

CHAPTER 10

RADIO WAVES

ELECTROMAGNETIC WAVE PROPAGATION

1000. Source Of Radio Waves

Consider electric current as a flow of electrons along a conductor between points of differing potential. A **direct current** flows continuously in the same direction. This would occur if the polarity of the electromotive force causing the electron flow were constant, such as is the case with a battery. If, however, the current is induced by the relative motion between a conductor and a magnetic field, such as is the case in a rotating machine called a **generator**, then the resulting current changes direction in the conductor as the polarity of the electromotive force changes with the rotation of the generator's rotor. This is known as **alternating current**.

The energy of the current flowing through the conductor is either dissipated as heat (an energy loss proportional to both the current flowing through the conductor and the conductor's resistance) or stored in an electromagnetic field oriented symmetrically about the conductor. The orientation of this field is a function of the polarity of the source producing the current. When the current is removed from the wire, this electromagnetic field will, after a finite time, collapse back into the wire.

What would occur should the polarity of the current source supplying the wire be reversed at a rate which greatly exceeds the finite amount of time required for the electromagnetic field to collapse back upon the wire? In the case of rapid pole reversal, another magnetic field, proportional in strength but exactly opposite in magnetic orientation to the initial field, will be formed upon the wire. The initial magnetic field, its current source gone, cannot collapse back upon the wire because of the existence of this second, oriented electromagnetic field. Instead, it "detaches" from the wire and propagates out into space. This is the basic principle of a radio antenna, which transmits a wave at a frequency proportional to the rate of pole reversal and at a speed equal to the speed of light.

1001. Radio Wave Terminology

The magnetic field strength in the vicinity of a conductor is directly proportional to the magnitude of the current flowing through the conductor. Recall the discussion of alternating current above. A rotating generator produces current in the form of a sine wave. That is, the magnitude of the current varies as a function of the relative position of the rotating conductor and the stationary magnetic field used to

induce the current. The current starts at zero, increases to a maximum as the rotor completes one quarter of its revolution, and falls to zero when the rotor completes one half of its revolution. The current then approaches a negative maximum; then it once again returns to zero. This cycle can be represented by a sine function.

The relationship between the current and the magnetic field strength induced in the conductor through which the current is flowing is shown in Figure 1001. Recall from the discussion above that this field strength is proportional to the magnitude of the current; that is, if the current is represented by a sine wave function, then so too will be the magnetic field strength resulting from that current. This characteristic shape of the field strength curve has led to the use of the term "wave" when referring to electromagnetic propagation. The maximum displacement of a peak from zero is called the **amplitude**. The forward side of any wave is called the **wave front**. For a nondirectional antenna, each wave proceeds outward as an expanding sphere (or hemisphere).

One **cycle** is a complete sequence of values, as from crest to crest. The distance traveled by the energy during one cycle is the **wavelength**, usually expressed in metric units (meters, centimeters, etc.). The number of cycles repeated during unit time (usually 1 second) is the **frequency**. This is given in **hertz** (cycles per second). A kilohertz (kHz) is 1,000 cycles per second. A megahertz (MHz) is 1,000,000 cycles per second. Wavelength and frequency are inversely proportional.

The **phase** of a wave is the amount by which the cycle has progressed from a specified origin. For most purposes it

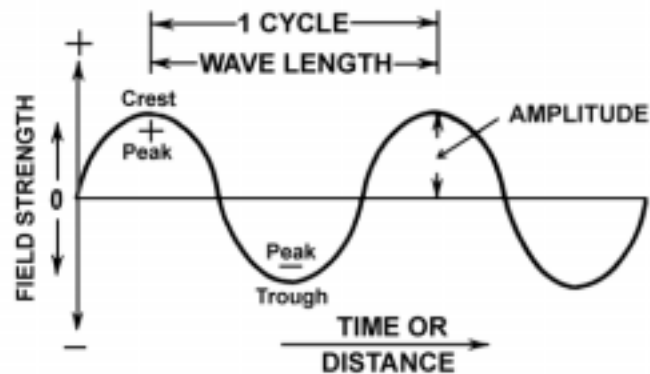


Figure 1001. Radio wave terminology.

is stated in circular measure, a complete cycle being considered 360°. Generally, the origin is not important, principal interest being the phase relative to that of some other wave. Thus, two waves having crests 1/4 cycle apart are said to be 90° “out of phase.” If the crest of one wave occurs at the trough of another, the two are 180° out of phase.

1002. Electromagnetic Spectrum

The entire range of electromagnetic radiation frequencies is called the **electromagnetic spectrum**. The frequency range suitable for radio transmission, the **radio spectrum**, extends from 10 kilohertz to 300,000 megahertz. It is divided into a number of bands, as shown in Table 1002. Below the radio spectrum, but overlapping it, is the audio frequency band, extending from 20 to 20,000 hertz. Above the radio spectrum are heat and infrared, the visible spectrum (light in its various colors), ultraviolet, X-rays, gamma rays, and cosmic rays. These are included in Table 1002. Waves shorter than 30 centimeters are usually called **microwaves**.

1003. Polarization

Radio waves produce both electric and magnetic fields. The direction of the electric component of the field is called the **polarization** of the electromagnetic field. Thus, if the electric component is vertical, the wave is said to be “vertically polarized,” and if horizontal, “horizontally polarized.” A wave traveling through space may be polarized in any direction. One traveling along the surface of the earth is always vertically polarized because the earth, a conductor, short-circuits any horizontal component. The magnetic field and the electric field are always mutually perpendicular.

1004. Reflection

When radio waves strike a surface, the surface reflects them in the same manner as light waves. Radio waves of all frequencies are reflected by the surface of the earth. The strength of the reflected wave depends upon grazing angle (the angle between the incident ray and the horizontal), type of polarization, frequency, reflecting properties of the surface, and divergence of the reflected ray. Lower frequency results in greater penetration. At very low frequencies, usable radio signals can be received some distance below the surface of the sea.

A phase change occurs when a wave is reflected from the surface of the earth. The amount of the change varies with the conductivity of the earth and the polarization of the wave, reaching a maximum of 180° for a horizontally polarized wave reflected from sea water (considered to have infinite conductivity). When direct waves (those traveling from transmitter to receiver in a relatively straight line, without reflection) and reflected waves arrive at a receiver, the total signal is the vector sum of the two. If the signals are in phase, they reinforce each other, producing a stronger signal. If there is a phase difference, the signals tend to cancel each other, the cancellation being complete if the phase difference is 180° and the two signals have the same amplitude. This interaction of waves is called **wave interference**. A phase difference may occur because of the change of phase of a reflected wave, or because of the longer path followed by it. The second effect decreases with greater distance between transmitter and receiver, for under these conditions the difference in path lengths is smaller. At lower frequencies there is no practical solution to interference caused in this way. For VHF and higher frequencies, the condition can be improved

Band	Abbreviation	Range of frequency	Range of wavelength
Audio frequency	AF	20 to 20,000 Hz	15,000,000 to 15,000 m
Radio frequency	RF	10 kHz to 300,000 MHz	30,000 m to 0.1 cm
Very low frequency	VLF	10 to 30 kHz	30,000 to 10,000 m
Low frequency	LF	30 to 300 kHz	10,000 to 1,000 m
Medium frequency	MF	300 to 3,000 kHz	1,000 to 100 m
High frequency	HF	3 to 30 MHz	100 to 10 m
Very high frequency	VHF	30 to 300 MHz	10 to 1 m
Ultra high frequency	UHF	300 to 3,000 MHz	100 to 10 cm
Super high frequency	SHF	3,000 to 30,000 MHz	10 to 1 cm
Extremely high frequency	EHF	30,000 to 300,000 MHz	1 to 0.1 cm
Heat and infrared*		10^6 to 3.9×10^8 MHz	0.03 to 7.6×10^{-5} cm
Visible spectrum*		3.9×10^8 to 7.9×10^8 MHz	7.6×10^{-5} to 3.8×10^{-5} cm
Ultraviolet*		7.9×10^8 to 2.3×10^{10} MHz	3.8×10^{-5} to 1.3×10^{-6} cm
X-rays*		2.0×10^9 to 3.0×10^{13} MHz	1.5×10^{-5} to 1.0×10^{-9} cm
Gamma rays*		2.3×10^{12} to 3.0×10^{14} MHz	1.3×10^{-8} to 1.0×10^{-10} cm
Cosmic rays*		$> 4.8 \times 10^{15}$ MHz	$< 6.2 \times 10^{-12}$ cm

* Values approximate.

Table 1002. Electromagnetic spectrum.

by elevating the antenna, if the wave is vertically polarized. Additionally, interference at higher frequencies can be more nearly eliminated because of the greater ease of beaming the signal to avoid reflection.

Reflections may also occur from mountains, trees, and other obstacles. Such reflection is negligible for lower frequencies, but becomes more prevalent as frequency increases. In radio communication, it can be reduced by using directional antennas, but this solution is not always available for navigational systems.

Various reflecting surfaces occur in the atmosphere. At high frequencies, reflections take place from rain. At still higher frequencies, reflections are possible from clouds, particularly rain clouds. Reflections may even occur at a sharply defined boundary surface between air masses, as when warm, moist air flows over cold, dry air. When such a surface is roughly parallel to the surface of the earth, radio waves may travel for greater distances than normal. The principal source of reflection in the atmosphere is the ionosphere.

1005. Refraction

Refraction of radio waves is similar to that of light waves. Thus, as a signal passes from air of one density to that of a different density, the direction of travel is altered. The principal cause of refraction in the atmosphere is the difference in temperature and pressure occurring at various heights and in different air masses.

Refraction occurs at all frequencies, but below 30 MHz the effect is small as compared with ionospheric effects, diffraction, and absorption. At higher frequencies, refraction in the lower layer of the atmosphere extends the radio horizon to a distance about 15 percent greater than the visible horizon. The effect is the same as if the radius of the earth were about one-third greater than it is and there were no refraction.

Sometimes the lower portion of the atmosphere becomes stratified. This stratification results in nonstandard temperature and moisture changes with height. If there is a marked temperature inversion or a sharp decrease in water vapor content with increased height, a horizontal radio duct may be formed. High frequency radio waves traveling horizontally within the duct are refracted to such an extent that they remain within the duct, following the curvature of the earth for phenomenal distances. This is called **super-refraction**. Maximum results are obtained when both transmitting and receiving antennas are within the duct. There is a lower limit to the frequency affected by ducts. It varies from about 200 MHz to more than 1,000 MHz.

At night, surface ducts may occur over land due to cooling of the surface. At sea, surface ducts about 50 feet thick may occur at any time in the trade wind belt. Surface ducts 100 feet or more in thickness may extend from land out to sea when warm air from the land flows over the cooler ocean surface. Elevated ducts from a few feet to more than 1,000 feet in thickness may occur at elevations of

1,000 to 5,000 feet, due to the settling of a large air mass. This is a frequent occurrence in Southern California and certain areas of the Pacific Ocean.

A bending in the horizontal plane occurs when a groundwave crosses a coast at an oblique angle. This is due to a marked difference in the conducting and reflecting properties of the land and water over which the wave travels. The effect is known as **coastal refraction** or **land effect**.

1006. The Ionosphere

Since an atom normally has an equal number of negatively charged electrons and positively charged protons, it is electrically neutral. An **ion** is an atom or group of atoms which has become electrically charged, either positively or negatively, by the loss or gain of one or more electrons.

Loss of electrons may occur in a variety of ways. In the atmosphere, ions are usually formed by collision of atoms with rapidly moving particles, or by the action of cosmic rays or ultraviolet light. In the lower portion of the atmosphere, recombination soon occurs, leaving a small percentage of ions. In thin atmosphere far above the surface of the earth, however, atoms are widely separated and a large number of ions may be present. The region of numerous positive and negative ions and unattached electrons is called the **ionosphere**. The extent of ionization depends upon the kinds of atoms present in the atmosphere, the density of the atmosphere, and the position relative to the sun (time of day and season). After sunset, ions and electrons recombine faster than they are separated, decreasing the ionization of the atmosphere.

An electron can be separated from its atom only by the application of greater energy than that holding the electron. Since the energy of the electron depends primarily upon the kind of an atom of which it is a part, and its position relative to the nucleus of that atom, different kinds of radiation may cause ionization of different substances.

In the outermost regions of the atmosphere, the density is so low that oxygen exists largely as separate atoms, rather than combining as molecules as it does nearer the surface of the earth. At great heights the energy level is low and ionization from solar radiation is intense. This is known as the **F layer**. Above this level the ionization decreases because of the lack of atoms to be ionized. Below this level it decreases because the ionizing agent of appropriate energy has already been absorbed. During daylight, two levels of maximum F ionization can be detected, the F₂ layer at about 125 statute miles above the surface of the earth, and the F₁ layer at about 90 statute miles. At night, these combine to form a single F layer.

At a height of about 60 statute miles, the solar radiation not absorbed by the F layer encounters, for the first time, large numbers of oxygen molecules. A new maximum ionization occurs, known as the **E layer**. The height of this layer is quite constant, in contrast with the fluctuating F layer. At night the E layer becomes weaker by two orders of magnitude.

Below the E layer, a weak D layer forms at a height of about 45 statute miles, where the incoming radiation encounters ozone for the first time. The D layer is the principal source of absorption of HF waves, and of reflection of LF and VLF waves during daylight.

1007. The Ionosphere And Radio Waves

When a radio wave encounters a particle having an electric charge, it causes that particle to vibrate. The vibrating particle absorbs electromagnetic energy from the radio wave and radiates it. The net effect is a change of polarization and an alteration of the path of the wave. That portion of the wave in a more highly ionized region travels faster, causing the wave front to tilt and the wave to be directed toward a region of less intense ionization.

Refer to Figure 1007a, in which a single layer of the ionosphere is considered. Ray 1 enters the ionosphere at such an angle that its path is altered, but it passes through and proceeds outward into space. As the angle with the horizontal decreases, a critical value is reached where ray 2 is bent or reflected back toward the earth. As the angle is still further decreased, such as at 3, the return to earth occurs at a greater distance from the transmitter.

A wave reaching a receiver by way of the ionosphere is called a **skywave**. This expression is also appropriately applied to a wave reflected from an air mass boundary. In common usage, however, it is generally associated with the ionosphere. The wave which travels along the surface of the earth is called a **groundwave**. At angles greater than the critical angle, no skywave signal is received. Therefore, there is a minimum distance from the transmitter at which

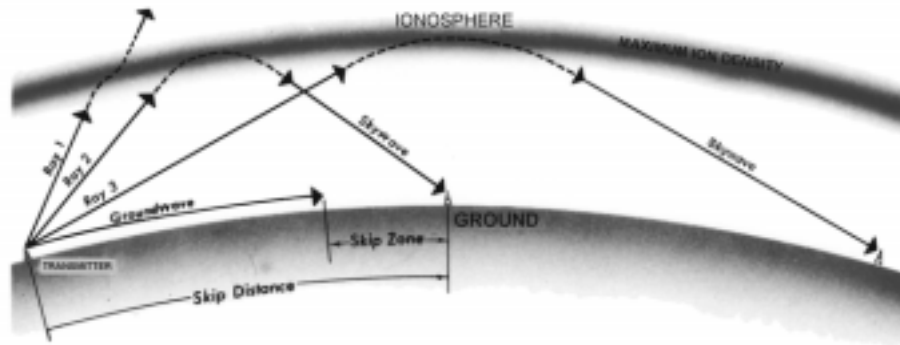


Figure 1007a. The effect of the ionosphere on radio waves.

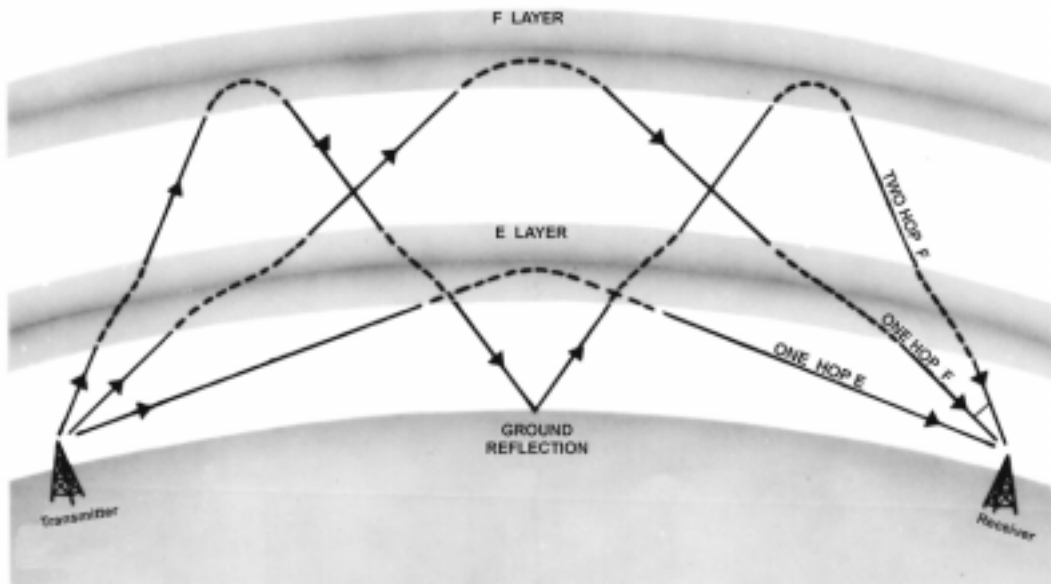


Figure 1007b. Various paths by which a skywave signal might be received.

skywaves can be received. This is called the **skip distance**, shown in Figure 1007a. If the groundwave extends out for less distance than the skip distance, a skip zone occurs, in which no signal is received.

The critical radiation angle depends upon the intensity of ionization, and the frequency of the radio wave. As the frequency increases, the angle becomes smaller. At frequencies greater than about 30 MHz virtually all of the energy penetrates through or is absorbed by the ionosphere. Therefore, at any given receiver there is a maximum usable frequency if skywaves are to be utilized. The strongest signals are received at or slightly below this frequency. There is also a lower practical frequency beyond which signals are too weak to be of value. Within this band the optimum frequency can be selected to give best results. It cannot be too near the maximum usable frequency because this frequency fluctuates with changes of intensity within the ionosphere. During magnetic storms the ionosphere density decreases. The maximum usable frequency decreases, and the lower usable frequency increases. The band of usable frequencies is thus narrowed. Under extreme conditions it may be completely eliminated, isolating the receiver and causing a radio blackout.

Skywave signals reaching a given receiver may arrive by any of several paths, as shown in Figure 1007b. A signal which undergoes a single reflection is called a "one-hop" signal, one which undergoes two reflections with a ground reflection between is called a "two-hop" signal, etc. A "multihop" signal undergoes several reflections. The layer at which the reflection occurs is usually indicated, also, as "one-hop E," "two-hop F," etc.

Because of the different paths and phase changes occurring at each reflection, the various signals arriving at a receiver have different phase relationships. Since the density of the ionosphere is continually fluctuating, the strength and phase relationships of the various signals may undergo an almost continuous change. Thus, the various signals may reinforce each other at one moment and cancel each other at the next, resulting in fluctuations of the strength of the total signal received. This is called **fading**. This phenomenon may also be caused by interaction of components within a single reflected wave, or changes in its strength due to changes in the reflecting surface. Ionospheric changes are associated with fluctuations in the radiation received from the sun, since this is the principal cause of ionization. Signals from the F layer are particularly erratic because of the rapidly fluctuating conditions within the layer itself.

The maximum distance at which a one-hop E signal can be received is about 1,400 miles. At this distance the signal leaves the transmitter in approximately a horizontal direction. A one-hop F signal can be received out to about 2,500 miles. At low frequencies groundwaves extend out for great distances.

A skywave may undergo a change of polarization during reflection from the ionosphere, accompanied by an alteration in the direction of travel of the wave. This is called **polarization error**. Near sunrise and sunset, when rapid changes are occurring in the ionosphere, reception may become erratic and

polarization error a maximum. This is called **night effect**.

1008. Diffraction

When a radio wave encounters an obstacle, its energy is reflected or absorbed, causing a shadow beyond the obstacle. However, some energy does enter the shadow area because of diffraction. This is explained by Huygens' principle, which states that every point on the surface of a wave front is a source of radiation, transmitting energy in all directions ahead of the wave. No noticeable effect of this principle is observed until the wave front encounters an obstacle, which intercepts a portion of the wave. From the edge of the obstacle, energy is radiated into the shadow area, and also outside of the area. The latter interacts with energy from other parts of the wave front, producing alternate bands in which the secondary radiation reinforces or tends to cancel the energy of the primary radiation. Thus, the practical effect of an obstacle is a greatly reduced signal strength in the shadow area, and a disturbed pattern for a short distance outside the shadow area. This is illustrated in Figure 1008.

The amount of diffraction is inversely proportional to the frequency, being greatest at very low frequencies.

1009. Absorption And Scattering

The amplitude of a radio wave expanding outward through space varies inversely with distance, weakening with increased distance. The decrease of strength with distance is called **attenuation**. Under certain conditions the attenuation is greater than in free space.

A wave traveling along the surface of the earth loses a certain amount of energy to the earth. The wave is diffracted downward and absorbed by the earth. As a result of this absorption, the remainder of the wave front tilts downward, resulting in further absorption by the earth. Attenuation is greater over a surface which is a poor conductor. Relatively little absorption occurs over sea water, which is an excellent conductor at low frequencies, and low frequency groundwaves travel great distances over water.

A skywave suffers an attenuation loss in its encounter with the ionosphere. The amount depends upon the height and composition of the ionosphere as well as the frequency of the radio wave. Maximum ionospheric absorption occurs at about 1,400 kHz.

In general, atmospheric absorption increases with frequency. It is a problem only in the SHF and EHF frequency range. At these frequencies, attenuation is further increased by scattering due to reflection by oxygen, water vapor, water droplets, and rain in the atmosphere.

1010. Noise

Unwanted signals in a receiver are called **interference**. The intentional production of such interference to obstruct communication is called **jamming**. Unintentional interfer-

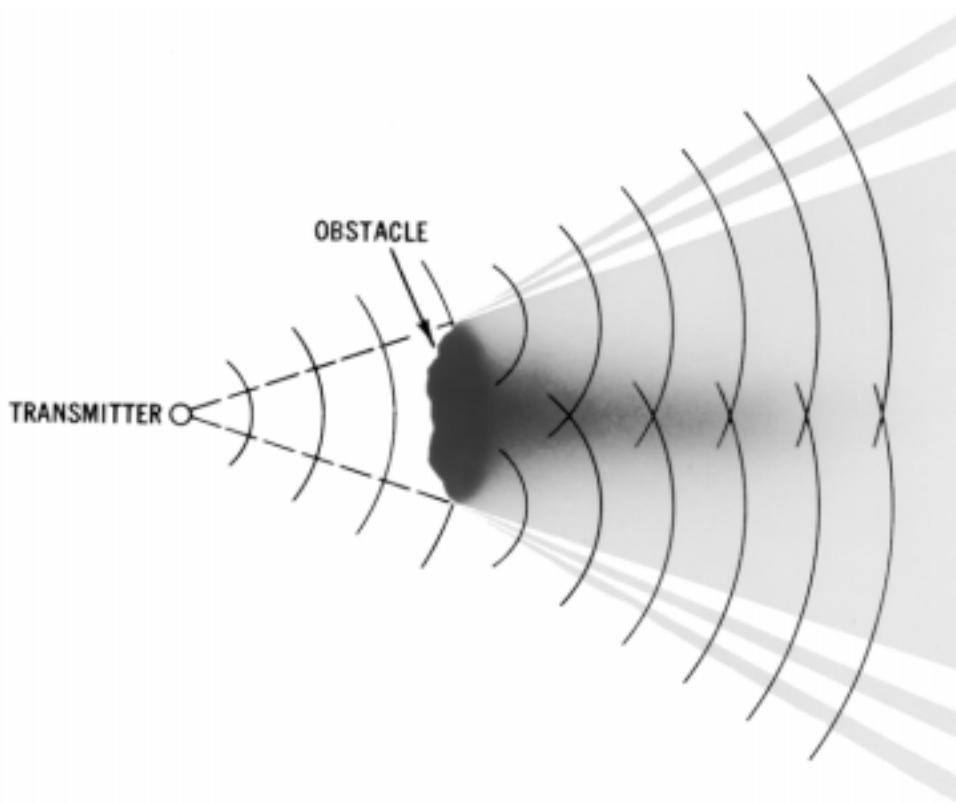


Figure 1008. Diffraction.

ence is called **noise**.

Noise may originate within the receiver. Hum is usually the result of induction from neighboring circuits carrying alternating current. Irregular crackling or sizzling sounds may be caused by poor contacts or faulty components within the receiver. Stray currents in normal components causes some noise. This source sets the ultimate limit of sensitivity that can be achieved in a receiver. It is the same at any frequency.

Noise originating outside the receiver may be either man-made or natural. Man-made noises originate in electrical appliances, motor and generator brushes, ignition systems, and other sources of sparks which transmit electromagnetic signals that are picked up by the receiving antenna.

Natural noise is caused principally by discharge of static electricity in the atmosphere. This is called **atmospheric noise**, **atmospherics**, or **static**. An extreme example is a thunderstorm. An exposed surface may acquire a considerable charge of static electricity. This may be caused by friction of water or solid particles blown against or along such a surface. It may also be caused by splitting of a water droplet which strikes the surface, one part of the droplet requiring a positive charge and the other a negative charge. These charges may be transferred to the surface. The charge tends to gather at points and ridges of the conducting surface, and when it accumulates to a sufficient extent to overcome the insulating properties of the atmosphere, it

discharges into the atmosphere. Under suitable conditions this becomes visible and is known as St. Elmo's fire, which is sometimes seen at mastheads, the ends of yardarms, etc.

Atmospheric noise occurs to some extent at all frequencies but decreases with higher frequencies. Above about 30 MHz it is not generally a problem.

1011. Antenna Characteristics

Antenna design and orientation have a marked effect upon radio wave propagation. For a single-wire antenna, strongest signals are transmitted along the perpendicular to the wire, and virtually no signal in the direction of the wire. For a vertical antenna, the signal strength is the same in all horizontal directions. Unless the polarization undergoes a change during transit, the strongest signal received from a vertical transmitting antenna occurs when the receiving antenna is also vertical.

For lower frequencies the radiation of a radio signal takes place by interaction between the antenna and the ground. For a vertical antenna, efficiency increases with greater length of the antenna. For a horizontal antenna, efficiency increases with greater distance between antenna and ground. Near-maximum efficiency is attained when this distance is one-half wavelength. This is the reason for elevating low frequency antennas to great heights. However, at the lowest frequencies, the required height becomes

prohibitively great. At 10 kHz it would be about 8 nautical miles for a half-wavelength antenna. Therefore, lower frequency antennas are inherently inefficient. This is partly offset by the greater range of a low frequency signal of the same transmitted power as one of higher frequency.

At higher frequencies, the ground is not used, both conducting portions being included in a dipole antenna. Not only can such an antenna be made efficient, but it can also be made sharply directive, thus greatly increasing the strength of the signal transmitted in a desired direction.

The power received is inversely proportional to the square of the distance from the transmitter, assuming there is no attenuation due to absorption or scattering.

1012. Range

The range at which a usable signal is received depends upon the power transmitted, the sensitivity of the receiver, frequency, route of travel, noise level, and perhaps other factors. For the same transmitted power, both the ground-wave and skywave ranges are greatest at the lowest frequencies, but this is somewhat offset by the lesser efficiency of antennas for these frequencies. At higher frequencies, only direct waves are useful, and the effective range is greatly reduced. Attenuation, skip distance, ground reflection, wave interference, condition of the ionosphere, atmospheric noise level, and antenna design all affect the distance at which useful signals can be received.

1013. Radio Wave Propagation

Frequency is an important consideration in radio wave propagation. The following summary indicates the principal effects associated with the various frequency bands, starting with the lowest and progressing to the highest usable radio frequency.

Very Low Frequency (VLF, 10 to 30 kHz): The VLF signals propagate between the bounds of the ionosphere and the earth and are thus guided around the curvature of the earth to great distances with low attenuation and excellent stability. Diffraction is maximum. Because of the long wavelength, large antennas are needed, and even these are inefficient, permitting radiation of relatively small amounts of power. Magnetic storms have little effect upon transmission because of the efficiency of the "earth-ionosphere waveguide." During such storms, VLF signals may constitute the only source of radio communication over great distances. However, interference from atmospheric noise may be troublesome. Signals may be received from below the surface of the sea.

Low Frequency (LF, 30 to 300 kHz): As frequency is increased to the LF band and diffraction decreases, there is greater attenuation with distance, and range for a given power output falls off rapidly. However, this is partly offset by more efficient transmitting antennas. LF signals are most stable within groundwave distance of the transmitter. A wider bandwidth permits pulsed signals at 100 kHz. This allows

separation of the stable groundwave pulse from the variable skywave pulse up to 1,500 km, and up to 2,000 km for over-water paths. The frequency for Loran C is in the LF band. This band is also useful for radio direction finding and time dissemination.

Medium Frequency (MF, 300 to 3,000 kHz): Groundwaves provide dependable service, but the range for a given power is reduced greatly. This range varies from about 400 miles at the lower portion of the band to about 15 miles at the upper end for a transmitted signal of 1 kilowatt. These values are influenced, however, by the power of the transmitter, the directivity and efficiency of the antenna, and the nature of the terrain over which signals travel. Elevating the antenna to obtain direct waves may improve the transmission. At the lower frequencies of the band, skywaves are available both day and night. As the frequency is increased, ionospheric absorption increases to a maximum at about 1,400 kHz. At higher frequencies the absorption decreases, permitting increased use of skywaves. Since the ionosphere changes with the hour, season, and sunspot cycle, the reliability of skywave signals is variable. By careful selection of frequency, ranges of as much as 8,000 miles with 1 kilowatt of transmitted power are possible, using multihop signals. However, the frequency selection is critical. If it is too high, the signals penetrate the ionosphere and are lost in space. If it is too low, signals are too weak. In general, skywave reception is equally good by day or night, but lower frequencies are needed at night. The standard broadcast band for commercial stations (535 to 1,605 kHz) is in the MF band.

High Frequency (HF, 3 to 30 MHz): As with higher medium frequencies, the groundwave range of HF signals is limited to a few miles, but the elevation of the antenna may increase the direct-wave distance of transmission. Also, the height of the antenna does have an important effect upon skywave transmission because the antenna has an "image" within the conducting earth. The distance between antenna and image is related to the height of the antenna, and this distance is as critical as the distance between elements of an antenna system. Maximum usable frequencies fall generally within the HF band. By day this may be 10 to 30 MHz, but during the night it may drop to 8 to 10 MHz. The HF band is widely used for ship-to-ship and ship-to-shore communication.

Very High Frequency (VHF, 30 to 300 MHz): Communication is limited primarily to the direct wave, or the direct wave plus a ground-reflected wave. Elevating the antenna to increase the distance at which direct waves can be used results in increased distance of reception, even though some wave interference between direct and ground-reflected waves is present. Diffraction is much less than with lower frequencies, but it is most evident when signals cross sharp mountain peaks or ridges. Under suitable conditions, reflections from the ionosphere are sufficiently strong to be useful, but generally they are unavailable. There is relatively little interference from atmospheric noise in this band. Reasonably efficient directional antennas are possible with

VHF. The VHF band is much used for communication.

Ultra High Frequency (UHF, 300 to 3,000 MHz): Skywaves are not used in the UHF band because the ionosphere is not sufficiently dense to reflect the waves, which pass through it into space. Groundwaves and ground-reflected waves are used, although there is some wave interference. Diffraction is negligible, but the radio horizon extends about 15 percent beyond the visible horizon, due principally to refraction. Reception of UHF signals is virtually free from fading and interference by atmospheric noise. Sharply directive antennas can be produced for transmission in this band, which is widely used for ship-to-ship and ship-to-shore communication.

Super High Frequency (SHF, 3,000 to 30,000 MHz): In the SHF band, also known as the microwave or as the centimeter wave band, there are no skywaves, transmission being entirely by direct and ground-reflected waves. Diffraction and interference by atmospheric noise are virtually nonexistent. Highly efficient, sharply directive antennas can be produced. Thus, transmission in this band is similar to that of UHF, but with the effects of shorter waves being greater. Reflection by clouds, water droplets, dust particles, etc., increases, causing greater scattering, increased wave interference, and fading. The SHF band is used for marine navigational radar.

Extremely High Frequency (EHF, 30,000 to 300,000 MHz): The effects of shorter waves are more pronounced in the EHF band, transmission being free from wave interference, diffraction, fading, and interference by atmospheric noise. Only direct and ground-reflected waves are available. Scattering and absorption in the atmosphere are pronounced and may produce an upper limit to the frequency useful in radio communication.

1014. Regulation Of Frequency Use

While the characteristics of various frequencies are important to the selection of the most suitable one for any given purpose, these are not the only considerations. Confusion and extensive interference would result if every user had complete freedom of selection. Some form of regulation is needed. The allocation of various frequency bands to particular uses is a matter of international agreement. Within the United States, the Federal Communications Commission has responsibility for authorizing use of particular frequencies. In some cases a given frequency is allocated to several widely separated transmitters, but only under conditions which minimize interference, such as during daylight hours. Interference between stations is further reduced by the use of channels, each of a narrow band of frequencies. Assigned frequencies are separated by an arbitrary band of frequencies that are not authorized for use. In the case of radio aids to navigation and ship communications bands of several channels are allocated, permitting selection of band and channel by the user.

1015. Types Of Radio Transmission

A series of waves transmitted at constant frequency and amplitude is called a continuous wave (CW). This cannot be heard except at the very lowest radio frequencies, when it may produce, in a receiver, an audible hum of high pitch.

Although a continuous wave may be used directly, as in radiodirection finding or Decca, it is more commonly modified in some manner. This is called **modulation**. When this occurs, the continuous wave serves as a carrier wave for information. Any of several types of modulation may be used.

In **amplitude modulation (AM)** the amplitude of the carrier wave is altered in accordance with the amplitude of a modulating wave, usually of audio frequency, as shown in Figure 1015a. In the receiver the signal is demodulated by removing the modulating wave and converting it back to its original form. This form of modulation is widely used in voice radio, as in the standard broadcast band of commercial broadcasting.

If the frequency instead of the amplitude is altered in accordance with the amplitude of the impressed signal, as shown in Figure 1015a, **frequency modulation (FM)** occurs. This is used for commercial FM radio broadcasts and the sound portion of television broadcasts.

Pulse modulation (PM) is somewhat different, there being no impressed modulating wave. In this form of transmission, very short bursts of carrier wave are transmitted, separated by relatively long periods of "silence," during which there is no transmission. This type of transmission, illustrated in Figure 1015b, is used in some common radio navigational aids, including radar and Lorán-C.

1016. Transmitters

A radio transmitter consists essentially of (1) a power supply to furnish direct current, (2) an oscillator to convert direct current into radio-frequency oscillations (the carrier wave), (3) a device to control the generated signal, and (4) an amplifier to increase the output of the oscillator. For some transmitters a microphone is needed with a modulator and final amplifier to modulate the carrier wave. In addition, an antenna and ground (for lower frequencies) are needed to produce electromagnetic radiation. These components are illustrated diagrammatically in Figure 1016.

1017. Receivers

When a radio wave passes a conductor, a current is induced in that conductor. A radio receiver is a device which senses the power thus generated in an antenna, and transforms it into usable form. It is able to select signals of a single frequency (actually a narrow band of frequencies) from among the many which may reach the receiving antenna. The receiver is able to demodulate the signal and provide adequate amplification. The output of a receiver

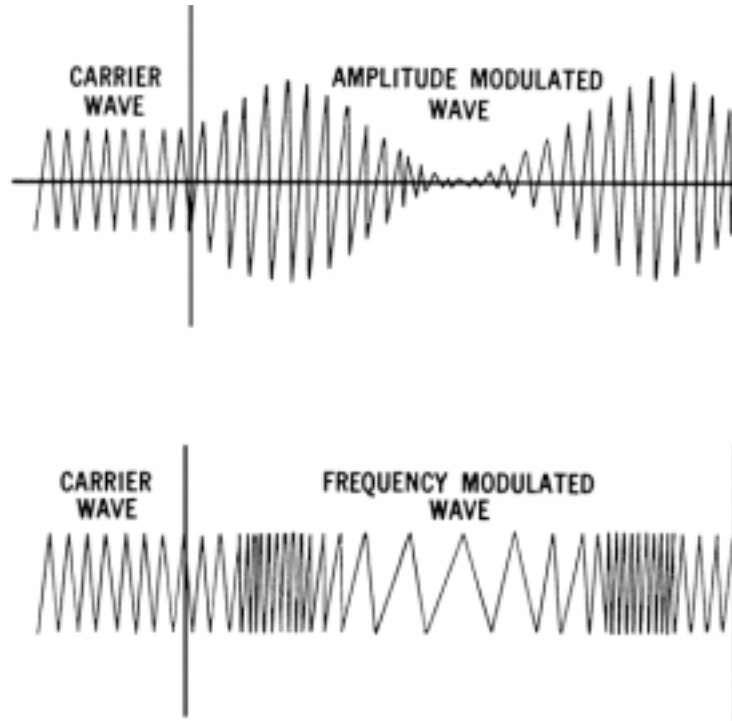


Figure 1015a. Amplitude modulation (upper figure) and frequency modulation (lower figure) by the same modulating wave.



Figure 1015b. Pulse modulation.

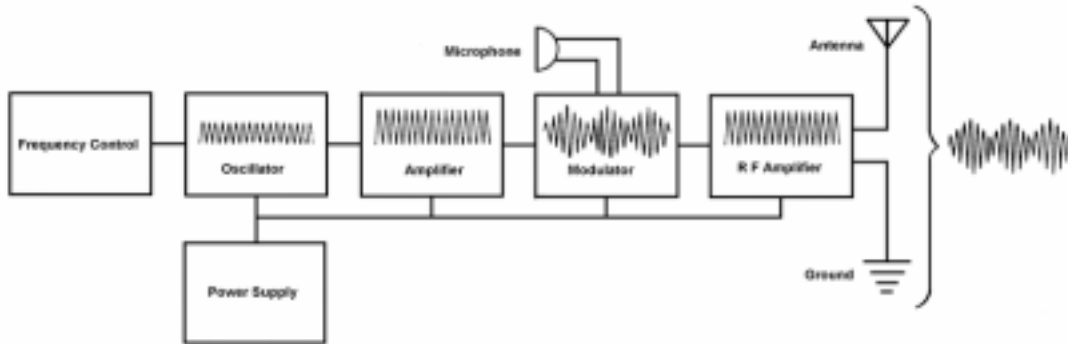


Figure 1016. Components of a radio transmitter.

may be presented audibly by earphones or loudspeaker; or visually on a dial, cathode-ray tube, counter, or other display. Thus, the useful reception of radio signals requires three components: (1) an antenna, (2) a receiver, and (3) a display unit.

Radio receivers differ mainly in (1) frequency range, the range of frequencies to which they can be tuned; (2) selectivity, the ability to confine reception to signals of the desired frequency and avoid others of nearly the same fre-

quency; (3) sensitivity, the ability to amplify a weak signal to usable strength against a background of noise; (4) stability, the ability to resist drift from conditions or values to which set; and (5) fidelity, the completeness with which the essential characteristics of the original signal are reproduced. Receivers may have additional features such as an automatic frequency control, automatic noise limiter, etc.

Some of these characteristics are interrelated. For instance, if a receiver lacks selectivity, signals of a frequency

differing slightly from those to which the receiver is tuned may be received. This condition is called spillover, and the resulting interference is called crosstalk. If the selectivity is increased sufficiently to prevent spillover, it may not permit receipt of a great enough band of frequencies to obtain the

full range of those of the desired signal. Thus, the fidelity may be reduced.

A transponder is a transmitter-receiver capable of accepting the challenge of an interrogator and automatically transmitting an appropriate reply.

U.S. RADIONAVIGATION POLICY

1018. The Federal Radionavigation Plan

The Federal Radionavigation Plan (FRP) is produced by the U.S. Departments of Defense and Transportation. It establishes government policy on electronic navigation systems, ensuring consideration of national interests and efficient use of resources. It presents an integrated Federal plan for all common-use civilian and military Radionavigation systems, outlines approaches for consolidation of systems, provides information and schedules, defines and clarifies new or unresolved issues, and provides a focal point for user input. The FRP is a review of existing and planned radionavigation systems used in air, space, land, and marine navigation. It is available from the National Technical Information Service, Springfield, Virginia, 22161.

The first edition of the FRP was released in 1980 as part of a Presidential report to Congress. It marked the first time that a joint Department of Transportation/Department of Defense plan had been developed for systems used by both departments. The FRP has had international impact on navigation systems; it has been distributed to the International Maritime Organization (IMO), the International Civil Aviation Organization (ICAO), the International Association of Lighthouse Authorities (IALA), and other international organizations.

During a national emergency, any or all of the systems may be discontinued due to a decision by the National Command Authority (NCA). The NCA's policy is to continue to operate radionavigation systems as long as the U.S. and its allies derive greater benefit than adversaries. Operating agencies may shut down systems or change signal formats and characteristics during such an emergency.

The plan is reviewed continually and updated biennially. Industry, advisory groups, and other interested parties provide input. The plan considers governmental responsibilities for national security, public safety, and transportation system economy. It is the official source of radionavigation systems policy and planning for the United States. Systems covered by the FRP include, Radiobeacons, Omega, TACAN, MLS, GPS, Loran C, VOR/VOR-DME/VORTAC, ILS, and Transit.

1019. Individual System Plans

In order to meet both civilian and military needs, the federal government has established a number of different

navigation systems. Each system utilized the latest technology available at the time of implementation and has been upgraded as technology and resources permitted. The FRP addresses the length of time each system should be part of the system mix. The 1992 FRP sets forth the following system policy guidelines:

RADIOBEACONS: Both maritime and aeronautical radiobeacons provide the civilian community with a low-cost, medium accuracy navigation system. They will remain part of the radionavigation mix at least until the year 2000. Those radiobeacons suitable for supporting Differential GPS (DGPS) will remain well into the next century. Many of the remaining maritime radiobeacons may be discontinued after the year 2000.

LORAN C: Loran C provides navigation, location, and timing services for both civil and military air, land, and sea users. It is the federally provided navigation system for the maritime Coastal Confluence Zone; it is also a supplemental air navigation system. The Loran C system serving the continental U.S., Alaska, and coastal areas with the exception of Hawaii, is expected to remain in place through the year 2015. Military requirements for Loran C ended in 1994, and U.S.-maintained stations overseas and in Hawaii will be phased out. Discussions between the U.S. and foreign governments may result in continuation of certain overseas stations after termination of the military requirements.

OMEGA: Omega serves civilian and military maritime and air navigation. The military requirement for Omega ended in 1994; the system may be maintained for civil users at least until the year 2005. Replacement of equipment at some stations may result in disruption or reduction of service in some areas. Also, the Omega system relies on support from several foreign nations whose cooperation may not be forthcoming.

TRANSIT: The Transit satellite system will end operations in December 1996.

GPS: The Global Positioning System, or GPS, will be the military's primary radionavigation system well into the next century. It is operated by the U.S. Air Force, and it will provide two basic levels of positioning service.

Standard Positioning Service (SPS) is a positioning and

timing service which will provide horizontal positioning accuracies of 100 meters (2 drms, 95% probability) and 300 meters (99.99% probability). **Precise Positioning Service (PPS)** will provide extremely accurate positioning to only military users.

DIFFERENTIAL GPS: DGPS services are planned by several DOT agencies to enhance civilian navigation without reliance on the PPS. The Coast Guard operates marine DGPS in U.S. coastal waters. DGPS is a system in which differences between observed and calculated GPS signals are broadcast to users using marine radiobeacons. The Coast Guard is implementing DGPS service in all U.S. coastal waters, beginning with important ports and harbors, to include Hawaii and the Great Lakes. It will provide 4-20 meter continuous accuracy.

A Memorandum of Agreement between DOD and DOT for radionavigation planning became effective in 1979. It was updated in 1984 and again in 1990. This agreement recognizes the joint responsibility of both agencies to provide cost-effective navigation systems for both military and civilian users, and requires the cooperation of both agencies in navigation systems planning.

Many factors influence the choice of navigation systems, which must satisfy an extremely diverse group of users. International agreements must be honored. The current investment in existing systems by both government and users

must be considered. The full life-cycle cost of each system must be considered. No system will be phased out without consideration of all these factors. The FRP recognizes that GPS may not meet the needs of all users; therefore, some systems are currently being evaluated independently of GPS. When GPS is fully implemented and evaluated, a further review will determine which systems to retain and which to phase out. The goal is to meet all military and civilian requirements with the minimum number of systems.

The Departments of Defense and Transportation continually evaluate the components which make up the federally provided and maintained radionavigation system. Several factors influence the decision on the proper mix of systems; cost, military utility, accuracy requirements, and user requirements all drive the problem of allocating scarce resources to develop and maintain marine navigation systems. The lowering cost and increasing accuracy of the Global Positioning System increase its attractiveness as the primary navigation method of the future for both military and civilian use. However, the popularity of GPS with navigation planners masks the fact that it is still much more expensive to the user than other radionavigation systems such as loran and omega, and many civilian mariners may balk at the cost of conversion. Planners' uncertainties over the future of the older navigation systems, especially in a time of shrinking resources, will contribute to the uncertainty which will mark the next five years in radionavigation planning and development.

RADIO DIRECTION FINDING

1020. Introduction

Medium frequency radio direction finders on board vessels enable measurement of the bearings of marine radiobeacons, aeronautical radiobeacons, and some commercial radio stations. This is the simplest use of radio waves in navigation.

Depending upon the design of the radio direction finder (RDF), the bearings of the radio transmissions are measured as relative bearings, or as both relative and true bearings. In one design, the true bearing dial is manually set with respect to the relative bearing dial, in accordance with the ship's heading. In another design, the true bearing dial is rotated electrically in accordance with a course input from the gyrocompass.

Radiobeacons established primarily for mariners are known as **marine radiobeacons**; beacons established primarily for airmen are known as **aeronautical radiobeacons**; other beacons established for both classes of user are sometimes known as **aeromarine radiobeacons**. The most common type of marine radiobeacon transmits radio waves of approximately uniform strength in all directions. These omnidirectional beacons are known as **circular radiobeacons**.

Except for calibration, radiobeacons operate continuously, regardless of weather conditions.

Simple combinations of dots and dashes are used for station identification. Where applicable, the Morse equivalent character or characters are shown in conjunction with the station characteristic. All radiobeacons superimpose the characteristic on a carrier wave which is on continuously during the period of transmission. This extends the usefulness of marine radiobeacons to an airborne or marine user of an automatic radio direction finder (ADF). Users of the "aural null" type radio direction finder notice no change. A 10-second dash is incorporated in the characteristic signal to enable the user of the aural null type of radio direction finder to refine the bearing.

Aeronautical radiobeacons are sometimes used by marine navigators for determining lines of position when marine radiobeacons are not available. Since it is not possible to predict the extent to which land effect may render the bearings of these beacons unreliable, they are not included in *Pub. 117, Radio Navigational Aids* unless they are within the marine frequency band and they are close enough to the coast to have negligible land effect. Their inclusion in *Pub. 117* does not imply that the beacons have been found reliable for marine use.

1021. Using Radio Direction Finders

Direction bearing measurement at the receiver is accomplished with a directional antenna. Nearly all antennas have some directional properties, but in the usual antenna used for radio communication, these properties are not sufficiently critical for navigational use.

Simple small craft RDF units usually have a ferrite rod antenna mounted directly on a receiver, with a 360° graduated scale. The rod can be rotated to the null and a reading taken off the scale, which is preset to either the boat's course or true north, according to the navigator's wishes. Some small craft RDFs have a portable hand-held combination ferrite rod and compass, with earphones to hear the null.

Two types of loop antenna are used in larger radio direction finders. In one of these, the crossed loop type, two loops are rigidly mounted in such manner that one is placed at 90° to the other. The relative output of the two antennas is related to the orientation of each with respect to the direction of travel of the radio wave, and is measured by a device called a goniometer. This is the type antenna used in an automatic direction finder. In the other variation, the rotating loop type, a single loop is kept in rapid rotation by means of a motor. The antenna output is shown on a cathode-ray tube, and the resulting display shows the direction of the signal.

1022. Errors of Radio Bearings

Bearings obtained by radio direction finder are subject to certain errors:

Quadrantal error: When radio waves arrive at a receiver, they are influenced somewhat by the immediate environment. An erroneous bearing results from currents induced in the direction finder antenna by re-radiation from the structural features of the vessel's superstructure and distortion of the radio wave front due to the physical dimensions and contour of the vessel's hull. This quadrantal error is a function of the relative bearing, normally being maximum for bearings broad on the bow and broad on the quarter. Its value for various bearings can be determined, and a calibration table made.

Coastal refraction: A radio wave crossing a coastline at an oblique angle undergoes a change of direction due to differences in conducting and reflecting properties of land and water. This is sometimes called **land effect**. It is avoided by not using, or regarding as of doubtful accuracy, bearings of waves which cross a shoreline at an oblique angle. Bearings making an angle of less than 15° to 20° with a shoreline should not be trusted. If the transmitter is near the coast, negligible error is introduced because of the short distance the waves travel before undergoing refraction.

Polarization error: The direction of travel of radio waves may undergo an alteration during the confused period near sunrise or sunset, when great changes are taking place in the ionosphere. This error is sometimes called night

effect. The error can be minimized by averaging several readings, but any radio bearings taken during this period should be considered of doubtful accuracy.

Reciprocal bearings: Unless a radio direction finder has a vertical sensing wire, there is a possible 180° ambiguity in the reading. If such an error is discovered, one should take the reciprocal of the uncorrected reading, and apply the correction for the new direction. If there is doubt as to which of the two possible directions is the correct one, one should wait long enough for the bearing to change appreciably and take another reading. The transmitter should draw aft between readings. If the reciprocal is used, the station will appear to have drawn forward. A reciprocal bearing furnished by a direction finder station should not be used because the quadrantal error is not known, either on the given bearing or its reciprocal.

1023. Accuracy Of Radio Bearings

In general, good radio bearings should not be in error by more than 2° for distances under 150 nautical miles. However, conditions vary considerably, and skill is an important factor. By observing the technical instructions for the equipment and practicing frequently when results can be checked by visual observation or by other means, one can develop skill and learn to what extent radio bearings can be relied upon under various conditions.

Other factors affecting accuracy include range, the condition of the equipment, and the accuracy of the calibration. Errors in bearing can result if the selectivity of a radio direction finder is poor.

1024. Factors Affecting Maximum Range

The service range of a radiobeacon is determined by the strength of the radiated signal. Field strength requirements for a given service range vary with latitude, being higher in the southern latitudes. The actual useful range may vary considerably from the service range with different types of radio direction finders and during varying atmospheric conditions.

Sensitivity is a measure of the ability of a receiver to detect transmissions. The sensitivity of a radio direction finder determines the degree to which the full range capability of the radiobeacon system can be utilized.

Selectivity is a measure of the ability of a receiver to choose one frequency and reject all others. Selectivity varies with the type of receiver and its condition.

1025. Using RDF Bearings

Due to the many factors which enter into the transmission and reception of radio signals, a mariner cannot practically estimate his distance from a radiobeacon either by the strength of the signals received or by the time at which the signals were first heard.

By setting the ship's head toward the null, the navigator can steer toward the transmitter, and this is the most

common use of RDFs today. In reduced visibility it is unwise to head directly toward the station unless there is certain sea room. Soundings should be watched carefully when homing, and a good lookout should be kept.

Alternatively, bearings can be taken on two or more stations and the lines plotted to determine a fix. A single RDF bearing can, of course, be crossed with any other LOP. An RDF bearing crossed with a sounding curve can give a rough position in the absence of any other systems. For emergency use, an ordinary transistor radio tuned to a commercial station can provide a rough bearing if the location of the transmitter is known.

Before taking bearings on a commercial broadcasting station, the mariner should consider the following, all of which lead to errors:

1. The frequency of the commercial station may differ widely from the frequency for which the radio di-

rection finder is calibrated.

2. The antenna may be remote from the broadcast station.
3. The commercial stations are usually inland.

Accordingly, the use of commercial broadcasting stations to obtain a direction finder bearing is not recommended for accurate navigation. If these stations are used, the mariner should recognize the limitations of the bearings obtained.

1026. Radio Direction Finder Stations

Radio direction finder stations are equipped with special apparatus to determine the direction of radio signals transmitted by ships. Many are for use only in emergencies, and none are now located in the U.S. See *Pub. 117, Radio Navigational Aids*, for a current worldwide list of RDF stations.

