Electromagnetic Radiation: Interactions in the Atmosphere

Outline for 4/7/2003

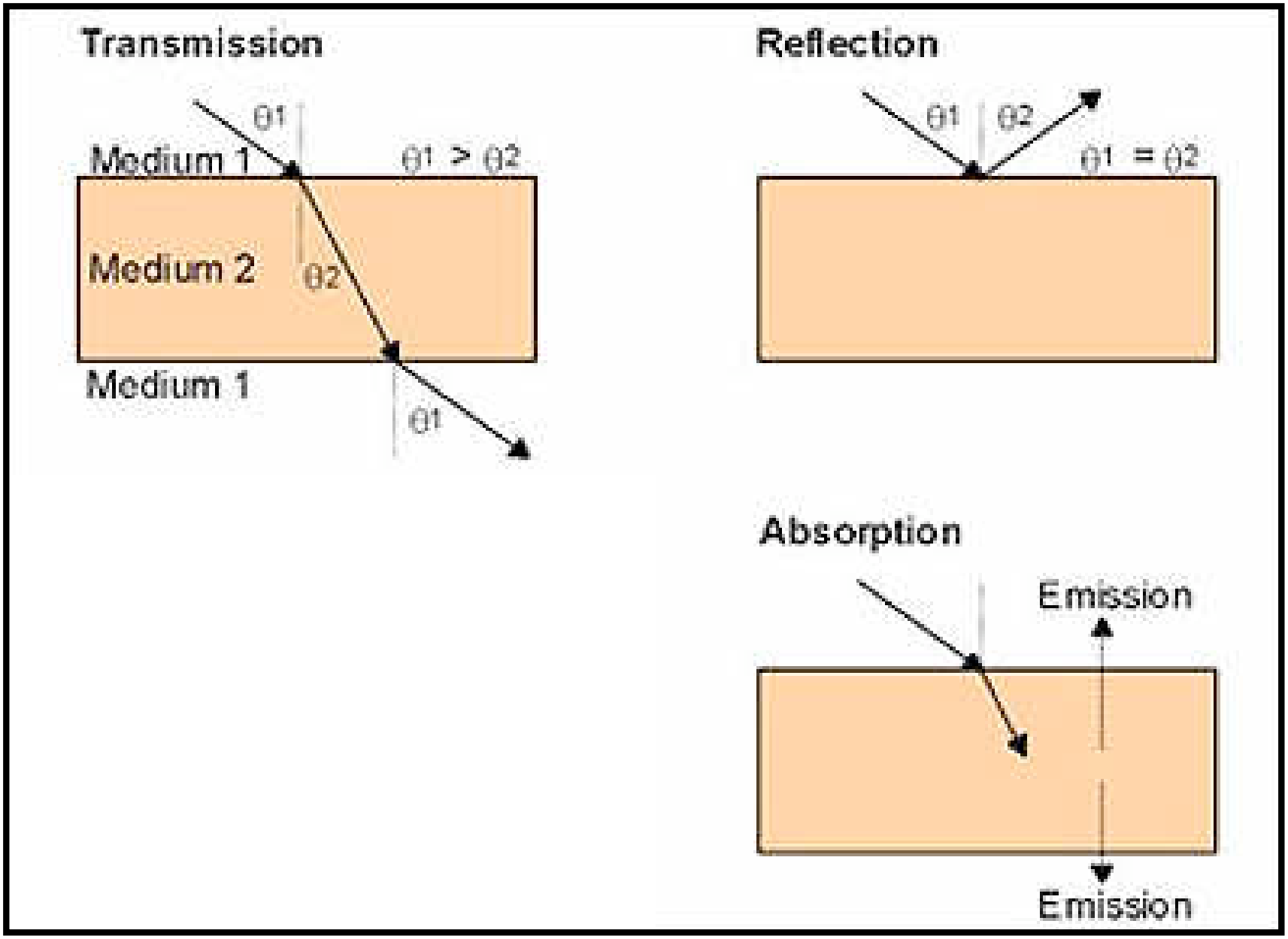
- EMR interaction with matter
- Atmospheric attenuation
- Atmospheric “windows”

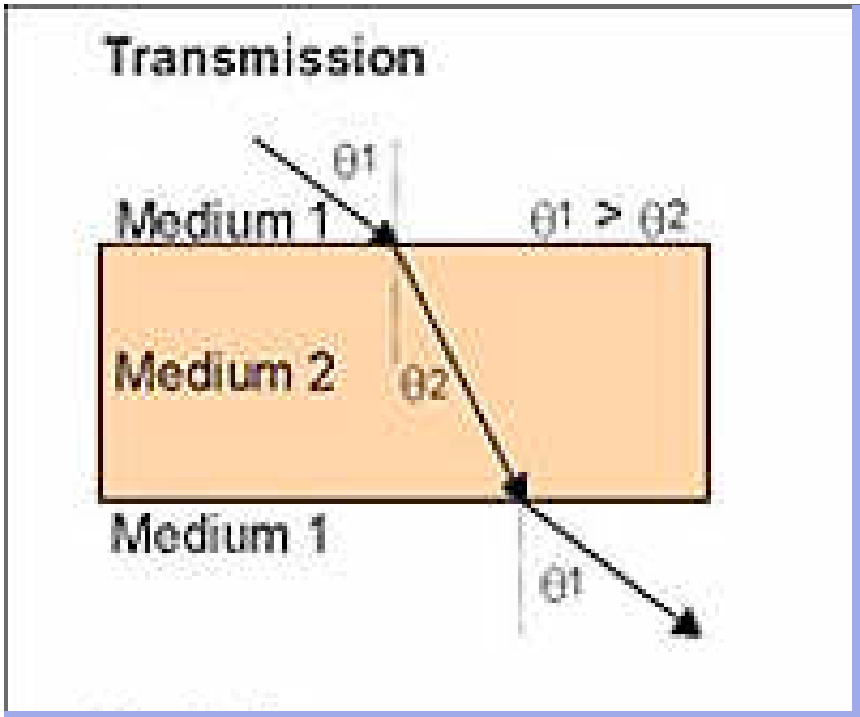
Electromagnetic Radiation Interactions with Matter

- Radiation is
  - transmitted (τ)
  - reflected (ρ)
  - absorbed (α)

Radiation Budget Equation:

$$\Phi_{i\lambda} = \Phi_{\tau\lambda} + \Phi_{\rho\lambda} + \Phi_{\alpha\lambda}$$


Transmission
θ1
Medium 1
θ1 > θ2
Medium 2
θ2
Medium 1
θ1
Reflection
θ1
θ2
θ1 = θ2
Absorption
Emission
Emission



- incident radiation passes through the material without attenuation
- change in the direction of radiation is given by the index of refraction of the material

Index of refraction (n) is the ratio of the speed of light in a vacuum relative to the speed of light through the material $\mathbf{n = c/c_n}$

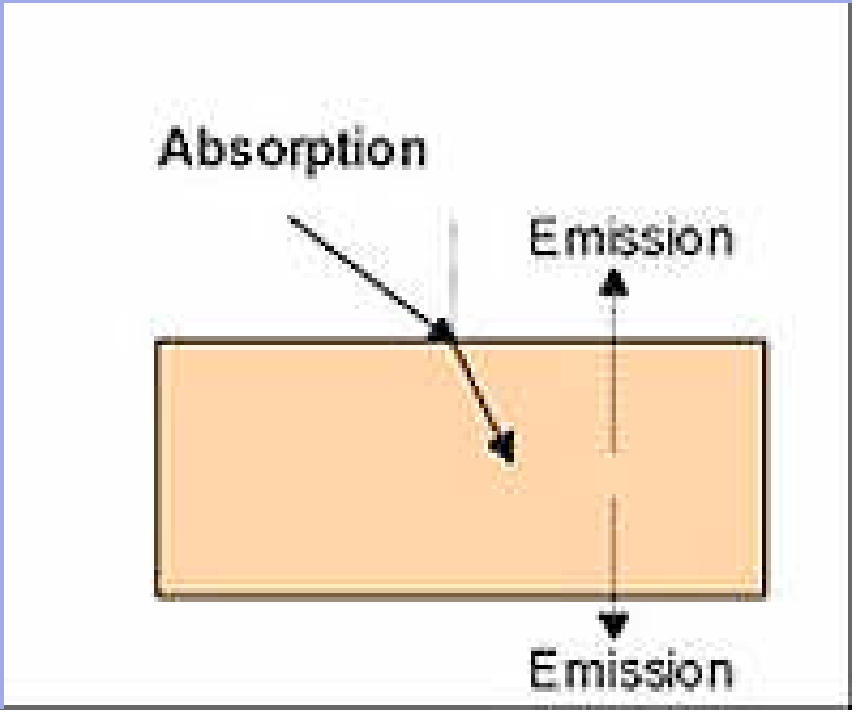
Snell's Law describes refraction angles:

$$\mathbf{n_1 \sin\theta_1 = n_2 \sin\theta_2}$$

Absorption

the material is opaque to incident radiation

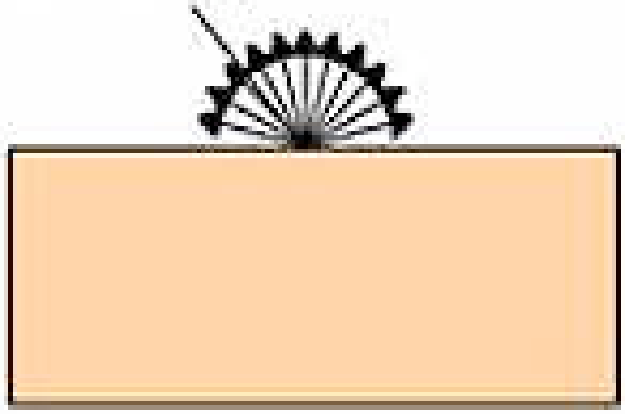
a portion of EMR is converted to heat (re-radiated)



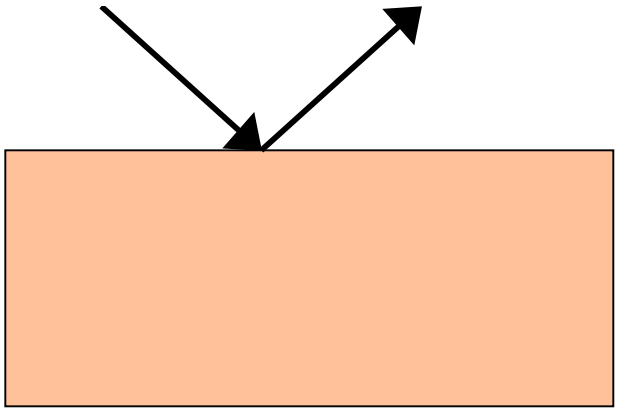
Reflection

- diffuse reflection (rough surface)
- specular reflection (smooth surface)

Diffuse



Specular



Atmospheric Effects

- EMR is attenuated by its passage through the atmosphere

Attenuation = scattering + absorption

- Scattering is the redirection of radiation by reflection and refraction
- Attenuation is wavelength dependent

Atmospheric Scattering

- Rayleigh Scattering (molecular scattering)
  - scattering by molecules and particles whose diameters are << wavelength
  - primarily due to oxygen and nitrogen molecules
  - scattering intensity is proportional to λ^{-4}
  - responsible for blue sky

A Clear Blue Sky

Blue radiation (λ = 0.46)

Red radiation (λ = 0.66)

$$(0.66/0.46)^4 = 4.24$$

Blue is scattered 4 $\times$ more than red radiation

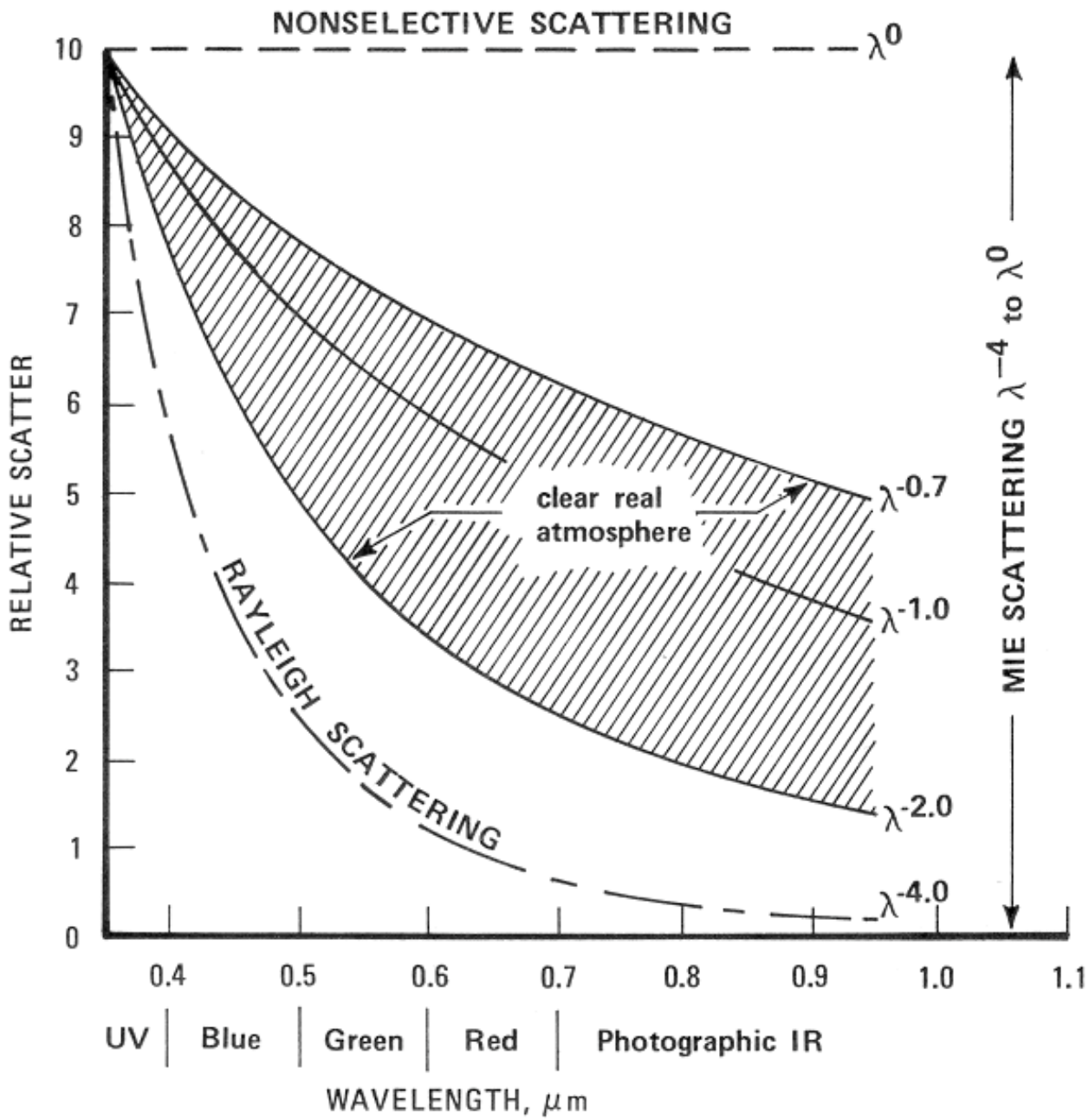
Atmospheric Scattering

- Mie Scattering
  - particles that have a mean diameter 0.1 to 10 times the incident wavelength
  - examples: water vapor, smoke particles, fine dust
  - scattering intensity is proportional to λ^{-4} to λ^{0} (depending on particle diameter)
- Clear atmosphere has both Rayleigh and Mie scattering. Their combined influence is between $\lambda^{-0.7}$ to λ^{-2}

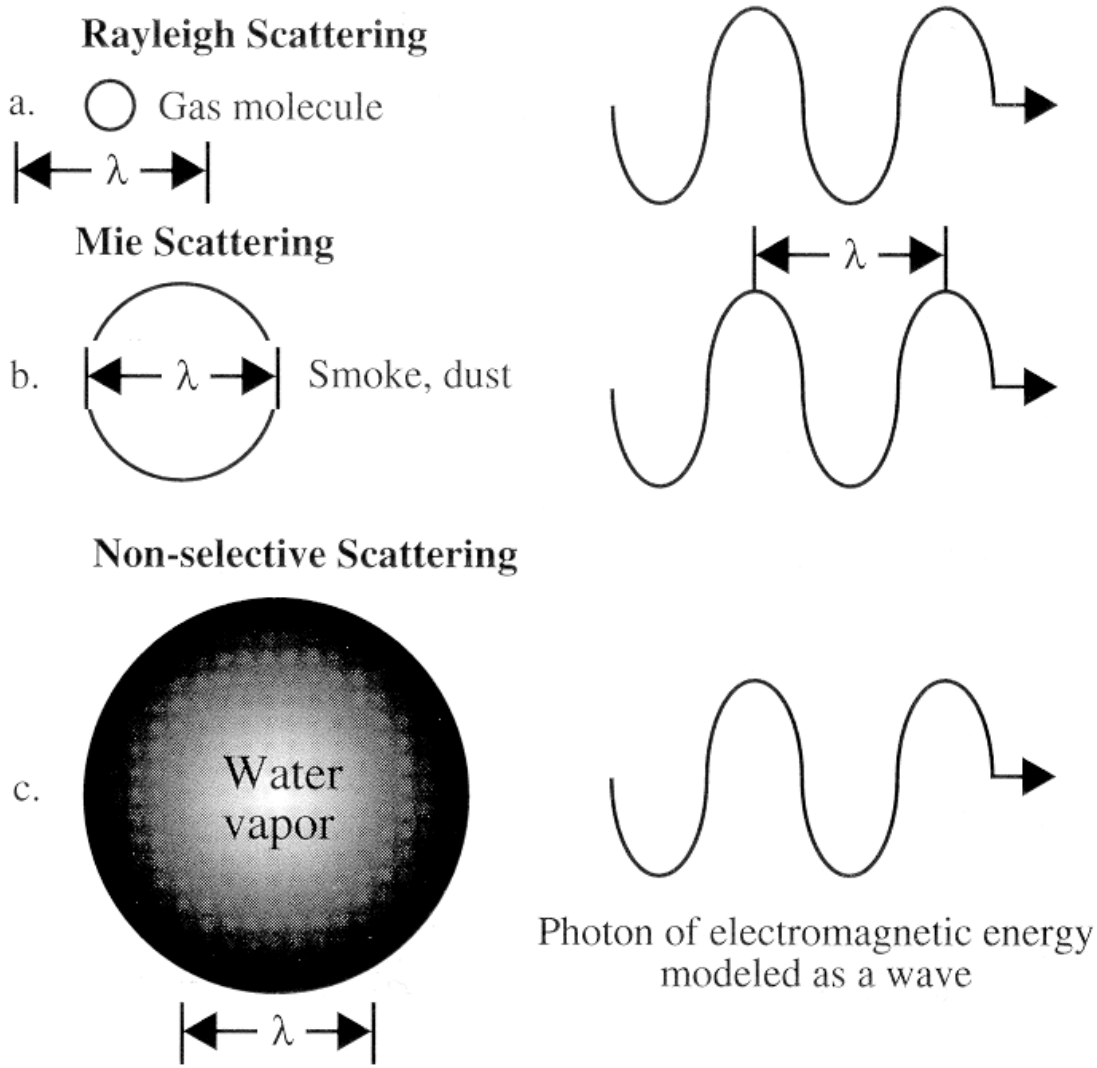
Red Sky at Night

- At sunset, solar radiation must traverse a longer path through the atmosphere. Viewing a setting sun, the energy reaching the observer is largely depleted of blue radiation, leaving mostly red wavelengths (Rayleigh). Dust/smoke adds additional scattering with a wavelength dependence that increases the red sky effect (Mie)

- Non-selective Scattering
  - aerosol particles much larger than the wavelength (> 10x)
  - examples: water droplets, ice crystals, volcanic ash, smog
  - independent of wavelength: λ^0


NONSELECTIVE SCATTERING
λ^0
RELATIVE SCATTER
10
9
8
7
6
5
4
3
2
1
0
clear real atmosphere
$\lambda^{-0.7}$
$\lambda^{-1.0}$
$\lambda^{-2.0}$
$\lambda^{-4.0}$
RAYLEIGH SCATTERING
MIE SCATTERING λ^{-4} to λ^0
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
UV
Blue
Green
Red
Photographic IR
WAVELENGTH, μm

Atmospheric Scattering



Types of scattering encountered in the atmosphere. The type of scattering is a function of 1) the wavelength of the incident radiant energy, and 2) the size of the gas molecule, dust particle, and/or water vapor droplet encountered.

Atmospheric Absorption

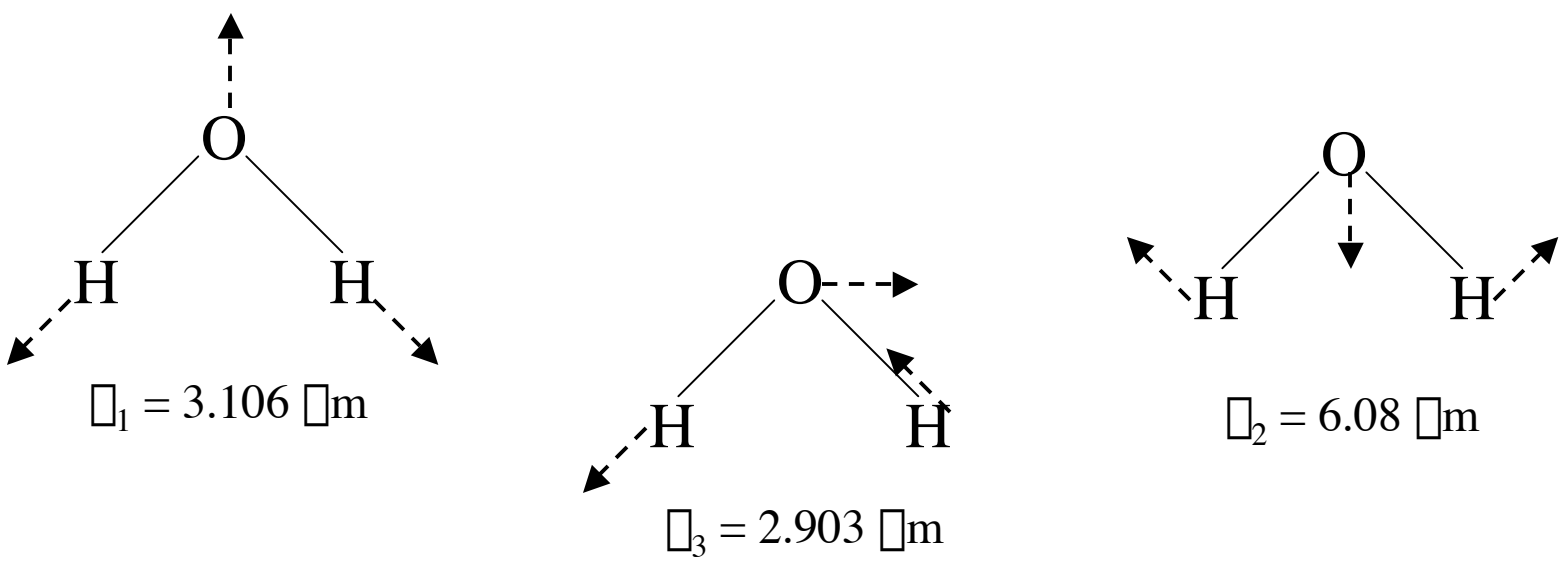
In the atmosphere EMR is primarily absorbed by

- H_2O water vapor, water droplets
- CO_2 carbon dioxide
- O_2 oxygen
- O_3 ozone
- dust

Atmospheric Attenuation Demo

Absorption

- Vibrational process
  - small displacements of the atoms from their equilibrium position
  - N atoms ⇨ 3N possible vibrational modes



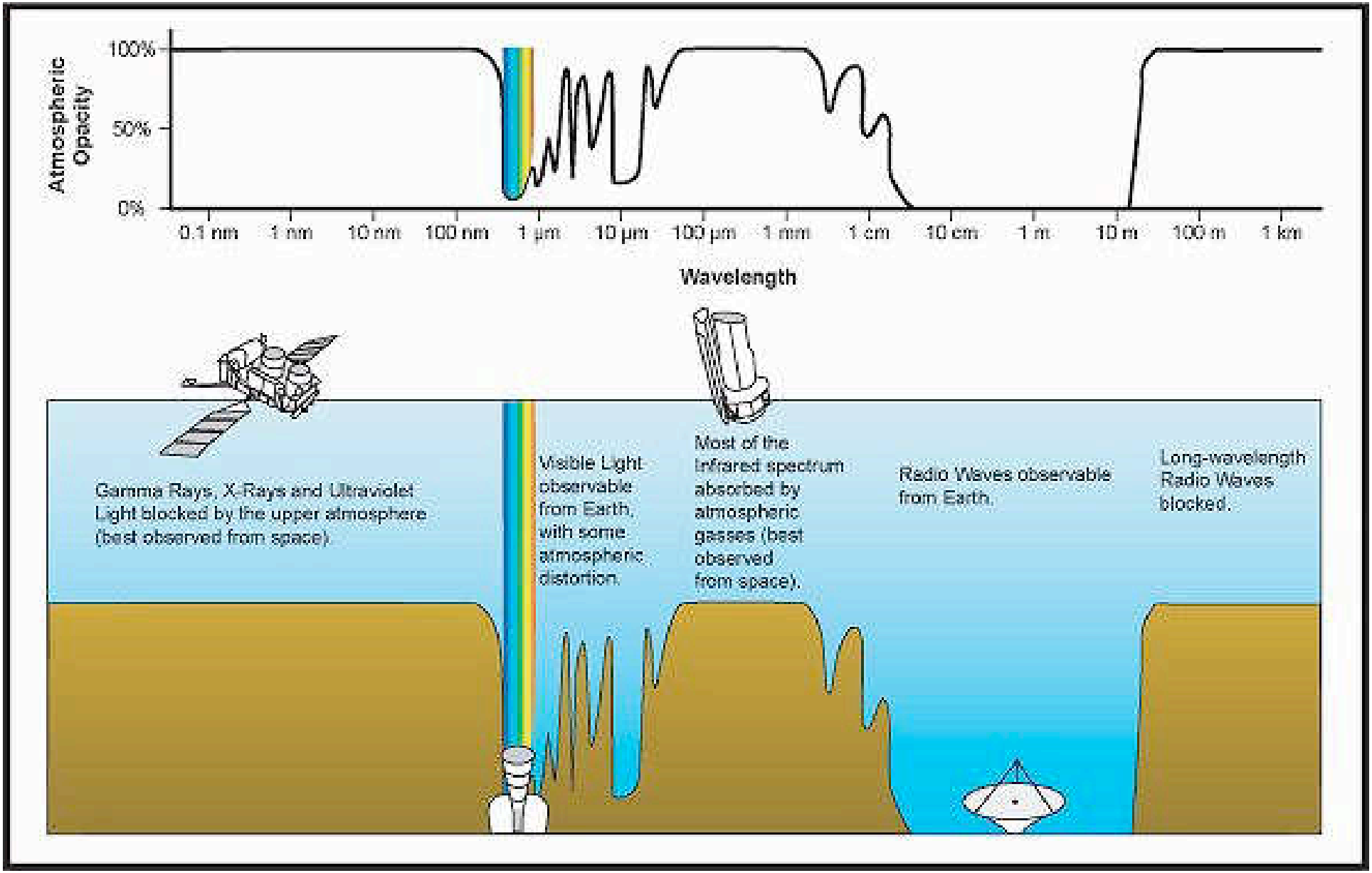
Water Vapor Absorption

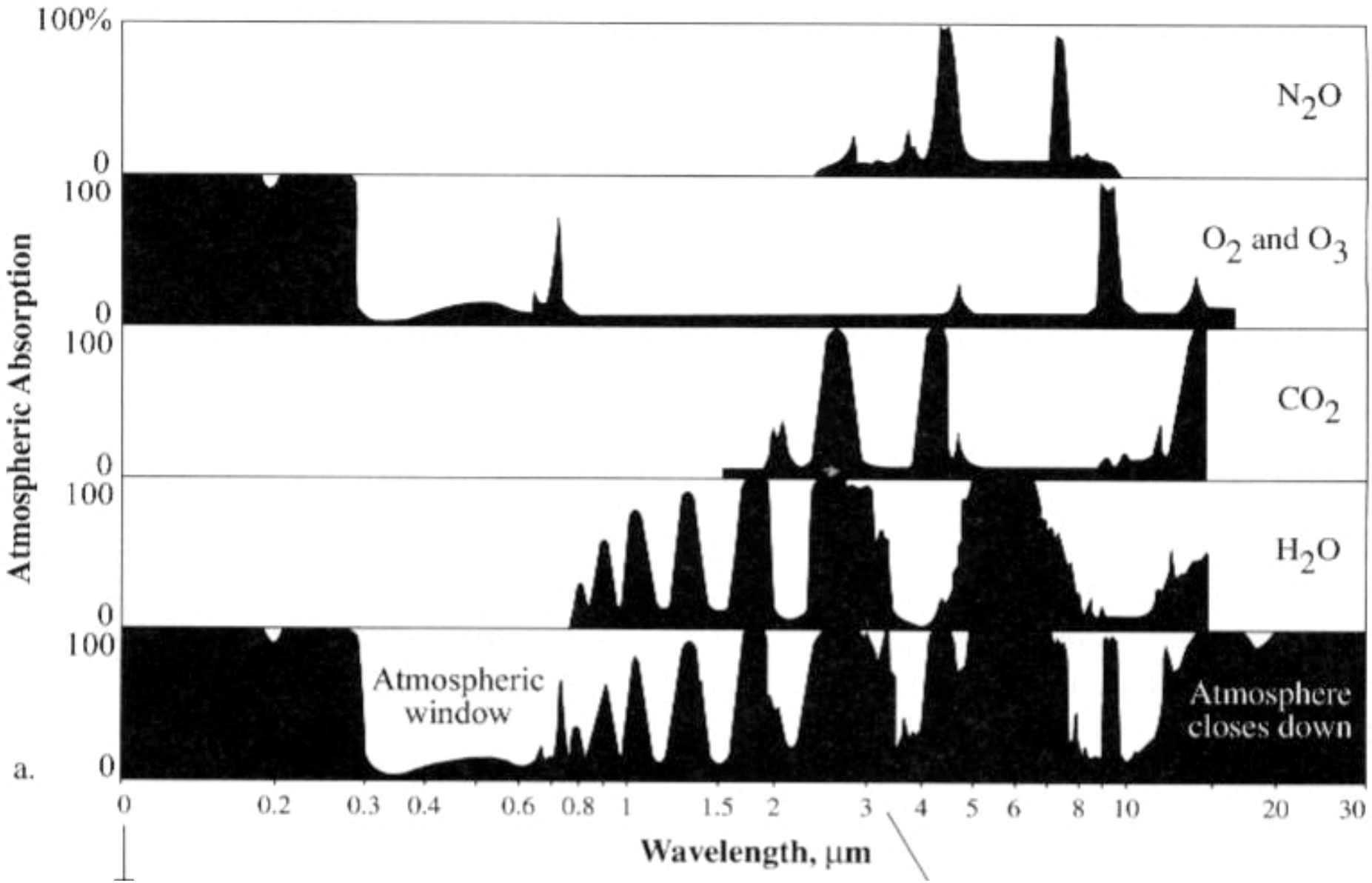
- The water molecule has three classical frequencies ν_1, ν_2, ν_3 that correspond to the three wavelengths:
  - λ_1 3.106 mm (symmetric OH stretch)
  - λ_2 6.08 (HOH bend)
  - λ_3 2.903 mm (asymmetric OH stretch)

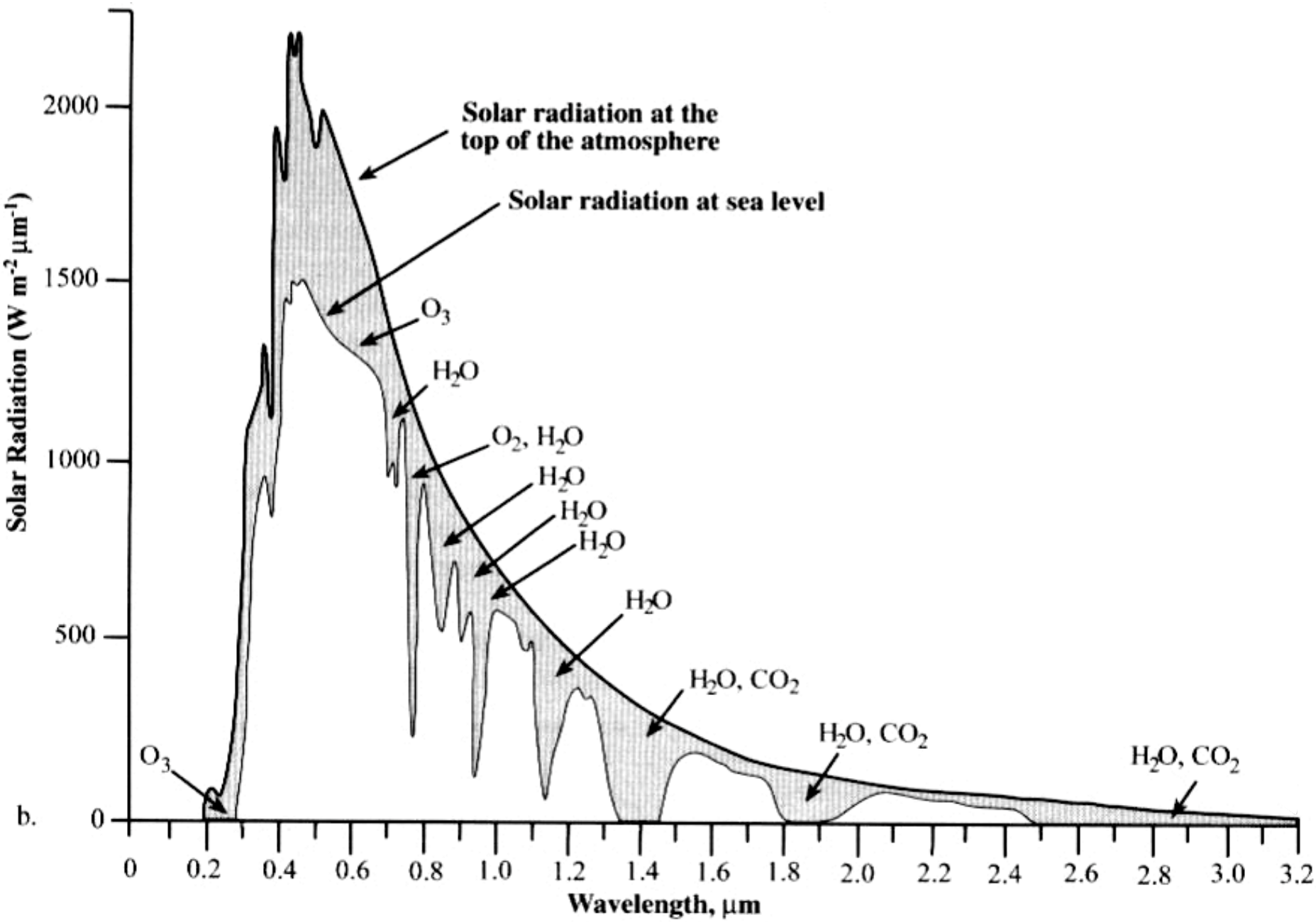
An example of combination: $\nu = \nu_2 + \nu_3$

$1/\lambda = 1/\lambda_2 + 1/\lambda_3 = 1/6.08 + 1/2.903$

$\lambda = 1.87\ \mu m$


Atmospheric Opacity
100%
50%
0%
0.1 nm
1 nm
10 nm
100 nm
1 µm
10 µm
100 µm
1 mm
1 cm
10 cm
1 m
10 m
100 m
1 km
Wavelength
Gamma Rays, X-Rays and Ultraviolet Light blocked by the upper atmosphere (best observed from space).
Visible Light observable from Earth, with some atmospheric distortion.
Most of the Infrared spectrum absorbed by atmospheric gasses (best observed from space).
Radio Waves observable from Earth.
Long-wavelength Radio Waves blocked.


100%
0
100
0
100
0
100
0
100
0
Atmospheric Absorption
N_2O
O_2 and O_3
CO_2
H_2O
Atmospheric window
Atmosphere closes down
a.
0
0.2
0.3
0.4
0.6
0.8
1
1.5
2
3
4
5
6
8
10
20
30
Wavelength, μm


Solar radiation at the top of the atmosphere
Solar radiation at sea level
O_3
H_2O
O_2, H_2O
H_2O
H_2O
H_2O
H_2O
H_2O, CO_2
H_2O, CO_2
H_2O, CO_2
O_3
Solar Radiation (W m^{-2} µm^{-1})
2000
1500
1000
500
0
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
3.0
3.2
Wavelength, µm

b.

Atmospheric Windows

- Regions in the EM spectrum where energy can be fully transmitted

0.3-0.7 μm	UV and visible light
3-5 μm	emitted thermal energy from Earth
8-11 μm	emitted thermal energy from Earth
1 mm-1 m	radar and microwave energy