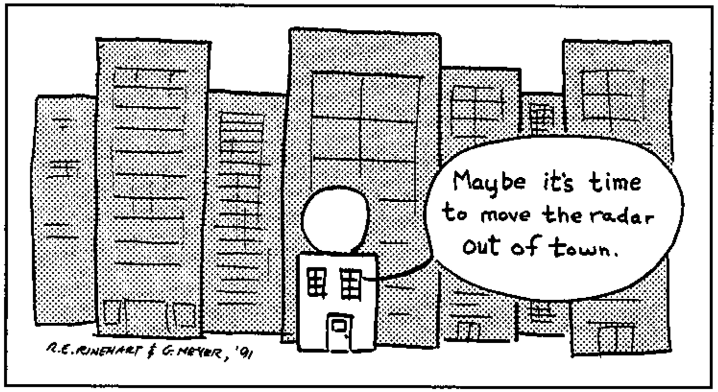
Weather radars:

Last, but certainly not least, we have weather radar, the subject of this book. There are many different kinds of weather radars in use today. Weather radars come in a variety of shapes and sizes, from X-, K- and W-band radars used as mobile radars and at other locations, to the 178 WSR-88D (NEXRAD) S-band radars used by the National Weather Service, the FAA and the Department of Defense. Most modern weather radars have Doppler capability. A few have the ability to change polarization. And some combine those capabilities with still more sophisticated capabilities. We will discuss weather radar and the various flavors they come in throughout this text, so we can conclude this introduction by simply saying that weather radars are one of the most important weather tools in use today.



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[3] Archie Trammell, AJT, Inc., gives a series of seminars on the use of radar onboard aircraft. In one of his presentations he related the story of the ultimate, ideal, ultra safe aircraft. In his story, the pilot and copilot are flying along. The copilot turns to the pilot and says, "Sir, we're having a problem with the number ten engine." The pilot asks the copilot, "Is that on the right side or left side?" Maybe we could add a 28-ft diameter S-band radar antenna to such an aircraft to make it even safer!

Radar Hardware

A complete radar system consists of several subsystems. Each of these, in turn, consists of many components and even smaller subsystems. It is beyond the scope of this text to describe in detail all the inner workings of a radar. Manufacturers usually provide complete sets of schematic diagrams, operating manuals, theory of operation, and other references that can be consulted for all the nitty-gritty details on a specific radar. Even if you are not a radar engineer, it would be worth spending some time examining these manuals because they contain a wealth of information on the capabilities and limitations of the radar you may be using. If you are a user of radar data and have no direct access to the radar itself, you should still be aware that these manuals exist. Manufacturers put a lot of effort into writing them. They are an excellent reference to learn more about how a specific radar operates. Sometimes information on a radar is also available on the Internet, so you might even look there.

For our purposes, we only need to consider the main components, those that are found on all weather radars. Figure 2.1 shows a very simple block diagram of a radar. Let's examine each of these components in a little more detail.

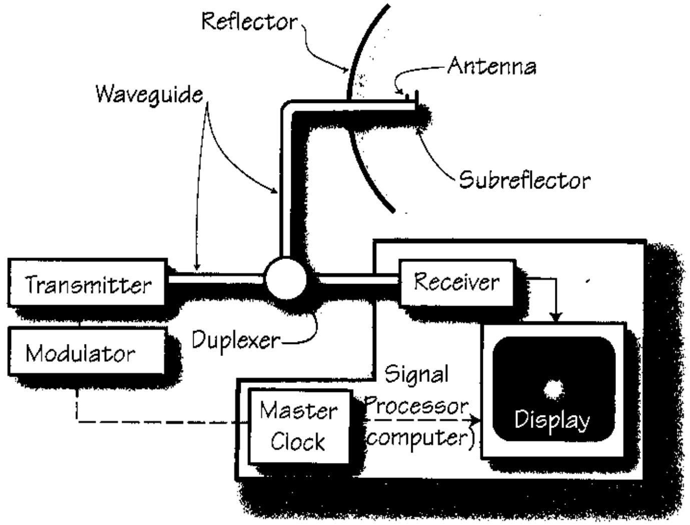

Figure 2.1 Block diagram of a simple radar

Transmitter

The source of the electromagnetic radiation emitted by a radar is the transmitter. It generates the high frequency signal which leaves the radar's antenna and goes out into the atmosphere. There are several kinds of transmitters used in modern radars, each of which has its own advantages and disadvantages. The three most important kinds for meteorological radars are the magnetron, the klystron, and solid-state transmitters. Each of these can be designed to optimize particular characteristics.

Magnetron: The magnetron tube for generating microwaves was invented by John Randall and Henry Boot in November 1939 (Buderi, 1996). Randall and Boot were working on the development of radar for the British during World War II. Magnetrons proved to be one of the most important developments of radar for the war. Their small size and high power output made them ideal for airborne use. Magnetron transmitters are now used at a variety of radar frequencies and can generate transmitted signals in excess of 1 MW.

Figure 2.2 is a sketch of the cross section of a magnetron, showing the various main components. The number of cavities depends upon a number of factors. When the British brought a magnetron to the United States early in WW II, they brought one that had eight cavities whereas most others they used had six. Consequently, during the war, magnetrons built by the Americans had eight cavities. Magnetrons used today typically have more than six or eight cavities [a magnetron I cut in half to show radar students had 12].

Klystron transmitters have several advantages over magnetron transmitters. Klystrons, while they are usually

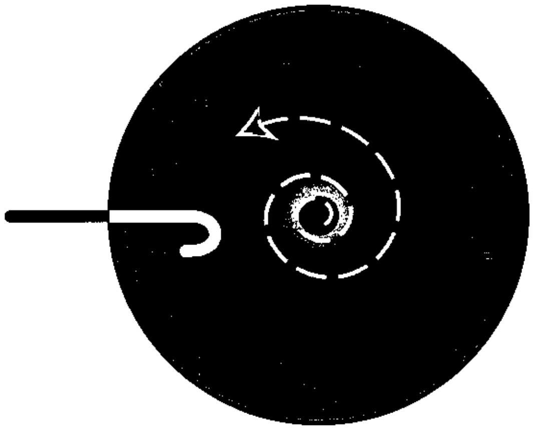

Figure 2.2. Cross-section of magnetron showing the central cathode and surrounding anode. The magnetic field goes into the page. As electrons move from the cathode to the anode, the magnetic field causes them to spiral, creating a kind of "electronic whistle" which generates the microwave signal. That signal is picked up by the probe at left and radiated into the waveguide.

bigger and bulkier, are true amplifiers. As such, it is easier to control the waveform of their transmitted pulses. Further, they are usually capable of transmitting more power than magnetrons (up to 2 MW or more) and their output signals are of purer frequencies. This latter characteristic is particularly suited to measuring the speed of motion of detected targets.

Solid-state transmitters usually have much lower transmitter powers than most magnetron and klystron transmitters. A single solid-state transmitter might transmit as little as 50 W of power. However, by combining multiple solid-state transmitters into an array and controlling the timing of each element appropriately, it is possible to achieve useful power outputs. Solid-state transmitters have not been used much for ground-based meteorological radars, but at least one manufacturer is selling an aircraft radar using this approach. Future weather radars may use solid state transmitters because they lend themselves to phased-array antennas, and this has great potential for improving the time it takes to collect radar data. Phased-array antenna radars are discussed in Chapter 10.

Modulator

No matter what kind of transmitter is used in the radar, it is usually controlled by another electronic device called the modulator. The purpose of the modulator is to switch the transmitter on and off and to provide the correct waveform for the transmitted pulse. That is, the modulator tells the transmitter when to transmit and for what duration.

The modulator also serves another function on some radars. It stores up energy between transmitter pulses so when it is time for the transmitter to fire, it will have a storehouse of energy available for its use.

Master Clock/Computer

Since weather radars are built so they can operate in a variety of ways, there must be some kind of interface between the operator and the radar to translate our wishes into radar commands. The control panel of the radar provides for a number of choices and a means to select them so we can communicate with the radar.

Inside the radar there must be some circuits to convert our selections into control signals for each function selected. For example, the operator usually selects the range to display, the elevation angles of the antenna, the azimuths to scan, and often the number of pulses transmitted each second and how long each of these pulses will be.

In older radars, the device which did much of this was called the master clock. It would generate the appropriate signals and send them to the various components of the radar. In modern radars, the function of the master clock has been taken over by the ubiquitous computer. Computers now control radars just as they control many other parts of modern technology.

Besides controlling the operation of the radar, computers (also called signal processors) control the processing of the received data. Signal processors can take the incoming signal, run data quality checks on the data, average the data, convert it into new products, store it for later replay, transmit it to remote locations, and display it for human consumption. Nowadays, the computer attached to a radar is probably more important than the hardware. In fact, radar hardware has not changed nearly as much in recent years as has the software used with the radar.

One of the main functions of the master clock/computer is to control how often and how long the transmitter transmits. The rate at which the radar transmits is called the pulse repetition rate or pulse repetition frequency (*PRF*). *PRF* is usually measured in pulses or cycles per second or in hertz (1 Hz = 1 cycle/second). *PRF*'s can be as low as

200 Hz and as high as 3000 Hz for various radars. Older, non-Doppler, ground-based weather radars used to operate with *PRF*'s on the order of 150 to 300 Hz. Doppler weather radars – those capable of detecting the speed of targets moving toward or away from the radar – typically operate with *PRF*'s on the order of 700 to 3000 Hz. Weather radars used onboard aircraft typically operate at 500 to 1500 Hz.

The duration of the transmitted signal goes by either of two different names. If measured in units of time, we call it the pulse duration (τ); if measured in units of distance, we call it pulse length (h). Typical pulse durations are from 0.1 to 10 μs (1 μs = 10^{-6} s). We can easily convert pulse duration into pulse length using *distance* = *rate* • *time* where *distance* is the pulse length h, the *rate* is the speed of light c, and the *time* is the pulse duration τ.

Waveguide

Figure 2.1 shows that the conductor connecting the transmitter and the antenna is waveguide. Regular wires work fine for conducting electricity and low-frequency signals. When electricity was first discovered, wires were all that were needed. As radio developed and higher and higher frequencies came into use, scientists discovered that simple wires were very lossy, i.e., too much energy was lost to make regular wires useful. Radio engineers soon found that a better way to carry radio-frequency signals was through special conductors called coaxial cables. Coaxial cable contains a center conductor surrounded by insulation and then by a layer of shielding conductor (and finally another layer of insulation). Coaxial cable works well at many radio frequencies.

At most radar frequencies, however, even coaxial cable is too lossy. To avoid these losses, another kind of conductor was invented which is even more efficient at carrying radar signals. This conductor is called waveguide. It is usually a hollow, rectangular (but sometimes round) metal conductor whose interior dimensions depend upon the wavelength of the signals being carried (see Figs. 2.4 and 2.4). Waveguide is put together much like the copper plumbing in a house. Long pieces of waveguide are connected together by special joints to connect the transmitter/receiver and the antenna. This allows the transmitter and receiver to be located at one place while the antenna is mounted elsewhere, usually up on a tower for conventional, ground-based weather radar.

Since there is seldom a straight line between the transmitter and the antenna, waveguide also has to be able to conduct its signals around corners. There are a number of special pieces of waveguide to account for this need. The signal conducted inside the waveguide consists of both an electric and a magnetic component (see the following chapter for a discussion of the characteristics of electromagnetic radiation). The cross section of waveguide is usually rectangular rather than square. The shorter dimension is the direction of the electric field while the longer direction is the direction of the magnetic field. Waveguide can bend in either of two directions: in the direction of the electric field (called an E-plane bend) or in the direction of the magnetic field (an H-plane bend). Given a choice, it is better to use E-plane bends rather than H-plane bends since the losses in H-plane bends are greater than those of E-plane bends.

Another kind of waveguide is flexible waveguide. This consists of a waveguide that is sort of like a goose-neck lamp. The metal part of the waveguide can bend to accommodate slight misalignment in waveguide or to allow for slight movement between adjacent components. The outside of flexible waveguide is usually rubber coated to make it air- and watertight.

A final special form of waveguide is a rotary joint. Antennas on weather radars must rotate so the antenna can scan horizontally (i.e., azimuthally) and in elevation. Rotary joints are used between the waveguide fixed to the radar tower and the waveguide fixed to the antenna. A second rotary joint is used so the antenna can scan up and down. The shape of the waveguide in a rotary joint is usually circular in cross section rather than rectangular.

Waveguide comes in straight pieces which must be assembled into the final run of waveguide. The manufacturer usually puts all the waveguide together when the radar is installed at its final site. When the distance between two points is too far to reach with a single piece of waveguide or when a long piece must be cut for a short distance of waveguide, connectors must be attached to the waveguide to allow the pieces to be connected together. Figure 2.3 shows the ends that are attached together. Both a flange joint (also called flat joint) and a choke joint must be used to connect the waveguide properly. If two flat joints are connected and even a very tiny crack exists, energy will be lost. To avoid that, the combination of a flat and a flange joint solve this problem. The choke joint contains two grooves. The groove near the outside is simply a grove for a rubber O-ring gasket to make the waveguide air tight. The inner groove is made a quarter of a wavelength long. This length causes energy entering the groove to be reflected back into the waveguide exactly in phase with the energy passing that point. The result is that the joint looks to the radar waves as if it is a perfect conductor and effectively prevents the loss of energy. If you ever assemble waveguide, be very careful that you do not connect two choke joints together. Doing that makes the equivalent of a half-wave groove. That is like a short circuit to radar waves!

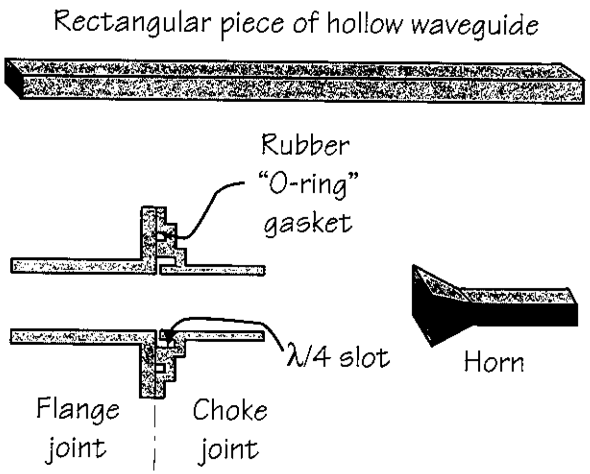

Figure 2.3. Waveguide (top), feedhorn (lower right), and a waveguide joint (lower left). The joints are held together with screws and contain an "O" ring to seal them. They also have a 1/4 wavelength slot to prevent loss of signal.

Waveguide pieces are held together with screws. The flat joint is threaded while the choke joint is not. By using this convention, it becomes impossible to inadvertently connect two flats or two chokes together.

Waveguide is an excellent conductor of microwave signals, but it is not perfect. Each waveguide component introduces losses. Skolnik (1980) discusses each of these losses in detail. Fig. 2.4 shows the losses of waveguide as a function of frequency. Notice that each waveguide size fits a range of frequencies. Also note that there is a limited number of waveguide sizes available. For WSR-88D radars, for example, the antenna is typically 60 to 70 ft from the transmitter/receiver cabinet; the two-way loss for this length of waveguide would be just over 1 dB. There are also some newer waveguides that operate at the higher frequencies (5 to 120 GHz) that have loss factors that are about 1/10th those shown on Fig. 2.4. One brand name of these is called Tallguide.

Antenna

Antennas are one of the most important components of a radar. At this point I feel a little like TV weatherman Willard Scott. Every time he would broadcast from a different

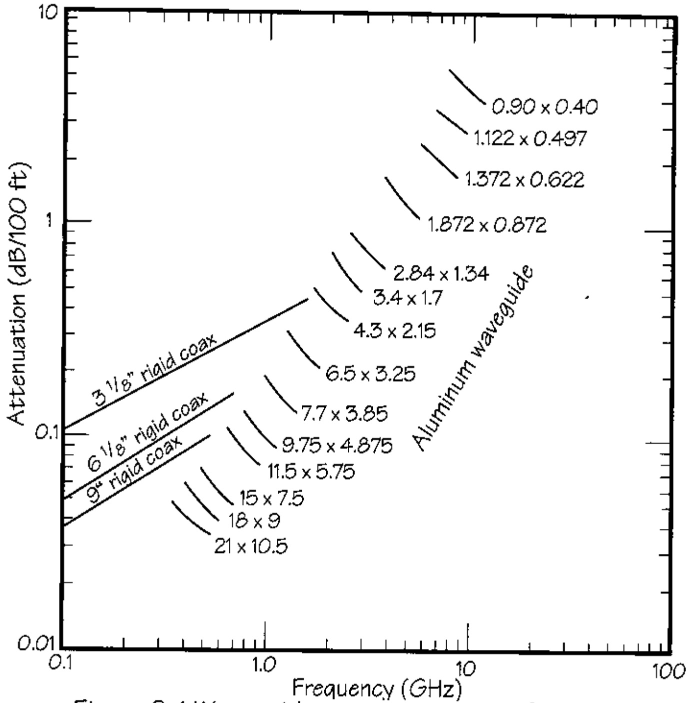

Figure 2.4 Waveguide attenuation as a function of waveguide size (dimensions are given in inches next to each particular size) and frequency. After Skolnik, 1980, Introduction to Radar Systems, with permission from McGraw-Hill. Inc.

city, he would say that "this is my favorite city in the whole country." Now that we are ready to discuss antennas, I have to say that antennas are one of my favorite parts of a radar!

The antenna is the device which sends the radar's signal into the atmosphere. Most antennas used with radars are *directional*; that is, they focus the energy into a particular direction and not in other directions. One of the great advantages of radar is its ability to determine the direction of a target from the radar. It is the ability of a radar's antenna to aim energy in one direction that makes it possible to locate targets in space.

An antenna that sends radiation equally in all directions is called an isotropic antenna. It can be compared to the light from a candle. A candle's light is approximately the same brightness in all directions, except, of course, directly below the candle. For weather radar, transmitting a signal equally in all directions would usually not be very useful. Instead, radars are more like flashlights. Flashlights have a shiny reflector behind the light bulb to direct the light in a specific direction.

Weather radars usually have both an antenna and a reflector (see Fig. 2.5). The *real* antenna is the radiating element which transmits the radar signal into the atmosphere toward the reflector; the reflector then reflects and directs the signal away from the radar. Most weather radars use a feedhorn as the true antenna although some use dipoles

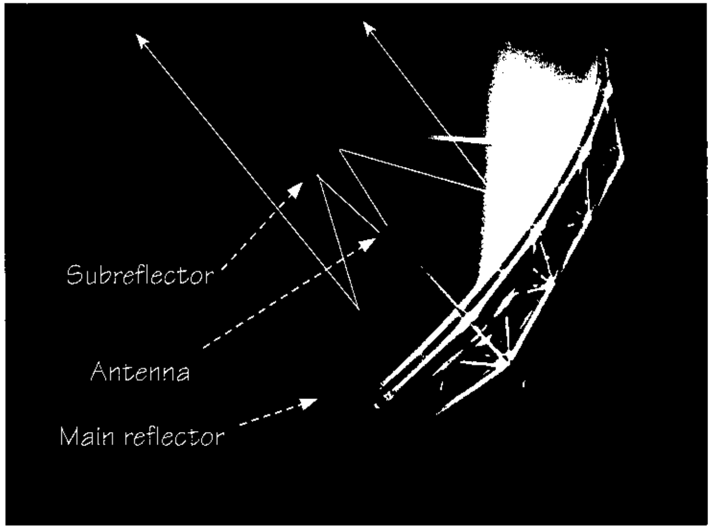

Figure 2.5 Photograph of a Cassegrain antenna with its antenna, main parabolic reflector, and hyperbolic subreflector. The thin white lines indicate the paths a couple of representative rays might follow for a transmitted signal.

or other radiating elements. For convenience, we typically speak of the combination of antenna and reflector as the antenna (or antenna system), but sometimes we need to be sure which of these components we are discussing (as in some of the following discussion).

The shape of the reflector determines the shape of the antenna beam pattern. Most meteorological radars have reflectors which are parabolic in cross-section and circular when viewed from the front or back; naturally, they are called circular parabolic reflectors. The beam pattern formed by a circular parabolic reflector is conical and usually quite narrow, typically 1° in width for the mainlobe of the pattern. The bigger the reflector, the better it is able to direct the signal and the narrower the beam of the antenna.

But there are other kinds of antennas used for meteorological radars. Figure 2.5 shows a Cassegrain-feed antenna. In this design, the actual antenna is located at the end of the tube coming out of the center of the main parabolic reflector. The signal is aimed at a hyperbolic-shaped subreflector. The signal then reflects back to the main parabolic reflector and then out into space. The received signal follows the reciprocal path from space, to the main reflector, to the subreflector, to the feedhorn, through the waveguide and into the receiver. One of the advantages of the Cassegrain feed is that they usually have better sidelobes for a given size antenna. The antenna beam pattern shown in Fig. 2.9 is from a Cassegrain antenna.

There are a number of things we need to know about an antenna. One is the wavelength it is designed for. The radar transmitter determines this parameter; the antenna must match the transmitter's wavelength.

A second parameter of interest is the size of the reflector. For circular parabolic reflectors, this is its diameter. Antennas on weather radars range from 1 ft (0.3 m) to as much as 30 ft (9 m) in diameter.

Another measure of importance to radar antennas is

the gain of the antenna. The gain g of an antenna is the ratio of the power that is received at a specific point in space (on the center of the beam axis, i.e., at the point where the maximum power exists) with the radar reflector in place to the power that would be received at the same point from an isotropic antenna. This is a unitless ratio since it is one power divided by another power, and units cancel. In equation form, gain is defined as

$$g = \frac{p_1}{p_2} \tag{2.1}$$

where p_1 is the power on the beam axis with the antenna and p_2 is the power at the same point from an isotropic antenna.

Usually antenna gain is measured logarithmically in decibels (see Appendix A for a more complete discussion of logarithmic units). A power ratio in decibels is defined as

$$P = 10\log_{10}\left(\frac{p_1}{p_2}\right)$$

where both powers p_1 and p_2 are measured in the same units, P is the logarithmic power ratio in decibels, and "log_{10} ( )" represents the logarithm to the base 10 of the term in parentheses.[1]

Since antenna gain g is actually a power ratio, we can thus write it in logarithmic form as

$$G = 10\log_{10}\left(\frac{p_1}{p_2}\right) \tag{2.2}$$

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[1] Throughout the text, I use lower-case letters for linear parameters and capital letters for logarithmic parameters (for those parameters which are commonly expressed in both linear and logarithmic units of measure). See Appendix A for a more complete discussion of logarithmic measurements and Appendix B for a discussion of error analysis using logarithmic parameters.

where gain G has units of decibels. Typical antenna gains for meteorological radars range from 20 to 45 dB. The gain of an isotropic radiator would be 0 dB (i.e., $p_1 = p_2$, so $p_1/p_2 = 1$ and $\log_{10}(1) = 0$).

Another important parameter of an antenna is its beamwidth. The beamwidth of an antenna is defined as the angular width of the antenna beam measured from the point where the power is exactly half what it is at the same range on the center of the beam axis. Figure 2.6 illustrates the beamwidth of an antenna.

Antenna gain and antenna beamwidth are related. One expression that can be used to calculate one from the other is (Battan, 1973)

$$g = \frac{\pi^2 k^2}{\theta \phi} \tag{2.3}$$

where θ and ϕ are the horizontal and vertical beamwidths of the antenna, respectively, and both are measured in radians. k^2 depends upon the kind and shape of antenna. For circular reflectors, $k = 1$.

For circular reflectors, the horizontal and vertical beamwidths would be equal, giving

$$g = \frac{\pi^2}{\theta^2} \tag{2.4}$$

For example, for an antenna with a 1° beamwidth, the gain would be

$$= 32400$$

or, in logarithmic units,

$$G = 45.1 \text{ dB}$$

Notice that gain is independent of wavelength. *Any* circular parabolic radar antenna with a 1° beamwidth would have the same antenna gain at any frequency, according to Eq. 2.4.

The shape of the mainlobe is often approximated by a Gaussian shape (Probert-Jones, 1962). A Gaussian beam pattern can be written in an equation of the form

$$g = g_0 \exp\left[-4\ln(2)\left(\frac{\theta}{\theta_0}\right)^2\right] \tag{2.5}$$

where g is the gain at any arbitrary angle θ from the center of the mainlobe axis, θ_0 is the beamwidth of the mainlobe, and g_0 is the maximum gain on the beam axis. If g_0 is set to 1, then g is the relative gain of the Gaussian beam pattern.

As mentioned, gain is frequently expressed logarithmically. One equation for doing this is (Doviak and Zrnić, 1993)

$$G = G_0 + 10\log_{10}\left[\exp\left[-4\ln(2)\left(\frac{\theta}{\theta_0}\right)^2\right]\right] \tag{2.6}$$

where G is the relative logarithmic gain (in decibels) at any angular distance θ from the beam axis, and θ_0 is the beamwidth of the pattern. By adding the maximum gain on the beam axis G_0, to the right side of Eq. 2.6, the gain G becomes the absolute gain in the direction of θ.

According to Eq. 2.6, a radar antenna's mainlobe beam pattern (measured in decibels) decreases in magnitude in proportion to the square of the angular distance from the beam axis. Real antennas sometimes differ slightly from this, however. For example, the National Center for Atmospheric Research CP2 S-band radar antenna had a mainlobe that decreased approximately to the 2.2 power of angular distance from the mainlobe.

Much as we would like to believe it, antennas are not perfect devices. The ideal antenna would direct all of the radar's energy into a single direction and none of it would

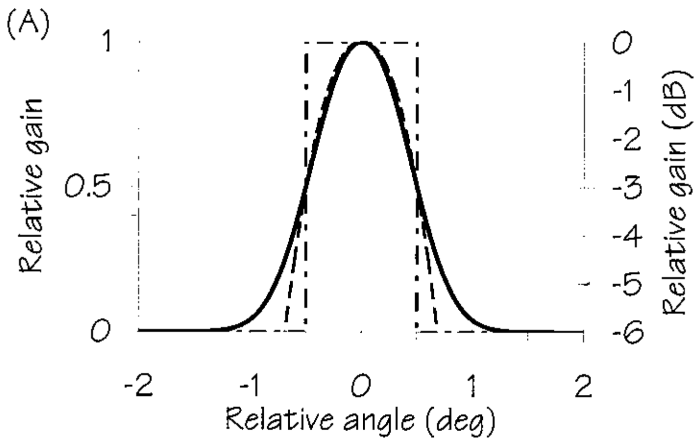

Figure 2.6 (A) The relative one-way gain of an ideal antenna as a function of angle. The antenna beamwidth of this antenna is 1° (0.5° either side of the center). The solid line is the linear antenna gain (left ordinate) while the dashed curve is the logarithmic gain (right ordinate). The beamwidth is the angular width where the power is exactly half of the maximum power. On the linear scale, this is at a relative power of 0.5 of the maximum. On the logarithmic scale, the half-power point is 3 dB below the maximum. The dash-dot-dash curve represents a top-hat profile; this is physically unrealizable, but it is what we would like a radar antenna to have (left scale applies to the top-hat profile).

go anywhere else. This is physically impossible. Even flashlights do not do this job perfectly. While most light from a flashlight does go in some preferred direction, some of the light can be seen well off to the sides of the brightest spot. Further, the illumination of the brightest spot is seldom uniform.

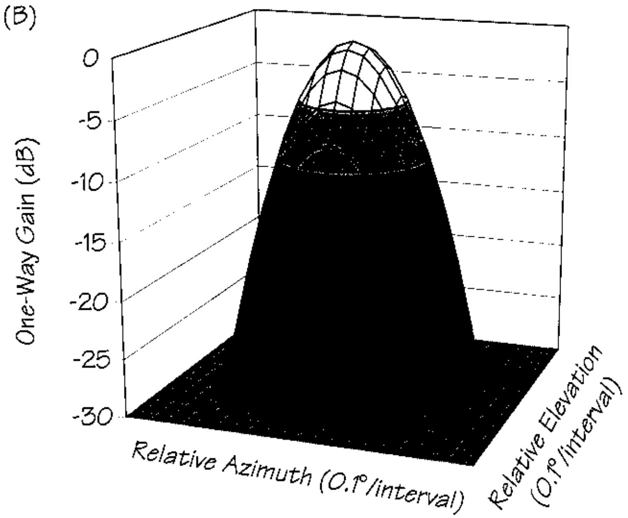

Figure 2.6 (B) 3-D view of parabolic beam for an antenna with a 1° beamwidth.

Real radar antennas are much like this. They will have a bright spot (called the mainlobe), but they will also transmit and receive energy off to the side of the mainlobe in what are called sidelobes. Further, the sidelobes exist in all directions away from the mainlobe and are different from one direction to another. One difference between radar antennas and flashlights is that some of the radar energy can actually go directly behind the antenna, forming a "backlobe."

The top-hat pattern shown in Fig. 2.6 is for a perfect antenna while the Gaussian antenna beam pattern is a reasonable approximation to the mainlobe of real antennas. But in either case, the pattern on Fig. 2.6 has no sidelobes whatsoever. Real antennas have sidelobes, and sometimes very strong sidelobes. Let's examine some sidelobes from a couple of radar antennas. When we examine antenna beam patterns, we usually only do so in one direction at a time, either in azimuth or in elevation. Figure 2.7 shows the antenna beam pattern in the horizontal direction for the AN/CPS-9

X-band antenna used by the Air Force and others during the 1950's and 1960's (Donaldson, 1964)[2]. This pattern is a smoothed, idealized fit to the real pattern. It shows that the simple, single lobe pattern of Fig. 2.6 is a good approximation only near the center of the mainlobe. Figure 2.6 does not represent the sidelobes at all! Figure 2.7C shows a 3-D like view of this beam pattern, assuming it is the same in all directions, not just azimuthally. We will see shortly that *real* antenna patterns are much more irregular. Nevertheless, Fig. 2.7C helps us visualize how beam patterns vary in both azimuth and elevation.

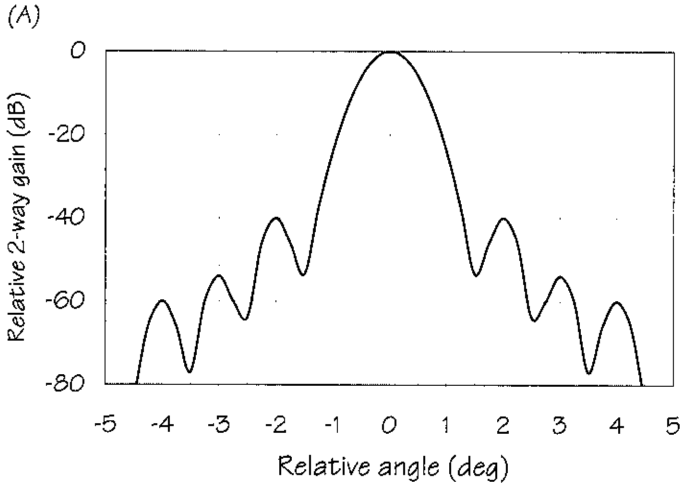

Figure 2.7 (A) Modeled two-way antenna beam pattern for the CPS-9 X-band antenna, showing the mainlobe and the first three sidelobes. This antenna has a mainlobe with a 1° beamwidth (from Donaldson, 1964). The figure shows the beam pattern as a function of gain and angle.

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[2] One of the interesting things about the CPS-9 radar is that it is the first radar designed specifically for the detection of weather. It was used extensively for radar research for more than 30 years.

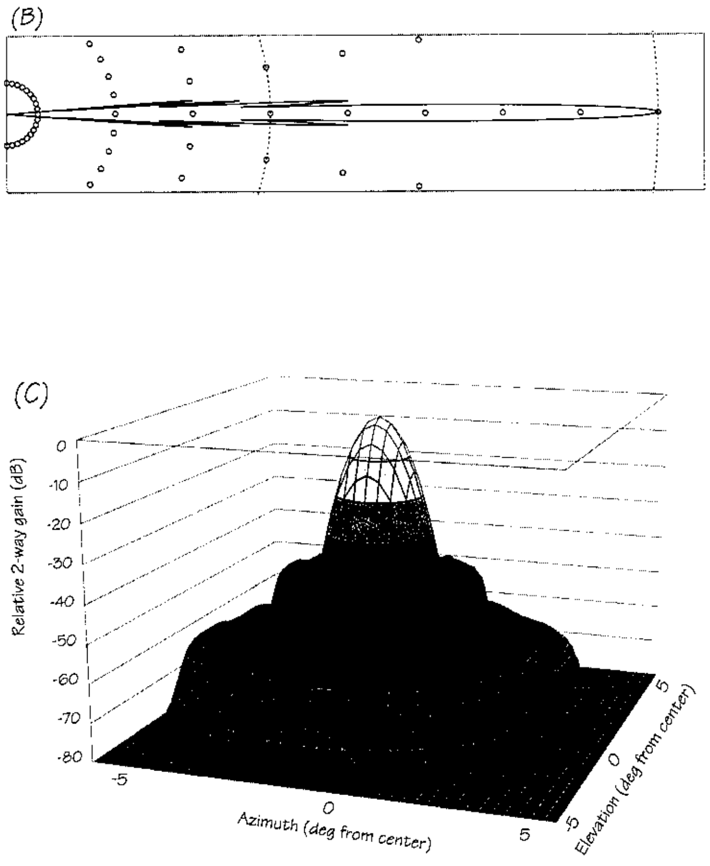

Figure 2.7 cont. The top view (B) shows the pattern in polar coordinates with the radar at the left; contours are 10 dB apart; tick marks are every 10° of azimuth. Notice that the sidelobes are really quite close to the mainlobe in (B). The bottom panel (C) shows a 3-D view with gain vertically and relative azimuths and elevations on the lower two scales.

Now let's look at the measured antenna beam pattern from a real antenna. Figure 2.8 shows part of the antenna beam pattern for the FL2[3] radar, an S-band (10-cm wavelength) radar operated by MIT Lincoln Laboratory (see Appendix D). This pattern was measured by placing a calibrated signal generator at some distance from the radar antenna and scanning the antenna slowly in azimuth through almost a full circle while receiving and recording the signal. The strong mainlobe is clearly evident when the antenna was aimed directly at the signal generator. Nearby sidelobes are also shown as moderately strong but narrow "spikes" on the pattern. Near 120° on either side of the mainlobe are regions of stronger sidelobes. Notice that some power was even detected when the antenna was aimed in the opposite direction from the signal generator (i.e., at an azimuth of 180°). [Note that this pattern is missing data between -180° and -120°. Data were likely collected for these azimuths, too, but the graph I had to use did not have this information.]

As complex as the antenna beam pattern shown in Fig. 2.8 is, it does not really portray the complexity of a complete antenna beam pattern. The pattern shown is, after all, a single slice through what is really a two-dimensional pattern. As an example of the complexity of a real pattern in *both* azimuth and elevation, Fig. 2.9 shows the antenna beam pattern for the CP2 X-band Cassegrain-feed antenna of the National Center for Atmospheric Research (Rinehart and Frush, 1983). The top part of this figure was obtained by transporting the antenna to the antenna range of the National Bureau of Standards in Boulder, Colorado, an expensive and time-consuming activity. As can be seen in the figure, there

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[3] Actually, FL2 operated at S-band for several years; it was a test bed to emulate the NEXRAD system. In the early 1990's it was converted to C-band to serve as a test bed for the development of the TDWR system. Appendix D gives FL2 specifications for its S-band incarnation.

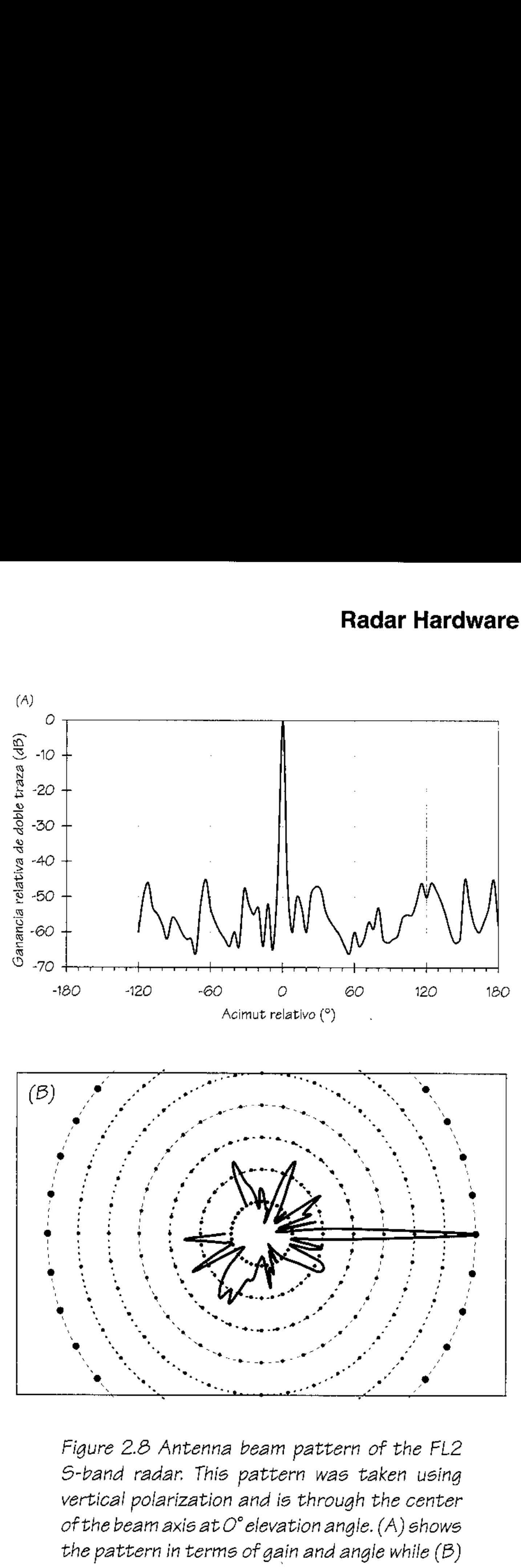


Figure 2.8 Antenna beam pattern of the FL2 S-band radar. This pattern was taken using vertical polarization and is through the center of the beam axis at 0° elevation angle. (A) shows the pattern in terms of gain and angle while (B) shows the pattern in polar coordinates (10-dB circles; dots every 10° of azimuth)

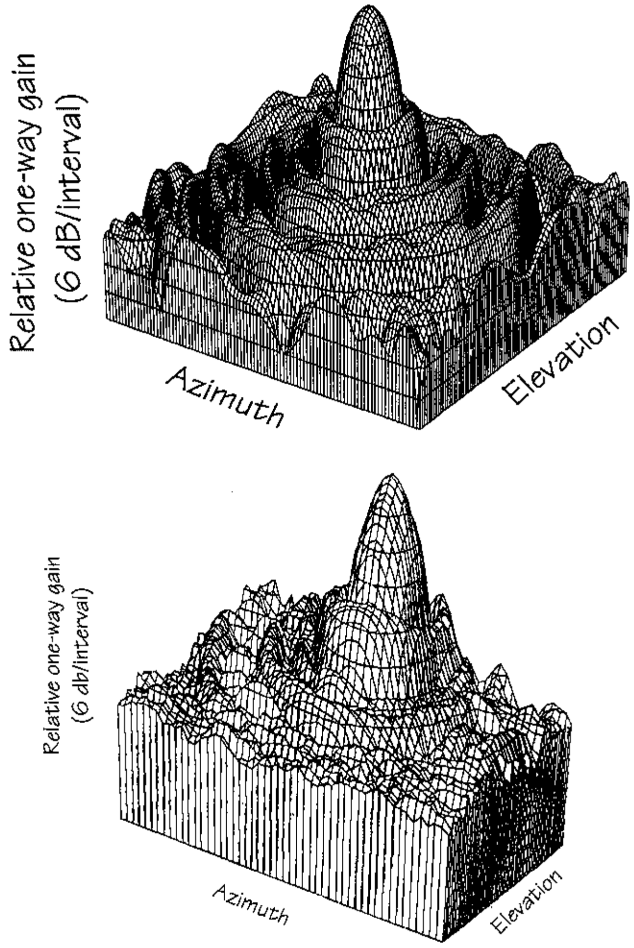


Figure 2.9 Antenna beam pattern of the NCAR CP2 X-band Cassegrain-feed antenna. The elevation and azimuth angles extend about 5° either side of the center of the mainlobe. Top image was done at National Bureau of Standards antenna range; bottom used a radio tower to make the measurements. After Rinehart and Frush, 1983.

are a number of sidelobes surrounding the mainlobe, with each successive sidelobe ring generally being of weaker strength. Note that this pattern only covers 10° of azimuth and elevation, 5° either side of the center of the mainlobe. A complete antenna beam pattern ±180° in azimuth and elevation around the mainlobe would be even more complex. The second part of the figure was obtained by scanning a strong ground target (nice, isolated ground target) in both elevation and azimuth. The result was noisier than that obtained at an antenna range, but was essentially free and did not require more than collecting and processing the data. One limitation was that the antenna could not be aimed below the horizon, so only the top half of the pattern was measured.

Transmit/Receive Switch

The transmit/receive (T/R) switch (i.e., duplexer) shown in Fig. 2.1 is a special switch added to the radar system to protect the receiver from the high power of the transmitter. Most radars transmit from a few thousand watts to more than 1 MW (1 MW = 10^6 watt) of power. Most radars are capable of receiving powers as small as 10^{-14} W or less. Because of this tremendous difference in power levels, if a transmitter sent much of its power into the receiver, it would very quickly burn up the very sensitive receiver.

In order to protect the receiver from this possibility, radar engineers have added the automatic switch (also called a duplexer or circulator) in the waveguide between the transmitter and the receiver. When the transmitter is turned on, the duplexer acts to direct the strong pulse of energy to the antenna and away from the receiver. As soon as the transmitter stops sending its signal, the duplexer switches so that the receiver is connected to the antenna while the transmitter is disconnected.

Transmit/receive switches do not respond instantaneously. As a result, there will be a short recovery time after the transmitter fires before the receiver is at full sensitivity. This recovery time depends upon the design of the T/R switch and the power of the transmitter, but is typically on the order of 1 to 10 μs; this corresponds to a distance of about 150 m to 1.5 km.

Receiver

The receiver is designed to detect and amplify the very weak signals received by the antenna. Radar receivers must be of very high quality because the signals that are detected are often very weak.

Most weather radar receivers are of the superheterodyne type in which the received signal is mixed with a reference signal at some frequency which is different from the transmitted frequency. Typically, the reference signal is 30 to 60 MHz above or below the transmitted frequency. This mixing process results in four frequencies: the original transmitted frequency, the reference signal frequency, the sum of these two frequencies, and the difference between these two frequencies. This last one, the difference, is only 30 (or 60) MHz. All others are very high and are easily filtered out. The difference frequency signal is much lower and is called the intermediate frequency (IF). It is "intermediate" between the original transmitted frequency and even lower frequencies used to drive the video amplifiers used in the display system. The IF signal is further amplified to the point that it can be used for displays, recording and signal processing. The connection between the receiver and the indicator on Fig. 2.1 is usually coaxial cable, since the IF signal is lower frequency and the distances between devices at this point in the receiver are quite short.

Some modern Doppler radars contain two receivers. One receiver is designed to cover the wide range of reflectivities that are present in the real world, sometimes up to 8 to 10 orders of magnitude. Logarithmic receivers are frequently used to handle this wide range of reflectivities. A logarithmic receiver produces an output which is proportional to the logarithm of the input power. Consequently, they can have a dynamic range (the difference from the weakest to the strongest power that it can handle) of 80 dB or more.

Modern weather radars now often use digital receivers or receivers which are able to dynamically measure and then adjust their gain such that they can measure very weak signals to very strong signals quite well. These new receivers have dynamic ranges that are on the order of 90 dB or more.

For Doppler velocity measurements, the receivers that are used are usually somewhat more sensitive to weak echoes but of much more limited dynamic range. Moderate and strong signals will overwhelm or saturate these receivers, making it impossible to measure the strength of the signal correctly, but they still give correct velocity data because velocity depends on the frequency of the signal, not its power. One consequence of using two receivers is that sometimes very weak echo will show up better on a display of velocity data than it does on the reflectivity display. A careful examination of some of the color figures shows slightly more echo area on the Doppler velocity image than the reflectivity image (See Color Figs. 4, 8 and 10, for examples).

Displays

There are many ways to display radar data. The earliest and easiest display for radar data was to put it onto a simple oscilloscope, where the horizontal axis was time and the vertical axis was signal strength or intensity; an oscilloscope used to display radar data is called an A-scope; it was the first display "named" when radar was first invented. Since electromagnetic radiation travels at the speed of light, the time base can also be a distance scale. The vertical scale can also be calibrated in power units. Figure 2.10 shows a schematic A-scope display.

One problem with the A-scope display is that it gives no direct information about where the radar antenna is point-

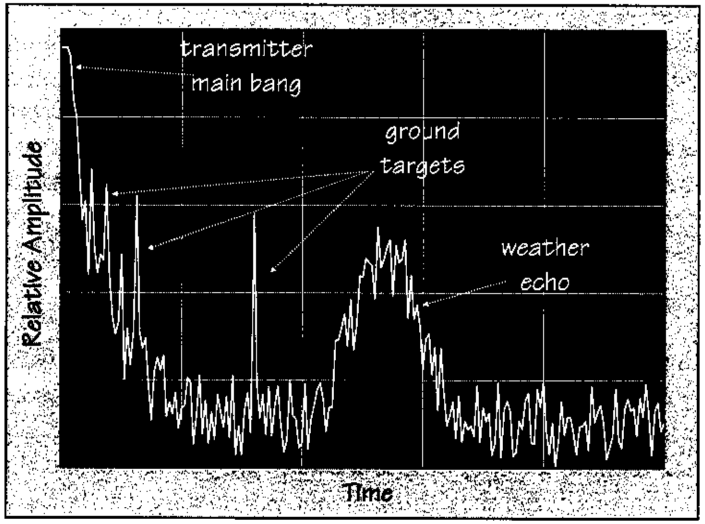


Figure 2.10 Schematic diagram of an A scope showing the transmitter pulse ("main-bang") leakage into the receiver, nearby ground targets, receiver noise, distant weather echo and an isolated point target. The radar is at the left; time and distance increase toward the right.

ing. Usually we want to know *where* the target is, not just its range and strength. In order to give position information, other displays had to be invented. Perhaps the most universal display for weather information is the plan position indicator (PPI). A PPI displays the radar data in a map-like format, usually with the radar at the center. Distance is given by adding range marks (also called range rings) around the radar. The direction from the radar is shown by the position of the echo relative to the radar. Most radars put north at the top and have east to the right, south at the bottom and west to the left. Occasionally a radar will be aligned with magnetic north at the top. This alignment to magnetic north is convenient if the radar is used to direct the activities of aircraft (which fly using magnetic compasses).

Mobile radars used on ships typically have PPI displays that show a full 360° of coverage. They will usually put the heading of the ship at the top of the display so that what is ahead of the vessel will always be easily recognized.

Airborne radars are usually mounted in the front of the aircraft and have restricted antenna movement. That is, the antennas are not able to look around in all directions but can only scan from the left to the right of the aircraft's path by perhaps ±45° to ±60°. Consequently, aircraft radar displays do not show full-circle PPI's but only the directions scanned by the antennas. They still portray the information in range and azimuth, however. The center of the radar display points in the direction the aircraft is flying.

Figure 2.11 shows a schematic example of a PPI display. The radar is located at the center of the display with

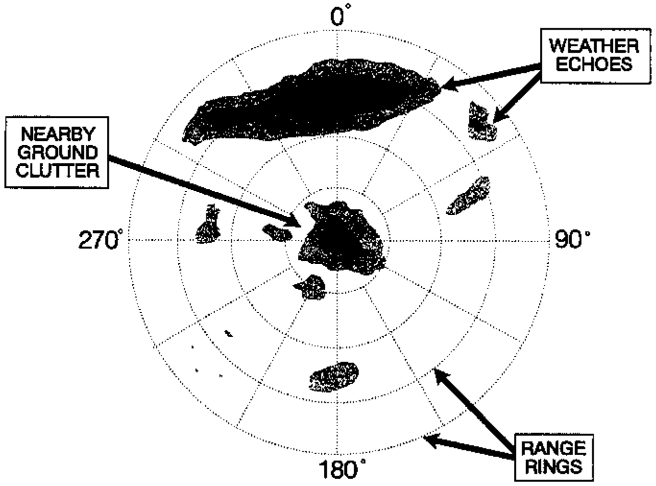


Figure 2.11 Schematic diagram of a PPI display showing nearby ground clutter and distant weather echoes. Echo intensity is indicated by shading, where the darker the shading, the stronger the echo.

range increasing outward to the maximum range of the radar (or display). This particular display shows radar targets as shaded. Near the radar is a large region of shading which could be either a storm echo over the radar or it could be nearby targets (often called ground clutter). Farther from the radar to the southwest are smaller targets. Again, these could be small weather echoes, but they are drawn to represent what aircraft echoes might look like (or ship echoes if the radar is located on a ship; in this case the center echo could be storm or sea clutter). To the north is a line of scattered storms; those with the darkest centers are the strongest.

Modern technology has added a new dimension to radar displays – color. Modern radars have computer-generated displays which show not only the position of the radar echoes as on old-fashioned PPI's, they also show the intensity of the echo in (false) colors.

Older displays showed intensity with varying degrees of brightness. It was not possible to determine more than a few levels of intensity with these monochrome displays. Modern displays can easily show several levels of intensity quite clearly using color coding; some can show 15 or more different intensity levels. Alternatively, now we can often move a cursor over an echo of interest and the display system will show the position (range and azimuth, X and Y, and/or latitude and longitude) as well as the reflectivity or rainrate and velocity of the point. This is quite useful to meteorologists for quantitatively determining rainfall intensity levels, for example.

Actually, modern displays can also show rainfall rate and accumulated rainfall directly. This way the user can tell at a glance how hard it is raining or how much rain has fallen. Color Fig. 16 shows rainfall totals during the passage of storms across Oklahoma.

Another advantage of computer-generated displays is that they can put the radar anywhere, not just at the center of the display. Quite often the region of interest is off on one side of the radar only. By offsetting the display to be centered on this region, the same storms can be shown bigger than they could be on older displays. Another modern feature is the ability to magnify or zoom the image to fill the display area with a specific region of radar coverage. Again, this makes it possible to see the smaller-scale features of storms in much greater detail. For example, Color Fig. 5 shows a microburst in much better detail because it is zoomed in to cover just the storm producing the microburst.

An example of a color display of real radar data in PPI format can be found in Color Fig. 1. It shows both the signal strength (radar reflectivity in units of dBz; right side of the figure) and Doppler radial velocity data (left side) for the UND radar operating at South Roggen, Colorado. At the time this picture was taken, there were no weather echoes present. All of the echo shown is from ground targets, a few aircraft, and noise in the radar system. The strong echoes to the west (left) are the Rocky Mountains west of Denver. Nearby ground clutter is also present, including a couple of small patches to the north at 30 to 45 km range. The velocity data show how fast the targets are moving. Except for a few aircraft in the area, nearly all of the echo shown has velocity near zero, evidence of the fact that it is from ground targets and are not moving. Other examples of PPI data are shown in the section of color figures.

Another kind of useful display for weather information is the range-height indicator (RHI). In this display the horizontal axis is again distance from the radar, but the vertical axis is height above the radar. Echoes are shown as bright or colored regions on the display. Color Fig. 4 (and others) shows an example of an RHI taken from the UND radar in Kansas City, Missouri, on 18 June 1989. The echo displayed is from a rapidly moving cold front approaching the radar from the northwest. The PPI in Color Fig. 3 shows the horizontal view of the same situation. It is often very helpful to have both the horizontal (PPI) and vertical (RHI) view of a storm to understand what is going on.

One problem with many RHI displays is that they exaggerate the vertical size of an echo. This is unfortunate because it gives a very distorted impression of what storms are really like. Convective storms are usually approximately spherical or even pancake shaped. Displaying them with vertical magnifications of 5 to 10 makes them look much taller than they are wide; such is not the case in nature. Color Figs. 4, 8, and 10 are not all exactly one-to-one in their vertical-to-horizontal scales. Be aware that many RHI's are far more distorted than those shown herein.

Another display that is now possible because computers are used to process the data is the vertical cross section. For this display, the operator selects a starting and an ending point. The computer processes all the data it has stored above the line connecting these two points and produces a synthetic vertical profile. The profiles can be quickly generated through any storm or region of interest and provide good insight into what the storm is doing in the vertical. Someone once wrote that the natural coordinate for storms is the vertical, so we should look at storms in the vertical to really understand them. Since some radars do not or cannot operate in RHI mode, the vertical profile allows us to see this without forcing the radar antenna to scan upward. One disadvantage to these vertical profiles, however, is that they are limited by the number of elevation scans available in memory, and sometimes there are only a few to use.

Figure 2.12 illustrates a vertical profile through an extensive region of convective precipitation. If you look carefully, you can see how the echo top steps from one point to the next. These artifacts are caused by the limited number of elevation angles available. Further, where line AB passes close to the radar site and there is a limited number of elevation angles looking upward, there is an artificial dip in the vertical profile. Some people have termed this the "cone of silence" above a radar (sort of like a black hole). Alas, the one blind spot of a radar is *at* the radar itself!

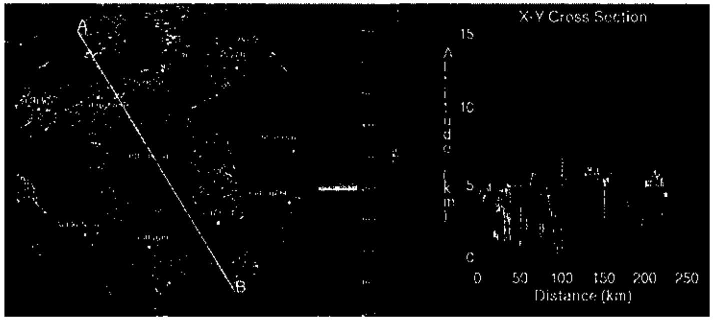
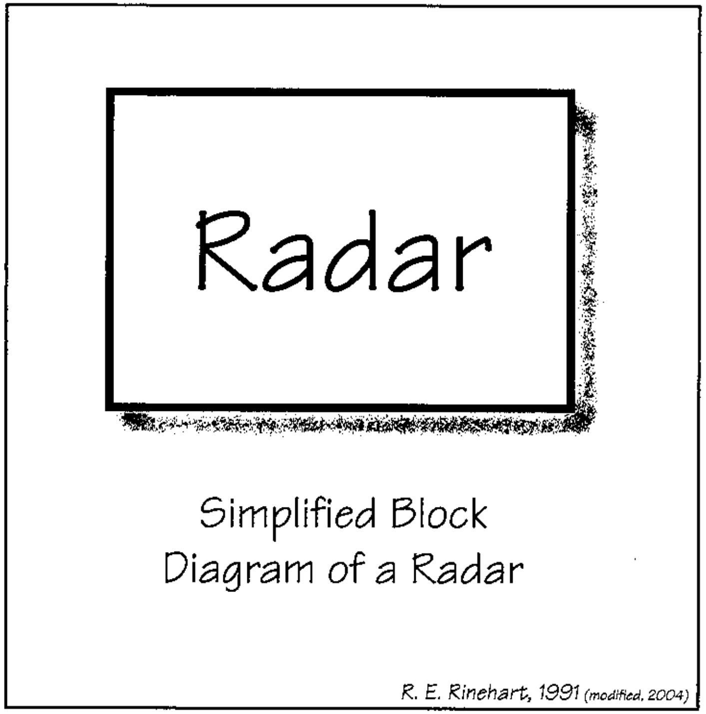


Figure 2.12 PPI display (left) and a vertical profile generated along the line on the PPI (from A toward the northwest to B toward the southeast). The steps in the echo top on the vertical profile are caused by the limited number of elevation angles available in the original data set.

Signal Processor

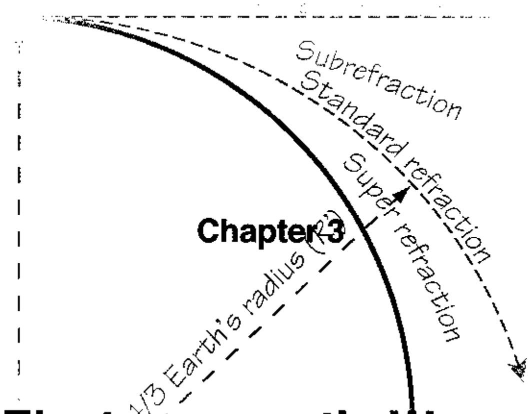
The block diagram shown in Fig. 2.1 ends with the indicator. However, modern radars have computer processors incorporated within the system which do some very useful things. The color displays described above are examples of one use of these processors.

Research and operational radars (e.g., WSR-88D) are also equipped to process the radar data to detect various hazardous weather situations using what are called computer algorithms or simply algorithms. An algorithm is a specific set of instructions that the computer will execute to see if the storm contains specific features. If the characteristic the computer is looking for exists, it will indicate that the event is present. For example, it could sound an alarm if a tornado mesocyclone is detected. The WSR-88D is able to automatically detect such things as hail, tornadoes, and microbursts. Automatic warnings of these events are available for dissemination through appropriate channels to the public. The use of warning algorithms have probably resulted in significant savings in life and property over the past few years and are a very valuable part of operational radar systems.



Simplified Block
Diagram of a Radar

R. E. Rinehart, 1991 (modified, 2004)



Chapter 3

Electromagnetic Waves

Radio and radar both operate using electromagnetic radiation. Electromagnetic radiation, as its name suggests, has both electric and magnetic components, each component of which is like a magnetic wave and an electric wave vibrating at right angles to each other, and both are at right angles to the direction of propagation. Electromagnetic radiation always travels at the speed of light (where light, itself, is just a special form of electromagnetic radiation; it just happens to be at a frequency and wavelength which is detectable by our eyes).

One of the important characteristics of electromagnetic radiation is its frequency. Another is its wavelength. These are related through the equation

$$f = \frac{c}{\lambda} \tag{3.1}$$

where f is frequency in hertz (1 Hz = 1 cycle/second), c is the speed of light (often measured in m/s) and λ is wavelength (in meters when c and f are in the units specified).

Electromagnetic spectrum

Electromagnetic radiation ranges from very low frequencies to very high frequencies. Figure 3.1 shows what is often called the electromagnetic spectrum and where