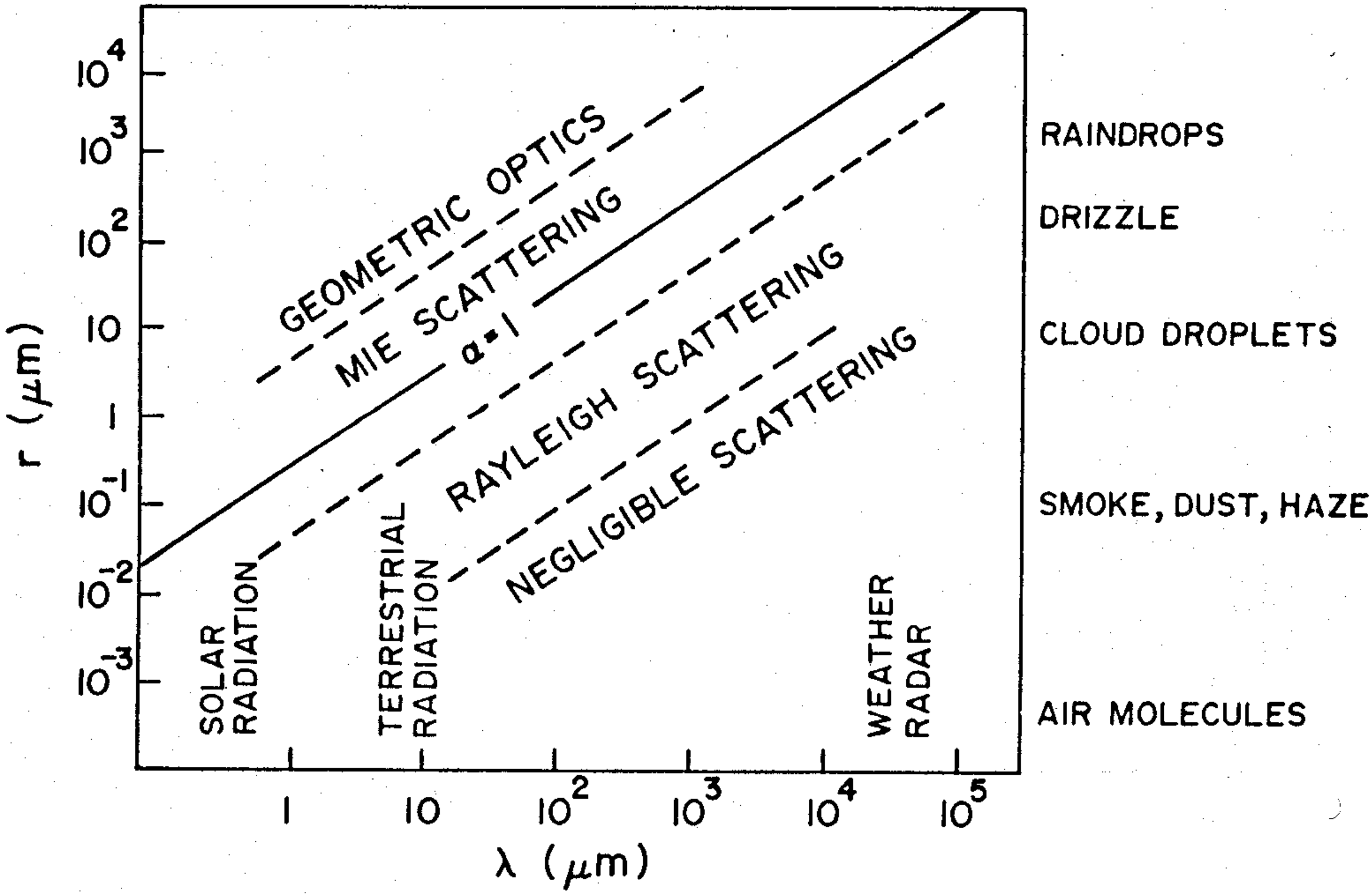


Relative Effects of Radiative Processes

Sun - Earth - Atmosphere Energy System

		Solar Radiation		Terrestrial Radiation	
		Absorption / Emission	Scattering	Absorption / Emission	Scattering
Clouds	Water	✓ Small	✓ Large	✓ Moderate	✓ Negligible
	Ice	✓ Variable	✓ Moderate	✓ Small	✓ Negligible
Molecules in the Atmosphere		✓ Small	✓ Moderate	✓ Variable	✓ Negligible
Aerosols in the Atmosphere		✓ Small	✓ Moderate	✓ Variable	✓ Negligible
Earth's Surface	Land	✓ Large	✓ Moderate	✓ Large	✓ Negligible
	Water	✓ Large	✓ Small	✓ Large	✓ Negligible
	Snow / Ice	✓ Variable	✓ Large	✓ Variable	✓ Negligible

Earth



GEOMETRIC OPTICS
MIE SCATTERING
α=1
RAYLEIGH SCATTERING
NEGLIGIBLE SCATTERING
SOLAR RADIATION
TERRESTRIAL RADIATION
WEATHER RADAR
RAINDROPS
DRIZZLE
CLOUD DROPLETS
SMOKE, DUST, HAZE
AIR MOLECULES
r (μm)
λ (μm)
10^4
10^3
10^2
10
1
10^-1
10^-2
10^-3
1
10
10^2
10^3
10^4
10^5

Aerosol Size Distribution

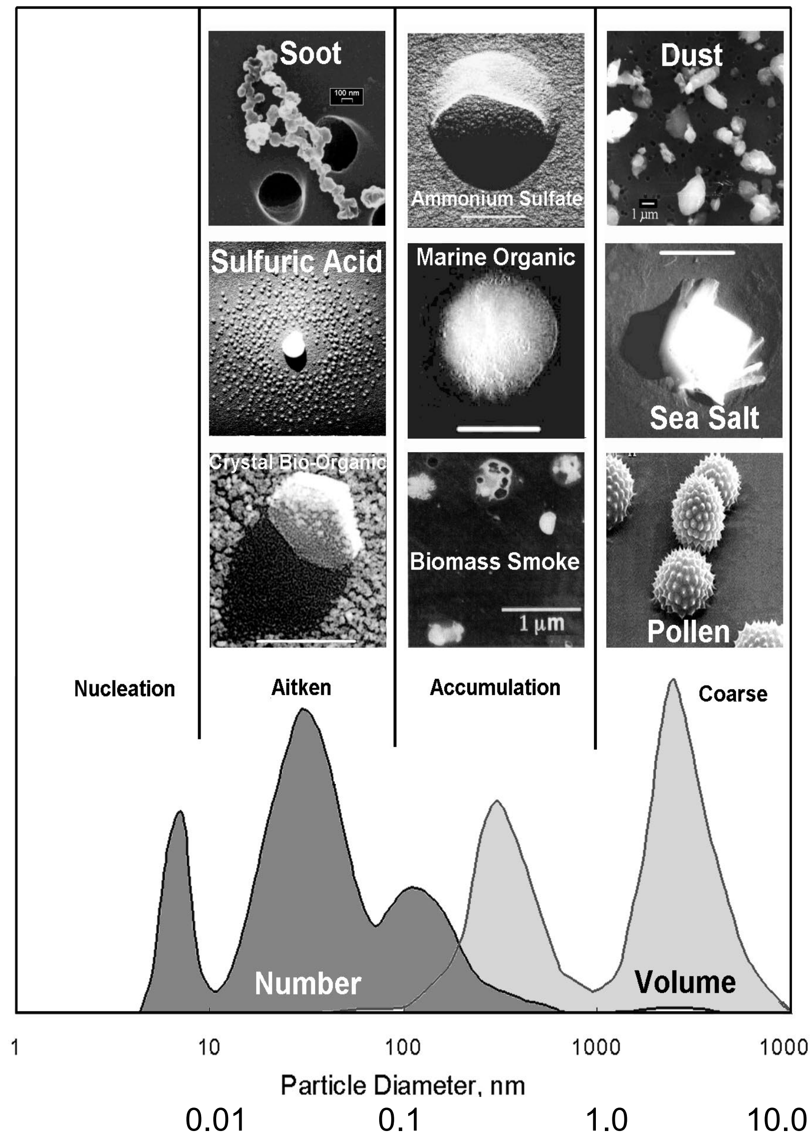
There are 3 modes :

- « **nucleation** »: radius is between 0.002 and 0.05 µm. They result from combustion processes, photo-chemical reactions, etc.

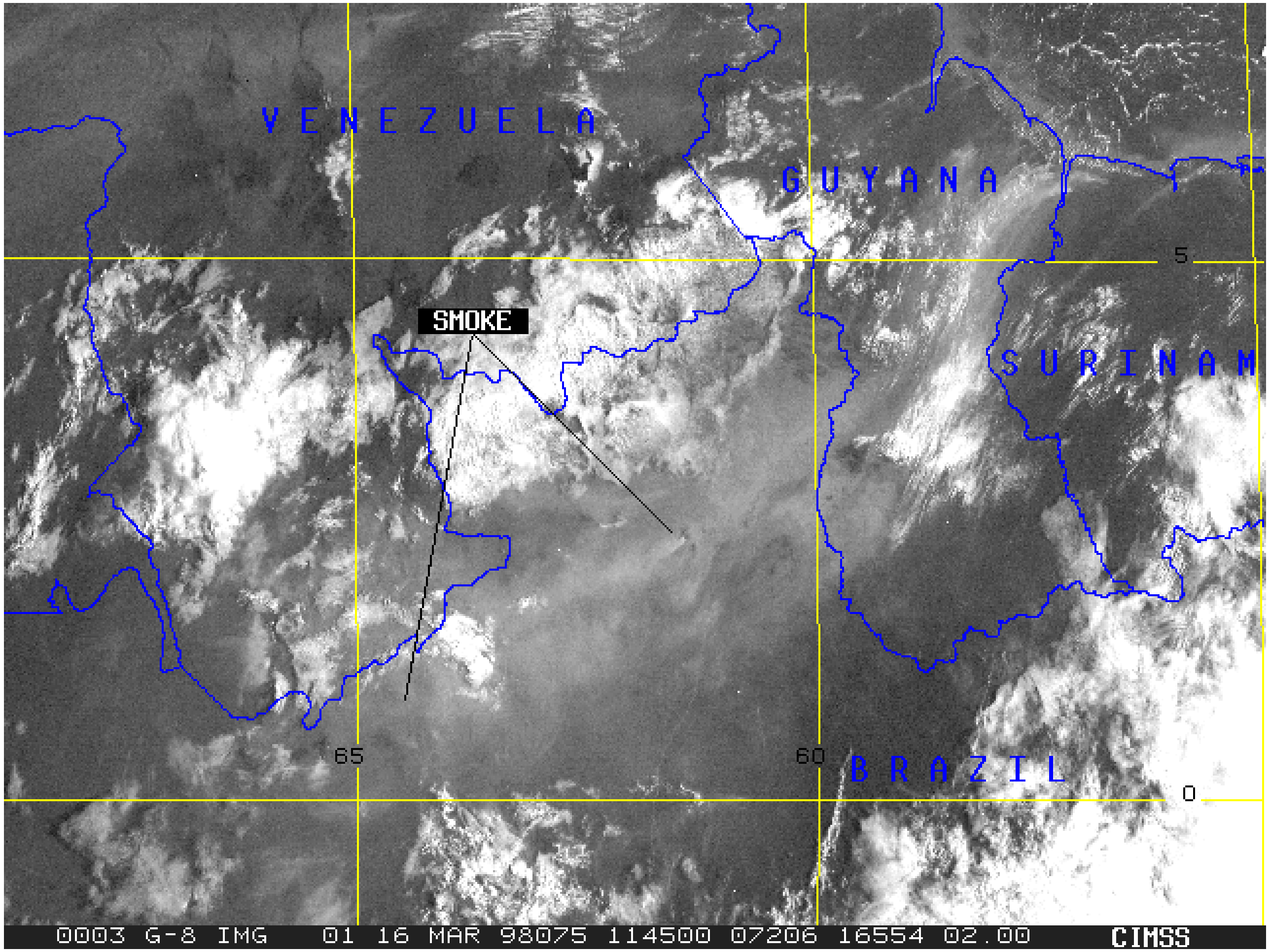
- « **accumulation »:** radius is between 0.05 µm and 0.5 µm**.** Coagulation processes.

- « **coarse** »: larger than 1 µm**.** From mechanical processes like aeolian erosion.

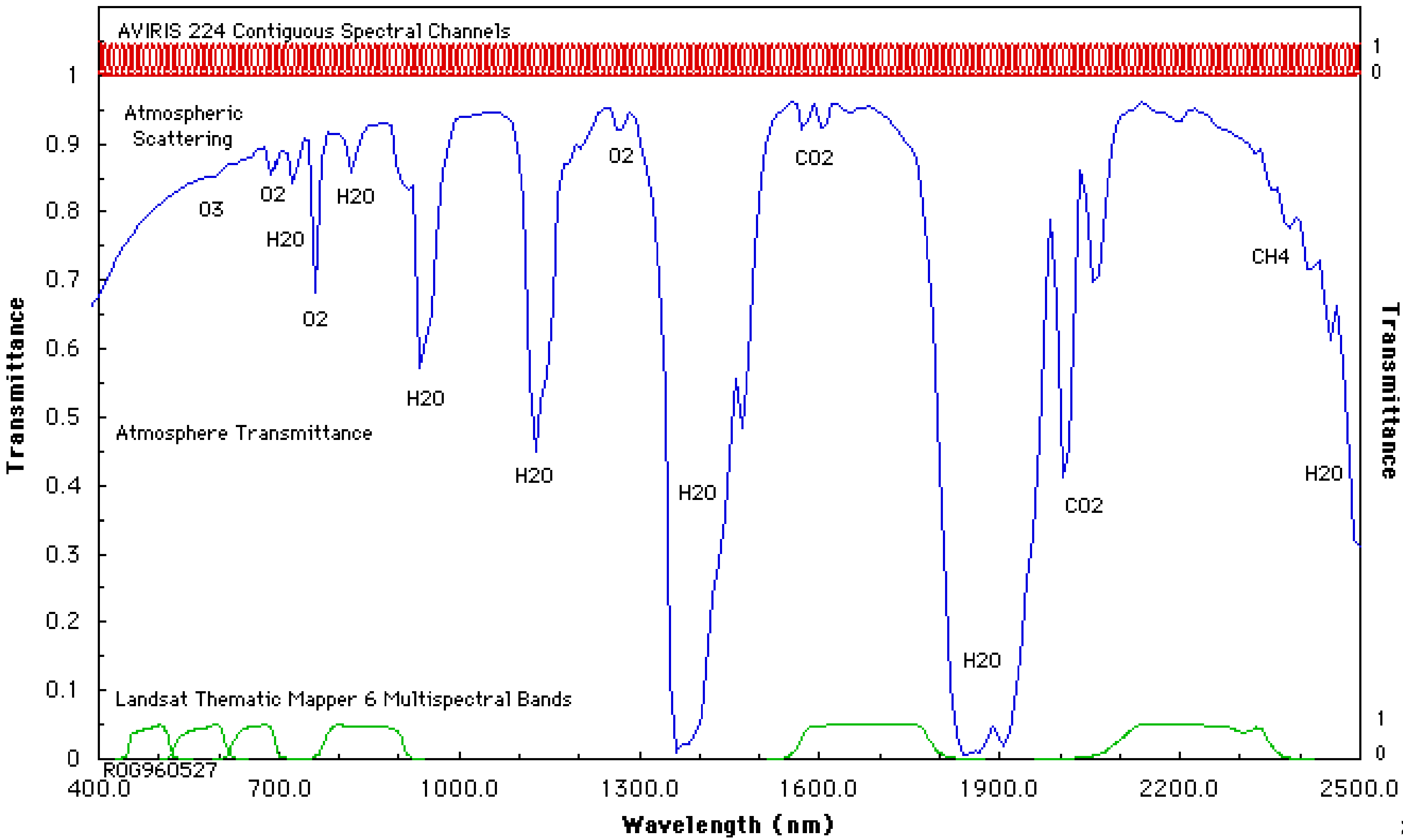
« fine » particles (nucleation and accumulation) result from anthropogenic activities, coarse particles come from natural processes.



Scattering of early morning sun light from smoke

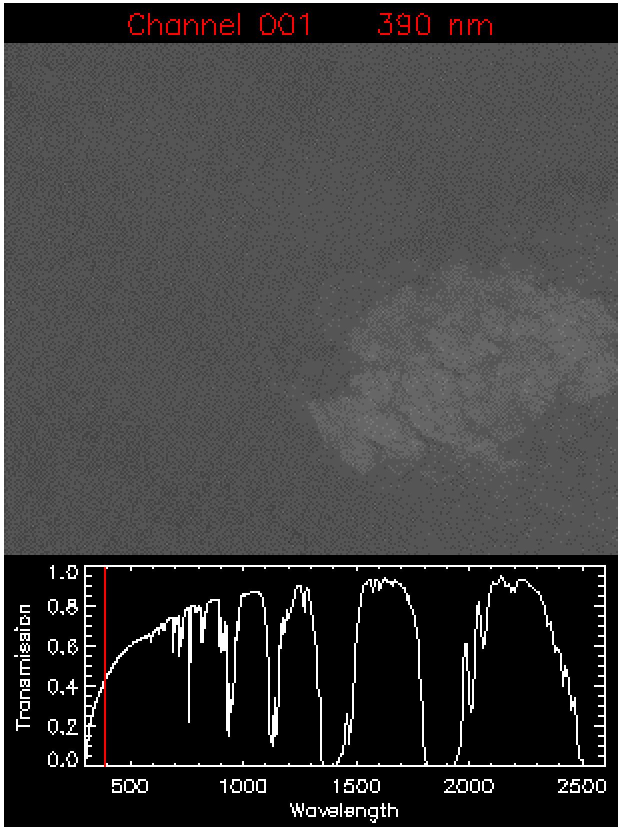


Measurements in the Solar Reflected Spectrum across the region covered by AVIRIS



AVIRIS Movie #1

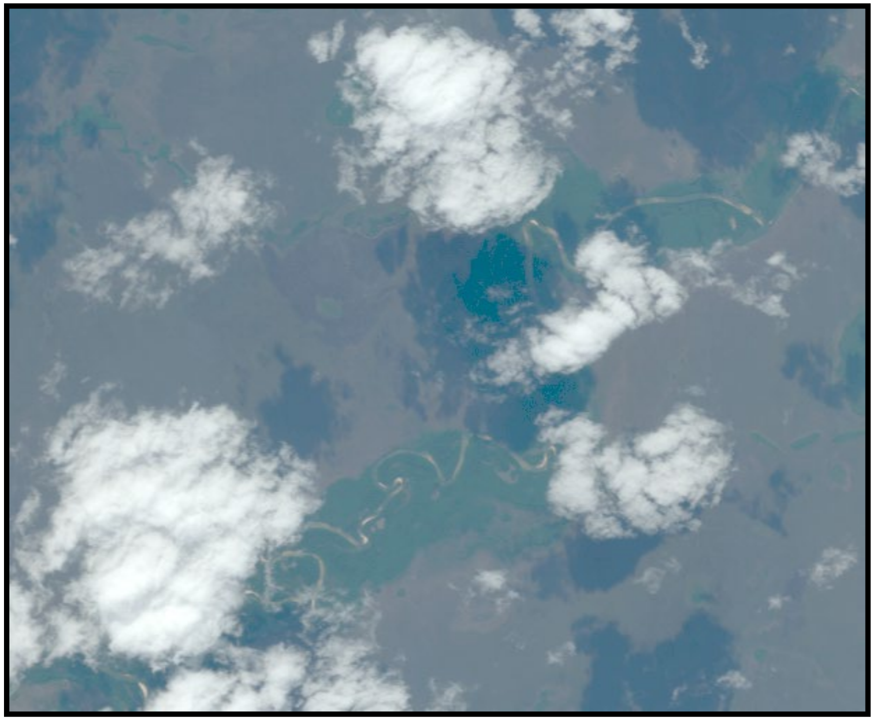
AVIRIS Image - Linden CA 20-Aug-1992
224 Spectral Bands: 0.4 - 2.5 μm
Pixel: 20m x 20m   Scene: 10km x 10km

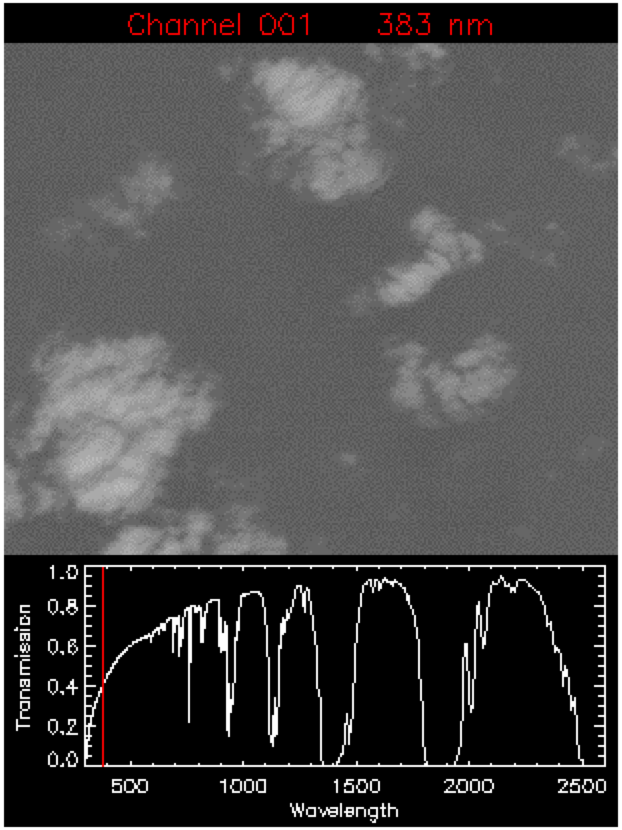


Movie from MIT/LL

AVIRIS Movie #2

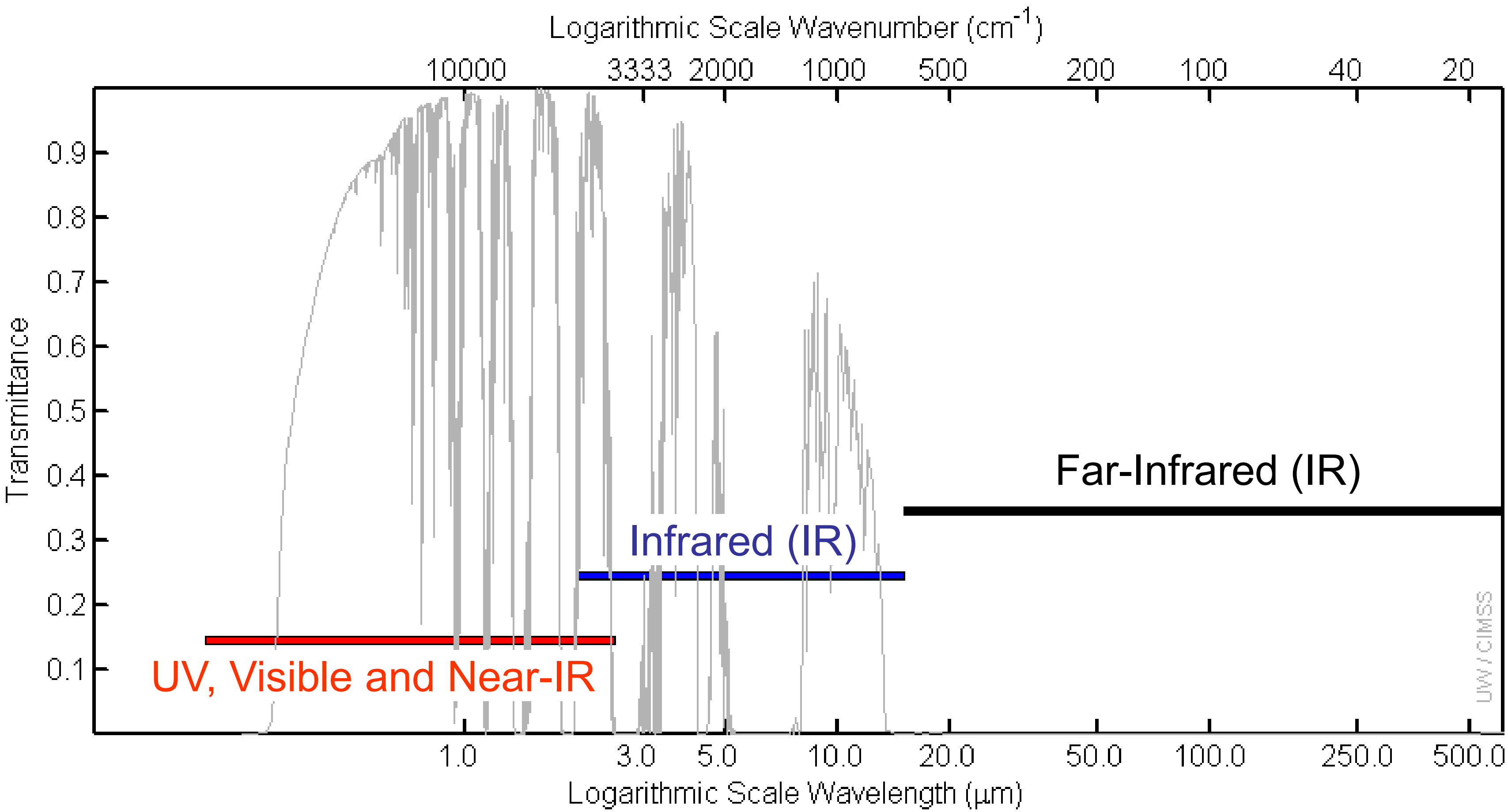
AVIRIS Image - Porto Nacional, Brazil
20-Aug-1995
224 Spectral Bands: 0.4 - 2.5 μm
Pixel: 20m x 20m   Scene: 10km x 10km





Movie from MIT/LL

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



Relevant Material in Applications of Meteorological Satellites

Radiative Transfer Equation

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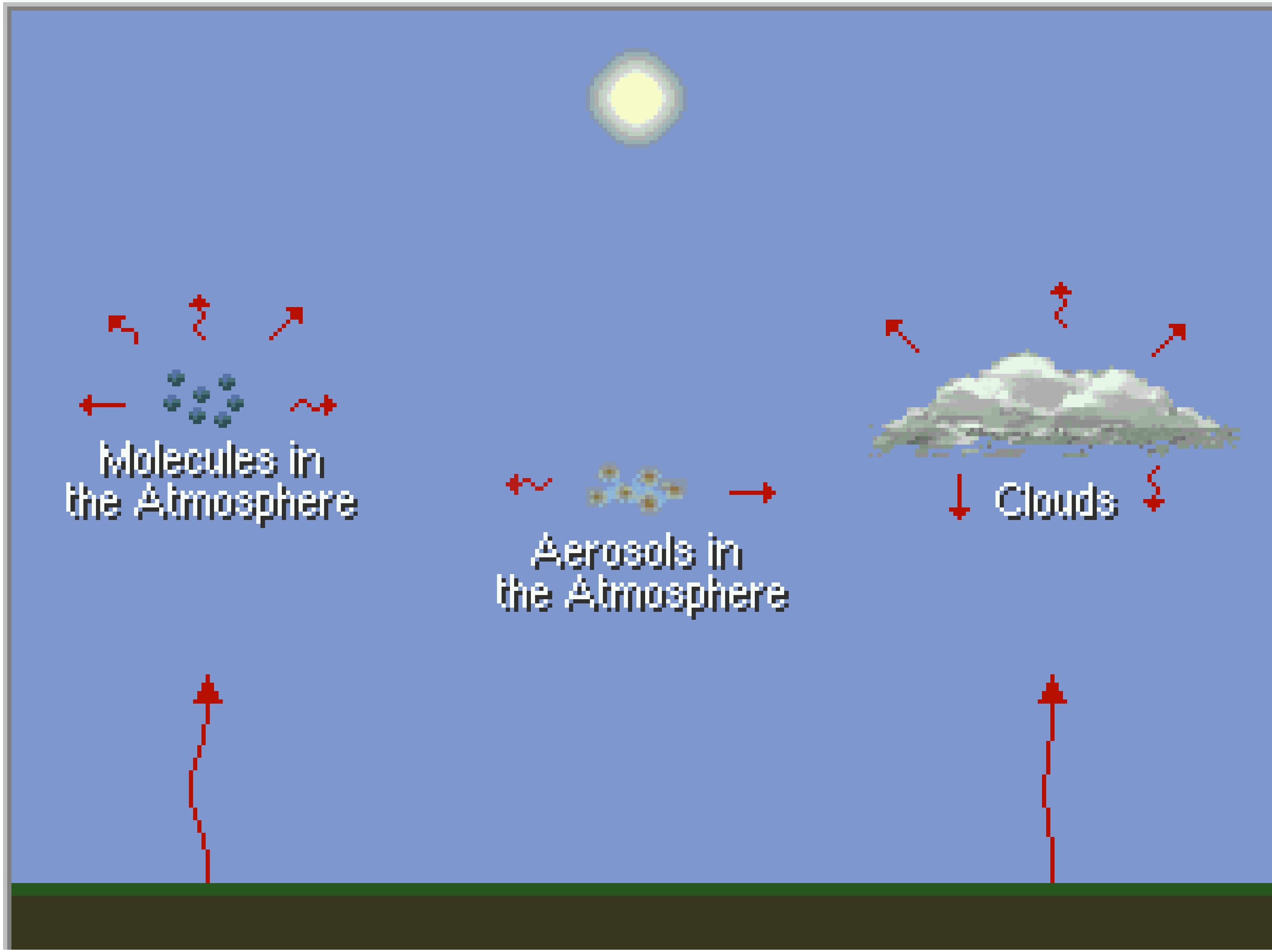
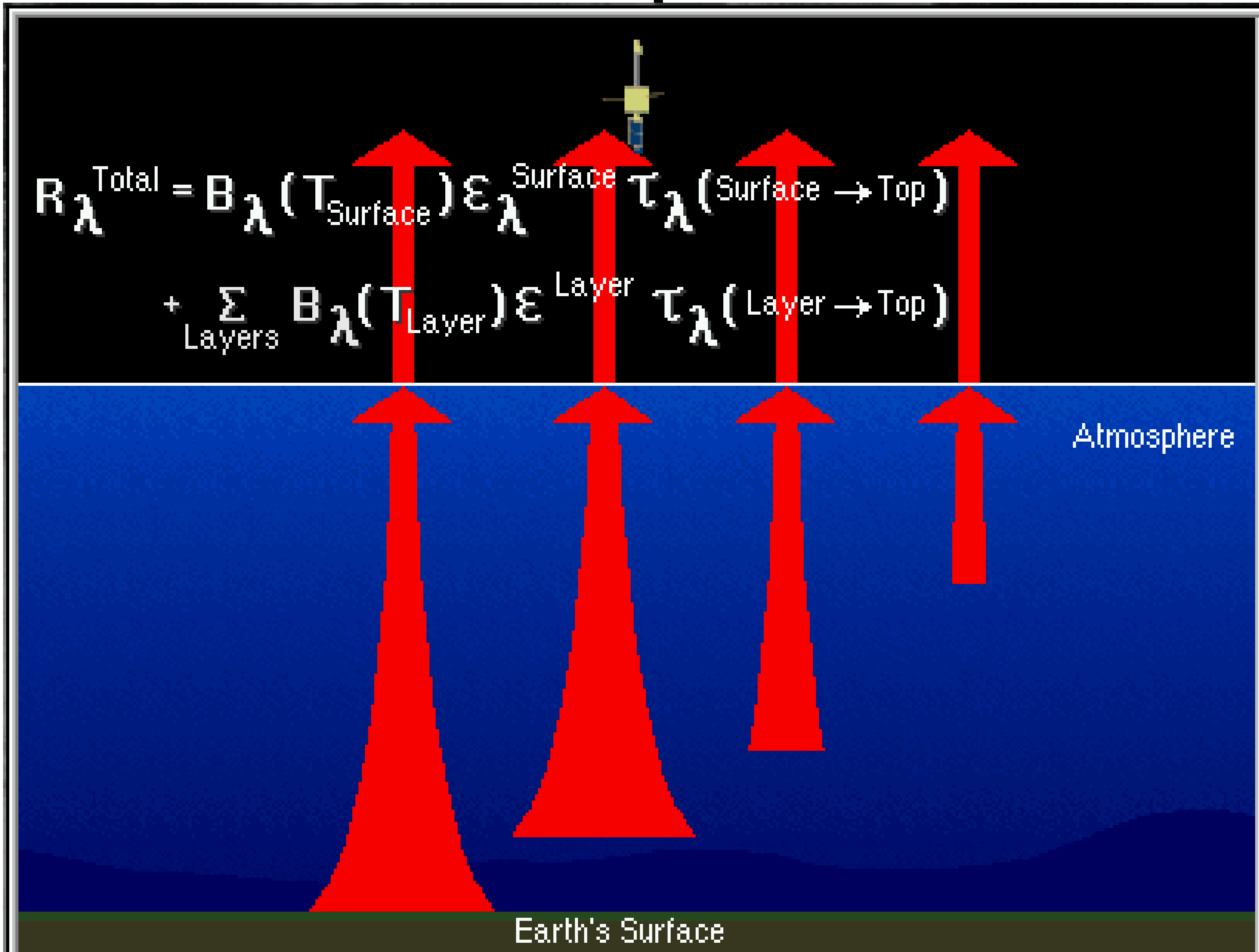
$$I_\lambda = \varepsilon_\lambda^{sfc} B_\lambda(T_{sfc})\, \tau_\lambda(sfc - top) + \sum_{layers} \varepsilon_\lambda^{layer} B_\lambda(T_{layer})\, \tau_\lambda(layer - top)$$

where the first term is the surface contribution and the second term is the atmospheric contribution to the radiance to space.

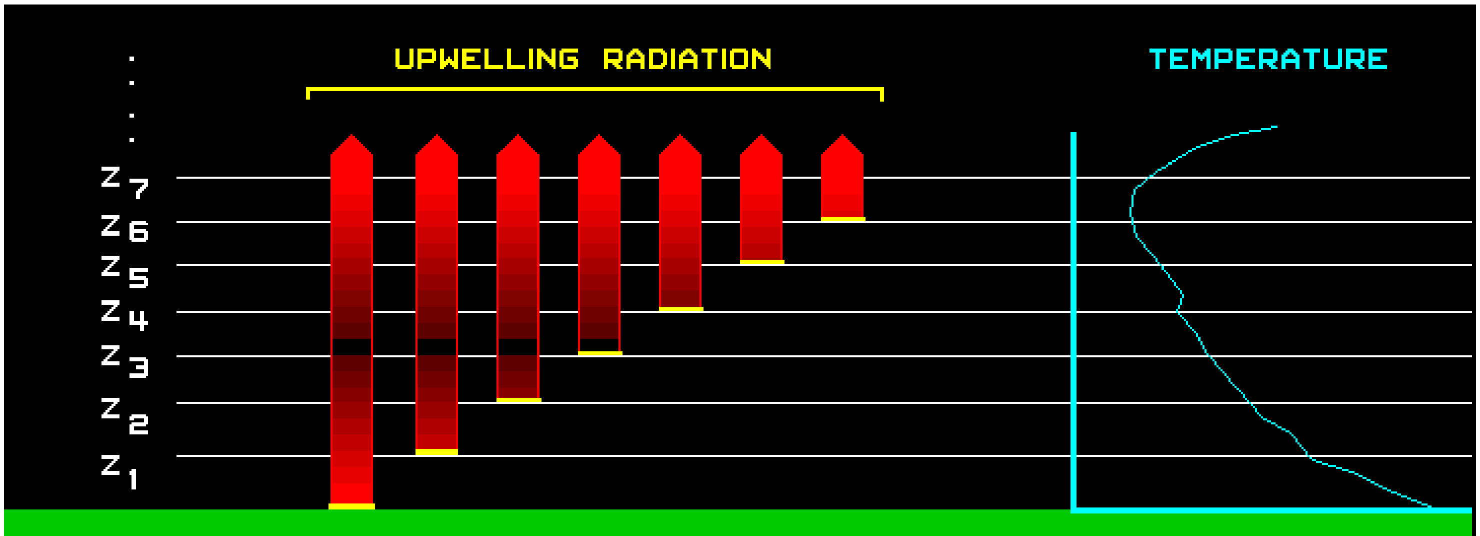
Re-emission of Infrared Radiation



Radiative Transfer through the Atmosphere

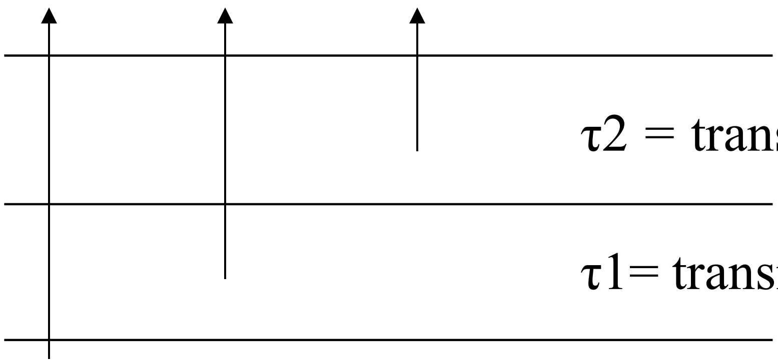


Radiative Transfer Equation



$$R(n) = B(n,T_0)\,\tau(n,0) + \int_{z_0}^{z_T} B(n,T[z])\,(d\tau[n,z]/dz)\,dz$$

Rsfc R1 R2



top of the atmosphere

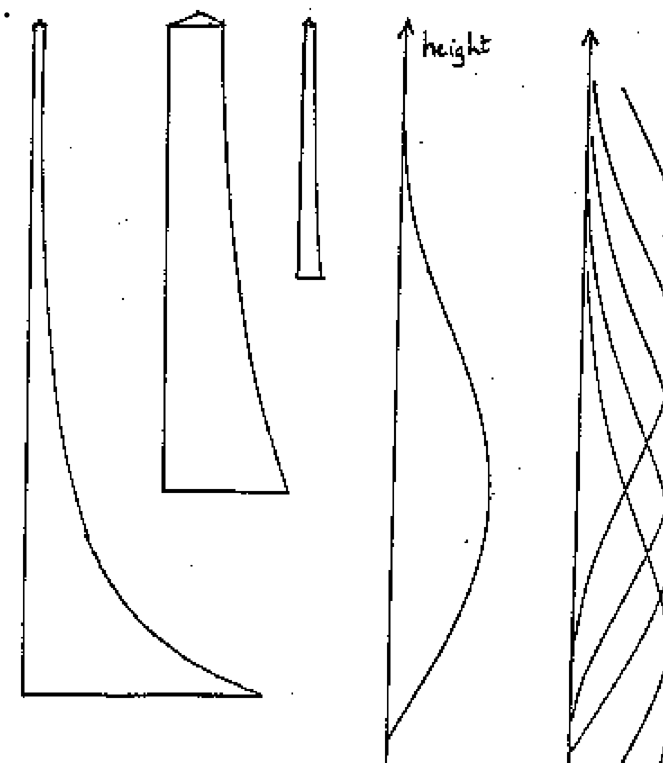
$\tau 2$ = transmittance of upper layer of atm

$\tau 1$= transmittance of lower layer of atm

bb earth surface.

Robs =

$$Rsfc\ \tau 1\ \tau 2 + R1\ (1-\tau 1)\ \tau 2 + R2\ (1-\tau 2)$$



In standard notation,

$$I_\lambda = \varepsilon_\lambda^{sfc} B_\lambda(T(p_s)) \tau_\lambda(p_s) + \sum_p \varepsilon_\lambda(\Delta p) B_\lambda(T(p)) \tau_\lambda(p)$$

The emissivity of an infinitesimal layer of the atmosphere at pressure p is equal to the absorptance (one minus the transmittance of the layer). Consequently,

$$\varepsilon_\lambda(\Delta p) \tau_\lambda(p) = [1 - \tau_\lambda(\Delta p)] \tau_\lambda(p)$$

Since transmittance is an exponential function of depth of absorbing constituent,

$$\tau_\lambda(\Delta p) \tau_\lambda(p) = \exp [- \int_p^{p+\Delta p} k_\lambda q g^{-1} dp] * \exp [- \int_o^p k_\lambda q g^{-1} dp] = \tau_\lambda(p + \Delta p)$$

Therefore

$$\varepsilon_\lambda(\Delta p) \tau_\lambda(p) = \tau_\lambda(p) - \tau_\lambda(p + \Delta p) = - \Delta\tau_\lambda(p) .$$

So we can write

$$I_\lambda = \varepsilon_\lambda^{sfc} B_\lambda(T(p_s)) \tau_\lambda(p_s) - \sum_p B_\lambda(T(p)) \Delta\tau_\lambda(p) .$$

which when written in integral form reads

$$I_\lambda = \varepsilon_\lambda^{sfc} B_\lambda(T(p_s)) \tau_\lambda(p_s) - \int_o^{p_s} B_\lambda(T(p)) [d\tau_\lambda(p) / dp] dp .$$

When reflection from the earth surface is also considered, the Radiative Transfer Equation for infrared radiation can be written

$$I_\lambda = \varepsilon_\lambda^{sfc} B_\lambda(T_s)\, \tau_\lambda(p_s) + \int_{p_s}^{o} B_\lambda(T(p))\, F_\lambda(p)\, [d\tau_\lambda(p)/ dp]\, dp$$

where

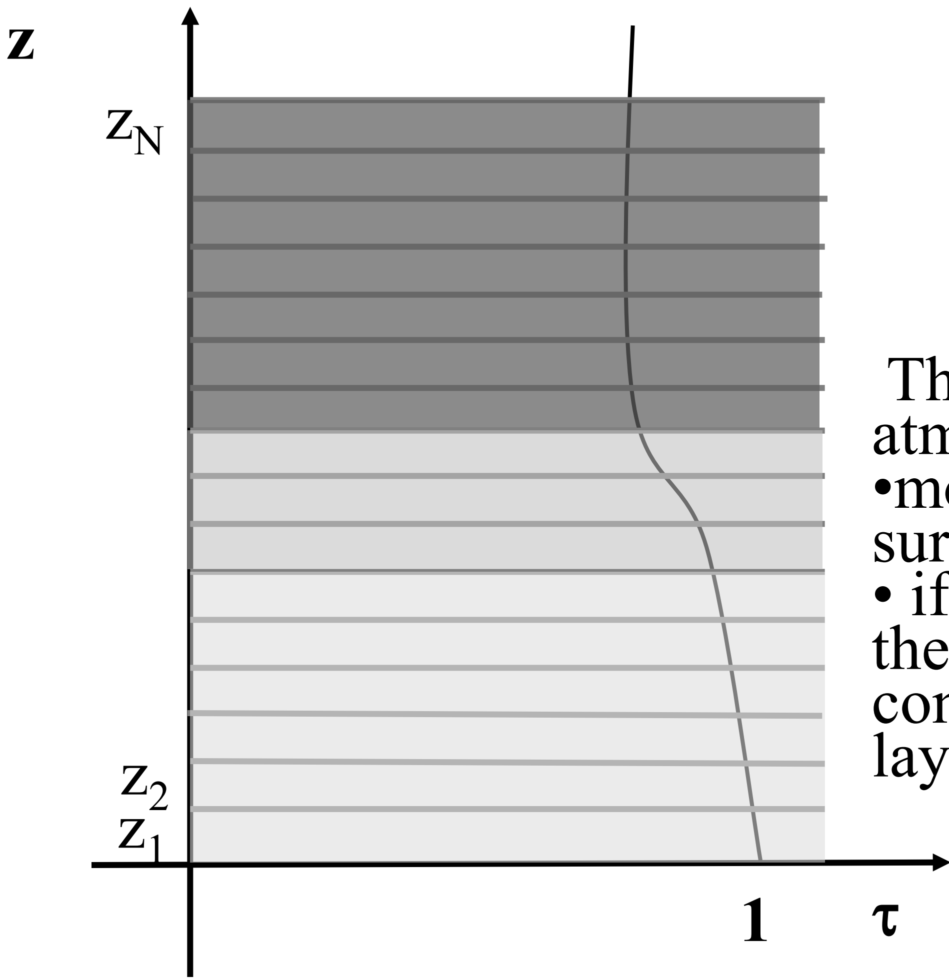
$$F_\lambda(p) = \{ 1 + (1 - \varepsilon_\lambda)\, [\tau_\lambda(p_s) / \tau_\lambda(p)]^2 \}$$

The first term is the spectral radiance emitted by the surface and attenuated by the atmosphere, often called the boundary term and the second term is the spectral radiance emitted to space by the atmosphere directly or by reflection from the earth surface.

The atmospheric contribution is the weighted sum of the Planck radiance contribution from each layer, where the weighting function is [$d\tau_\lambda(p) / dp$]. This weighting function is an indication of where in the atmosphere the majority of the radiation for a given spectral band comes from.

Transmittance for Window Channels

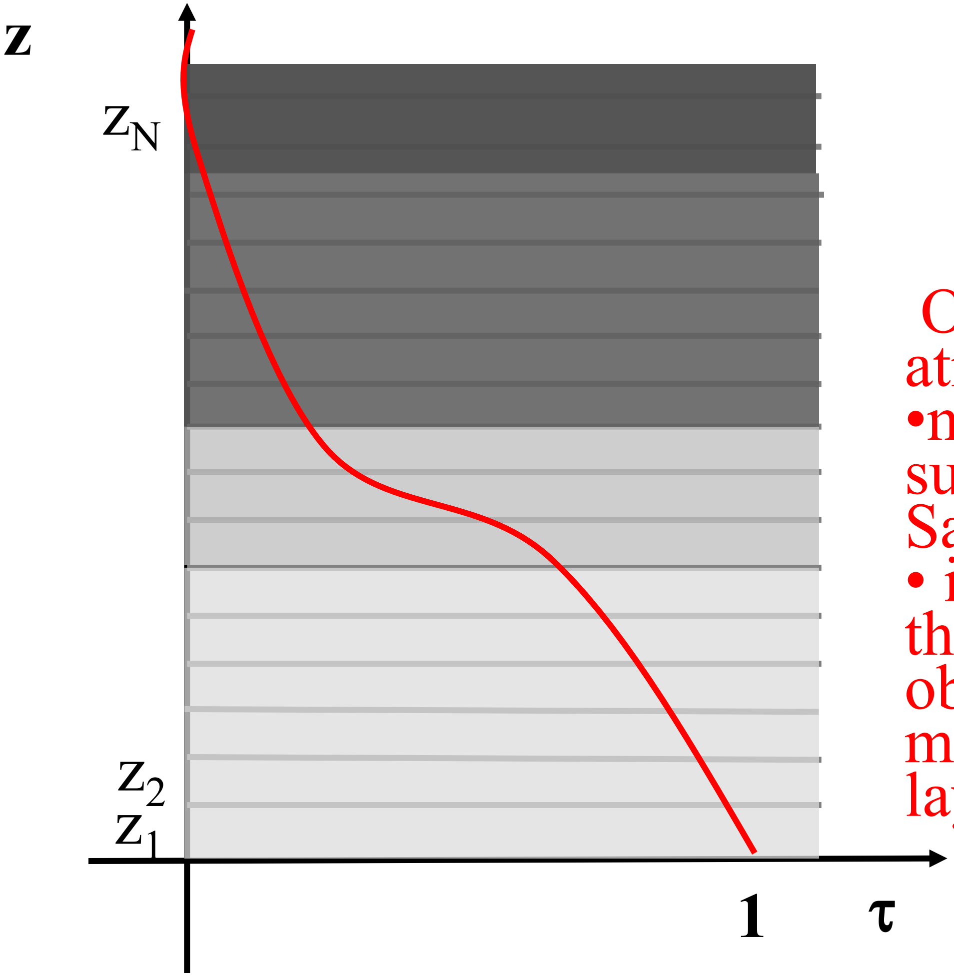
$$\boldsymbol{\tau} + a + \cancel{r} = 1$$



τ close to 1
a close to 0

The molecular species in the atmosphere are not very active:
- most of the photons emitted by the surface make it to the Satellite
- if a is close to 0 in the atmosphere then ε is close to 0, not much contribution from the atmospheric layers

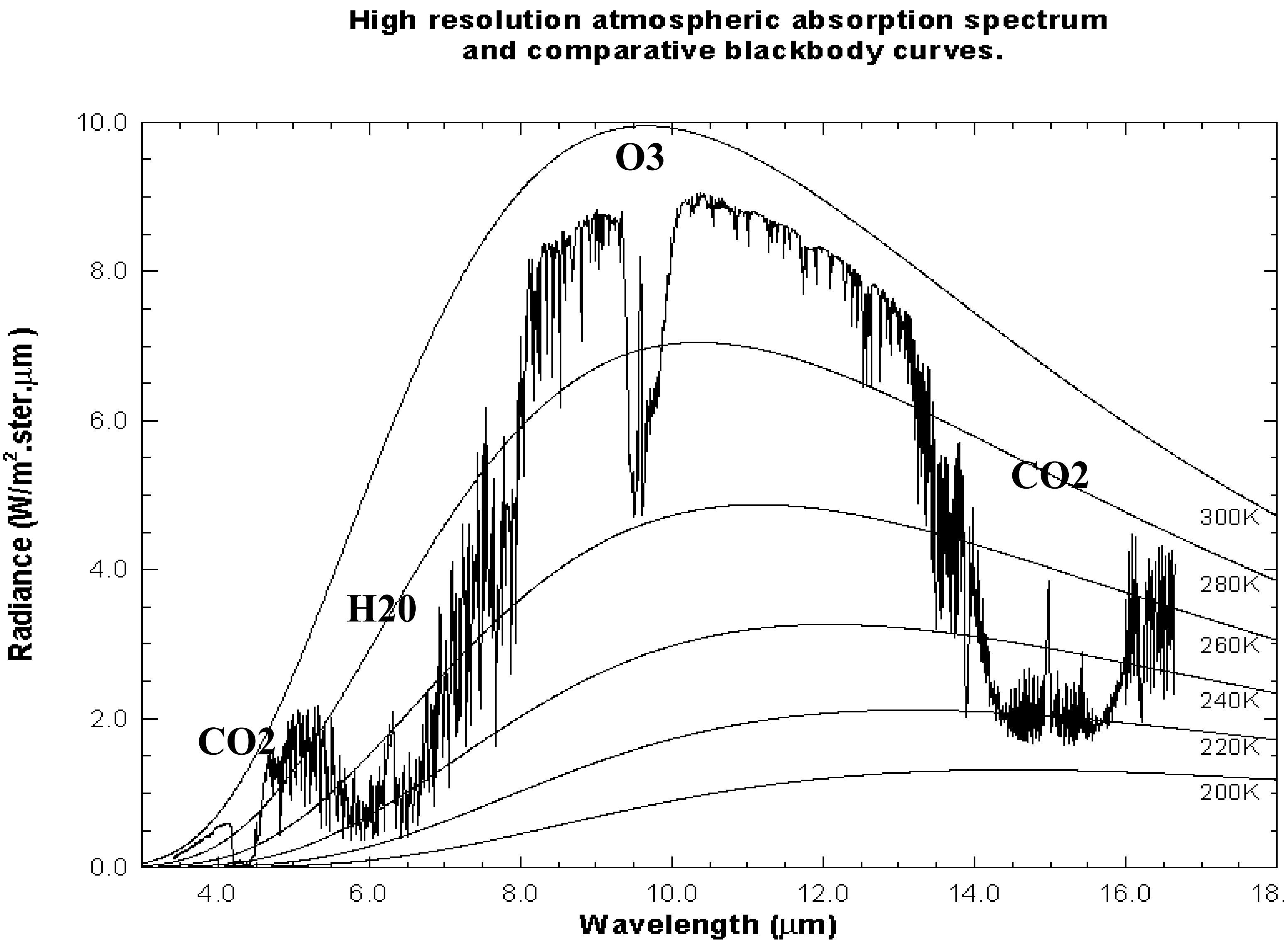
Trasmittance for Absorption Channels



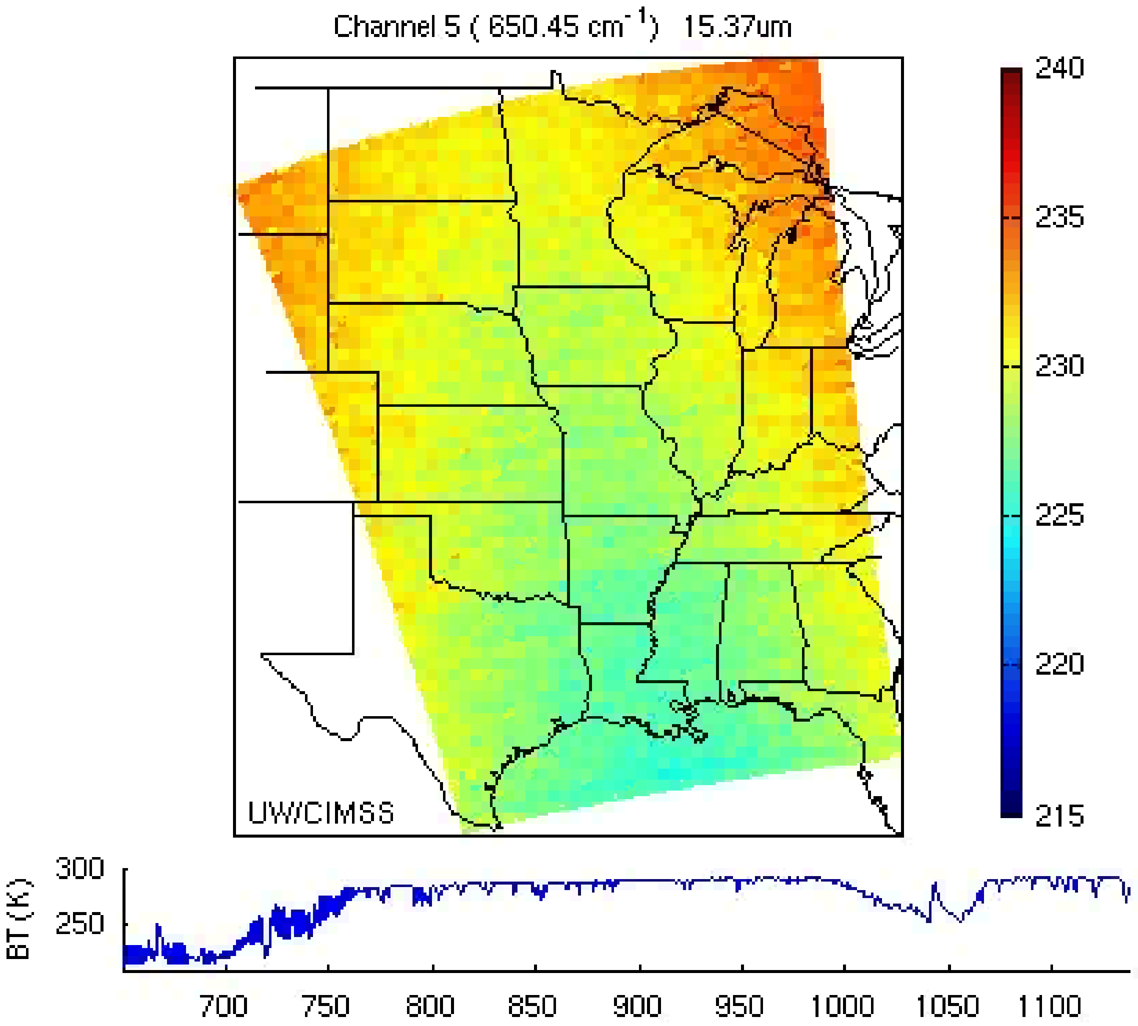
Absorption Channel:
τ close to 0
a close to 1

One or more molecular species in the atmosphere is/are very active:
•most of the photons emitted by the surface will not make it to the Satellite (they will be absorbed)
• if a is close to 1 in the atmosphere then ε is close to 1, most of the observed energy comes from one or more of the uppermost atmospheric layers

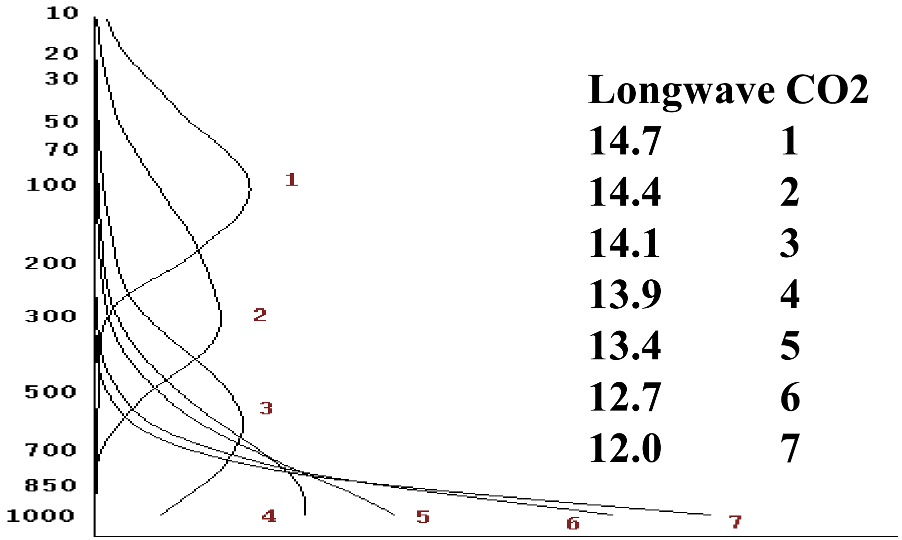
Earth emitted spectra overlaid on Planck function envelopes



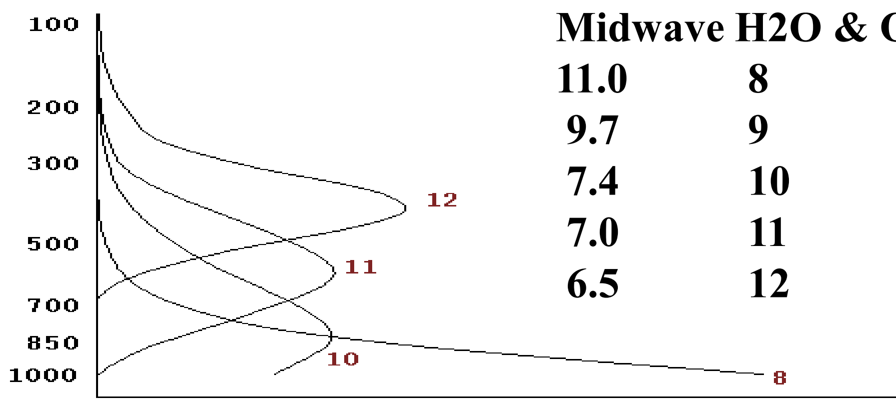
AIRS – Longwave Movie



GOES Sounder Weighting Functions

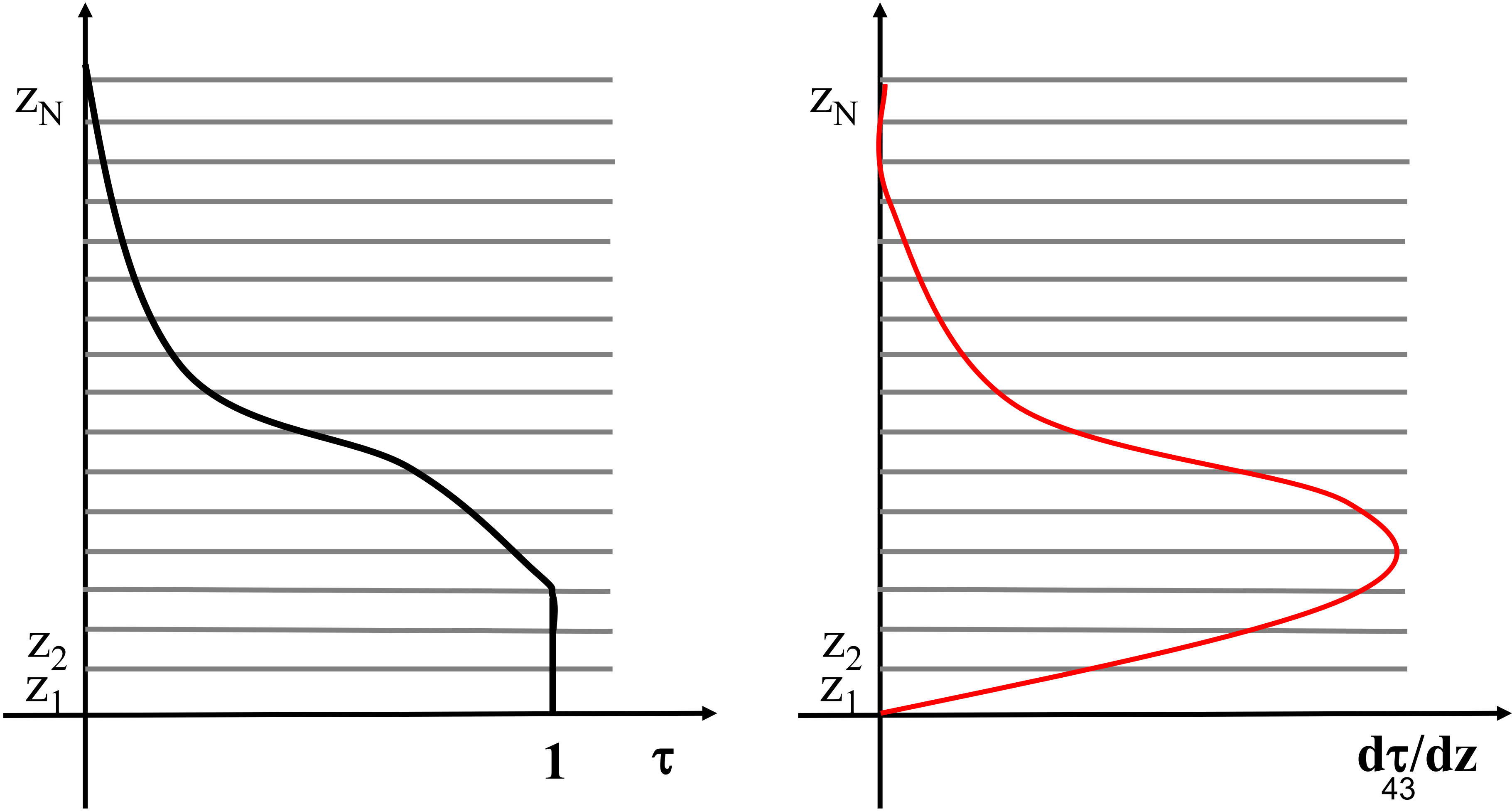


Longwave CO_2			
14.7	1	680	CO_2, strat temp
14.4	2	696	CO_2, strat temp
14.1	3	711	CO_2, upper trop temp
13.9	4	733	CO_2, mid trop temp
13.4	5	748	CO_2, lower trop temp
12.7	6	790	H_2O, lower trop moisture
12.0	7	832	H_2O, dirty window

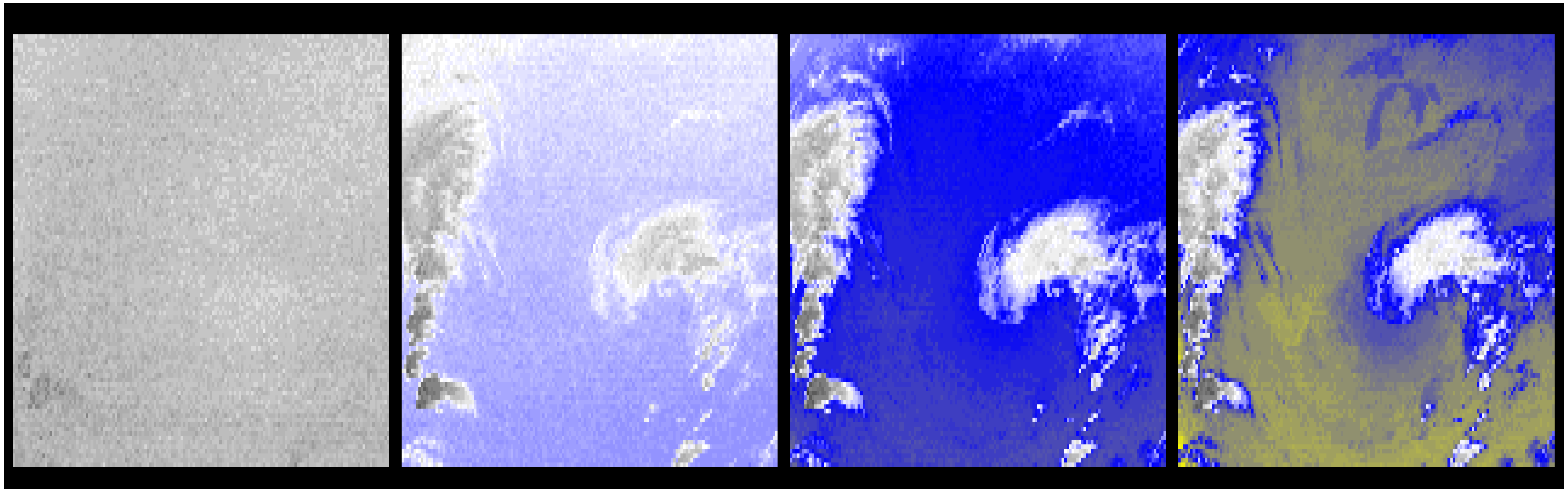


Midwave H_2O & O_3			
11.0	8	907	window
9.7	9	1030	O_3, strat ozone
7.4	10	1345	H_2O, lower mid trop moisture
7.0	11	1425	H_2O, mid trop moisture
6.5	12	1535	H_2O, upper trop moisture

Weighting Functions



CO2 channels see to different levels in the atmosphere



14.2 um 13.9 um 13.6 um 13.3 um

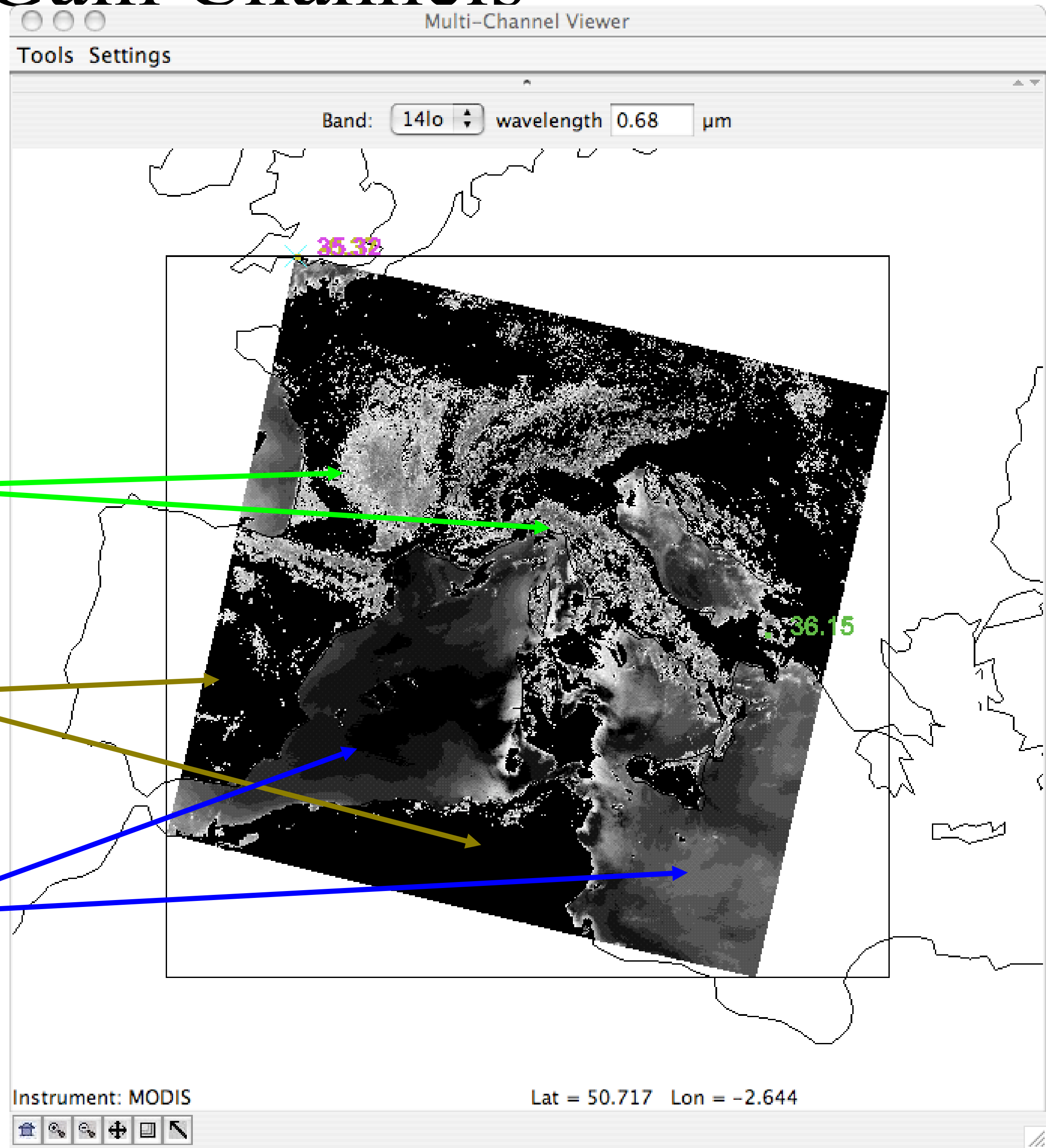
Low Gain Channels

Band 14 low
0.68 µm

Vegetated areas
Are visible

Saturation over
Barren Soil

Visible details
over water



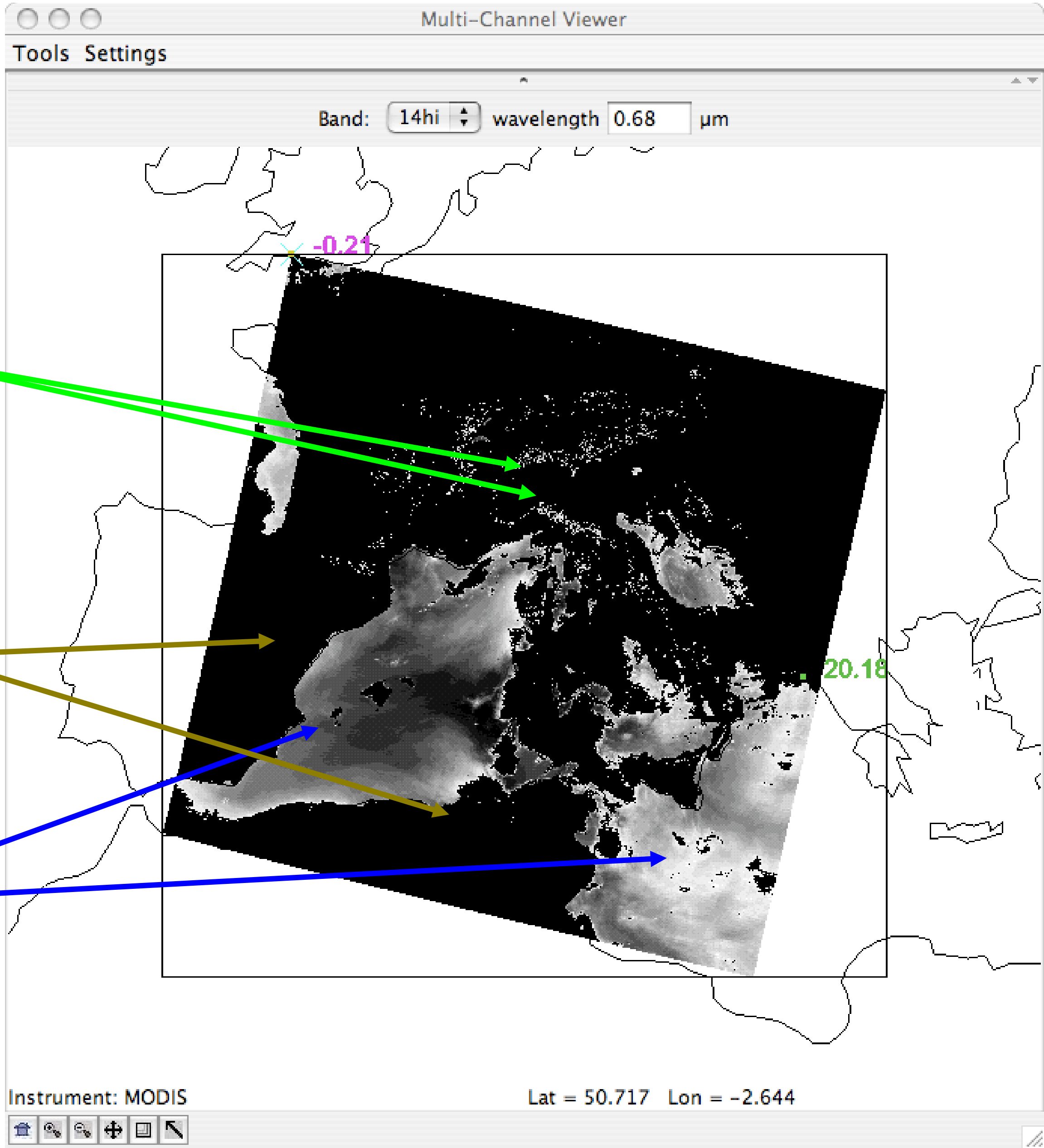
High Gain Channels

Band 14 hi
0.68 µm

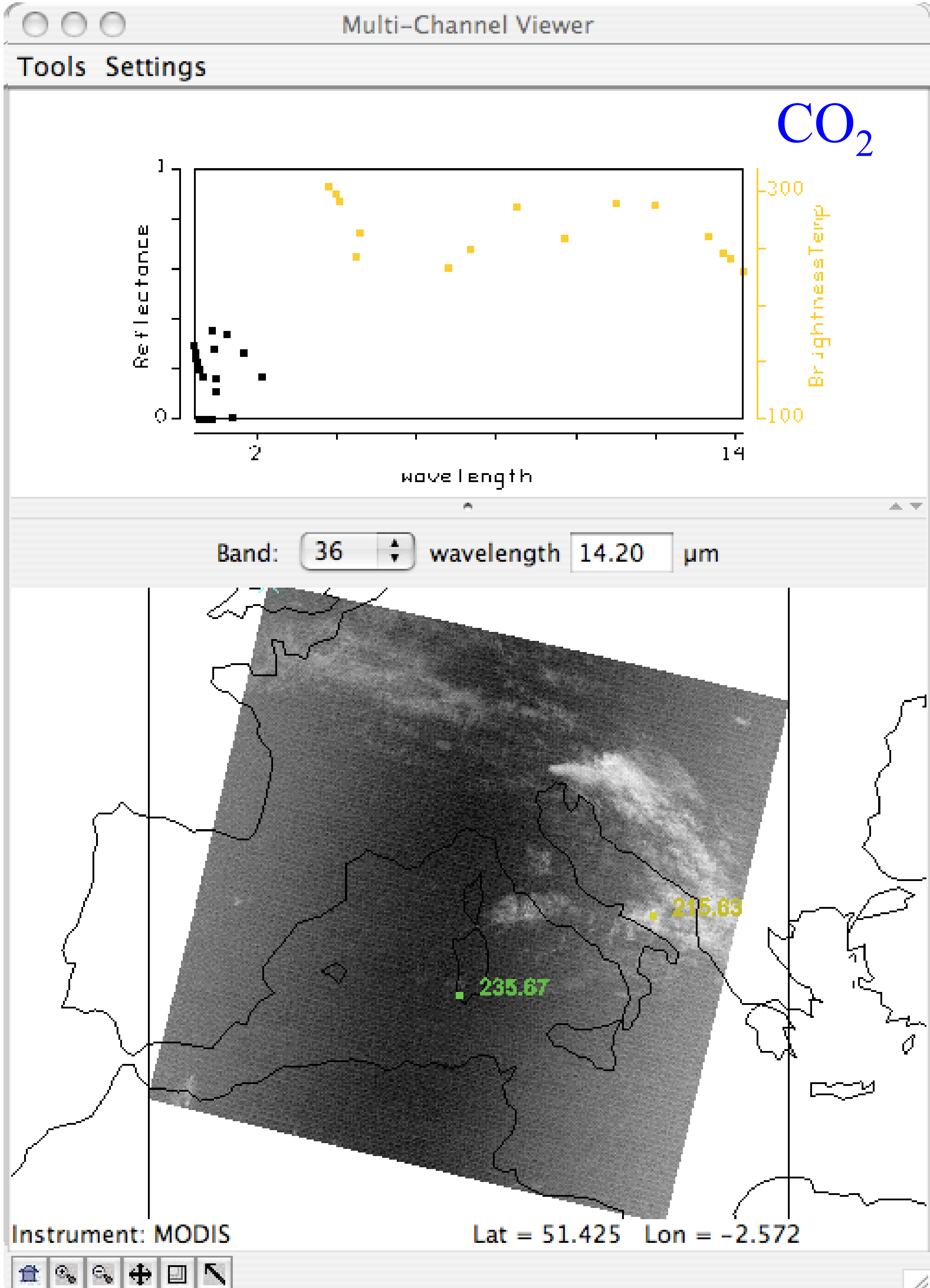
Saturation over Vegetated areas little barely visible

Saturation over Barren Soil

Visible details over water

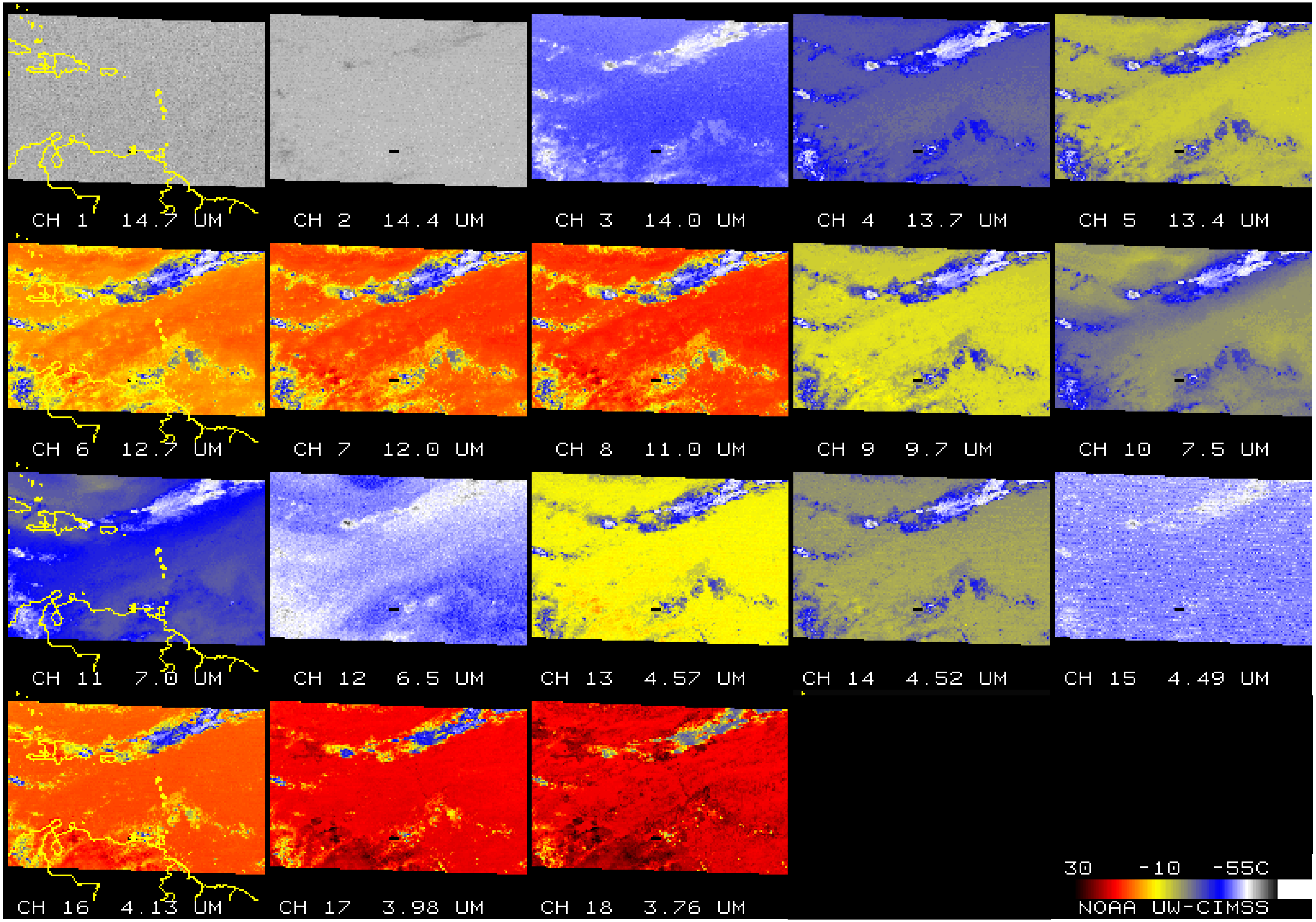


MODIS absorption bands



Conclusion

- Radiative Transfer Equation (IR): models the propagation of terrestrial emitted energy through the atmosphere



What time of day is this image from?