

CHAPTER 21

RADIO WAVES

ELECTROMAGNETIC WAVE PROPAGATION

2100. Source of Radio Waves

Consider electric current as a flow of electrons through a conductor between points of differing potential/voltage/electric field. A **direct current** flows continuously in one direction. This occurs when the polarity of the electromotive force (EMF, or voltage) causing the electron flow is 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, as is the case in a rotating machine (**motor/generator**) or an **electrical oscillator**, signal generator, or **radio transmitter**, then the resulting current changes direction in the conductor as the polarity of the electromotive force changes with a period (or frequency) that ranges from fractions of a hertz (cycles per second) to hundreds of billions of hertz (i.e., gigahertz). This is known as **alternating current**.

The energy contained in the current flowing through the conductor due to a gradient of voltage 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 conductor, this electromagnetic field will, after a finite time associated with the speed of light, collapse back into the conductor.

What would occur should the polarity of the current source supplying the wire be reversed at a rate which exceeds the finite amount of time required for the electromagnetic field to collapse back upon the wire? In this case, another magnetic field, proportional in strength but exactly opposite in magnetic orientation to the initial field, sometimes referred to as a "back EMF," particularly when associated with an inductor or coil, will be formed upon the wire. This time-varying behavior of the combined electric and magnetic fields creates an electromagnetic wave that propagates, according to Maxwell's famous equations, into space. This is the basic principle of a radio antenna, which transmits a wave at a frequency proportional to the rate of current reversal and at a speed equal, in vacuum, to the speed of light. In materials, such as the dielectrics associated with coaxial cables, the waves travel at a velocity that can be considerably slower than the speed of light in vacuum.

2101. 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 sinusoidal function of time. Note that the electromagnetic waves described above can be represented as sinusoidal functions of both time and position.

The relationship between the current and the magnetic field strength induced in the conductor through which the current is flowing is shown in Figure 2101. 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

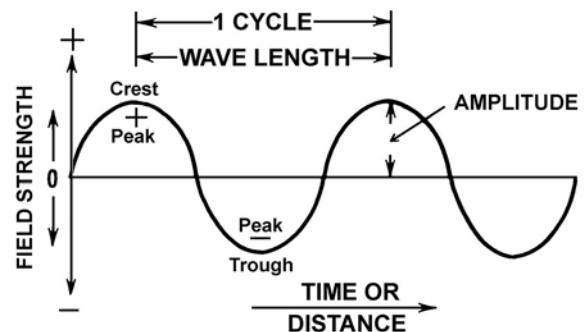


Figure 2101. Radio wave terminology.

is called the **wave front**. For a non-directional 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 of time or position. For most purposes it is stated in radians or degrees, a complete cycle being considered 360°. Generally, the origin is not important, with the 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,” often being referred to as being in “phase quadrature”. If the crest

of one wave occurs at the trough of another, the two are 180° out of phase, and are of “opposite polarity.”

2102. The 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 kHz to 300,000 MHz, or 300 GHz. It is divided into a number of bands, as shown in Table 2102.

Below the radio spectrum, but overlapping it, is the audio frequency band, extending from 20 to 20,000 Hz. Above the radio spectrum are infrared (often associated with heat), the visible spectrum (light in its various colors), ultraviolet, X-rays, gamma rays, and cosmic rays. These are included in Table 2102. Waves shorter than 30 centimeters are usually called **microwaves**.

Within the frequencies from 1 to 40 GHz (1,000 to 40,000 MHz), additional bands are defined as follows:

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 $3.9 \cdot 10^8$ MHz*	0.03 to $7.6 \cdot 10^{-5}$ cm*
Visible spectrum		$3.9 \cdot 10^8$ to $7.9 \cdot 10^8$ MHz*	$7.6 \cdot 10^{-5}$ to $3.8 \cdot 10^{-5}$ cm*
Ultraviolet		$7.9 \cdot 10^8$ to $2.3 \cdot 10^{10}$ MHz*	$3.8 \cdot 10^{-5}$ to $1.3 \cdot 10^{-6}$ cm*
X-rays		$2.0 \cdot 10^9$ to $3.0 \cdot 10^{13}$ MHz*	$1.5 \cdot 10^{-5}$ to $1.0 \cdot 10^{-9}$ cm*
Gamma rays		$2.3 \cdot 10^{12}$ to $3.0 \cdot 10^{14}$ MHz*	$1.3 \cdot 10^{-8}$ to $1.0 \cdot 10^{-10}$ cm*
Cosmic rays		$>4.8 \cdot 10^{15}$ MHz	$<6.2 \cdot 10^{-12}$ cm

* values approximate.

Table 2102. Electromagnetic spectrum.

L-band: 1 to 2 GHz (1,000 to 2,000 MHz)

S-band: 2 to 4 GHz (2,000 to 4,000 MHz)

C-band: 4 to 8 GHz (4,000 to 8,000 MHz)

X-band: 8 to 12.5 GHz (8,000 to 12,500 MHz)

Lower K-band: 12.5 to 18 GHz (12,500 to 18,000 MHz)

Upper K-band: 26.5 to 40 GHz (26,500 to 40,000 MHz)

Marine radar systems commonly operate in the L, S and X bands, while satellite navigation system signals (e.g., GPS) are found in the L-band.

The break of the K-band into lower and upper ranges is necessary because the resonant frequency of water vapor occurs in the middle region of this band, and severe absorption of radio waves occurs in this part of the spectrum.

2103. 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.” If the horizontal and vertical components of an electric field are equal, and in phase, the polarization is sometimes called “slant right” or “slant left”. If the two polarizations vary in phase by 90° , in either time or position, the polarization becomes left hand circularized or right hand circularized.

A radio 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 moderate conductor, “short-circuits” any horizontal component. The magnetic field and the electric field of an electromagnetic wave are always mutually perpendicular.

2104. 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 angle of incidence (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 frequencies penetrate the Earth’s surface more than higher ones. 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**, and the reflected wave is called a **multipath wave**.

A phase difference may occur because of the change of phase of a reflected wave, or because of the longer path it follows. 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 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.



Figure 2104a. Specular reflection.



Figure 2104b. Specular reflection from bird bath.

Figure 2104a and Figure 2104b show, at optical frequencies (i.e., light), the reflection of electromagnetic waves from water. The first figure shows direct and the reflected views of the sun, in this case known as specular reflection. The reflection of the sun is evident in even a small body of water, in this case a bird-bath. Radio waves exhibit this same behavior.

2105. 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 of different densities.

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**.

2106. 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, where the air pressure is considerably lower than that at sea level, 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

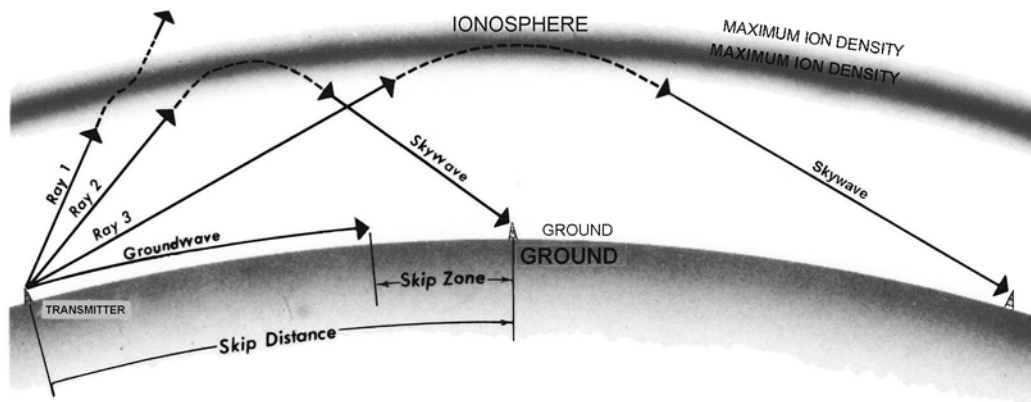


Figure 2106. The effect of the ionosphere on radio waves.

layer at about 125 statute miles above the surface of the Earth, and the F_1 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.

2107. The Ionosphere and Radio Waves

When a radio wave encounters an atom or molecule having an electric charge, it causes that atom/molecule to vibrate. The vibrating particle absorbs electromagnetic energy from the radio wave and can re-radiate 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 2106, 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 ray 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 sky waves can be received. This is called the **skip distance**, shown in Figure 2106. If the groundwave extends for less distance than the skip distance, a skip zone occurs, in which no usable 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 sky waves 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 radio receiver and causing a radio blackout.

Skywave signals reaching a given receiver may arrive by any of several paths, as shown in Figure 2107. 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 "multi-hop" signal undergoes several reflections. The layer at which the reflection occurs is usually indicated, also, as "one-hop E," "two-hop F," etc.

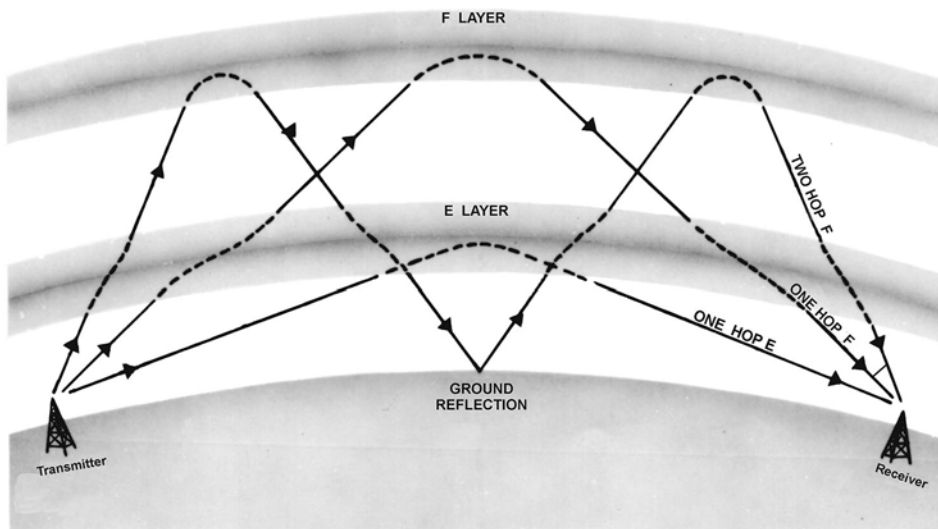


Figure 2107. Various paths by which a skywave signal might be received.

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, ground waves 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**.

2108. 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 2108.

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

2109. Absorption and Scattering

The amplitude of a radio wave's electric or magnetic field expanding outward through space varies inversely with distance, weakening with increased distance. The combined electric and magnetic fields yield the **power flux density**, or pfd, which varies in inverse proportion to the square of distance. The decrease of strength with distance, due to spherical spreading of the electromagnetic wave, is called **attenuation**. Under certain conditions, typically due to absorption of energy in air, the attenuation is greater than in free space.

A wave traveling along the surface of the Earth loses a certain amount of energy as 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 ground waves travel great distances over water.

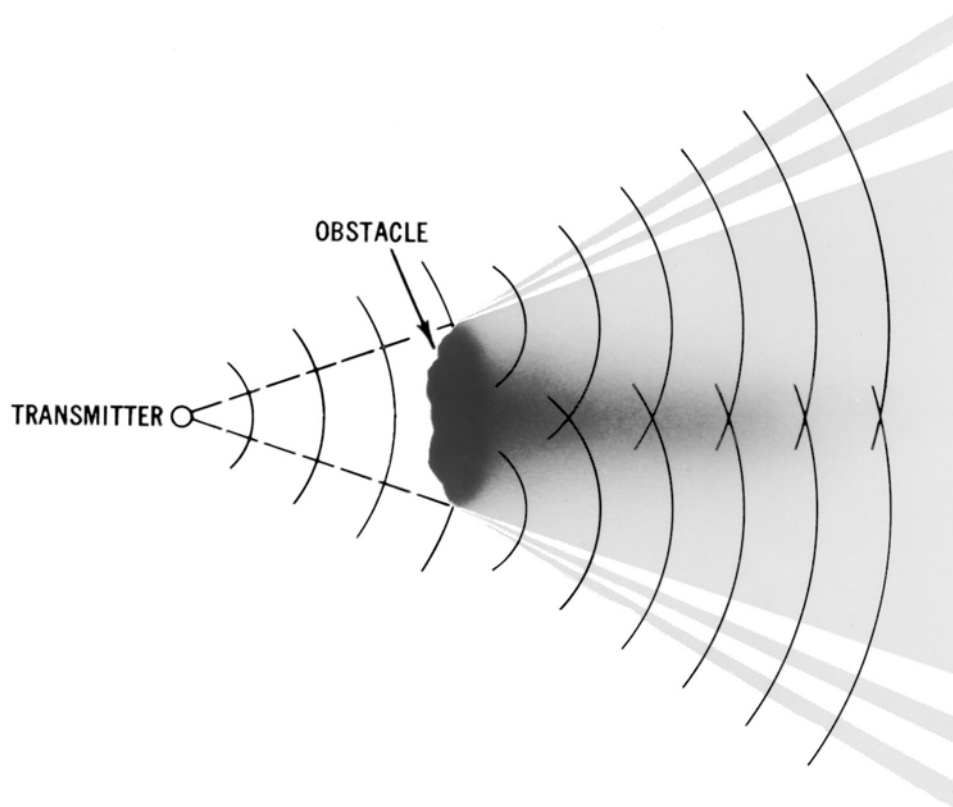


Figure 2108. Diffraction.

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.

2110. Noise

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

2111. 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 the 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 of practical length 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, as described previously, assuming there is no attenuation due to absorption or scattering.

2112. 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 groundwave 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 range at which useful signals can be received.

2113. Radio Wave Spectra

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, which is being replaced by enhanced Loran, or eLoran, 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): Ground waves 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 sky waves. 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 in the higher band, 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 used for most 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. Ground waves 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 sky waves, 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.

2114. 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 (FCC) has responsibility for authorizing civil use of particular frequencies. However, military and government use is reconciled with the FCC by the National Telecommunication and Information Administration (NTIA) of the Department of Commerce. 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. The international allocation and sharing of radio frequencies is regulated by the International Telecommunication Union (ITU), in accordance with decisions made at World Radio Conferences, which are held every three to four years.

2115. Types of Radio Transmission

A series of waves transmitted at constant frequency and amplitude is called a **continuous wave**. 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, 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 2115a. 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 2115a, **frequency modulation (FM)**

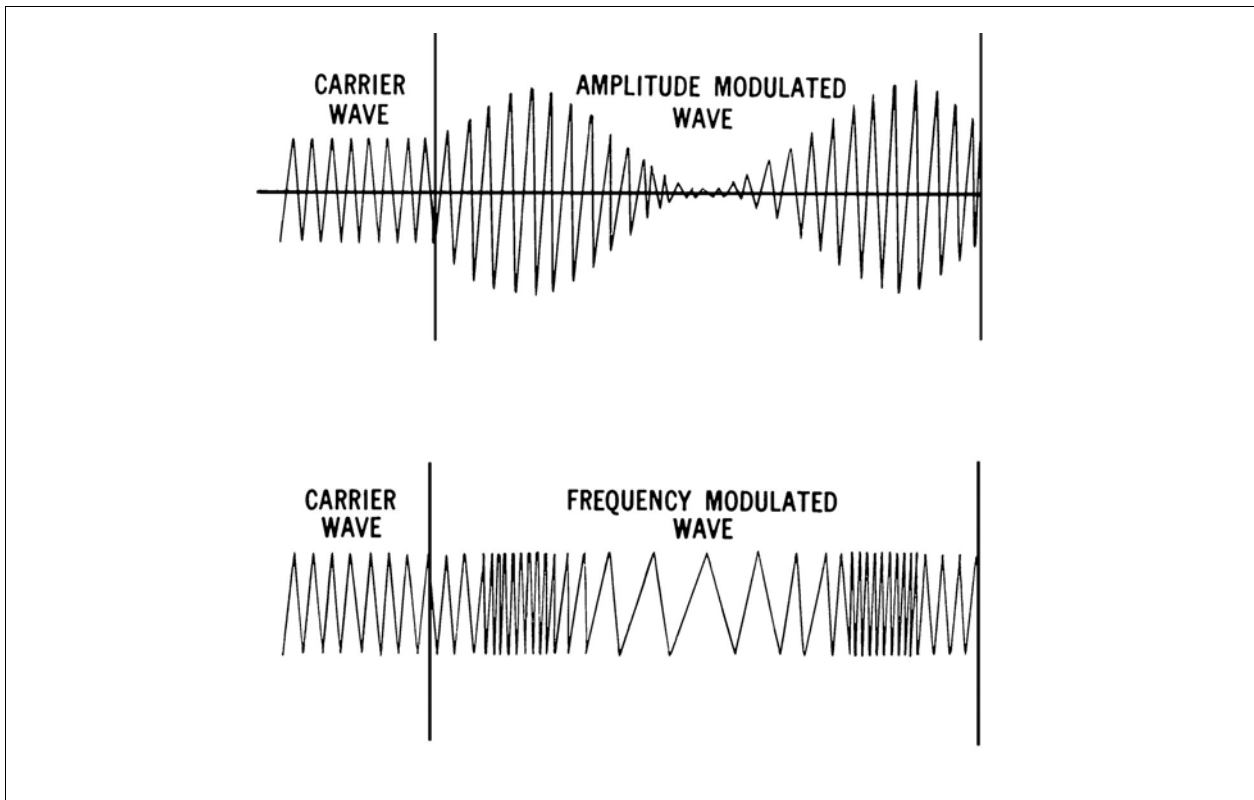


Figure 2115a. Amplitude modulation (upper figure) and frequency modulation (lower figure) by the same modulating wave.



Figure 2115b. Pulse modulation.

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 2115b, is used in some common radio navigational aids, including radar, and eLORAN.

2116. 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 used 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 in Figure 2116.

2117. 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 may be presented audibly by earphones or loudspeaker; or visually video display, or as digital data processed by a computer and either displayed or used to command and control other systems. In any case, the useful reception of radio signals requires three components: (1) an antenna, (2) a receiver, and (3) a display or data processing 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 frequency; (3) sensitivity, the ability to amplify a weak signal to usable strength against a background of noise; (4)

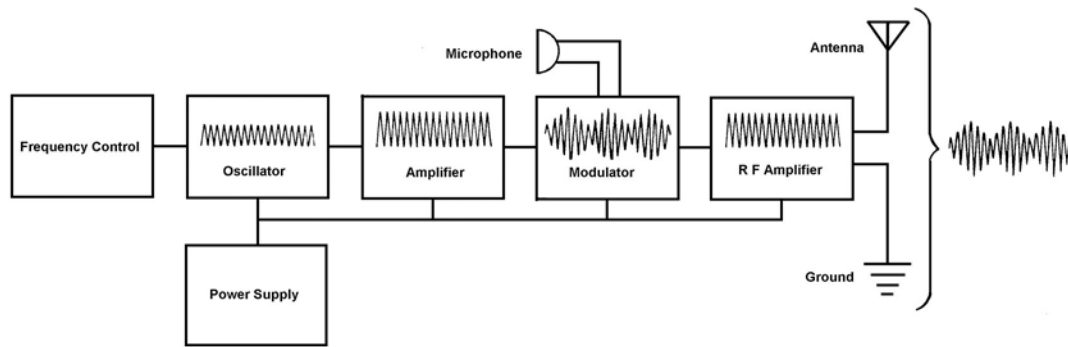


Figure 2116. Components of a radio transmitter.

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 being interrogated and automatically transmitting an appropriate reply.

U.S. RADIO NAVIGATION POLICY

2118. The Federal Radionavigation Plan

The ideal navigation system should provide three things to the user. First, it should be as accurate as necessary for the job it is expected to do. Second, it should be available 100 percent of the time, in all weather, at any time of day or night. Third, it should have 100 percent integrity, warning the user and shutting itself down when not operating properly. The mix of navigation systems in the U.S. is carefully chosen to provide maximum accuracy, availability, and integrity to all users, marine, aeronautical, and terrestrial, within the constraints of budget and practicality.



Figure 2118. Link to Federal Radionavigation Plan (2014): http://ntl.bts.gov/lib/55000/55100/55108/20150526_Final_Signed_2014_FRP.pdf

The **Federal Radionavigation Plan** (FRP) is produced by the U.S. Departments of Defense and Transportation. It establishes government policy on the mix of electronic nav-

igation 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. The complete 2014 FRP is available via the link provided in Figure 2118.

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 (DOT)/Department of Defense (DOD) plan for position, navigation and timing (PNT) had been developed for used by both departments. With the transfer of the United States Coast Guard (USCG) from the DOT to the Department of Homeland Security (DHS), DHS was added as a signatory to the FRP. The FRP was designed to address coordinated planning of federally provided radionavigation systems. Since that time, the Federal planning process has evolved to include other elements of navigation and timing, now referred to as PNT. The FRP has had international impact on navigation systems; PNT services and systems are provided in a manner consistent with the standards and guidelines of in-

ternational groups including the North Atlantic Treaty Organization (NATO) and other allies, the International Maritime Organization (IMO), the International Civil Aviation Organization (ICAO), the International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA), and other international organizations.

During a national emergency, any or all of the systems may be temporarily discontinued by the federal government. The government'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 the Global Positioning System (GPS), differential GPS DGPS, Wide area augmentation system (WAAS), Local area augmentation system (LAAS), Loran C or eLORAN, TACAN, Microwave Landing System (MLS), VHF Omnidirectional Range/ Distance Measurement Equipment (VOR/VOR-DME/VORTAC), and Instrument Landing System (ILS).

2119. System Plans

In order to meet both civilian and military needs, the federal government has established a number of different navigation systems. Each system utilizes the latest technology available at the time of implementation and is upgraded as technology and resources permit. The FRP addresses the length of time each system should be part of the system mix. The 2014 FRP sets forth the following system policy guidelines:

RADIOBEACONS: All U.S. marine radiobeacons have been discontinued and most of the stations converted into DGPS sites.

LORAN C: Provides navigation, location, and timing services for both civil and military air, land, and maritime users. LORAN C was replaced in the United States, by GPS, but due to its importance as an alternative to GPS, it is expected to be reactivated as *enhanced* LORAN, or eLORAN.

GPS: The Global Positioning System is the nation's, and the world's, primary radionavigation system. It is operated by the U.S. Air Force.

2120. Enhancements to GPS

Differential GPS (DGPS): DGPS is a ground based system in which differences between observed and calculated GPS signals are broadcast by radiobeacons to

users using medium frequencies. The USCG, in cooperation with the U.S. Army Corp of Engineers, operates the maritime DGPS system in U.S. coastal waters including Hawaii, parts of Alaska, portions of the Western Rivers, and the Great Lakes. It provides 10 meter continuous accuracy and integrity alarms, with a typical observed position error of 1-3 meters in a coverage area. In 2016, the inland portion of the National DGPS system, previously funded by the Department of Transportation, was decommissioned and ceased broadcasting.

Wide Area Augmentation System (WAAS): WAAS is a service of the Federal Aviation Administration (FAA), similar to DGPS, and is intended for cross-country and local air navigation, using a series of reference stations and broadcasting correction data through geostationary satellites. WAAS is not optimized for marine use, and while not certified for maritime navigation, may provide additional position accuracy if the signal is unobstructed. Accuracies of a few meters are possible, about the same as with DGPS.

Local Area Augmentation System (LAAS): LAAS is a precision positioning system provided by the FAA for local navigation in the immediate vicinity of airports so equipped. The correctional signals are broadcast on HF radio with a range of about 30 miles. LAAS is not intended or configured for marine use, but can provide extremely accurate position data in a local area.

2121. Factors Affecting Navigation System Mix

The navigator relies on simple, traditional gear, and on some of the most complex and expensive space-based electronic systems man has ever developed. The success of GPS as a robust, accurate, available, and flexible system has made older systems obsolete. Some of the systems which have already met their demise are Transit, Omega, and marine radiobeacons in the U.S. Some might say that the days are numbered for others systems too, as GPS currently retains its primacy in navigation technology.

In the U.S., the DOD, DHS, and DOT 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 navigation systems.

Many factors influence the choice of PNT 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 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. The goal is to meet all military and civilian requirements in the most efficient way possible.

RADIO DIRECTION FINDING

2122. Introduction

The simplest use of radio waves in navigation is radio direction finding, in which a MF radio signal is broadcast from a station at a known location. This signal is omnidirectional, but a directional antenna on a vessel is used to determine the bearing of the station. This constitutes a **Line of Position** (LOP), which can be crossed with another LOP to determine a fix.

Once used extensively throughout the world, radiobeacons have been discontinued in the U.S. and many other areas. They are now chiefly used as homing devices by local fishermen, and very little of the ocean's surface is covered by any radiobeacon signal. Because of its limited range, limited availability, and inherent errors, radio direction finding is of limited usefulness to the professional navigator.

In the past, when radiobeacon stations were powerful and common enough for routine ocean navigation, correction of radio bearings was necessary to obtain the most accurate LOP's. The correction process accounted for the fact that, while radio bearings travel along great circles, they are most often plotted on Mercator charts (Aviation charts use the Lambert proportional projection, for which straight lines represent great circles). The relatively short range of those stations remaining has made this process obsolete. Once comprising a major part of *NGA Pub. 117, Radio Navigational Aids*, radiobeacons are now listed in the back of each volume of the geographically appropriate *List of Lights*.

A radio direction finding station is one which the mariner can contact via radio and request a bearing. Most of these stations are for emergency use only, and a fee may be involved. These stations and procedures for use are listed in *NGA Pub. 117, Radio Navigational Aids*.

2123. Using Radio Direction Finders

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. The most common type of marine radiobeacon transmits radio waves of approximately uniform strength in all directions. Except during calibration, radiobeacons operate continuously, regardless of weather conditions. Simple combinations of dots and dashes comprising Morse code letters are used for station identification. All radiobeacons superimpose the characteristic on a carrier wave, which is broadcast continuously during the period of transmission. A 10-second dash is incorporated in the characteristic signal to enable users of the aural null type of radio direction finder to refine the bearing.

Bearing measurement is accomplished with a directional antenna. Nearly all types of receiving antennas have some directional properties, but the RDF antenna is designed to be as directional as possible. Simple small craft RDF units usually have a ferrite rod antenna mounted directly on a receiver, with a 360 degree graduated scale. To get a bearing, align the unit to the vessel's course or to true north, and rotate the antenna back and forth to find the exact null point. The bearing to the station, relative or true according to the alignment, will be indicated on the dial. Some small craft RDF's 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 degrees 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**.

2124. Errors of Radio Direction Finders

RDF bearings are subject to certain errors. Quadrantal error occurs when radio waves arrive at a receiver and are influenced by the immediate shipboard environment.

A radio wave crossing a coastline at an oblique angle experiences a change of direction due to differences in conducting and reflecting properties of land and water known as coastal refraction, sometimes called land effect. It is avoided by not using, or regarding as of doubtful accuracy, bearings which cross a shoreline at an oblique angle.

In general, good radio bearings should not be in error by more than two or three degrees 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, 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 calibration.

The strength of the signal determines the usable range of a radiobeacon. The actual useful range may vary considerably from the published range with different types of RDFs and during varying atmospheric conditions. The sensitivity of a RDF determines the degree to which the full range of a radiobeacon can be utilized. Selectivity varies with the type of receiver and its condition.