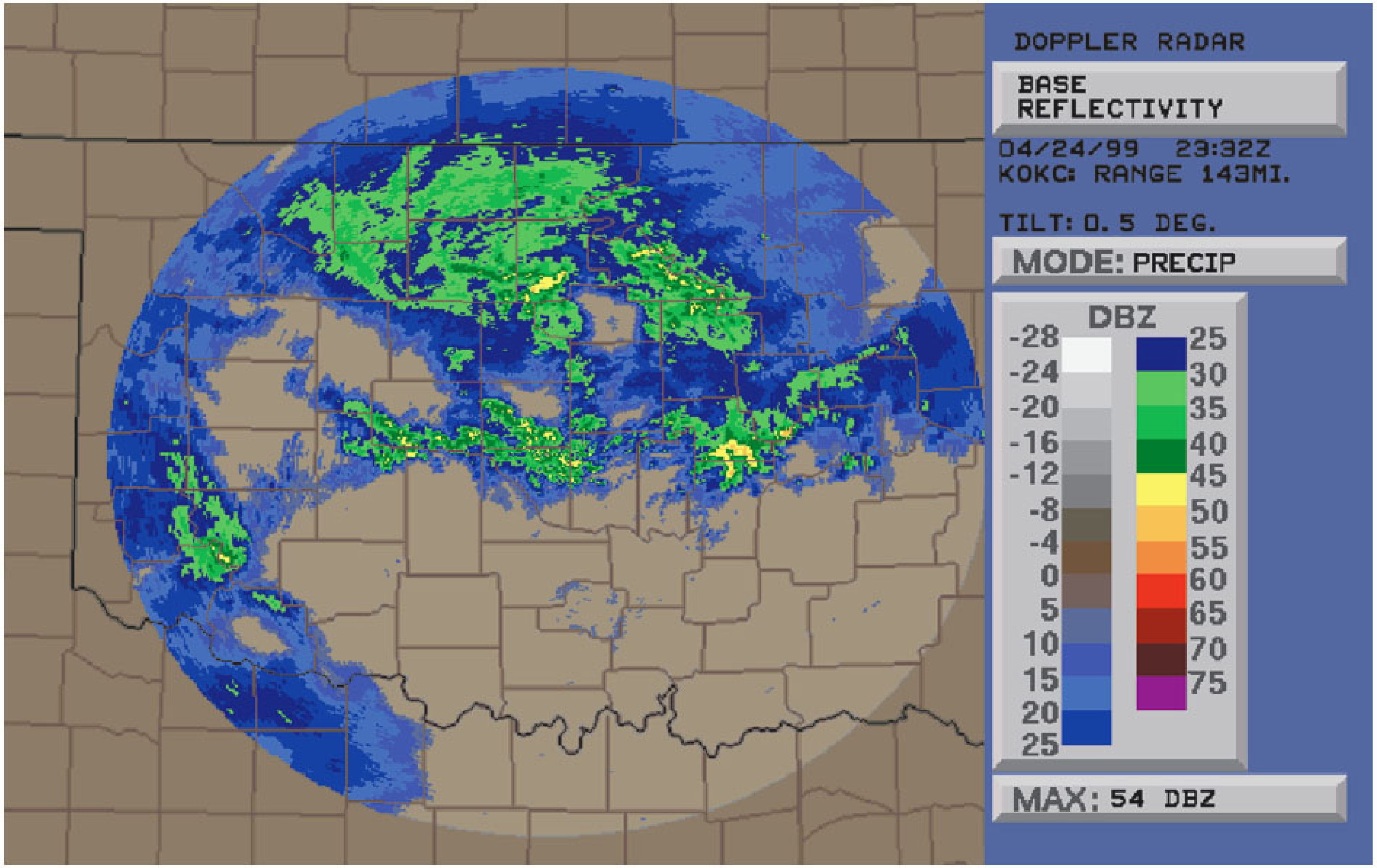
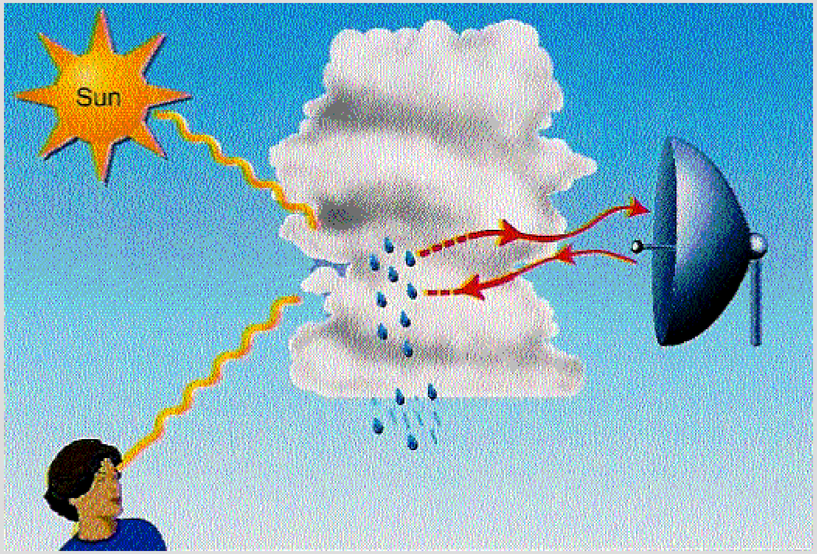
Atmospheric radar primer

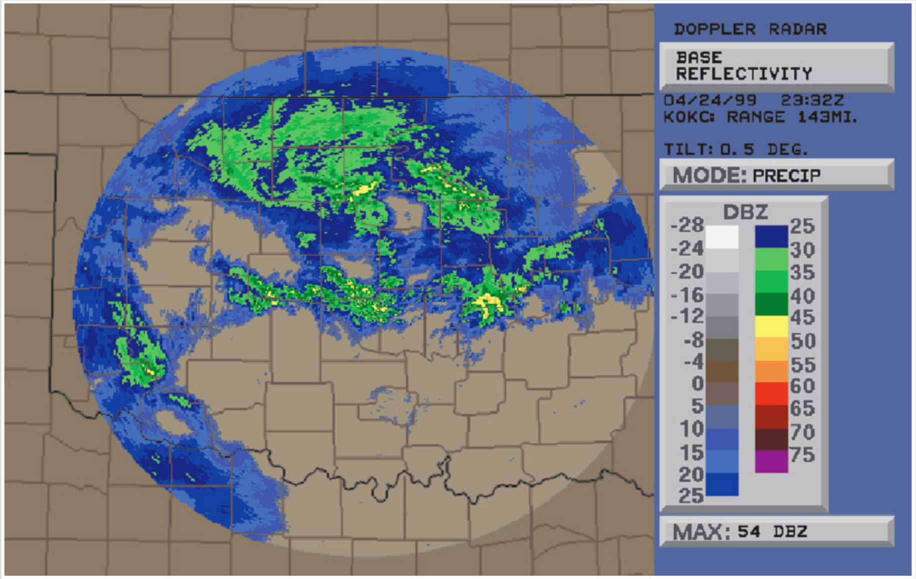
A vitally important source of observational data on the mesoscale—and it even helped to define ‘the mesoscale’ in the first place!

RADAR = ???


DOPPLER RADAR
BASE REFLECTIVITY
04/24/99 23:32Z
KOKC: RANGE 143MI.
TILT: 0.5 DEG.
MODE: PRECIP
DBZ
-28
-24
-20
-16
-12
-8
-4
0
5
10
15
20
25
25
30
35
40
45
50
55
60
65
70
75
MAX: 54 DBZ

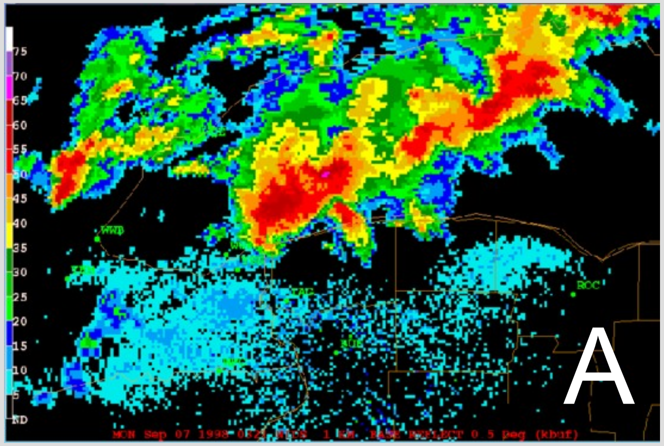
RADAR
(<u>RA</u>dio <u>D</u>etection <u>A</u>nd <u>R</u>anging)

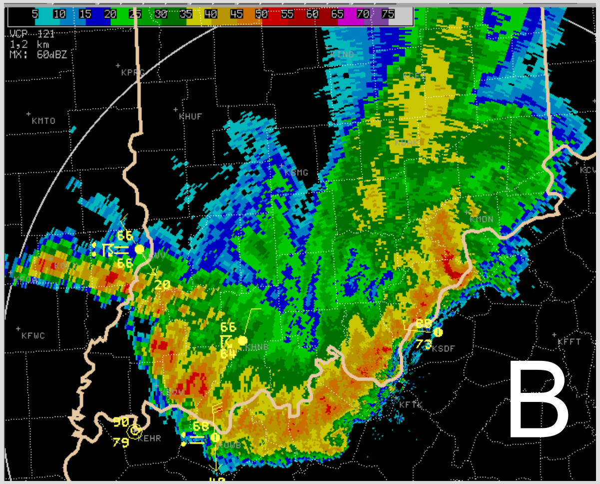


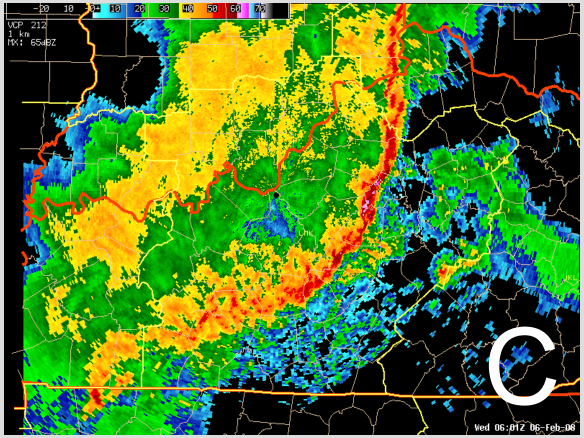


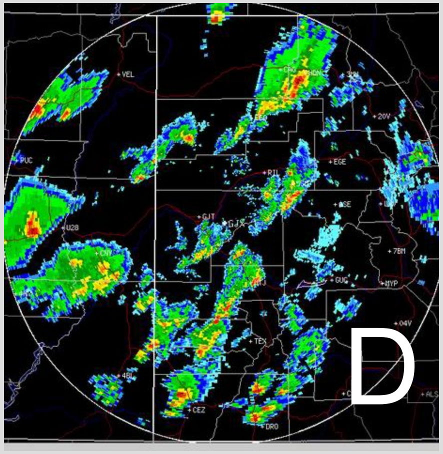
<u>Principle</u>: Detects reflected radiation emitted for short wavelength radio waves. The degree of reflectivity corresponds with the intensity of precipitation (or what ever else in the beam path).

REFLECTIVITY





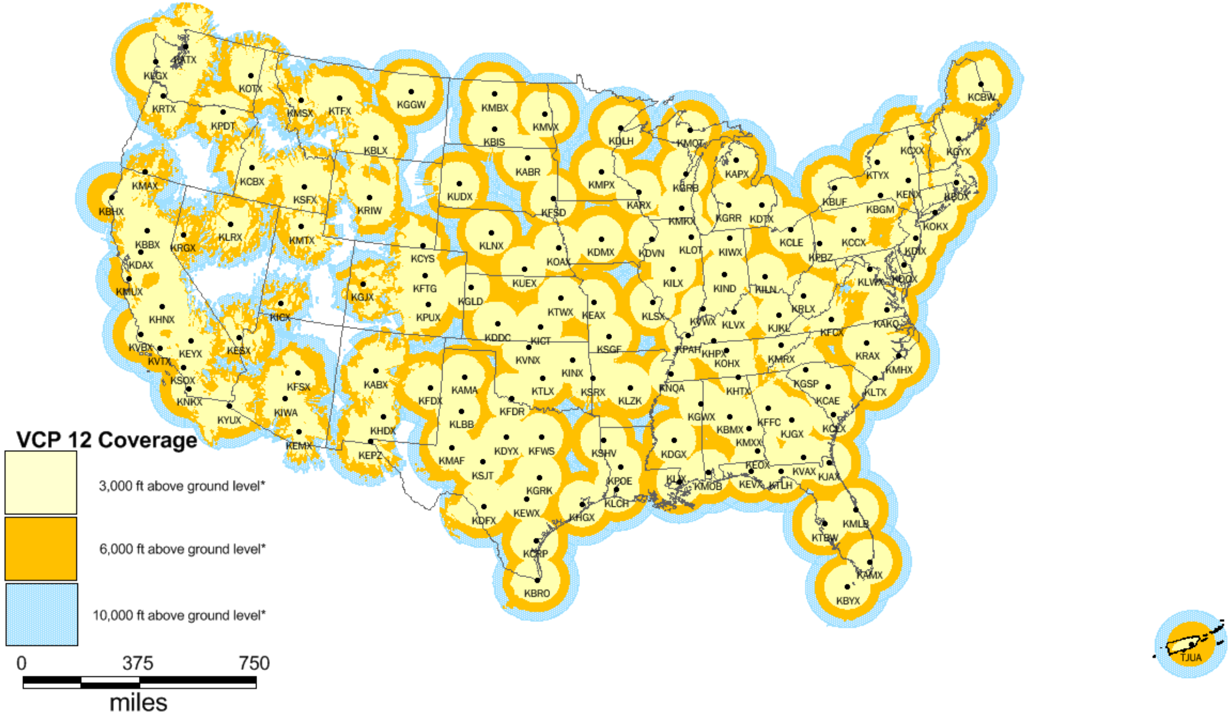




For our purposes, want to know basics of data from WSR-88D NEXRAD radar system in CONUS

https://www.weather.gov/iwx/wsr_88d

NEXRAD COVERAGE BELOW 10,000 FEET AGL



*Center of beam height (assuming Standard Atmospheric Refraction)
Terrain Blockage Indicated where 50% or more of beam blocked

https://www.roc.noaa.gov/WSR88D/

How does radar work? Transmission

Transmission of microwaves that interact with hydrometeors as they propagate through atmosphere.

Range of frequencies 3-10 GHz.

Transmitted waves are focused into concentrated beam by (rotating) antenna

When radar beam hits a hydrometeor target energy is absorbed and scattered.

Some of the radar beam signal is attenuated as it passes through the atmosphere, meaning the signal is scattered or absorbed in the atmosphere in other directions.

Why do radars operate on the low energy end of the EM spectrum?

Want long, low-frequency waves because can then be in a Rayleigh scattering regime with respect to most hydrometeors (e.g. raindrops).

Size of the target small relative to the wavelength, so scattered energy is just proportional to sixth power of diameter of target. Majority of energy is backscattered.

If wavelengths were smaller, then would fall in Mie scattering regime, where there would be greater forward scattering. So the scattering equation would be much more complicated and difficult to solve.

Long wavelengths have less attenuation.

How does radar work?
Signal reception

A receiver detects, amplifies and converts reflected signal back to radar device.

Backscattered power is 18 orders of magnitude less than what is originally transmitted.

Range of backscattered power can vary by 9 orders of magnitude, depending on the hydrometeors, so this requires a logarithmic scale for radar reflectivity.

A pulse repetition frequency of 1000 Hz allows for detection of backscattered signals every few 10s of m.

Additional algorithmic processing of the raw data necessary to generate the WSR-88D radar images we would actually see, beyond the scope of what we need to cover here…

Reflectivity (Z)

$$Z = 10\ \log_{10}\left(\frac{z}{1\ \mathrm{mm}^6/\mathrm{m}^3}\right),$$

Units of dBZ: decibels relative to 1 unit reflectivity factor

z = reflectivity factor

$$z = C\,P_\mathrm{r}\,r^2,$$

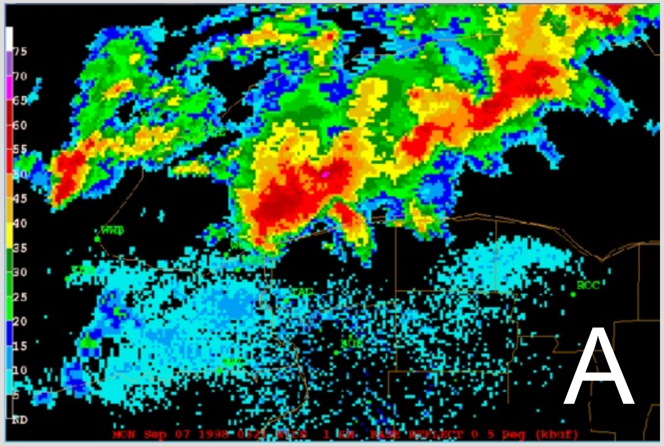
P_r = received backscattered power

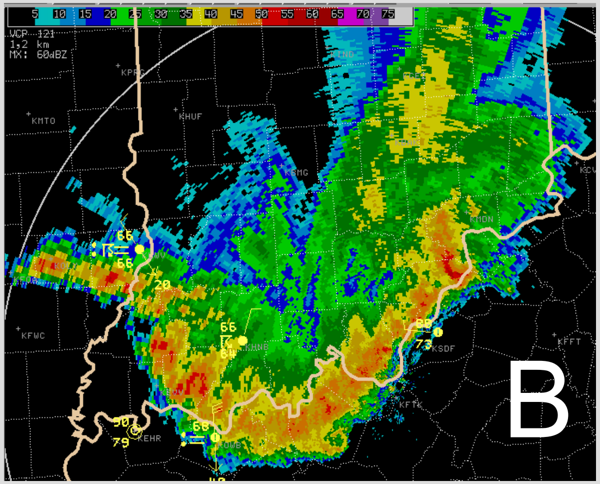
r = distance to target

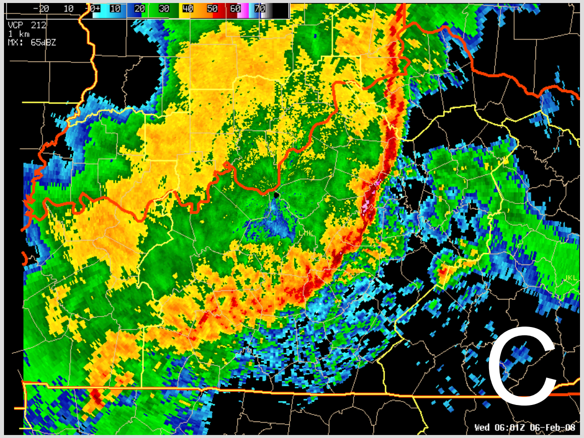
C = radar constant

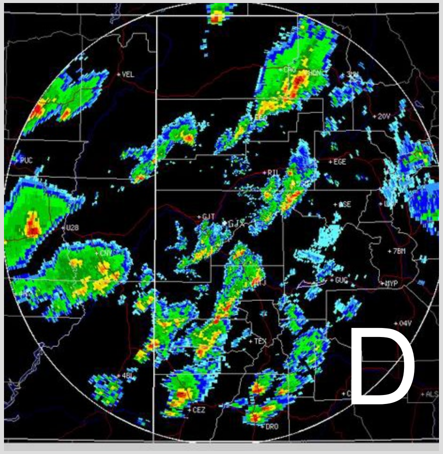
Note that the backscattered power follows a $1/r^2$ relationship.

REFLECTIVITY


A


B


C


D

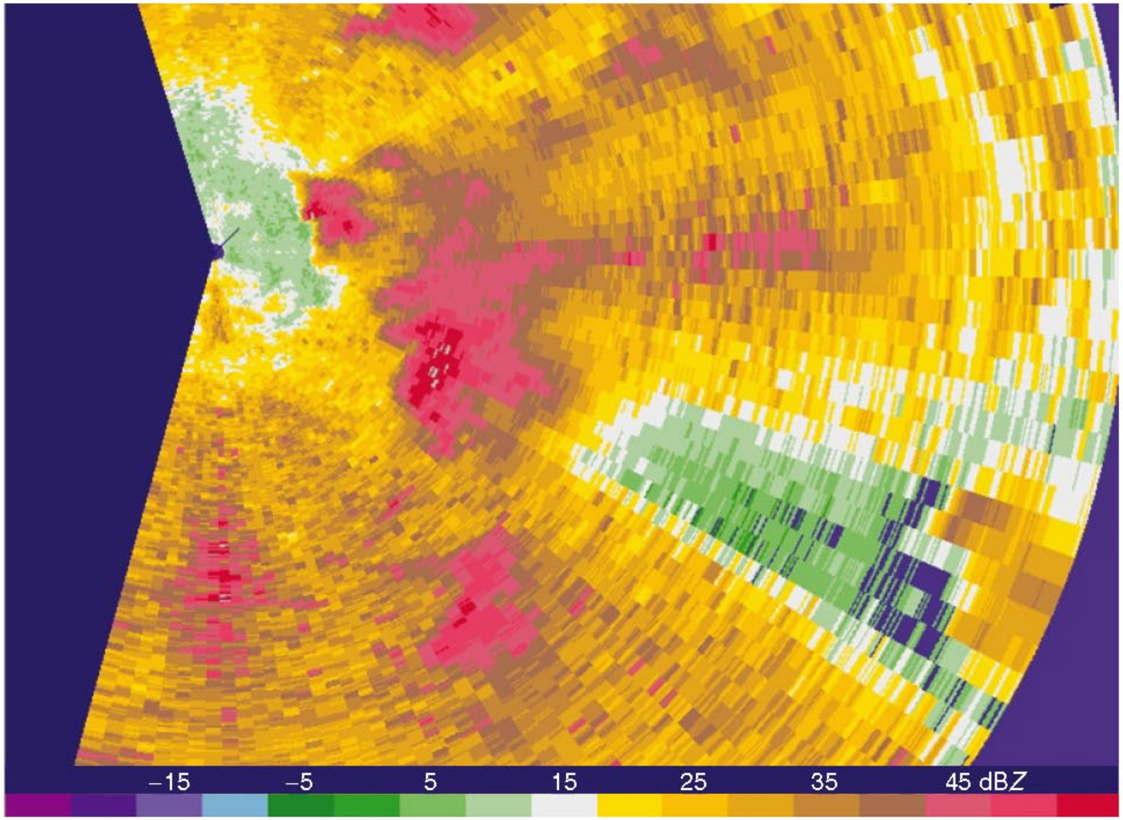


Figure A.1 When relatively short wavelengths are used, both scattering and absorption are significant, and attenuation can be severe. In this example, a 5-cm radar mounted in the tail section of an aircraft is scanning a broken line of severe thunderstorm from the west. Significant loss of power is occurring within the heavy precipitation core (which likely contains large hail) located southeast of the radar; thus, the reflectivity at ranges beyond this heavy precipitation core has been underestimated.

Considerations in choice of radar system design in relation to wavelength

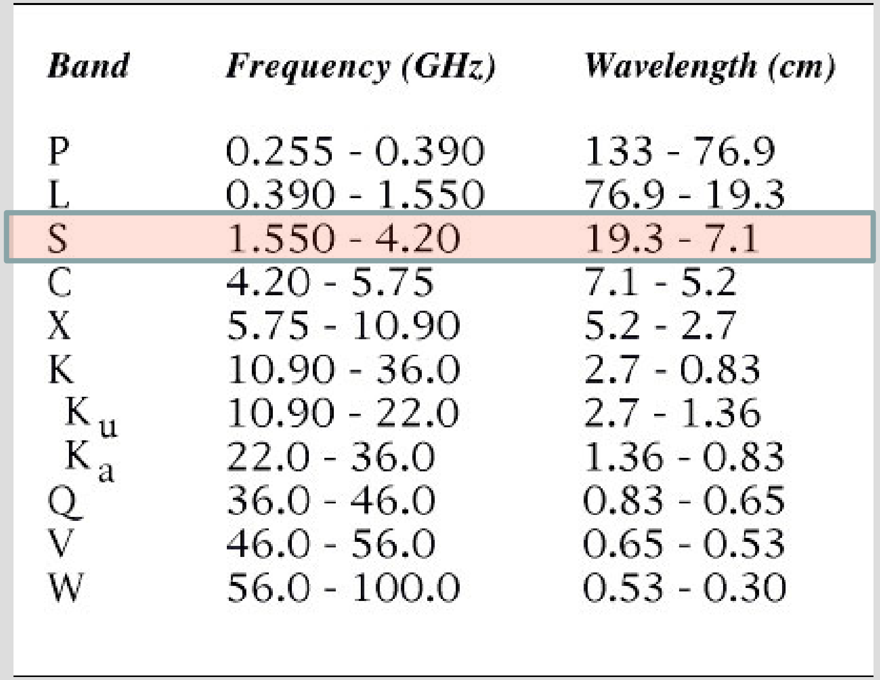
Sensitivity: Can detect targets at sufficient range?

Resolution: Enough frequency of pulses to resolve target, motion?

What types of targets want to focus on?

Attenuation of beam

Cost: Shorter wavelength is cheaper, devices more easily mobile.



Band	*Frequency (GHz)*	*Wavelength (cm)*
P	0.255 - 0.390	133 - 76.9
L	0.390 - 1.550	76.9 - 19.3
S	1.550 - 4.20	19.3 - 7.1
C	4.20 - 5.75	7.1 - 5.2
X	5.75 - 10.90	5.2 - 2.7
K	10.90 - 36.0	2.7 - 0.83
K_u	10.90 - 22.0	2.7 - 1.36
K_a	22.0 - 36.0	1.36 - 0.83
Q	36.0 - 46.0	0.83 - 0.65
V	46.0 - 56.0	0.65 - 0.53
W	56.0 - 100.0	0.53 - 0.30

WSR-88D system is S-band radar system, with wavelength of 10 cm.

Location of target

Function of

1. Azimuth angle: Angle of beam with respect to north
2. Elevation angle: Angle of beam with respect to horizontal
3. Distance to target

Radar beam is pointed at an elevation angle > 0, so that the beam height increases with range, so further out away from the radar you are looking up higher in the atmosphere. So probably don't trust the radar signatures at very edge of the system's range!

Distance traveled (r)

$$r = \frac{ct}{2},$$

t = pulse travel time

c = speed of light

Effects of Earth's curvature and refraction on beam path

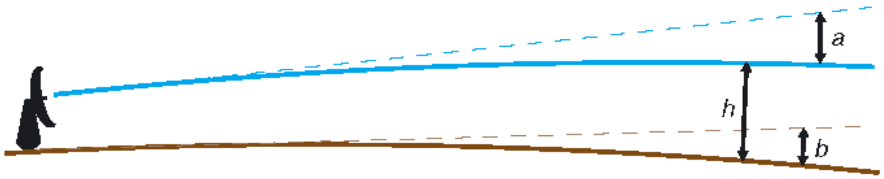


Figure A.2 Effect of Earth's curvature and refraction on the height of distant targets above the ground. The solid blue line is the path of the transmitted and reflected beam, and the solid brown line is the Earth's surface (the curvature is somewhat exaggerated for illustrative purposes). The dashed blue line is the path that the beam would take in the absence of refraction. The dashed brown line represents the line tangent to the Earth's surface at the location of the radar. The Earth's radius and oblateness determine a, and the variation of static stability along the beam determines b (usually a standard atmosphere is assumed). The height of targets above the ground (h) is known if a and b are known.

Base reflectivity: NWS definition

This is a display of echo intensity (reflectivity) measured in **dBZ** (decibels of Z, where Z represents the energy reflected back to the radar). "Reflectivity" is the amount of transmitted power returned to the radar receiver. Base Reflectivity images are available at several different elevation angles (tilts) of the antenna and are used to detect precipitation, evaluate storm structure, locate atmospheric boundaries and determine hail potential.

The base reflectivity image currently available on this website is from the lowest "tilt" angle (0.5°). This means the radar's antenna is tilted 0.5° above the horizon.

The maximum range of the **"short range"** (S Rng) base reflectivity product is **124 nm (about 143 miles)** from the radar location. This view will not display echoes that are more distant than 124 nm, even though precipitation may be occurring at greater distances. To determine if precipitation is occurring at greater distances, select the **"long range"** (L Rng) view **(out to 248 nm/286 mi)**, select an adjacent radar, or link to the National Reflectivity Mosaic.

Composite reflectivity: NWS definition

This display is of maximum echo intensity (reflectivity) from any elevation angle at every range from the radar. This product is used to reveal the highest reflectivity in all echoes. When compared with Base Reflectivity, the Composite Reflectivity can reveal important storm structure features and intensity trends of storms.

The maximum range of the **"long range"** (L Rng) composite reflectivity product is **248 nm (about 286 miles)**from the radar location. The "blocky" appearance of this product is due to its lower spatial resolution on a **2.2 * 2.2 nm grid**. It has one-fourth the resolution of the Base Reflectivity and one-half the resolution of the Precipitation products.

Although the Composite Reflectivity product is able to display maximum echo intensities 248 nm from the radar, the beam of the radar at this distance is at a very high altitude in the atmosphere. Thus, only the most intense convective storms and tropical systems will be detected at the longer distances.

Because of this fact, special care must be taken interpreting this product. While the radar image may not indicate precipitation it's quite possible that the radar beam is overshooting precipitation at lower levels, especially at greater distances. To determine if precipitation is occurring at greater distances link to an adjacent radar or link to the National Reflectivity Mosaic.

For a **higher resolution (1.1 * 1.1 nm grid)** composite reflectivity image, select the **short range** (S Rng) view. The image is less "blocky" as compared to the long range image. However, the maximum range is reduced to 124 nm (about 143 miles) from the radar location.

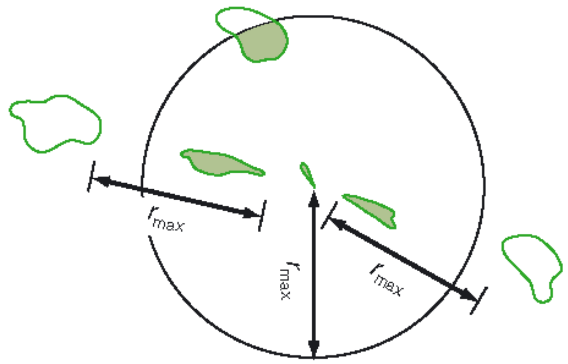
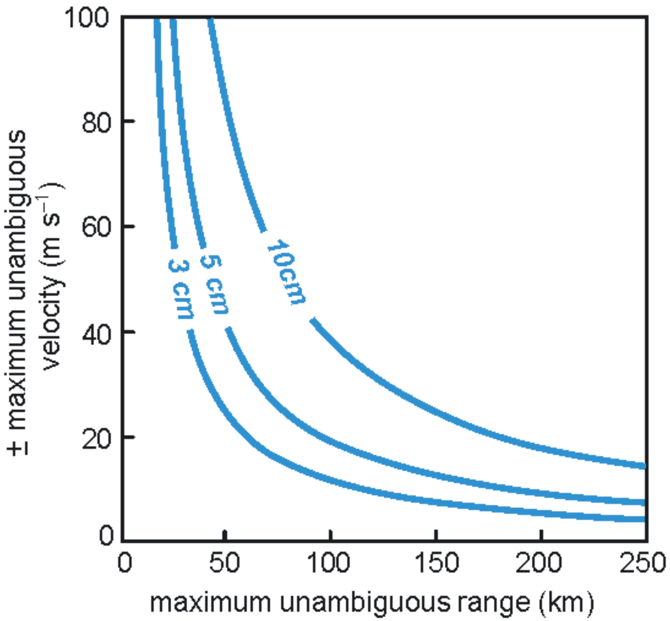


Figure A.4 Illustration of range-folding. Radar echoes beyond the maximum unambiguous range ($r_{\max}$) (unshaded echoes) are *folded* back into the area within the maximum unambiguous range. Echoes actually located within the maximum unambiguous range, as well as folded echoes, are both shaded.



Basically the radar's range is limited by the pulse frequency.

Clear Air Returns

Ground clutter (worst about 20 km of the radar)

Flying insects or birds

Turbulence and suspended aerosols

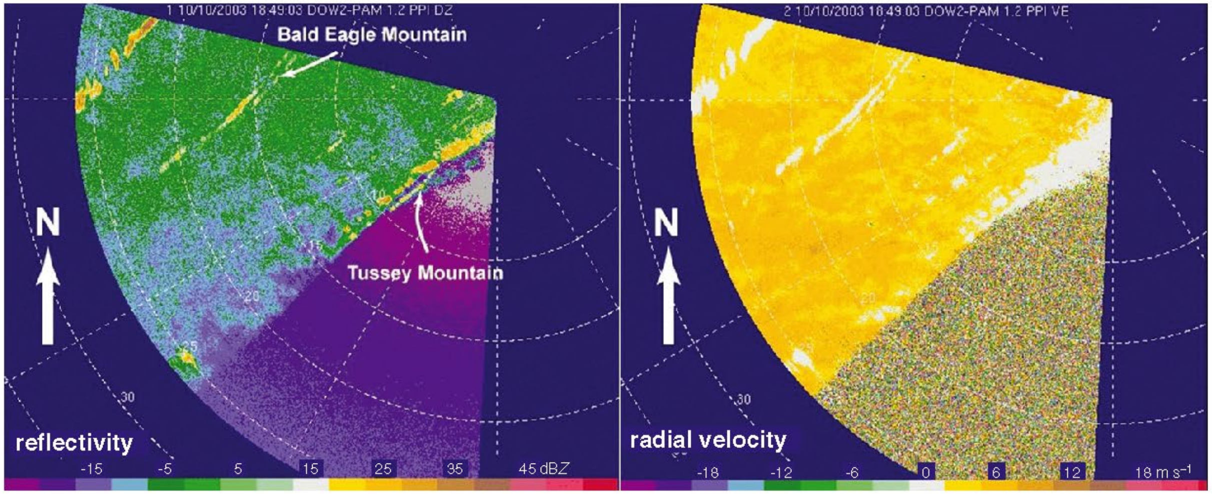


Figure A.8 Example of ground clutter in radar imagery obtained by the Doppler On Wheels (DOW) radar southwest of State College, PA. Reflectivity is displayed on the left and radial velocity is displayed on the right. Range rings are at 5 km intervals and azimuth spokes are at 30° intervals. At locations where the radar beam intersects mountains, reflectivities are large and radial velocities are approximately zero. The echoes from the valley between the two mountain ridges are largely from insects.

Doppler radar basics

Radial velocity: component of target velocity parallel to radar beam

There is a phase shift as a result of differences a wave must travel from one pulse to the next

Radial velocity

$$v_{\mathrm{R}} = \frac{\Delta r}{\Delta t} = \frac{\lambda}{4\pi} \frac{\Delta \phi}{\Delta t},$$

Phase shift

$$\Delta \phi = \frac{4\pi\,\Delta r}{\lambda},$$

Δr = distance target travels between pulses
λ = wavelength
Δt = time between pulses

Variance in radial velocity related to scattering, turbulence, wind shear

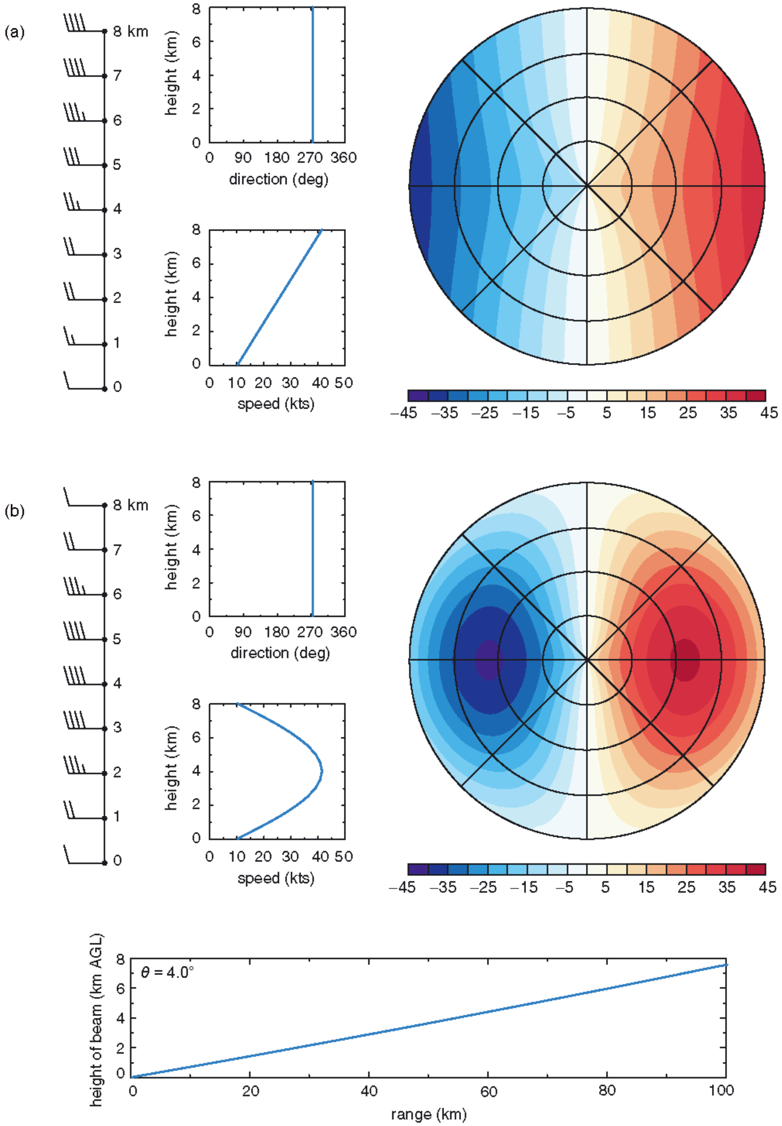


Figure A.10 (a) A velocity display in the presence of linear, unidirectional, westerly wind shear given an elevation angle of 4°. Range rings are drawn every 25 km and azimuth spokes are drawn every 45°. (b) As in (a), but for the case of unidirectional wind shear with a sinusoidal wind speed profile. The beam height versus range is displayed beneath (a) and (b).

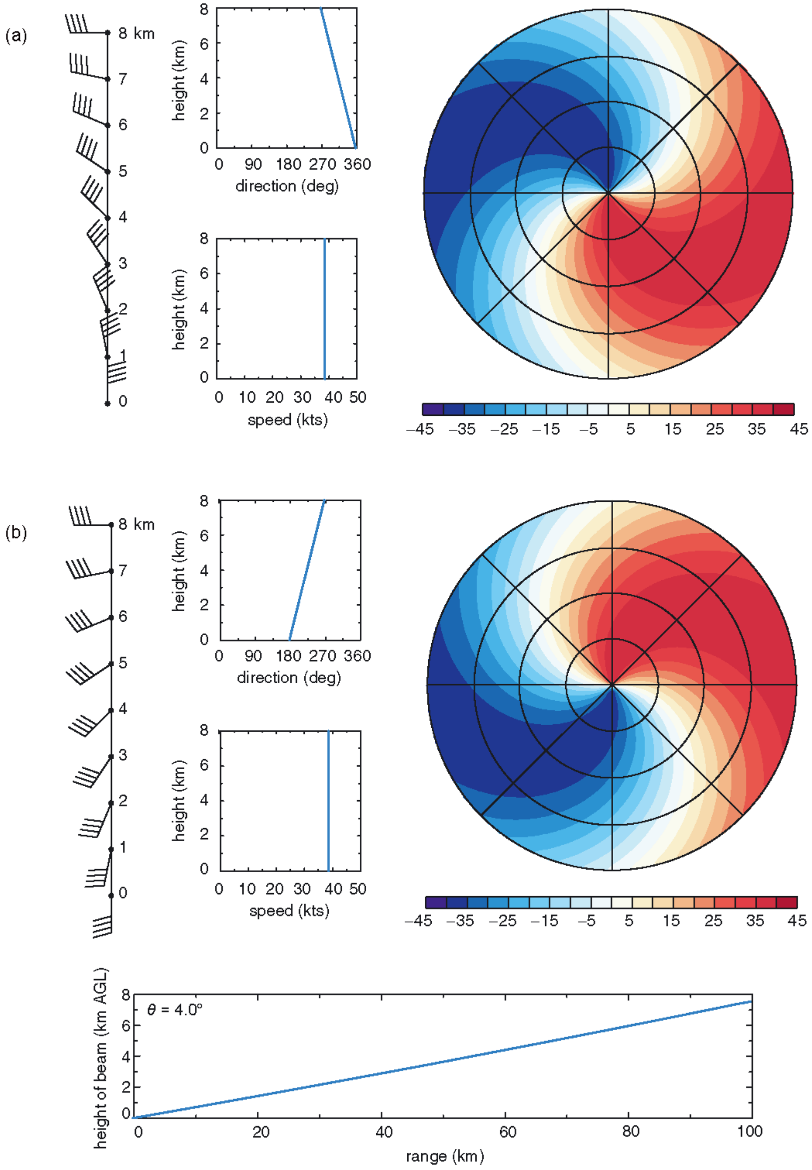


Figure A.11 (a) A velocity display in the presence of backing winds with height. As in Figure A.10, the elevation angle of the radar beam is 4°. Range rings are drawn every 25 km and azimuth spokes are drawn every 45°. (b) As in (a), but for the case of veering winds with height.

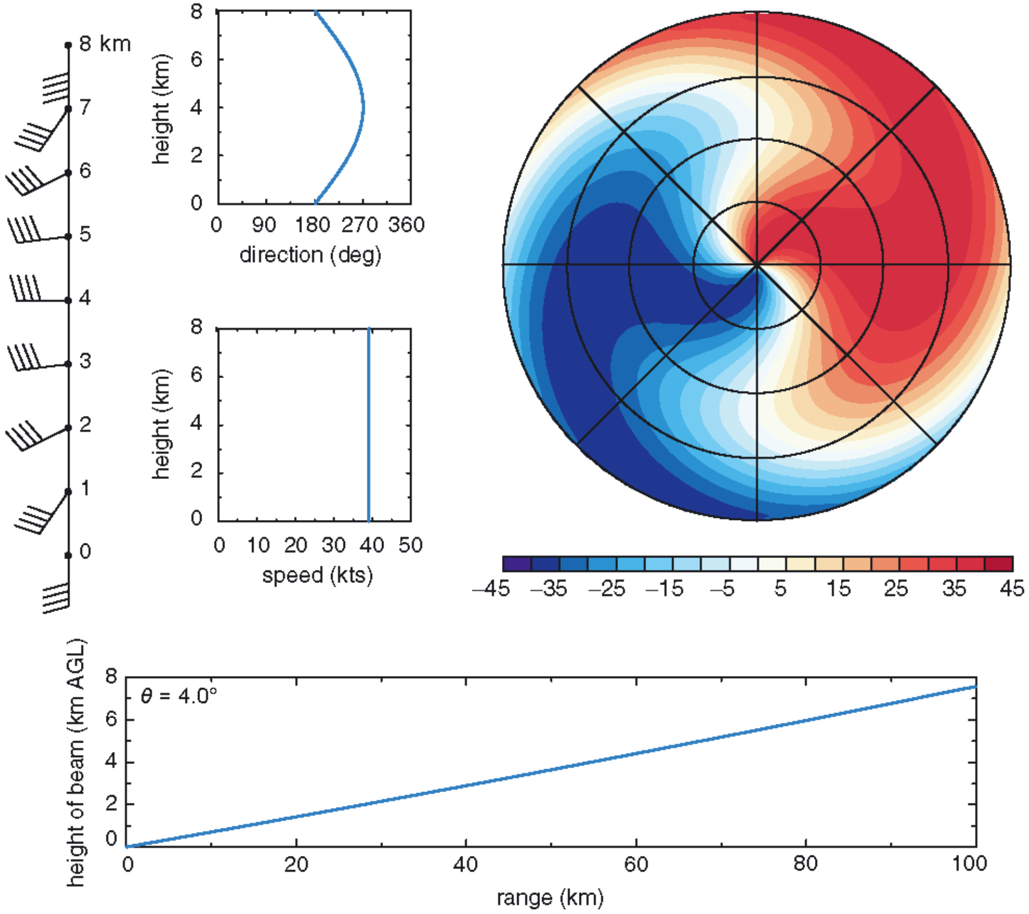


Figure A.12 As in Figure A.11, but for the case of veering winds with height overlain by a layer of backing winds with height.

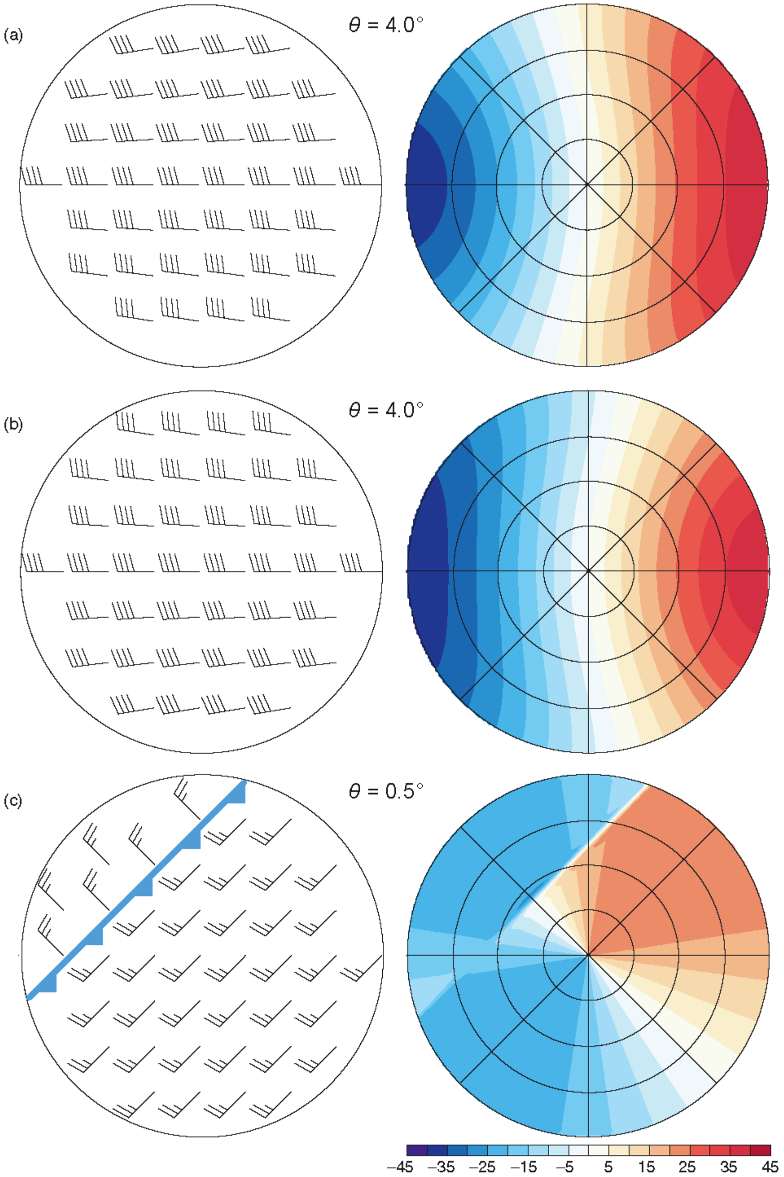


Figure A.13 Idealized Doppler velocity displays in the presence of horizontal inhomogeneity in the wind field. (a) A diffluent wind field (left; horizontal cross-section is at 8 km) and its corresponding radial velocity display (right) for a 4° elevation angle. The wind speed increases linearly with height as in Figure A.10a. (b) The same as (a), but for a confluent wind field. (c) The case of a cold front approaching the radar from the northwest. Wind barbs in the horizontal cross-section (left) are at 0.5 km, and the corresponding radial velocity display (right) is based on a 0.5° elevation angle.

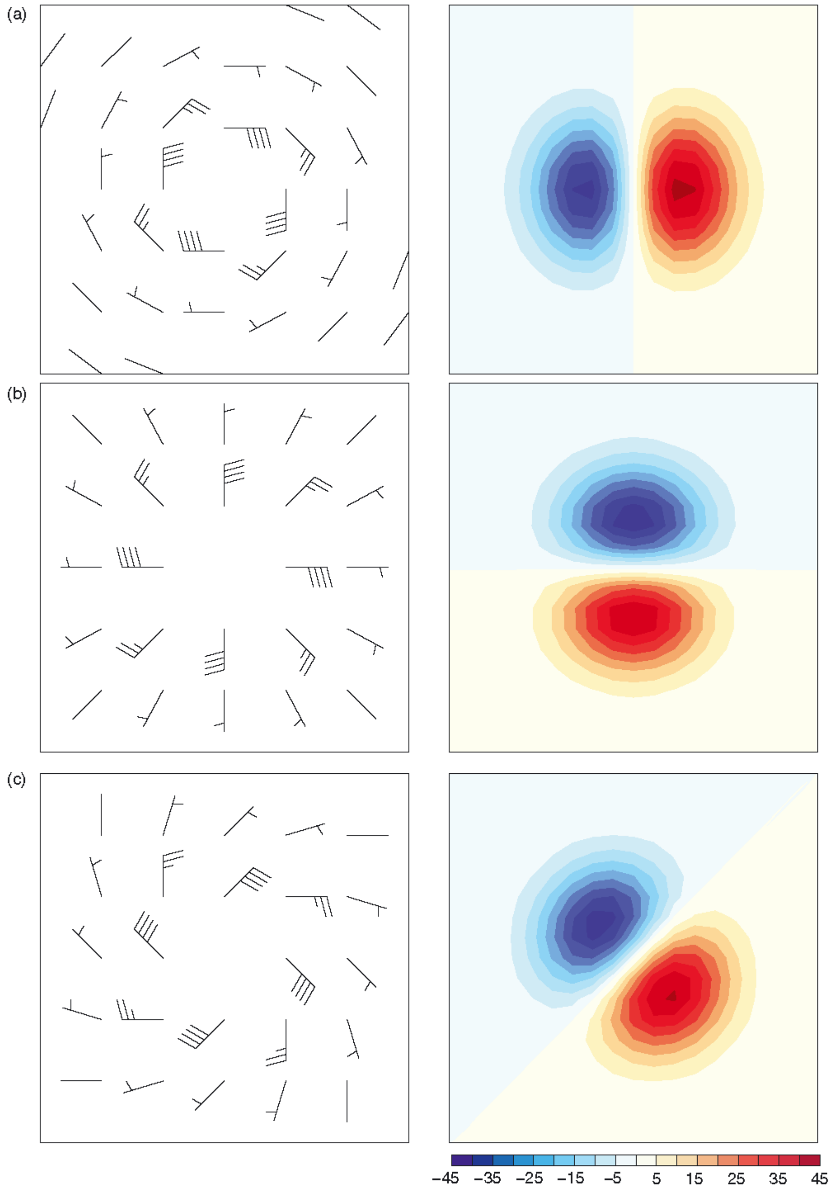
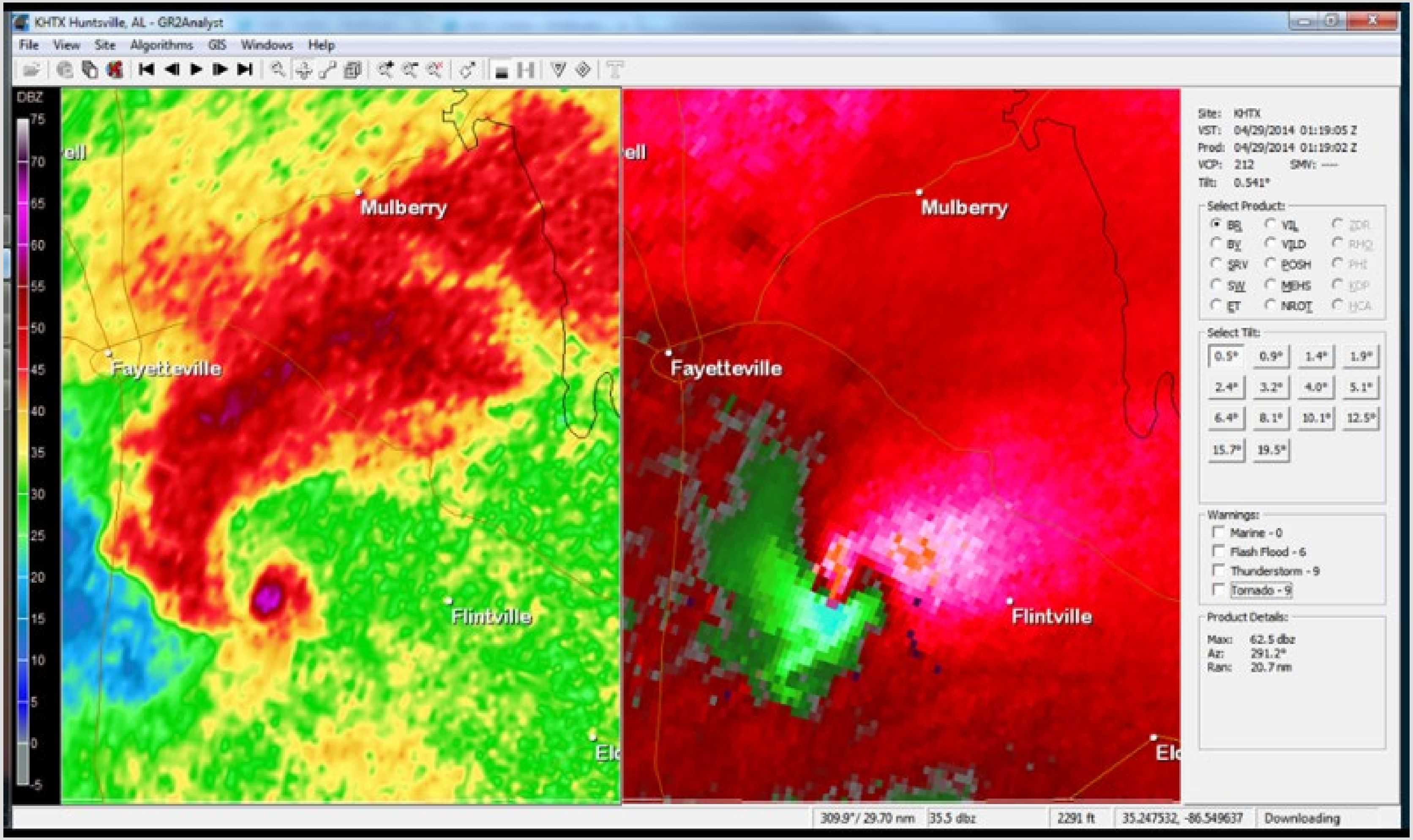


Figure A.15 (a) Idealized Doppler velocity display for the case of a mesocyclone having cyclonic vorticity (the radar is located to the south, e.g., the domain might be in the same location relative to the radar as the domain shown in Figure A.14). The elevation angle of the radar beam is 0.5°. Wind barbs are shown on the left and the Doppler velocity display is shown on the right. (b) As in (a), but for a purely convergent wind field. (c) As in (a), but for a wind field consisting of equal amounts of cyclonic vorticity and convergence.

Tornadic signatures in Doppler-derived wind velocity



Site: KHTX
VST: 04/29/2014 01:19:05 Z
Prod: 04/29/2014 01:19:02 Z
VCP: 212 SMV: ---
Tilt: 0.541°

Select Product:
● BR ○ VIL ○ ZDR
○ BV ○ VILD ○ RHO
○ SRV ○ POSH ○ PHI
○ SW ○ MEHS ○ KDP
○ ET ○ NROT ○ HCA

Select Tilt:
0.5° 0.9° 1.4° 1.9°
2.4° 3.2° 4.0° 5.1°
6.4° 8.1° 10.1° 12.5°
15.7° 19.5°

Warnings:
☐ Marine - 0
☐ Flash Flood - 6
☐ Thunderstorm - 9
☐ Tornado - 9

Product Details:
Max: 62.5 dbz
Az: 291.2°
Ran: 20.7 nm

309.9° / 29.70 nm | 35.5 dbz | 2291 ft | 35.247532, -86.549637 | Downloading

Quantitative precipitation estimation (QPE) using radar data

Must assume a Z-R relationship: relates the reflectivity factor to rainfall rate

$$Z = A\,R^B,$$

A and B are constants that depend on the drop size distribution, usually assumed to follow a Marshall-Palmer drop size distribution

CAVEATS:

- No simple formula to relate these two quantities without knowing the drop size distribution
- Subject to errors in radar data, beam blockage
- Significant weather may impact it: bright bands and ice particles, strong vertical motion, evaporation below cloud base

Often the Z-R relationship is specific to the given radar site.

Dual-polarization radar

Conventional radars transmit and receive energy with a single horizontal polarization.

Dual-polarization radars transmit and receive horizontally and vertically polarized pules.

Advantages of Dual-pol radar

- Can infer microphysical characteristics of precipitation regions.
- Differential reflectivity can be used to estimate hydrometeor shape and drop size.
- Vertical profiling

Differential reflectivity

$$Z_{\mathrm{DR}} = 10\ \log_{10}\left(\frac{z_{\mathrm{hh}}}{z_{\mathrm{vv}}}\right) = Z_{\mathrm{hh}} - Z_{\mathrm{vv}}.$$

units of dB

Dual-polarization radar and precipitation type in relation to Z_{DR}

$$Z_{\mathrm{DR}} = 10\ \log_{10}\left(\frac{z_{\mathrm{hh}}}{z_{\mathrm{vv}}}\right) = Z_{\mathrm{hh}} - Z_{\mathrm{vv}}.$$

Hail and drizzle: Near zero db.

Rain: ~2 db

Snow: ~1db

Melting bands: > 3.5 db

Falling graupel particles falling vertical:
Negative values of db

<u>Other dual-pol metrics:</u>

Linear depolarization ratio
Specific differential phase
Co-polar correlation coefficient

These further distinguish between hydrometeor species (see text for details)

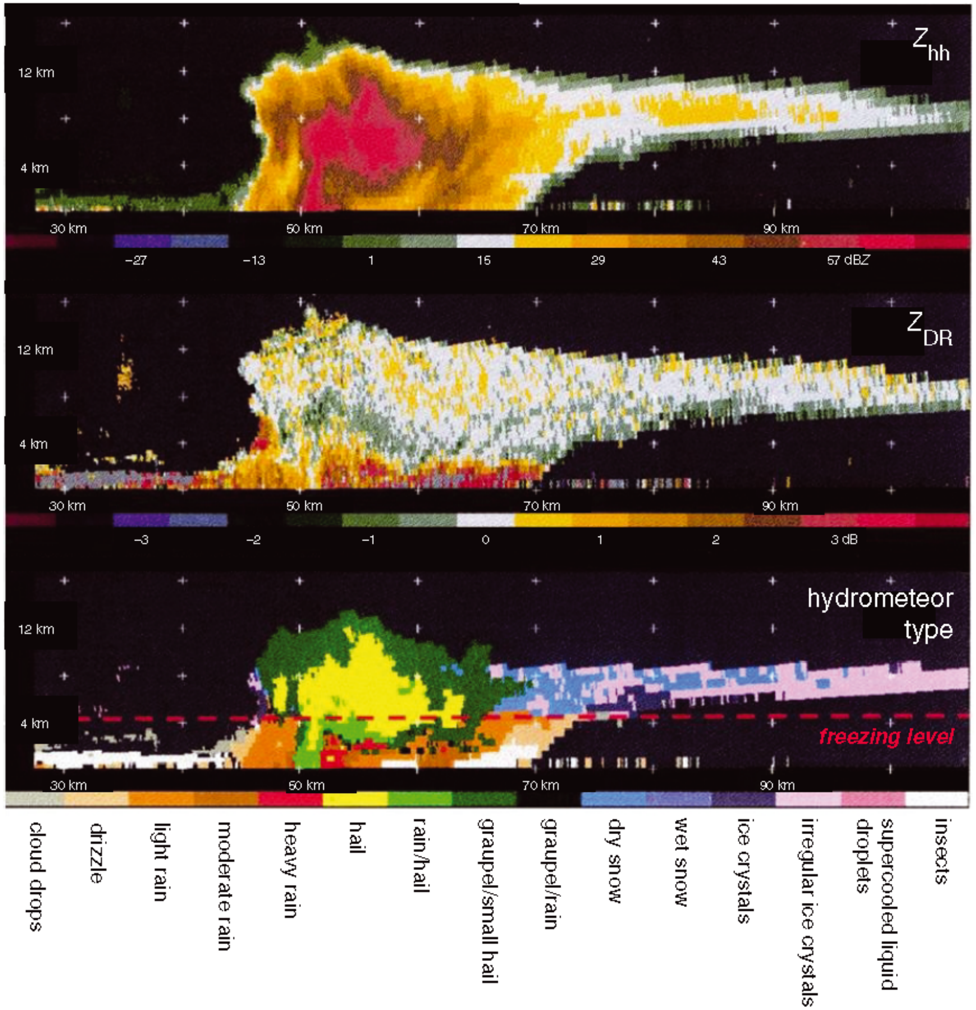


Figure A.17 Example of hydrometeor classification in a vertical cross-section of a thunderstorm using data from a dual-polarization radar (c); images (a) and (b) are reflectivity and differential reflectivity, respectively. Such classifications can improve rainfall estimations and perhaps warnings for severe hail and tornadoes as well. (From Vivekanandan *et al.* [1999]. Courtesy of the American Meteorological Society.)