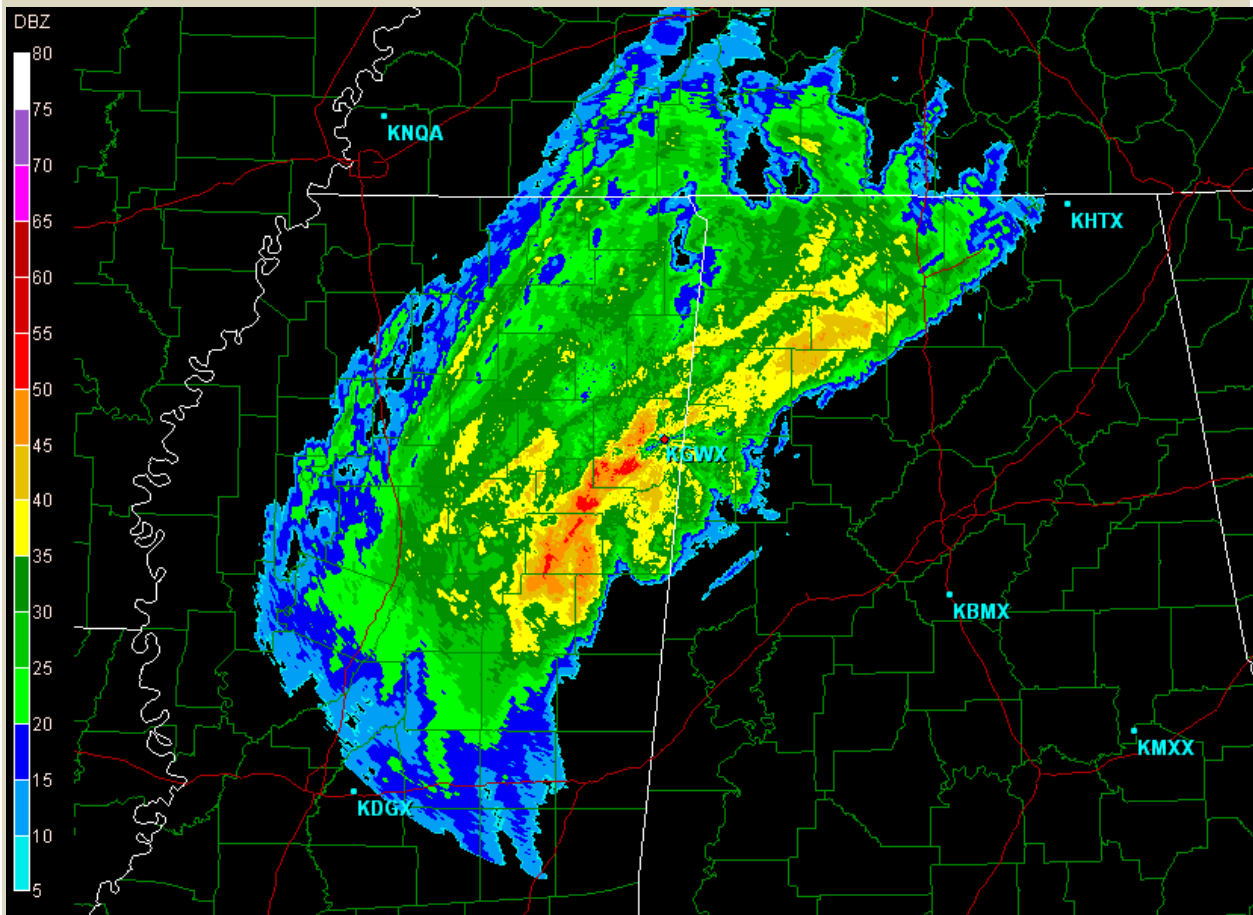# How to use and interpret Doppler weather radar

A novice guide to understanding the principles of radar and how to use base reflectivity and base velocity to show that more than rain and wind is occurring

Jeff Duda

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Introduction

This guide is intended for those who have very little or no experience using Doppler weather radar. A glossary is provided to define basic terms or terms that are frequently used in this guide. Words that appear in **bold** type are words that can be found in the glossary in the back of this guide. They will only be highlighted the first time they appear. More advanced topics are included for those who have more experience with radar and still wish to learn more. The base reflectivity and base velocity topics are the most important topics to learn.
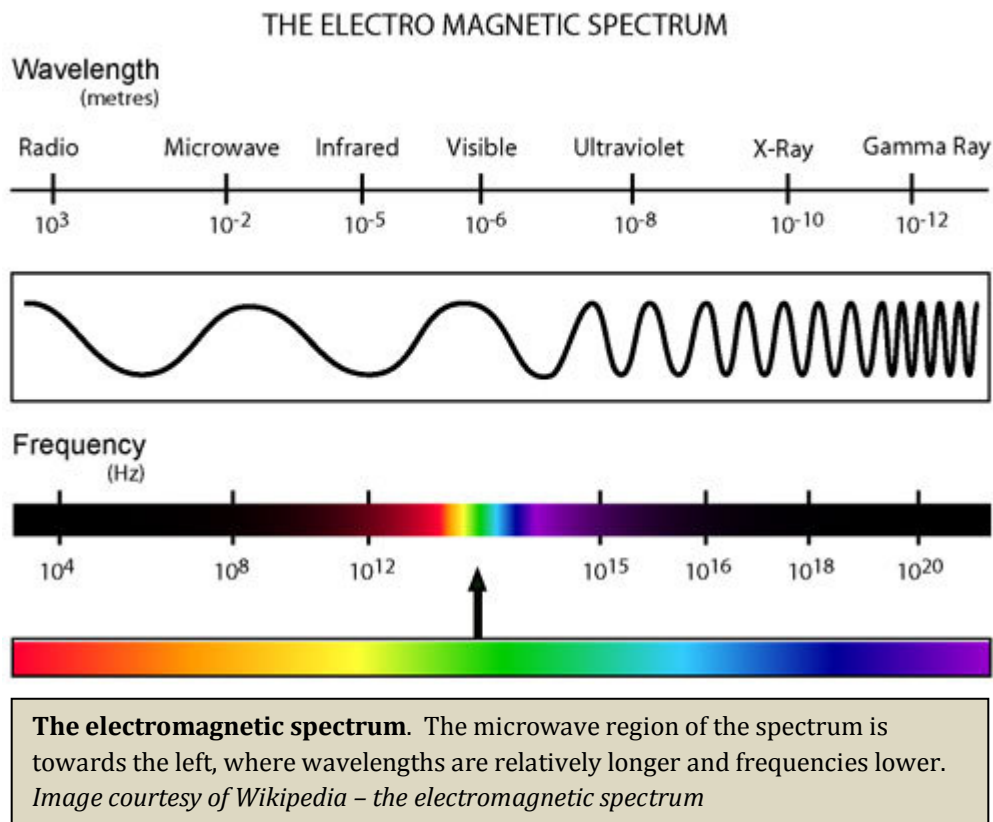
This guide is organized using the color bars that highlight the titles and headings. The <mark>yellow</mark> color refers to headings for major topics. The <mark>green</mark> color highlights subtopic headings within the major topics. <mark>Light red</mark> color indicates subtopics within other subtopics.

Table of contents

Fundamentals of radar

The weather radar you see on your local TV news program, The Weather Channel, or other news channel is Doppler radar. Doppler radar emits beams (**pulses**) of **microwave** energy from a transmitter into the atmosphere (see the figure below for a diagram of the electromagnetic spectrum). When these beams collide with objects in the atmosphere such as raindrops, hail stones, snowflakes, cloud droplets, birds, insects, dust particles, trees, and even the ground, some of the energy bounces back towards the radar. A receiver on the radar then collects the reflected energy and displays it in different ways.

The electromagnetic spectrum. The microwave region of the spectrum is towards the left, where wavelengths are relatively longer and frequencies lower. *Image courtesy of Wikipedia – the electromagnetic spectrum*

Doppler radar has not always been used for weather radar. Doppler radar came into common use when the Weather Surveillance Radar – 1988 Doppler radar (WSR-88D) was installed in place of the Weather Surveillance Radar – 1974 (WSR-74) and Weather Surveillance Radar – 1957 (WSR-57) radars that were in place until the early 1990s. Currently, there are 158 such WSR-88Ds that operate around the United States and other U.S. territories. They are part of a network of Doppler radars called **NEXRAD**, which stands for NEXt generation RADar. There are two radar sites in Iowa: one near Des Moines and one near Davenport. All radar sites in the lower 48 U.S. states are given a four-letter call number that starts with "K." The Des Moines radar is KDMX. The Davenport radar is KDVN. Other neighborhing radar sites include Sioux Falls, SD (KFSD), Omaha, NE (KOAX), Kansas City, MO (KEAX), St. Louis, MO (KLSX), Lincoln, IL (KILX), La Crosse, WI (KARX), and Minneapolis, MN (KMPX). See the figure below for a map of all radar locations in the U.S. and other territories.

When you see a radar image on TV, it is likely a combination of individual Doppler radars or a section of the NEXRAD network that you are looking at. Why is this? An individual radar sits inside a dome that rests on a tower about 100 feet tall. As the transmitter on the radar emits beams of microwave energy, it also rotates in all horizontal directions to send energy to every part of the lower atmosphere. Radar beams can only travel out so far before they become useless. Therefore, the effective range of a Doppler radar is a filled circle with a radius of about 217 miles (250 nautical miles, a frequently used unit in measuring distance for radar), centered at the radar apparatus itself. If you see a radar image that has a circular boundary, then you are looking at the radar image from just one radar. If not, then data from multiple radars are being displayed.

National Doppler Radar Sites
Select radar location and click.

The NEXRAD network. Shown are the 158 radar sites that compose the NEXRAD network. Note the two sites in Iowa (KDMX and KDVN). *Image courtesty of the National Climatic Data Center*
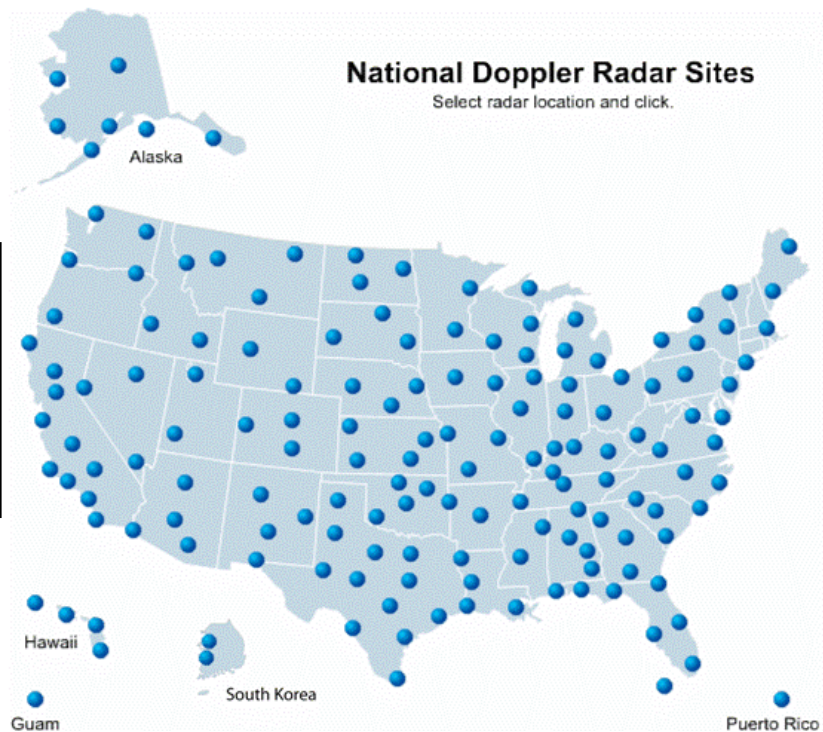
Radar resources

There are many resources you can use to view Doppler radar images. Here are the internet links to some preferred sites. Note that you may have to follow other links once you get to these sites to view actual radar images. These other links should be easy to find and to follow:

- www.rap.ucar.edu/weather/radar
- www.weather.gov/radar
- weather.cod.edu/analysis
- www.wunderground.com

Note that you can only view current radar data on these sites (or data that is less than a few hours old). Radar products are discarded after a certain amount of time to save storage space on computers. However, a few organizations save radar data, archive it, and make it available for people to download and view, free of charge! Anyone interested in looking at old radar imagery can do so by following these steps:

1) Know the year, month, date, approximate time during the day, and nearest radar site to the event that occurred. Note that you need to know the time in Greenich Mean Time, also called Universal Time Coordinates (UTC) in most meteorological publications. The Central Time Zone is six hours behind UTC, so when it is midnight in the Central Time Zone, it is 6:00 AM UTC.

2) Go to www.ncdc.noaa.gov/nexradinv.

3) Select the site, the time of the event, and a product to view. There are tons of products. The most common ones to use are labeled as SHORT RANGE BASE REFLECTIVITY and BASE VELOCITY and should be found near the top of the pull-down menu.

4) Select the range of time (in hours UTC) for which you want to get data.

5) Enter an email address to where you want the data sent.

6) When your application goes through, a HAS number will be shown to you. This is the code number for your product. When the data arrives in your email inbox it will be in code. You will need to open a program from this URL: www.ncdc.noaa.gov/oa/radar/jnx/jnt-install.php (and click on the link that says Launch the STABLE Version 1.9.11 Java NEXRAD Viewer) to view the data. When that program opens, simply enter the HAS number in the input box that opens with the program and click "submit." The data should then show up and you can begin to view the data.

Basic terms for viewing radar

Since radars have a certain spatial resolution, the radar patterns you see will look gridded and blocky, especially if you zoom in far enough on a radar image. Note that many radar programs (especially the ones you see on TV) use smoothing algorithms which smooth the blocks of data and make the data look less gridded and more natural. All of the websites mentioned in the previous section as sources for radar do not use smoothing algorithms. The view of radar looking blocky and gridded is how radar is truly displayed. Therefore, the terms about to be described only apply to radar images that are in their true form and that have not been smoothed.

Each individual block, box, or square of data you see on radar is called a **pixel**, **bin**, or **gate**.

As you move outward from a radar site along a straight line (think of moving towards the edge of the circle along a radius of it), the bins that form a connected line as you move out are called a **radial**.
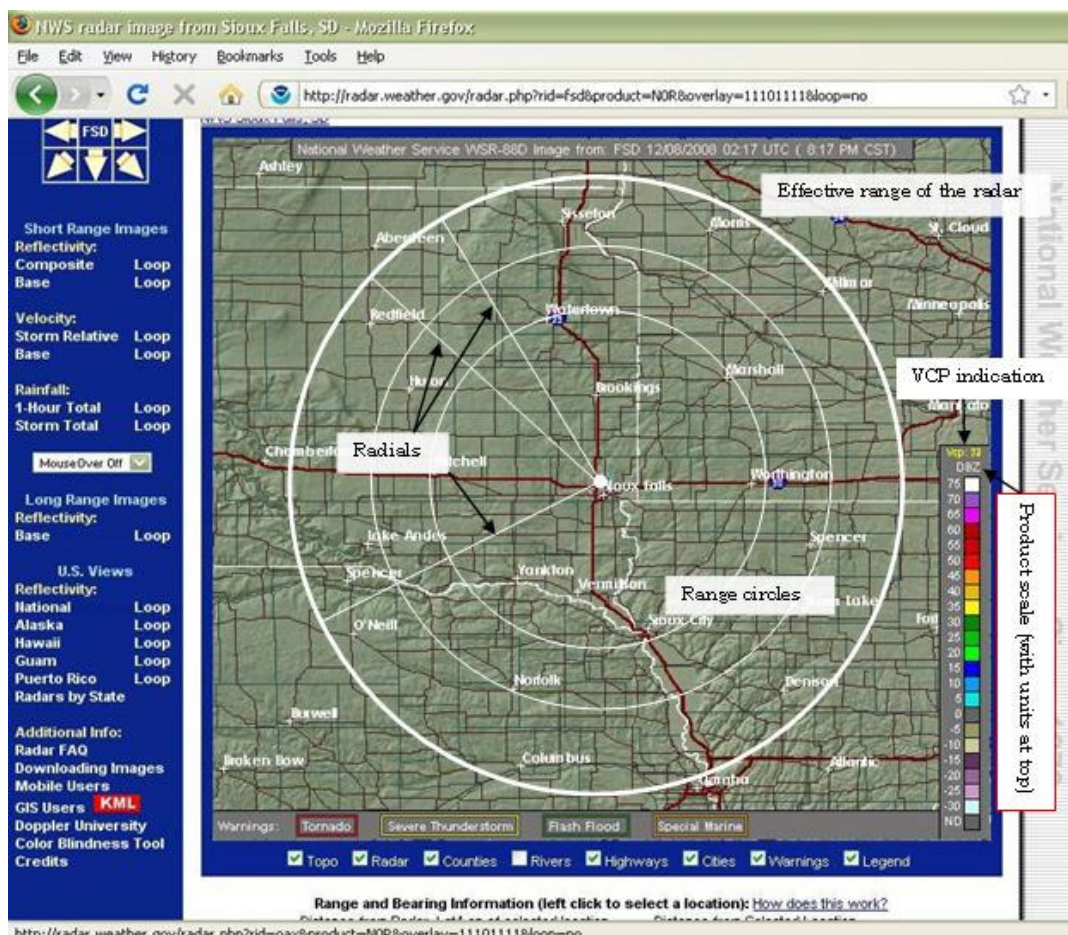
Sample image of internet radar. A basic free source of radar via the internet is shown with radials, range circles, and the scale of the reflectivity product shown. *Image courtesy of the National Weather Service*
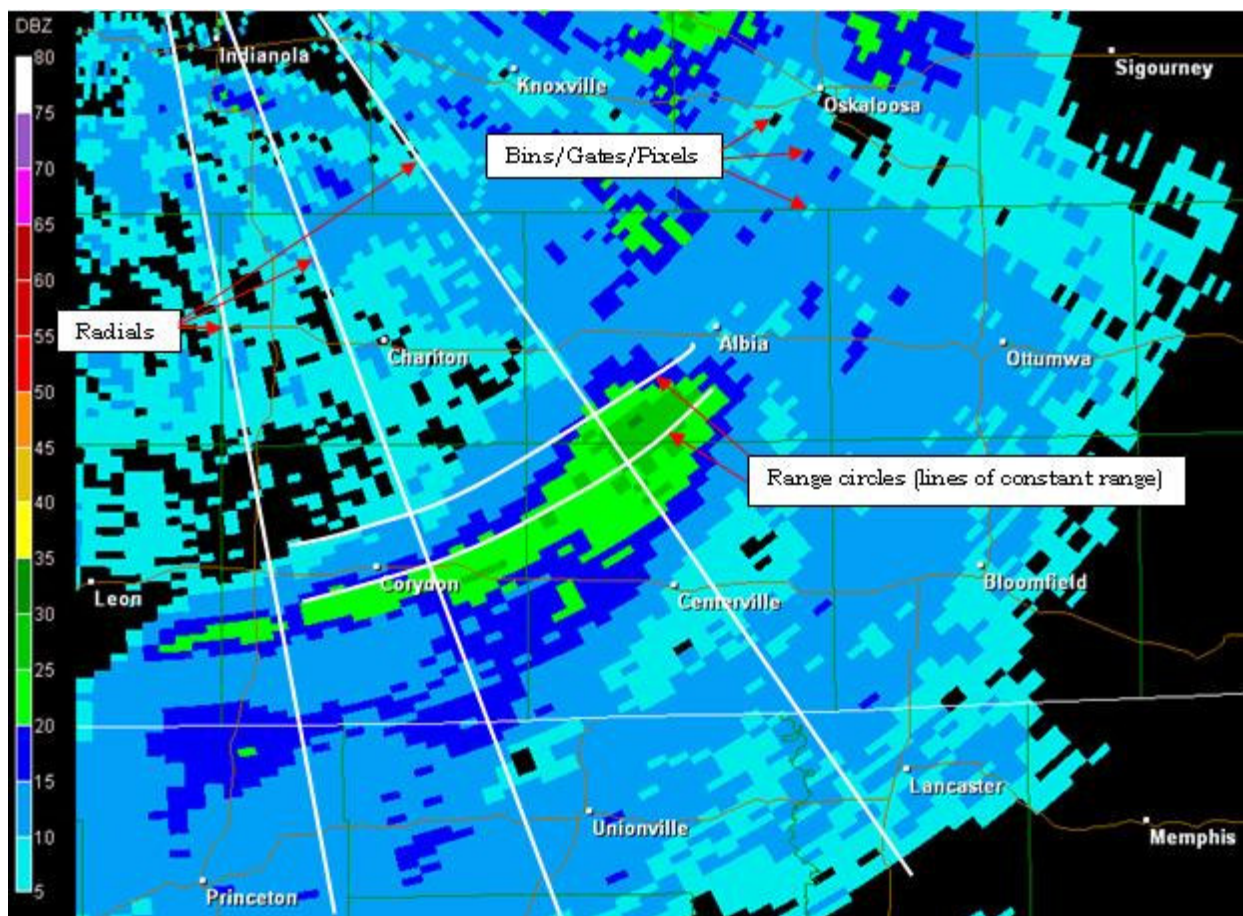
Basic radar vocabulary. A sample image of base reflectivity is shown with example radials, range circles, and bins marked. This image was made using a radar program called Gibson Ridge, which is, unfortunately, not free. However, it is showing the same radar product that you can find from the online radar resources. Although smoothing is an option with this radar software, it has not been applied here.

Radar does not use Rectangular or Cartesian (i.e., x-coordinate, y-coordinate) axes for measuring location on a radar. Instead, the **range** – or distance in **nautical miles** (one nautical mile is 1.15 regular miles) from the radar site – and **azimuth** – or angle made between the radial that points to true north and the radial that points to the bin of interest – are used to determine location on a radar. This is actually an example of Polar coordinates, where instead of using an x-coordinate and y-coordinate, distance from center and angle from some given reference line is used instead.

If the radar is detecting something (anything that reflected the energy the radar sent) then that data is represented by a bin colored a certain color to correspond with a value of a given unit for whatever product you are viewing. This colored bin is called an **echo** or **return**, which makes sense nominally, since an echo is repetition of a sound or wave that was emitted. The energy from the wave emitted by the radar was returned or echoed back to the radar. Echo and return also apply to a large group of bins, not just a single one.

Characteristics of Doppler radar

All Doppler radars share some common components and characteristics that describe how they scan the atmosphere. All radars have a transmitter, a receiver, and an antenna. The transmitter emits pulses of microwave energy. The reciever recieves reflected energy. The antenna sends the information to another source to be processed and displayed to meteorologists and the general public. All Doppler radars rotate horizontally as they transmit energy. Not only do radars rotate horizontally, but they also can tilt vertically. In fact, depending on the volume coverage pattern, which will be described later, a radar may scan horizontally 360° at anywhere from four to fourteen different vertical angles. The standard elevation angle is 0.5° above the horizontal, which is referred to as a **base** angle. This elevation gives the name "base X" to many radar products, where X is one of many products, such as **reflectivity** or velocity. When radar finishes scanning in 360 degrees at one elevation angle, it tilts up to the next elevation angle and scans 360 degrees at that angle, too. It does this until it has scanned at all elevation angles. For this reason, with some software, it is possible to visualize radar data in 3D. However, none of the products at the links provided will allow you to see that. Unfortunately, you must purchase software that can cost upward of $250 to view radar in 3D. Therefore, this manual will not focus on methods of observing 3D radar. However, it will show some cool things that can be seen with higher than 0.5° tilts.

Radar can only detect reflected energy when it is listening for it. Like a school teacher of mine used to say, "speaking and listening are mutually exclusive activities." This is true for radar, also. While radar is transmitting energy, it cannot detect reflected energy. This will be visually apparent as a very small circle surrounding a radar site, inside of which no data is displayed. Curiously, you can even determine for how long the radar is transmitting a pulse by measuring the radius of that circle. The larger the circle, the longer the radar is transmitting. Since radar alternates between transmitting and receiving energy, a term called the **pulse repetition frequency** (**PRF**) – defined as the rate at which the radar sends pulses – is used to characterize a radar. For example, a PRF of 1000 Hz means that the radar is transmitting 1000 pulses per second, or one pulse every thoussandth (0.001) of a second. The PRF has mathematical significance to reflectivity and velocity products, and will be discussed more fully later.

One must remember (or realize) that the microwave energy emitted by radar is, in fact, a wave. Since it is a wave, it has all the characteristics of waves. One of them is wavelength, defined as the distance between successive peaks or valleys in a wave. In the microwave portion of the electromagnetic spectrum, wavelengths vary between 1 millimeter and 1 meter. For Doppler radar, different wavelengths are used, including 10 centimeter (C-band), 5 centimeter (S-band), and 2 centimeter (X-band). The NEXRAD network's 158 radars are predominantly C-band radars. TV news stations that own their own radars commonly use S-band radars. Much research is done using X-band radar. The wavelength used for radar has three major effects:
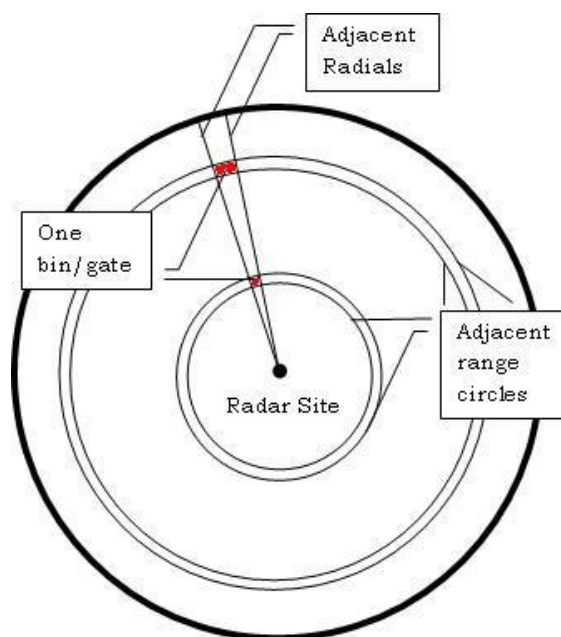1) How small of particles the radar can detect
2) How much the beam is attenuated as it bounces off of reflectors
3) How large a value of velocity can be measured

The shorter the wavelength, the smaller the particles the radar can detect. Attenuation means weakening of the beam due to energy being deflected away or absorbed by particles as the beam travels away from the radar. Imagine throwing a baseball into a grove of trees. The thicker the grove (i.e., the more trees), the slower the ball will be traveling when it emerges from the grove (if it emerges at all). Attenuation of the path of the baseball has occurred here. A practical application of this effect is when a radar beam has to travel through several intense thunderstorms, or along a line of intense thunderstorms. The beam will encounter a very large number of raindrops as it passes through the thunderstorms. The more raindrops the beam bounces off of, the less energy is left to travel farther to more distant storms. The product called base reflectivity displays the amount of energy that has returned to the radar. If there is less energy emitted to reflect from particles, there will be less reflected back to the radar. This will make it seem like the thunderstorms that are farther out are less intense, when in fact they may be as intense as or more intense than the storms closer to the radar.
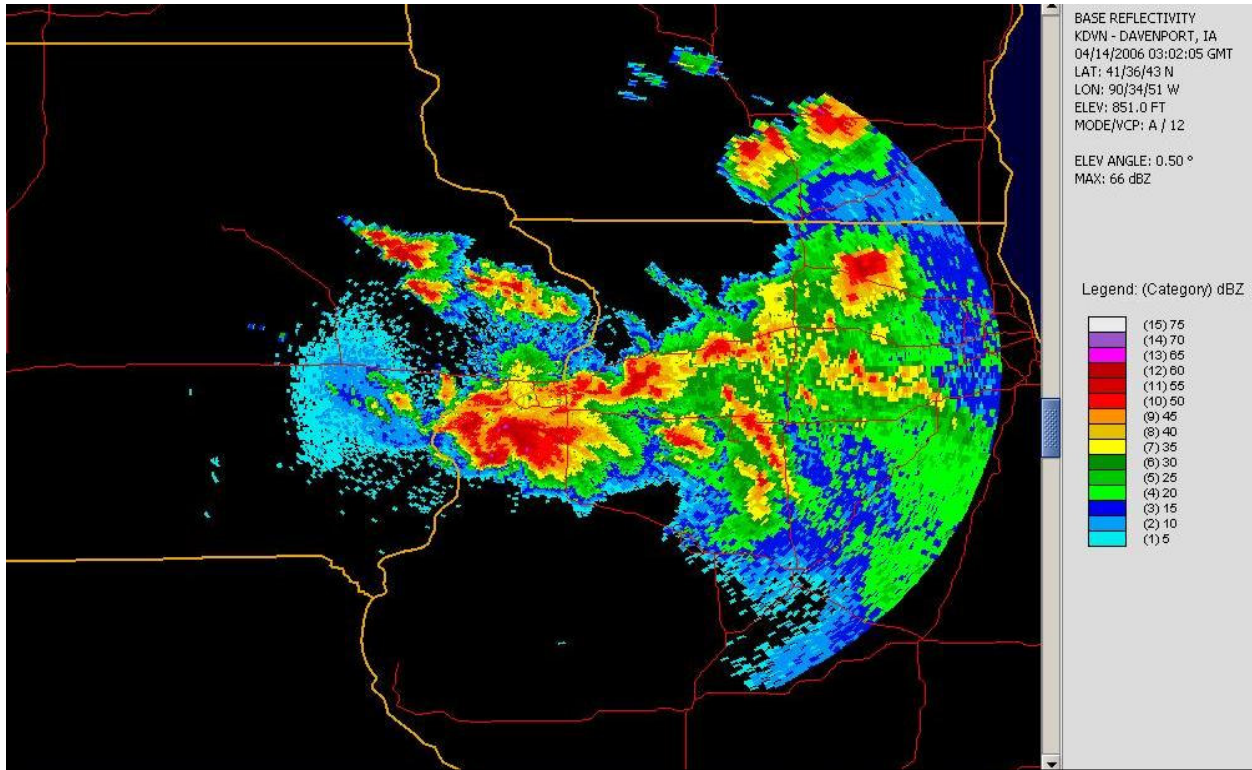
Beam spreading

Radars have a certain resolution of data (both by radial and by azimuth). The **radial resolution** of a radar is the number of bins for a given distance that the beam travels. For example, current advances in some types of radar have one bin for every 250 meters of travel away from the radar. Thus, these kinds of radars have 250 meter radial resolution. The radar products you will usually see on the websites given have radial resolution of 1000 meters. The **azimuthal resolution** (also called **beamwidth** or **beam separation**) of a radar is the number of radials that the radar can depict in terms of degrees of a circle. For example, if there are 360 radials that can be shown by radar, then that radar has one radial for every degree in azimuth. Therefore, the azimuthal resolution for that radar is 1°. Another way to think of it is how far apart (in azimuth degrees) two adjacent radials are. The radar products you will most commonly see have 1° azimuthal resolution, but some advanced radars have 0.5° azimuthal resolution.

The concept of beam spreading. The fat outer circle corresponds to the effective radar range. Adjacent radials and range cirlces are marked along with a sample bin determined by each pair of radials and range circles. Notice that the outer bin is much larger than the inner bin, demonstrating the idea of beam spreading.

Beam spreading is a term that describes the change in the size of a bin as distance from the radar site increases due to the spreading of radar beams at adjacent radials as they move away from the radar site. Consider the figure shown. Assuming the distance between the range circles are the same

An example of beam spreading. Base reflectivity imagery from the Davenport, IA radar (KDVN) late on April 13, 2006. Notice how the storms that are very close to the radar (near the center of the image) appear much finer and less blocky than the storms in southern Wisconsin, far from the radar. This image was obtained using the Java NEXRAD Viewer program from www.ncdc.noaa.gov.

for both pairs of adjacent range circles, the two bins colored in red have the same azimuthal and radial size (one unit of radial resolution by one unit of azimuthal resolution), but you can clearly see that the outer bin is larger than the inner bin. As an example, with a radar that has radial and azimuthal resolutions of 1000 meters and 1°, respectively, the areal size of one bin ranges from around 0.02 square miles very close to the radar to around 1.5 square miles near the end of the radar's effective range, a size difference of a factor of about 70! Thus, it is clear that since a single bin only represents one point of data, then the radar data is at a seemingly lower resolution farther from the radar than it is closer to the radar. This causes differences in appearance of radar returns far from and close to the radar site. This is one way that radar data is naturally distorted, and beam spreading must be taken into consideration when observing radar data.
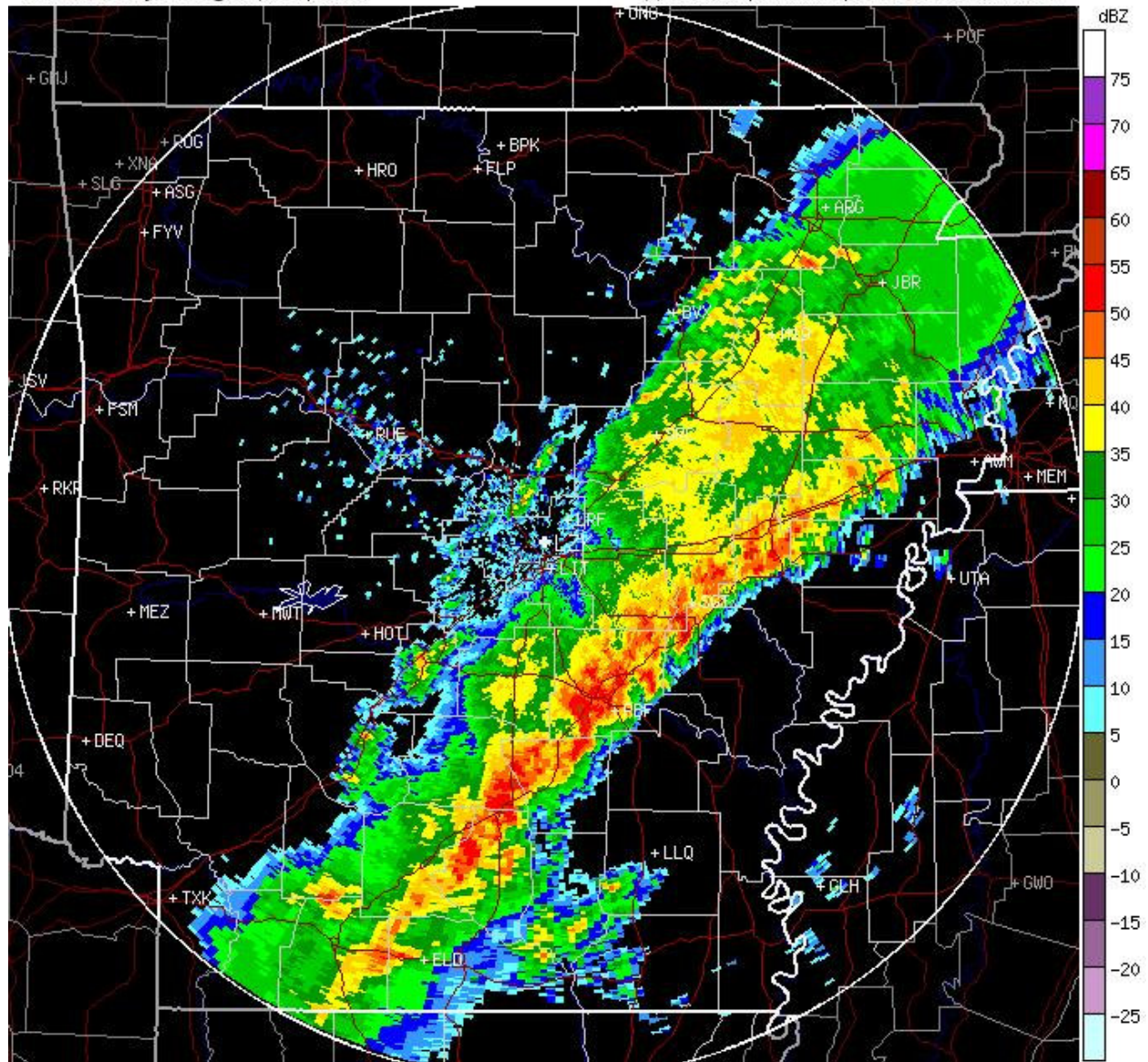
Base reflectivity

      Base reflectivity is a radar product that displays the amount of power returned to the radar after it has reflected off particles in the atmosphere. The actual amount of energy returned is not displayed. What is displayed is a term called reflectivity (hence why this product is named base reflectivity), and is measured in decibels (dBZ). A decibel is a measure of the energy transmitted by a wave, or a measure of the amplitude of a wave. For

Base reflectivity. An example base reflectivity image from the Little Rock, AK (KLZK) is shown. Note the information that is given in the title above the image. Also note the scale on the right, indicating the strength of returns to the radar, measured in decibels (dBZ). The orange and red colors indicate a line of thunderstorms is currently moving across Arkansas. *Image courtesy of UCAR: www.rap.ucar.edu/weather/radar*

reference, sound waves are also measured in decibels. The usual range of reflectivity that is displayed by this product is between 0 dBZ and 80 dBZ, with 0 dBZ indicating very little return of energy and 80 dBZ indicating extremely intense returned energy, usually a value never reached in meteorological scenarios. Note that reflectivity values can be negative since the reflectivity scale is actually a logarithmic scale, which means the numbers on the scale are actually powers of 10. 0 dBZ actually means 10^0, or 1 of some other measurement in the processing of returned energy. Although radar scans 360° of the atmosphere at many tilts, only the lowest one (which is usually 0.5° above horizontal) is displayed. This gives the product name the "base" prefix, and means the same thing in all other products. Also note that the value of reflectivity in a bin of data is actually the average of all the reflectivity values detected within that bin (there will almost always be multiple targets that reflected the energy within the areal space of one bin, and they won't all reflect the same amount of energy). This is most useful to know when dealing with a tight reflectivity **gradient**, or large change of reflectivity over a distance of a few bins, and is most obvious at large distances from the radar site.

## Interesting things that can be seen with base reflectivity

Base reflecitivity is interesting in the sense that it will show echoes whenever energy from the radar beam bounces back to it. *Anything* in the atmosphere that can reflect microwave energy will cause echoes to appear on a radar display. Many times, these echoes are not **precipitation**, but are meteorological in nature. If base reflectivity shows echoes that are not meteorological in nature, the echoes are called anomalous propagation, which is discussed later.

Frequently, a boundary between warm, moist air, and cool, dry air causes reflection of a wave. This boundary will be seen as a very narrow line of light reflectivity. This boundary can be a warm or cold front, a dryline, or outflow boundary from thunderstorms. When the atmosphere is unstable and thunderstorms are likely to form, it is common to see storms form directly on boundaries.

A TBSS is an anomalous echo caused by very large hail in a storm bending the radar beam. When the radar beam moves through a storm containing large hail, the beam may deflect off of the large hail and move towards the ground. When hitting the ground, the energy then reflects off the ground, back up to the hail, and back to the radar. There will be a noticeable time delay between the arrival to the radar site of the energy reflected from the contact of the beam and hail and the energy reflected from the ground after the collision. The radar will interpret this delay as echoes farther from the radar site. Therefore, a TBSS will appear on radar as a "spike," or long, narrow extension of light reflectivity on the backside of the storm. *Note: by the nature of the scenario that produces them, this spike must occur directly along a radial. A TBSS does not exist going across radials.* There are other ways to identify TBSSs, but they involve using products that are not discussed in this manual. Any curious readers are invited to learn about the radar product called "spectrum width" if they would like to know more about TBSSs and radar products in general.

Three Body Scattering

Heavy Rain or Wet Hail

Hail Spike

Reflection from Wet Ground
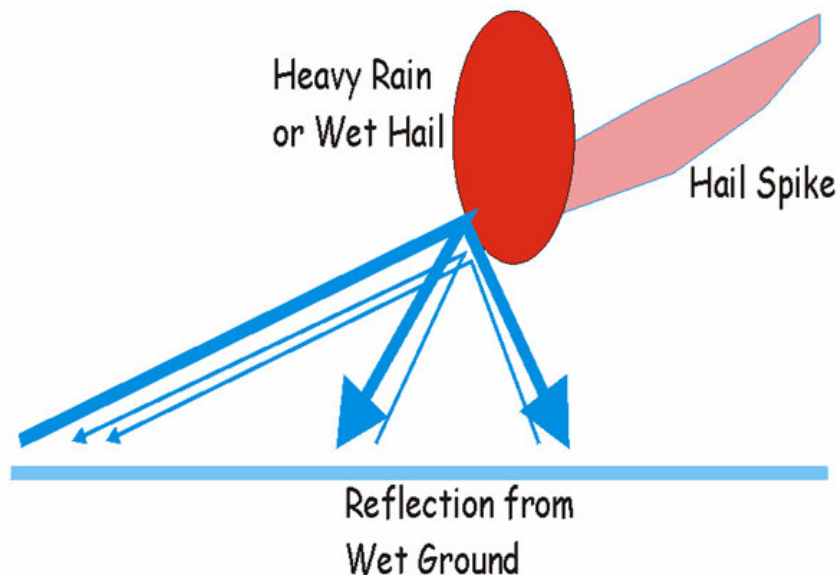
Three-body scatter spike. A schematic for the cause of a three-body scatter spike is shown. The red oval indicates a region in the atmosphere that contains rain and hail (which would typically be colored red on base reflectivity anyway). The blue arrows show the path of the radar beam as it deflects off the hail, bounces to the ground, and then reflects off the ground to the radar or back to the hail and then to the radar. The three-body scatter spike is named due to the three reflections of the radar beam that occur to give this reflectivity pattern. *Image courtesy of Wikipedia – three-body scatter spike*
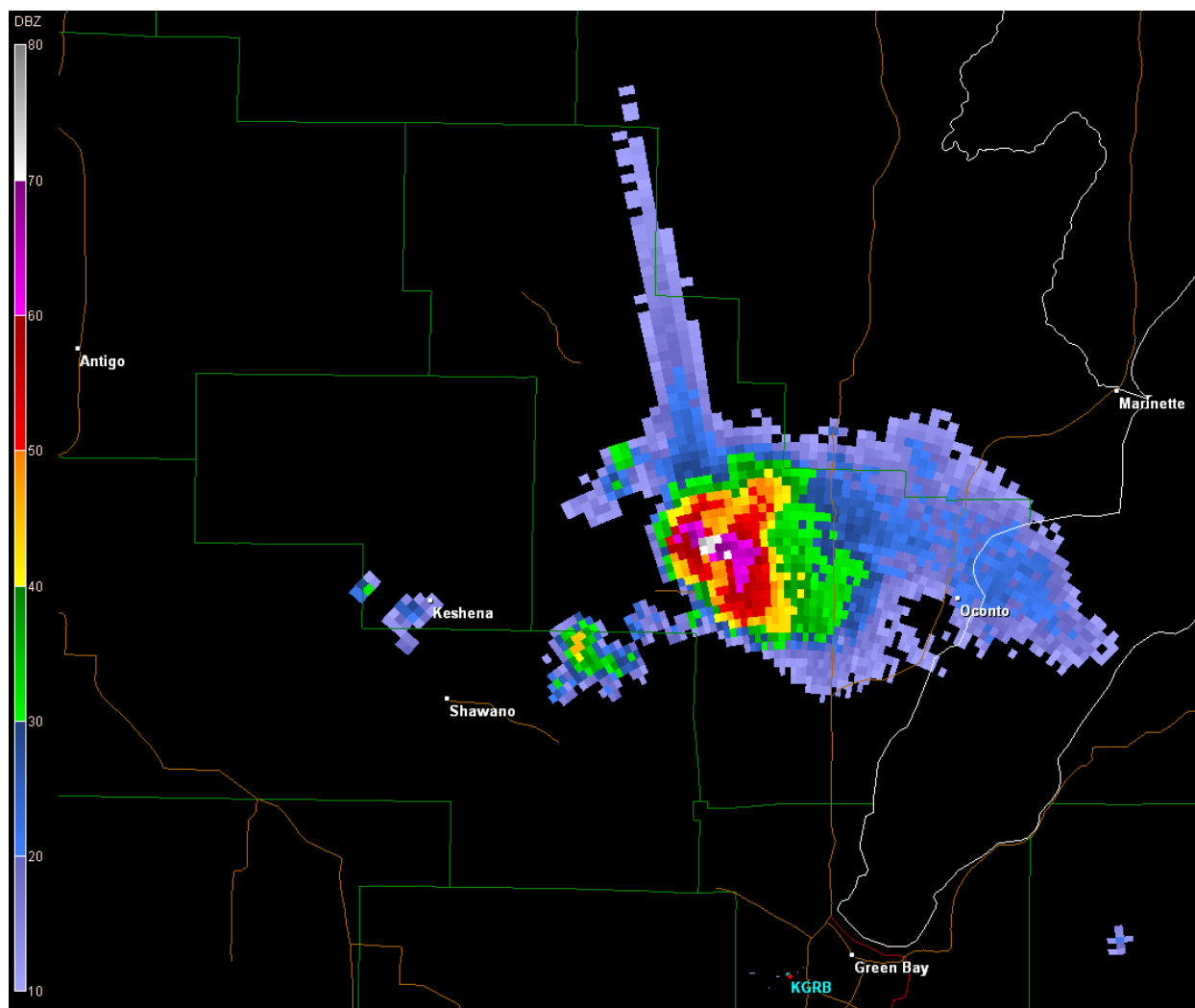
A three-body scatter spike. An example of a three-body scatter spike is shown from the Green Bay, WI (KGRB) radar using the Gibson Ridge software. The TBSS is evident as the streak of low reflectivity extending past the storm in the image along five radials. The white bins in the storm show reflectivity values of over 70 dBZ, a strong indication of large hail in the storm. The TBSS is an even stronger indicator that large hail is present. Although this particular scan is at 8.0°, TBSSs can occur at any elevation angle. The 8.0° scan showed this example the best.

Bright banding

Bright banding is a region of relatively intense reflectivity found in an area where frozen precipitation is likely occurring, or along a boundary between frozen and liquid precipitation. The high reflectivity is not an indication of very heavy precipitation falling, but is rather an indication of liquid coating on frozen precipitation. Liquid water reflects microwave energy much better than does frozen water. At the boundary between frozen and liquid precipitation, there will be a mix of both phases of water. The liquid coating on the frozen particles will make the particles appear much larger to the radar due to reflecting much more energy. Therefore, the reflectivity will be much higher where this is occurring. The difference in reflective abilities of liquid and frozen water enables an observer of radar to determine where frozen and liquid precipitation are occurring. Frozen precipitation will appear much smoother, with very small reflectivity gradients and overall
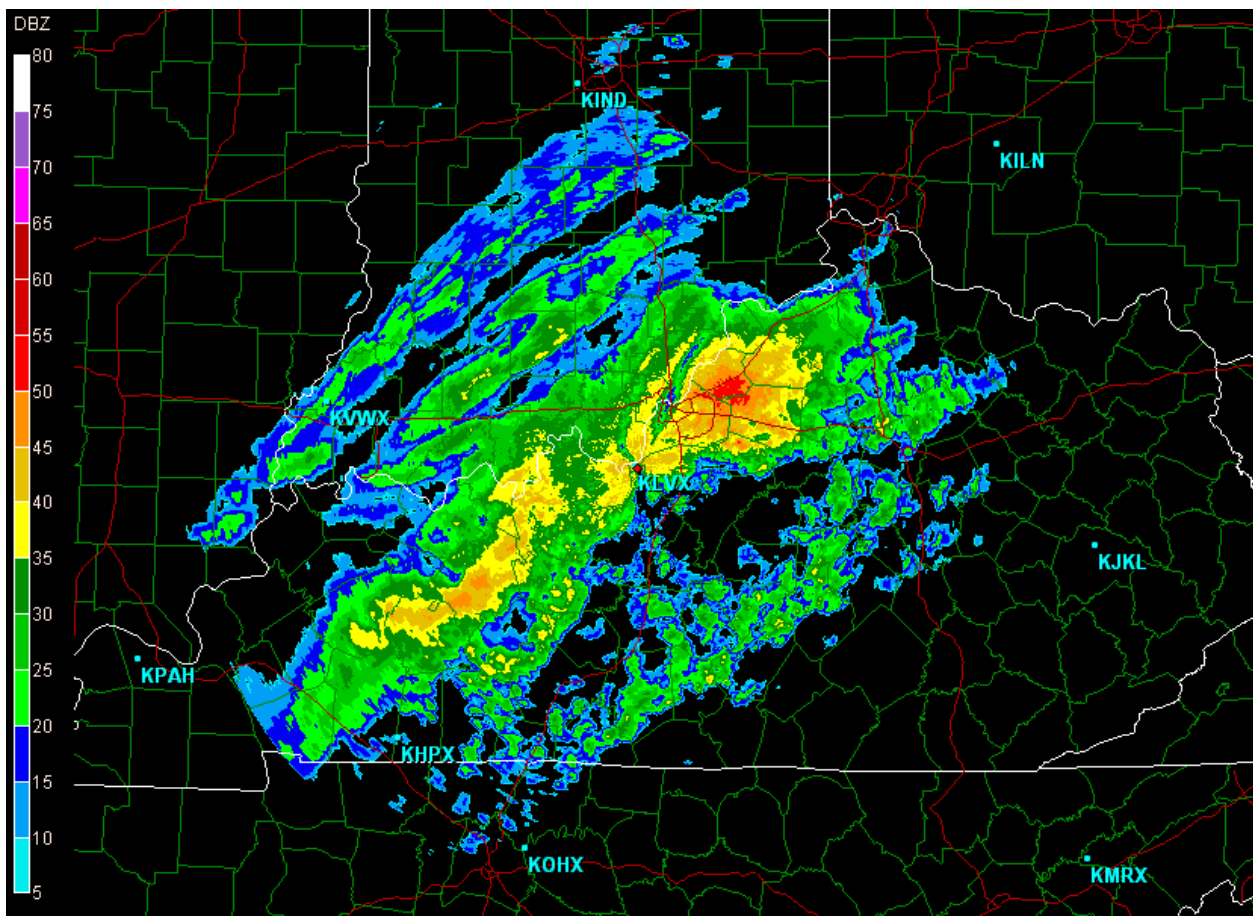
Bright banding. Shown is a base reflectivity image using the Gibson Ridge software from the Louisville, KY (KLVX) radar site. Note the reflectivity scale on the left, and note that smoothing has been applied to this image. Bright banding is occurring just to the northeast of the radar site, indicated by the orange and red colored reflectivity. Close observation of this image would reveal that the frozen precipitation to the northwest of the bright banding region appears smoother (in a different sense than due to the smoothing algorithm) in the image than the liquid precipitation to the southeast. It is unlikely that precipitation heavy enough to reflect that much energy is falling in the bright banding region. The high reflectivity is due to bright banding.

lower reflectivity than will liquid precipitation, which will appear more coarse with higher gradients and higher reflectivity.

This same principle is also used to explain why hail appears as very high values of reflectivity on radar. In fact, reflectivity values above 60 dBZ are usually an indication that hail, or a mixture of heavy rain and hail, is being detected. Reflectivity values greater than 70 dBZ likely indicate large hail is being detected. Hail grows by collecting liquid water on the surface of an already existing hail stone. The liquid water then freezes and adds a layer to the stone. The liquid water coating the hail stone reflects a very large amount of energy emitted by radar and results in very high values of reflectivity showing up on radar.
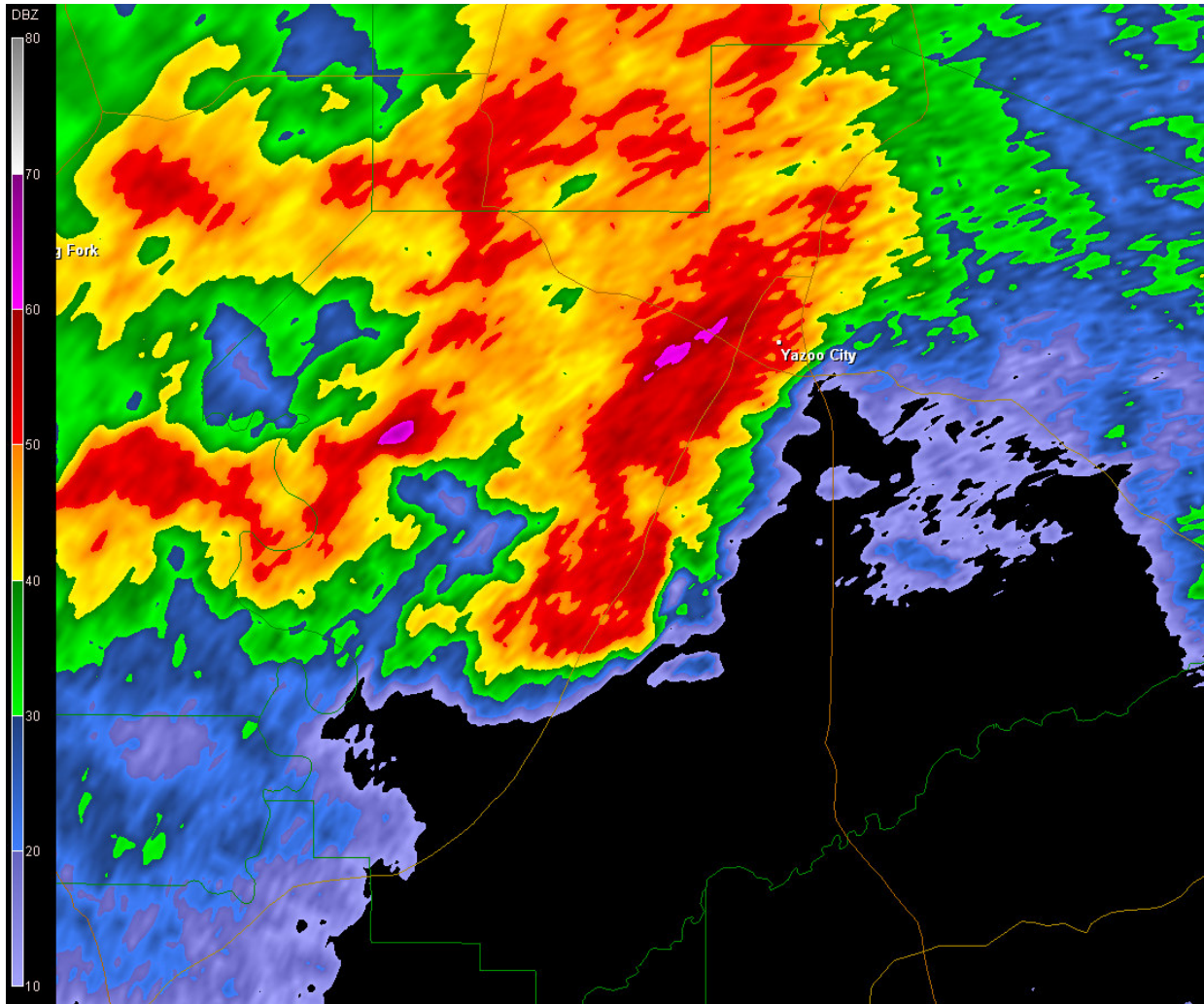
High reflectivity. Shown is a base reflectivity image from the Jackson, MS (KDGX) radar using the Gibson Ridge software. Note the reflectivity scale on the left. The high reflectivity values (>60 dBZ) shown in the pink color are likely indicators of hail, or a mixture of very heavy rain and hail. The liquid coating on hailstones causes them to reflect more of the energy in the radar beam back to the radar, resulting in higher reflectivity values there.

Base velocity

Base velocity is a radar product that displays the average wind speed (and in some sense, the direction, hence velocity) of particles that are detected by the radar. The radar can measure the speed due to a phenomenon called the Doppler Effect, in which the frequency of a wave changes as it bounces off a particle that is moving (e.g., the particle in the atmosphere) with respect to an object that is not moving (i.e., the radar). Since radar only sends pulses of energy in one direction per pulse, the wind speed detected is necessarily a speed in the direction of the beam. *An individual Doppler radar cannot measure or calculate wind in more than one dimension.* However, two Doppler radars that are not in the same location can. It is important for you to know that when you are looking at a display of base velocity, you are looking at the wind speed either directly towards or directly away from the radar. Since there are more than 360 different angles along which you can approach a radar, the wind velocity detected at one location may not be the same wind velocity detected at a different location, even if the product indicates the same magnitude of wind at both locations.
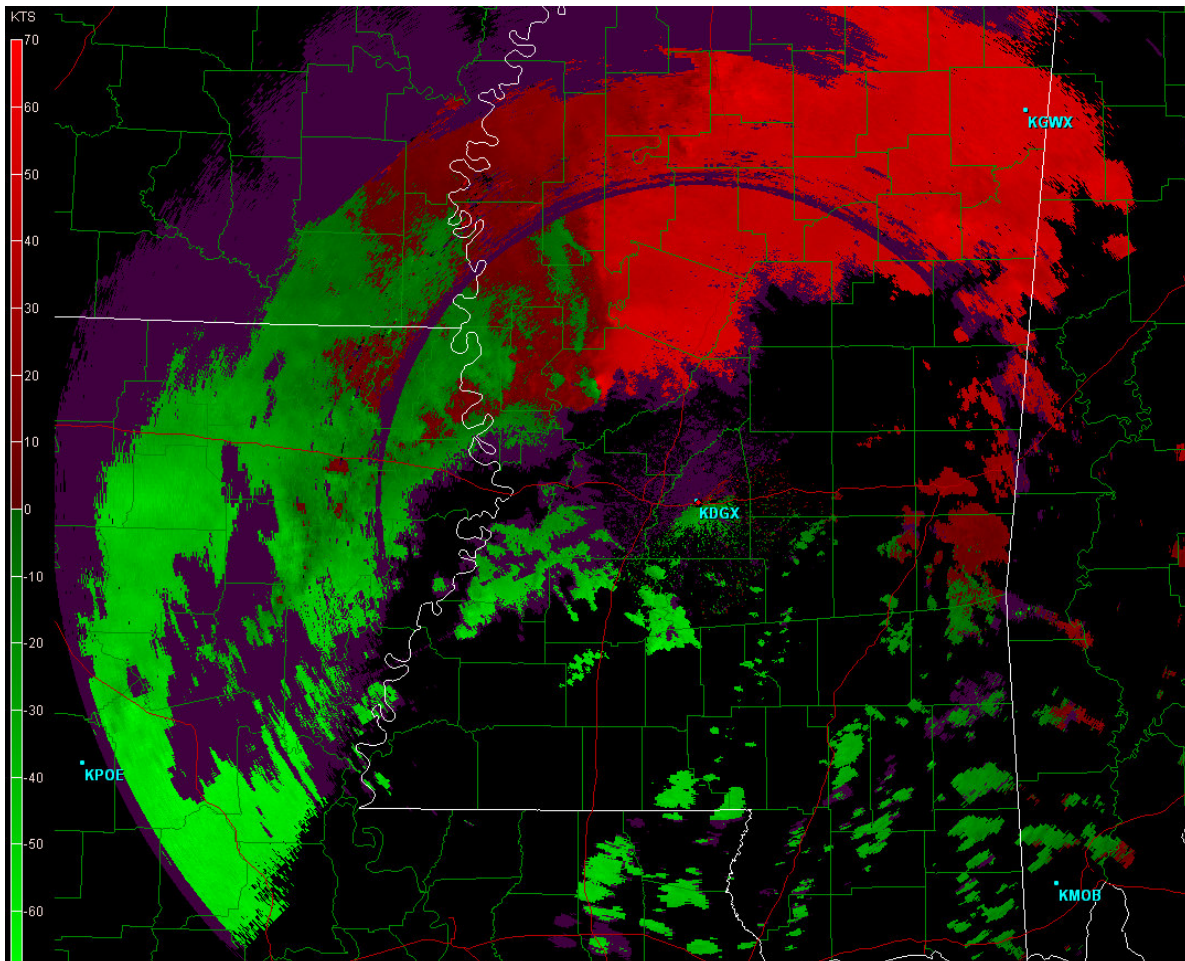
**Base Velocity.** An example of base velocity is shown from the Jackson, MS radar (KDGX) using the Gibson Ridge software. Note the scale on the left, showing wind speed in knots (kts), which are nautical miles per hour. One knot equals 1.15 miles per hour. The green colors to the southwest of the radar site along with the red colors to the northeast of it indicate that winds are flowing towards the north and east.

Positive values of velocity mean that there is a positive correlation between distance and direction (i.e., if you're moving away from the radar site, the wind is in the same direction as the one in which you are traveling). This means the wind direction is away from the radar when values are positive and towards the radar when values are negative. This is commonly marked with a green color for velocities towards the radar and red for velocities away from the radar. Usually, the most interesting areas are those where red and green colors meet, especially if the values are large where they meet. Several examples follow.

## Interesting things you can see with base velocity

Base velocity is a very useful radar product in many different situations and can tell you a great deal about what is happening in the atmosphere. One thing you can determine with base velocity is the amount, if any, wind shear that is occurring over the radar site. Wind shear is a change of velocity with height, so a change in wind speed or direction as you ascend is wind shear. Look at the figure on page 20. It shows a base velocity image over Wisconsin on a winter day. Careful observation of the "zero isodop" – the line where velocity is displayed as zero because the velocity vector is exactly perpendicular to a radial at that point, or the line where the biggest mass of green meets the biggest mass of red – shows that the winds are curving clockwise with height (called veering with height). Since green means towards the radar and red away, imagine drawing a line that follows the wind direction at a point close to the radar. Remembering that radar beams ascend as they move out, follow the zero isodop away from the radar and observe any curvature that occurs. If you notice curvature, redraw the wind direction at that point and observe that it is in a different direction than the one you drew before. You are observing wind shear since the wind direction is changing with height!
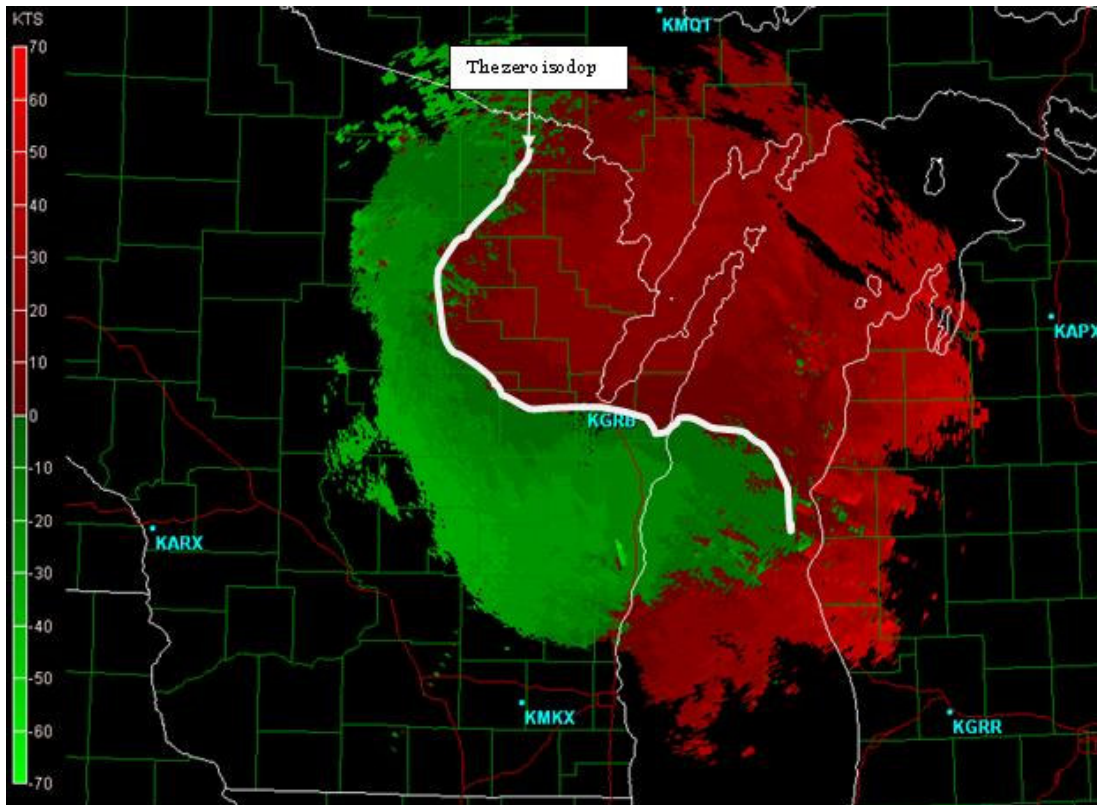
Wind shear on base velocity. A base velocity image from the Green Bay, WI (KGRB) radar site is shown using the Gibson Ridge software. A clockwise turning of the winds with height is evident as the curving of the zero isodop as one moves away from the radar site. The figure below shows the same product and time, but using the 4.5° elevation scan to show how much more clearly wind shear appears on a more sloped plane of elevation (due to the higher tilt angle).
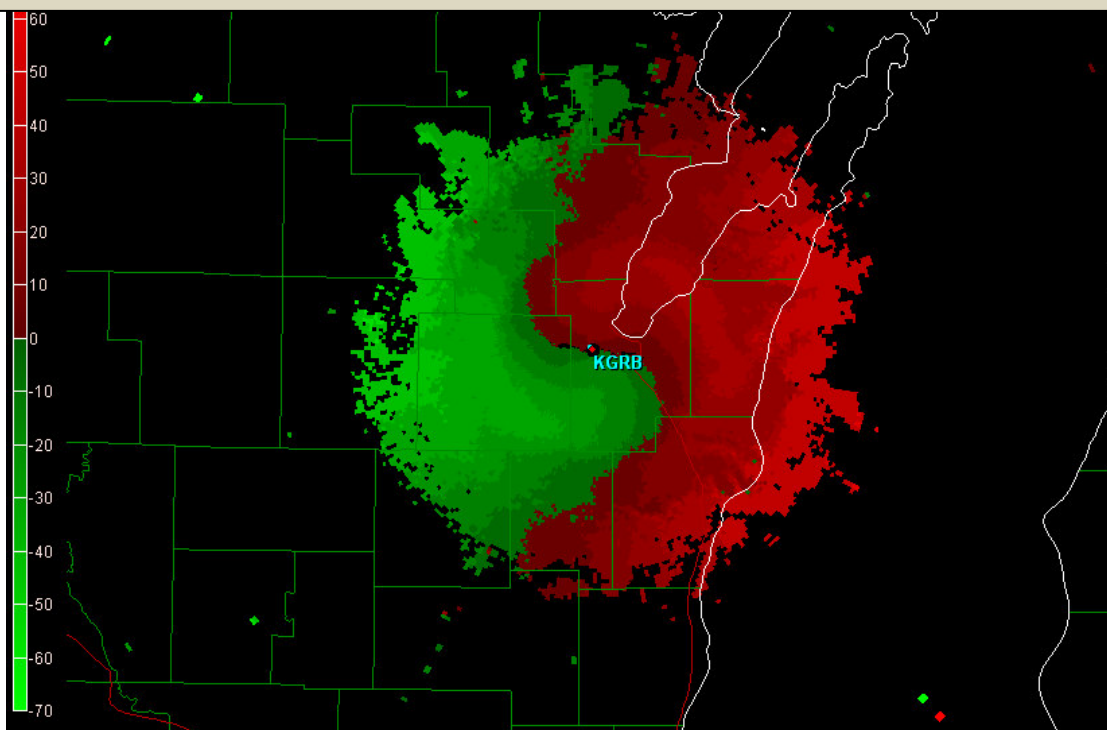
When a front is approaching the radar, you can determine where it is and see the change of wind across the front as long as enough echoes are visible. Consider the example shown in the figure below.
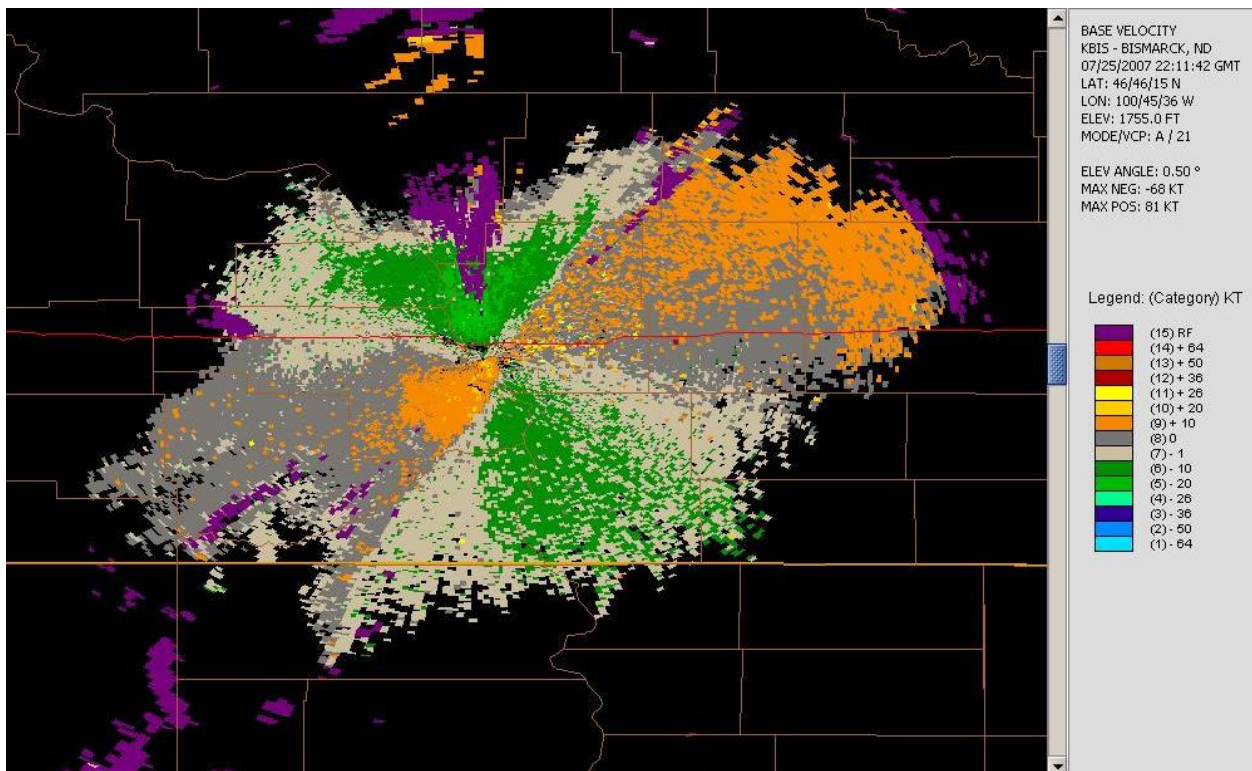
Frontal passage on base velocity. A base velocity image from the Bismarck, ND (KBIS) radar is shown using the Java NEXRAD Viewer. Note the information given on the right, including the scale, which uses slightly different colors than the typical red/green pattern. Use the definition of negative and positive values of velocity to determine that winds to the southeast and northwest of the radar site (towards the center of the image where the radials converge) are towards the radar and winds to the northeast and southwest of the radar site are away from the radar. This may seem confusing at first, but find the zero isodop running nearly due west to east across the image also. This indicates that winds are south to north to the east of the radar site and north to south to the west of the radar site. There appears to be a boundary across which wind directions drastically change. It is oriented south-southwest to north-northeast and passes almost directly over the site. It is a cold front!

When thunderstorms are present, you can detect the amount of rotation present in the storms. Look for areas where red and green meet along adjacent radials. If the green is to the left of the red (as you move away from the radar along a radial) then the rotation is counterclockwise, or cyclonic. This also applies to clockwise rotation if the colors are switched. If red and green meet along the same radial (as you go outward) then this represents convergence or divergence – flowing together or flowing apart of air – respectively.
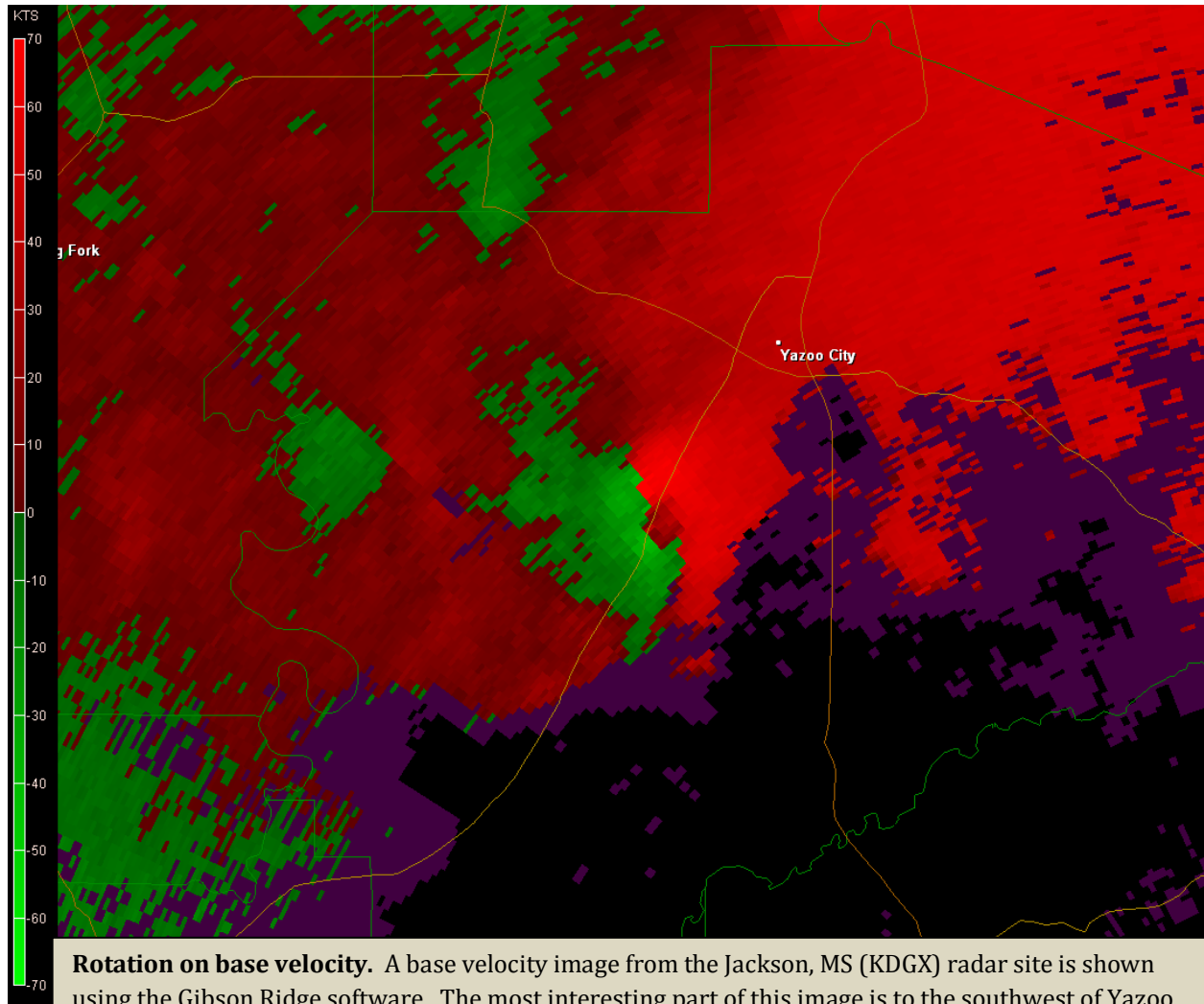
Rotation on base velocity. A base velocity image from the Jackson, MS (KDGX) radar site is shown using the Gibson Ridge software. The most interesting part of this image is to the southwest of Yazoo City where bright red and green colors meet. Large values of velocity are occurring there. The location of the radar site is not shown, but you can judge by the way the radials are converging to a point to the lower right of the image that the radar is to the lower right of the image also. This means that winds in the area of interest are rotating counterclockwise, and rapidly, due to the brightness of the colors indicating large velocity values. In fact, there are two adjacent bins in this region whose velocities are both between 70 and 100 kts (81 to 115 mph). This rotation is depicting a mesocyclone – a large rotating region of air in the updraft of a thunderstorm. When a meteorologist sees an image like this, he/she should assume a tornado is likely or imminent. A Tornado Warning had been issued by the Jackson, MS National Weather Service Office for this storm at the time of this image. After the storms passed, a survey crew from the National Weather Service confirmed that an EF2 tornado (with winds approaching 115 mph) had torn through this area.

Purple haze and the Doppler dilemma

Remember the term pulse repetition frequency? This term plays a significant role in what is called the "Doppler Dilemma," and what is visible in a base velocity image as purple haze – range folded data.

Range folding

Radar can only accurately detect and synthesize data when the reflected energy from one pulse returns to the radar before the next pulse leaves. If the reflected energy from one pulse does not make it back before the next pulse is emitted, the radar becomes confused and usually throws the data out or marks it as bad data. The reason reflected energy may not make it back in time is because it traveled too far from the radar. Since the amount of time a pulse has to go out and come back depends on how long the radar waits between sending pulses, and because the PRF is a measure of that wait, the PRF influences the maximum distance a pulse can travel. This distance is called the maximum unambigous range, or R_{max}, and is inversely proportional to the PRF. As the PRF increases (i.e., more pulses per second are emitted, or that the time between pulses is decreasing), the less time a pulse has, and the less distance it can travel and still make it back in time. Purple haze – also called range folded data – is a region of purple data colored in on a base velocity image. When purple appears on a base velocity image, it means the reflected energy from pulses that traveled into this region was unable to make it back to the radar before the next pulse was emitted. The energy arrived late, and is called a "second trip echo." This confused the radar, and so it threw the data out as bad data. This is the principle of range folding.

The Doppler dilemma

Regarding the issue of range folding, one might say, "So just decrease the PRF so that the pulses have more time and can go farther out." While this is true, the highest wind velocity that can be detected by radar – called the maximum unambiguous velocity, or V_{max} – is directly proportional to the PRF and wavelength of the radar. As the PRF increases or longer wavelength radars are used, higher values of velocity can be detected. Therefore, R_{max} and V_{max} cannot both be very high. An optimal point that balances the two must be found. Since changing the PRF negatively affects either one or the other, this is called the "Doppler Dilemma." Although an optimal point for maximizing both R_{max} and V_{max} has been found, it involves only the wavelength of the radar and the speed of light, not the PRF. The formula is $Rmax \times Vmax = \lambda c / 8$, where λ – the Greek letter "lambda" – represents wavelength, and c represents the speed of light. The maximum point on this curve is where R_{max} and V_{max} together are both optimal. Velocity aliasing occurs when the actual velocity detected by radar is larger than the maximum unambiguous velocity. When this occurs, the radar also throws out the data as bad data. Some algorithms are currently in use and attempt to dealias velocity values, but with limited success.
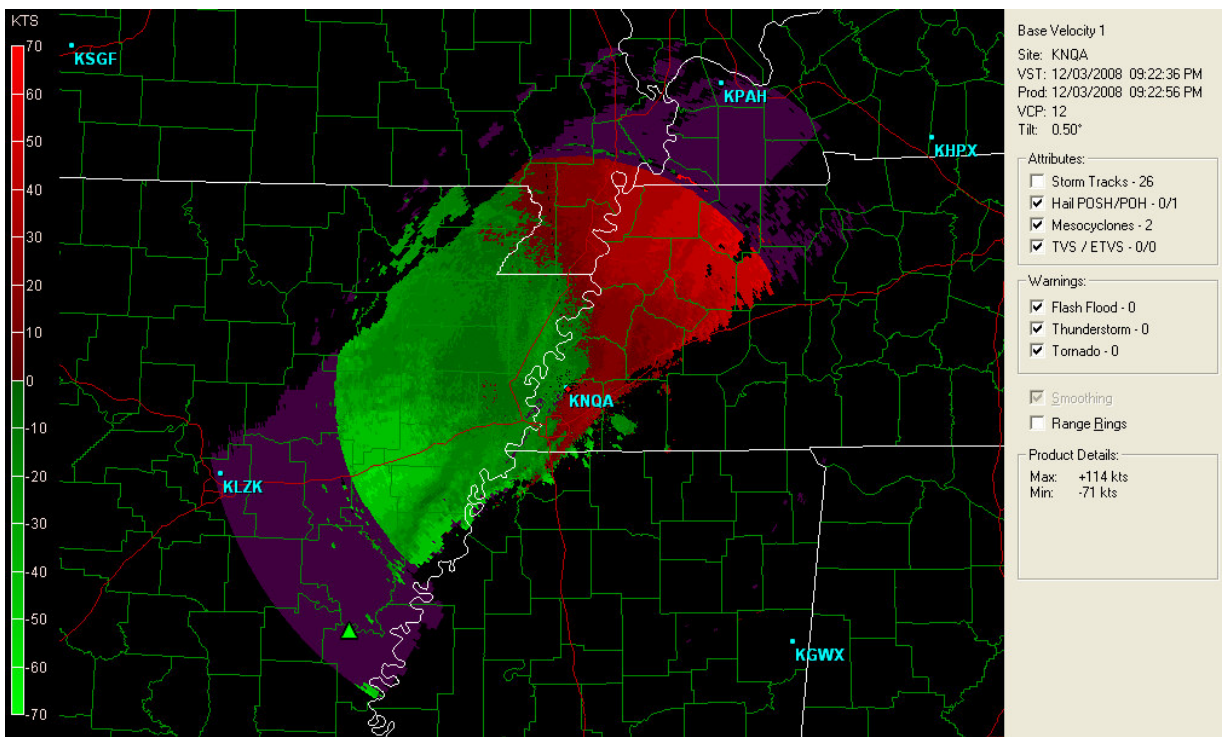
Range folding. A base velocity image from the Memphis, TN (KNQA) radar site is shown using the Gibson Ridge software. Purple haze is apparent towards the outer edges of the radar's range. The PRF of the Memphis radar was such that pulses that traveled into the purple region did not make it back before the next pulse was emitted. All of the echoes that are colored purple are range folded, and nothing can be said about what is happening with the winds in this region. The first base velocity image shown at the beginning of the section also contained purple haze.

This guide will now move into some more advanced topics. The more advanced topics include a discussion on volume coverage patterns and anomalous propagation.
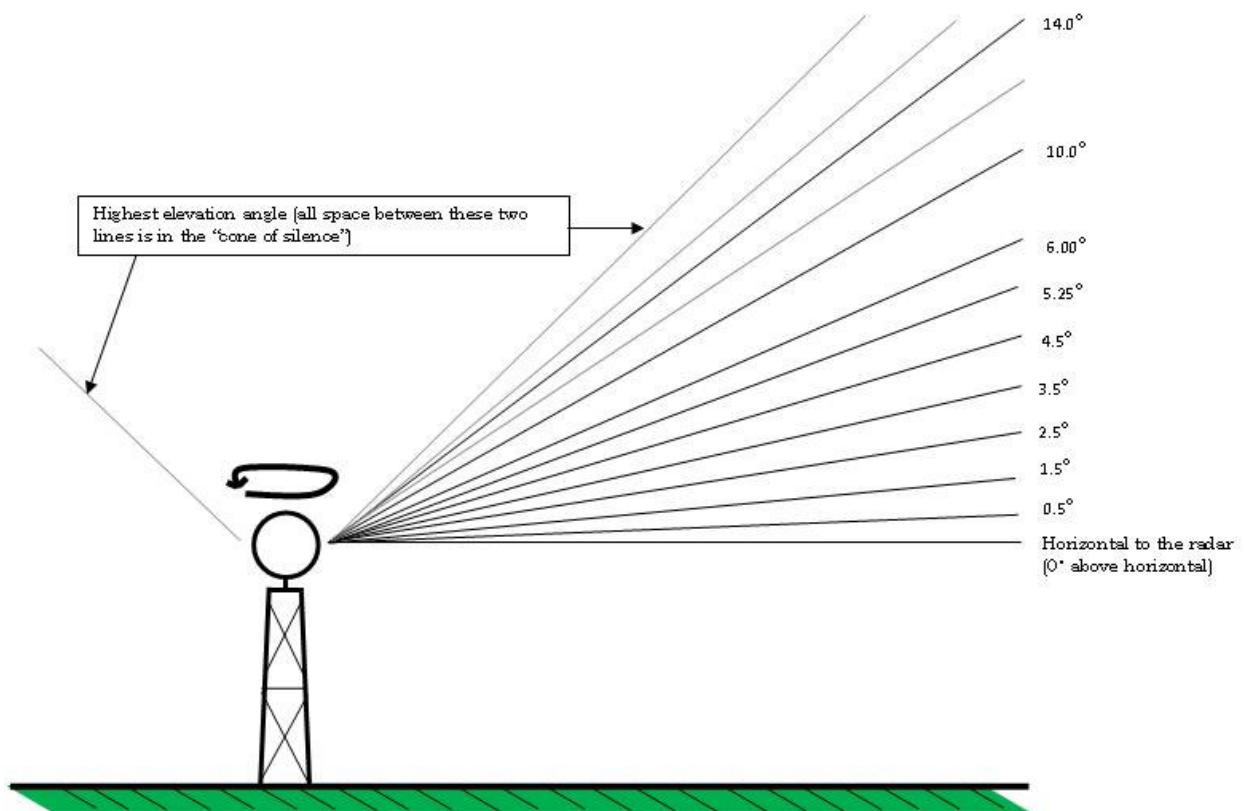
Volume coverage patterns (VCPs)

By now you may have noticed the abbreviation VCP with a number next to it on some radar displays. VCP stands for volume coverage pattern, and describes the pattern by which the radar scans the atmosphere. Radar can scan at a number of different elevation angles above the horizontal. As you learned about base reflectivity, you learned that product uses the lowest elevation angle, 0.5°. Depending on the VCP, the radar may scan at up to 14 different elevation angles. VCPs are labeled as a two or three-digit number, but the digits can only be 1, 2, or 3. The first number denotes whether the pattern is clear-air mode or precipitation mode. Consult the table below for a better description of the VCPs. For reference, a volume scan is a scan of all elevation angles together as a set.

Table of volume coverage patterns. The various VCPs are described.					
First digit	Second digit	VCP	Special characteristic or used for	Number of elevation angles	Length of time for one complete volume scan
3	1	Clear-air mode	Lower PRF than VCP 32	5	10 minutes
3	2	Clear-air mode	Higher PRF than VCP 31	5	10 minutes
2	1	Precipitation mode	Lighter or distant precipitation	9	6 minutes
1	1	Precipitation mode	Thunderstorms	14	4 – 5 minutes
1	2	Precipitation mode	Works the same as VCP 11 but uses denser vertical sampling in the lowest few elevation angles	14	4 – 5 minutes

The three-digit VCPs are 121, 211, 212, and 221. These VCPs cover the same number of elevation angles and schemes as VCPs 21, 11, and 12, respectively (just take off the leftmost number), but include special algorithms and filters designed to reduce problems with anomalous propagation or the Doppler Dilemma. The elevation angles used for each VCP are listed in the table on page 27. Listings are staggered for precipitation mode scans to show the layers that are omitted for VCPs 21, 121, and 221.

14.0°

10.0°

6.00°

5.25°

4.5°

3.5°

2.5°

1.5°

0.5°

Horizontal to the radar
(0° above horizontal)

Highest elevation angle (all space between these two lines is in the "cone of silence")

A schematic for radar scanning. Radar scans in 360° horizontally at multiple elevations. Base reflectivity only shows the 0.5° scan, though. Lines represent planes through which the radar scans according to the different elevation angles. The cone of silence is denoted as the region above the highest elevation scan where the radar cannot detect anything. Drawing is not to scale.

Table of elevation scans for various VCPs. The angles above horizontal for the elevation scans used in each VCP are listed. Angles are staggered for VCPs 21 (121, 221) to show that some are omitted relative to VCPs 11/12 (211, 212).

31 and 32	11, 12 (211, 212)	21 (121, 221)
0.5°	0.50°	0.50°
1.5°	1.45°	1.45°
2.5°	2.40°	2.40°
3.5°	3.35°	3.35°
4.5°	4.30°	4.30°
	5.25°	
	6.20°	6.00°
	7.50°	
	8.70°	
	10.0°	9.90°
	12.0°	
	14.0°	14.6°
	16.7°	
	19.5°	19.5°

Note: Since VCPs 31 and 32 correspond to clear-air mode, the radar rotates more slowly to detect finer particles. The radar is also more sensitive in this mode, and can only detect low values of reflectivity. Typically the radar will not be able to detect reflectivity values above 30 dBZ. If echoes stronger than 30 dBZ exist, the radar will only represent them as having reflectivity of 30 dBZ. This is like capping a sound wave for an amplifier that has too much gain. When this happens, sound becomes distorted. Like the amplifier, the radar is distorted, too.

The cone of silence

If you have seen the movie *Twister*, you likely heard one of the actors refer to a particular part of a storm chasing scene the "cone of silence." This reference was incorrect, but there is such a thing called the cone of silence in radar. The cone of silence is a cone-shaped region directly above the radar site wherein nothing can be detected because no radar beams travel at a high enough angle from the radar to detect data there. If a storm passes directly over the radar site, it will seem to disappear in the radar image because the radar cannot detect the storm while it is directly over the site.

Anomalous propagation (AP)

Anomalous propagation is a term used to describe any radar returns that don't represent precipitation or other meteorological objects. These strange, or anomalous, echoes result from certain atmospheric properties and man-made objects. The two types of anomalous propagation that will be discussed are ground clutter and superrefraction (ducting).
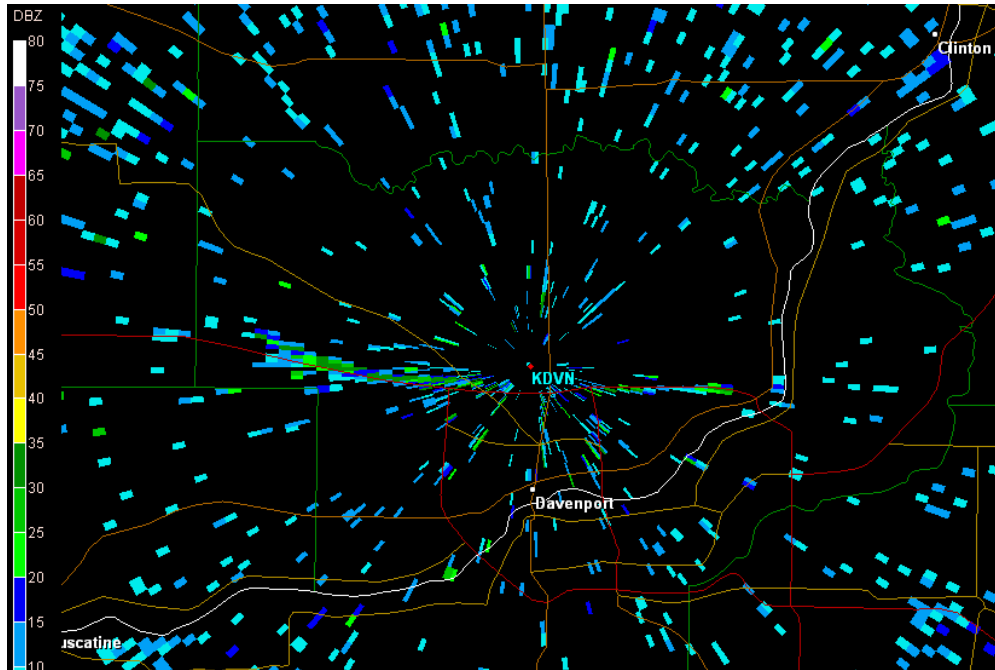
Ground clutter

Ground clutter is a type of anomalous propagation in which the radar beam bounces off objects on or near the ground. Things like tall buildings (especially if the radar site is near a large city or in a valley), cars on a high-traffic road, TV/Radio towers, and wind farms can be seen on radar if the conditions are right. The way to identify ground clutter is by the movement and intensity of the echoes on radar. Ground clutter objects will not move with time and sometimes appear very intense, unrealistically intense, on base reflectivity. Also, base velocity will usually have a problem detecting the velocity of ground clutter and will usually alias or throw it out as bad data. Sometimes ground clutter can simply be dust in the lower thousand or so feet of the

Ground Clutter. Ground clutter is shown as random scattered low reflectivity very close to the radar site (KDMX). No precipitation is falling where this reflectivity is occurring. Imagery is from the National Weather Service website.

atmosphere. This is shown by random isolated points of very low reflectivity within a few tens of miles of the radar site (once the beam travels high enough, it no longer samples the lower atmosphere and doesn't detect the dust anymore).

Ground clutter can also be created by **side lobes**. A full description of side lobes is beyond the scope of this manual, but the general idea is that radar beams are not perfect focused lines of energy like a laser. Rather, radar beams have additional weak pulses of energy that radiate in other directions (other than straight from the radar). Sometimes those weaker pulses (side lobes) can reflect off of objects near the radar and give the appearance of weak reflectivity. This can contaminate the radar image, creating ground clutter.
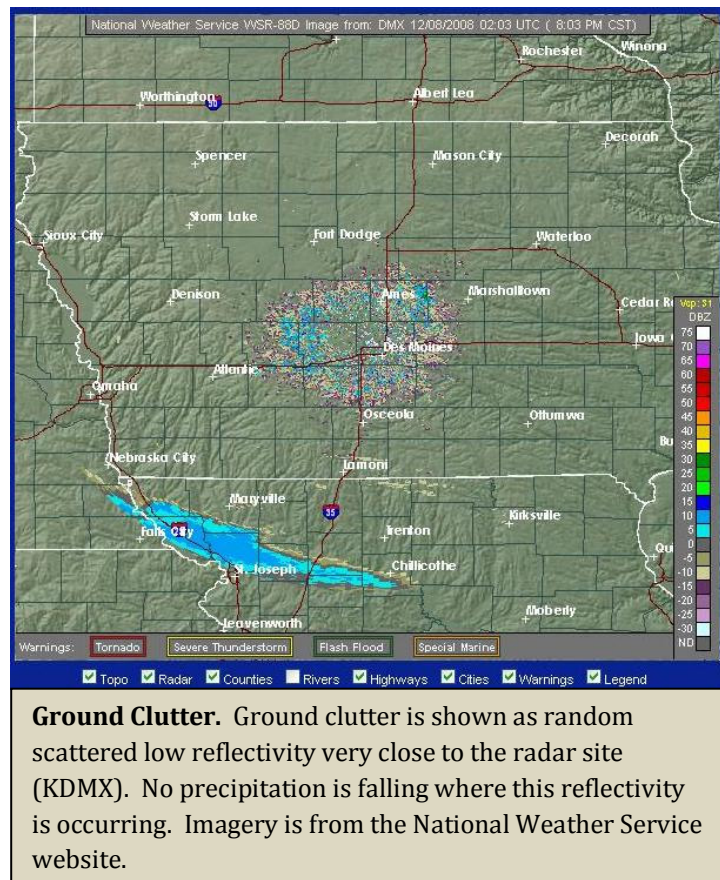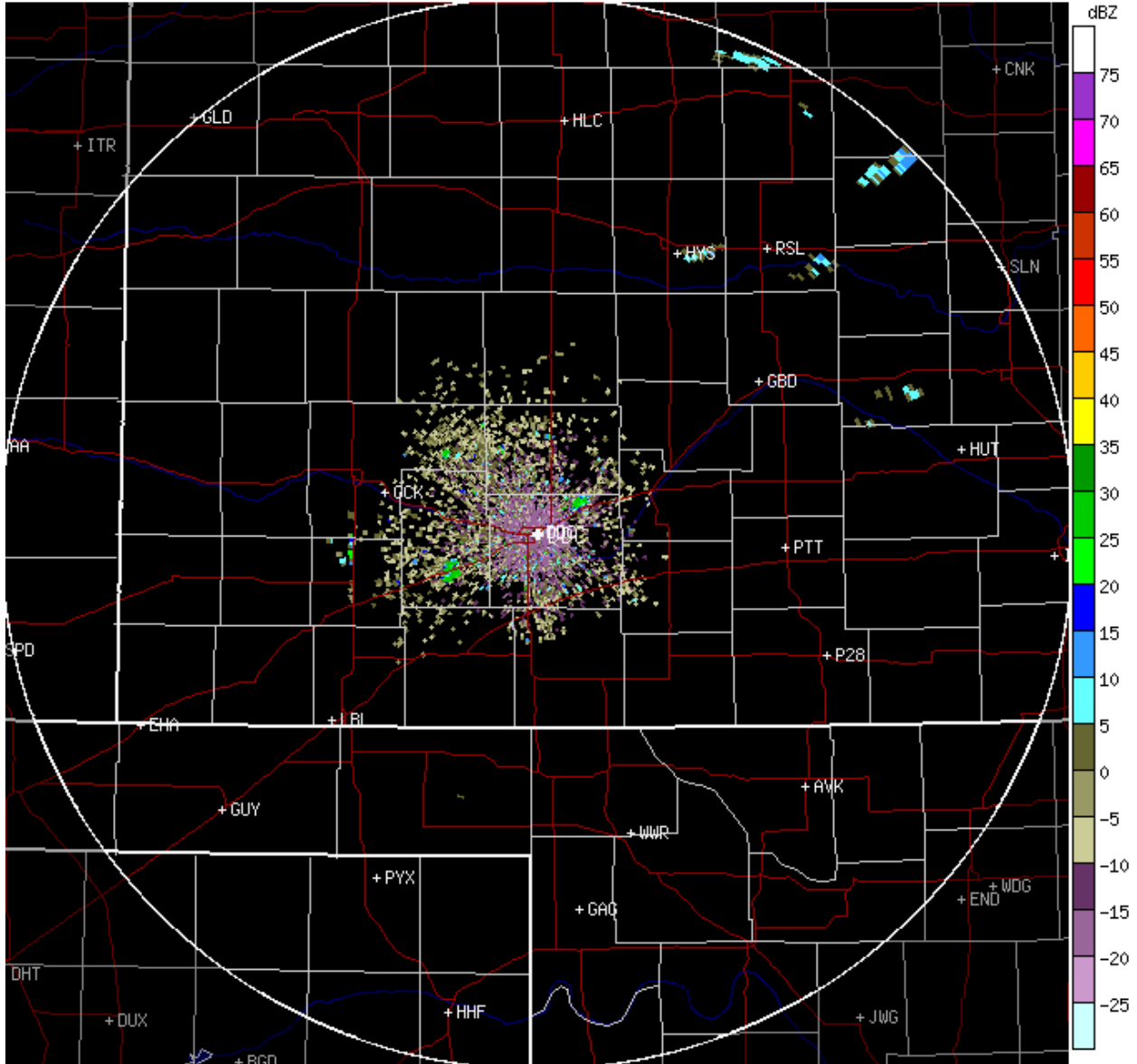
Wind farm ground clutter. Base reflectivity from the Dodge City, KS (KDDC) radar site is shown. Ground clutter is evident as the very low reflectivity scattered about the site. A closer look at image reveals several green blotches near the site. Animation of this imagery shows those blotches are not moving, nor are they changing in intensity. These are actually wind farms being detected by the radar. The beams from the radar are bouncing off the individual turbines and towers in the wind farm, thus showing up as reflectivity in the image. Note that the radar is in clear-air mode so that the maximum reflectivity it can detect is only about 30 dBZ, which is what the reflectivity from the wind farms is. If the radar were in precipitation mode, the reflectivity from the wind farms would likely be higher. *Image courtesy of UCAR: www.rap.ucar.edu/weather/radar*

Traffic ground clutter. Base reflectivity (above) and base velocity (below) are shown from the Davenport, IA (KDVN) radar using the Gibson Ridge software. Note the ground clutter scattered throughout each image. There are particular echoes, however, near the center of the images, very near the radar site. These echoes are actually a result of radar beams bouncing off cars on interstate 80 (thin red line running across the image). Similar echoes are faint also along highway 61 running due north from the center of the image (thin orange line). The large velocity values are a result of the speed of the traffic as it travels down interstate 80. It might seem odd that, given the color, the direction of travel appears only east to west. Remember that, like reflectivity, the velocity displayed is an average of the velocities of all particles in each bin. Thus, it is likely that there are vehicles traveling both ways on all roads, but there are more traveling one way than another, thus giving the large values of velocity moving from right to left.
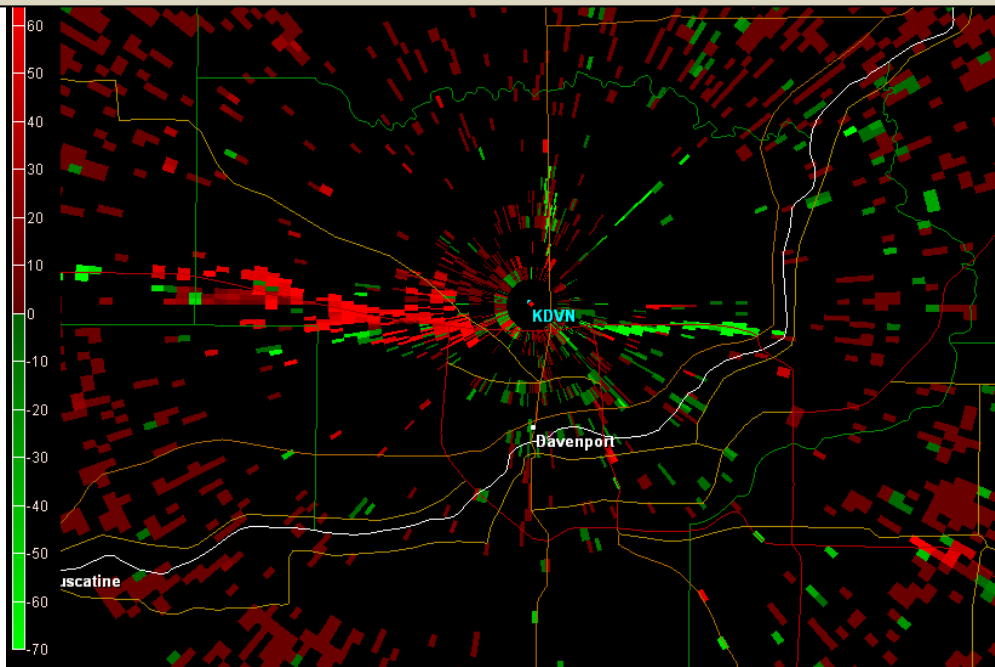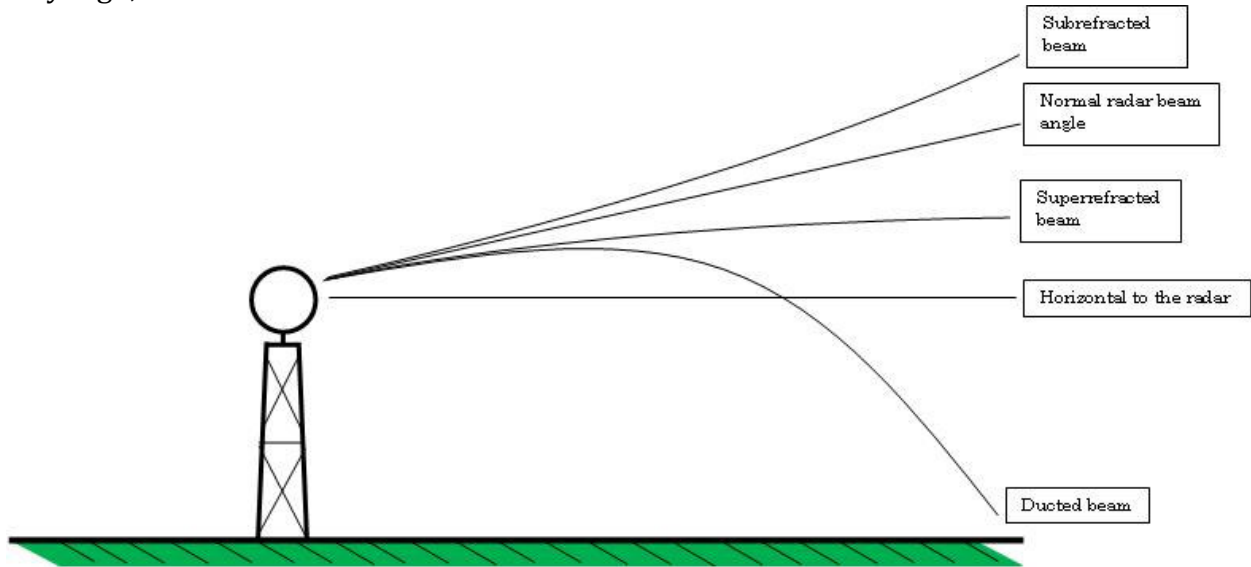
Superrefraction

Superrefraction is a term that describes bending of the radar beam up or down as it moves away from the radar. The microwave energy from the radar travels at light speed, but the speed of light varies according to the medium through which it travels. The speed of light in a vacuum is about 186,000 mph, or 300,000,000 meters per second, but slows down in any other medium. The change is extremely minor (for example, in an atmosphere with normal weather conditions, the speed of light is about 185,950 mph instead), but greatly effects how the radar beam travels.

The ratio of the speed of light in a vacuum to that in the medium at hand is called the **index of refraction**, and is usually expressed using the formula $N = (1-n)*10^6$, where n is the index of refraction and N is an integral number used to express it. A common value for N is 300, but can vary between 225 and 350. *The higher the value of N, or the higher the index of refraction, the slower the speed of light in the medium.* The index of refraction depends on many atmospheric variables, including air density, water vapor pressure, and temperature. Therefore, a change in any of those variables with distance away from the radar will cause a change in the index of refraction and N, and will bend the radar beam. Both density and water vapor pressure greatly decrease with height in the atmosphere, so the index of refraction always decreases as height of the beam increases. Since the index of refraction decreases, the speed of light increases and the beam bends downward. Imagine the top part of the wave moving into the area where its speed is faster before the bottom part of the wave. Therefore, the top of the wave will move faster than the bottom of the wave and the wave will appear to bend away from the faster region. Remember that since the earth is curved, as the wave moves out and above the horizontal angle it will curve up naturally due simply to the earth curving away from the beam. However, the curvature of the earth is so small relative to the distance the beam travels that this affects the wave much less than does the change in the index of refraction. The issue is how much the index of refraction decreases.

The biggest affect a variable can have on bending radar beams is temperature. Increasing temperature decreases the index of refraction and thus, increases the speed of the wave. Temperature usually decreases with height, but sometimes remains constant with height or even increases with height, a term called an "inversion." (Inversions usually only happen in the lower few thousand feet of the atmosphere.) If the atmospheric conditions over a radar's coverage area are such that temperature is increasing with height, beams that travel from this radar will be bent downward even more than usual. This is called superrefraction. In extreme cases, the bending can be so great that the radar beam actually bends back down to the surface and hits it, a term called "ducting." When a radar beam hits the surface, the energy from the beam reflects back towards the radar and causes reflectivity to appear. Since the conditions that cause this are usually uniform across the radar's coverage area, the reflectivity will appear as a uniform circle centered on the radar site with about the same reflectivity value throughout (usually a low value). This can interfere with any actual precipitation echoes near the site by masking the reflectivity of that precipitation from the ducting that is occurring. Since the conditions that favor the occurrence of an inversion occur mostly at night and very early in the morning, this is when superrefraction or ducting is most likely to be seen on radar. Also, the presence of a large change of water vapor pressure with height (called a vertical moisture gradient), especially

when the amount of water vapor (measured by the dewpoint temperature) at the surface is very high, can enhance this effect.

Schematic of beam refraction. The approximate paths taken by radar beams being refracted are shown.
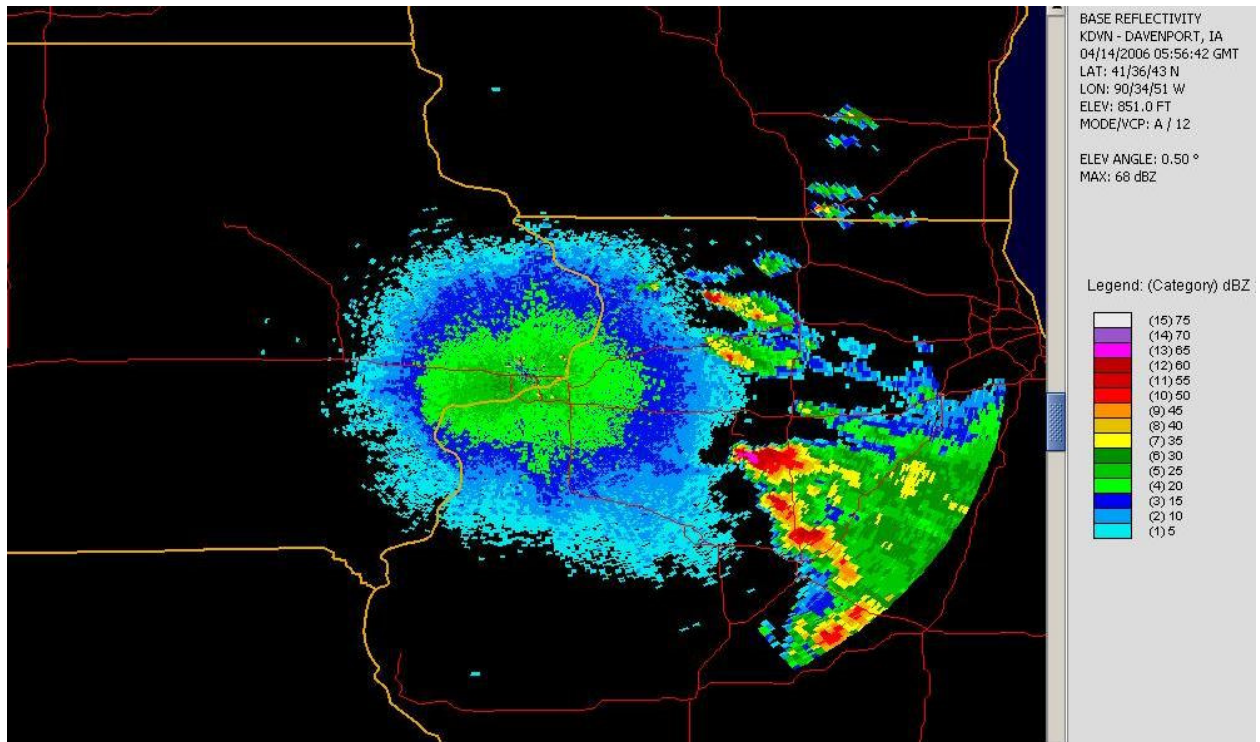
Superrefraction and ducting. Base reflectivity from KDVN is shown using the Java NEXRAD Viewer. Ducting of the radar beams is causing the ground to reflect energy back towards the radar, giving the nearly uniform circle of reflectivity centered over the site. No precipitation is occurring within this reflectivity, but distant storms are apparent farther from the radar. Superrefraction is likely occurring with the beams traveling further to the storms, so the heights of those storms are probably being overestimated.

Since there is such a thing as superrefraction, you may be asking if there is such a thing as subrefraction. In fact, there is. If the atmospheric conditions are such that the index of refraction increases with height (the speed of light decreasing with height), then the radar beam can be bent upward relative to where it would normally be. This has little significance in the scope of this guide, and you will likely not experience any effects from it occurring. For those who are curious, however, subrefraction will cause cloud and echo heights to be undercalculated since the radar, which doesn't know that its beams are being bent after they are emitted, will think the echoes are lower than they will really be.

Summary and conclusions

The topics covered in this guide included: the fundamentals of radar, including the NEXRAD network and what a Doppler radar is; resources for viewing radar data; basic characteristics of Doppler radar including the idea of beam spreading; base reflectivity and the many things that can be seen with it, including bright banding and three-body scatter spikes; base velocity and the many things that can be seen with it, including wind shear, frontal boundaries, and rotation within thunderstorms; the Doppler Dilemma and purple haze; volume coverage patterns and the cone of silence; and anomalous propagation, including ground clutter and superrefraction.

You should now be able to view radar imagery on your own and discern what is happening in the imagery and why. Also, if you happen to see strong rotation in a thunderstorm coming your way, you will know where it is and will have lead time to take cover and possibly save your life.

Glossary of terms

Azimuth: the measure in degrees of the angle between the radial that points to true north and the radial that points to a bin

Azimuthal resolution: the number of degrees azimuth per radial

Base: a word affixed to a radar product to specify the product is using the lowest elevation angle of 0.5°

Beamwidth: same as azimuthal resolution and beam separation

Beam separation: same as azimuthal resolution and beamwidth

Bin: one single bit of radar data represented as a colored box on radar imagery; same as pixel or gate

Echo: the representation of radar data on radar imagery from reflected microwave energy returning to the radar; same as return

Gate: same as bin and pixel

Gradient: a change in a value with distance

Index of refraction: the ratio of the speed of light in a vacuum to the speed of light in a medium

Microwave: a type of wave that propagates (transports) energy that is characterized as being in the microwave part of the electromagnetic spectrum

NEXRAD: an acronym that names the radar network currently in use across the U.S. Stands for NEXt generation RADar

Pixel: same as bin and gate

Pulse: a transient stream of microwave energy emitted by radar; same as (radar) beam

Pulse repetition frequency (PRF): the number of pulses emitted by a radar per second; measured in Hertz (Hz)

Precipitation: any water-based object created by meteorological processes that falls to the ground. Some examples include rain drops, hail stones, sleet pellets, and snow flakes.

RADAR: an acronym that stands for RAdio Detection And Ranging

(Radar) Beam: same as pulse

Radial: a line of bins that move outward from a radar site along a constant azimuth

Radial resolution: the number of bins per some unit of distance along a radial

Range: the distance from the radar site

Reflectivity: the measure (in decibels, dBZ) of microwave energy returned to a radar after reflecting off particles in the atmosphere.

Return: same as echo

Side lobes: additional weak radar pulses that travel in a different direction than the main pulse