Lecture 12.

Principles of active remote sensing: Radar.

Radar sensing of clouds and precipitation.

Objectives:

1. Radar basics. Main types of radars.
2. Basic antenna parameters.
3. Particle backscattering and radar equation.
4. Sensing precipitation and clouds with ground-based and space-borne radars (weather radars, TRMM, and CloudSat).

Required reading:

S: 8.1, p.401-402, 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

CloudSat web site: http://cloudsat.atmos.colostate.edu/
CloudSat overview: http://cloudsat.atmos.colostate.edu/CloudSat_overview.pdf
CloudSat Data Center: http://www.cloudsat.cira.colostate.edu/
Stephens et al., 2002, The CloudSat mission and the A-Train: A new dimension of space-based observations of clouds and precipitation. BAMS, 1771-1790, 2002.

1. Radar basics. Main types of radars.

- Radar is an active remote sensing system operating at the microwave wavelength.
- Radar is a ranging instrument: (RAdio Detection And Ranging)

Basic principles:

The sensor transmits a microwave (radio) signal towards a target and detects the backscattered radiation. The strength of the backscattered signal is measured to discriminate between different targets and the time delay between the transmitted and reflected signals determines the distance (or **range**) to the target.

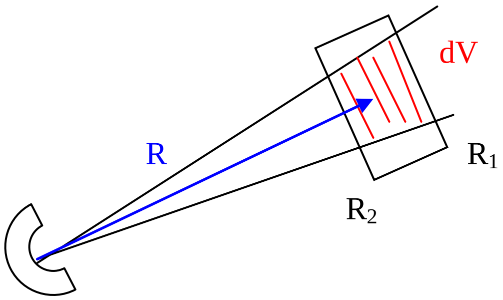
✓ Two primary advantages of radars: **all-weather and day /night imaging**

Radar modes of operation:

- Constant wave (CW) mode: continuous beam of electromagnetic radiation is transmitted and received => provides information about the path integrated backscattering radiation
- Pulsed mode: transmits short pulses (typically 10^{-6}-10^{-8} s) and measures backscattering radiation (also called echoes) as a function of range.

Radar range resolution:

Consider a radar with pulse duration $\mathbf{t_p}$



$t-t_p/2 \Rightarrow R_2 = c\,(t-t_p/2)/2$

$t \Rightarrow R = ct/2$

$t+t_p/2 \Rightarrow R_1 = c\,(t+t_p/2)/2$

Thus **radar range resolution is**

$$R_1-R_2 = \mathbf{ct_p/2 = h/2} \qquad [12.1]$$

where c is the speed of light.

Problem: A police pulsed speed-measuring radar must be able to resolve the returns from two cars separated by 10 m. Find the maximum pulse duration that can be used to prevent overlapping of the returns from the two vehicles. Ignore the Doppler effect.

Solution:

R_1-R_2 = 10 m thus **t_p =** 2*10m/3*10^8 m/s = 6.67*10^{-7} s

Polarizing Radar has four possible combinations of both transmit and receive polarizations as follows:

- HH - for horizontal transmit and horizontal receive,
- VV - for vertical transmit and vertical receive,
- HV - for horizontal transmit and vertical receive, and
- VH - for vertical transmit and horizontal receive.

Microwave bands commonly used in radar remote sensing:*(see also Table 1.3, Lecture 1)*

- Ka, K, and Ku bands: very short wavelengths used in early airborne radar systems but uncommon today.
- X-band: used extensively on airborne systems for military terrain mapping.
- C-band: common on many airborne research systems (CCRS Convair-580 and NASA AirSAR) and spaceborne systems (including ERS-1 and 2 and RADARSAT).
- S-band: used on board the Russian ALMAZ satellite.
- L-band: used onboard American SEASAT and Japanese JERS-1 satellites and NASA airborne system.
- P-band: longest radar wavelengths, used on NASA experimental airborne research system.

Types of radars:

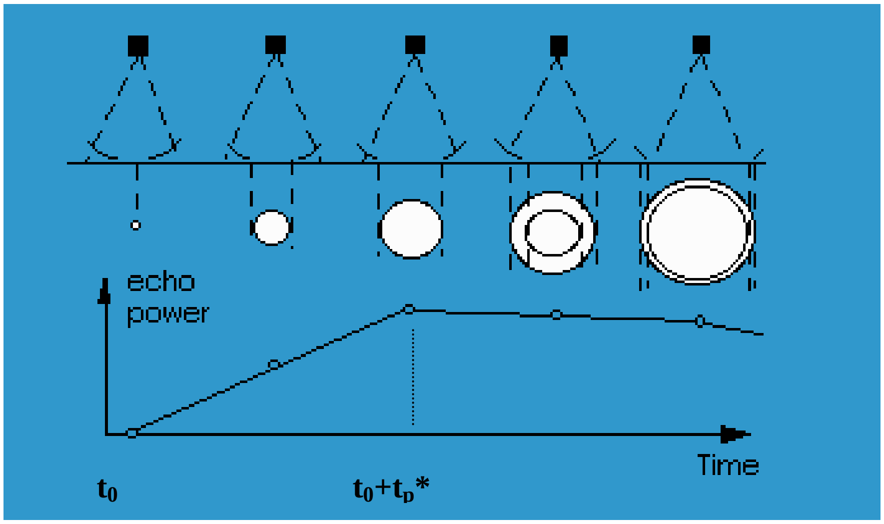
➢ **Non-imaging: (altimeters and scatterometers):**

- ***Altimeters*** (often nadir-looking)

Operation principles: transmit short microwave pulses and measure the round trip time delay to targets to determine their distance from the sensor;

Applications: used on aircraft for altitude determination and on aircraft and satellites for topographic mapping, sea surface height measurements from which wind speed can be estimated

Example: ERS altimeter



$t_0=2H/c$ $t_p*> t_p$ t_p is the duration of the pulse

Figure 12.1 Reflection of an altimeter pulse from a flat surface. As the pulse advances, the illuminated area grows rapidly from a point to a disk, as does the returned power. Eventually, an annulus is formed and the geometry is such that the annulus area remains constant as the diameter increases. The returned signal strength, which depends on the reflecting area, grows rapidly until the annulus is formed, remains constant until the growing annulus reaches the edge of the radar beam, where it starts to diminish.

- **Scatterometers**

Operation principles: transmit microwave signal and measures the strength of the backscattering radiation (reflection);

Applications: measurements of wind speed and wind direction over the oceans. Ground-based scatterometers are used extensively to accurately measure the backscatter from various targets in order to characterize different materials and surface types.

Example: NASA Quick Scatterometer (QuikSCAT):

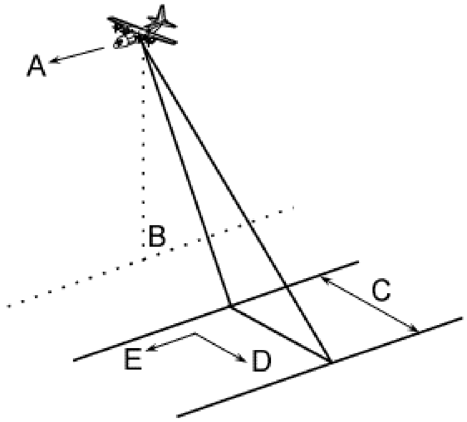
- Radar: 13.4 gigahertz; 110-watt pulse at 189-hertz pulse repetition frequency (PRF)
- Antenna: 1-meter-diameter rotating dish that produces two spot beams, sweeping in a circular pattern

QuikSCAT measurement capability:

- 1,800-kilometer swath during each orbit provides approximately 90-percent coverage of Earth's oceans every day.
- Wind-speed measurements of 3 to 20 m/s, with an accuracy of 2 m/s; direction, with an accuracy of 20 degrees. Wind vector resolution of 25 km.

➢ **Imaging radars**:

The two-dimensional representation of imaging sensors:



Side-looking viewing geometry of imaging radar systems:

The platform travels forward in the **flight direction** (A) with the **nadir** (B) directly beneath the platform. The microwave beam is transmitted obliquely at right angles to the direction of flight illuminating a **swath** (C). **Range** (D) refers to the across-track dimension perpendicular to the flight direction, while **azimuth** (E) refers to the along-track dimension parallel to the flight direction.

2. Basic antenna parameters.

Antenna is a structure which serves as a transition between wave propagating in free space and the fluctuating voltages in the circuit to which it is connected.

Basic antenna parameters (in free space):

1) Field pattern: 3-D quantities involving the variation of EM field or EM power as a function of the spherical coordinates θ and φ: power pattern $\boldsymbol{P}(\theta, \varphi)$ (in W sr^{-1}) and normalized power pattern: $\boldsymbol{P_n}(\theta, \varphi) = \boldsymbol{P}(\theta, \varphi) / \boldsymbol{P_{max}}(\theta, \varphi)$

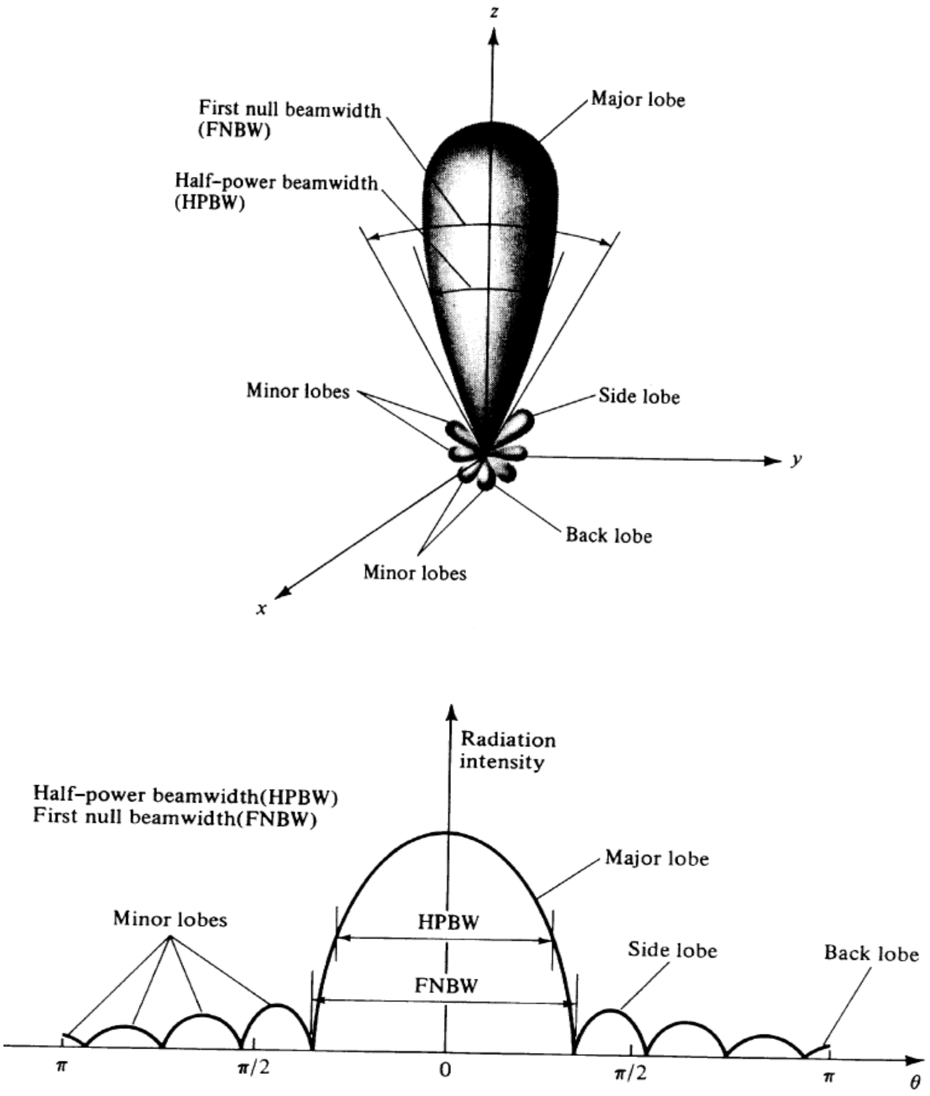


Figure 12.2 Antenna power pattern in polar coordinates and in rectangular coordinates.

NOTE: “same name”: Major lobe=Main lobe = Main beam

Since the difference between the power transmitted by an antenna, $\boldsymbol{P_t}$ (in W), and the power received from backscattering is typically several orders of magnitude, the received signal is expressed in **Decibels (dB):**

$$P(in\ \ dB) = 10\log\frac{P}{P_t} \qquad [12.2]$$

2) **Antenna gain** is defined as the ratio of the intensity at the peak of the transmission pattern, $\boldsymbol{I_p}$, to an isotropic intensity that is derived assuming that the total power, $\boldsymbol{P_t}$ (in W), is distributed equally in all direction

$$G = \frac{I_p}{P_t / 4\pi R^2} \qquad [12.3]$$

_R_ is the range.

3) **Beam area (or** beam solid angle) (in sr) is defined as

$$\Omega_A = \int_{4\pi} P_n(\theta,\varphi)d\Omega \qquad [12.4]$$

The beam area is a solid angle through which all of the power radiated by the antenna would stream if $\boldsymbol{P}(\theta, \varphi)$ maintained its maximum value over Ω_A and was zero elsewhere => **Power radiated** (in W) = $\boldsymbol{P_{max}}(\theta, \varphi)\ \Omega_A$

The beam area can be approximated by the product of the half-power beamwidths (HPBW, see Fig.12.2) in two principal planes

$$\Omega_A \approx \theta_{HP}\varphi_{HP} \qquad [12.5]$$

where θ_{HP} is $\Delta\theta$ of the HPBW and φ_{HP} is the $\Delta\varphi$ of the HPBW.

4) **Effective aperture**, A_e, (in m^2) is defined as

$$\lambda^2 = A_e\Omega_A \qquad [12.6]$$

where λ is the wavelength (in m)

5) **Directivity**, D, (≥ 1, dimensionless) is defined as the ratio of the maximum power to its average value: $\boldsymbol{D} = \boldsymbol{P_{max}}(\theta, \varphi) \,/\, \boldsymbol{P_{av}}(\theta, \varphi)$

Other expressions for the **directivity**

$$D = \frac{4\pi}{\Omega_A}$$ directivity from pattern [12.7]

$$D = 4\pi \frac{A_e}{\lambda^2}$$ directivity from aperture [12.8]

- **Friis transmission formula**

Consider a transmitting antenna of effective aperture A_{et} and receiving antenna with effective aperture A_{er}. The distance between the antennas is R.

If transmitted power P_t is radiated by an isotropic source, the power received per unit area at the receiving antenna if

$$F = \frac{P_t}{4\pi R^2} \qquad [12.9]$$

and the power available to the receiver is

$$P_r = F A_{er} \qquad [12.10]$$

But the transmitting antenna has an effective aperture A_{et} and hence a directivity D (from Eq.[12.8]):

$$D = 4\pi \frac{A_{et}}{\lambda^2}$$

Thus the power available to the receiver is D times greater

$$P_r = F A_{er} D = F A_{er} \frac{4\pi A_{et}}{\lambda^2} \qquad [12.11]$$

Substituting Eq.[12.9] into Eq.[12.11] gives

$$P_r = \frac{P_t A_{er}}{4\pi R^2} \frac{4\pi A_{et}}{\lambda^2} \qquad [12.12]$$

or

$$\boxed{\frac{P_r}{P_t} = \frac{A_{er}}{R^2} \frac{A_{et}}{\lambda^2}} \qquad [12.13]$$

3. Particle backscattering and radar equation.

Recall Lecture 4 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

$$\sigma_d(\Theta) = \frac{\sigma_s}{4\pi} P(\Theta) \qquad [12.14]$$

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

Bistatic scattering cross-section, σ_{bi}, is defined as

$$\sigma_{bi} = 4\pi\sigma_d(\Theta) \qquad [12.15]$$

Backscattering cross-section, σ_b, is defined as

$$\sigma_b = 4\pi\sigma_d(\Theta = 180^0) \qquad [12.16]$$

Using Eq.[12.14], Eq.[12.16] can be re-written as

$$\sigma_b = \sigma_s P(\Theta = 180^0) \qquad [12.17]$$

The incident intensity I_i and scattered intensity I_s by a particle relates as (Lecture 4)

$$I_s(\Theta) = I_i \frac{\sigma_s}{R^2} \frac{P(\Theta)}{4\pi} \qquad [12.18]$$

where R is the distance from the particle.

For the backscattering case, we can write

$$F_{bs}(\Theta = 180^0) = F_i \frac{\sigma_s}{R^2} \frac{P(\Theta = 180^0)}{4\pi} \qquad [12.19]$$

or

$$F_{bs}(\Theta = 180^0) 4\pi R^2 = F_i \sigma_b \qquad [12.20]$$

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

$$k_b = \int_{r_1}^{r_2} \sigma_b(r) N(r) dr \qquad [12.21]$$

and thus

$$k_b = k_s P(\Theta = 180^0) \qquad [12.22]$$

where $P(\Theta)$ is the scattering phase function averaged over the size distribution.

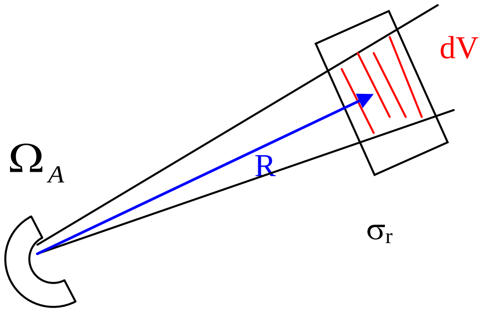
Small size parameter limit (Rayleigh limit): it can be shown from Mie theory (see S: 5.7.1) that

$$\sigma_b = \frac{\pi^5}{\lambda^4} |K|^2 D^6 \qquad [12.23]$$

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

$$P_{\text{int}}(by\ object) = \frac{P_t}{R^2}\frac{A_{et}}{\lambda^2}\sigma_r \qquad [12.24]$$

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.[12.8]). And using the Friis transmission formula, we can find the power received by the antenna

$$P_r = \frac{P_{\text{int}}(by\ object)A_{er}}{R^2\lambda^2}\frac{\lambda^2}{4\pi} \qquad [12.25]$$

Substituting Eq.[12.24] into Eq.[12.25], we obtain the **radar equation**

$$\boxed{\frac{P_r}{P_t} = \frac{A^2}{4\pi R^4}\frac{\sigma_r}{\lambda^2}} \qquad [12.26]$$

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

$$\frac{P_r}{P_t} = \frac{A^2}{4\pi R^4}\frac{k_b dV}{\lambda^2} \qquad [12.27]$$

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

$$dV \approx R^2\theta_{HP}\varphi_{HP}h/2 \qquad [12.28]$$

and using Eq.[12.21] for k_b, we have

$$\frac{P_r}{P_t} = \frac{A^2}{4\pi R^2\lambda^2}\frac{h\theta_{HP}\varphi_{HP}}{2}\int \sigma_b(r)N(r)dr \qquad [12.29]$$

Assuming that particle are in the **Rayleigh limit** and using Eq.[12.23], we have

$$\frac{P_r}{P_t} = \frac{\pi^4 A^2}{4\lambda^6} \frac{h\theta_{HP}\varphi_{HP}}{R^2} |K|^2 \int D^6 N(D) dD \qquad [12.30]$$

the above equation can be re-written as

$$\boxed{P_r = C \frac{|K|^2}{R^2} Z} \qquad [12.31]$$

where factor C depends on the antenna characteristics; and

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

NOTE: Eq.[12.31] is often called the radar equation.

The backscattering coefficient and radar reflectivity relates as

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

[12.32]

- 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.[12.31] 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):

$$\overline{P}_r = C \frac{|K|^2}{R^2} Z \exp(-2\int_o^R k_e(r')dr') \qquad [12.33]$$

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

4. 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)

$$Z = A\, Rr^b \qquad [12.34]$$

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

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

Stratiform rain: $Z = 200\ Rr^{1.6}$ [12.35]

Orographic rain: $Z = 31\ Rr^{1.71}$ [12.36]

Snow: $Z = 2000\ Rr^{2}$ [12.37]

The power returned to a radar (see Eq.[12.31]) can be normalized using Eq.[12.2] :

$$P_r(in\ \ dBZ) = 10\log\frac{P_r}{P_{ref}} \qquad [12.38]$$

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^6m^{-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.

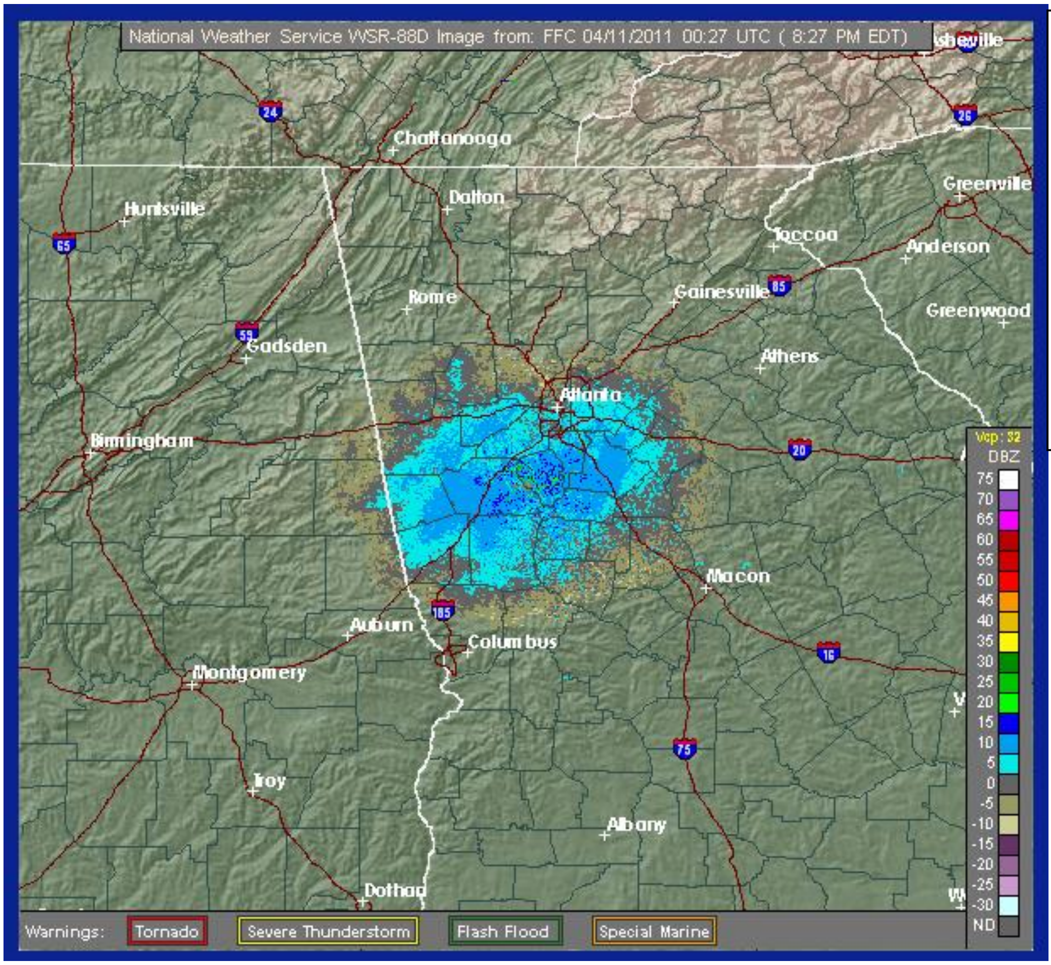
NOTE: Retrievals of precipitation from radars depend on an assumed Z-R relationship.

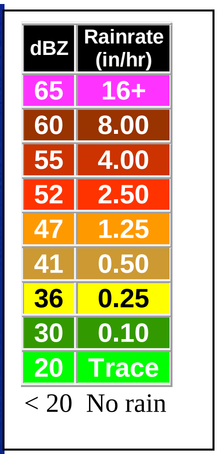
- ***National Weather Service radars (http://radar.weather.gov/)***

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.





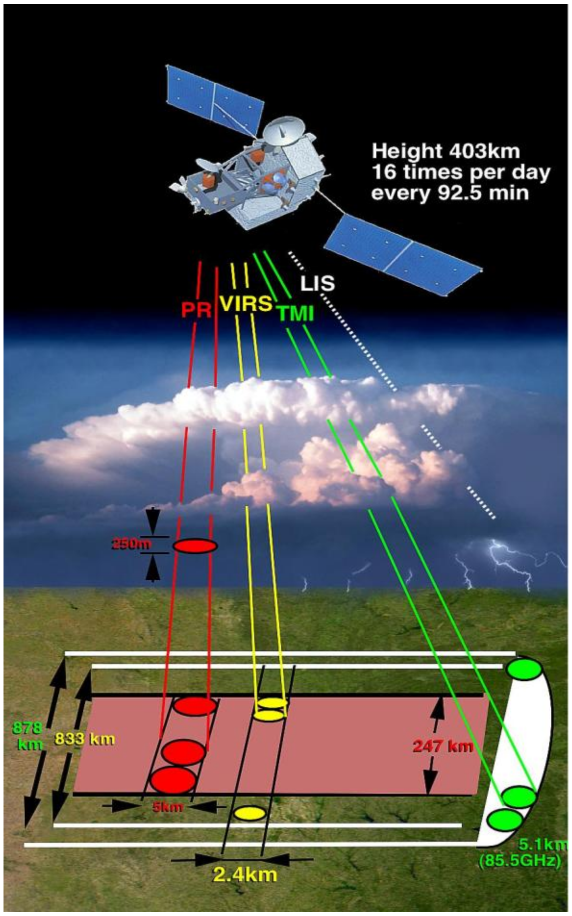
dBZ	Rainrate (in/hr)
65	16+
60	8.00
55	4.00
52	2.50
47	1.25
41	0.50
36	0.25
30	0.10
20	Trace
< 20	No rain

- **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.

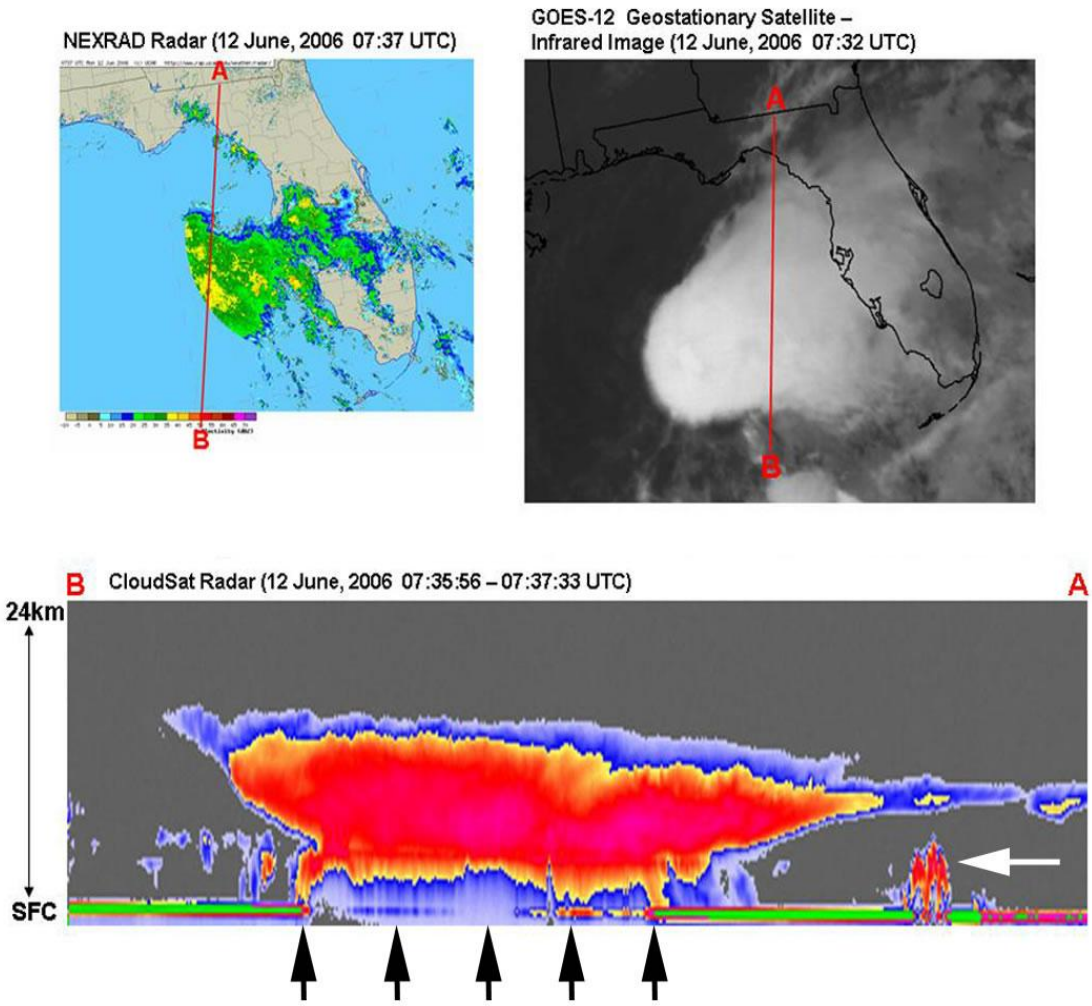


Figure 12.3 Tropical storm Alberto over the Gulf of Mexico. The collection of images reveals how CloudSat "sees" the storm differently from other weather satellites and sensors. The NEXRAD storm detection radar is limited by distance, preventing it from mapping all of the storm's precipitation. The infrared 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.