# Radar Meteorology

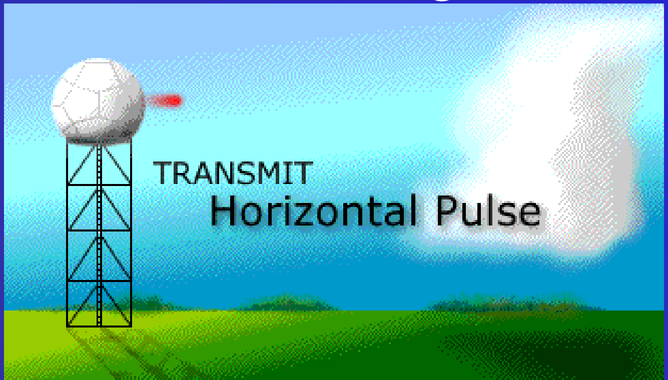
***Purpose***:

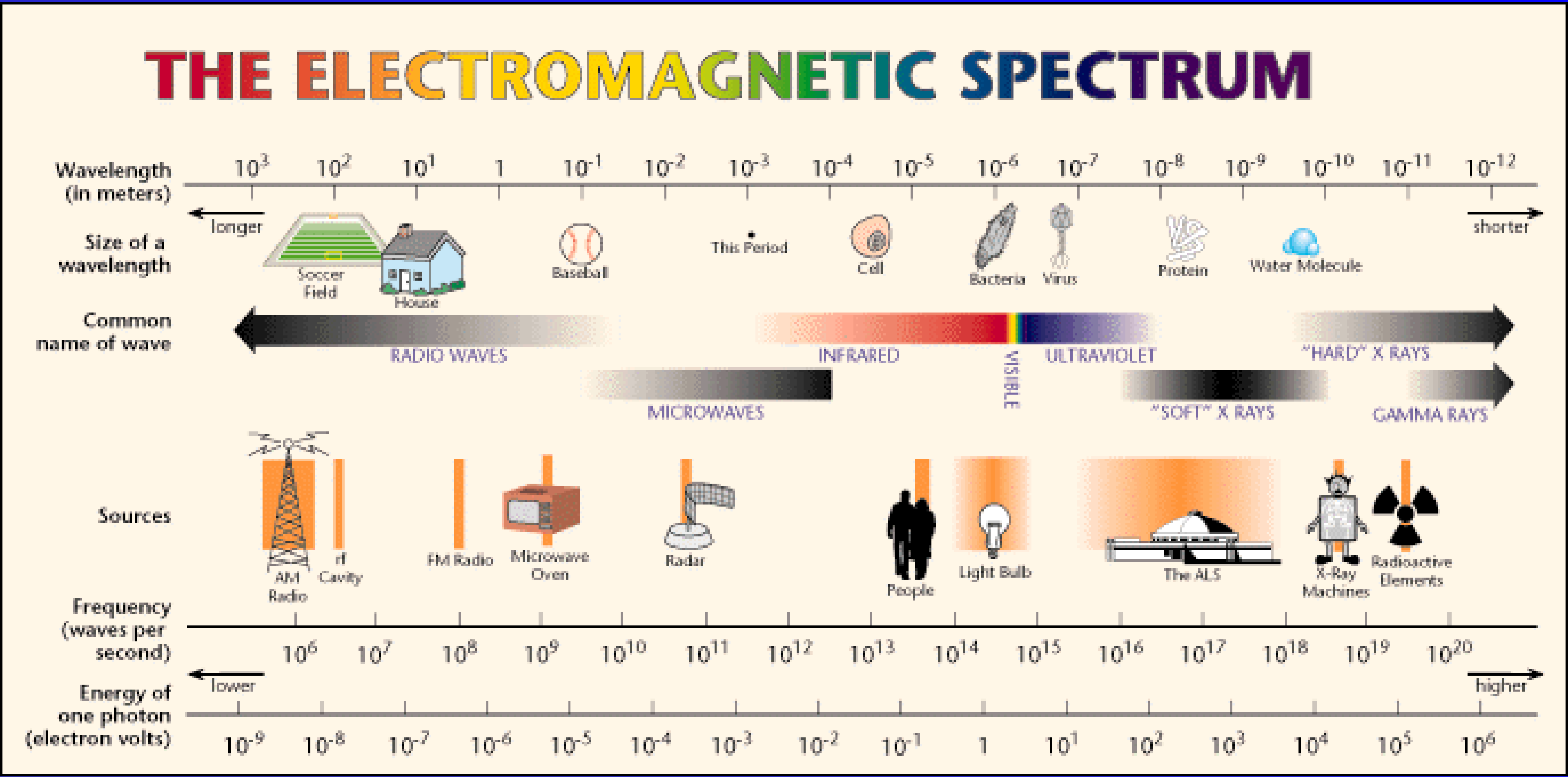
1. Explain the basic principles of radar.  What is dbz? This is related to the power backscattered by hydrometeors.

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 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

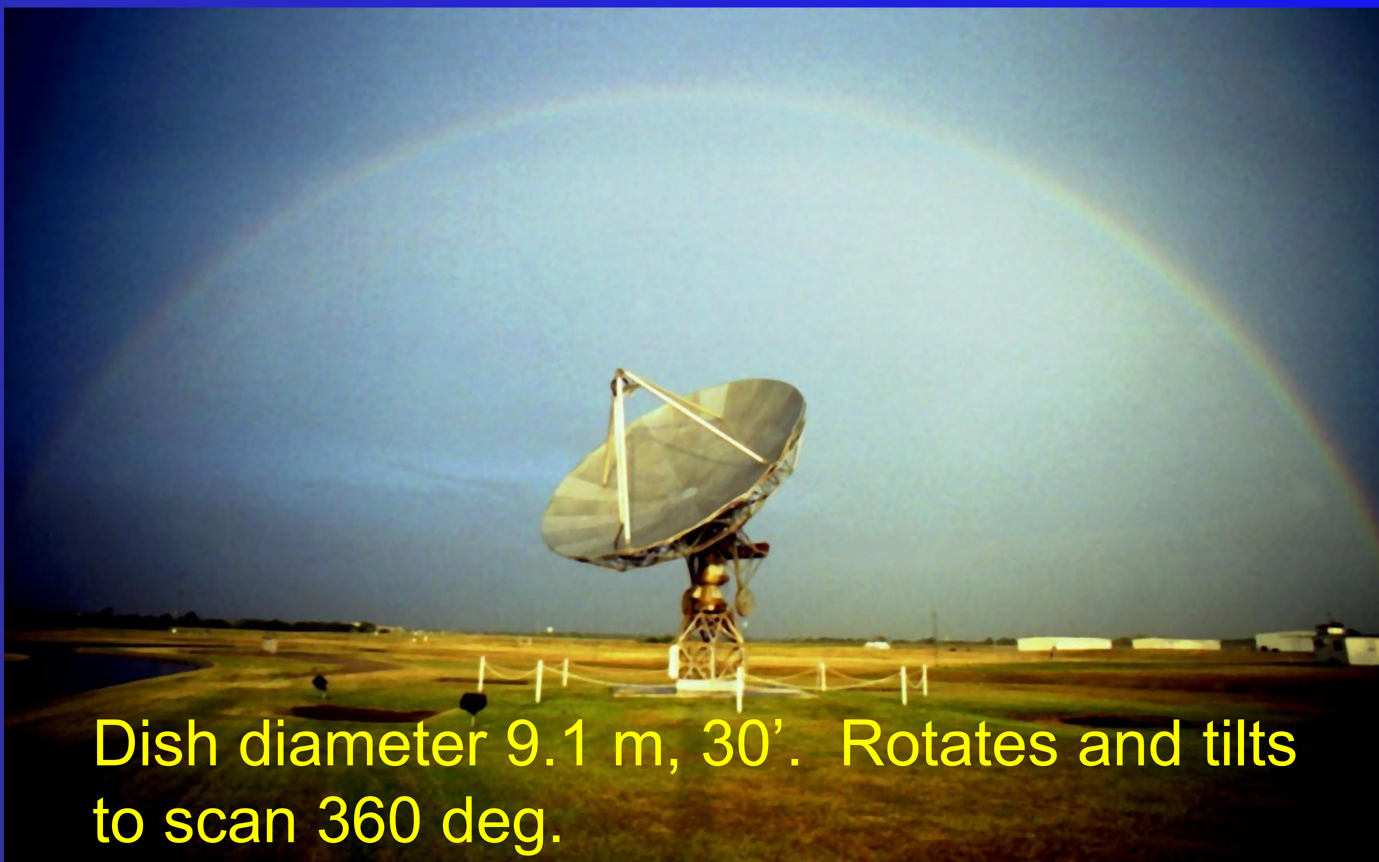
# Definitions

**RADAR** is an acronym. RAdio Detection And Ranging.


NEXRAD Weather Radar

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

# NEXRAD RADAR: What's in the dome




https://en.wikipedia.org/wiki/NEXRAD

# NEXRAD RADAR

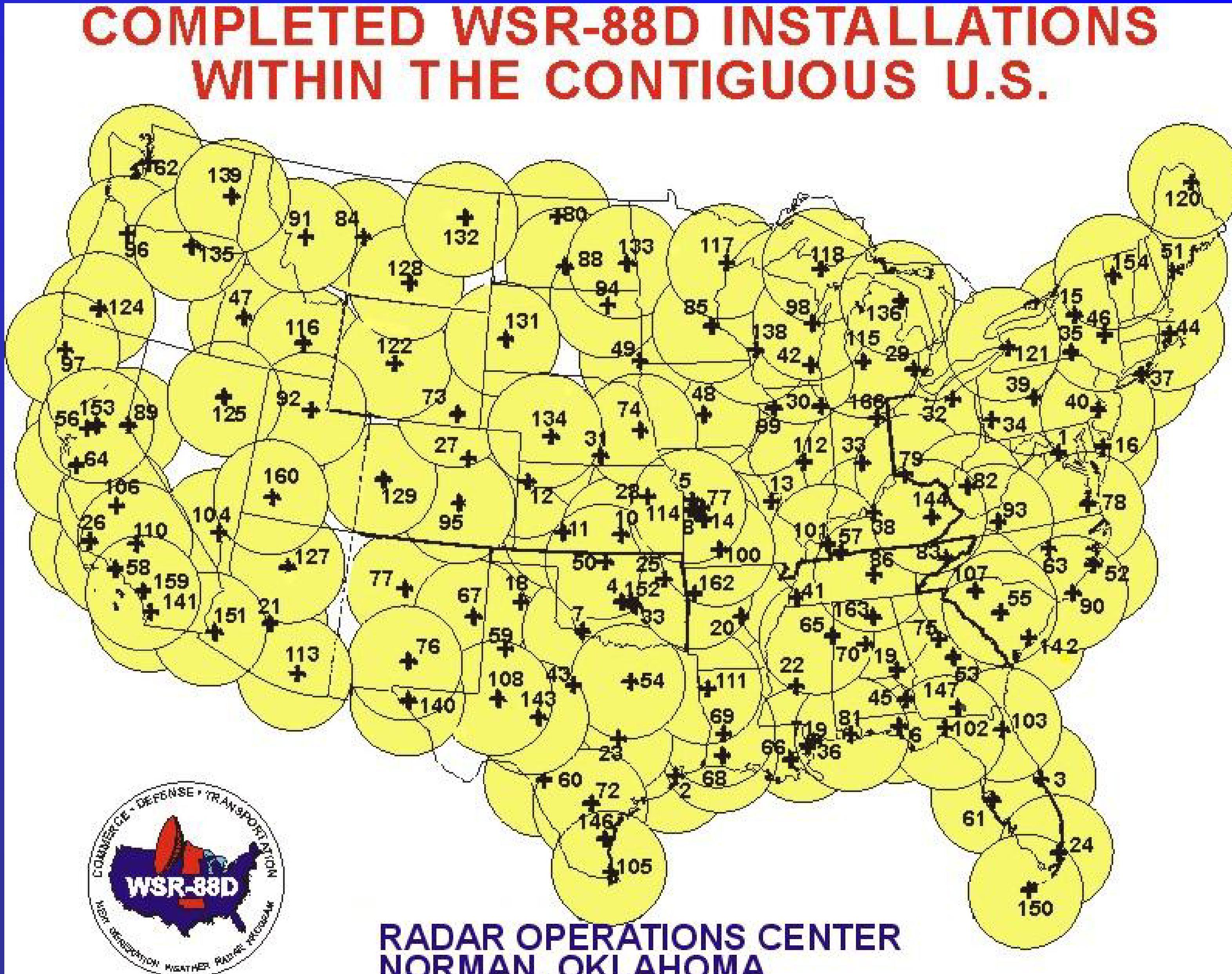
NEXRAD (background) and weather balloon launch facility.

# NEXRAD RADAR

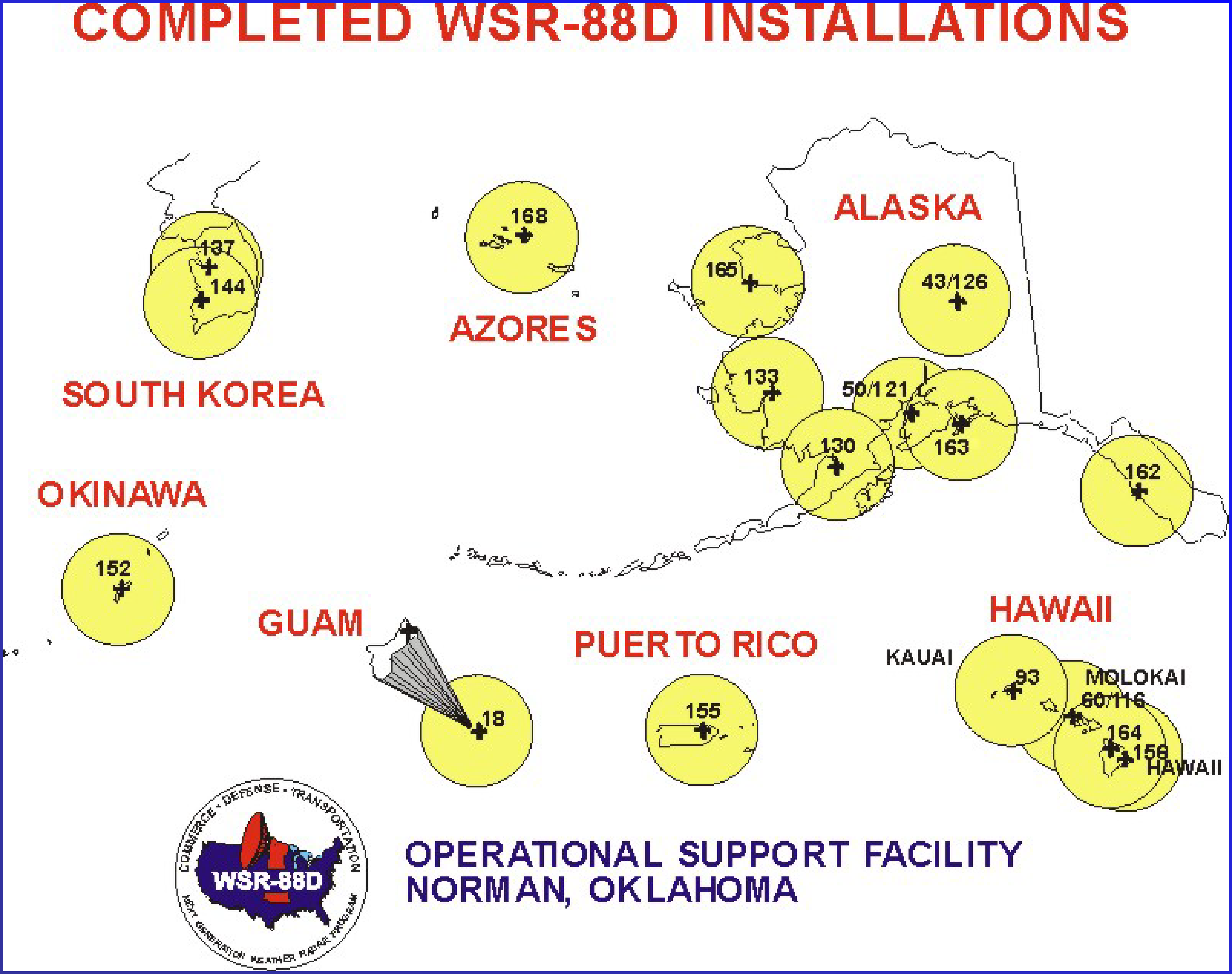
- Named WSR-88D
  Weather surveillance radar, 1988, doppler
- S-band radar
- Radiation wavelength is $\lambda$ = 10.7 cm
- Power is 750 kW

  - Can be damaged by winds and lightning strikes

# NEX RAD SITES IN THE U.S.

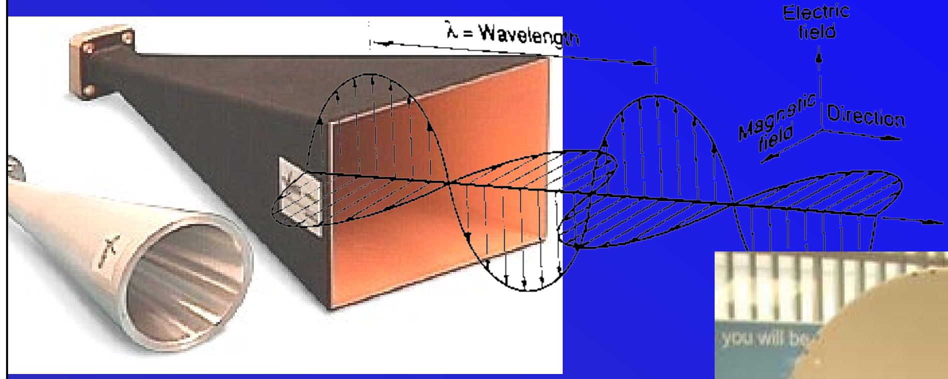


# NEXRAD SITES IN THE OUTSIDE OF THE CONTINENTAL US.



# 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

$$\theta \cong \frac{\lambda}{D}$$ radians

D is the antenna diameter

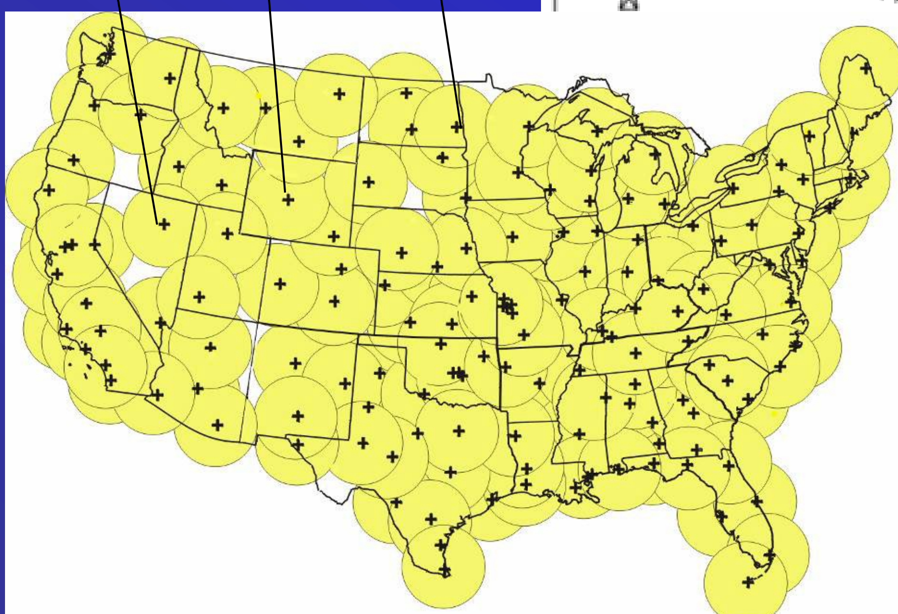
λ is the wavelength of signal in air

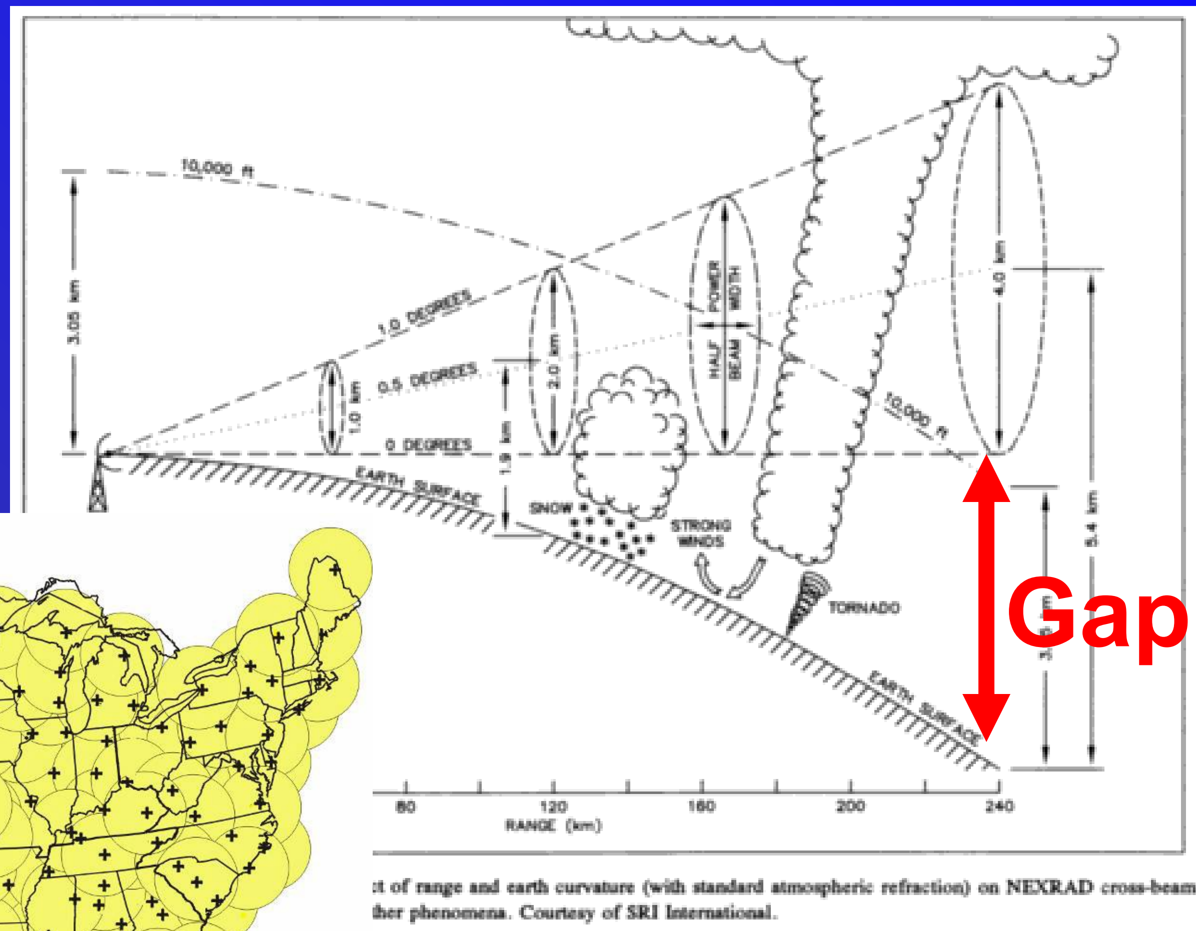
Tradeoff:

Small wavelengths (high frequencies) = small antennas

But small wavelengths attenuate more

# NEXRAD Location Issues





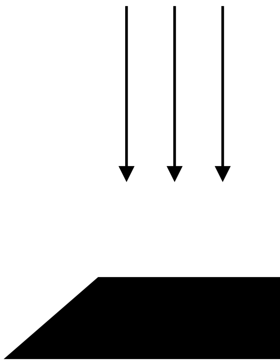
# Radar: The Quickest Path to dbZ, The Quantity Commonly Reported By Weather Radar

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

Sunlight
$I_0$ (W/m$^2$)
$\lambda$



Black Surface
Area $A$ (m$^2$)
$a$ = albedo = 0
Absorptance = (1-$a$) = 1

**Power Scattered, Power Absorbed**

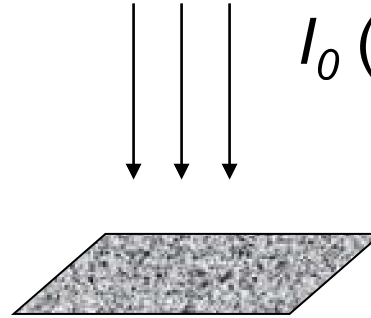
$P_{sca} = 0$

$P_{abs} = I_0 A$

$\sigma_{abs} = A$

*Flat Surface*
$\sqrt{A} >>> \lambda$

Sunlight
$I_0$ (W/m$^2$)
$\lambda$



Arbitrary Surface
Area $A$ (m$^2$)
$a$ = albedo
Absorptance=(1-$a$)

**Power Scattered, Power Absorbed**

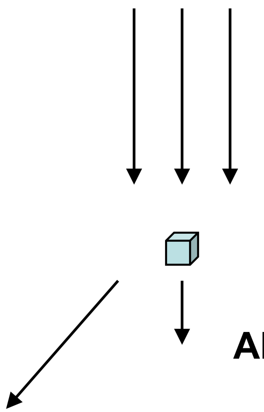
$P_{sca} = I_0 A\, a$

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

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

# Definitions: Optical Coefficients for a Surface and a Particle

Beam of Sunlight
$I_0$ (W/m$^2$)
$\lambda$



Thing (particle, molecule, flea, etc)

Absorption, less light through thing.

Scattering, light redirected by thing.

**Power Removed From Beam**

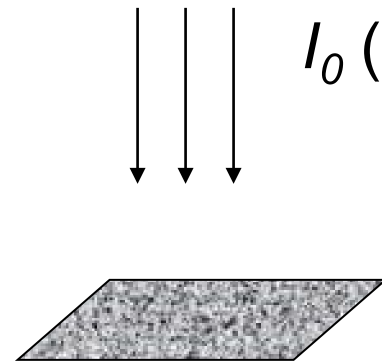
$$I_0 \, \sigma_{ext} = P_{ext}$$
$$I_0 \, \sigma_{abs} = P_{abs}$$
$$I_0 \, \sigma_{sca} = P_{sca}$$

$$\varpi = \frac{\sigma_{sca}}{\sigma_{ext}} = Single\ Scatter\ Albedo$$

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

$$P_{abs} = (1-\varpi) \ \sigma_{ext} \ I_0 \qquad \sigma_{abs} = (1-\omega) \ \sigma_{ext}$$

Sunlight
$I_0$ (W/m$^2$)
$\lambda$

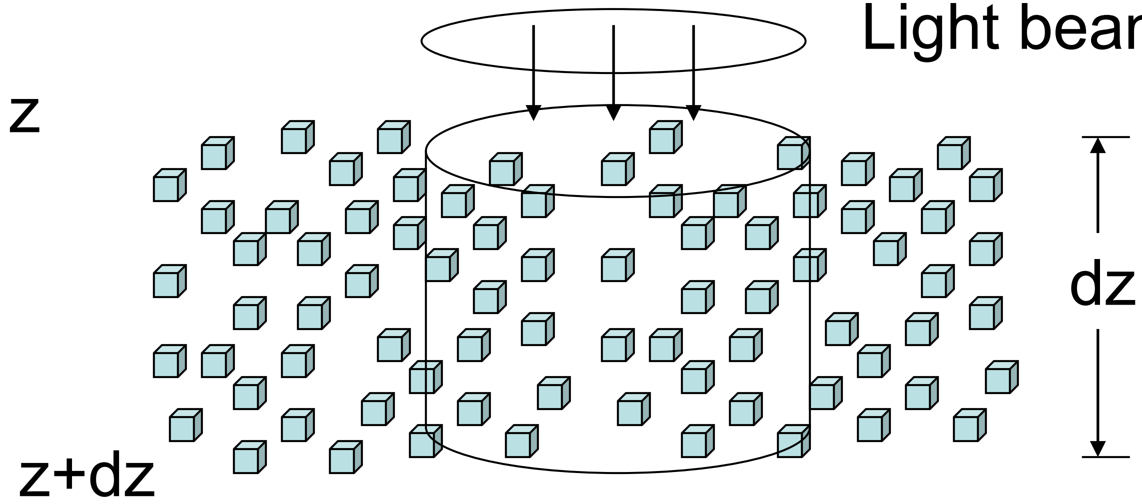


Arbitrary Surface
Area $A$ (m$^2$)
$a$ = albedo
Absorptance=(1-$a$)

**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)




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

Bouger-Beer "law" (direct beam only!)

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

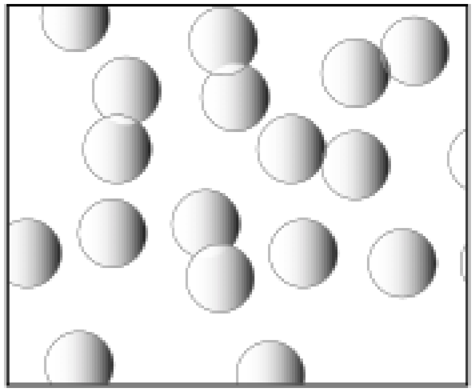
$$-dI = I(z)\ N\ \sigma_{ext}\ dz$$

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

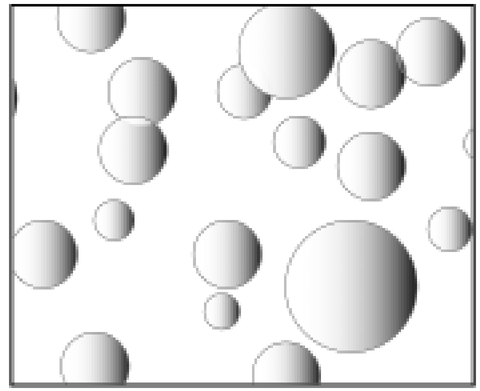
$$I(z) = I_0 \exp(-N\ \sigma_{ext}\ z) = I_0 \exp(-\beta_{ext}\ z)$$

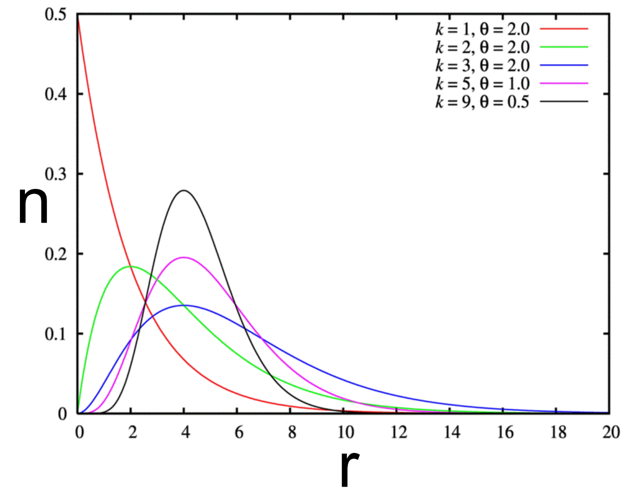
# Monodispersons and Polydispersions

Monodisperse



Polydisperse






N particles / volume.
All of radius r.

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

$$N = \int_0^\infty n(r)\, dr$$

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

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

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

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

# Radar Theory Part 1

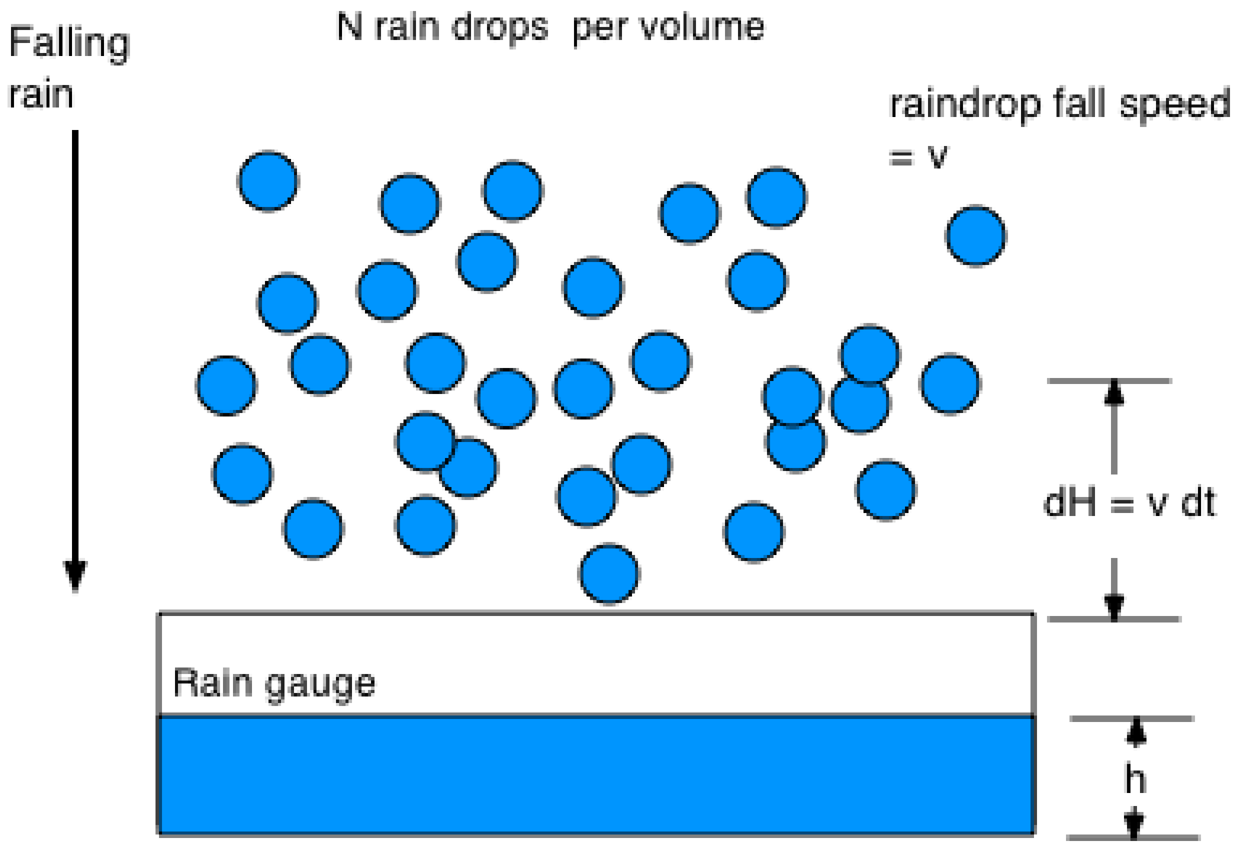
# Radar Theory Part 2: Typical Values of $Z_{dbZ}$

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



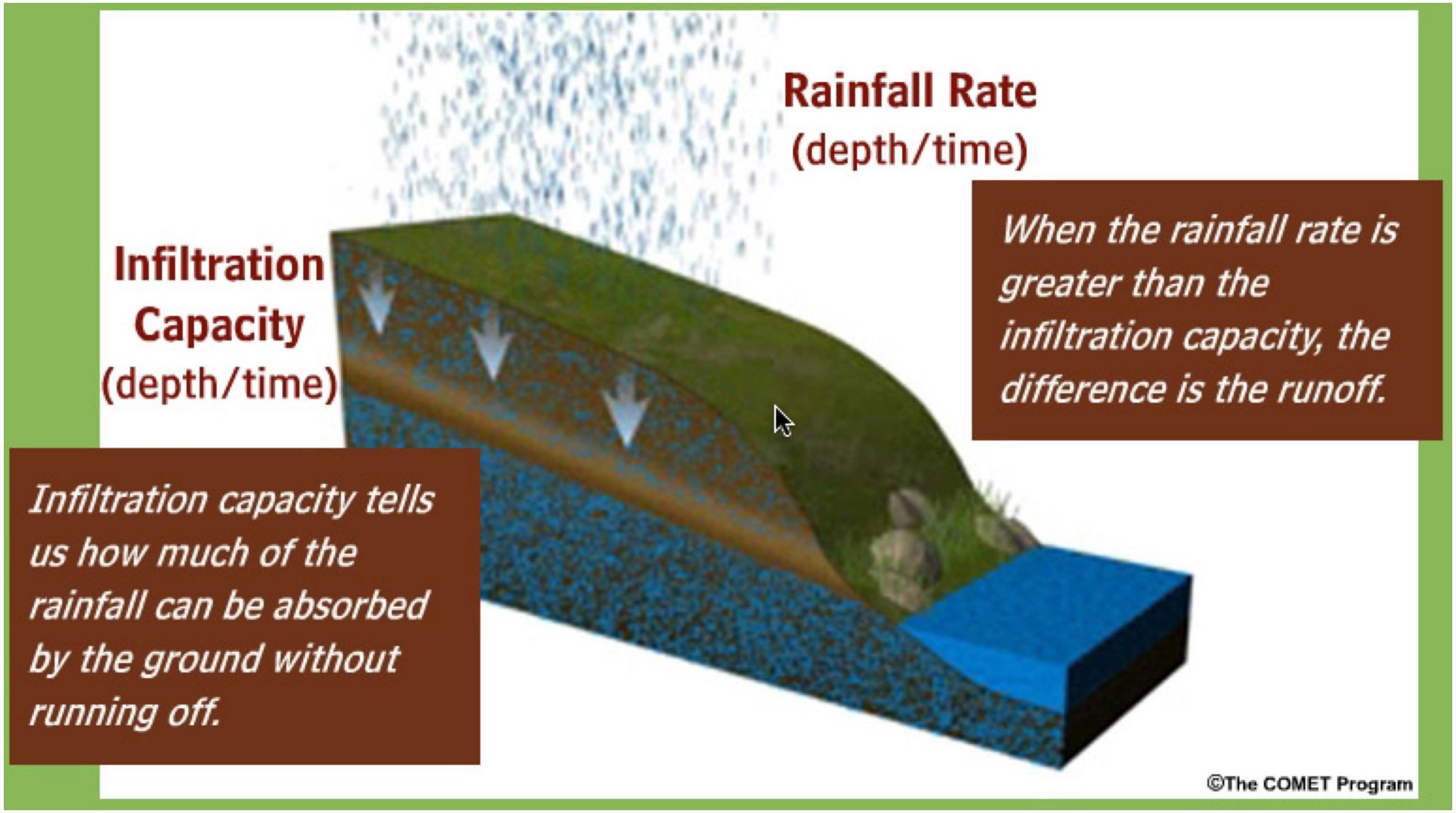

h = height of rain water in raing gauge. Rainfall rate = dh/dt
In time dt, drops from a height dH = v dt will land in the rain gauge.
Drops have diameter D. A = area of the rain gauge opening.
Then total water volume added in time dt to the rain gauge is

$N\ A\ dH\ \pi D^3/6$ = # Rain Drops going into rain gauge * drop volume

$= N\ A\ v dt\ \pi D^3/6 = A\ dh$

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

# 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.

Rainfall Rate = 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:

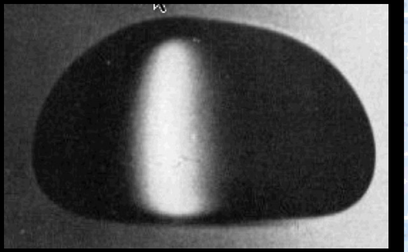
$$m\, g = C_d\, r\, V_t^2\, A$$

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 mm < D < 6 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

| diameter: mm | fallspeed: m/s |
|---|---|
| 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:

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

*Example:*

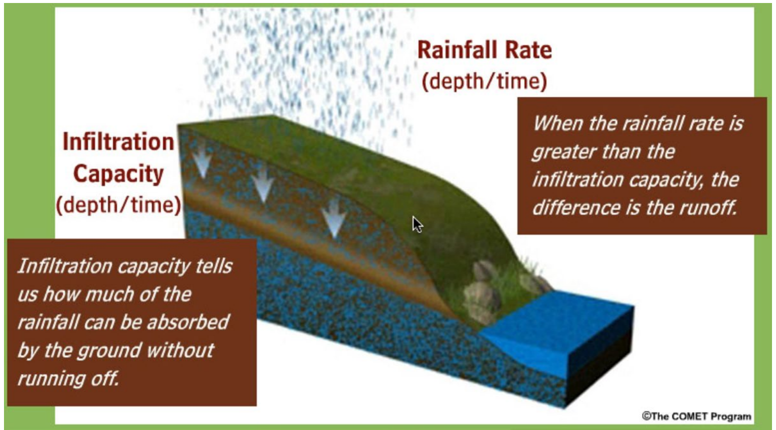
Use the Marshall Palmer Z-R relationship to calculate rain rates R for radar reflectivities of a) 10 dbZ, b) 30 dbZ, and c) 50 dbZ.

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?????



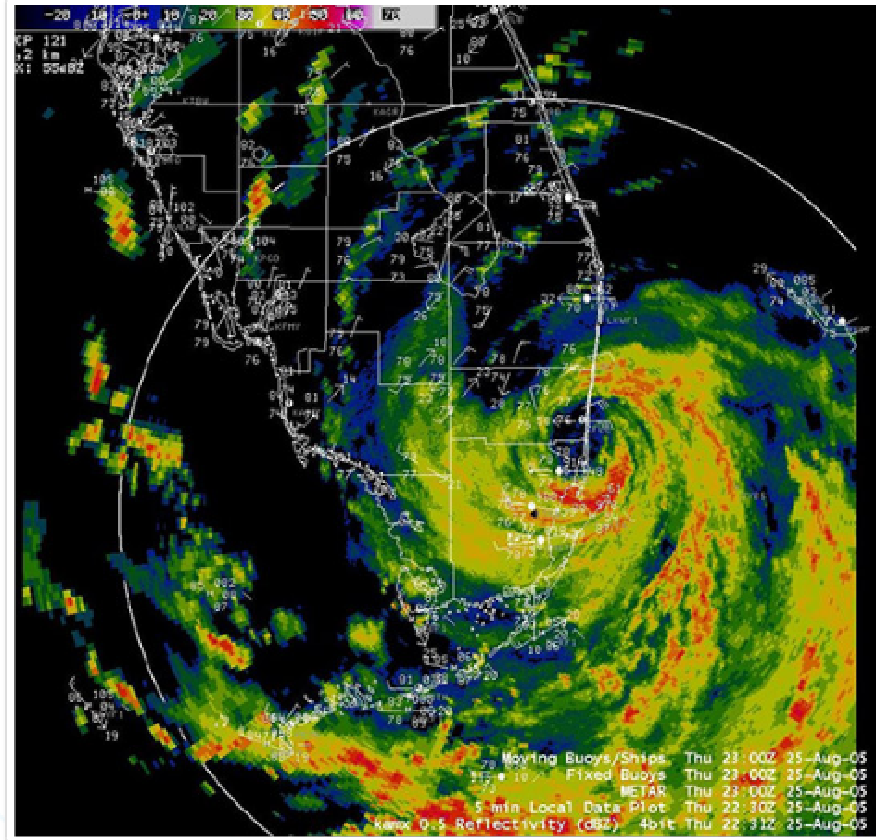

$$Z = 10^{dBz/10}$$

$$R = \left(\frac{Z}{200}\right)^{0.625}$$

# *Rain* Rates

*Rainfall* rate is a measure of the intensity of *rainfall*. It is measured by calculating the amount of *rain* that falls to the earth surface per unit area per unit of time. This image (right) is a sample base *reflectivity* image from the *Doppler Radar* from *Hurricane* Katrina coming ashore in Southeast Florida in August 2005. The colors represent the strength of returned energy to the *radar* expressed in values of decibels (dBZ). The table to the right shows how the color scale for the dBZ values are used to approximate *rainfall* rates.

# Rainfall Rate Example

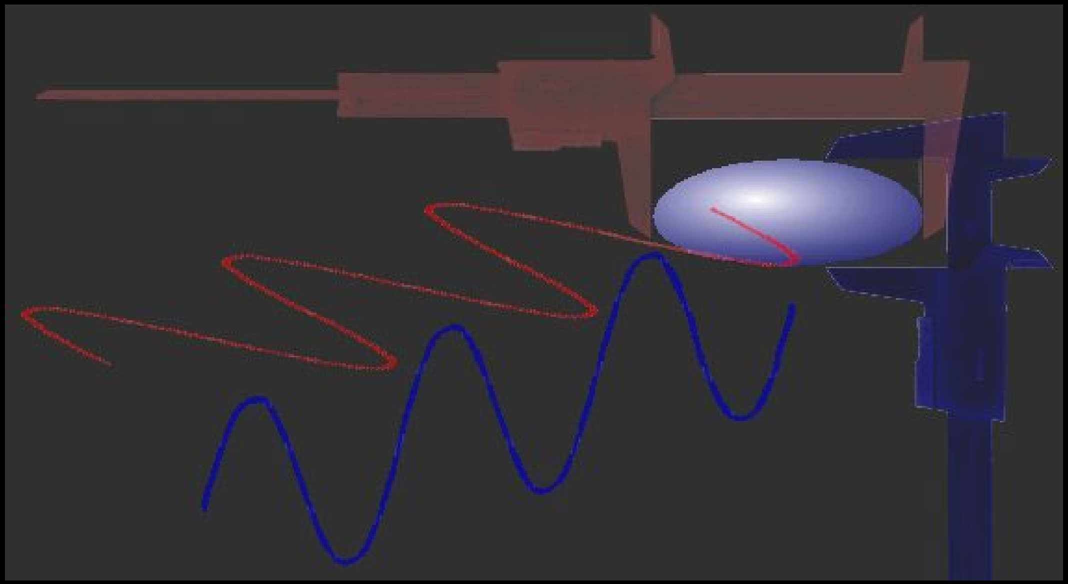



Source: Doppler Radar: Hurricane Katrina | NOAA

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

From https://learn.weatherstem.com/modules/learn/lessons/114/12.html

# Polarization Diverse Radar: Update of the WSR88D.



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

$$Raindrops : Z_{DR} > 1$$

$$Hailstones : Z_{DR} \approx 1$$

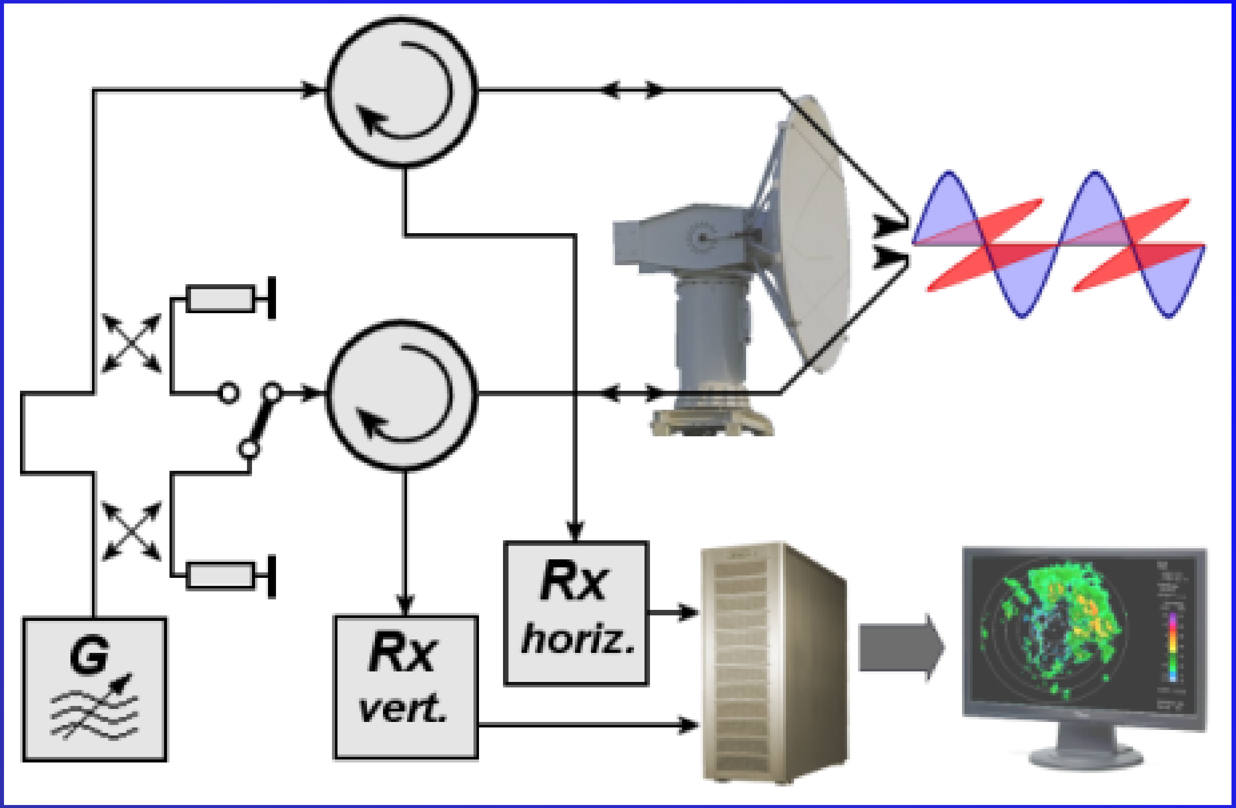
- Radar sends out horizontally and vertically polarized pulses.

- 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.

# WSRP-2010D:  Polarization Diverse Radar

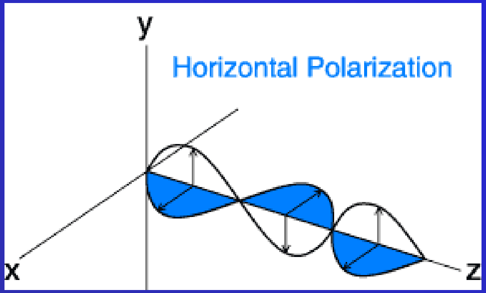



**Polarimetric radar**

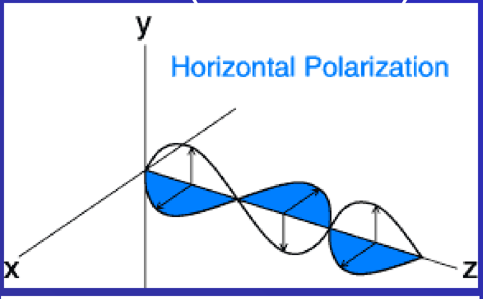
The next major upgrade was polarimetric radar, which adds vertical polarization to the current horizontal radar waves, in order to more accurately discern what is reflecting the signal. This so-called dual polarization allows the radar to distinguish between rain, hail and snow, something the horizontally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

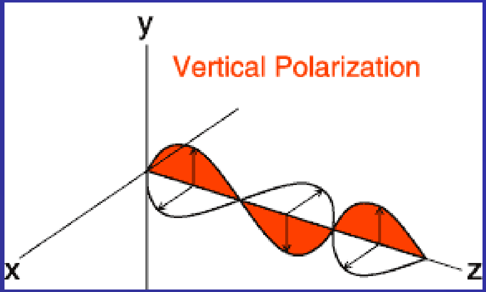
# POLARIMETRIC RADAR?

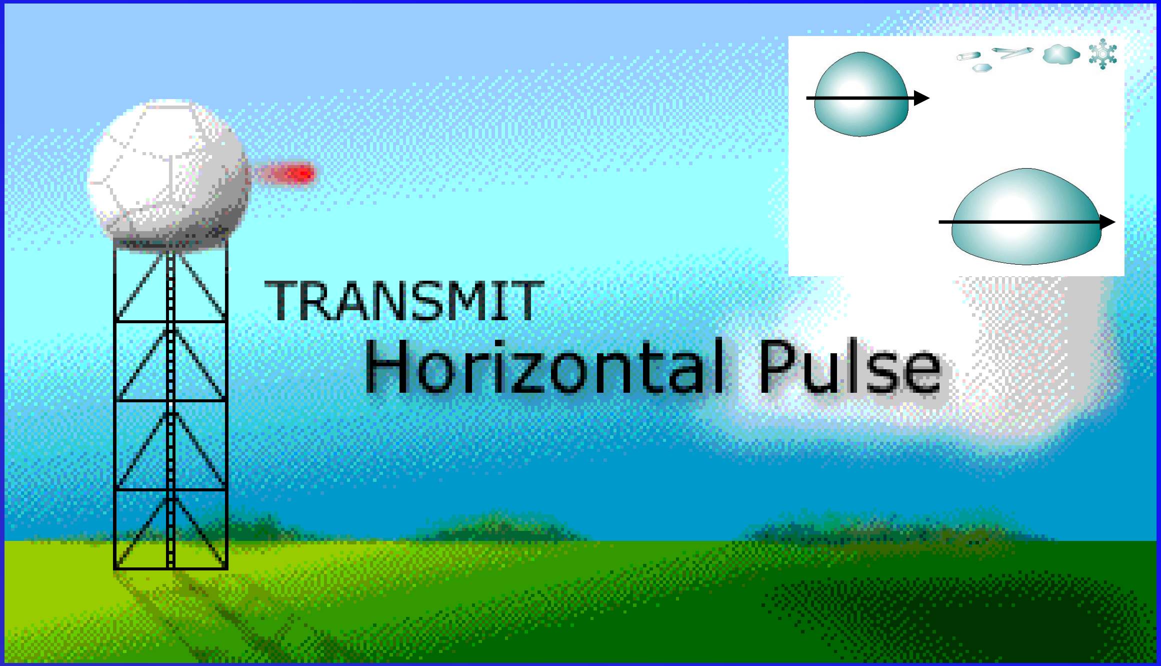
Conventional Radar (NEXRAD)

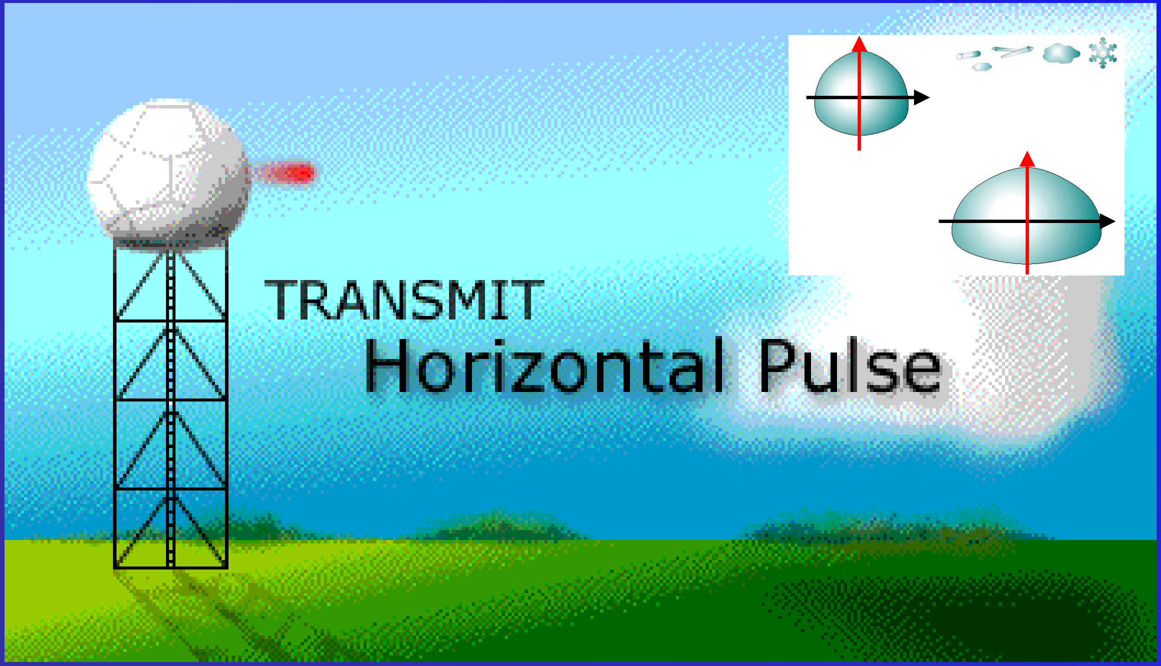



Polarimetric Radar (ARMOR)

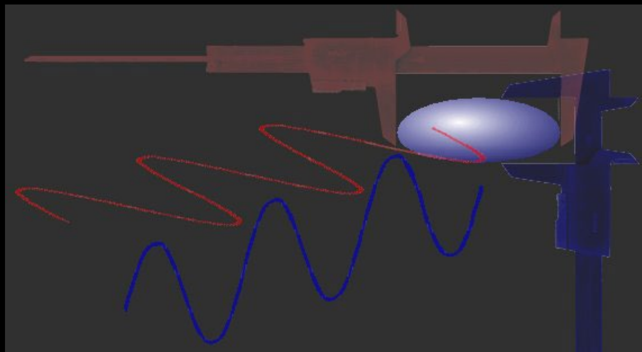


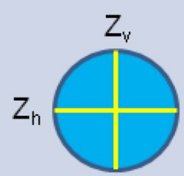
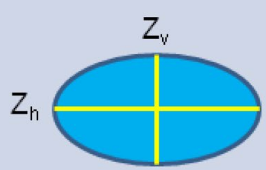



# ZDR is usually reported in logarithm form

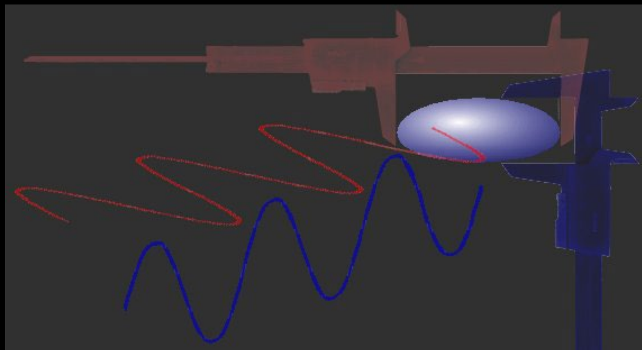


$$10\ log_{10}\left(\frac{Z_{horizonal}}{Z_{vertical}}\right)\ \text{dB}$$

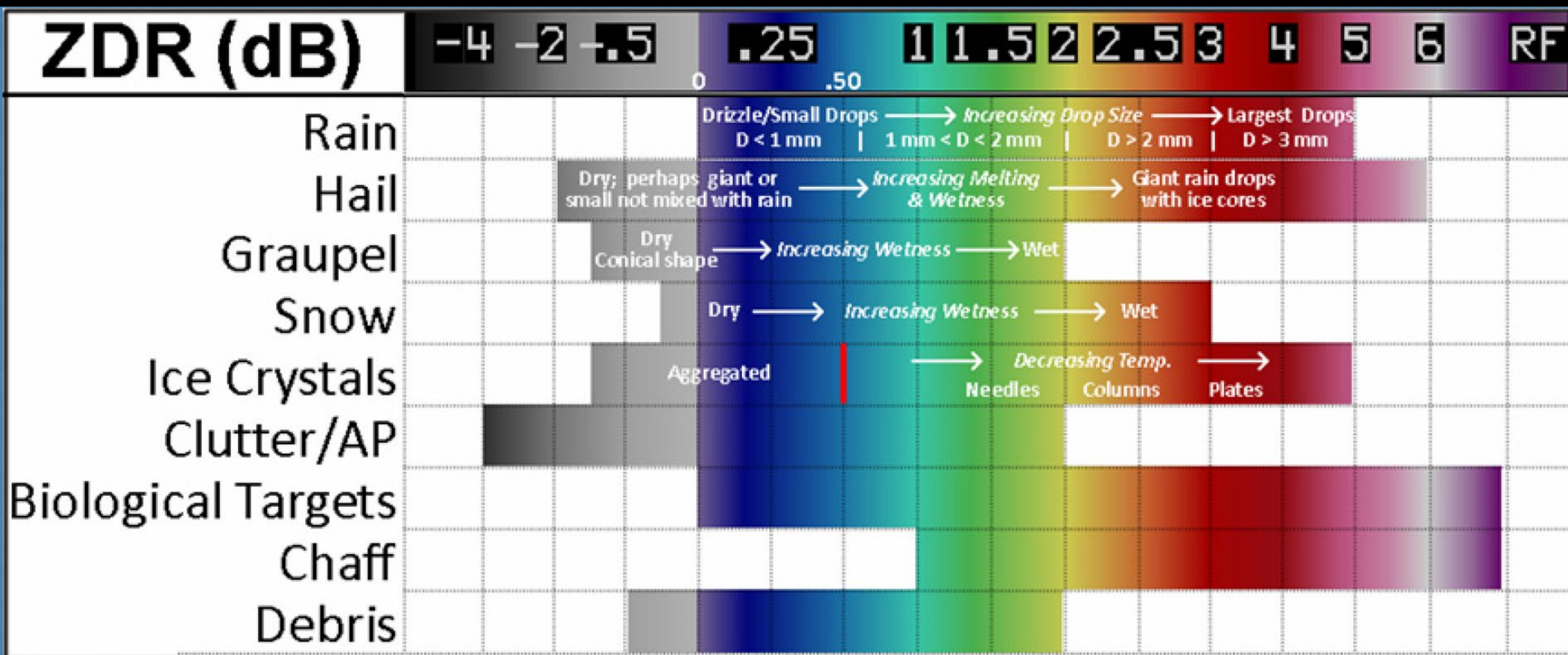
| **Spherical** (drizzle, small hail, etc.) | **Horizontally Oriented** (rain, melting hail, etc.) | **Vertically Oriented** (i.e. vertically oriented ice crystals) |
|---|---|---|
|   |  |  |
| $Z_h \sim Z_v$ | $Z_h > Z_v$ | $Z_h < Z_v$ |
| $10\log_{10}\left(\frac{Z_h}{Z_v}\right) \sim 0$ | $10\log_{10}\left(\frac{Z_h}{Z_v}\right) > 0$ | $10\log_{10}\left(\frac{Z_h}{Z_v}\right) < 0$ |
| ZDR ~ 0 dB | ZDR > 0 dB | ZDR < 0 dB |

*Adapted from Radar Operations Center notes*

# Typical $Z_{dr}$ Values



$$10\ log_{10}\left(\frac{Z_{horizonal}}{Z_{vertical}}\right)\ \text{dB}$$




*Adapted from Radar Operations Center notes*

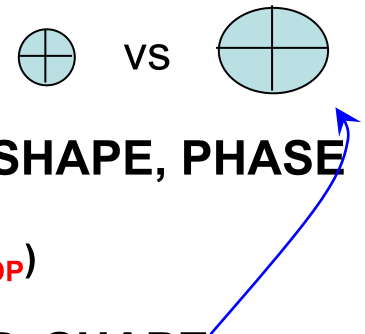
# Polarimetric Variables

1. **Reflectivity factor Z at horizontal polarization**

   - Measure of size and concentration of scatters

     (dominated by **SIZE**)

2. **Differential reflectivity $Z_{DR}$**

   - Measure of median drop diameter→ **SIZE**, **SHAPE**

   - Useful for rain / hail / snow discrimination→ **SIZE**, **SHAPE, PHASE**

3. **Differential phase $\Phi_{DP}$** **(Specific Differential Phase- $K_{DP}$)**

   - Efficient for accurate rainfall estimation→ **NUMBER, SHAPE**

   - Immune to radar miscalibration, attenuation, and partial beam blockage

4. **Correlation coefficient $\rho_{hv}$**

   - Indicator of mixed precipitation → **SHAPE, PHASE**

   - Efficient for identifying nonmeteorological scatterers

# Advantages of a Dual-Polarization Radar

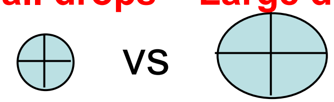
**A method for distinguishing hydrometeor types, rain, snow, hail, against debris, insects, birds, bats, etc.**

- **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!**

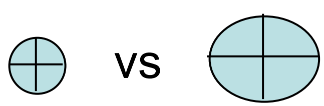
**Small ZDR**
**Small drops**

**Large ZDR**
**Large drops**

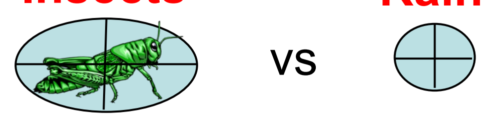



- **Identification of precipitation types and discrimination between meteorological and non-meteorological scatterers**

**Hail** **Rain**



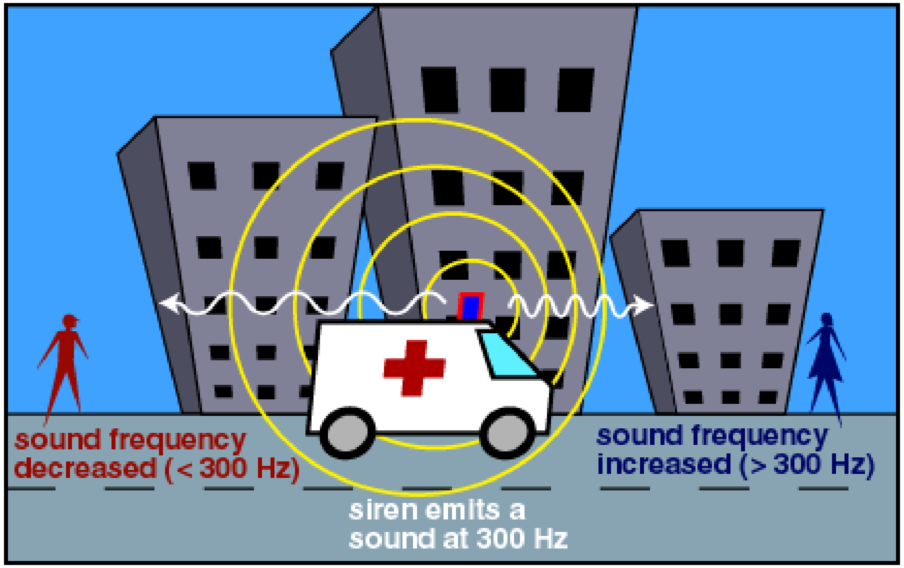

**Insects** **Rain**




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

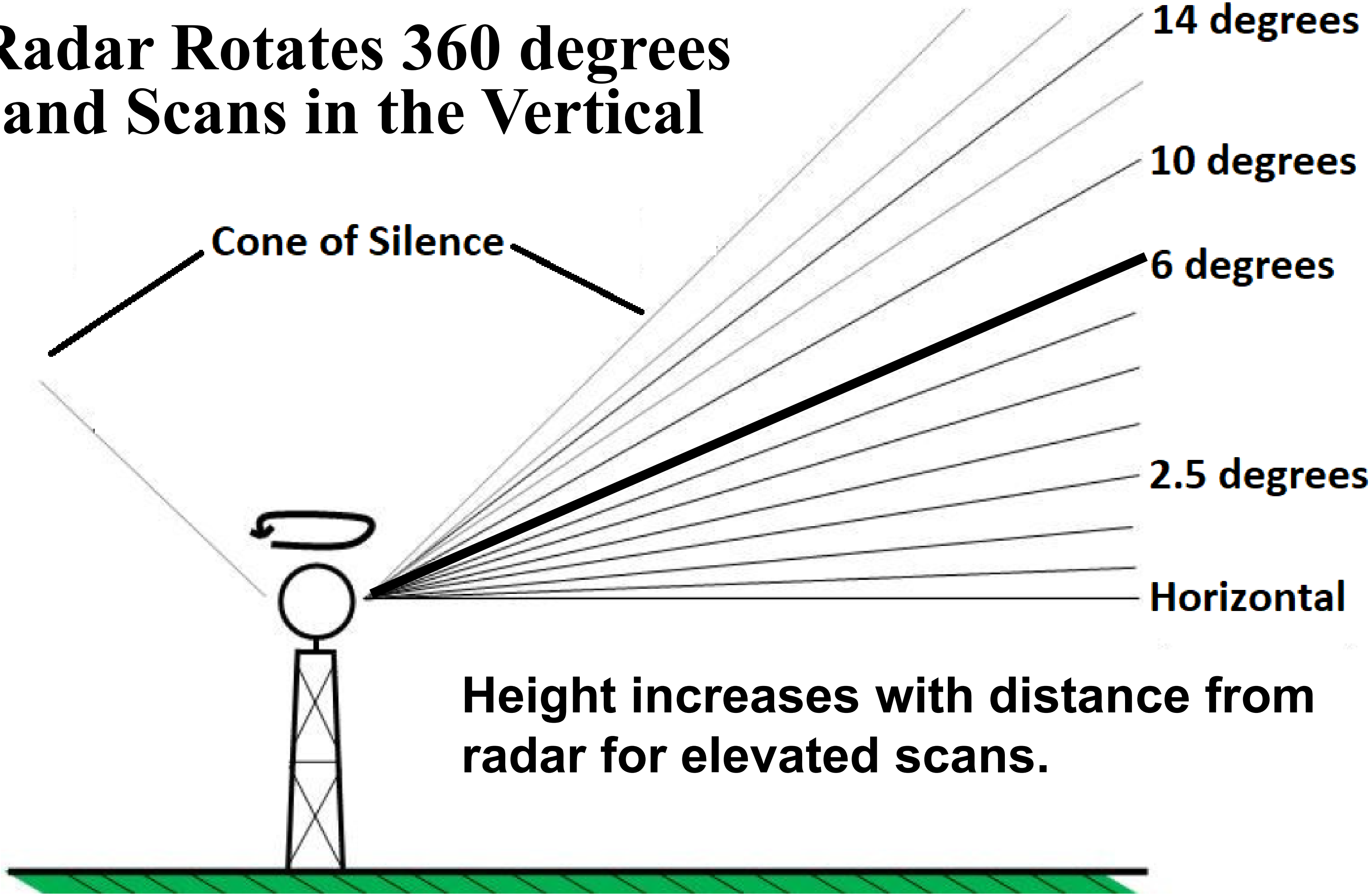
# Doppler Effect: Frequency Change Due to Relative Motion

- No Doppler shift perpendicular to the direction of motion
- $\Delta f = V/\lambda = Vf_0/c$ where $V = \vec{V} \cdot \hat{r}$.
  $\vec{V}$ is the wind vector.
  $\hat{r}$ is a unit vector that goes from the point of interest to 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

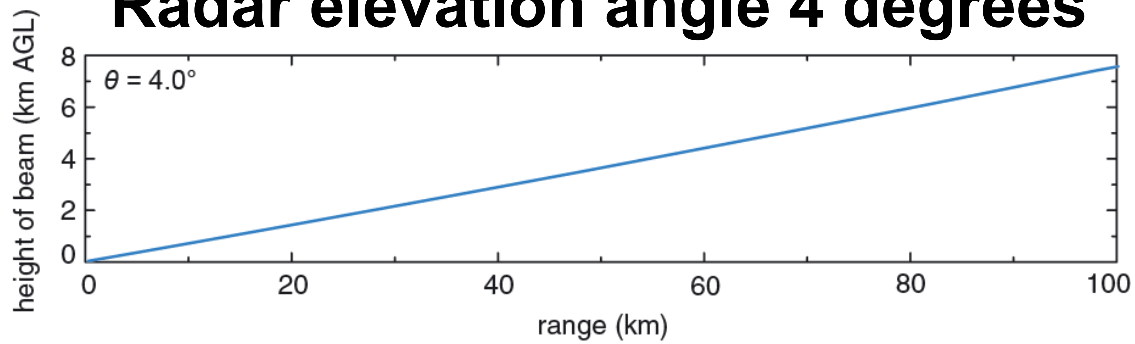



The **base reflectivity** images in Precipitation Mode are available at four **radar "tilt" angles**, 0.5°, 1.45°, 2.40° and 3.35°

# Doppler examples: Radar is in the Center

**Wind increasing with height**

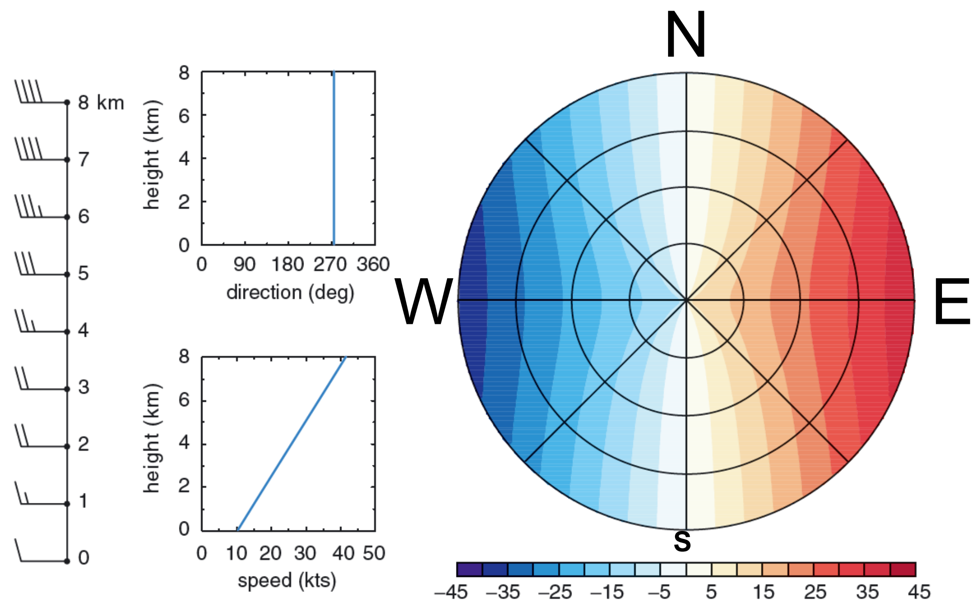

**Example:**
**Radar elevation angle 4 degrees**




**Wind convention**
**1 knot=1.15 mph**

Blue colors:
Wind towards radar.
Named inbound wind.

Red colors:
Wind away from radar.
Named outbound wind.



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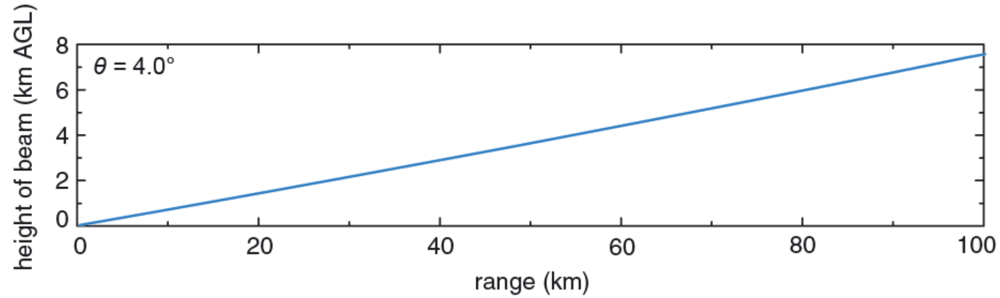
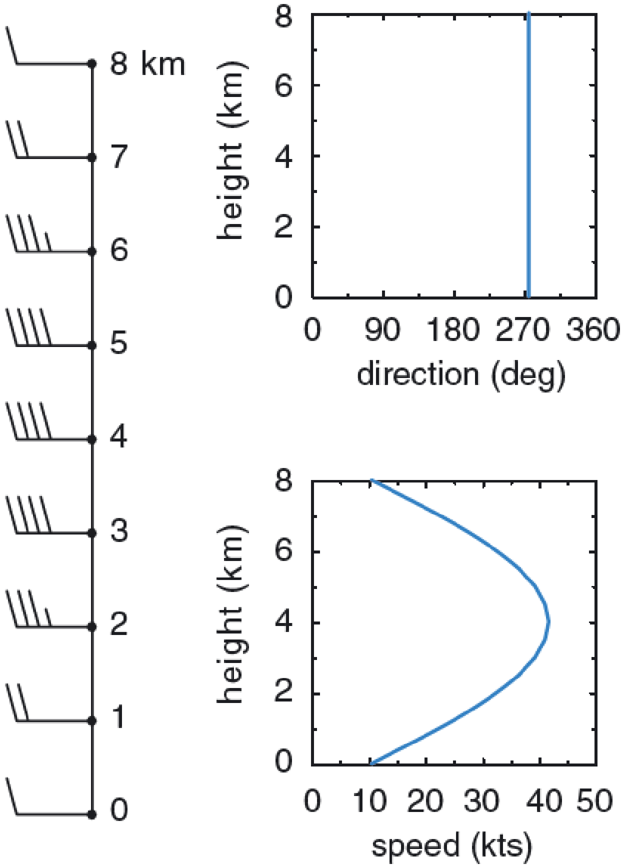
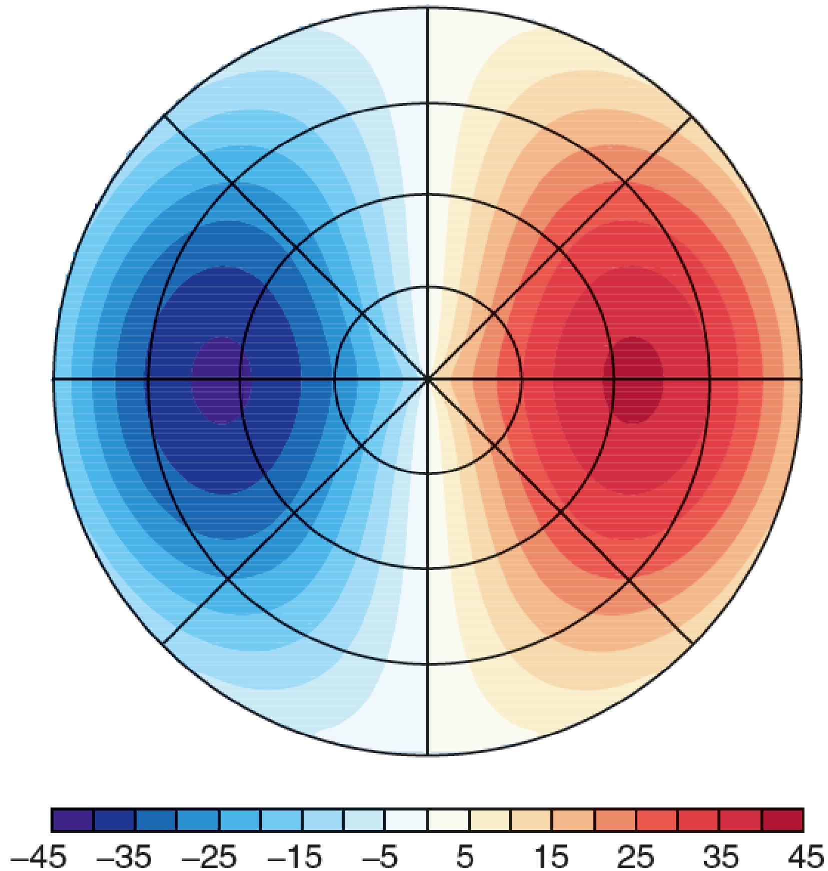
## Radar elevation angle 4 degrees



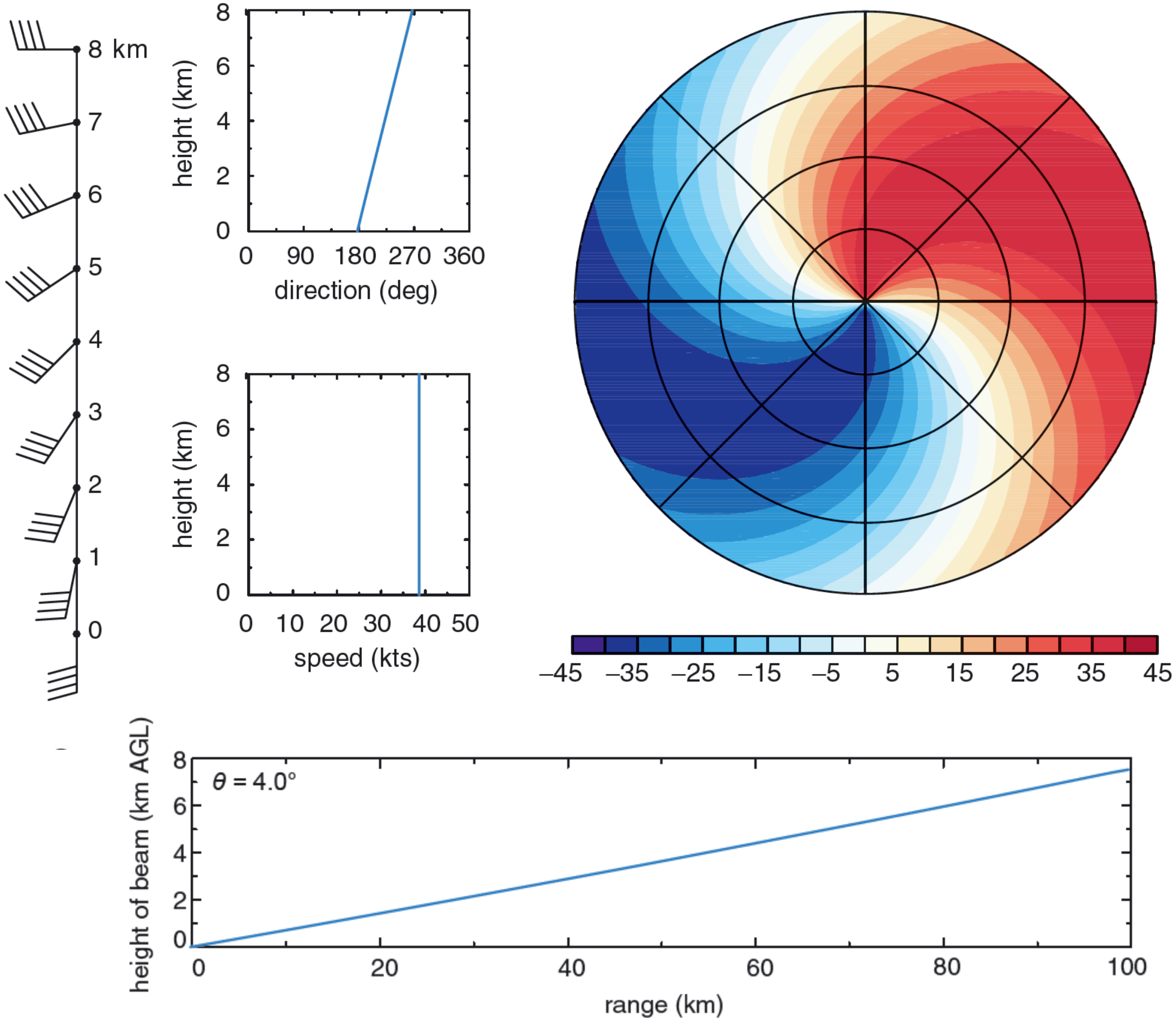
# Veering Wind

**CVW**:

**C**lockwise rotation of wind with height.

Known as **v**eering wind.

**W**arm air moving in.



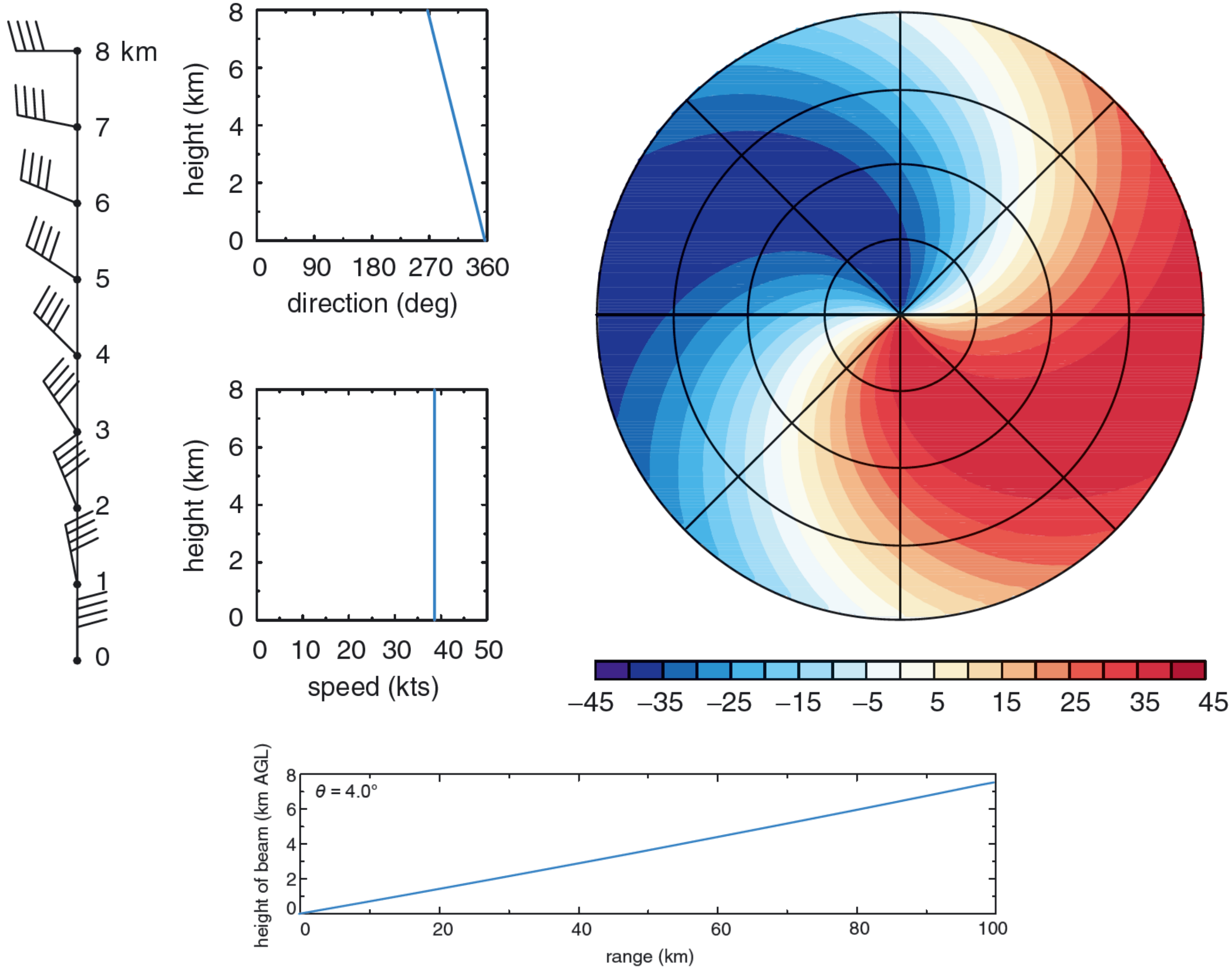
# Backing Wind

**CCBC:**

**C**ounter-**c**lockwise rotation of wind with height.

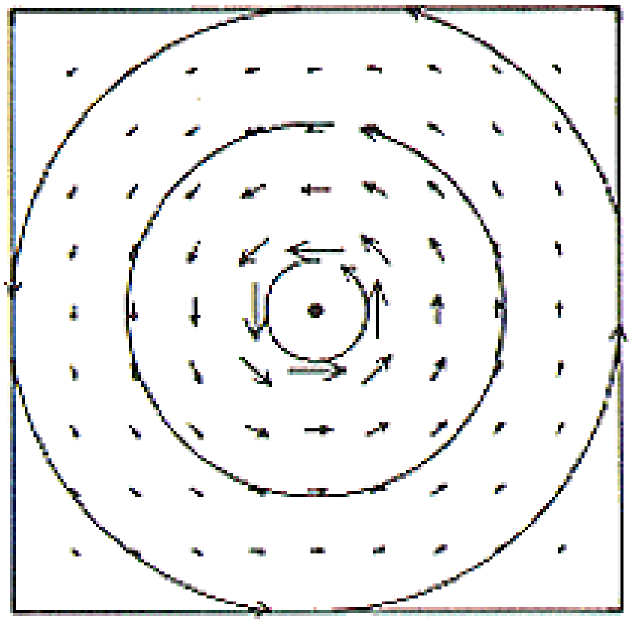
Known as **b**acking wind.

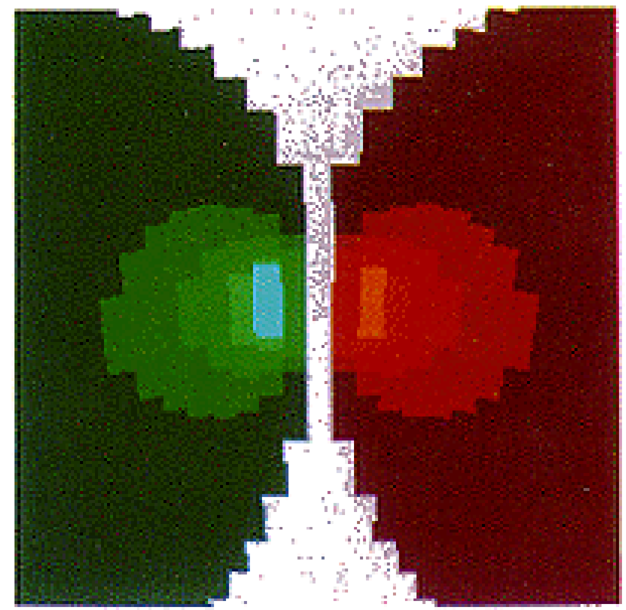
**C**old air moving in.



# Rotation: Tornado

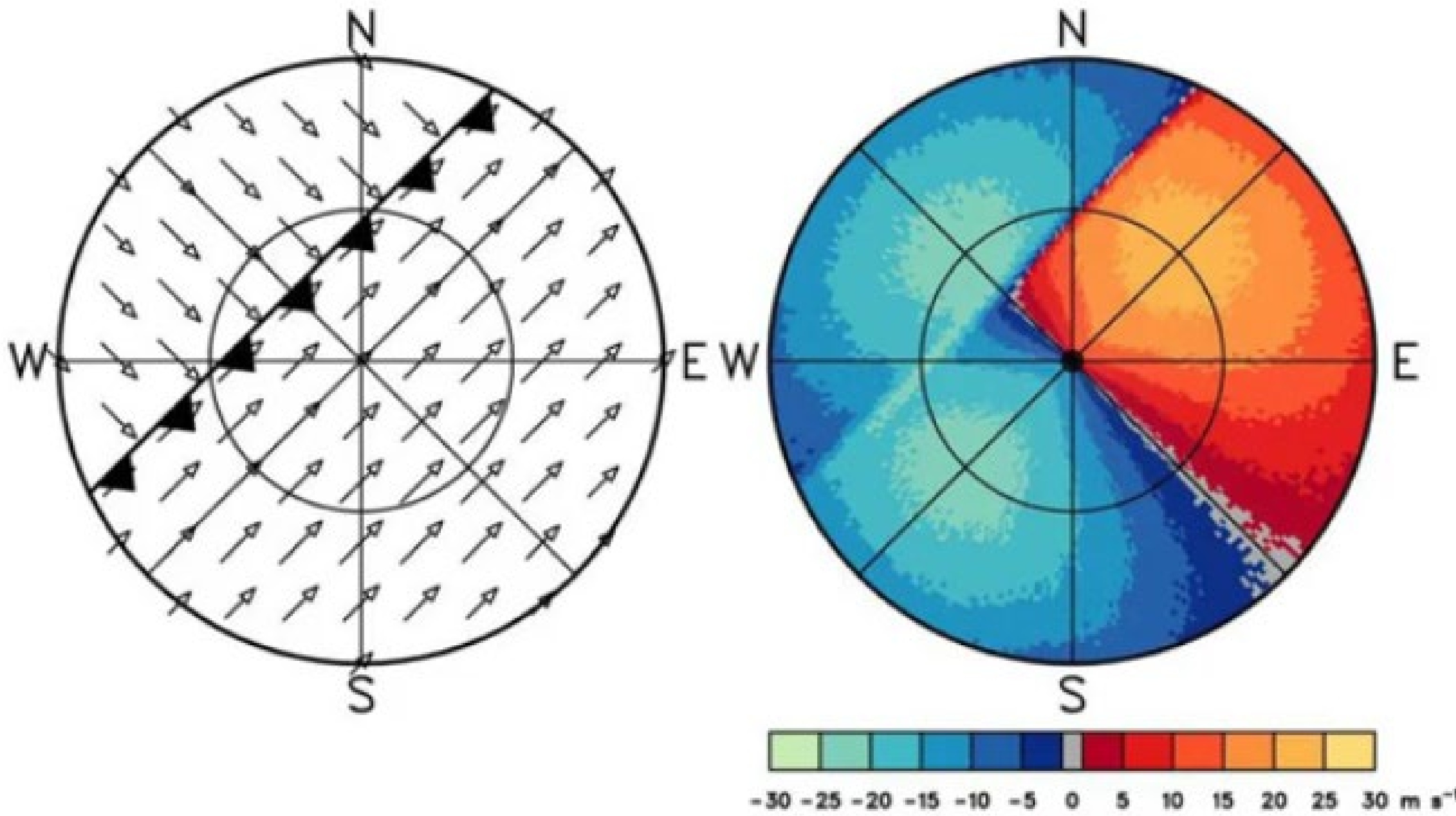
Note intense flow near center.
Tornado not right over the radar.



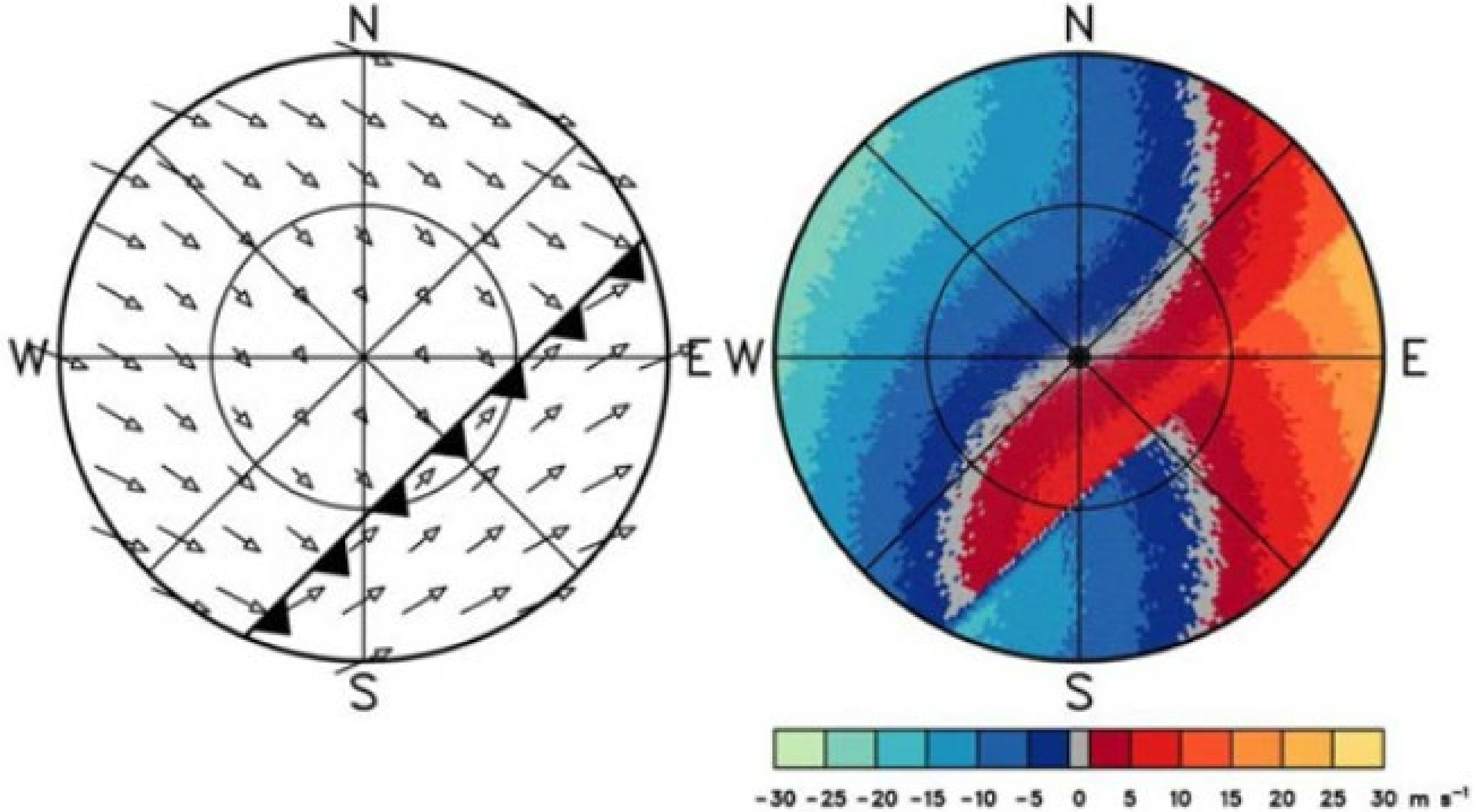


○ Radar location relative to rotation

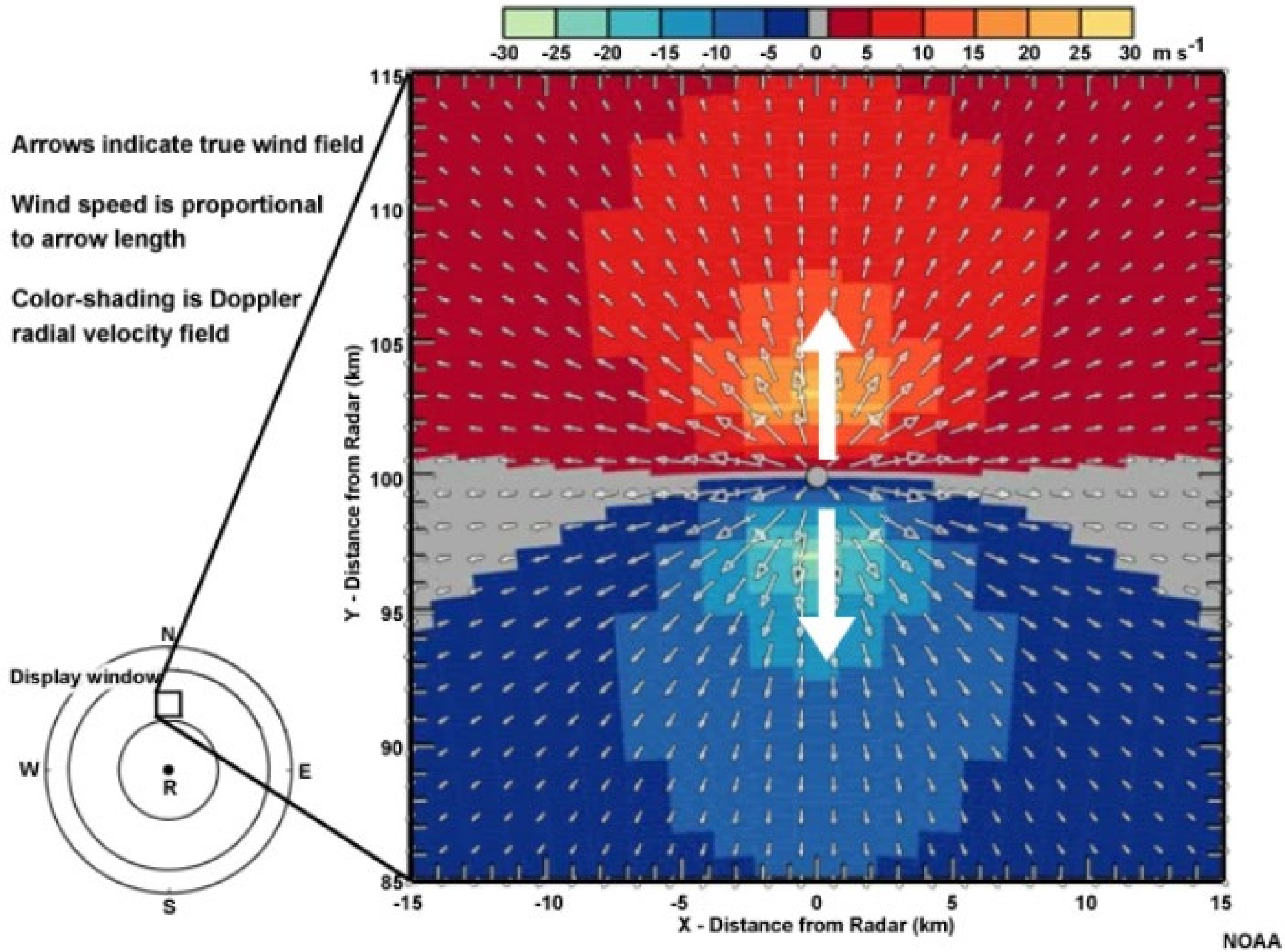
# Incoming Cold Front And Constant Flow:



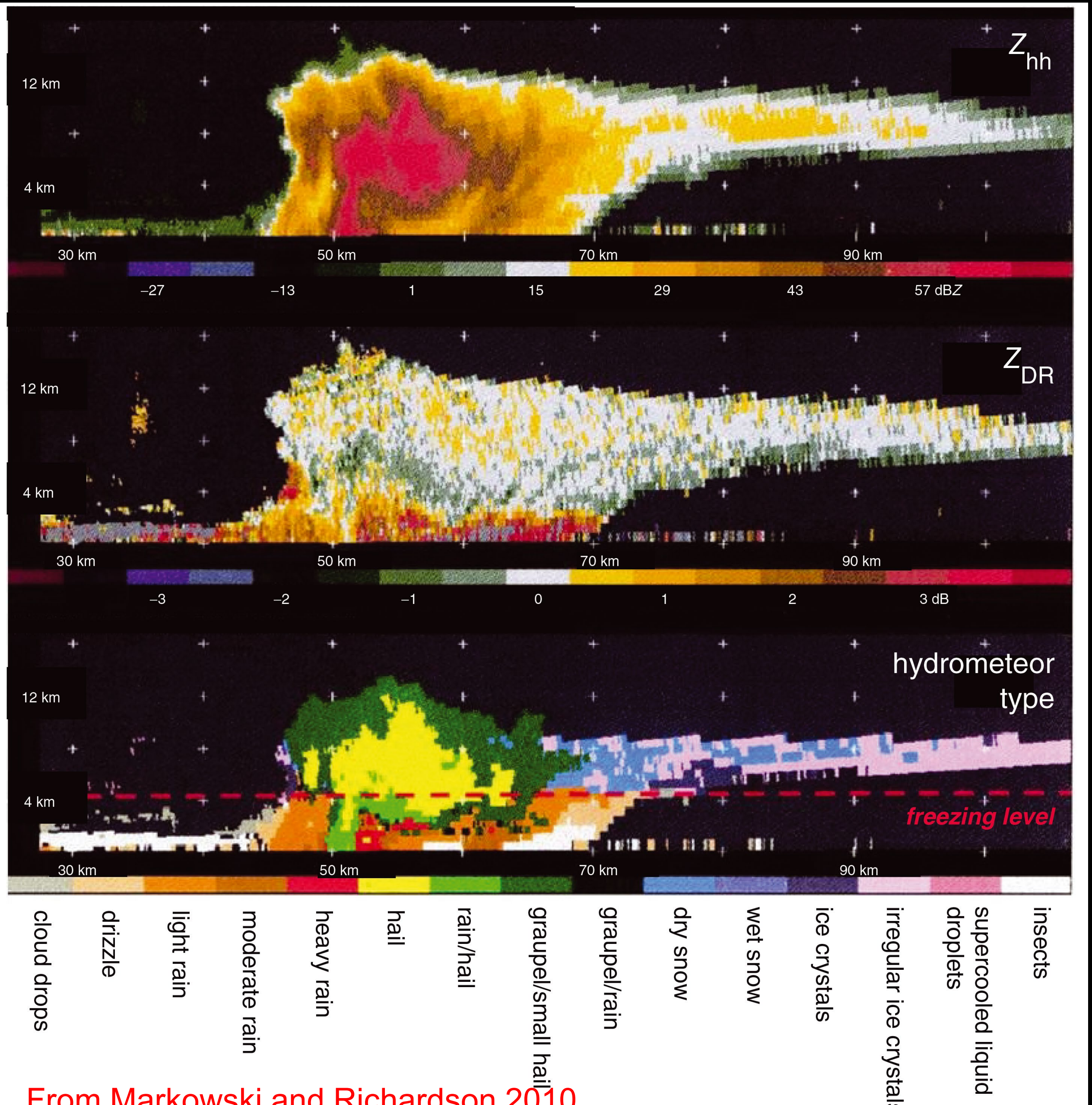
# Outgoing Cold Front Veering and Backing Winds:



# Divergence: For example, from a thunderstorm downdraft

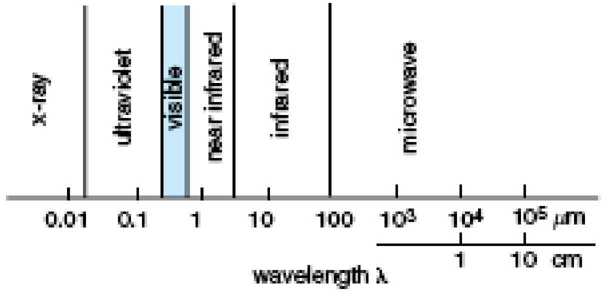


# Putting it all together…spatial and temporal variation of storms

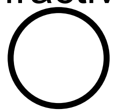



From Markowski and Richardson 2010

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



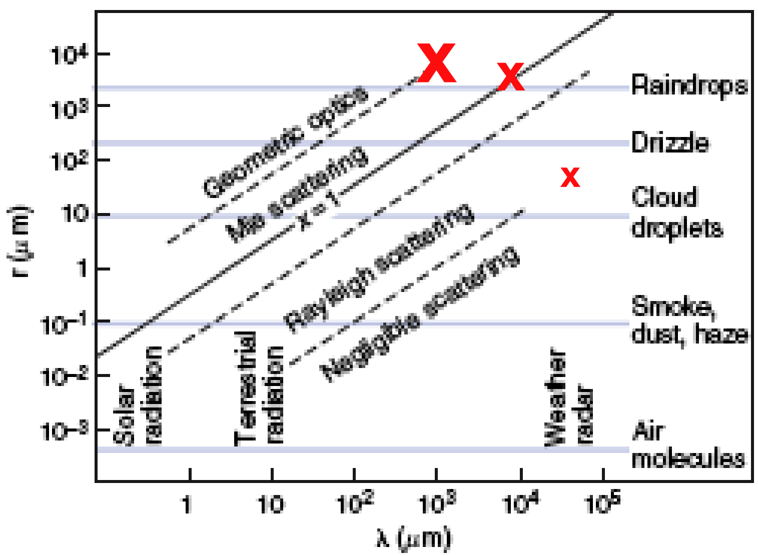

Sphere, radius r, complex refractive index $n=m_r + im_i$



Dimensionless Parameters:

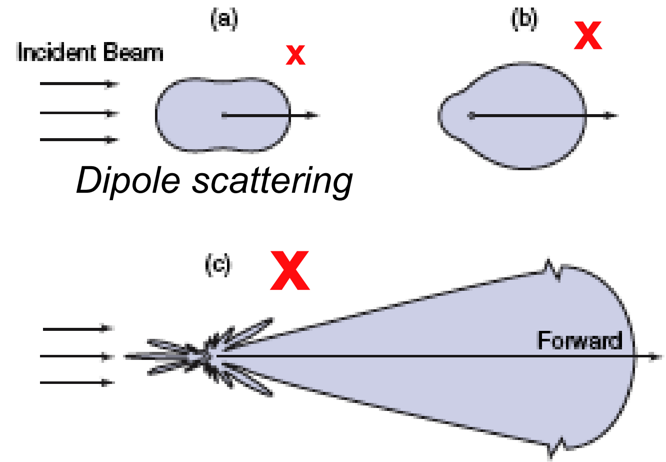
Size Parameter=$x=\frac{2\pi r}{\lambda}$

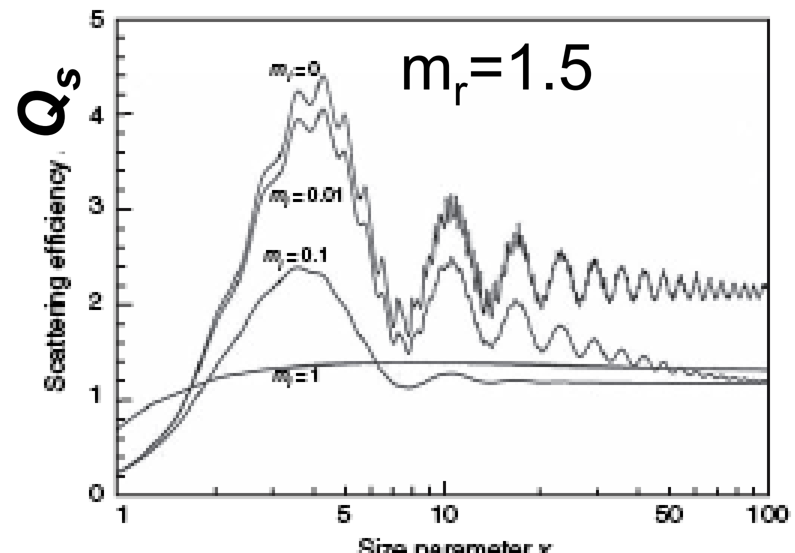
Scattering Efficiency=$Q_s=\frac{\sigma_{sca}}{\pi r^2}$




***Lines***: $r=\frac{x}{2\pi}\lambda$

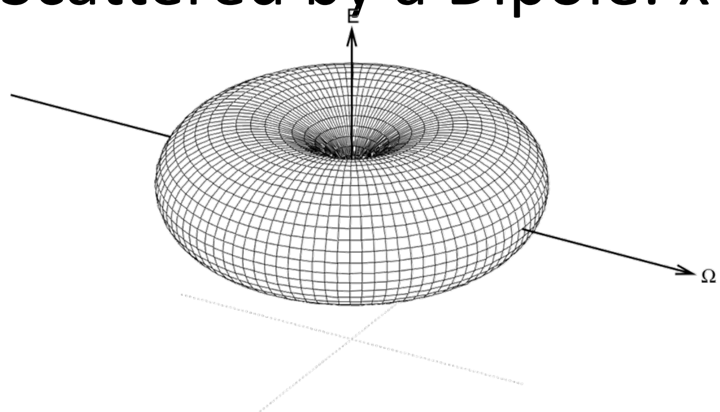
Angular Distribution of scattered radiation (phase function)



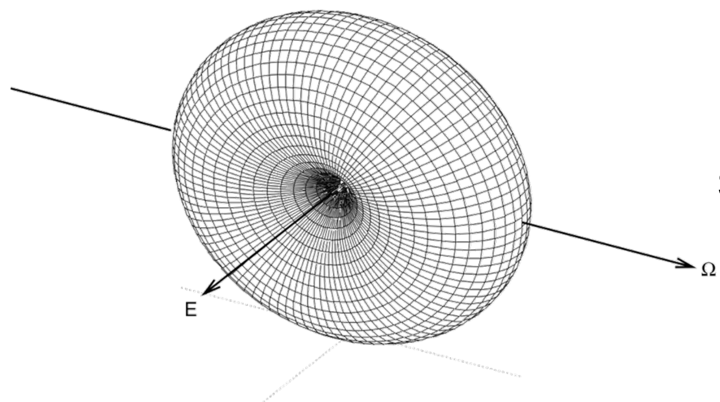



# Rayleigh Scattering Phase Function: Angular Distribution of Light Scattered by a Dipole: x << 1

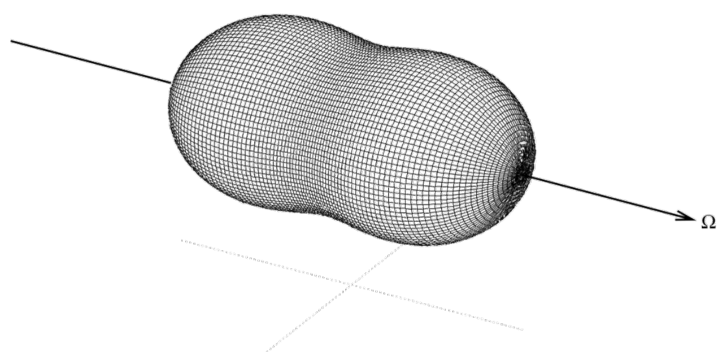
3D rendering




vertical polarization state



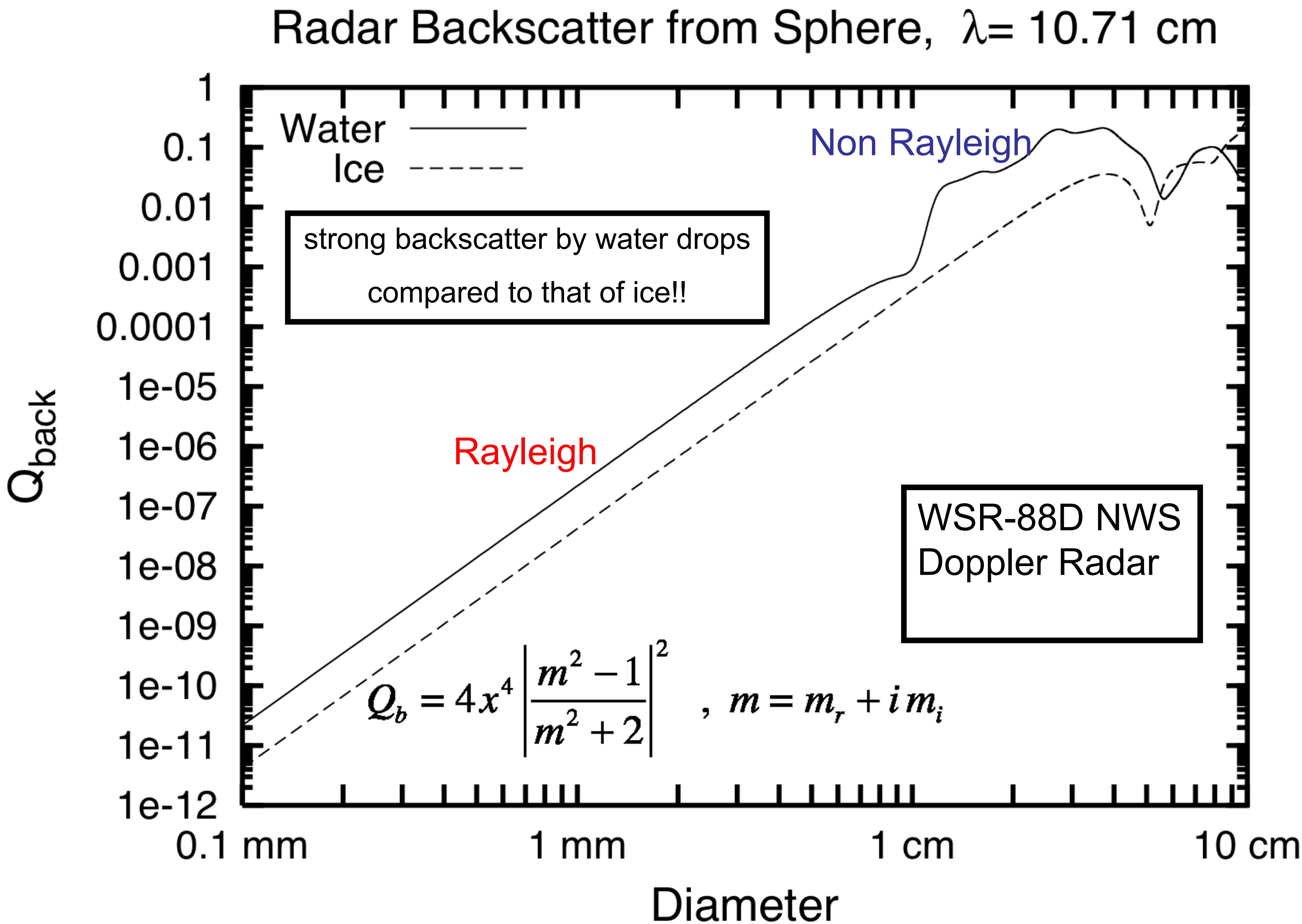

horizontal polarization state




The Peanut!
Average of both polarization states.

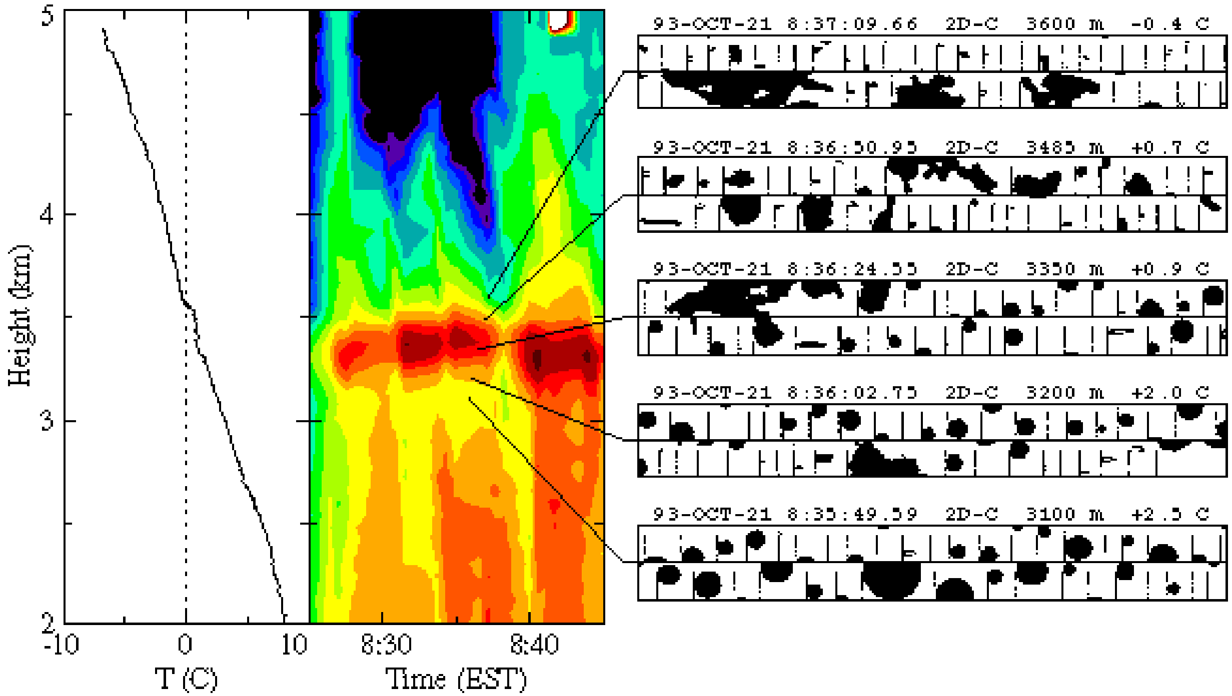
Pat Arnott, ATMS360

# Mie Radar Backscatter Efficiency for Water and Ice Spheres



# Radar Bright Band: Strong Scattering from Melting Hydrometeors

Melting level




Snowflakes

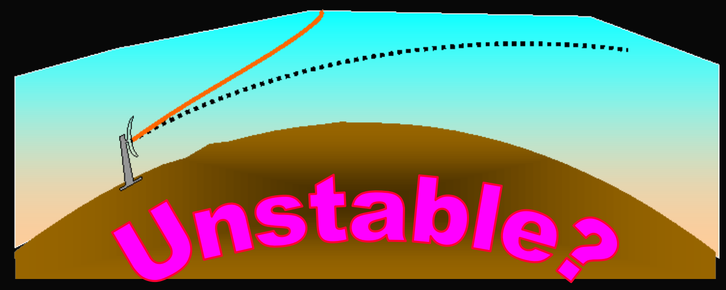
Raindrops

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

http://www.radar.mcgill.ca/bright_band.html

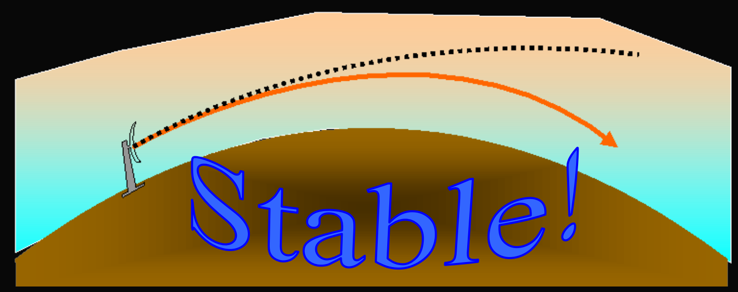
# abnormal atmospheric conditions

subrefraction



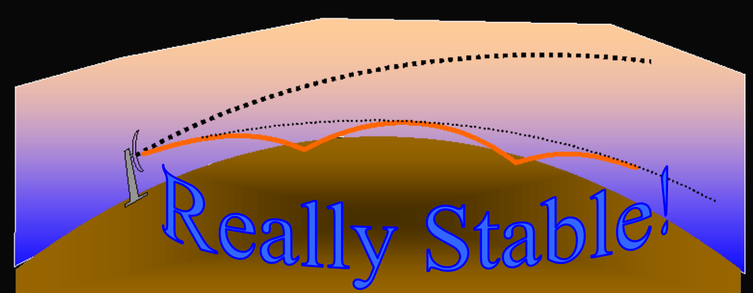

cool, moist air aloft
warm, dry air below

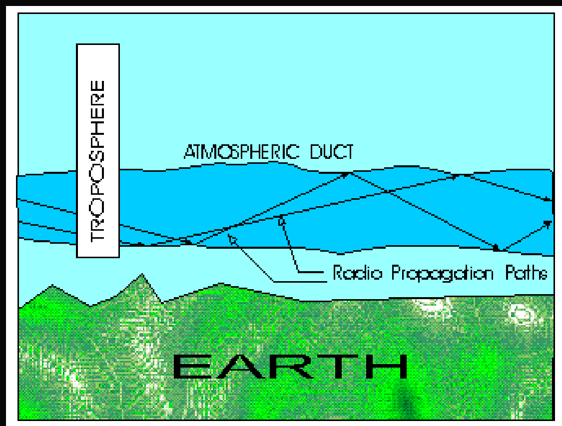
superrefraction




warm dry air aloft
cool, moist air below

ducting

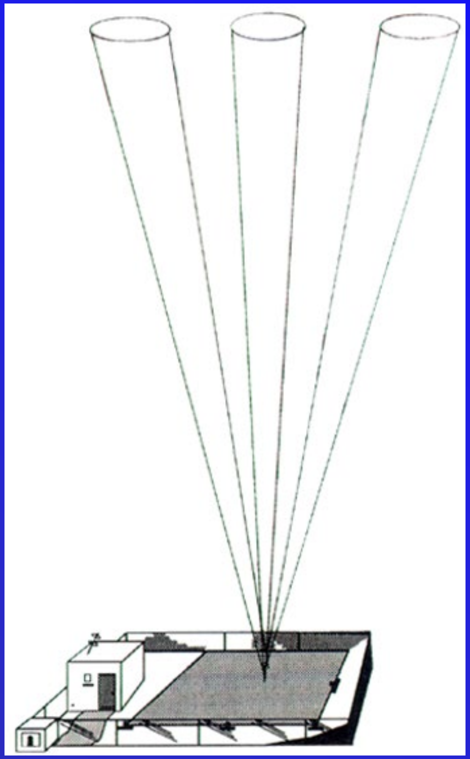



atmospheric ducting

## *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