U.S. ARMY ST 44-188-1

INTRODUCTION TO RADAR

MILITANT

U.S. ARMY AIR DEFENSE SCHOOL

FORT BLISS, TEXAS

NOTE: Supersedes ST 44-188-1, Sep 58

MAY 1960

U.S. ARMY AIR DEFENSE SCHOOL
Fort Bliss, Texas

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CHAPTER 1

INTRODUCTION

1. PURPOSE

The purpose of this publication is to provide a reference which gives the background necessary to understand the theory of radar.

2. SCOPE

This publication covers the history, development, and basic theory of radar operation.

CHAPTER 2

HISTORY OF RADAR

3. EARLY METHODS OF WARNING

a. The earliest armies recognized the importance of knowing the whereabouts of their enemies. They stationed men at lookout points so that they would be aware of the approach of their enemy without revealing their own positions. Down through the centuries, man's principal early warning system has been a lookout stationed at a high vantage point. The invention of the high-powered telescope increased the range of early warning for a particular vantage point, but the position selected as a lookout point was still restricted in range due to the need for communication with the main body of troops. As communication systems progressed from the drum to the telephone and radio, it readily can be seen how early warning progressed proportionally.

b. With the advent of airplanes, visual means of detection were not dependable, particularly on cloudy days and at night. A device that could detect unseen targets was needed. One method included the use of listening devices which detected and amplified engine noises to an audible level, long before they could be heard by the unaided human ear. These devices were able to determine the direction of the approach by utilizing the binaural or two-ear effect of the human auditory system. This method was cumbersome and would be completely useless in the age of supersonic flight. As aircraft increased their speed and altitude, it became evident that new equipment must be developed which could detect and locate fast-moving high-flying targets and track them automatically. This resulted in the development of radar.

4. RADAR DEVELOPMENT

a. The word radar, formed from the initial letters in radio detection and ranging, indicates a method of employing radio waves to detect and locate material objects. The location of an object is accomplished by determining the distance and direction from the radar equipment. The measurement of three coordinates is generally required — range, azimuth, and elevation.

b. The invention of radar cannot be ascribed to a particular person or organization. Earliest credit belongs to the first radio physicist, Heinrich Hertz, who, in 1887 revealed experiments that proved radio waves were reflected like light rays and could be formed into beams by metallic mirrors similar in shape to mirrors that reflect light. In 1922 Marconi urged the use of short waves for purpose of detection. During the same year Dr. A. Hoyt Taylor and L. C. Young of the U.S. Naval Research Laboratory at Anacostia, D.C. noted that signals received on 60 megacycles were subject to occasional rapid variations in signal strength and finally identified the cause to be the passage of boats on nearby Anacostia River. Dr. Taylor suggested that surface vessels might be detected by this means. In 1925 Drs. Bruit and Tuve of the Carnegie Institute first employed the principles of pulse radar in measuring the height of the ionosphere.

c. In 1930, Dr. Taylor resumed his research at the U.S. Naval Research Laboratory and began a definite program leading to a device to detect the enemy and give knowledge of his movements. In 1932, the Secretary of the Navy communicated all information to the Secretary of War in the belief that radar would prove essential to antiaircraft activities of the Army. In 1934 a cw source of radio waves at a frequency of about 3,000 mc and about 1/2 watt of power was tested by the Army Signal Corps Laboratories. Harbor traffic was detected at distances of less than a mile. In July 1934, Major Blair, director of the Army Signal Corps Laboratories, reported that consideration was being given to "the scheme of projecting an interrupted sequence of trains of oscillations against the target and attempting to detect the echoes during the interstices between the projections." This was one of the first proposals to use pulses in a radio detection device.

d. Early in 1935, Sir Robert Watson-Watt of the National Physical Laboratory in England made the same proposal independently. In May, pulse equipment had been constructed by Watson-Watt and coworkers that tracked aircraft. In December 1936, Army Signal Corps research turned wholly to pulse systems. Work began on the first U.S. Army radar set, the SCR-268, designed to direct searchlights to aircraft and for the measurement of slant range. Work on the radar set was completed in May 1937. The British embarked on a program of large scale early-warning radar development that resulted, in 1937, in the establishment of radar stations on the Thames estuary. These stations operated on a frequency of 25 mc. They were put on a 24-hour watch in September 1938. The British were far in advance of the rest of the world in radar development during this period.

e. In 1939, radar equipment designed and built by the Naval Research Laboratories was installed on the U.S.S. New York and was tested during battle maneuvers. In 1940, England developed a multicavity magnetron which met the requirements of high peak power and high frequency. The magnetron was an important milestone in the development of the high-power, high-frequency techniques of present-day radar. British and American interests were pooled in 1940-41, and joint work on radar began in early 1941. In the late spring of 1941, the U.S. destroyer Semmes was equipped with a search-type radar which employed a PPI presentation. During 1941, the first radar was built which would track an aircraft automatically in azimuth and elevation; the principles of this equipment were incorporated in the design of the SCR-584. Later, automatic range tracking was developed and employed in the SCR-784 providing fully automatic tracking in range, azimuth, and elevation.

f. The first public announcement of the existence of radar was made in June 1941 when an appeal was made for American technicians to man British radars. A description of the radar principle was released in May 1943. The total expenditure for radar research development, and procurement during 1941-1945 was 2.7 billion dollars. The work on radar development continued at a slower pace after the war ended, and was directed toward industrial and commercial uses. All large commercial aircraft are now equipped with radar to measure absolute altitude, to aid navigation, and to detect mountains and other objects along their course. Ground control approach (GCA) equipment has been perfected to the point where air traffic may be handled with the same speed and safety in bad weather as in clear weather. GCA equipment was used during the Berlin airlift to maintain 24-hour operation regardless of the weather. The range detection capabilities of radar equipment have been greatly increased in recent years.

CHAPTER 3

THEORY OF RADAR

5. CHARACTERISTICS OF RADAR WAVES

a. Radar is an application of radio principles by means of which it is possible to detect the presence of objects, determine their direction and range, and recognize their character.

b. Detection is accomplished by directing a beam of radio-frequency energy over a region to be searched. When the beam strikes a reflecting object, energy is reradiated. A very small part of this reradiated energy is returned to the radar system. A sensitive receiver can detect the echo signal and, therefore, the presence of the object or target. The determination of the actual range is based on the fact that radio-frequency energy travels at the constant velocity of light, 186,000 miles (328 million yards) per second. Making the receiving system directional, the direction, or azimuth of the target, may be determined.

6. RADAR METHODS

a. Continuous-wave (cw) method. When radio-frequency energy which is transmitted continuously strikes an object which moves toward or away from the source of energy, this energy is reflected and its frequency is changed. The change in frequency is known as the doppler effect. The difference in frequency between the transmitted and reflected energy is measured to determine the presence and speed of the moving target. This method works well with fast-moving targets, but does not work satisfactorily with those targets which are slow or stationary.

b. Frequency-modulation method. If the frequency of the transmitted energy is varied continuously and periodically over a specified band, the frequency of the energy being radiated by the antenna differs from that received from the target. This difference occurs because of the time required for the energy to reach the target and return. The frequency difference depends on the distance traveled, and can be used as a measure of range. Moving targets produce a frequency shift in the returned signal because of the doppler effect which affects the accuracy of range measurement.

c. Pulse-modulation method. The radio-frequency energy can also be transmitted in short pulses whose time duration may vary from 1 to 50 microseconds. If the transmitter is turned off before the reflected energy returns from the target, the receiver can distinguish between the transmitted pulse and the reflected pulse. After all reflections have returned, the transmitter can again be turned on and the process repeated. The receiver output is applied to an indicator which measures the time interval between the transmission of the energy and its return as a reflection. Since the energy travels at a constant velocity, the time interval becomes a measure of the distance traveled, or range. Since this method does not depend on the relative frequency of the returned signal, or on the motion of the target, difficulties experienced in the cw and frequency-modulation methods are not present. The pulse-modulation method is used almost universally in military and naval applications. Therefore, it is the only method which will be discussed in this text.

7. DETERMINATION OF RANGE

a. The successful employment of pulse-modulated radar systems depends primarily on the ability to measure distance in terms of time. Radio-frequency energy, once it has been radiated into space, continues to travel with constant velocity. When it strikes a reflecting object there is no loss in time, but merely a redirecting of the energy. Its velocity is that of light, or in terms of distance traveled per unit of time, 186,000 land miles per second, 162,000 nautical miles per second, or 328 yards per microsecond.

b. The constant velocity of radio-frequency energy is applied in radar to determine range by measuring the time for a pulse to travel to a target and return. The speed of the radar pulse is so great that the second is a rather useless unit of measure and must be further subdivided into millionths of a second, or microseconds. The radar pulse, traveling at a speed of 328 yards per microsecond, will reach a target 164 yards away and return in 1 microsecond. The figure, 164 yards per microsecond, is an important unit in radar system measurements and is known as radar range time.

c. The minimum range of a radar will be determined by the time it takes the receiver to recuperate from the pulse width and the strong transmitted pulse. Peak power developed by the radar transmitter, size and reflecting characteristics of targets, receiver sensitivity, and the length of the listening period between pulses will all be limiting factors as far as the maximum range of a particular radar is concerned.

d. In order to employ the time-range relationship, the radar system must have a time-measuring device. In addition, since there may be more than one target in the region under search, some means of separating and identifying pulses must be included. The cathode-ray oscilloscope is well suited to such a task, since it retains the information on its screen and also forms a time scale. The time scale is provided by using a linear sweep to produce a known rate of motion of the electron beam across the screen of the cathode-ray tube.

8. DETERMINATION OF AZIMUTH

a. The measurement of the direction of a target from the radar system is usually given as an angular position. The angle may be measured from true north if the installation is stationary, or with respect to the heading of a vessel or aircraft containing the radar set. The angle at which the echo signal returns is measured by utilizing the directional characteristics of the radar antenna system.

b. The dimensions of the individual element (the dipole) cause it to send out more energy in some directions than in others. When several elements are used together to form an antenna system, the energy is further concentrated. Radar antennas are constructed of radiating elements, reflectors, and directors to produce a single narrow beam of energy in one direction. The pattern produced in this manner permits the beaming of maximum energy in a desired direction. The transmitting pattern of an antenna is also its receiving pattern. An antenna can therefore be used to transmit energy, receive reflected energy, or both.

c. The simplest form of antenna for measuring azimuth or bearing is one that produces a single-lobe pattern. The system is mounted so that it can be rotated. Energy is directed across the region to be searched, and the beam is scanned in azimuth until a return signal is picked up. The position of the antenna is then adjusted to give a maximum return signal. A maximum signal is received only when the axis of the lobe passes through the target. The sensitivity of the single-lobe system depends on the angular width of the lobe pattern. The position of the antenna system is adjusted for maximum received signal. If the signal strength changes rapidly with angular rotation, the accuracy with which the on-target position can be selected is great. If the energy is concentrated in a narrow beam, the accuracy is better.

d. The use of two lobes instead of a single lobe greatly increases the accuracy of azimuth measurement. The amount of increase depends on the configuration of the antenna array. In general, the increase is at least five times, but it can be much greater. In addition to the greater accuracy of the double lobe, there is another advantage in the sense of direction available. If the antenna array is off-target on the side of a lobe, the signal received by that lobe is greater. The antenna can then be rotated until the signals become equal; the antenna is then on-target. The two lobe patterns intersect at one point only, known as the crossover point, at which equal signals are produced by the two lobes for this particular azimuth. At all other positions of the array, unequal signals are produced.

9. DETERMINATION OF ELEVATION

a. The remaining dimension necessary to locate completely an object in space can be expressed either as an angle of elevation, or as an altitude. If one is known the other can be calculated from the right-triangle relationship and the slant range.

b. The free-space pattern of an antenna array is based on the arrangement of the individual elements within the system. If the same array is placed close to the earth, however, the vertical free-space pattern may be changed by the effect of ground reflections. The target will then receive energy from two directions and the effective field is the sum of the two fields so produced. The reflected wave travels farther than the direct ray in reaching the target. The addition of the fields at the target depends on the difference in the distances traveled expressed in wavelengths. For example, if the path difference for a given target position is a half-wavelength, the fields cancel. If the position of the target is changed so that the path difference is a full wavelength, the fields add. The result of ground reflection is to break the single free-space lobe into a number of smaller lobes, with gaps between them.

c. Any method used for determining the angle of elevation, or the altitude, must either make use of ground reflections, or completely avoid them. The threshold-pickup method and the signal-comparison method use the effect of ground reflections to find altitude. The tilted-antenna method avoids ground reflections and measures the angle of elevation.

(1) The threshold-pickup method makes use of the vertical-coverage pattern of an antenna system whose lobe axis is parallel to the earth. The positions of the lobes and gaps are determined by flying an aircraft toward the radar installation at known altitudes, and recording the ranges at which a minimum usable signal is returned. The chart obtained in this way is used by observing the range at which an unknown target first appears, and then reading its altitude from the chart. This method is very inaccurate, primarily because the graph of the antenna pattern is determined by the use of a single aircraft while the target may be any number of aircraft; in general, the greater the number of aircraft, the greater is the strength of the returned signal.

(2) The signal-comparison method is an extension of the threshold-pickup method. Two antennas are placed one above the other to give slightly different vertical-coverage patterns. The lobes, therefore, overlap but do not coincide. The signals received on the two antennas are compared in magnitude, and their ratio, together with the range of the target, is applied to a height-range chart from which altitude is read. Under favorable conditions, the altitude can be determined within 500 feet. Inaccuracies due to the number of aircraft in a given target are largely eliminated because a ratio is used.

(3) The tilted-antenna method measures the angle of elevation directly in the same way that azimuth is measured. Ground reflections are avoided by using the system on targets that are sufficiently high so that transmitted energy does not strike the ground. The accuracy of this method depends on the free-space pattern and the ability of the operator to locate the on-target position of the antenna array. Double-lobe systems are commonly used to increase the precision with which the antenna is pointed.

10. RADAR TRANSMISSION

a. System constants. Any radar system has associated with it certain constants. The choice of these constants for a particular system is determined by its tactical use, the accuracy required, the range to be covered, the practical physical size, and the problem of generating and receiving the signal.

b. Carrier frequency. The carrier frequency is the frequency at which radio energy is generated. The principal factors influencing the selection of the carrier frequency are the desired directivity and the generation and reception of rf energy.

(1) For the determination of direction and for the concentration of the transmitted energy so that a greater portion of it is useful, the antenna should be highly directive. The higher the carrier frequency, the shorter the

wavelength, and hence the smaller is the antenna array for a given sharpness of pattern, since the individual radiating element is normally a half-wavelength. For an antenna array of a given physical size the pattern is sharper for a higher frequency.

(2) The problem of generating and amplifying reasonable amounts of radio energy at extremely high frequencies is complicated by the physical construction of the tubes to be used. The common triode becomes impractical and must be replaced by tubes of special design. Among these are such types as the lighthouse triode, grounded-grid triode, klystron, and magnetron. In general, the modifications are designed to reduce interelectrode capacitances, transit time, and stray inductance and capacitance in the tube leads.

(3) The lowest carrier frequency normally used is 100 mc in order to limit the antenna array to a practical size and yet obtain the desired directional beam. There are inherent difficulties in generating and amplifying rf energy at extremely high frequencies. Frequencies beyond 10,000 mc are used in order to produce very narrow beams that provide more accurate data.

c. Pulse-repetition frequency. Sufficient time must be allowed between transmitted pulses for an echo to return from any target located within the maximum workable range of the system, otherwise the reception of the echoes from distant targets will be obscured by succeeding transmitted pulses. This time interval fixes the highest frequency that can be used for the pulse repetition. The persistence of the indicator screen and the rotational speed of the antenna determine the lowest repetition rate that can be used; a sufficient number of pulses must be transmitted in order to return a signal that will produce a lasting impression on the PPI screen. The repetition frequency must be very stable if accurate range measurement is desired; successive traces should appear in exactly the same position to avoid blurring on the indicator screen.

d. Pulse width. The minimum range at which a target can be detected is determined largely by the width of the transmitted pulse. If a target is so close to the transmitter that the echo is returned to the receiver before the transmitter is turned off, the reception of the echo obviously will be masked by the transmitted pulse.

e. Power relation. A radar transmitter generates radio-frequency energy in the form of extremely short pulses and is then turned off between pulses for comparatively long intervals. The useful power of the transmitter is that contained in the radiated pulses and is termed the peak power of the system. Power is normally measured as an average value over a relatively long period of time. Since the radar transmitter is resting for a period that is long with respect to its operating time, the average power delivered during one cycle of operation is quite low compared to the peak power available during the pulse time.

(1) A definite relationship exists between the average power dissipated over an extended period of time and the peak power developed during the pulse

time. The time of one cycle of operation is the reciprocal of the repetition frequency, $T = 1/f$. Other factors remaining constant, the greater the pulse width, the higher the average power; the longer the pulse-repetition time, the lower the average power:

$$\frac{\text{average power}}{\text{peak power}} = \frac{\text{pulse width}}{\text{pulse-repetition time}}$$

These general relationships are shown in figure 1.

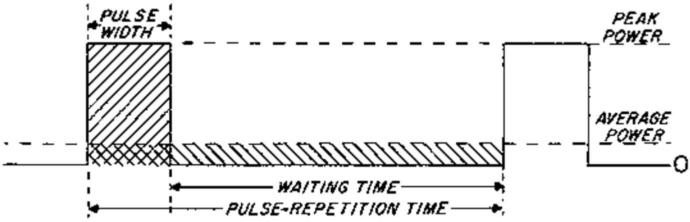


Figure 1. Relationship of peak and average power.

(2) The operating cycle of the radar transmitter can be described in terms of the fraction of the total time that the rf energy is radiated. This time relationship is called the duty cycle and may be represented as:

$$\frac{\text{pulse width}}{\text{pulse-repetition time}} = \text{duty cycle}$$

(3) Likewise, the ratio between the average power and peak power may be expressed in terms of the duty cycle:

$$\frac{\text{average power}}{\text{peak power}} = \text{duty cycle}$$

(4) High peak power is desirable to produce a strong echo over the maximum range of the equipment. Low average power enables the transmitter tubes and circuit components to be made smaller and more compact. Thus it is advantageous to have a low duty cycle. The peak power that can be developed is dependent upon the interrelation between peak and average power and pulse width and pulse-repetition time, or duty cycle. The number of times that pulses occur during one second of transmitter operation, the pulse recurrence frequency or prf, can be computed if the pulse-repetition time is known by this formula:

$$\text{prf} = \frac{1}{\text{pulse-repetition time}}$$

CHAPTER 4

THE BASIC RADAR SYSTEM

11. FUNDAMENTAL ELEMENTS

a. Radar systems now in existence vary greatly as to detail. They may be very simple or, if more accurate data are required, may be highly refined. The principles of operation, however, are essentially the same for all systems. Thus a single basic radar system can be visualized in which the functional requirements hold equally well for all specific equipment. The varying details are due to a choice of specific circuits to fulfill these general functional requirements. In general, the degree of refinement of these circuits increases with the frequency, since the microwave region lends itself to a higher degree of precision in angular measurement.

b. The functional breakdown of the pulse-modulated radar system resolves itself into six essential components. These are shown in figure 2 and may be summarized as follows:

(1) The timer, also known as synchronizer key, or control central, supplies the synchronizing signal to initiate transmitter action and start indicator sweeps.

(2) The transmitter generates the rf energy in the form of short, powerful pulses.

(3) The antenna system takes the rf energy from the transmitter, radiates it in a highly directional beam, receives any returning echoes, and passes these echoes on to the receiver.

(4) The receiver amplifies the weak rf pulses returned by the target and reproduces them as video pulses to be applied to the indicator.

(5) The indicator produces a visual indication of the echo pulses in a manner that furnishes the required information.

(6) The power supply furnishes all ac and dc voltages necessary for the operation of the system components.

c. Any radar system can be subdivided on the basis of the functional block diagram shown in figure 2. An actual system may contain several functional components within one physical component, or a single function may be performed in several physical components. However, the analysis of the operation of a given set is greatly simplified by applying the functional block diagram without considering the physical location of the circuits.

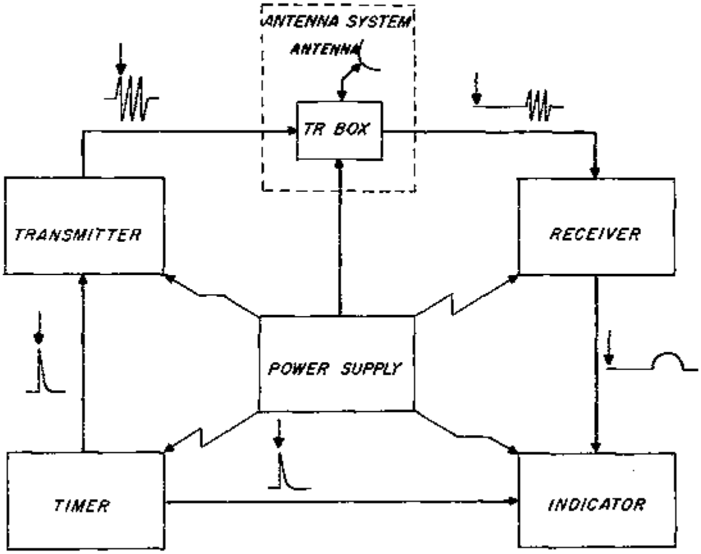


Figure 2. Basic radar block.

12. TIMER

a. Function. The function of the timer is to insure that all circuits connected with the radar system operate in a definite time relationship with each other and that the interval between pulses is of the proper length. In general, there are two practical method of supplying the timing requirements.

b. Timing by separate unit. The pulse-repetition frequency can be determined by an oscillator of any stable type such as a sine-wave oscillator, a multivibrator, or a blocking oscillator. The output is then applied to necessary pulse-shaping circuits to produce the required timing pulse. Figure 3 shows several typical combinations of circuits that may be used. The timing of associated components can be accomplished with the output of the timer, or by obtaining a timing signal from the transmitter as it is turned on.

c. Timing within transmitter. The transmitter, with its associated circuits, may establish its own pulse width and pulse-repetition frequency and provide the synchronizing pulse for the other components of the system. This action may be accomplished by a self-pulsing or blocking rf oscillator with properly chosen circuit constants. This method of timing eliminates a number of special timing circuits, but the pulse width or pulse-repetition frequency obtained may be less rigidly controlled than is desirable for some

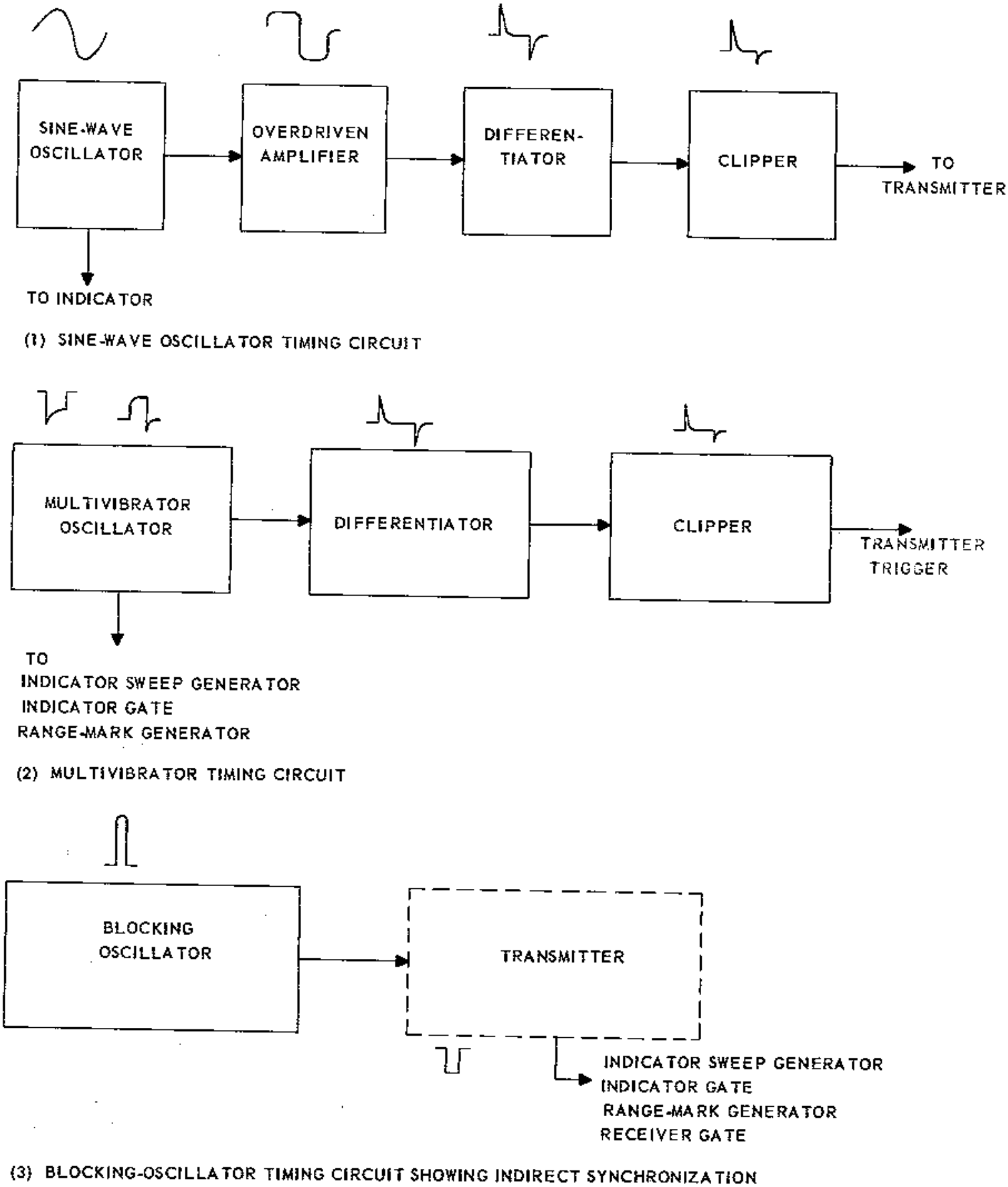


Figure 3. Methods of timing radar systems.

applications. A crystal-controlled vacuum tube oscillator can be used in timers to generate the master timing frequency. This device is used because its output frequency is dependent on the predetermined physical characteristics of the quartz crystal which are altered very little by atmospheric or temperature changes. Since range measurement in the radar is based on extremely accurate time measurements, the circuits in the timer must be very stable.

13. TRANSMITTER

a. The purpose of the transmitting system is to produce high-powered, radio-frequency energy for very short predetermined periods of time. The pulse repetition frequency is determined by the time. A typical transmitter is composed of a driver, modulator, high-voltage rectifier, and magnetron, as shown in figure 4.

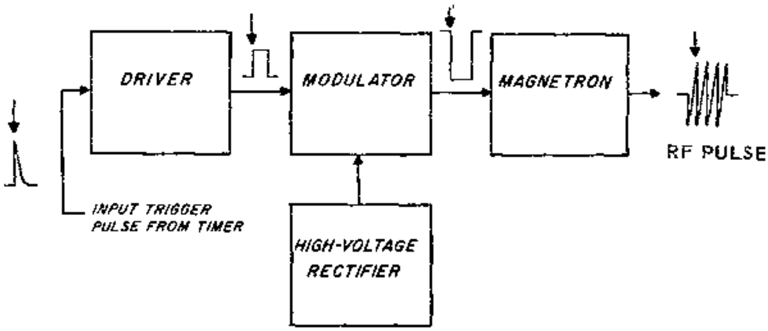


Figure 4. Transmitter block.

b. The manner in which the modulator controls the high voltage that it applies to the magnetron is governed by the driver. The driver stages amplify, shape, and establish the polarity and pulse duration of the trigger pulses that originated in the timer. Correct shaping insures that the pulse of voltage applied to the magnetron will cause it to oscillate at a stable frequency for a definite period of time.

c. The circuit which pulses the magnetron, or connects the high-voltage rectifier to the magnetron, is called the modulator. Its name is derived from the fact that it varies the current through the magnetron from zero to about 30 amperes within an almost instantaneous time. The modulator conducts each time that a pulse is received from the driver. When the modulator conducts, a high-voltage pulse of short duration is applied to the magnetron.

d. The stable high voltage and power required by the magnetron is provided by the high-voltage rectifier and its associated filter circuits. Filter circuits allow the magnetron to be pulsed without affecting the output of the high-voltage rectifier, which in turn would affect the magnetron frequency.

e. The high-frequency, high-powered oscillator used in most radars is the magnetron. A high-voltage pulse applied to the magnetron from the modulator causes it to oscillate and generate a high power output for only a short period of time, usually from about

1/3 to 4 microseconds, depending upon the type of radar. The output frequency of this oscillator is primarily established by the magnetron's physical dimensions, which may be varied to obtain a change in frequencies over a narrow band. The output rf pulse can also be affected by the shape of the pulse which is applied into the magnetron. The output of the magnetron is transferred directly to the antenna for transmission into space.

14. ANTENNA

a. The function of the antenna system is to take the energy from the transmitter, radiate it in a directional beam, pick up the returning echo, and pass it to the receiver with minimum loss. The antenna system may be considered to include the transmission lines from the transmitter to the antenna array, the antenna array itself, the transmission line from the antenna array to the receiver, and any antenna-switching device and receiver-protective device that may be present (fig 5).

b. When a radar receiver is operated in close proximity to a powerful radar transmitter, a certain amount of signal inevitably finds its way into the receiver directly from the transmitter by way of the stray capacitance of the input circuit leads. In certain instances, such signals resulting from the main transmitted pulse must be entirely eliminated from the output of the receiver. Therefore the receiver must be gated or turned off during the pulse time so that it may be completely insensitive.

c. It may be desirable to couple a small amount of the transmitted rf energy to the receiver for timing purposes. However, the signal available from the transmission line is so strong that the receiver input circuit may be burned out. Because of the sensitivity of the receiver, the strong signal may also cause blocking of tubes which employ RC grid circuits. This blocking occurs because the strong signal will overdrive the tubes, causing grid current to flow which charges the capacitors. After the signal is removed, the charge remains for some time, providing a bias which keeps the tubes below cutoff. Both of these conditions place a limit on the permissible amount of transmitted pulse that can reach the receiver, and are the reasons for employing receiver-protective devices.

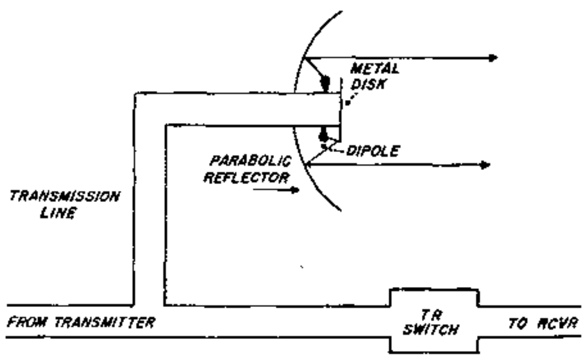


Figure 5. Antenna system.

d. Radio-frequency energy may be transferred from point to point by transmission lines in much the same way as industrial power is transferred by means of high-tension powerlines. However, at high frequencies the two-wire transmission lines (fig 6(1)) used for power frequencies and the lower radio frequencies are no longer practicable. The most common types of transmission systems are the coaxial line and the waveguide. The coaxial line, as the name implies, consists of two tubes with a common axis (fig 6(2)). The outer tube surrounds the inner tube and is separated from it by an insulating material such as dry air. The operation of this line is similar to that of an ordinary transmission line, but with less radiation loss along the line. The waveguide is a pipe, either rectangula or circular in cross section (fig 6(3) and (4)). Transmission is effected by causing the waves of energy to be reflected back and forth along the pipe in a forward direction. The construc tion of the waveguide is much simpler than the coaxial line, since the inner conductor with its various supporting elements has been eliminated. Because of its simple construction, the waveguide can handle high voltages more efficiently than the coaxial line. The dimensions of the waveguide depend upon the wavelength and it becomes rather bulky above 10-centimeter wavelengths (3,000 megacycles); a coaxial line is used with longer wavelengths.

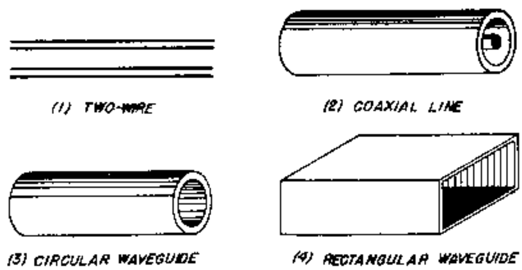


Figure 6. Types of transmission lines.

e. A radar system employs a single antenna and an antenna switch capable of connecting the antenna to the transmitter during the transmission time and to the receiver during the remainder of the pulse cycle. The switch is necessary to protect the receiver from the transmitter during the pulse time and also to isolate the transmitter during the receiving time. Otherwise, the weak receiver echoes might be wholly or partially lost. The transmitted pulse width and the repetition frequency of the system eliminate the possibility of using a mechanical switch.

(1) A system for using a single antenna for both transmission and reception should be as efficient as possible; all of the energy produced by the transmitte should reach the antenna, and all of the received energy should reach the receiver. This efficiency is most easily obtained by matching the antenna to the characteristic impedance of the transmission line. During transmission of the pulse, the transmitter should be matched to the transmission line and the receiver must present an open circuit, or high impedance to the transmission line. During the reception time the conditions should be reversed.

(2) The problem of switching is usually simplified because most transmitters have a different output impedance when they are on than when they are off. If properly matched to the transmission line during the pulse, the transmitter will be mismatched for the receiving time and the transmission line

will be resonant. Figure 7 illustrates a typical elementary system in which the receiver and transmitter are connected by branch lines to the antenna feed line. The junction of the three lines is known as the T-junction. During the off period, the switch in the receiver branch is closed and the transmission

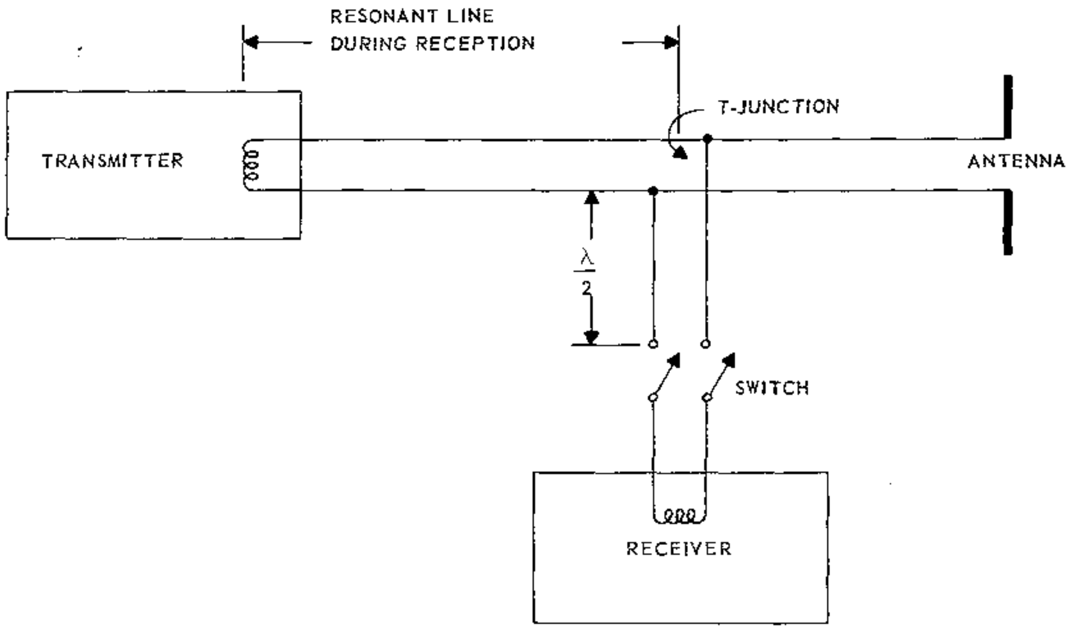


Figure 7. Elementary switching system.

line from antenna to receiver is properly matched. The resistance seen from the T-junction looking toward the transmitter can be controlled by the length of the resonant section between them. If the transmitter impedance decreases when it is turned off, the length should be a quarter-wavelength, or some odd multiple thereof, in order to see a high impedance. The high impedance presented by the transmitter and its feed line to the T-junction is in parallel with the relatively low characteristic impedance of the remainder of the transmission line system, but being high, has little effect. If the transmitter impedance increases when it is turned off, the resonant-line length should be a half-wavelength, or a multiple thereof.

(3) When the transmitter is turned on to transmit the next pulse, it again will be properly matched to the antenna. The open switch (fig 7) will prevent the pulse from reaching the receiver, and will cause a mismatch to the line between the switch and T-junction. By using some multiple of a half-wavelength, the open circuit of the switch will be presented as an open circuit across the transmitter-antenna line.

(4) In a broad sense the switching problem consists of providing what amounts to a double-pole, single-throw switch (fig 7) for connecting the antenna

alternately to the transmitter and to the receiver. The switching device must be capable of acting within a time interval of a few microseconds, as the receiver should be in the antenna circuit immediately after the transmission of the pulse in order to detect close-range targets. This microsecond timing requires that the device be electronic in type. Under various operational circumstances it may take the form of rf amplifiers, klystrons, spark gaps, resonant transformers, spark-gap tubes, and (in waveguides) resonant slits. It is commonly known as the TR (transmit-receive) switch or TR box. Other terms frequently encountered are duplexer, reprod, and, in certain instances, polyplexer.

Figure 8. TR tube.

(5) The TR tube (fig 8) consists of two conical-shaped metal electrodes inclosed in a glass envelope that is mounted in a resonant cavity. When excited by the transmitted energy, it causes an arc to be formed between the two electrodes. This action electrically blocks the line to the receiver and causes all of the energy to be conveyed to the antenna. As soon as the transmitted pulse has passed, the TR tube returns to its normal condition. Electrical characteristics of the line cause the magnetron to appear as an open circuit, and the very weak echo signals pass into the receiver system.

(6) ATR (antitransmit-receive) and TR tubes are resonant cavities, whose resonant frequency corresponds to the transmitter frequency. They are filled with gas under a low pressure. In the case of the TR tube, spark gaps shorten the time required for ionization and provide maximum protection for the receiver. The ATR tubes prevent the reflections (rf energy echoes) from entering the magnetron. Since the energy contained in these echoes is not sufficient to cause arcing of the TR tube, the energy enters and travels through the TR tube to the preselector. During the transmitting cycle, the rf energy traveling down the waveguide finds an open circuit at the TR tubes, but the transmitted power enters the resonant cavities, causing oscillation. The power in the cavities, which is great because of the energy contained in the transmitted pulse, causes the gas in the cavities to ionize. This reflects a short circuit across the ATR cavities, and the rf energy continues down the waveguide.

f. The principal types of radiators employed in the radar antenna system include the stacked-dipole array with untuned reflector, the dipole with tuned reflectors and directors (Yagi), the dipole with parabolic reflector, and various arrangements of dielectric radiators used in conjunction with waveguides.

(1) The stacked-dipole array may be composed of one or more banks of dipoles and may be adapted for lobe switching. The entire assembly usually can be rotated in either azimuth or elevation, or both.

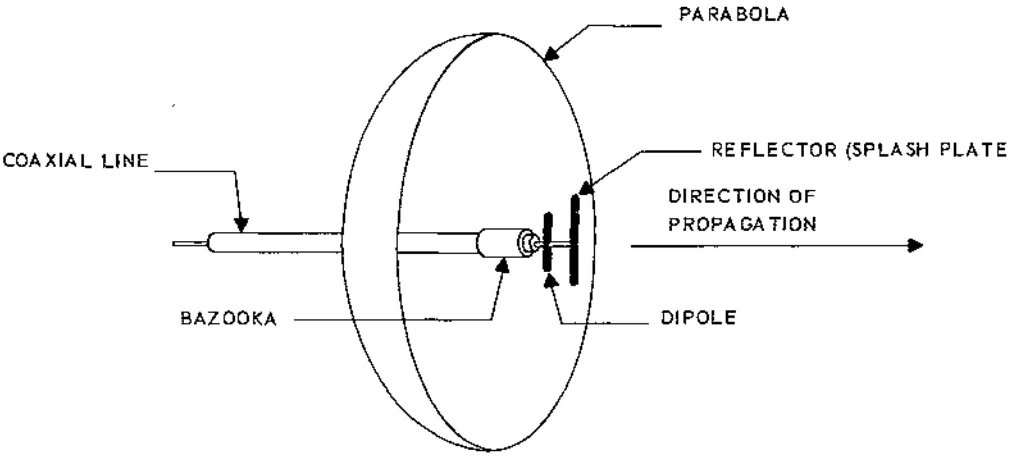


Figure 9. Dipole with parabolic reflector.

(2) A Yagi array can be of a type utilizing both director and reflector parasitic antennas in conjunction with a driven element. Only the driven element is connected to the transmission line. The other elements are excited parasitically, picking up energy from the driven element and reradiating it with such a phase relation with respect to the driven dipole that the field is reinforced in the forward direction.

(3) Figures 5 and 9 show the parabolic reflector type of antenna, which is a practical means of producing a narrow beam pattern in the region of the microwavelengths. The reflection of rf energy by the parabola or dish is closely analogous to the reflection of light by a parabolic mirror. The dish is large in comparison with the operating wavelength; in general, the larger the reflector, the narrower the beam pattern. The rf energy is fed to a dipole located at the focal point of the parabola. A parasitic reflector is placed about one-quarter wavelength in front of the dipole to reflect practically all of the radiated energy back to the dish from which it is reflected ahead in the form of a narrow beam. Modifications of this type of radiating system include cylindrical and other types of parabolas. Parabolic reflectors are frequently used in conjunction with waveguides.

(4) A bank of dielectric radiators can be fed by waveguides. These radiators may be considered merely as extensions of the waveguides and are designed to provide the proper termination to transfer the energy from the waveguides to space.

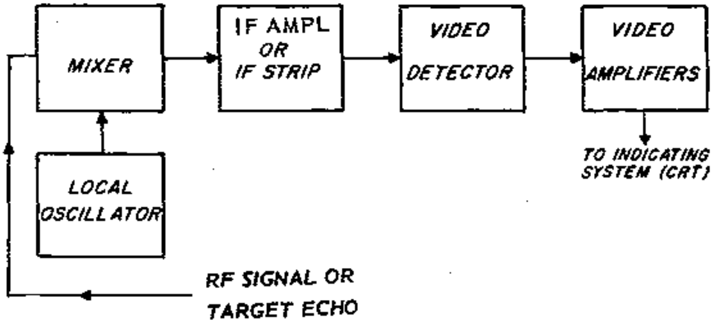


Figure 10. Receiver system.

15. RECEIVER SYSTEM

a. The function of the receiver is to take the weak echoes from the antenna system, amplify them sufficiently, detect the pulse envelope, amplify the pulses, and feed them to the indicator. The receivers used in radars are capable of accepting weak echoes and increasing their amplitudes by a factor of 20 or 30 million. Since radar frequencies are not easily amplified, a superheterodyne receiver changes the radio frequency to an intermediate frequency for amplification. Stability of operation is maintained in the microwave range of frequencies by careful design, and the overall sensitivity of the receiver is greatly increased by the use of many intermediate-frequency stages. Special types of tubes having low interelectrode capacitances have also been developed for use in rf, local-oscillator, and if stages.

b. Figure 10 illustrates the receiver components of the radar system. The rf amplifier may not be present in the higher frequency ranges and thus the received signal may be fed directly to the mixer. In this case it is desirable to use as short a receiver input transmission line as the design requirements allow. Thus the mixer and local oscillator may be located close to the T-junction of the transmission line in order that the received rf energy may be converted to the lower intermediate frequency before being relayed to the remaining receiver components. One or two stages of if amplification are sometimes located immediately after the mixer-local oscillator stage, functioning as a preamplifier to offset the considerable attenuation encountered in coupling the very weak received signal to the remote receiver components. The components of the radar receiver may be distributed throughout the system in such a manner that their physical identity becomes lost.

16. INDICATOR

a. The indicator uses the received signals to produce a visual indication of desired information. The cathode-ray oscilloscope is an ideal instrument for the presentation of radar data since it not only shows a variation of a single quantity such as voltage, but gives an indication of the relative values of two or more synchronized variations. The usual indicator is basically the same in function as the low-frequency test oscilloscope.

The focusing intensity and positioning controls are similar. The sweep frequency of the radar indicator is determined by the pulse-repetition frequency of the system and the sweep duration is established by the setting of the range-selector switch (fig 11).

(1) The simpler systems of data presentation generally use the electrostatic cathode-ray tube in which the electron beam is made to follow some pattern by controlled differences in potential between pairs of deflecting plates.

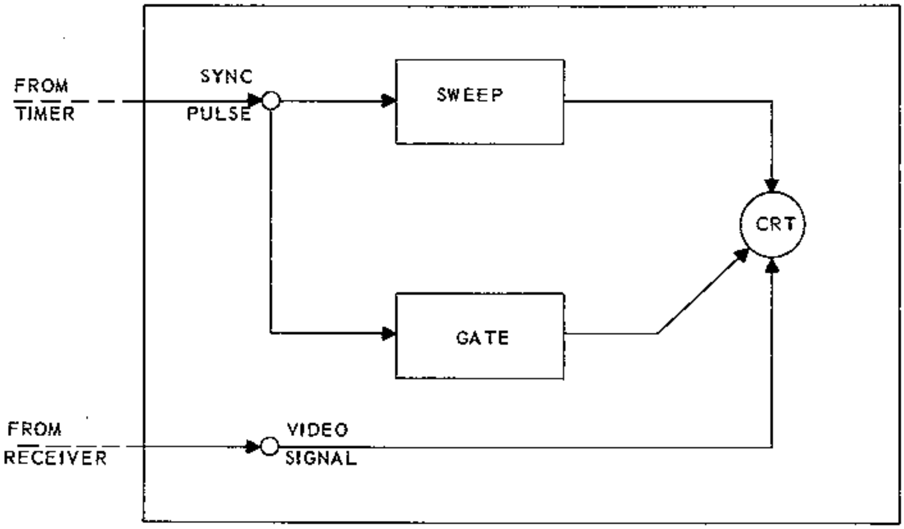


Figure 11. Basic components of radar indicator.

(2) The more highly refined systems of data presentation generally utilize the electromagnetic cathode-ray tube with a long-persistence screen. The position of the electron beam at any instant is determined by causing it to pass through a magnetic field produced by controlled currents through deflecting coils mounted outside the tube. If intensity modulation is used, the bias is such that the tube is held just beyond cutoff, and the video output of the receiver is applied to either the grid or cathode with such polarity as to release the beam and allow the trace to appear on the screen. Thus the bright spots on the screen represent returning echoes detected by the radar receiver.

b. The A-scan (fig 12) uses an electrostatic cathode-ray tube with a linear sweep applied to the horizontal deflecting plates to establish a time base, and with the video output of the receiver applied to the vertical deflecting plates. Since the sweep is linear with time, a scale calibrated in range may be placed on the oscilloscope screen. This scale permits the reading of range directly. Since the antenna beam is highly directive, the maximum received echo appears when the antenna is pointing directly at the target. Thus, by rotating the antenna until the echo pulse produces maximum deflections on the screen, an indication of direction in azimuth or elevation can be obtained.

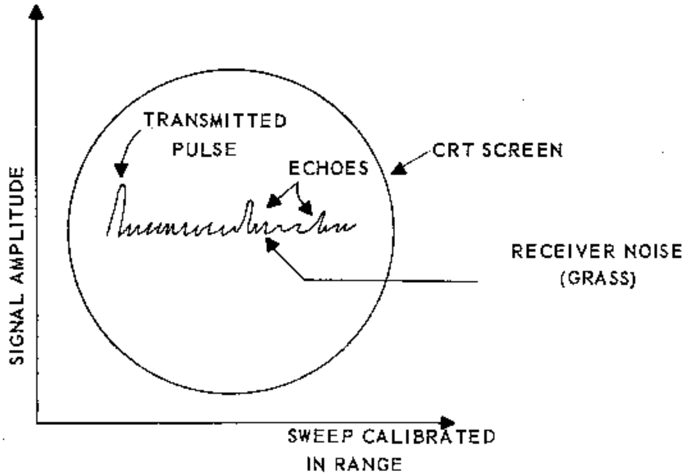


Figure 12. Type A-scan presentation.

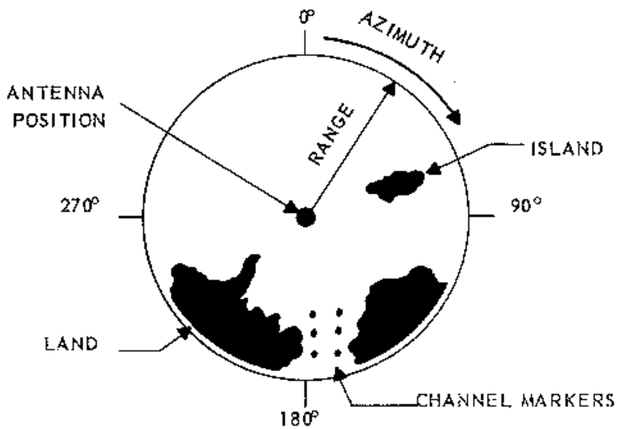


Figure 13. Type PPI-scan presentation.

c. The PPI-scan (fig 13) presents, in polar coordinates, a map of the area being covered with the antenna position occupying the center of the screen. The tube is intensit modulated with the sweep moving from the center radially outward. The sweep position is controlled by, and synchronized with, the antenna position throughout 360° of rotation. The top of the screen represents north. If the antenna is pointing north, the sweep moves from the center of the screen toward the edge. Likewise, if the antenna points 90°, the sweep moves from the center of the screen radially outward at an angle of 90° from north

Thus, a polar map is developed on which the range is plotted radially against the position in azimuth, or bearing, through 360°. The PPI scan finds considerable application in equipment designed for search, harbor control, convoy keeping, ground-controlled interception, and navigation.

d. The basic components of a radar indicator are a cathode-ray tube, a sweep circuit, and a gate circuit (fig 11). Various refinements may be added to improve the data presentation and to meet specific operational requirements. In order that the data supplied by the indicator may be useful, the indicator's performance must be synchronized with that of the other components of the system. Thus the start of the sweep must bear a definite time relation to the beginning of the transmitted pulse. The gating of the cathode-ray tube also must be timed with the sweep duration. Various methods of data presentation requiring sweep controls of varying degrees of complexity may be used.

e. Most radars use at least two cathode-ray tubes to display the video returns from targets and other objects. The indicators are most generally used to present range and azimuth but may also show elevation. The basic cathode-ray tube (fig 14) consists of an electron gun, two pairs of deflecting plates, and a fluorescent screen, all contained within an evacuated funnel-shaped glass envelope. The electron gun is the source of electrons. Whenever a positive voltage is applied to the control grid, the gun is triggered and a stream of electrons is emitted toward the fluorescent screen, causing it to emit light. Since electrons represent negative charges, a positive voltage applied to plate 2 will cause the electron beam to be deflected to the right. If the electrons are caused to sweep across the scope many times per second, a bright line, which is the time baseline, will appear on the scope. Positive echo signals from the receiver applied to plate 1, the vertical deflection plate, will cause the electrons to be deflected upward during the time the echo is present.

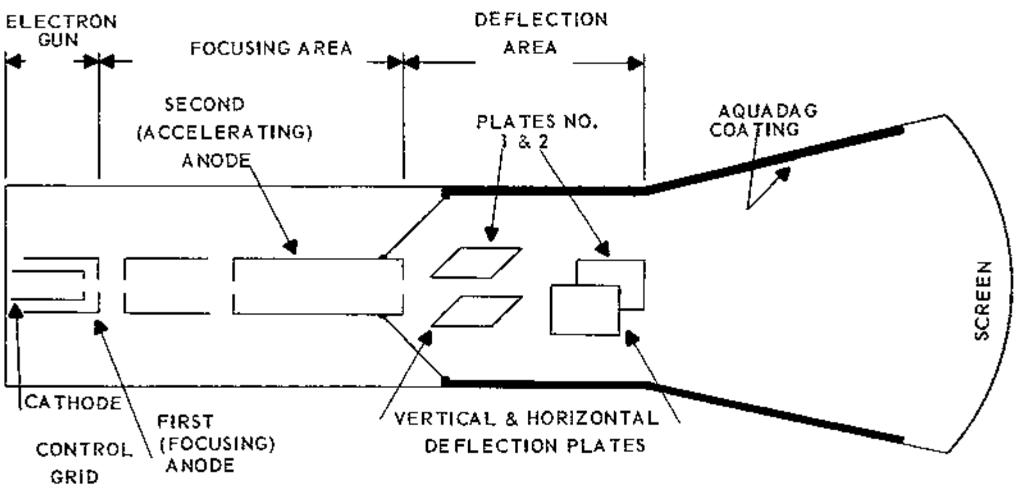


Figure 14. Basic electrostatic cathode-ray tube.

17. INDICATOR SCOPE RANGING

As an example of the operation of the cathode-ray tube, assume that the tube is to be used as an A-scope presenting the range to a target. Consider a beam of electrons starting at the left edge of the tube and sweeping to the right at a linear rate in a period of 100 microseconds. At the instant the transmitted pulse is sent out (fig 15(2)) a positive voltage is applied to the control grid of the CRT, allowing electrons to strike the screen. A sweep voltage synchronized with the transmitted pulse causes the beam to move toward the right. At some point in space, the signal hits a target (fig 15(3)) and is reflected back as an echo signal that is fed to the cathode-ray tube through the receiver. At the instant the echo is applied to the CRT (fig 15(4)), assume the sweep to be about half-way across the face of the screen. The echo coming in at this time causes the sweep to deflect vertically for a brief instant after which the sweep continues on its normal path. This happens so many times per second that a horizontal line will appear on the screen with a large pip (fig 15(5)), which represents the transmitted pulse, appearing at the left end of the sweep and a small pip indicating the echo near the center. Since the baseline is 100 microseconds long and the pip is in the center, the period from the start of the outgoing pulse until the echo returns represents an elapsed time of 50 microseconds. The 50 microseconds represent the round trip time; hence, the time required to travel one way is 25 microseconds. It is a simple matter to calibrate the scope at the rate of 164 yards per microsecond (radar range per microsecond) and determine the range to the target. The range to the aircraft may be computed by:

$$\text{range} = \text{radar range time} \times \text{time}$$

$$= 164 \text{ yards}/\mu\text{sec} \times 50\mu\text{sec}$$

$$= 8,200 \text{ yards}$$

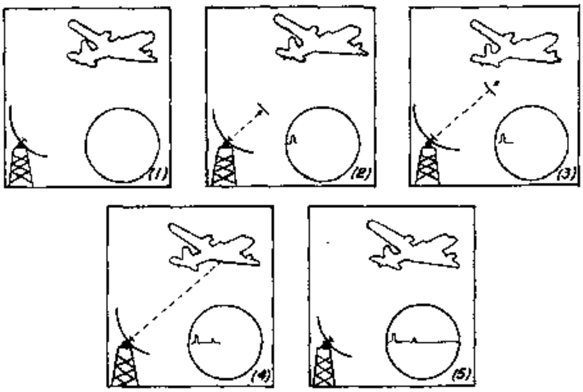


Figure 15. Radar ranging by indicator scope.

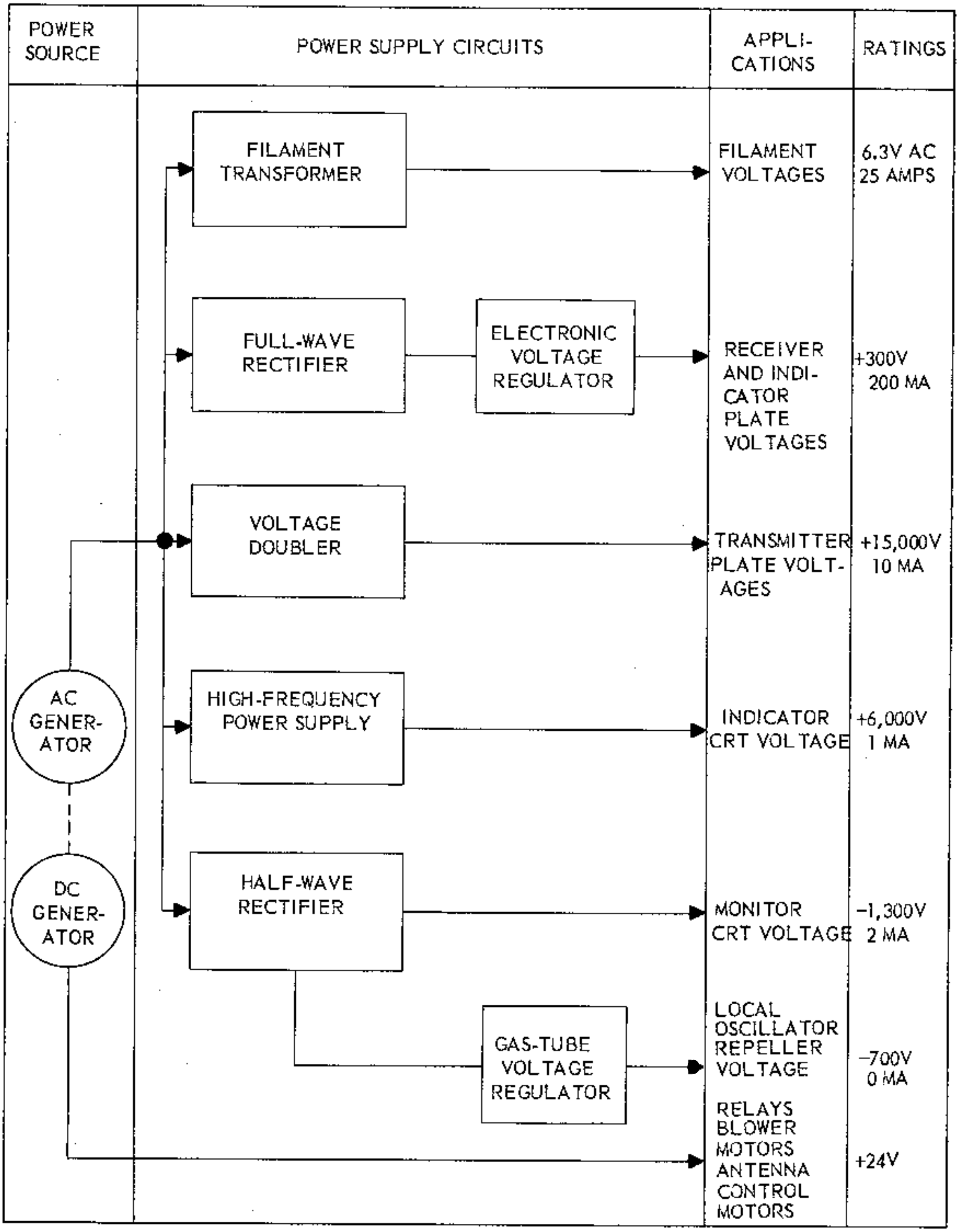


Figure 16. Power requirements for typical microwave equipment.

18. POWER SUPPLY

a. In the functional diagram of the radar system (fig 2), the power supply is represented as a single block. Functionally, this block is representative; however, it is unlikely that any one power supply could meet all the power requirements of a radar set. The distribution of the physical components of the system may be such as to make it impractical to lump the power supply circuits into a physical unit. Thus, different supplies are needed to meet the varying requirements of the system and must be designed accordingly. The power supply function is performed, therefore, by various types of supplies distributed among the circuit components of the radar equipment.

b. Figure 16 illustrates the power requirements of a typical microwave radar equipment. It shows a representative method of supplying the various components of any radar system with power.

TYPES OF AIR DEFENSE RADARS

19. GENERAL

a. The characteristics of any radar are determined by the specific use for which it is needed. Peak power, pulse width, operating frequency, pulse repetition frequency, receiver bandwidth, and antenna beam pattern are some of the important differences.

b. Air defense battalions in the Army employ several types for specific applications. They include:

(1) Defense acquisition radars, formerly called surveillance radars, such as those used with Nike battalions.

(2) Battery acquisition radars such as those used with Nike battalions.

(3) CW (continuous wave) acquisition radars and cw track radars such as those used with Hawk battalions.

(4) Target-track radars (TTR) and missile-track radars (MTR) such as those used with Nike Ajax and Nike Hercules battalions.

20. DEFENSE ACQUISITION RADAR

The defense acquisition radar has a medium pulse width (from 1 to 2 microseconds), medium to high peak power (in excess of 200 kilowatts), medium pulse repetition frequency (400 to 1,000 cycles per second), medium operating frequency (1,000 to 1,500 megacycles—L band), and a medium receiver bandwidth (2 megacycles or greater). Defense acquisition radar is used to observe all activity in a designated area. Its range is between the early-warning radar of the Air Force and the battery acquisition radar of the Army air defense battalions. The AN/TPS-1G and the AN/FPS-36 radars are the defense acquisition radars of the Army air defense battalions.

21. BATTERY ACQUISITION RADAR

The battery acquisition radar possesses characteristics similar to those of the defense acquisition radar. The principal differences are the antenna design and the purpose for which it is used. This radar is used to select targets which are then passed electronically to the target-track radar so that this radar may provide present position data to the computer at its maximum range.

22. CW (CONTINUOUS WAVE) ACQUISITION RADAR AND CW TRACK RADAR

The cw acquisition radar is used in conjunction with the pulse acquisition radar (similar to the battery acquisition radar) in the Hawk system. It has a comparatively low power output, a medium antenna beam width, and wide receiver bandwidth. The cw track radar also has a low power output, but its antenna beam width is narrow. The cw radar employs the doppler system. In this system radio energy is transmitted continuously at a fixed frequency; when the energy strikes an object moving toward or away from the transmitter, the frequency of the reflected energy is changed.

23. TARGET-TRACK RADAR (TTR) AND MISSILE-TRACK RADAR (MTR)

The target-track radar and missile-track radar of the Nike system are interchangeable. The TTR furnishes the present position data of a target to a computer so that the correct future position may be calculated and conveyed to the MTR. Since a kill is impossible unless the data from the radar and the computer are accurate, this radar is designed to provide precise and accurate target information. Tracking radars are characterized by high peak power, medium pulse repetition period, narrow pulse width, narrow antenna beam width, and wide receiver bandwidth. The narrow pulse width provides for minimum radar range. The narrow antenna beam improves target discrimination through increased accuracy in azimuth and elevation. The wide receiver bandwidth improves range accuracy by causing a faithful reproduction of the echo pulse. Air defense tracking radars have provisions for tracking in azimuth, elevation, and range automatically, manually, or by means of aided tracking.

24. SPECIAL PURPOSE RADARS

a. Radars or equipment employing radar techniques are frequently used in conjunction with air defense radars. They are called IFF (identification, friend or foe) and ground-to-air radar jammers.

b. The IFF equipment is employed with defense acquisition, battery acquisition, and pulse acquisition radars to determine whether the aircraft detected by one of these radars is friend or foe.

c. Ground-to-air jammers are designed to jam the radar bombing and navigational aids of a hostile air force to deter blind bombing and navigation.

d. Air-to-ground jammers are radio transmitters designed to jam and prevent air defense radars from detecting air targets. Other type jammers may be employed on the ground to cause air defense radars to experience difficulty in detecting air targets.

CHAPTER 6

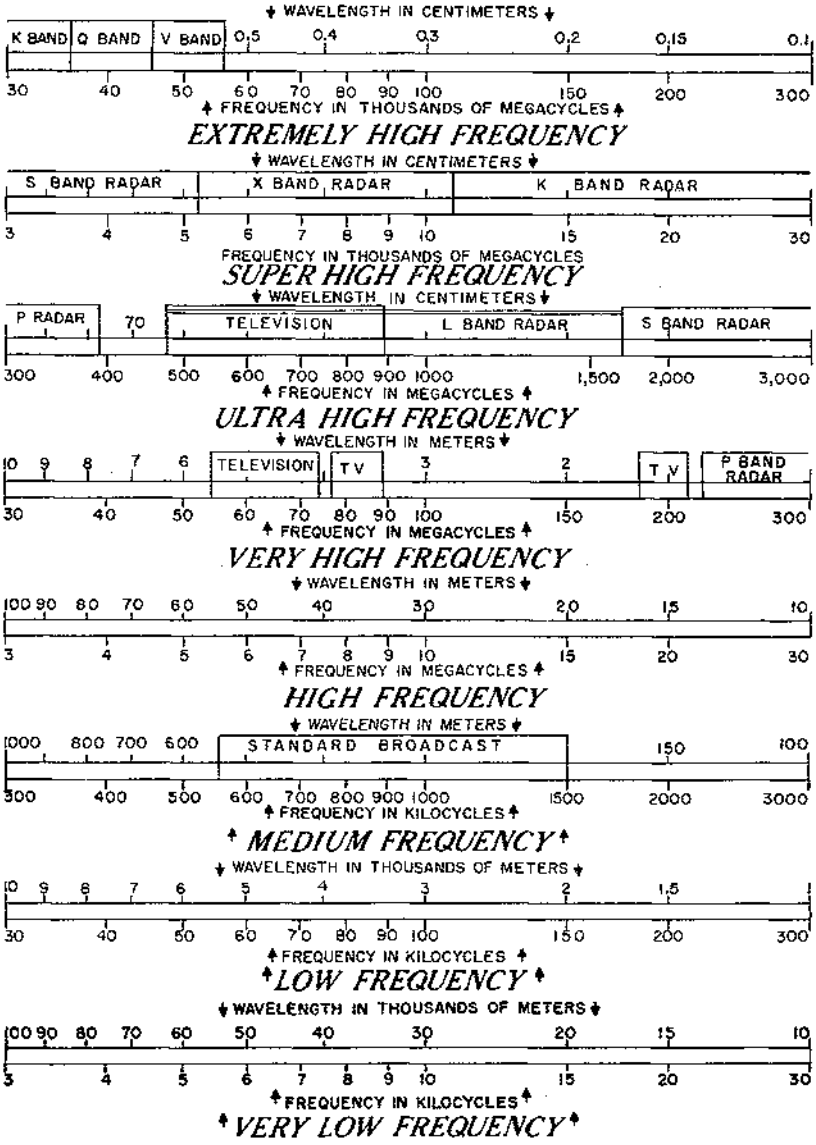
THE ELECTROMAGNETIC FREQUENCY SPECTRUM

25. RADIANT ENERGY FREQUENCIES

The series of radio-frequency bands arranged continuously in order of wavelengths or frequencies is known as the electromagnetic frequency spectrum. These spectrum data may be shown in either graphic form or as systematically arranged numerical data. Actually, the radio-frequency bands form only a part of the entire spectrum which extends far beyond the frequencies of radio and radar and includes other forms of radiant energy such as infrared, visible light, ultraviolet, X-rays, and gamma rays, in the order named. These designations are those of the radio-frequency bands in an international agreement (Atlantic City, 1947), and the radar-band designations are those of the armed services. It should be recognized that each radio-frequency band includes ten times the number of megacycles as the next lower frequency band; for example, the ultra-high-frequency band extends from 30 to 3,000 mc, or covers 2,700 mc, while the very-high-frequency band extends from 30 to 300 mc, or covers 270 mc. Viewed historically, the main reason for short wave experiments and development was the crowded lower frequency bands. In addition to the problem of congestion, certain natural characteristics of the higher frequencies encouraged intensive large scale research and experimentation, beginning about 1935, in this part of the rf spectrum. Not only do different bands of frequencies produce different effects, such as the line-of-sight signal propagation and signal reflection phenomenon, but the different frequency bands require different types of circuitry. For example, coaxial circuitry is employed between 450 and 1,000 mc. This, however, does not imply that there is an abrupt ending between two types of circuitry. Rather, there is an overlap or gradual blending of frequency circuitry limits; and this limit should be thought of as the center of transition region and not as an absolute limit. Thus at 1,300 mc either coaxial or waveguide transmission lines may be used as in the case of the AN/TPS-1G.

26. GRAPHIC PRESENTATION

Frequencies for the various types of services are assigned by the Federal Communications Commission; the frequency bands and some types of services are shown in graphic form in figure 17. This graph shows only the radar, television, and standard broadcasting bands, since a complete listing would require excessive space. It also shows both the frequency and wavelength limits of each band and includes, at the bottom of the page, the formula for converting wavelength to frequency as well as the frequency limits of circuitry types.



CONVERSION FORMULA:

$$\lambda \text{ IN METERS} = \frac{300{,}000}{\text{FREQ. IN KC.}} = \frac{300}{\text{FREQ. IN MC}}$$

FREQUENCY OF CIRCUITRY:

< 30 KC TO 75 MC	LUMPED COMPONENT
75 MC TO 450 MC	LINE SECTION
450 MC TO 1,000 MC	COAXIAL
1,000 MC & ABOVE	WAVEGUIDE

Figure 17. Electromagnetic frequency spectrum.

CHAPTER 7

SUMMARY AND QUESTIONS

27. SUMMARY

a. The basic principle of radar, that radio waves are reflected by solid objects, was initially established as early as 1887. Since radio waves are reflected by solid objects, it is possible to have radio detection and ranging, or radar. The countries that have added the most to radar development have been England and the United States.

b. Radio waves travel at a speed of 186,000 miles per second or 328 yards per microsecond. The common means of transmitting radar energy is by emitting short-duration bursts of energy, known as pulses. The number of recurring pulses per second is the pulse recurrence frequency (prf). Range determination depends upon the measurement of the time that it takes for the propagated wave of energy to travel from the radar to a target and return. Resolution in azimuth and elevation is obtained by focusing the radar waves into a narrow beam, the size of the beam being determined by the degree of accuracy desired.

c. The basic radar is divided into six components; however, most radars will have more than the six units. It is composed of a timer, transmitter, antenna system, receiver, indicator, and power supply. The function of each component is outlined below.

(1) Timer. The timer originates, shapes, and amplifies a high-voltage pulse that is used to trigger the transmitter.

(2) Transmitter. The transmitter usually employs a magnetron as its oscillator. Upon the application of the pulse from the timer, the transmitter oscillates at radio frequencies for the duration of the trigger pulse.

(3) Antenna system. The rf energy from the transmitter is propagated from a unidirectional antenna, and should a solid object be in the path of the energy in space, a reflected signal will return to the same antenna.

(4) Receiver. In the receiver the reflected signal is changed to an intermediate frequency, which is amplified and detected for video.

(5) Indicator. The video pulse is applied to presentation scopes in the indicator for purposes of obtaining information data.

(6) Power supply. The five previous units are dependent upon the power supply to provide the necessary direct-current potentials for operation.

d. Many types of radar are necessary in order to satisfy the various air defense requirements. They include target-track (TTR), missile-track (MTR), defense acquisition, battery acquisition, and cw track or cw acquisition radars. Regardless of the mission, each radar provides detection of aircraft, missiles, and other objects.

e. The range of frequencies for all electronic equipment employing radio waves is known as the frequency spectrum. Frequencies that are generally considered for radar operation are above those for radio broadcasting and the very-high-frequencies of television. The mission of the radar determines the necessary operating frequency.

28. DISCUSSION QUESTIONS

a. In present-day warfare, why is visual detection of aircraft insufficient?

b. What does the word radar mean?

c. What is the speed of radio waves per second? Per microsecond?

d. What is meant by the pulse recurrence frequency (prf)?

e. What is the purpose of the:

(1) Timer?

(2) Transmitter?

(3) Antenna system?

(4) Receiver?

(5) Indicator?

(6) Power supply?

f. If it takes 150 microseconds for rf energy to travel to an object and return, what is the range to that object?

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