Lecture 21

Radar sensing of clouds and precipitation.

Objectives:

1. Particle backscattering and radar equation.

2. Sensing precipitation and clouds with ground-based and space-borne radars (weather radars, TRMM, and CloudSat).

Required reading:

S: 5.7, 8.2.1, 8.2.2, 8.2.3, 8.3

Additional/advanced reading:

Tutorials on ground-based weather radars:

http://www.srh.noaa.gov/srh/jetstream/doppler/doppler_intro.htm

http://www.weathertap.com/guides/radar/weather-radar-tutorial.html

Tropical Rainfall Measuring Mission (TRMM) web site:

http://trmm.gsfc.nasa.gov/

http://www.eorc.jaxa.jp/en/hatoyama/satellite/satdata/trmm_e.html

Liu, Zhong, Dana Ostrenga, William Teng, Steven Kempler, 2012: Tropical Rainfall Measuring Mission (TRMM) Precipitation Data and Services for Research and Applications. Bull. Amer. Meteor. Soc., 93, 1317–1325.

CloudSat web site: http://cloudsat.atmos.colostate.edu/

CloudSat Data Center: http://www.cloudsat.cira.colostate.edu/

1. Particle backscattering and radar equation.

Recall Lecture 10 in which we introduced the **efficiencies (or efficiency factors), cross-sections and volume coefficients** for extinction, scattering and absorption. Let's introduce backscattering characteristics needed 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 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

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

Using Eq.[21.1], Eq.[21.3] can be re-written as

$$\sigma_b = \sigma_s P(\Theta = 180^0) \qquad [21.4]$$

The incident intensity I_i and scattered intensity I_s by a particle relates as (Lecture 8, Eq. 8.21)

$$I_s(\Theta) = I_i \frac{\sigma_s}{R^2} \frac{P(\Theta)}{4\pi} \qquad [21.5]$$

where R is the distance from the particle.

For the backscattering case, we can write

$$F_{bs}(\Theta = 180^0) = F_i \frac{\sigma_s}{R^2} \frac{P(\Theta = 180^0)}{4\pi} \qquad [21.6]$$

or

$$F_{bs}(\Theta = 180^0) 4\pi R^2 = F_i \sigma_b \qquad [21.7]$$

Thus, the physical meaning of the back-scattering cross-section is the area that, when multiplied by the incident flux, gives the total power radiated by an isotropic source such that it radiates the same power in the backward direction as the scatterer.

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

$$k_b = \int_{r_1}^{r_2} \sigma_b(r) N(r) dr \qquad [21.8]$$

and thus

$$k_b = k_s P(\Theta = 180^0) \qquad [21.9]$$

where *P(Θ)* is the scattering phase function averaged over the size distribution.

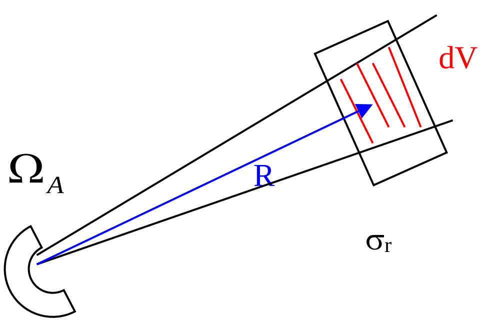
Small size parameter limit (Rayleigh limit): it can be shown from Mie theory (see S: 5.7.1) that

$$\sigma_b = \frac{\pi^5}{\lambda^4} |K|^2 D^6 \qquad [21.10]$$

where $|K| = \left| \frac{m^2 - 1}{m^2 + 2} \right|$; ***m*** if the refractive index of the particle; and ***D*** is the particle diameter.

- **Radar equation**

Consider a transmitting radar with an antenna of effective aperture A_{et} and pulse duration t_p (or length $h = ct_p$). The radar illuminates an object (e.g., a cloud) at the distance R. Suppose that the object has the backscattering cross-section (called radar cross-section) σ_r.



Using the Friis transmission formula, we can find the power intercepted by the object P_{int} as

$$P_{\text{int}}(by\ object) = \frac{P_t}{R^2}\frac{A_{et}}{\lambda^2}\sigma_r \qquad [21.11]$$

Using that the scattering object can be considered as an isotropic source such that it radiates the same power in the backward direction, it has directivity D=1 and effective aperture $A_e = \lambda^2/4\pi$ (see Eq.[20.8]). And using the Friis transmission formula, we can find the power received by the antenna

$$P_r = \frac{P_{\text{int}}(by\ object)A_{er}}{R^2\lambda^2}\frac{\lambda^2}{4\pi} \qquad [21.12]$$

Substituting Eq.[21.11] into Eq.[21.12], we obtain the **radar equation**

$$\boxed{\frac{P_r}{P_t} = \frac{A^2}{4\pi R^4}\frac{\sigma_r}{\lambda^2}} \qquad [21.13]$$

where $A = A_{et} = A_{er}$ is the effective aperture of antenna (same for transmitting and receiving).

If the object is a cloud with size distribution N(r) and the volume backscattering coefficient k_b. The power backscattered by the volume ***dV*** and received by a radar (or a lidar) can be expressed as

$$\frac{P_r}{P_t} = \frac{A^2}{4\pi R^4}\frac{k_b dV}{\lambda^2} \qquad [21.14]$$

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

$$dV \approx R^2\theta_{HP}\varphi_{HP}h/2 \qquad [21.15]$$

and using Eq.[21.8] for k_b, we have

$$\frac{P_r}{P_t} = \frac{A^2}{4\pi R^2\lambda^2}\frac{h\theta_{HP}\varphi_{HP}}{2}\int \sigma_b(r)N(r)dr \qquad [21.16]$$

Assuming that particle are in the **Rayleigh limit** and using Eq.[21.10], we have

$$\frac{P_r}{P_t} = \frac{\pi^4 A^2}{4\lambda^6} \frac{h\theta_{HP}\varphi_{HP}}{R^2} |K|^2 \int D^6 N(D) dD \qquad [21.17]$$

the above equation can be re-written as

$$\boxed{P_r = C \frac{|K|^2}{R^2} Z} \qquad [21.18]$$

where factor C depends on the antenna characteristics; and

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

NOTE: Eq.[21.18] is often called the radar equation.

The backscattering coefficient and radar reflectivity relates as

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

[21.19]

- 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.[21.18] 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):

$$\overline{P}_r = C \frac{|K|^2}{R^2} Z \exp(-2\int_o^R k_e(r')dr') \qquad [21.20]$$

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

2. Sensing precipitation and clouds with radars.

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

$$Z = A\, Rr^b \qquad [21.21]$$

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

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

Stratiform rain: $Z = 200\ Rr^{1.6}$ [21.22]

Orographic rain: $Z = 31\ Rr^{1.71}$ [21.23]

Snow: $Z = 2000\ Rr^{2}$ [21.24]

The power returned to a radar (see Eq.[21.18]) can be normalized using Eq.[20.2] :

$$P_r(in\ dBZ) = 10\log\frac{P_r}{P_{ref}} \qquad [21.25]$$

where 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= 1 mm (Z = 1 $mm^6 m^{-3}$).

NOTE: The higher the dBZ value, the more power is reflected and received by the radar. Light snow is very inefficient at reflecting radiation, so it might be 5-20 dBZ, while moderate rain might be 30-45 dBZ, and large hail might be around 60-75 dBZ.

NOTE: dBZ values can be negative if Z < 1.

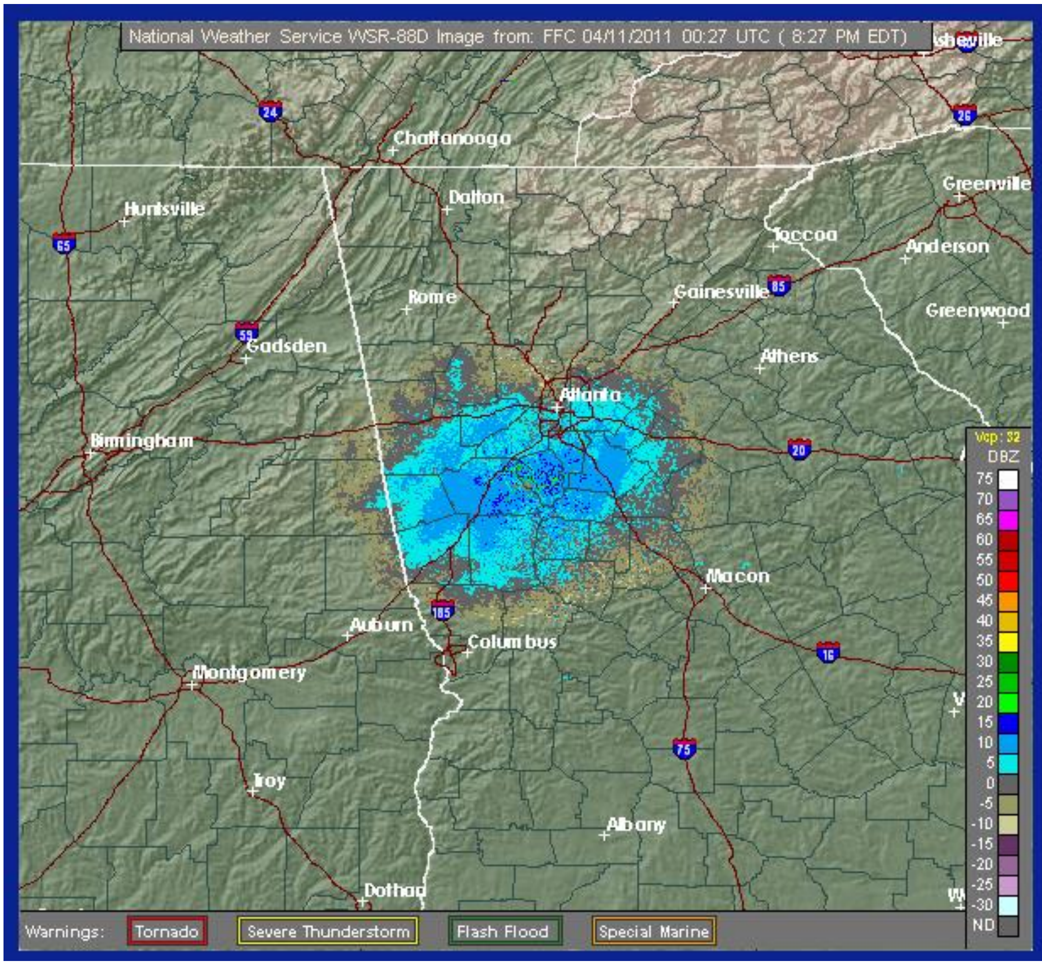
NOTE: Retrievals of precipitation from radars depend on an assumed Z-R relationship.

- ***National Weather Service radars (http://radar.weather.gov/)***

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)

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

Example of a WSR radar image for Georgia, 10 Apr, 2011: Clear-air mode - no precip.



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
< 20	No rain

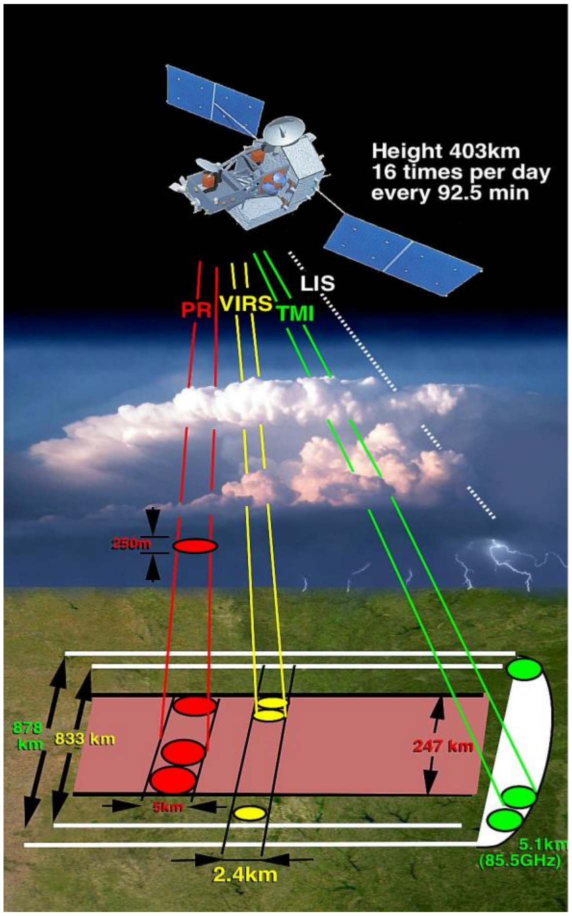
➢ **Space radars: TRMM and CloudSat:**

TRMM precipitation radar- first radar in space (launched in 1997):

coverage 35 N to 35 S http://trmm.gsfc.nasa.gov/

- 13.8 GHz, 4.3-km footprint, 250-m vertical resolution, 1.67 μs pulse duration, cross-track scanning, 215-km swath.
- provides vertical profiles of the rain and snow from the surface up to a height of about 20 km. The Precipitation Radar is able to detect fairly light rain rates down to about .027 inches (0.7 millimeters) per hour. At intense rain rates, where the attenuation effects can be strong, new methods of data processing have been developed that help correct for this effect. The Precipitation Radar is able to separate out rain echoes for vertical sample sizes of about 820 feet (250 meters)

when looking straight down. It carries out all these measurements while using only 224 watts of electric power—the power of just a few household light bulbs.



TRMM has following instruments:

PR –Precipitation Radar

VIRS – Visible and Infrared Scanner

TMI – Microwave Imager

LIS - Lightning Imaging Sensor

CERES - Clouds and the Earth's Radiant Energy System

CloudSat radar: Cloud Profiling Radar (CPR) (launched on 28 April 2006):

http://cloudsat.atmos.colostate.edu/

- CloudSat is an experimental satellite that uses radar to observe clouds and precipitation from space. CloudSat orbits in formation as part of the A-Train constellation of satellites (Aqua, CloudSat, CALIPSO, PARASOL, and Aura).
- 94-GHz nadir-looking radar which measures the power backscattered by clouds as a function of distance from the radar;

CPR System Characteristics

Nominal Frequency	94 GHz
Pulse Width	3.3 µsec
PRF	4300 Hz
Minimum Detectable Z*	-26 dBZ
Antenna Size	1.95 m
Dynamic Range	70 dB
Integration Time	0.3 sec
Vertical Resolution	500 m
Cross-track Resolution	1.4 km
Along-track Resolution	2.5 km

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.

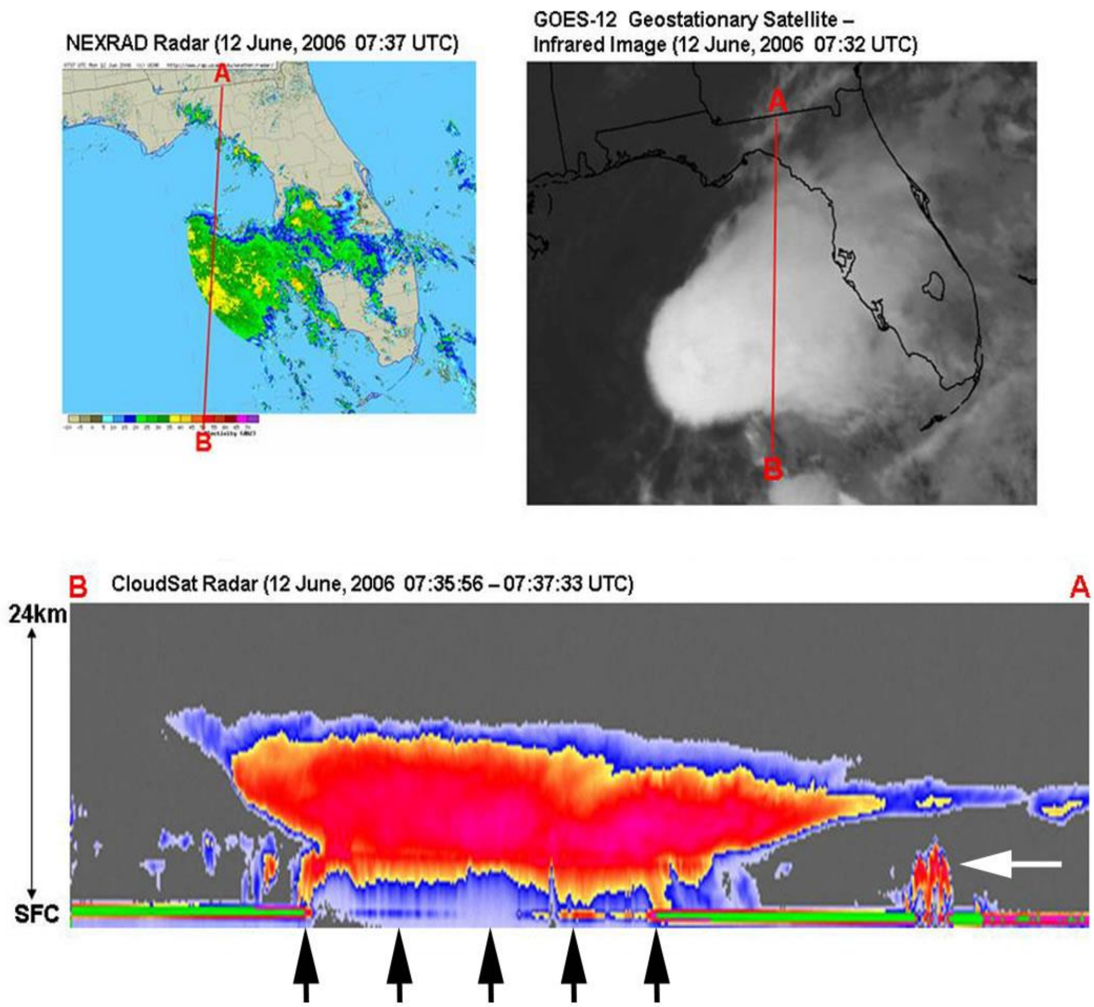


Figure 21.1 Tropical storm Alberto over the Gulf of Mexico. The collection of images reveals how CloudSat "sees" the storm differently from other weather satellites and sensors. The NEXRAD storm detection radar is limited by distance, preventing it from mapping all of the storm's precipitation. The infrared imager on the GOES-12 satellite can detect cloud cover but cannot provide details beneath the storm's cloud tops. Data collected by CloudSat reveal the true height and extent of the storm. Very heavy rainfall (black arrows) was detected over about 400 kilometers of the satellite's track. CloudSat also located a smaller thunderstorm (white arrow) hidden under the clouds.