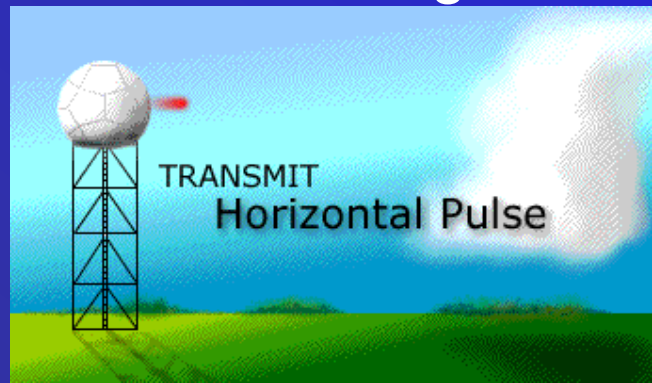


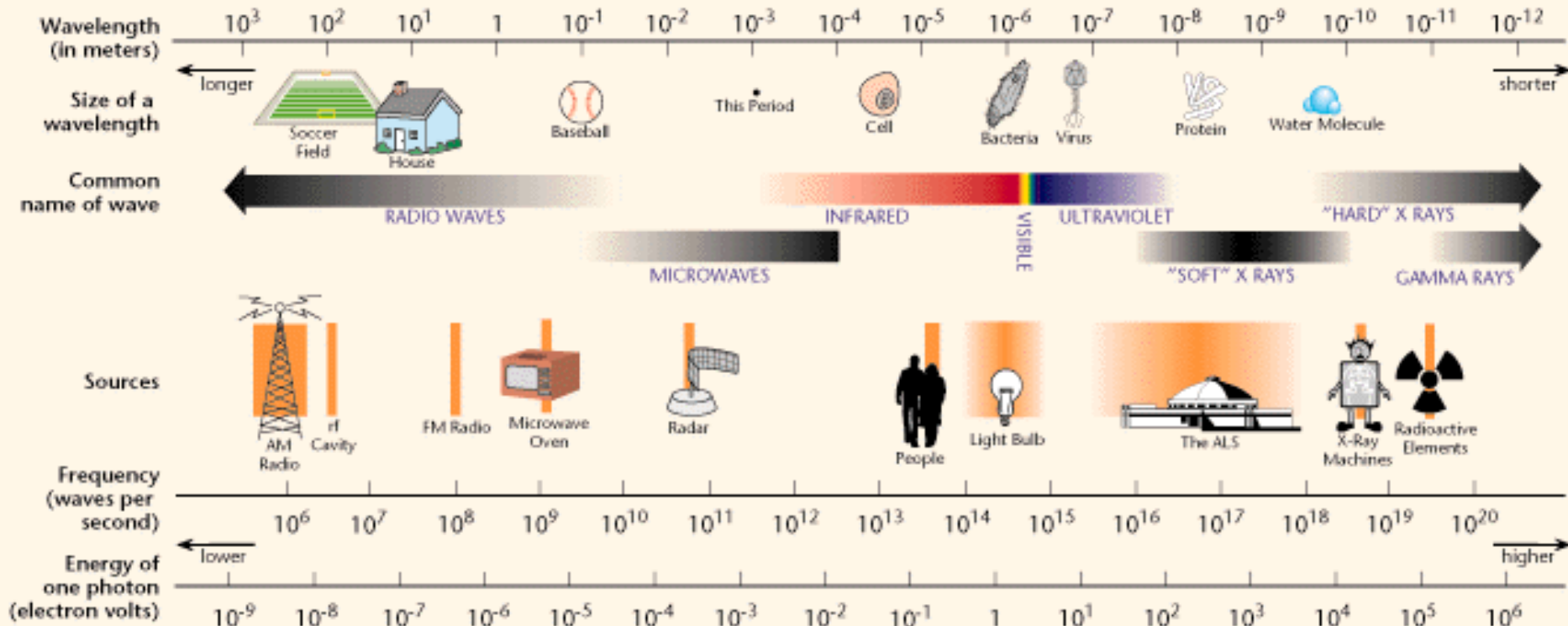
Radar Meteorology

Purpose:

1. Explain the basic principles of radar. What is dbz? This is related to the power backscattered by hydrometeors.
2. Explain how radar can be used to measure the fall speed of hydrometeors and the wind direction.
3. Discuss the NEXRAD radar used by the National Weather Service.
4. Become aware of the advantages and disadvantages of radar.



THE ELECTROMAGNETIC SPECTRUM



The frequency of the *em* wave used depends on the application. Some frequencies travel through clouds with virtually no attenuation.

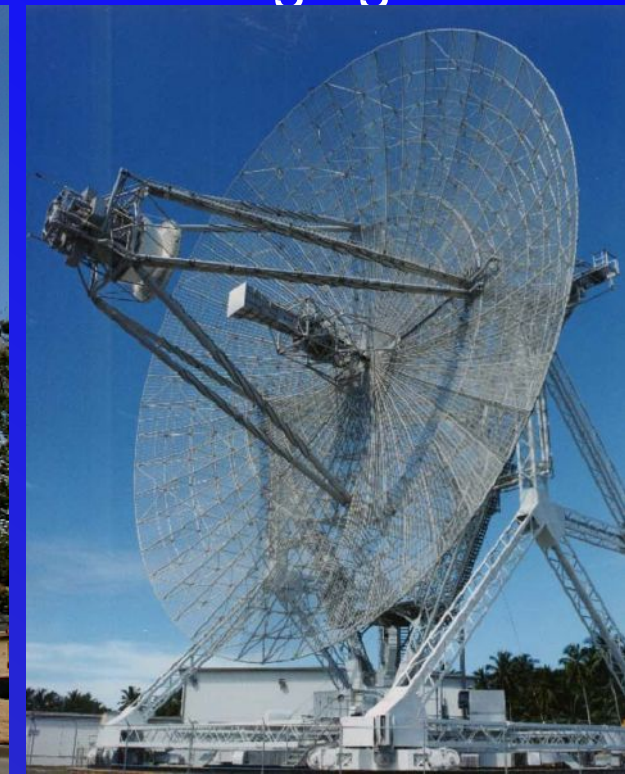
ALL *em* waves move at the speed of light

Definitions

RADAR is an acronym. **RA**dio **D**etection **A**nd **R**anging.

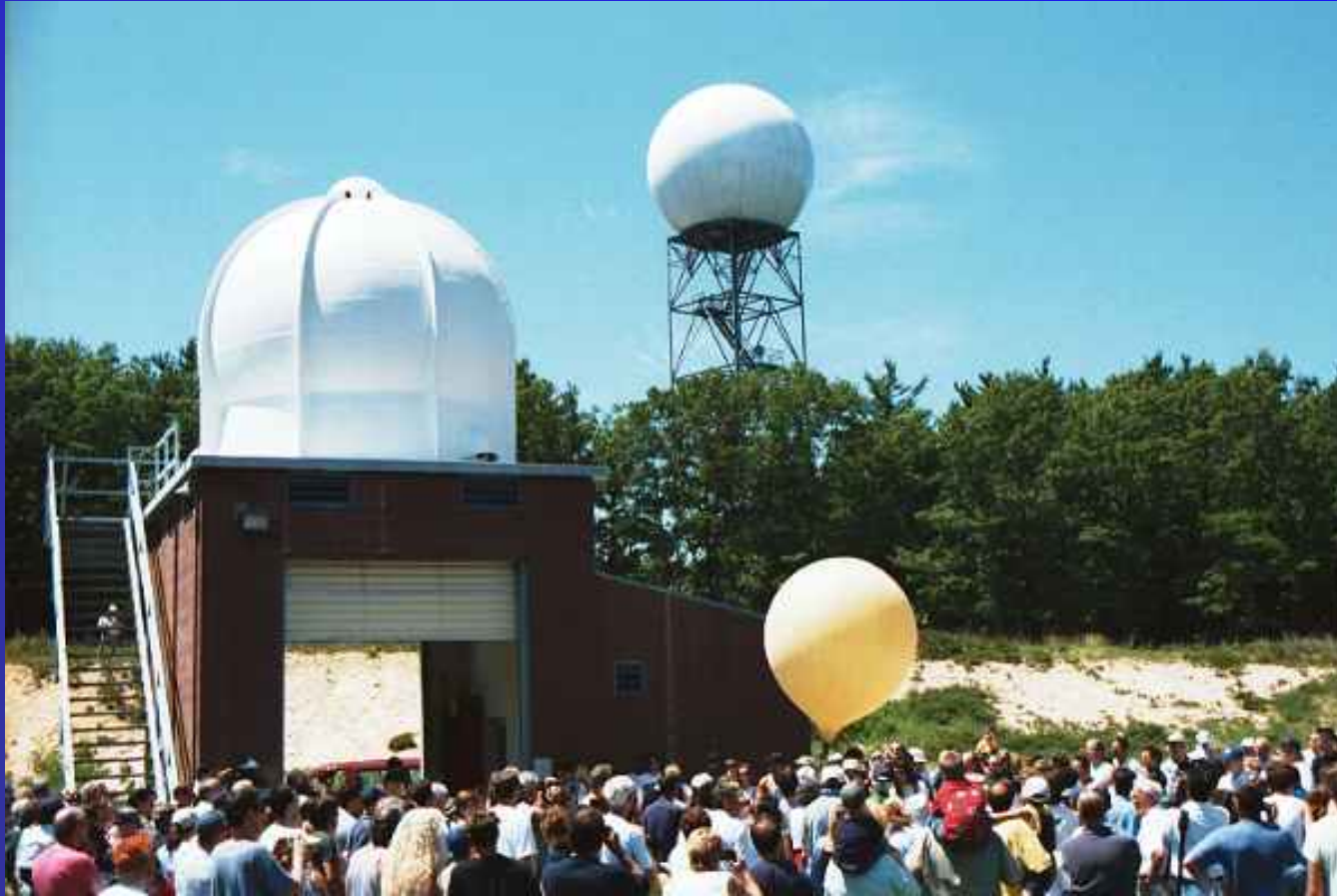


NEXRAD Weather Radar



Advanced Research
Project Agency (ARPA)
Long-range Tracking and
Identification Radar
(ALTAIR). Ballistic Missiles
and Space Surveillance
(military).

NEXRAD RADAR



NEXRAD (background) and weather balloon launch facility.

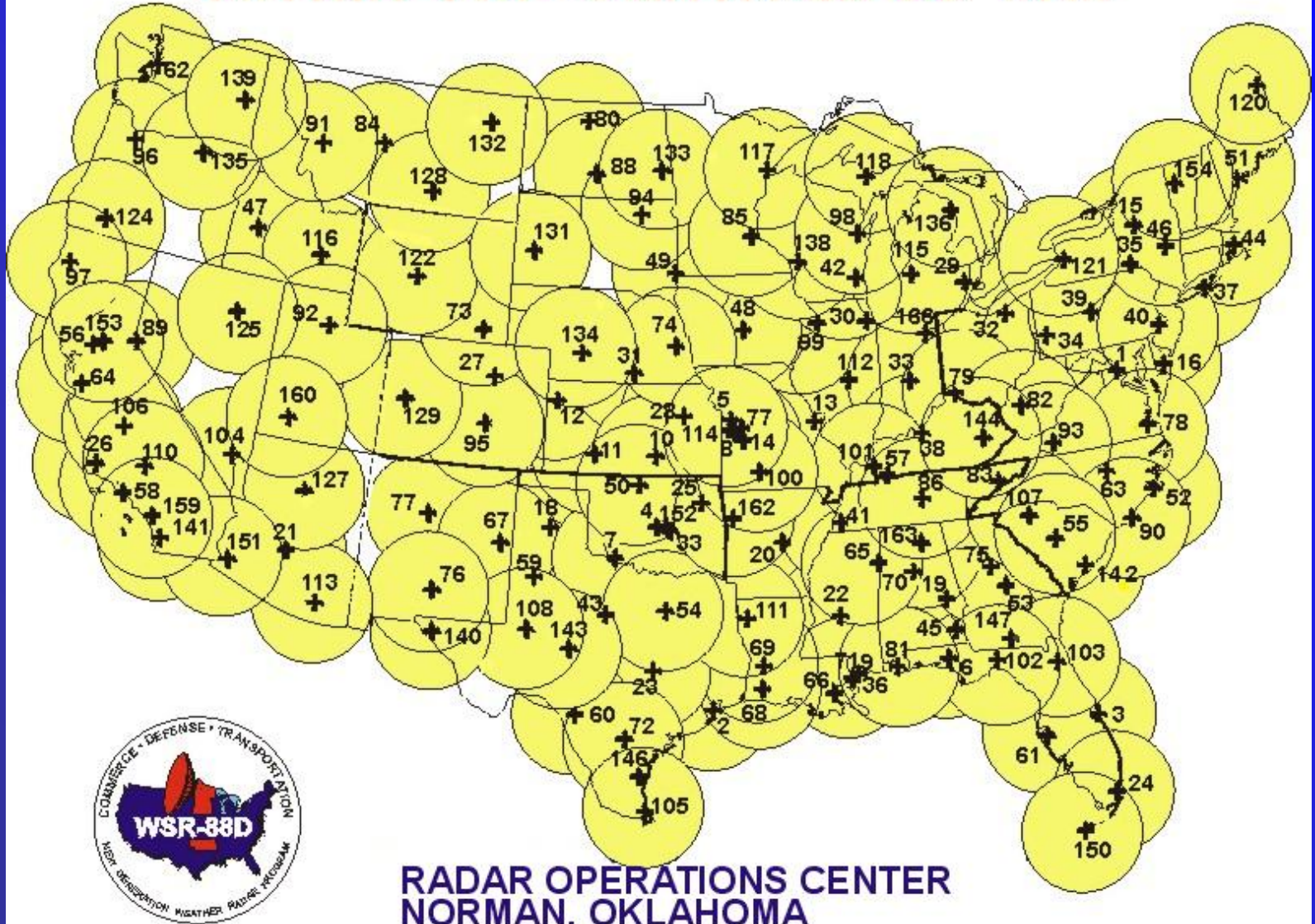
NEXRAD RADAR

- Named WSR-88D
Weather surveillance radar, 1988,
doppler
- S-band radar
- Radiation wavelength is $\lambda = 10.7$ cm
- Power is 750,000 kW
 - Can be damaged by winds and lightning strikes



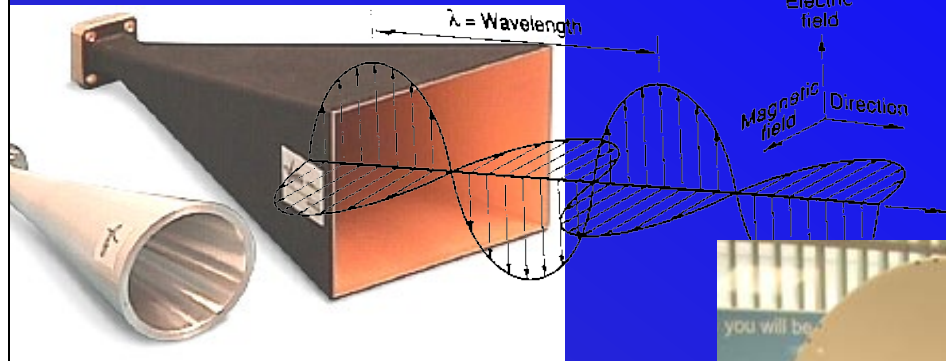
NEX RAD SITES IN THE U.S.

COMPLETED WSR-88D INSTALLATIONS WITHIN THE CONTIGUOUS U.S.



Antennas

- **Antenna** is a transition passive device between the air and a transmission line that is used to **transmit or receive electromagnetic waves.**



Antenna Beamwidth



$$\theta = \frac{\lambda}{D} \text{ radians}$$

D is the antenna diameter

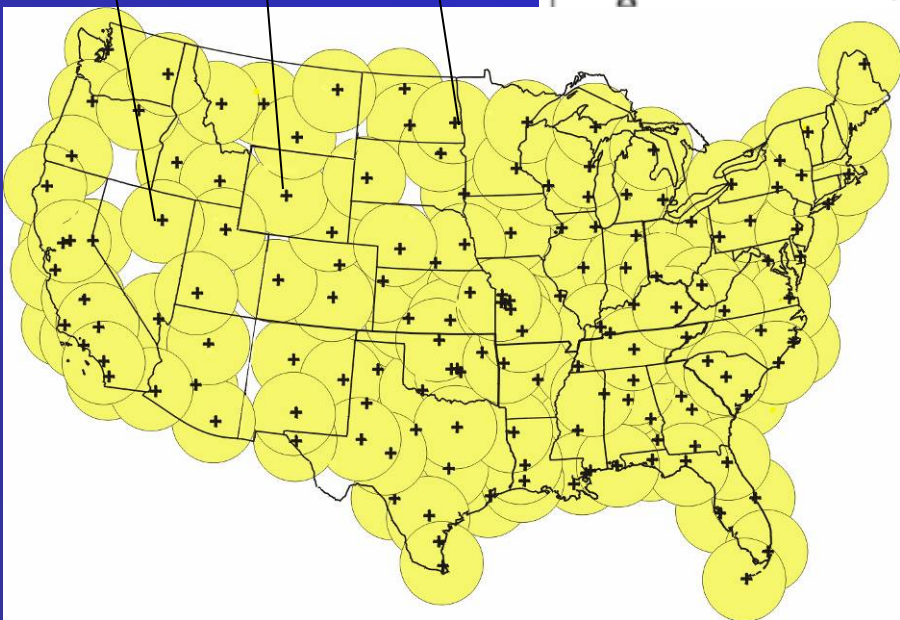
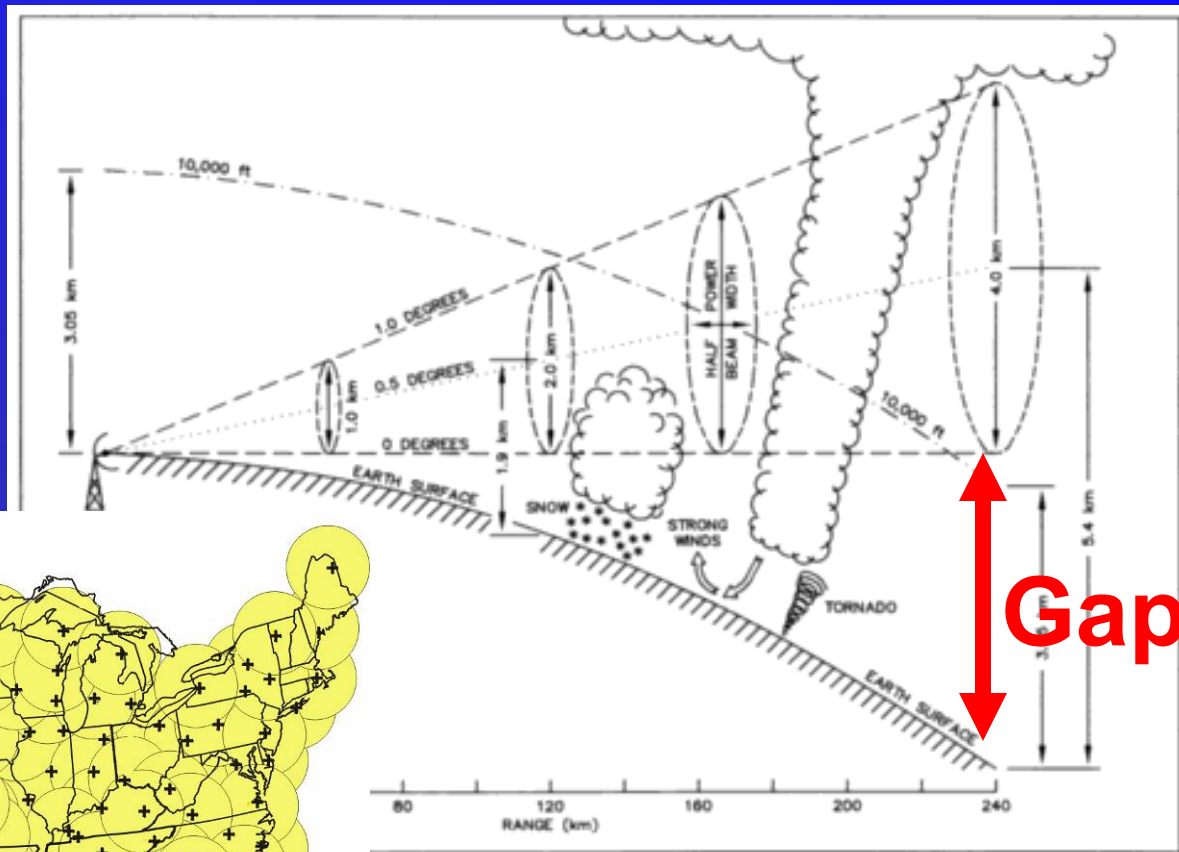
λ is the wavelength of signal in air

Tradeoff:

Small wavelengths (high frequencies)
= small antennas

But small wavelengths attenuate more

NEXRAD Location Issues



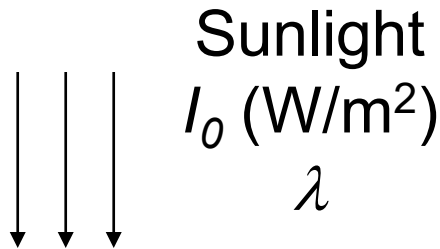
Effect of range and earth curvature (with standard atmospheric refraction) on NEXRAD cross-beam radar coverage of weather phenomena. Courtesy of SRI International.

Radar: The Quickest Path to dbZ, The Quantity Commonly Reported By Weather Radar

1. Absorption, scattering and extinction cross sections.
2. Backscattering cross section.
3. Cross section in the Rayleigh limit (particle diameter is much smaller than the wavelength of the radiation.)
4. Radar cross section for a particle in the Rayleigh limit.
5. Radar cross section for N particles in the Rayleigh limit.

Note: Key results are circled by a red box like this. A possible homework assignment is also given by a red box.

Definitions: Optical Coefficients for a Flat Surface



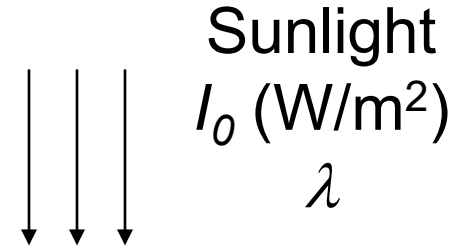
Black Surface
Area A (m²)

$a = \text{albedo} = 0$

Absorptance = $(1-a) = 1$

Flat Surface

$$\sqrt{A} \gg \lambda$$



Arbitrary Surface
Area A (m²)

$a = \text{albedo}$

Absorptance = $(1-a)$

Power Scattered,
Power Absorbed

$$P_{sca} = 0$$

$$P_{abs} = I_0 A$$

$$\sigma_{abs} = A$$

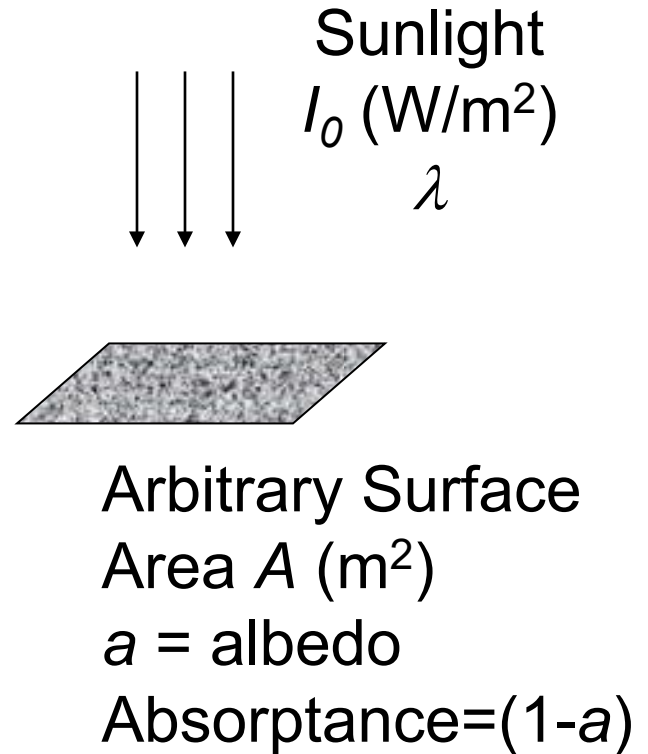
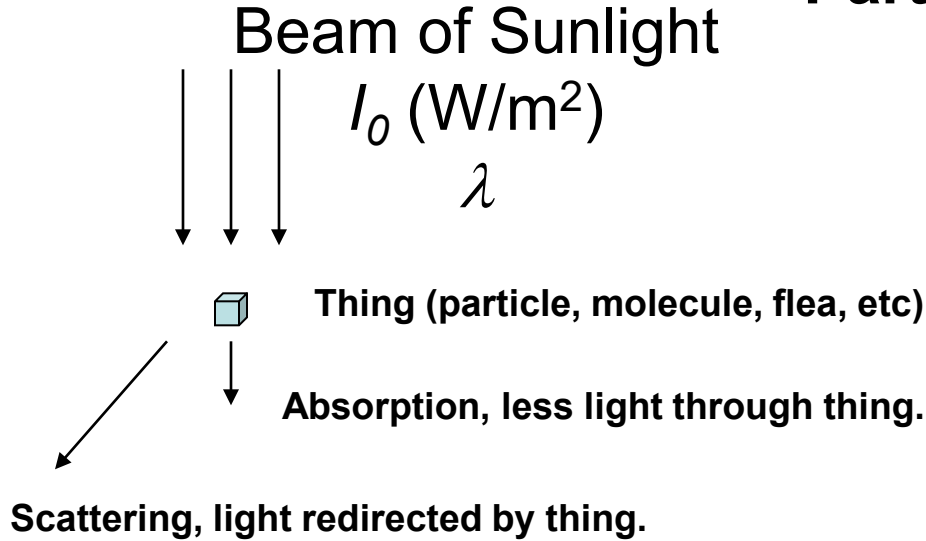
Power Scattered,
Power Absorbed

$$P_{sca} = I_0 A a$$

$$P_{abs} = I_0 A (1-a)$$

$$\sigma_{abs} = (1-a) A$$

Definitions: Optical Coefficients for a Surface and a Particle



Power Removed From Beam

$$I_0 \sigma_{ext} = P_{ext}$$

$$I_0 \sigma_{abs} = P_{abs}$$

$$I_0 \sigma_{sca} = P_{sca}$$

$$\bar{\omega} = \frac{\sigma_{sca}}{\sigma_{ext}} = \text{Single Scatter Albedo}$$

$$P_{sca} = \bar{\omega} \sigma_{ext} I_0$$

$$P_{abs} = (1 - \bar{\omega}) \sigma_{ext} I_0 \quad \sigma_{abs} = (1 - \bar{\omega}) \sigma_{ext}$$

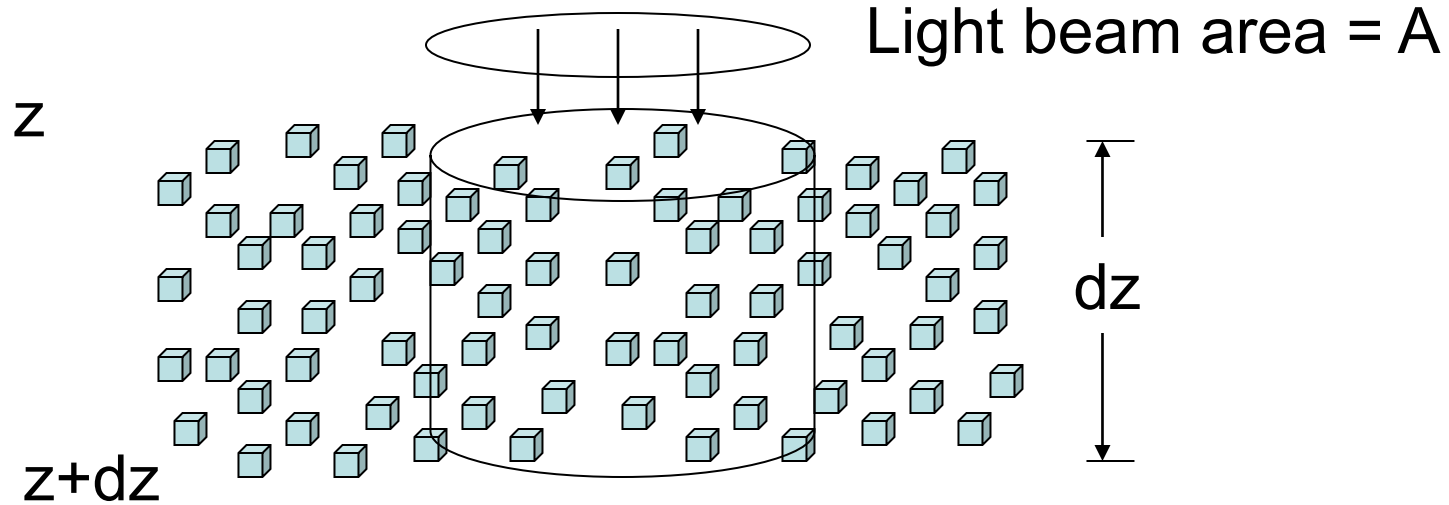
Power Scattered, Power Absorbed

$$P_{sca} = I_0 A a$$

$$P_{abs} = I_0 A (1-a)$$

$$\sigma_{abs} = (1-a) A$$

Optics of N identical (particles / volume)



$$\text{Power removed in } dz: = I(z) N A dz \sigma_{ext}$$

Bouger-Beer
“law”
(direct beam only!)

$$(I(z) - I(z + dz)) A = I(z) N A dz \sigma_{ext}$$

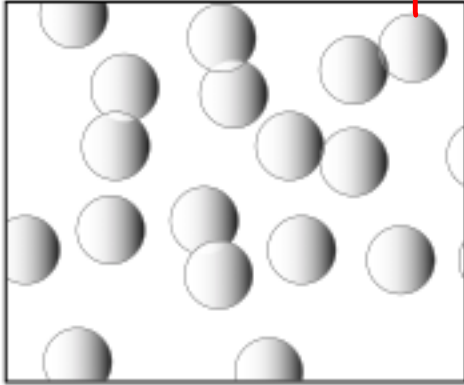
$$-dI = I(z) N \sigma_{ext} dz$$

$$\int_{I_0}^{I(z)} \frac{dI}{I} = - \int_0^z N \sigma_{ext} dz', \quad \ln\left(\frac{I(z)}{I_0}\right) = -N \sigma_{ext} z$$

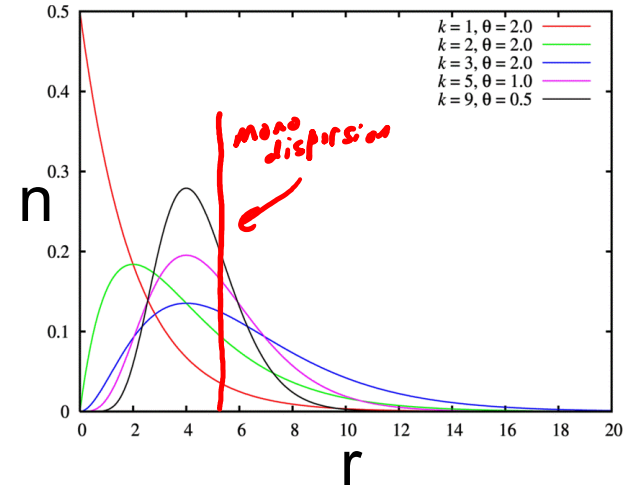
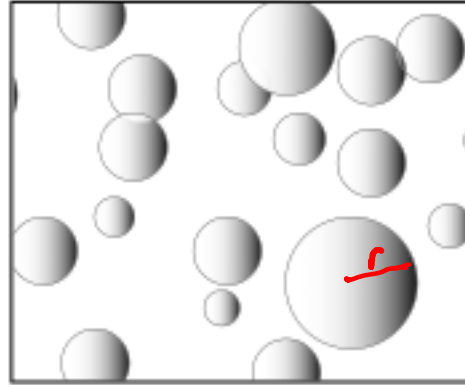
$$I(z) = I_0 \exp(-N \sigma_{ext} z) = I_0 \exp(-\beta_{ext} z)$$

Monodispersions and Polydispersions

All the same size
(Monodisperse) raindrops



Different size raindrops
(Polydisperse)



N particles / volume.
All of radius r .

$$\beta_e = N\sigma_{ext} = NQ_{ext}\pi r^2$$

total raindrops
Volume $N = \int_0^{\infty} n(r) dr$

$$\beta_e = \int_0^{\infty} n(r) \sigma_{ext}(r) dr$$

$$\beta_e = \int_0^{\infty} n(r) Q_{ext}(r) \pi r^2 dr$$

$$n(r) = n_0 r^{k-1} \frac{\exp(-r/\theta)}{\theta^k \Gamma(k)} \text{ for } k, \theta > 0.$$

$$\Gamma(k) = (k-1)! \text{ if } k \text{ is a positive integer.}$$

Radar Theory Part 1

$$d = \frac{c\Delta t}{2}$$

$P_r(d) \propto \frac{\eta}{d^2}$ Power backscattered by hydrometeors a distance d from the radar.

η = backscatter cross section per unit volume of air.

$\eta = \frac{1}{V} \sum_i \sigma_{b,i}$. $\sigma_{b,i}$ is the backscattering cross section (meters) of the i th particle in the volume V .

$\sigma_b \equiv \sigma_s p(\Theta = \pi)$. This is the backscatter cross section in terms of the total scattering cross section and phase function.

$$\eta = \int_0^{\infty} \sigma_b(D) n(D) dD, \text{ or } \eta = \int_0^{\infty} Q_b(D) \frac{\pi D^2}{4} n(D) dD, \text{ where } \sigma_b(D) = Q_b(D) \frac{\pi D^2}{4} .$$

$Q_b(D)$ is the back scattering efficiency factor (dimensionless).

In the Rayleigh regime where $D \ll$ radar wavelength λ ,

$$Q_b(D) = \frac{64\pi^4 D^4}{\lambda^4} \left| \frac{m^2 - 1}{m^2 + 1} \right|^2 \text{ where } m = n_r + i n_i \text{ is the complex refractive index of ice or water, related to the speed of light and the absorption in the water or ice.}$$

Then

Radar Theory Part 2: Key Results!!!

$$\eta = \frac{\pi^5}{\lambda^4} \left| \frac{m^2 - 1}{m^2 + 1} \right|^2 \int_0^\infty n(D) D^6 dD.$$

The measured radar powered is modeled as ...

$$P_r^{measured} \propto \left| \frac{m^2 - 1}{m^2 + 1} \right|^2 \frac{Z}{d^2}. \text{ Now solve for } Z, \text{ using } m \text{ for water, and } d, \text{ the distance to the hydrometeor.}$$

$$Z = \int_0^\infty n(D) D^6 dD. \text{ Note that } Z \text{ is the reflectivity factor by definition, and } Z \propto P_r^{measured}.$$

FINALLY!!!

$$Z_{dbZ} = 10 \log_{10}(Z)$$

This is what is reported on radar graphs!!!

NOTICE THAT $Z_{dbZ} = 10 \log_{10}(P_r^{measured}) + 20 \log_{10}(\Delta t) + \text{constant}$.

NOTE: The factor $\left| \frac{m^2 - 1}{m^2 + 1} \right|^2$ for ice is 0.2 of the value for water.

For the same size particles then, $Z_{dbZ}^{ice} = 0.2 Z_{dbZ}^{water}$.

Hail often has a liquid water layer on it, so being both large and water, it has a very large Z_{dbZ} .

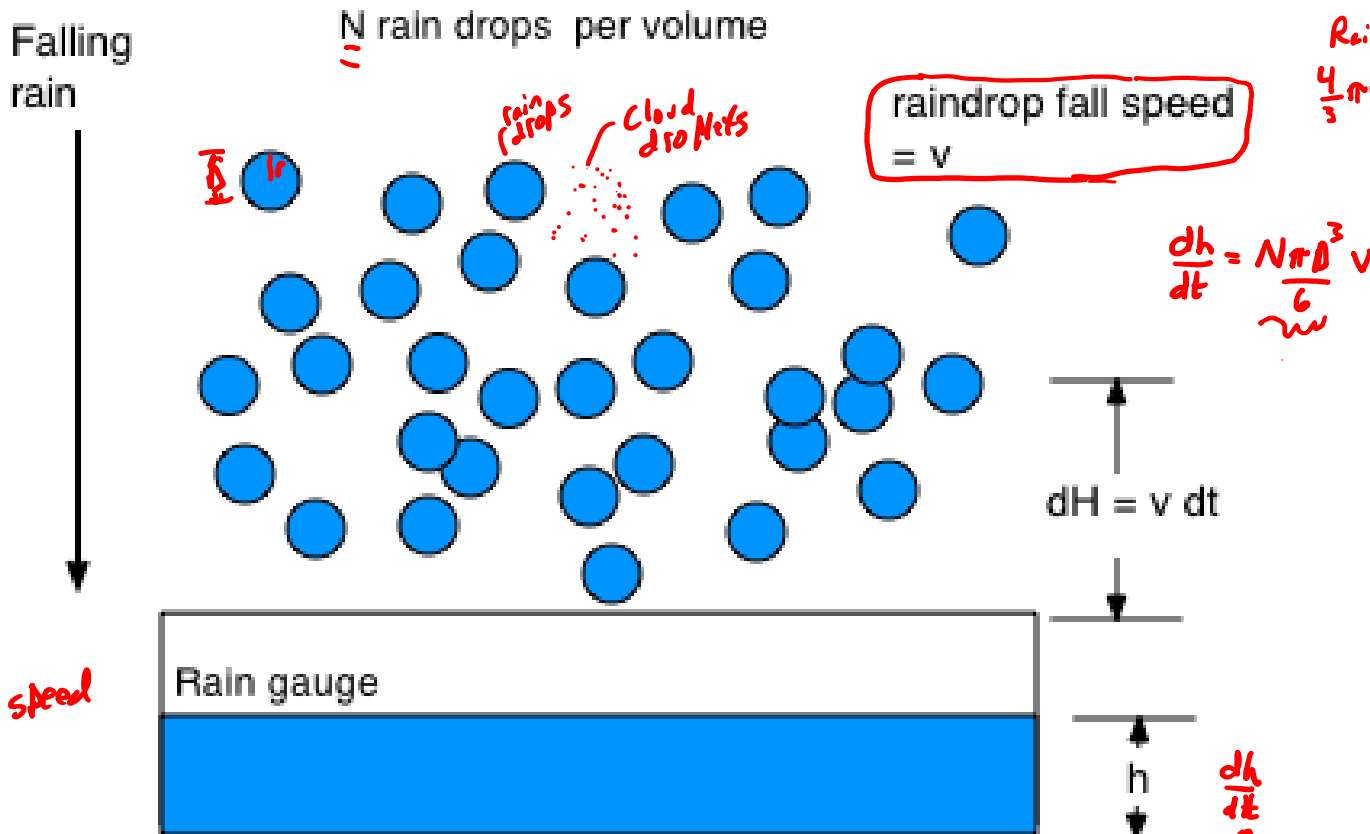
Radar Theory Part 2: Typical Values of Z_{dbZ}

Clear air mode of NEXRAD: -28 dbZ to 28 dbZ.

Precipitation mode of NEXRAD: 5 dbZ to 75 dbZ.

Light rain: 20 dbZ.

Rain Fall Rate for Monodispersion



Raindrop Volume
 $\frac{4}{3}\pi r^3 = \frac{\pi D^3}{6}$
 $r = D/2$

Rainfall rate

$\frac{dh}{dt} = \frac{N\pi D^3}{6} v$
 ↑ fall speed

$V = V(D)$
 fall speed depends on diameter.

$\frac{dh}{dt} \sim D^3$
 $\propto D^4$

Scattering of radar by raindrops
 $N D^6$

h = height of rain water in rain gauge. Rainfall rate = dh/dt
 In time dt , drops from a height $dH = v dt$ will land in the rain gauge.
 Drops have diameter D . A = area of the rain gauge opening.
 Then total water volume added in time dt to the rain gauge is
 $N A dH \pi D^3/6 = \# \text{ Rain Drops going into rain gauge} \cdot \text{drop volume}$
 $= N A v dt \pi D^3/6 = A dh$

Then rain rate is $dh/dt = N v \pi D^3/6$.

Raindrop Volume
 $\frac{4}{3}\pi r^3 = \frac{\pi D^3}{6}$

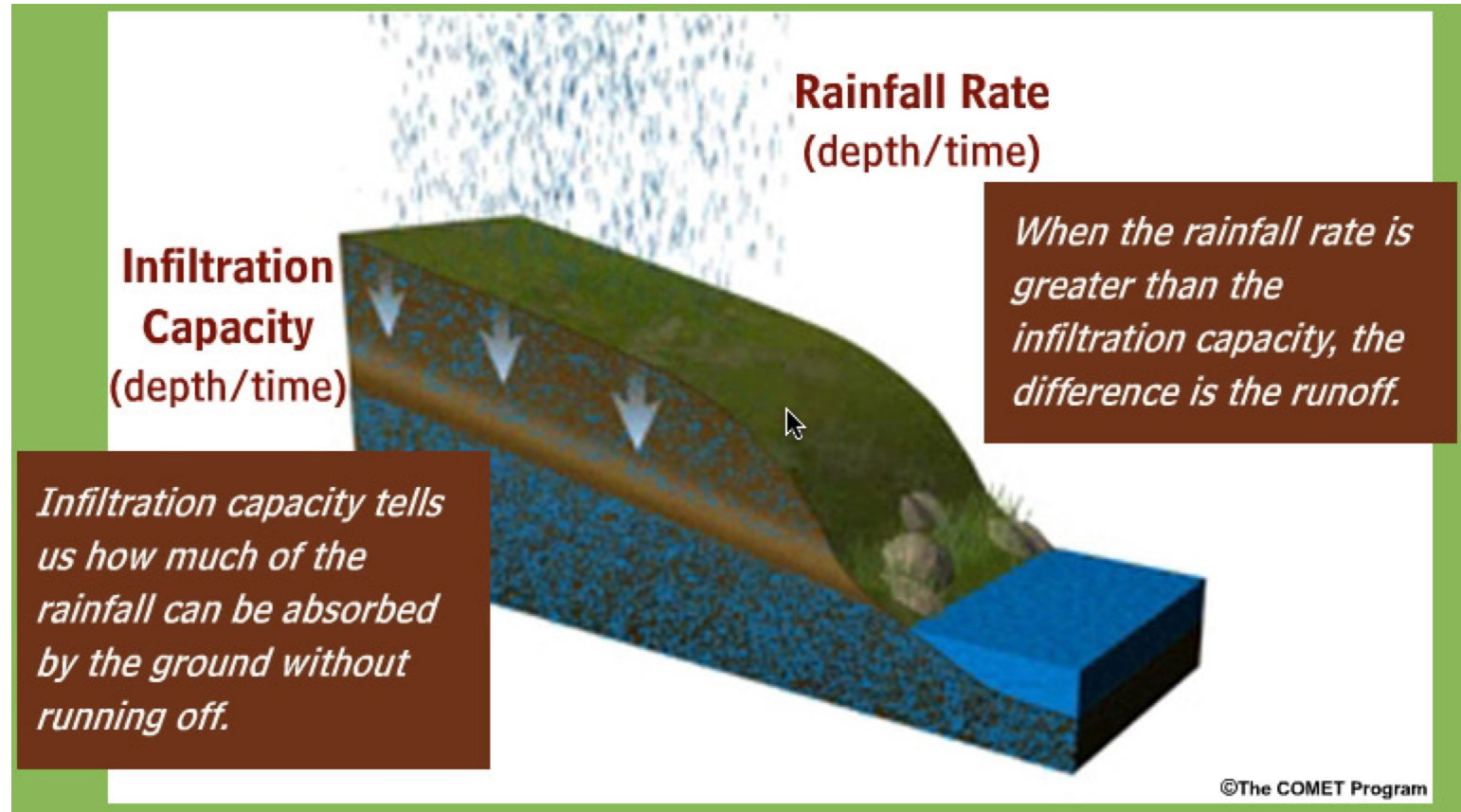
$\frac{dh}{dt} = \frac{N\pi D^3}{6} v$

$dH = v dt$

$\frac{dh}{dt}$
 ↑
 Rainfall rate

$\frac{dh}{dt} = \text{function of Radar Back Scatter}$
 Rainfall rate

Radar Theory Part 3: Rainfall Rate Estimate From Radar

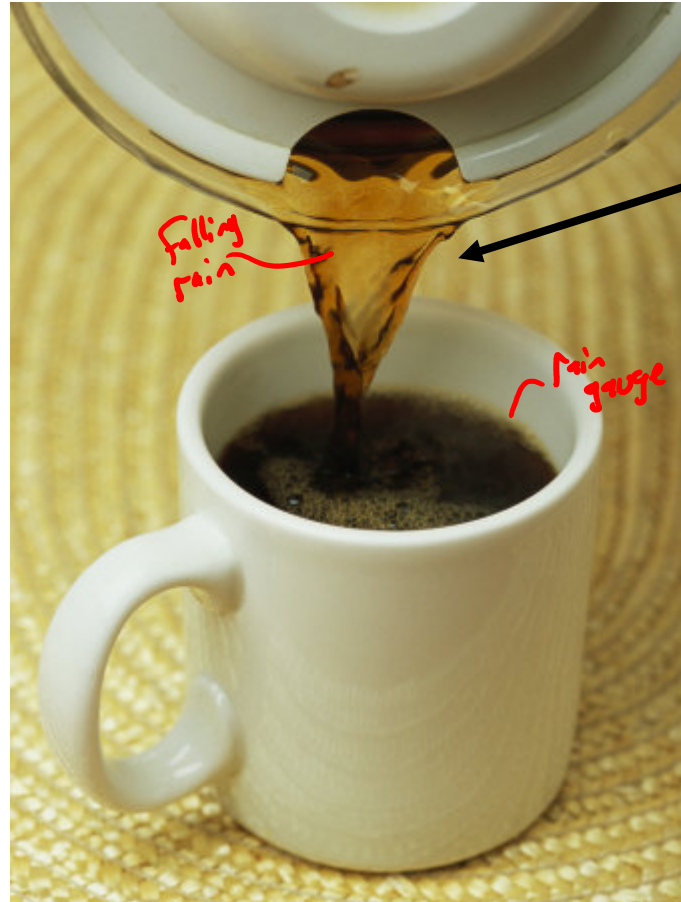


Definition of rainfall rate and what happens after rain hits the surface. Rainfall rate depends on the mass of water droplets and their fall speed.

Rainfall Rate:

$$R = \int_0^{\infty} n(D) v(D) \frac{\pi}{6} D^3 dD$$

Rainfall Rate Analogy



Falling rain: Coffee is being poured at some rate.

Height of coffee = H

Rainfall Rate = Height of Coffee / time elapsed pouring it.

$$\text{Rainfall Rate} = \frac{dH}{dt}$$

Rain Drop Fall Speed

Falling raindrops hit 5 to 20 mph speeds



What is the speed of a falling raindrop? [Ed, Las Vegas Nevada](#)

Umbrella with raindrops. Photo courtesy of Fir0002 and Wikipedia

It depends on the size and weight of the raindrop how fast it falls: the heavier, the faster. At sea level, a large raindrop about 5 millimeters across (house-fly size) falls at the rate of 9 meters per second (20 miles per hour). Drizzle drops (less than 0.5 mm across, i.e., salt-grain size) fall at 2 meters per second (4.5 mph).

A raindrop starts falling and then picks up speed because of gravity. Simultaneously, the drag of the surrounding air slows the drop's fall. The two forces balance when the air resistance just equals the weight of the raindrop. Then the drop reaches its terminal velocity and falls at that speed until it hits the ground. This simple view neglects updrafts, downdrafts, and other complications.

The air resistance depends on the shape of the raindrop, the cross-sectional area presented to the airflow, and the raindrop's speed. Most drops are fairly round — the small ones spherical, larger ones flattened on the bottom by the airflow. At high speeds, the air resistance increases with the square of the velocity.

By the way, a falling human hurtles to the ground at a terminal velocity of about 125 miles per hour.

Rain Drop Fall Speed: A balance of Forces, Drag and Gravity

'Hydrometeors' include all types of precipitation (rain, snow, hail, graupel, sleet ❄️). Droplets found in clouds or fog, as well as ice crystals in high clouds (like cirrus), are generally not included in the term, because their fallspeed is negligible. That is because their weight is too small relative to their surface area (1).

When hydrometeors fall, an equilibrium quickly establishes between two forces, gravity (downward) and aerodynamic drag (upward). The resulting velocity is called the *terminal velocity*, or simply fallspeed, V_t . The gravitational force is proportional to the drop mass m , hence the 3rd power of its diameter D , while the frictional force is proportional to the cross-sectional area A of the drop, hence the 2nd power of D . The force balance is as follows:

$$m g = C_d r V_t^2 A$$

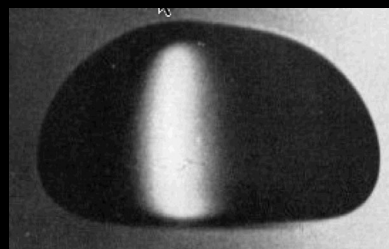
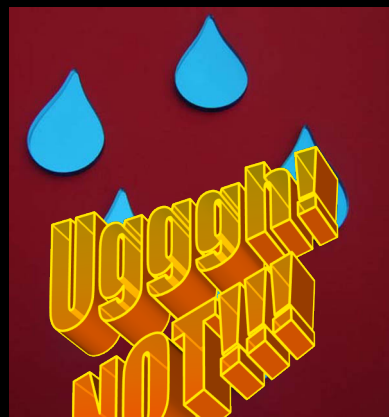
where g is the gravitational acceleration, r the air density, and C_d the *drag coefficient*. The problem is that C_d is not constant; rather, it is a function of both diameter D , fallspeed V_t , and the *kinematic viscosity* of the air. The latter in turn is variable; it depends on the eddy characteristics of the air flowing around the falling drop. Hence viscosity cannot be expressed in a simple formula. The result is that the best determination of the fallspeed is an empirical one. Foote and Dutoit (1969) proposed this relationship for raindrop fallspeed V_t (in m/s) as a function of D (in mm), for $0.1 \text{ mm} < D < 6 \text{ mm}$ (2):

$$V_t = [-0.193 + 4.96 D - 0.904 D^2 + 0.0566 D^3] \exp(z/20)$$

The factor $\exp(z/20)$, where z is height in km, accounts for the decrease in density (and hence drag) with height in the atmosphere. Drops larger than 3 mm have a good chance of breaking up into smaller drops. The break-up probability rapidly increases at diameters around 5 mm. Some typical fallspeeds for liquid drops are shown in **Table 1**.



Fall Speed Is a Function of Size: Note the Shape in Terminal Flow



LONG-DISTANCE DROPS

The water drops on the opposite page had fallen three stories, the drop above had fallen eight stories, down an elevator shaft when caught by the high-speed camera. In falling these distances the drops pulsating as they fall, do not always fall straight but slip sideways after flattening out. After thus slipping their shapes apparently change, and they start again dropping in a straight line, again flatten out.

Notable in these pictures are the irregular shapes of the drops, the absence of the oft-mentioned teardrop shape

<u>diameter: mm</u>	<u>fallspeed: m/s</u>
0.001	0.0003
0.01	0.03
0.1	0.27
0.2 (cloud)	0.72
0.3 (cloud)	1.2
0.8 (drizzle)	3.3
0.9 (drizzle)	3.7
1.8 (rain)	6.1
2.2 (rain)	6.9
3.2 (drop breaks up)	8.3
5.8 (ditto)	9.2

Radar Theory Part 3: Rainfall Rate Estimate From Radar

Assume the Marshall-Palmer Size Distribution for Rain Drops:

$$n(D) = N_0 \exp(-\Lambda D).$$

Rain rate: depth of rain accumulated at the surface per unit time (typically mm/hr).

Assume a rain drop fall speed distribution.

Then the Z-R relationship for the Marshall-Palmer distribution relating rainfall rate and radar Z is:

$$Z \text{ [units } mm^6 m^{-3}] = 200R^{1.6} \text{ , [units for } R \text{ are } mm hr^{-1}] .$$

HOMWORK :

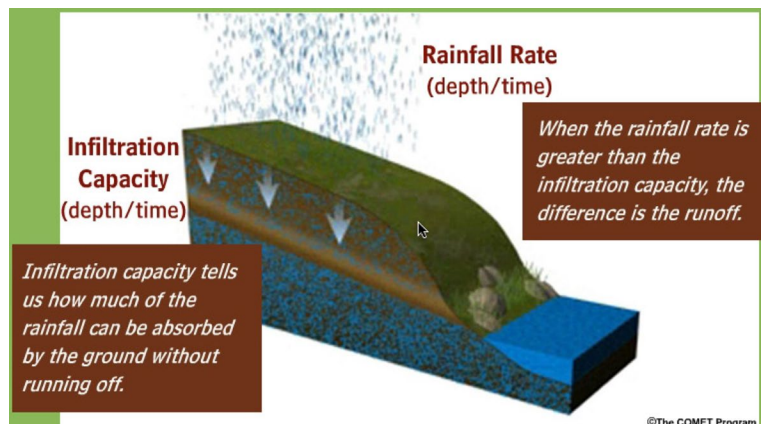
Use the Marshall Palmer Z-R relationship to calculate rain rates R for radar reflectivities of a) 10 dbZ, b) 30 dbZ, and c) 50 dbZ.

Be sure to convert reflectivities back to linear form.

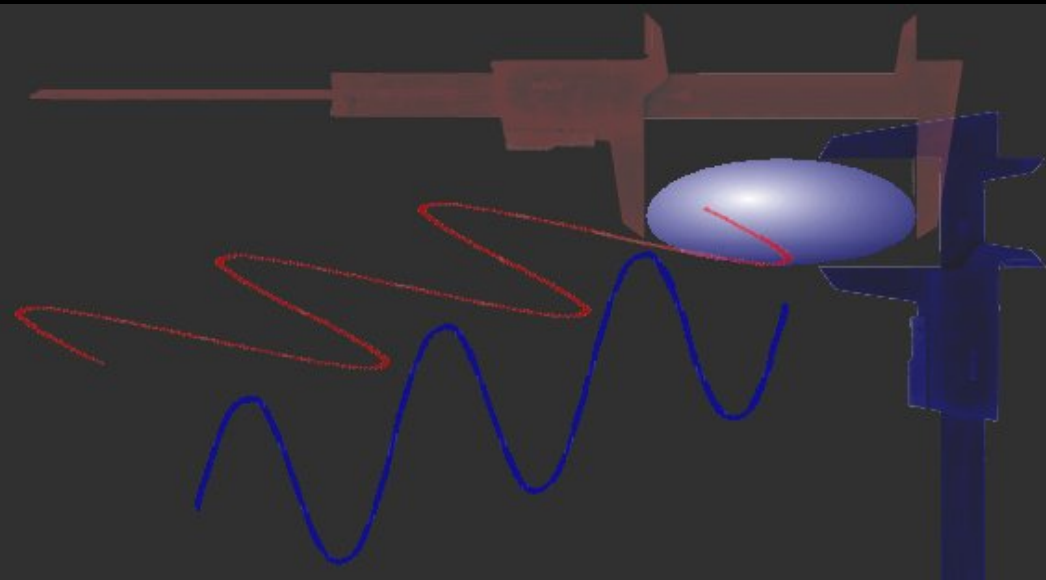
Where would you expect to routinely find rain rates for each?

This is one relationship used to get rainfall rate (depth / time) from radar.

Problem: People have developed many such relationships! Which is correct, if any?????



Polarization Diverse Radar: Update of the WSR88D.



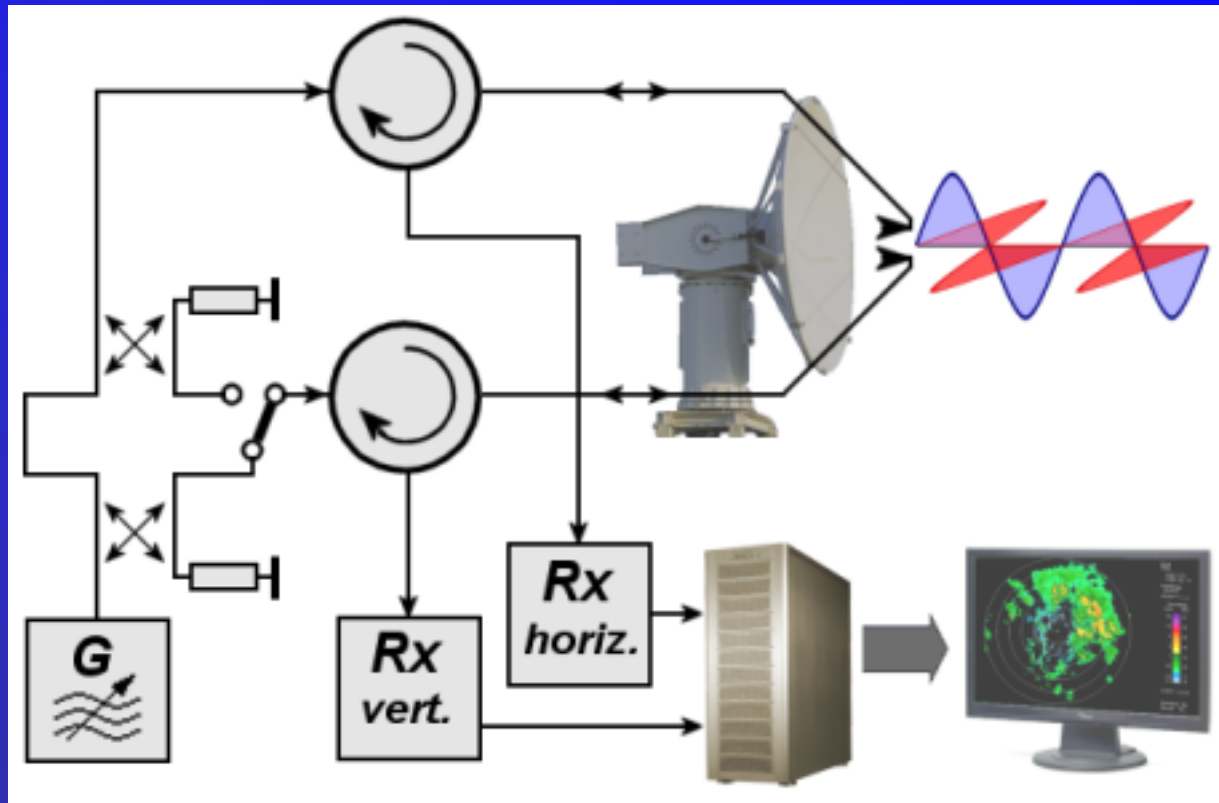
$$Z_{DR} = \frac{Z_{\text{horizontal polarization}}}{Z_{\text{vertical polarization}}}$$

Raindrops : $Z_{DR} > 1$

Hailstones : $Z_{DR} \approx 1$

- Radar sends out horizontally and vertically polarized pulses.
- Hydrometeors like raindrops are flattened. The horizontal cross sections are larger than the vertical.
- Therefore for large raindrops the horizontal polarization backscatter amount is larger than the vertical amount.
- Hail stones are more symmetrical and have less polarization diversity.

What Next for NEXRAD? WSRP-2010D

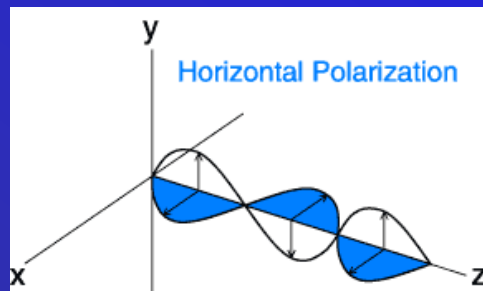


Polarimetric radar

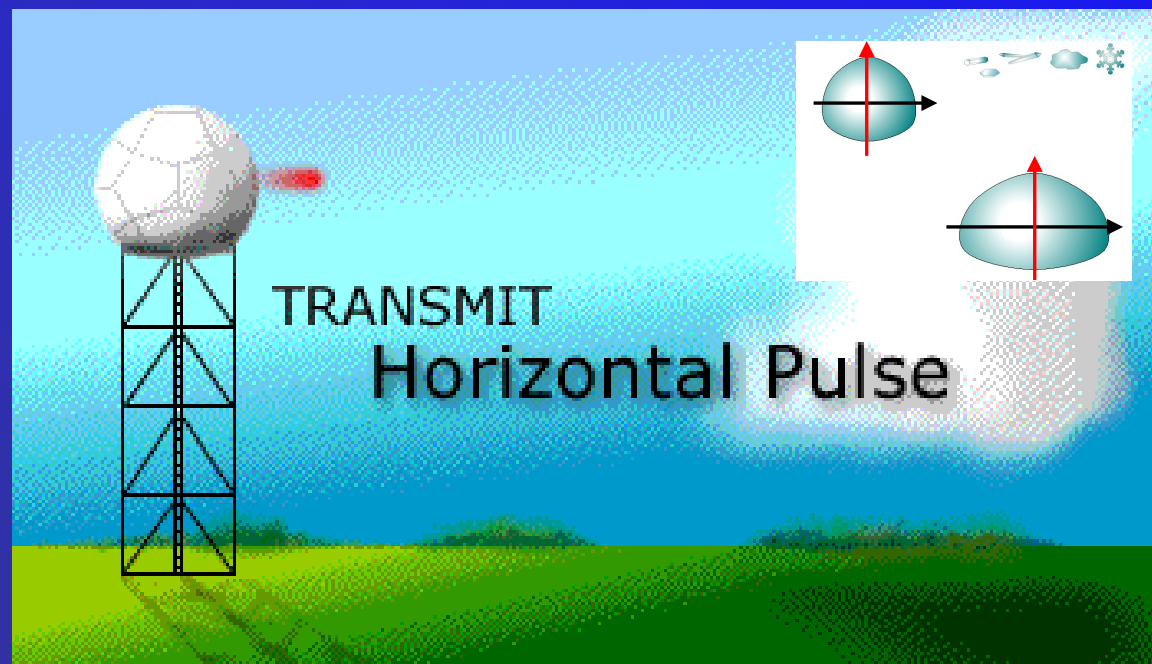
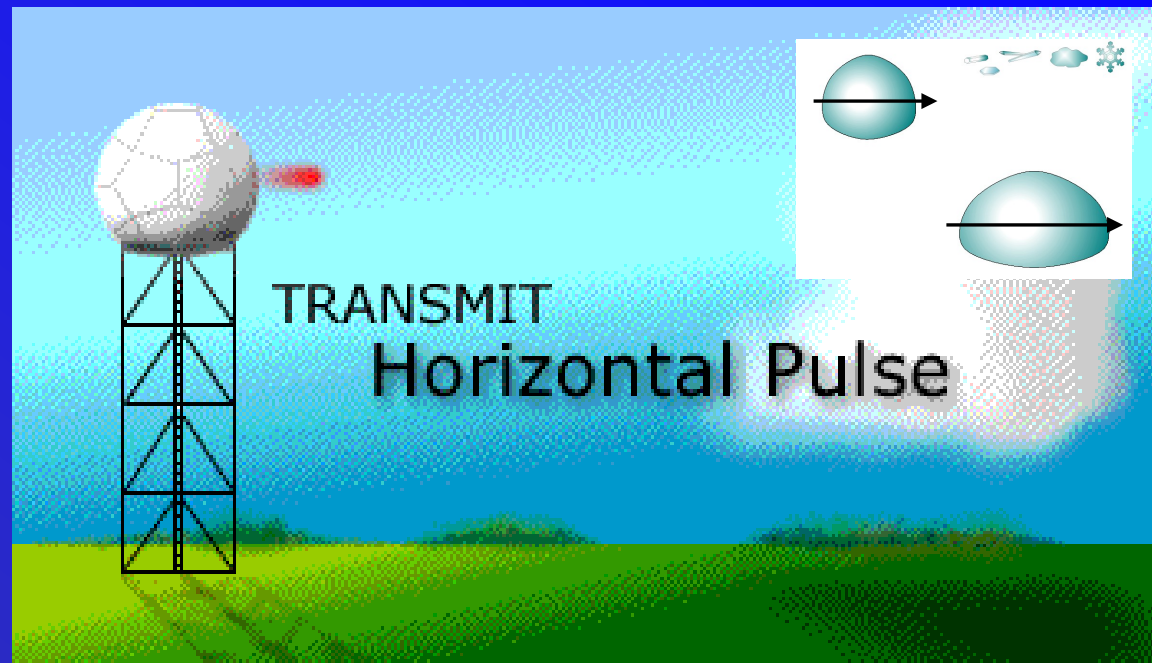
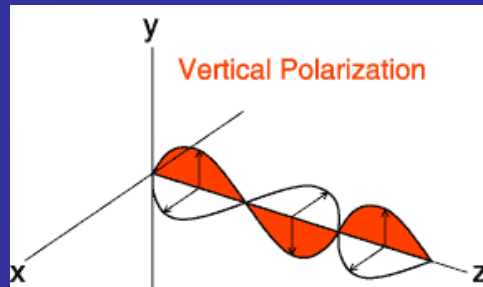
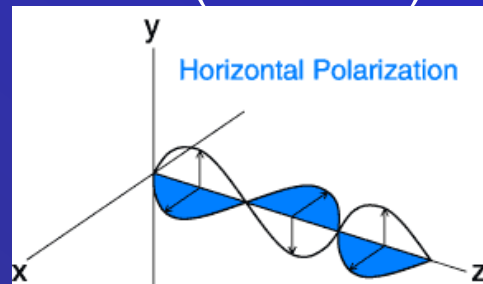
The next major upgrade is polarimetric radar, which adds vertical polarization to the current horizontal radar waves, in order to more accurately discern what is reflecting the signal. This so-called dual polarization allows the radar to distinguish between rain, hail and snow, something the horizontally polarized radars cannot accurately do. Early trials have shown that rain, ice pellets, snow, hail, birds, insects, and ground clutter all have different signatures with dual-polarization, which could mark a significant improvement in forecasting winter storms and severe thunderstorms. The deployment of the dual polarization capability to nexrad sites will begin in 2010 and last until 2012.

POLARIMETRIC RADAR?

Conventional Radar (NEXRAD)



Polarimetric Radar (ARMOR)



Polarimetric Variables

1. Reflectivity factor Z at horizontal polarization

- Measure of size and concentration of scatters
(dominated by **SIZE**)

Operational:
NEXRAD, TV

2. Differential reflectivity Z_{DR}

- Measure of median drop diameter → **SIZE/SHAPE**
- Useful for rain / hail / snow discrimination → **SIZE/SHAPE/PHASE**

Small ZDR Large ZDR



3. Differential phase Φ_{DP} (Specific Differential Phase- K_{DP})

- Efficient for accurate rainfall estimation → **NUMBER/SHAPE**
- Immune to radar miscalibration, attenuation, and partial beam blockage

4. Cross-correlation coefficient ρ_{hv}

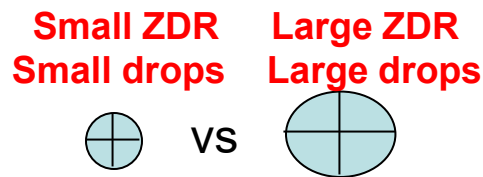
- Indicator of mixed precipitation → **SHAPE/PHASE**
- Efficient for identifying nonmeteorological scatterers

Advantages of a Dual-Polarization Radar

Really just a self-consistent way of obtaining a more complete description of the particle types and shapes present in a given volume of space.

- More accurate rainfall estimation (10-20% max accumulation error as opposed to 200-300%).
 - Why? Because we collect information on drop size/shape/concentration and are able to mitigate hail contamination.

Mitigates the multiple Z-R issues!



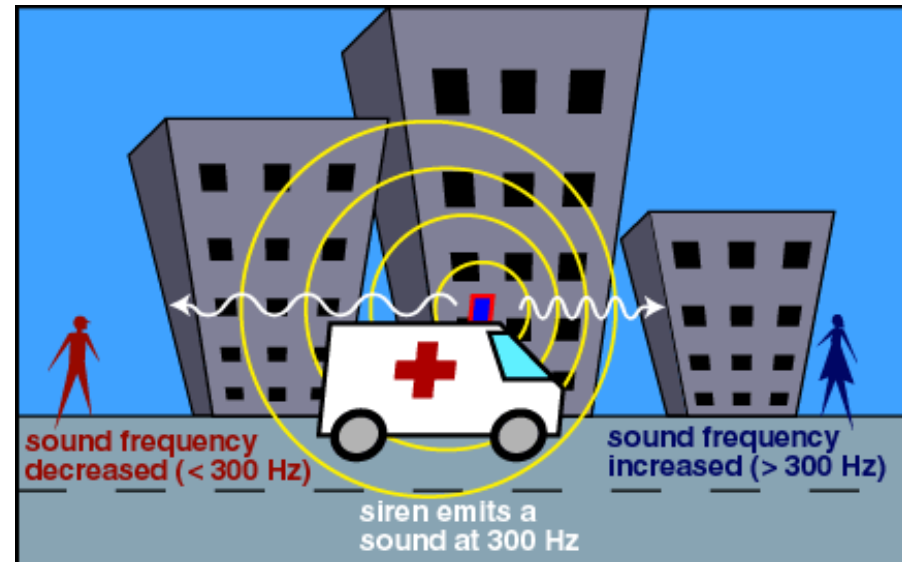
- Identification of precipitation types and discrimination between meteorological and non-meteorological scatterers



- Improvement in radar data quality: Self consistent way to calibrate using polarimetric variables

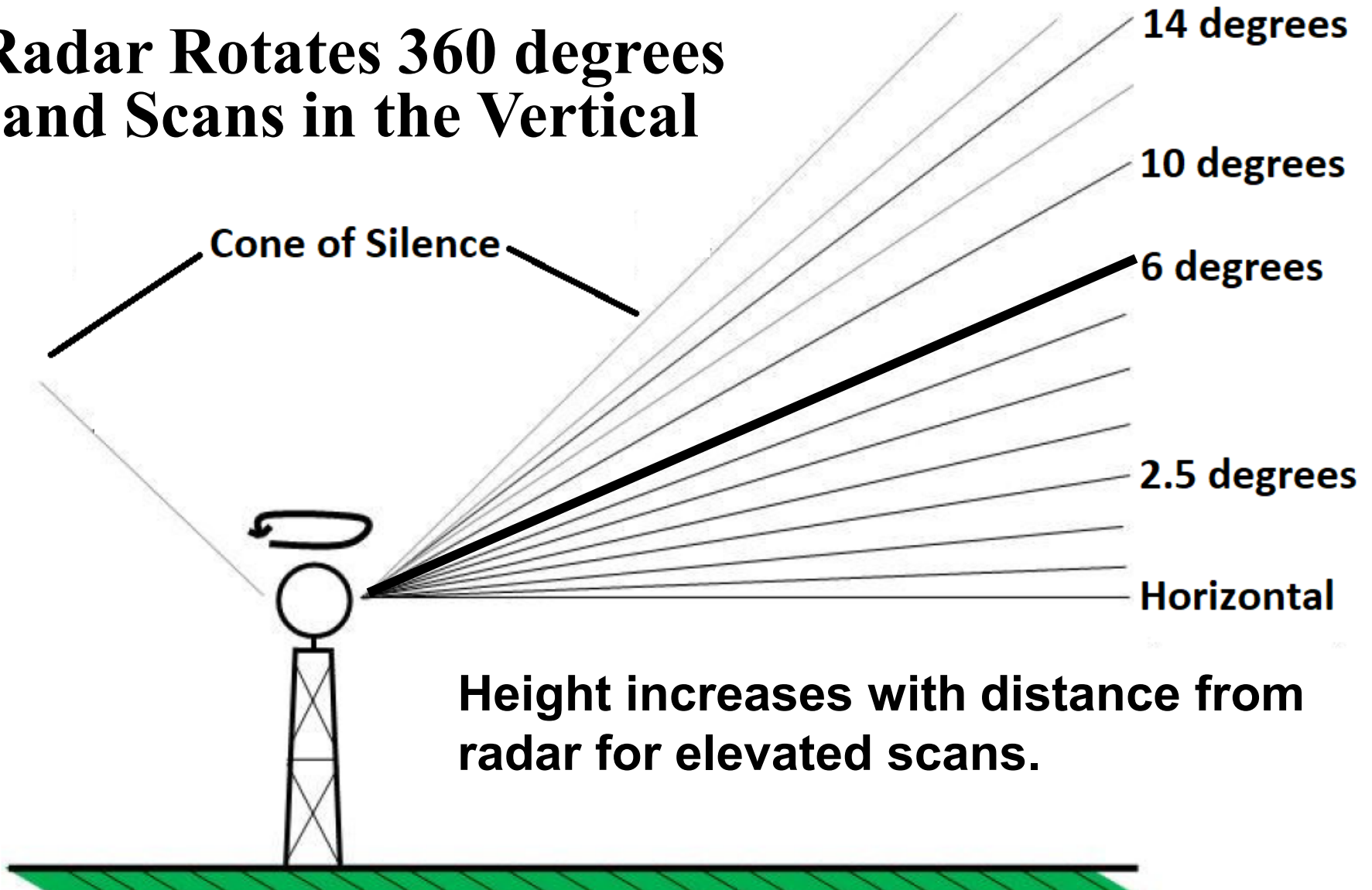
Doppler Effect: Frequency Change Due to Relative Motion

- No Doppler shift perpendicular to the direction of motion
- Moving closer, shift to higher frequency
- $\Delta f = 2V/\lambda$ where $V = \vec{V} \cdot \hat{r}$.
 \vec{V} is the wind vector.
 \hat{r} unit vector points radially out from the radar.
- Inbound: negative and cool colors
- Outbound: positive and warm colors (“red shifted”).
- Zero Contour: zero velocity component (perpendicular to the beam). Called a “zero isodop”.



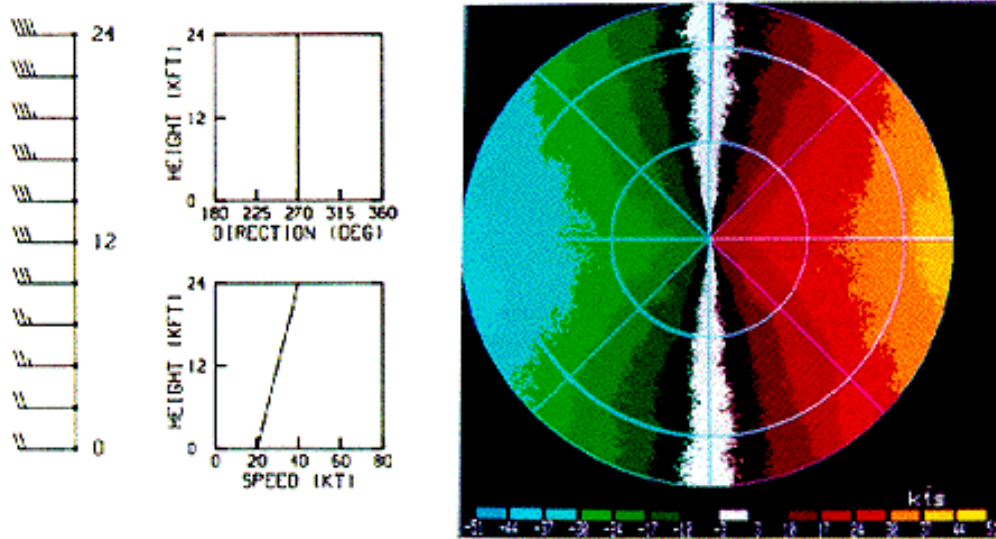
Doppler Effect for Sound and Light

Radar Rotates 360 degrees and Scans in the Vertical



The **base reflectivity** images in Precipitation Mode are available at four radar "tilt" angles, 0.5° , 1.45° , 2.40° and 3.35°

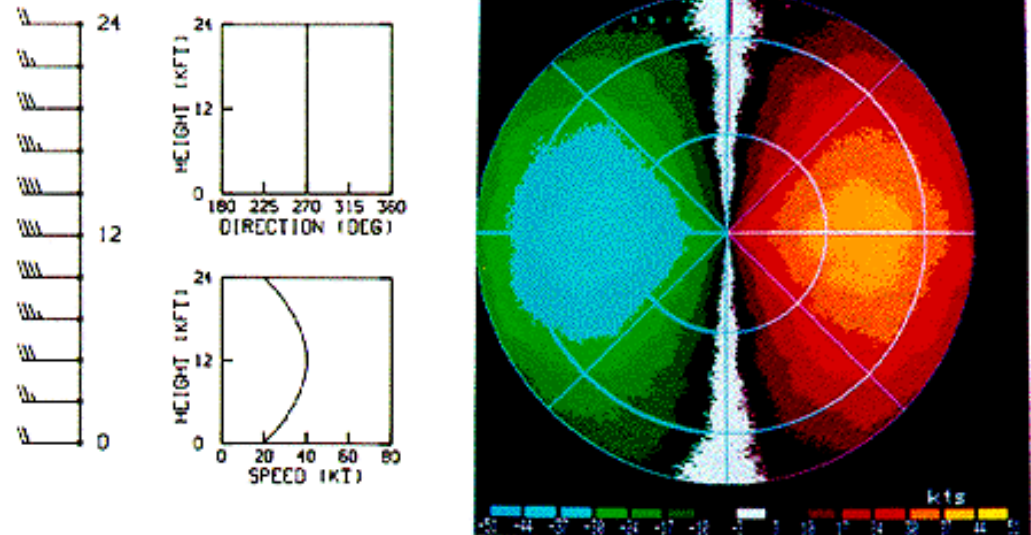
Doppler examples: Radar is in the Center



Blue color: $\Delta f < 0$
Wind towards radar.
Named inbound wind.

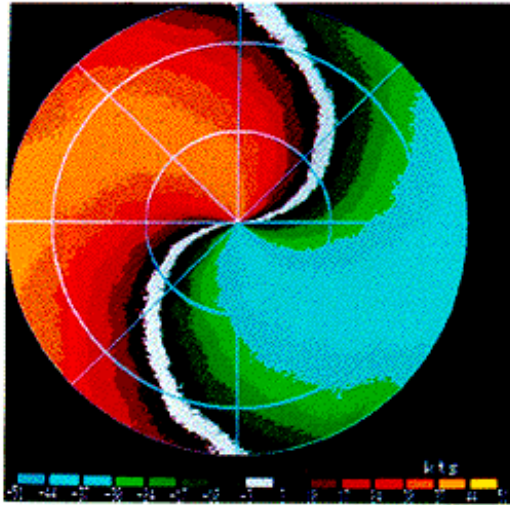
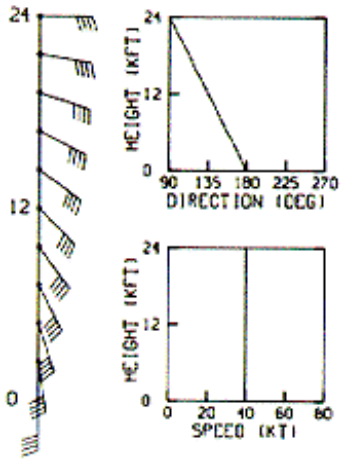
Red color: $\Delta f > 0$
Wind away from radar.
Named outbound wind.

Wind increasing with height



Wind convention
1 knot=1.15 mph

Veering and Backing winds



CVW:

Clockwise rotation of wind with height.

Known as **v**eering wind.

Warm air moving in.

Likely to have updrafts.

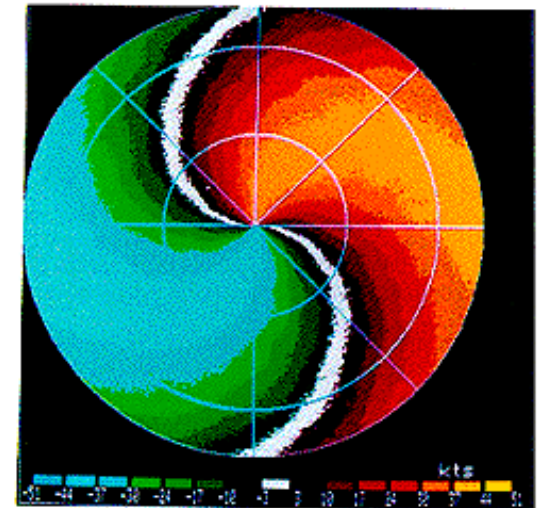
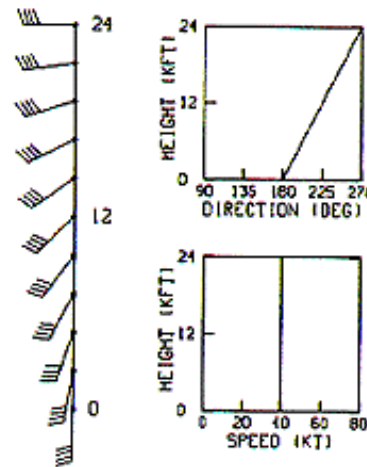
CCBC:

Counter-**c**lockwise rotation of wind with height.

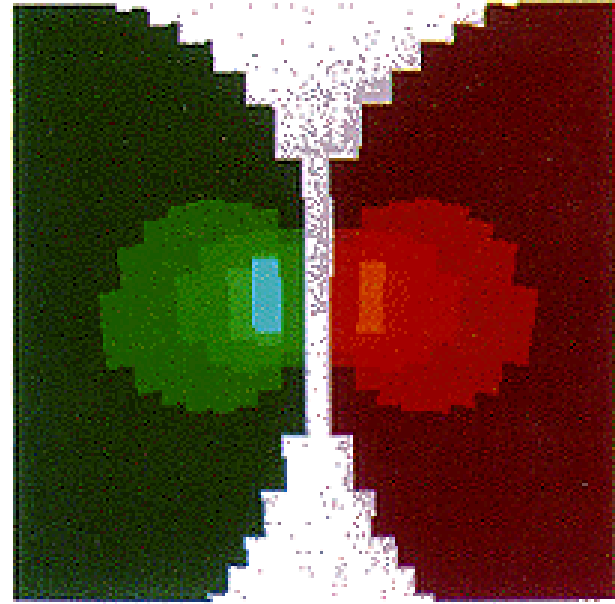
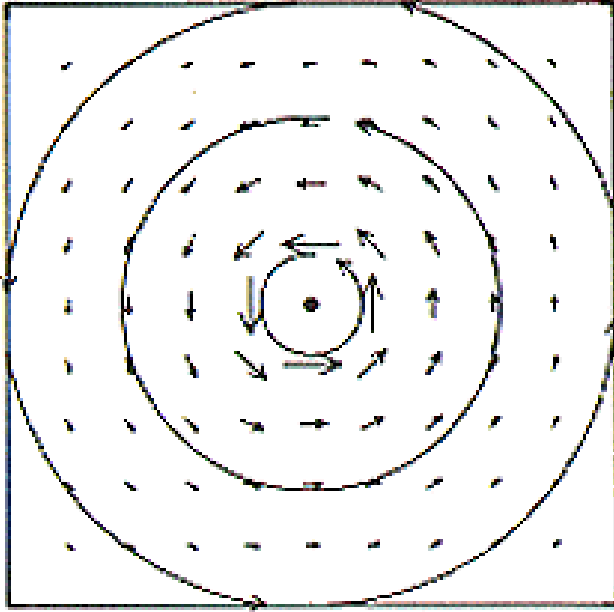
Known as **b**acking wind.

Cold air moving in.

Likely to have downdrafts.

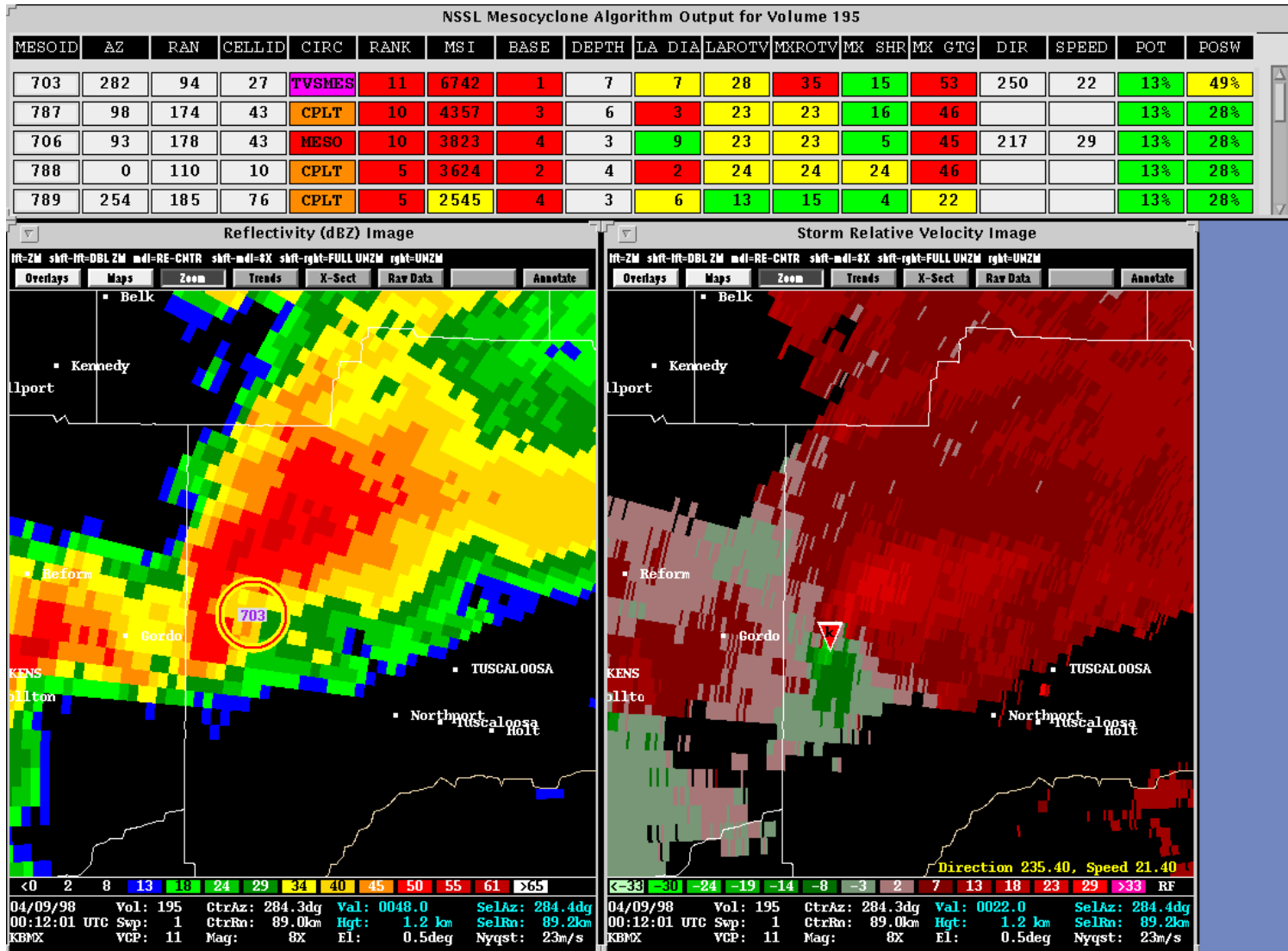


Rotation: Tornado

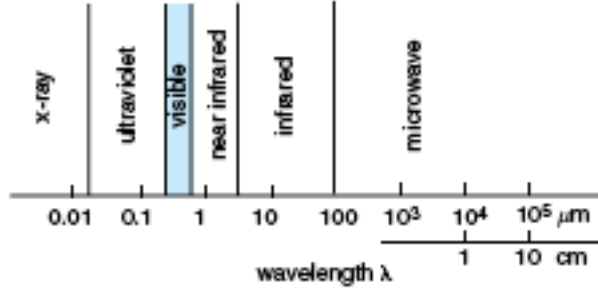


Note intense flow near center.
Tornado not right over the radar.

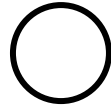
Tornado Vortex Signature



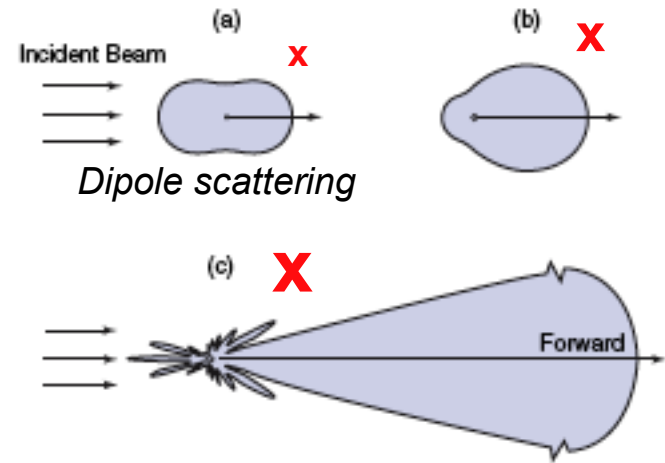
Light Scattering Basics (images from Wallace and Hobbs CH4).



Sphere, radius r , complex refractive index $n = m_r + im_i$



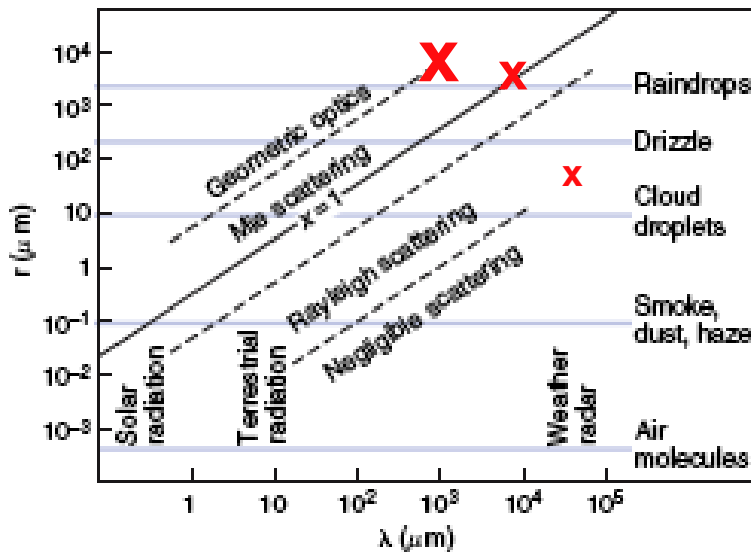
Angular Distribution of scattered radiation (phase function)



Dimensionless Parameters:

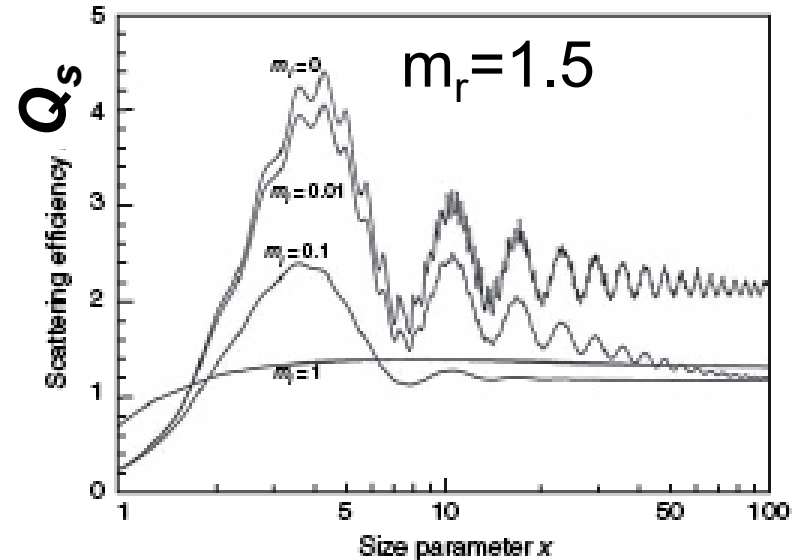
$$\text{Size Parameter} = x = \frac{2\pi r}{\lambda}$$

$$\text{Scattering Efficiency} = Q_s = \frac{\sigma_{sca}}{\pi r^2}$$



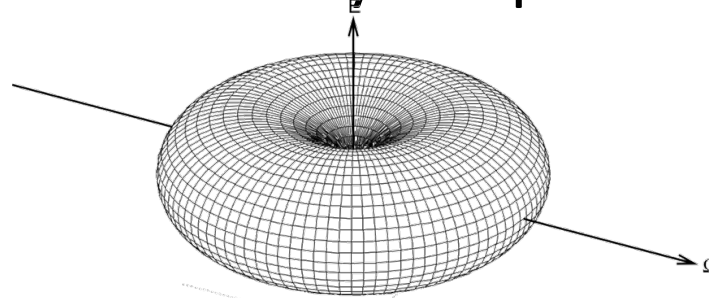
Lines:

$$r = \frac{x}{2\pi} \lambda$$

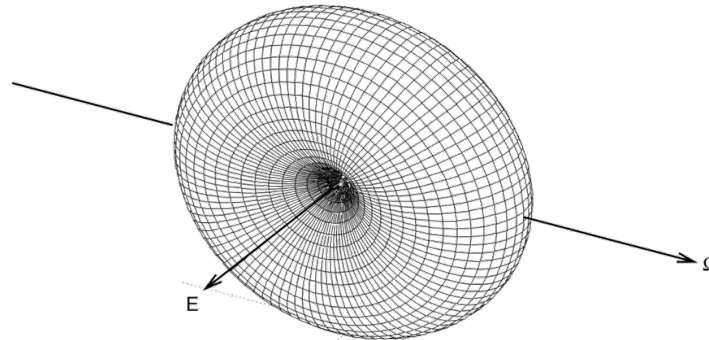


Rayleigh Scattering Phase Function: Angular Distribution of Light Scattered by a Dipole: $x \ll 1$

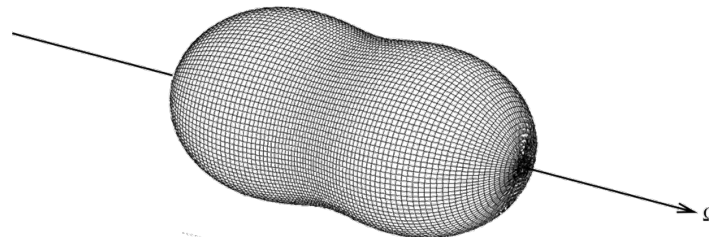
3D rendering



vertical polarization state



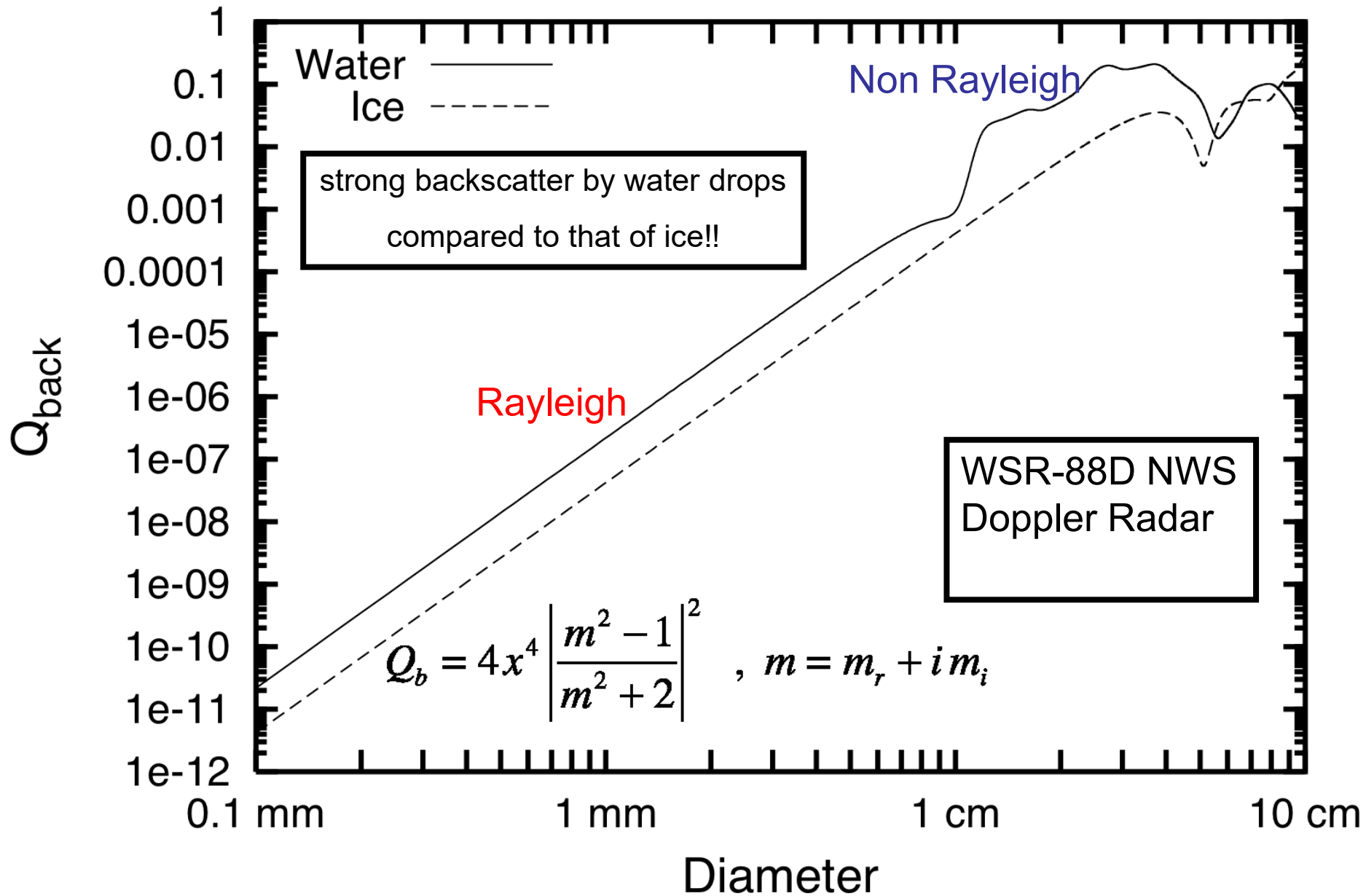
horizontal polarization state



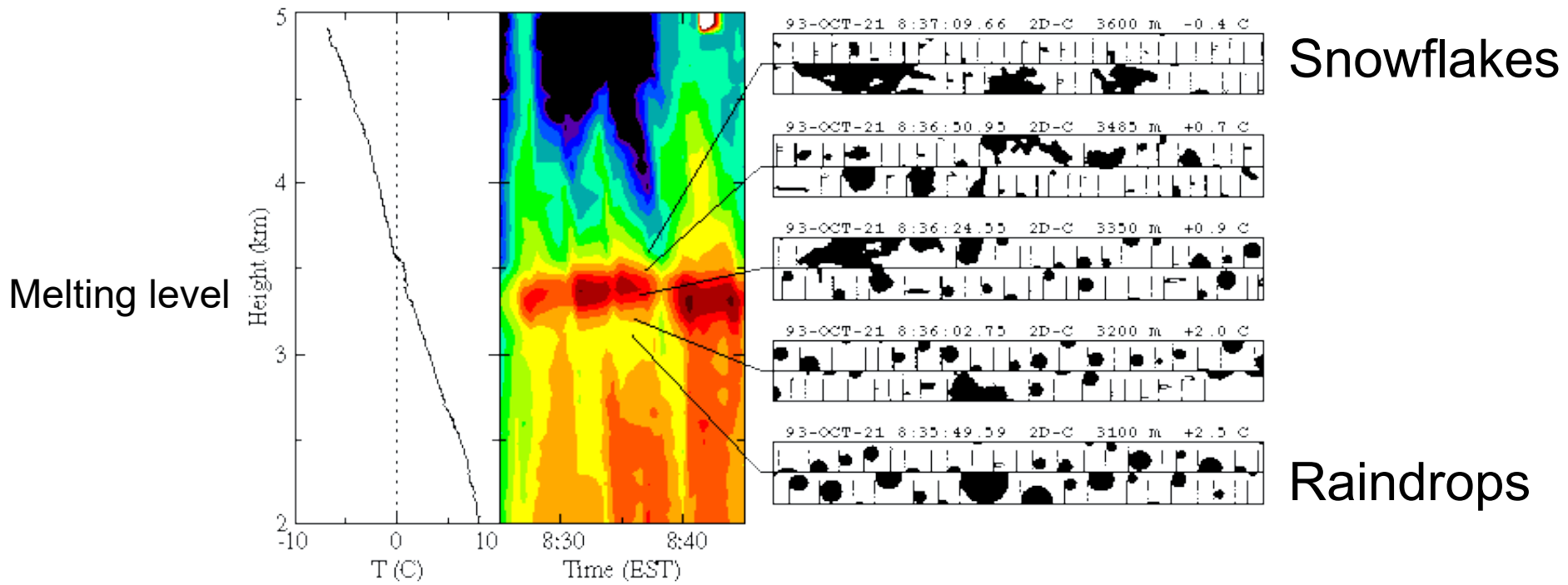
The Peanut!
Average of both
polarization states.

Mie Radar Backscatter Efficiency for Water and Ice Spheres

Radar Backscatter from Sphere, $\lambda = 10.71$ cm



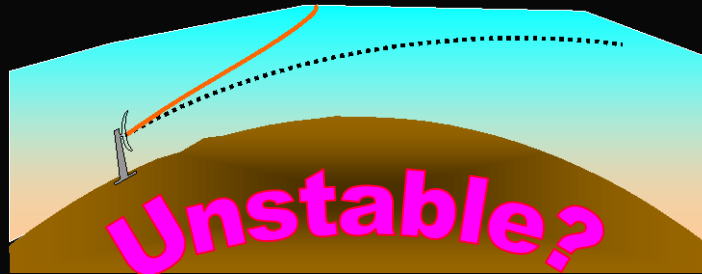
Radar Bright Band: Strong Scattering from Melting Hydrometeors



Most intense radar backscatter from melting level due to both liquid water and large hydrometeor diameter

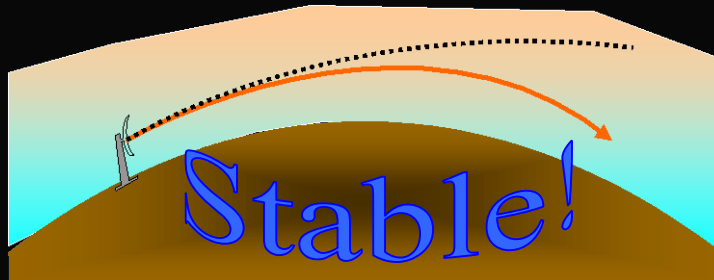
abnormal atmospheric conditions

subrefraction



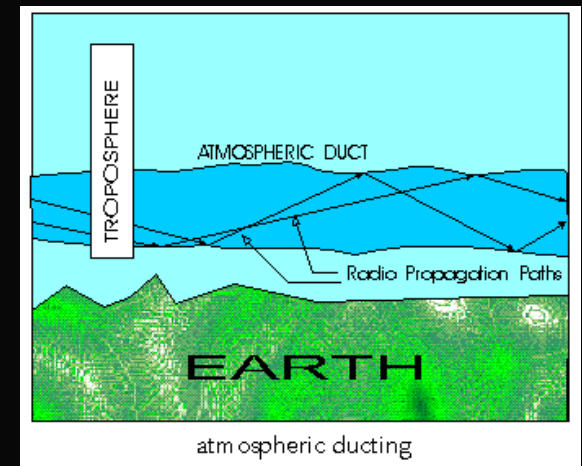
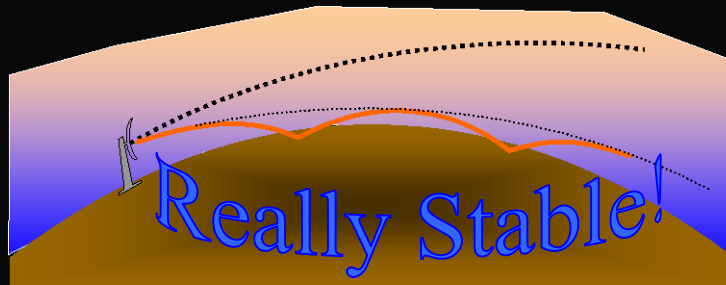
cool, moist air aloft
warm, dry air below

superrefraction



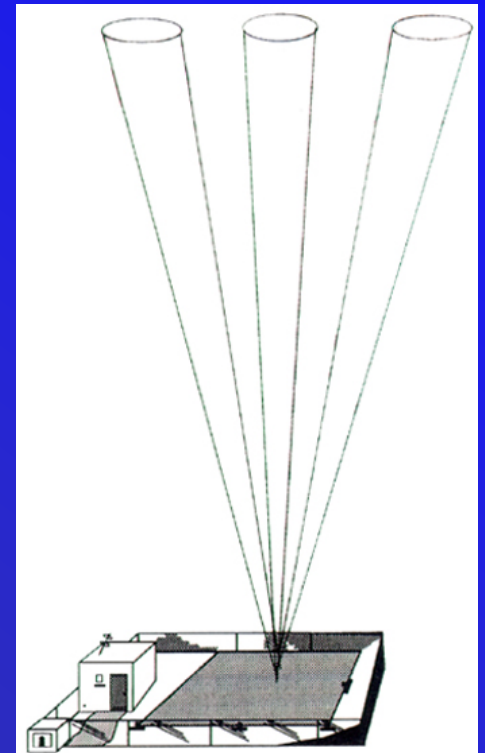
warm dry air aloft
cool, moist air below

ducting



WIND PROFILER

The wind profiler is a ground based array of multiple beam *Doppler radar units* which measures and displays wind information up to an altitude of 16 km. This instrument is generally used to detect low level *wind shear*.



Clear-Air Wind Profilers

