Radar Meteorology Tutorial

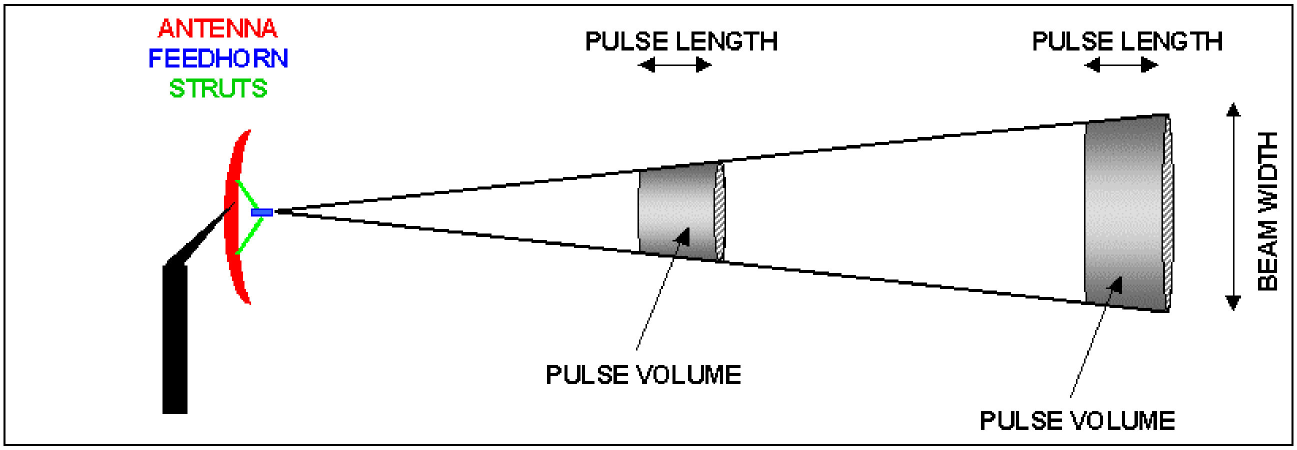
1. HISTORY

RADAR, or RAdio Detection And Ranging, has been in use since before World War II. It was developed to detect aircraft while they were still out of visual range and then to monitor them as they approached. This tool was widely used during the war, but servicemen operating the radar would sometimes be confounded by blobs of precipitation that would block their view of the aircraft. To their frustration, radar was just as good at detecting rain as it was at detecting aircraft. It was only in February 1941 that radar was first used for intentionally looking at precipitation. Since then, huge advancements have been made in radar technology and its use in meteorology is widespread now (over 150 public-access radars in use by the National Weather Service, plus numerous radars owned and operated by private companies such as television stations). Radars are also being used on aircraft and even satellites to look down at clouds and precipitation.

2. HOW IT WORKS

A radar transmits a focused high-power beam of radiation and receives a meager amount of radiation back from whatever the beam encounters. The antenna transmits a narrow beam from the feedhorn, which is suspended in front of the parabolic dish by struts. There are three fundamental properties of the emitted beam: pulse repetition frequency (PRF), transmission time, and beam width. The PRF is how many pulses of radiation are transmitted per second; for typical weather radars, this is around 325. The transmission time is the duration of each pulse. Since the beam travels at the speed of light, the pulse length can be easily calculated from the transmission time; this length is also known as the spacing between "range gates" and is 1 km on average. The beam width describes the angular width of the emitted beam, and is typically about 1°. Combined with the pulse length, the beam width allows one to calculate the pulse volume. The pulse volume can be huge at long ranges, meaning that consecutive pulses will receive backscattered radiation from a *large* number of targets. The pulse length defines the radial resolution, while the beam width defines the angular resolution.

The radar does more listening than talking, like 1000 times more. More specifically, it might emit a pulse for 0.000003 seconds then listen for 0.003 seconds (remember it goes through this transmit/receive cycle about 325 times every second!). So, 99.9% of the time, the radar is receiving, and 0.1% of the time, it's transmitting.



a) Attenuation

When the beam encounters a target in the atmosphere --suppose a raindrop-- a lot of interesting processes take place. The raindrop will attenuate the energy in two ways: scattering and absorption. Upon contact with the raindrop, the energy is scattered in all directions, so only a very small fraction of the incident radiation is sent back in the direction of the radar. Secondly, the raindrop will actually absorb some of the energy. These two processes, *scattering* and *absorption*, are collectively known as *attenuation*. However, it's not just raindrops to be concerned about. Atmospheric gases and small aerosols are responsible for some absorption (too small for scattering), but particles such as hail, snow, graupel, and insects are also responsible for both absorption and scattering. Attenuation becomes significant when the beam has to travel through a lot of targets and/or through a lot of atmosphere; i.e., through heavy precipitation and/or long distances. This means that the power received back at the antenna is even less than it would otherwise be. Scanning through a heavy thunderstorm, gaseous absorption might cause a 5% decrease in backscattered power, while the intervening rain and hail could cause an 80% decrease. You may sometimes notice a void in reflectivity directly behind (from the radar's point of view) a heavy thunderstorm when looking at radar imagery. It might still be precipitating there, but the radar's beam has been so severely attenuated that very little power remains to be reflected back.

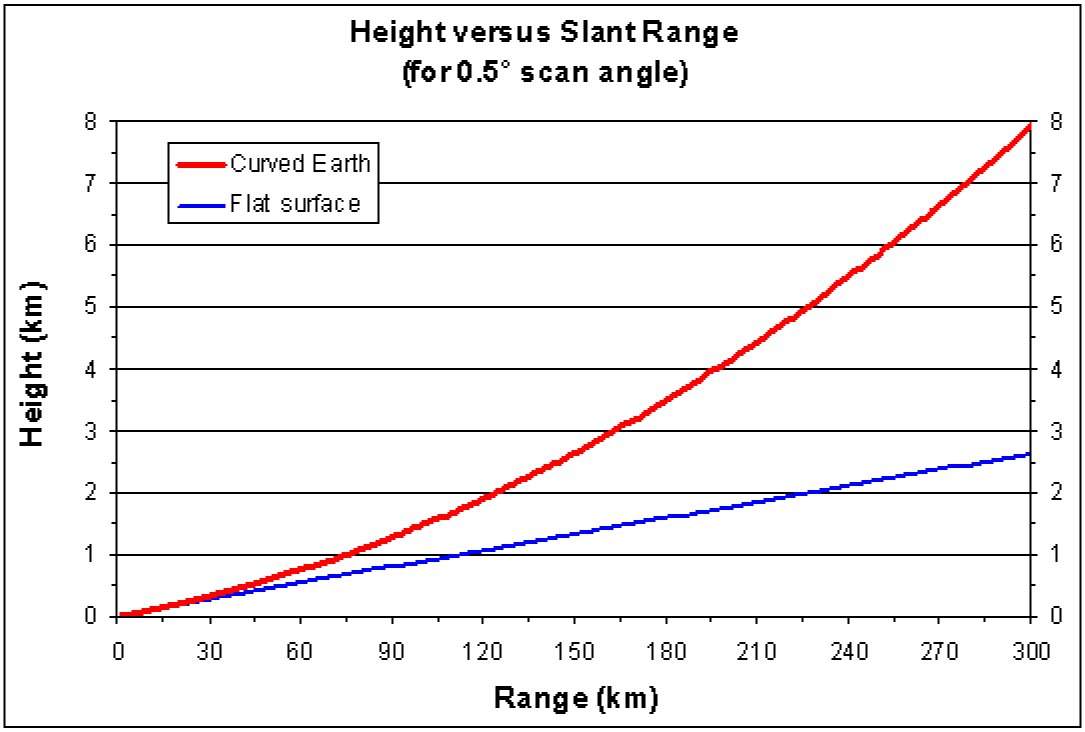
b) Frequencies

There are a variety of radar frequencies used for different reasons. The table below outlines the six common "bands", or frequencies used to probe the atmosphere with radio waves. The first two are high-frequency, short-wavelength bands, so they are readily attenuated by even light precipitation, making them most useful for detecting clouds and aerosols. The remaining four bands are all useful for detecting precipitation. The longer the wavelength, the less attenuation will occur, but it also cannot even "see" the smaller targets. In other words, an L-band radar will see heavy rain and hail (among other things like birds and aircraft), but won't see clouds, snow, or light rain. S-band radars are widely used by the National Weather Service because they are a fair compromise between high sensitivity and minimal attenuation. They can't see clouds, but they aren't significantly attenuated by all but the most heavily-precipitating thunderstorms.

WEATHER RADAR BANDS		
frequency (GHz)	**wavelength (cm)**	**band**
90	0.1	W (cloud)
30	1.0	K (cloud)
10	3.0	X (precip)
5	6.0	C (precip)
3	10.0	S (precip)
1.5	20.0	L (precip)

c) Scan Angle

Something to keep in mind when looking at radar imagery is that it's not truly a flat map of precipitation. To keep the beam from hitting objects on the ground such as hills, buildings, and trees, the lowest scan angle used is 0.5° above horizontal. That's a pretty small angle… if the radar were on a flat surface and you were 100 miles (161 km) away from the radar, the beam would only be 4600' (1.4 km) over your head. However, the Earth is curved, and so the beam deviates from the surface even more rapidly. So, at 100 miles (161 km) away, the beam is actually 9800' (3 km) over your head. The figure below illustrates how the beam sees higher in the atmosphere the further out it goes. [300km = 186mi, and 8km = 5mi]



This may seem like an inconvenience, but in fact it has uses and they will be discussed in greater detail in Section 3. In addition to the curvature of the Earth, the atmospheric lapse rate and moisture content play roles in controlling the exact path of the beam, but they are small compared to the curvature effect.

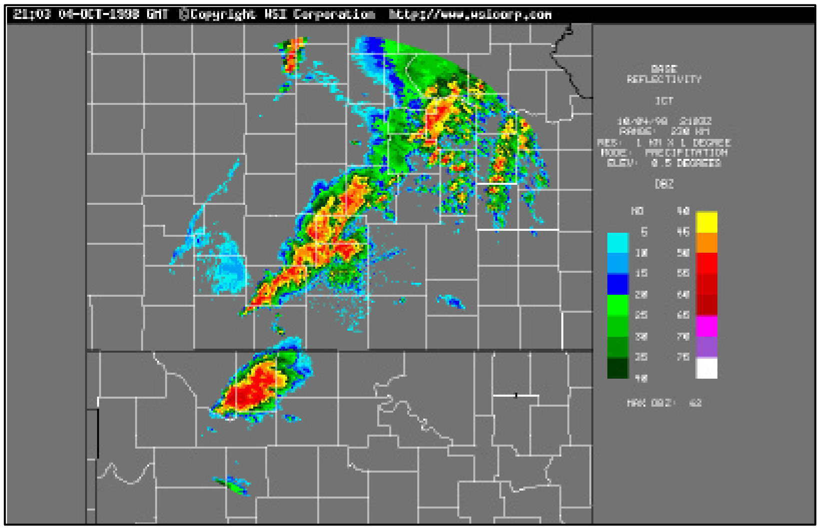
d) Moments

Another important aspect of understanding what you see in a radar image is exactly *which* product you're looking at! A Doppler radar is one that can use consecutive pulses to determine motion of the targets, not just how much power they backscatter. There are three "moments of power distribution" that arise from the beam encountering targets. The 0th moment is called *reflectivity*. This is simply some power returned from a pulse volume… a very small fraction of the power that was originally transmitted into that volume. This is the product you see most often; on television, on websites, etc. Higher values indicate heavier precipitation. Extremely high values indicate hail, because hail is very effective at reflecting power back. The 1st moment is *radial velocity*, and is found by measuring the time variation of reflectivity… how the targets move. This product is very useful in determining low-level wind shear and rotation within a thunderstorm. Finally, the 2nd moment of power distribution is called *spectrum width*, and is found by measuring the time variation of radial velocity. Basically, this might be described as turbulence. One would expect a large spectrum width near gust fronts, tornadoes, updrafts, etc. Let's take a closer look at these products and how to make sense of them.

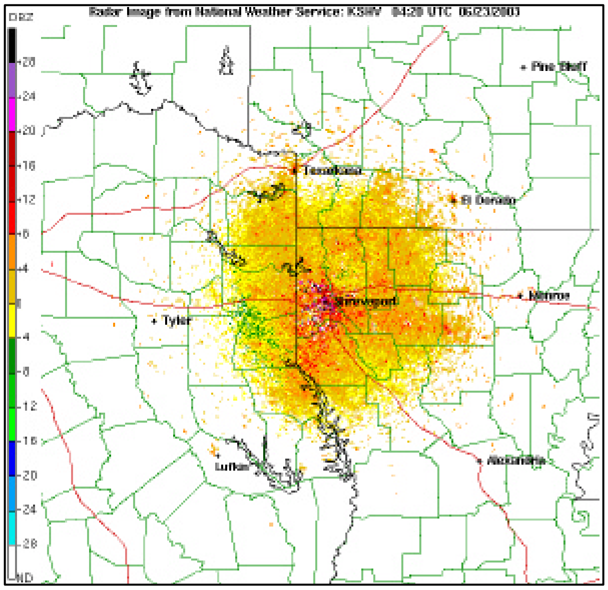
3. PRODUCT INTERPRETATION

a) Reflectivity

The most common radar product available is the reflectivity… this is simply a measure of how much power was scattered back to the radar from any targets. If there are no targets, none of the power is reflected back and there are no echoes. The term "echo" refers to a returned signal, whether it be from airplanes, birds, insects, snow, hail, or rain. The units of reflectivity are a convoluted form of decibels: dBZ. The higher the dBZ value, the more power was reflected and received by the radar. Light snow is very inefficient at reflecting radiation, so it might be 5-20 dBZ, while moderate rain might be 30-45 dBZ, and large hail might be around 60-75 dBZ. For completeness, it should be noted that these values take advantage of some



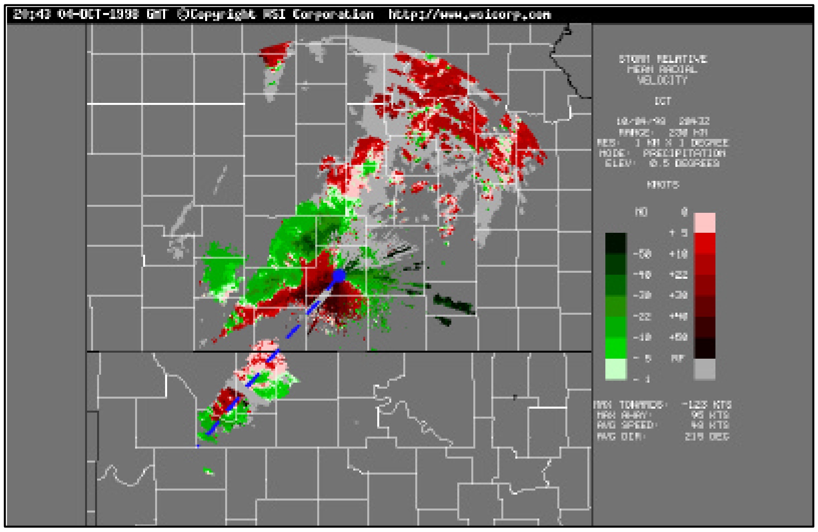
assumptions about the properties of the precipitation. Radar software must use different equations to calculate dBZ from received power depending on if it's in the deep tropics or in the mid-latitudes, for example (this is due to differences in moist thermodynamics, raindrop size distribution, etc). In the image on the previous page, taken from the Wichita, KS radar site operated by the National Weather Service, there are some scattered strong thunderstorms in southern Kansas, and one very intense isolated storm in northwest Oklahoma in the southern tip of Woods County. The scale on the right shows intensity of the storms in dBZ; the peak in these particular thunderstorms is 62 dBZ, which undoubtedly indicates some large hail.



Other features you can find using reflectivity include smoke plumes, outflow boundaries (e.g. from thunderstorms or rain complexes), drylines (if conditions are favorable), and insects. You can also easily spot mountains or hills if the radar site is near any such features. The figure to the left is an example of an evening radar image taken from Shreveport, LA, where the circular blob of yellows and oranges shows the extent of airborne insects. Once the evening hours set in, especially during the summer in a humid climate, watch a radar loop and you'll invariably see the blob grow and perhaps eventually fill the entire scan area with reflectivity values.

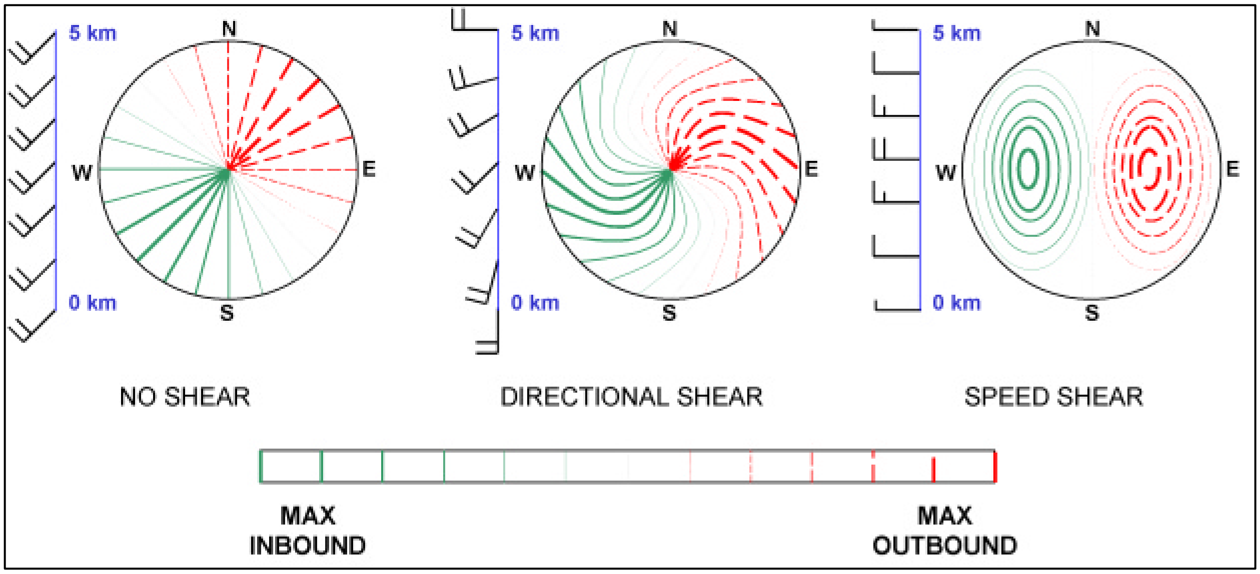
b) Radial Velocity

There are two primary pieces of information one can gather from a radial velocity image. Of foremost importance is rotation. A single radar cannot see an entire vortex (whether it be a mesocyclone, tornado, hurricane, etc) but rather just the components of the wind that are moving toward or away from the radar. The component of the wind moving tangential to it will appear as very low radial velocities.



So, in the figure to the right, a dashed blue line is drawn from the radar (blue dot) through a suspicious feature… a velocity couplet. In this case, the part to the right of the line (red) is moving away from the radar, while the part to the left of the line (green) is moving toward the radar, implying a strong (~30kt) counter-clockwise rotation. Indeed, this was a powerful mesocyclone, and the parent supercell was tornadic. Note that this image corresponds to the previous reflectivity figure taken from the Wichita radar.

A second use of radial velocity stems from the scan angle, as discussed in Section 2c. Even at the lowest scan angle of 0.5°, the beam "sees" 8km up in the atmosphere by the time it's 300km away from the radar. Of course, *at* the radar site, it's essentially looking at ground level. While one might find it convenient to look at a constant level across the atmosphere, this scan geometry provides a wonderful way of getting a vertical profile of precipitation and wind! The further a storm is from the radar, the higher the level from which power is received. Also on radial velocity images, one can deduce the lower-tropospheric vertical wind profile. The following figure illustrates three ideal examples… the center of each circle represents the radar site, and the outer boundary of each circle represents a distance of approximately 230km from the radar site (assuming a 0.5° scan angle). The vertical line to the left of each circle represents a vertical wind profile that one can deduce from the idealized radial velocity plots. Note that at the center of the circle, the elevation is 0km and at the edge of the circle the elevation is about 5km. So, a radial beam of power transmitted and received at an angle above horizontal also acts as a proxy for a vertical wind profile.



c) Spectrum Width

This product is available from Doppler radars, but is rarely used or shown except for specialized applications, and so will not be discussed here at any length besides what was explained in Section 2d.

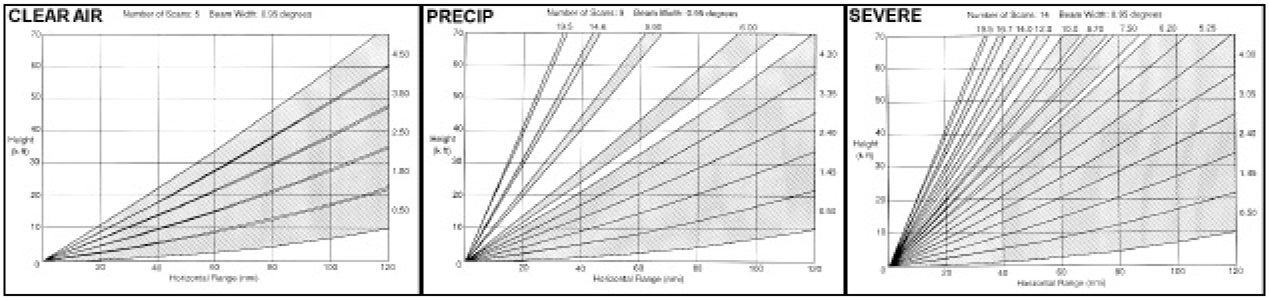
4. NEXRAD WSR-88D

NEXRAD is NEXt-generation RADar, and WSR-88D stands for Weather Surveillance Radar, the 88 is for 1988 (the year this technology was commissioned and implemented), and D is for Doppler (meaning that it's capable of retrieving not only reflectivity, but also radial velocity and spectrum width). There are 158 of these radars scattered over the United States, leaving very few gaps. More populated areas are covered better, while less populated areas are likely to be covered by only one radar or maybe not well at all. Each is a giant antenna enclosed in a spherical protective dome, and placed atop a tall tower to elevate it off the ground to minimize ground clutter. The tower is typically 50-100' tall, the fiberglass "radome" (the white sphere that encloses the antenna) is 39' in diameter, and the parabolic antenna inside the radome is 28' in diameter. From the outside you can't see anything move, but if you were to stand inside the radome during operation, you'd witness a mechanical and electrical engineering wonder. Imagine this 28' antenna whirling around, gears interlocking like clockwork, belts and motors driving the whole show, and completing a full 360° scan in just 10 seconds, then adjusting itself to the next higher elevation scan, then doing another 360° scan, then again and again, only to repeat the cycle as soon as it finishes the last cycle. This feat by itself would be impressive, but then one has to realize the immense of amount of genius and computing power involved with transmitting the radiation, receiving it, making sense of it, and storing it… all while rapidly rotating.

These are S-band radars that emit a 0.75 megawatt beam and are configured to have a 460 kilometer maximum range (286 miles). This range only applies to the reflectivity product; the radial velocity is much trickier to "unfold", or arrive at an unambiguous solution, and for reasons beyond the scope of this article, its range is half that of the reflectivity product, or 230 km (143 miles).

There are two basic modes that the NEXRADs can operate in: Clear Air and Precipitation. In Clear Air mode, the radar rotates slower and performs fewer scan angles. This allows for higher resolution of fine targets such as aerosol particles (smoke plumes for example), insects, and snow. In Precipitation mode, the radar rotates faster and performs more scan angles, sacrificing resolution for more rapid updates.

The following figures show the different "volume coverage patterns" (VCP) used by NEXRAD operators to accomplish the various scan types. Note the one on the right is a special case of Precipitation mode called Severe mode. In this mode, the rotation rate is increased even further and more scans are made at higher angles to capture the full structure of the towering thunderstorms. Typically all you find available on public websites is the lowest scan angle (0.5°), and just the reflectivity and radial velocity, but forecasters at each of the National Weather Service offices and the Storm Prediction Center have the full suite of data available to them.



Clear Air mode is more sensitive and is better at detecting drylines (which typically contain a rapid shift in the index of refraction), smoke plumes and other large aerosols, insects, birds, light rain, and light to moderate snow. Snow is effective at scattering radiation, not reflecting, so it can be difficult to detect in Precipitation mode unless it's fairly heavy (usually when you look at a radar image of snow, you'd underestimate its intensity just by appearance). Clear Air mode involves only five scan angles, ranging from 0.5° to 4.5° and completes a full VCP in ten minutes. Precipitation mode has a shorter "dwell time", or time spent listening for returned signals at various ranges. This makes it less sensitive but it also completes a full scan in less time. It has nine scan angles ranging from 0.5° to 19.5° and completes a VCP in six minutes. Finally, the Severe mode has fourteen scan angles (same angle range as Precip mode, but more of them to fill in the gaps) and completes the full VCP in only five minutes. In this mode, the goal is rapid updates and complete coverage of the entire storm, not fine radial resolution. It's remarkable that the mode with the greatest number of scan angles to complete takes the least amount of time… this puts the entire mechanical and electrical system to a true test!

5. RESOURCES

http://www.crh.noaa.gov/radar/mosaic/DS.p19r0/ar.us.conus.shtml *[View current NEXRAD imagery]*
http://www.roc.noaa.gov/ *[NOAA Radar Operations Center]*
http://weather.gov/radar/radinfo/radinfo.html *[radar tutorial]*
http://weather.cod.edu/sirvatka/radar.html *[radar tutorial]*
http://www.weathertap.com/unprotected/static/radar_tutorial.html *[radar tutorial]*
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Doviak, R. J., and D. S. Zrnic, 1984: *Doppler Radar and Weather Observations*. Academic Press, 458pp.

Brian McNoldy for *MESO, November 2003*

http://www.mcwar.org