Review for Exam 1:

1. Types of platforms used for remote sensing. General characteristics of satellite sensors: active vs. passive, orbits, types of sensor's resolutions.

   Lecture 2

2. The nature of electromagnetic radiation, electromagnetic spectrum; main radiometric quantities (energy, flux (or irradiance), and intensity (or radiance), polarization and Stokes parameters.

   Lecture 1, Eqs.[1.2]-[1.10] ; Table 1.2

3. Polarization, Stokes parameters.

   Lecture 3, Eqs.[3.3-3.6]

4. Concepts of a blackbody. Planck function. Main radiation laws. Brightness temperature.

   Lecture 3, Eqs.[3.10.1-3.13];[3.15-3.18]

5. Emission from surfaces. Emissivity spectra of natural surfaces.

   Lecture 3,Eqs. [3.21-3.24]

6. Basic properties of atmospheric gases. Structure of molecules and associated dipole moment. Basic principles of molecular emission/absorption. Spectral line shapes: Lorentz profile and Doppler profile. Gas absorption coefficient and transmission function. Absorption spectra of radiatively active atmospheric gases.

   Lecture 4, Eqs. [4.5-4.8], [4.1-4.13]

7. Molecular (Rayleigh) scattering. Rayleigh scattering phase function. Scattering cross section of air molecules and optical depth due to molecular scattering

   Lecture 5, Eqs.[5.18-5.25], [5.28-5.29]

8. Basic properties of atmospheric aerosols and clouds. Spectral refractive indices. Scattering and absorption by aerosols and cloud drops: concepts of scattering and absorption efficiencies and cross sections; volume extinction, scattering and absorption coefficients; scattering phase function and single scattering albedo.

   Lectures 5-6, Eqs.[5.1-5.7], [5.8-5.10], [6.10]-[6.18]

9. Effective optical properties of an atmospheric layer consisting of gas and aerosols (or clouds).

   Lecture 6, Eqs. [6.20-6.24]

10. The Beer-Bouguer-Lambert (extinction) law.

    Lecture 6, Eqs.[6.26-6.28]

11. Direct and diffuse radiation. Single and multiple scattering. Single scattering approximation.

Lectures 6- 7, Eqs. [6.29], [7.3-7.8], [7.9], [7.12-7.13]

12. Reflection from surfaces. Bi-directional reflectance distribution function. Specular and diffuse reflactenses. Lambertian reflection. Representative spectral surface albedo of natural surfaces.

Lecture 7,Eqs. [7.16-7.17]

13. Principles of ocean color retrievals.

Lecture 7

14. Retrieval of aerosol optical depth from ground-based sunphotometer measurements and satellite passive sensors.

Lecture 6, Eqs.[6.30-6.37]

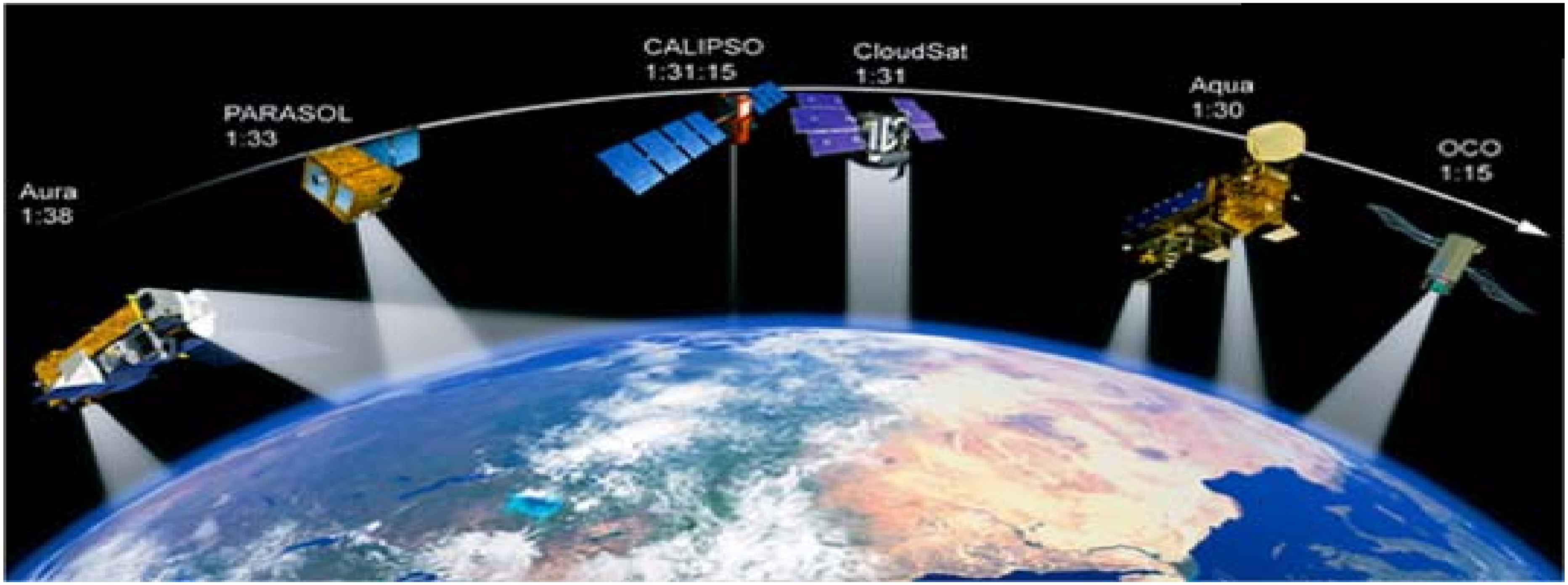
15. Retrievals of aerosol optical depth from passive remote sensing in the visible and near-IR.

Lecture 8, Eqs.[8.1]

Lecture 9.

Review for mid-term exam

"A-Train" satellite constellation and more..



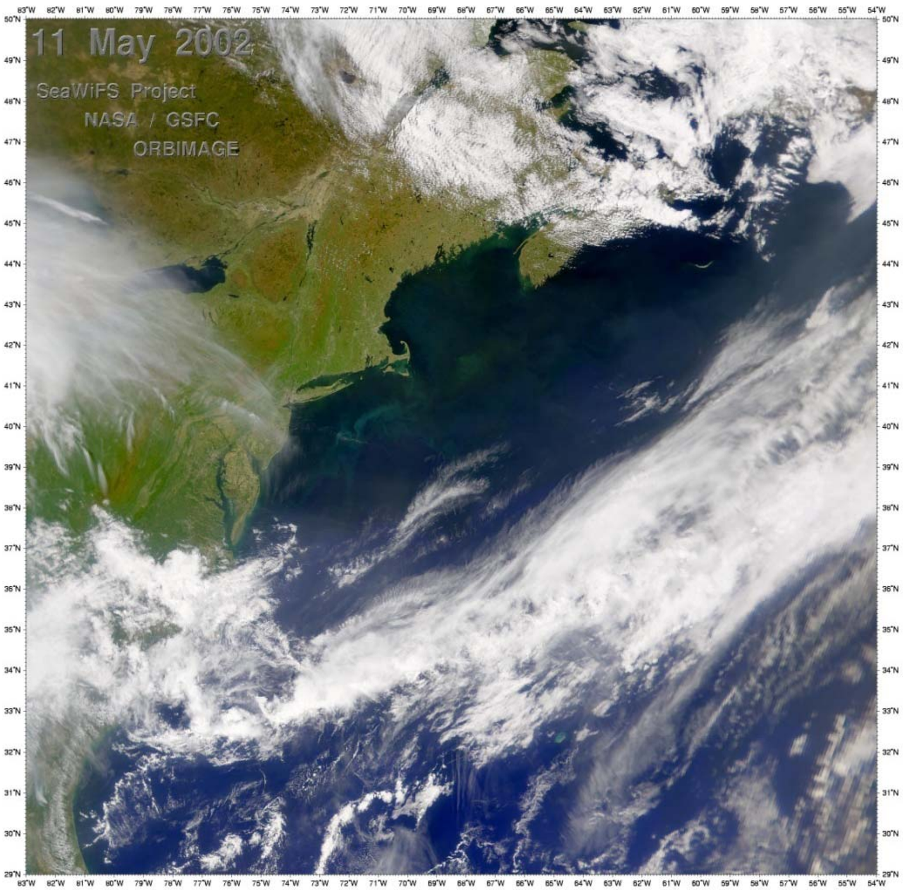
***<u>Current satellite technologies</u>*:**

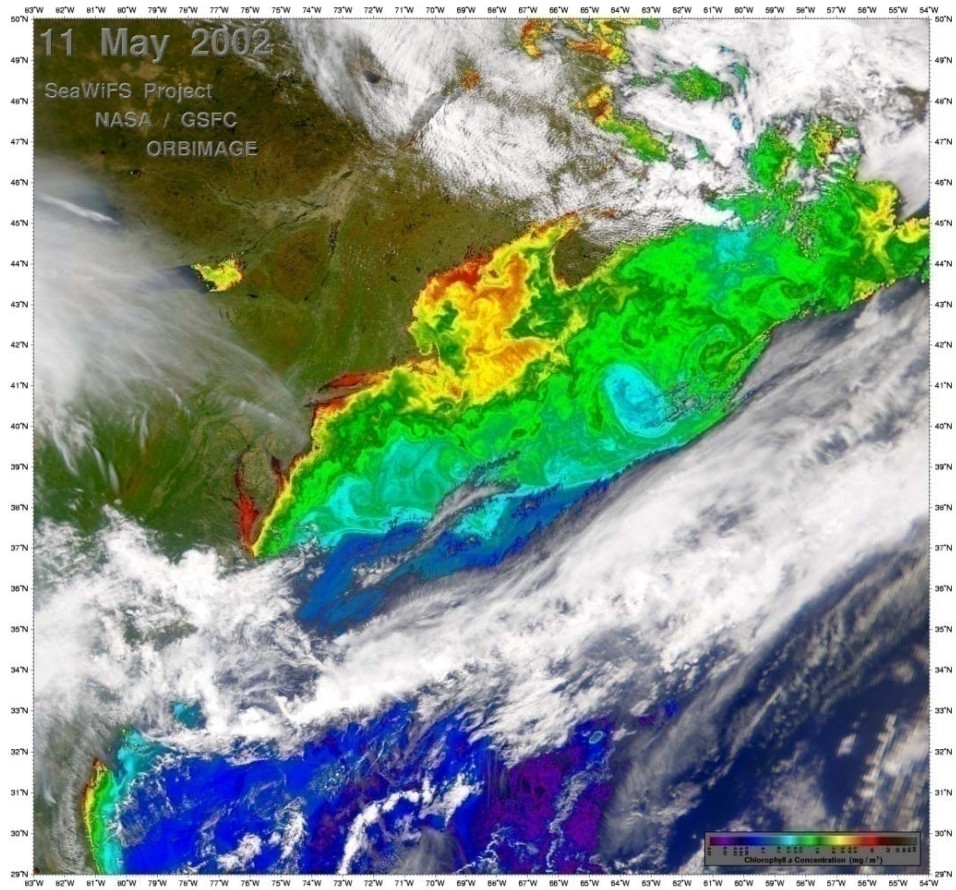
- **Polar orbiting and geostationary**
- **Various viewing geometry (downlooking, limb, etc.)**
- **Passive and active**
- **Various spectral coverage and resolution (broad-band, narrow-band, hyperspectral, etc)**
- **Various spatial and temporal sampling**

“Ocean” Color Example

True color image

Retrieved Chlorophyll





What can one see on a RGB image?

Propagation of the electromagnetic radiation in the atmosphere is governed by

its composition (gases, aerosol particles, and cloud particles)

and

by its state (temperature, pressure, air density)

Gases:

Absorption (emission):

- **depends on molecular structure (dipole!)**
- **wavelength-selective**

Scattering:

- **a point dipole approach – Rayleigh scattering**
- **~ wavelength $^{-4}$**

Most commonly used absorption coefficients:

$\boldsymbol{k}_{a,\nu}$ Volume absorption coefficient (in LENGTH-1)

$\boldsymbol{k}_{m,a,\nu}$ Mass absorption coefficient (in LENGTH2/MASS)

$\boldsymbol{k}_{cs,a,\nu}$ Absorption cross section (in LENGTH2)

Absorbing gas (path length *u*)	Absorption coefficient	Line intensity (S)
cm	cm^{-1}	cm^{-2}
$g\ cm^{-2}$	$cm^{2}\ g^{-1}$	$cm\ g^{-1}$
molecule cm^{-2}	cm^{2}/molecule	cm/molecule
cm atm	$(cm\ atm)^{-1}$	$cm^{-2}\ atm^{-1}$

$$\tau_{a,\nu}(s_1, s_2) = \int_{s_1}^{s_2} k_{a,\nu}\, ds = \int_{s_1}^{s_2} \rho k_{m,a,\nu}\, ds = \int_{s_1}^{s_2} N k_{cs,a,\nu}\, ds$$

Lorentz profile of a spectral line is used to characterize the pressure broadening and is defined as:

$$f_L(\nu - \nu_0) = \frac{\alpha / \pi}{(\nu - \nu_0)^2 + \alpha^2}$$

where $f(\nu - \nu_0)$ is the shape factor of a spectral line;

ν_0 is the wavenumber of a central position of a line;

α is the half-width of a line at the half maximum (in cm^{-1}), (often referred as a line width)

- **The half-width of the Lorentz line shape is a function of pressure P and temperature T and can be expressed as**

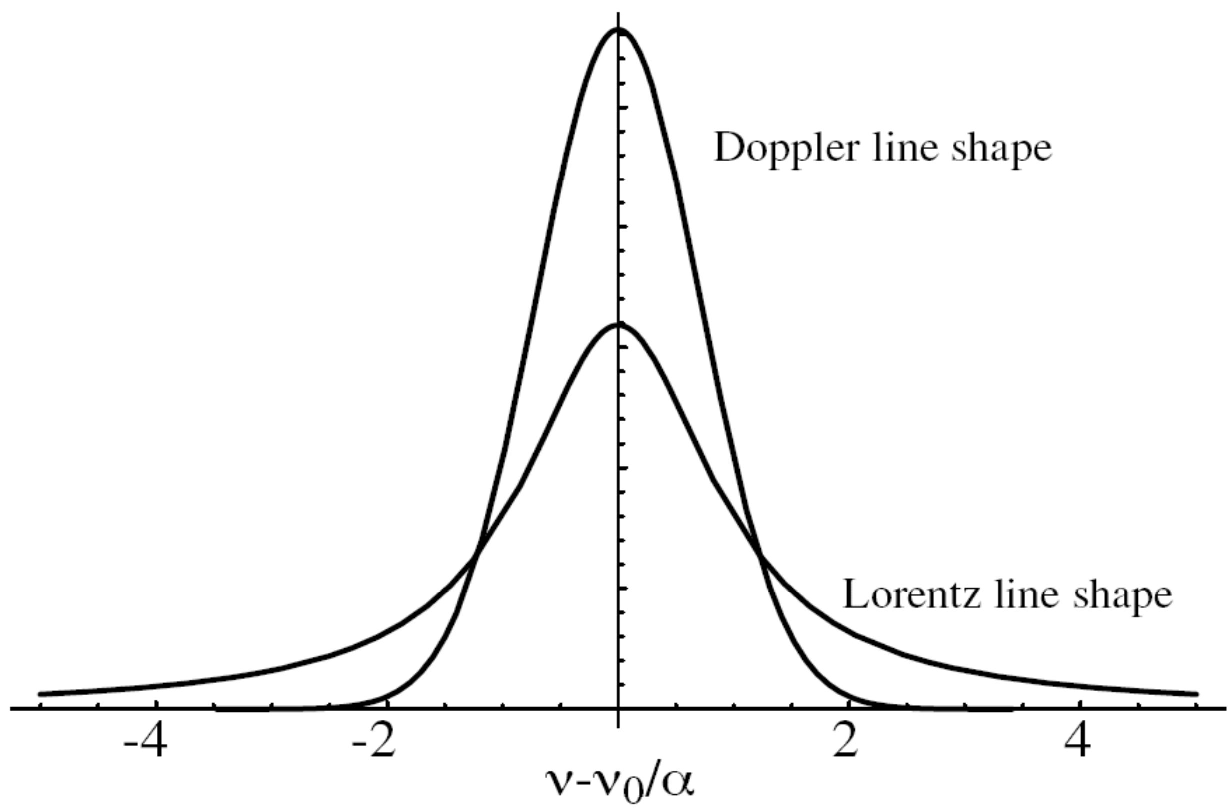
$$\alpha(P,T) = \alpha_0 \frac{P}{P_0}\left(\frac{T_0}{T}\right)^n$$

where α_0 is the reference half-width for STP: T_0 = 273K; P_0=1013 mb.

α_0 is in the range from **about 0.01 to 0.1 cm^{-1}** for most atmospheric radiatively active gases.

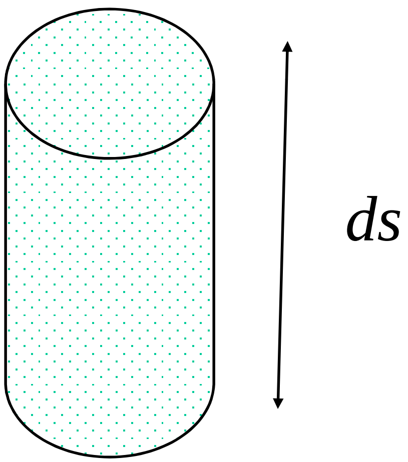
NOTE: The above **dependence on pressure** is very important because atmospheric pressure varies by an order of 3 from the surface to about 40 km.

Comparison of the Doppler and Lorentz profiles for equivalent line strengths and widths.



Optical depth due to absorption:

$$\tau_\nu(s_2;s_1) = \int_{s_1}^{s_2} k_\nu(s)ds$$



Transmission Function is

$$T_\nu = \exp(-\tau_\nu)$$

Absorbance (or absorption)

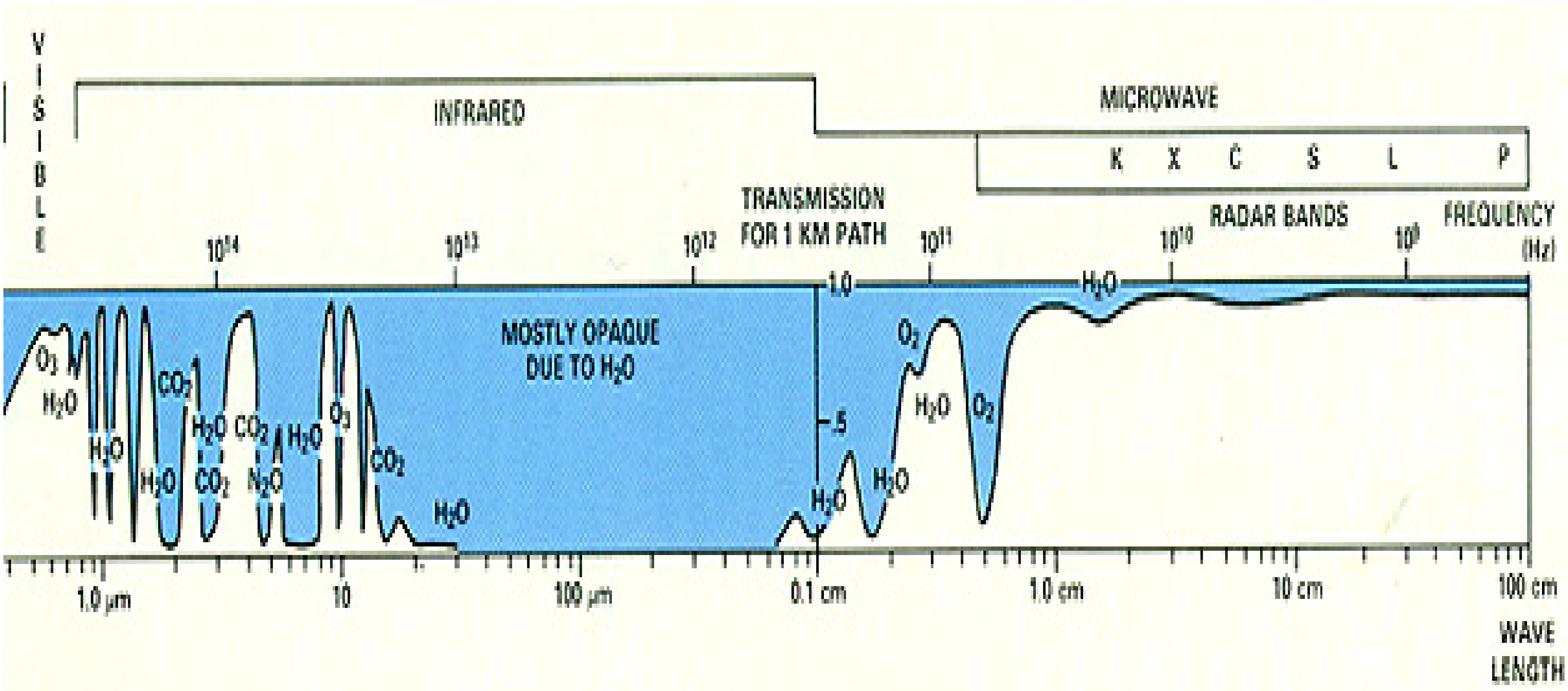
$$A_\nu = 1 - T_\nu = 1 - \exp(-\tau_\nu)$$

For the path length (or amount of gas):

$$\tau_\nu = \int_{u_1}^{u_2} k_\nu du$$

Effect of atmospheric gases

- In this course we study the UV, visible, infrared and microwave radiation



A generalized diagram showing relative atmospheric radiation **transmission** at different wavelengths. Blue zones show low passage of incoming and/or outgoing radiation and white areas denote atmospheric windows, in which the radiation doesn't interact much with air molecules and hence, isn't absorbed.

Problem solving example

What is the spectral range of the atmospheric window in the infrared (4 to 100 μm) in the Earth's atmosphere?

What spectral range do you expect for the atmospheric window in the Martian atmosphere?
Why?

Rayleigh scattering of unpolarized natural light:

$$I = I_r + I_l = \frac{I_0}{r^2}\alpha^2\left(\frac{2\pi}{\lambda}\right)^4 \frac{1+\cos^2(\Theta)}{2}$$

Rayleigh scattering phase function:

$$P(\cos(\Theta)) = \frac{3}{4}(1+\cos^2(\Theta))$$

$$I(\cos(\Theta)) = \frac{I_0}{r^2}\alpha^2 \frac{128\pi^5}{3\lambda^4}\frac{P(\Theta)}{4\pi}$$

$$\sigma_s = \alpha^2 \frac{128\pi^5}{3\lambda^4}$$

$$\alpha = \frac{3}{4\pi N}\left(\frac{m^2-1}{m^2+2}\right)$$

$$I(\cos(\Theta)) = \frac{I_0}{r^2}\sigma_s \frac{P(\Theta)}{4\pi}$$

Scattering and absorption by aerosol (or cloud) particles depend on

size,

shape,

and refractive index (i.e., composition)

Scattering domains:

Rayleigh scattering: $2\pi r/\lambda \ll 1$, and the refractive index m is arbitrary (applies to scattering by molecules and small aerosol particles)

Rayleigh-Gans scattering: **$(m - 1) \ll 1$** (not useful for atmospheric application)

Mie-Debye scattering: $2\pi r/\lambda$ and m are both arbitrary but for spheres only (applies to scattering by aerosol and cloud particles)

Geometrical optics: $2\pi r/\lambda$ is very large and m is real (applies to scattering by large cloud droplets).

The size parameter $x = 2\pi r/\lambda$ is a key factor determining how a particle interacts with EM radiation

Efficiencies (or efficiency factors) for extinction, scattering and absorption are defined as

$$Q_e = \frac{\sigma_e}{\pi r^2} \qquad Q_s = \frac{\sigma_s}{\pi r^2} \qquad Q_a = \frac{\sigma_a}{\pi r^2}$$

$$Q_a = Q_e - Q_s$$

From Mie theory:

$$Q_e = \frac{2}{x^2}\sum_{n=1}^{\infty}(2n+1)\,\mathrm{Re}[a_n + b_n]$$

$$Q_s = \frac{2}{x^2}\sum_{n=1}^{\infty}(2n+1)[|a_n|^2 + |b_n|^2]$$

Integration over the size distribution:

For a given type of particles characterized by the size distribution N(r)dr, the **extinction, scattering and absorption coefficients** (in units $LENGTH^{-1}$) are determined as

$$k_e = \int_{r_1}^{r_2} \sigma_e(r) N(r) dr \qquad k_s = \int_{r_1}^{r_2} \sigma_s(r) N(r) dr \qquad k_a = \int_{r_1}^{r_2} \sigma_a(r) N(r) dr$$

Single scattering albedo:

$$\varpi_0 = \frac{k_s}{k_e}$$

Scattering phase function:

$$P(\Theta) = \frac{\int_{r_1}^{r_2} P(\Theta) \sigma_s N(r) dr}{\int_{r_1}^{r_2} \sigma_s N(r) dr}$$

Problem solving example

Determine the optical properties of an atmosphere layer with molecular water vapor absorption and aerosol scattering. The water vapor density is ρ_w =10g/m^3 and mass absorption coefficient is $k_{a,\lambda}$ =0.03m^2/kg.
The aerosol has a volume extinction coefficient of k_{ext} =0.2 km^{-1}, single scattering albedo of ω=0.9, and asymmetry parameter of g=0.75.

How to calculate the effective optical properties of an atmospheric layer consisting of gas and aerosols (or clouds):

Effective (also called total) optical depth:

$$\tau_\lambda = \tau_{a,\lambda}^M + \tau_{s,\lambda}^M + \tau_{a,\lambda}^A + \tau_{s,\lambda}^A$$

Effective single scattering albedo:

$$\omega_{0,\lambda} = \frac{\tau_{s,\lambda}^M + \tau_{s,\lambda}^A}{\tau_\lambda}$$

Effective scattering phase function:

$$P_\lambda(\Theta) = \frac{\tau_{s,\lambda}^M P_\lambda^M(\Theta) + \tau_{s,\lambda}^A P_\lambda^A(\Theta)}{\tau_{s,\lambda}^M + \tau_{s,\lambda}^A}$$

Effective asymmetry parameter:

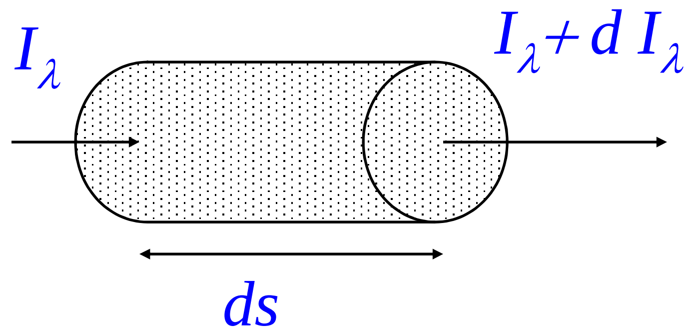
$$g_\lambda = \frac{\tau_{s,\lambda}^A g_\lambda^A}{\tau_{s,\lambda}^M + \tau_{s,\lambda}^A}$$

The Beer-Bouguer-Lambert law

The fundamental law of extinction is the **Beer-Bouguer-Lambert law**, which states that the extinction process is linear in the intensity of radiation and amount of matter, provided that the physical state (i.e., T, P, composition) is held constant.

For extinction:

$$dI_\lambda = -k_{e,\lambda} I_\lambda ds$$



$$I_\lambda = I_{0,\lambda} \exp(-\int_{s1}^{s2} k_{e,\lambda}(s) ds) = I_{0,\lambda} \exp(-\tau_\lambda)$$

For emission

(or scattering):

$$dI_\lambda = k_{e,\lambda} J_\lambda ds$$

Transmission function:

$$T_\lambda = I_{s1,\lambda} / I_{0,\lambda} = \exp(-\tau_\lambda)$$

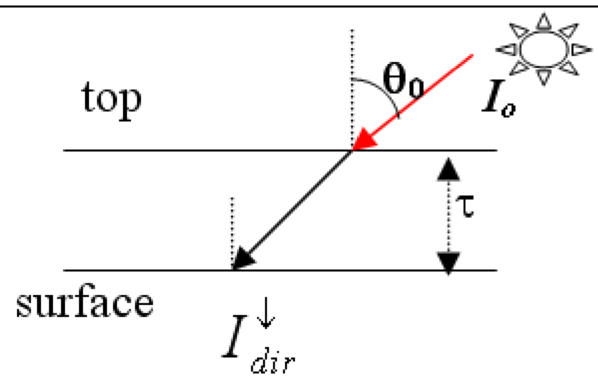
Direct and diffuse radiation.

The solar radiation field is traditionally considered as a sum of two distinctly different components: **direct** and **diffuse:**

$$I = I_{dir} + I_{dif}$$

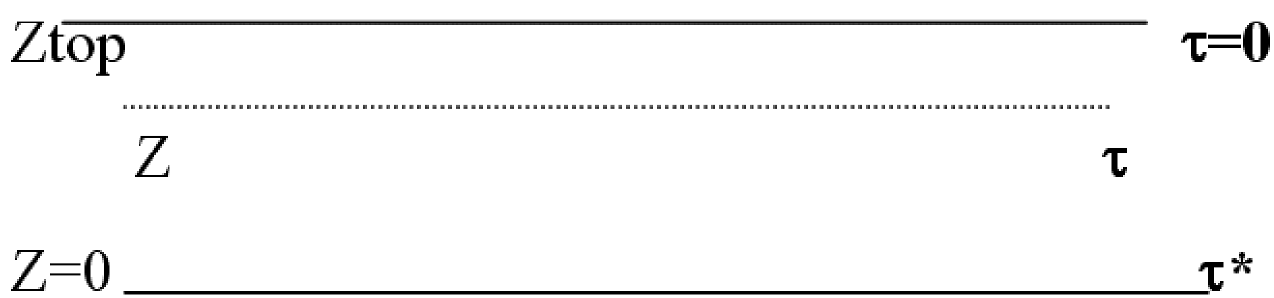
Direct radiation is a part of the radiation field that has survived the extinction passing a layer with optical depth τ and it obeys the Beer-Bouguer-Lambert law (or Extinction law):

$$I_{dir}^{\downarrow} = I_0 \exp(-\tau / \mu_0)$$



The monochromatic radiative transfer equation for a plane-parallel atmosphere expresses the net change in intensity due to extinction and scattering along path ***dz:***

dI = dI (extinction) + dI(scattering)



The radiative transfer equation:

$$\cos(\theta)\frac{dI_\lambda(z,\theta,\varphi)}{k_{e,\lambda}dz} = -I_\lambda(z,\theta,\varphi) + J_\lambda(z,\theta,\varphi)$$

Introducing $\tau_\lambda(z,0) = \int_0^z k_{e,\lambda}(z)dz$ and using $d\tau_\lambda = -k_{e,\lambda}(z)dz$

$$\mu\frac{dI_\lambda(\tau;\mu;\varphi)}{d\tau} = I_\lambda(\tau;\mu,\varphi) - J_\lambda(\tau,\mu,\varphi)$$

Solution for the upward intensity in the plane-parallel atmosphere

$$I_\lambda^\uparrow(\tau, \mu, \varphi) = I_\lambda^\uparrow(\tau^*, \mu, \varphi)\exp\left(-\frac{\tau^* - \tau}{\mu}\right)$$

$$+ \frac{1}{\mu}\int_\tau^{\tau^*} \exp\left(-\frac{\tau' - \tau}{\mu}\right) J_\lambda^\uparrow(\tau', \mu, \varphi)\, d\tau'$$

Solution for the downward intensity in the plane-parallel atmosphere

$$I_\lambda^\downarrow(\tau, -\mu, \varphi) = I_\lambda^\downarrow(0, -\mu, \varphi)\exp\left(-\frac{\tau}{\mu}\right)$$

$$+ \frac{1}{\mu}\int_0^{\tau} \exp\left(-\frac{\tau - \tau'}{\mu}\right) J_\lambda^\downarrow(\tau', -\mu, \varphi)\, d\tau'$$

Assuming no surface reflection (dark surface), the upwelling intensity at the level Z (or τ) is

$$I^{\uparrow}(\tau,\mu,\varphi) = \int_{\tau}^{\tau^*} J(\tau',\mu,\varphi)\exp[-(\tau'-\tau)/\mu]d\tau'/\mu$$

Substituting in the source function

$$I^{\uparrow}(\tau,\mu,\varphi) = \frac{\omega_0}{4\pi}F_0 P(\Theta)\int_{\tau}^{\tau^*} \exp[-(\tau'-\tau)/\mu-\tau'/\mu_0]d\tau'/\mu$$

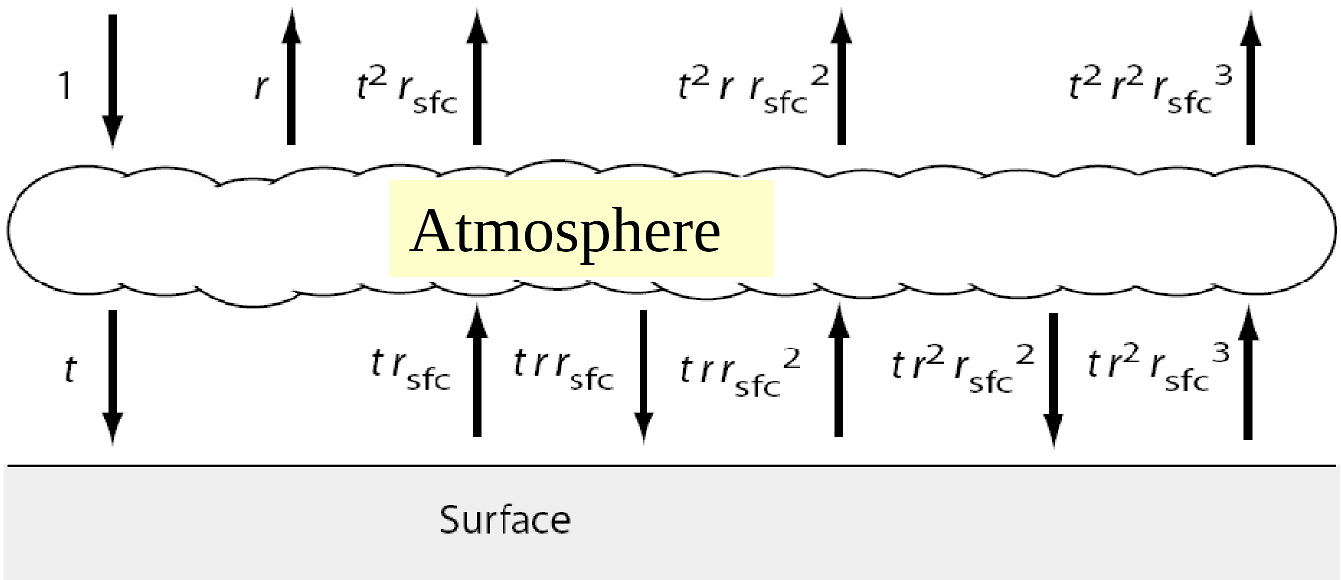
Satellite sensor measures

$$I^{\uparrow}(0,\mu,\varphi) = \frac{\omega_0}{4\pi}F_0 P(\Theta)\frac{\mu_0}{\mu+\mu_0}[1-\exp(-(\frac{1}{\mu_o}+\frac{1}{\mu})\tau^*)]$$

In the single scattering approximation when **τ* <1**:

$$I^{\uparrow}(0,\mu,\varphi) = \frac{\omega_0}{4\pi}F_0 P(\Theta)\frac{\tau^*}{\mu}$$

Atmosphere-underlying surface system



$$r_{as} = r + r_s \frac{t^2}{1 - r\, r_s}$$

Brightness temperature

Brightness temperature, T_b, is defined as the temperature of a blackbody that emits the same intensity as measured. Brightness temperature is found by inverting the Planck function.

$$B_\lambda(T) = \frac{2hc^2}{\lambda^5(\exp(hc/k_B T\lambda) - 1)} \quad \Longrightarrow \quad T_b = \frac{C_2}{\lambda \ln[1 + \frac{C_1}{\lambda^5 I_\lambda}]}$$

where $C_1 = 1.1911 \times 10^8$ W m^{-2} sr^{-1} μm^4

$C_2 = 1.4388 \times 10^4$ K μm