CHAPTER 48

RADAR TECHNOLOGIES IN SUPPORT OF FORECASTING AND RESEARCH

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1 INTRODUCTION

Forecasters and researchers, and the computer models that support them, require detailed information concerning the three-dimensional state of the atmosphere and how it evolves with time. Some forecasting and research needs overlap; others are particular to those respective tasks. But whether the goal is weather prediction or scientific understanding, no tool can provide more wealth and diversity of information than existing and emerging technologies in weather radar (Fig. 1). Weather radars can sample large volumes of the atmosphere nearly continuously in space and time at fairly high resolution vertically, horizontally, and temporally. Radars can penetrate through clouds and precipitation to measure precipitation intensity, precipitation type, and wind motions in many weather conditions, throughout the depth of the atmosphere. They are a uniquely versatile tool.

A forecaster needs to know where it is raining or snowing, how hard, and whether snow or hail is occurring. He needs to know whether the precipitation is caused by convective systems or more stratiform uplift, whether it is moving toward the forecast area or away, whether it is strengthening or weakening. He needs to know if an airport runway will soon be affected by a gust front or microburst, or if a mesocyclone will move into his forecast area, whether a snow band will move onshore, or whether a sea breeze will initiate storms. For many forecasts of 6 h or less, radar is the crucial tool that provides the most up-to-date and comprehensive information to a forecaster. Mesoscale forecasting models

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Figure 1 The MIT 5-cm (C-band) research radar deployed in Albuquerque, New Mexico. The nearly spherical radome protects the radar antenna and sits on top of a tower that places the antenna above blocking objects. The transmitter, receiver, and operating consoles are located in the buildings below the tower. (Photo courtesy of MIT Weather Radar Lab, D. Boccippio.) See ftp site for color image.

of the future will become more and more dependent on initializations and nudgings provided by the nation's radar network.

Research needs are similarly diverse. A scientist may want to study large-scale rainfall patterns, not only at weather stations, but in between, or to study much smaller scales, down to suction vortices in tornadoes or rolls in microbursts. He may want to understand the microphysical processes that cause hail, icing, or charging of particles and lightning, or to study the flow along a front or dry line, or the wind field of a hurricane rain band. Researchers use radar to probe the upper atmosphere and the boundary layer, intense and violent weather, and quiescent overturning on clear days. Almost all atmospheric phenomena with scales of 10 m to 100 km have been and are being intensively studied using radar.

2 BASIC RADAR OPERATION

This chapter is not a radar textbook, but it is valuable to briefly review some basics of the theory and operation of radars to understand the nature and quality of the data that they produce, the limitations of these data, and potential uses both now and in the future. The following discussion will not be exhaustive and will cover only some major technologies.

Most weather radars focus pulsed beams of microwaves on meteorological targets and listen for returned signals. (Not all radars operate in this fashion. But the exceptions are primarily fairly exotic research systems.) By measuring the strength, timing, and other parameters of these signals, information about the targets can be obtained. A pulse of focused radiation, typically about 1 to 2 μs in duration, leaves the radar (Fig. 2). At various points along its travel, the pulse encounters precipitation, insects, suspended particles, airplanes, mountains, or density discontinuities in the air and some of the radiation is scattered back toward the radar and elsewhere, while the remainder continues to travel outward. After the pulse leaves the radar, hardware and software listen for returned energy. The delay time between transmission and return uniquely defines the distance to the precipitation that caused the scattering, $R = c\ \Delta t/2$, where R is the distance to the precipitation, c is the speed of light, and Δt is the time between transmission and return of the energy. The returned signals are grouped or sampled at intervals, typically about 1 to 2 μs, resulting in distance resolution, using the above formula, of 150 to 300 m. After approximately 0.5 to 2 ms, another pulse is transmitted and the process is repeated. The strength of

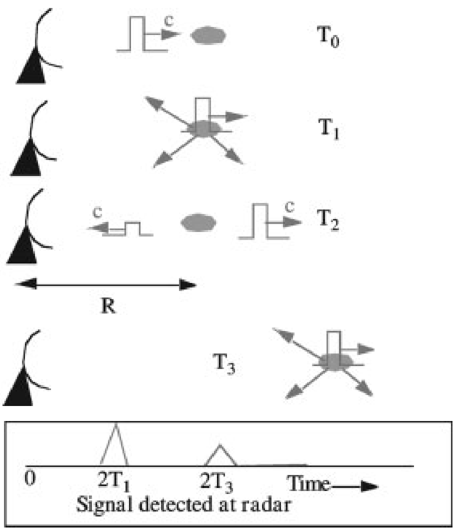


Figure 2 Pulse of microwaves travels from a radar toward a raindrop at T_0. At T_1, the pulse encounters the raindrop, which acts as an antenna and radiates in many directions. At T_2, the transmitted pulse continues outward while some of the microwaves emitted by the raindrop continue back toward the radar. The microwaves travel at the speed of light, c, from the radar to the drop and back again, so the distance to the drop can be calculated from the round-trip time, $2T_1$. Radiation emitted by drops encountered further along the transmitted pulse's travel T_3, will return to the radar at later times. See ftp site for color image.

the returned signals can be used to estimate the intensity of precipitation that causes the scattering, using what is known as the radar equation. The difference in phase of the returned radiation from subsequent pulses is used to calculate the motion of the precipitation. (Most radars do not, in fact, actually measure the Doppler shift of returned radiation.) The transmitting antenna rotates, usually horizontally, surveying a wide area, then inclines and repeats the rotation, surveying a similar area at greater elevation. Some of these processes will be discussed further below.

Choice of Wavelength: Attenuation Versus Antenna Size

A typical weather radar generates microwaves with a wavelength of 3 cm (X-band), 5 cm (C-band), or 10 cm (S-band). Other wavelengths are used for specialized research purposes as will be discussed later. (For comparison, a fluorescent light bulb generates energy at about 500 nm, an FM radio station 300 m, and a cordless phone at 40 cm.)

All other things being equal, it is usually best to use the longest practical wavelengths for a weather radar. This is because when a radar beam of microwaves passes through precipitation, it becomes attenuated due to scattering by the raindrops. Essentially, the beam is consumed by the process of scattering (back toward the radar and in other directions), and some is absorbed and converted to heat. (Not much heat, however; you cannot evaporate a cloud with a normal weather radar.) Shorter wavelength radiation suffers much more from attenuation; the effect is proportional to worse than the inverse square of wavelength $1/\lambda^2$. Precisely calculating how much a beam will be attenuated is difficult since complex scattering effects and absorption must be taken into account, but a rough approximation is possible. The attenuation rate is roughly proportional to the intensity of rain occurring in the cloud. A beam will lose a certain fraction of its intensity each kilometer: attenuation (dB/km) $= CR$ where R is in mm/h and $C = 0.01$ (3 cm), 0.02 (5 cm) or 0.003 (10 cm). So, if the rain rate is 10 mm/h, a 5-cm radar beam will lose $0.02 \times 10 = 0.2$ dB/km, a fairly significant amount since the effect is cumulative during the outward and return travel of the beam. After passing through 50 km of 10 mm/h rain and returning to the radar, the measured signal will be 20 dB weaker than otherwise expected. There are techniques for correcting for this attenuation, but they are prone to large errors. The velocity data from attenuated beams can still be good, but, in intense rain or hail, the beams can become mostly or completely extinguished, complicating or preventing the retrieval of useful data. In heavy rain all data from ranges beyond 20 km can be lost if a 3-cm radar is used. Additional attenuation can be caused by heavy rain forming opaque sheets of water on the radomes that protect antennas from the weather, sun, and wind.

But, all other things are not equal. Due to the physics of diffraction, the ability of an antenna to focus radiation into a narrow beam is proportional to its size. A large antenna can produce a much more focused beam than a small antenna. The focusing power of an antenna is also dependent, inversely, on the wavelength being transmitted, with longer wavelengths being more difficult to concentrate into a narrow beam. Thus, the beamwidth of the transmitted energy is roughly equal to $80\lambda/D$,

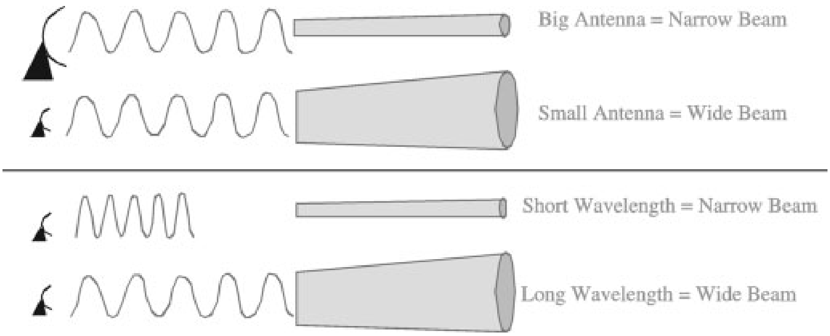


Figure 3 How beamwidth is affected by antenna size and wavelength. See ftp site for color image.

where λ is the radar wavelength and D the antenna diameter. As a result, it requires a 8-m diameter antenna to produce a 1° wide beam of 10-cm radiation, but only a 2.4-m antenna if 3-cm microwaves are used (Fig. 3). The area, weight, wind resistance to rotation, and the power required to turn an antenna are proportional to the square, or worse, of its diameter. The design trade-off is between penetration ability, better at 10 cm, versus low cost and logistical ease, better with smaller antennas transmitting at 3 cm. When the current operational weather radar network in the United States was constructed, a significant investment was required to produce radars with 1° beamwidths using 10-cm wavelengths. Each radar used a 8.5-m diameter antenna inside a 12-m radome, and cost approximately $5 million, requiring significant infrastructure, power, and maintenance. The benefit is that the network of WSR-88D radars can penetrate through many kilometers of intense rain and hail. Many other countries, researchers, and media have chosen lower cost, shorter wavelength options with the limitation of only moderate or poor penetration ability.

In certain specialized cases, other factors enter into the choice of wavelength, notably with mobile and airborne systems as will be discussed later.

Transmitter Type

Weather radars usually use one of two basic types of transmitter, magnetron or klystron, though some are designed with other mechanisms. Klystron transmitters are most expensive but produce very stable and coherent signals. Transmitted radiation varies very little in frequency and the phase of the radiation is synchronous from pulse to pulse. Until very recently, klystron radars were far superior in their ability to measure velocities since the phase of returned radiation is used in these calculations. Cheaper magnetron transmitters produce radiation that exhibits random phase from pulse to pulse, and the frequency drifts rapidly within a narrow band from second to second. In the past, many radars that did not attempt to measure precipitation motion (non-Doppler radars) used magnetron transmitters. Today, however, almost all

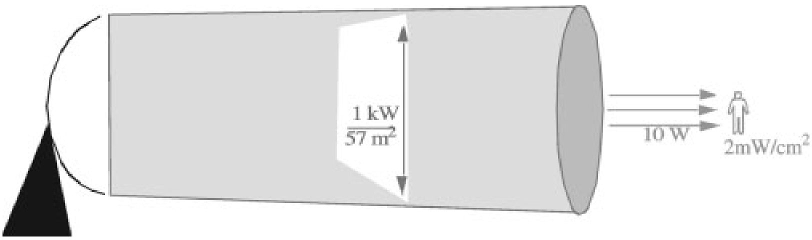


Figure 4 Intensity of microwaves emitted by typical weather radar. A person standing directly in front of a typical weather radar would absorb 10 W of microwave radiation with an exposure of $2\,\mathrm{mW/cm^2}$. See ftp site for color image.

weather radars in the United States, including magnetron systems, measure precipitation motion (Doppler) using modern hardware or software techniques.

A more intense transmitted beam results in more energy scattered back toward the radar, permitting the measurement of the properties of smaller or more tenuous weather targets. More intense beams also penetrate further into precipitation, despite attenuation. As with antenna and frequency choice, there are trade-offs involving transmitter strength. It costs more to construct high-intensity transmitters. It requires more power to transmit large amounts of energy. Also, intense electric fields can be hazardous and can complicate system design requiring pressurization of parts of the system with common or exotic gasses (SF_6) to prevent arcing. Transmitter strength is usually reported in terms of peak power, the power transmitted during the short pulses. Typical weather radars transmit pulses with 40 kW to 1 MW power. Some military systems use much more; some specialized research radars much less. Since the transmitter is off most of the time between pulses (e.g., on 1 μs, then off 999 μs, . . .), the average transmitted power is about 500 to 1000 times less, typically 100 W (like a light bulb) to 1 kW (like a hair drier). U.S. federal safety standards prohibit exposure to more than $10\,\mathrm{mW/cm^2}$ average power (other nations have similar standards, but with different levels of allowable exposure). If a person stood immediately in front of a WSR-88D 1000 W radar with a 8.5-m diameter antenna (area $57\,\mathrm{m^2}$), he or she would be exposed to approximately $2\,\mathrm{mW/cm^2}$, well below the safety limit (Fig. 4). The person (cross-sectional area about $0.5\,\mathrm{m^2}$) would intercept about 1% of the radar beam, or about 10 W total. The intensity at the center of the beam might be a couple of times higher. However, if one were to place a hand over the feedhorn (area $< 0.05\,\mathrm{m^2}$), much higher levels would be experienced.

Scattering

When the pulse of radiation impinges on raindrops in its path, scattering occurs. This is a complex electromagnetic process but, with some approximations, some simple statements can be made. When radiation interacts with a raindrop, it excites the water molecules in the drop. The molecules become electrically polarized. The radar beam causes this polarization to change orientation rapidly, at the radar frequency.

Thus, opposite sides of the drops become charged one way, then the next, billions of times per second. The drops become miniature antennas, analogous to the antenna of a walkie talkie, and radiate microwaves outward. Some of this radiation is radiated back toward the transmitting radar. (In drops that are similar in size to the transmitted radiation, e.g., hailstones, this process is considerably more complicated.)

The amount of radiation that a drop emits is proportional to D^6, the sixth power of the drop's diameter, so a 5-mm diameter drop radiates 15,000 times more than a 1-mm drop and 10^8 times more than a 50-μm cloud droplet. This complicates the interpretation of returned data since a single 5-mm drop returns as much energy as 15,000 1-mm drops, but the latter contain 125 times as much mass (Fig. 5). Therefore, it is difficult to know whether a particular strength of radar echo is due to a few large drops or a plethora of smaller ones. A particular amount of water mass scatters more microwaves if the water is contained in a few large drops. Raindrops are more efficient radiators than ice particles, scattering about 5 times as much than equivalent diameter ice particles. The D^6 approximation, called the Rayleigh approximation, applies only to drops that are much smaller than the radar wavelength. So, when short wavelength radars are used or when hail is present, more complicated formulations must be used.

Scattering can occur off other airborne objects, most notably insects and birds. Being mostly composed of water, these animals scatter in a fashion similar to raindrops of similar diameter. Importantly, however, they may not be passively moving with the wind. Bird echoes, moving at a different velocity than the air, can cause significant contamination to measured wind fields. Sometimes the military or researchers will release small strips of aluminized mylar or other objects into the air, called chaff. In the former case this is to confuse enemy radars, in the latter to provide passive scatterers carried by the wind in regions of little natural scattering. Scattering will occur where there is any contrast in the refractive index, usually caused by density changes, in the air. So, where turbulence is mixing cold and warm air parcels, or along precipitation-free dry lines or gust fronts, some energy is reflected back toward the radar by this process, called Bragg scattering. Researchers use these signals to observe the edges of clouds and other phenomena.

Scattering or reflections also occur when radar energy hits land, vegetation, or water surfaces. These echoes, called ground clutter or sea clutter, can be very intense and overwhelm the signals from the raindrops in the air near them. Often, clutter signals are filtered out by software that effectively blocks signals that have very low velocity and are presumed to originate from stationary objects. But this technique

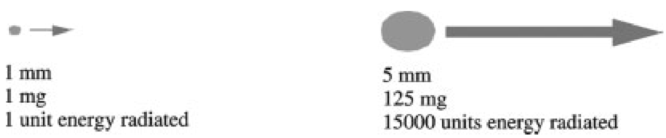


Figure 5 Relative diameter, mass, and scattered energy from small and large drops. Large drops scatter much more energy than small drops. See ftp site for color image.

does not work well with sea clutter contamination. Much of the clutter contamination arises from scattering from stray radiation that is not perfectly focused by the antenna into a narrow beam. This energy, called side-lobe radiation, hits objects in all directions and is scattered back to the radar. Since side-lobe energy scattered back by a very strong radar target, like a mountain or water tower, can be stronger than the weak signals scattered back by raindrops arriving back at the radar at the same time, this can cause significant contamination to weather radar data.

Propagation Paths

The narrow beam produced by a radar spreads with increasing distance from the radar. Even a 1° beam is 160 m wide at 10-km range and 1.6 km wide at 100-km range. At the maximum range measured by typical radars, 200 to 300 km, the beam may have spread to 3 to 5 km in extent. This critically affects the ability of the radar to detect weather, since objects smaller than the beamwidth cannot be resolved and only objects several times larger than a beamwidth can be accurately measured. Thus, microbursts and tornadoes are often difficult to detect at great range. Some very specialized research radars use extremely large antennas or short wavelengths to produce ultra-narrow beams, but this is not practical for most weather radar applications.

To a first approximation, radar beams travel in straight lines. Since Earth is curved, this means that a radar beam aimed at the horizon will soon become significantly raised from the surface and eventually depart into space (Fig. 6). This means that objects behind the horizon cannot be detected, preventing the resolution of near surface weather beyond a limited range. Fortunately, the atmosphere is more dense near the ground, resulting in an index of refraction gradient that bends radar beams partially back toward the curving surface of Earth, permitting some over-the-horizon visibility. The approximate height of the center of a beam aimed 0.5° above the ground, in "average" weather conditions, is 1.5 km at 100-km range and 3.5 km at 200-km range. The bottom of the beam would be approximately 400 m and 1.5 km above the ground at the same ranges.

Sometimes the gradient of atmospheric density is so high that it can bend the radar beams back into the earth. This can occur if very cold dense air lies near the surface. In this case, called anomalous propagation, energy will reflect off the ground or water surface, some back toward the radar.

Figure 6 (see color insert) Beam paths assuming straight propagation (red), typical atmospheric density gradient bending beam partially back toward Earth (blue), strong density gradient, possibly temperature inversion, bending beam back into Earth (green) where scattering off surface sends energy back toward radar. See ftp site for color image.

Data Processing

Once the transmitter generates a pulse, it is focused by the antenna, interacts with objects in its path, and scattered energy returns to the radar. The returned signal must be converted into useful meteorological data. This is accomplished by the radar receiver and signal processing system. This is one of the most complex, varied, and rapidly evolving areas of radar technology. The basic concepts are relatively straightforward, however.

Radar Gates Most radars digitize (sample) the received signals. The digitalization rate determines the gate size and is one determiner of the resolution of a radar. If the returned signals are digitized at a rate of 1 MHz, or every 1 μs, the gate size will be 150 m ($c\ \Delta t/2$). Faster sampling will result in shorter gates. However, sampling intervals less than the duration of a pulse of the radar have diminishing added utility since the length of the transmitted pulse effectively blurs the returned signals and is another determining factor in true radar resolution. Frequently, the pulse length and gate length are matched.

Reflectivity The amount of power that returns to the radar from any scattering volume (defined by the beamwidth and sampling interval) is dependent on the amount of energy that impinges on the volume, the nature, number, size, shape, and arrangement of the scattering particles, radar wavelength, and distance to the weather target, attenuation, and other factors. These are related through the radar equation, which appears in many forms, but can be simplified to $P_r = CZ_e/R^2$, where P_r is the returned power, C is called the radar constant and contains all information about the transmitter, pulse length, antenna, wavelength, etc., R is the distance to the target, and Z_e is equivalent radar reflectivity factor, more commonly referred to as Z, or reflectivity. Z is a rather strange parameter; it has units of volume (mm^6/m^3) and it is usually expressed in terms of 10 times its base 10 logarithm, or $\text{dB}Z = 10 \log_{10} Z$. The amount of Z that would be measured from a raindrop is proportional to D^6, the sixth power of the drop diameter. The Z measured from a volume of drops is thus $\Sigma N_i D^6$, where N_i is the number of drops of each diameter in the volume. Because large drops are much more effective radiators, a certain value of Z can be due to a very small number of large particles or a large number of small particles; it is impossible to tell which by using Z alone.

It is difficult to precisely relate Z values to meteorologically useful quantities like liquid water content or rain rate. This is because it is dependent on the sum of the sixth power of raindrop sizes, not the sum of the masses of the raindrops. Numerous theoretical and empirical relationships, called Z–R relationships, exist to convert between Z, rain rate (R) and other quantities. Very roughly, 15 dBZ corresponds to light rain, 30 dBZ to moderate rain of several mm/h, 45 to 50 dBZ to 50 mm/h, 50 to 57 dBZ to 100 mm/h, and higher dBZ levels, 55 to 70, to hail or rain/hail mixes.

Typically Z is averaged over many pulses, 32 to 256, since it can vary greatly due to constructive and destructive interference from the radiation emitted from each drop in the illuminated volume. It is necessary to obtain several “independent” measurements to calculate an accurate value of Z. Independence means that the particles in the illuminated volume have reshuffled so that their arrangement is effectively decorrelated with their arrangement during the passage of the previous pulse. It can require a time spacing of several pulses before independence occurs, so the measurement of Z cannot take full advantage of all the 32 to 256 pulses mentioned above. The time to independence is shortest when there is high turbulence and/or short (i.e., X-band) transmissions. It is very difficult to calculate the radar constant, C, accurately, and the measurement of Z is prone to errors of approximately ± 2 dB. This can be very significant since small changes of Z can result in large differences in predicted R, particularly at high Z and R, where one cares the most.

The minimum power that a typical weather radar can measure is about 10^{-14} W, which corresponds to about -5 dBZ at a range of 50 km. This depends on the wavelength, antenna, quality of electronics, pulse length, number of pulses per average, etc. Though rarely an issue except in very close range research applications, there is a maximum power that can be detected before radar hardware/software saturates and is effectively blinded. This is seldom realized except in heavy rain within a few kilometers of a radar.

Doppler Velocity Most weather radars can measure the component of scatterer motion toward or away from the radar. While these radars are usually called Doppler, most do not directly use the Doppler effect to measure this motion. Typically the radar measures the path length to a raindrop (actually the sum of the path lengths to a volume of raindrops) during subsequent pulses (actually the remainder, noninteger portion) to calculate the motion (Fig. 7). The most common calculation technique is called pulse-pair processing, whereby the phase of the returned energy from each pulse is measured. Another technique called spectral processing, or Fourier processing, can be used also. While an acceptable velocity measurement can be made using just two pulses (in stark contrast to the several independent measurements needed to get an accurate Z measurement), typically many pulses are averaged to reduce error.

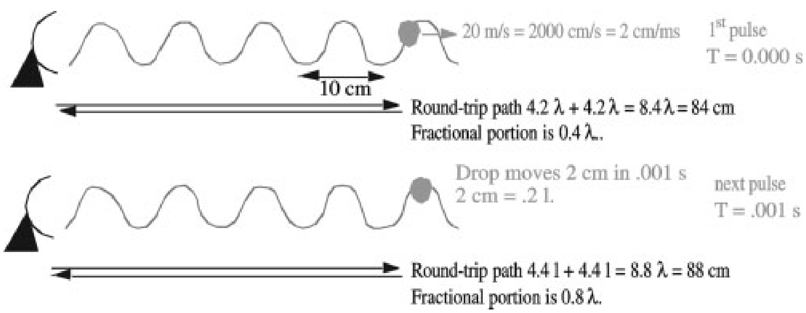


Figure 7 Illustration of pathlength changes used to calculate toward/away component of velocity. Signal processing is able to measure the fractional portion of the pathlength change. In reality, this calculation is performed on the energy scattered by many raindrops. See ftp site for color image.

The calculation is conceptually simple when the energy from just one raindrop is considered. However, typical radar volumes contain many raindrops, each moving with the wind, but with some random component, each radiating an amount of energy proportional to D^6, interfering constructively and destructively. If a radar beam is pointed horizontally, it is usually assumed that the drops are moving with the wind, $V_d = V_a$. But, if the radar beam is inclined, the terminal velocity of the drop will enter into the measurement: $V_d = V_a + V_t \sin\theta$. Estimation of V_t is difficult, and must take into account that V_d is the D^6 weighted average. Typically, it is assumed that V_t is a function of Z and atmospheric density, and is about 8 m/s in heavy rain near sea level.

A critical limitation of single radar "wind" measurements is that they can only detect the wind component toward and away from the radar (the radial wind) of the three-dimensional wind field. Even very strong cross-beam wind components cannot be detected with a single normal weather radar (see multiple Doppler and bistatic sections below).

Spectral Width In addition to the radial wind, averaged over many pulses, many radars also calculate the spectral width, which is just the standard deviation of the individual pulse-to-pulse wind measurements or frequency domain calculations. The drops in a radar volume can exhibit different motions for several reasons. They may have different terminal velocities as just discussed. They may be embedded in sub-resolution-volume-scale turbulence. The resolution volume may span a large-scale meteorological feature like a front or mesocyclone, so different portions of the beam illuminate different portions of the phenomena containing different characteristic velocities. There is also always some measurement error.

Range Ambiguity Once a pulse is transmitted from a radar, it will continue indefinitely until it is totally consumed by reflection, absorption, or scattering. Elevated radar beams quickly pass above the troposphere into regions where there are few scatterers other than the moon and planets. But, beams that are oriented almost horizontally can remain in the troposphere for hundreds of kilometers. However, the useful range of a radar is frequently limited by what is called the ambiguous range. The ambiguous range is determined by the maximum range to which a pulse can travel and return before the next pulse is sent. If the pulse repetition time (PRT) is 1 ms, then this range is 150 km. It takes 1 ms for the pulse to travel to 150 km, scatter off raindrops at that range, and return to the radar. Energy emitted by raindrops beyond that range will reach the radar after the next pulse is sent. The radar has no simple way of knowing whether this energy originated from raindrops illuminated by the first pulse beyond 150 km or by the second pulse just a short distance from the radar (Fig. 8). Since the energy returning from both pulses is superimposed, the data is contaminated. The amount of energy that is returned by the raindrop at great range is reduced significantly due to distance ($P_r \sim 1/R^2$), but if the distant weather system is intense, and the nearby weather weak, the data from the nearby weather can be obscured.

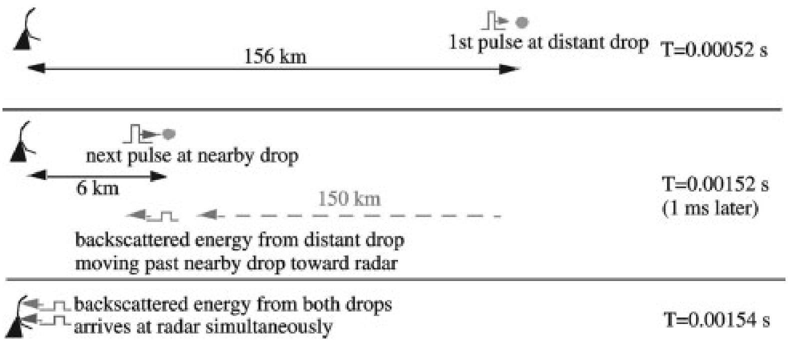


Figure 8 Illustration of range ambiguity phenomena. Energy scattered back from raindrops at 156-km range arrives at the radar simultaneously with energy from the next transmitted pulse scattered back from raindrops at 6-km range. See ftp site for color image.

The ambiguous range can be increased by slowing the PRT. This is frequently done to measure storms at great range. A PRT of 2 ms increases the range to 300 km. But this may complicate velocity processing as discussed in the next section. Newer techniques include the addition of phase offsets to the transmitted pulses so that the true range to the scatterers can be retrieved.

So-called second-trip echoes can be detected by trained observers since they have elongated and unrealistic shapes. In the case of random phase magnetron radars, the Doppler velocities in the second-trip echoes will be incoherent, not smoothly varying as in correctly ranged echoes.

Velocity Ambiguity: The Nyquist Interval For a given transmitted wavelength and PRT, there is a maximum velocity that can be ambiguously measured. This is because Doppler radars do not actually measure the Doppler shift of returned radiation. Referring back to Figure 7, the fractional portion of the path length from radar to target back to the radar is measured. It is usually assumed that this path length changes by less than one full wavelength during the PRT. But, this may not be so. Consider a 10-cm radar with a PRT of 1 ms. If a raindrop is embedded in a strong wind, say 40 m/s away from the radar, then it will move 4 cm during the PRT. This means that the round-trip path length will increase by 8 cm, say from 10^9 to $10^9 + 0.8$ wavelengths. Ambiguity arises because it is difficult to distinguish between a 8 cm increase in path length and a 2-cm decrease since each will result in the same fractional portion difference, namely 0.8 wavelengths [i.e., $\mathrm{frac}(10^9 + 0.8) = \mathrm{frac}(10^9 - 0.2) = 0.8$]. The Nyquist interval is the range of velocities that will produce path length changes between $\pm\frac{1}{2}$ wavelength and can be calculated as Nyquist Interval $= \pm\lambda/(4\ \mathrm{PRT})$. Thus, in the above case, the Nyquist interval would be $0.1\ \mathrm{m}/(4 \times 0.001) = \pm 25\ \mathrm{m/s}$.

The Nyquist interval can be increased by decreasing the PRT, essentially giving the raindrops less time to change the round-trip path length. Note, however, that this would increase data contamination from storms beyond the now shortened ambiguous range. There is a trade-off between maximizing Nyquist interval and maximizing ambiguous range. Some research radars use techniques called dual PRT or staggered PRT whereby alternating (or other patterns) of long and short PRTs are used to gain a least-common-multiple effect and much larger effective Nyquist intervals.

Data from regions exhibiting velocities greater in magnitude than the ambiguous velocity are considered to be folded or aliased and need to be corrected, or unfolded, or dealiased, to produce correct values (Fig. 9). This can be a difficult process and can be conducted either automatically or manually.

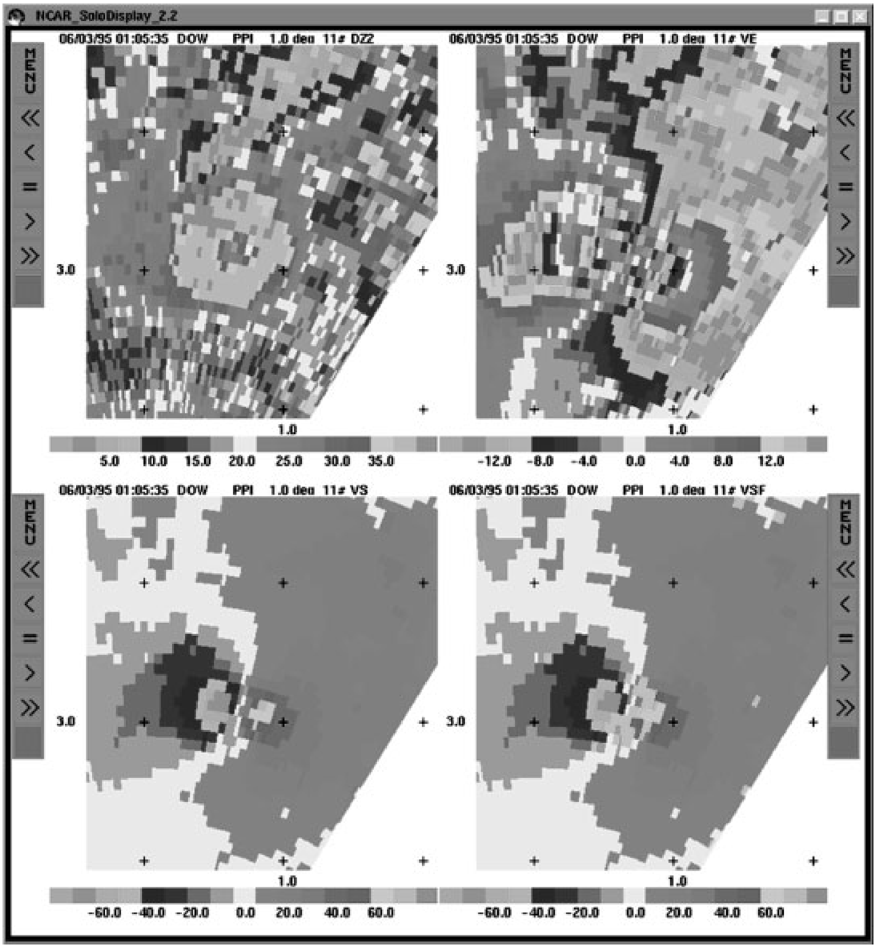


Figure 9 (see color insert) Illustration of dealiasing and cleaning of radar data. (*Top left*) Reflectivity in tornado showing ring debris. (*Top right*) Raw Doppler velocity with aliasing. (*Bottom left*) Velocity after dealiasing. Strong away and strong toward velocities adjacent to each other imply rotation, in this case over 70 m/s. (*Bottom right*) Velocity after values with high spectral width or contaminated by echoes from the ground (ground clutter) have been removed. Data is from DOW mobile radar in the Dimmitt, Texas, Tornado on June 2, 1995, from a range of 3 km. See ftp site for color image.

Scanning Techniques and Displays Most radars scan the sky in a very similar way most of the time. They point the antenna just above the horizon, say 0.5° in elevation, then scan horizontally (in azimuth), until 360° is covered. Then the radar is moved to a higher elevation, say 1.0° or 1.5°, and the process is repeated. This continues for several to many scans. Using this method, several coaxial cones of data are collected. These can be loaded (interpolated) onto three-dimensional grids or displayed as is to observe the low and mid/high levels of the atmosphere. There are infinite variations on this theme, including interleaving scans, fast and slow scans, repeated scans at different PRTs, scanning less than 360° sectors, etc. When a single scan is displayed, it is usually called a plan position indicator (PPI).

Sometimes, mostly during research applications, a radar will keep azimuthal angle constant and move in elevation, taking a vertical cross section through the atmosphere. These can be very useful when observing the vertical structure of thunderstorms, the melting layer, the boundary layer, and other phenomena. These types of scans are called range height indicators (RHI).

Since PPI scans have a polar, conical, geometry, lower near the radar and higher as the beams travel outward, it is often useful to use a computer to load the data from several scans into a Cartesian grid and display data from several different scans as they pass through a roughly constant altitude above Earth's surface, say 1 or 5 km above ground level (agl). These reconstructions are called constant altitude plan position indicators (CAPPIs). Since the data at a given altitude can originate from several scans, there can be ringlike interpolation artifacts in these displays.

Scanning strategy strongly influences the nature of the collected data. Operational radars typically scan fairly slowly through 360°, using many scans, requiring about 5 to 6 min for each rotation. This provides excellent overall coverage, but can miss the rapidly evolving weather such as tornadoes and microbursts. In specialized research applications, much more rapid scanning, through limited regions of the sky, is often employed.

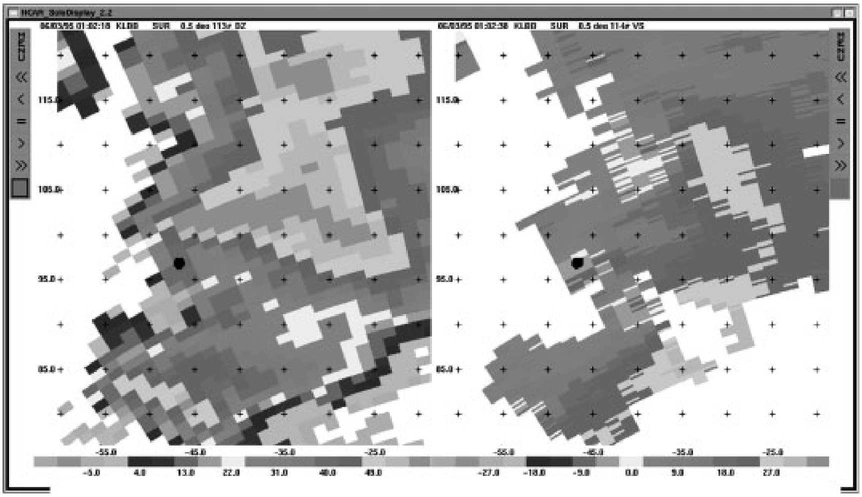
New radar technology is being developed that may someday permit very rapid scanning of the entire sky as discussed below.

3 RADAR OBSERVATIONS OF SELECTED PHENOMENA

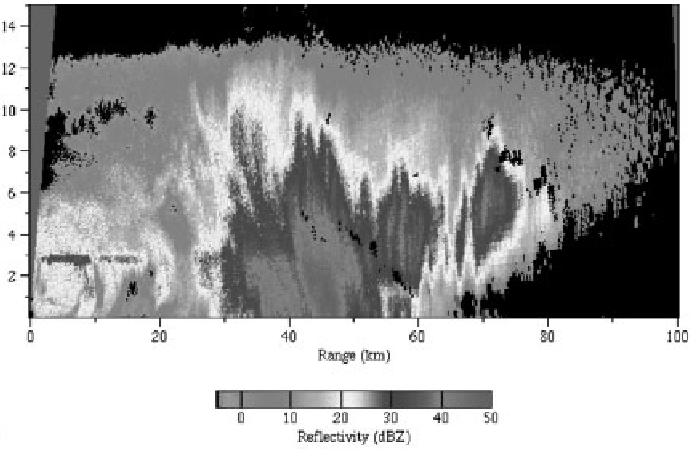
There are literally thousands of examples of weather phenomena observed by weather radars. Only a few will be illustrated here in Figure 10 to show some the range of phenomena that can be observed and the typical nature of the data. The interpretation of the data from weather radar is a complete study unto itself and could occupy far more space than is appropriate in this short overview.

4 GOAL: TRUE WIND VECTORS

Radial velocities provide much qualitative information about weather phenomena. However, the true wind field is a three-dimensional wind field comprised of three-

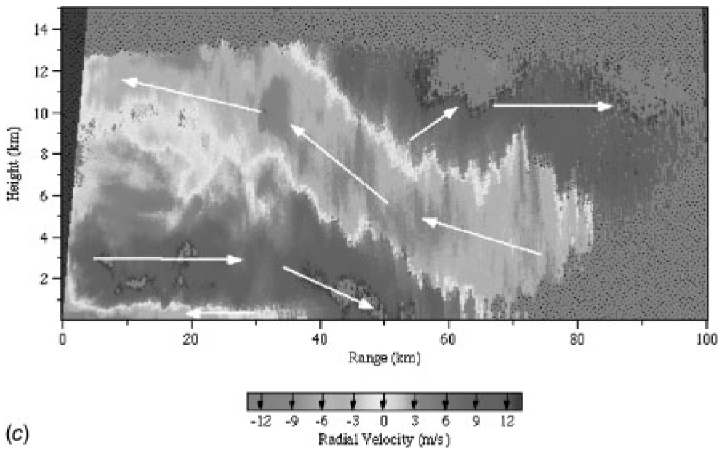


(*a*)



(*b*)

Figure 10 (see color insert) (*a*) A tornadic supercell thunderstorm observed by a WSR-88D operational radar. Reflectivity (*left*) and Doppler velocity (*right*) are shown. Classic hook echo extends from the western side of the supercell. An intense circulation, suggested by the strong away and toward velocities near the hook, is the mesocyclone associated with a tornado that was occurring. (*b, c*) Reflectivity and Doppler velocity in a vertical cross section (RHI) through a portion of a squall line. The high reflectivity core and lower reflectivity extending to 12 km are visible. Strong toward and away Doppler velocities are associated with the up and down drafts of the cell, as indicated by arrows. Data from the MIT radar in Albuqurque, New Mexico. (Courtesy of MIT Wea. Rad. Lab. D. Boccippio.) (*d*) Reflectivity (*lower*) and Doppler velocity (*upper*) in a winter storm. Reflectivity is somewhat amorphous but is enhanced in a ring corresponding to the melting layer. In the melting layer, large, wet slow-moving particles cause high reflectivity. The velocity pattern provides a vertical sounding of the atmosphere. Winds are from the NNW at low levels (near the radar), but from the southwest aloft (away from the radar as the beams diverge from Earth's surface). Cold advection is implied. Data from the MIT radar in Cambridge, Massachusetts. (Courtesy of MIT Wea. Rad. Lab. D. Boccippio.) See ftp site for color image.



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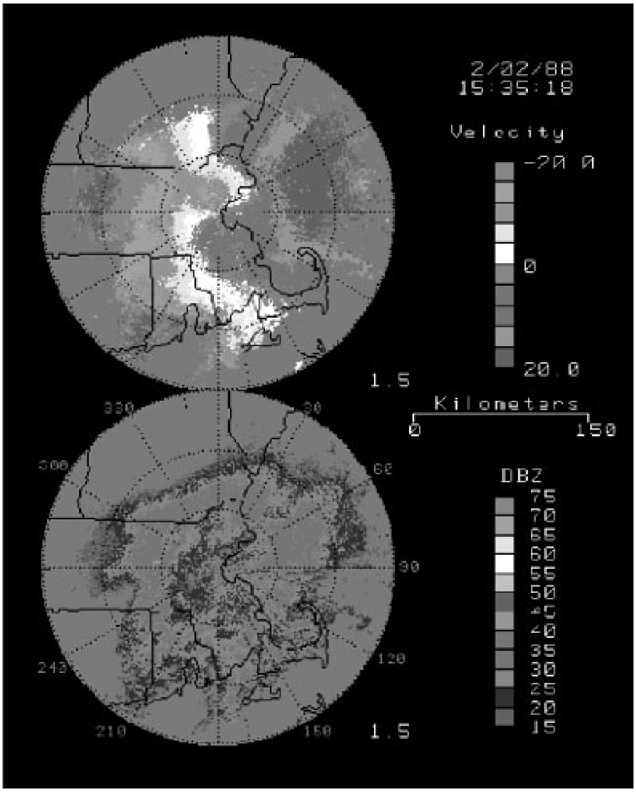

(*d*)

Figure 10 (*continued*)

dimensional vectors, evolving in time. Physical equations used in research and in forecasting models operate on these vector wind fields, which really contain the physics of the phenomena. So there is great value in estimating or measuring the full vector wind field and several techniques have been developed.

Single-Doppler Retrievals

One class of techniques for obtaining the vector wind field is called single-Doppler wind field retrievals. These techniques use various physical assumptions to convert data from a single radar into vector wind fields. One simple method assumes that the reflectivity field is a passive tracer that moves with the wind. In simple terms the Z field is examined at different times, and the wind field necessary to move the Z features from one place to another is calculated. Of course, evolving systems complicate these analyses. Another assumes that the wind field is composed of certain simple mathematical components. These are extensions of what radar meteorologists do visually when they look at the zero line of the Doppler velocity and assume that the wind is moving perpendicularly to it. Several sophisticated and combination methods are in development.

These techniques are very useful since they work with just one radar, but they are limited by the validity of the physical assumptions. Some also only work in cases of high reflectivity or velocity gradients, others only when precipitation covers much of the surveyed volume.

Currently, these techniques are being developed in the research environment, but it is hoped that they will be used to introduce wind fields into operational computer forecasting models in the future.

Dual and Multiple Doppler

In some research experiments, two or more radars can be deployed. Each radar can survey a target region from a different vantage point. A simple mathematical calculation can convert the two or more Doppler velocity measurements into a wind vector (Fig. 11). This technique is very powerful and has been a favorite of research meteorologists. It is not used frequently in operational forecasting because few permanent radars are close enough for dual-Doppler calculations to be useful. The large spacing of the U.S. WSR-88D network makes dual-Doppler calculations, while possible, not very useful due to the large beamwidths at the typical 200-km ranges to weather targets.

Typically, but not always, the horizontal components of the vector wind are calculated directly from the radar measurements. The vertical component is calculated by integrating the equation of mass conservation. Essentially, this says that if there is strong divergence in the boundary layer as in, say, a microburst, the air must have come from above, implying downward vertical motion (Fig. 12). Strong convergence near the ground implies an updraft. Similarly, strong divergence at storm top indicates an updraft from below, etc. Unfortunately, the vertical motions calculated in this manner result from the integration of quantities that are derivatives

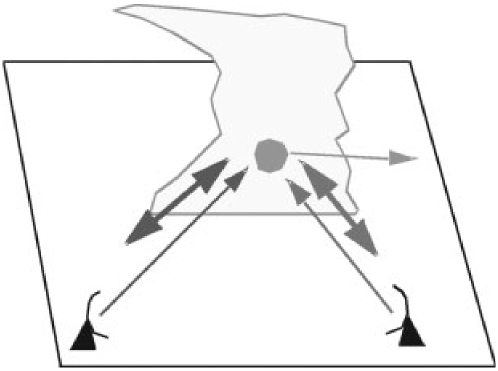

Figure 11 Dual-Doppler network with radars measuring motion of raindrops from different vantage points. The different Doppler radial winds (red and green) are combined mathematically to produce the horizontal projection of the true raindrop motion vector (blue). See ftp site for color image.

of actual measurements. Both the integration and differential processes are prone to errors. The resultant vertical wind estimates can be substantially incorrect. Accurate determination of vertical motions from radar data is probably the largest unsolved problem in radar meteorology today. An example of a dual-Doppler reconstruction of the vector wind field near and in a tornado is shown in Figure 13.

Rarely, three or more radars are in close enough proximity that the vertical component of the raindrop motion vector can be calculated directly. This method is called triple-Doppler and is exclusively a research technique.

There are two major limitations to multiple-Doppler techniques. The first is that radars are very expensive. Multiple-Doppler data is only affordable in a small frac-

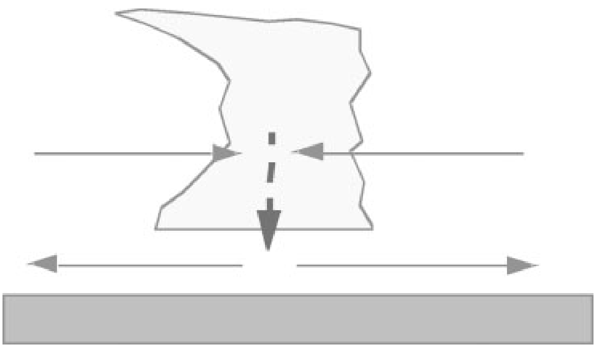

Figure 12 Since the vertical component of motion is rarely measured directly, the equation of mass continuity is usually used (sometimes in very complex formulations) to derive the vertical component of air motion. The physics of the method is very straightforward. If divergence is observed at low levels (*right*), then air must be coming from above to replace the departing air, implying a downdraft. See ftp site for color image.

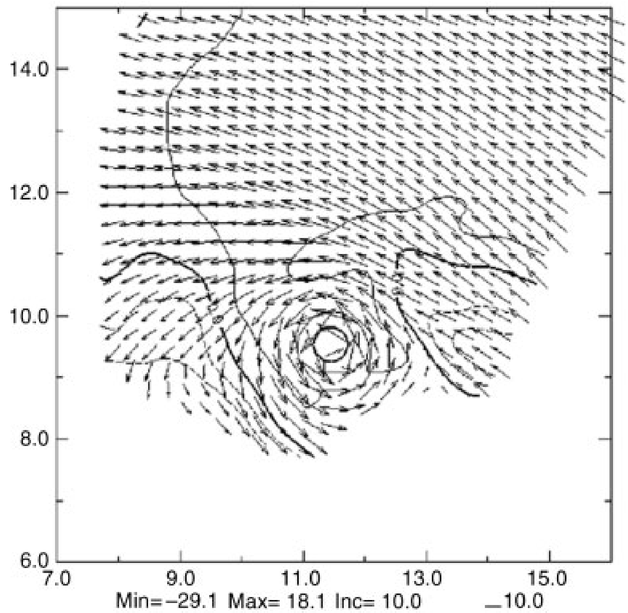

Figure 13 Dual-Doppler analysis showing horizontal component of the vector wind field in a tornado. Contours are Z with the small circle representing the low Z "eye" of the tornado. The axes are labeled in kilometers. Peak winds are about 60 m/s. (Courtesy Y. Richardson.)

tion of short-term research experiments and rarely in operational applications. The second is that the observations of weather targets by the different radars may occur at different times, sometimes a few minutes apart. Rapid evolution of some of the most interesting phenomena between these observations will contaminate the calculated vector wind fields.

A common expression among multiple-Doppler users is "you always get a vector," meaning that the technique always produces a result, but the result can be quite bogus. Multiple-Doppler and single-Doppler reconstructions should always be viewed with a sceptical eye.

Bistatic Radars

When the transmitted radar beam interacts with raindrops, only some of the reemitted energy travels back toward the transmitter. Most is scattered in other directions. The bistatic radar technique involves placing small passive radar receivers (Fig. 14) at various places to measure this stray radiation. The data from the bistatic receivers is combined with that from the transmitter using a variation on standard multiple-Doppler formulations.

The biggest advantage of the bistatic technique is the comparatively low cost of the bistatic receivers, less than 10% that of a WSR-88D. Several to many receivers

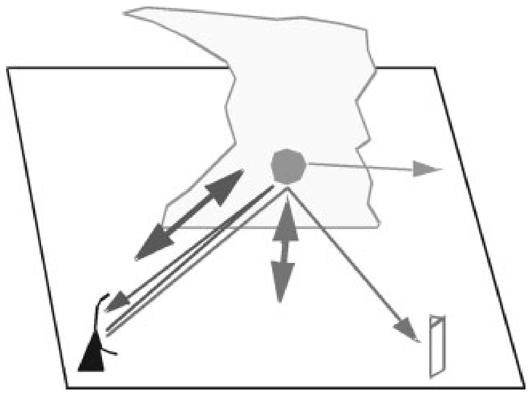

Figure 14 Bistatic dual-Doppler network with receive-only radar (red) measuring a different component (red arrow) of the raindrop motion vector (blue arrow) than the transmitter (green arrow). The components are combined mathematically in a fashion similar to that used in traditional dual-Doppler radar networks to calculate the horizontal projection of the raindrop motion vector (blue arrow). See ftp site for color image.

can result in more accurate data at a low cost. Another advantage is that the observations of individual weather targets are made simultaneously since there is only one source of radar illumination. Rapidly evolving weather can be well resolved. Thus two of the major limitations of traditional dual-Doppler networks are avoided.

Currently there are several research bistatic networks. Data from one are illustrated in Figure 15. It is anticipated that operational networks and operational computerized forecast models will use bistatic data in the future.

5 DATA ASSIMILATION INTO COMPUTER MODELS

Computerized weather forecasting models require accurate initializations to produce meaningful predictions. A major thrust of current modeling research involves how to best introduce radar data into these initializations, particularly into mesoscale simulations. Some models have successfully ingested both reflectivity and single-Doppler-retrieved wind fields, but none are yet used operationally.

6 NEW AND NONCONVENTIONAL TECHNOLOGIES

Dual and Multiple Polarization Radars

Most radars emit microwaves with just one polarization. This means that when they cause charge to move in raindrops as discussed above, the charge moves one direction then the opposite (say left, then right), but the charge distributions in other directions (say up and down) are largely unaffected. The intensity of microwaves

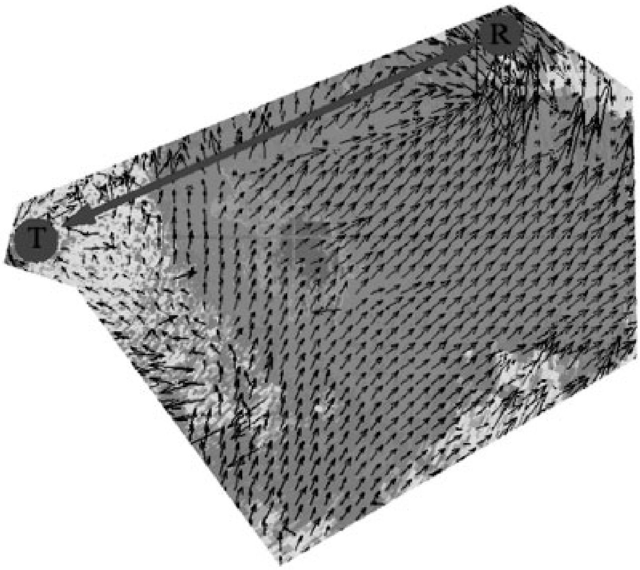

Figure 15 Bistatic dual-Doppler horizontal wind field. The transmitter (T) and passive, receive-only radar (R) are located 35 km distant. *Z* field is shaded. Data from NCAR CASES experiment in Kansas in 1997. See ftp site for color image.

emitted by a drop is proportional to D^6. But, large raindrops are hamburger bun shaped, ice particles have many shapes, and hail and insects can be very irregular. The intensity of the emitted microwaves is proportional to the D^6 in the direction of polarization of the radar.

It is possible to obtain information about the shape of the rain or ice particles by transmitting both horizontally and vertically polarized radiation. (There are other exotic techniques too, like using circularly polarized radiation, or radiation polarized at intermediate values between *H* and *V*.) If the beam hits a large hamburger-shaped drop, more horizontal energy will return than vertical energy (Fig. 16). The sixth power dependence means that small differences in D_h and D_v can cause large

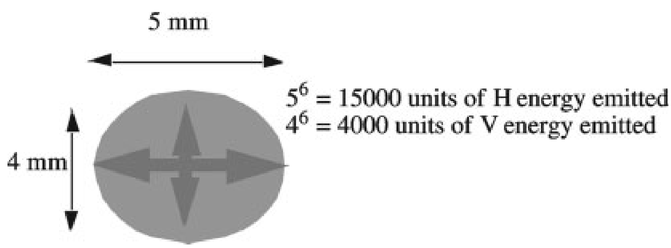

Figure 16 Oblate, hamburger-shaped raindrops scatter much more horizontally polarized energy than vertically polarized energy. See ftp site for color image.

differences in the emitted energy. This difference is called ZDR and can be as much as several decibels. Even though hailstones are often very irregular, they tumble randomly and the sum of the ZDR returns from thousands of hailstones is very close to zero (Fig. 17). Ice particles, however, can exhibit preferred orientations just like raindrops, and can produce ZDR. A good rule of thumb is that high Z with high ZDR = heavy rain while high Z with low ZDR = hail.

New techniques are in development to make use of other measurements possible with multiple polarization radars, such as the linear depolarization ratio (LDR), which measures how much radiation from the horizontal beam is reemitted from drops with vertical polarization, and specific differential phase, Φ_{dp}, which measures the differences in the phase of the horizontally and vertically polarized returned energy. Some of these hold promise to refine the identification of particle types (rain, hail, large hail, ice, etc.) and rain rate. Φ_{dp} holds particular promise since changes in Φ_{dp} are thought to be proportional to D^3, the volume of water in a resolution volume, and therefore more directly related to rain rate than Z. LDR is a very difficult measurement that requires a very precisely manufactured, therefore expensive, antenna.

Polarization radars are now primarily used in research but will probably be used operationally by forecasters in coming decades.

Mobile Radars

No matter which choices are made for radar wavelength and antenna size, the radar beam will always spread out with distance. Few radars have beams that are much narrower than 1°. This means that at 60-km range the beams are 1 km wide, and at 120 km they are 2 km wide, much too large to resolve small phenomena such as tornadoes, microbursts, etc. The best solution found to this problem so far has been

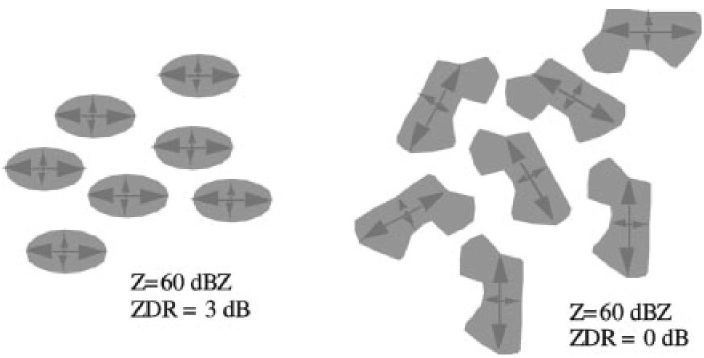

Figure 17 Large raindrops (*left*) are oriented similarly, so the ZDR effect from individual drops adds constructively to produce large ZDR values. Hailstones (*right*) tumble and are therefore oriented randomly so individual ZDR values tend to cancel out producing ZDR = 0. See ftp site for color image.

to put the radars on vehicles: ground based, in the air, and on the ocean. The vehicles are then deployed near the weather to be measured.

These systems tend to be very specialized and, with the exception of the hurricane hunter aircraft, are used mostly for research. Their mobile nature makes design and operation difficult.

Ground-Based Mobile Radars A leading example of the mobile radar concept is the Doppler On Wheels (DOW) research radars (Fig. 18). These radars have obtained unprecedented high-resolution three-dimensional data in tornadoes, hurricane boundary layers, etc., at scales as small as 3 to 60 m. Typically two or more DOWs are deployed in a mobile multiple-Doppler network to retrieve high-resolution vector wind fields. The DOWs use 3-cm radiation and 2.44-m antennas to produce 0.93° beam widths, which are comparable to the WSR-88Ds (but 3-cm radiation suffers more from attenuation in heavy precipitation). Fast scanning and very short pulses and gate lengths are combined for fine spatial and temporal scale observations. Other mobile radars using energy with wavelengths ranging from 3 mm to 10 cm have also been used by researchers to study similar phenomena.

None are currently in use for forecasting. But the idea of using DOW-type radars to augment the stationary radar network, part of a concept called adaptive observations, is being explored. In the future, forecasters who need information in specific areas, say a hurricane landfall, severe weather outbreak, flood, or the Olympics, may be able to request high-resolution tailored multiple-Doppler radar measurements.

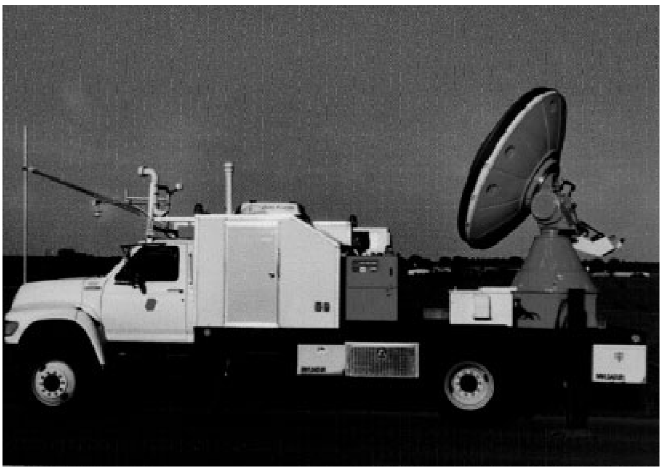

Figure 18 DOW2 mobile radar. The DOW2 uses a 2.44-m antenna transmitting 3-cm radiation with a 0.93° beam. It is used to intercept tornadoes, hurricanes, and is deployed in mountain valleys or wherever an easily movable system is needed. See ftp site for color image.

Airborne and Ship-Based Radars Since many areas are inaccessible to DOW-type trucks, particularly oceanic areas that cover 70% of Earth including hurricane spawning grounds, and because trucks are limited to highways speeds of 30 m/s, limiting deployment ranges, researchers and operational meteorologists use radars mounted on aircraft (Fig. 19) and ships to get closer to the weather of interest. These aircraft regularly fly into hurricanes before they make landfall to aid in predictions. They have been used to study meteorology as diverse as tornadoes in the Midwest and tropical climates in the western Pacific.

Bistatic Radar Networks

These collect stray radiation emitted in many directions by raindrops to measure vector wind fields and were discussed above.

Rapid Scan Radars

Military radars have long been able to move their beams electronically rather than having to mechanically move an antenna. Since the beam can be moved almost instantaneously, these hold the promise of extremely rapid scanning of weather. Instead of requiring 6 min to survey the entire sky, it might be sampled in only 10 to 30 s. A type of antenna called a phased array is used. Very few exist outside military applications, in part due to the high cost of construction. There are efforts being made to adapt this military technology to meteorological use.

A new type of rapid scan radar is under development and holds promise as a research and operational tool primarily due to its low cost, compared to phased array systems. These radars transmit multiple frequencies from an unusual antenna designed to split the various frequencies into simultaneous multiple beams (Fig. 20).

Figure 19 ELDORA airborne radar can be deployed quickly to almost any point in the world, even over oceans. It has a sophisticated radar in the protuberance extending beyond the normal tail. Similar systems are used operationally to intercept hurricanes. (Courtesy NCAR/ATD.) See ftp site for color image.

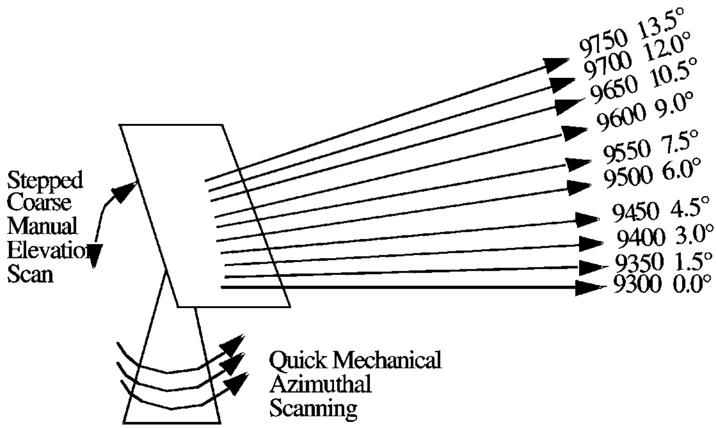

Figure 20 A flat panel, slotted waveguide array with 100 individual slotted waveguide antennas produces beams that emanate at different elevation angles depending on the frequency of the transmitted radiation. Therefore, nearly simultaneous transmissions at multiple frequencies, can be simultaneously received from several elevation angles at once. Ten or more elevation angles can be surveyed in ~10 s, providing truly rapid scanning with a nonphased array system.

Figure 21 NCAR ISS in Kapingamarangi, Pohnpei State, Federated States of Micronesia. A wind profiler antenna is pointed vertically and shrouded by a clutter fence visible on top of the shelter. Aluminum cylinders shield a portion of a RASS radio acoustic sounding system. See ftp site for color image.

A single mechanical sweep of this antenna produces multiple beams, as many as 10 or more, permitting a typical volumetric scan to occur in just 2 sweeps, in as little as 10 s.

Wind Profilers

There is another class of radars called wind profilers that usually point vertically, do not scan, and sample vertical cross sections of wind and temperature. The principles of operation share some similarities to conventional weather radars, but there are substantial differences. They usually collect just one vertical sounding, averaged over about 30 min. Many can collect wind velocity data in clear air, in the absence of precipitation, through substantial depths of the lower troposphere. There is a network of profilers in the Midwest that augments the balloon sounding network by providing half hourly measurements at intermediate locations. Data from wind profilers is valuable for the forecasting of severe weather outbreaks in the Midwest. Deployable wind profilers are used by researchers to provide vertical soundings of wind between balloon launches (Fig. 21). An instrument called a RASS, or radio acoustic sounding system, uses an ingenious method whereby emitted sound waves disturb the atmosphere in a manner that can be measured by the profiler radar to measure the temperature of the atmosphere in the vertical column.