Lecture 16.

Course Summary&Review for Exam II

Upward/downward intensity in the plane-parallel atmosphere with scattering/absorption (Lecture 5):

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

$$I_\lambda^\downarrow(\tau,-\mu,\varphi) = I_\lambda^\downarrow(0,-\mu,\varphi)\exp(-\frac{\tau}{\mu}) + \frac{1}{\mu}\int_0^{\tau}\exp(-\frac{\tau-\tau'}{\mu})\ J_\lambda^\downarrow(\tau',-\mu,\varphi)d\tau'$$

$$J(\tau,\mu,\varphi) = \frac{\omega_0}{4\pi}\int_0^{2\pi}\int_{-1}^{1} I(\tau,\mu',\varphi')P(\mu,\varphi,\mu',\varphi')d\mu'd\varphi' + \frac{\omega_0}{4\pi}F_0P(\mu,\varphi,\mu_0,\varphi_0)\exp(-\tau/\mu_0)$$

Upward/downward intensity in the plane-parallel atmosphere with emission/absorption (Lecture 9):

$$I_\lambda^\uparrow(\tau;\mu;\varphi) = I_\lambda^\uparrow(\tau^*;\mu;\varphi)\exp(-\frac{\tau^*-\tau}{\mu}) + \frac{1}{\mu}\int_\tau^{\tau^*}\exp(-\frac{\tau'-\tau}{\mu})\ B_\lambda(\tau')d\tau'$$

$$I_\lambda^\downarrow(\tau;-\mu;\varphi) = I_\lambda^\downarrow(0;-\mu;\varphi)\exp(-\frac{\tau}{\mu}) + \frac{1}{\mu}\int_0^{\tau}\exp(-\frac{\tau-\tau'}{\mu})\ B_\lambda(\tau')d\tau'$$

Clouds:

Cloud amount/coverage (cloud mask)

Visible+ IR => Lecture 12 and Lab 10

Principles: based on a combination of thresholds for solar reflectivity and brightness temperature (in the IR)

Active (CALIPSO, CloudSat) => Lectures 13-14

Cloud liquid water content (column integrated)

Microwave => Lecture 9

Cloud type

ISCCP classification => Lecture 12

Cloud particle size distribution (effective size) and optical depth

MODIS retrieval technique => Lecture 12 and Lab 10

Cloud thermodynamic phase

MODIS retrieval technique => Lecture 12

Cloud–top pressure

O2 absorption technique" and "CO2 slicing technique = > (see textbook)

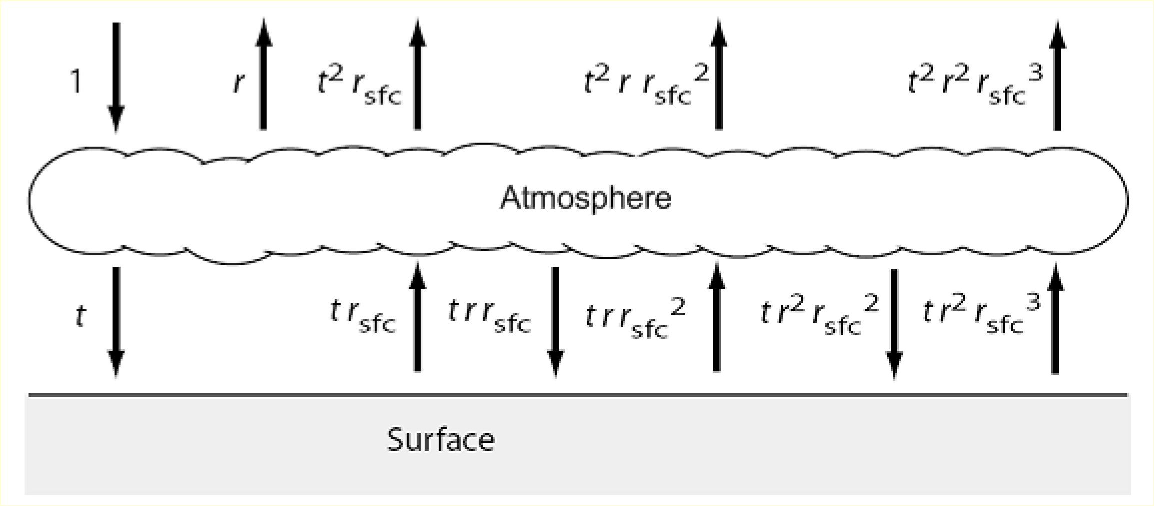
Cloud height and cloud detection

Lidars/Radars => Lectures 13-14 and Lab 12

Problem solving example

You analyze a satellite image of two clouds with one appearing brighter at the visible wavelengths. In general, would you expect more, less, or unknown infrared radiance emitted by the brighter-looking cloud?

Correct answer: unknown



$$R_{total} = R_{atm} + \frac{R_{sur} T_{atm}^2}{1 - R_{sur} R_{atm}}$$

For optically thin atmosphere (R_{atm} <<1 and T_{atm} ~ 1):

$$R_{total} \approx R_{atm} + R_{sur}$$

Approximate eqs:

SOLAR SPECTRUM

Cloud reflectivity (conservative scattering: ω_0 =1):

$$R_{cld} = \frac{(1-g)\tau}{1+(1-g)\tau}$$

THERMAL SPECTRUM

Atmospheric features (cloud) with emission/absorption

$$I_\nu^{\uparrow}(0;\mu) = B_\nu(T_{src})(1-\varepsilon_{cld}) + B_\nu(T_{cld})\varepsilon_{cld}$$

Problem solving example

Consider a cloud with temperature of 220 K overlying a surface with T=285 K. Assume that the atmosphere above and below the cloud is transparent to the radiation at 11 μm.

If the cloud emissivity is 1, what is the brightness temperature that will be measured by a nadir looking satellite radiometer at **11 μm?**

Solution: Use the following Eq., and then find BT from I by inverting the Planck function :

$$I_\lambda^\uparrow(0;\mu) = B_\lambda(T_{sur})T_\lambda(\tau^*,\mu) + B_\lambda(T_{cloud})[1 - T_\lambda(\tau^*,\mu)]$$

Brightness temperature (Lecture 2)

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

$C_2 = hc/k_B = 1.4388 \times 10^4$ K μm

Aerosols:

Aerosol optical depth/particle size distribution/Angstrom exponent

Sunphotometers (AERONET) => Lecture 5 and Lab 4

Principles: based on measurements of direct solar radiation that permit to retrieve the aerosol optical depth

Visible-near IR satellite remote sensing (MODIS, MISR, AVHRR, SeaWiFS) => Lecture 5

Principles: based on measurements of reflected solar radiation and look-up tables for pre-defined aerosol models (size distribution and refractive index)

Vertical profile of backscattering, extinction and optical depth (lidars) => Lecture 14 and Lab 12

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

$$I^{\uparrow}(\tau,\mu,\varphi)=\frac{\omega_0}{4\pi}F_0P(\Theta)\int_{\tau}^{\tau^*} \exp[-(\tau'-\tau)/\mu-\tau'/\mu_0]d\tau'/\mu$$

Satellite sensor measures

$$I^{\uparrow}(0,\mu,\varphi)=\frac{\omega_0}{4\pi}F_0P(\Theta)\frac{\mu_0}{\mu+\mu_0}[1-\exp(-(\frac{1}{\mu_o}+\frac{1}{\mu})\tau^*)]$$

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

$$I^{\uparrow}(0,\mu,\varphi)=\frac{\omega_0}{4\pi}F_0P(\Theta)\frac{\tau^*}{\mu}$$

Lidar equations

***MIE lidar*:**

$$P_r(R) = \frac{C}{R^2}\frac{h}{2}\frac{k_b}{4\pi}\exp(-2\int_o^R k_e(r')dr')$$

***RAMAN lidar*:**

$$P_r(R,\lambda_L,\lambda_R) = \frac{C}{R^2}\frac{h}{2}\frac{k_b(R,\lambda_L,\lambda_R)}{4\pi}\exp(-\int_o^R [k_e(r',\lambda_L)+k_e(r',\lambda_R)]dr')$$

Scattering domains:

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

Rayleigh-Gans scattering: **(m –1) <<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

MIE theory:

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

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

$$Q_a = Q_e - Q_s$$

$$Q_b = \frac{\sigma_b}{\pi r^2}$$

$$\sigma_b = \sigma_s P(\Theta = 180^0)$$

(Lecture 13)

From Mie theory:

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

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

In Rayleigh scattering regime:

$$Q_a \approx -4x\,\mathrm{Im}\left(\frac{m^2-1}{m^2+2}\right)$$

$$Q_s \approx \frac{8}{3}x^4\left|\frac{m^2-1}{m^2+2}\right|^2$$

$$Q_b \approx 4x^4\left|\frac{m^2-1}{m^2+2}\right|^2$$

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

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

Backscattering coefficient (Lecture 14)

$$k_b = \int_{r_1}^{r_2} \sigma_b(r) N(r) dr$$

Gases:

Absorption (emission):

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

Scattering:

- **a point dipole approach – Rayleigh scattering**
- **~ wavelength $^{-4}$ => important in UV-vis**
  negligible in IR&microwave

Ozone and trace gases (NO_2, SO_2, BrO, OClO):

Ozone profile

Sounding => Lecture 10

Other gases => see Table 15.1 in Lecture 15

Lidars (profile) => Lecture 14

Water vapor:

Integrated column (total precipitable water) from microwave => Lecture 9

Profile from IR sounding => Lecture 10

Profile from microwave sounding => Lecture 10

Profile from Raman lidar, DIAL => Lecture 14

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

$$\tau_\nu = \int_{z'}^{z} k_\nu \rho_{gas} dz''$$

$$T_\nu(z, z', \mu) = \exp(-\frac{1}{\mu}\int_{z'}^{z} k_\nu \rho_{gas} dz'')$$

$$\frac{dT_\nu(z, z', \mu)}{dz'} = -\frac{k_\nu \rho_{gas}}{\mu}\exp(-\frac{1}{\mu}\int_{z'}^{z} k_\nu \rho_{gas} dz'')$$

$$I_\nu^\uparrow(z, \mu) = I_\nu^\uparrow(0, \mu) T_\nu(z, 0, \mu) + \int_0^z B_\nu(T(z')) \left| \frac{dT_\nu(z, z', \mu)}{dz'} \right| dz'$$

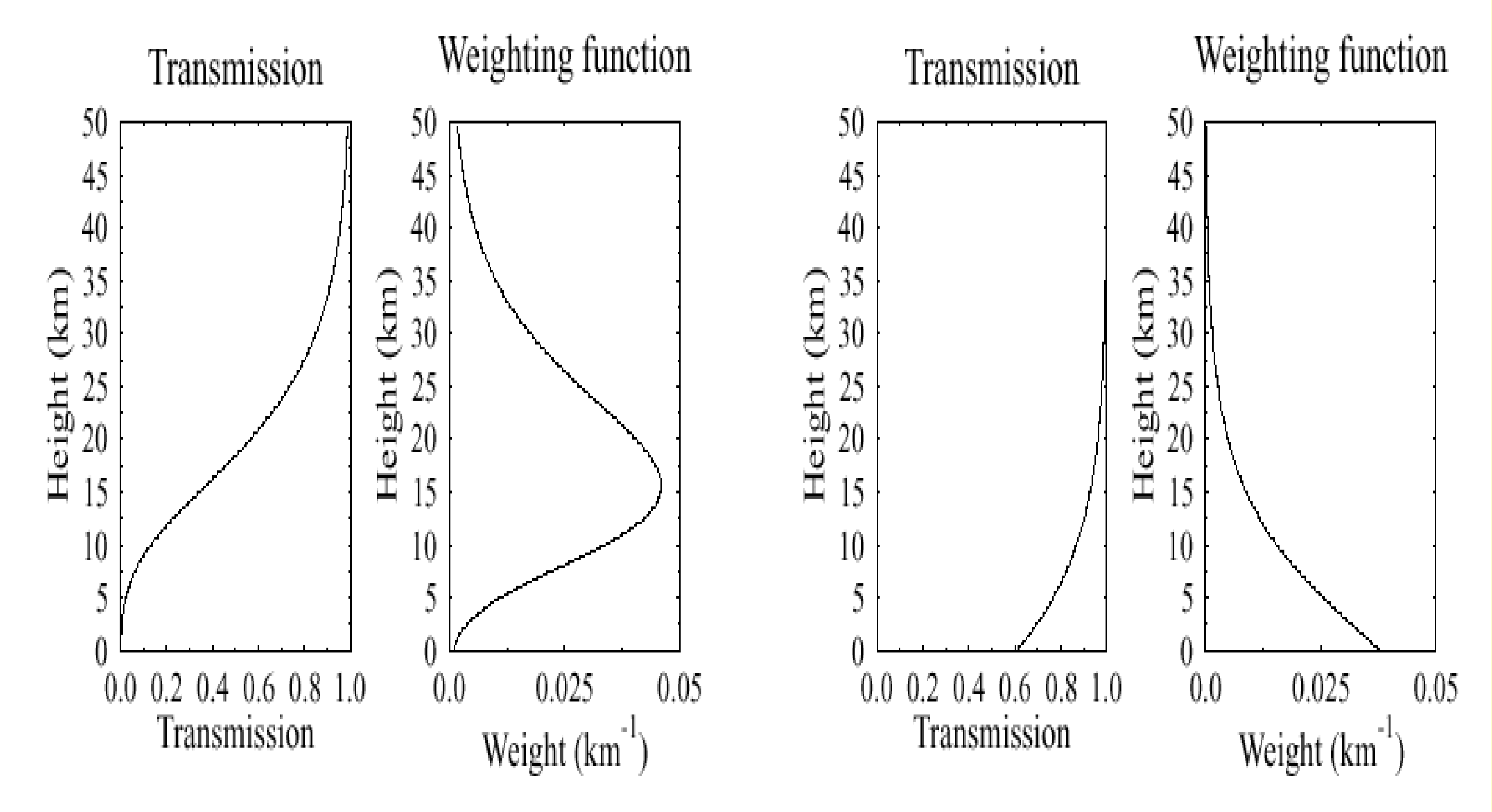
$$I_\nu^\uparrow(z, \mu) = I_\nu^\uparrow(0, \mu)\exp\left[-\frac{1}{\mu}\int_0^z k_\nu \rho_{gas} dz'\right] + \frac{1}{\mu}\int_0^z \exp\left[-\frac{1}{\mu}\int_{z'}^{z} k_\nu \rho_{gas} dz'\right] B_\nu(T(z')) k_\nu \rho_{gas} dz'$$

Weighting functions for near-nadir sounding:

For a satellite sensor looking down:

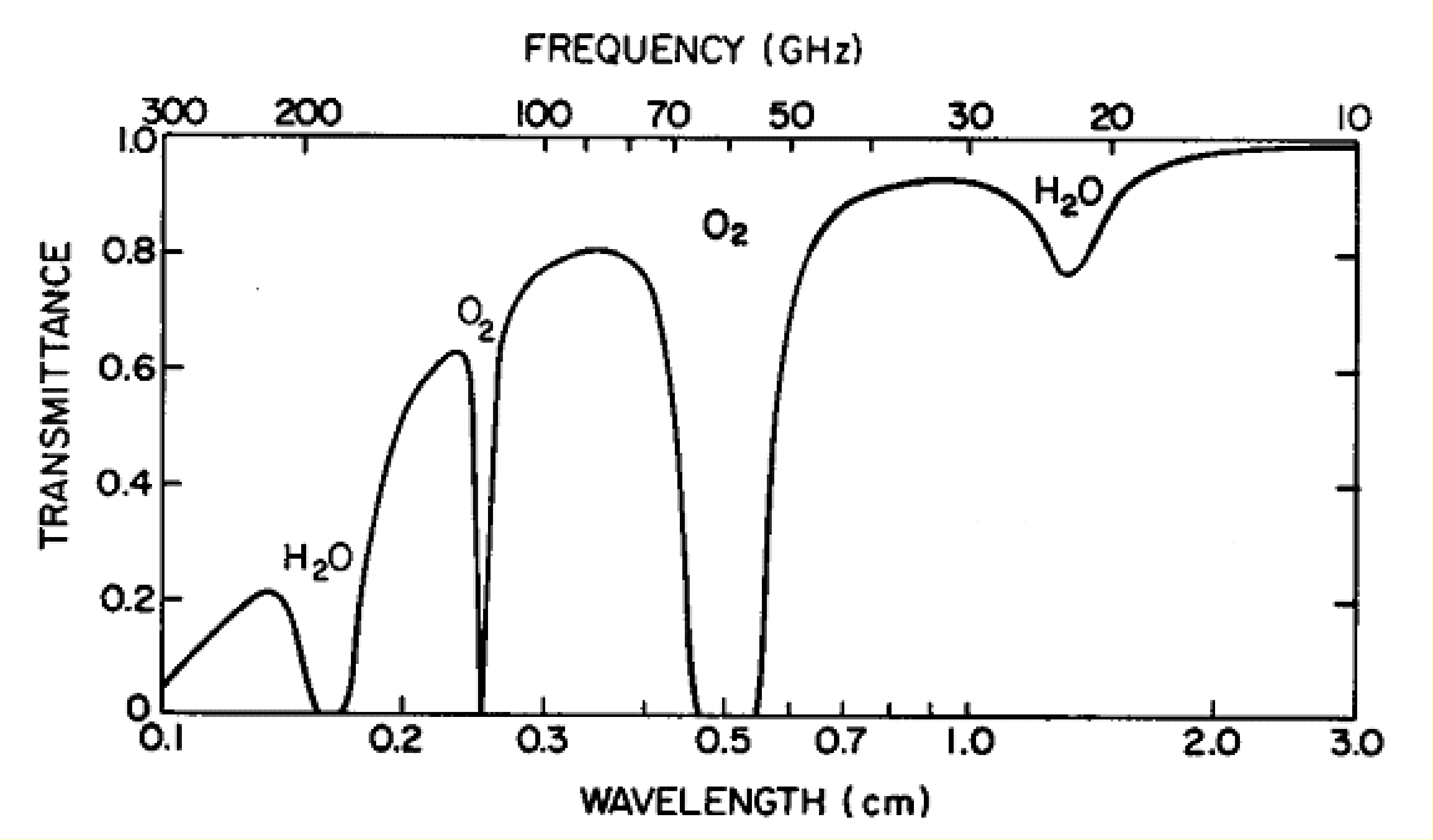
$$I_\nu^{\uparrow}(\infty,\mu) = I_\nu^{\uparrow}(0,\mu)T_\nu(\infty,0,\mu) + \int_0^\infty B_\nu(T(z'))\left|\frac{dT_\nu(\infty,z',\mu)}{dz'}\right|dz'$$

$$W_\nu(\infty,z,\mu) = \left|\frac{T_\nu(\infty,z,\mu)}{dz}\right| = \frac{k_\nu\rho_{gas}}{\mu}\exp(-\frac{1}{\mu}\int_z^\infty k_\nu\rho_{gas}dz)$$



Microwave

$$\lambda(in\ cm) = \frac{30}{\tilde{\nu}(in\ GHz)}$$



Precipitation

Visible/IR techniques => Lecture 12

Principles: indirect method that relates properties of clouds to precipitation

Microwave techniques => Lecture 12

Principles: direct method that relates the optical depth associated with the emitting rain drops and brightness temperature measured by a passive microwave radiometer.

Radar => Lecture 13 and Lab 11

Principles: measured backscattering from rain drops is related to the Z factor (size distribution) and then to precipitation via the Z-R relationship

Radar equation

$$\frac{P_r}{P_t} = \pi^2 G^2 \frac{h\theta_{HP}\varphi_{HP}}{128R^2} |K|^2 \int N(D) D^6 dD$$

$$P_r = C \frac{|K|^2}{R^2} Z$$

$$P(dBz) = 10\log(Z) \quad \rightarrow \quad Z = 10^{(P(dBz)/10)}$$

Problem solving example:

Precipitation is a key component of the hydrological cycle. Briefly explain the principles and discuss advantages and disadvantages of the following remote sensing techniques:

- **passive IR sensing of precipitation**
- **passive microwave sensing of precipitation**
- **active microwave sensing of precipitation**

Atmospheric temperature (profile)

IR (or microwave) sounding techniques => Lecture 9 and Lab 7

Principles: multi-spectral remote sensing in the 15 μm CO2 absorbing band (in microwave in the O2 absorbing region)

Sea Surface Temperature

IR split-window technique => Lecture 9

Microwave techniques => Lecture 9

Ocean color mapping

Solar remote sensing (MODIS, SeaWiFS) = > Lecture 6

Sea ice

Passive microwave = > Lecture 2 and Lab 1

Active microwave (radars) => (see textbook)