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Monostatic Radar

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Dedicated to my Mum

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ABSTRACT

This project is about monostatic radar which is the most commonly used type nowadays ın our life, due to its low cost besides the high quality of receiving and sending electromagnetic waves. Further, this subject is considered as a good introduction to all communication knowledges.

Additionlly, this work is helpful to our knowledge while studying the system of communication while we are talking about the radars commonly. So, we investigate the monostatic radar.

The most important properties of monostatic radar is how to receive and send from the same antenna. In the past, the radars were having two antennas, one is for receiving and the other is for sending the signals, and actually in some old radars we can find more than two antennas and every antenna has its special work without doing any other work. That is why we had alot of errors in many subjects from those radars, but by developing those types of radars we would get better results.

The world's technology always tries to get from any technical machines the best results besides the least errors, that is why we got nowadays the monostatic radar which one can find in it mostly the advanced technology conditions. These informations and more can be exist in this project which we hope that it might be useful for all readers.

INTRODUCTION

In modem times, radar is used in a wide variety of applications including air traffic control, defense, meteorology, and even mapping, Radar is "radio detecting and ranging", an electromagnetic sensor used for detecting, locating, tracking, and identifying objects of various kinds at considerable distances.

It operates by transmitting electromagnetic energy toward object, commonly referred to as targets, and observing the echoes returned from them. The targets may be aircraft, ships spacecraft, automotive vehicles, and astronomical bodies, or even birds, insects, and raindrops. Radar can not only determine the presence, location, and velocity of each objects but can sometimes obtain their size and shape as well. What distinguishes radar from optical and infrared sensing devices is its ability to detect far objects under all weather conditions and to determine their range with precision. Here in this project we shall investigate one of these radars that perform all these functions which is the monostatic radar. Further, the monostatic radar has one antenna for transmitting and receiving.

Chapter 1, describes the fundamentals of radar system, radar pulse, components, target information, target recognition, also its components, transmitters, receivers, and its antennas.

Chapter 2, introduces radar waveforms as Pulse compression, using modulated waveforms, is attractive since Signal-to-Noise Ratio (SIN) is proportional to pulse duration rather than bandwidth in matched filter implementations. Detection processing consists of comparing the amplitude of each range gate/Doppler filter output with a threshold. Detection is reported if the amplitude exceeds that threshold. A false alarm occurs when noise or other interference produces an output of sufficient magnitude to exceed the detection threshold. As the detection threshold is decreased, both the detection probability and the false alarm probability increase.

Chapter 3, describes Radar types, the radar transmits a pulse of RF energy and then receives returns (reflections) from desired and undesired targets. Desired targets may include space, airborne, and sea- and/or surface-based vehicles. They can also include the earth's surface and the atmosphere, depending on the application.

Chapter four which is mainly about monostatic radar and how it works, further the main properties ofthis type of radar, finally all the informations about this special type ofradar have been presented.

CONCLUSION

Radar systems maybe classified into two general categories according to their geometrical configurations: monostatic and bistatic. Very simply, monostatic radar uses a single antenna to receive and transmit radar signals, while bistatic radar uses separate antennas.

This project is about monostatic radar which is the most commonly used type nowadays in our life, due to its low cost besides the high quality of receiving and sending electromagnetic waves. Further, this subject is considered as a good introduction to all communication knowledge's

Monostatic radar, with its single antenna design, is likely to be less expensive to construct and maintain, and this type of radar can be used in many applications like air traffic control, military, ship safety, and space.

Separating the transmitter and receiver results in considerably different radar characteristics than those obtained with the monostatic.

Monostatic radar is versatile because of its ability to scan large volume in space and because of the relative ease with which usable information concerning the targets position and relative velocity can be extracted from the received signal.

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1. FUNDAMENTALS OF RADAR

1.1 Basic Principle

Typical radar operates by radiating a narrow beam of electromagnetic energy into space from an antenna (Figure 1.1).

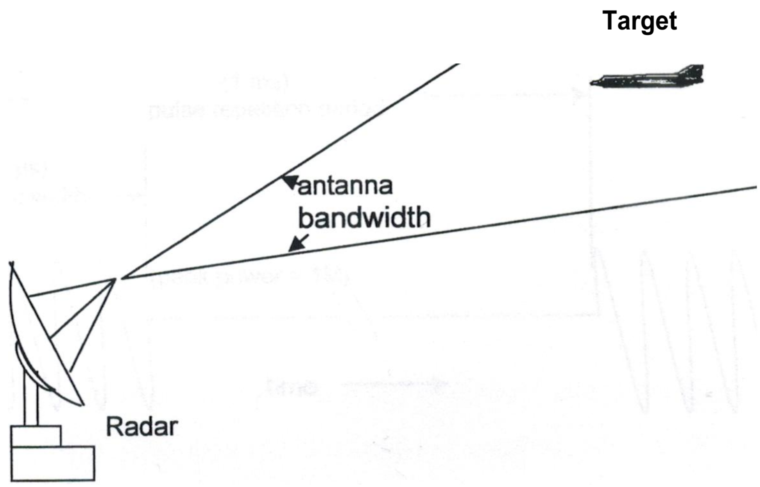


Figure 1.1 Principle of radar operation.

The transmitted pulse which has already passed the target, has reflected a portion of the radiated energy back toward the narrow antenna beam is scanned to search a region where targets are expected.
When a target is illuminated by the beam, it intercepts some of the radiated energy and reflects a portion back toward the radar system. Since most radar systems do not transmit and receive at the same time, a single antenna can be used on a time-shared basis for both transmitting and receiving.
A receiver attached to the output element of the antenna extracts the desired reflected signals and (ideally) rejects those that are of no interest. For example, a signal of interest might be the echo from an aircraft signals that are not of interest might be echoes from the ground or rain, which can mask and interfere with the detection of the desired echo from the aircraft. The radar measures the location of the target in range and angular direction. Range is determined by measuring the total time it takes for the radar signal to make the round trip to the target and back (Figer 1.2). The angular direction of a target is usually

found from the direction in which the antenna points at the time the echo signal is received. Through measurement of the location of a target at successive instants of time, its track can be determined. Once this information has been established, the target's location at a time in the future can be predicted, in many surveillance radar aplications, the target is not considered to be "detected" until its track has been established.

1.1.1 Radar Pulse

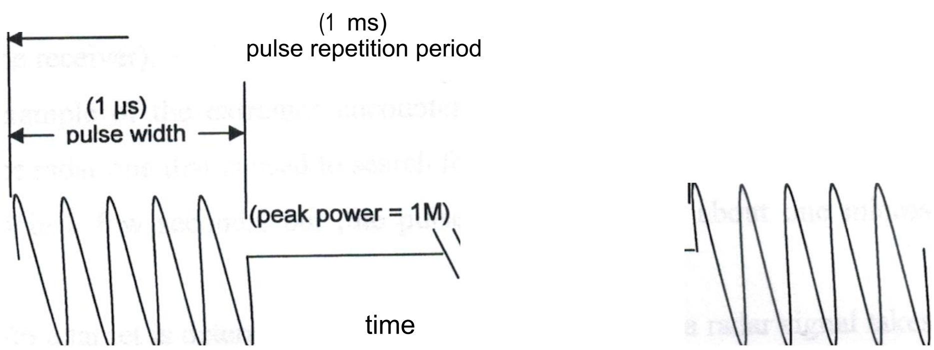


Figure 1.2 *A* typical pulse waveform transmitted by radar.

The most common type of radar signal consists of a repetitive train of short-duration pulses. Figure 1.2 is a simple representation of a sine-wave pulse that might be generated by the transmitter of medium-range radar designed for aircraft detection. This sine wave in the figure represents the variation with time of the output voltage of the transmitter. The numbers given in brackets in the figure are only meant to be illustrative and are not necessarily those of any particular radar. They are atıumbers however, similar to what might be expected for a ground-based radar system with a range of about 50 to 60 nautical miles (or 90 to 110 kilometers), such as the kind used for air traffic control at airports. The pulse width is given in the figure as one millionth of a second (one microsecond). it should be noted that the pulse is shown as containing only a few cycles of the sine wave; however, in a radar system.having the values indicated, there would be 1,000 cycles within the pulse. in Figure 1.2 the time between successive pulses is given as one thousandth of a second (one millisecond), which corresponds to a pulse repetition frequency of 1,000 hertz. The power of the pulse, called the peak power, is taken here to be 1,000,000 watts. Since pulse radar does not radiate continually, the average power us much less than the peak power. In this example, the average power is 1,000 watts. The average power, rather than the peak power, is the measure of the capability of a radar system. Radars have average powers from a few milliwatts to as much as one or more megawatts, depending on the application.

A weak echo signal from a target might be as low as one trillionth of a watt (10^{-12} watt). In short, the power levels in a radar system can be very large (at the transmitter) and very small (at the receiver).

Another example of the extremes encountered in a radar system is the timing. An air-surveillance radar one that is used to search for aircraft) might scan its antenna 360 degrees in azimuth in a few seconds, but ,the pulse width might be about one microsecond in duration.

The range to a target is determined by measuring the time that a radar signal takes to travel out to the target and back. The range to the target is equal to cT/2, where *c* is the velocity of propagation of radar energy, and T is the round-trip time as measured by the radar. From this expression, the round-trip travel of the radar signal is at a rate of 150 meters per microsecond. For example, if the time that it takes the signal to travel out to the target and back were measured by the radar to be 600 microseconds, then the range of the target would be 90 kilometers.

1.1.2 Components

Figure 1.3 shows the basic parts of a typical radar system. The transmitter generates the high-power signal that is radiated by the antenna. The antenna is often in the shape of a parabolic reflector, similar in concept to an automobile headlight but much different in construction and size. It also might consist of a collection of individual antennas operating together as a phased-array antenna.

The duplexer permits ultemate transmission and reception with the same antenna, it is a fast-acting switch that protects the sensitive receiver from the high power of the transmitter. The receiver selects and amplifies the weak radar echoes so that they can be displayed on a television-like screen for the human operator or be processed by a computer. The signal processor separates the signals reflected by the target *(e.g.,* echoes from an aircraft) and from unwanted echo signals (the clutter from land, sea, rain, etc).

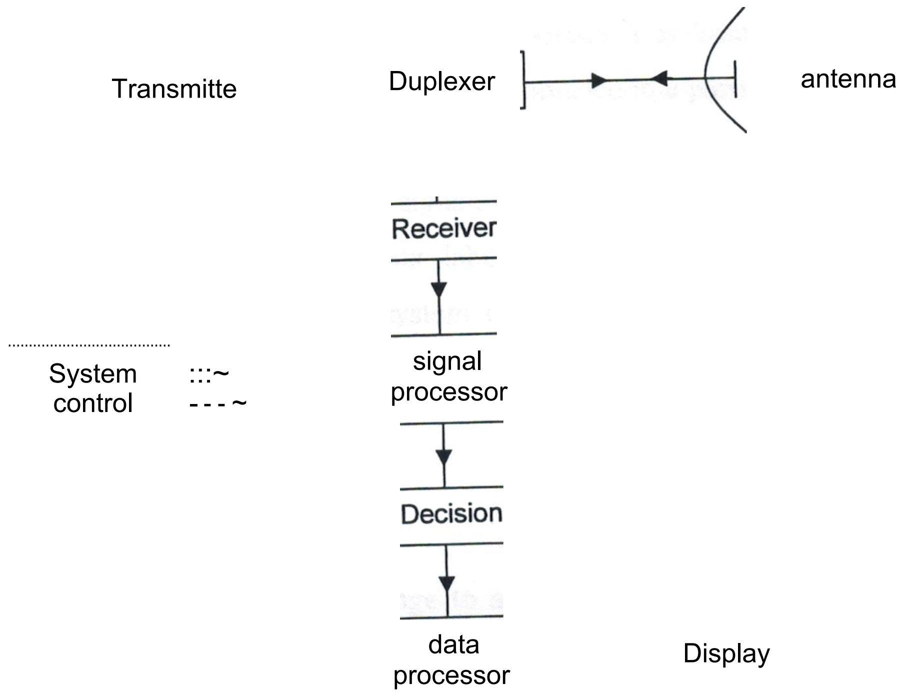


Figure 1.3 Basic parts of a radar system

It is not unusual for these undesired reflections to be much larger than desired target echoes, in some cases more than one minion times larger. Large clutter echoes from stationary objects can be differentiated from small echoes from a moving target by noting the shift in the observed frequency produced by the moving target. This phenomenon is called the Doppler frequency shift (Figure 1.3) At the output of the receiver a decision is made as to whether or not a target echo is present. If the output of the receiver is larger than a predetermined value, a target is assumed to be present.

Once it has been decided that a target is present and its location has been determined, the track of the target can be obtained by measuring the target location at different times. During the early days of radar, target tracking was performed by an operator marking the location of the target "blip" on the face of a cathode-ray tube (CRT) display with a grease pencil. Manual tracking has been largely replaced by automatic electronic tracking, which can process a much greater number of target tracks than can an operator who can handle only a few simultaneous tracks. Automatic tracking is an example of an operation performed by a data processor The type of signal waveform transmitted and the associated received-signal processing in a radar system might be different depending on the type of target involved and the environment in which it is located. An operator can select the parameters of the radar to maximize perfomance in a particular environment. Altrnatively, electronic circuitry in the radar system can automatically analyze the.environmet and select the proper transmitted signal, signal processing, and other radar parameters to optimize performance. The box labeled "system control" in Figurel.3 is intended to represent this function. The system control also can provide the timing and reference signals needed .to permit the various parts of the radar to operate effectively as an integrated system.

1.1.3 Target Information

The ability to measure the range to a target accurately at long distances and to operate under adverse weather conditions are radar's most distinctive attributes. There are no other devices that can compete with radar in the measurement of range The range accuracy of a simple pulse radar depends on the width of the pulse, the shorter pulse, the better accuracy. Short pulses, require wide bandwidths in the receiver and transmitter. A radar with a pulse width of one microsecond can measure the range to an accuracy of a few tens of meters or better. Some special radars can measure to an accuracy of a few centimeters. The ultimate range accuracy of the best radars is limited not by the radar system itself, but rather by the known accuracy of the velocity at which electromagnetic waves travel.

Almost all radars use a directive antenna-i.e, one that directs its energy in a narrow. The direction of a target can be found from the direction in which the antenna is beam pointing when the received echo is at a maximum. A dedicated tracking radar-one that follows automatically a single target so as determine its trajectory-generally has a narrow symmetrical "pencil" beam. Such a radar system can determine the location of the target in both azimuth angle and elevation angle. An aircraft-surveillance radar generally employs an antenna that radiates a "fan" beam, one that is narrow in azimuth (about 1 or 2 degrees) and broad in elevation. A fan beam allows only the measurement of the azimuth angle.

Radar can extract the Doppler frequency shift of the echo produced by a moving target .by noting how much the frequency of the received signal different from the frequency of the signal that was transmitted. A moving target will cause the frequency of the echo signal to increase if it is approaching the radar or to decrease if it is receding from the radar. For example, if a radar system operates at a frequency of 3,000 megahertz and an aircraft is moving toward it at a speed of 400 knots (740 kilometers per hour), the frequency of the received echo signal will be greater than that of the transmitted signal by about 4.1 kilo hertz. The Doppler frequency shift in hertz is equal to $3.4 f_o v_r$, where f_o is the radar frequency in gigahertz and vr is the radial velocity in knots.

Since the Doppler frequency shift is proportional to radial velocity, a radar system that measures such a shift in frequency can provide the radial velocity of a target. The Doppler frequency shift also is used to separate moving targets from stationary ones (land or sea clutter) even when the undesired clutter power might be much greater than the power of the echo from the targets. A form of pulse radar that uses the Doppler frequency shift to eliminate stationaıy clutter is called either a moving target indication (MTI) radar or a pulse Doppler radar, depending on the particular parameters of the signal wavefom.

The above measurements of range, angle, and radial velocity assume that the target is like a point. Actual targets, however, are of finite size and can have distinctive shapes. The range profile of a finite-sized target can be determined if the range resolution of the radar is small compared to the target's size in the range dimension. Some radars can have resolutions smaller than one meter, which is quite suitable for determinig the radiai. size and profile of many targets of interest.

The resolution in angle that can be obtained with conventional antennas is poor compared to that which can be obtained in range. It is possible, however, to achieve good resolution in angle, or cross range, by resolving in Doppler frequency if the radar is moving relative to the target, the Doppler frequency shift will be different for different parts of the target. Thus the Doppler frequency shift can allow the various parts of the target to be resolved. The resolution in cross range derived from the Doppler frequency shift is far better than that achieved with a narrow-beam antenna. It is not unusual for the cross-range resolution obtained from Doppler frequency to be comparable to that obtained in the range dimension.

Cross-range resolution obtained from Doppler frequency, along with range resolution, is the basis for synthetic aperture radar (SAR). SAR produces an image of a scene that is similar to, but not identical with, an optical photograph. One should not expect the image seen by radar "eyes" to be the same as that obseıved by optical ones. Each provides different information. Radar and optical images differ because of the large difference in the :frequencies involved, optical :frequencies are approximately 100,000 times higher than radar frequencies.

Tue SAR can operate from long range and through clouds of other atmospheric effects that limit optical and infrared imaging sensors. The resolution of a SAR image can be made independent of range, an advantage over passive optical imaging, where the resolution worsens with increasing range. Synthetic aperture radars that map areas of the Earth's suıface with resolutions of a few meters can provide information about the nature of the terrain and what is on the surface.

A SAR operates on a moving vehicle, such as an aircraft or spacecraft, to image stationary object or planetary surfaces. Since relative motion is the basis for the Doppler resolution, high resolution (in cross range) also can be accomplished if the radar is stationaıy and the target is moving. This is called inverse synthetic aperture radar (ISAR). Both the target and the radar can be in motion with ISAR.

1.1.4 Target Recognition

Radar can distinguish one kind oftarget from another (such as a bird from an aircraft), and some systems are able to recognoze specific classes of targets. Target recognition is accomplished by measuıing the size and speed of the target and by observing the target with high resolution in one or more dimensions. Propeller or jet engines modify the radar echo from aircraft and can assist in target recognition. Tue flapping of the wings of a bird in flight produces a characteıistic modulation, which can be used to recogize that a bird is present or even to identify one type of bird from another.

1.2 Developments

1.2.1 Early Experiments

Serious developmental work on radar began in the 1930s, but the basic idea of radar had its origins n the classical experiments on electromagnetic radiation conducted by the German physicist Heinrich Hertz during the late 1880s. Hertz set out to verify experimentally the earlier theoretical work of the Scottish physicist James Clerk Maxwell. Maxwell had formulated the general equations of the electromagnetic field, determining that both light and radio waves are examples of electromagnetic waves gove.med by the same fundamental laws but having widely different frequencies. Maxwell's work led to the conclusion that radio waves can be reflected from metallic objects and refracted by a dielectric medium just like light waves. Hertz demonstrated these properties in 1888, using radio waves at a wavelength of 66 centimeters (which corresponds to a frequency of about 455 MHz).

The potential utility of Hertz's work as the basis for the detection of targets of practical interest did not go unnoticed at the time. in 1904 a patent for "an obstacle detect of and ship navigation device," based on the principles demonstrated by Hertz, was issued in several countries to Christian Hulsmeyer, a German engineer. Hulsmeyer built his invention and demonstrated it to the German navy, but failed to arouse any interest. There was simply no economic, societal, or military need for radar until the early 1930s when a long-range military bomber capable of carrying large payloads was developed. This prompted the major countries of the world to look tor a means with which to detect the approach of hostile aircraft.

Most of the countries that developed radar prior to World War II first experimented with other methods of aircraft detection, These,included listening for the acoustic noise of aircraft engines and detecting the electrical noise from their ignition. Researchers also experimented with infrared sensors. None of these, however, proved effective

1.2.2 First Military Radars

During the 1930s, efforts to use radio echo for aircraft detection were initiated independently and almost simultaneously in several countries that were concerned with the prevaiting militaıy situation and that already had practical experience with radio technoiogy. The United States, Great Britain, Germany, France, the Soviet Union, Italy, and Japan all began experimenting with radar within about two years of one another and embarked, with vaıying degrees of motivation and success, on its development for militaıy purposes. Most of these countries had some fonn of operational radar equipment in military service at the start of World War II in 1939.

The first observation of the radar effect at the U.S. Naval Research Laboratoıy (NRL) in Washington, D.C., was made in 1922. NRL researchers positioned a radio transmitter on one shore of the Potomac River and a receiver on the other. A ship sailing on the river caused fluctuations in the intensity of the received signals when it passed between the transmitter and receiver. (Today, such a configuration would be called bistatic radar.) in spite of the promising results of this experiment, U.S. Navy officials were unwilling to sponsor further work.

1.3 Radar Subsystems

Figure 1.3 shows the major subsystems that make up a typical radar system. These subsystems are described in greater detail here.

1.3.1 Antennas

A widely used from of radar antenna is the parabolic retlector, the principle of which is shown in cross section in (Figure 1.4-A). A horn antenna or other small antenna is Placed at the focus of the parabola to illuminate the parabolic surface of the reflector.After being reflected by this surface, the electromagnetic energy is radiated as a narrowbeam. A paraboloid, which is generated by rotating a parabola about its axis, forms a symmetrical beam called a pencil beam. A fan beam, one with a narrow beam width in azimuth and a broad beam width in elevation, can be obtained by illuminating an asymmetrical section of the paraboloid. An example of an antenna that produces a fan beam is shown in the photograph.

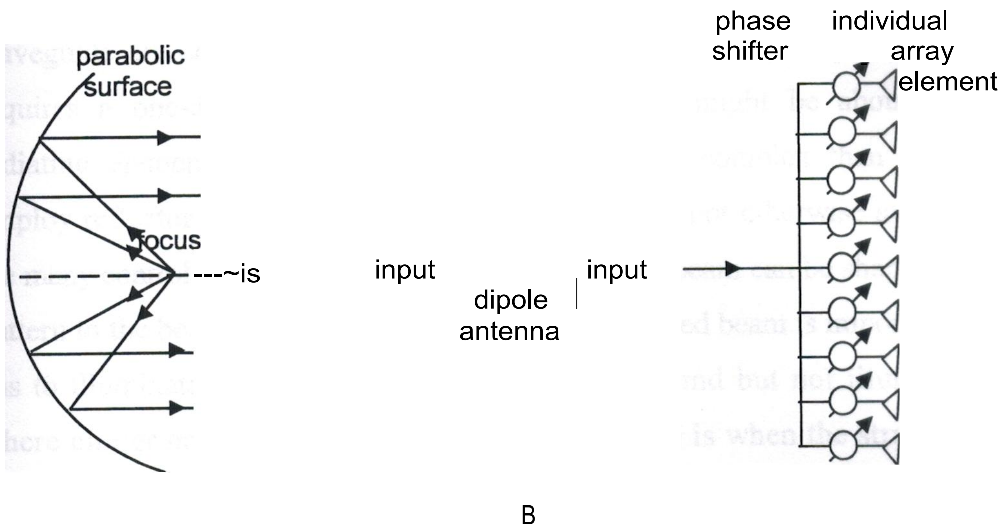


Figure 1.3 Radar amennas. (A) A parabolic reflector antenna in which the energy radiated from the focus is reflected from the parabolic surface as a narrow beam. (B) A dipole antenna. (C) A phased-array antenna composed of many individual radiating elements.

The half-wave dipole (Figure 1.4-B), whose dimension is one-half of the radar wave length, is the classic type of electromagnetic antenna. A.single dipole is not of much use tor radar, since it produces a beam width too wide for most applications. Radar requires a narrow beam (a beam width of only a few degrees) in order to concentrate its energy on the target and .to detemline the target location with accuracy. Combining many individual dipole antennas so that the signals radiated or received by each elemental dipole are in unison, or in step can form such narrow beams.

The phase shifters at each radiating antenna-element shift the phase of the signal, so that all signals received from a particular direction will be in step with one another. Similarly, all signals radiated by the individual elements of the antenna wıll be ın step whh one another in some specific direction. Changing the phase shift at each element alters the direction of the antenna beam. An antenna of this kind is called an electronically steered phased-array. It allows rapid changes in the position of the beam without moving large mechanical structures. in some systems, the beam can be changed from one direction to another within microseconds.

The individual radiating elements of a phased-array antenna need not be dipoles; various other types of antenna elements also can be used. For example, slots cut in the side of a waveguide are common, especially at the higher microwave frequencies. in a radar that requires a one-degree, pencil-b.eam antenna, there might be about 5,000 individual radiating elements. The phased-array radar is more complex than radar systems that employ reflector antennas, but it provides capabilities not otherwise available. Since there are many control points in a phased-array,the radiated beam can be shaped to give a desired pattern to the beam. Controlling the shape of the radiated beam is important when the beam has to illuminate the air space where aircraft are found but not illuminate the ground, where clutter echoes are produced Another example is when the stray radiation (called antenna side lobes) outside the main beam of the antenna pattern must be minimized.

The electronically steered phased-array is attractive for applications that require large antennas or when the beam must be rapidly changed from one direction to another Satellite surveillance radars and ballistic missile detection radars are examples that usually require phased-arrays The U.S. Army's Patriot battlefield air-defense system and the U.S. Navy's Aegis system for ship air-defense also depend on the electronically steered phased-array antenna

The phased-array antenna is also used without the phase shifters in Figure 1.4 (C). The beam is steered by the mechanical movement of the entire antenna. Antennas of this sort are preferred over the parabolic reflector for airborne applications, in land-based air-surveillance radars requiring multiple beams, and in applications that require ultra antenna side lobe radiation.

1.3.2 Transmitters

The transmitter of a radar system must be efficient, reliable, not too large in size and weight, and easily maintained, as well as have the wide bandwidths and high power that are characteristic of radar applications. In MT, pulse Doppler, and CW applications, the transmitter must generate noise-free, stable transmissions so that extraneous (unwanted) signals from the transmitter do not interfere with the detection of the small Doppler frequency shift produced by weak moving targets.

It was observed earlier that the invention of the magnetron transmitter in the lasted 1930s resulted in radar systems that could operate at the higher frequencies known as microwaves. The magnetron transmitter has certain limitations, but it continues to be widely used-generally in low-average-power applications such as ship navigation radar and airborne weather-avoidance radar. The magnetron is a power oscillator in that it self-osciııates when voltage is applied. Other radar transmitters usually are power amplifiers in that they take low-power signals at the input and amplify them to high power at the output. This provides stable high-power signals, as the signals to be radiated can be generated with precision at low power.

The klystron amplifier is capable of some of the highest power levels used in radar. It has good efficiency and good stability. The disadvantages of the klystron are that it is usually large and it requires high voltages *(e.g.* about 90 kilovolts for one megawatt of peak power). At low power the instantaneous bandwidth of the klystron is small, but the klystron is capable of larg.e bandwidth at high peak powers of a few megawatts.
The traveling-wave tube (TWT) is related to the klystron. It has veıy wide bandwidths at low peak power, but, as the peak power levels are increased to those needed for radar, its bandwidth decreases. As peak power increases, the bandwidths of the TWT and the klystron approach one another.
Solid-state transmitters, such as the silicon bipolar transistor, are attractive because of their potential for long life, ease of maintenance, and relatively wide bandwidth. An individual solid-state device generates relatively low power and can be used only when the radar application can be accomplished with low power (as in short-range applications or in the radar altimeter). High power can be achieved, however, by combining the outputs of many individual solid-state devices.
While the solid-state transmitter is easy to maintain and is capable of wide-band operation, it has cellaİn disadvantages It is much better suited for long pulses (milliseconds) than for the short pulses (microseconds). Long pulses can complicate radar operation because signal processing (such as pulse compression) is needed to achieve the desired range resolution. Furthermore, a long-pulse radar generally requires several different pulse widths: a long pulse for long range and one or more shorter pulses to observe targets at the

ranges masked when the long pulse is transmitting. Every kind of transmitter has its disadvantages as well as advantages. in any particular application, the radar engineer must continually search for compromises that give the results desired without too many negative effects that cannot be adequately accommodated.

1.3.3 Jleceivers

Like most other receivers, the radar receiver is a classic superheterodyne. It has to filter the desired echo signals from unwanted clutter signals and receiver noise that interfere with detection. It also must amplify the weak received signals to a level where the receiver output is large enough to actuate a display or a computer. The technology of the radar receiver is well established and seldom sets a limit on radar performance.

The receiver must have a large dynamic range in situations where it is necessary to detect weak signals in the presence of very large. clutter echoes by recognizing the Doppler frequency shift of the desired moving targets. Dynamic range can be loosely described as the ratio of the largest to the smallest signals that can be handled adequately by a receiver without distortiofı. A radar receiver might be required to detect signals that vaıy in power by a million to one-and sometimes much more.

In most cases, the sensitivity of a radar receiver is determined by the noise generated internally at its input. Because it does not generate much noise of its own, a transistor is usually used as the first stage of a receiver.

1.3.4 Signal and Data Processors

The; signal processor is the part of the receiver that extracts the desired. signal and rejects clutter. Doppler filtering in an MTI radar or in a pulse Doppler systym is an example. Most signal processing is performed digitally with computer technology. Digital processing has significant capabilities in signal processing not previously available with analog methods. Without digital methods many of the signal processing techniques found in today's high performance radars would not be possible. Digital processing also has made practical data processing, such as required for automatic tracking. Pulse compression (described below in Pulse-compression radar) is sometimes included under signal processing. It too benefits from digital technology, but analog processors *(e.g.* surface acoustic wave delay-lines) are used rather than digital methods when pulse compression must achieve resoiutions of a few meters or less.

1.3.5 Display

The cathode-ray tube has been the traditional means of displaying the output of a radar system.. Although it has its limitations, the CRT has been the preterred technology ever since the early days of radar. The CRT has undergone continual improvement that has made it even more versatile.

Plan position indicator, or PPI is a maplike presentation in po l ar coordinates of range and angle. The CRT screen is dark (other than for slight noise background) except when echo signals are present. The PPl is called an intenşity-modulated display because the intensity of the electron beam of the CRT is increased sufficiently to excite the phosphor of the screen whenever an echo signal is present. The PPI is the most common form of display in use with radar. Another variety, the B-scope, is also an intensity-modulated display that presents the same information and the same coordinates as the PPl but in rectangular rather than polar format. ln still another format, the A-scope, the received signal amplitude is displayed as the vertical coordinate and the range as the horizontal coordinate. The A-scope is called an amplitude-modulated display because echo signals are indicated by the increased amplitude (the vertical coordinate) on the CRT .The A-scope is not a suitable display for a surveillance radar that must search 360 degrees in azimuth, but it is used for tracking radars and in experimental radars when examining the nature of the echo signal is important.

Alıopractical radar displays have been two dimensional, yet most radars provide more information than can be displayed on the two coordinates of a flat screen. Colour coding of the intensity-modulated signal on the PPI is sometimes used to provide additional information about the echo signal. Colour has been employed, for example, to indicate the strength of the echo. Doppler weather radars good use of colour coding to indicate on a two-dimensional display the rain intensity associated with each echo shown. They also utilize colour to indicate the radial speed of the wind, the wind shear, and other information relating to severe storms. The PPI displays targets as if seen in a horizontal plane. On the other hand, a range-height indicator, or RIIl, is an intensity-modulated display that presents the echoes that appear in a vertical plane-e.g., a vertical cut through the cloud of a severe storm.

The radar display has benefited from the availability of digital technology. Digital memory allows the radar to store data from an entire scan period (usually one rotation of the radar antenna) and present the information to the operatof all at once (as in the case of a television-type monitor) rather than display targets only when they are actually within the antenna beam. This allows the operator to view the entire scene all the time and to manipulate the output to display the type oftarget information of most interest.

Modem surveillance radars rarely display the output of a radar receiver without further processing (raw video). When automatic detection of targets is employed in a radar system, the rejection ofun.wantedechoes such as land or sea clutter, the addition of the radar pulses received from a target, and the decision.as to whether a target is present or not are all performed electronically without assistance from a human operator. The display then shows only detected targets without the background noise. This has been called a "cleaned-up" display or processed video. When automatic traclang is performed electronically (in a digital data processor), only processed target tracks are displayed and no individual target detections are indicated. The speed of a target and its direction of travel can be indicated on the CRT by the length of the line defining the track and its orientation. Near each target track on the display, alphanumeric information can be entered automatically to indicate information that is known about the target. For example, when the air-traffic-control radar-beacon system (ATCRBS) is used in conjunction with an air-surveillance radar, the alphanumeric data on the display can indicate the flight number of the aircraft and its altitude.

1.4 Factors Affecting Radar Performance

The performance of a radar system can be judged by the following: (1) the maximum range at which it can see a target of a specified size, (2) the accuracy of its measurement of target location in range and angle, (3) its ability to distinguish one target from another, (4) its ability to detect the desired target echo when masked by large clutter echoes, unintentional interfering signals from other "friendly" transmitters, or intentional radiation from hostile jamming (if a military radar), (5) its ability to recognize the type of target, and (6) its availability (ability to operate when needed), reliability, and maintainability Some of the major factors that affect performance are discussed in this section.

1.4.1 Transmitter Power and Antenna Size

The maximum range of a radar system depends in large part on the average power of its transmitter and the physical size of its antenna. (In technical terms, this is the power-aperture product.) There are practical limits to each. As noted before, some radar systems have an average power of roughly one megawatt. Phased-array radars about 100 feet in diameter are not uncommon, some are much larger. Likewise, mechanically scanned reflector antennas about 100 feet or larger in size can be found. There are specialized radars with (fixed) antennas, such as some HF over-the-horizon radars and the U.S. Space Surveillance System (SPASUR), that extend more than one mile.

1.4.2 Receiver Noise

The sensitivity of a radar receiver is determined by the unavoidable noise that appears at its input. At microwave radar frequencies, the noise that limits detectability is usually generated by the receiver itself *(i.e.* by the random motion of electrons at the input of the receiver) rather than by external noise that enters the receiver via the antenna. The radar engineer often employs a transistor amplifier as the first stage of the receiver even though lower noise can be obtained with more sophisticated devices. This is an example Of the application of the basic engineering principle that the "best" peıformance that can be obtained might not necessarily be the solution that best meets the needs of the user.

The receiver is designed to enhance the desired signals and to reduce the noise and other undesired signals that inteıfere with detection. The designer attempts to maximize the detectability of weak signals by using what radar engineers call a "matched filter which is a filter that maximizes the signal-to-noise ratio at the receiver output. The matched filter has a precise mathematical tormulation that depends on the shape of the input signal and the character of the receiver noise. A suitable approximation to the matched filter for the ordinary pulse radar, however, is one whose bandwidth in hertz is the reciprocal of the pulse width in seconds.

1.4.3 Target Size

The size of a target as "seen" by radar is not always related to the physical size of the object. The measure of the target size as observed by radar is called the radar cross section and is given in units of area (square meters). It is possible for two targets with the same physical cross sectional area to differ considerably in radar size, or radar cross section. For example, a flat plate one square meter in area will produce a radar cross section of about 1,000 square meters at a frequency of 3,000 megahertz (S band; see below) when viewed perpendicular to the surface. A cone-sphere (an object resembling an ice-cream cone) when viewed in the direction of the cone rather than the sphere could have a radar cross section one thousandth of a square meter even though its projected area is also one square meter. in theory, this value does not depend to a great extent on the size of the cone or the cone angle. Thus the flat plate and the cone-sphere can have radar cross sections that differ by a million to one even though their physical projected areas are the same.

The sphere is an unusual target in that its radar cross section is the same as its physical cross section area (when its circumference is large compared to the radar wavelength). That is to say, a sphere w.ith a projected area of one square meter has a radar cross section of one square meter.

Commercial aircraft might have radar cross sections from about 10 to 100 square meters, except when viewed broadside, where it is much larger. (This is an aspect that is seldom of interest, however.) Most air-traffic-controi radars are required to detect aircraft with a radar cross section as low as two square meters, since some small general-aviation aircraft can be of this value. For comparison, the radar cross section of a man has been measured at microwave frequencies to be about one square meter .A bird can have a cross section of 0.0l square meter. Although this is a small value, a bird-can be readily detected at ranges of several tens of miles by long-range radar. In general, many birds can be picked up by radar so that special measures must usually be taken to insure that echoes from birds do not interfere with the detection of desired target:

The radar cross section of an aircraft and most other targets of practical interest is not a constant but, rather, fluctuates rapidly as the aspect of the target changes with respect to the radar unit. It would not be unusual for a slight change in aspect to cause the radar cross section to change by a factor of 10 to 1,000. (Radar engineers have to take this fluctuation in the radar cross section oftargets into account in their design.)

1.4.4 Clutter

Echoes from land, sea, rain, snow, hail, birds, insects, auroras, and meteors are of interest to those who observe and study the environment, but they are a nuisance to those who want to detect and follow aircraft, ships, missiles, or other similar targets. Clutter echoes can seriously limit the capability of a radar system; thus a significant part of radar design is devoted to minimizing the effects of clutter without reducing the echoes from desired targets. The Doppler frequency shift is the usual means by which moving targets are distinguished from the clutter of stationary objects. Detection of targets in rain is less of a problem at the lower frequencies, since the radar echo from rain decreases rapidly with decreasing frequency and the average cross section of aircraft is relatively independent of frequency in the microwave region. Because raindrops are more or less spherical (symmetrical) and aircraft are asymmetrical, the use of circular polarization can enhance the detection of aircraft in rain. With circular polarization the electric field rotates at the radar frequency. Because of this, the electromagnetic energy reflected by the rain and the aircraft will be affected differently, thereby making it easier to distinguish between the two. (in tair weather, most radars use linear polarization-i.e.. the direction of the field is fixed).

1.4.5 Atmospheric Effects

As was mentioned, rain and other forms of precipitation can cause echo signals that mask the desired target echoes There are other atmospheric phenomena that can affect radar pertormance as well. the decrease in density of the Earth's atmosphere with increasing altitude causes radar waves to bend. as they propagate through the atmosphere this usually increases the detection range at iow angles to a slight extent. The atmosphere can torm !"ducts" that trap and guide radar energy around the curvature of the Eanh and allow detection at ranges beyond the normal horizon. Ducting over water is more likely to occur in tropical climates than in coider regions. Ducts can sometimes extend the range of an airborne radar, but on other occasions they may cause the radar energy to be diverted and not illuminate regions below the ducts. This results in the formation of what are called radar holes in the coverage. Since it is not predictable or reliable, ducting can in some instances' be more of a nuisance than a help. Loss of radar energy,when propagation is through the clear atmosphere or rain, is usually in significant for systems operating at microwave frequencies.

1.4.6 Interference

Signals from nearby radars and other transmitters can be strong enough to enter a radar when propagation is through the clear atmosphere or rain, is usually insignificant for systems operating at microwave frequencies receiver and produce spurious responses. Well-trained operators are not often deceived by interference, though they may find it a nuisance. Interference is not as easily ignored by automatic detection and tracking systems, however, and so some method is usually needed to recognize and remove interference pulses before they enter the automatic detector and tracker of a radar.

1.4.7 Electronic Countermeasures

The purpose of hostile electronic countenneasures (ECM) is to deliberately degrade the effectiveness of military radar. ECM can consist of (1) noise jamming that enters the receiver via the antenna and increases the noise level at the input of the receiver , (2) false target generation, or repeater jamming, by which hostile jammers introduce additional signals into the radar receiver in an attempt to confuse the receiver into thinking they are real target echoes, (3) chaff, which is an artificial cloud consisting of a large number of tiny metallic retlecting strips that create strong echoes over a large area to mask the presence of real target echoes or to create confusion, and (4) decays, which are small, inexpensive air vehicles or other objects designed to appear to the radar as if they were real targets. Military radars are also subject to direct attack by conventional weapons or by antiradiation missiles (ARMs) that use radar transmissions to find the target and home on it.

Military radar engineers have developed various ways of countering hostile ECM and maintaining the ability of a radar system to perform its mission. It might be noted that a military radar system can often accomplish its mission satistactorily even though its perfonnance in the presence of ECM is not what it would be if such measures were absent.

1.5 Antenna

The radar antenna function is to first provide spatial directivity to the transmitted EM wave and then to intercept the scattering of that wave from a target. Most radar antennas may be categorized as mechanically scanning or electronically scanning. Mechanically scanned reflector antennas are used in applications where rapid beam scanning is not required. Electronic scanning antennas include phased arrays and frequency scanned antennas.

Phased array beams can be steered to any point in their field-of-view, typically within 10 to 100 ms, depending on the latency of the beam steering subsystem and the switching time of the phase shifters. Phased arrays are desirable in multiple function radars since they can interleave search operations with multiple target tracks.

There is a Fourier transform relationship between the antenna illumination function and the far-field antenna pattern. Hence, tapering the illumination to concentrate power near the center of the antenna suppresses side lobes while reducing the effective antenna aperture area. The phase and amplitude control of the antenna illumination determines the achievable side lobe suppression and angle measurement accuracy.

Perturbations in the illumination due to the mechanical and electrical sources distort the illumination function and constrain performance in these areas. Mechanical illumination error sources include antenna shaJ?e deformation due to sag and thermal effects as well as manufacturing defects.

Electrical illumination error is of particular concern in phased arrays where sources include beam steering computational error and phase shifter quantization. Control of both the mechanical and electrical perturbation errors is the key to both low side lobes and highly accurate angle measurements. Control denotes that either tolerance are closely held and maintained or that there must be some means for monitoring and correction.

Phased arrays are attractive for low side lobe applications since they can provide element-level phase and amplitude control.

1.5.1 Transmitter

The transmitter function is to amplify waveforms to a power level sufficient for target detection and estimation.

There is a general trend away from tube-based transmitters toward solid-state transmitters. In particular, solid-state transmit/receive modules appear attractive for constructing phased array radar systems. In this case, each radiating element is driven by a module that contains a solid-state transmitter, phase shifter, low-noise amplifier, and associated control components. Active arrays built from such modules appear to offer significant reliability advantages over radar systems driven from a single transmitter. However, microwave tube technology continues to offer substantial advantages in power output over solid-state technology.

1.5.2 Receiver and Exciter

This subsystem contains the precision timing and frequency reference source or sources used to derive the master oscillator and local oscillator reference frequencies. These reference frequencies are used to down convert received signals in a multiple-stage super heterodyne architecture to accommodate signal amplification and interference rejection. The receiver front end is typically protected from overload during transmission through the combination of a circulator and a transmit/receive switch.

The exciter generates the waveforms for subsequent transmission. As in signal processing, the trend is toward programmable digital signal synthesis because of the associated flexibility and performance stability.

1.5.3 Antenna Directivity and Aperture Area

The directivity of the antenna is

$$D = \frac{47rA77}{A,2} \tag{1.1}$$

where 77. is aperture efficiency and A . is radar carrier wavelength. Aperture inefficiency is due to the antenna illumination factor.

The common form of the radar range equation uses power gain rather than directivity.

Antenna gain is equal to the directivity divided by the antenna losses. In the design and analysis of modem radars, directivity is a more convenient measure of performance because it permits designs with distributed active elements, such as solid-state phased arrays, to be assessed to permit direct comparison with passive antenna systems.

Beam-width and directivity are inversely related; a highly directive antenna will have a narrow beam-width. For typical design parameters,

$$D = \frac{10^7}{\theta_{az}\theta cl}$$

where θ_{az} and θ_{cl} are the radar azimuth and elevation beam-widths, respectively, in mill radians.

2. RADAR WAVEFORMS

2.1 Pulse Compression

Pulse compression, using modulated waveforms, is attractive since Signal-to-Noise Ratio (SIN) is proportional to pulse duration rather than bandwidth in matched filter implementations. Ideally, the interpose modulation is chosen to attain adequate range resolution and range side-lobe suppression performance while the pulse duration is chosen to provide the required sensitivity. Pulse compression waveforms are characterized as having a time bandwidth product (IBP) significantly greater than unity, in contrast to an un-modulated pulse, which has a TBP of approximately unity.

2.2 Pulse Repetition Frequency

The radar system pulse repetition frequency (PRF) determines its ability to unambiguously measure target range and range rate in a single CPI as well as determining the inherent clutter rejection capabilities of the radar system. In order to obtain an unambiguous measurement of target range, the interval between radar pulses (1/PRF) must be greater than the time required for a single pulse to propagate to a target at a given range and back. The maximum unambiguous range is then given by C/(2PRF) where C is the velocity of electromagnetic propagation.

Returns from moving targets and clutter:sources are offset from the radar carrier frequency by the associated Doppler frequency. As a function of range rate, *R;* the Doppler frequency, f_D, is given by *2R IJA* . A coherent pulse train samples the returns Doppler modulation at the PRF. Most radar systems employ parallel sampling in the in-phase and quadrature base-band channels so that the effective sampling rate is twice the PRF.

The target's return is folded in frequency if the PRF is less than the target Doppler.

Clutter returns are primarily from stationary or near-stationary surfaces such as terrain. In contrast, targets of interest often have a significant range rate relative to the radar clutter. Doppler filtering can suppress returns from clutter with the exception of frequency ambiguity. Ambiguous measurements can be resolved over multiple CPis by using a sequence of slightly different PRFs and correlating detections among the CPis.

2.3 Detection and Search

Detection processing consists of comparing the amplitude of each range gate/Doppler filter output with a threshold. Detection is reported if the amplitude exceeds that threshold. A false alarm occurs when noise or other interference produces an output of sufficient magnitude to exceed the detection threshold. As the detection threshold is decreased, both the detection probability and the false alarm probability increase. S/N must be increased to enhance detection probability while maintaining a constant false alarm probability.

The Radar Cross Section, RCS fluctuation effects must be considered in assessing detection performance. The Swerling models which use chi-square probability density functions (PDFs) of2 and 4 degrees of freedom (DOF) are commonly used for this purpose. The Swerling 1 and 2 models are based on the 2 DOF PDF and can be derived by modeling the target as an ensemble of independent scatterers of comparable magnitude. This model is considered representative of complex targets such as aircraft.

The Swerling 3 and 4 models use the 4 DOF PDF and correspond to a target with a single dominant scatterer and an ensemble of lesser scatterers. Missiles are sometimes represented by Swerling 2 and 4 models.

Further the Swerling 1 and 3 models presuppose slow fluctuation such that the target's RCS is constant from pulse to pulse within a scan. In contrast, the RCS of Swerling 2 and 4 targets is modeled as independent on a pulse to pulse basis. Single-pulse detection probabilities for nonfluctuating, Swerling 1/2, and Swerling 3/4 targets are depicted in figure 2.1. This curve is based on a typical false alarm number corresponding approximately to a false alarm probability of 10^{-6}. The difference in S/N required for a given detection probability for a fluctuating target relative to the nonfluctuating case is termed the fluctuation loss.

The detection curves presented here and in most other references presuppose noise-limited operation.

In many cases, the composite interference present at the radar system output will be dominated by clutter returns or electromagnetic interference such as that imposed by hostile electronic countermeasures. The standard textbook detection curves cannot be applied in these situations unless the composite interference is statistically similar to thermal noise with a Gaussian PDF and a white power spectral density. The presence of non-Gaussian interference is generally characterized by an elevated false alarm probability. Adaptive detection threshold estimation techniques are often required to search for targets in environments characterized by such interference.

2.4 Estimation and Tracking

2.4.1 Measurement Error Sources

Radars measure target range and angle position and Doppler frequency. Angle measurement performance is emphasized here since the corresponding cross-range error dominates range error for most practical applications. Target returns are generally smoothed in a tracking filter, but tracking performance is largely determined by the measurement accuracy of the subject radar system. Radar measurement error can be characterized as indicated in Table 2.1.

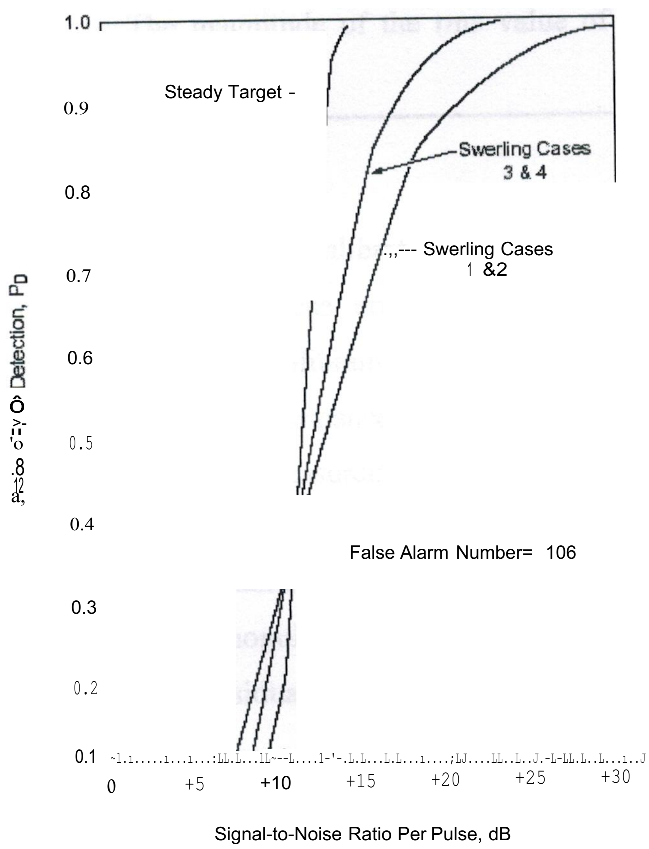


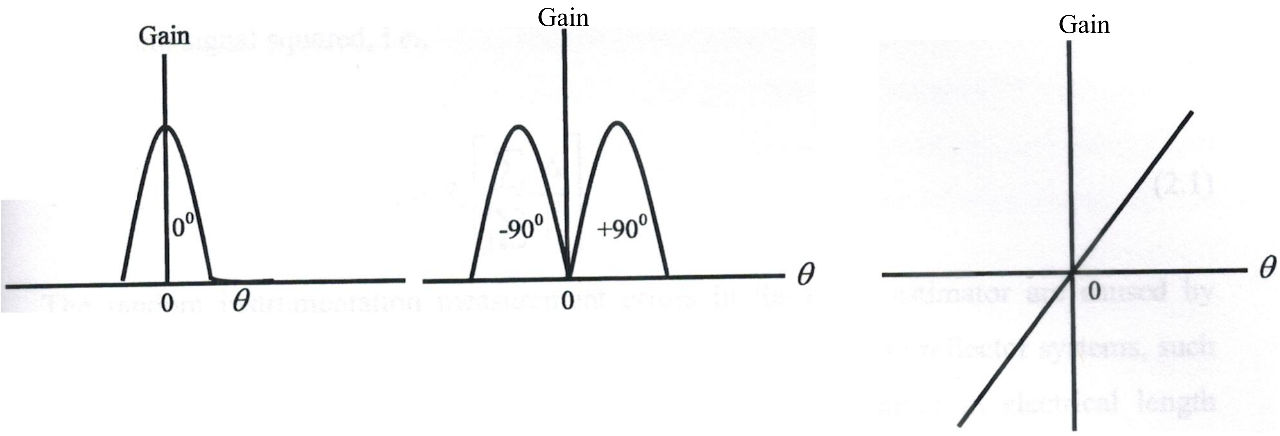
Figure 2.1 Detection Probabilities for Various Target Fluctuation Models.

Table 2.1 Radar Measurement Error

Random errors	Those errors that cannot be predicted except on a statistical basis. The magnitude of the random error can be termed the *precision* and is an indication of the repeatability of a measurement.
Bias error	systematic error whether due to instrumentation or propagation conditions. A nonzero mean value of a random error.
Systematic error	An error whose quantity can be measured and reduced by calibration.
Residual systematic	Those errors remaining after measurement and calibration. A function of the systematic and random errors in the calibration process.
Accuracy	The magnitude of the rms value of the residual systematic and random errors.

The radar design and the alignment and calibration process development must consider the characteristics and interaction of these error components. Integration of automated techniques to support alignment and calibration is an area of strong effort in modem radar design that can lead to significant performance improvement in fielded systems.

As indicated previously, angle measurement generally is the limiting factor in measurement accuracy. Target azimuth and elevation position is primarily measured by a monopulse technique in modem radars though early systems used sequential lobbing and conical scanning. Specialized monopulse tracking radars utilizing reflectors have achieved instrumentation and *SIN* angle residual systematic error as low as $50\,\mu$ rad. Phased array antennas have achieved a random error of less than $60\,\mu$ rad, but the composite systematic residual errors remain to be measured. The limitations are primarily in the tolerance on the phase and amplitude of the antenna illumination function.



(a) (b) (c)

Figure 2.2 Monopulse Beam Patterns and Difference Voltage: (a) Sum; (b) Difference; (c) Difference Voltage

E1

)./2 ~

E1 .,)./2 ~

Figure 2.3 Monopulse Comparator

Figure 2.2 shows the monopulse beam patterns. The first is the received sum pattern that is generated by a feed that provides the energy from the reflector or phased array antenna through two ports in equal amounts and summed in phase in a monopulse comparator shown in figure 2.2. The second is the difference pattern generated by providing the energy through the same two ports in equal amounts but taken out with a phase difference of π radians, giving a null at the center. A target located at the center of the same beam would receive a strong signal from the sum pattern with which the target could be detected and ranged. The received difference pattern would produce a null return, indicating the target was at the center of the beam. If the target were off the null, the signal output or difference voltage would be almost linear proportional to the distance off the center (off-axis), as shown in the figure 2.2. This output of the monopulse processor is the real part of the dot product of the complex sums and the difference signals divided by the absolute magnitude of the sum signal squared, i.e.,

$$e_d = R_e\left[\frac{\sum \Delta}{\left|\sum\right|^2}\right] \tag{2.1}$$

The random instrumentation measurement errors in the angle estimator are caused by phase and amplitude errors of the antenna illumination function. In reflector systems, such errors occur because of the position of the feedhom, differences in electrical length between the feed and the monopulse comparator, mechanical precision of the reflector, and its mechanical rotation. In phased array radars, these errors are a function of the phase shifters, time delay units, and combiners between the antenna elements and the monopulse comparator as well as the precision of the array. Although these errors are random, they may have correlation intervals considerably longer than the white noise considered in the thermal-noise random error and may depend upon the flight path of the target. For a target headed radially from or toward the radar, the correlation period of angle-measurement instrumental errors is essentially the tracking period. For crossing targets, the correlation interval may be pulse to pulse.

As in the estimate of range, the propagation effects of refraction and multipath also enter into the tracking error. The bias error in range and elevation angle by refraction can be estimated as

$t\iota R = 0.007N,$ ese E_0 *(m)* (2.2)

$l\iota E_0 = N,$ cot E_0 *(μ rad)* (2.3)

where $N,$ is the surface refractivity and E_0 is the elevation angle.

One can calculate the average error iri multipath. However, one cannot correct for it as in refraction since the direction of the error cannot be known in advance unless there are controlled conditions such as in a carefully controlled experiment. Hence, the general approach is to design the antenna sidelobes to be as low as feasible and accept the multipath error that occurs when tracking close to the horizon. There has been considerable research to find means to reduce the impact, including using very wide bandwidths to separate the direct path from the multipath return.

2.4.2 Tracking Filter Performance

Target tracking based on processing returns from multiple CPis generally provides a target position and velocity estimate of greater accuracy than the single-CPI measurement accuracy delineated in Table 2.1. In principle, the error variance of the estimated target position with the target moving at a constant velocity is approximately 4/n.cl m where *n* is the number of independent measurements processed by the track filter and crm is the single measurement accuracy. In practice, the variance reduction factor afforded by a track filter is often limited to about an order of magnitude because of the reasons summarized in the following paragraphs.

Track filtering generally provides smoothing and prediction of target position and velocity via a recursive prediction-correction process. The filter predicts the target's position at the time of the next measurement based on the current smoothed estimates of position, velocity, and possibly acceleration. The subsequent difference between the measured position at this time and the predicted position is used to update the smoothed estimates.

The update process incorporates a weighting vector that determines the relative significance given the track filter prediction versus the new measurement in updating the smoothed estimate.

Target model fidelity and adaptivity are fundamental issues in track filter mechanization. Independent one dimensional tracking loops may be implemented to control pulse-to-pulse range gate positioning and antenna pointing. The performance of one-dimensional polynomial algorithms, such as the alpha-beta filter, to track targets from one pulse to the next and provide modest smoothing is generally adequate. However, one dimensional closed-loop tracking ignores knowledge of the equations of motion governing the target so that their smoothing and long-term prediction performance is relatively poor for targets with known equations of motion.

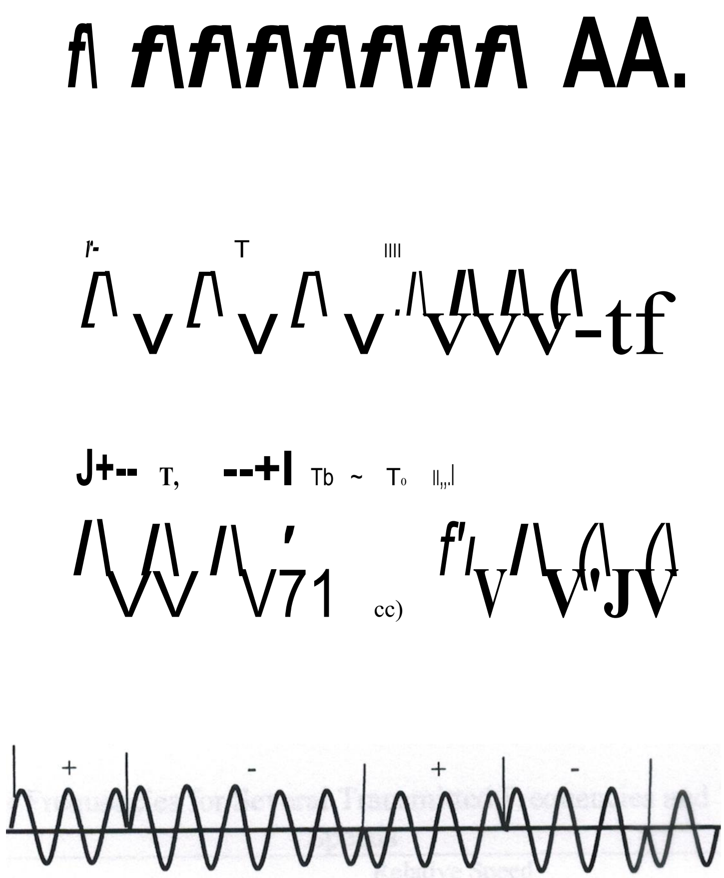
In addition, simple one-dimensional tracking-loop filters do not incorporate any adaptivity or measure of estimation quality. Kalman filtering addresses these shortcomings at the cost of significantly greater computational complexity. Target equations of motion are modeled explicitly such that the position, velocity, and potentially higher-order derivatives of each measurement dimension are estimated by the track filter as a state vector. The error associated with the estimated state vector is modeled via a covariance matrix that is also updated with each iteration of the track filter.

The-covariance matrix determines the weight vector used to update the smoothed state vector in order to incorporate such factors as measurement SIN and dynamic target maneuvering. Smoothing performance is constrained by the degree of *a priori* knowledge of the target's kinematic motion characteristics. For example, Kalman filtering can achieve significantly better error reduction against ballistic or orbital targets than against maneuvering aircraft. In the former case the equations of motion are explicitly known, while the latter case imposes motion model error because of the presence of unpredictable pilot or guidance system commands. Similar considerations apply to the fidelity of the track filter's model of radar measurement error. Failure to consider the impact of correlated measurement errors may result in underestimating track error when designing the system.

2.5 Continuous Wave Radar

Continuous wave (CW) radar employs a transmitter which is on all or most of the time. Unmodulated CW radar is very simple and is able to detect the Doppler-frequency shift in the return signal from a target which has a component of motion toward or away from the transmitter. While such a radar cannot measure range, it is used widely in applications such as police radars, motion detectors, burglar alarms, proximity fuzes for projectiles or missiles, illurninators for semiactive missile guidance systems (such as the Hawk surface-to-air missile), and scatterometers (used to measure the scattering properties of targets or clutter such as terrain surfaces).

Modulated versions include frequency-modulated (FM/CW), interrupted frequency-modulated (IFM/CW), and phase-modulated. Typical waveforms are indicated in figure 2.4. Such systems are used in altimeters, Doppler navigators, proximity fuzes, over-the-horizon radar, and active seekers for terminal guidance of air-to-surface missiles. The term *continuous* is often used to indicate a relatively long waveform (as contrasted to pulse radar using short pulses) or a radar with a high duty cycle (for instance, 50% or greater, as contrasted with the typical duty cycle of less than 1% for the usual pulse radar). As an example of a long waveform, planetary radars may transmit for up to 10 hours and are thus considered to be CW. Another example is interrupted CW (or pulse-Doppler) radar, where the transmitter is pulsed at a high rate for 10 to 60% of the total time. All of these modulated CW radars are able to measure range.



(d)

Figure 2.4 Waveforms for the general class of CW radar: (a) continuous sine wave CW; (b) frequency modulated CW; (c) interrupted CW; (d) binary phase-coded CW.

The first portion of this section discusses concepts, principles of operation, and limitations. The latter portion describes various applications. In general, CW radars have several potential advantages over pulse radars. Advantages include simplicity and the facts that the transmitter leakage is used as the local oscillator, transmitter spectral spread is minimal (not true for wide-deviation FM/CW), and peak power is the same as (or only a little greater than) the average power. This latter situation means that the radar is less detectable by intercepting equipment.

The largest disadvantage for CW radars is the need to provide antenna isolation (reduce spillover) so that the transmitted signal does not interfere with the receiver. In a pulse radar, the transmitter is off before the receiver is enabled (by means of a duplexer and/or receiver-protector switch). Isolation is frequently obtained in the CW case by employing two -antennas, one for transmit and one for reception. When this is done, there is also a reduction of close-in clutter return from rain or terrain. A second disadvantage is the existence of

2.6 CW Doppler Radar

If a sine wave signal were transmitted, the return from a moving target would be Doppler-shifted in frequency by an amount given by

$$f_d = \frac{2v_r f_T}{c}$$

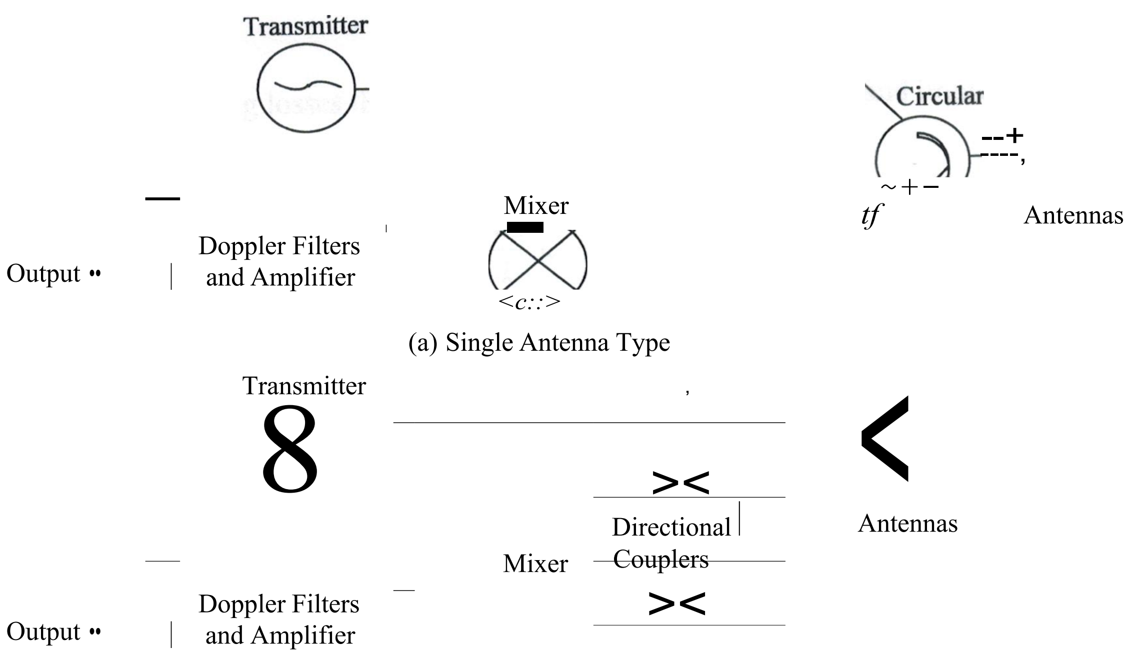
where f_d is Doppler frequency, f_T is the transmitted frequency; c is the velocity of propagation, 32108 m/s; and v, is the radial component of velocity between radar and target noise sidebands on the transmitter signal which reduce sensitivity because the Doppler frequencies are relatively close to the carrier.

Table 2.2 Doppler Frequencies for Several Transmitted Frequencies and Various Relative Sneed

Microwave Frequency fT	Relative Speed			
	1 mis	300 mis	1 mph	600mph
3 GHz	20Hz	6KHz	8.9 Hz	5.4 KHz
10GHz	67Hz	20KHz	30Hz	17.9 KHz
35GHz	233 Hz	70:KHz	104 Hz	63:KHz
95 GHz	633 Hz	190 KHz	283 Hz	170 KHz

The Doppler frequencies have been calculated for several speeds and are given in Table 2.2. As seen, the Doppler frequencies at 10 GHz (X-band) range from 30 Hz to about 18 kHz for a speed range between 1 and 600 mph. The spectral width of these Doppler frequencies will depend on target fluctuation and acceleration, antenna scanning effects, frequency variation in oscillators or components (e.g., due to microphonism from vibrations), but most significantly by the spectrum of the transmitter, which inevitably will have noise sidebands that extend much higher than these Doppler frequencies. At higher microwave frequencies the Doppler frequencies are also higher and more widely spread. In addition, the spectra of higher frequency transmitters are also wider and, the transmitter noisesideband problem is usually worse at higher frequencies, particularly at millimeter wavelengths (i.e., above 30 GHz). These characteristics may necessitate frequency stabilization or phase locking of transmitters to improve the spectra.

Simplified block diagrams for CW Doppler radars are shown in Figure 2.4. The transmitter is a single-frequency source, and leakage (or coupling) of a small amount of transmitter power serves as a local oscillator signal in the mixer. The transmitted signal will produce a Doppler-shifted return from a moving target. In the case of scatterometer measurements, where terrain reflectivity is to be measured, the relative motion may be produced by moving the radar (perhaps on a vehicle) with respect to the stationary target. The return signal is collected by the antenna and then also fed to the mixer. After mixing with the transmitter leakage, a difference frequency will be produced which is the Doppler shift. As indicated in Table 2.1, this difference is apt to range from low audio to over 100 kHz, depending on relative speeds and choice of microwave frequency. The Doppler amplifier and filters are chosen based on the information to be obtained, and this determines the amplifier bandwidth and gain, as well as the filter bandwidth and spacing. The transmitter leakage may include reflections from the antenna and/or nearby clutter in front of the antenna, as well as mutual coupling between antennas in the two-antenna case.



(a) Single Antenna Type

(b) Double Antenna Type

Figure 2.5 Block Diagrams of CW-Doppler Radar Systems: (a) Single Antenna Type; (b) Double Antenna Type.

$$R^4 = \frac{\overline{P}_T G_T L_T A_e L_R L_P L_a L_S \delta_T}{(4\pi)^2 K T_S b (S/N)} \tag{2.5}$$

where R is the detection range of the desired target.

PT is the average power during the pulse,

Ae is the effective aperture of the antenna, which is equal to the projected area in the direction of the target times the efficiency,

LR is the receive antenna losses defined in a manner similar to the transmit losses,

Lp is the beam shape and scanning and pattern factor losses,

L_a is the two-way-pattern propagation losses of the medium; often expressed as exp(-*2a R),* where q is the attenuation constant of the medium and the factor 2 is for a two-way path,

Ls is signal-processing losses that occur for virtually every waveform and implementation,

$öT$ is the radar cross-sectional area of the object that is being detected,

b is Doppler filter or *speedgate* bandwidth,

SIN is signal-to-noise ratio,

and Smin is the minimum detectable target-signal power that, with a given probability of success, the radar can be said to *detect, acquire,* or *track* in the presence of its own thermal noise or some external interference. Since all these factors (including the target return itself) are generally noise-like, the criterion for a detection can be described only by some form of probability distribution with an associated probability of detection *PD* and a probability that, in the absence of a target signal, one or more noise or interference samples will be mistaken for the target of interest.

While the Doppler filter should be a matched filter, it usually is wider because it must include the target spectral width. There is usually some compensation for the loss in detectability by the use of postdetection filtering or integration. The SIN ratio for a CW radar must be at least 6 dB, compared with the value of 13 dB required with pulse radars when detecting steady targets.

The Doppler system discussed above has a maximum detection range based on signal strength and other factors, but it cannot measure range. The rate of change in signal strength as a function of range has sometimes been used in fuzes to estimate range closure and firing point, but this is a relative measure.

2.7 **FM/CW Radar**

The most common technique for determining target range is the use of frequency modulation. Typical modulation waveforms include sinusoidal, linear sawtooth, or triangular, as illustrated in figure 2.6.

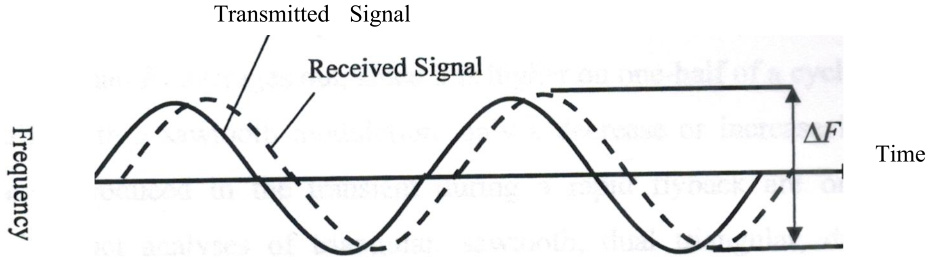
For a linear sawtooth, a frequency increasing with time may be transmitted. Upon being reflected from a stationary point target, the same linear frequency change is reflected back to the receiver, except it has a time delay which is related to the range to the target. The time is $T = 2Rlc,$ where R is the range. The received signal is mixed with the transmit signal, and the difference or beat frequency *(Fb)* is obtained for a stationary target this is given by

$$F_b = \frac{4R}{C}.\Delta F.F_m, \qquad (2.6)$$

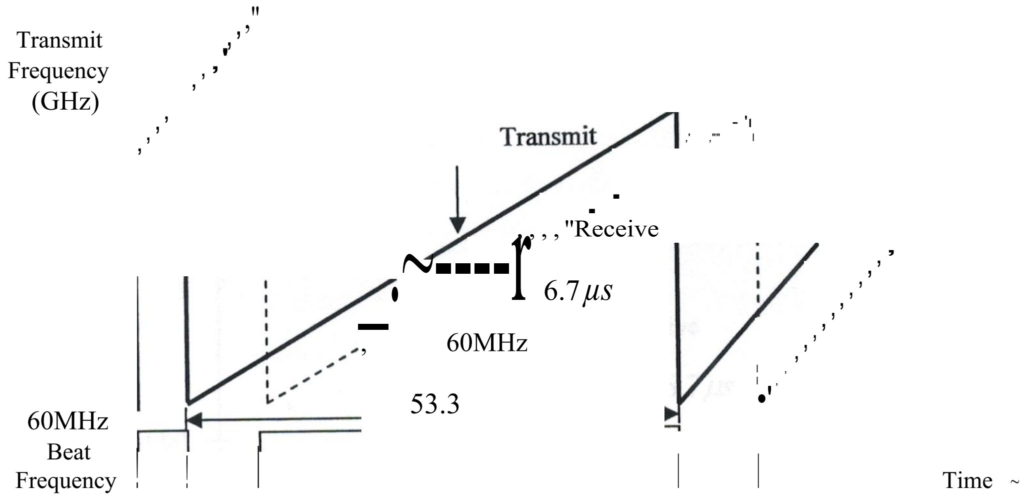
where Af' is the frequency deviation and *Fm* is the modulation rate.

The beat frequency is constant except near the tum-around region of the sawtooth but it is different for targets at different ranges. If it is desired to have a constant intermediate frequency for different ranges, which is a convenience in receiver design, then the modulation rate or the frequency deviation must be adjusted. Multiple targets at a variety of ranges will produce multiple-frequency outputs from the mixer and frequently are handled in the receiver by using multiple range-bin filters.

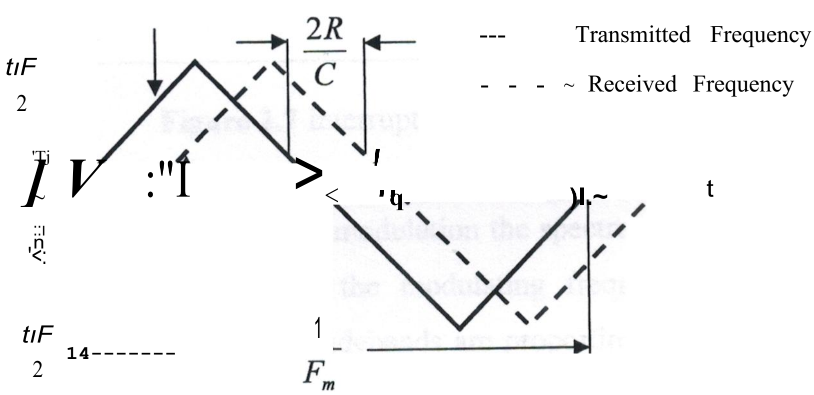
If the target is moving with a component of velocity toward (or away) from the radar, then there will be a Doppler frequency component added to (or subtracted from) the difference frequency *(Fb)*, and the Doppler will be slightly higher at the upper end of the sweep range than at the lower end. This will introduce an



(a) Sinusoidal



(b) Linear Sawtooth



(c) Triangular

Figure 2.6 Frequency vs. Time Waveforms for FM/CW Radar: (a) Sinusoidal, (b) Linear Sawtooth, (c) Triangular Modulations.

uncertainty or ambiguity in the measurement of range, which may or may not be significant, depending on the parameters chosen and the application. For example, if the Doppler frequency is low (as in an altimeter) and/or the difference frequency is high, the error in range measurement may be tolerable. For the symmetrical triangular waveform, a Doppler less than *Fb* averages out, since it is higher on one-half of a cycle and lower on the other half. With a sawtooth modulation, only a decrease or increase is noted, since the frequencies produced in the transient during a rapid flyback are out of the receiver passband. Exact analyses of triangular, sawtooth, dual triangular, dual sawtooth, and combinations of these with noise have been carried out by Tozzi.

Specific design parameters are given later in this chapter for an application utilizing sawtooth modulation in a missile terminal guidance seeker.

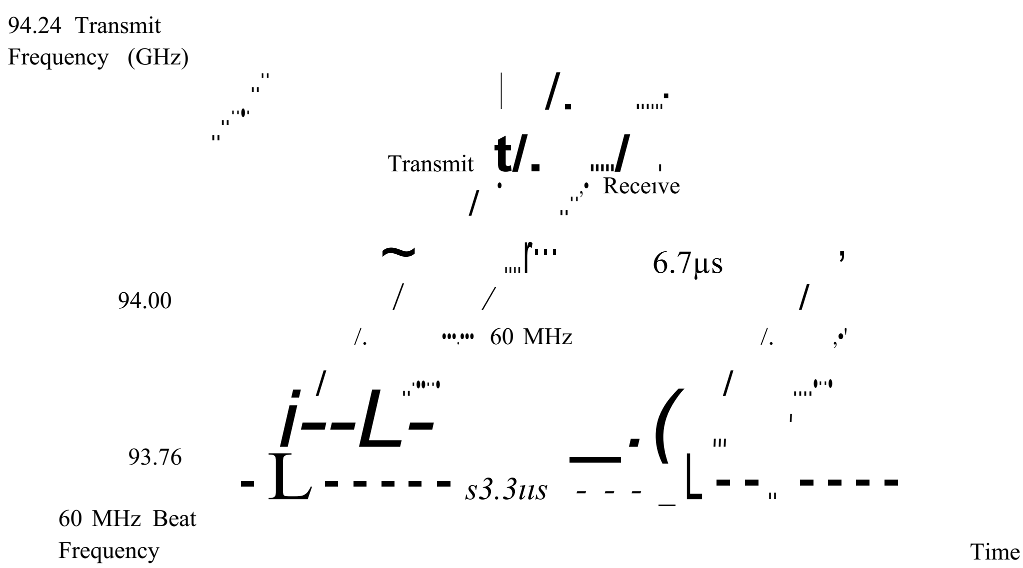


Figure 2.7 Interrupted FM/CW-Waveform

For the case of sinusoidal frequency modulation the spectrum consists of a series of lines spaced away from the carrier by the modulating frequency or its harmonics. The amplitudes of the carrier and these sidebands are proportional to the values of the Bessel functions of the first kind (J_n , n = 0, ... 1, ... 2, ... 3, ...), whose argument is a function of the modulating frequency and range. By choosing a particular modulating frequency, the values of the Bessel functions and thus the characteristics of the spectral components can be influenced.

For instance, the signal variation with range at selected ranges can be optimized, which is important in fuzes. A short-range dependence that produces a rapid increase in signal, greater than that corresponding to the normal range variation, is beneficial in producing well-defined firing signals. This can be accomplished by proper choice of modulating frequency and filtering to obtain the signal spectral components corresponding to the appropriate order of the Bessel function. In a similar fashion, spillover and/or reflections from close-in objects can be reduced by filtering to pass only certain harmonics of the modulating frequency *(Fm).* Receiving only frequencies near 3 *Fm* results in considerable spillover rejection, but at a penalty of 4 to 10 dB in signal-to- noise.

For the sinusoidal modulation case, Doppler frequency contributions complicate the analysis considerably.

2.8 Interrupted Frequency-Modulated CW (IFM/CW)

To improve isolation during reception, the IFM/CW format involves preventing transmission for a portion of the time during the frequency change. Thus, there are frequency gaps, or interruptions, as illustrated in figure 2.10. This shows a case where the transmit time equals the round-trip propagation time, followed by an equal time for reception. This duty factor of 0.5 for the waveform reduces the average transmitted power by 3 dB relative to using an interrupted transmitter. However, the improvement in the isolation should reduce the system noise by more than 3 dB, thus improving the signal-to-noise ratio. For operation at short range, Piper points out that a high-speed switch is required. He also points out that the ratio of frequency deviation to beat frequency should be an even integer and that the minimum ratio is typic~lly 6, which produces an out-of-band loss of 0.8 dB.

IFM/CW may be compared with pulse compression radar if both use a wide bandwidth. Pulse compression employs a "long" pulse (i.e., relatively long for a pulse radar) with a large frequency deviation or "chirp." Along pulse is often used when a transmitter is peak-power limited, because the longer pulse produces more energy and gives more range to targets. The frequency deviation is controlled in a predetermined way (frequently a linear sweep) so that a matched filter can be used in the receiver. The large time-bandwidth product permits the received pulse to be compressed in time to a short pulse in order to make an accurate range measurement.

A linear-sawtooth IFM/CW having similar pulse length, frequency deviation, and pulse repetition rate would thus appear similar, although arrived at from different points of view.

2.9 Applications

Space does not permit giving a full description of the many applications mentioned at the beginning of this chapter, but several will be discussed.

2.9.1 Radar Proximity Fuzes

Projectiles or missiles designed to be aimed at ships or surface land targets often need a height-of-burst (HOB) sensor (or target detection device) to fire or füze the warhead at a height of a few meters. There are two primary generic methods of sensing or measuring height to generate the warhead fire signal. The most obvious, and potentially the most accurate, is to measure target round trip propagation delay employing conventional radar ranging techniques. The second method employs a simple CW Doppler radar or variation thereof, with loop gain calibrated in a manner that permits sensing the desired burst height by measurement of target return signal amplitude and/or rate of change. Often the mission requirements do not justify the complexity and cost of the radar ranging approach. Viable candidates are thus narrowed down to variations on the CW doppler füze.

In its simplest form, the CW Doppler füze consists of a fractional watt RF oscillator, homodyne detector, Doppler amplifier, Doppler envelope detector, and threshold circuit. When the Doppler envelope amplitude derived from the returned signal reaches the preset threshold, a fire signal is generated. The height at which the fire signal occurs depends on the radar loop gain, threshold level, and target reflectivity. Fuze gain is designed to produce the desired height of burst under nominal trajectory angle and target reflectivity conditions, which may have large fluctuations due to glint effects, and deviations from the desired height due to antenna gain variations with angle, target reflectivity, and füze gain tolerances are accepted. A loop gain change of 6 dB (2 to 1 in voltage), whether due to a change in target reflection coefficient, antenna gain, or whatever, will result in a 2 to 1 HOB change.

HOB sensitivity to loop gain factors can be reduced by utilizing the slope of the increasing return signal, or so-called rate-of-rise. Deriving HOB solely from the rate-of-rise has the disadvantage of rendering the füze sensitive to fluctuating signal levels such as might result from a scintillating target. The use of logarithmic amplifiers decreases the HOB sensitivity to the reflectivity range. An early (excessively high) fire signal can occur if the slope of the signal fluctuations equals the rate-of-rise threshold of the füze. In practice a compromise is generally made in which Doppler envelope amplitude and rate-of-rise contribute in some proportion of HOB.

Another method sometimes employed to reduce HOB sensitivity to füze loop gain factors and angle of fall is the use of FM sinusoidal modulation of suitable deviation to produce a range correlation function comprising the zero order of a Bessel function of the first kind. The subject of sinusoidal modulation is quite complex, but has been treated in detail by Saunders. The most important aspects of füze design have to do with practical problems such as low cost, small size, ability to stand very high-g accelerations, long life in storage, and countermeasures susceptibility.

2.9.2 Police Radars

Down-the-road police radars, which are of the CW Doppler type, operate at 10.525, 24.150, or in the 33.4 to 36.0 GHz range, frequencies approved in the United States by the Federal Communications Commission. Halfpower beamwidths are typically in the 0.21 to 0.31 radian range. The sensitivity is usually good enough to provide a range exceeding 800 meters. Target size has a dynamic range of 30 dB (from smallest cars or motorcycles to large trucks). This means that a large target can be seen well outside the antenna 3-dB point at a range exceeding the range of a smaller target near the center of the beam. Thus there can be uncertainty about which vehicle is the target. Fisher has given a discussion of a number of the limitations of these systems, but in spite of these factors probably a hundred thousand have been built.

The designs typically have three amplifier gains for detection of short, medium, or maximum range targets, plus a squelch circuit so that sudden spurious signals will not be counted. The Doppler signal is integrated and this direct current provides a speed readout. Provision is made for calibration to assure the accuracy of the readings.

Table 2.3 Parameters for Two Commercial Altimaters

Modulation Frequency	Frequency Deviation	Prime Power	Weight (Pounds)	Radiated Power
Bendix	150Hz	130MHz	30W	11
ALA-52A Collins	100 KHz	100MHz	8	350mW
ALT-55	lOOKHz	lOOKHz	8	350mW

2.9.3 Altimaters

A very detailed discussion of FM/CW altimeters has been given by Saunders, in which he has described modem commercial products built by Bendix and Collins. The parameters will be summarized below and if more information is needed, the reader may want to tum to other references. In his material, Saunders gives a general overview of modem altimeters, all of which use wide-deviation FM at a low modulation :frequency. He discusses the limitations on narrowing the antenna pattern, which must be wide enough to accommodate attitude changes of the aircraft.

Triangular modulation is used, since for this waveform the Doppler averages out, and dual antennas are employed. There may be a step error or quantization in height (which could be a problem at low altitudes), due to the limitation of counting zero crossings. A difference of one zero crossing (i.e., 1/2 Hz) corresponds to 3/4 meter for a :frequency deviation of 100 MHz. Irregularities are not often seen, however, since meter response is slow. Also, if terrain is rough, there will be actual physical altitude fluctuations. Table 2.2 shows some of the altimeters' parameters. These altimeters are not acceptable for military aircraft, because their relatively wide-open front ends make them potentially vulnerable to electronic countermeasures. A French design has some advantages in this respect by using a variable :frequency deviation, a difference :frequency that is essentially constant with altitude, and a narrowband front-end amplifier.

2.9.4 Doppler Navigators

These systems are mainly sinusoidally modulated FM/CW radars employing four separate downward looking beams aimed at about 15 degrees off the vertical. Because commercial airlines have shifted to non-radar forms of navigation, these units are designed principally for helicopters. Saunders cites a particular example of a commercial unit operating at 13.3 GHz, employing a Gunn oscillator as the transmitter, with an output power of 50 mW, and utilizing a 30-kHz modulation frequency. A single microstrip antenna is used. A lowaltitude equipment (below 15,000 feet), the unit weighs less than 12 pounds. A second unit cited has an output power of 300 mW, dual antennas, dual modulating frequencies, and an altitude capability of 40,000 feet.

2.9.5 Millimeter-Wave Seeker for Terminal Guidance Missile

Terminal guidance for short-range (less than 2 km) air-to-surface missiles has seen extensive development in the last decade. Targets such as tanks are frequently immersed in a clutter background which may give a radar return that is comparable to that of the target. To reduce the clutter return in the antenna footprint, the antenna beamwidth is reduced by going to millimeter wavelengths. For a variety of reasons the choice is usually a frequency near 35 or 90 GHz. Antenna beamwidth is inversely proportional to frequency, so in order to get a reduced beamwidth we would normally choose 90 GHz; however, more deleterious effects at 90 GHz due to atmospheric absorption and scattering can modify that choice. In spite of small beamwidths, the clutter is a significant problem, and in most cases signal-to-clutter is a more limiting condition than signal-to noise in determining range performance. Piper has done an excellent job of analyzing the situation for 35- and 90-GHz pulse radar seekers and comparing those with a 90-GHz FM/CW seeker. His FM/CW results will be summarized below.

In his approach to the problem, Piper gives a summary of the advantages and disadvantages of a pulse system compared to the FM/CW approach. Most of these have already been covered in earlier sections, but one difficulty for the FM/CW can be emphasized again. That is the need for a highly linear sweep, and, because of the desire for the wide bandwidth, this requirement is accentuated. The wide bandwidth is desired in order to average the clutter return and to smooth the glint effects. In particular, glint occurs 'from a complex target because of the vector addition of coherent signals scattered back to the receiver from various reflecting surfaces. At some angles the vectors may add in phase (constructively) and at others they may cancel, and the effect is specifically dependent on wavelength. For a narrowband system, glint may provide a very large signal change over a small variation of angle, but, of course, at another wavelength it would be different. Thus, very wide bandwidth is desirable from this smoothing point of view, and typical numbers used in millimeter-wave radars are in the 450- to 650-MHz range.

Piper chose 480 MHz. Another tradeoff involves the choice of FM waveform. Here the use of a triangular waveform is undesirable because the Doppler frequency averages out and Doppler compensation is then required. Thus the sawtooth version is chosen, but because of the large frequency deviation desired, the difficulty of linearizing the frequency sweep is made greater. In fact many components must be extremely wideband, and this generally increases cost and may adversely affect performance. On the other hand, the difference frequency *(Fb)* and/or the intermediate frequency *(FIF)* will be higher and thus further from the carrier, so the phase noise will be lower. After discussing the other tradeoffs, Piper chose 60 MHz for the beat frequency.

With a linear FM/CW waveform, the inverse of the frequency deviation provides the theoretical time resolution, which is 1.1 ns for 480 MHz (or range resolution of 0.3 meter). For an RF sweep linearity of 300 kHz, the range resolution is actually 5 meters at the 1000-meter nominal search range. (The system has a mechanically scanned antenna.) An average transmitting power of 25 mW was chosen, which was equal to the average power of the SW peak IMPATT assumed for the pulse system. The antenna diameter was 15 cm. For a target radar cross section of 20 rn2 and assumed weat~er conditions, the signal-to-clutter and signal-to-noise ratios work calculated and plotted for ranges out to 2 km and for clear weather or 4 mm per hour rainfall. The results show that for 1 km range the target-to-clutter ratios are higher for the FM/CW case than the pulse system in clear weather or in rain, and target-to-clutter is the determining factor.

3. RADAR TYPES

3.1 Basic Concepts

The radar transmits a pulse of RF energy and then receives returns (reflections) from desired and undesired targets. Desired targets may include space, airborne, and sea-and/or surface-based vehicles. They can also include the earth's surface and the atmosphere, depending on the application. Undesired targets are termed *clutter.* Clutter sources include the ground, natural and man-made objects, sea, atmospheric phenomena, and birds. Short-range/low-altitude radar operation is often con-strained by clutter since the multitude of undesired returns masks returns from targets of interest such as aircraft.

The range, azimuth angle, elevation angle, and range rate can be directly measured from a return to estimate target position and velocity. Signature data can be extracted by measuring the amplitude, phase, and polarization of the return.

Pulse radar affords a great deal of design and operational flexibility. Pulse duration and pulse rate can be tailored to specific applications to provide optimal performance. Modem computer-controlled multiple-function radars exploit this capability by choosing the best waveform from a repertoire for a given operational mode and interference environment automatically.

It also predicts the target's flight path to provide range gating and antenna pointing control to the radar system.

Signature measurement applications include remote sensing of the environment as well as the measurement of target characteristics. In some applications, synthetic aperture radar (SAR) imaging is conducted from aircraft or satellites to characterize land usage over broad areas. Moving targets that present changing aspect to the radar can be imaged from airborne or ground-based radars via inverse synthetic aperture radar (ISAR) techniques.

As defined in the subsection "Resolution and Accuracy," cross-range resolution improves with increasing antenna extent. SARIISAR effectively substitutes an extended observation interval over which coherent returns are collected from different target aspect angles for a large antenna structure that would not be physically realizable in many instances.

In general, characterization performance improves with increasing frequency because of the associated improvement in range, range rate, and cross-range resolution. However, phenomenological characterization to support environmental remote sensing may require data collected across a broad swath of frequencies.

Multiple-function phased array radar generally integrates these functions to some degree. Its design is usually driven by the track function. Its operational frequency is generally a compromise between the lower frequency of the search radar and the higher frequency desired for the tracking radar.

The degree of signature measurement implemented to support such functions as non cooperative target identification depends on the resolution capability of the radar as well as the operational user requirements. Multiple-function radar design represents a compromise among these different requirements. However, implementation constraints, multiple-target handling requirements, and reaction time requirements often dictate the use of phased array radar systems integrating search, track, and characterization functions.

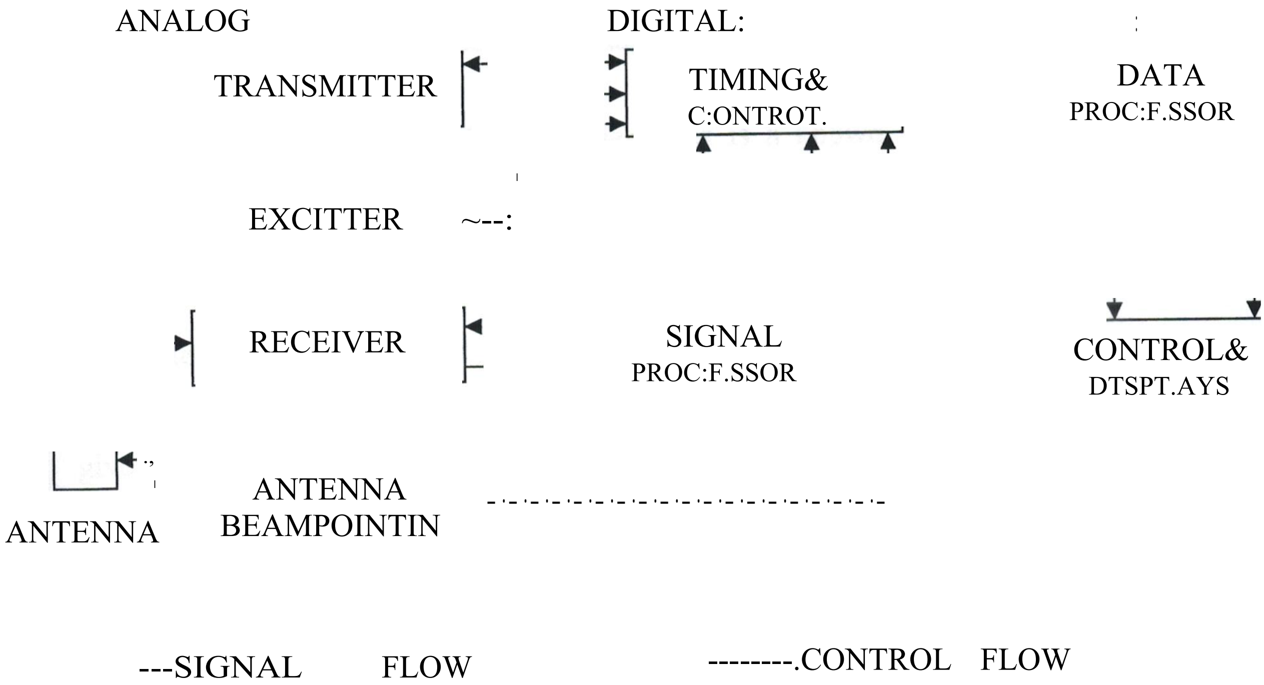


Figure 3.1 Radar System Architecture

3.2 Weather Radar

Weather radar has made many improvements in the. last 10 years. There are more improvements on the way. All of the radars of the past and present work off the same basic principle: the radar equation below.

$$P_r = \frac{P_t G^2 \theta^2 H \pi^3 K^2 L}{1024(\ln 2)\lambda^2} \times \frac{Z}{R^2} \tag{3.1}$$

Equation (3.1) involves variables that are either known or are directly measured. There is only one value that is missing, but it can be solved for mathematically. Below is the list of variables, what they are, and how they are measured.

Pr : Average power returned to the radar from a target. The radar sends up to 25 pulses and then measures the average power that is received in those returns. The radar uses multiple pulses since the power returned by a meteorological target varies from pulse to pulse. This is an unknown value of the radar, but it is one that is directly calculated.

Pt: Peak power transmitted by the radar. This is a known value of the radar. It is important to know because the average power returned is directly related to the transmitted power.

G: Antenna gain of the radar. This is a known value of the radar. This is a measure of the antenna's ability to focus outgoing energy into the beam. The power received from a given target is directly related to the square of the antenna gain.

B: Angular beamwidth of the radar. This is a known value of the radar. Through the Probert-Jones equation it can be learned that the return power is directly related to the square of the angular beamwidth. The problem becomes that the assumption- of the equation is that precipitation fills the beam for radars with beams wider than two degrees. It is also an invalid assumption for any weather radar at long distances. The lower resolution at great distances is called the aspect ratio problem.

H: Pulse Length of the radar. This is a known value of the radar. The power received from a meteorological target is directly related to the pulse length.

K: This is a physical constant. This is a known value of the radar. This constant relies on the dielectric constant of water. This is an assumption that has to be made, but also can cause some problems. The dielectric constant of water is near one, meaning it has a good reflectivity. The problem occurs when you have meteorological targets that do not share that reflectivity. Some examples of this are snow and dry hail since their constants are around 0.2.

L: This is the loss factor of the radar. This is a value that is calculated to compensate for attenuation by precipitation, atmospheric gases, and receiver detection limitations. The attenuation by precipitation is a function of precipitation intensity and wavelength. For atmospheric gases, it is a function of elevation angle, range, and wavelength. Since all of this accounts for a 2dB loss, all signals are strengthened by 2 dB.

;ι: This is the wavelength of the transmitted energy. This is a known value of the radar. The amount of power returned from a precipitation target is inversely since the short wavelengths are subject to significant attenuation. The longer the wavelength, the less attenuation caused by precipitate.

Z : This is the reflectivity factor of the precipitate. This is the value that is solved for mathematically by the radar. The number of drops and the size of the drops affect this value. This value can cause problems because the radar cannot determine the size of the precipitate. The size is important since the reflectivity factor of a precipitation target is determined by raising each drop diameter in the sample volume to the sixth power and then summing all those values together. A *W'* drop reflects the same amount of energy as 64 1/8" drops even though there is 729 times more liquid in the 1/8" drops.

R : This is the target range of the precipitate. This value can be calculated by measuring the time it takes the signal to return. The range is important since the average power return from a target is inversely related to the square of its range from the radar. The radar has to normalize the power returned to compensate for the range attenuation.

Using a relationship between Z and R, an estimate of rainfall can be achieved. A base equation that can be used to do this is Z=200*R"l.6. This equation can be modified at the user's request to a better fitting equation for the day or the area.

The basic concept of weather radar works off of the idea of a reflection of energy as shown in figure 3.2. The radar sends out a signal, as seen to the right, and the signal is then reflected back to the radar. The stronger that the reflected signal is, the larger the particle. For more basic information on weather radar

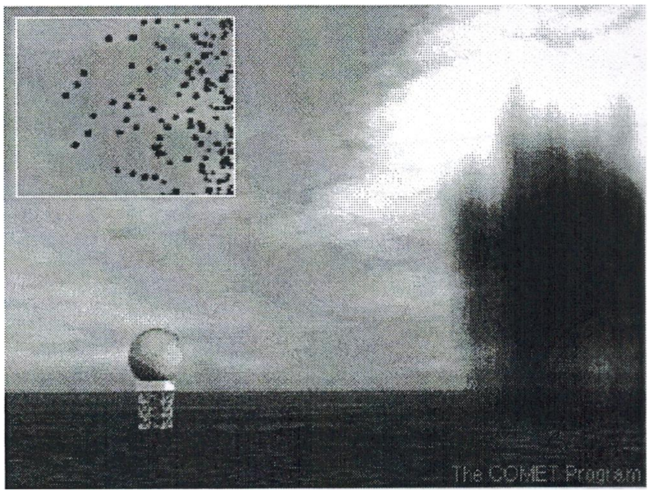


Figure 3.2 Basic Concepts of Weather Radar

3.3 Object Classification with Automotive Radar

Automotive radar systems offer the capability to measure simultaneously range, relative speed and azimuth angle of all observed objects inside the observation area. This measurement is processed with high resolution and accuracy in range, Doppler frequency and azimuth angle domain respectively. For all these reasons and excellent technical performances, present driver assistance systems are almost always based on the use of radar sensors.

In addition to the precise measurement results of all targets inside the observation area, the knowledge of target recognition is required. Each individual object (e.g. vehicle, pedestrian, cyclist, tree, traffic sign, etc.) should be classified into an object class. The assignment of detected targets to specified object classes will be called classification. This additional requirement is of increasing interest for future automotive applications (see Figure 3.3). Especially safety related applications like lane departure warning or pre-crash-applications will benefit from this additional information if the classification results are of high performance.

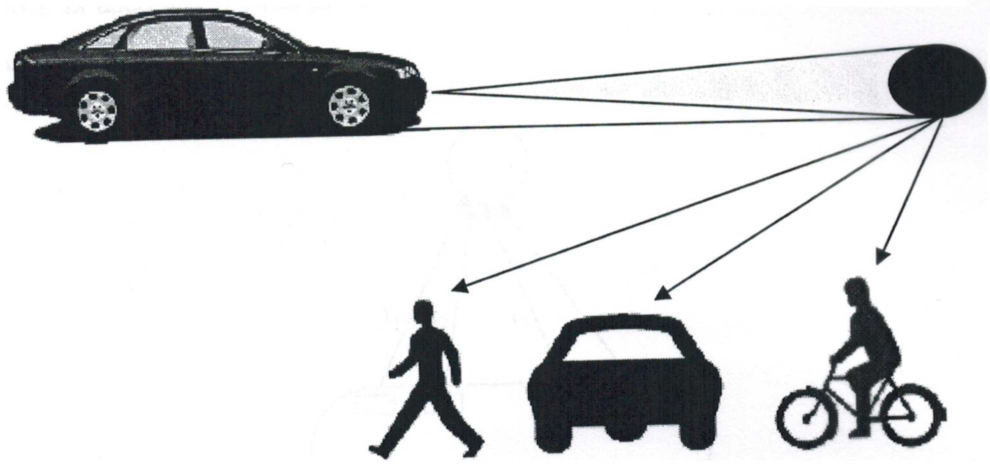


Figure 3.3 Target recognition for automotive radar applications

So far, mainly video systems have been used to perform the object classification in specific automotive applications. These technical solutions need high computation power for image processing and are therefore expensive. There are even strong limitations for video systems in automotive applications due to bad weather conditions in general. Radar systems can overcome all these drawbacks and limitations of video systems, but a radar based target classification system for automotive applications is a pure novelty and technical challenge which has never been realized before.

3.4 Radar Network Based on 24 GHz Sensors

A radar sensor network based on four 24 GHz high range resolution (HRR) pulse radars has been integrated into the front bumper of an experimental car. Each sensor is capable of measuring the target range with very high accuracy of ±4 cm and very high resolution over the complete range of up to 20 m. The angular coverage of each sensor in azimuth direction is approximately ±30°. Thus, a system of four distributed sensors in the front bumper covers a large observation area in front of the vehicle. Figure 3.4 shows the example of a single target situation indicating the measured distances.

The object position is determined by trilateration of the measured distances. This radar network is used as an example for the automotive target recognition system described in this contribution.

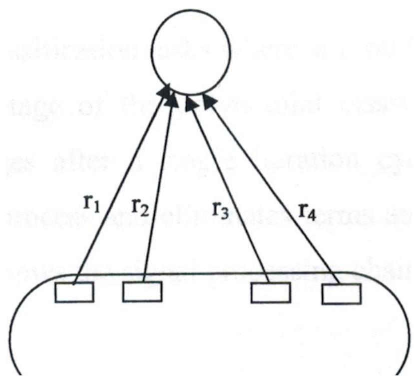


Figure 3.4 Example of a single target situation

3.5 Radar Based Object Classification

To distinguish between different object classes, several features are needed which describe the characteristic behavior of the echo signal in a local environment. A single feature is insufficient to solve the target recognition task. Thus, a couple of different, well-chosen features gained from the echo signal are needed to solve this challenging target classification task. The characteristics of the reeeived echo signal depend on the considered radar sensor system. The signal features must be defined in accordance with the implemented radar sensor system. A multi-dimensional feature vector is determined and a classification system is developed, capable of learning the target signal properties and automatically calculating the resulting decision for target recognition. The main objective of a target classification system is to compute a class membership for a given vector of signal features. The set of different target classes is given by the classifier definition. For all classifiers, the application can be split into a learning and a classification phase. Throughout the learning phase, a number of characteristic and individually labeled feature vectors is automatically analyzed by the classifier. During the classification phase, the feature vector is generated for each detected target and the recognition algorithm makes a decision with maximum likelihood to which class the feature vector belongs to.

A polynomial classifier is used for the considered automotive application, because it is well suited for complex classification tasks where several features are considered inside a feature vector. The advantage of the polynomial classifier is the automatic learning procedure, which converges after a single iteration cycle. It evaluates the features' influence on the decision process and eliminates terms automatically which have only a minor impact. Figure 3.5 shows the signal processing chain of the classification system as a block diagram.

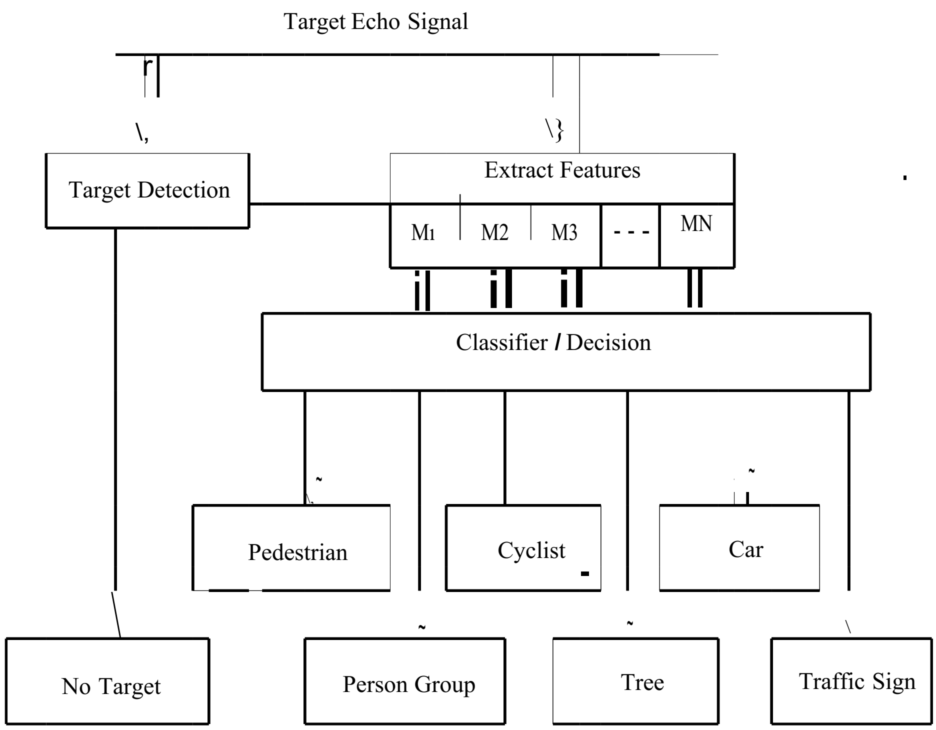


Figure 3.5 Signal processing chain for target recognition

3.6 Critical Subsystem Design and Technology

The major subsystems making up a pulse radar system are depicted in figure 3.1. The associated interaction between function and technology is summarized in this subsection.

3.6.1 Signal and Data Processing

Digital processing is generally divided between two processing subsystems, i.e., signals and data, according to the algorithm structure and throughput demands. Signal processing includes pulse compression, Doppler filtering, and detection threshold estimation and testing. Data processing includes track filtering, user interface support, and such specialized functions as electronic counter-counter measures (ECCM) and built-in test (BIT), as well as the resource management process required to control the radar system.

The signal processor is often optimized to perform the repetitive complex multiply-and-add operations associated with the fast Fourier transform (FFT). FFT processing is used for implementing pulse compression via fast convolution and for Doppler filtering. Fast convolution consists of taking the FFT of the digitized receiver output, multiplying it by the stored FFT of the desired filter function, and then taking the inverse FFT of the resulting product. Fast convolution results in significant computational saving over performing the time-domain convolution of returns with the filter function corresponding to the matched filter. The signal processor output can be characterized in terms of range gates and Doppler filters corresponding approximately to the range and Doppler resolution, respectively.

In contrast, the radar data processor typically consists of a general-purpose computer with a real-time operating system. Fielded radar data processors range from microcomputers to mainframe computers, depending on the requirements of the radar system. Data processor software and hardware requirements are significantly mitigated by off loading timing and control functions to specialized hardware. This timing and control subsystem typically functions as the two-way interface between the data processor and the other radar sub-systems.

The increasing inclusion of BIT (built-in-test) and built-in calibration capability in timing and control subsystem designs promises to result in significant improvement in fielded system performance.

3.7 Radar Performance Prediction

3.7.1 Radar Line-of-Sight

With the exception of over-the-horizon (OTH) radar systems, which exploit either sky-wave bounce or ground-wave propagation modes and sporadic ducting effects at higher frequencies, surface and airborne platform radar operation is limited to the refraction-constrained line of sight. Atmospheric refraction effects can be closely approximated by setting the earth's radius to 4/3 its nominal value in estimating horizon-limited range.

The resulting line-of-sight range is depicted in figure 3.6 for surface-based radar, airborne surveillance radar, and space-based radar.

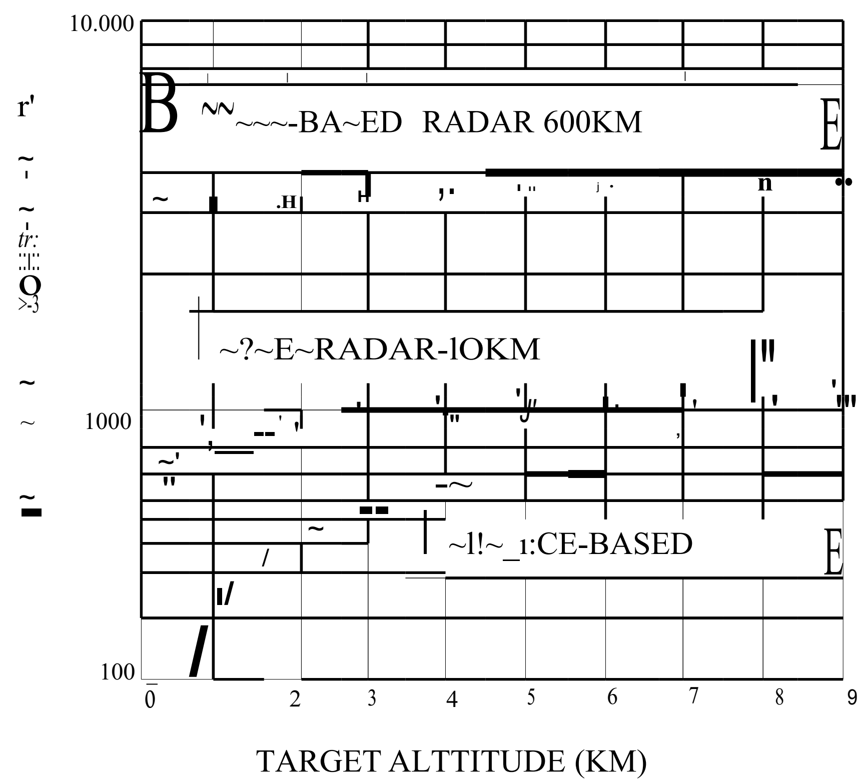


Figure 3.6 Maximum line-of-sight range for surface-based radar, an airborne surveillance radar, and a space-based radar.

As evident in the plot, airborne and space-based surveillance radar systems offer significant advantages in the detection of low-altitude targets that would otherwise be masked by earth curvature and terrain features from surface-based radars. However, efficient clutter rejection techniques must be used in order to detect targets since surface clutter returns will be present at almost all ranges of interest.

3.8 Radar Interactions with Geologic Surfaces

The correct geologic interpretation of radar images depends critically on a knowledge of how radar waves interact with natural surfaces. There are significant differences between the microwave and more familiar optical wavelengths in the mechanics of imaging and in the measured characteristics of the target. Because of the side-looking illumination geometry, all radar images are distorted to some extent. In addition, the longer wavelength of radar waves makes them most sensitive to surface roughness at scales near the radar wavelength. Of secondary importance are variations in the dielectric constant of the target; this parameter is similar for dry geologic materials except metallic compounds, which may be present at high elevations on Venus. The geometric and electromagnetic interactions of radar waves with natural surfaces, then, must be considered for accurate interpretation of Magellan SAR images.

Since radars depend on the measurement of range to create an image in the cross-track direction, they are forced to look to the side to allow the sensor to differentiate between objects to the left and right of the ground track; in the alongtrack direction, platform motion and Doppler frequency shift create the image. Synthetic aperture and matched-filter techniques, described by Elachi [1988], are used to obtain high resolution in these directions.

Ibis side-looking geometry has a number of descriptive terms and peculiarities that must be understood when interpreting radar images. The angle at which the radar images the target as measured from the horizontal at the antenna is called the depression angle. The look angle, B_1, is the complement of the depression angle. At the target, local undulations combined with the look angle create a local incidence angle, θ_i. Note that even for horizontal terrain, the look angle does not equal the local incidence angle because of planetary curvature. This effect is small for aircraft sensors but significant for spacecraft:

$$\theta_i = \arcsin\left(\frac{r+H}{r}\sin\eta\right) \tag{3.2}$$

where r is the radius of Venus and H is the altitude of the spacecraft.

The fact that imaging radars divide the range into small intervals to create range pixels yields a projected geometry when the slant-range pixels are written to film. A slant-range image appears compressed in the near range because of this projection. Assuming a horizontal surface, the simple transformation

$$G = H\sqrt{\frac{1}{\cos^2\theta_i} - 1} \tag{3.3}$$

produces a ground-range image, where G is the ground-range distance. Note, however, that topographic variations are not accounted for in this transformation.

Topographic variations are distorted in the same way as the overall image: Their near-range points are compressed relative to their far-range points. The general case of radar foreshortening compresses the image of a mountain's near-range slope and extends the image of its back slope. The effect is obviously exacerbated by small look angles and steep slopes to the extreme case of layover, in which the top of the mountain is imaged before the bottom of the near-range slope. Image data in the laid-over area are lost. Image data can also be lost on the backslope if the slope is steep enough and the look angle large enough to put the slope in radar shadow. Layover and shadow can be seen in a Seasat SAR image of the Alaska Range, where the top of a mountain is superimposed on the glacier at its foot, while the backslopes of the mountains are in shadow. Seasat SAR had a look angle of about 20 deg.

As a generalization, since most slope angles on Earth are less than about 35 deg, imaging radars with small look angles, such as Seasat, enhance the topography at the expense of surface roughness information (discussed later). Conversely, larger look angles, such as SIR-A's 47 deg, reduce the effect of topography and enhance the sensitivity to surface roughness.

These aspects of imaging radar geometry are especially important in interpreting Magellan SAR images, as the look angle varies systematically with latitude . The wide range oflook angles extends beyond the range of the Seasat SAR and SIR-A angles and encompasses shallow slope angles typical of eroded terrain, through angles equal to the angle of repose of loose granular material (i.e., sand and talus), to over-steepened angles typical of tectonically active mountains. Thus, different types of relief will be accentuated depending on latitude.

The orientation of linear features relative to the radar look direction or azimuth also controls the visibility of the features. Where the illumination is *parallel* to the structure, there is little effect on the local incidence angle and therefore no enhancement of the structure. Conversely, topographic variations stand out where illumination is *normal* to the structure. Obviously, this effect is accentuated by a small look angle.

4. MONOSTATIC RADAR LAYOUT

4.1 Introduction

In a monostatic radar, the antenna sharing is made possible by a duplexer which isolates the sensitive receiver from the high power transmitted pulse. We shall go into more details later as to how this isolation is achieved.

When the target moves radially with respect to the radar antenna, a Doppler shift is introduced to the transmitted frequency f_t. The received signal is therefore $f_t + f_d$ where the Doppler shift is negative if the target is moving away from the antenna, and positive if it is moving towards the antenna. This Doppler shift is an important method of removing unwanted signals in the signal processing part of a radar system as shown in figure 4.1.

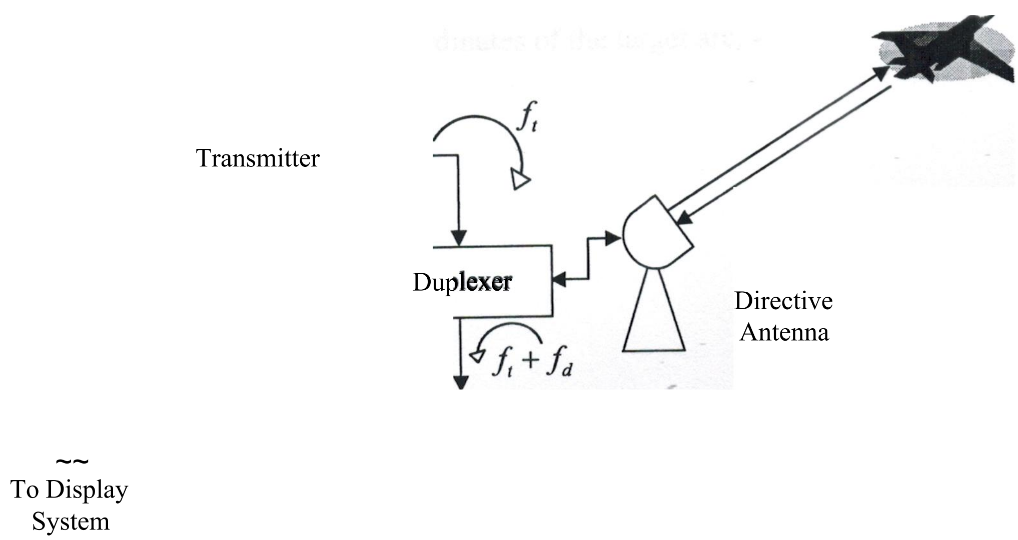


Figure 4.1 Monostatic Radar Layout

4.2 Co-ordinate System

We have seen how a radar can determine the range and azimuth of a target utilising an antenna rotating in the horizontal plane. In a height finding radar, the antenna beam also scans in a vertical plane. A radar is therefore capable of positioning the target in 3-dimensional space and the generalised position in spherical coordinates is shown in the slide.

The origin of the coordinate system has been chosen in the middle of the radar antenna. The y-axis points in the North direction, and the z-axis in the direction of the Zenith. Normally, true North is the reference direction in azimuth (historically magnetic north was used to be compatible with compass navigation). The Zenith is the point in space immediately above the observer. The point P represents the target and P' is the perpendicular projection of P on the xy-plane. In radar, elevation is defined as the elevation above the horizon. The coordinates of the target are: -

- range (or "slant" range) R.
- azimuth (Az) angle az.
- elevation (El) angle el.

Most ATC radars only give range and azimuth and are called 2D-radars (2D - two-dimensional). 3D-radars or dedicated height finding radars give additionally the elevation angle.

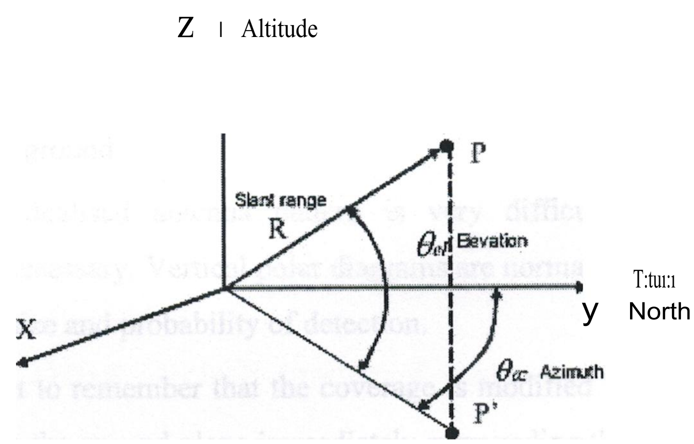


Figure 4.2 The Coordinate System

4.3 Antenna Vertical Polar Diagram

In an air traffic control radar, targets lie in a thin flat cylinder whose radius is many times its height. This leads to a requirement for a fan shaped beam or vertical polar diagram. The slide shows the coverage diagram for an approach/TMA radar. Typically, the range requirement is of the order of 80Nm and the height requirement is about 40,000 feet. The beam must be designed to illuminate targets within the coverage volume without transmitting energy where it is not required. Apart from the basic range and altitude requirements, the antenna must minimise the overhead gap or cone of silence. This gap is the inverted cone mapped out by the rotating antenna as a result of the antenna back angle being less than 90 degrees. Hence, the back angle is an important antenna parameter. If the back angle is shallow then aircraft will fall outside radar cover as they over-fly the radar site.

A further important parameter relates to the need to avoid too much illumination of the ground. If the antenna transmits too much energy at ground level, then the level of ground returns from physical features such as mountains or buildings may swamp the aircraft returns. A key parameter is therefore the rate of cut off (defined in terms of the rate of cut of antenna gain at low elevation angles). A high rate of cut off on the under edge of the beam permits maximum illumination of airborne targets while minimising the illumination of the ground.

In practice, the idealised antenna pattern is very difficult to achieve and some compromises are necessary. Vertical polar diagrams are normalised to defined parameters such as the target size and probability of detection.

It is also important to remember that the coverage is modified by local obstructions and by interaction with the ground plane immediately surrounding the antenna. These aspects will be covered later in the module.

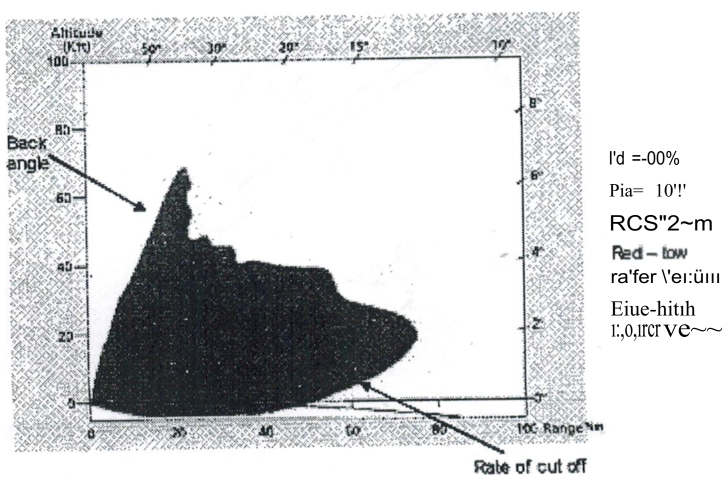


Figure 4.3 Antenna Vertical Polar Diagram

4.3.1 Doppler Shift

Doppler shift is the shift in frequency between the transmitted RF carrier and the echoes reflected from moving objects. The frequency J; received by an observer on the ground in figure 4.5, predicted by the theory ofrelativity, is given by

$$f_l = f_t \frac{c + v_R}{\sqrt{c^2 - v_R^2}} \tag{4.1}$$

where

fi. = transmitted frequency

VR = component of aircraft velocity in direction of observer (radial speed)

c = speed oflight (= 3.108 mis).

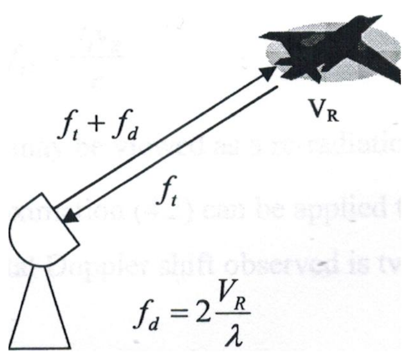


Figure 4.4 Doppler Frequency Shift is Due to Radar Speed

Monostatic Radar Layout

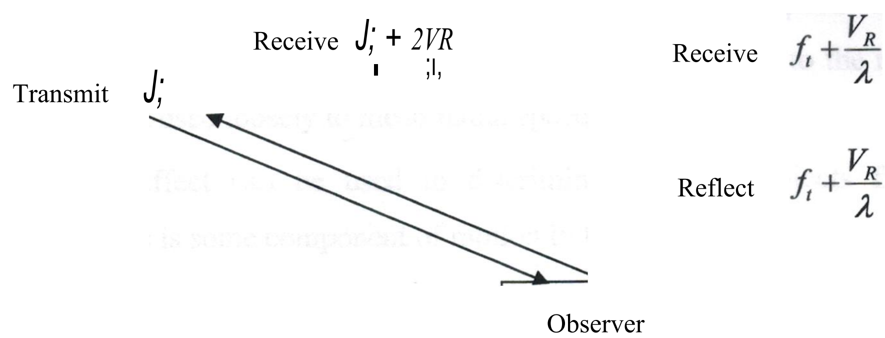


Figure 4.5 :frequency f_t received by an observer on the ground

Defining the doppler shift as $f_D = f_r - f_t$ and using the fact that the aircraft speed is very small compared to the speed of light ($v_R \ll c$), equation (4.1) reduces to

$$f_D = \frac{f_t v_R}{c} \tag{4.2}$$

The reflection from the ground may be viewed as a re-radiation at frequency f_r. Equation (4.1) or the very accurate approximation (4.2) can be applied to calculate the doppler shift observed in the aircraft. The total Doppler shift observed is twice the one way shift and is given by the following formula:

$$f_D = \frac{2f_t V_R}{c} = \frac{2v_R}{\lambda} \tag{4.3}$$

Where

$c = f_t \lambda$

λ = wavelength.

The frequency change of the echo will depend upon the radial speed of the target. Note that radial speed is the component of the target velocity relative to the radar site. Radial velocity is often used loosely to mean radial speed.

The Doppler effect can be used to discriminate moving objects from fixed ones (providing there is some component of motion in the radial direction).

However, the Doppler signal processing that is used extensively in primary surveillance radar does not directly measure the Doppler frequency change.

The processing used by pulsed primary surveillance radar is actually measuring the relative phase change from one pulse to the next.

Returns from the same fixed object (such as a building) will produce the same relative phase difference between transmitted and received pulses. Returns from the moving aircraft will produce a relative phase change from pulse to pulse (received whilst the aircraft is still in the antenna beam).

The doppler shift can be derived in another way which is perhaps more instructive for radar applications. Consider a target at a range R. The round trip distance is 2R, and the total phase difference between the transmitted and received wave is given by

$$\Phi = -2\pi\left(\frac{2R}{\lambda}\right) \tag{4.4}$$

where the negative sign indicates a phase delay. Using the definition of frequency:

$$f = \frac{1}{2\pi}\left(\frac{d\Phi}{dt}\right) \tag{4.5}$$

the change in frequency (i.e., the doppler shift f_D), seen at the radar, resulting from a target with changing range, is given by

$$f_D = -\frac{2}{\lambda}\left(\frac{dR}{dt}\right) = \frac{2v_R}{\lambda} \qquad (4.6)$$

Equation (4.6) indicates that the doppler shift will be positive; that is, at a higher frequency if the target is approaching ($\frac{dR}{dt}$ negative) and negative if the target is receding. The ability to discriminate between closing (approaching) and opening (receding) targets is often a valuable attribute. Most radars do not perform the frequency comparison between the transmitted wave and the received wave directly at radio frequency (RF), but down convert the received signal to a convenient intermediate frequency (IF).

Equation (4.4) shows the total phase delay between the transmitted and receive waveforms. The phase change between pulses (i.e., samples) is

$$\Delta\Phi = 2\pi\left(\frac{2\Delta R}{\lambda}\right) \qquad (4.7)$$

where

ΔR = range change between successive pulses.

The phase change will depend upon the radial velocity of the target, the radar wavelength (Φ) and its operating PRF.

For example, consider a target with a radial speed of 1 metre/sec, detected by a 10cm (0.1m) radar with PRF=400Hz (i.e. PRI=0.0025 s).

The motion of the target between pulses (ΔR) = 1 X 0.0025 = 0.0025 metres.

Phase change Φ can be expressed as follows: -

$$\Phi = -2\pi\left(\frac{2R}{\lambda}\right)$$

This equation shows the total phase delay between the transmitted and received waveforms. The negative sign indicates a phase delay. The phase change between pulses (i.e., samples) is: -

$$\Delta\Phi = 2\pi\left(\frac{2\Delta R}{\lambda}\right)$$

where

ΔR = range change between successive pulses.

Using this equation, the phase change for our target moving at a radial speed of 1 metre per second is $(\Delta\Phi)$ = 0.314 radians or 18 degrees [i.e. phase change per metre per second of speed].

The problem with phase measurement, is that it will become ambiguous for phase changes beyond 360 degrees. In the above example an aircraft with radial speed of 20 metres/sec will produce the same phase change as a static target. This is known as a blind speed.

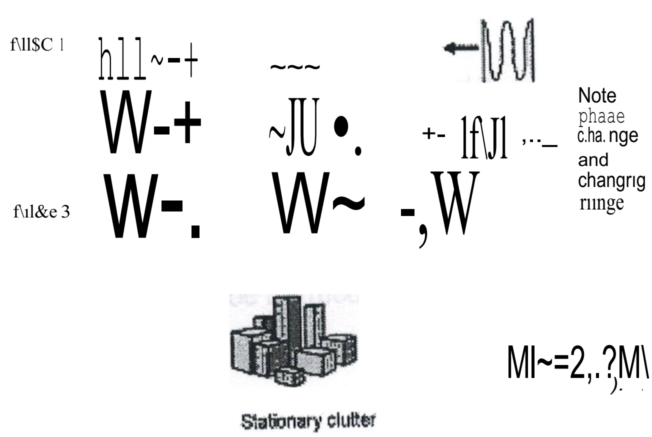


Figure 4.6 Doppler Shift

4.3.2 Signal to Noise Ratio

If we rearrange the expression for noise factor given in the previous section in terms of signal input as follows: -

$$S_{in} = \frac{FN_{in}S_{out}}{N_{out}} \tag{4.8}$$

and use the expression for noise power input to the system in terms of standard temperature

$$S_{in} = \frac{FkT_0BS_{out}}{N_{out}} \tag{4.9}$$

where kT_0B equals the noise into the receiver.

The minimum signal input to the receiver corresponds to the signal to noise ratio that can be detected at the output of the receiver is therefore as follows :-

$$S_{\min} = FkT_0B\left(\frac{S_{out}}{N_{out}}\right)_{\min} \tag{4.10}$$

We had previously derived the basic radar equation in terms of minimum signal input as follows: -

$$R_{\max} = \left[P_p \frac{G^2\sigma\lambda^2}{(4\pi)^3 P_{r(\min)}}\right]^{1/4} \tag{4.11}$$

($P_{r(\min)}$ is equal to the minimum signal input $S_{\min}$)

Then the basic radar equation can be defined in terms of the required signal to noise ratio as follows : -

$$R_{\max} = \left[P_p \frac{G^2\sigma\lambda^2}{(4\pi)^3 FkT_0B\left(\frac{S_{out}}{N_{out}}\right)_{\min}}\right]^{1/4} \tag{4.12}$$

The advantage of this form of the radar equation is that signal to noise ratio can be expressed in terms of probability of false alarms and detection. Next we will examine this approach.

4.3.3 False Alarms

Like signal echoes, the noise passes through the receiver and can then be detected. As we have already discussed, the IF amplifier is usually a high-Q matched filter amplifier which controls the overall bandwidth of the receiver. So the noise reaching the detector is narrowband. A typical portion of such noise is shown in the upper part of the slide. It looks rather like an amplitude-modulated sine wave, although it in fact contains a range of frequencies and has a random envelope. When the noise waveform is detected, the upper envelope ve(t) is extracted. It may be shown that the envelope has the so-called Rayleigh pdf: -

$$p(v_e) = \frac{v_e}{\sigma} \exp\left(\frac{-v_e^2}{2\sigma^2}\right), \quad v_e > 0 \tag{4.13}$$

The characteristic of this distribution is that it is mainly centred on the value o but there are occasional very large peaks as shown in figure 4.7.

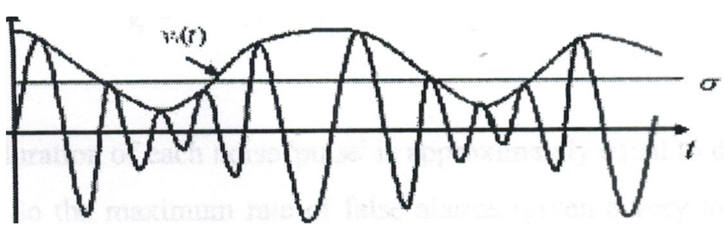


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Figure 4.7 False Alarms

The output from the detector is compared with a threshold level (threshold detection), to decide whether any target echoes are present. This may be shown to be the statistically optimum approach. Even so, there is unfortunately a danger that the noise will itself exceed the threshold, giving rise to a false alarm. (This leads to the definition of a probability of false alarm pra.) This is shown by the slide. The time-scale of the envelope ve(t) has been considerably compressed, compared with the slide in the previous section. But, as before, it fluctuates around the value , with occasional high peaks. One of these peaks exceeds the threshold voltage Vr, causing a false alarm. In other words, a noise peak has been wrongly interpreted as a target echo.

We may, of course, reduce the probability of false alarms by raising the detection threshold. But we are then less likely to detect genuine targets. This calls for a compromise. Too low a value of Vr gives many false alarms; but too high a value causes misses on targets, reducing the probability of successful detection. It now becomes clear that we cannot sensibly talk about target detection without also considering false alarms.

The probability of finding a random waveform above some threshold level Vr equals the area of its pdf between Vr. Hence the probability of obtaining a false alarm due to noise is given by the integral of the Rayleigh distribution: -

$$p_{fa} = \int_{V_r}^{\infty} \frac{v_e}{\sigma^2} \exp\left(\frac{-v_e^2}{2\sigma^2}\right), \qquad v_e > 0 \tag{4.14}$$

Now the average duration of each noise 'pulse' is approximately equal to the reciprocal of the bandwidth B. So the maximum rate of false alarms (given a very low threshold) is about B per second.

What rate of false alarms can be tolerated in a practical radar system? The answer must depend very much on the application. The acceptable false-alarm rate in a strategic early-warning radar may be quite different from that in a system designed to track weather balloons. Note, however, that a wide range of false alarm rates is encompassed by a narrow range of threshold values i.e. the false alarm rate can be significantly modified by a small change in the threshold value. In many practical cases we may expect v; /2a-2 to be set between about 11 and 14 dB.

The false-alarm probabilities corresponding to acceptable false-alarm rates are very small. For example, an average of one false alarm per minute in a receiver of bandwidth 1 MHz corresponds to *P1•* = 1.7 x 10". This implies that, in practice, the detection threshold must be set well into the extreme 'tail' of the Rayleigh distribution.

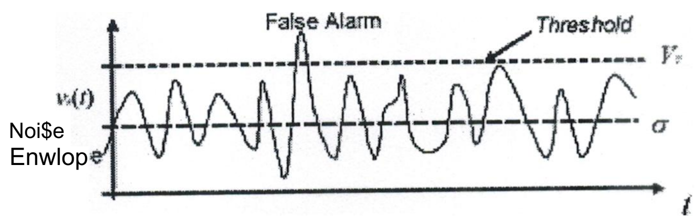

Figure 4.8 False Alarm (Rayleigh Distribution)