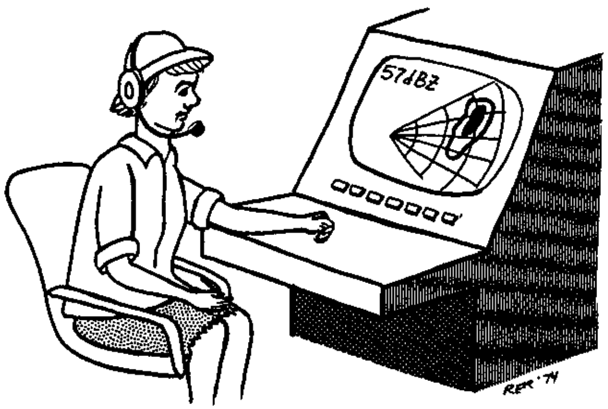

NO, NANCY. THAT'S DECIBEL, NOT DECIBULL.

Doppler Velocity Measurements

Most of what has been discussed until now in this text has dealt with measurements of echo power from a radar. These are used to determine the backscattering cross-sectional area of point targets and the radar reflectivities and rain rates from meteorological targets (see Chapter 8). Of course, conventional, reflectivity-only radars also provide very useful information on the positions of storms, their movement, development and other properties. Most new radars, however, now provide direct measurements of the speed of movement of targets by using the Doppler effect mentioned earlier.

Christian Doppler discovered that a moving object will shift the frequency of electromagnetic radiation in proportion to the speed of movement. The same thing happens with sound waves. The classic example used to explain this in terms people would understand is that of the train whistle approaching a stationary observer. If the train blows its whistle while approaching and continues blowing it as it passes and goes off in the other direction, anyone listening to the sound will hear the pitch of the whistle decrease when the train passes.

Exactly the same thing happens with electromagnetic radiation as happens with sound. In the case of sound, however, the frequency shift was usually noticed by having a moving source and a stationary listener. In the case of radar, the usual situation is to have a stationary radar observing moving targets. Each target that is moving will shift the frequency of the radar signal an amount which depends upon its speed.

Consider a single target at distance r from a radar. The total distance a radar pulse will have to travel to detect this target is $2r$ since the wave has to go out to the target and back to the radar.

$$\textit{total distance} = 2r$$

This distance can also be measured in terms of the number of wavelengths from the radar to the target.

$$\textit{distance in wavelengths} = 2r/\lambda$$

where λ is the wavelength of the radar signal. We can also measure this distance in radians by using the fact that 1 wavelength = 2π radians. So,

$$\textit{distance in radians} = (2r/\lambda)2\pi$$

The phase of an electromagnetic wave is essentially the fraction of a full wavelength a particular point is from some reference point, measured in radians or degrees (see Fig. 6.1). The reference point of a wave is usually the point on a sine wave where the cosine is one and sine is zero. If our point of interest is at the very beginning of the sine wave, its phase is zero. If it is a quarter of the way from the start of the wave toward the next wave, its phase is $2\pi/4 = \pi/2$ radians (90°). Phase shifts can be either positive or negative but are always less than 2π radians (360°). In fact, if the phase shift is more than π radians (180°) we usually consider the phase difference to be the difference in angle between our point of interest and the *nearest* reference point. That way, our phase shift will never be more than $\pm\pi$ radians or ±180°. The second (dashed) curve on Fig. 6.1 has a phase shift of 30° from the solid curve.

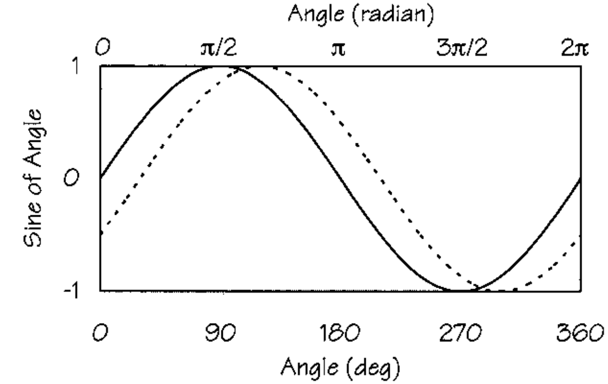

Figure 6.1 Sine wave (solid curve) and a second signal 30° out of phase with the first wave (dashed curve).

If a radar signal is transmitted with an initial phase of ϕ_0, then the phase of the returned signal will be

$$\phi = \phi_0 + \frac{4\pi r}{\lambda} \tag{6.1}$$

The change of phase with time from one pulse to the next is given by

$$\frac{d\phi}{dt} = \frac{4\pi}{\lambda}\frac{dr}{dt} \tag{6.2}$$

where $d(\,)/dt$ is the time derivative or time rate of change of the parameter. The velocity of an object is given by

$$V = \frac{dr}{dt}\,. \tag{6.3}$$

Angular frequency Ω is the time rate of change of angle (or phase) and is defined by

$$\Omega = \frac{d\phi}{dt} = 2\pi f \qquad (6.4)$$

where f is the frequency shift in cycles per second (hertz). Thus, by combining Eqs. 6.2, 6.3, and 6.4, we get the frequency shift caused by a moving target;

$$f = \frac{2V}{\lambda} \qquad (6.5)$$

So a given phase shift ($\delta\phi$) in a given interval of time (δt) becomes a frequency shift which the radar can measure.

This, then, is the frequency shift caused by a target moving relative to a radar. Notice that it is linearly proportional to velocity and inversely proportional to wavelength. For a given radar, wavelength is a constant, so the frequency shift is dependent only upon velocity of the target.

If the target is not moving directly toward or away from the radar, we can easily correct for this by determining the *radial component* of motion using

$$f = \frac{2V\cos(\alpha)}{\lambda} \qquad (6.6)$$

where angle α is shown in Fig. 6.2.

Block diagram of Doppler radar

Now let's examine how a Doppler radar measures the speed of a target. Figure 6.3 shows the block diagram of a pulsed-Doppler radar. It has all of the components of the simple radar given earlier (Fig. 2.1), but it also has some additional components. The ability of a Doppler radar to detect slight phase shifts depends critically upon the system maintaining a constant transmitter frequency and phase relationship from one pulse to the next. Many Doppler radars use what are known as coherent transmitters (generally using

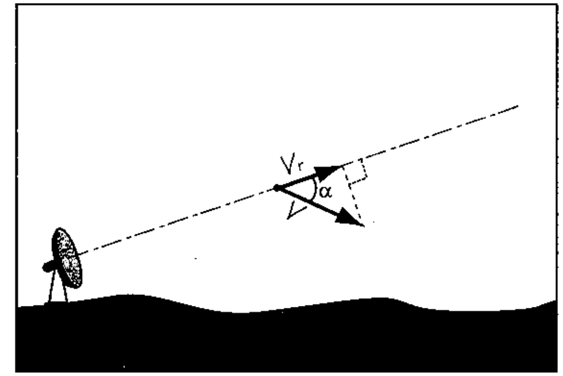

Figure 6.2 Geometric relationship of a target located on the center of the antenna beam axis moving with velocity V at an angle α relative to the pointing direction. The radar detects the radial component of velocity V_r.

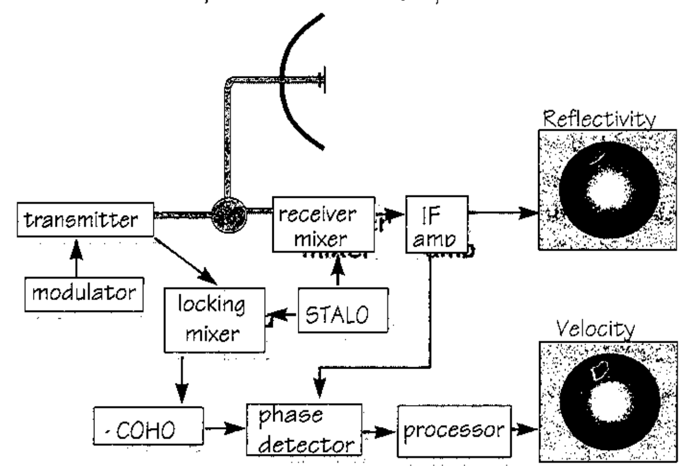

Figure 6.3 Block diagram of a simple Doppler radar. IF amp = intermediate frequency amplifier; STALO = stable local oscillator; COHO = coherent oscillator. The top "display" shows radar reflectivity factor while the bottom "display" show Doppler radial velocity.

klystron transmitting tubes). These radars transmit exactly the same frequency and initial phase from one pulse to the next. Other Doppler radars, using magnetron transmitting tubes, do not maintain the same frequency and phase stability but have components which sample and remember the phase and frequency of each pulse so that it can be compared with the received signal. Both kinds of transmitters give excellent velocity measurements.

In order to determine the frequency shift from one pulse to the next, Doppler radars contain a device called a stable local oscillator (STALO) which maintains a very stable frequency from one pulse to the next. The signal from the STALO is mixed with the frequency from the transmitter in a locking mixer. This signal is sent through a coherent oscillator which amplifies this signal while maintaining the phase relationship with the initially transmitted signal. The signal from the STALO is also mixed with the received signal in the receiver/mixer. This signal is amplified in the intermediate frequency (IF) amplifier. The received signal and the sample of the transmitted signal are sent to a phase detector which compares the phases of the two signals and determines how much the received signal has been shifted relative to the transmitted signal. This is processed and displayed and/or recorded by additional components in the system and gives the radial velocity of the echo.

Maximum unambiguous velocity

There are limitations in the velocities and ranges that a radar can resolve unambiguously. Let us consider velocity ambiguities first. When a target is not moving toward or away from a radar, it will have zero *radial* velocity. This does not necessarily mean that the target is stationary. It simply means that the target is remaining at a constant distance from the radar. It could be moving quite rapidly, in fact, but any movement it has must be perpendicular (i.e., transverse) to the radar's beam. Since the only velocity a

Doppler radar can detect using phase-shift principles is the radial velocity, we usually omit the qualifier "radial" and simply talk about the "velocity" (see Fig. 6.2 again). While this is convenient, be careful to recognize that a Doppler radar detects only the radial components of velocities.

If the velocity of a target relative to a radar is zero, there will be zero phase shift in the frequency of the received signal relative to the frequency of the transmitted signal. If the target is moving slightly away from or toward the radar, there will be a slight phase shift. As the speed of the target increases, the phase shift will also increase, producing an increasing Doppler frequency shift. There is a limit, however, of how large a phase shift a radar can detect. For example, if a target were moving away from a radar just fast enough that it traveled 1/2 a wavelength between two consecutive radar pulses, it would produce a phase shift of π radians. If it were moving toward the radar at the same velocity, it would produce a phase shift of $-\pi$ radians. We could not tell the difference between the two velocities because $+\pi$ and $-\pi$ radians represent the same phase shift. As another example, if a target were moving so fast that it traveled exactly a whole wavelength between two consecutive pulses, the radar would detect zero phase shift and think that the target was stationary.

The maximum velocity a Doppler radar can detect correctly or unambiguously is given by the velocity which produces a phase shift of $\pm\pi$ radians. This is also called the Nyquist[1] frequency or Nyquist velocity, depending upon whether we are referring to the maximum unambiguous frequency or velocity, respectively. Mathematically, we can express this as

$$V_{max} = \frac{\pm f_{max} \lambda}{2} \tag{6.7}$$

[1] Harry Nyquist received his BA and BSEE in 1914 and his MA in 1915 from the University of North Dakota.

where the maximum frequency f_{max} is given by

$$f_{\max} = \frac{PRF}{2} \tag{6.8}$$

and PRF is the pulse repetition frequency of the radar. Thus, the maximum unambiguous velocity detectable by a Doppler radar is

$$V_{\max} = \frac{\pm PRF\lambda}{4} \tag{6.9}$$

This is an important result. It says that if we want to be able to detect high velocities, we must use long wavelengths, large PRF's or both.

Maximum unambiguous range

Now, what about the limitations on range? We know that electromagnetic radiation travels at the speed of light. The time it takes for a signal to go out to and back from a target is $t = 2r/c$, where c is the speed of light, r is range and t is time. The "2" accounts for the distance out and back from the target. If a radar transmitted a single pulse and waited forever for a returning echo, there would be no limit to the distance at which the correct range to a target could be determined. In the real world, we do not wait very long before sending out the next pulse.

There are a number of reasons for this. One is that we cannot detect targets at extremely long ranges or we are not interested in them. The tallest meteorological targets are usually only 10 to 15 km tall. Even though the radar waves bend downward somewhat in their travel through the atmosphere, the Earth's surface curves away even faster, so the radar beam usually gets so high above the Earth's surface that even very tall storms are not detectable beyond 400 to 500 km from a ground-based radar (see Fig. 3.7).

Another reason we are not interested in distant targets is that the inverse square law decreases the power received

from a meteorological target according to $1/r^2$. If a target is too far away, the power received from it will be so weak that the radar will be unable to detect it. For these and other reasons, radars are designed to send out subsequent pulses of energy at fairly frequent intervals.

A radar transmits many pulses each second. The rate is given by the PRF. The time T between pulses is thus

$$T = \frac{1}{PRF}. \tag{6.10}$$

Now, given T, we can determine the maximum range a radar signal can travel and return before the next pulse is sent out. This is simply

$$r_{\max} = \frac{cT}{2}$$

$$r_{\max} = \frac{c}{2PRF}. \tag{6.11}$$

The Doppler dilemma

The combination of maximum unambiguous velocity and maximum unambiguous range form two constraints which must be considered in choosing the PRF for use with a Doppler radar. Notice that non-Doppler radars are only constrained by the maximum unambiguous range; since they cannot measure velocity, the velocity constraint does not apply.

Unfortunately, PRF appears in both Eqs. 6.9 and 6.11, but in the denominator of one and the numerator of the other. This forms what has been called the "Doppler dilemma." By solving both equations for PRF and equating them, we find that

$$V_{\max} r_{\max} = \frac{c\lambda}{8}. \tag{6.12}$$

If we want to have a large V_{max}, we must have a small r_{max}

since the right side of the equation is a constant for a given radar. Conversely, if we want to detect echoes at long ranges, we can only detect small velocities.

Figure 6.4 (based on Gossard and Strauch, 1983) shows the Doppler dilemma graphically. Note that the ordinate (Y-axis) on this figure gives the maximum velocity interval corresponding to the Nyquist frequency. Normally we divide this interval in half with the maximum unambiguous velocity being divided into plus *and* minus half of the V_{max} interval. For example, from the figure we can see that for an S-band (10-cm wavelength) radar, if the *PRF* is 1000 Hz, the maximum unambiguous range is 150 km while V_{max} is ±25 m/s. For an X-band (3-cm wavelength) radar using the same *PRF*, r_{max} is still 150 km, but V_{max} is now only ±8 m/s. For meteorological situations, we may want to measure velocities as large as ±50 m/s out to ranges beyond 200 km, so neither of the limits calculated above is completely adequate. The S-band system comes much closer to being useful than the X-band system, however. And C-band (5-cm wavelength) will be intermediate to these two.

One partial solution to the Doppler dilemma is in our choice of wavelength. We can increase V_{max} by using a longer wavelength radar. Unfortunately, longer wavelength radars are more expensive and bigger, and they don't detect weather targets as well as shorter wavelength radars, so using a longer wavelength is not necessarily a solution to the problem. The result is that most Doppler weather radars usually suffer significant range or velocity ambiguities or both.

Since range ambiguities (also called aliasing or folding) are so common with modern Doppler radars, let us examine the causes of this in a little more detail. Range aliasing occurs because we don't wait long enough between transmitted pulses. Instead, we transmit pulses close together (mostly to make the Doppler side of the radar work better), not giving one pulse enough time to cover the distance between the radar and some storms before the radar sends

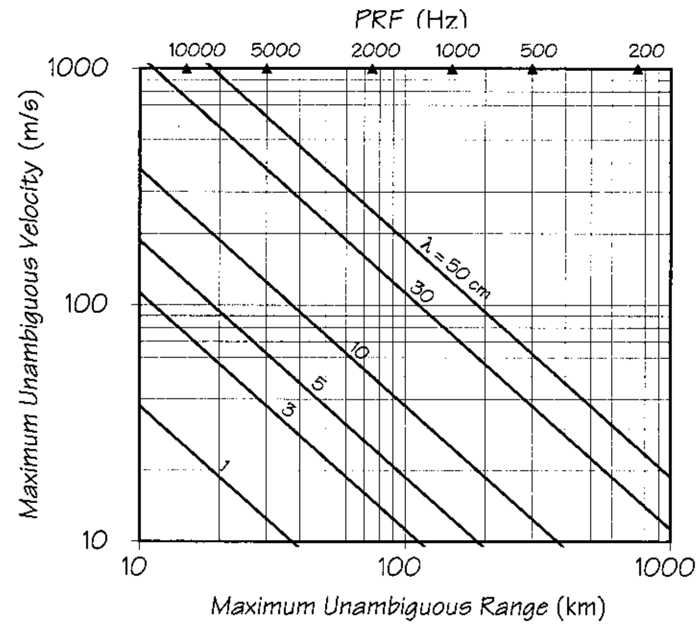

Figure 6.4 Summary of conditions for range and velocity folding (i.e., the Doppler dilemma). The numbers along the diagonal lines are wavelength. Numbers along the top are pulse repetition frequency. Notice that r_{max} depends only on PRF and is independent of wavelength. (After Gossard and Strauch, 1983).

out the next pulse of energy. Consequently, a storm at range r can be detected beyond r_{max} (see Fig. 6.4). That is, a first pulse of energy goes beyond r_{max} and detects a storm. The radar does not know the signal is from beyond r_{max}, however, and displays it at a distance of $(r - r_{max})$.

Echoes which are displayed in the wrong range interval are called multitrip or second-trip echoes. If the *PRF* is high enough and distant echoes tall enough and strong enough, sometimes third or even fourth trip echoes can be detected.

Recognizing range-aliased echoes

How are second-trip echoes recognized on a radar? There are a number of ways multitrip echoes can be recognized. One of the easiest is to simply look outside and see what is going on in the real world. Slim Summerville, one of my instructors at Colorado State University, once said: "Never make a forecast with your back to the window." That's great advice for interpreting radar echoes, too. If the radar shows a nearby storm in a particular direction but there is nothing outside, it is probably a multitrip echo.

A second way to recognize multitrip echoes is by their shapes (see Fig. 6.5a and 6.5b). Isolated real storms are usually somewhat circular, elliptical, or irregular in shape. Storms certainly should not know where the radar is located. Anytime a narrow, wedge-like echo is detected which points toward the radar, second-trip echoes should be suspected (see Fig. 6.5b).

Another clue to the existence of multitrip echoes is height (see Fig. 6.5a). Real echoes, especially from convective storms, usually extend up into the atmosphere several kilometers. Thunderstorms are frequently 8 to 15 km in height. If a convective-like echo appears on the radar display but it has an indicated height which is much less than normal, it may be a second-trip echo. For example, a real thunderstorm which is 10 km tall at a range of 200 km would be detectable at an elevation angle of about 2.2° (see Fig. 3.6). If it is a second-trip on a radar with a *PRF* of 1000 Hz, it would show up at 200 km - 150 km = 50 km. If the echo from this storm disappears just above 2.2°, its indicated height would only be 2 km. This is a ridiculously small height for a strong storm, so you should expect range aliasing.

Finally, second-trip echoes can sometimes be recognized by their reflectivities. The power received from a storm decreases according to $1/r^2$. If our storm being displayed at 50 km were real, it would have a certain reflectivity. If it is really at 200 km, however, the power returned

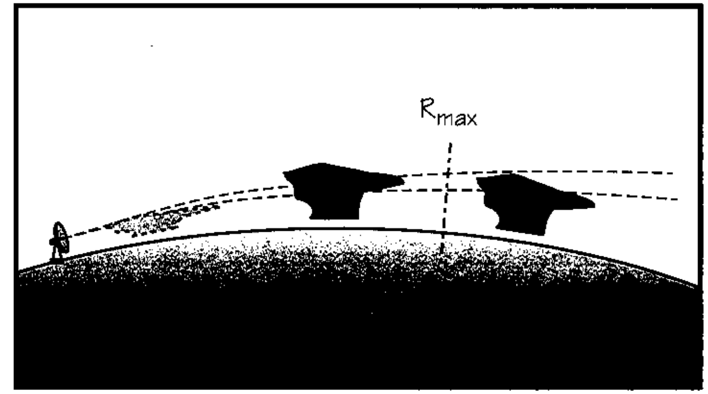

Figure 6.5a Illustration of how a storm beyond r_{max} can be displayed at the wrong range. Two real echoes exist. The first is less than r_{max} away and is displayed at the correct range. The second is beyond r_{max}; it is displayed at a range of $(r - r_{max})$. The faint, dashed storm near the radar is where the radar would display the distant storm.

from it would be $(200/50)^2$ less than if it were at 50 km. So the returned signal would be 16 times less. On a decibel scale this would be 12 dB less than if it were at its indicated range. Unfortunately, since we do not know the true reflectivity of a storm without the radar giving it to us, we cannot be sure that a weak echo is simply a weak storm and not a second-trip storm. Nevertheless, low reflectivity (combined with shape and height information) can help differentiate real from multitrip echoes.

There is one guaranteed-or-double-your-money-back way to unambiguously determine if echoes are range aliased or not: *Change the PRF!* If we change the *PRF* and watch the positions of echoes, all correct echoes will not change their range whereas range-aliased echoes will shift in or out in range, depending upon whether the *PRF* is decreased or increased, respectively. Alternatively, we can avoid range

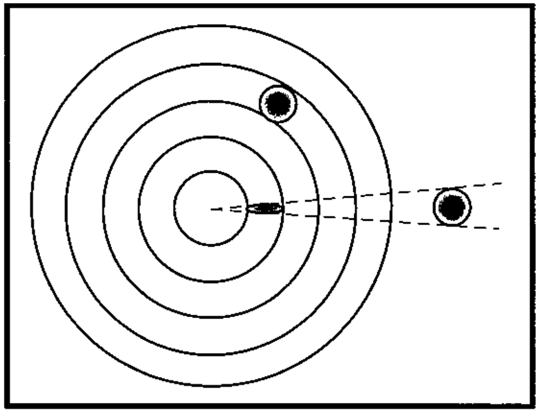

Figure 6.5b Simulated PPI display showing a real echo located to the northeast. To the east is an echo beyond r_{max}. It is displayed at a distance of $r - r_{max}$ from the radar. It also has a very narrow shape. Both the range and azimuthal extents are exactly the same in the real and the aliased positions, but its aliased azimuthal width is much narrower.

aliased echoes by using a *PRF* so low that r_{max} is so large that range aliasing cannot take place.

Some examples of second-trip echoes are shown in Color Figs. 6, 7, 9 and 10. In Color Fig. 6 there is some real echo toward the west to northwest near 60 km. The second-trip echoes are visible mostly on the reflectivity display and are weak echoes extending along radials from near the maximum range in toward the nearby ground clutter. Further evidence that the suspicious echoes are really second-trip echoes is that they do not show much at all in the velocity data. The signal processor on the UND radar rejects velocity data that do not meet certain quality checks (i.e., signal strength above some threshold and velocity variance smaller than some upper limit plus another check or two); second-trip echoes frequently fail these tests and are not displayed;

because the reflectivity data are not subject to the same battery of tests and because the reflectivity data come from a different receiver, they are not eliminated on the reflectivity display.

In Color Fig. 7 there are some weak (green) echoes in the reflectivity data pointing toward the radar from about 10 to 40 km range at an azimuth of about 290° to 310°. Unfortunately – and this is frequently the case – the second-trip echo occurs in the same place as real echo of importance. In this case, there is a weak gust front in this same location. Again, these second-trip echoes show best on the reflectivity display and barely at all on the velocity display.

Color Fig. 9 also has some suspicious echoes which appear to be second trippers toward the very south end of the figure. In this region there are several small wedge-like echoes pointing toward the radar. Their reflectivities are not particularly strong, generally not exceeding 25 dBz. In this case, however, the suspicious echoes do have velocities associated with them. The reason for this is that the velocity quality tests have been turned off (as indicated by the "SQI" value of 0.0 in the radar housekeeping data; see the comments about the interpretation of the housekeeping data in the section on Color Figures later in this text). As a result, range aliased velocities are not filtered out of the velocity display. Their velocities do seem to fit with those of the major echo to the west of the radar reasonably well, so it is not absolutely clear that they really are second-trip echoes from this single PPI. However, there is a long line of very strong reflectivities approaching the radar from the west. When strong lines of echoes exist, they are often very long. It is likely that this line of echo seen on the limited area of the radar display has more echo on the south end that is not shown – except as second-trip echoes.

Further evidence that second-trip echoes are a possibility in Color Fig. 9 is the narrow band of bright red velocity near 10 km range and 240° azimuth. This is a case of a velocity not fitting the surrounding area. Color Fig. 10 shows a very shallow layer of reflectivity near the surface that is not connected to the main storm echo. This echo, which is only a kilometer or so tall, has reflectivities near 40 dBz, yet it does not appear to be ground clutter (because it seems we are seeing some weaker echo below it; also because it appears smooth rather than rapidly changing as most ground clutter does). This supports the suspicion that this (and possibly others) are second-trip echoes and not correctly displayed by the radar.

Velocity aliased echoes

Now let's return to velocity aliasing. Recall that velocity aliasing occurs when the phase shift is more than ±180° or $\pm\pi$ radians from the transmitted phase at a given range. But how does this appear on a radar display? And how does the speed of a target produce this much phase shift? To begin with, let's consider a simple case where a Doppler radar is detecting an echo in the presence of a uniform wind; that is, the wind is the same speed and direction at every point the radar looks. When this occurs, the radial velocity detected by the radar depends upon both the direction the wind is blowing and the azimuth the radar is pointing. Equation 6.6 applies, and it suggests that the radial velocity detected is a function of the cosine of the angle between the radar beam and the wind direction.

Most Doppler weather radars display fields of radial velocity on color displays, usually showing the velocities on a scale going from the maximum unambiguous negative velocity to the maximum unambiguous positive velocity as a series of colors. And usually the color bar that is the key to determining velocities on the display is shown as a horizontal or vertical bar (see the color figures for both the UND radar and the NEXRAD radar).

When an echo contains a region that is faster (either away or toward the radar) than V_{max}, it will usually be evi-

dent by having fast approaching and fast receding velocities next to each other. But the linear color bar used to describe this is not always helpful in explaining *why* the aliasing is occurring. One way to maybe make this more obvious is to change the color bars into a circular format. By doing this it becomes a little more obvious that the velocity scale is really a continuum which has an artificial boundary between the maximum receding and maximum approaching velocities.

Consider Figure 6.6 which illustrates such a Doppler "speedometer." It shows the radial velocity detected for a radar when the environmental wind is from the west at various speeds. In the first case (top panel and top speedometer), the wind is perhaps 5 m/s. The radial velocity detected by the radar varies sinusoidally with azimuth. The speedometer is showing the speed that would be detected looking toward the east. In this direction the radar would be showing the maximum receding velocity of about 5 m/s. In the middle panel, the speed is faster and the speedometer is showing a receding velocity near 10 m/s.

The bottom panel shows what happens when the environmental wind exceeds the maximum unambiguous velocity of the radar. Now the approaching speed is on the order of 17 m/s or so. But the speedometer would now show a speed of -13 m/s, i.e., it now shows a fast *approaching* velocity. The correct velocities will be displayed from north through ENE and from ESE to WSW and from WNW to north again. Where the sine wave exceeds the V_{max} limits on the right panels, it will be folded or aliased into the unambiguous region, but will have a velocity of the opposite sign.

Notice that the color displayed by the radar for a particular echo is a function of the azimuth where the radar is pointing. If the radar is pointing perpendicular to the movement of the echo, the velocity displayed will be zero. This occurs on Fig. 6.6 where the sine wave crosses at zero velocity, i.e., north and south.

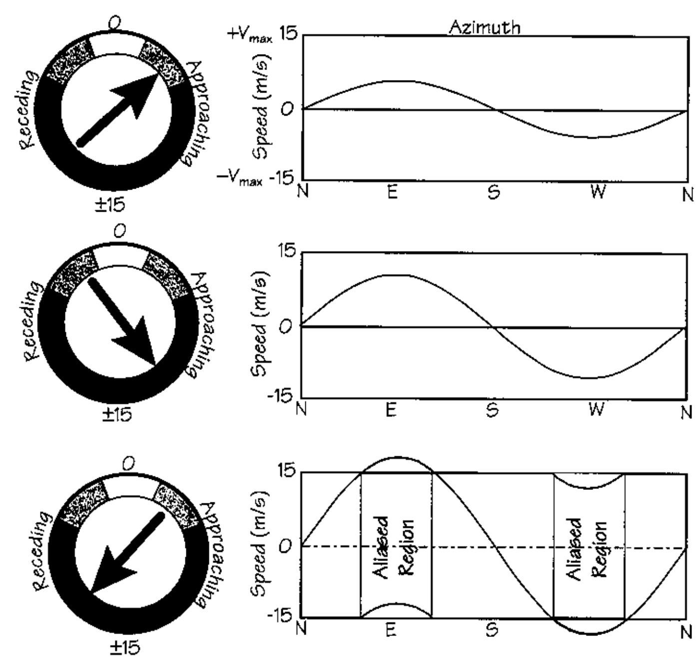

Figure 6.6. The "Doppler speedometer". The abscissa is the direction the antenna is pointing and the ordinate is the speed detected. In all three cases, the radar is detecting a uniform wind blowing from the west (made detectable, for example, by the presence of insects). For the case at top right, the velocity is about a third of V_{max}. For the middle case, the velocity is about two-thirds of V_{max}. For the bottom case, the speed is just over V_{max} and is aliased when the radar looks both upwind and downwind.

Recognizing velocity aliasing

How do velocity-aliased echoes appear on a radar display? The answer to this depends upon where the aliasing takes place. If a large region of echo is being detected by a Doppler radar and a region within it exceeds V_{max}, then there

will be an abrupt change in velocities surrounding the aliased region. For example, if the storm is moving away and part of it is moving away faster than V_{max}, then strong receding velocities would surround a region with apparently strong approaching velocities. Such a discontinuity is usually quite visible, and it is obvious that velocity folding is taking place.

If the storm causing range folding is completely isolated such that there is no surrounding echo, the velocities from the storm may appear entirely correct even though they have been folded into the wrong velocities. This would make recognizing velocity-folded data much more difficult. Fortunately, such isolated situations are not very common, so this is usually not a major problem. There are almost always several echoes on a display at the same time (perhaps even more so when velocities are so strong as to be folded), so velocities of nearby echoes are often useful to indicate whether folding is taking place or not.

A more difficult situation, however, occurs when C- or X-band radars are measuring storm velocities. For these radars V_{max} can be moderately small. Thus, it is possible to have velocities which are not just folded once but are folded twice or more. This can make it extremely difficult to tell what the true velocities are from a quick visual inspection of the radar display.

Velocity aliasing is a very common feature with the 5-cm wavelength UND radar. Except for Color Figures 1, 2, 6, and 12, *all* of the velocity figures from the UND radar have at least some velocity aliasing in them. In the 25 May 1989 example shown in Color Fig. 10, the velocities are so fast toward the radar that the velocities are wrapped around the color bar *twice!* This occurs, for example, in the region above 20 km range. Near the surface at 20 km range, velocity is quite strong (aliased from the reds into the blue) at about 15.5 m/s away from the radar. These receding velocities decrease to zero at about 2.5 km altitude above the radar and then become greater and greater toward the radar. Above 4 km the blue velocities abruptly change to reds and continue in the same direction through zero and into the blues again; at about 8 km they again abruptly change into reds and peak out in the yellows. Above this they start to decrease back through the reds and blues. At the point where the velocities are strongest, they are approximately 55 m/s.[2]

A few (belated?) words are in order about how reflectivities and velocities are presented on modern radar displays. Most modern radars currently use color displays to show their data. We have already seen several examples of these. Reflectivities typically are shown using a color scale which has blues or greens for weak echoes and oranges, yellows and reds for stronger reflectivities. Depending upon the color resolution of the system, reflectivities might be displayed in as few as three or four colors to as many as several hundred. A dozen to 16 colors is quite common. With storm intensity we know that as we go from outside the storm to inside the storm, the reflectivities must increase (from 0 mm^6/m^3 to z_{max}). Thus, we should always expect to see at least a narrow band of low reflectivities surrounding the stronger reflectivities.

Velocity displays usually show colors going away from the radar as browns, yellows and reds and those approaching as greens and blues. This convention was chosen to correspond to the "red shift" of visible light in our expanding universe. Since an entire storm may be going away or coming towards the radar, we cannot know ahead of time whether it should appear as all greens, all reds or some

[2] This value was obtained by calculating V_{max} using the PRF of 1100 Hz given on the color display; this gives V_{max} = 14.9 m/s. Then, since we went from zero to V_{max} and then all the way across the color bar to V_{max} again, we covered a total velocity range of $3 \cdot 14.9$ m/s = 44.6 m/s. In addition to that, the highest velocity reached was about 3 color bars beyond the left side, or $3 \cdot 3.3$ m/s $\approx$ 10 m/s faster. Adding all these together gives 54.4 m/s. This was indeed a fast moving part of the storm.

combination of the two. But we can usually expect to see a gradual transition from one color to the next. In principle, we should always see a gradual transition from one speed to another. This transition may take place over a very short distance, however, so it may still appear to be fairly abrupt.

This normal progression is useful in looking for folded velocities. If the echo shows a region of near-maximum approaching velocity immediately adjacent to an area of near-maximum receding velocity, folding is almost certainly the cause.

Most newer radars and their computerized signal processors have an "interrogate" mode. By placing the cursor on a display over a point of interest, the reflectivity, radial velocity, and position of the point will be displayed. Among other things, this makes it very easy to detect the large velocity changes that occur when aliasing is taking place.

Other reasons for velocity discontinuities

Discontinuities in the displayed velocity field may come from at least three other sources other than velocity folding. If second-trip echoes are being detected and if they happen to overlay first-trip echoes, the velocities in the second-trip echo will probably not match those of the first-trip echoes. As a result, there may be a discontinuity in the velocity field. This is another way to recognize the presence of multitrip echoes.

A second way that strange velocities can be detected by a radar is by having the radar beam reflect off of a nearby building or other object and detect a storm in some other direction. The returned echo will have the velocity associated with the storm detected, but it will be displayed in the direction the antenna was pointing when it hit the building. After all, the radar "thinks" it is detecting an echo in the direction it is looking. It is not smart enough to know the source of the echo is in some other direction (*you*, however, are smart enough to know this, so you will have to mentally adjust the image to the real situation outside). Sometimes reflections give very clear discontinuities in the velocity field. Unfortunately, there is no easy solution to this except to move the radar to a different location (or remove the cause of the reflection). Fortunately, once the sources of these reflections are identified, they will always occur at the same azimuths, so recognizing them in the future becomes easier.

Color Fig. 1 shows some examples of this problem with the UND radar but from ground echoes instead of storm echoes. If you look carefully at the velocity data you can see some narrow spikes of zero velocity data at the edge of the nearby ground clutter which are pointed toward the east northeast and southeast; these are also detectable in the reflectivity data. If you go out to 80 to 100 km range along the same azimuths, some more weak reflectivity/zero velocity lines are shown; at this range there is also another such line at about 185° azimuth. Color Fig. 6 shows this same problem with slightly greater magnification.

All of these echoes appear to be caused by the radar signal being reflected off of buildings at nearby farms. This was confirmed by climbing the radar tower at South Roggen, Colorado, where the radar was located at this time, and looking in the directions at which these spikes were detected. In all cases there was a farm within a mile or two of the radar along these exact azimuths. Each of the farms had several buildings which could have caused the reflections. The nearby spikes are visible because the terrain rises gently toward the east and acts as a natural clutter barrier; little real ground clutter is seen toward the east. Consequently, the nearby buildings reflect the radar signal back toward the west where the local ground clutter extends farther away.

In the case of the echo at 80 to 100 km, the target detected by the radar was the Rocky Mountains! That is, the radar antenna would be aimed, for example, toward 70° azimuth; the transmitted pulse would hit a building a mile or two away, be reflected back towards the west, and detect the

very strong ground targets 80 to 100 km away. The echoing signal would follow the reverse path and be displayed on the radar at the range corresponding to the distance from the radar to the building plus the distance from the building to the mountains, but the azimuth would be that of the building. It is possible to detect storm echo in exactly the same way; in this case, however, the velocity would be the velocity of the part of the storm which is detected. In both cases, the reflected echoes make very interesting artifacts in the radar data. Beware of artifacts in your data!

A third way that incorrect velocity information can be displayed on the radar display is caused by the rotation of the antenna and the imperfect antenna beam patterns that all radars have. The feed horn of a radar antenna is usually located out in front of the antenna reflector and aimed back toward it. The electromagnetic radiation leaves the feed horn, hits the reflector, and is directed and focused out into space in the direction the antenna is pointing. There are two problems here. One is that not all of the energy hits the reflector. Some misses and goes more or less behind the radar while some of it goes off to the sides (actually, it goes in all directions, i.e., the beam pattern is really three dimensional). If the sidelobe energy hits a strong reflector, it can produce an echo at the range of the target, but it is displayed in the direction the antenna is pointing. The second problem is that, if the radar antenna is rotating when it is transmitting its energy, the frequency of the energy leaving the antenna will be a combination of the transmitted frequency *and* the frequency shift caused by the velocity of the feed horn.

Most feed horns are located at least a short distance from the center of rotation of the antenna. The speed of rotation of the feed horn is the product of the angular velocity of the antenna (e.g., radians/second) and the distance from the feed horn to the pivot point. For radars with big antennas, S-band radars, for example, this distance can be fairly large. The FL2 S-band radar operated by MIT Lincoln Laboratory had the feed horn about 19 ft from the center of rotation. If this radar scans at a speed of 30°/s, the feed horn will be moving at a speed of 3.1 m/s. Faster scan speeds give correspondingly faster velocities.[3]

Now, when a radar transmits a signal in the direction the antenna is pointing, the angular velocity of the feed horn is perpendicular to this direction, so it does not add any *radial* movement; the transmitted frequency is unchanged. When the energy leaves a sidelobe, however, it will have a slight shift in velocity caused by the movement of the feedhorn. If this portion of the transmitted signal hits a stationary ground target such as a building, it will appear to the radar that the building is moving at the velocity the feedhorn is moving. This produces an echo on the radar display that has the velocity of the antenna relative to the target.

Many very strong, stationary reflectors can produce sidelobe echoes which completely or nearly completely surround a radar. The correct position of this echo will be found when the antenna is pointed directly at it; here it will have its strongest reflectivity and a zero radial velocity. The apparent velocity of this target will vary sinusoidally as the antenna rotates around. It will have a maximum receding velocity when the antenna has rotated 90° away from it. At 180° rotation, the velocity will again be zero. As the feedhorn approaches from the other side, the velocity will then appear to be approaching the radar, with the maximum being reached at 90° from the correct position. If the antenna scans in the opposite direction, the approaching and receding sidelobe echoes will shift to the opposite sides.

[3] The Lincoln Laboratory FL2 radar (converted to C-band) was the prototype of the TDWR radar now in use by the FAA (see Appendix D).

Automatic Dealiasing

Modern radar processing can reduce the effects of both range and velocity aliasing. Velocity folding can be reduced by applying algorithms to the data which look for velocity discontinuities with range and removing or reducing them by the Nyquist velocity. There are several schemes being developed for doing this. Automatic velocity unfolding is done with WSR-88D radar data so that users will not normally see any incorrect velocities.

There are times when velocities are not recoverable. Color Fig. 18 has some of these at long range toward the north through to the east. The large areas of purple indicate regions where the radar's signal processor cannot determine good velocities; these regions are indicated by "RF" on the bottom of the color bar. These regions are sometimes call "the purple haze." They are fairly commonly seen on velocity displays for WSR-88D radars.

There are also a number of schemes being tested to eliminate range aliasing. In some ways this is a more difficult problem, requiring more complex solutions. Some of the solutions involve changing the *PRF* in some clever ways to allow both long unambiguous ranges and high unambiguous velocities. These more complicated transmission schemes require more complicated processing to use them, but the results are worth the effort.

There are also automatic ways to select the *PRF* to give optimum coverage of a preselected location. For example, if we want to give warnings of microbursts over an airport, we want to select a *PRF* which minimizes the obscuration of the airport region by distant storms. Since these storms will move with time, the *PRF* will have to be changed to accommodate this movement. By examining the locations of echoes at long ranges (using low *PRF*'s), it is possible to find the optimum *PRF* to give the least amount of obscuration in a nearby region of interest. This technique is used with the TDWR radars (C-band) operating near major airports in the US.

Multi-trip echo map projection

An alternative to changing the way the radar transmits or displays the radar data is to change the map on which the range-aliased data are displayed (Rinehart, 1989). By redrawing the map so that geographic and political points are distorted in the same way the second-trip echoes are, it is possible to determine the correct location for storms relative to the ground quite easily. Use of such a map projection makes it possible to tell what cities might be going to get rain soon or where a tornado might be right now.[4]

An example of such a map display is shown in Fig. 6.7. The map on the upper left (Fig. 6.7a) shows the several-state region around the UND radar site near Denver, Colorado, during 1987 and 1988. The range circles are drawn at intervals of 150 km which is the maximum unambiguous range r_{max} corresponding to a *PRF* of 1000 Hz. Various weather stations are shown on the map. Figure 6.7b shows the area shown on a radar display set to cover 150 km range.

Figures 6.7c and d show what the region would look like if all of the area within one or two r_{max} intervals, respectively, were eliminated and all locations farther away were shifted directly toward the radar by a distance 1 or 2 r_{max}. Obviously, the shape of the map becomes quite distorted.

[4] I was really going to remove this section since it was put in earlier editions as much for fun as it was as a serious topic (another cartoon?). However, since the Rinehart projection is now officially defined on page 650 of the *Glossary of Meteorology, Second Edition* (Glickman, 2000), I felt obligated to leave it here. Sorry!

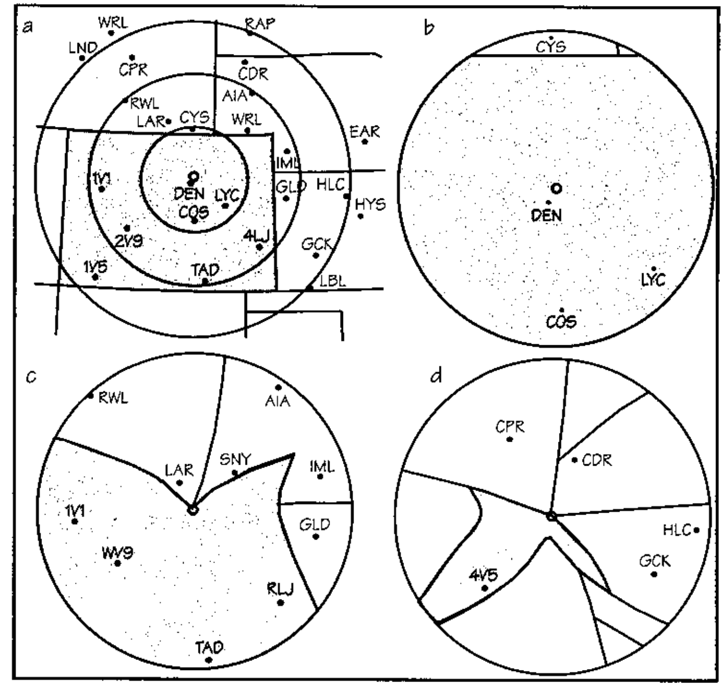

Figure 6.7 Maps showing the several-state region around the UND radar location at Denver, Colorado. Range circles on all panels are at r_{max} = 150 km intervals. The state of Colorado is shaded gray on all images. By removing 150 km or 300 km from the center of the first display, second- (c) and third-trip (d) Rinehart projection maps are generated, respectively.