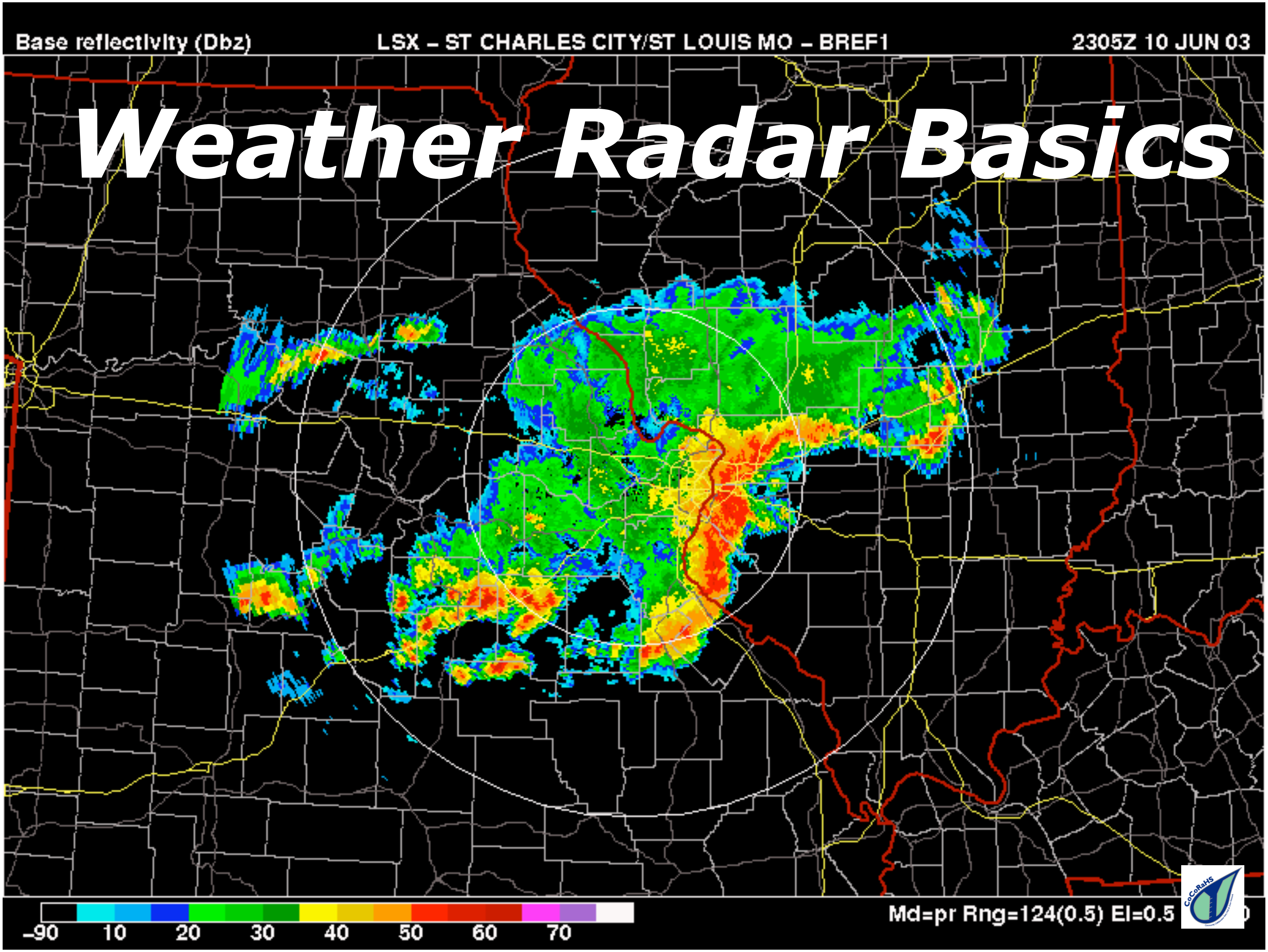
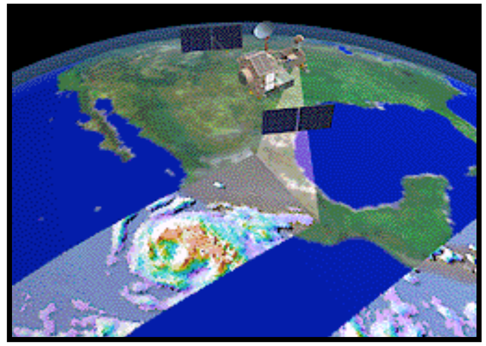
Weather Radar Basics



RADAR: Radio Detection And Ranging



- Developed during World War II as a method to detect the presence of ships and aircraft (*the military considered weather targets as noise*)

- Since WW II, there have been many advances in radar technology (e.g., Doppler techniques) and it's used on land, sea, and in space for both research and operational needs

Anatomy of a Weather Radar

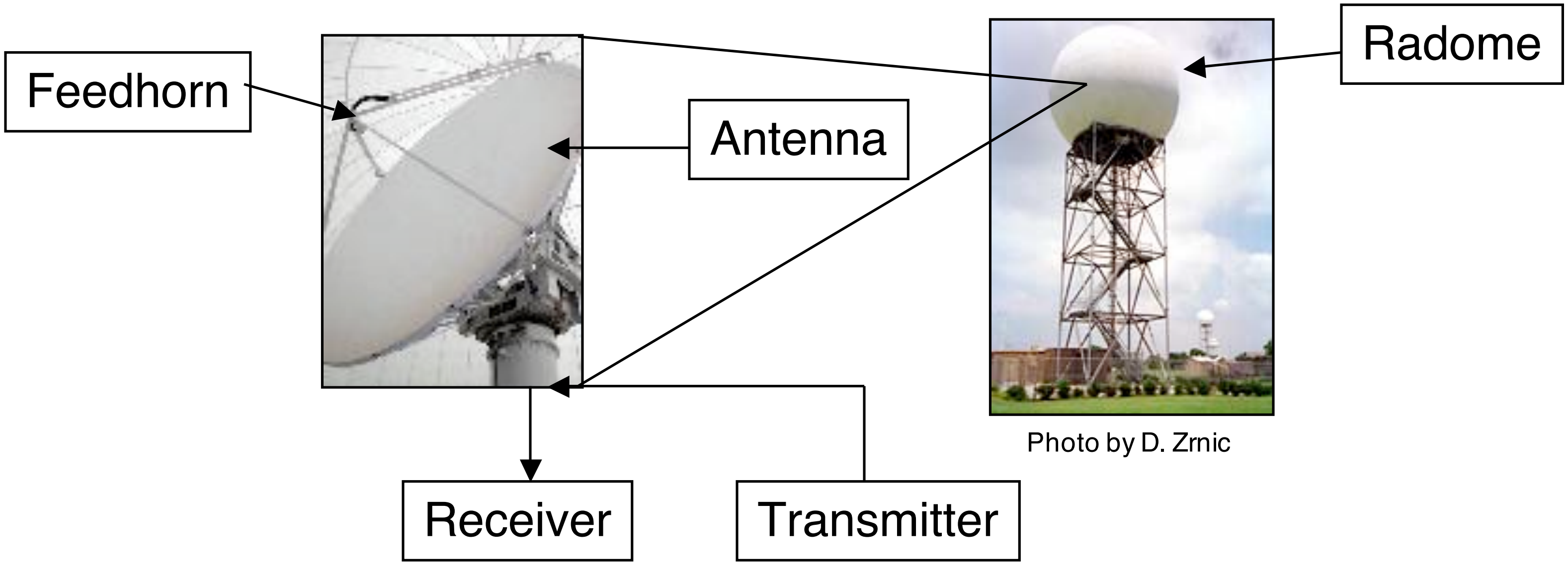


Photo by D. Zrnic

- **Transmitter** - generates the microwave signal of the correct phase and amplitude. For a weather radar, the wavelength of the signal is ~ 10cm

- **Antenna** - the main purpose of the antenna (also called the "dish") is to focus the transmitted power into a small beam and also to listen and collect the returned signal

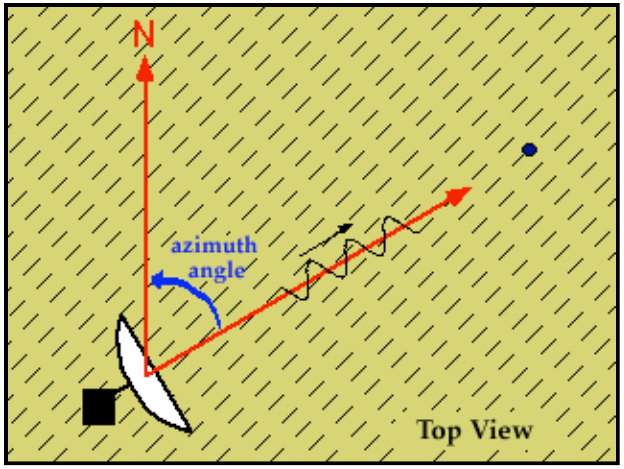
- **Feedhorn** - directs the signal from the transmitter onto the antenna (also directs the return signal from the antenna to the receiver)

- **Receiver** - detects the signal returned from a target

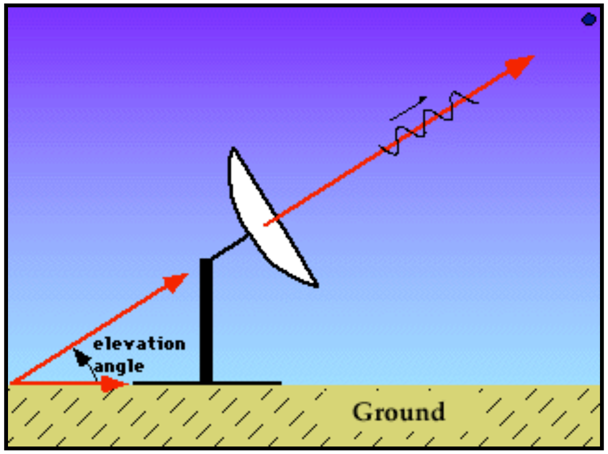
- **Radome** - protects the antenna from high winds

Weather Radar Scanning

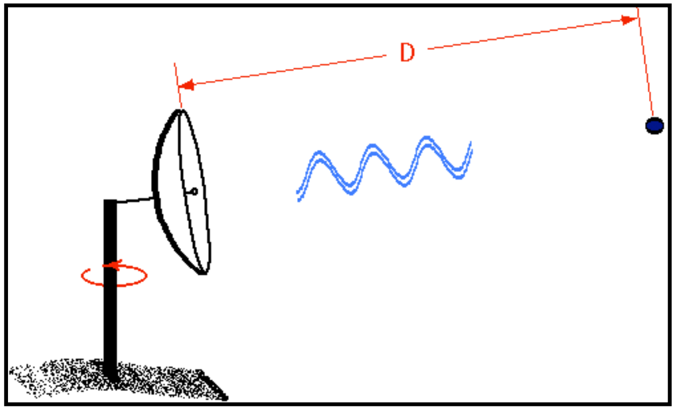
For a radar to find a target of interest (e.g., a cloud), 3 pieces of information are needed:



• *Azimuth angle (direction relative to north)*



• *Elevation angle (angle above the ground)*

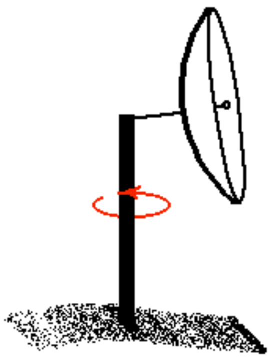


• *Distance to the target of interest*

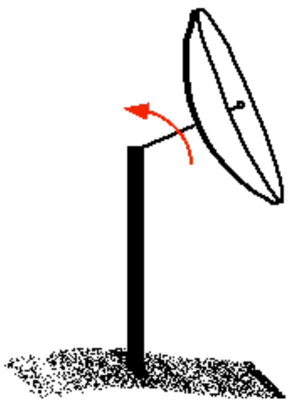
Images on this page made available from the University of Illinois WW2010 Project

Weather Radar Scanning

In meteorology, radars usually employ one of two scanning techniques:



- **Plan Position Indicator (PPI)**: The radar holds its *elevation angle* constant but varies its *azimuth angle*. If the radar rotates through 360 degrees, the scan is called a "*surveillance scan*". If the radar rotates through less than 360 degrees, the scan is called a "*sector scan*".



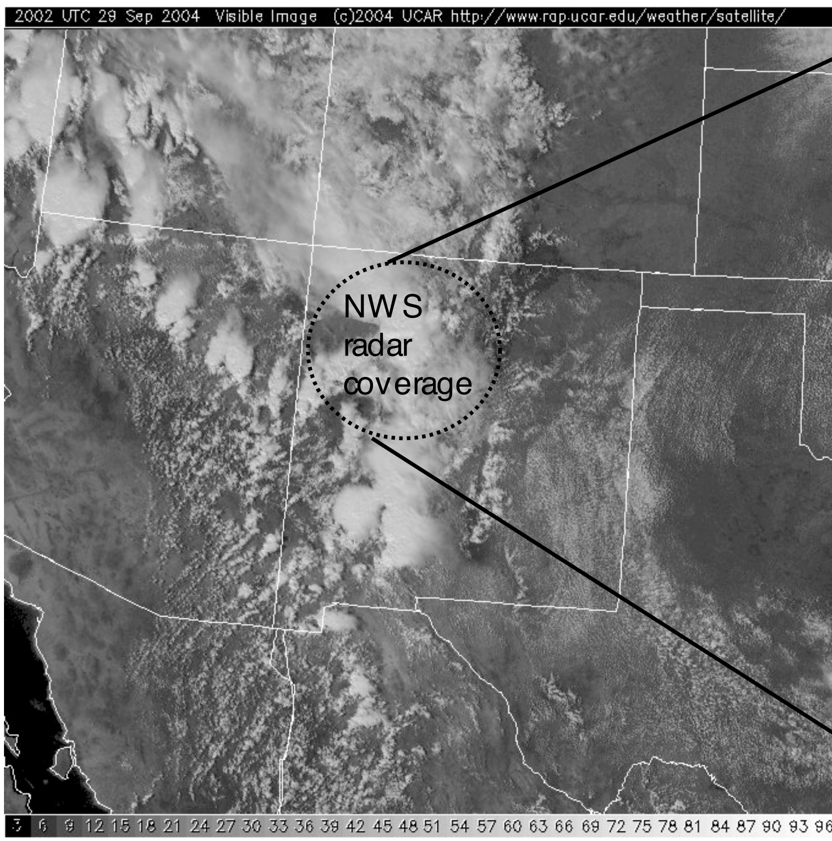
- **Range Height Indicator (RHI)**: the radar holds its *azimuth angle* constant but varies its *elevation angle*. The elevation angle normally is rotated from near the horizon to near the zenith (the point in the sky directly overhead).

Images from the University of Illinois WW2010 Project

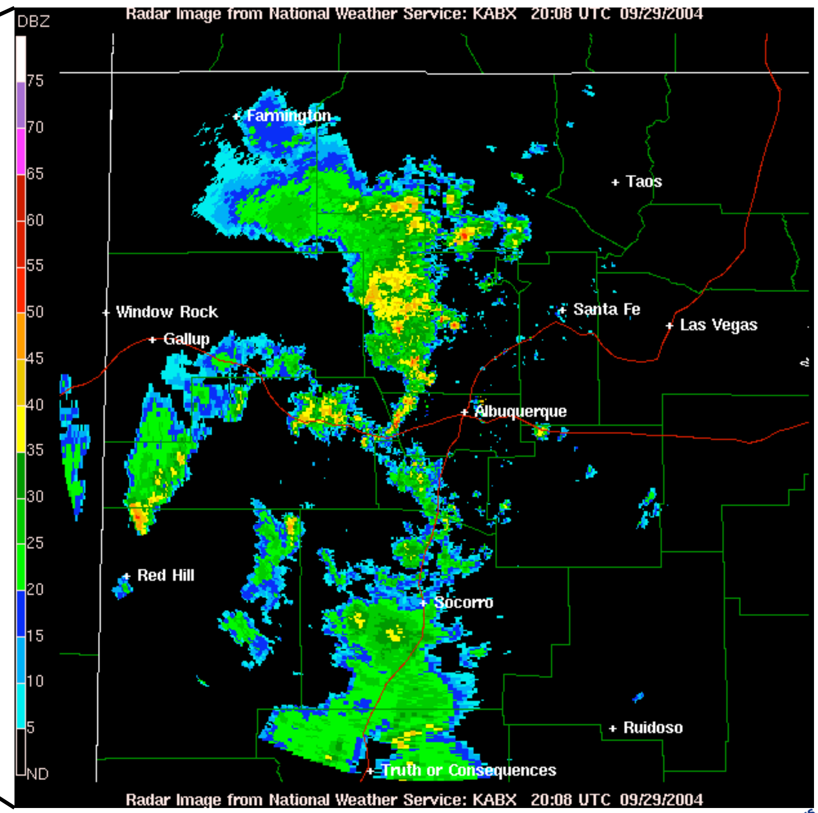
We are most concerned with the PPI scan. The Weather Service radars operate by collecting a series of surveillance scans at increasing elevation angles. It takes the radar ~ 5 minutes to collect the data, depending on how many elevation angles are used. The radar then repeats the cycle.

Applications of Weather Radar: National Weather Service

Radar is an important component in the arsenal of forecaster tools to understand both the current state of the atmosphere as well as what might happen in the near future. While satellite data gives a forecaster a sense of the "big picture", radar provides more detail on at smaller scales of weather.



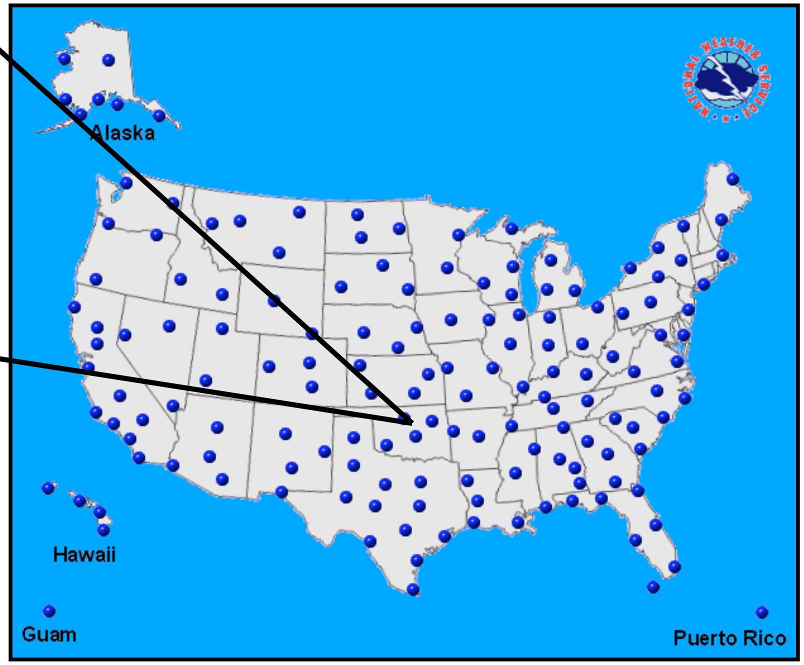
NOAA GOES Visible image 29 September 2004 20:15 UTC



NWS NEXRAD (KABX) Radar Reflectivity 29 September 2004 20:08 UTC

NWS Next Generation Weather Radar (NEXRAD) Sites

D. Zrnic



- *The NWS currently operates 158 NEXRAD sites across the US*

- Significant improvements over older weather radar systems:
    - Ability to see motion of air (precipitation) using Doppler effect
    - Increased sensitivity and resolution allows observation of cold fronts, dry lines, and thunderstorm gust fronts

Weather Service forecasters use radar to help determine:

- the movement and trend of thunderstorms
- variability and concentration of precipitation

There are two important aspects of radar that we're concerned with:

- **Amount of energy scattered back from a target to the radar**

  estimate the intensity of storms and the amount of precipitation

- **Velocity of a target relative to the radar**

  estimate air motions and circulations within clouds

How Does the Radar Sense a Target in the Atmosphere?

- Radars operate by sending out energy from a source and "listening" to the amount that is reflected (scattered) from targets

- Targets can be trees, cloud, bumblebees or anything else the radar pulse intercepts

- Weather radars utilize frequency of ~ 3000 MHz (10 cm wavelength) - radio waves

- The radar transmits short pulses of these radio waves at rate of ~ 1000 pulses/s

- Each pulse is very short, lasting only about 1/1,000,000 s

Image from The USA TODAY Weather Book *by Jack Williams*

- After each pulse, there is a short period for radar to “listen” to the scattered signal from the target of interest

- The scattered signal is a result of energy from the transmitted pulse interacting with the target (*snow, rain, hail, etc*)

- A small portion of the transmitted power is returned to the radar (the echo), received by the antenna, and analyzed by the radar signal processor. Once that’s done, precipitation rates can be determined (we’ll talk about this in more detail later)

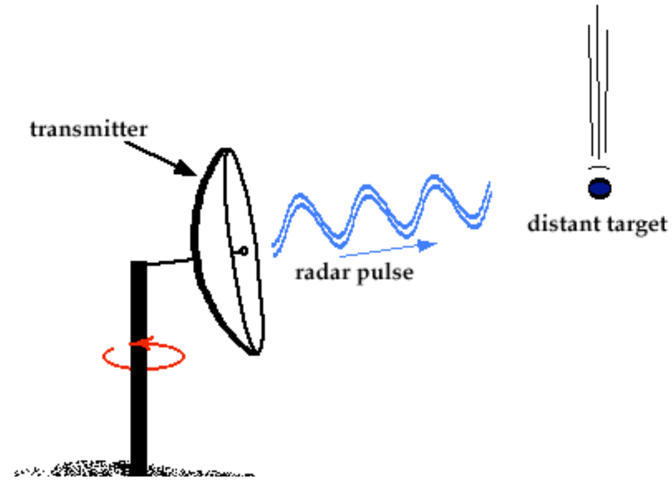


Image from the University of Illinois WW2010 Project

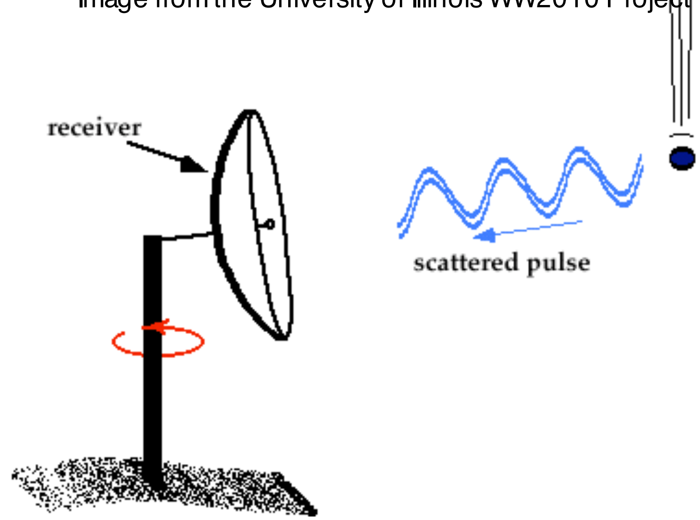


Image from the University of Illinois WW2010 Project

Detecting Targets *(continued)*

The return signal received by the radar is related to the diameter of the particles in our target echo: the bigger the particles the bigger the amount of return signal.

It turns out that the target echo is related to the diameters of the precipitation particles in a very <u>non-linear</u> way: $P_r \sim \sum D_i^6$

- *Increase particle diameter by factor of 2 ⇒ P_r increases by factor of **64***
- *Increase particle diameter by factor of 3 ⇒ P_r increases by factor of **729***

Detecting Targets *(continued)*

- The term $\sum D_i^6$ has a special name in radar meteorology: *reflectivity factor (Z)*

- Z can take on a tremendous range of values: 0.001 (fog) - 50,000,000 (hail)

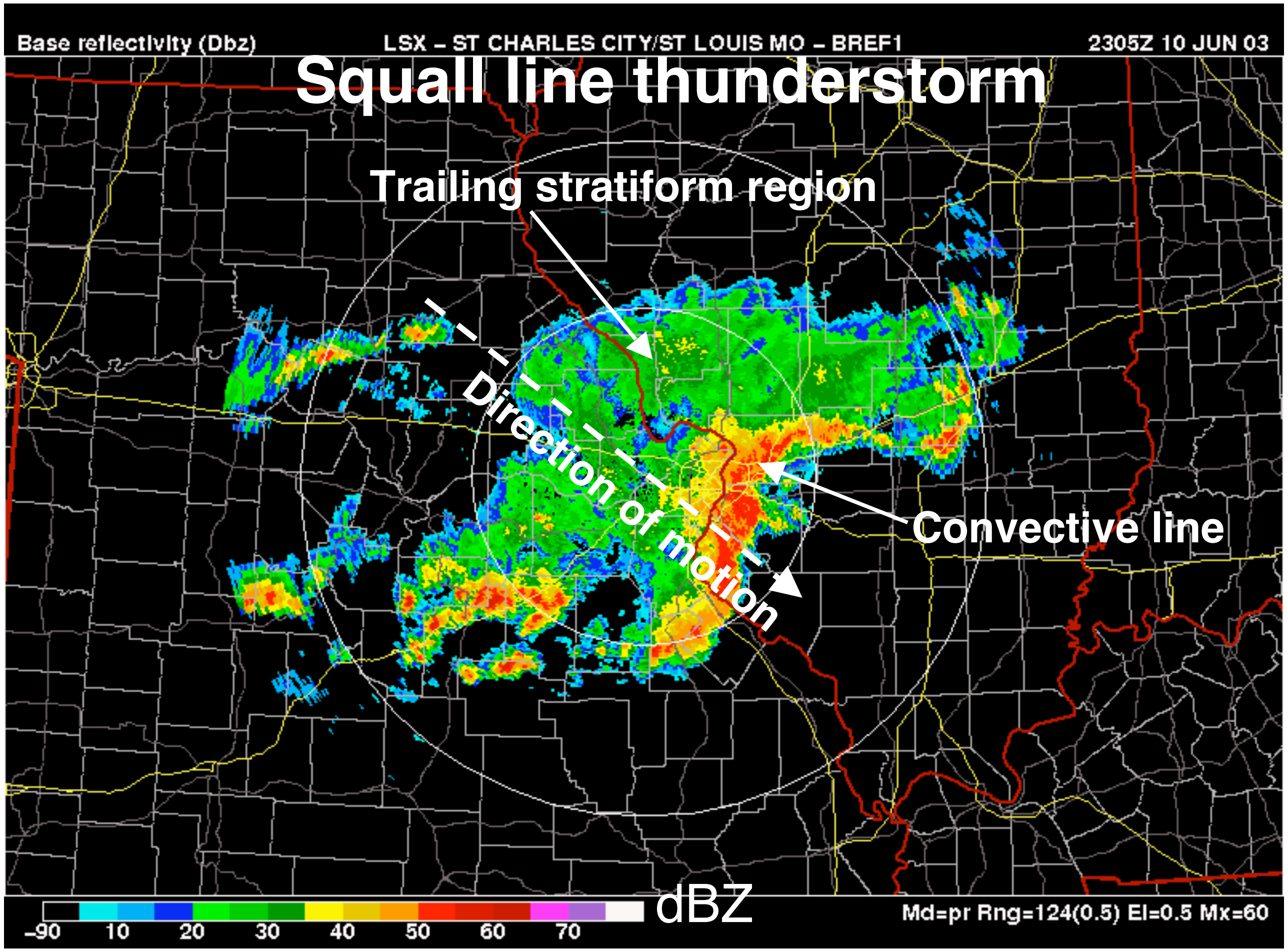
- To compress this into a more manageable range, define another parameter: $dBZ = 10\log_{10}(Z)$

- *dBZ values are what you typically see on radar displays (e.g., on T.V.)*

Try this:

What are the corresponding “dBZ” values of fog and hail?

Radar Display Example



NWS NEXRAD (KLSX) Radar Reflectivity 10 June 2003 2305 UTC

Squall lines are made up of a number of individual thunderstorms. Although the lifetime of an individual thunderstorm cell (identified as red areas in the radar echo pattern) may only be an hour or so, new cells continually regenerate along the convective line and the whole squall line system may last many hours or up to several days.

Questions to Consider

1. What do you notice about the echo pattern of the squall line?

2. Where are the largest particles (and likely the most intense precipitation) concentrated?

3. What features in the radar echo display distinguish the convective line from the trailing stratiform region?

4. Pick an averge *dBZ* value from the convective line and trailing stratiform region and determine the corresponding *Z* values

Estimating Precipitation with Radar

- We saw earlier that the reflectivity factor (*Z*) is related to the size of precipitation particles in the radar echo.

- If we assume that our radar echo has a known distribution of precipitation particles (i.e., number of drops of different size categories), we can relate the reflectivity factor (*Z*) to the rainfall rate (*R - mm/hr*) in our echo feature:

$Z=A*R^B$ *(A and B are constants determined by the assumed drop size distribution)*

This kind of equation between reflectivity factor and rain rate is called a “Z-R” relation

The NWS utilizes a single *Z-R* relation almost exclusively for all NEXRAD radar data around the US:

$$Z=300*R^{1.4} \rightarrow R=(Z/300)^{(1/1.4)}$$

Now, let's practice estimating rainfall from radar data:

1. Using our squall line example and the above NWS Z-R relationship, estimate an average rain rate in the convective line and stratiform regions

2. What assumption do we have to make in order to apply this Z-R relation in different part of the squall line?

As you’ve probably noticed, the precipitation estimates from radar data don’t always agree with rain gauges! Meteorologists have been working on this problem for over 50 years now.

Why is it so difficult to compare rain gauge and radar measurements?

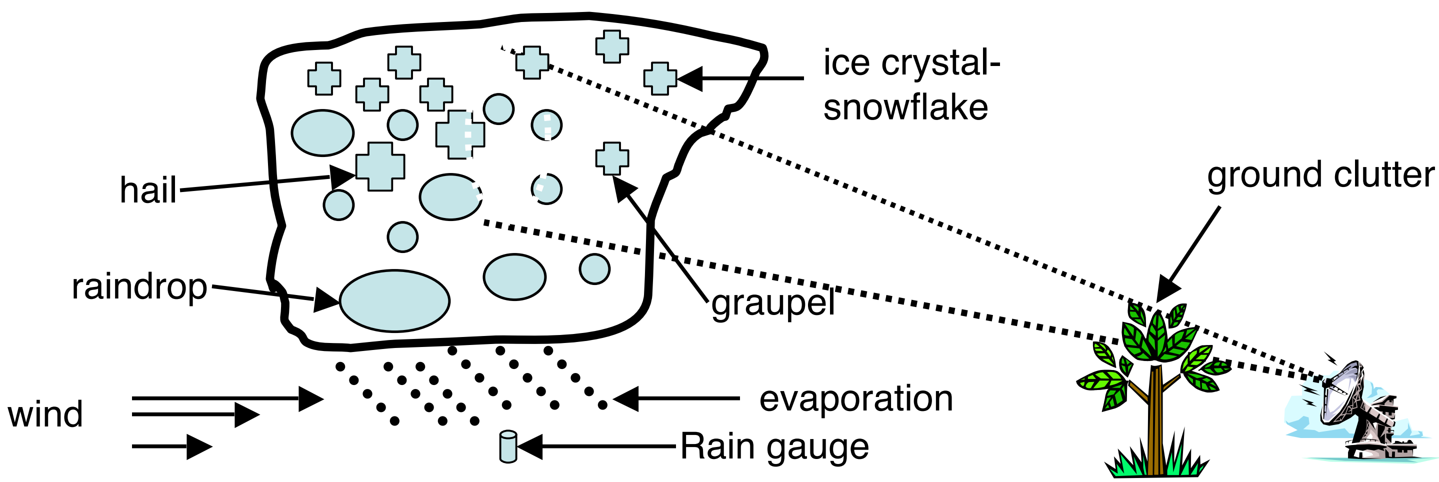
- Besides assumptions in the Z-R relation, there are a number of other complications:

- The radar samples precipitation in the cloud some distance above the ground. Particles may evaporate or otherwise be modified before they hit the surface.

- Clouds and precipitation frequently consist of a variety of particle types (e.g., ice and rain). Each particle interacts with the radar's energy in its own unique way.

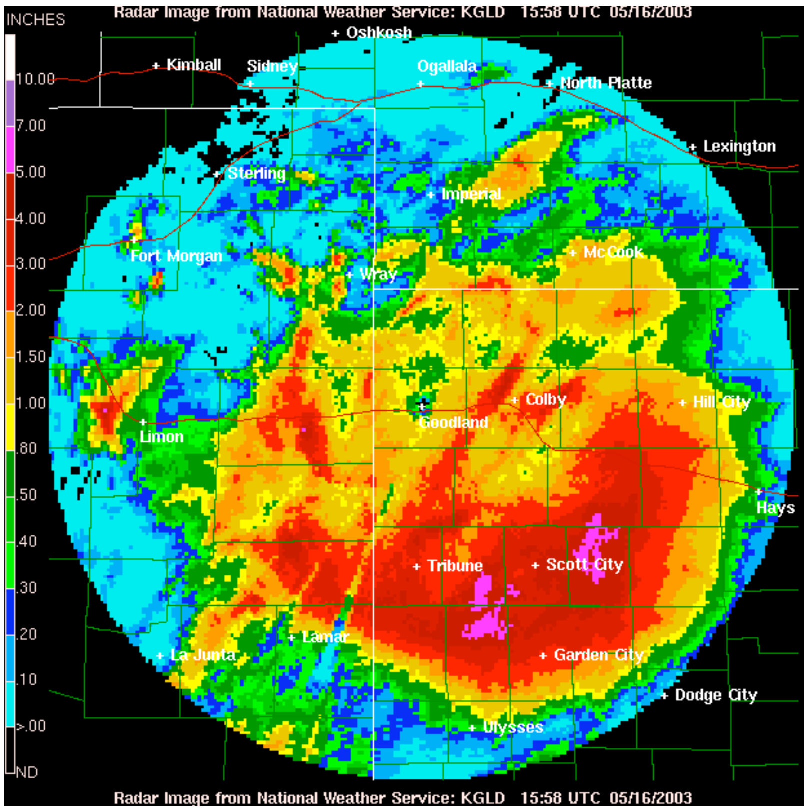
Other factors complicating the comparison of radar and rain gauge estimates of precipitation

- The region sampled by the radar increases with distance. The wider the beam, the greater the likelihood of sampling a mixture of precipitation types, or the greater the likelihood of sampled both inside and outside of a cloud.



- Obstacles frequently block a portion of the radar beam, resulting in an artificially high power return.

Given all the issues, why use radar to measure precipitation?

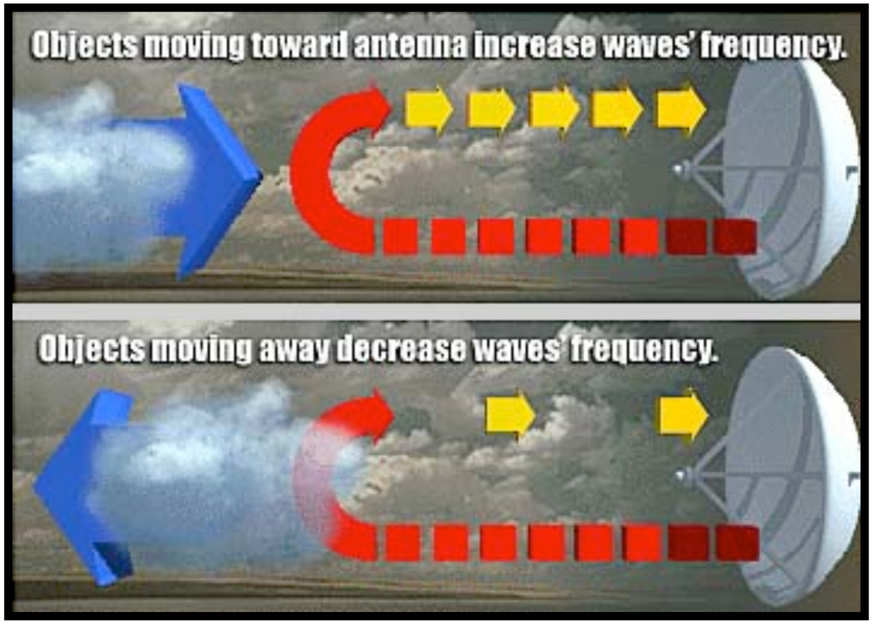


NWS NEXRAD (KGLD) Storm Total Precipitation 16 May 2003 15:58 UTC

- Radar is the only way to map the spatial distribution of precipitation over large areas
- Topography or other logistics may prevent locating gauges in many areas
- Radar can be used as a forecasting tool for flash flooding and severe thunderstorms

Measuring Air Motion with Radar

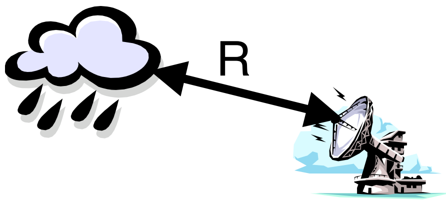
In addition to measuring the amount of signal returned from targets, *NEXRAD* radar has the added capability of being able to measure a frequency shift that is introduced into the reflected signal by the motion of the precipitation particles. This frequency shift is then used to determine wind speed (*we assume that the particles are instantaneously moved around by the wind*).



Images from The USA TODAY Weather Book *by Jack Williams*

- The amount of "shift" can be determined by comparing the frequency of the transmit pulse with the frequency of the reflected pulse
- Particles moving toward the radar are shifted to higher frequency
- Particles moving away from the radar are shifted to lower frequency

How Much Frequency Shift Does the Wind Produce?



The equation that determines how much frequency shift is produced by a moving target is:

$f_t = 2V/\lambda$ = Doppler frequency shift of target *(this equation is derived on the next page)*

<u>Questions to consider:</u>

1. If the wind speed (V) = 10 m/s, what is the resulting frequency shift of the wind (*assume λ = 10 cm for a weather radar*)?

2. How does this frequency shift compare to the frequency of the radar wave? To figure this out, we need to determine the radar frequency:

$f_r = V_w/\lambda$, where $V_w = c$ = the speed of light = 3×10^8 m/s

Deriving the Frequency Shift of Moving Target

Total distance traversed by pulse = 2R
Total distance in terms of λ = $2R/\lambda$
Total distance in radians = $(2R/\lambda)*2\pi = 4\pi R/\lambda$

Assume radar emits wave with phase = Ψ_0
Return wave phase to radar = $\Psi_R = \Psi_0 + 4\pi R/\lambda$
Frequency shift (ω) = $\Delta \Psi_R / \Delta t = (4\pi/\lambda)* \Delta R/\Delta t$

Setting $\Delta R/\Delta t = V$ (velocity of target)
and recalling that $\Delta \Psi_R / \Delta t = \omega = 2\pi f$

$f_t = 2V/\lambda$ = Doppler frequency shift of target

Examples of Air Motions Detected with Doppler Radar

- The NWS utilizes the Doppler capability of the NEXRAD radars to detect storm circulations (e.g., tornados and hurricane spiral bands) as well as to identify air flow boundaries created by storms (e.g., outflows and microbursts).

- In cases when only one radar is available, the air motion that is detected is relative to the location of the radar: radar meteorologists call this *radial velocity*

- flow toward the radar is called "inbound" and flow away from the radar is called "outbound".

- By convention, velocities toward the radar (inbound) are negative and velocities away from the radar (outbound) are positive.

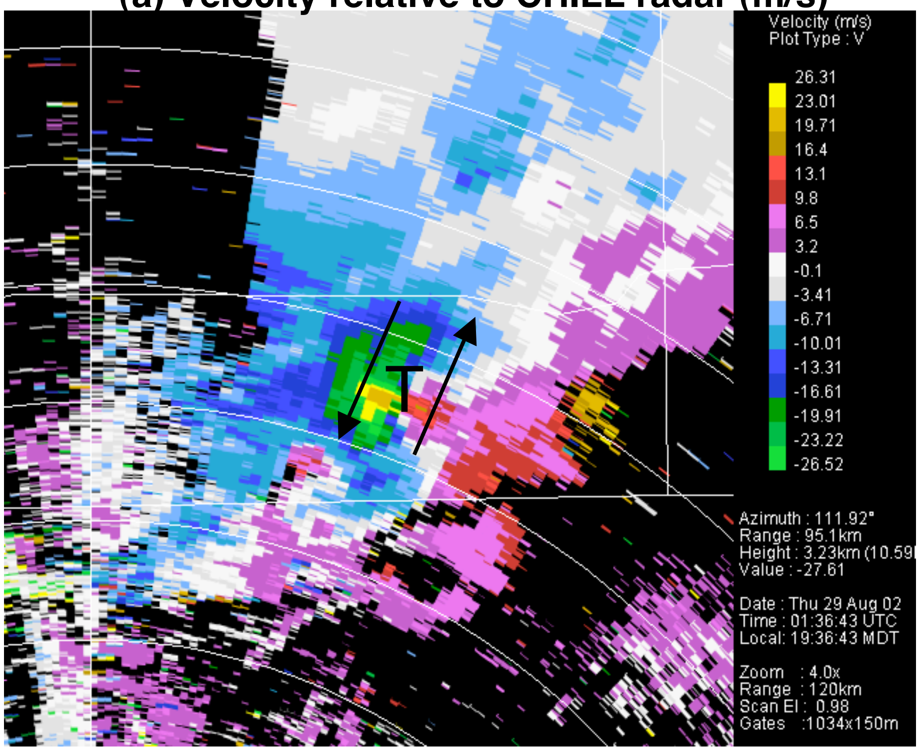
- We'll consider two examples for the purposes of our discussion: tornados and microbursts

Example of a tornado observed by the CSU-CHILL radar

The image on the left (a) shows the velocity signature seen on the CHILL radar display. The white arcs across the image represent “range rings” and show the distance from the radar to the echo of interest. The tornado is located at the “T”, marking the boundary of the outbound and inbound velocities. Note that in this case, the inbound velocities are so large that they are “folded” to positive values.

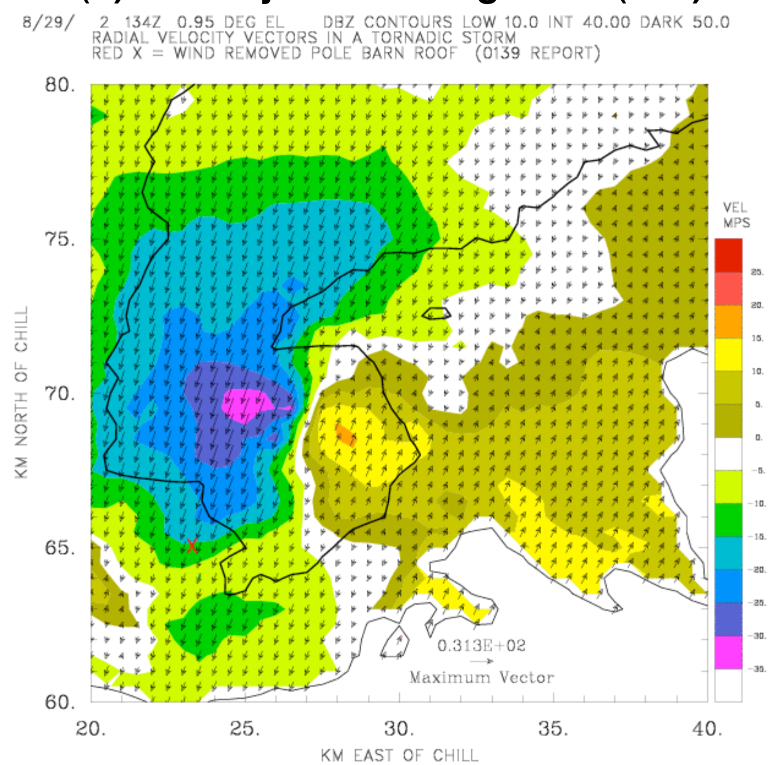
Because another radar was also sampling this storm, the velocities from each radar could be combined to reconstruct the actual wind direction and speed relative to the ground. The image on the right (b) shows the actual wind vectors in the vicinity of the tornado

(a) Velocity relative to CHILL radar (m/s)



Radial velocity signature observed from the CSU-CHILL on 29 August 2002 01:36 UTC. Negative (blue-green colors) represent flow toward the radar.

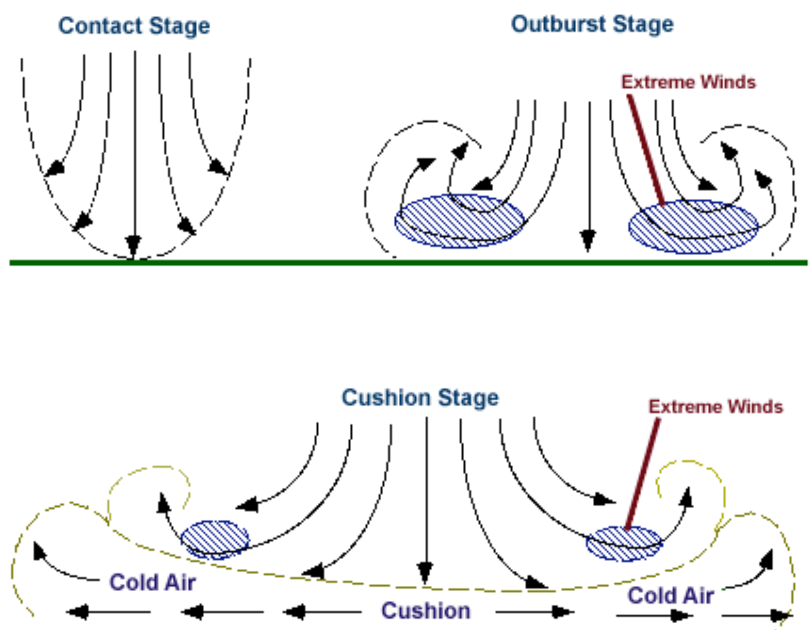
(b) Velocity relative to ground (m/s)



Radial velocity vectors corresponding to (a). Color contours represent wind speed in m/s. Reflectivity contours are indicated by the solid lines.

Microbursts

Microbursts are formed in regions where thunderstorm downdrafts are concentrated in a very small area (less than ~4 km in width). Microbursts can be “wet” or “dry” depending on the humidity of the air surrounding the thunderstorm. Dry microbursts are quite common in arid portions of the western U.S.

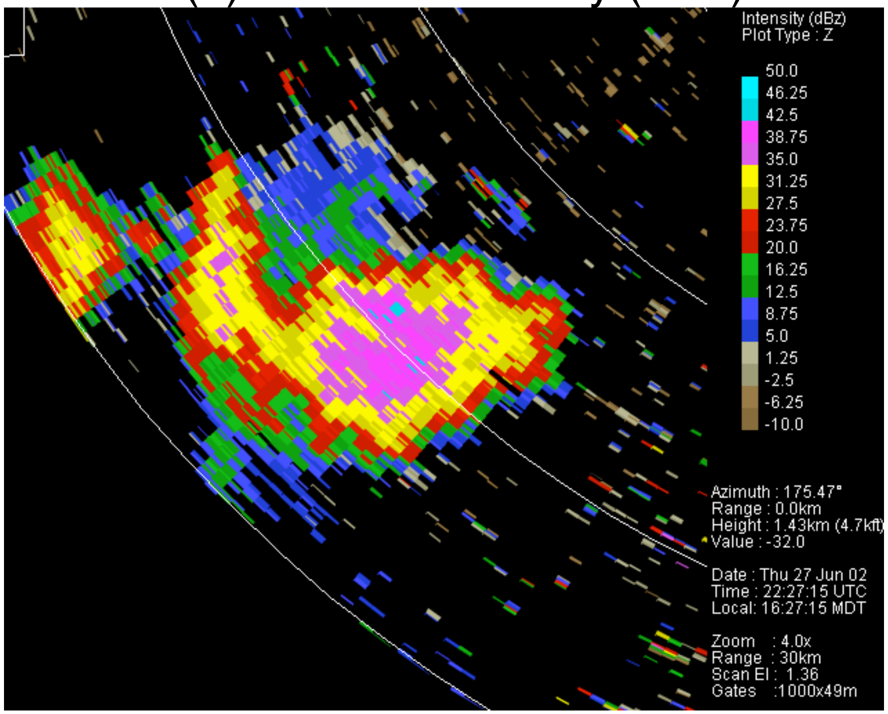


Images from the University of Illinois WW2010 Project

Example of a microburst observed by the CSU-CHILL radar

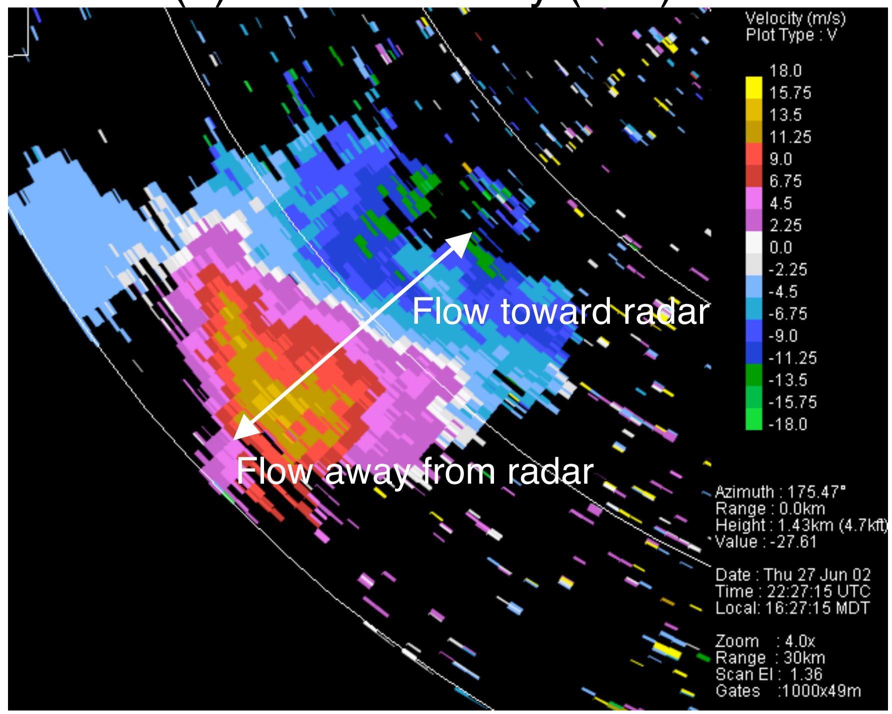
The images below show a fairly typical microburst signature on the radar display. The left image (a) shows the radar reflectivity (*dBZ*) and the right image(b) shows the corresponding radial velocity (m/s) relative to the CHILL radar. In a microburst, the spreading out of the air near the ground surface is similar to turning a garden hose on and aiming the end toward the pavement.

(a) Radar reflectivity (dBZ)



Radar reflectivity (dBZ) observed from the CSU-CHILL on 27 June 2002 22:27 UTC.

(b) Radial velocity (m/s)



Radial velocity signature observed from the CSU-CHILL on 27 June 2002 22:27 UTC.

<u>Question to Consider:</u>

Draw a cartoon of a vertical slice through a microburst and describe how it would be an aviation hazard