DIRECTIONAL ANTENNAS. A directional antenna is one which either transmits or receives energy more efficiently in one or more directions than others. Thus, directional information can be obtained by orienting a directional antenna for either maximum or minimum signal strength from a received signal.

There are many methods of achieving directional transmission and reception, but the *loop antenna* is perhaps the simplest and the most widely used in airborne navigational equipment. The loop antenna can be used for either directional transmission or directional reception.

When the plane of the loop antenna is parallel to the path of a transmitted signal, maximum voltage is induced in its coils, causing the signal to be received at maximum strength (see figure 9-6). When the plane of the antenna is perpendicular to the path of a transmitted signal, minimum voltage is induced in its coil, and the signal is received at minimum strength. These characteristics give the loop antenna its ability to "sense" the direction of the path traveled by the signals it receives.

The convenient properties of a combined signal from a loop and wire antenna system make possible the automatic direction finder (ADF) which continuously presents the bearing of the radio transmitting station to which it is tuned.

RADIO AIDS TO NAVIGATION

Radio Beacons

Radio beacons transmit a nondirectional signal which is easily identified as a specific station. If an aircraft has ADF equipment, the direction of the beacon from the aircraft can be determined. Several names are given to radio beacons, depending on their specialized functions. A *compass locator* is a radio beacon, usually of low power, associated with an instrument landing system (ILS). A *homer* is a radio beacon associated with an airport. Most radio beacons transmit on frequencies between 200 and 400 kHz.

Fixing with the radio compass is relatively easy, but depends on the availability and proximity of stations. ADF bearings are used as LOPs and are treated as explained in Chapter 6. To obtain a bearing, the navigator rotates the compass card on the bearing indicator (figure 9-7) until any desired reference is under the index. Set 360° under the index for relative bearings; set true heading for true bearings, and set magnetic heading for magnetic bearings.

Marker Beacons

Most marker beacons operate on a frequency of 75 kHz and are designed to give local position

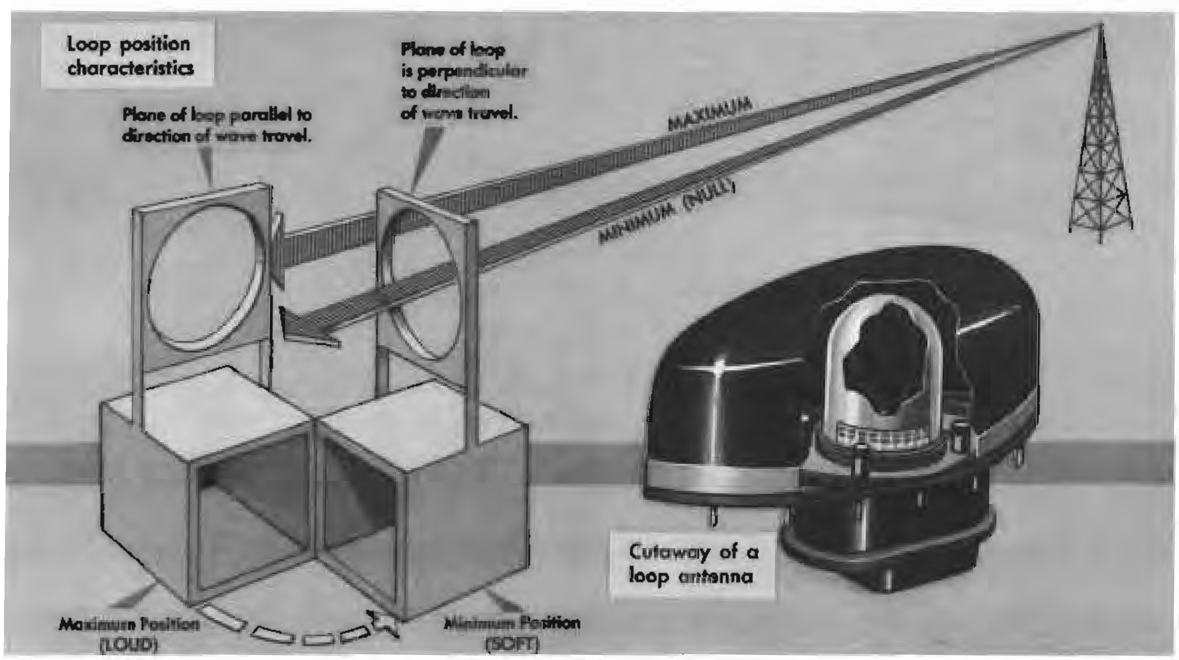


Figure 9-6. Loop Antenna

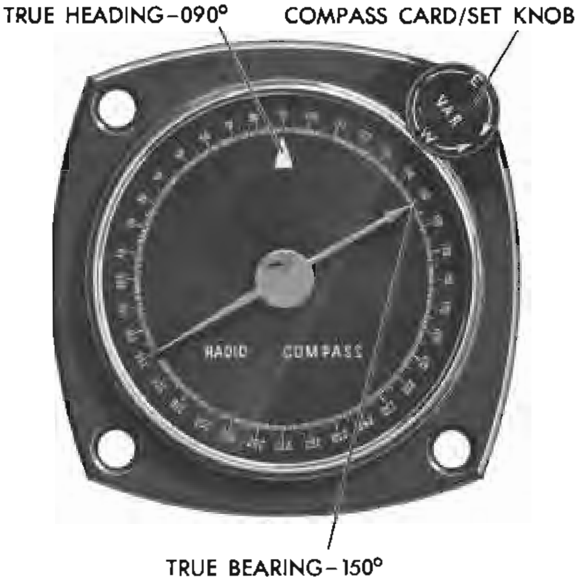


Figure 9-7. Radio Compass Bearing Indicator

information, usually by narrow vertical beams. A *fan marker* transmits a vertical beam whose cross section is either lens shaped or bone shaped. *Z markers* provide vertical beams with a circular cross section. The coded flashes of a light on the pilot's instrument panel are the only indication of passing over a marker beacon.

Radio Ranges

LOW FREQUENCY. Low frequency radio ranges are directional transmitting stations which operate between 200 and 400 kHz. Although other aids have made them obsolete, some range stations still exist in the U.S. and they are more common in other countries. The directional transmission of a radio range station is limited to four beams or legs which are approximately 3° in width. If an aircraft is not positioned exactly on one of the four beams, it is possible to identify only the quadrant between beams in which the aircraft is located. The four quadrants are alternately identified as "A" or "N" with the quadrant containing true north always being an "N" quadrant. The "A" and "N" signals are transmitted in International Morse Code with precise spacing such that a solid tone is heard when the aircraft is positioned on one of the station's four beams. This tone is called the "on course" signal. (See figure 9-8.)

It must be noted that after identifying the course signal or the "A" or "N" signal, good dead reckoning information is necessary to identify the correct course or quadrant. The direction to the station can also be determined through the use of ADF equipment.

Directly over the range is a characteristic cone of silence; an area in which no signal is heard.

A "Z" marker is usually located at a low-frequency radio range station, and its vertical beam, centered in the cone of silence, is used to identify station passage.

OMNIRANGE. The VHF omni-directional range

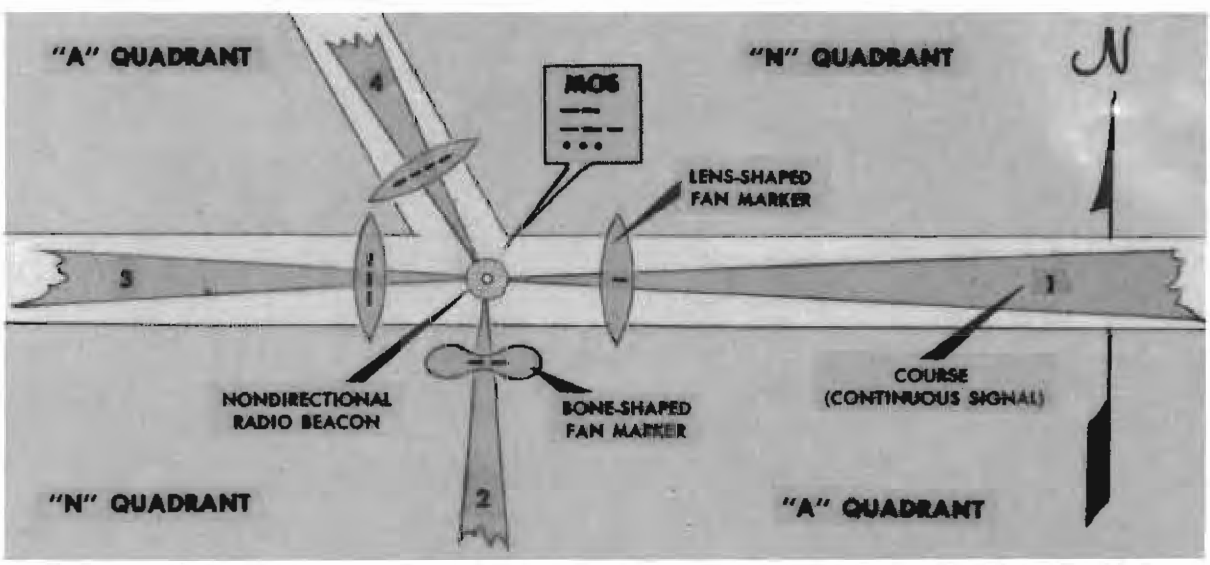


Figure 9-8. Radio Beacon Symbols

(VOR) is a radio facility which has eliminated many of the difficulties associated with low-frequency radio navigation. VOR stations operate between 108.0 and 117.0 mHz. Station identifiers are given in code or voice, or by both code and voice transmission. Unlike the low-frequency radio range, a VOR station provides an infinite number of radials or courses.

For simplicity, however, only 360 radials are considered possible. These radials are identified by their magnetic bearing *from* the station. Regardless of heading, an aircraft on the 090° radial is physically located east of the station. Flying to the station on this radial, the magnetic course (MC) is 270°.

Since VOR transmissions are in the VHF band, signals are not affected by atmospheric disturbances or other factors common to lower frequencies. They are, however, subject to line-of-sight reception, and reception distance varies directly with the altitude of the aircraft.

Control Panel. A VOR control panel contains a power switch, frequency selector knobs, a frequency window, and a volume control (figure 9-9). To tune a VOR receiver, turn the power switch ON, select the desired frequency, and identify the station.

Indicators. VOR equipment has two indicators. These are the course indicator and the radio magnetic indicator (RMI). They are shown in figures 9-10 and 9-11 respectively.

The course indicator has eight significant features:

Figure 9-9. VOR Control Panel

- TO-FROM indicator
- Glide slope and course warning flags.
- Course selector window
- Marker beacon light
- Glide slope indicator
- Heading pointer
- Course deviation indicator (CDI)
- Course set knob

The TO-FROM indicator shows whether the radial set in the course selector window is to or from the station, and the CDI represents this radial. If the aircraft is to the right of the radial, the CDI is to the left of center on the course indicator. The glide slope indicator is similar to

Figure 9-10. Course Indicator

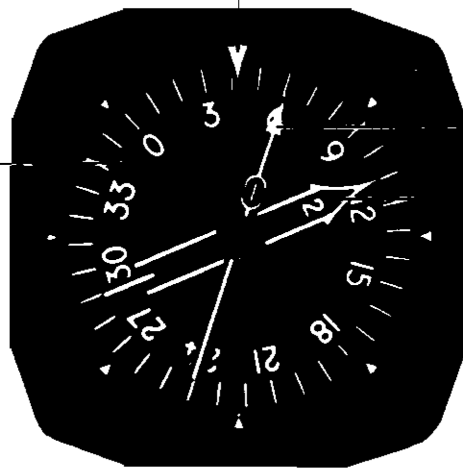


Figure 9-11. Radio Magnetic Indicator (RMI)

the CDI but represents the glide slope transmitted by an instrument landing system. If the glide slope indicator is below the center of the course indicator, the aircraft is above the glide slope. The glide slope and course warning flags inform the user that either the glide slope indicator or the CDI is inoperative, or that the signals received are too weak to be used. The heading pointer indicates the difference, to the right or left, between the aircraft magnetic heading and the radial set in the course selection window. The marker beacon light flashes when passing over a marker beacon.

The RMI is a bearing indicator, usually with two pointers and a movable compass rose. The compass rose rotates as the aircraft turns indicating the compass heading of the aircraft under the top index at all times. Therefore, all bearings taken from the RMI pointers are magnetic bearings.

Fixing with the VOR is similar to fixing with the low frequency radio; however, since all VOR bearings are magnetic, variation must be applied to obtain true bearing. One rule to remember is to use the variation at the VOR station for VOR LOPs and variation at the aircraft for ADF LOPs. LOPs may be taken from the pointers on the RMI or by centering the CDI and reading the radial in the course selection window.

TACAN

Tactical Air Navigation (TACAN) is a short-range navigation system which supplies continuous, accurate, slant-range distances and bearings. The station identifier is transmitted at 35-second intervals in International Morse Code.

As with VOR, the major disadvantages of low-frequency ranges (static interference and a limited number of navigational courses) are eliminated with TACAN. Much like VOR, TACAN provides an infinite number of courses to or from the TACAN station, and the same instruments (course indicator and RMI) are used to obtain bearing information.

TACAN operates in the UHF band and has a total of 126 channels. Airborne Distance Measuring Equipment (DME) transmits on channels in the 1025-1150 mHz range; associated ground-to-air transmissions are made between 962-1024 mHz or 1151-1213 mHz.

Position information is obtained by using a multi-channel airborne transmitter-receiver (transceiver). Radio signals transmitted over a selected channel convey both distance and bearing information. The equipment is designed to present range information out to 195 nautical miles at high altitudes.

Accuracy of the DME is on the order of plus or minus 600 feet, plus two tenths percent of the distance being measured. Thus, at a distance of 10 nautical miles from the facility, the maximum distance error is plus or minus 720 feet. Distance is measured slant-range. For practical purposes, this may be regarded as horizontal distance except when the aircraft is very close to the station.

The ground equipment consists of a receiver-transmitter combination (transponder) and a rotating antenna for transmission of distance and bearing information. Transmission of erroneous signals is possible during calibration of the station; therefore, when calibration or ground maintenance is done, the station identifier is turned off. Always monitor *and identify* the station before using any bearing or range information.

If an aircraft is in a position to receive two stations on the same frequency, the strongest signal will predominate. In an area of approximately equal signal strength from two stations on the same frequency, TACAN equipment may seek first one station and then the other.

TUNING. TACAN control box is shown in figure 9-12. Turning the OFF, REC, T R switch to the T/R or REC position turns the equipment on. (If the switch is moved to the REC position, the DME will not operate and only bearing information will be displayed.) After the equipment is turned on, select the desired channel between 1 and 126 by using the outer knob to select the first two digits in the channel number (0 to 12) and the inner knob to select the third digit (0-9). For example, to select channel 115, select the first two digits (11) with the outer knob and the third digit (5) with the inner knob. Adjust the volume and identify the station.

DISTANCE MEASURING EQUIPMENT (DME). Distance is determined with TACAN equipment by measuring the elapsed time between transmission of interrogating pulses from the airborne set and reception of corresponding reply pulses from the ground station. The aircraft transceiver starts the process by sending out the distance interrogation pulse signals. Receipt of these signals by the ground station receiver triggers its transmitter and it sends out the distance reply pulse signals. These pulses require about 12 microseconds round-trip travel time per NM of distance from the ground station. The range indicator (figure 9-13) displays distance to the TACAN station in NM.

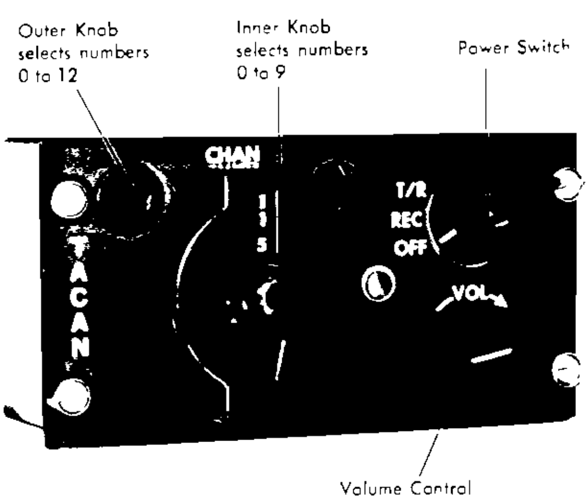


Figure 9-12. TACAN Control Box

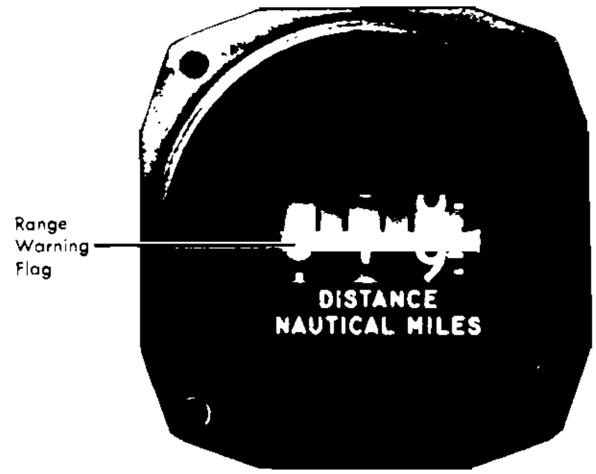


Figure 9-13. Range Indicator

Since a large number of aircraft could be interrogating the same station, the airborne set must sort out only the pulses which are replies to its own interrogations. Interrogation pulses are transmitted on an irregular, random basis by the airborne set which then "searches" for replies synchronized to its own interrogations. If the signals are interrupted, a memory circuit maintains the last distance indication on the range indicator for approximately 10 seconds to prevent the search operation from recurring. The searching process starts automatically whenever the airborne set is tuned to a new station or when there is a major interruption in signals. Depending upon the actual distance of the aircraft from the station, the searching process may require up to 22 seconds.

POSITIONING BY TACAN. Bearing information is obtained in the same manner and on the same instruments as VOR bearings. Magnetic variation at the station is used to convert magnetic bearing to a true bearing. The position of the aircraft is determined by obtaining the bearing and the reading from the range indicator simultaneously and then plotting the true bearing and range from the station towards the aircraft.

VORTAC

VORTAC is a system consisting of a VOR station and a TACAN station operating simultaneously with the antennas of both located at a common geographical point. Aircraft equipped with VOR and distance measuring equipment are able to receive bearings from the VOR station and distances from the TACAN station. Aircraft equipped with TACAN receive bearings and distances from the TACAN portion of the station.

CONSOL/CONSOLAN. During World War II, Germany developed a navigation system called *Sonne*. Following the war the British further developed the system under the name *Consol* and several stations operating in the LF band have been installed in western Europe. The U.S. system called *Consolan*, also has several stations operating in the same band.

Consol and Consolan differ from other hyperbolic systems in that three antennas are located in a straight line (antenna base line) and are closely spaced. This aid is often considered directional rather than hyperbolic because great-circle bearings are plotted from the position of the center antenna.

The usable range of Consol and Consolan is approximately 1,000 miles during the day and 1,200 to 1,400 miles at night. Bearings are most accurate along a line perpendicular to the antenna base line and accuracy decreases toward the base line extensions. The total usable area is approximately 240° for Consol and 280° for Consolan. The usable circumference is divided into two sections, one on each side of the base line and centered on a perpendicular bisector to the base line (see figure 9-14). Two unreliable areas, of approximately 40° each for Consolan and 60° each for Consol, are centered on the base line extensions. Unreliable sections are labeled on Consol charts. A typical Consol chart is shown in figure 9-15.

In the daytime, at 1000 miles from the station, LOP errors of from 6 miles at the bisector centerline to 24 miles at the outer edges of the usable areas (approaching the base line) are not uncommon. At night these LOP errors may increase to as much as 10 and 40 miles from the station. Interaction between sky waves and ground waves or high atmospheric noise can cause even larger errors.

CONSOL/CONSOLAN SIGNALS. Consol and Consolan signals are transmitted as a series of dots and dashes. The phase of signals transmitted from the two end antennas is rotated with respect to the signal of the center antenna such that the radiation pattern consists of many lobes rotating around the middle antenna. Rotation is clockwise on one side of the base line and counterclockwise on the other side. Alternate lobes, or sectors, contain dot and dash signals which merge into a tone or *equisignal* at the sector boundaries.

The duration of a transmission sequence may be as short as 30 seconds or as long as a minute depending on the particular station being used. During each sequence, a total of 60 dots and dashes is transmitted. The transmission sequence, heard by the operator, is shown in figure 9-16.

To obtain LOPs from a Consol or Consolan station, only a LF receiver equipped with a beat frequency oscillator (BFO) is needed. Tune the receiver to the desired station frequency and turn on the BFO.

The procedure for obtaining an LOP is shown in the following example:

1. Tune the receiver as stated above.
2. Identify the station.

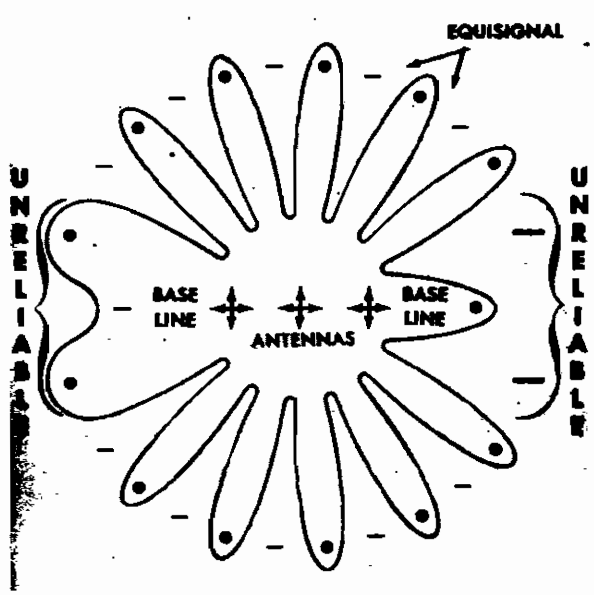


Figure 9-14. Consolan Station

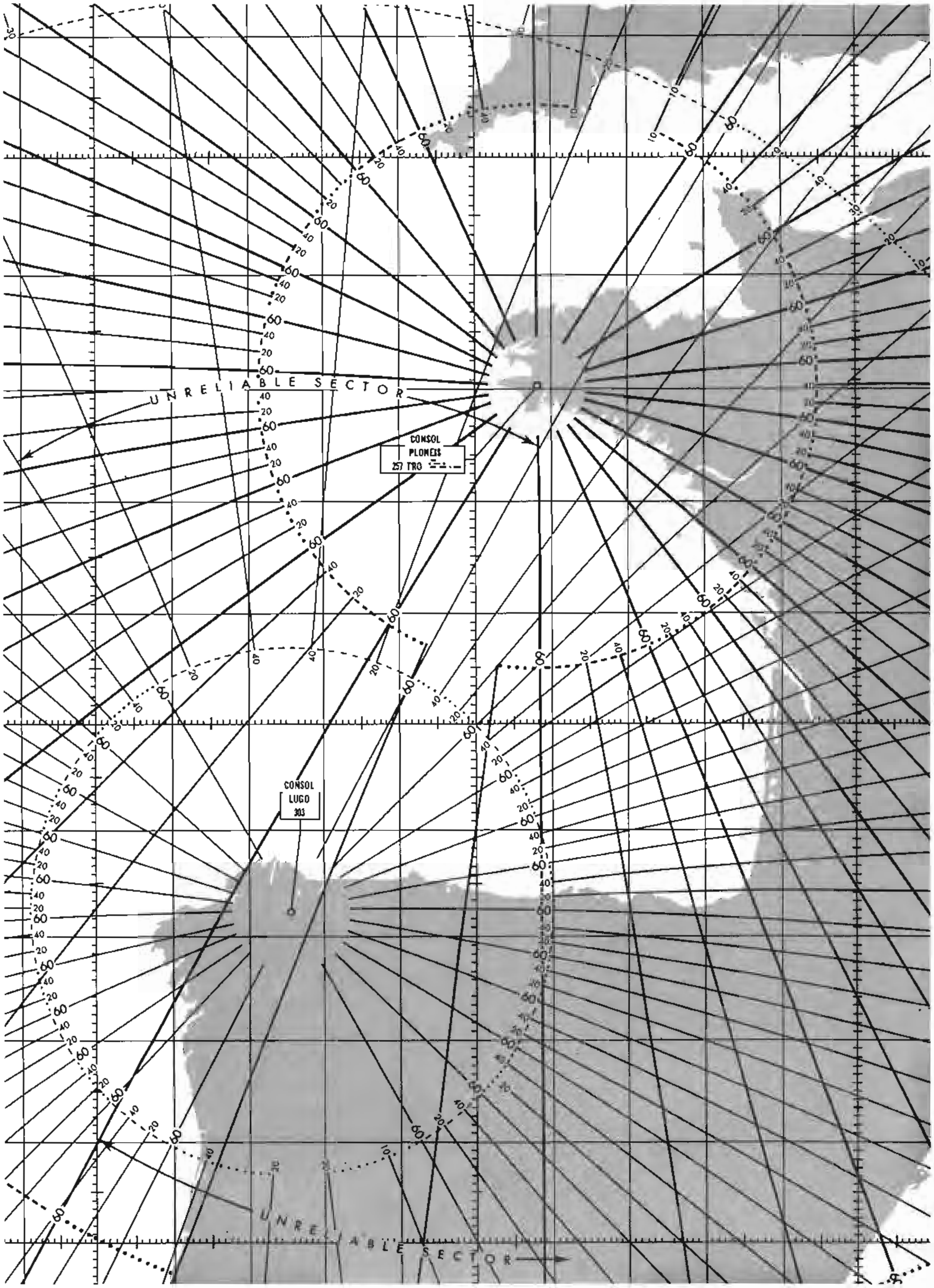
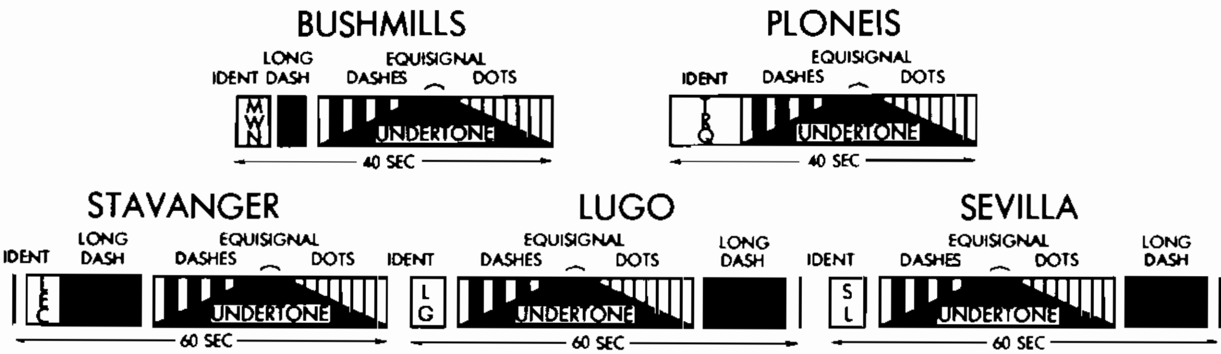


Figure 9-15. Consol Chart



Each position line is identified by a number which corresponds to the number of dots (or dashes) transmitted by the beacon following the continuous long dash or identification.

Bearings shown on Consol Sector Lines are inbound True Bearings measured at the Transmitter.

Figure 9-16. Consol Transmission and Sequence

3. Count the number of dots or dashes transmitted before the equisignal (for example, 15 dots are heard).

4. Note the time of the equisignal (this is the time of LOP).

5. Count the number of dots or dashes after the equisignal (dashes—39).

6. Total the number of characters received before and after the equisignal (dots and dashes—54). This total is subtracted from 60 and the remainder (6) is applied equally between the dots and dashes to obtain the corrected dot and dash count (18 dots and 42 dashes).

7. Plot an LOP representing the sum of dots or dashes (18 dots) heard before the equisignal. To plot the LOP, locate the number of dots (or dashes) on the chart which corresponds to those counted and draw a line as is shown in figure 9-17. A DR position or an ADF bearing to the station is used to determine in which dot (or dash) sector the LOP is located. Only a gross error in either the bearing to the station or the DR position could cause the LOP to be plotted in the wrong sector.

NOTE: AVC (automatic volume control) cannot be used in the reception of Consol signals. This is because the dot-dash signals from the Consolan transmitter are signals of relative intensity. Since AVC causes all signals to be of the same intensity, the variations in the signal could not be detected.

CAUTION

1. At night, always take a series of readings, particularly when 300 to 700 miles from the station. Wide variation in successive counts is an indication of ground wave/sky wave interference. These bearings should be used with caution or disregarded altogether.

2. Consol LOPs should never be used within 25 miles of the station and Consolan LOPs should not be used within 50 miles of the station.

COMMUNICATION

Air/ground communications can be achieved through the use of many types of equipment. Although older LF radios are still sometimes used, greater reliability has come with equipment which uses higher frequency ranges (HF, VHF, and UHF). These frequency bands are relatively static free and are less susceptible to outside interference. It must be remembered, however, that the higher the frequency the more nearly the transmission will follow a line-of-sight path. As frequency increases, therefore, communication range is decreased.

Long Range

Systems used for long range radio communication between aircraft and ground stations may be

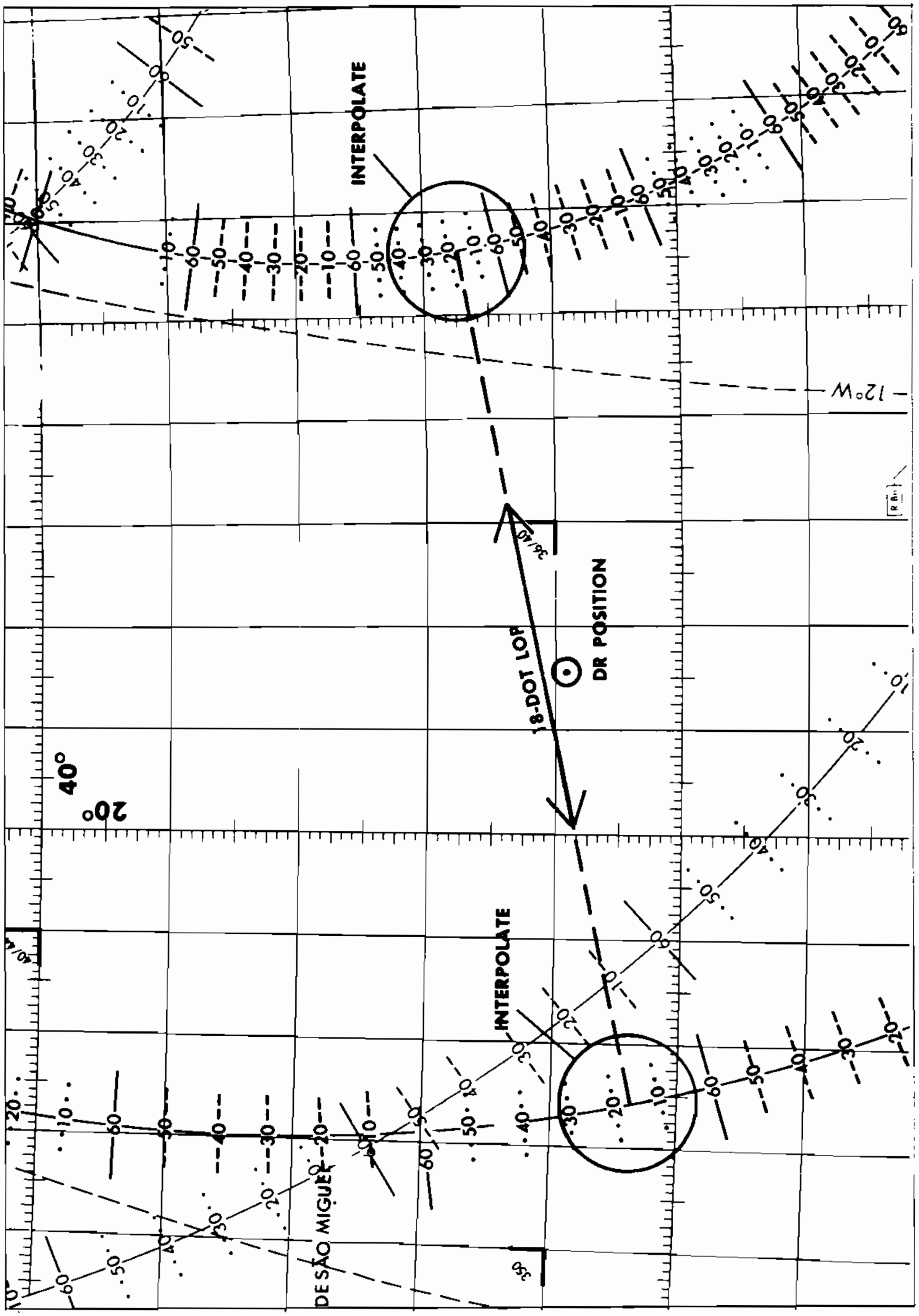


Figure 9-17. Plotting a Consol LOP

either amplitude modulation (AM) or single sideband (SSB) transmission. Single sideband transmitters concentrate all available power into one sideband; therefore, SSB is much more efficient and has greater range than an AM transmitter of the same power.

Although HF ground waves attenuate rapidly, sky waves at these frequencies are capable of transmitting communication at distances up to 12,000 miles or more, depending on ionospheric conditions. HF equipment on aircraft is used mostly in remote areas where VHF or UHF communication is not possible because of the distances which must be spanned.

Short Range Air-to-Air and Air-to-Ground

Short range air-to-air and air-to-ground communications are confined to the VHF and UHF bands. Transmission and reception frequencies are crystal controlled on all newer pieces of equipment. VHF channels are spaced at 50 kHz intervals from 116 to 149.95 mHz and UHF channels are spaced 100 kHz apart from 225.0 to 399.9 mHz. Most UHF transceivers have a manual frequency selection capability in addition to a number of preset channels. Transmission and reception is accomplished with a single antenna.

IFF/SIF

Identification Friend or Foe (IFF) was first used during World War II and is a small airborne transponder which transmits coded signals when triggered (interrogated) by a ground-based search radar. Pulses received from the airborne equipment produce "blips" on the ground-based radar scope and are used to positively identify and locate aircraft.

The addition of a Selective Identification Feature (SIF) allows faster isolation and identification of any aircraft under surveillance. Positive identification can be established and maintained by the ground controller when a designated SIF "mode" and "code" is set into the airborne transponder. See figure 9-18. Initial identification is usually established by using the "IP" or "flash" function of the airborne set. Tracking is maintained by setting the requested mode and code into the airborne equipment.

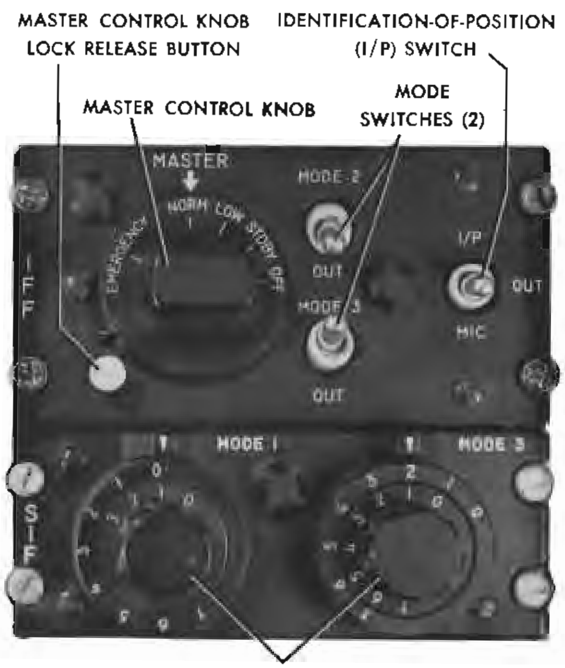


Figure 9-18. IFF/SIF Control Panel

CHAPTER 10

Radar

BASIC PRINCIPLES

The manner in which a bat successfully avoids the walls and jutting stalactites of a totally dark cave makes fascinating reading. Investigation has shown that if its mouth is gagged or its hearing impaired the bat can no longer avoid such obstacles. From this, it has been concluded that the bat's uncanny ability to navigate derives from the emission of cries—inaudible to the human ear—which are then reflected from any obstacles in its path. These reflected echoes allow the bat to orient himself with respect to the obstacles and thus maneuver to avoid them.

The fundamental principle of radar is closely akin to that used by the bat. The basis of the system has been known theoretically since the time of Hertz, who in 1888 successfully demonstrated the transfer of electromagnetic energy in space and showed that such energy is capable of reflection. The *transmission* of electromagnetic energy between two points was developed as "radio," but it was not until 1922 that practical use of the *reflection* properties of such energy was conceived. The idea of measuring the elapsed time between the transmission of a radio signal and receipt of its reflected *echo* from a surface originated nearly simultaneously in the United States and England. In the United States, two scientists working with air-to-ground signals noticed that ships moving in the nearby Potomac River distorted the pattern of these signals. In 1925, the same scientists were able to measure the time required for a short burst, or pulse, of radio energy to travel to the ionosphere and return. Following this success, it was realized that the radar principle could be applied to the detection of other objects, including ships and aircraft.

By the beginning of World War II, the Army and Navy had developed equipment appropriate to their respective fields. During and following the war, the rapid advance in theory and technological skill brought improvements and additional applications of the early equipment. By suitable instrumentation it is now possible to measure accurately the distance and direction of a reflecting surface in space—whether it is an aircraft, a ship, a hurricane, or a prominent feature of the terrain—even under conditions of darkness or restricted visibility. For these reasons, radar has become a valuable navigational tool.

There are many different types of radar sets currently in use in the Air Force. For the navigator, they can be divided into two classes: (1) those designed for navigation, search, and weather identification, to which no computer has been attached, and (2) those designed principally for use with high accuracy bombing-navigation computers. With the former, fixing can be accomplished only by using ranges or bearings, or both. With the latter, the position of the aircraft in latitude and longitude is continuously displayed on the navigation computer which is periodically corrected by the radar.

In view of the great variety of radar sets in use, it would be impractical to cover in this manual the specific operating procedures for each. Therefore, the following material is limited to the *general* procedures for using radar as an aid to navigation. For detailed information concerning a specific set, consult the appropriate manual or technical order.

As noted previously, the fundamental principle of radar may be likened to that of relating sound to its echo. Thus, a ship sometimes determines its distance from a cliff at the water's edge by blowing its whistle and timing the interval until the echo is received. Since sound travels at a known speed (approximately 1,100 feet per second in air), the total distance traveled equals the speed times the time interval, and one-half this distance (because the sound must travel to the cliff and *back* before the echo is heard) is the distance to the cliff. Thus, if the time interval is 8 seconds, the distance to the cliff is

$$\frac{1{,}100 \times 8}{2} = 4{,}400 \text{ ft} = 0.725 \text{ NM}$$

The same principle applies to radar, which uses the reflected echo of electromagnetic radiation traveling at the speed of light. This speed is approximately 162,000 nautical miles per second; it may also be expressed as 985 feet per microsecond. If the interval between the transmission of the signal and return of the echo is 200 microseconds, the distance to the target is

$$\frac{985 \times 200}{2} = 98{,}500 \text{ ft} = 16.2 \text{ NM}$$

TYPICAL RADAR SET

Components

In addition to the power supply, a radar set contains five major units: the timer, the transmitter, the antenna, the receiver, and the indicator as shown in figure 10-1. Their functions are briefly described as follows:

The *timer*, or modulator, is the heart of the radar system. Its function is to insure that all circuits connected with the system operate in a definite time relationship with each other and that the time interval between transmitted pulses is of the proper duration. The timer "triggers" the other units into operation.

The *transmitter* is similar to the radio transmitters described in the chapter on radio except that it operates in the super high frequency band and operates for very short periods of time.

The *antenna* is a "parabolic dish" which directs the transmitted energy into a narrow wedge or into a conical beam like that of a searchlight. It serves not only for transmission but for reception as well.

The *receiver*, like the transmitter, is similar to a radio receiver. Its main function is to amplify the relatively weak echoes which return to the antenna.

The *indicator* for the radar set is a special vacuum tube called a *cathode ray tube (CRT)*. It is similar to the picture tube of a television receiver. The CRT is commonly called the *scope* (from oscilloscope). An electromagnetic CRT, the type used in most radar sets, is illustrated in figure 10-2. It is composed of an electron gun, a focusing magnet, and a set of deflection coils. The function of the electron gun is to produce a thin electron stream, or beam. This beam is so acted upon by the focusing magnet that the focal point of the beam in a properly adjusted CRT is at the face of the tube. The CRT face is coated with a fluorescent compound which glows when struck by the electron beam. The picture seen is thus a small bright spot.

The location of an object by means of these five units of a radar set involves the simultaneous

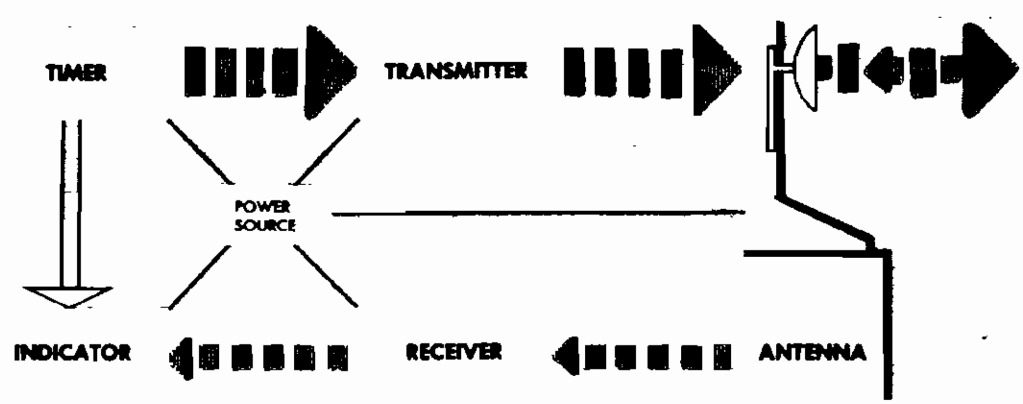


Figure 10-1. Components of a Typical Radar System

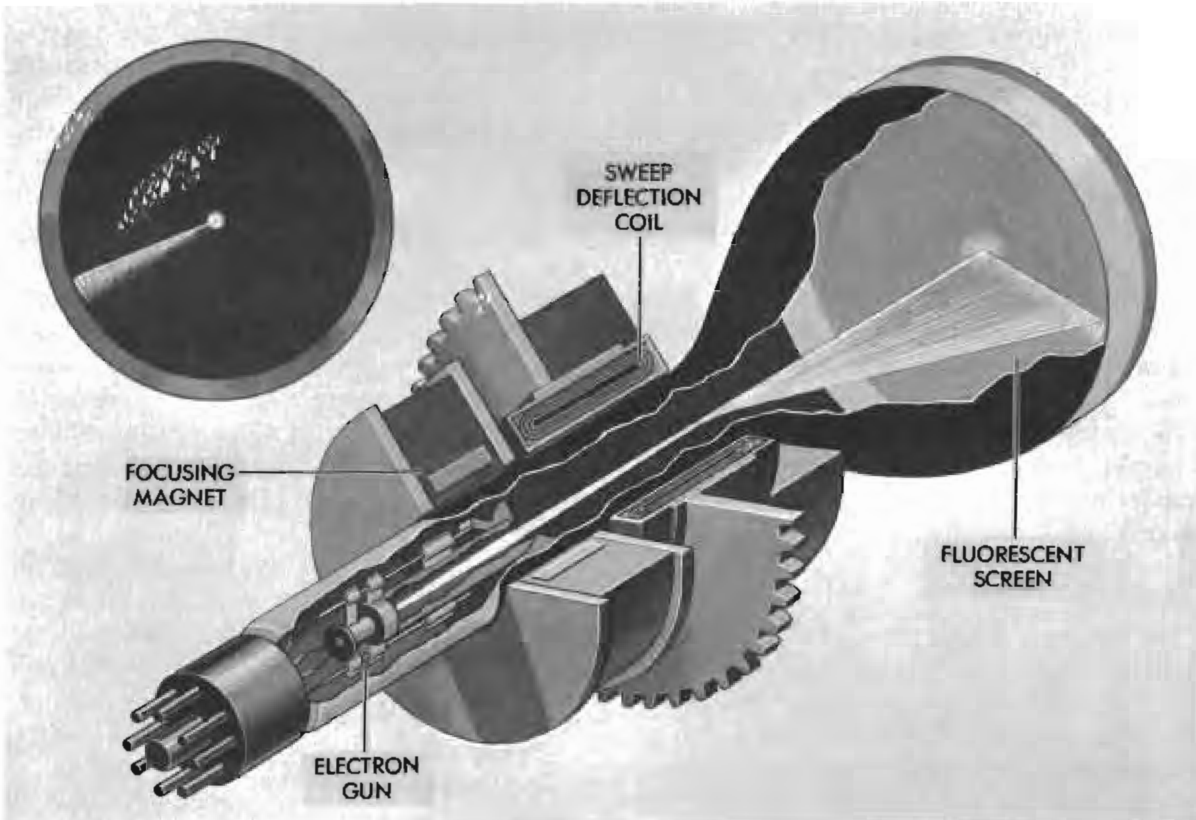


Figure 10-2. Electromagnetic Cathode Ray Tube (CRT)

solution of two separate problems. First, the time interval between the transmitted pulse and its echo must be accurately measured and presented as *range* on the indicator. Second, the direction in which each signal is transmitted must be indicated, giving the *bearing* of the object.

Measurement of Range

The radar cycle may best be explained by discussing first the life of a single pulse as it is affected by each of the components shown in figure 10-1. The cycle begins when the timer triggers the transmitter. A powerful pulse of radio energy is generated there which is then emitted from the antenna. As soon as the pulse leaves the antenna, the antenna is automatically disconnected from the transmitter and connected to the receiver. If an echo returns, it is amplified by the receiver and sent to the indicator for display.

At the same time that the timer triggers the transmitter, it also sends a trigger signal to the indicator. Here, a circuit is actuated which causes the current in the deflection coils to rise at a linear (uniform) rate. The rising current, in turn, causes the spot to be deflected radially outward from the center of the scope. The spot thus traces a faint line on the scope; this line is called the *sweep*. If no echo is received, the intensity of the sweep remains uniform throughout its entire length. However, if an echo is returned, it is so applied to the CRT that it intensifies the spot and brightens momentarily a short segment of the sweep. Since the sweep is linear and begins with the emission of the transmitted pulse, the point at which the echo brightens the sweep will be an indication of the range to the object causing the echo.

The progressive positions of the pulse in space also indicate the corresponding positions of the electron beam as it sweeps across the face of the CRT. If the radius of the scope represents 40 miles and the "return" appears at three-quarters of the distance from the scope center to its periphery, the target is represented as being about 30 miles away.

Of interest here is the extremely short time scale which is used. In the preceding example, the radar is set for 40-mile range operation. The sweep circuits will thus operate *only* for an equivalent time interval, so that targets beyond 40 miles will not appear on the scope. The time equivalent to 40 miles of radar range is only 496 microseconds (0.000496 seconds). Thus, 496 microseconds (plus an additional period of perhaps 100 microseconds to allow the sweep circuits to recover) after a pulse is transmitted, the radar is ready to transmit the next pulse. The actual pulse repetition rate in this example is about 800 pulses per second. The return will therefore appear in virtually the same position along the sweep as each successive pulse is transmitted, even though the aircraft and the target are moving at appreciable speeds.

Measurement of Bearing

The deflection coils, illustrated in figure 10-2, are mounted so they surround the neck of the CRT. *The direction taken by the sweep corresponds directly to the orientation of the deflection coils.* In the previous discussion of range, it was assumed that the deflection coils were stationary, so that the sweep formed by the deflection current always fell along the same radial. However, if the antenna (which forms the transmitted energy into a narrow beam) is rotated slowly in azimuth and the deflection coils are rotated mechanically in synchronism with the antenna, the sweep trace will point in the same direction as the antenna. Therefore, the relative bearing, as well as the range, of reflecting objects will be shown on the scope.

Plan Position Indicator (PPI)

The type of cathode ray tube display just discussed is called a *plan position indicator (PPI)*. It presents a map-like picture of the terrain below and around the aircraft. This is the presentation usually available in radar-equipped aircraft. In figure 10-3, the center of the scope represents the aircraft radar antenna. A radar target is shown at its correct bearing and at a distance from the scope center proportional to its range. To facilitate the measurement of range, "false" echoes called *fixed range markers* are generated electrically at regular intervals after each transmitted pulse and introduced at the indicator in the same manner as the actual echoes.

Since these markers always appear at the same position on the sweep for a given range setting, they trace concentric range circles on the scope. On some radar sets, the range mark circles are traced at appropriate intervals, such as every 2 miles when maximum range is 5 or 10 miles, every 5 miles on the 30-mile scale, and every 25 miles on the 100- or 200-mile scales.

To facilitate the measurement of bearing, a compass rose surrounds the scope, providing a convenient bearing reference. On most sets, the bearing of any particular return may be determined by bisecting the return with a cursor (a radial line inscribed on a transparent overlay) which can be rotated manually about an axis coincident with the center of the scope. The corresponding bearing is then read on the compass rose at the periphery of the scope.

In the plan position indicator illustrated in figure 10-3, the range scale is 100 miles; the range marker interval is 25 miles. Thus, the large target shown is at a relative bearing of 060° at a range of 50 miles.

SCOPE INTERPRETATION

The plan position indicator presents a map-like picture of the terrain below and around the aircraft. Just as map reading skill is largely dependent upon the ability to correlate what is seen on the ground with the symbols on the chart: so "radar" skill is largely dependent upon the ability to correlate

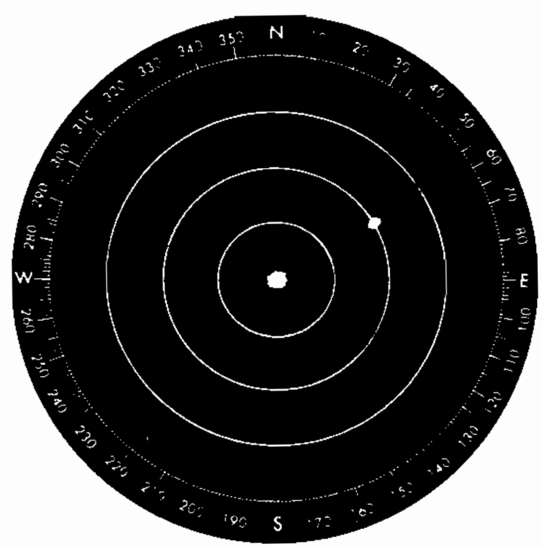


Figure 10-3. Plan Position Indicator (PPI)

what is seen on the scope with the chart symbols. Accordingly, a sound knowledge of the factors affecting radar reflection is a prerequisite to intelligent radarscope interpretation. Furthermore, a knowledge of these factors, applied in reverse, enables the navigator to *predict* the probable radarscope appearance of any area.

Factors Affecting Reflection

There are four primary factors which determine whether a usable portion of the transmitted energy will be reflected from a given object. No one factor, however, determines the amount of reflection; total reflection is based on a combination of all four factors. These factors are:

- Vertical and horizontal size.
- Material of the object.
- Radar range.
- Reflection angle.

VERTICAL AND HORIZONTAL SIZE. Assuming equal width, the *taller* of two structures presents the greater reflecting area. Its radar reflection potential is therefore greater.

Assuming equal height, the *wider* of two structures presents the greater reflecting area. This will cause it to appear as the larger return on the scope.

MATERIAL OF THE OBJECT. It is a basic law of physics that all substances reflect some electromagnetic energy. All substances also absorb some electromagnetic energy. Whether or not a substance may be considered a good radar reflector depends upon the ratio of the energy reflected to the energy absorbed. In general, this ratio depends primarily on the electrical conductivity of the substance. The reflection properties of the various materials from the best through the poorest are as follows:

Metals. Because of their high electrical conductivity, steel, iron, copper, aluminum, and most other metals are excellent reflectors of radio energy. A metal-clad building usually has high radar reflection potential. Those buildings which use steel or some other metal as structural reinforcement follow closely behind metal-clad buildings. This group includes concrete structures built around steel frameworks, commonly called "mixed" structures.

Water. Water is an excellent reflector of radio energy. However, an aircraft flying over a smooth water surface receives very little reflected energy from the surface because the angle of reflection is away from the aircraft. If the sea surface is not smooth, considerable energy is reflected resulting in large areas of *sea clutter* similar to *ground clutter.*

Masonry. Masonry by itself is a fair reflector. Masonry materials include stone, concrete, and clay products. However, masonry is often mixed with structural steel. These mixed structures have greater radar reflection potential than masonry alone.

Wood. In comparison to metal or masonry, wood is a poor reflector. Wooden structures do not normally reflect sufficient radar energy for display unless other important reflecting factors (such as unusual size) are present.

Dirt, Sand, and Stone. Although their reflection potential will vary to some extent with the particular chemical composition involved, dirt, sand, and stone are not normally considered good reflecting materials. Also, radar return from flat land areas is not nearly so great as that from land which exhibits irregular surfaces, such as sand dunes, hills, gravel pits, quarries, and similar prominences.

Glass. Glass by itself is not a good radar reflector. However, structures using glass walls usually have steel framing and such structures often can be considered among the better reflectors.

The diagram in figure 10-4 shows the relative reflection potential of the basic structural materials. These relationships will hold true, of course, only on the assumption that the other factors affecting reflection—size, range, and reflection angle—are equal.

RADAR RANGE. Range affects radar reflection in two ways. First, the *nearer* of two objects of equal size occupies a greater percentage of the beam width and so has more energy incident upon it. It will therefore appear as the brighter return. Second, as the radar waves travel through space, many minute particles of dust and other foreign matter intercept the beam. The resulting absorption decreases the strength of, or attenuates, the signal. The farther the energy travels, the more attenuation occurs. The attenuation effect is compensated for by automatic increase of the power output as the operating range is increased to the next higher increment.

REFLECTION ANGLE. In all cases of true reflection, the angle of reflection is equal to the

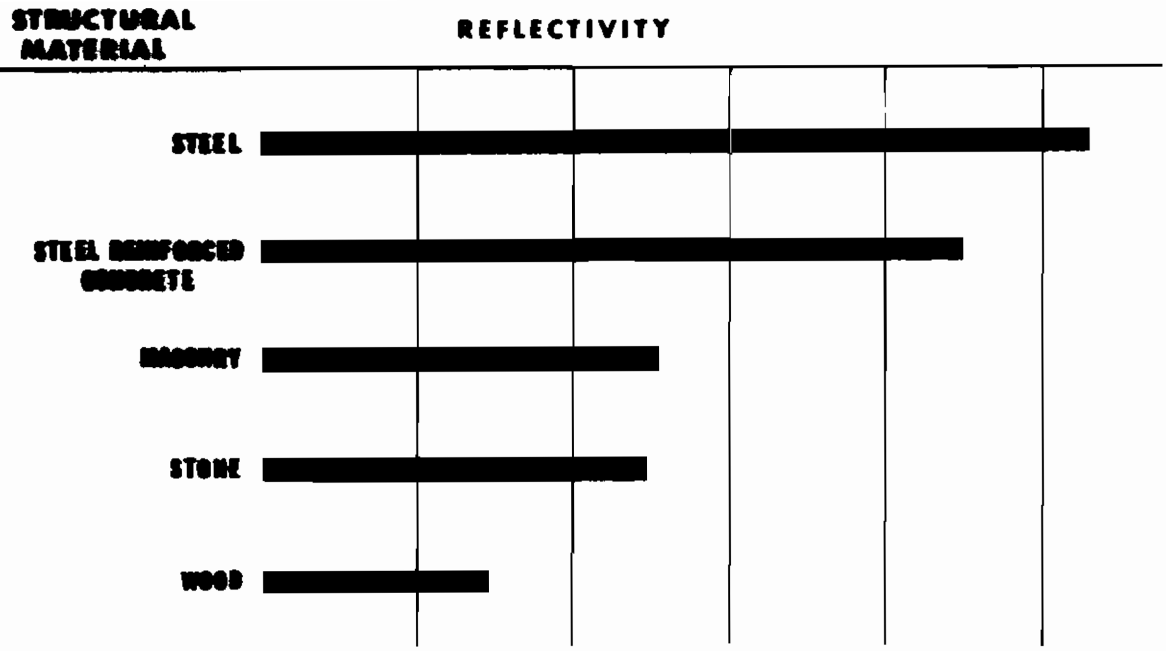


Figure 10-4. Relative Reflectivity of Structural Materials

angle of incidence. Therefore, maximum reflection back to a radar set occurs when the reflecting surfaces are at right angles to the radar beam. For this reason, flat surfaces can give a momentarily intense directional reflection, just as the windshield of an automobile does when it flashes in the sunlight. However, such radar echoes, though very strong, are normally not usable for navigational purposes because the brevity of their existence does not allow sufficient time for identification. Fortunately, the great majority of radar targets are multifaceted rather than smooth, so that at any given instant some part of the target will be at right angles to the beam. The more closely the incident wave approaches a direct right angle with respect to the overall surface, the greater will be the radar reflection.

Horizontal. The effect of the horizontal reflection angle is shown in figure 10-5. Because of the particular configuration between the aircraft and reflecting objects, the aircraft at *A* gets no return from building 1 and maximum return from building 2 and the railroad tracks. At *B*, the aircraft gets no reflection from building 2 and maximum reflection from the railroad tracks. At *C*, maximum reflection is again being obtained from building 2. This entire discussion oversimplifies the problem for purposes of clarity. It should be emphasized again that smooth surfaces such as those shown are rarely encountered, and for normal structures, the amount of reflection would be *minimum* where *zero* reflection has been implied.

Vertical. The effect of the vertical reflection angle is not nearly so pronounced as that of the horizontal reflection angle. This is because of the much greater beam width in the vertical dimension as compared to the horizontal when the normal mapping beam is used. The vertical beam width may be on the order of 50 degrees and the horizontal beam width on the order of 1½ degrees. The effect of the vertical reflection angle cannot, however, be neglected. Figure 10-6 shows that the vertical energy pattern contains a main lobe. To obtain maximum reflection, this main lobe should strike the overall reflecting surface at right angles to it. In most buildings, the overall reflecting surface is vertical. Thus, as an aircraft approaches a building or group of buildings, the actual vertical reflection angle becomes more and more removed from the optimum. The final result is that, when the vertical reflection angle approaches 45 degrees, many of the structures scanned by the beam do not reflect enough energy back to the set to appear on the scope (see figure 10-7). The zone in which this lack of reflection is likely to occur is equal in radius to the altitude of the aircraft. For example,

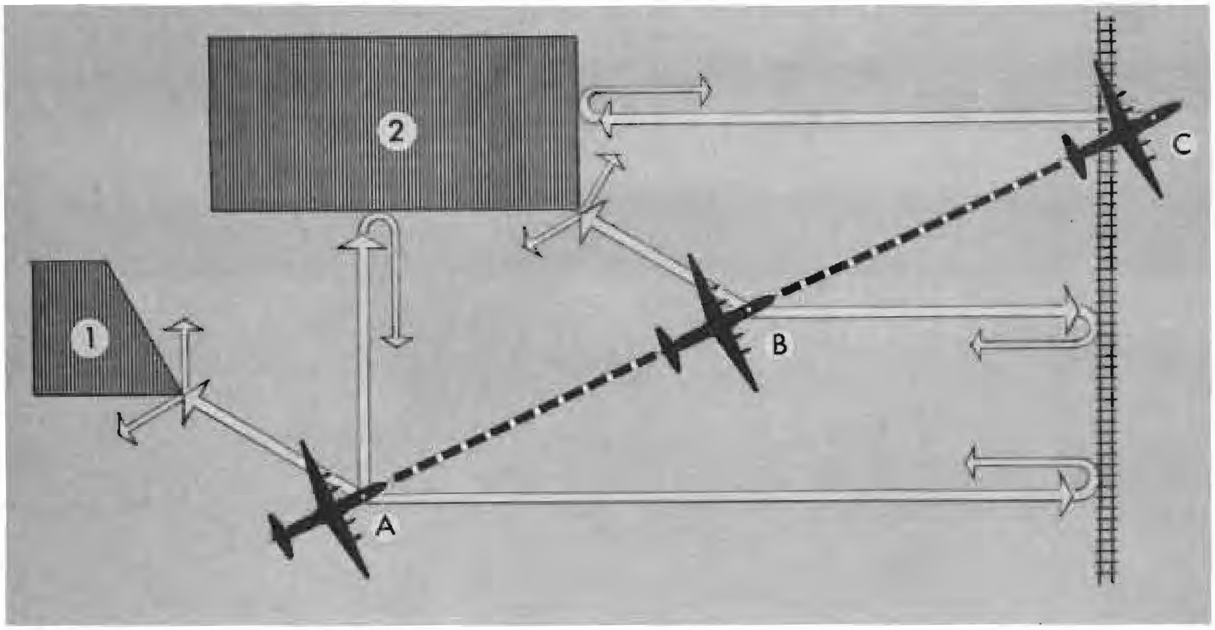


Figure 10-5. Horizontal Reflection Angle

an aircraft flying at extremely high altitudes might display only the returns from the very best types of reflectors—such as steel mills—in the area within eight or ten miles from the aircraft.

Adjustment of the antenna tilt control can compensate to a degree for the above effect. By tilting the antenna downward as the target is approached, more energy is made to strike the target at the optimum reflection angle. However, this reduces the overall coverage of the radar scan because the energy directed out ahead of the aircraft is reduced.

SUMMARY. It is important to re-emphasize that no one factor determines the reflection potential of a given reflector. However, a single factor may prevent sufficient reflection to create a return on the scope. The following general rules will apply:

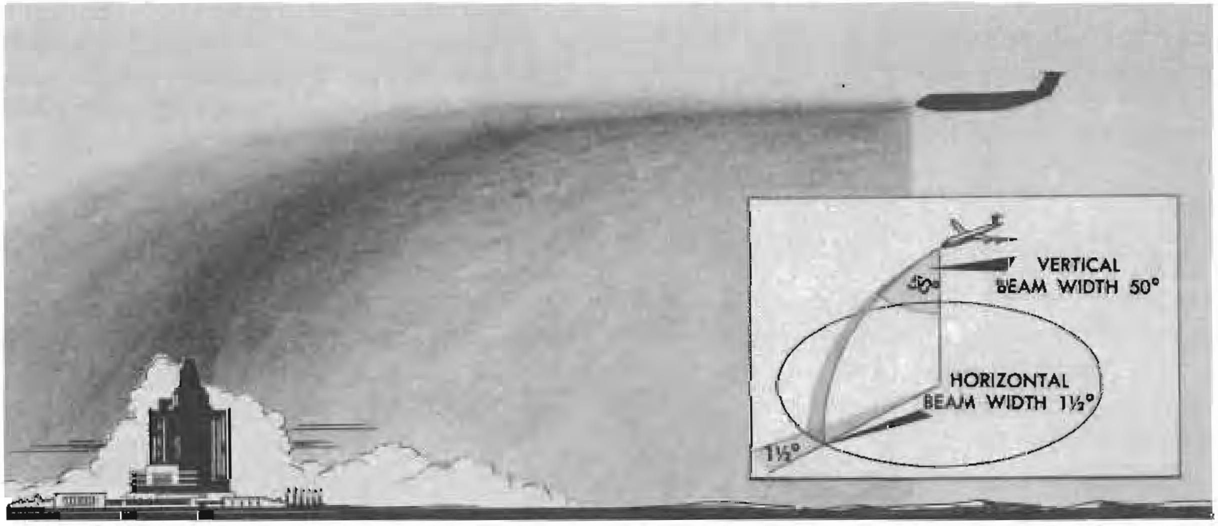


Figure 10-6. Radiation Pattern of Antenna

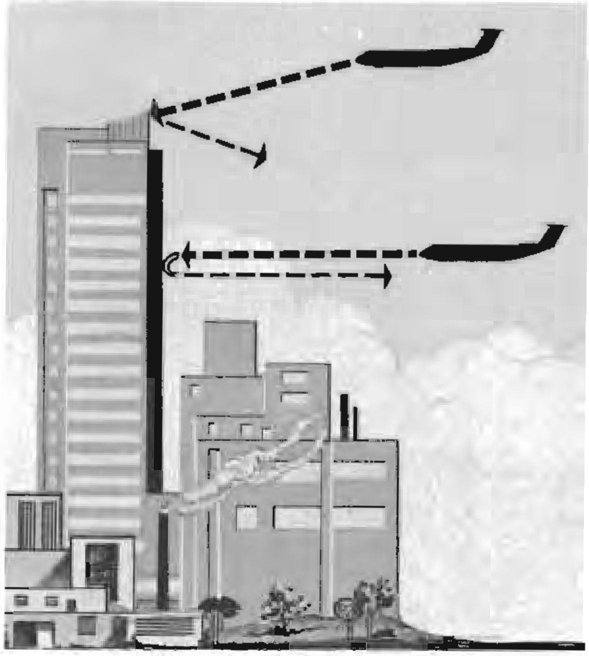


Figure 10-7. Vertical Reflection Angle Varies With Aircraft Position and Altitude

1. The greatest return potential exists when the radar beam forms a horizontal right angle with the frontal portion of the reflector.
2. Radar return potential is roughly proportional to structure size and the reflective properties of the construction material used.
3. Radar return potential is greatest within the zone of the greatest radiation pattern of the antenna, as illustrated in figure 10-6.
4. Radar return potential decreases as altitude increases because the vertical reflection angle becomes more and more removed from the optimum. (There are many exceptions to this general rule since there are many structures which may present better reflection from roof surfaces than from frontal surfaces.)
5. Radar return potential decreases as range increases because of the greater beam width at long ranges and because of atmospheric attenuation.
6. All of the factors affecting reflection must be considered to determine the radar return potential.

Typical Scope Returns

There are certain characteristics peculiar to returns from specific ground features such as rivers, lakes, mountains, railroads, cities, etc. To consolidate the knowledge of the general rules on the factors affecting reflection, this section describes and illustrates how these rules may be applied to specific ground features.

The principal problem in radarscope interpretation is finding the meaning of contrasts in brightness. This comes ahead of the purely navigational problem because a particular feature must be identified before it becomes useful. Figure 10-8 shows a representative ground area and its associated radarscope presentation. In the discussion which follows, it would be well to refer back to this illustration, noting in particular the relative brightness of the different parts of the scope.

Returns From Land. All land surfaces present minute irregular parts of the total surface for reflection of the radar beam, and thus there is usually a certain amount of radar return from all land areas. The amount of return varies considerably according to the nature of the land surface scanned. This variance is caused by (1) the difference in reflecting materials of which the land area is composed, and (2) the texture of the land surface. These are the primary factors governing the total radar return from specific land areas.

Flat land. A certain amount of any surface, however flat in the overall view, is irregular enough to reflect the radar beam. Surfaces which are apparently flat are actually textured and may cause return on the scope. Ordinary soil absorbs some of the radar energy and thus the return that emanates from this type of surface is not strong. Ray *B* in figure 10-9 shows that flat land will reflect most of the energy away from the aircraft.

Plowed Fields. Plowed fields and other irregularly textured land areas present more surface to the radar beam than flat land and thus create more return. Returns from plowed fields may be a problem to the radar navigator because such returns are not readily identifiable, are often not persistent, and tend to confuse the overall radarscope interpretation problem. The returns from plowed fields and other irregularly textured land areas are most intense when the radar beam scans the upright furrows or similar features at a right angle. This type of return is exemplified by ray *F* in the illustration.

Hills and Mountains. Hills and mountains will normally give more radar return than flat land because the radar beam is more nearly perpendicular to the sides of these features. The typical return is a bright return from the near side of the

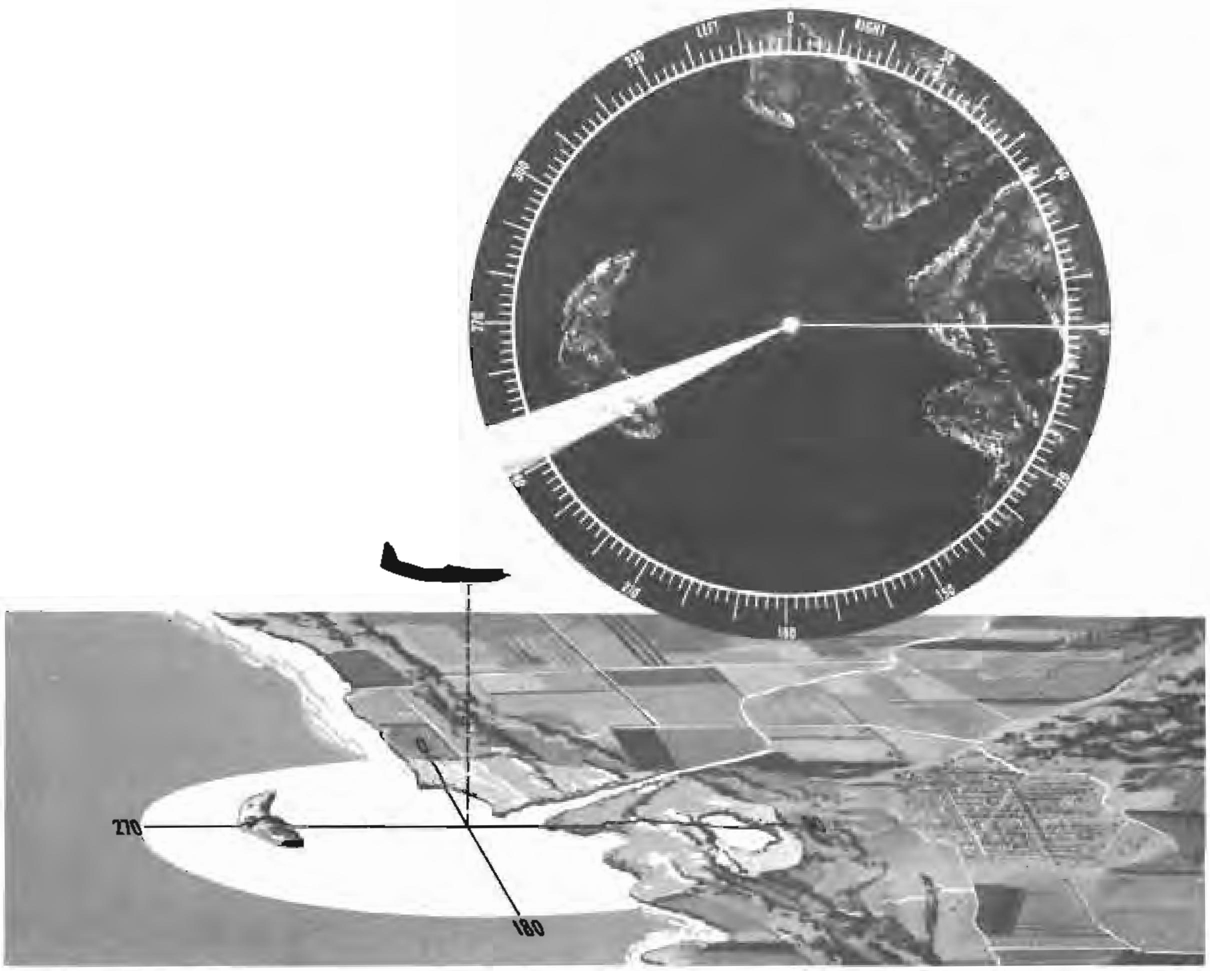


Figure 10-8. Radar Returns

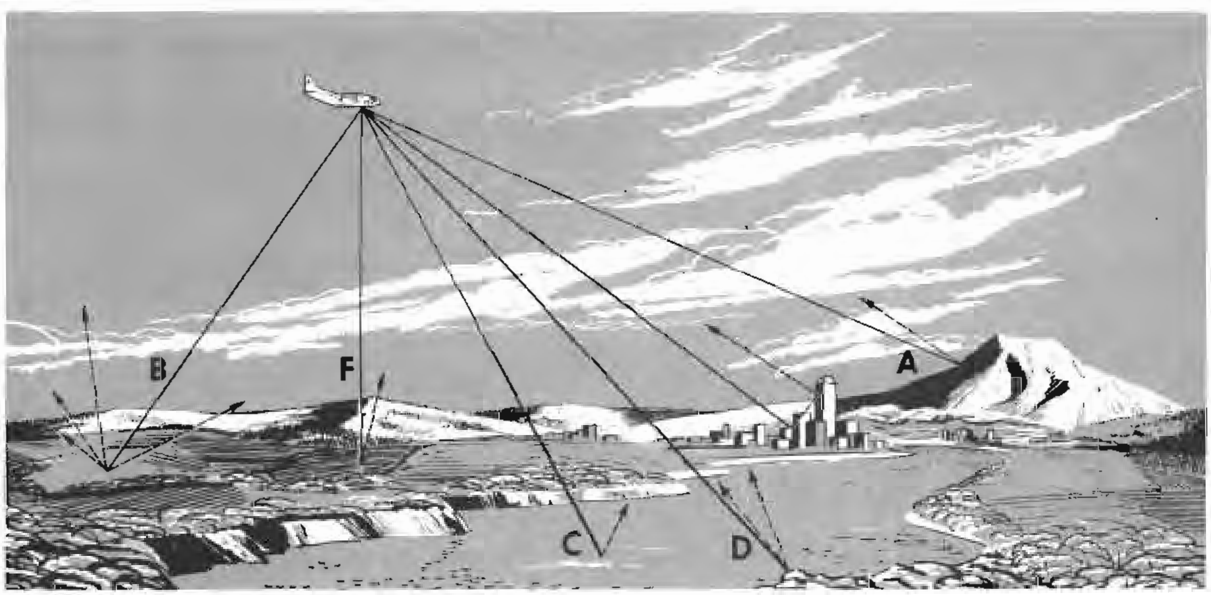


Figure 10-9. Reflections from Various Types of Terrain

feature and an area of no return on the far side. This is shown by ray *A*. The area of no return is called a mountain shadow and exists because the radar beam cannot pentrate the mountain, and its line-of-sight transmission does not allow it to intercept targets behind the mountain. The shadow area will vary in size, depending upon the height of the aircraft with respect to the mountain. As an aircraft approaches a mountain, the shadow area becomes smaller and smaller. Furthermore, the *shape* of the shadow area and the brightness of the return from the peak will vary as the aircraft's position changes.

Recognition of mountain shadow is important because any target in the area behind the mountain cannot be seen on the scope. A striking example of this is illustrated in figure 10-10. Note that the mountains obscure the area in which the town of Adams lies.

In areas with isolated high peaks or mountain ridges, contour navigation may be possible because the returns from such features assume an almost three-dimensional appearance. This allows specific peaks to be identified.

In more rugged mountainous areas, however, there may be so many mountains with resulting return and shadow areas that contour navigation is almost impossible. Note the complexity of the mountain returns in figure 10-11. In an area such as this, the radar might still be used for general orientation. For example, the aircraft is flying over the line of demarkation between a mountainous and a level area. This line of demarkation might serve as a *line of position* even though the complexity of the scope picture makes positive position finding impossible.

Coastlines and Riverbanks. The contrast between water and land is very sharp, so that the configuration of coasts and lakes are seen with map-like clarity. When the radar beam scans the banks of a river, lake, or larger body of water, there is little or no return from the water surface itself, but there is usually a strong return from the adjoining land. This may be seen from rays *C* and *D* in figure 10-9. The more rugged the bank or coastliue, the more return will be experienced.

A nearby shoreline will be very clearly delineated when an aircraft is out over the adjoining water. However, the shoreline tends to lose its clearcut separation from the water when the aircraft is flying over the land. This is because the coastline presents upright banks to the overwater radar beam and relatively flat land to the overland beam. This also explains why the *far* side of a lake will appear brighter than the near side. Notice in figure 10-12 that the lake at 320° shows a much stronger return from the far side than from the near side.

Since both mountains and lakes present a "dark" area on the scope, it is sometimes fairly easy to mistake a mountain shadow for a lake.

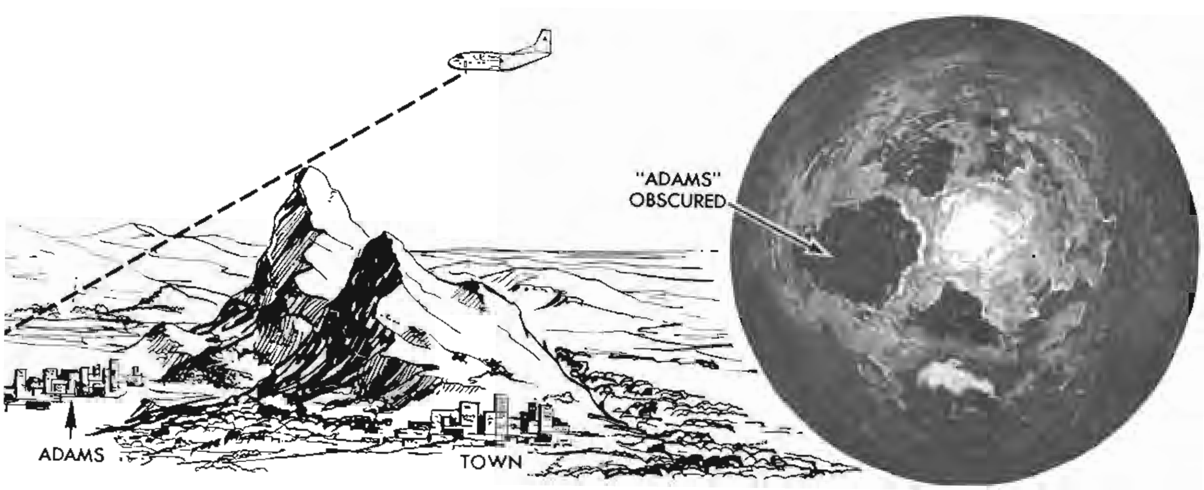


Figure 10-10. Significant Areas are Sometimes Obscured by Mountains

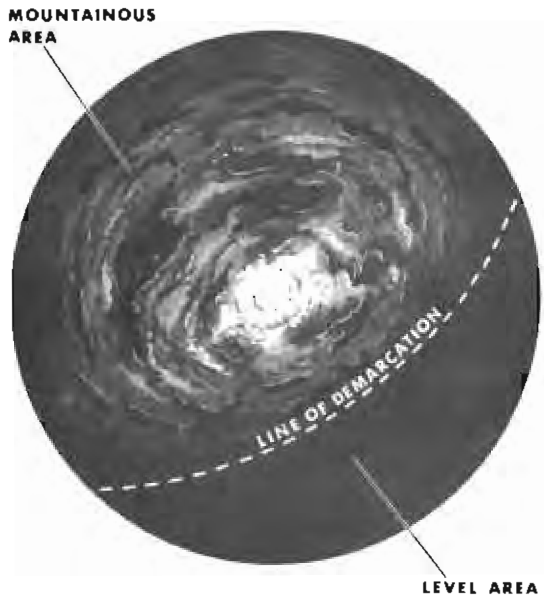


Figure 10-11. Individual Peaks are Difficult to Identify

This is particularly true when navigating in mountainous areas which also contain lakes.

The essential difference between returns from mountain areas and lakes is that returns from mountains are bright on the near side and dark on the far side; returns from lakes are bright on the far side and vague on the near side. Another characteristic of mountain returns is that the dark area changes shape and position quite rapidly as the aircraft moves, returns from lakes change only slightly.

URBAN AREAS. The overall size and shape of the radar return from any given city can usually be determined with a fair degree of accuracy by referring to a map of the area. However, the brightness of one urban area as compared to another may vary greatly, and this variance can hardly be forecast by reference to the navigation chart. In general, the industrial and commercial centers of cities and towns produce much greater brightness than the outlying residential areas.

ISOLATED STRUCTURES. Many isolated or small groups of structures create radar returns. The size and brightness of the radar returns these features give are dependent on their construction. Most of these structures are not plotted on the navigation charts; hence, they are of no navigational value. However, some of them give very strong returns—such as large concrete dams, steel bridges, etc.—and if they can be properly identified they give valuable navigational assistance.

GLITTER AND CARDINAL POINT EFFECT.

Glitter, Glitter or glint, is the cause of most fluctuating returns that appear on the scope. It occurs when the radar beam scans a relatively small reflector which is able to present sufficient reflection for display on the scope only when the radar beam is at right angles to the structure. Since the aircraft is moving, the conditions necessary for the display of such an object exist only momentarily; hence, the return appears only momentarily on the scope (see figure 10-13).

Cardinal Point Effect. This is glitter that occurs when the radar beam scans a large number of structures at right angles. In this case, the return may remain for more than the customary instant. Because most cities and towns are laid out along

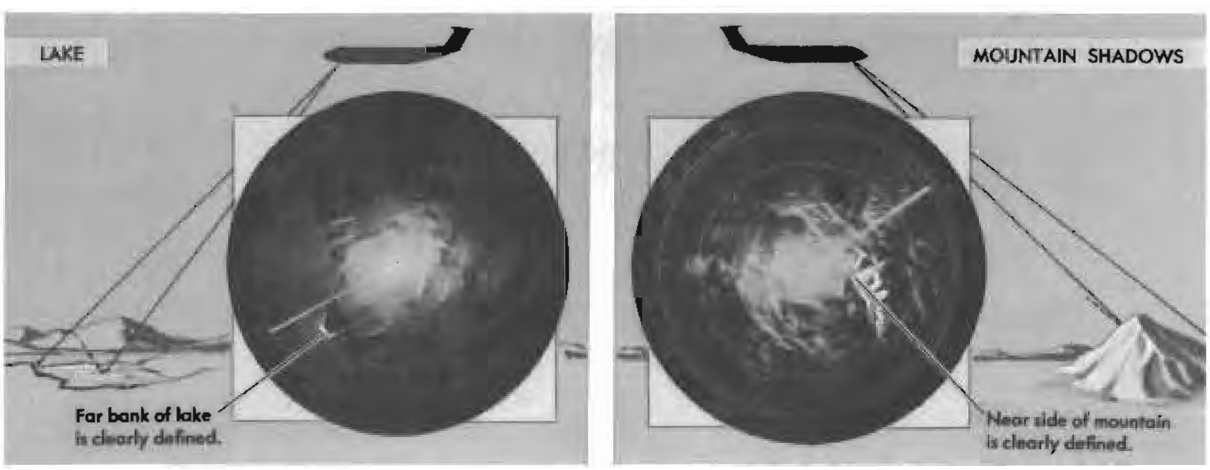


Figure 10-12. Mountains and Lakes

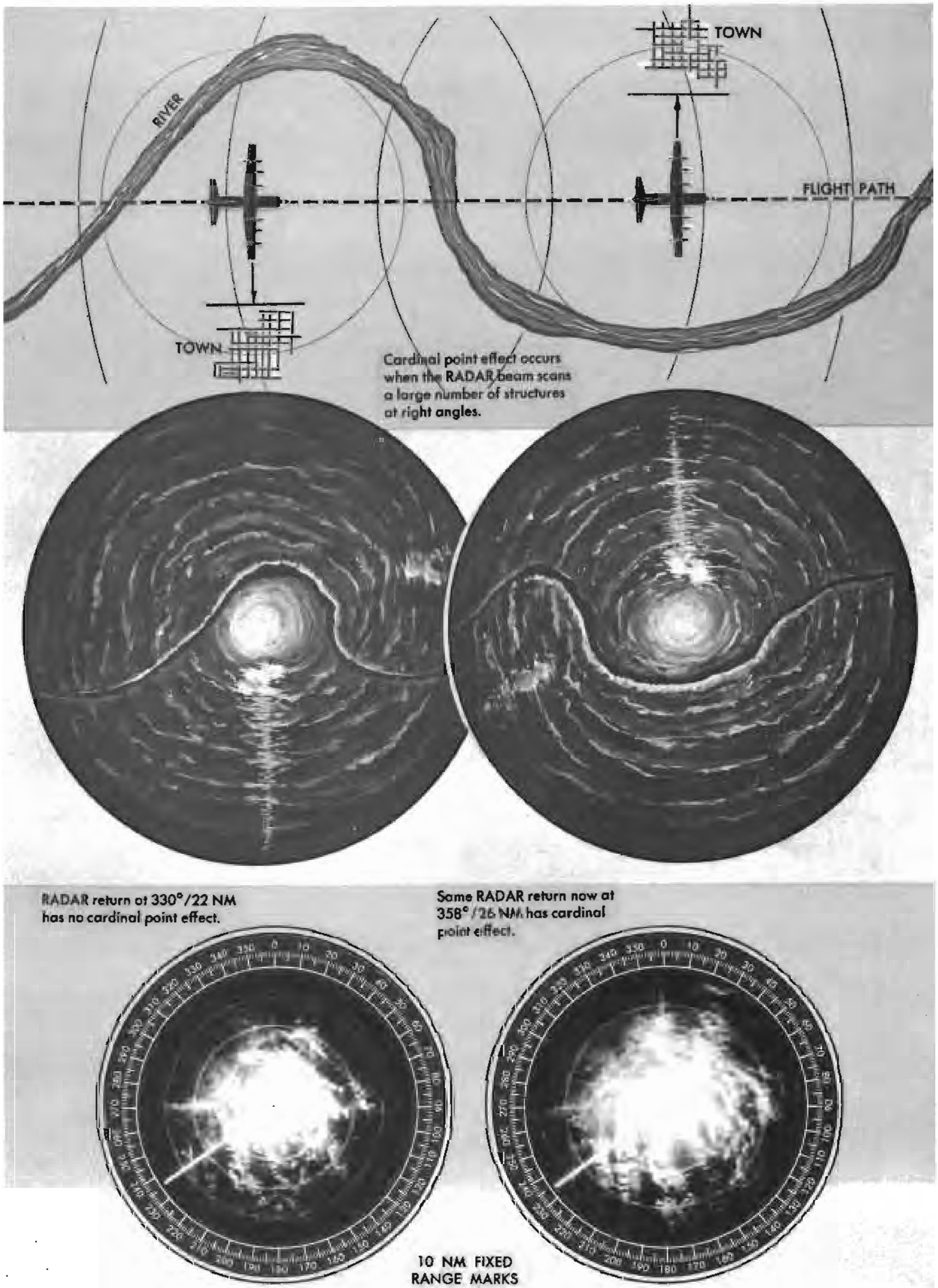


Figure 10-14. Cardinal Point Effect

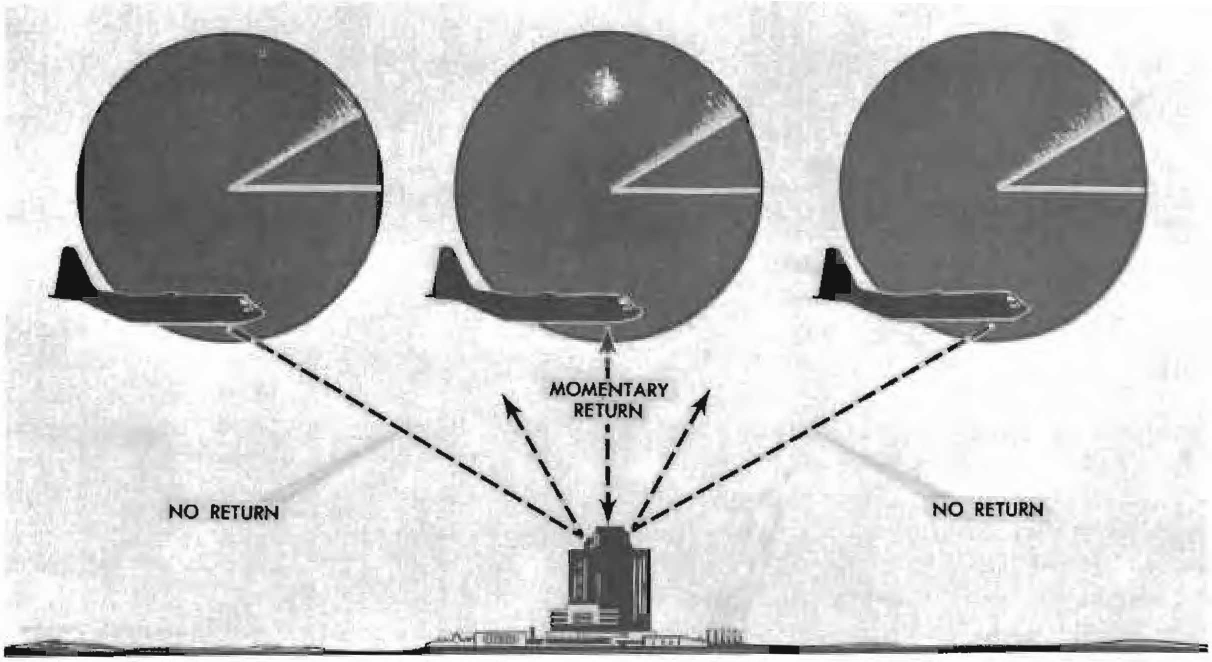


Figure 10-13. Glitter

north-south and east-west axes, cardinal point effect usually occurs when the true bearing of a city is equal to one of the cardinal directions. However, the effect can occur on any axis according to the particular geographical alignment involved. Cardinal point effect is illustrated in figure 10-14.

WEATHER RETURNS. Cloud returns which appear on the scope are called *precipitation or meteorological echoes.* They are of interest for two reasons. First, since the brightness of a given cloud return is an indication of the intensity of the weather within the cloud, intense weather areas can be avoided by directing the pilot through the darker scope areas or by completely circumnavigating the entire cloud return. Second, cloud returns obscure useful natural and cultural features on the ground. They may also be falsely identified as a ground feature, which can lead to gross errors in radar fixing.

Clouds must be reasonably large to create a return on the scope. However, size alone is not the sole determining factor. Cloud layers covering hundreds of square miles will not always create returns. As a matter of fact, clouds covering such wide areas rarely show on the scope. The one really important characteristic that causes clouds to create radar returns is the size of the water droplets forming them. Radar waves are reflected from large water droplets falling through the atmosphere as rain or suspended in the clouds by strong vertical air currents. Thunderstorms are characterized by strong vertical air currents; therefore, they give very strong radar returns (see figure 10-15).

Figure 10-15. Thunderstorm Returns

Cloud returns may be identified by the following characteristics:

- Brightness varies considerably, but the average brightness is greater than normal ground return.
- Returns generally present a hazy, fuzzy appearance around their edges.
- Terrain features are not present.
- Returns often produce a shadow area similar to mountain shadow because the radar beam does not penetrate clouds with sufficient strength to create echoes beyond them.
- Returns do not fade away as the antenna tilt is raised, whereas ground returns tend to decrease in intensity with an increase in antenna tilt.
- Returns appear in the altitude hole when altitude delay is not used and the distance to the cloud is less than the altitude.

EFFECTS OF SNOW AND ICE. The effects of snow and ice, most prevalent in arctic regions, are similar to the effect of water. If a land area is covered to any great depth with snow, the radar beam will reflect from the snow rather than from the features which lie beneath. The overall effect is to *reduce* the return which would normally come from the snow-blanketed area.

Ice will react in a slightly different manner, depending upon its roughness. If an ice coating on a body of water remains smooth, the return will appear approximately the same as a water return. However, if the ice is formed in irregular patterns, the returns created will be comparable to terrain features of commensurate size. For example, ice ridges or ice mountains would create returns comparable to ground embankments or mountains, respectively. Also, offshore ice floes tend to disguise the true shape of a coastline so that the coastline may appear vastly different in winter as compared to summer.

Inherent Scope Errors

Another factor which must be considered in radarscope interpretation is the inherent distortion of the radar display. This distortion is present to a greater or lesser degree in every radar set, depending upon its design. It can be minimized by a proper understanding of its causes and by proper use of the radar controls. Inherent scope errors may be laid to three causes: the width of the beam, the length (time duration) of the transmitted pulse, and the diameter of the electron spot.

BEAM WIDTH ERROR. The magnitude of this error may be as great as the width of the radar beam. Suppose, for example, that an isolated structure, 1000 feet wide, is being scanned by a beam one and one-half degrees wide at a range of 20 miles. If the target is an excellent reflector, it will begin to create a return as soon as the leading edge of the beam contacts it, while the center of the beam is still half the beam width away. Similarly, the target continues to create a return until the trailing edge of the beam leaves it. Thus, the target appears too wide by half the beam width on either side, or by a total of one beam width. However, this is the maximum error that could occur. The beam seldom intercepts targets of such excellent reflective characteristics as to induce the maximum error. Also, the beam subtends less linear arc as the range decreases so that beam width error decreases with range.

Actually, beam width error is not overly significant in radar navigation (although it must be taken into account in radar bombing). Since the distortion is essentially symmetrical, it may be nullified by bisecting the return with the bearing cursor when bearing is measured. Beam width distortion is also lessened by reduction of the receiver gain control. The principle and effect of beam width error on reflecting targets are illustrated in figures 10-16 and 10-17.

PULSE LENGTH ERROR. Pulse length error is caused by the fact that the radar transmission is not instantaneous but lasts for a brief period of time. Imagine a huge steel plate so large that no radar pulse can penetrate beyond it. Such a reflector has no range dimension, therefore, the return on the scope should have no range dimension. However, if the pulse emitted by the radar transmitter is of one microsecond duration, this pulse will continue to strike the steel plate for one microsecond. It is obvious, then, that the target will reflect energy throughout this period of time, and a return will be displayed on the scope throughout this period. Since time is translated into distance on the scope face (1 microsecond equals 490 feet) and corrected for a radar mile, the target will appear to be approximately 490 feet longer than it actually is. Thus, there is a distortion in the range direction on the far side of the reflector, and this pulse length error is equal to the range equivalent of one-half the pulse time.

Since pulse length error occurs on the far side of the return as shown in figure 10-18, it may be

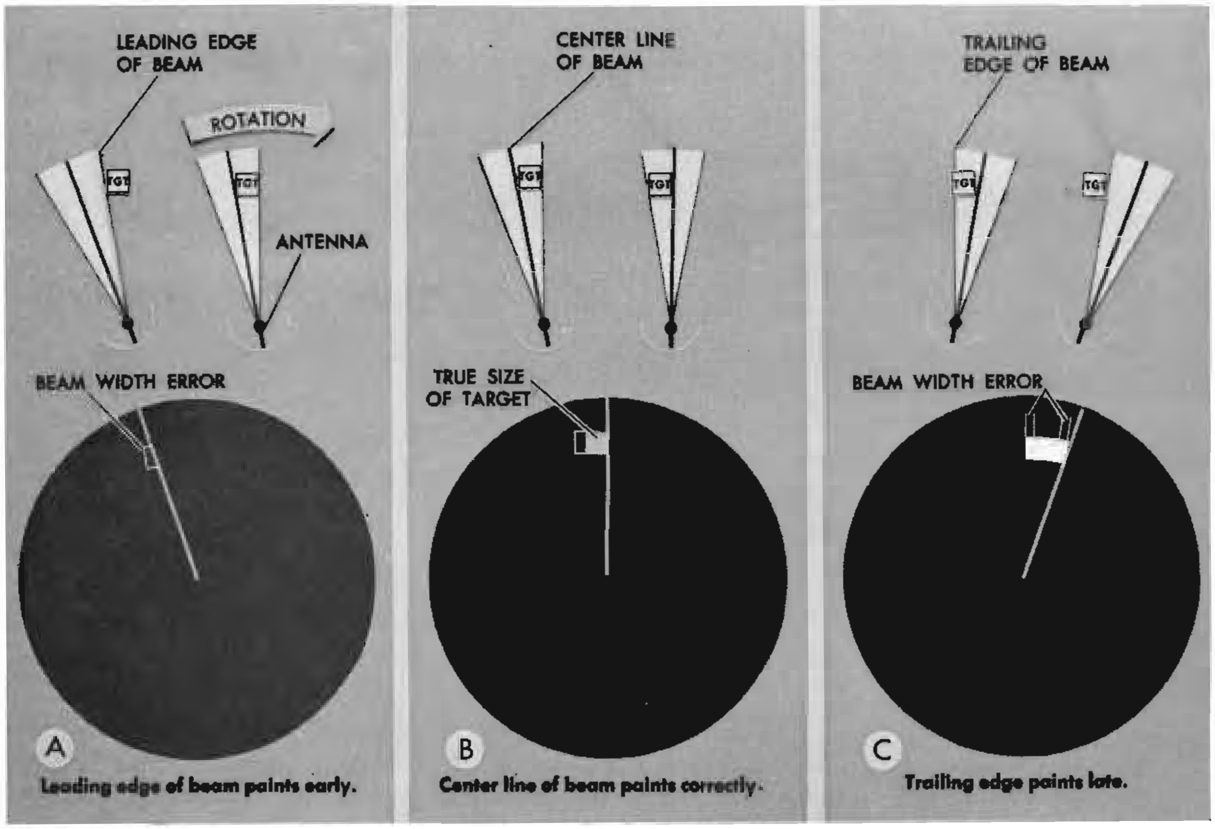


Figure 10-16. Beam Width Error

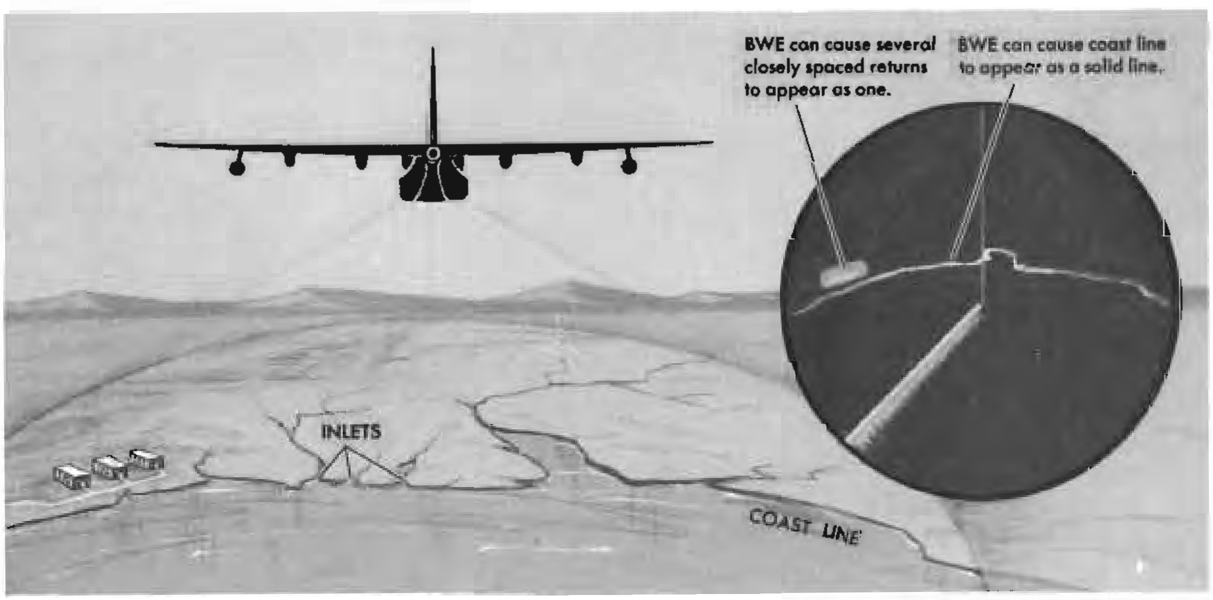


Figure 10-17. Effect of Beam Width Error

nullified by reading the range to (and plotting from) the near side of the target when taking radar ranges. It should also be mentioned that the radar set is so designed that the pulse length (and hence the pulse length error) increases as the operating range increases. Therefore, failure to employ the proper range measuring technique will produce greater errors at the longer ranges.

The pulse length also has a primary effect on the *range resolution* of a radar set. Theoretically, two sharply defined targets at the same bearing should be resolved into two separate returns on the scope if their ranges differ by the distance light travels during one-half the pulse length. Thus, with a one microsecond pulse length, two targets would have to be more than 490 feet apart in range to appear as two separate returns on the scope. (See figure 10-19.)

SPOT SIZE ERROR. Spot size error is caused by the fact that the electron beam which displays the returns on the scope has a definite physical diameter. No return which appears on the scope can be smaller than the diameter of the beam. Furthermore, a part of the glow produced when the electron beam strikes the phosphorescent coating of the CRT radiates laterally across the scope. As a result of these two factors, all returns displayed on the scope will appear to be slightly larger in size than they actually are. (See figure 10-20.)

Here again, as in the case of pulse length and beam width distortions, the effect is to reduce the *resolution* of the set. This may make it difficult for the radar navigator to isolate and identify returns.

Spot size distortion may be reduced by using the lowest practicable receiver gain, video gain, and bias settings and by keeping the operating

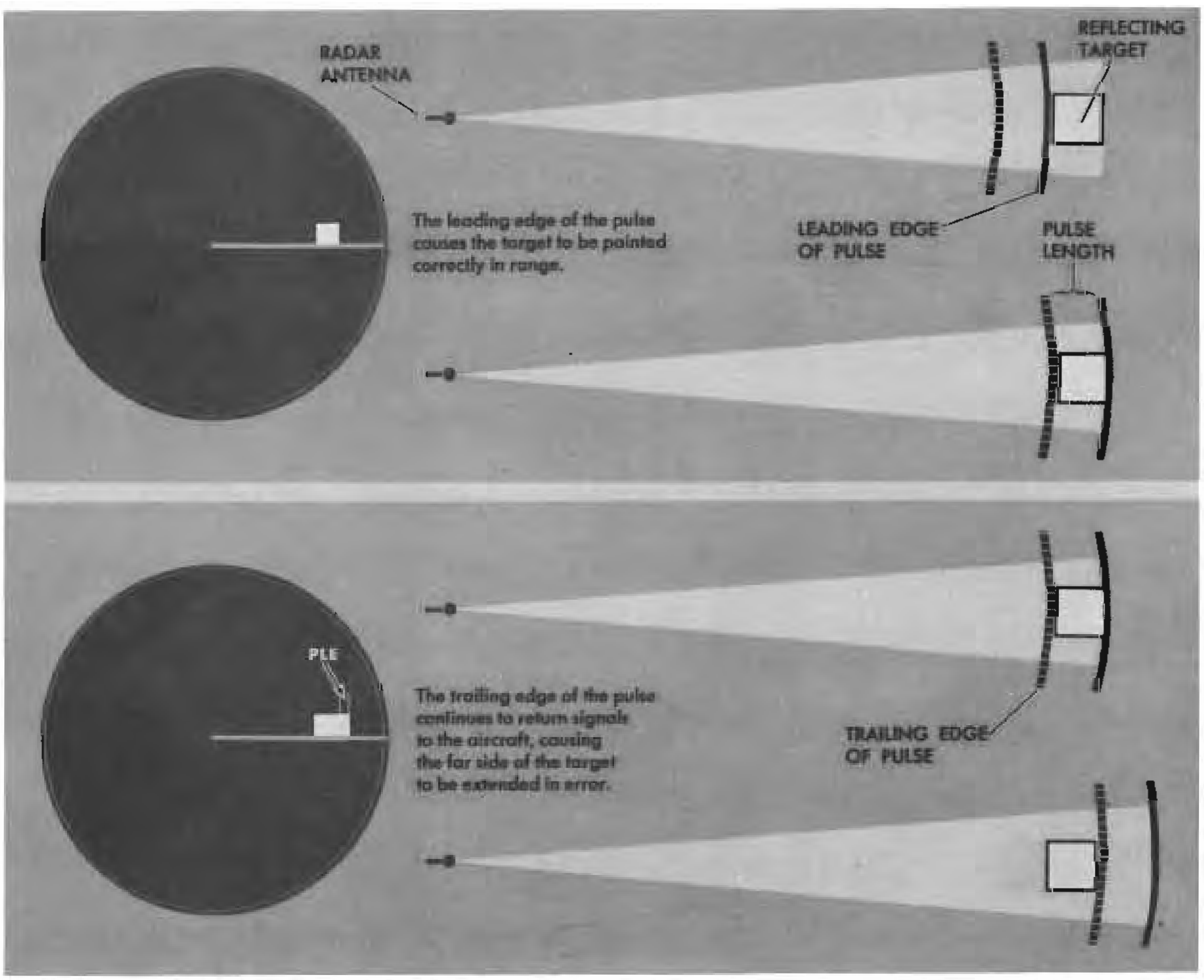


Figure 10-18. Pulse Length Error

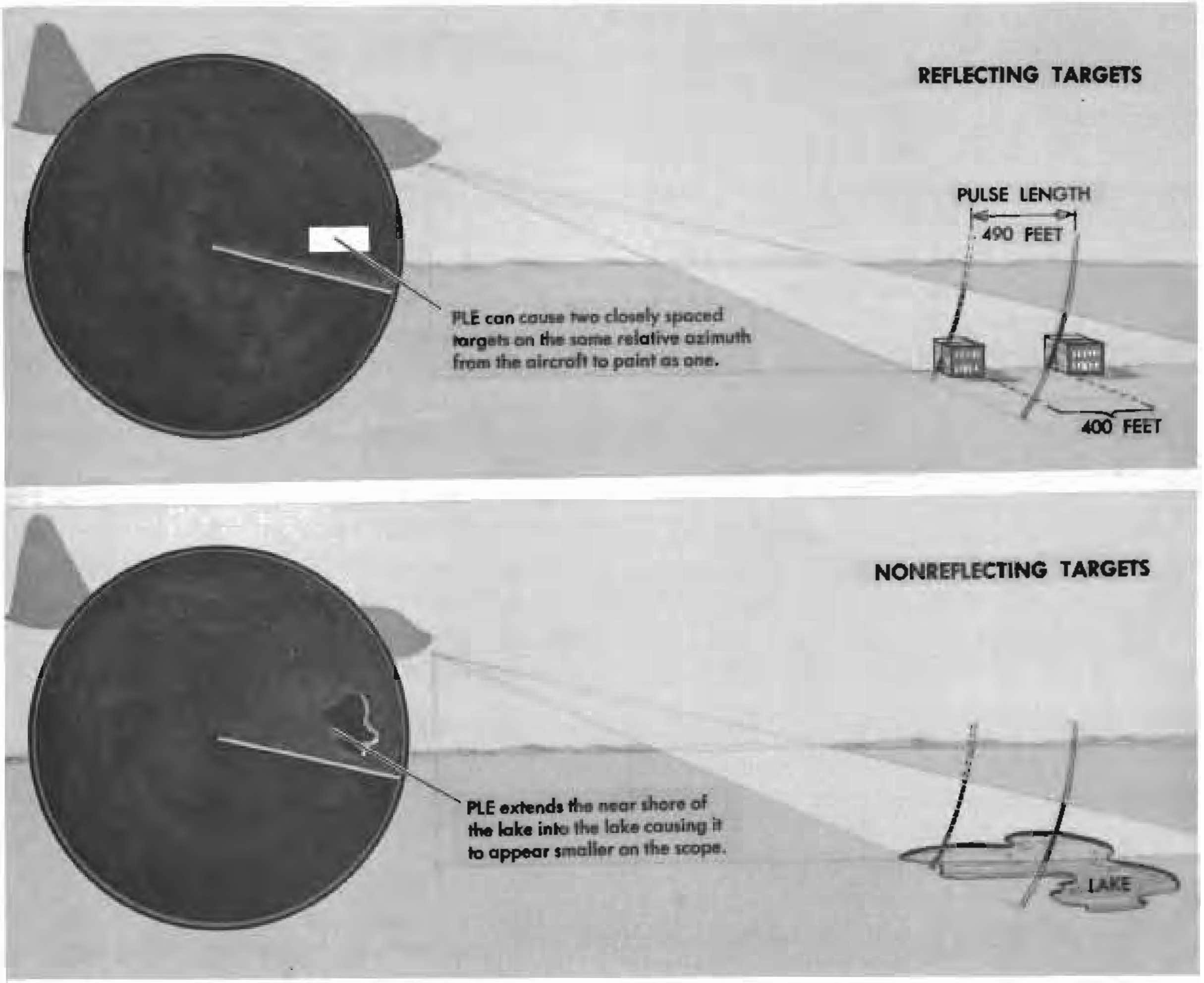


Figure 10-19. Effect of Pulse Length Error

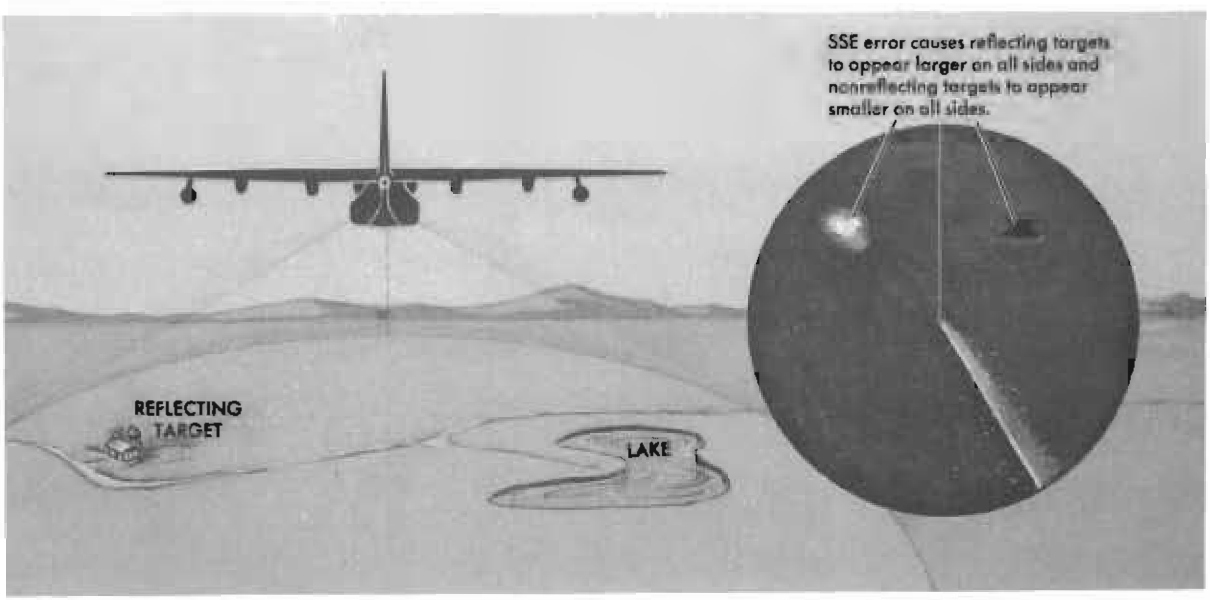


Figure 10-20. Effect of Spot Size Error

range at a minimum so that the area represented by each spot is kept at a minimum. Further, the operator should check the focus control for optimum setting.

TOTAL DISTORTION. The radar presentation is distorted by three inherent errors: pulse length, beam width, and spot size. The combined effect of these errors is illustrated in figure 10-21. For navigational purposes, the errors are often negligible. However, the radar navigator should realize that they do exist and that optimum radar accuracy demands that they be taken into account.

NAVIGATIONAL FEATURES OF RADAR

The airborne radar sets used throughout the Air Force vary slightly in the navigational refinements offered. All of the sets in use, however, possess some of the following features.

Radar Range Selection

The range of any radar system depends upon the transmitted power, the receiver sensitivity, the antenna gain, and the various factors affecting reflection. However, since radar is a line-of-sight instrument, the ultimate limitation on the range of any radar is the curvature of the earth. In practice, it is found that the horizontal stratification of the atmosphere causes refraction of the microwave rays, usually bending them downward so that they tend to follow the curvature of the earth. This results in a theoretical radar range which may be determined by the following formula:

$$D = \sqrt{2h} \times .87$$

when D is nautical miles and h is the altitude in feet.

Though it is possible to receive returns from objects at great distances, it is not always necessary or desirable to have the maximum range portrayed on the scope. Therefore, the operating range of all radar sets can be controlled by the operator. The various sets differ as to the maximum and minimum ranges obtainable. Most sets currently in use may be varied from 3 to 400 miles. The range selected determines the comparative size of the various returns, and proper use of the range selector control can simplify the scope interpretation problem. For example, decreasing range will show a particular area in much greater detail, while increasing range (altitude permitting) will give a much greater coverage.

Fixed Range Markers

Fixed range markers have already been discussed under the heading, Plan Position Indicator. These markers describe concentric circles on the scope at fixed range intervals. They may be used to measure the *slant range* (the direct line-of-sight range) to any return appearing on the scope. It is often necessary to interpolate when using the fixed range markers because the return appears between two markers. On some sets, one of the several range intervals available—2, 5, 10, etc.—may be arbitrarily selected. On other sets, the range mark interval is automatically determined by the setting of the range selector control.

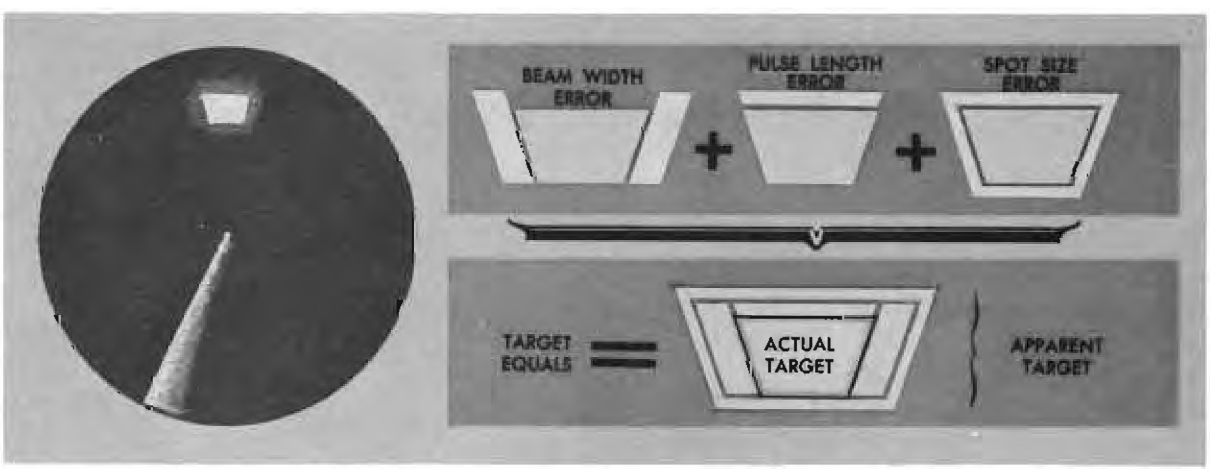


Figure 10-21. Combined Effect of Inherent Errors