Lecture 21

Applications of radars: Sensing of clouds and precipitation.

Objectives:

1. Particle backscattering and radar equation.
2. Weather radars.
3. Space radars: TRMM radar and CloudSat radar

Required reading:

G: 5.7, 8.2.2, 8.2.3, 8.3

1. Particle backscattering and radar equation.

Recall Lecture 9 in which we introduced introduce the **efficiencies (or efficiency factors), cross-sections and volume coefficients** for extinction, scattering and absorption. Let's introduce backscattering characteristics used in active remote sensing (radar and lidars)

Differential scattering cross-section, σ_d**,** is defined as the amount of incident radiation scattered into the direction Θ per unit of solid angle

$$\sigma_d(\Theta) = \frac{\sigma_s}{4\pi} P(\Theta) \qquad [21.1]$$

where ***P(Θ)*** **is the scattering phase function**

Bistatic (radar) scattering cross-section, σ_{bi}**,** is defined as

$$\sigma_{bi} = 4\pi\sigma_d(\Theta) \qquad [21.2]$$

Backscattering cross-section, σ_b**,** is defined as

$$\sigma_b = 4\pi\sigma_d(\Theta = 180^0) \qquad [21.3]$$

For the particle number size distribution N(r), the backscattering volume coefficient, κ_b, is

$$k_b = \int_{r_1}^{r_2} \sigma_b(r) N(r) dr \qquad [21.4]$$

Small size parameter limit (Rayleigh limit): it can be shown from Mie theory (see G 5.7.1) that

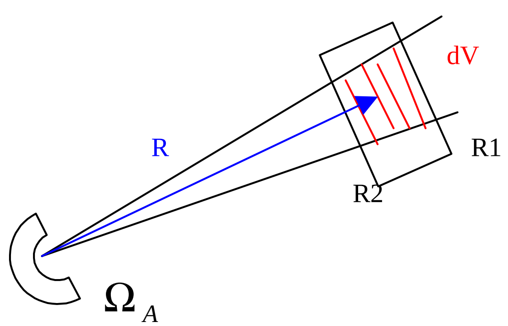
$$\sigma_b = \frac{\pi^5}{\lambda^4} |K|^2 D^6 \qquad [21.5]$$

where ***K*** denotes

$$K = \left| \frac{m^2 - 1}{m^2 + 2} \right|$$

m if the refractive index of the particle; and ***D*** is the particle diameter

Consider a transmitting radar with antenna of effective aperture A_e and pulse duration t_p (or length $h=ct_p$). The radar illuminates the volume of the atmosphere at the distance R. Suppose that the volume contains particles with size distribution N(r) so k_b is the backscattering coefficient.



$t-t_p/2$ => $R2=c\,(t-t_p/2)/2$

t => $R=ct/2$

$t+t_p/2$ => $R1=c\,(t+t_p/2)/2$

$R1-R2= ct_p/2=h/2$ is radar resolution

The power backscattered by the volume ***dV*** and received by lidar can be expressed as

$$P_r = \frac{P_t}{\Omega_A R^2} \frac{A_e}{4\pi R^2} k_b dV \qquad [21.6]$$

where P_t is the power transmitted by the radar, and Ω_A is the radar beam area.

Recall that $\lambda^2 = A_e \Omega_A$ (see Eq.[20.5])

Thus we have

$$P_r = \frac{P_t}{\lambda^2 R^2} \frac{A_e^2}{4\pi R^2} k_b dV$$

and using that $A_e = G\lambda^2 / 4\pi$

$$\frac{P_r}{P_t} = \frac{G^2 \lambda^2}{(4\pi)^3 R^4} k_b dV$$

From lidar beam geometry, the illuminated volume can be approximated as

$$dV \approx R^2 \theta_{HP} \varphi_{HP} h/2$$

and using Eq.[21.4] for k_b, we have

$$\frac{P_r}{P_t} = \frac{G^2 \lambda^2}{(4\pi)^3 R^2} \frac{h\theta_{HP}\varphi_{HP}}{2} \int N(r)\sigma_b(r)dr$$

Assuming that particle are in the Rayleigh limit, we have

$$\frac{P_r}{P_t} = \pi^2 G^2 \frac{h\theta_{HP}\varphi_{HP}}{128 R^2} |K|^2 \int N(D) D^6 dD \qquad [21.7]$$

the above equation can be re-written as

$$P_r = C \frac{|K|^2}{R^2} Z \qquad [21.8]$$

where factor C depends on the antenna characteristics; and

$Z = \int N(D) D^6 dD$ is called the radar reflectivity factor;

Eq.[21.8] is often called the radar equation.

We can relate the backscattering coefficient and radar reflectivity as

$$k_b = \int \sigma_b(D) N(D) dD = \int \frac{\pi^5}{\lambda^4} |K|^2 D^6 N(D) dD = \frac{\pi^5}{\lambda^4} |K|^2 \int D^6 N(D) dD = \frac{\pi^5}{\lambda^4} |K|^2 Z$$

If particle are not in the Rayleigh limit and/or nonspherical (e.g., ice crystals), the effective radar reflectivity factor, Z_e , is introduced

- In the more general case, Eq.[21.8] must be corrected to account for the attenuation along the path to and from the scattered volume (a cloud) (i.e., attenuation may arise from absorption by atmospheric gases, absorption by cloud drops and precipitation):

$$\overline{P_r} = C \frac{|K|^2}{R^2} Z \exp(-2\int_o^R k_e(r')dr') \qquad [21.9]$$

where $\boldsymbol{k_e}$ is the extinction coefficient along the path.

- Precipitation from radar: use a relationship between the radar reflectivity Z (or Z_e) and the rainfall rate, ***Rr*** (mm/hour) in the form (called Z-R relationships)

$$Z = A\,Rr^b$$

where A and b are constants depending on the type of rains.

<u>Empirical Z-R relationships</u> (***Rr*** in (mm/h) and Z in (mm^6m^{-3})):

Stratiform rain: $Z = 200Rr^{1.6}$

Orographic rain: $Z = 31Rr^{1.71}$

Snow: $Z = 2000Rr^2$

The power returned to a radar (see Eq.[21.8]) can be normalized using Eq.[20.1] (see Lecture 20):

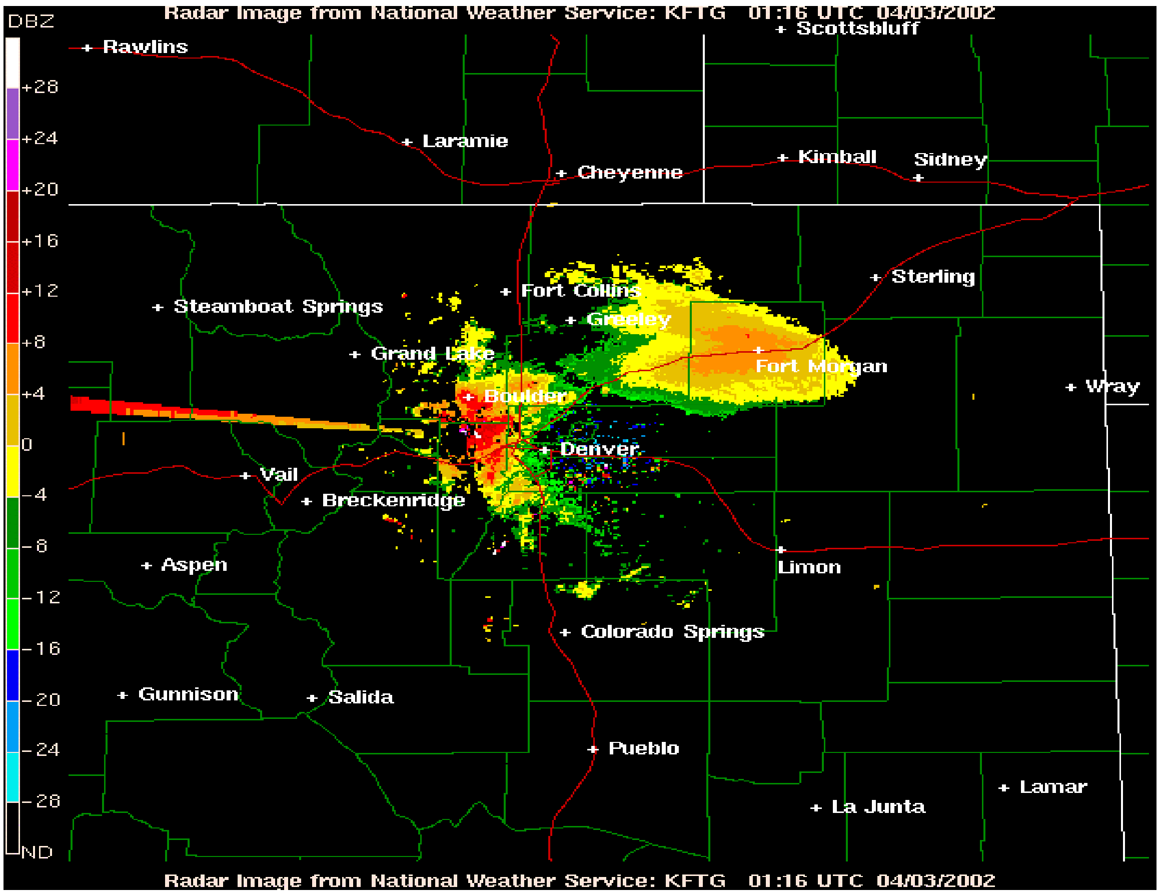
$$P_r\,(in\ \ dBZ\ ) = 10\ \log \frac{P_r}{P_{ref}}$$

where $\boldsymbol{P_{ref}}$ is the reference power which is often taken to be that power which would be returned if each m^3 of the atmosphere contained one drop with D= 1mm (Z = $1mm^6m^{-3}$).

2. National Weather Service radars

The National Weather Service (NWS) Weather Surveillance Radars (WSR) are of three types: WSR-57S, WSR-74C, and WSR-88D (D stands a Doppler radar (see Lecture 25);

Radar	Wavelength (cm)	Dish Diameter (feet)	Pulse (microsecond)
WSR-57	10.3	12	0.5 or 4
WSR-74C	5.4	8	3
WSR-88D	11.1	28	1.57 or 4.5



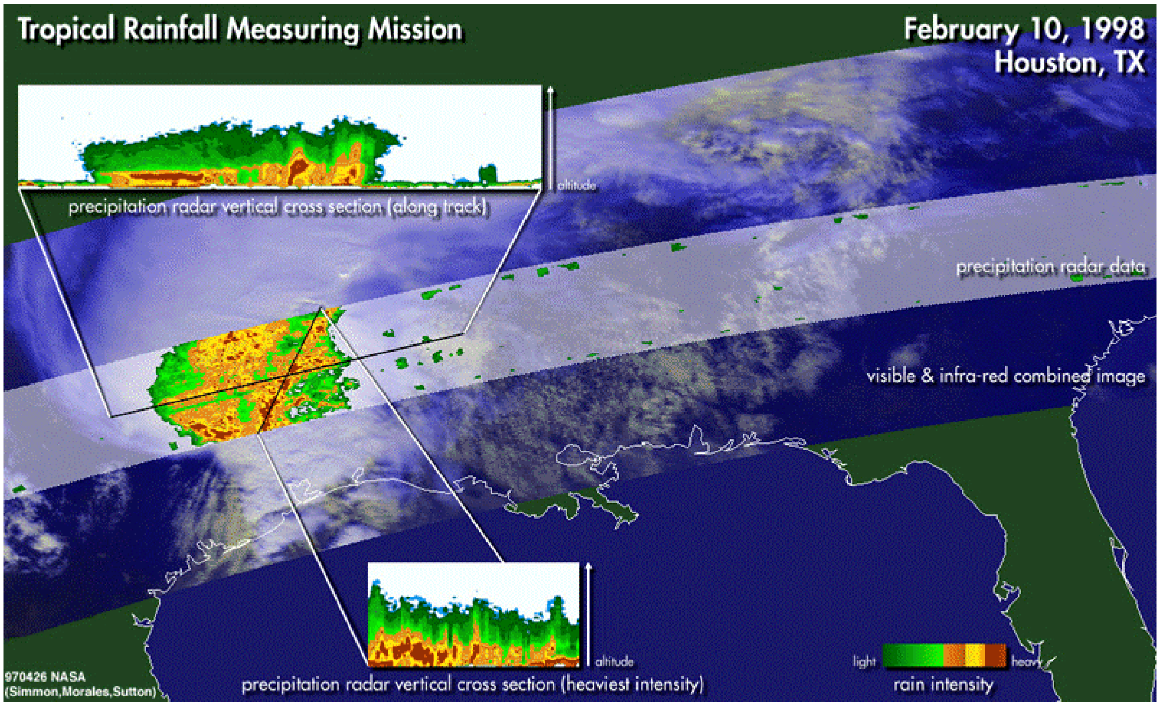
dBZ	Rainrate (in/hr)
65	16+
60	8.00
55	4.00
52	2.50
47	1.25
41	0.50
36	0.25
30	0.10
20	Trace

Example of the WSR radar image for Colorado for April 2.

3. Space radars: TRMM radar and CloudSat radar

TRMM radar – first radar in space (launched in 1997)

- 13.8 GHz, 4.3-km footprint, 250-m vertical resolution, 1.67 μs pulse duration, cross-track scanning, 215-km swath,



CloudSat radar (http://cloudsat.atmos.colostate.edu/cloudsat.html)
(will be launched in April 2004)

The primary science objectives:

- Quantitatively evaluate the representation of clouds and cloud processes in global atmospheric circulation models, leading to improvements in both weather forecasting and climate prediction;
- Quantitatively evaluate the relationship between the vertical profiles of cloud liquid water and ice content and the radiative heating by clouds.

Cloud Profiling Radar (CPR):

- 94-GHz nadir-looking radar which measures the power backscattered by clouds as a function of distance from the radar;
- sensitivity defined by a minimum detectable reflectivity factor of -30 dBZ, along-track sampling of 2 km, a dynamic range of 70 dB, 500 m vertical resolution and calibration accuracy of 1.5 dB.