RADIO NAVIGATION

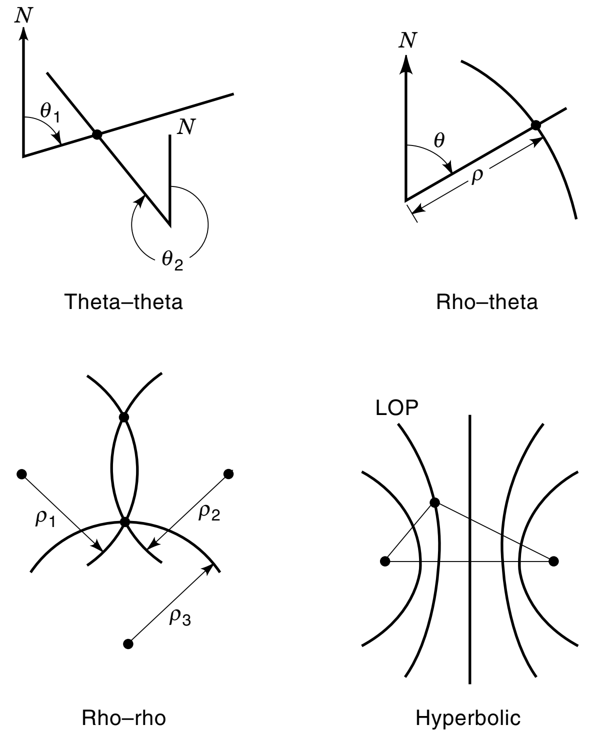
A key function of navigation is the estimation of current position of a vessel. The reception of radio signals from transmitters whose location is known is a common means of implementing the position estimation functions. Several different schemes have been developed. They can be classified according to the means of determining a position from radio signals. Figure 1 provides the geometric relationships for the different schemes.

A theta–theta system determines the position by the vessel's bearing with respect to two transmitters. This scheme is not common in aviation due to its low accuracy when compared with other available systems.

Rho–theta systems use radio signals to determine distance and bearing with respect to the transmitter. This scheme has been in common use in aviation for many years. Most of the airspace can be flown using this basic means of navigation. Errors in bearing measurement will result in position errors that depend on the distance from the station.

Rho–rho systems are based on distance measuring equipment (DME) that determines the position of an aircraft using two or more distance values. When only two distance values are available, there is potentially an ambiguity of position. This ambiguity is usually resolved by using the last computed position to determine the most reasonable position. The position accuracy of the rho–rho solution is dependent upon the accuracy of the measured distance and the bearing angles to the stations. If the aircraft is close to the line through two stations, the error in the position solution using only those two stations becomes large.

Hyperbolic systems measure the time delay of signals simultaneously transmitted from three or more stations. The locus of all points which have a constant delay of signals from two stations is hyperbolic in shape and is called a line of position (LOP). The intersection of two LOP determine a unique position.



Theta–theta Rho–theta Rho–rho Hyperbolic

Figure 1. Geometric relationship of different radio navigation schemes.

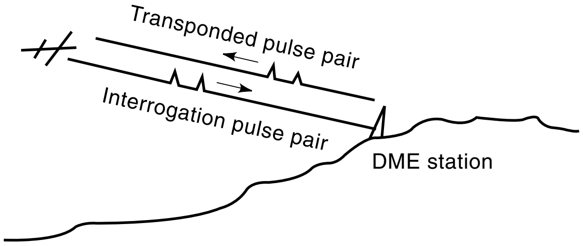


Figure 2. DME operation.

The accuracy of each navigation scheme is dependent upon the particular implementation. The following sections describe the characteristics of the different equipment.

DME CHARACTERISTICS

Distance measuring equipment (DME) is a transponder system combining both airborne and ground equipment to provide distance information. The distance information may be used by other equipment or provided on an indicator to the pilot. In addition, the DME may provide ground speed information. Data from DME is used for both rho–rho and rho–theta navigation systems (see Fig. 2).

The major units of the airborne DME equipment are a receiver-transmitter together with an antenna. In addition, a control unit and distance display may be provided in the airborne equipment. The ground-based equipment is a transponder consisting of a receiver-transmitter and an antenna.

The DME ground-based facility is usually part of a VOR/DME, ILS/DME, VORTAC, or TACAN facility. A VOR/DME station is a VHF omnidirectional station combined with the DME. An ILS/DME facility is an instrument landing system with DME. TACAN is a military navigation system providing both azimuth and distance information. A VORTAC is a VOR facility together with TACAN equipment.

DME ground stations are capable of handling approximately 100 aircraft simultaneously. If more than 100 aircraft interrogate the ground station, the ground station reduces its sensitivity and replies to the 100 strongest interrogations. Most airborne DME units will operate down to a 50% reply efficiency, so operation is continued even when the ground stations does not respond to all interrogations.

The ground station continually transmits a 2700 pulse pair per second squitter signal. At 30 s intervals, the ground station transmits a 1350 pulse pair per second signal that encodes the station identifier in Morse code. When interrogated by an airborne DME pulse pair, the ground station replaces the squitter pulse pair with a pulse pair 50 μs after interrogation.

The airborne equipment operates in two modes, search and track. In the search mode, the airborne equipment transmits 90 or more pulse pairs per second. The transmission rate is randomly shifted to prevent possible confusion effects due to another airborne DME transmitter. After each pulse pair is transmitted, the receiver equipment waits for a reply pulse pair that arrives with a consistent delay after the transmission. If such a reply is found, the airborne DME switches to the track mode and tracks the regular delays of the replies. In the track mode the airborne equipment reduces the interrogation rate to 20 or less pulse pairs per second. The reduction in the interrogation rate allows more airborne units to be serviced by the ground based DME facility.

The airborne equipment converts the time duration between the transmission of the interrogation pulse pair and the reception of the reply pulse pair into distance. Because the speed of the radio signal is a known constant, the distance from the DME facility can be determined. To be more precise,

$$\text{Distance in nm} = (\text{Time duration in microseconds} - 50\,\text{ms})/12.359\,\text{ms/nm}$$

The airborne DME unit has memory that handles the situation when the reception of the DME reply is momentarily interrupted. The equipment uses the memory to remain in the track mode and provide distance data during the reply interruption. The memory allows the DME to provide distance information for up to 10 s after loss of reception.

It is common for airborne DME units to handle up to five DME ground facilities simultaneously by multiplexing the receiver-transmitter circuits. This allows the equipment to simultaneously provide distance information for up to five DME navaids.

The airborne DME transmits and receives on one of 252 channels. There are 126 X and 126 Y channels. The transmit and receive frequencies of any one channel are separated by 63 MHz. In the first 63 X channels, the ground-to-air frequency is 63 MHz below the air-to-ground frequency. For X channels 64 through 126, the ground-to-air frequency is 63 MHz above the air-to-ground frequency. For Y channels the situation is reversed. The ground-to-air frequency of the first 63 Y channels is 63 MHz above the air-to-ground frequency. Channels 64Y to 126Y, the ground-to-air frequency is 63 MHz below the air-to-ground frequency. The 252 ground-to-air frequencies are each whole MHz frequencies from 962 MHz to 1213 MHz. The air-to-ground frequencies are each whole MHz frequencies from 1025 MHz to 1150 MHz.

The duration between each pulse of the pulse pair transmitted by the airborne equipment and that of the ground equipment is different for X and Y channels. The table below shows the pulse spacing.

	Air-to-ground	Ground-to-air
X-channel	12 μs	12 μs
Y-channel	36 μs	30 μs

Most DME channels are paired with a VHF frequency allocated to VOR or ILS. That is, for each VOR or ILS frequency there is an assigned DME channel for use when DME equipment is part of the navaid facility. The X channels are paired with VHF frequencies in 100 kHz increments (108.00, 108.10, 108.20, etc.). The Y channels are paired with VHF frequencies in 100 kHz increments but offset by 50 kHz (108.05, 108.15, 108.25, etc.). The table below shows the DME channel pairing with VHF frequencies.

DME Channels	Assignment	VHF Frequencies
1 to 16	Unpaired	134.4 MHz to 135.9 MHz
17 to 56 Even channels with ILS Odd channels with VOR	ILS and VOR	108.00 MHz to 112.00 MHz
60 to 69	Unpaired	133.3 MHz to 134.2 MHz
57 to 59, 70 to 126	VOR	112.00 MHz to 117.9 MHz

DME operation requires that the aircraft and the ground facility be in a direct line-of-sight connection. Terrain and the curvature of the earth limit the range. The formula below provides an approximate limit on the range of DME equipment due to earth curvature with an assumption that the ground station antenna is about 16 ft. above the surface.

$$\text{DME range limit (nm)} = 1.23\sqrt{\text{aircraft altitude (ft)}} + 4$$

The DME provides the slant range distance from the aircraft to the DME navaid facility. If the DME range is large com-

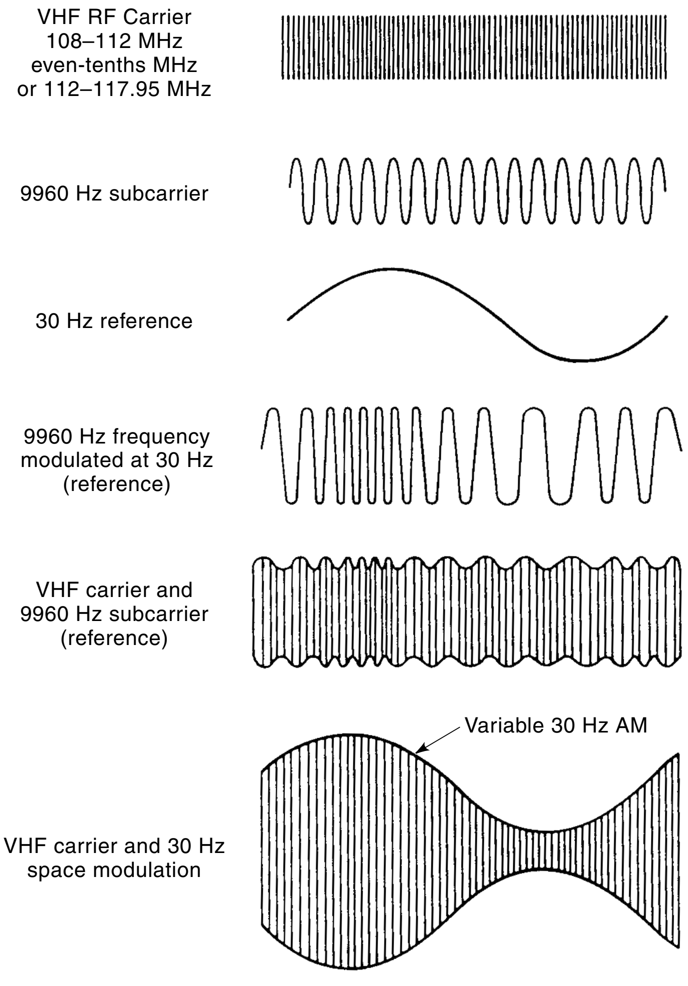


Figure 3. Components of VOR signal.

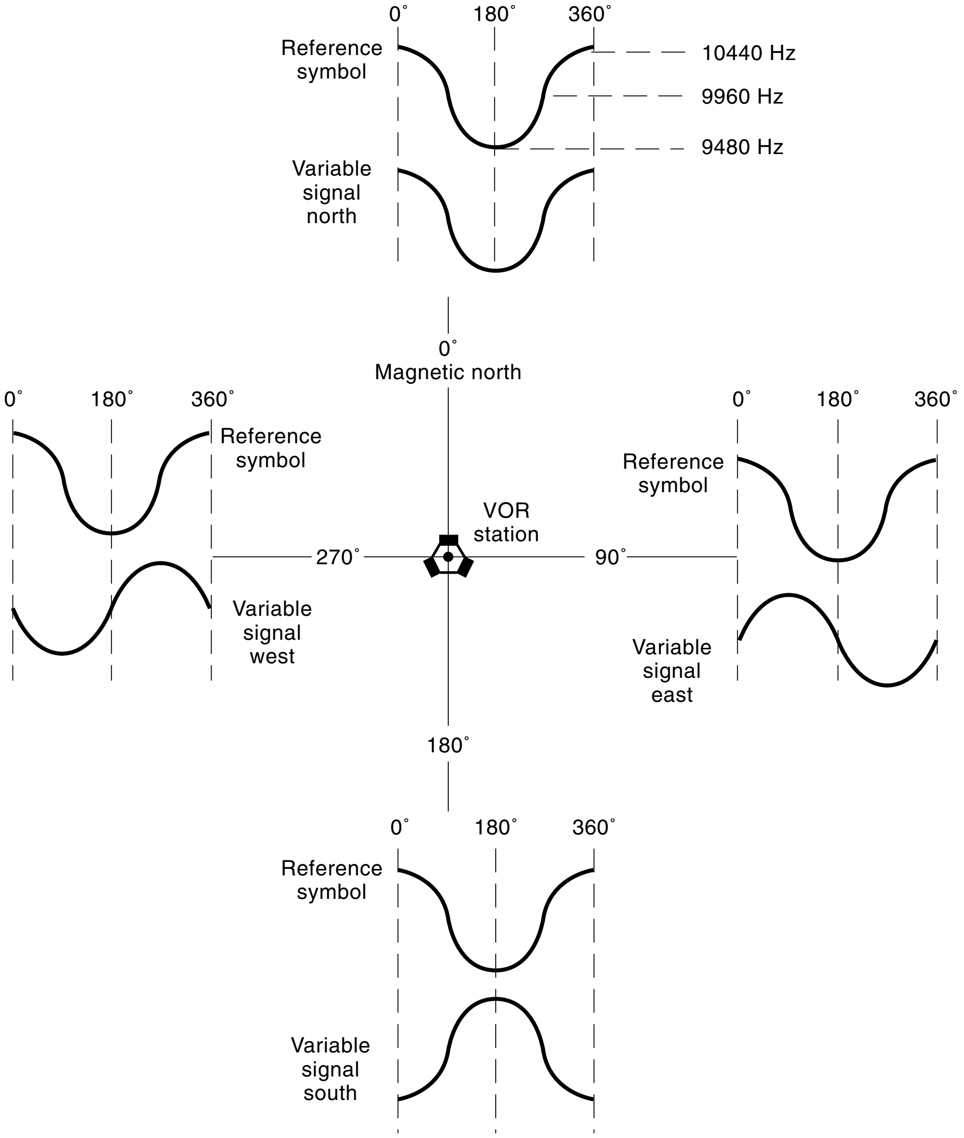


Figure 4. Phase relationship of VOR signal.

pared with the aircraft altitude the slant range is essentially the same as the ground distance. Navigation equipment that uses the DME range data can remove the effect of the aircraft altitude by incorporating in the calculation both the measured aircraft altitude and the elevation of the navaid as retrieved from the navigation database.

The accuracy of DME range measurement is dependent upon the range, environmental conditions, and the equipment being used. A nominal 95% accuracy is about 0.1 nm at shorter ranges. For longer ranges the accuracy degrades due to atmospheric conditions and lower signal-to-noise ratio.

VOR EQUIPMENT CHARACTERISTICS

VHF Omnidirectional Range (VOR) equipment consists of a ground station (transmitter) and an airborne receiver. The VOR ground station continuously transmits a signal that may be used by all aircraft within reception range of the signal. Using the VOR signal, the receiver determines the bearing from the ground station to the receiver. VOR stations are often colocated with other navigational aids such as DME and TACAN stations. The frequency of VOR stations ranges from 108.00 MHz to 117.95 MHz.

There are two types of VOR transmitters, Doppler VOR and conventional VOR. Doppler VOR has limited usage. The details of conventional VOR follow.

The transmitted signal from the VOR station consists of a VHF carrier and a 9960 Hz subcarrier. The VHF carrier is amplitude modulated by a variable 30 Hz signal whose phase is dependent upon the bearing with respect to the ground station. The 9960 subcarrier is frequency modulated by a 30 Hz reference signal. The subcarrier is modulated between 10440 Hz and 9480 Hz (see Fig. 3).

Figure 4 illustrates the phase-bearing relationship of the two components of the VOR signal. At 0° bearing, the phase of the variable signal is the same as the phase of the reference signal. At 90° bearing from the ground station, the variable signal is 90° out of phase with respect to the reference signal. The phase difference between the two signals is proportional to the bearing from the ground station to the receiver.

The phase difference between the variable signal and the reference signal is used by the receiver to determine the bearing from the ground station to the receiver. Essentially, the receiver separates the subcarrier from the VHF carrier, detects the phase of the 30 Hz signal in each and then determines the phase relationship.

In a conical area above the VOR station, the phase difference between the two signals cannot be detected reliably. This area is called the VOR cone of confusion. Receivers have monitors that detect this condition and provide alerts to the pilot that the signal is unreliable.

In general, the VOR ground station antenna is physically aligned so that the VOR signal indicates 0° bearing when the receiver is magnetically north of the ground station. That is, in general, the VOR bearing from the ground station to the receiver is the same as the magnetic bearing to the receiver. However, the magnetic field of the earth is constantly changing. In Europe and the United States there are regions where the magnetic north is changing 1° every seven years. Therefore even if the VOR signal was aligned with magnetic north at one instant in time, after some period of time there can be a significant difference. When the difference becomes too large (2° or so), the VOR antenna is usually realigned.

The accuracy of VOR signals is degraded by range and terrain. Generally, the VOR signal error is less than 1°. As the range from the VOR station is increased, the VOR signal bearing often oscillates around the true bearing. This effect is known as scalloping.

There are several types of VOR indicators that are in common use. Most of the indicators provide bearing as a rotating arrow pointing to the bearing angle on an azimuth card. The azimuth card is slaved to the heading sensor so that the current heading is at the top directly under the lubber line. The indicators often include a distance indication that is connected to the DME.

ILS CHARACTERISTICS

An instrument landing system (ILS) consists of ground-based transmitters and airborne equipment that provides lateral, along-track, and vertical guidance. The lateral signal is provided by a localizer transmitter and the vertical signal is provided by the glideslope transmitter. The airborne ILS receiver is capable of receiving and processing both the localizer and the glideslope signals. The along-track information is provided by marker beacons (transmitters located along the descent path that provide a narrow vertical radio signal) or distance measuring equipment (DME). The marker beacon receiver can be part of the ILS receiver or it can be a separate receiver (see Fig. 5).

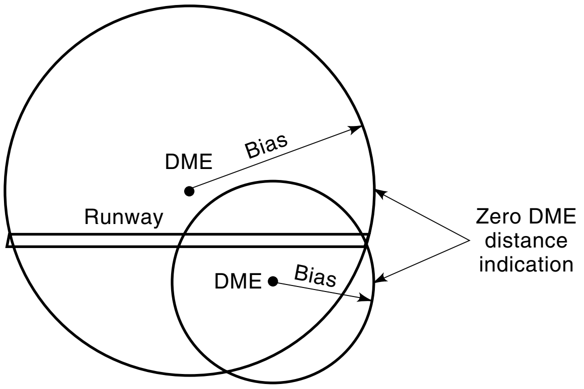


Figure 6. Biased DME antenna situations.

The localizer beam is almost always aligned to guide the aircraft directly over the runway threshold. In certain situations, only a localizer signal is provided and no electronic glideslope signal is provided. In some localizer-only situations, the localizer signal is not aligned to the runway but instead provides guidance to some location from which the pilot has other means to complete the landing.

In some cases, the ILS DME transponder delay is adjusted so that the sensed DME distance is zero at the runway threshold instead of at the DME antenna. Such DMEs are known as biased DMEs and the bias is indicated on the approach chart. There are two general arrangements of biased DMEs (see Fig. 6). In one case the DME antenna is located at the glideslope antenna and adjusted to read zero at the corresponding runway threshold. In the other case, the DME antenna is located midway between the two runway thresholds at opposite ends of the runway. In this case the single DME will support approaches from either direction and will read zero at both runway thresholds.

The localizer signal is transmitted on assigned frequencies between 108.1 MHz to 111.95 MHz. As shown in Fig. 5, the localizer antenna is usually located past the far end of the runway very near the extended runway centerline.The signal pattern are two main lobes on each side of the center line. The left lobe is predominantly modulated at 90 Hz and the right lobe is predominately modulated at 150 Hz. Along the center line, the two modulated signals are equal (see Fig. 7).

The localizer signal also extends backwards and is called the back course. This signal can be used for guidance but the modulation convention is reversed. There is no glideslope signal provided on the backcourse region. When flying the backcourse, either the equipment must reverse the localizer indications or the pilot must recognize and fly the reversed indications.

The glideslope signal is transmitted on assigned frequencies between 328.6 MHz and 335.4 MHz. The glideslope antenna is located on the side of the approach end of the runway. The glideslope signal consists of two main lobes on each

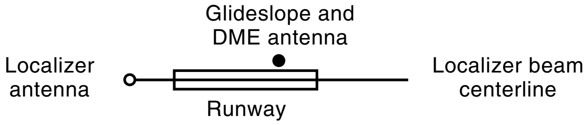


Figure 5. Common layout of ILS facility.

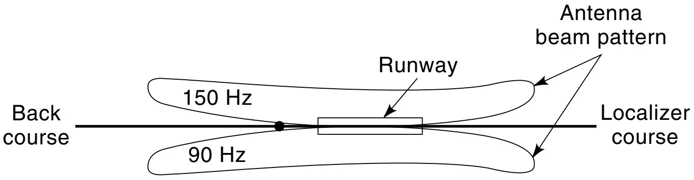


Figure 7. Localizer antenna lobe patterns.

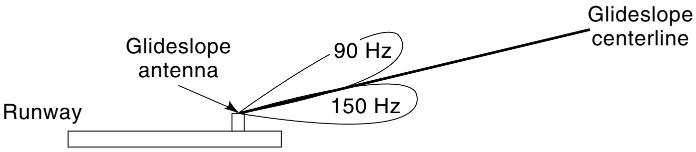


Figure 8. Glideslope antenna lobe patterns.

side of the desired glideslope path. The glideslope descent angle is usually three degrees. To provide obstacle clearance or to reduce noise, steeper glideslope paths are used. The upper glideslope lobe is predominantly modulated at 90 Hz and the lower lobe is predominantly modulated at 150 Hz (see Fig. 8).

Marker beacons signals are transmitted at 75 MHz and are modulated at 400 Hz, 1300 Hz, or 3000 Hz. The transmitters are located along the descent path of to the runway. Figure 9 shows the general arrangement of the beacons. When the aircraft passes over the beacons, the marker beacon receiver detects the signal and provides an indication to the pilot of the passage. The exact location of the marker beacons is given on the approach procedure chart. Inner marker beacons are installed at runways with Category II and Category III operations.

In typical operation, the pilot maneuvers the aircraft to cross the localizer signal centerline. At this time, the localizer receiver provides an indication that the localizer signal is being received and provides a lateral deviation indication showing the aircraft displacement from the centerline. Using the lateral deviation indication, the pilot steers to the localizer centerline until the glideslope receiver indicates reception of the glideslope signal. At that time the pilot has both lateral and vertical indications to guide the aircraft on the desired glideslope path. The marker beacons or DME indications provide along-track indications of the progress of the descent.

ADF NAVIGATION

Automatic direction finder (ADF) is the oldest and most widely used radio navigation system. The ADF system consists of a ground-based transmitter and an airborne receiver. The ADF system provides an indication of the bearing of the station from the aircraft centerline. The ADF receiver is capable of receiving AM signals from 190 kHz to 1750 kHz. The transmitter can be either commercial AM broadcast stations or nondirectional beacons (NDB) that are installed expressly for radio navigation.

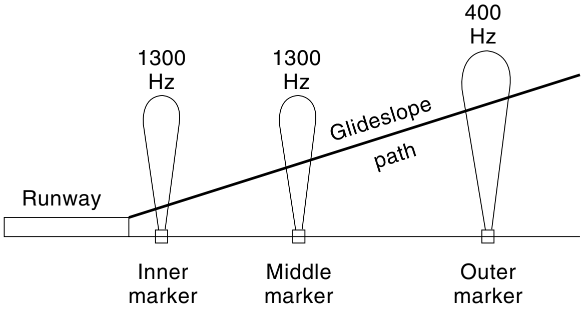


Figure 9. Marker beacon locations.

An omnidirectional antenna is used to receive the signal to aid in tuning the receiver. The ADF receiver determined the bearing of the station using the directional sensitivity of loop antenna. The loop antenna may be physically rotated to determine the bearing to the signal or the bearing may be determined using electronic sensing of the signal strength from more than one loop.

LONG-RANGE NAVIGATION (LORAN)

Low frequency long range navigation (LORAN) was first developed for military applications during World War II. Since then it has evolved into today's LORAN-C system that is also used for civil applications. Marine applications were the first to appear, followed by aviation applications.

The LORAN system consists of a group or chain of transmitting stations and a receiver. Within each chain there is one master station and several slave stations identified by a single letter. Associated with each chain is a unique group repetition interval (GRI) that identifies the chain. A single chain provides navigation coverage for several hundred miles from the master station. The frequencies of transmitted signal are between 90 kHz and 110 kHz. The pulse patterns of the transmitters are different allowing the receiver to separate the received signals.

Within each chain, each station simultaneously transmits a pulse at the specified GRI. Each station has an assigned pulse pattern that allows the receiver to distinguish between the different signals. By determining the time differences between the set of received pulses, the receiver can determine the difference in distance from each of the transmitting stations. If three or more signals are received, the receiver can determine the best estimate of the location of the receiver. The accuracy of the LORAN position estimate depends upon the position of the receiver with respect to the location of stations providing signals. The nominal accuracy of the LORAN system is 0.25 nm when within the groundwave range.

To improve accuracy, LORAN receivers compensate for the differences in velocity of the ground wave when the signal is propagating over land rather than water.

GLOBAL POSITIONING SYSTEM (GPS)

The space segment of the global positioning system (GPS) consists of a set of orbiting satellite transmitters that provide two L-Band, 1575.42 MHz (L1) and 1227.6 MHz (L2) signals. The two frequencies allow the appropriately equipped user to correct for errors due to ionospheric refraction. Civil receivers use only the L1 signal. The basic satellite configuration is a set of 24 satellites in 6 orbital planes.

The signals provided by the satellites are modulated with two pseudorandom noise (PRN) codes: a coarse/acquisition (C/A) signal and a precise (P) signal. The P code component of the signal allows higher precision ranging and information necessary to decode the signal which has restricted distribution.

The airborne GPS receiver receives the L1 signal of all satellites in view and by the use of correlation techniques can detect the unique C/A code for each satellite. The C/A code has a chipping rate of 1.023 MHz and a length of 1023 bits so it repeats every millisecond. By use of signals from four or more satellites, the receiver can determine the time reference and the range to each satellite and hence estimate the receiver position.

To deny the accuracy of GPS to unfriendly forces, the satellite signals are intentionally degraded using a concept known as selective availability (SA). This technique degrades to L1 signal characteristics to the extent that navigation accuracy is about 100 m (95%).

MICROWAVE LANDING SYSTEM (MLS)

Microwave landing systems consist of an azimuth and elevation microwave transmitters, a conventional DME transponder, and the airborne receivers. The azimuth transmitter provides coverage for 40° to each side of the centerline. The elevation transmitter provides coverage up to 15° of elevation.

Microwave landing transmitters operate on one of 200 assigned frequencies between 5.031 GHz and 5.1907 GHz. The azimuth transmitter provides a narrow beam signal that sweeps the azimuth coverage area (±40°) at a rapid rate. By detecting the timing between the reception of the microwave signal, the receiver can determine the azimuth angle from the centerline. A preamble microwave signal is transmitted from a broad beam antenna to indicate the beginning of the azimuth sweep. Various information is digitally encoded in the preamble signal. The elevation function is provided in the same manner as the azimuth function. High sweep rates provide about 40 samples per second for azimuth and elevation.

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