CHAPTER 18

Radar Basics

Radar stands for **R**adio **D**etection **a**nd **R**anging. It can be used to detect target range, direction, and motion. It was developed during World War II and has continually evolved since. Early radars were composed of analog circuits, but since the 1960s, radars have become increasingly digital. Today, radar systems contain some of the most sophisticated and powerful digital signal processing systems anywhere.

Radar has widespread use in both commercial and military applications. Air traffic control, mapping of ground contours, automotive traffic enforcement are just a few civilian applications. Radar is ubiquitous in military applications being used in air defense system, aircraft, missiles, ships, tanks, helicopters, and so forth.

18.1 Radar Frequency Bands

Radar systems transmit electromagnetic or radio waves. Most objects reflect radio waves, which can be detected by the radar system. The frequency of the radio waves used depends on the radar application. Radar systems are often designated by the wavelength or frequency band in which they operate using the band designations (Table 18.1).

The choice of frequency depends on the application requirements. The minimum antenna size is proportional to wavelength and inversely proportional to frequency. Airborne applications often are limited in the size of antenna that can be used, which will dictate a higher frequency and lower wavelength choice. Beamwidth, or the ability of the radar to focus the radiated and received energy in a narrow region, is also dependent on both

Table 18.1: Radar Frequency Bands

Radar Band	Frequency (GHz)	Wavelength (cm)
Millimeter	40—100	0.75—0.30
Ka	26.5—40	1.1—0.75
K	18—26.5	1.7—1.1
Ku	12.5—18	2.4—1.7
X	8—12.5	3.75—2.4
C	4—8	7.5—3.75
S	2—4	15—7.5
L	1—2	30—15
UHF	0.3—1	100—30

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antenna size and frequency choice. Larger antennas allow the beam to be more tightly focused. Therefore, a higher frequency also allows the beam to be more tightly focused, for a given antenna size. The "focusing" ability of the antenna is often described using an antenna lobe diagram, which plots the directional gain of an antenna over the azimuth (side to side) and elevation (up and down).

The range of the radar system is also influenced by the choice of frequency. Higher frequency systems usually are of lower power due to electronic circuit limitations and experience greater atmospheric attenuation. The ambient electrical noise that can impair operation of analog circuitry also becomes more pronounced at higher frequencies. Most of the radar signal absorption and scattering is due to oxygen and water vapor. Water vapor, in particular, has high absorption in the "K" band. When this was discovered, the band was divided into Ka, for "above" and Ku for "under," the frequencies where radar operation is limited due to water vapor absorption. At higher frequencies in portions of the millimeter band, oxygen causes similar attenuation through absorption and scattering.

Another consideration, discussed more fully in the next chapter, is the effect of the radar operating frequency on Doppler frequency measurements. Doppler frequency shifts are proportional to both the relative velocity and the radar frequency. Doppler frequency shifts can provide important information to the radar system.

Most airborne radars operate between the L and Ka bands, also known as the microwave region. Many short range targeting radars, such as on a tank or helicopter, operate in the millimeter band. Many long range ground-based operations utilize UHF or lower frequencies, due to the ability to use large antennas and minimal atmospheric attenuation and ambient noise. At even lower frequencies, the ionosphere can become reflective, allowing very long range over-the-horizon operation.

18.2 Radar Antennas

A critical function in any radar system is the antenna. Early radars often used mechanical parabolic antennas. The antenna is capable of focusing both the receive and transmit energy in a given direction. The antenna could be moved mechanically using motors and aimed to search over different parts of the sky (Fig. 18.1).

The degree of directionality is often shown in azimuth and elevation gain diagrams. The diagram in Fig. 18.2 below shows an antenna that has a fairly wide or broad main lobe. Most radar antennas may have a much narrower main lobe, on the order of a few degrees. Frequently, the width of the main lobe is specified by the point at which the receive or transmit signals are attenuated by 3 dB or about one half. The antenna shown below has a lobe width of about 20 degrees. However, all antennas will receive some level of signal from undesired directions, even from behind. The antenna gain plots visually quantify the

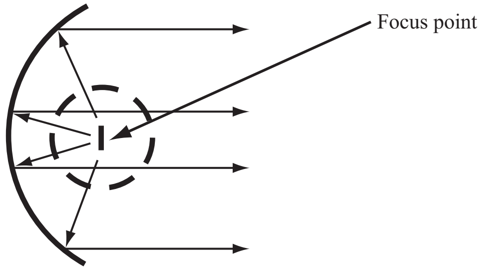

Figure 18.1
Parabolic antenna operation.

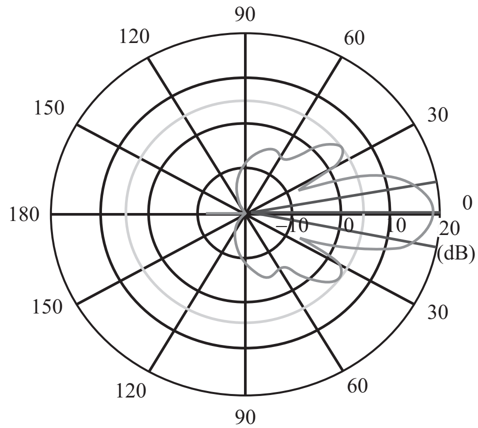

Figure 18.2
Antenna lobe diagram.

relative gain across both azimuths and elevations (usually a separate plot for each). In general, the narrower the main lobe, the higher the antenna gain will be.

The antenna design influences both the amount of energy the radar can transmit at the desired target space, as well as how much energy it can receive from the same direction. It also determines how much unwanted energy from other directions is attenuated (for example, reflections from the ground in an airborne search radar). Having a narrow or focused beam allows the energy to be more focused. To search across a wide area, the antenna must steer its beam across the entire search space. As just mentioned, this was done mechanically in early radars. However, more advanced radars, especially airborne, use electronically steerable antennas.

An electronically steerable antenna is built from many small antennas or individual elements. Each element can individually vary the phase of both receive and transmitted signals, as well as the signal strength using analog or digital electronic circuits. It is the

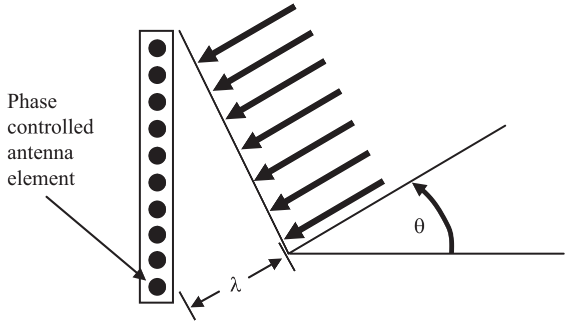

Figure 18.3
Planar antenna phase alignment.

changes in phase that provide for steerable directivity of the antenna beam over both azimuth and elevation. Only when the receive signal arrives in-phase across all the antenna elements will the maximum signal be received. This provides the ability to "aim" the main lobe of the antenna in a desired direction. The process is reciprocal, meaning that the same antenna lobe pattern will exist on both receive and transmit.

Each antenna element must have a delay, or phase adjustment, such that after this adjustment, all elements will have a common phase of the signal. If the angle $\theta = 0$, then all the elements will receive the signal simultaneously, and no adjustment is necessary. At a nonzero angle, each element will have a delay to provide alignment of the wavefront across the antenna array (Fig. 18.3).

This has several advantages. It can be steered very rapidly, which can allow fast searching as well as tracking of objects. Using a technique called "lobing," the radar beam can be rapidly steered on either side of a target. By noting where the stronger return is, the target location can be tracked. Further, different regions of the antenna can be aimed in different directions to scan or track multiple regions or targets, albeit with a reduced transmit power and receive gain. A disadvantage of an electrically steered antenna is the reduced aperture at larger incident angles. The aperture is one factor in the antenna gain and will decrease by the cosine θ, where θ is the angle of the steering direction, relative to the perpendicular vector from the antenna (Fig. 18.4).

18.3 Radar Range Equation

Detection of objects using radar involved sophisticated signal processing. However, all of this is first dependent on the amount of energy received from the target echo.

$$\text{Receiver Power } P_{receive} = P_t G_t A_r \sigma F^4 (t_{pulse}/T) \Big/ \left((4\pi)^2 R^4\right)$$

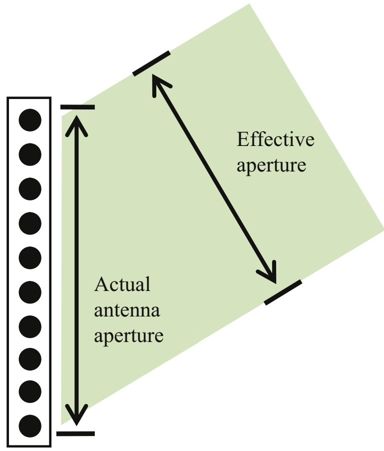

Figure 18.4
Antenna aperture.

where P_t = transmitted power, G_t = antenna transmit gain, A_r = Receive antenna aperture area, σ = radar cross section (function of target geometric cross section, reflectivity of surface, and directivity of reflections), F = pattern propagation factor (unity in vacuum, accounts for multipath, shadowing, and other factors), t_{pulse} = duration of receive pulse, T = duration of transmit interval (the inverse of the PRI), and R = range between radar and target.

Notice that the received power drops with the fourth power of the range, so radar systems must cope with very large dynamic ranges in the receive signal processing. The radar energy seen by the target drops proportional to the range squared. The reflected energy seen by the radar receive antenna further drops by a factor of the range squared. The ability to detect very small signals is crucial to operate at longer ranges.

18.4 Stealth Aircraft

Military planes have been developed with "stealth" characteristics. This means that such a plane has a very small σ, or radar cross section, relative to other aircraft of similar size. It can still be detected by a sufficiently powerful radar or at sufficiently close ranges. Because the size of stealth aircraft is similar to other military aircraft, the stealth characteristic is achieved by reducing the amount of radar signal power that is reflected back from the stealth aircraft to the transmitting radar. There are two fundamental methods to reduce the reflected energy: either absorb the radar signal or deflect it in a different direction that the radar transmitter. Special radar absorbant materials are used in stealth aircraft. The shape and contours of the aircraft greatly influence effective radar cross section. A concave surface tends to reflect radar waves in the general direction of the direction of arrival, back to the transmitter. This is to be avoided in stealth aircraft. Examples of concave surfaces are engine inlets, right angles where wings join the fuselage, open bomb bays, and even the cockpit if the windscreens are transparent to radar signals. Convex surfaces, on the other hand, tend to scatter the radar waves in widely separated directions, reducing the amount of energy reflected back to the source. For example, the B2 stealth bomber is shaped like a flying wing, which is basically a convex shape when viewed from nearly all directions. Smaller features, such as the engine air inlets, have a geometry designed to reflect impinging radar signals in a direction other than that of the illuminating radar.

18.5 Pulsed Radar Operation

Most radar systems are pulsed, which means the radar will transmit a pulse and then listen for receive signals or echoes. This avoids the problem of a sensitive receiver trying to operate simultaneously with a high power transmitter. The pulse width or duration is an important factor. The shorter the pulse width, the easier it is to determine range, as the receive signal is of short duration also. Radars operate by "binning" the receive signals. The receive signal returns are sorted into a set of bins by time of arrival relative to the transmit pulse. This is proportional to the round-trip distance to the object(s) reflecting the radar waves. By analyzing the receive signal strength in the bins, the radar can sort the objects by radar cross section size and across different ranges. This is performed over for all desired azimuths and elevations.

Having many range bins allows more precise range determinations. A short duration pulse is likely to be detected and mapped into only one or two range bins, rather than being spread over many bins. However, a longer pulse duration or width allows for greater amount of signal energy to be transmitted, and a longer time for the receiver to integrate the energy. This means longer detection range. To optimize for both fine range resolution and long range detection, radars use a technique called pulse compression.

18.6 Pulse Compression

The goal of pulse compression is to transmit a long duration pulse of high energy, but to detect a short duration pulse to localize the receive filter output response to one or at most two radar range bins. Early radars accomplished this by transmitting a signal with linear frequency modulation. The pulse would start at a low frequency sinusoid, and increase the frequency over the duration of the radar pulse. This is referred to a "chirp." A special analog filter is used at the receive end, with nonlinear phase response. This filter has a time lag that decreases with frequency. When this rate of time lag decrease is matched to the rate of increase in the chirp, the result is a very short, high amplitude output from the filter. The response of the pulse detection has been "compressed."

All digital radars can also perform pulse compression, but using a different method. Recall the matched filter in the chapter on Complex Modulation and Demodulation. The matched filter will perform the same effect as the analog pulse compression technique just described. If the transmitted radar pulse uses a pseudo random sequence of phase modulations and is detected using a matched filter, then the resulting output will be of high amplitude for only when the receive signal sequence matches up in phase (or delay) to the transmitted pulse sequence. This can be used to precisely identify delay or time of arrival of the receive pulse. The sequence used for radar transmit pulses must have strong autocorrelation properties (sequence of length N correlates to value N with zero offset, and to 0 for any nonzero sequence offset). In radar systems, sequences known as Barker sequences are sometimes used.

18.7 Pulse Repetition Frequency

A high pulse repetition frequency (PRF) has several advantages. First, the higher the PRF, the greater the average power the radar is transmitting (assuming the peak power of each pulse is limited by the transmit circuitry), and the better the chance of detection of targets. A high or fast PRF also allows for more rapid detection and tracking of objects, as range measurements at a given azimuth and elevation can be performed during each PRF interval. A high PRF also allows easier discrimination of the Doppler frequency, a topic discussed in the next chapter. But a low PRF also has an important advantage, which is to allow unambiguous determination of range over longer distances. This is our next topic.

Range to target is measured by round-trip delay in the received echo. It is the speed of light multiplied by the time delay and divided by two to account for the roundtrip.

$$R_{measured} = v_{light} t_{delay}/2$$

The maximum range that can be unambiguously detected is limited by the PRF. This is more easily seen by an example. If the PRF is 10 kHz, then we have 100 μs between pulses. Therefore, all return echoes should ideally be received before the next transmit pulse. This range is simply found by multiplying the echo delay time by the speed of light and dividing by two to account for the roundtrip.

$$R_{maximum} = \left(3 \times 10^8 \ \text{m/s}\right)\left(100 \times 10^{-6} \ s\right)/2 = 15 \ \text{km}$$

Let us suppose the radar system sorts the returns into 100 range bins, based on the time delay of reception. The range resolution of this radar system is then 0.15 km or 150 m. However, there may be returns from distances beyond 15 km. Suppose that a target aircraft 1 is 5 km distant, and a target aircraft 2 is 21 km distant. Target aircraft 1 will have a delay of

$$t_{delay} = 2R_{measured}/v_{light} = 2\left(5 \times 10^3\right)/3 \times 10^8 = 33 \ \mu s$$

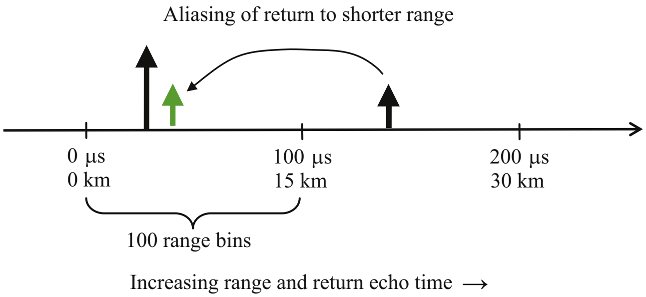

Figure 18.5
Range aliasing.

Target aircraft 2 will have a delay of

$$t_{delay} = 2R_{measured}/v_{light} = 2\left(21 \times 10^3\right)/3 \times 10^8 = 140 \ \mu s$$

The first target return will be mapped into the 33rd out of 100-range bin, and the second target to 40th range bin. This is called a range ambiguity. The target(s) that are within the 15 km are said to be in the unambiguous range. This is analogous to the sampling rate. The range ambiguity is analogous to aliasing during the sampling process (Fig. 18.5).

One solution to this problem is to transmit different pulses at each PRF interval. However, this has the downside of complicating the receiver, as it must now use multiple matched filters at each range bin, and at each azimuth and elevation. This will effectively double the rate of digital signal processing required for each separate transmit pulse and matched filter pair used.

Another approach can be used instead. If we periodically change the PRF slightly, we will find that the returns in the unambiguous range do not move. However, those beyond that range will have shifted in their apparent ranges. This can be illustrated using an example.

Suppose we switch the PRF to 11 kHz, from 10 kHz, or 90.9 µs. The maximum unambiguous range is

$$R_{maximum} = \left(3 \times 10^8 \ m/s\right)\left(90.9 \times 10^{-6} s\right)/2 = 13.6 \ km$$

The target aircraft at 5 km distance will still have a 33-µs delay. Using 100 bins like before, the target return will appear in bin number 100 × 33/90.9 = 36th bin. The target aircraft 2 at 21 km will have a target return delay of 140 µs. This will appear as a return at 140 − 90.9 = 49.1 us, and in 100 × 49.1/90.9 = 54th bin.

So by switching PRFs, we are able to determine that at least one of our targets is beyond the ambiguous range.

PRF = 10 kHz: Target aircraft returns in bin 33, and in bin 40
PRF = 11 kHz: Target aircraft returns in bin 36, and in bin 54

We assume Scenario A:

Target1 moved from bin 33 → 36 when we changed PRF
Target2 moved from bin 40 → 54 when we changed PRF

Instead, what if Scenario B:

Target1 moved from bin 33 → 54
Target2 moved from bin 40 → 36

From this information, we cannot be sure that the first target was at 5 km, and the second at 21 km. We will not work this out here, but if Target1 is at 34.8 km (or 232 μs) and Target2 is at 141 km (or 940 μs), the result would be scenario B.

The way to tell which scenario is in fact occurring is to use a third PRF, perhaps at 9 kHz, or 111 μs.

$$R_{\text{maximum}} = \left(3 \times 10^8 \text{m/s}\right)\left(111 \times 10^{-6} s\right)/2 = 16.7 \text{ km}$$

The target aircraft at 5 km will appear in bin number 100 × 33/111 = 30th bin. The target aircraft 2 at 21 km will appear in bin number 100 × (140 − 111)/111 = 26th bin.

This additional information allows us to know that scenario A is the true one.

In reality, there may be many target returns, and they may also be obscured by noise or clutter in the return. The higher the PRF, the more ambiguity will be present in the range returns. For these reasons, radar detection is at best a statistical process, with calculated probability of detections (at a given range for a given radar cross section). There is also a probability of false detection, which must also be considered when setting detection thresholds.

18.8 Detection Processing

Most radars have thousands of range bins. They may scan wide sweeps of azimuth and elevation. Or in tracking mode, may be focused in narrow regions containing targets, which have been detected. In either case, the rate of digital signal processing can be very high.

A matched filter can be used to detect incoming radar pulses. The radar will focus at a particular azimuth and elevation for one or many PRFs. For each PRF, the incoming data is filtered using an FIR filter with an impulse response that is the complex conjugate of radar transmit pulse. This will produce a large peak in the filter output at the point where the incoming data stream contains radar pulse, which will correspond to a particular range bin.

The computation load in modern radars can be very high. To reduce the amount of computations, filtering, or convolving the receive signals by using matched filters usually not performed using an FIR filter.

An alternative is to perform a fast Fourier transform (FFT) transform of the receive signal sequence from each PRF. The spectral representation of the receive signal can then be multiplied by the frequency response of the radar pulse. After this multiplication, the result can then be transformed back into the time domain using an inverse fast Fourier transform. This will perform the equivalent function as FIR filtering. This sounds counterintuitive, but due to the efficiency of the FFT algorithm, this is often a less computationally intensive process than a large FIR filter. In any case, once the receive pulse has been processed, the amplitude of the matched filter operation is compared to a threshold to determine if this is a valid radar pulse return. Use of results over multiple PRFs can be used to discard or confirm valid target radar returns, maximize the probability of detection and minimize the probability of false detections.

In the next chapter, Doppler processing will be discussed. This also requires use of the FFT algorithm. In radar systems, the FFT is the most common digital signal processing algorithm, and efficient implementation of FFTs is critical for any digital radar system.