A COMPARATIVE ANALYSIS OF AREA NAVIGATION SYSTEMS IN GENERAL AVIATION

By Stephen Malcolm Dodge
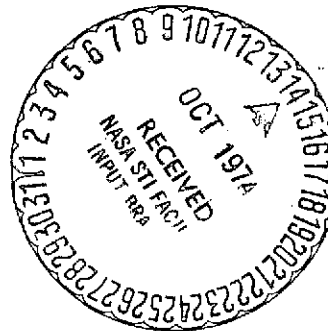
1. Report No. NASA CR-132504	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle A COMPARATIVE ANALYSIS OF AREA NAVIGATION SYSTEMS IN GENERAL AVIATION		5. Report Date
		6. Performing Organization Code
7. Author(s) Stephen Malcolm Dodge		8. Performing Organization Report No. FTL Report R74-1
9. Performing Organization Name and Address Massachusetts Institute of Technology Flight Transportation Laboratory Cambridge, MA 02139		10. Work Unit No.
		11. Contract or Grant No. NGL 22-009-640
12. Sponsoring Agency Name and Address National Aeronautics & Space Administration Washington, DC 20546		13. Type of Report and Period Covered Contractor Report
		14. Sponsoring Agency Code

15. Supplementary Notes Submitted to the Department of Aeronautics and Astronautics, MIT, June 1973 in partial fulfillment of the requirements for the degree of Master of Science

16. Abstract

Within the next decade, area navigation is to become the primary method of air navigation within the United States. There are numerous radionavigation systems that offer the capabilities of area navigation to general aviation operations. In this analysis the author investigates three such systems: (1) the VORTAC system; (2) the Loran-C system; and (3) the Differential Omega system. The initial analyses are directed toward a comparison of the systems with respect to their compliance to specified performance parameters and to the cost-effectiveness of each system in relation to those specifications. Further analyses lead to the development of system cost sensitivity charts, and the employment of these charts allows conclusions to be drawn relative to the cost-effectiveness of the candidate navigation systems.

17. Key Words (Suggested by Author(s)) (STAR category underlined) General Aviation	18. Distribution Statement Unclassified - Unlimited		
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 188	22. Price* $5.50

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CHAPTER 1

AREA NAVIGATION AND ITS APPLICATION TO GENERAL AVIATION

Navigation systems with particular application to general aviation are
entering a crucial period in their development. In fact, a recent FAA/Industry Task
Force report [1] designates the ten year period 1973 ± 1982 as the decade for com-
plete implementation of an evolutionary concept in air navigation. Area navigation
(RNAV) is to become the primary method of directing the movement of aircraft in
the United States.

1.1   Introduction

The adoption of a new mode of operation is not a novel experience for navi-
gators. It is a process which has been continuous throughout history. Navigation
in the earliest days of flight was more of an art than the application of sound
scientific principles. Early airborne cross-country navigation was conducted solely
by a means called "pilotage". Pilotage requires the recognition of various landmarks
along the route and then flying between them. One of the major limitations of this
method is the necessity of maintaining visual contact with the ground. Gradually
airmen became aware of the effects of nature and how to compensate for them. With
the advent of this knowledge pilots developed techniques to aid in the navigation task.
"Dead reckoning" was such a technique. In dead reckoning, estimates of the wind
effect on the aircraft groundspeed and track are made and then used to apply correc-
tions to the aircraft heading in order to reach the destination. Again the require-
ment of visual contact with the ground limits the capabilities of this method.

The solution to that problem came with the development of radionavigation.
Electronic landmarks were established, and the pilot could then conduct a cross-
country leg by flying from one radio facility to another. Visual ground contact was
necessary only during the takeoff and landing phases of the trip.

By definition, navigation is accomplished by fixing one's position and then
using that information to aid in directing the motion of the aircraft toward its des-
tination. The navigation instruments are used to determine a line of position, and the
intersection of two lines of position determines a fix.

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In early navigation efforts raw information as to position location was provided by assorted instruments. It was then up to the human navigator to interpret this information and to accomplish the navigation task. When the determination of position required extensive calculations, the information provided the answer to the somewhat untimely question "Where was I?". This was sufficient in the days of slow moving aircraft and low traffic density. The navigator could use the information to adjust his course and estimates for arrival. As the vehicle speeds increased and the traffic density grew, however, different information was required. "How can I proceed to my destination with minimum traffic conflict?" became the question of importance. This destination may be a terminal or it may be a designated waypoint along the route. The radios and related airborne instruments which were developed to provide the answer to this query were more complex than the earlier equipment. They provided full navigation command information rather than just position location data. The present developments in avionics are a further refinement of these electronic techniques. They enable the pilot to guide his aircraft along routes that do not necessarily connect the fixed ground facilities. Rather than being just a one-dimensional navigation system comprised of linear paths to fixed facilities, the system has expanded into a two-dimensional, area-wide network.

This analysis is primarily concerned with the application of such area navigation techniques to general aviation. General aviation can be defined as all civil flying of aircraft owned and operated by individuals and corporations other than the air carriers. This definition encompasses a wide range of air activity. It includes personal flying in small, single-engine piston aircraft and also includes scheduled air taxi and business flying operations in large turbine powered aircraft. In early 1970 there were approximately 130,000 general aviation aircraft in the United States. This number is forecast to increase to 235,000 by the beginning of 1981. A large majority (83%) of the fleet in 1970 was single-engine aircraft. While this percentage is expected to decrease to 78.6% by 1981, it still yields a forecast of approximately 185,000 single-engine aircraft in use by that date. [2]

If the airspace of the United States was allocated vertically by user, one would find that most of the air carrier and military vehicles would occupy the higher altitudes. However, the vast majority of the aircraft, because of their limited high altitude performance, would be at the lower levels, mostly below 10,000 feet. Consequently, as the number of general aviation aircraft grows, more efficient utilization of this lower segment of the airspace must be accomplished. In order to operate efficiently and effectively at these levels, a navigation system which can provide good coverage, accuracy, and availability is mandatory.
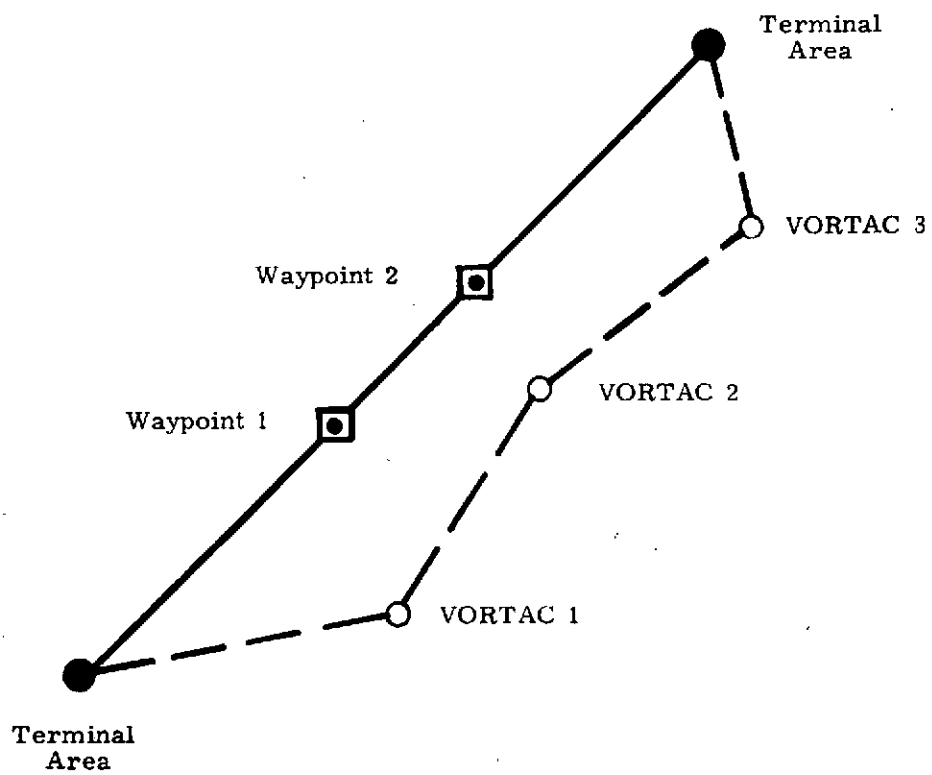
Figure 1-1.   Improvement to Route Directivity as a Result
of Area Navigation Capability

1.2   The Benefits of Area Navigation

Operator expense, pilot workload, and traffic congestion are important problems encountered by general aviation. The present navigation techniques which are based on the use of VORTAC ground facilities that require routes directly to and from fixed stations contribute to the problem. Relief lies in the more efficient utilization of airspace, aircraft, and airports. The use of airborne navigation systems that permit flight over predetermined tracks without the requirement of overflying the ground based facilities would yield a large improvement in airspace utilization. Area navigation (RNAV) offers this capability.

There are three principle applications of the area navigation capability:

(1)   between any given departure and arrival points along a route structure so organized as to permit reduction in flight distances or reduction in traffic congestion;

(2)   in terminal areas to permit aircraft to be flown on preorganized arrival and departure flight paths to assist in expediting traffic flow and reduce pilot and controller workload; and

(3)   to permit instrument approaches within certain limitations to airports/runways not equipped with local landing aids. [3]

The enroute advantages of area navigation capabilities demonstrate themselves in numerous applications. It provides for improved directivity of routes. Figure 1-1 illustrates the improvement that is possible. The dashed line shows the route that is followed if the ground facilities must be overflown. The solid line indicates the route that can be flown with area navigation. In the low altitude structure this direct routing can result in significant savings of flight time and, consequently, a savings in operating expense. Area navigation capability also allows for an unlimited number of routes between two terminals. Any course within the coverage area of the reference navigation station can be flown. This permits multiple or parallel route assignment, and traffic can be segregated according to performance level. The result will be less enroute delay and more efficient operation. A third major advantage afforded by area navigation to enroute operation is the flexibility provided in the selection of weather avoidance routes, restricted area detours, and congested area bypass routes. RNAV allows this operation to be performed in the most efficient manner possible. Using precise course offset and navigation control, the reroute time can be minimized.

Operations with area navigation in the terminal area can result in a reduction of departure and arrival delays by following RNAV standard instrument departures (SID's) and standard terminal arrival routes (STAR's). The adoption of RNAV SID's and STAR's will provide for pilot navigation of commonly flown radar vector paths

and a reduction in communication between the pilots and ground controllers since the pilots can adhere to printed instructions without continuous transmissions from the controllers. This procedure will allow the pilots more time for flight management and return the navigation function to the cockpit where many people feel that it rightfully belongs.

Area navigation implementation also offers an improvement for airport instrument approach operations. RNAV can provide continuous guidance on any track to the end of the runway. This allows straight-in approaches to the uninstrumented runways and can eliminate the requirement for circling approaches under conditions of low ceiling and visibility. It also furnishes continuous measurement of distance along the approach track, and if three-dimensional RNAV is used, the pilot has continuous vertical guidance with selectable glide slope capability and minimum descent altitude (MDA) alarm. Each of these capabilities will result in an increase to instrument approach safety. Furthermore, with this additional approach capability pilots can operate under instrument flight rule (IFR) conditions into airports which might not otherwise be available. This can result in increased operational reliability and makes possible the convenient use of satellite airports so as to avoid the high density traffic areas.

The application of area navigation in general aviation operations can result in higher safety, higher operational reliability, and lower operating cost. The increase in safety results from better weather avoidance routes, better flight management because of the lower communications requirement, and the ability to fly straight-in instrument approaches to uninstrumented runways. The higher operational reliability is a result of the capability to operate under IFR conditions into airports that might not otherwise be available. And finally, the lower operating cost is a direct consequence of the capability to fly more direct routes between origin and destination rather than overflying ground facilities, the provision of less enroute delay due to more efficient traffic management, and the more precise bypass routes. Each of these improvements reduces the total flight time and, therefore, the operating cost to the user. Area navigation implementation offers a great deal of promise for general aviation.

1.3   Specification of Operational Requirements

The present study is a comparative analysis of different area navigation systems applicable to general aviation. In order to properly evaluate the systems, performance specifications must be outlined. The FAA/Industry Task Force on Area Navigation recommended some minimum operational characteristics. One can separate the recommendations into two major divisions: those required of the computer/display functions and those required of the radionavigation system. The computer/display requirements include provision for display consisting of selected course, distance to waypoint, and cross-track deviation from the selected course; provision

for waypoint storage and manual insertion of waypoints with a method available for the pilot to check the correctness of his input; parallel offset capability and turn anticipation; and a failure warning indicator on the total system as well as the sub-systems thereof. These are all very important elements. However, in this analysis it will be assumed that the computer/display capabilities of the different RNAV equipment are essentially equal. The system characteristics that are important to this study are those which are factors of the radionavigation system itself. These can be specified in terms of area of coverage, the availability of the signal, and the system accuracy. The area of coverage is the area within which the system delivers navigation signals that can be received and processed resulting in a navigation accuracy within the specified limits; the signal availability is a measure of the ability of the system to provide a signal within the coverage area to the accuracy tolerance specified; and the system accuracy is the repeatable accuracy that the system provides with a 95% (2σ) probability of error less than the stated value.

When planning the implementation of future navigation systems, it is a practical necessity to make modifications consistent and compatible with existing navigation equipment. FAA Advisory Circular AC 90-45, which deals with the subject of area navigation systems for use in the U.S. National Airspace System, states:

> "Application of area navigation equipment and procedures in the National Airspace System requires that they be compatible with the VOR/DME system on which route structure and air traffic control are based. Implementation, therefore, requires that area navigation devices employed assure proper positioning with respect to the VOR/DME route structure by reference to the geographic locations of VOR/DME ground facilities. Such systems must further permit navigation along, and within the protected airspace of, conventional VOR routes, airways, and terminal procedures." [4]

A great deal of money has been expended on the VORTAC facilities, and it is expected that "VOR/DME. . . will continue to be the primary reference for short-range navigation for the forseeable future." [5] The RNAV system that is used can employ sensor inputs other than VORTAC if equivalent performance can be demonstrated by means of compliance suitable to such systems. While the author recognizes the inherent limitations of specifying performance requirements in terms of an existing navigation structure, he believes that the practical realities of the navigation and air traffic control situation must be satisfied and that these specifications are sufficient for the initial development.

In order to achieve the maximum utility from RNAV equipment the area of coverage should include the contiguous United States and Alaska. The off-airway operational capability and the potential for approaches to uninstrumented runways

all over the country are major improvements offered by area navigation over the present structure. In this analysis the specification of the coverage area will be that the system must provide service everywhere within the conterminous United States and Alaska from an altitude of 1,500 feet above ground level to 45,000 feet. This service area will encompass that airspace necessary for enroute and terminal area operations.

The ideal signal availability is 100%. A system can approach this ideal value. However, in order to actually achieve it, the reliability of the navigation system components would have to be 100%. This would be prohibitively expensive. Therefore, in this analysis the specification of 100% signal availability will be treated as a goal, and the actual compliance will be dependent on the performance of each system.

The accuracy requirement that has been recommended by the FAA/Industry Task Force for the post-1982 period is that the enroute tolerance be ±2.5 nautical miles and the accuracy in the terminal area be ±1.5 nautical miles. These tolerances are for total system performance. Allowances are made for navigation system error, computer error, and flight technical error. This study will require the same performance.

In addition to the requirements relating to performance and safety, economic factors must also be considered. The cost-effectiveness of each system is essential to any comparison among them.

1.4   The Cost-Effectiveness Assessment

Area navigation cost-effectiveness can be evaluated in relation to all classes of airspace users, the government, and the air traffic control system. This study is primarily concerned with a comparative analysis of different area navigation systems for general aviation operations. The cost elements of the cost-effectiveness assessment are:

(1)   the facilities and equipment costs for the ground based navigation system installations;

(2)   the operations and maintenance costs of the ground based facilities; and

(3)   the user cost in terms of the purchase price of the required airborne equipment.

The effectiveness of the different navigation systems will be measured as to how well they can meet the performance requirements as specified earlier in this report.

VORTAC, Loran-C, and Differential Omega have been selected as the radio-navigation systems of interest. In order to evaluate the systems, one must have an understanding of the individual methods of operation, performance characteristics, and costs. The following three chapters will describe each of the three systems; Chapter Five will furnish the comparative analysis; and finally Chapter Six will display the conclusions.

CHAPTER 2

THE VORTAC SYSTEM OF RADIONAVIGATION

The VORTAC radionavigation system broadcasts the signals which furnish the present method of short-range air navigation in the United States. This system is actually a combination of two independent navigation systems: the very high frequency omnidirectional range (VOR) and the tactical aerial navigation system (TACAN). The VOR provides azimuth (theta) information to primarily civil users, and the TACAN provides distance (rho) information to civil aircraft as well as azimuth and distance information to military aircraft. Figure 2-1 illustrates the cooperative arrangement and its service. The azimuth information from VORTAC is supplied as a bearing to or from the reference station, and the distance data is furnished in terms of the slant range in nautical miles from the station. The combination of VOR and the distance measuring equipment (DME) portion of TACAN has been adopted by the International Civil Aviation Organization (ICAO) as its standard short-range air navigation system, with the anticipated employment of this arrangement now extending through 1985. The short-range air navigation system in the United States consists of approximately 900 VOR facilities, with slightly over 700 of them having collocated TACAN equipment. [6] This large number of VORTAC ground facilities has been acquired and installed at considerable expense to support the air route structure which connects all major sources of traffic flow.

The VORTAC system has been in use for a number of years, and its primary purpose is to provide guidance along designated routes or airways throughout the United States. However, these routes are all aligned radially from the VORTAC stations, and this application ignores the fact that the rho-theta information provided is sufficient to furnish two coordinate position information anywhere within the coverage area of a VORTAC station. When appropriate data processing and displays are available, the VORTAC radionavigation system is capable of providing the information necessary to accomplish area navigation, and, in this light, has been chosen by the author as one of the candidate systems for study in this analysis.
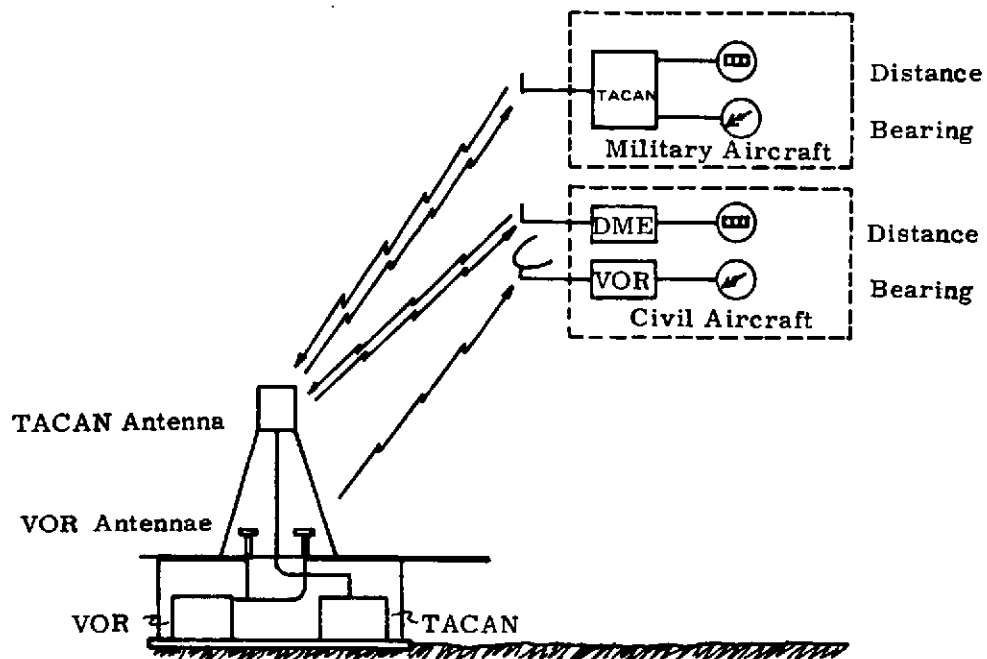
Figure 2-1. VORTAC Operation

Source: Kayton, M. and Fried, W., Avionics Navigation Systems, John Wiley
and Sons, Inc., 1969, p. 193.

2.1   The Very High Frequency Omnidirectional Range

The VORTAC radionavigation system, as stated earlier, is actually the combination of two independent navigation systems, i.e., VOR and TACAN. The present analysis will consider each of these systems separately and then combine the capabilities of the two in order to examine the area navigation potential of the complete VORTAC system. The very high frequency omnidirectional range was developed by the U.S. Civil Aeronautics Administration (CAA) in the 1940's and gained rapid acceptance as the recognized short-range navigational aid. It was designed to incorporate several basic considerations founded on CAA experience with earlier navaids. These include:

(1)   The indications received by the aircraft are heading insensitive, i.e., they are not affected by the direction of aircraft flight or its flight attitude;

(2)   The transmitted signals emanate from one point, originate in one transmitter and are radiated by a closely spaced antenna array;

(3)   The azimuth indications are presented to the pilot in such a manner that he may determine his bearing, or fly a course toward or away from the station without resorting to charts or communications with ground stations;

(4)   The portion of the frequency spectrum used was chosen to obtain the most consistent reception of signals, day or night, in spite of weather conditions. It also provides for the minimum interference between VOR stations in the system;

(5)   Ground station equipment that provides reliability from both an accuracy of signals and a continuity of service basis; and

(6)   A provision for simultaneous transmission of voice communications and identification on the same frequency. [7]

The VOR provides navigation information on one of eighty frequencies spaced 100 kHz apart in the 108.0-118.0 MHz segment of the very high frequency (VHF) band. The portion of the band between 108.0 and 112.0 MHz is shared with the localizer facilities of the instrument landing system. The VOR operates on the even tenths of megahertz in this segment, and the localizer operates on the odd tenths. For example, 108.6 MHz could be used for a VOR frequency; however, 108.7 MHz would be reserved for localizer functions. The VHF band is relatively free of atmospheric disturbances and precipitation static, and it can, through the use of VOR signals, provide guidance to or from the station on any course the pilot may select.

The quest for a navigation system that provides this omnidirectional information has been underway for a long time. In fact, in 1916 a simple light system was utilized which introduced the principle of operation to be applied in the much later developed VOR's. In this early system a rotating light beam and a non-directional signal were combined in such a manner that the rotating beam swung continuously at a predetermined rate, and every time that beam swung past magnetic north the nondirectional signal was lighted momentarily. The time interval between the receptions of the nondirectional signal and the rotating beam could be used to compute the observer's azimuth in relation to magnetic north. As an example, assume that the rotating beam completes one cycle every 18 seconds. Since this beam would revolve through 360° every 18 seconds, its angular velocity could be computed to be 20° per second. If the nondirectional signal is sighted exactly 6.4 seconds before the rotating beacon, the observer would know that he was on the 128° [6.4 seconds x 20° per second] radial from the station.

The VOR system of today provides navigation information using essentially the same principle as the rotating beam of 1916. However, the entire process is accelerated by rotating the beam at an angular velocity of 30 revolutions per second. This high speed makes the measurement of the time interval between the reception of the two signals quite difficult. The problem is resolved by measuring the phase difference between the two signals rather than the time interval. At north azimuth the signals transmitted by these two sources are adjusted to be in phase. As the directional signal rotates it goes out of phase with the signal from the nondirectional source. The airborne receiving equipment measures this phase difference and from it determines the bearing to or from the reference station.

VOR is a phase comparison system. This means simply that the phase of one signal is compared with the phase of another. However, a problem arises in that this type of comparison is possible only between signals whose frequencies are identical, and one also needs to be able to identify the source of each signal. Sometimes this identification can be accomplished by time multiplexing the signals and storing the phase information in the receiver circuitry for later comparison. But in the VOR system both signals are transmitted simultaneously, and there needs to be a way to prevent the two from producing a resultant as they pass through space. This is accomplished by transmitting one signal as amplitude modulation and the other as frequency modulation. Detection in the receiver produces two separate audio signals of exactly the same frequency but with measurable phase difference.

The two signals being compared are both 30 Hz signals. One is transmitted in a manner so as to produce a circular radiation pattern. Thus all aircraft at the same instant in time, and at the same distance from the transmitter, receive the same exact phase of this 30 Hz signal. Consequently, this signal is called the

reference signal. The other signal has a radiation pattern shaped like a cardioid, and this pattern is caused to rotate about the station 30 times per second. Figure 2-2 illustrates the cardioid pattern. The airborne equipment which receives this cardioid signal detects a signal strength which depends on which part of the cardioid it is receiving at any particular instant of time. By the rotation of this pattern amplitude modulation is created, and the received signal strength from the variable signal undergoes a cyclic change which is repeated 30 times per second.

Since both signals occur at the same 30 Hz rate there is a repetitive synchronization betweeen the two, and all that is needed is an index point so that they may be compared for phase difference. This index point is established on the reference signal, and the phase of the variable signal is initially adjusted so that the phase difference between the two is 0° at magnetic north. The rotation of the variable signal from north azimuth creates a phase difference of one electrical degree for each rotational degree; therefore, an observer can determine his geographical azimuth by simply measuring the phase difference between the phase of the reference signal and the phase of the variable signal. Figure 2-3 illustrates the phase difference that would be measured at the cardinal points of the compass rose. A receiver anywhere within the coverage area of a facility will receive two 30 Hz signals-one from the reference field and one from the variable field cardioid that is passing by. The phase of the signal from the variable field will lag that of the reference field by the exact number of degrees the receiver bears from magnetic north.

The practical application of almost any theoretical concept, including, most certainly, that pertaining to a radionavigation system, introduces errors into the picture. The VOR system is no exception. While its performance is relatively consistent it is limited by two major factors:

(1)   site errors due to radiowave reflection from objects near the transmitting facilities; and

(2)   measurement errors which occur while reading the phase difference of the 30 Hz signals in the airborne receivers .

In order to understand the operation of the VOR system one must examine the characteristics of the transmitting and receiving equipment and then look at some of the improvements that have been adopted or suggested for future implementation so as to increase the accuracy and limit the effects of the errors.

2.1.1   Conventional VOR Transmitter Operation

During the operation of a conventional VOR transmitter two signals, one omnidirectional and one dependent on azimuth, are radiated by an antenna system comprised
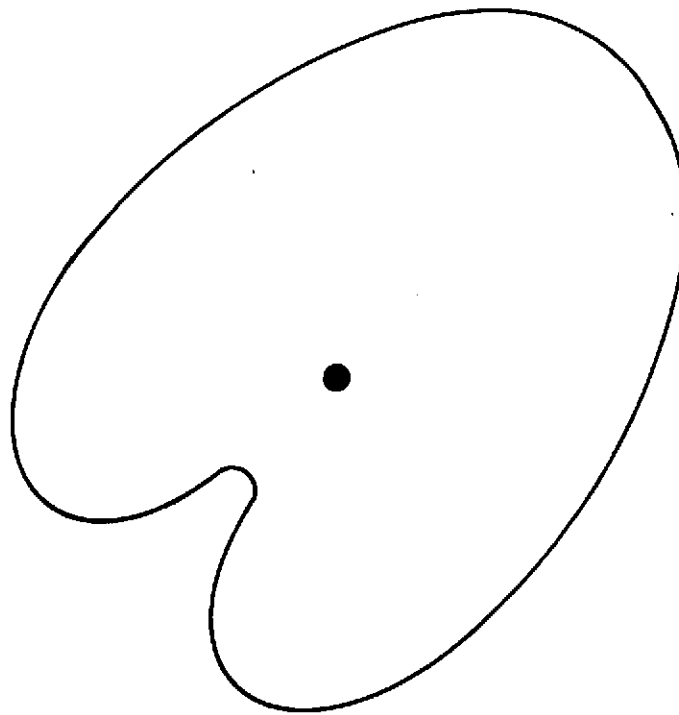
Figure 2-2.   VOR Variable Signal Cardioid
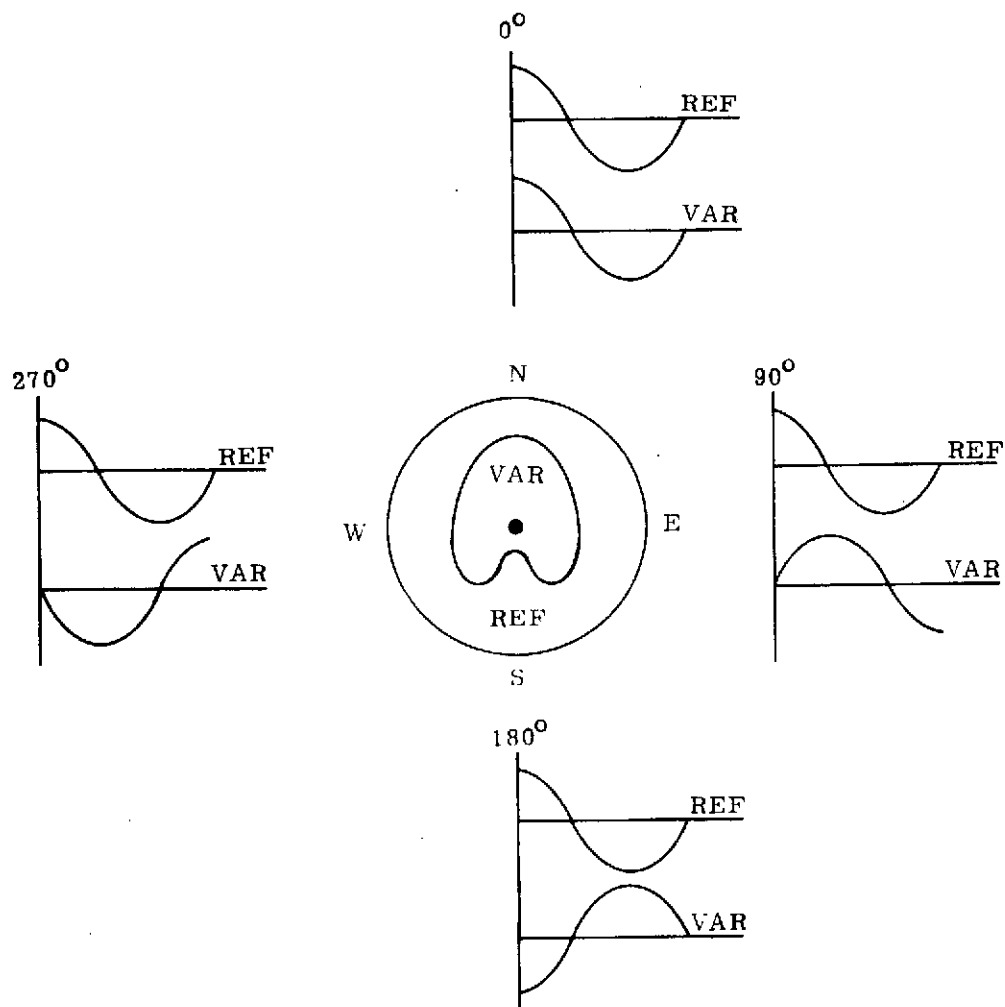
Figure 2-3. Phase Relationship Between VOR REF and VAR
at the Cardinal Compass Points

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of four Alford loops. The omnidirectional signal carries three separate elements of intelligence to the receiver:

(1)   voice modulation;

(2)   a 1020 Hz station identity tone; and

(3)   the bearing reference signal.

The voice modulation and the 1020 Hz station identity tones are actually extraneous to the navigation function. However, they do provide an important service and will be described briefly. The capability to voice modulate the omnidirectional signal from a VOR transmitter furnishes an additional route of communication to flight service stations or similar air traffic control functions. This is a simplex type of communication where the ground facility can only transmit and the airborne equipment can only receive, but it does provide a useful emergency outlet. In addition, some VOR stations use the voice modulation to identify the facility, e.g., every 15 seconds the voice transmission "This is Lake Henry VOR" may be carried by the omnidirectional signal. Identification of all stations is made by using the 1020 Hz station identity tones. The VOR station identification code consists of a three letter characteristic formed by dots and dashes in accordance with the Morse Code, e.g., the Anchorage (ANC) VOR would be coded as $\cdot - / - \cdot / - \cdot - \cdot$. This signal is transmitted by the station every 6 seconds, and the lack of the identity tone is used to indicate that a station is out of tolerance or off the air.

The third element of intelligence in the omnidirectional transmission is the bearing reference signal. Its presence is, obviously, crucial to the navigation function. The reference field is generated when an audio signal, whose frequency is constantly being changed, is used to amplitude modulate the VOR carrier transmission. This audio signal is a 9960 Hz transmission which is frequency modulated ± 480 Hz sinusoidally at the rate of 30 Hz. If this signal were received on a conventional receiver it would sound like a high pitched tone with a 30 Hz wobble. This wobble is a means of carrying 30 Hz intelligence through space.

The mechanical process which initiates this transmission is quite simple. A tone wheel is driven by an 1800 rpm (30 rps) motor; and on this wheel are 332 teeth which are arranged in a slightly staggered manner so as to impart a cyclical variation between 9480 Hz and 10,440 Hz with the rotation of the motor. The frequency modulated signal from this tone wheel is then used to amplitude modulate the VOR carrier signal. The airborne receiver uses numerous filters, limiters, and discriminators to reproduce the 30 Hz intelligence which will provide the reference for the bearing phase comparison.

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The azimuth related signal is generated coincidentally with the reference transmission. The same shaft that drives the aforementioned tone wheel also drives a capacitative goniometer which is being fed by the station transmitter. This goniometer is responsible for furnishing the cardioid shaped pattern that creates the azimuth related signal.

The creation of this azimuth related signal occurs through the use of a clever radio frequency (RF) feed arrangement. A portion of the energy that was generated by the transmitter and modulated at the 9960 Hz rate is removed and fed, after demodulation, to a goniometer. This goniometer has two functions:

(1)   it converts the carrier frequency into upper and lower 30 Hz sideband frequencies; and

(2)   it provides two outputs, separated 90° in phase, each feeding an Alford loop antenna pair.

The four Alford loops that comprise the VOR antenna system are mounted on the corners of a square. They are combined in such a manner that the northwest and southeast loops are designated as pair No. 1, and the northeast and southwest loops as pair No. 2. Figure 2-4 illustrates this arrangement. The RF feed to the loops of a pair is from a common feed line but connected so as to make the radiation of one loop 180° out of phase with the radiation from its companion loop. Therefore, the radiation from a pair produces a figure eight pattern with one lobe having energy phased directly opposite to that of the other lobe. Figure 2-5 illustrates this principle. If one considers a moment of time when the power fed to both pairs of loops is equal, the radiation pattern is four lobes of equal intensity - one figure eight from pair No. 1 and one figure eight from pair No. 2. Since pair No. 2 is configured 90° from pair No. 1, its radiation pattern is adjacent. The phasing between the pairs is such that the two lobes pointing north have the same phase, and this arrangement produces one resultant lobe of that phase. See Figure 2-6. The same thing happens to the two lobes directed south. Consequently, when equal power is furnished to all loops, the resultant radiation pattern is one large figure eight with lobes having opposite phase. As previously mentioned, the goniometer provides two outputs, separated 90° in phase, to the Alford loop antenna pairs. One output has an amplitude proportional to the sine, and the other an amplitude proportional to the cosine, of the rotational angle of the goniometer rotor. Hence, as the RF energy from the No. 2 antenna system is building to a maximum, the energy from the No. 1 system will be collapsing to 0. For example, at 30° azimuth the goniometer plates are in a position where antenna pair No. 1 would be producing $\frac{1}{2}$, i.e., sin 30°, of its total available power, while pair No. 2 is generating 0.866, i.e., cos 30°, of its total available power. The addition of the two would produce a resultant figure eight pattern with its maximum positive lobe directed toward 30° of azimuth. The collapsing and building of the two patterns is a continuous process that produces a smoothly rotating figure eight resultant.

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MAGNETIC
NORTH

WEST —————————————————————— EAST

NW   NE

SW   SE
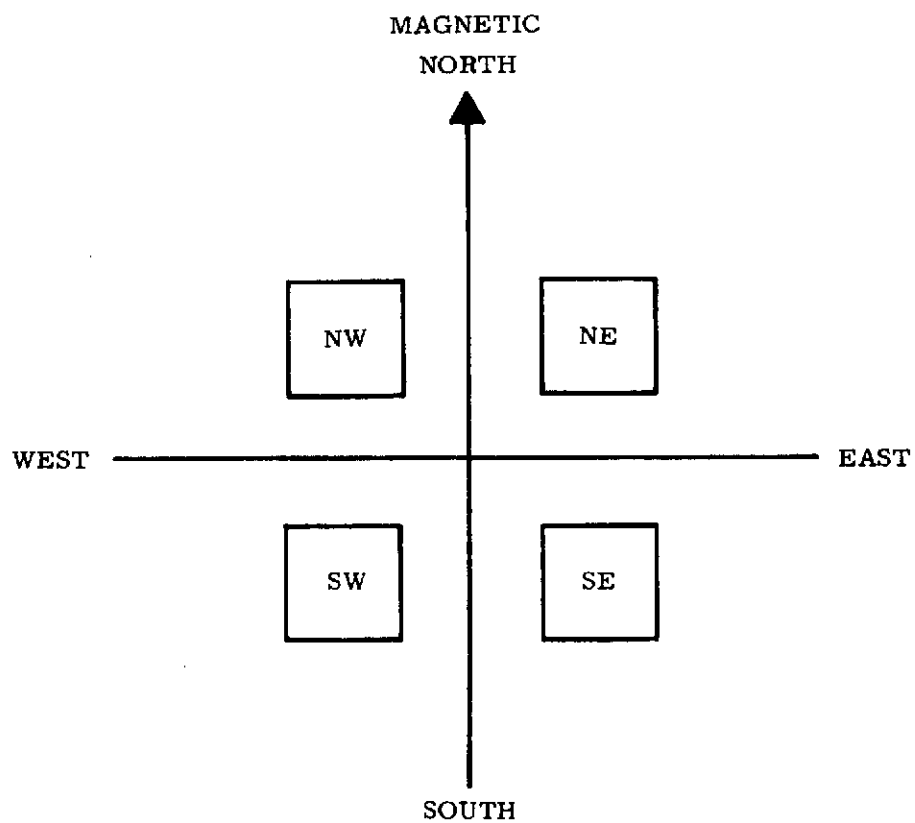
SOUTH

NORTHWEST-SOUTHEAST LOOPS: PAIR NO. 1
NORTHEAST-SOUTHWEST LOOPS: PAIR NO. 2

Figure 2-4. Orientation of the Four Alford Loops
in the VOR Antenna System

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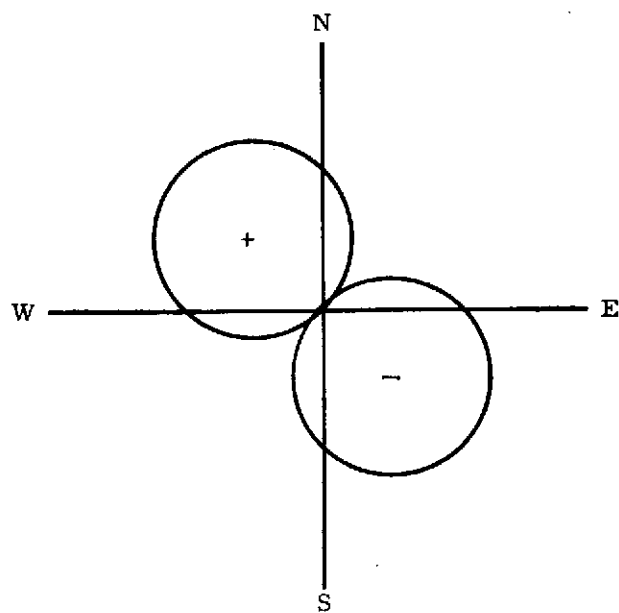
FIGURE 8 from PAIR NO. 1
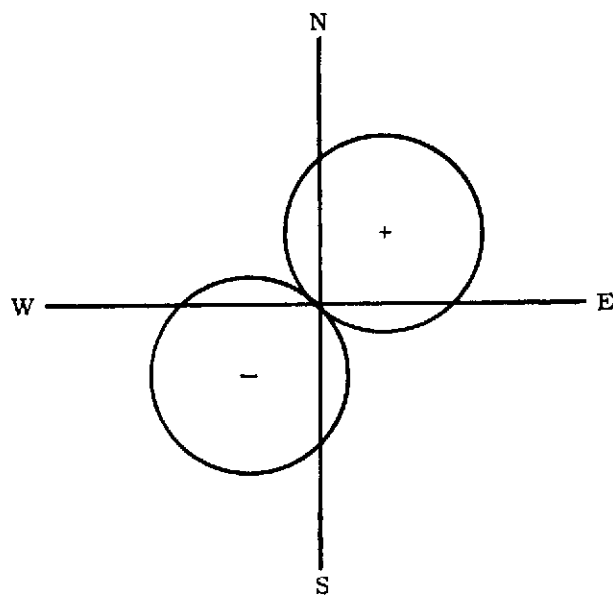
FIGURE 8 from PAIR NO. 2

Figure 2-5. Radiation Patterns from Alford Loop Pairs
in the VOR Antenna System

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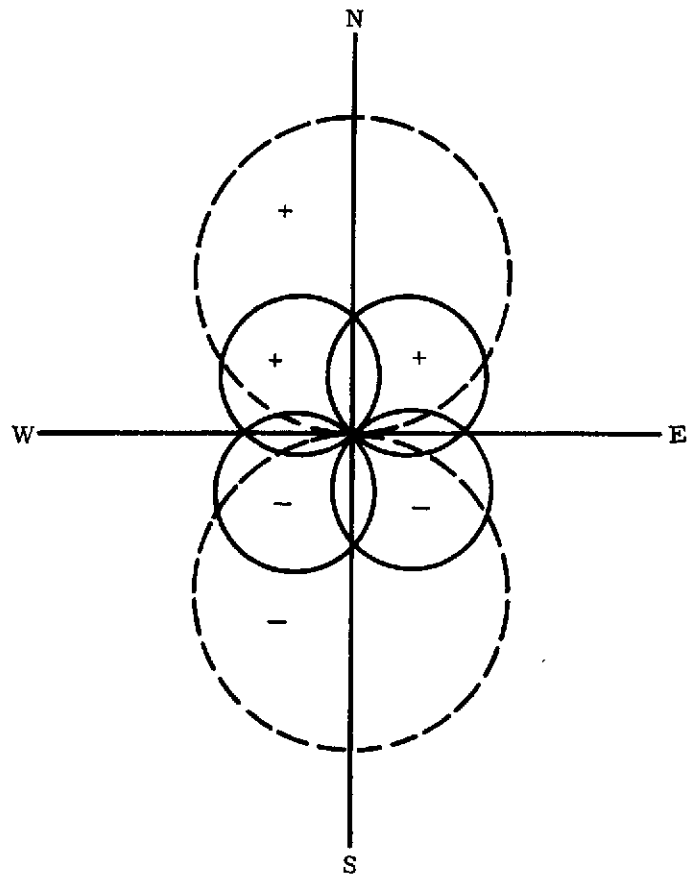
Figure 2-6. Resultant Figure 8 Radiation Pattern for All
Alford Loops Having Equal Power Input

When the figure eight pattern from the sideband antenna pairs is combined in space with the uniform phase field of the carrier, there is a reinforcement between the positive phase of the figure eight pattern and the positive phase of the uniform phase field; vice versa for the negative phase of the figure eight. This, in effect, creates a rotating cardioid shaped pattern for the variable field. Figure 2-7 portrays this phenomenon. This cardioid shaped pattern amplitude modulates the VOR carrier signal and, once detected in the airborne equipment, provides the azimuth related signal used for phase comparison purposes.

In summary, the two navigation intelligence bearing signals of the VOR system are transmitted simultaneously. One, the azimuth dependent signal, is radiated as simple 30 Hz amplitude modulation of the VHF carrier. The other, the omnidirectional signal, is transmitted as frequency modulation of a 9960 Hz subcarrier which in turn amplitude modulates the VHF carrier. Figure 2-8 illustrates schematically the design of a conventional VOR transmitter.

2.1.2 VOR Receiver Operation

The primary purpose of the airborne equipment associated with the VOR system is to detect the 30 Hz amplitude modulated signal produced by the rotating cardioid pattern and compare it with the 30 Hz frequency modulated reference. Figure 2-9 depicts the basic receiver functions. At the output of the 108.0-118.0 MHz receiver is an AM detector. The purpose of this detector is to pick off the various amplitude modulating signals from the VHF carrier. The detector output is comprised of four elements:

(1) voice modulation, if it has been used at the transmitter;

(2) coded 1020 Hz identification tones;

(3) a 30 Hz signal produced by the rotating cardioid; and

(4) a 9960 Hz tone which has been frequency modulated ± 480 Hz by the 30 Hz reference signal.

The voice frequencies and the identification tone are relayed to the audio distribution system of the aircraft. The 30 Hz information which was amplitude modulating the carrier, i.e., the azimuth dependent signal, is filtered to remove other components and fed to the phase comparison circuitry. The 9960 Hz subcarrier information is removed by the 10kHz filter and then limited and applied to an FM detector whose output is the 30 Hz reference signal. After appropriate filtering this is compared with the azimuth dependent signal, and bearing information is the result.

There is a good deal of experimental evidence that indicates that a major portion of the ills of the VOR system can be attributed to the airborne equipment and the airborne environment. Professor McFarland of Ohio University has stated that all evidence collected during the experimental portion of a fairly extensive investigation definitely indicates that the receiver is the major contributor to the course error in the information presented to the pilot. [8] It has been established that, in

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VARIABLE FIELD FIGURE 8

REFERENCE FIELD
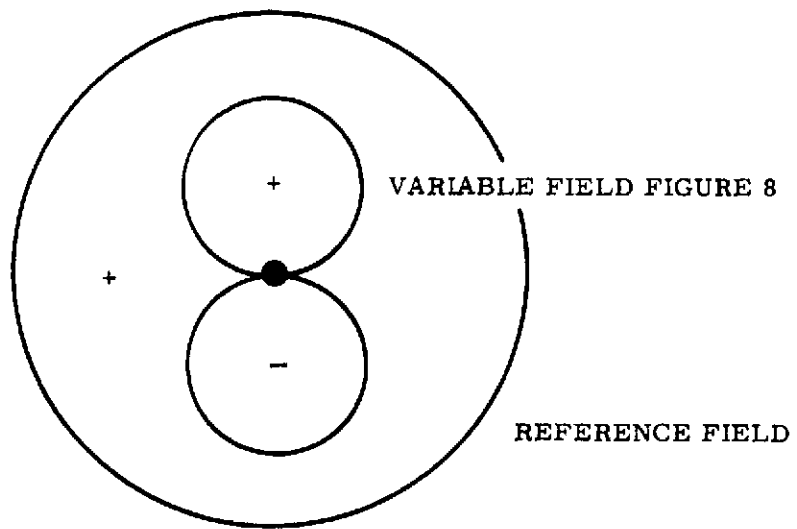
INDIVIDUAL RADIATION PATTERN
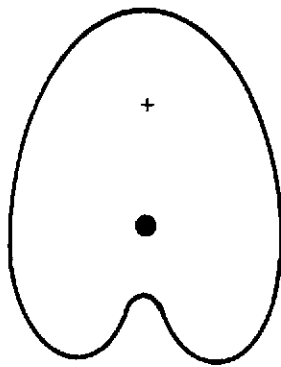
COMPOSITE RADIATION PATTERN OF CARDIOID SHAPE

Figure 2-7. Formation of Cardioid Shaped Composite
Pattern in the VOR System

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Four Alford Loops
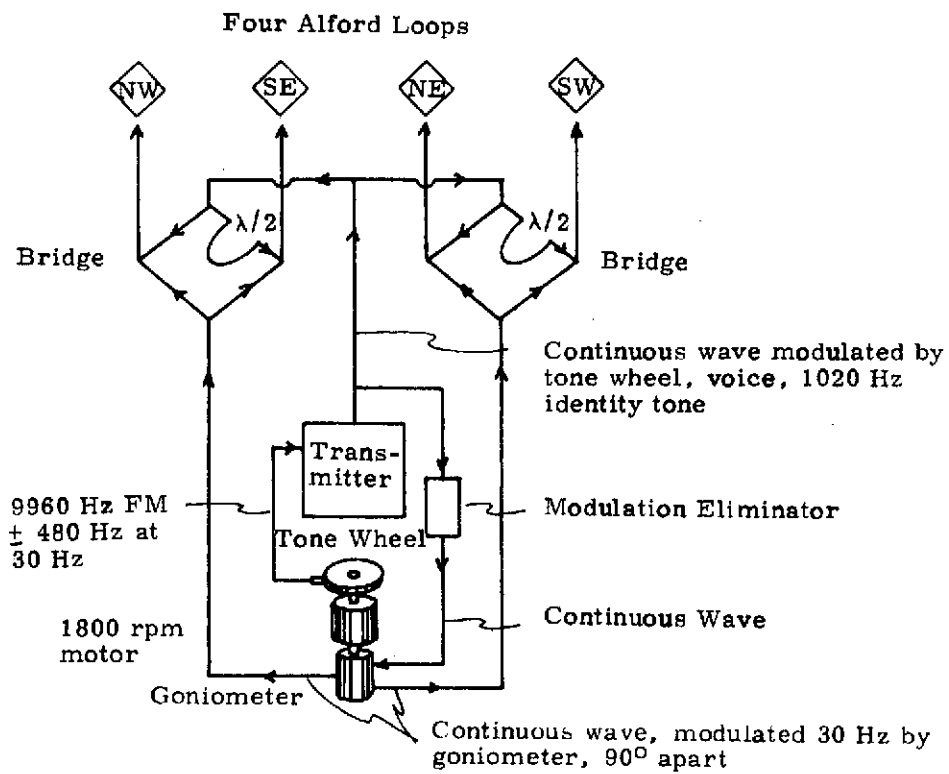
Figure 2-8. Schematic Drawing of Conventional VOR Transmitter

Source: Kayton, M. and Fried, W., <u>Avionics Navigation Systems</u>, John Wiley and Sons, Inc., 1969, p. 165.

VOR Antenna

Audio Output


```
┌──────────┐    ┌──────────┐    ┌────────┐    ┌──────────┐    ┌──────────────┐
│ Receiver │    │          │    │ 10 kHz │    │          │    │  Frequency   │
│108.0-118.0├──→│    AM    ├──→│ Filter ├──→│ Limiter  ├──→│Discriminator │
│   MHz    │    │ Detector │    │        │    │          │    │              │
└──────────┘    └──────────┘    └────────┘    └──────────┘    └──────────────┘

              ┌────────┐    ┌────────────┐    ┌────────┐
              │ 30 Hz  │    │   Phase    │    │ 30 Hz  │
              │ Filter ├──→│ Comparator │←──┤ Filter │
              └────────┘    └────────────┘    └────────┘
```

Bearing
Information
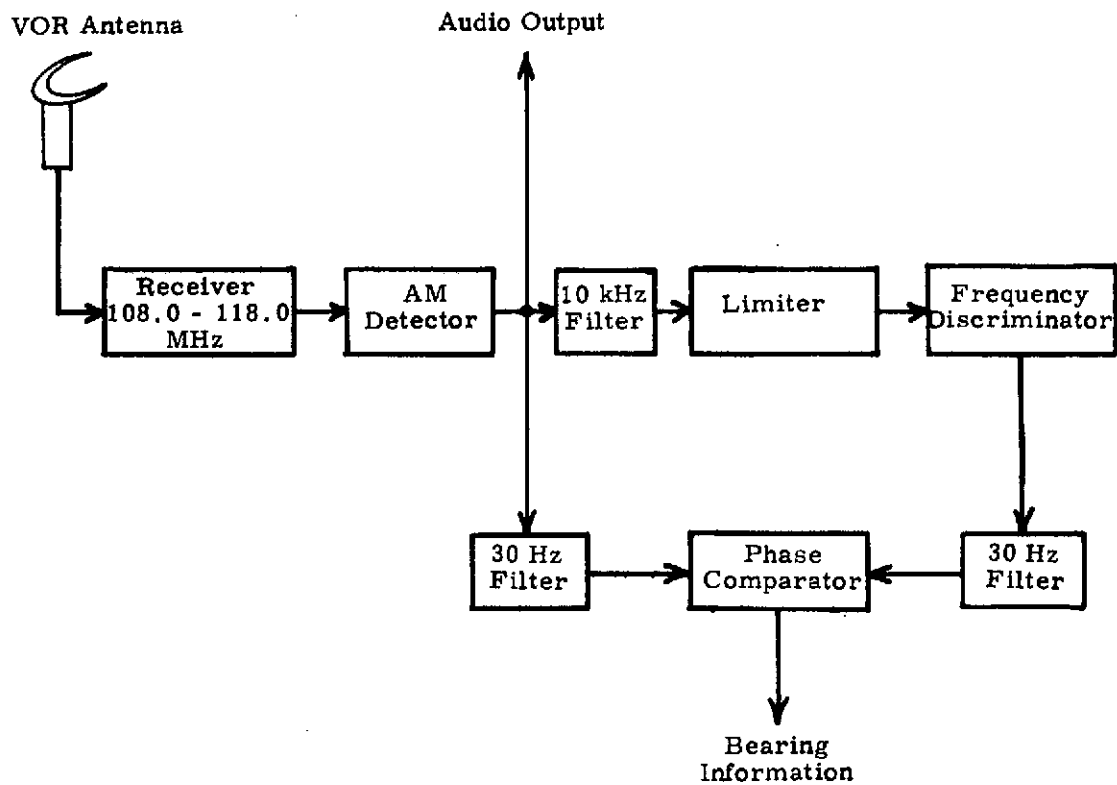
Figure 2-9. Schematic Drawing of Conventional VOR Receiver

Source: Kayton, M. and Fried, W., Avionics Navigation Systems, John Wiley
        and Sons, Inc., 1969, p. 167.

order to make theoretical calculations match observed facts with respect to VOR scallops and bends, reflection coefficients of from 100 to 1000 times predicted values would have to be assumed. [9] On the other hand, there is good agreement between theory and observed facts with respect to low frequency modulation of the VOR space field as a result of aircraft motion in the multipath space field. It appears that the receiver processing of the low percentage low frequency modulation is introducing large errors. McFarland's most distressing discovery was that new receivers do not necessarily provide improved performance in the rejection of signals which produce the course errors. Demonstrations, both in the air and on the test bench, showed that old and new receivers alike were, in themselves, producing excessive scallops and bearing errors when operated in the real-life VOR environment. Because different receivers were used in parallel, and different reactions were obtained, the receiver design is believed to be the most critical in determining the extent to which multipath will affect indicated course position. [10] The errors that result do not reflect the effects of receiver calibration, but rather the receiver design itself which inherently provides characteristics that either favor or reject the effects of the multipath signals. The receivers need the capability to be calibrated accurately and reject the low percentage low frequency amplitude modulation. Along with the normal improvements intended to capitalize on the various advantages of solid state devices, such as increased reliability and performance with reduced size, weight, and cost, there is a trend toward designing receivers with the above capability in mind. The resultant receiver accuracy in such cases can be assumed to be on the order of 1°. Table 2-1 enumerates the characteristics of several representative VOR receivers presently available on the market. The cost of the VOR receivers for general aviation operations can vary anywhere from $800 up to $7000, but, for the purposes of the present analysis, it is assumed that a highly accurate VOR receiver can be obtained for about $1500-2000.

2.1.3 VOR Accuracy Capability

The performance, with respect to accuracy, of any radionavigation system is dependent upon essentially three elements:

(1) calibration and control of the transmitter operation;

(2) propagation of the signal through space; and

(3) receiver processing and display.

The FAA employs extensive monitoring and flight check programs to ensure that the VOR system provides signals within specified accuracy tolerances.

Table 2-1

REPRESENTATIVE VOR RECEIVERS

Model	Characteristics	Price
Aircraft Radio Corp.		
841 Nav System (Cessna nav 800)	200 channels; panel mtd. cntrl. & ind.; remote rcvr. & cnvrtr.; solid state; RMI	$3,495
R-442A Nav System (Cessna nav 400)	200 channels; panel mtd.; solid state	$1,600
Collins Radio		
51R-7A	380 channel; covers VHF comm.; remote mtd.; solid state; RMI; RNAV	$2,640
51RV-1	200 channel; remote mtd.; solid state; RMI; RNAV	$6,468
King Radio		
KNR 600A	200 channel; panel mtd. sel.; remote mtd. rcvr.; solid state	$2,550
KNR 660A	200 channel; panel mtd. sel.; remote mtd. rcvr.; solid state; RMI	$3,475
Narco Avionics		
NAV-11	200 channel; panel mtd. self-contained; solid state	$ 925
NAV-111	200 channel; panel mtd. rcvr.; solid state; HSI or RMI	$1,170
RCA Avaition Equip.		
AVN-210A	200 channel; 40 GS; MB; panel mtd.; solid state	$4,140

The basic control of the transmitter operation is related to the antenna system and its adjustments. Modifications to the current amplitudes and phase relationships in the system are accomplished by mechanical adjustments to the current dividing and phasing networks; and once adjusted they remain constant over a long period of time. The system must be adjusted so that the phase difference between the omnidirectional signal and the azimuth related one is as close as possible to 0° at magnetic north and then varies accordingly around the compass rose. The ground station accuracy is determined from measurements made at the edge of the station counterpoise, and in order to commission the facility, the maximum spread of the error must not exceed 1.5°. Most of the errors are cyclic in nature, and an analysis of the error curves can be made to determine which of the current amplitude or phase relationships needs correction. Once this is accomplished, a VOR monitor is used to keep a constant check on the signals and determine that their level and phase are maintained within prescribed tolerances. The monitor performs the following functions:

(1)   it keeps a continuous check on the amplitude of the transmitted reference signal and will cause an alarm if this signal decreases by 13% or more;

(2)   it keeps a continuous check on the variable signal amplitude and will cause an alarm if this signal decreases by 13% or more;

(3)   it keeps a continuous check on the omnicourse at a selected azimuth about the station and will cause an alarm if the input phasing changes more than 1°;

(4)   it isolates the 1020 Hz identification signal and routes this audio frequency to a monitor amplifier either at the VOR or at the station controlling the VOR facility. Loss of this 1020 Hz identification, as seen at the monitor amplifier, will cause the monitor to indicate an alarm;

(5)   it incorporates a means of self test through the use of the tone wheel output so as to check for phase shifts or faulty stages within the monitor itself; and

(6)   it incorporates circuits that allow the monitor to be used for ground checking of the VOR. [11]

By employing this monitor system the FAA can be confident that the phase and strength of the signals from the transmitter facility are maintained at the desired level.

Errors due to the propagation of the signal through space occur primarily as a result of the multipath effect. This phenomenon is present when signals from the transmitter are reflected by objects and then relayed to the airborne receiving equipment. The two signals, one direct and the other reflected, interfere at the receiver

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and can cause significant bearing errors. The source of reflection can be any number of things, ranging from raindrops and snowflakes to building and trees. In practice, the errors that result from the reflections are divided into two categories:

(1)   atmospheric propagation errors; and

(2)   siting errors.

The atmospheric propagation errors yield very small excursions from the norm. Experimental work performed by Professor McFarland and his cohorts at Ohio University has demonstrated that the atmospheric propagation effects produce only about 0.2° course error with a 3 σ probability. [12]   In that we cannot hope to control, improve, or change the medium in which the VOR signal is propagating, this is felt to be the ultimate limit to VOR system accuracy.

The siting errors are another matter. The bearing discrepancies that appear as a result of siting errors can be very large. Locating suitable VOR sites is a difficult problem because buildings, wires, fences, and trees reflect the electromagnetic radiation from the transmitter and cause numerous bearing errors. These errors appear as course scalloping, course roughness, course bends, and, in special cases, fixed errors. The reader is referred to reference 13 for a good description of the siting problem and summary of experimental results. In an effort to minimize these errors siting criteria have been established. The transmitter must be located on relatively flat terrain or on top of a knoll which has reasonably uniform contours over a radial distance of 1500 feet from the station. The area should be cleared of all obstacles capable of providing serious reradiation, and the line of sight to clear all obstacles within a radius of 2000 feet should subtend a vertical angle of less than 2°. In addition, the power and telephone lines to the station should be installed underground up to a distance of 750 feet from the transmitter. However, some sites are not capable of meeting these standards, and compromises must be accepted. In fact, it is estimated that a significant percentage of present VOR's (25%) are currently restricted due to poor signal quality, and a large percentage are impaired to a lesser extent. [14]

Because actual station performance may be degraded to an unacceptable level by things far removed from the station, e.g., terrain reflections causing scalloping, roughness, and bends, the ground monitor system, as described above, is incapable of guaranteeing acceptable performance by the VOR station. Specially equipped flight inspection aircraft are used to remove this limitation. They check all facilities before commissioning and accomplish periodic performance checks to ensure that the signal made available to the user is within tolerance. The standards established are such that the alignment of all electronic radials will be within 2.5° of the correct magnetic azimuth; momentary deviations of the course due to roughness, scalloping,

or combinations thereof will not exceed 3.0^O from the average course; deviations of the course due to bends will not exceed 3.5^O from the computed course alignment and must remain within 3.5^O of the correct magnetic azimuth; and finally, the effects of any one or any combination of the above conditions will not render the radial unusable of unsafe. [15]

At present, on a statistical basis, the overall ground station error (2σ) of the VOR's installed in the United States is somewhat less than $\pm 2.0^O$. [16] This figure by itself does not provide enough information to evaluate the suitability of VOR as a component in an area navigation system, but it does provide a general evaluation of its potential. The VOR system has a problem in that a constant angular error results in an increase in displacement with range from the station. If the system is to be used for future RNAV applications, better accuracy than presently available is desirable.

2.1.4 VOR System Improvements

Various techniques have been developed to improve the performance of the VOR radionavigation system. The prime emphasis of these efforts is to provide greater bearing accuracy or to permit the use of poorer quality sites with acceptable bearing accuracy. These techniques include Doppler VOR, precision VOR, and the use of vertical directivity in the antenna systems.

2.1.4.1 Doppler VOR

It is a well known fact that the VOR can suffer serious degradation of received signal quality due to the reflections and reradiation of signals from surrounding objects. Area navigation implementation tends to magnify this problem. The terrain requirements for the installation of a VOR can be quite stringent, and this makes it difficult to realize the full potential of the system. As early as 1957 studies indicated that the Doppler principle could be used to reduce the siting errors of the VOR. While the Doppler VOR (DVOR) is not necessarily more accurate than the conventional VOR on an ideal site, the degree of signal quality improvement it offers on a poor site is quite high. DVOR facilities were first installed in 1958 at a few sites for operational evaluation purposes, and at present there are approximately 30 such installations around the country. [17]

The Doppler VOR applies the principle of wide antenna aperture to the reduction of site error. The configuration used by the FAA involves a 44 foot diameter circle of 52 Alford loop antennae, together with a single Alford loop in the center. The central loop radiates an omnidirectional VHF continuous wave that is amplitude modulated at 30 Hz by any conventional means. This creates the reference phase signal. The circle of 52 Alford loops is fed by an evolving commutator so as to simulate the rotation of a single antenna at a radius of 22 feet. The commutator rotates

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at 30 rps, and it is fed by a signal whose frequency is 9960 Hz higher than that radiated from the central antenna. This 9960 Hz higher signal is frequency modulated by the simulated rotation of the antenna. Demonstrating the classic Doppler effect, the signal increases in frequency as the antenna appears to move toward the receiver and decreases in frequency as it appears to move away. With a 44-foot diameter and a rotation speed of 30 rps, the peripheral speed is on the order of 4145 feet per second, or about 480 wavelengths per second at the VHF carrier frequencies. This results in the 9960 Hz signal being varied by ± 480 Hz at the 30 Hz rate, with a phase dependent on the bearing of the receiver. This forms the azimuth dependent signal.

In the Doppler VOR the roles of the central antenna and the array are reversed from those used in the conventional system. However, the phase relationships remain the same, and this allows a standard airborne receiver to operate without any modification. The output of the AM detector in the receiver contains all the signals present with the conventional VOR. Phase comparison between two 30 Hz sine waves is performed as before with the only difference being that the 30 Hz AM signal is the reference and the 30 Hz FM signal is azimuth dependent. Since the instrumentation in the receiver is concerned only with the difference between the two, normal operation results.

The system described above, where a 30 Hz FM signal is carried on a single sideband with respect to the central radiator, does not affect all receivers in quite the manner intended. Some amplitude modulation is introduced by radiator conditions changing with the location of the instantaneous radiator in the circular array, and this considerably lowers the bearing measuring accuracy of some receivers. It has been found, however, that if two sidebands are radiated, one below and one above the carrier, all conventional receivers will react as intended.

The reduced susceptibility to course accuracy deterioration resulting from obstacles around the site is due to the fact that the azimuth dependent signal is now contained in the subcarrier frequency modulation. A phenomenon known as frequency modulation capture effect prevails. For a bearing error to exist at the receiving point there must be a combination of correct bearing information and incorrect or reflected information. The frequency deviation cycle of the incorrect information is displaced in time from that of the correct intelligence. If the reflected signal is shifted 90° in phase and has an amplitude 1/20 of the direct signal, when added to the direct signal, it will have little or no effect on the instantaneous frequency of the subcarrier. The antenna aperture is related to the capture effect in that, with greater aperture, the overriding of unwanted signals is greater since the frequency modulation deviation is greater. Since the aperture of the ground antenna system for a Doppler VOR is approximately 5 wavelengths as compared with less than one-half a wavelength in a conventional VOR, a ten-fold reduction in site error is theoretically possible. Actual

measurements bear this out. At a good site, the maximum deviations due to course scalloping and bending, measured during a 20 mile orbital flight, were reduced from 2.8^O with the conventional VOR to 0.4^O with the Doppler VOR. [18] These perturbations are over and above those specified for radial alignment accuracy. The final assessment of ground station performance using the Doppler VOR can be assumed to be on the order of 1^O, and this can be accomplished without any change in the airborne equipment.

2.1.4.2 Precision VOR

The development of the precision VOR in this country has progressed along essentially two tracks. Applications of the multilobe principle were explored first, and later, additional signals to the aforementioned Doppler VOR were introduced.

The multilobe arrangement took the 52 antennae of the Doppler VOR and electrically arranged them into thirteen groups of four so as to produce a rotating 13 lobe pattern. This configuration generated coarse and fine navigation signals. The phase comparison frequency for the fine pattern had to be chosen so as not to interfere with the existing receivers or with the 30 Hz signal format used in the coarse pattern. A frequency of 53 Hz was used in some of the experimental models. When the receiver was controlled by the 13 lobe pattern, a 13-fold increase in instrumental accuracy theoretically became possible. However, since the 13 lobe pattern repeated itself every 28°, it was important for the coarse information to always be correct within $\pm 14^O$ or a serious ambiguity would occur. With the Doppler VOR signal being used as the coarse information there was little danger of this.

However, the multilobe principle was not adopted as the standard method of achieving precision VOR. The reasons for nonacceptance were complex and involved factors other than purely technical ones:

(1)   at the time of system testing there was no full realization of the need for a highly accurate VOR;

(2)   there were fears with regard to the integrity of the multilobe systems in general; and

(3)   there was hope that airborne techniques (signal processing) could achieve comparable results at a lower cost. [19]

These reasons did prevail and other efforts were undertaken for precision VOR development.

The Doppler VOR system inherently contains bearing information of precision quality, but the high accuracy in the signal can only be realized by proper processing in the airborne receiver. There has been an overriding philosophy in all VOR improvement programs to maintain the highest possible degree of compatibility with the thousands of airborne receivers currently in use. In the case of precision VOR

it is clear that some modification to the airborne equipment is required in order to fully realize the benefits of the improved accuracy. FM/FM precision VOR offers an opportunity for improved accuracy while maintaining the required compatibility. In the following material the author relies heavily on the description of the FM/FM precision VOR contained in Reference 20. The basic approach chosen in the FM/FM precision VOR consists of introducing another subcarrier onto the radiated signal on which the 30 Hz reference signal is frequency modulated. This subcarrier, in turn, then frequency modulates the VHF carrier. At the same time, the conventional 30 Hz amplitude modulating signal is still radiated for compatibility with unmodified receivers. In order to leave room for the 30 Hz amplitude modulation and the voice modulation of the VHF carrier, the new FM reference subcarrier was chosen at 6480 Hz. Figure 2-10 depicts the frequency spectrum of the compatible frequency modulating signal introduced into the Doppler VOR. This precision VOR method utilizes the Doppler VOR as its starting point and cannot be achieved by addition to a conventional VOR ground station.

The modifications necessary to convert a Doppler VOR to a FM/FM precision VOR are quite modest and capable of being accomplished at reasonable cost. They consist of:

(1) providing a mechanical linkage to the motor driven distributor which, by means of a tone wheel, will generate the 6.5 kHz subcarrier, phase locked to the 30 Hz variable signal; and

(2) installing a voltage controlled crystal oscillator which is substituted for the conventional crystal oscillator. Minor modification in the airborne equipment is also required.

Analysis has shown that there are a number of factors that contribute to the improvement obtainable through the use of FM/FM precision VOR. These are:

(1) reduction of cross modulation in the second detector of the receiver;

(2) isolation from the reference signal of unwanted amplitude modulation of the 9960 Hz subcarrier due to counterpoise effect;

(3) rejection of unwanted 30 Hz components at the second detector due to multipath; and

(4) improved signal to noise ratio by virtue of the frequency modulation capture effect.

Engineering test results show that a bearing accuracy improvement of 3 to 1 over Doppler VOR can be achieved by using the frequency modulating reference.

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.CARRIER

30 Hz AM
REFERENCE

30 Hz AM
REFERENCE

PRECISION DVOR
FM REFERENCE

PRECISION DVOR
FM REFERENCE

SSB DVOR
FM VARIABLE

VOICE

VOICE

8   6   4   2 f_c 2   4   6   8   10

6.5 kHz
± 480 Hz

-kHz

+kHz

6.5 kHz
± 480 Hz

9.96 kHz
± 480 Hz
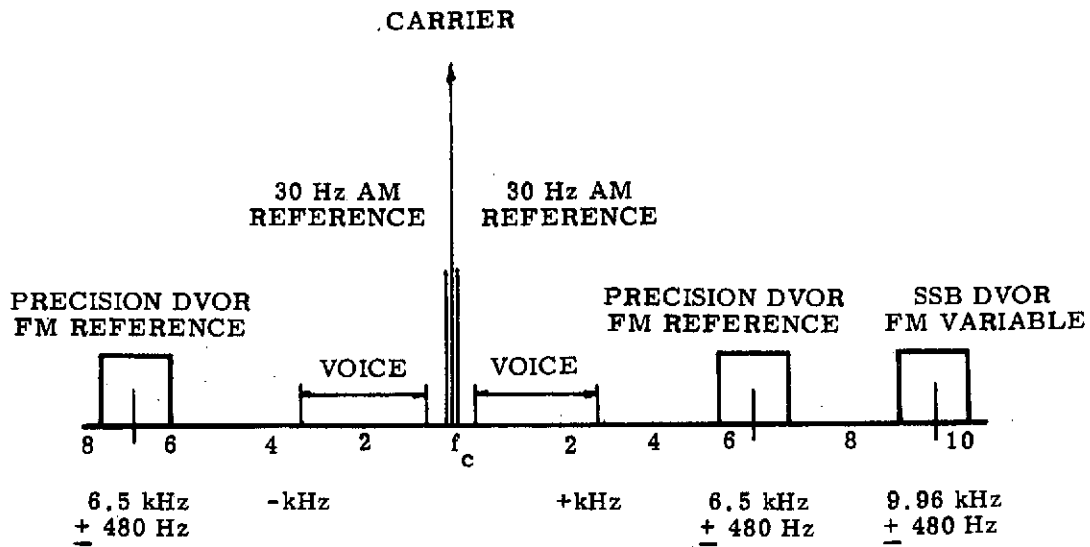
Figure 2-10. Spectrum of Single Sideband Doppler VOR
with Precision FM Reference

2.1.4.3   Antenna System Improvements

In addition to the development work in the Doppler and precision VOR's,
there has been an effort toward the production of antenna systems having appreciable
directivity in the vertical plane. The primary purpose of this directivity is to reduce
the amount of energy radiated at angles below the horizon and responsible for re-
radiation from low objects near the transmitter site. These antenna systems are
referred to as high gradient antennae. Two designs for high gradient antennae are
now being tested by the FAA. One is a stacked array of five bays without a counter-
poise so driven as to provide the necessary gradient and minimum signal below the
horizon, and the other is a parasitic ring array in which a conventional VOR four
loop antenna, installed above an elevated counterpoise, parasitically drives one or
more reradiating rings which surround it producing a similar high gradient and sig-
nal minima at negative vertical angles. These systems are being developed to pro-
vide operation at sites which present extreme difficulties. Congested areas where
there is a high probability of reradiation and remote areas where snow, ice, and
new vegetation growth would be difficult to control are considered as prime candidates
for this installation.

All of the improvements to the VOR navigation system are directed with the
intent of increasing the availability of a highly accurate resultant bearing signal.
This bearing signal forms but one part of the navigation intelligence required. To
operate successfully with the VORTAC navigation system, distance information, as
well as bearing data, must be provided. The next section describes this provision.

2.2   Distance Measuring Equipment

Distance measuring equipment (DME) furnishes the navigation intelligence
required to provide the pilot with an accurate determination of his distance from a
selected ground navigation aid. The operation of this equipment is based on the radio
interrogation-response principle using signals in the 960-1215 MHz segment of the
ultra high frequency (UHF) band. The need for an international agreement concern-
ing the establishment of such a distance measuring service was recognized by ICAO
in 1946, and by 1949 standards were established. However, a problem arose in that
these standards were not compatible with the military system of navigation (TACAN),
and it took the better part of six years to resolve this quandary. In 1955 the United
States Air Coordinating Committee decided to scrap the previous DME system and
employ the distance measuring portion of the TACAN. This resulted in the config-
uration as it exists today.

As with any new radio system, a chicken and egg problem tended to exist at
the outset. There would be no airborne equipment until there were ground beacons,
and there would be no ground beacons until there was airborne demand. Thus, while

ICAO adopted the present DME system as its standard in 1959, a few years elapsed before much civil use occurred. However, by 1969 there were approximately 13,000 civilian DME's in use, [21] and its adoption rate has been accelerating at such a pace that there may be as many as 20,000 civil sets in use today. While operating with the line of sight characteristics of VHF /UHF, DME furnishes distance information with a very high degree of accuracy and provides the second source of navigation intelligence in the VORTAC RNAV system.

2.2.1 General Method of Operation

The DME portion of the VORTAC system determines distance by measuring the travel time of a pulse pair from an airborne interrogator to a ground transponder beacon and return. The distance between the airborne interrogator and the ground station is directly proportional to this round trip travel time which has a value of 12.36 μ seconds for each nautical mile of slant range. The system is essentially composed of two elements: the airborne interrogator and the ground transponder beacon. The functions of the interrogator are to:

(1) produce a coded interrogation pulse train on any one of the assigned 126 channels;

(2) receive, decode, and process the ground transponder beacon replies into accurate distance information; and

(3) receive and reproduce the identification signal provided by the beacon.

At the same time, the functions of the ground transponder are to:

(1) receive and decode interrogations from the airborne equipment;

(2) encode and transmit appropriate replies on the assigned frequency; and

(3) transmit station identification signals.

The DME operational sequence begins when the airborne interrogator transmits a pulse pair on one of the 126 frequencies spaced 1 MHz apart in the 1025-1150 MHz band. Once the signals have been transmitted by the interrogator, the ground transponder beacon receives the pulse pair and, after a fixed delay of 50 μ seconds, retransmits them back to the aircraft on a frequency 63 MHz above or below the airborne transmitting frequency. The interrogator compares the elapsed time between its original transmission and the reception of the reradiated signals, subtracts the fixed delay at the ground station, and displays the results on a meter calibrated in nautical miles. Figure 2-11 illustrates the DME operational principle.

Examination of the particular elements of the system is necessary in order to more fully understand the principles of operation.

DISTANCE INDICATOR

SYNCHRONIZATION

RANGING CIRCUITS

126 CHANNEL TRANS-MITTER

126 CHANNEL RECEIVER

INTERROGATOR

INTERROGATOR OUTPUT

BEACON OUTPUT

TRANSPONDER BEACON

SINGLE CHANNEL RECEIVER

SINGLE CHANNEL TRANS-MITTER

ENCODING CIRCUITS & 50 μSEC DELAY
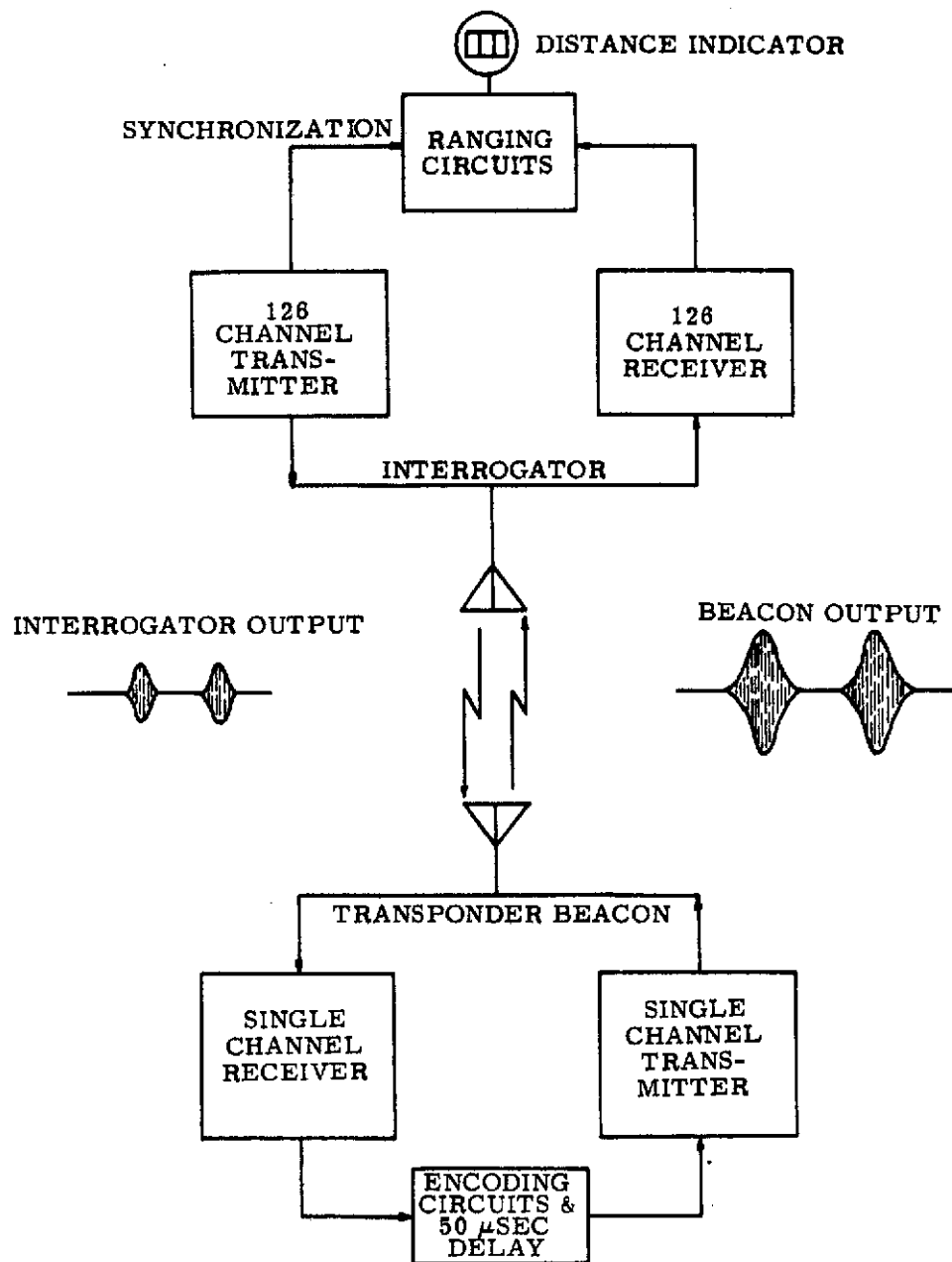
Figure 2-11. DME Operational Principle

2.2.2 The Airborne Interrogator

The functions of the airborne interrogator, as enumerated above, are to:

(1)   produce a coded interrogation pulse train on any of the assigned 126 channels;

(2)   receive, decode, and process the ground beacon replies into accurate distance information; and

(3)   receive and reproduce the identification signal provided by the beacon.

Channel selection capability is essential to DME operation. There are 126 different channels of operation in the DME, and the airborne equipment must be able to select the appropriate frequency for navigation operations with a designated ground station. In the present configuration 26 of the 126 channels are used exclusively for military operations, and the remaining 100 are designated for civil and military use. Most of the civil DME's are colocated with VOR facilities, and their operating channels are matched by a frequency assignment plan. This assignment plan is designed so that the pilot can tune the same frequency (the very high frequency channel of the VOR) onto the control head of the DME and automatically select the corresponding DME site. Table 2-2 illustrates the VHF/UHF Navaid Frequency Channel Assignment Plan.

Once the appropriate channel has been selected by the pilot, the airborne interrogator transmits a sequence of signals as the first step in DME operation. The airborne interrogation signals are approximately Gaussian shaped pulse pairs with the following characteristics:

(1)   rise time, i.e., the time interval as measured from the 10% to the 90% voltage amplitude points on the leading edge of the pulse - 2.5μ seconds $\pm$ 0.1μ seconds;

(2)   duration, i.e., the time interval as measured between the 50% voltage amplitude points on the leading and trailing edges of the pulse - 3.5μ seconds $\pm$ 0.5μ seconds;

(3)   decay time, i.e., the time interval as measured from the 90% to the 10% voltage amplitude points on the trailing edge of the pulse - 2.5μ seconds $\pm$ 0.1μ seconds; and

(4)   pulse pair spacing, i.e., the time interval between pulses of a pair as measured from the leading edge 50% amplitude point of the first pulse to the leading edge 50% amplitude point of the second pulse - 12.0μ seconds $\pm$ 0.5μ seconds. [22]

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Table 2-2
VHF/UHF NAVAID FREQUENCY CHANNEL ASSIGNMENT PLAN

Channel No.	VOR Freq MHz	Interrogate Freq MHz	Reply Freq MHz	Channel No.	VOR Freq MHz	Interrogate Freq MHz	Reply Freq MHz
1		1025	982	64		1088	1151
2		1026	963	65		1089	1152
3		1027	964	66		1090	1153
4		1028	965	67		1091	1154
5		1029	966	68		1092	1155
6		1030	967	69		1093	1156
7		1031	968	70	112.3	1094	1157
8		1032	969	71	112.4	1095	1158
9		1033	970	72	112.5	1096	1159
10		1034	971	73	112.6	1097	1160
11		1035	972	74	112.7	1098	1161
12		1036	973	75	112.8	1099	1162
13		1037	974	76	112.9	1100	1163
14		1038	975	77	113.0	1101	1164
15		1039	976	78	113.1	1102	1165
16		1040	977	79	113.2	1103	1166
17	108.0	1041	978	80	113.3	1104	1167
18		1042	979	81	113.4	1105	1168
19	108.2	1043	980	82	113.5	1106	1169
20		1044	981	83	113.6	1107	1170
21	108.4	1045	982	84	113.7	1108	1171
22		1046	983	85	113.8	1109	1172
23	108.6	1047	984	86	113.9	1110	1173
24		1048	985	87	114.0	1111	1174
25	108.8	1049	986	88	114.1	1112	1175
26		1050	987	89	114.2	1113	1176
27	109.0	1051	988	90	114.3	1114	1177
28		1052	989	91	114.4	1115	1178
29	109.2	1053	990	92	114.5	1116	1179
30		1054	991	93	114.6	1117	1180
31	109.4	1055	992	94	114.7	1118	1181
32		1056	993	95	114.8	1119	1182
33	109.6	1057	994	96	114.9	1120	1183
34		1058	995	97	115.0	1121	1184
35	109.8	1059	996	98	115.1	1122	1185
36		1060	997	99	115.2	1123	1186
37	110.0	1061	998	100	115.3	1124	1187
38		1062	999	101	115.4	1125	1188
39	110.2	1063	1000	102	115.5	1126	1189
40		1064	1001	103	115.6	1127	1190
41	110.4	1065	1002	104	115.7	1128	1191
42		1066	1003	105	115.8	1129	1192
43	110.6	1067	1004	106	115.9	1130	1193
44		1068	1005	107	116.0	1131	1194
45	110.8	1069	1006	108	116.1	1132	1195
46		1070	1007	109	116.2	1133	1196
47	111.0	1071	1008	110	116.3	1134	1197
48		1072	1009	111	116.4	1135	1198
49	111.2	1073	1010	112	116.5	1136	1199
50		1074	1011	113	116.6	1137	1200
51	111.4	1075	1012	114	116.7	1138	1201
52		1076	1013	115	116.8	1139	1202
53	111.6	1077	1014	116	116.9	1140	1203
54		1078	1015	117	117.0	1141	1204
55	111.8	1079	1016	118	117.1	1142	1205
56		1080	1017	119	117.2	1143	1206
57	112.0	1081	1018	120	117.3	1144	1207
58	112.1	1082	1019	121	117.4	1145	1208
59	112.2	1083	1020	122	117.5	1146	1209
60		1084	1021	123	117.6	1147	1210
61		1085	1022	124	117.7	1148	1211
62		1086	1023	125	117.8	1149	1212
63		1087	1024	126	117.9	1150	1213

Figure 2-12 illustrates the airborne interrogator pulse parameters. The DME signals are sent in pairs of pulses so as to minimize interference with other pulse systems. The pulse pair repetition rate for conventional DME varies from 22 pulse pairs per second up to a maximum of 150 pulse pairs per second. The circuit that basically determines this rate is a pulse repetition frequency (PRF) generator. This unit is a free running multivibrator having a semirandom variation in the repetition rate. Its repetition frequency during the search process varies between 120 and 150 pulse pairs per second. Once the interrogator has acquired the desired replies, the repetition rate retards and varies between 22 and 30 pulse pairs per second. The semirandom variation in repetition rate is intentional. It is incorporated so that the rates of any two interrogators using the same ground transponder beacon for distance information are not identical for any appreciable length of time. This insures relatively interference free operation of the system. The airborne receiver responds only to the incoming signals that possess its unique jitter rate, thereby enabling it to select its personalized distance replies from among all the other signals being received.

The process of realizing distance information begins in the range circuits of the airborne equipment. Accurate measurements of time are initiated at regular intervals along with the generation of the interrogation signal pulse pairs. After the transmission of each signal pulse pair, range gates examine the time interval for the presence of a reply intended for that particular transmission. When this response is repeatedly located at some particular time delay an indication of the range is presented on the cockpit indicator. The most common range circuits are only capable of handling distances up to 200 nautical miles or time delays up to 2472μ seconds; therefore, it is not necessary to examine the entire interval between interrogations since this interval may normally extend from 6670 to 45454μ seconds during the different operational conditions of the unit. These values clearly demonstrate that ample time is provided for the return of a reply before another interrogation is transmitted.

Two distinct phases of operation take place during the range determining process. The initial phase is known as searching. This occurs whenever the interrogator is initially energized, a different channel is selected, or a major interruption occurs in the air-to-ground or ground-to-air signal. Since the ranging circuit receives all pulses transmitted by the ground station (approximately 2700 pulse pairs per second) it must be able to select its own replies and reject all the others. The searching operation accomplishes this task. The search process is conducted at the highest possible pulse pair repetition rate, i.e., 120-150 pulse pairs per second. At the same time that the pulse pairs are transmitted, a gate is generated at the transmitter interrogation rate. This gate is slowly moved outward from a delay corresponding to 0 miles to one corresponding to the system maximum range. When a received

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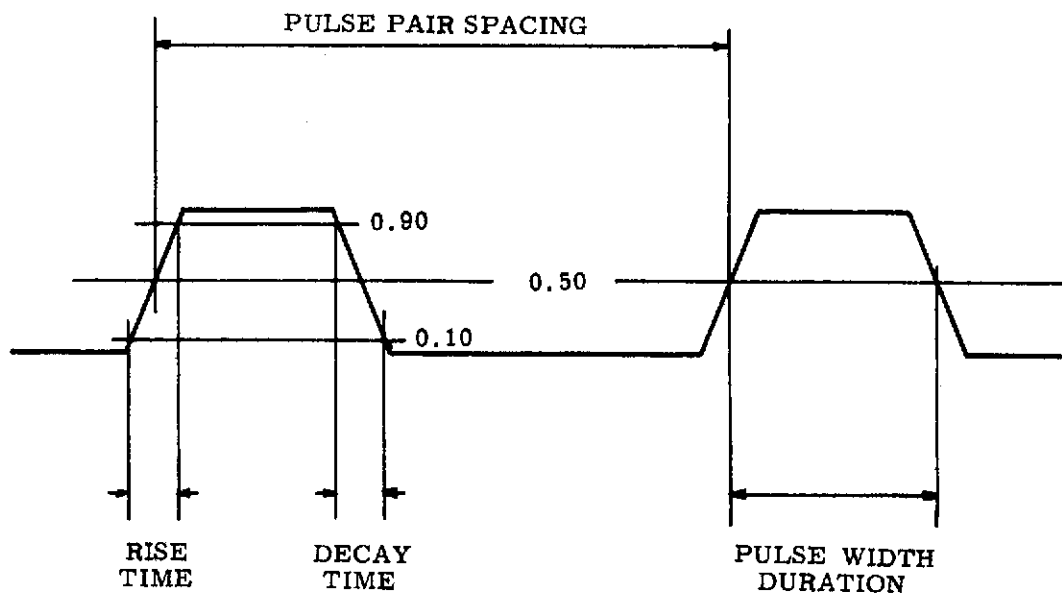
Figure 2-12. DME Pulse Parameters

pulse pair coincides in time with the range gate, the search process is frozen at that range. Successive interrogations determine if the received pulse pair is merely a random pulse that happened to occur once at that point of progress of the range gate or a range reply that will reoccur at that range. If it is a random pulse pair, the range gate will continue its search; however, if it is a range reply, the system will go into the second phase of operation.

The interrogator enters the tracking phase of its operation after repeatedly locating the desired replies. Tracking can be conducted at a much lower pulse repetition rate (22-30 pulse pairs per second) than is required for the search process. The same gate that is instrumental in the searching process also follows the desired replies during the tracking phase. It is the position of this tracking gate which is eventually measured in order to determine the distance from the ground facility. As the aircraft's distance to a ground station changes, the DME is required to react so that the range displayed on the cockpit indicator is accurate. When the aircraft is headed toward the ground station, the reply pulses will tend to appear in the early part of the gate. When this happens the gate advances and causes the displayed range in the cockpit to decrease. When the aircraft is headed away from the ground station, the reply pulses will appear during the late portions of the gate, and this will cause an opposite correction to that described above. Since the possible change of aircraft position is quite small from one pulse to the next, the interrogation rate can be safely reduced during this tracking period. At an interrogation rate of 30 pulse pairs per second even the fastest aircraft does not move as much as a pulse width from one interrogation to the next. Some desired replies may be missing, but the ranging circuits are based on the principle that within a given time slot more desired replies will be present than undesired replies.

The tracking gate is usually arranged to have some memory functions so that a momentary loss of signal will not cause the interrogator to immediately return to the search phase of operation. For ten seconds or so, it is arranged to stay in its last position (static memory) or to move at its last rate (velocity memory). If the interruption lasts for less than the memory period, normal operation is resumed upon reestablishment of the signal. For longer interruptions the system reverts to the search mode, and when the signal is once again established, the system will transfer from the search to the track mode.

It is the combination of the search and track operations that allows the airborne interrogator to fulfill its function of receiving, decoding, and processing the ground beacon replies into accurate distance information.

The last function of the airborne interrogator is to receive and reproduce the identification signal which is provided by the ground transponder beacon. Under the control of an external keyer, ususally common to the associated VOR, the beacon

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transmits an identity signal. Typically, this occurs for about three seconds every thirty-seven seconds. During this time the random pulses are replaced by regularly spaced pulses at 1350 pulse pairs per second. These regularly spaced pulses are keyed with a three letter Morse Code identifier, and they activate a 1350 Hz tuned circuit in the aircraft equipment. The absence of this identifier is used to indicate a facility that is not available for service.

2.2.3 The Ground Transponder Beacon

The primary function of the ground transponder beacon is to receive and decode interrogations from the airborne equipment and then encode and transmit replies on the assigned frequency. Unlike the airborne equipment, which must be able to operate on any one of the 126 different channels, the ground equipment usually stays on one frequency for long periods of time. Consequently, a more powerful transmitter and a a more sensitive receiver can be used. In any single ground transponder beacon the receiver and the transmitter operate at frequencies 63 MHz apart. Table 2-2 lists the associated transmitter and receiver frequencies. The frequencies associated with the particular station determine its channel number, and adjacent stations have their channels assigned so as to avoid interference.

The timing principles of the ground transponder beacon operation are very similar to those of the airborne equipment. After the beacon receives a signal from an interrogator it waits the required delay time and then retransmits the signal on to the aircraft. The pulse pair which is returned to the aircraft conforms to the following general characteristics:

(1) rise time (10%-90%) – 2.5μ seconds;

(2) duration (50% points) – 3.5μ seconds;

(3) decay time (90%-10%) – 2.5μ seconds; and

(4) pulse pair spacing – 12.0μ seconds.   [23]

It should be noted that these pulse pairs are more accurately controlled than those of the airborne interrogator.

The duty cycle and average power consumption of the ground equipment are much greater than those of the airborne equipment. Most beacons are operated on a constant duty cycle principle, whereby the receiver gain is increased until approximately 2700 pulse pairs per second appear at the output of the receiver. It is the appearance of these pulse pairs that triggers a reply from the ground transponder beacon. If there are no airborne interrogations, all the pulse pairs at the output of the receiver appear as the result of noise; with less than approximately 100 aircraft in the ground transponder beacon service area, the pulse pairs appear as the result of a mixture of noise and interrogations; and with 100 or more aircraft in the service area, all the pulse pairs that appear are the result of interrogations, and the capacity of the ground

transponder beacon can be exceeded. When this capacity is exceeded, the ground station only replies to the interrogations from the nearest aircraft. The constant duty cycle operation has the following advantages:

(1) the beacon is automatically maintained in its most sensitive condition;

(2) the transmitter duty cycle is maintained within safe limits;

(3) the automatic gain control circuit always has a constant number of pulses to work on, thereby simplifying its design; and

(4) in the case of interrogation by too many aircraft, the nearest aircraft are the last to be deprived of service.   [24]

In order to realize the most accurate operation of the system, it is important that the ground transponder beacon incorporate into its design a means to reduce errors introduced by multipath signals. This is accomplished by reducing the ground station receiver gain immediately after receiving an interrogation. Any signal, primarily the multipath signals, that arrive during this short reduced gain period will be ignored. However, some interrogations are also lost, but the airborne tracking circuits are designed to compensate for this by use of their memory functions.

The time delay between the reception of an interrogation and the transmission of a reply is nominally 50μ seconds. DME system accuracy is very dependent on the control of this value. Considerable circuit refinement is used to retain this value independent of interrogation strength and environmental effects. Careful control of the timing and designs which restrict possible error sources allow the DME ground transponder beacon to perform the function of receiving and decoding inter- rogations and encoding and transmitting replies as accurately as possible.

2.2.4 DME System Operation and Its Future Potential

The National Aviation System Plan [25] states that, in order to meet the service requirements of the aircraft densities forecast for the terminal areas of the future, a higher capacity DME ground station will be required. In the manner that the system is presently being operated the ground transponder beacons have a capac- ity of approximately 100 aircraft on each channel. This capacity is determined by assuming that 95% of the aircraft that the beacon is servicing in the track mode at 22-30 interrogations per second, and the remaining 5% are in the search mode at 120-150 pulse pairs per second. This results in about 2700 pulse pairs per second being transmitted by the ground station. The present transponder beacons are limited by design to this number of replies, and a cursory analysis yields the fact that the transmitter power is being used only 2% of the time. A large increase in DME capacity can be achieved with some modifications to both the airborne interrogators and the ground transponder equipment. First, one needs to examine the changes in the airborne equipment which would increase the system capacity.

The reduction of the average interrogation rate is one method to increase DME system capacity. Most interrogators on the market today utilize an average interrogation rate of somewhere between 22 and 30 pulse pairs per second when operating in the track mode. A reduction in this rate would greatly increase the number of aircraft that could be handled by a single ground transponder beacon. This improvement already exists in some designs. Receivers have been demonstrated that use an interrogation rate as low as 2 pulse pairs per second, and they displayed the ability to hold lock if the aircraft was moving on a constant speed track. [26] Even though this advance was realized with developmental equipment it appears technically feasible to significantly reduce the average airborne interrogation rate and, as a direct consequence of this reduction, increase the capacity of the ground beacons.

Another method of increasing the DME system capacity by modification to the airborne equipment is to reduce the required reply efficiency of the airborne units. It has become necessary to introduce newer techniques of data processing into the receivers of the airborne equipment which allow receivers and interrogators to track with as low as 25% reply efficiency rather than the 50% minimum now specified. Although the majority of the existing interrogators require between 35% and 50% replies to their interrogations for proper operation, a significant number have been found that will operate at the 25% level. More precise control of the interrogator circuit parameters and improvements to performance tolerances should allow an extension of this ability to all interrogators. This will approximately double the number of aircraft that can be handled by a single ground station.

Heretofore the DME equipment had depended on a slow-moving, analog type search gate to look for a reply to an interrogation. This slow-moving gate was necessary to distinguish the desired replies from among the many other squitter pulses or replies meant for other aircraft. The result was a variety of long search times, typically on the order of 20-30 seconds, before tracking could be established. Since the search process requires approximately 6 times as many interrogations as tracking requires, this was a limit to the capacity of the system. The adoption of digital signal processing techniques has reduced this search time to fractions of a second.

The primary means of increasing system capacity that has been adopted up to this time is that of channel doubling. This is accomplished by making changes in both the ground transponder beacons and the airborne equipment. The solution has been to use two different pulse codes with the result that 252 channels become available for use.

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The only practical change to the ground transponder equipment that would result in an increase in system capacity is to enlarge the duty cycle of the ground transmitter. Presently the duty cycle is limited to approximately 2%. An increase could be made without exceeding the average power design of the equipment. A modification, however, is necessary to the interrogation overload protection circuitry in order to delay receiver gain reduction to correspond to the new maximum number of interrogations.

Each of the modifications described above results in a significant increase in the traffic handling capacity of the DME system. Future traffic projections clearly indicate that at least some, if not all, of these modifications will be required. The DME airborne equipment is described as "active" equipment in that it transmits and receives signals required for navigation. The transmission of signals leads to circumstances that result in system capacity limitations. It is these capacity limitations and not the standard performance shortcomings in terms of range, accuracy, and reliability that limit the overall effectiveness of the DME system.

An evaluation of the performance of the DME can be assessed in terms of range, accuracy, and reliability. The range of future equipment available for general aviation is expected to remain within 200-300 nautical miles. There has been a good deal of experimental work to improve the accuracy of the DME system. The ICAO requires the accuracy of the overall system to be +0.5 nautical miles or 3% of the slant range, whichever is greater. The airborne equipment typically has errors of +0.1 to 0.2 nautical miles; however, developmental equipment applying digital techniques has displayed significantly less error. When using this later equipment the overall system accuracy is limited by ground transponder beacon accuracy which includes the stability of the beacon delay, the accuracy of the pulse rise times, etc.

The adoption of solid state electronics has done a good deal to improve the reliability of the airborne equipment. With these improvements and the advances in internal calibration and self checking of the airborne units the user can be quite certain that his equipment will perform as intended.

The cost of the DME airborne interrogators for general aviation operations can vary anywhere from $1500 up to $15,000, but, for the purposes of the present analysis, it is assumed that a highly accurate DME interrogator can be obtained for about $1500-2000. Table 2-3 enumerates the characteristics of several representative DME interrogators presently available on the market.

Table 2-3

REPRESENTATIVE DME INTERROGATORS

Model	Characteristics	Price
King Radio		
KN 60C	100 n. mi. range; 75 watts peak power output; 100 channel; 0.5 n. mi. accuracy	$1,860
KDM 705	199.4 n. mi. range; 500 watts peak power output; 200 channels 0.1 n. mi. accuracy	$4,995
Narco Avionics		
UDI-4	100 n. mi. range; 40 watts peak power output; 100 channels; 0.5 n. mi. accuracy	$1,595
DME 70	100 n. mi. range; 40 watts peak power output; 100 channels; 0.5 n. mi. accuracy	$2,295
RCA Aviation Equip.		
AVQ-75	196 n. mi. range; 1000 watts peak power output; 100 channels; 0.1 n. mi. accuracy	$5,780

2.3 VORTAC Area Navigation Operations

In the previous two subchapters the author has discussed the creation of two position determining signals. The first was the azimuth determining signal from the VHF omnidirectional range, and the second was the distance datum realized from the distance measuring equipment. If the two signal sources are collocated, as in a VORTAC or VOR/DME ground facility, area navigation operations are feasible.

In order to determine the position of the aircraft at least two unambiguous lines of position must be realized. The VOR system provides one such unambiguous line of position. The resulting intelligence from VOR operation determines the azimuth of the aircraft from the ground station in relation to magnetic north. Figure 2-13(a) illustrates this situation. In this example the VOR datum indicates that the

a) VOR Line of Position

b) DME Line of Position

26 n. mi.

c) Final Position Fix

60°

AIRCRAFT

26 n. mi.
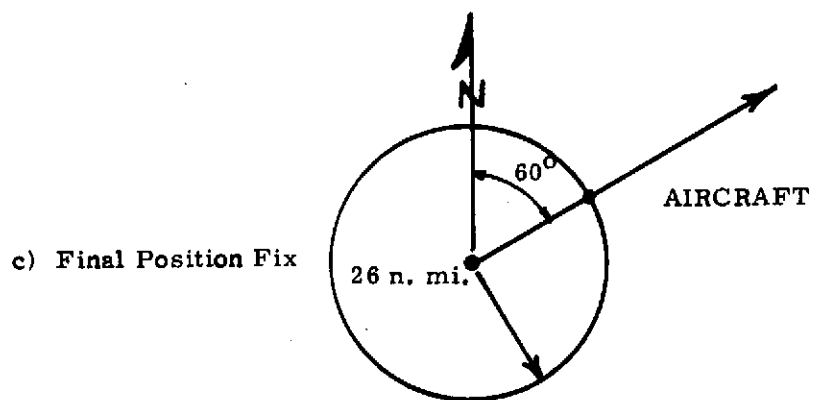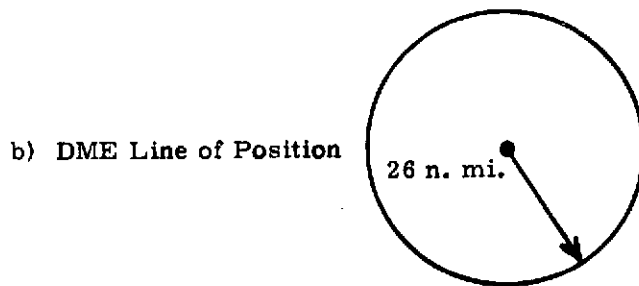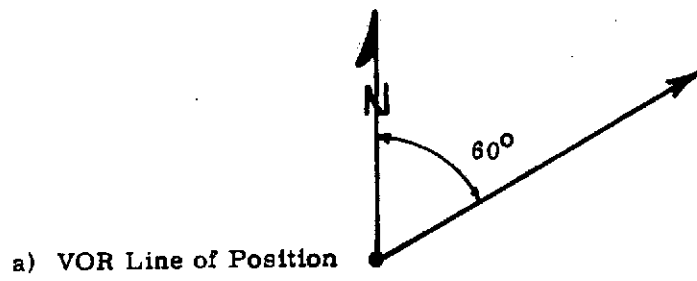
Figure 2-13.   VORTAC Position Fix

aircraft is on the 60° radial from the ground station. The ray originating at the station and extending outward at 60° from magnetic north is the line of position generated by this information. This is not sufficient, however, to completely determine the aircraft's position. An ambiguity arises in that the aircraft can be situated anywhere along this line. More information is required to uniquely determine the position.

The position location information from the distance measuring equipment is given in nautical miles from the ground facility. Figure 2-13(b) depicts the DME resultant line of position. In the example the DME has determined that the aircraft is 26 nautical miles from the ground facility. Again a position ambiguity arises in that the aircraft can be located anywhere on the circle having a 26 nautical mile radius from the ground station. However, when one combines the information from the collocated VOR and DME ground facilities the ambiguity is resolved. There is only one position that satisfies both constraints. Figure 2-13(c) illustrates the final position fix.

This unambiguous position fix information provides the foundation for navigation using the VORTAC system. Conventional processing of the signals from the VOR and DME facilities enables the pilot to navigate only on routes which emanate radially from the VORTAC. However, if the airborne equipment includes a suitable area navigation device, it is possible to navigate on routes originating and terminating anywhere within the service area of the ground facility. The area navigation device takes the information from the VOR and DME airborne equipment, performs the mathematical computations required, and displays the navigation information to the pilot.

The mathematical computation required to generate area navigation is simply a trigonometric analysis of the navigation problem. Figure 2-14 illustrates the process. The two fundamental elements of navigation information required by the pilot are the distance and course to the waypoint. The determination of Side C in Figure 2-14 realizes this information.

Side A of the navigation triangle is determined when the pilot tunes to the VORTAC ground station, and the VOR and DME airborne equipment function properly. It is simply the VORTAC radial and the distance between the aircraft and the ground facility.

Side B is established when the pilot manually sets the waypoint distance and bearing from the ground station into the area navigation device. Since both Angle 1 and Angle 2 are related to magnetic north, the computer can compare the two and determine Angle 3, the interior angle of the navigation triangle. With the knowledge of the distance along Side A, the distance along Side B, and the interior angle, the computer has enough information to solve for Side C, which will result in the distance and magnetic course to the waypoint from the present position of the aircraft.

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MAGNETIC
NORTH

SIDE A

VORTAC

SIDE C

SIDE B

WAYPOINT

Angle 1 = Bearing of Aircraft from VORTAC
Angle 2 = Waypoint Bearing from VORTAC
Angle 3 = Angle 2 - Angle 1
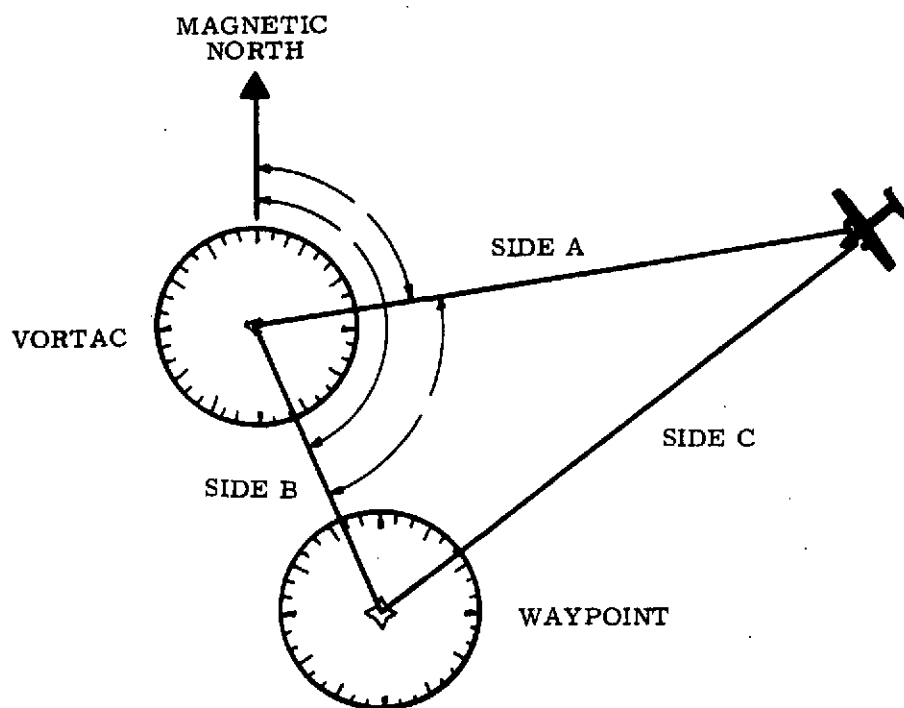
Figure 2-14. Navigation Triangle for VORTAC Area Navigation

Whenever the pilot desires to navigate along a predetermined area navigation route between two waypoints, one additional computation is required. It is necessary to determine the cross-track deviation of the aircraft. This computation is also accomplished by simple trigonometric analysis. Figure 2-15 depicts the situation. The sine of the interior angle multiplied by the distance to the waypoint generates the magnitude of the cross-track deviation. When this information is displayed to the pilot he can initiate the corrective action required.

The ability to navigate to any predetermined point or along any predetermined route within the service area of a VORTAC ground facility enables the pilot to perform area navigation successfully while implementing the VORTAC radionavigation system.

2.4   VORTAC Performance

Three major criteria will be used to evaluate the performance of the VORTAC radionavigation system. They are accuracy, coverage, and availability of signal. None of these measures is completely independent of the others. However, in this analysis they will be examined separately and then combined to generate the performance characteristics of a representative VORTAC area navigation system.

2.4.1 System Accuracy

In the VORTAC area navigation system there are five major sources of contribution to system error. They are:

(1) ground VORTAC radiated signals;
(2) airborne VORTAC equipment;
(3) slant range errors;
(4) airborne area navigation equipment; and
(5) flight technical errors.

Each of these error sources needs to be examined by itself and then combined with the others to generate the overall VORTAC area navigation system accuracy.

As discussed earlier in this chapter the ground radiated signal of the VORTAC radionavigation system is composed of two distinct elements, one from the VOR and the other from the DME. One needs to examine each of these in turn.

The error contribution from the VOR ground signal is primarily the result of three factors:

(1) atmospheric propagation;
(2) siting errors; and
(3) calibration of ground station equipment.

50
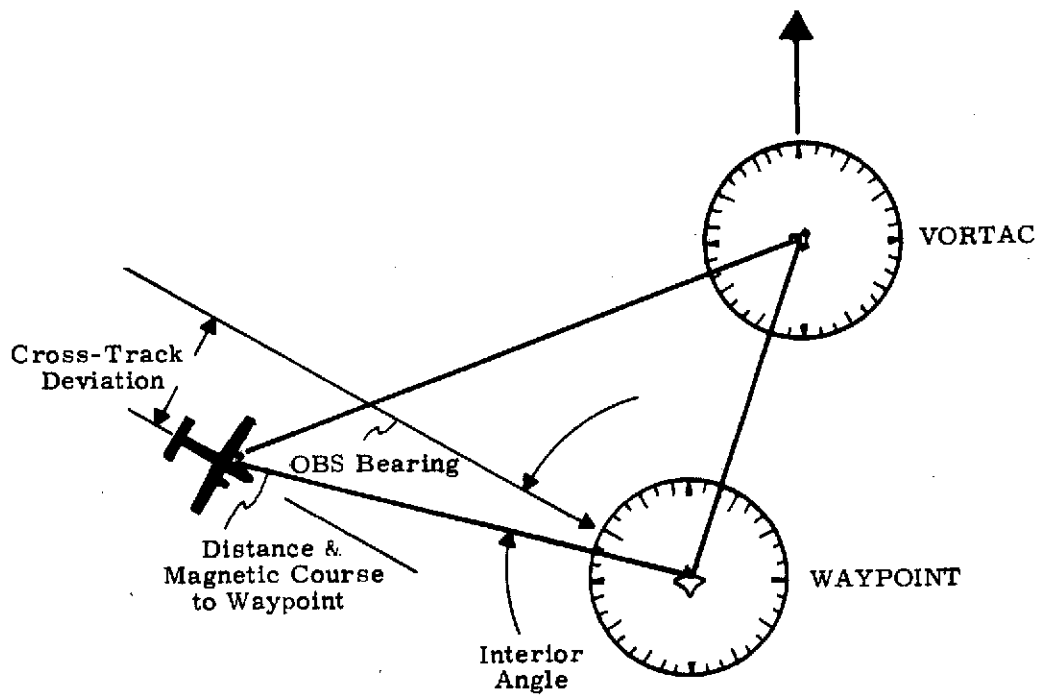
Figure 2-15. Determination of Cross-Track Deviation

Source: King Radio Corp., Pilot's Guide: King Gold Crown KNC 610 Area
Navigation Computer, April 1973, p. 11.

The conventional VOR is capable of providing signals with accuracies on the level of $\pm 1.9^\circ$. If the ground station is modified to produce Doppler or precision VOR signals an increase in the ground station signal accuracy can result. Studies have shown that $\pm 1.0^\circ$ is an appropriate value for these configurations. The angular error that results from the VOR ground station operation needs to be converted to a displacement value. This value is directly proportional to the distance from the ground station to the receiver location.

$$\epsilon_d = \rho \, \epsilon_\theta \qquad\qquad \text{Eqn. 2.1}$$

where

ϵ_d = the error in position;

ϵ_θ = the angular error; and

ρ = the radial distance of the receiver from the ground station.

Figure 2-16 illustrates the relationship described by Eqn. 2.1 for conventional and Doppler or precision VOR ground stations.

The signal from the DME portion of the VORTAC ground station can be maintained to an accuracy of ± 0.1 nautical mile.

The assessment of airborne VORTAC equipment errors is more difficult. The Technical Standard Order (TSO) for VOR airborne receivers has established two categories of airborne equipment: "airline" type with $\pm 2.7^\circ$ accuracy, and "general aviation" type with $\pm 4.2^\circ$ accuracy. [27] These TSO's have not been updated to take into account the more recent receiver design improvements. For the purposes of accuracy assessment the entire receiver population can presently be evaluated at about $\pm 3.0^\circ$ and improvements to $\pm 1.0^\circ$ can be anticipated by 1982. [28]

The present DME TSO calls for a total error of ± 0.5 nautical miles or $\pm 3\%$ of the slant range distance, whichever is greater, when the airborne equipment and ground station errors are combined. It is anticipated that airborne DME equipment refinements should result in accuracies on the order of ± 0.25 nautical miles by 1982. [29]

The slant-range contribution to total system error arises from the fact that the actual distance between the aircraft in flight and the ground navigational aid is greater than the geographical range because of the altitude of the aircraft. Figure 2-17 illustrates this effect. This error is a bias error in the total system error budget and is greatest when the aircraft is directly over the ground station. It is anticipated that slant range error will be compensated for automatically in the future implementation of area navigation equipment.

The contribution to total system error that arises from the employment of area navigation equipment in the aircraft is a result of any error components that

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ρ: The Radial Distance Between the Receiver and the Ground Station (nautical miles)
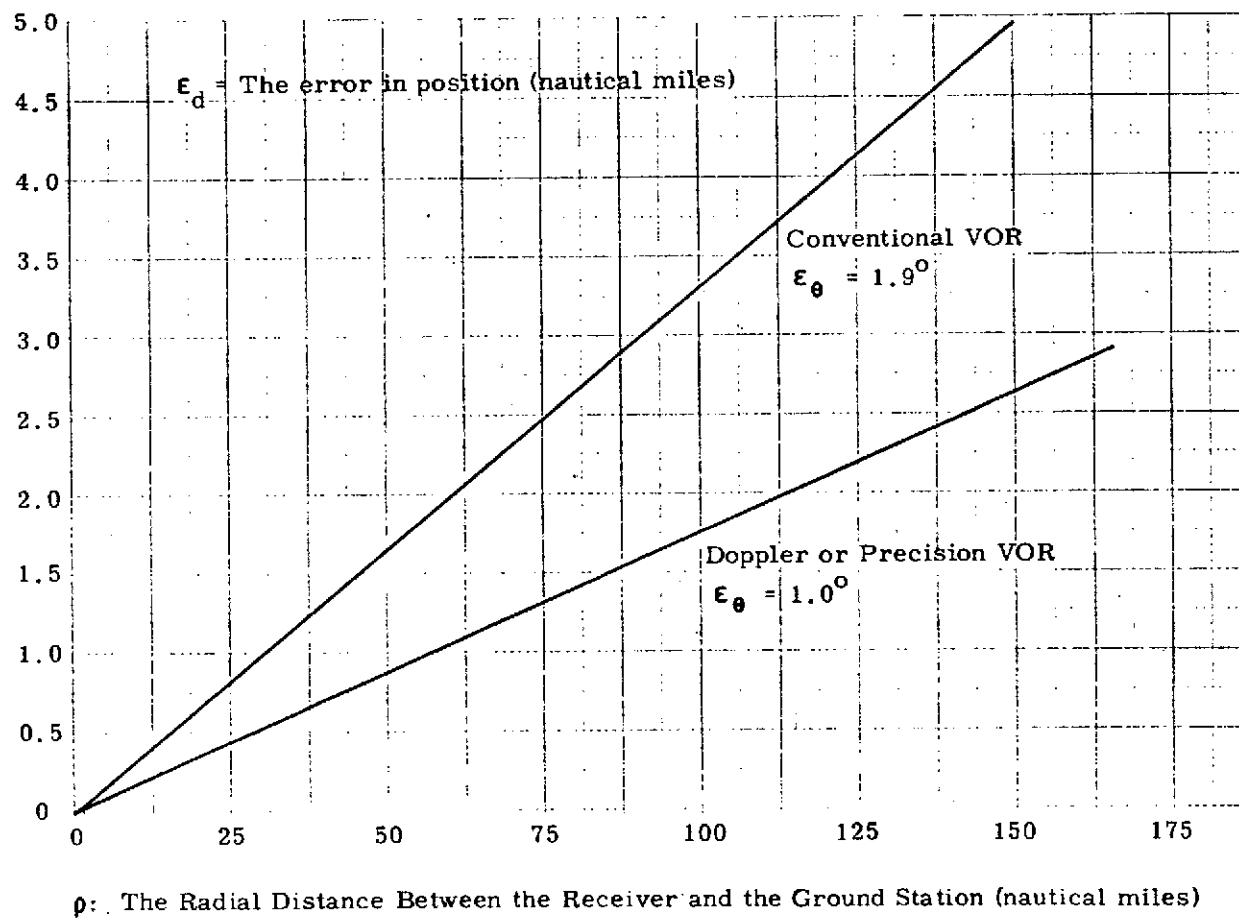
Figure 2-16. Position Error vs. Separation Distance
for Conventional and Post-1982 VOR's

are contributed by course definition entry devices, displays, input, output, and signal conversion equipment, or any computing elements that have been employed. Since the errors introduced by this equipment are actually independent of the radio-navigation system utilized and, therefore, equal for each system under study, the contribution to total area navigation system error has been removed and will be included later in the analyses of Chapter Five.

Flight technical error refers to the accuracy to which the pilot controls the aircraft. This is measured by the pilot's success in causing the indicated aircraft position to match the indicated command or desired position on the display. This error, like that of the area navigation equipment, is independent of the radionavigation system utilized and will be discussed further in the analyses of Chapter Five.

Slant Range > Geographical Range
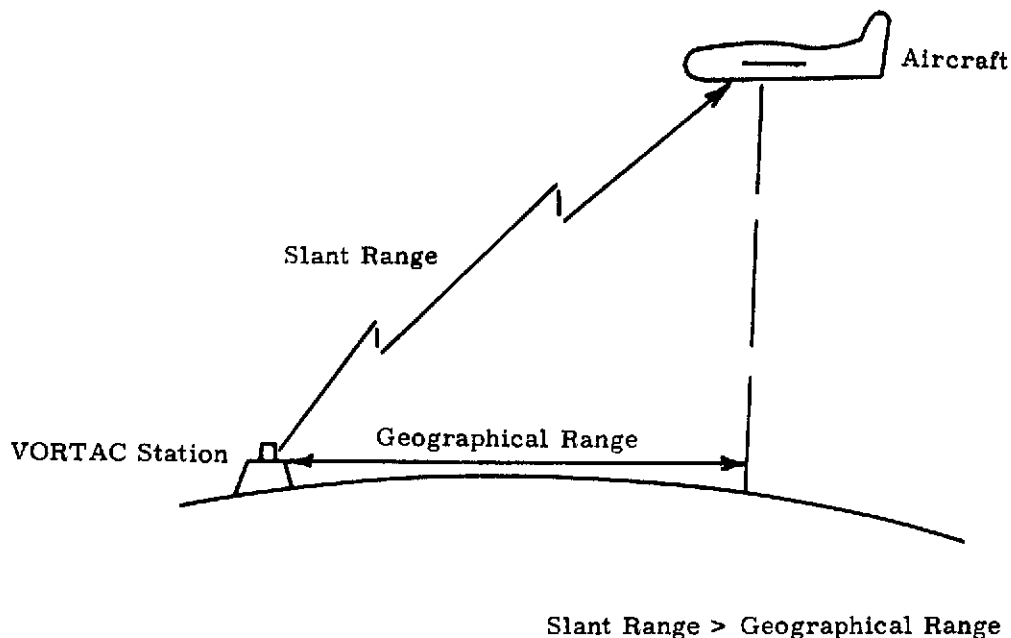
Figure 2-17. Slant Range Error

In summary, only three of the five elements of the total VORTAC area navigation system error budget are dependent on the characteristics of the VORTAC radionavigation system itself. One of these, the slant range error, can be compensated for automatically; therefore, only two major error sources actually combine to form the VORTAC radionavigation system error contribution.

If one assumes that the errors from the two sources are normally distributed and independent of each other, they may be combined in a root sum square (RSS) fashion. In this manner the standard deviations from the various error sources are combined geometrically rather than arithmetically by taking the square root of the sum of the square.

The error contribution from the VOR system has elements from both the ground station and the airborne equipment. The ground station error of the conventional VOR is assessed at $\pm 1.9^\circ$, and the present day airborne equipment error is evaluated at $\pm 3.0^\circ$. If one combines these two in a root sum square fashion, as in Eqn. 2.2, the total present day VOR system error contribution can be determined.

$$\left[\epsilon_{\theta g}^{\ 2} + \epsilon_{\theta a}^{\ 2} \right]^{\frac{1}{2}} = \epsilon_\theta \qquad \text{Eqn. 2.2}$$

where

$\epsilon_{\theta g}$ = VOR ground station error;

$\epsilon_{\theta a}$ = VOR airborne equipment error; and

ϵ_θ = total VOR system error contribution.

For the error values assessed above, the total present day VOR system error contribution is $\pm 3.55^\circ$:

$$\pm \left[(1.9^\circ)^2 + (3.0^\circ)^2 \right]^{\frac{1}{2}} = \pm 3.55^\circ \qquad \text{Eqn. 2.3}$$

Figure 2-18 depicts the displacement error that results from this angular error as a function of the distance between the receiver and the ground station.

If there are no changes to the VORTAC ground station equipment, but the airborne equipment is improved to the $\pm 1.0^\circ$ accuracy by 1982, the total conventional VOR system error can be computed, from Equation 2.2, to be $\pm 2.15^\circ$.

$$\pm \left[(1.9^\circ)^2 + (1.0^\circ)^2 \right]^{\frac{1}{2}} = \pm 2.15^\circ \qquad \text{Eqn. 2.4}$$

55
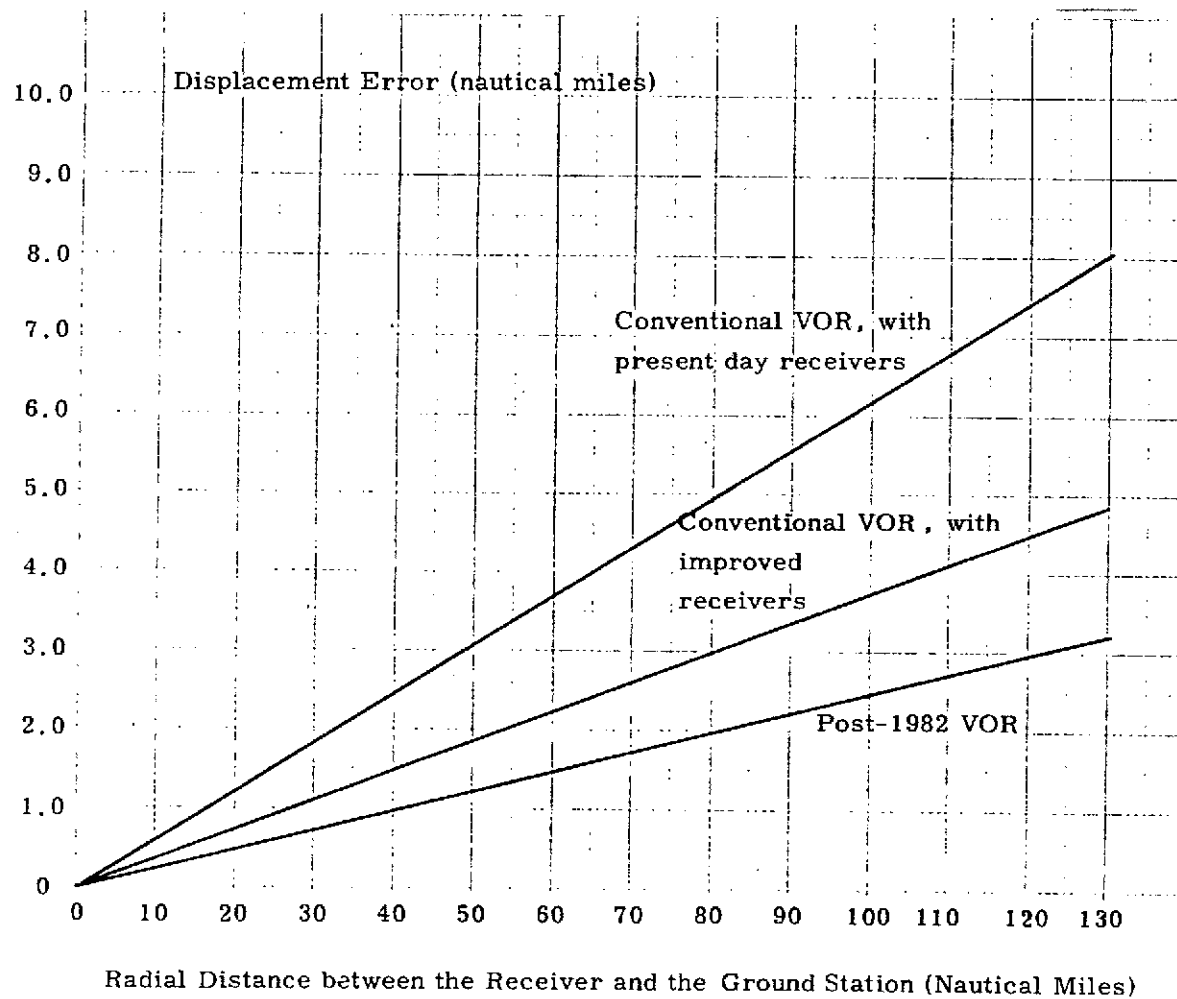
Figure 2-18. Displacement Errors for VOR Configurations

Figure 2-18 also depicts the displacement error that results from this angular error as a function of the distance between the receiver and the ground station.

If a Doppler or precision VOR system is utilized, along with improved airborne equipment, the total VOR system error is on the order of $\pm 1.4^{\circ}$:

$$\pm \left[(1.0^{\circ})^2 + (1.0^{\circ})^2 \right]^{\frac{1}{2}} = \pm 1.4^{\circ} \qquad \text{Eqn. 2.5}$$

Figure 2-18 also illustrates this value.

The DME error contributions from the ground station and airborne equipment can also be combined in a root sum square fashion. Present day DME system errors are on the order of ± 0.5 n. mi. or 3% of the slant range distance, whichever is greater. Figure 2-19 illustrates these values. Anticipated accuracy of the post-1982 period results in DME system errors of ± 0.27 n. mi.:

$$\pm \left[(0.1 \text{ n. mi.})^2 + (0.25 \text{ n. mi.})^2 \right]^{\frac{1}{2}} = \pm 0.27 \text{ n. mi.} \qquad \text{Eqn. 2.6}$$

The total VORTAC radionavigation system error values can be determined by combining the contributions from the VOR and DME elements. For the conventional VORTAC system, with present day airborne equipment, the VOR contribution is $\pm 3.55^{\circ}$ or $\pm 0.06 d$, where d is the distance between the aircraft and the ground stations:

$$\frac{\pm 3.55^{\circ}}{57.4^{\circ}/\text{radian}} = \pm 0.06 \text{ radians} \qquad \text{Eqn. 2.7}$$

From Figure 2-19, the DME error contribution for any distance greater than 16.6 nautical miles is approximately $\pm 0.03 d$ (3% of the slant range distance), where d is defined as above.

If one combines these errors in a root sum square fashion the total conventional VORTAC radionavigation system error, whenever employing present day airborne equipment, can be determined to be approximately $\pm 0.067 d$, where d is defined as above:

$$\left[(0.06 d)^2 + (0.03 d)^2 \right]^{\frac{1}{2}} = \pm 0.067 d \qquad \text{Eqn. 2.8}$$

Figure 2-20 depicts this error.

If improved airborne equipment is utilized, the conventional VOR system error contribution is $\pm 2.15^{\circ}$ or $\pm 0.037 d$, where d is the distance between the aircraft and the ground station:

$$\frac{\pm 2.15^{\circ}}{57.4^{\circ}/\text{radian}} = 0.037 \text{ radians} \qquad \text{Eqn. 2.9}$$

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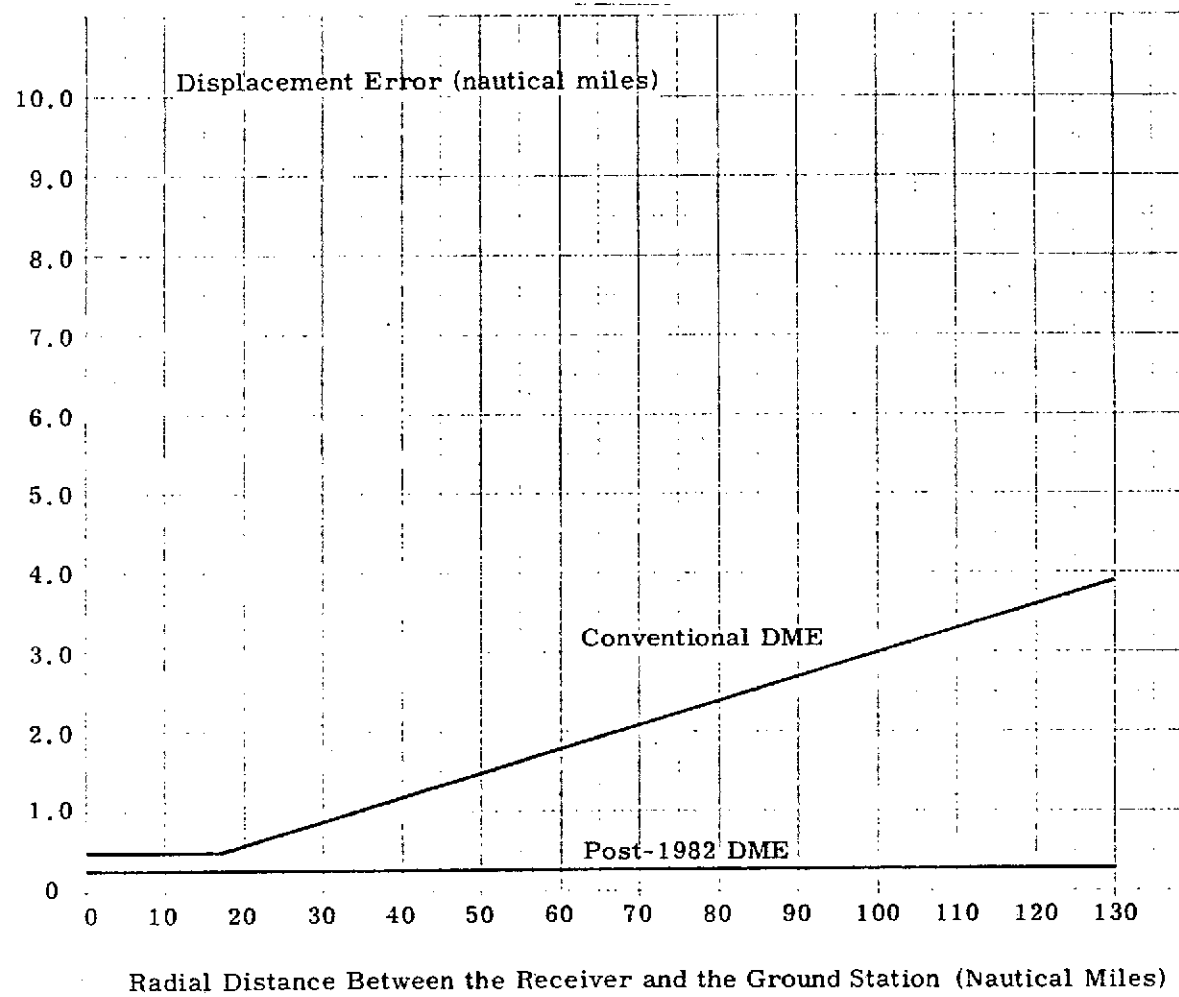
Figure 2-19. DME System Errors

Displacement Error (nautical miles)

Conventional VORTAC with
Present Day Receivers

Conventional VORTAC with
Improved Receivers

10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0

10   20   30   40   50   60   70   80   90   100   110   120   130   140

Radial Distance between the Receiver and the Ground Station (Nautical Miles).
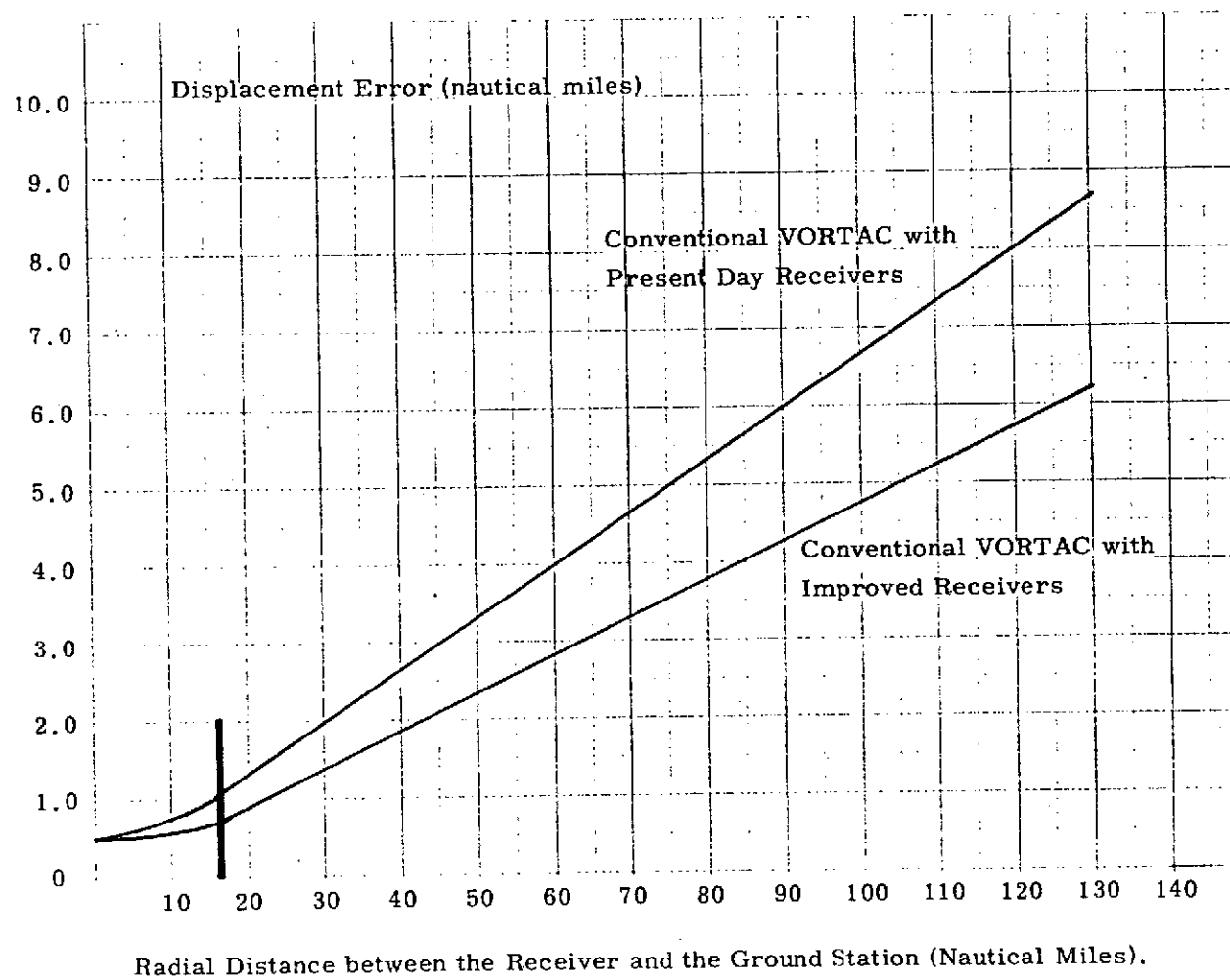
Figure 2-20. Combined VORTAC Radionavigation System Error

When this is combined with the conventional DME error contribution the total conventional VORTAC radionavigation system error, when utilizing advanced airborne equipment, can be determined to be approximately $\pm 0.048\,d$, where d is defined as above:

$$\pm \left[(0.037\,d)^2 + (0.03\,d)^2 \right]^{\frac{1}{2}} = \pm 0.048\,d = \epsilon_d \qquad \text{Eqn. 2.10}$$

Figure 2-20 also depicts this error.

If there are improvements to the VORTAC ground station facilities, such as the adoption of Doppler or precision VOR installations and future DME ground station improvements, coupled along with improved airborne equipment, the error will be somewhat less:

$$\pm \left[(0.024\,d)^2 + (0.27)^2 \right]^{\frac{1}{2}} = \pm \left[0.000576\,d^2 + 0.0729 \right]^{\frac{1}{2}} = \epsilon_T \qquad \text{Eqn. 2.11}$$

where

ϵ_T = the total displacement error in the improved post-1982 VORTAC radionavigation system; and

d = the radial distance between the receiver and the ground station.

The actual displacement figures will be developed after the system constraints of coverage and availability have been discussed.

2.4.2 Coverage

The area of coverage for a radionavigation system is the area within which that system delivers navigation signals that can be received and processed to generate navigation accuracies within the specified limits. The requirements of Chapter One of this analysis specify that the coverage area for each radionavigation system under study will be such that the system must provide service everywhere within the conterminous United States and Alaska from an altitude of 1,500 feet above ground level to an altitude of 45,000 feet. One needs to examine two separate aspects of the provision of VORTAC navigation signals before an assessment of VORTAC area navigation coverage can be assigned.

The first of these aspects of signal provision is the line-of-sight propagation characteristics of VHF/UHF transmissions. The signals associated with the VORTAC system have transmission paths which are highly predictable but subject to the limitations of the radio horizon. Figure 2-21 illustrates the situation. Aircraft A will receive the signal continuously. Aircraft B, however, will not receive the
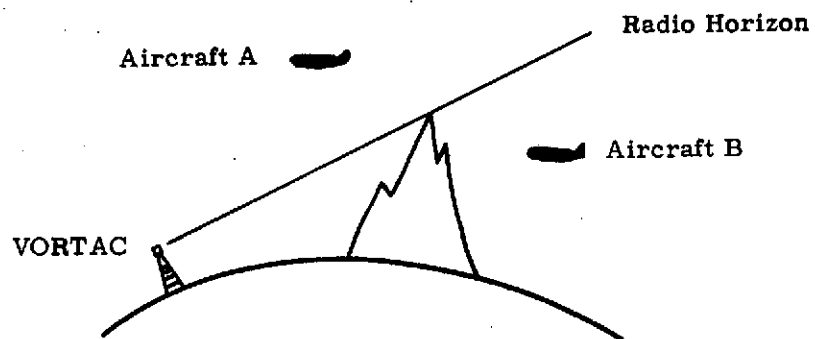
Figure 2-21. VHF/UHF Radio Horizon.
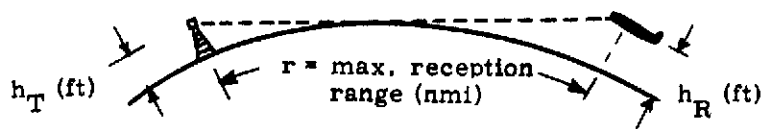
$$r = 1.23 \sqrt{h_T} + 1.23 \sqrt{h_R}$$

Figure 2-22. Line-of-Sight Range

the signal unless it climbs so that it is above the radio horizon line. Even in the absence of intervening mountainous terrain there is a maximum reception range for the VORTAC system. Figure 2-22 illustrates the phenomenon described by Equation 2.12.

$$r = 1.23 \sqrt{h_T} + 1.23 \sqrt{h_R} \qquad \text{Eqn. 2.12}$$

where

r = the maximum reception range in nautical miles;

h_T = the height of the transmitting antenna in feet; and

h_R = the height of the receiving antenna in feet.

Table 2-4 enumerates some representative values of maximum reception range for $h_T = 0$ and various aircraft altitudes.

Table 2-4

MAXIMUM RECEPTION RANGE OF VORTAC NAVIGATION SIGNALS

Aircraft Altitude (feet)	Range (nautical miles)
500	28
1000	39
1500	48
2000	55
3000	69
5000	87
10000	122
15000	152
20000	174
30000	213
40000	246

The coverage specification of Chapter One, where signals are required from 1,500 feet above ground level to 45,000 feet, places a constraint on the coverage area of a VORTAC station. From Table 2-4, the maximum range for signal reception at 1,500 feet above ground level is approximately 48 nautical miles from the ground station. Additionally, VORTAC coverage is required throughout the service area in order to achieve area navigation capability, and, due to site shielding effects, intervening terrain, and the limitations of the radio horizon, there are many areas where this just cannot exist. The FAA Engineering and Development Program Plan

[30] describes the situation exactly when it says, "The VOR/DME system does not provide adequate signal coverage to significant areas within and near the continental United States and Alaska. Specifically, VOR/DME coverage in mountainous areas, and off the coast-line at low altitudes is not complete."

The other aspect of signal provision which deserves attention is that of navigation signal frequency protection. The Frequency Management Division of the FAA has been assigned the responsibility of ensuring that the navigation signals are protected from radio frequency interference (RFI). In order to curb this interference the Frequency Management Division controls the frequency assignments for all VORTAC stations. Geographical separation criteria have been developed for co- and adjacent-channel frequency arrangements, and they are used in making all frequency assignments. The usable distances and altitudes of all VORTAC stations are determined by the protection from RFI caused by co- or adjacent-channel facilities, rather than by the transmitter power output.

If there were sufficient frequencies available to assign a separate channel to each VORTAC, then the usable distance would only be limited by the radio horizon and free-space signal attenuation. However, this is not the case. Due to the limited number of frequencies available, it is necessary to operate stations on the same channel, and interference is present beyond certain distances. The presence of this interference has led the Frequency Management Division to establish standard service volumes for each facility. Inside this service volume the co- and adjacent-channel radio frequency interference is controlled and determined to be less than certain values.

In the United States the radionavigation signals are provided for a two layer airway or route structure. Low altitude enroute airways are designated for use up to 18,000 feet. Jet routes are designated for use from 18,000 feet up to 45,000 feet. The facilities which are used to provide navigation signal coverage for the low altitude airway system are designated as "Class L" or low altitude facilities. Those facilities used to support the jet route system are classified "Class H" or high altitude facilities. The "Class H" facilities are used for the low altitude system as well as the jet routes. In addition, a third type of facility, "Class T", is used to provide navigation signals in terminal areas where enroute coverage is not required. The usable distances and altitudes of all three types of facilities are determined by the frequency protection provided. Table 2-5 enumerates the types of facilities and their associated cylindrical service volumes.

Table 2-5

VORTAC: NORMAL USABLE ALTITUDES AND RADIUS DISTANCES [31]

Class	Altitudes	Distance (nautical miles)
T	12,000 and below	25
L	Below 18,000	40
H	Below 18,000	40
H	14,500 - 17,999	100*
H	18,000 - FL 450	130
H	Above FL 450	100

*Applicable only within the 48 contiguous United States.

The radio frequency protection constraint determines the maximum range for signal reception unless special testing is accomplished by flight inspection aircraft.

The two aspects of radionavigation signal provision, the limitations due to line-of-sight propagation and the requirements of radio frequency interference protection, determine the constraints within which the VORTAC coverage area can be established. From Table 2-4 it can be ascertained that reception at 1,500 feet above ground level requires the receiver to be within 48 nautical miles of the transmitting antenna. Frequency interference protection for low-altitude facilities is only afforded within 40 nautical miles, as can be determined from Table 2-5. Unless the frequency protected area can be expanded, the 40-nautical-mile constraint of the low-altitude facilities is binding. If the facilities can be protected to a greater radius, then the reception limitations of line-of-sight propagation are binding.

2.4.3 Availability of Signal

The final measure of system performance in this analysis is that of signal availability. Availability has been defined as the measure of the ability of the system to provide a signal within the coverage area to the accuracy tolerance specified. When one examines this facet of VORTAC radionavigation system performance, three major areas of interest become apparent. They are:

(1)   the propagation characteristics of the VORTAC signal;
(2)   the occurrence of saturation in DME operations; and
(3)   the reliability of the ground station equipment.

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The propagation of the VORTAC navigation signals is highly predictable but subject to the limitations of line-of-sight coverage and radio frequency interference. Both of these problems were discussed somewhat in the preceding section. The line-of-sight propagation characteristics severely limit the signal availability in the mountainous terrain and beyond the radio horizon. The radio horizon limitation can be circumvented by increasing the number of facilities, but the restriction due to intervening terrain just cannot be overcome. In mountainous areas there just is no practical way that the VORTAC system can provide signals everywhere.

The free-space attenuation of VHF/UHF signals is not very large, and this gives rise to the co- or adjacent-channel interference problems. The current expansion of aviation services has generated a requirement for additional enroute and terminal navigation facilities. The problem of radio frequency congestion for these facilities has become acute. In fact, there are many areas of the country where frequency congestion has reached the saturation point, and no channels are available for the additional facilities. Even with the refinements in geographical separation criteria and the application of computer techniques to the optimum utilization of all channels, there is still an unfulfilled demand for additional navigation frequencies. The frequency band that is available cannot be expanded in that it is sandwiched between the FM broadcast band and the air-to-ground communications band. The next logical step to generate more frequencies is to channel split.

At present the VOR navigation channels are spaced 100 kHz apart. New facilities require that this spacing be reduced to 50 kHz. This means utilizing the midpoints between presently assigned frequencies, e.g., 114.35 MHz between 114.3 MHz and 114.4 MHz. Ground station operation on a 50 kHz channel assignment plan can be achieved without much difficulty since the required frequency stability can be obtained with equipment now in existence. Modern receivers of the "air carrier" type are capable of operating on a 50 kHz spacing also; however, a large number of "general aviation" type receivers are not sufficiently selective to provide unrestricted service. These receivers will not only not tune the new frequencies, but their receiver bandpass characteristics will not permit their use in the new frequency environment. It is possible that a receiver of this type, while being used on a 100 kHz facility, could receive disruptive interference from an adjacent 50 kHz channel. There would be a requirement of modification or reequipment of all aircraft using this type of receiver. The introduction of 50 kHz frequency assignments must be accomplished in such a manner so as to result in minimum user impact. Eventually this transition will be accomplished; but, for the present, the radio frequency interference problem will continue to impose a limitation on the VORTAC signal availability.

The DME segment of the VORTAC radionavigation system is an "active" navigation system in that action by the airborne equipment is required before initiation of the appropriate ground navigation signal. This inherently establishes a finite capacity to the system. The number of facilities and their associated capacity does not appear to be sufficient to meet the demands of future area navigation applications as they are presently envisioned. Today the capacity of each DME ground station is approximately 100 aircraft.

There has been numerous methods proposed to expand the system capacity including an increase to ground transmitter duty cycles, a reduction in the average interrogation rate of the airborne equipment, and a reduction in the required reply efficiency for the airborne gear. In addition, "Y" channel operation to pair with the new 50 kHz VOR facilities has been proposed. These channels employ different pulse spacings on unused ground-to-air frequencies in the present DME operational band. The adoption of any of these proposals would significantly affect the capacity of the DME system; but, until they are instituted, DME channel saturation will offer a possible restriction to VORTAC signal availability.

The third and final potential limitation to VORTAC signal availability can be determined by an evaluation of the VORTAC ground station reliability. Table 2-6 summarizes the performance of the VOR and TACAN stations in this regard. This table describes the availability of the signal as seen by the user. The values for the VOR system are 99.41% and for the TACAN system 99.22% of the maximum available hours. The high figures for the availability are the result of an extensive FAA control program. They are achieved by the procurement of high quality equipment, installation to rigid specifications, careful and efficient maintenance of that equipment, and inspection and control programs designed to permit statistical analysis to function as a basis for engineering and management decisions.

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Table 2-6

VOR and TACAN SIGNAL AVAILABILITY
July 1972 to June 1973

	VOR	TACAN
No. of Commissioned Facilities	902	705
Maximum Available Hours	7,902,840	6,172,008
Total Scheduled Outages		
Number	4,290	3,375
Hours	33,865	18,588
Total Unscheduled Outages		
Number	3,871	5,786
Hours	12,672	29,522
Total All Outages		
Number	8,161	9,161
Hours	46,537	48,110
Operational Availability Percentage	99.41	99.22
Mean Time to Restore in Hours (All Causes)	5.70	5.25

Source: Federal Aviation Administration, Airways Facility Service, Air Navigation
and Air Traffic Control Facility Performance and Availability, RIS:SM
6040-20, Report for Fiscal Year 1973, 27 August 1973.

Even though it should be remembered that the limitations due to line-of-sight propagation, radio frequency interference, and DME channel saturation could significantly lower the figure, the 99.22% availability for the TACAN system will be used as the availability value for the VORTAC radionavigation system in the present analysis.

2.5   Implementation Plans/Costs of the System

This chapter has been dedicated to a description of the VORTAC radionavigation system and its performance in light of the enroute and terminal requirements specified in Chapter One. In actuality, the present discussion of the VORTAC system has focused not only on the system as it is presently configured, but on advanced arrangments as well. This section of the analysis describes the costs associated with the different configurations.

For the purposes of this study the costs are divided into three main categories:

(1) facilities and equipment costs;

(2) operations and maintenance costs; and

(3) relocation and modification costs.

The facilities and equipment costs are those costs which can be described as one-time-only expenditures for the installation of new equipment and/or the establishment of new facilities. These costs include the land costs, facility engineering costs, the costs of construction material and labor, the costs of the electronic equipment and its installation, and the associated freight costs.

The operations and maintenance costs are the annual costs are the annual costs required to operate and maintain the particular facility in the FAA inventory. For the navigation systems under study in this analysis the operations and maintenance costs are primarily related to maintenance which includes direct maintenance personnel costs, all stocks and stores costs, the expense of flight checks, and the overhead costs needed to support the particular facilities and equipment.

The relocation and modification costs are those funds required to modify and renovate existing facilities, replace out of date equipment, and/or expand the existing capacity. The respective values for each of these costs are enumerated in Table 2-7.

The figures as stated have been projected to 1973 price levels based on historic trends of the escalation factors for both labor and equipment. [32] These costs represent national averages for the particular type of facility and do not reflect any local variations due to special conditions at a particular site. For this reason these figures should not be used to estimate the costs for any individual site, but they can be used to generate approximate figures for a system-wide analysis.

Table 2-7

APPROXIMATE UNIT COSTS OF VORTAC FACILITIES

	VORTAC	Doppler VOR with DME	Precision VOR with DME
Facilities and Equipment:	$315,000	$397,000 (single DME)	$426,000
		$428,000 (double DME)	$457,000
Operations and Maintenance:	$24,000	$27,000	$28,000
Relocation and Modification:			
relocate VORTAC site	$167,000		
modify to Doppler VOR/DME	$100,000		
modify to Precision VOR/DME	$130,000	$30,000	
modify VOR to VORTAC	$68,000		

With these figures in mind, one must reexamine the accuracy and coverage requirements of Chapter One, and evaluate the implementation plans necessary to satisfy those requirements.

The accuracy specification was such that the enroute tolerance be ±2.5 nautical miles, and the tolerance in the terminal area be ±1.5 nautical miles. These figures include the errors contributed by the radionavigation system, the airborne area navigation computer equipment, and the flight technical error. After the flight technical and computer errors have been discounted, as will be discussed in Chapter Five, the allowable error for the radionavigation system is reduced to ±2.28 nautical miles for the enroute segments and ±1.09 nautical miles for the terminal areas. These figures determine an effective coverage area for each facility.

For the convention VORTAC, with present day airborne equipment, from Equation 2.8, the magnitude of the total radionavigation system error was determined to be ±0.067d, where d is the radial distance of the receiver from the ground station. Therefore, in order to satisfy the accuracy requirement for the enroute segments, the maximum effective range for a conventional VORTAC with present day airborne equipment, is limited to 34.0 nautical miles:

$$\pm 0.067d \ \leq \ \pm 2.28 \ \text{n. mi.} \qquad \text{Eqn. 2.13}$$

$$d \ \leq \ \frac{2.28 \ \text{n. mi.}}{0.067} \ \leq \ 34.0 \ \text{n. mi.} \qquad \text{Eqn. 2.14}$$

The terminal area accuracy requirement determines that the effective range of a conventional VORTAC, with present day airborne equipment, for terminal area operations, is only 16.3 nautical miles:

$$\pm 0.067d \leq \pm 1.09 \text{ n. mi.} \qquad \text{Eqn. 2.15}$$

$$d \leq \frac{1.09 \text{ n. mi.}}{0.067} \leq 16.3 \text{ n. mi.} \qquad \text{Eqn. 2.16}$$

If the present VORTAC ground stations are utilized in conjunction with improved airborne equipment, from Equation 2.10, the enroute accuracy requirement limits the effective range to 47.5 nautical miles:

$$\pm 0.048d \leq \pm 2.28 \text{ n. mi.} \qquad \text{Eqn. 2.17}$$

$$d \leq \frac{2.28}{0.048} \leq 47.5 \text{ n. mi.} \qquad \text{Eqn. 2.18}$$

The terminal area accuracy requirement determines that the effective range for a conventional VORTAC ground station, used in conjunction with improved airborne equipment, is 22.7 nautical miles:

$$\pm 0.048d \leq \pm 1.09 \text{ n. mi.} \qquad \text{Eqn. 2.19}$$

$$d \leq \frac{1.09}{0.048} \leq 22.7 \text{ n. mi.} \qquad \text{Eqn. 2.20}$$

Equation 2.11 relates the accuracy of the post-1982 VORTAC facilities, with appropriate airborne equipment modifications, to the radial distance from the ground facility. The enroute accuracy requirement determines that the aircraft must be within 94.33 nautical miles:

$$\pm \left[(0.024d)^2 + (0.27)^2 \right]^{\frac{1}{2}} \leq \pm 2.28 \text{ n. mi.} \qquad \text{Eqn. 2.21}$$

$$0.000576d^2 + 0.0729 \leq 5.1984 \qquad \text{Eqn. 2.22}$$

$$d^2 \leq 8898.4 \qquad \text{Eqn. 2.23}$$

$$d \leq 94.33 \text{ n. mi.} \qquad \text{Eqn. 2.24}$$

The terminal area specification determines that, for this type of operation, the maximum range is 44.0 nautical miles:

$$\pm \left[(0.024d)^2 + (0.27)^2 \right]^{1/2} \leq \pm 1.09 \text{ n. mi.} \qquad \text{Eqn. 2.25}$$

$$0.000576d^2 + 0.0729 \leq 1.1881 \qquad \text{Eqn. 2.26}$$

$$d^2 \leq 1963.1 \qquad \text{Eqn. 2.27}$$

$$d \leq 44.0 \text{ n. mi.} \qquad \text{Eqn. 2.28}$$

The coverage requirement of Chapter One was such that the radionavigation system must provide service everywhere within the conterminous United States and Alaska from an altitude of 1,500 feet above ground level to 45,000 feet. From Table 2-4 it can be determined that the maximum effective range for a VORTAC navigation signal being received at 1,500 feet above ground level is 48 nautical miles over flat terrain. In mountainous areas the requirement for complete coverage is impossible to satisfy because of the line-of-sight propagation characteristics of VHF/UHF signals. An attempt to remedy this shortcoming can be accomplished by increasing the number of facilities in these areas. By determining the mountainous terrain areas to be approximately one-third of the total area of the conterminous United States and Alaska, and arbitrarily assuming that in these mountainous terrain areas one-third again as many facilities will be installed as would normally be required for flat terrain, the author was able to determine a multiplier of 1.1 to account for non-flat terrain in the required coverage area.

The frequency protection criteria for the low altitude facilities was such that a 40 nautical mile limit was imposed. However, the author believes that this particular limitation will be overcome with the adoption of the 50kHz channel plan and the application of systems techniques to the frequency assignment procdures.

The terminal area accuracy requirements are the most restrictive, and they will be the binding constraint in this analysis. In the post-1982 navigation realm there will not necessarily be a radionavigation facility at all locations which require terminal area accuracies. This fact necessitates that terminal area accuracy be achieved everywhere within the effective coverage area of the facility.

The computations preceding Equation 2.28 derived the maximum effective range of 44.0 nautical miles for the post-1982 VORTAC radionavigation system. The total service area for such a facility is 6,082 square nautical miles:

$$A_s = \pi r_{max}^2 \qquad \text{Eqn. 2.29}$$

$$A_s = \pi (44.0 \text{ n. mi.})^2 = 6,082 \text{ sq. n. mi.} \qquad \text{Eqn. 2.30}$$

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where

$$A_s = \text{the maximum service area of the radionavigation facility; and}$$

$$r_{max} = \text{the maximum effective range of the navigation facility.}$$

The combination of a number of these circular facility service areas must completely cover the conterminous United States and Alaska. However, before a determination can be made of the total number of facilities required, account must be taken of one other circumstance. Whenever circular areas are used to completely cover a larger area, overlap must occur. Figures 2-23 and 2-24 illustrate the situation. Area ABCD must be completely covered by circles. If a circle is centered at each vertex of ABCD, there is an area in the center of ABCD which is not covered. This can be remedied by placing an additional circle which is centered on the uncovered area. Whenever this is done, overlap exists among the coverage areas of the circles. This is shown in Figure 2-24 by the shaded areas. The ratio of the shaded areas to the total area of ABCD can be computed to be 0.57:

$$\text{Area ASET} = \frac{\pi r^2}{4} \qquad \text{Eqn. 2.31}$$

$$\text{Area ASOT} = r^2 \qquad \text{Eqn. 2.32}$$

$$\text{Area TESO} = r^2 \left(1 - \frac{\pi}{4}\right) \qquad \text{Eqn. 2.33}$$

$$\text{Area ASFT} = \text{Area TESO} \qquad \text{Eqn. 2.34}$$

$$\text{Area TFSET} = \text{Area ASOT} - 2(\text{Area TESO}) \qquad \text{Eqn. 2.35}$$

$$\text{Area TFSET} = r^2 - 2\left[r^2\left(1 - \frac{\pi}{4}\right)\right] = r^2\left[1 - 2\left(1 - \frac{\pi}{4}\right)\right] \qquad \text{Eqn. 2.36}$$

$$\frac{\text{Area TFSET}}{\text{Area ASOT}} = \frac{r^2}{r^2}\left[1 - 2\left(1 - \frac{\pi}{4}\right)\right] = 1 - 2\left(1 - \frac{\pi}{4}\right)$$
$$= 0.570 \qquad \text{Eqn. 2.37}$$

where all areas and dimensions are defined as in Figure 2-24. This same ratio applies for the relationship between the total shaded area and the original area to be covered, ABCD. As the dimensions of the area to be covered grow large compared to the radius of the service area circles, the percentage of the service area circles that lies outside the bounds of the required coverage area gets small. Therefore, to determine the actual number of facilities necessary to completely cover the required area, one must simply take the required area plus the overlap area and divide that figure by the
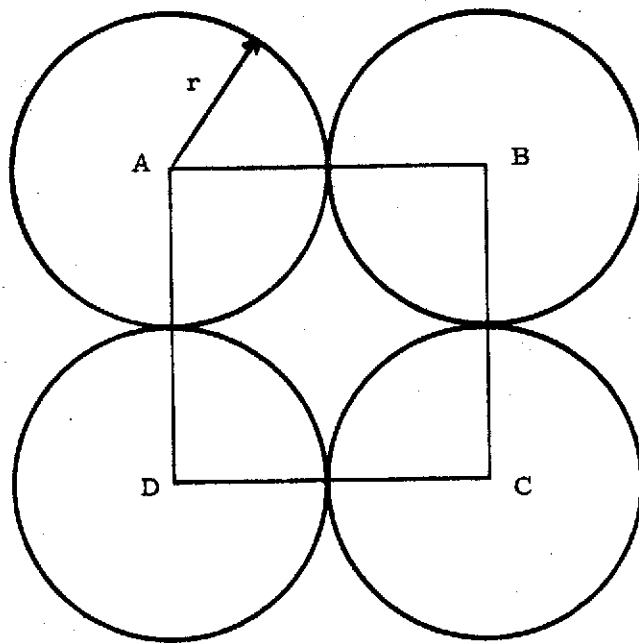
Figure 2-23. Circular Coverage Situation
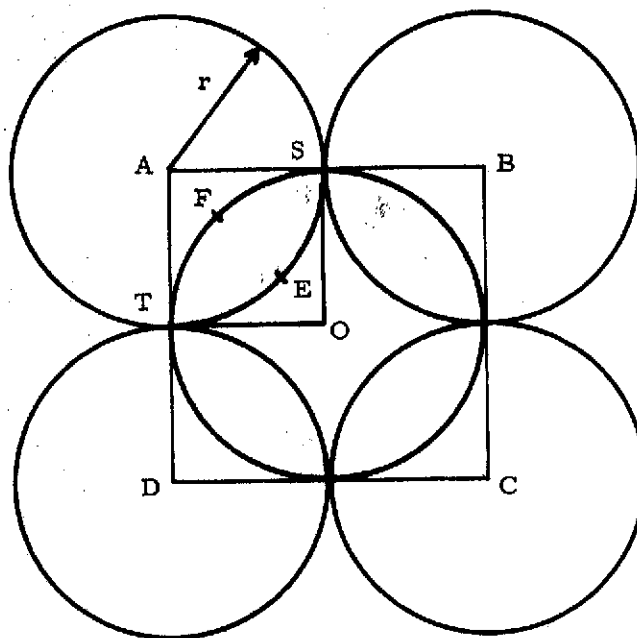
Figure 2-24. Circular Overlap Phenomenon

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unit facility service area. This computation is accomplished in Equation 2.38, and the required number of post-1982 VORTAC radionavigation facilities to satisfy the constraints of Chapter One is determined to be 780:

$$n = K_1 \times K_2 \times \frac{A_T}{A_S} = 1.1 \times 1.57 \times \frac{2,750,000}{6,082} = 780 \qquad \text{Eqn. 2.38}$$

where

n = the number of post-1982 VORTAC radionavigation facilities required;

A_T = the area of the conterminous United States and Alaska, i.e., approximately 2,750,000 square nautical miles;

A_S = the maximum unit service area of a single facility, i.e., approximately 6,082 square nautical miles (from Eqn. 2.30);

K_1 = multiplier to account for non-flat terrain = 1.1; and

K_2 = multiplier to account for service area overlap = 1.57.

The determination of the number of conventional VORTAC radionavigation facilities, utilizing present day airborne equipment, that would be required to satisfy the terminal area accuracy requirement can be accomplished in a similar manner. This computation yields the result that 5,690 facilities would be needed:

$$n = K_1 \times K_2 \times \frac{A_T}{A_S} = 1.1 \times 1.57 \times \frac{2,750,000}{835} = 5,690 \qquad \text{Eqn. 2.39}$$

where

n = the number of conventional VORTAC radionavigation facilities required;

A_T = the area of the conterminous United States and Alaska, i.e., approximately 2,750,000 square nautical miles;

A_S = the maximum unit service area for a convention VORTAC facility, utilizing present day airborne equipment, i.e., approximately 835 square nautical miles (from Eqn. 2.16 and Eqn. 2.29);

K_1 = multiplier to account for non-flat terrain = 1.1; and

K_2 = multiplier to account for service area overlap = 1.57.

If the conventional VORTAC ground stations are utilized in conjunction with improved airborne equipment, a lower number of facilities would be required to satisfy the terminal area accuracy requirement. Computation yields the result that 2,934 facilities would be needed:

$$n = K_1 \times K_2 \times \frac{A_T}{A_S} = 1.1 \times 1.57 \times \frac{2,750,000}{1,618.8} = 2,934 \qquad \text{Eqn. 2.40}$$

where

n = the number of conventional VORTAC radionavigation facilities required;

A_T = the area of the conterminous United States and Alaska, i.e., approximately 2,750,000 square nautical miles;

A_S = the maximum unit service area for a conventional VORTAC facility, utilizing improved airborne equipment, i.e., approximately 1,618.8 square nautical miles (from Eqn. 2.20 and Eqn. 2.29);

K_1 = multiplier to account for non-flat terrain = 1.1; and

K_2 = multiplier to account for service area overlap = 1.57.

The costs of implementation associated with these numbers of facilities can be determined by multiplication of the incremental number of facilities or modifications times the appropriate unit cost. Table 2-8 displays the results. It should be clarified that these are the costs of providing a navigation system that meets the requirements as specified in Chapter One. Any adjustment to those requirements would be reflected in a corresponding change to these costs. Chapter Five will contain an analysis of the sensitivity of the cost elements to a change in requirements. Table 2-9 summarizes the performance and costs of the candidate VORTAC radionavigation systems.

Table 2-8

APPROXIMATE IMPLEMENTATION COSTS FOR THE VORTAC RADIONAVIGATION SYSTEM

	No. of Facilities Required	No. of Facilities Installed	Incremental No. of Facilities Required	Facilities & Equipment Unit Cost
Conventional VORTAC ground stations				
with present day airborne equipment	5,690	900 (700/200)[1]	4,790/200	$315,000/$68,000
with improved airborne equipment	2,934	900 (700/200)[1]	2,034/200	$315,000/$68,000
Post-1982 VORTAC radionavigation facilities	780	30/700/200[2]	0	$30,000/$130,000/ $198,000

Notes:

1. There are approximately 900 VOR facilities, with slightly over 700 of them having collocated DME equipment. The remaining 200 have to have this DME equipment installed at a unit cost of approximately $68,000.

2. There are approximately 30 Doppler VOR's in existence. They have to be converted to precision VOR's at a unit cost of $30,000. The 700 VORTAC's have to be converted to precision VORTAC's at a unit cost of $130,000. The 200 VOR's without DME facilities have to be converted to precision VOR's and have DME equipment added at a unit cost of $198,000.

Table 2-8 (Cont.)

APPROXIMATE IMPLEMENTATION COSTS FOR THE VORTAC RADIONAVIGATION SYSTEM

	Annual Operations & Maintenance Unit Cost	Total Facilities & Equipment Cost	Total annual Operations & Maintenance Cost
Conventional VORTAC ground stations			
with present day airborne equipment	$24,000	$1,522,450,000	$136,560,000
with improved airborne equipment	$24,000	$ 654,310,000	$ 70,416,000
Post-1982 VORTAC radionavigation facilities	$28,000	$ 112,000,000[3]	$ 21,840,000

Notes (Cont'd.):

3. The Total Facilities and Equipment Cost for the Post-1982 VORTAC radionavigation configuration was computed by adding the amounts necessary to (1) convert the 30 Doppler VORTAC's to precision VORTAC's; (2) install 200 DME's at the unequipped VOR facilities and then convert those facilities to precision VORTAC's; and (3) convert 550 VORTAC's to precision VORTAC's.

Table 2-9

VORTAC PERFORMANCE AND COSTS

Performance

System Accuracy:	± 1.09 nautical miles
System Coverage:	Continuous, except in some mountainous areas
System Availability:	0.992

Costs

Conventional VORTAC Ground Stations, used in conjunction with present day airborne equipment

Facilities and Equipment:	$1.522 billion
Operations and Maintenance/year:	$136.6 million

Conventional VORTAC Ground Stations, used in conjunction with improved airborne equipment

Facilities and Equipment:	$654.3 million
Operations and Maintenance/year:	$70.4 million

Post-1982 VORTAC radionavigation facilities

Facilities and Equipment:	$112.0 million
Operations and Maintenance/year:	$21.8 million

Cost of Airborne Equipment:	$3-4 thousand

CHAPTER 3

THE LORAN-C RADIONAVIGATION SYSTEM

Loran-C is a low frequency, pulsed, hyperbolic radio aid to navigation. In proper configuration it has demonstrated the capability to provide the coverage, accuracy, and availability required for the area navigation of aircraft; and, therefore, was selected as a system of interest in this investigation.

3.1   Low Frequency Propagation

Loran-C operates in the low frequency (LF) band. It is centered around a carrier frequency of 100 kHz, with 99% of its radiated energy inside the band of 90-110 kHz. After an analysis of numerous factors that determine the "optimum" frequency for groundwave propagation, e.g., atmospheric noise, antenna efficiency, groundwave propagation characteristics, and system accuracy, the 90 - 110 kHz band was selected by the International Telecommunications Union (ITU) as the frequency spectrum where long-range navigation systems would be established. This "optimum" frequency was a compromise between the requirements of low attenuation, which improves as the frequency decreases, and the bandwidth needed for the short rise times of the pulses. In addition, a plot of field intensity vs. frequency, for the same power, shows that for frequencies above 120 kHz the curves for propagation over a good conductor (seawater) and a poor conductor (land) diverge rapidly beyond 500 miles; and, therefore, intervening changes in conductivity do not affect 100 kHz propagation as much as at higher frequencies. [33]

Radio frequency (RF) energy travels in all directions from the transmitting antenna. A portion of the energy travels parallel to the earth's surface — this is known as the groundwave; another portion is emanated upward and outward until it strikes the ionosphere and is reflected back to the earth — this is known as the skywave. Figure 3-1 is an illustration of the situation. The height and composition of the ionosphere, which are very important to skywave propagation, exhibit variable properties and result in propagation which is not nearly as predictable as that for the groundwave. At 100 kHz a single cycle represents $10\,\mu$ seconds of time interval. Present techniques enable one to measure radio frequency phase to one degree or $0.03\,\mu$ seconds. Since measurements can be made this closely, one of the chief determinants of accuracy is the stability of propagation.
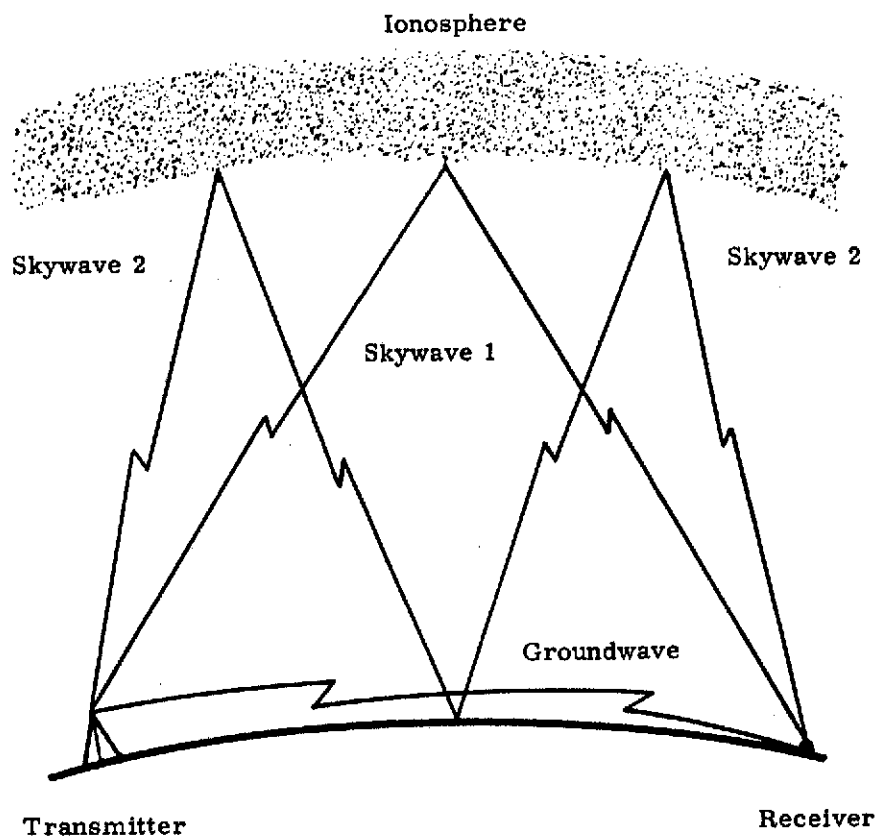
Figure 3-1   Low Frequency Propagation Paths

The groundwave is the most stable mode of propagation for Loran-C. A National Bureau of Standards study that paid particular attention to the groundwave mode concluded "low frequencies exhibit properties which are quite favorable to high reliability and precise radio navigation — timing. In particular, the ground-wave signal is especially favorable." [34]

Groundwave propagation depends upon the diffraction effects of waves propagating over a spherical earth, the earth conductivity along the path, the atmospheric lapse rate, and the refractive index of the air. If the transmitting stations were located on a perfectly spherical earth, with a surface of uniform conductivity, the propagation characteristics could be determined to a high degree of accuracy. However, this is not the case. Groundwave coverage extends approximately 1200 nautical miles. With this range changes in conductivity and, hence, propagation are likely to occur. Tests have revealed significant variation (as large as $5\,\mu$-seconds) between actual and predicted propagation times. To reduce this error, predictive methods have been developed which improve the discrepancy to values as low as $0.5\,\mu$ seconds; and with calibration at a specific site, this can be further reduced to $0.05\,\mu$ seconds. An article by Potts and Wieder [35] contains an excellent description of the various effects and is recommended reading for a detailed explanation of the ground propagation characteristics. It should be pointed out that these deviations do not vary with time; and, therefore, do not disturb the ability of the aircraft to locate a known position.

The long-term stability of skywave propagation is not nearly so good as that of the groundwave. After transmission of the RF energy, the ionosphere acts as a retractive medium to bend some of the energy back toward the earth. The skywaves are echoes of the transmitted pulses. The accuracy of the skywave is dependent on the stability of the ionosphere. For 100 kHz signals the short-term stability is fairly high, but wide variations will occur between day and night, season to season, and place to place. Extensive tests have shown that the Loran-C signal suffers distortion and phase changes on reflection from the ionosphere. The nature of the distortion and phase changes depends on the direction of propagation (the ionosphere is anisotropic), the earth's magnetic field near the reflection point of the wave, and the explicit electron density distribution in the ionosphere. [36] Recent tests have determined synchronization capability on the order of several microseconds. First-hop skywave range can be nearly 2,300 nautical miles. In the areas beyond the groundwave coverage navigation can be achieved, but with reduced accuracy. Figure 3-2 demonstrates the relative field intensities of the groundwave and various modes of the skywave as the range increases. The groundwave attenuation increases approximately with the fourth power of the range, while the skywave intensity (free-space) decreases with the square of the distance from the station. As the knowledge

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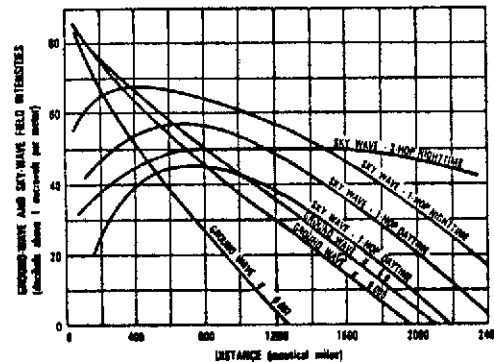
Figure 3-2. Variation of 100-kHz groundwave and skywave field intensities
with distance for a transmitted power of 100 kilowatts. Con-
ductivities ⊱ for the groundwaves are for seawater (5 mhos
per meter), good earth conductivity (0.005 mho per meter),
and poor earth conductivity (0.001 mho per meter). For the
skywave curves the conductivity is 0.005 mho per meter.
Ionosphere height is 70 kilometers (43 miles) during the day
and 90 kilometers (56 miles) at night. The two 1-hop daytime
skywave curves roughly bound the seasonal and diurnal varia-
tions.

Source: Van Etten, J. P., "Navigation Systems: Fundamentals of Low- and
Very-Low-Frequency Hyperbolic Techniques," Electrical Communi-
cation, Vol. 45, No. 3, 1970, p. 9.
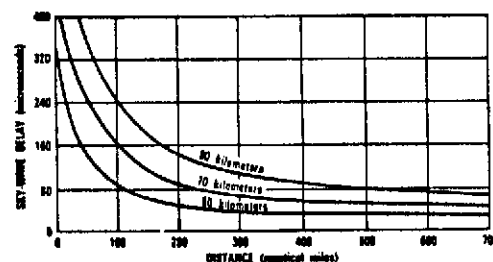
Figure 3-3. Variation of the skywave delay with distance for different effective
ionosphere heights.

Source: Van Etten, J. P., "Navigation Systems: Fundamentals of Low- and
Very-Low-Frequency Hyperbolic Techniques," Electrical Communi-
cation, Vol. 45, No. 3, 1970, p. 9.

of the properties of the ionosphere grows, the skywave will yield more accurate
navigation information. However, for the present, precise navigation is not feasible
with use of skywaves, and in areas of significant skywave intensity they can cause
severe fading of the useful groundwave signal.

The ability to select and utilize a particular transmission mode provides
the maximum fix accuracy for the Loran-C system. Reference to Figure 3-1
clearly illustrates that the skywave signals must travel a greater distance than the
groundwave to reach the receiver. This generates a delay in the time of arrival of
a skywave signal. Figure 3-3 is a plot relating delay to range from the transmitter
site and to ionospheric height which varies normally from 70 kilometers during the
day to 90 kilometers at night. The delay can range from 35 μ seconds where the
skywave overlaps its own groundwave to 1,000 μ seconds where the skywave over-
laps the groundwave of the succeeding pulse. Figure 3-4 illustrates the signal
detected at the receiver for a single pulse transmission. Fading and pulse shape
changes could cause serious problems with the signal. Large navigation errors
would result if these conditions were not taken into account in the selection of the
Loran-C signal format and in receiver design.

3.2   Pulsing of Loran-C Signals

The Loran-C radionavigation system uses pulsed transmissions from its
fixed ground stations to provide signals that enable the navigator to determine his
position within the coverage area. The use of pulses and the capability to identify
those from a particular station enable Loran-C to have many ground stations
operating on a single carrier frequency. Two further advantages are also realized
by pulsing the transmissions. It provides for the discrimination between components
of the received signal (enabling the user to get maximum utility from the ground-
waves without skywave contamination), and it increases the average power trans-
mitted without requiring higher peak power capability in the transmitter.

In a specific area of coverage the Loran-C navigation information is provided
by a network of stations called a "chain". The chain consists of one "master" station
(designated M) and at least two secondary stations (designated X, Y, Z, or W, based
on the order in which they transmit). The stations are located so that the signals
from the master and at least two of the secondary stations can be received throughout
the coverage area. The secondary stations can be separated from the master by
distances of 500 - 700 nautical miles. A Loran-C signal period, for a particular
chain, is initiated by a transmission from the master station. After specified delay
periods each secondary station will transmit a similar signal. The delay periods
are such that no two signals overlap in time anywhere within the service area;
therefore, they always arrive at the receiver in the same sequential order. The

GROUND WAVE

SKY WAVE 1

SKY WAVE 2

PART OF GROUND·
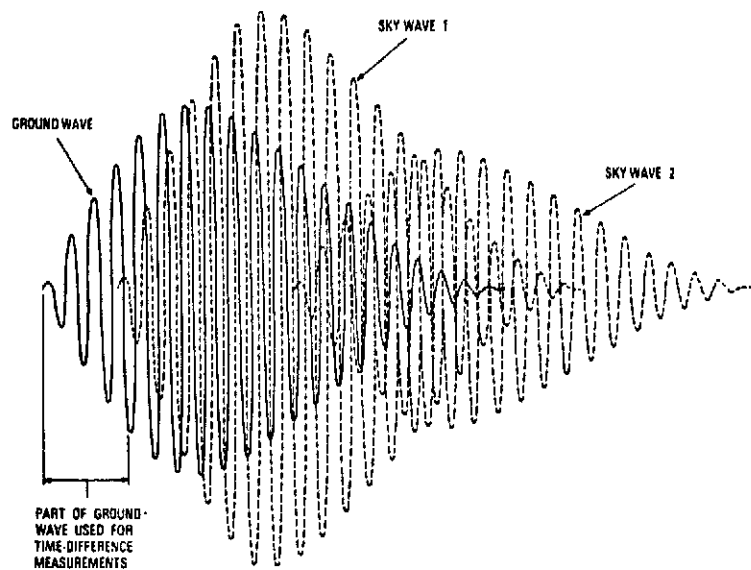WAVE USED FOR
TIME-DIFFERENCE
MEASUREMENTS

Figure 3-4. Groundwave and skywaves showing how Loran-C overcomes
the problem of skywave contamination.

Source: Van Etten, J. P., "Loran-C System and Product Development,"
Electrical Communication, Vol. 45, No. 2, 1970, p. 101.

signal from the master station is a group of nine pulses, while each secondary station emits eight pulses. In the initially configured chains the master station generated the basic time reference pulse; each secondary station would receive this transmission and wait a specified period of time (coding delay) before generating its own signal. Now the chains are operated in what is known as the "free running" mode. All stations are equipped with Cesium beam frequency standards, and they each derive their own time of transmission. Active phase locked synchronization to the master station pulse is not maintained, but through system area monitors the control of timing tolerances can be kept extremely precise.

Because all of the Loran-C stations share the same frequency, and only the time difference measurements from one chain at a time are of use to the navigator, identification of a particular chain must be provided by some means other than channel selection. This is accomplished by setting the receiver to synchronize on a desired pulse group repetition interval. A specific group repetition interval (GRI) is determined for each chain. There are five basic intervals and they are coupled with eight specific intervals. Table 3-1 lists the group repetition intervals available. For example: to receive the chain designated SS-7 (U.S. East Coast chain), one would select a GRI on the receiver of 99,300 μ seconds. This selection process has excluded the transmissions from all chains except the one on the U.S. East Coast. Each station transmits one pulse group per GRI. The GRI is selected to be long enough so that the signals from the individual stations maintain their sequential order throughout the coverage area. It is a function of the number of stations and the distance between them. Adjacent chains employ repetition rates that minimize cross-rate interference. Occasionally a single station may be shared by adjacent chains, in which case that station is pulsed at the two different rates.

Once a particular chain has been chosen, the operation sequence of that chain becomes important. The master station is the first to transmit. Its signal is in the form of eight pulses spaced 1,000 μ seconds apart and a ninth pulse spaced 2,000 μ-seconds from the eighth pulse. This ninth pulse is used to aid in master station identification and to provide the system with a method of transmitting information relative to the usability of stations within the chain. In addition, the master station transmits one additional pulse per second which the user may utilize to recover Universal Time. Each secondary station will transmit its signal at a unique time specified after the master station. The secondary station signal is in the form of eight pulses spaced 1,000 μ seconds from each other. Figure 3-5 illustrates the Loran-C format for the U.S. East Coast chain.

In order to utilize the very accurate groundwave position information, it must arrive at the receiver uncontaminated by skywave reflections. As was discussed earlier, the skywave delay can range from 35 μ seconds to 1,000 μ seconds. If the

Table 3-1

GROUP REPETITION INTERVALS
(GRI In Microseconds)

SPECIFIC GRI	BASIC GRI				
	SS	SL	SH	S	L
0	100,000	80,000	60,000	50,000	40,000
1	99,900	79,900	59,900	49,900	39,900
2	99,800	79,800	59,800	49,800	39,800
3	99,700	79,700	59,700	49,700	39,700
4	99,600	79,600	59,600	49,600	39,600
5	99,500	79,500	59,500	49,500	39,500
6	99,400	79,400	59,400	49,400	39,400
7	99,300	79,300	59,300	49,300	39,300

NOTE: The designation of a chain GRI is a combination of the identification of the basic and specific GRI. For example, SL-7 designates a chain having a GRI of 79,300 μ sec.

Source: U.S. Coast Guard, The Loran-C and Loran-D Systems of Radionavigation, Engineering Report, U.S.C.G. Electronics Engineering Center.

Master Station

Secondary Stations

W   X   Y   Z

GRI: 99,300 μ seconds

Carolina   Jupiter   Cape Race   Nantucket   Dana   Carolina
Beach   Beach
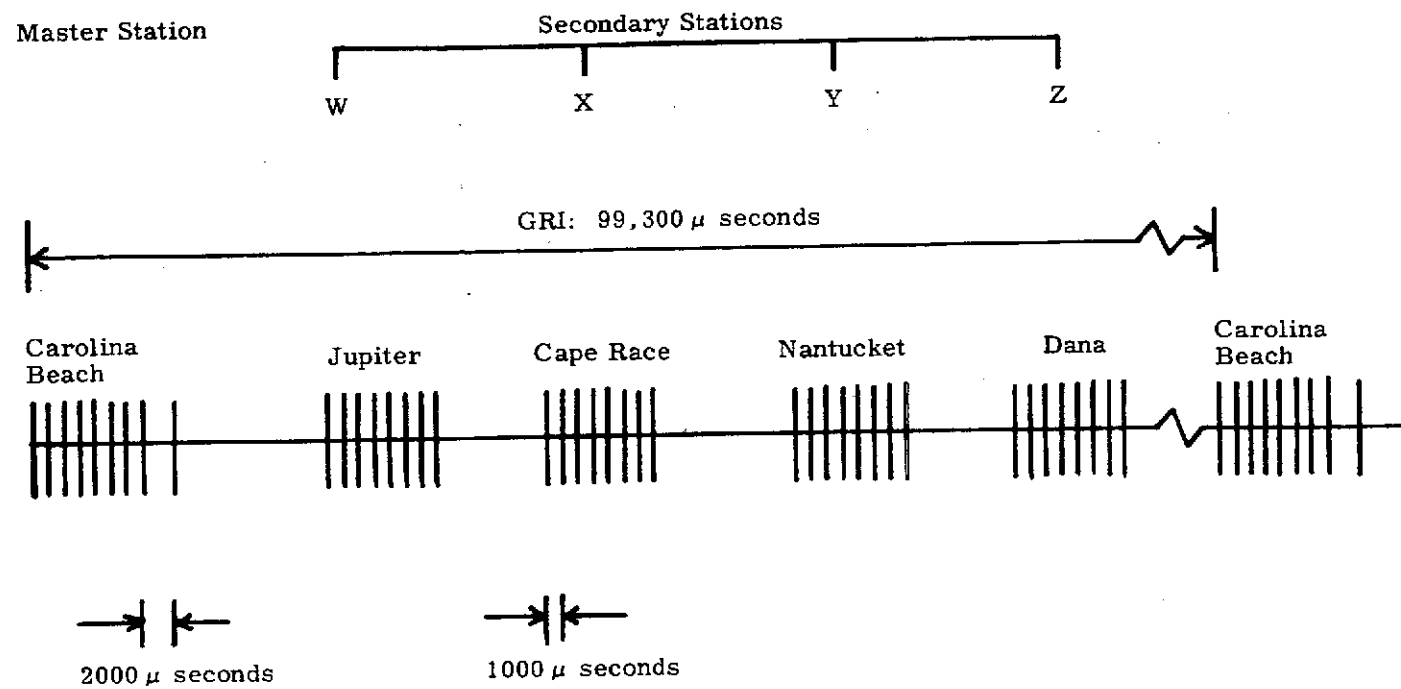
2000 μ seconds   1000 μ seconds

Figure 3-5.   Loran-C Format for U.S. East Coast Chain

reflection arrives exactly 1,000 μ seconds later, it will overlap and contaminate the succeeding groundwave pulse. The Loran-C signal format was designed to alleviate this problem. Each pulse in a group transmitted from a station has its RF carrier in phase or 180 degrees out of phase with the pulse envelope. A phase coding system is used for each transmission. Table 3-2 illustrates the code. The phase code of the master is different from that used at the secondary stations, but all the secondaries use the same code. This phase coding system prevents interference between pulses in the event of extended skywave delay, assists in rejecting interfering signals from outside sources, and aids in the identification of master and secondary transmissions; thus allowing the automatic signal acquisition to be accomplished unambiguously and also simplifying the automatic search apparatus.

The accuracy of the Loran-C system depends upon the correct synchronization of the transmissions from each station. In order to ensure that the timing is within tolerance, monitor receivers are installed in the coverage area. Many of the monitors are located at the transmitter sites themselves, but some are established at various remote areas. The objective for control of the chain is to maintain a constant time difference at a particular point in the coverage area. When this objective is not met, and the Loran-C stations are transmitting signals which are not suitable for accurate navigation, this fact must be transmitted to the users. The "blink" process accomplishes this. The ninth pulse of the master station is turned on and off (blinked) in a specific sequence to indicate the type of problem that exists. The secondary station(s) that is (are) transmitting the unusable signals will blink its (their) first two pulses of the pulse group. Table 3-3 illustrates the Loran-C blink code.

3.3 Loran-C Position Fixing: Time Difference

Loran-C is a hyperbolic radio aid to navigation. Position fixing is accomplished by determining the difference in distance to at least three transmitters. Each difference in distance will define a hyperbola, and the intersection of the two hyperbolae will determine a fix.

The distance differences are measured as the differences in times of arrival of signals transmitted from each of the stations. Since RF energy propagates at a known and finite velocity, the differences in times of arrival can be converted to differences in distance. Figure 3-6 illustrates the principle of position fixing by the Loran-C system. The master station emits a pulse signal at time $t = 0$, and the secondary station transmits a similar pulse at $t = \beta + \Delta$, where β equals the transmission time of the master signal to the secondary station and Δ equals the time after receiving the master pulse before the secondary station transmits its own pulse.

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Table 3-2

LORAN-C PHASE CODE

	MASTER	EACH SECONDARY
A GRI	++--+-+- +	+++++--+
B GRI	+--+++++ -	+-+-++--

NOTE: (+) Indicates 0° Carrier Phase

(-) Indicates 180° Carrier Phase

Loran-C Intervals A & B Alternate in Time

Source: U.S. Coast Guard, The Loran-C and Loran-D Systems of Radionavigation, Engineering Report, U.S.C.G. Electronics Engineering Center.

Table 3-3

LORAN-C BLINK CODE

MASTER STATION NINTH PULSE:

UNUSABLE TD (S)	ON-OFF PATTERN
None	
X	
Y	
Z	
W	
XY	
XZ	
XW	
YZ	
YW	
ZW	
XYZ	
XYW	
XZW	
YZW	
XYZW	

SECONDARY STATION FIRST TWO PULSES:

Turned on (blinked) for approximately 0.25 seconds every 4.0 seconds. All secondaries use the same code.

Source: U.S. Coast Guard, The Loran-C and Loran-D Systems of Radionavigation, Engineering Report, U.S.C.G. Electronics Engineering Center.

Figure 3-6. The Principle of Position Fixing by the Loran-C System
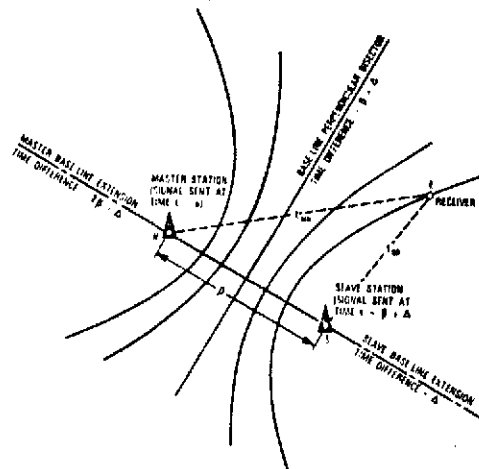
t = time

t_{MR} = time taken for a radiowave to travel between the master station and the receiver

t_{SR} = time taken for a radiowave to travel between the slave station and the receiver

β = time taken for a radiowave to travel between the master station and the slave station

Δ = time after receiving the master pulse signal before the slave station transmits its pulse signal

Figure 3-6. The Principle of Position Fixing by the Loran-C System

Source: Van Etten, J. P., "Navigation Systems: Fundamentals of Low- and Very-Low-Frequency Hyperbolic Techniques," Electrical Communication, Vol. 45, No. 3, 1970, p. 4.

A navigation receiver at R measures the difference in times of arrival of the master and secondary signals. The time difference (TD) equals $(\beta + \Delta) + t_{SR} - t_{MR}$, where t_{MR} and t_{SR} are the propagation times from the master and secondary stations to the aircraft R respectively. The range of time differences is well defined. If R is located on the secondary base line extension, $TD = \Delta$. If R is located on the master base line extension, $TD = 2\beta + \Delta$. All time difference hyperbolae in the service area are determined such that $2\beta + \Delta \geq TD \geq \Delta$. Since one of the design criteria for the Loran-C system is that no two signals from different stations will overlap in time within the coverage area, the time difference $2\beta + \Delta$ determines the minimum group repetition interval that can be selected for the chain.

Two or more pairs of stations must be received within the service area to establish a fix. In Figure 3-7 the two time differences TD_A and TD_B determine the position of the aircraft R. The time difference measurement is crucial to the operation of Loran-C. Consistent with the geometry of the hyperbolic grid, the accuracy of the system depends upon the user's ability to measure the time difference between the arrival of the radio signals and his knowledge of the propagation characteristics, so that the time difference can be converted to a line of position.

3.4 Loran-C Transmitter Characteristics

The function of the Loran-C transmitters is to emit carefully timed pulses with enough power to ensure groundwave coverage throughout the service area. In order to measure a time difference precisely in a pulse transmission system, a particular cycle must be identified within the pulse envelope. The high accuracy in the system results from the ability to separate the uncontaminated groundwave signal from the skywave and the ability to detect a particular zero crossing of the pure groundwave. This requires a steep rise time for the pulse, so that maximum power can be transmitted in the first few cycles. The present system uses the zero crossing between the third and fourth RF cycles (@ 30 μ seconds) as its tracking point. Fifty percent of the pulse peak amplitude is being generated by this time. The pulse specification is a compromise between steep rise times, the spectrum limitations imposed by international agreement, and the economics of using the minimum total average power.

Figure 3-8 illustrates a Loran-C pulse. The maximum power is reached at the positive peak of the eighth cycle (@ 72.5 μ seconds for a positive phase coded pulse), and the pulse decays exponentially in 400 μ seconds. By careful control of the leading edge of the envelope the relative amplitudes of the first few cycles are identical for every transmitter. This will aid in cycle identification. Since the navigation information must be extracted before skywave contamination, the pulse is sampled at the third cycle, where the power is only 25 percent of the peak. For thi., reason pulsed systems require more power than an equivalent range CW system.

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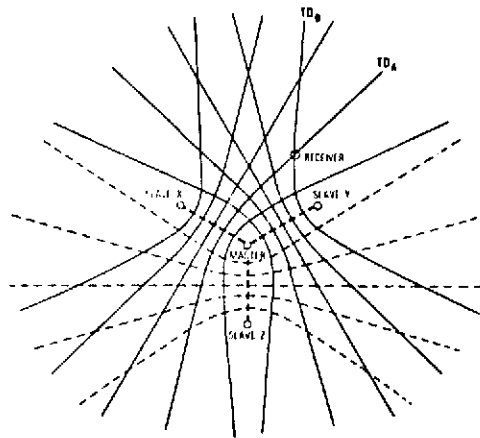
Figure 3-7. Triad and star transmitter configurations. Solid hyperbolas correspond to the triad configuration formed by the master station and the slave stations X and Y. The complete array of hyperbolas corresponds to the star configuration obtained by adding the slave station Z.

Source: Van Etten, J. P., "Navigation Systems: Fundamentals of Low- and Very-Low-Frequency Hyperbolic Techniques," Electrical Communication, Vol. 45, No. 3, 1970, p. 4.
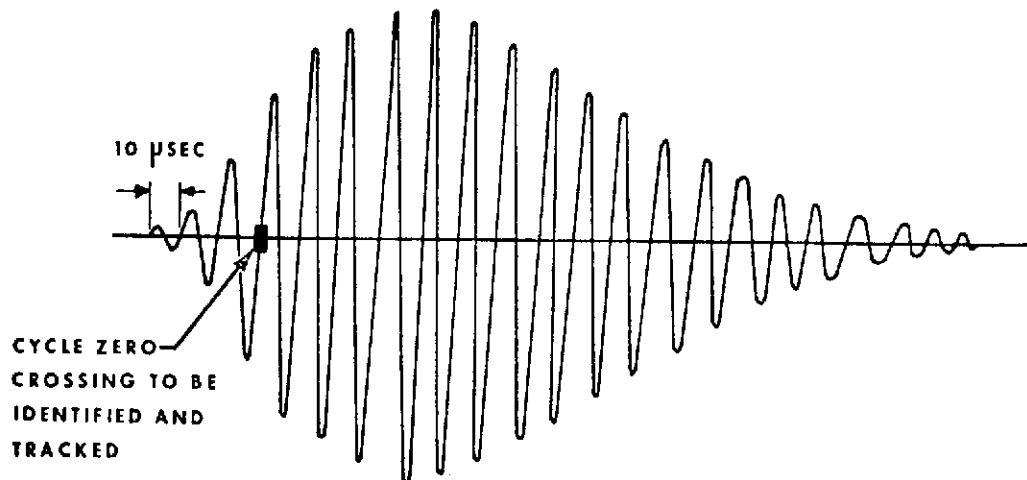
Figure 3-8. Loran-C Transmission Pulse

The chains are timed by synchronizing the master station transmission with the U.S. Naval Observatory master clock. Each of the secondary stations is synchronized with the master station. All stations are equipped with Cesium beam frequency standards whose error is less than one part in 7×10^{12}, or if two stations are calibrated against each other, one part in 10^{13}, i.e., 10 η sec/day if no additional calibration takes place. The overall synchronization errors in the system are expected to be within ± 40 η seconds with equipment being developed at this time. [37]

In order to realize absolute accuracies from the navigation system, it is necessary to calibrate the service area. This calibration entails recording the time differences at numerous known geographical points. The information is used to:

(1)   verify initial chain synchronization;

(2)   establish the control time differences;

(3)   ensure the accuracy of the control time differences; and

(4)   provide survey data for charting. [38]

Once the calibration is completed, constant monitoring is conducted by each transmitter site and by separate area monitors to ensure that station synchronization is maintained within specific control tolerances.

3.5   Loran-C Receiver Characteristics

The Loran-C receiver must perform two functions. It has to acquire the signals from at least three stations, and it must measure the differences in times of arrival of the three signals. Signal acquisition must be accomplished in an extremely noisy environment. The high accuracy of the system results from the ability of the receiver to separate the groundwave from the interfering skywave and then to locate a particular cycle in the RF carrier. The time difference measurement is made using both the pulse envelope arrival time and the phase arrivals of the 100 kHz carrier. Processing this time difference information within the receiver provides position location data to the navigator.

Figure 3-4 illustrates the received pulse in the presence of skywave interference. The signal is also subjected to atmospheric noise and man-made CW interference. The atmospheric noise is the result of lightning discharges in thunderstorms. The intensity of the noise is a function of time of day, the weather, the season, and the geographic location. It has been found that the noise generally decreases with increasing latitude on the surface of the earth. [39] The atmospheric noise is characterized by sharp impulses and periods of relative quiet in

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between. Hard limiting receivers can censor the signals during high noise bursts and are very effective against the discharge phenomenon. Examination of the relative values of the noise to signal ratios can give one a feeling for the magnitude of the problem. Skywave interference can be 30dB larger than the desired ground-wave; atmospheric noise 20dB larger; and CW interference 35dB larger. In addition, the signals themselves have an amplitude that may fall anywhere within a 120dB range depending on the distance from the station. The environment in which the receiver must operate places very demanding requirements on the selectivity and signal processing characteristics of the user equipment.

The operation by which the receiver acquires the signal and prepares it for processing is referred to as the search and settle process. Figure 3-9 illustrates in block form the operation of the Loran-C receiver. The search sequence can be broken down into three steps: (1) master search: searching in time for a group of master signal pulse transmissions of known repetition rate (GRI) and identifiable by a phase coding sequence; (2) achieving lock-on to the master signal using a coherent detector; and (3) secondary search: searching and locking on to two secondary transmissions with the aid of a time base synchronized with the master signal. [40] The settling process requires the receiver to lock on to a particular cycle of the input. In Loran-C receivers the third cycle of the groundwave signal is the target for settling. Settling is accomplished by making a measurement of the slope of the leading edge of the received pulse envelope and then using look-ahead detectors ensuring that the groundwave signal is the one being tracked. The pulse is designed so that the relative values of the cycle amplitudes are the same for all pulses, and the receiver can identify the third cycle in the pulse by its normalized slope. The look-ahead detectors can determine when a skywave is being tracked. When the receiver locks on to a signal and an advance signal is detected, the advance signal will be assumed to be the groundwave of interest. The receiver time base will then be advanced to track on the groundwave signal.

After the search and settle sequence is accomplished, the receiver must track the signal. This is accomplished by using a second order phase lock control. The loops have slow speeds of response and integration times on the order of ten seconds. This time is required to overcome noise and CW interference and to follow the aircraft maneuvers. The design of the phase lock control is a compromise between the wide bandwidth required to maintain track during aircraft maneuvers and the narrow bandwidth which produces higher accuracy. The time difference measurements are made as the signal is tracked. In Loran-C there are two types of time difference measurement. The pulse envelope provides a coarse measurement and the phase of the 100 kHz carrier provides a vernier or fine measurement. The envelope measurement enables Loran-C to sort out the skywave and to resolve the

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Master Signal
Timing

| START → | Signal
Acquisition

1. Master Search
2. Secondary Search | → | Signal
Settling

1. Ground Wave
2. Cycle Ident | → | Signal
Tracking | → | Time
Difference
Counter | → | Display |

Select GRI
for Triad

Select Secondary
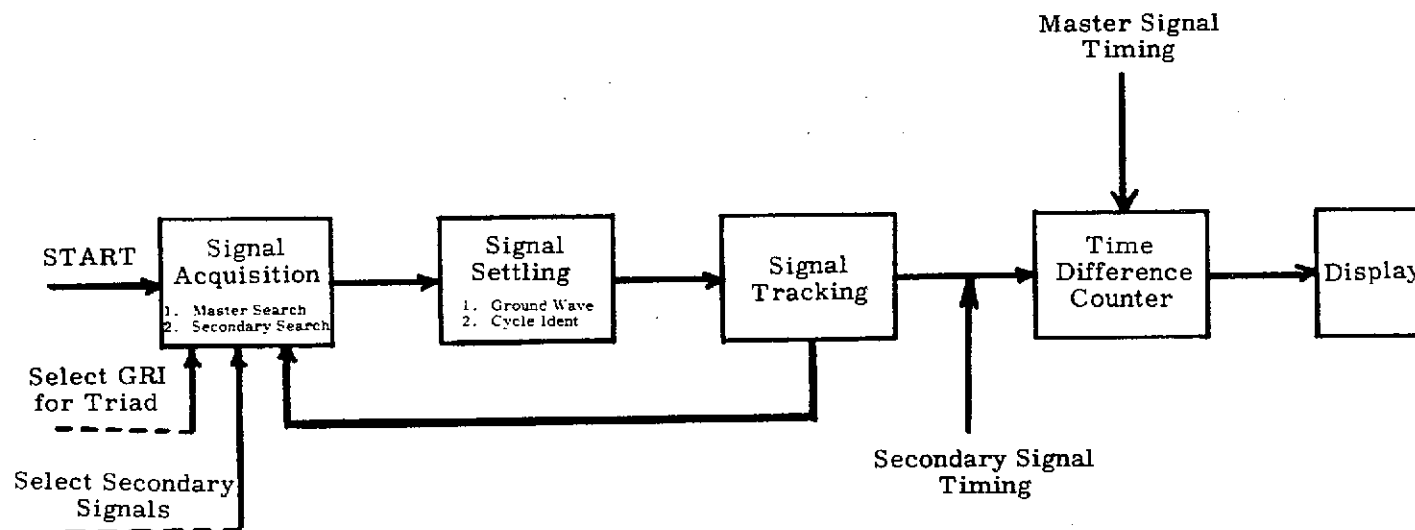Signals

Secondary Signal
Timing

Figure 3-9 Operation of a Loran-C Receiver

Source: Frank & Phillips, "Digital Loran-C Receiver Uses Microcircuits",
Electronics, January 31, 1964.

lane ambiguity problems. Since one can determine RF phase to one degree, the phase measurement provides the high accuracy for the system. Typical receivers are capable of timing accuracy to 0.05μ seconds. The two complementary methods of measurement work very well and resolve the problems associated with each single means. There is, however, one problem that can arise. It is referred to as envelope to cycle discrepancy. In pulsed signals there is a distinct propagation velocity for the group signal and the phase information. This will result in a phase shift of the pulse envelope with respect to the 100 kHz carrier. If the shift is larger than ± five μ seconds, whole cycle ambiguities will result in the line of position determination. By careful monitoring of the signals and careful calibration in the receiver, the five μ second tolerances can be met in the service areas.

The Loran-C automatic receiver measures at least two time differences simultaneously and continuously. The time difference information is then processed and presented to the navigator in the form most useful to him. It can be displayed as two time difference measurements, as latitude-longitude, or as distance to go and orientation from centerline on a preset course.

In avionics applications a display which presents navigation information rather than just position location has been found to be most useful. This involves a slight increase in cost, but is felt to be a good investment. Recent U.S. Coast Guard sponsored developments have resulted in the production of fully automatic Loran-C receivers available to the general user at a price of approximately $3000. It will be assumed in this study that a Loran-C navigator will be available to general aviation priced at approximately $4000.

3.6   Loran-C Performance

Three major criteria will be used to evaluate the performance of the Loran-C navigation system. They are accuracy, coverage, and availability of signal. Each of these measures is not completely independent of the others. all a function somewhat of station characteristics, chain configuration, and environmental conditions. However, they will be examined separately in this analysis and then finally combined to generate the performance characteristics of a proposed system.

3.6.1 System Accuracy

The present evaluation of Loran-C system accuracy will be based on the repeatable performance of the groundwave. It is necessary for the user to be receiving the groundwave mode of transmission in order to realize the highly accurate position fixes afforded by this system. Repeatable accuracy is the ability of the system to output the same position fix information on successive overflights of the same geographical point, i.e., how well one can return to a previously desig- nated position. When one calibrates a portion of the service area, designated positions

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are established. For air navigation predetermined waypoints and the airports themselves can be used. Once the calibration has been completed, the repeatable accuracy figure is applicable to the analysis of system performance in the terminal and approach requirements of the present study. Repeatability is not affected by fixed anomalies within the system. Repeatable position accuracy is affected, however, by a number of other factors. Three of the more important are:

    (1)   instrumental errors in the ground station and user equipment;

    (2)   random noise errors; and

    (3)   the geometrical configuration of the stations contributing to a position fix.

Instrumental errors in the ground station equipment are primarily the result of secondary station synchronization error. This error refers to the synchronization accuracy achieved between the master and secondary transmissions in the hyperbolic time difference method of operation. The new generation of transmitter equipment has four operational modes:

    (1)   Optimum - achieved 95% of the time; full power - timing precision of $\pm 40 \, \eta$ seconds;

    (2)   Precision - achieved 97% of the time; half power - timing precision of $\pm 40 \, \eta$ seconds;

    (3)   Enhanced - achieved 98.6% of the time; full power - timing precision of $\pm 200 \, \eta$ seconds; and

    (4)   Standard - achieved 99.7% of the time; half power - timing precision of $\pm 200 \, \eta$ seconds. [41]

The Optimum and Precision modes are designated as the normal operating modes for this study. Therefore, a timing precision of $\pm 40 \, \eta$ seconds is assumed.

Receiver error or user measurement error refers to the uncertainty in the time difference measurement due to characteristics of the user's equipment. Timing accuracy, phase measurement, band limiting, and receiver resolution all contribute to this error. Instrumental errors of between $\pm 25 \, \eta$ seconds and $\pm 50 \, \eta$ seconds are standard in quality receivers.

The most predominant error in repeatable accuracy analysis is that due to noise. The operational limit of most radio navigation systems, including Loran-C, is usually determined by the signal to noise ratio (SNR) in which the receiver must operate. In a recent analysis the error in the observed time difference due to noise was determined to be $\pm 0.05 \, \mu$ second for SNR = 1:1 and increasing to $\pm 0.14 \, \mu$ - second for SNR = 1:3. [42]

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In order to get a useful figure for this analysis, one must combine all of the instrumental error figures and the noise error into a single error figure. For this analysis a total system time difference error of less than ± 0.20 μ seconds has been accepted as appropriate. This value is applicable only to the repeatable accuracy case. When one is determined to measure the accuracy at noncalibrated points, e.g. , to satisfy the enroute navigation requirement in this study, an additional error becomes important. This is the error of prediction. Prediction error refers to the uncertainty in the determination of the propagation velocity from the transmitter site to the user position. After the calibration of a large number of points in the service area, the conductivities between any particular point and the transmitter site can be estimated fairly accurately. Numerous methods exist to convert the estimated conductivities into predicted propagation velocities and consequently predicted time differences. While the methods work quite well, uncertainty still exists in the prediction process. A value of ± 0.20 μ - seconds has been adopted to account for these variations. The propagation anomaly causes a fixed bias error at a point. When one sums this error with the errors that appear at the calibrated points, absolute (geodetic) accuracy will result. The overall system error for the noncalibrated point is less than ± 0.40 μ seconds.

The errors in time difference measurement are converted into position errors by factors which depend on the geometry of the station configuration. Geometric dilution of precision (GDOP) is defined as the ratio of rms position error to rms time difference error, assuming equal rms error in the time differences between the master station and the appropriate secondary stations. GDOP is only a function of the geometry and is independent of receiver or transmitter characteristics. In order to evaluate a specific configuration it is necessary to develop the mathematical relationship between the timing and position errors. Because of the hyperbolic divergence, which is variable, and the crossing angle at the fix, which is also variable, the accuracy of position determination can assume a wide range of values throughout the service area. Figure 3-10 illustrates the phenomenon of hyperbolic divergence. On the baseline between the master and secondary station a time difference error of ± 1 μ second is equivalent to a position error of ± 492 feet. As one moves away from the baseline, a given time difference error, ϵ_{td}, results in larger values for ϵ_d, the position error. Equation 3.1 allows one to determine the effect of hyperbolic divergence for a given point within the service area.

$$\epsilon_d = w \times csc \ (\theta/2) \times \epsilon_{td} \qquad \qquad \text{Eqn. 3.1}$$

where

$\qquad \epsilon_d$ = the error in position;
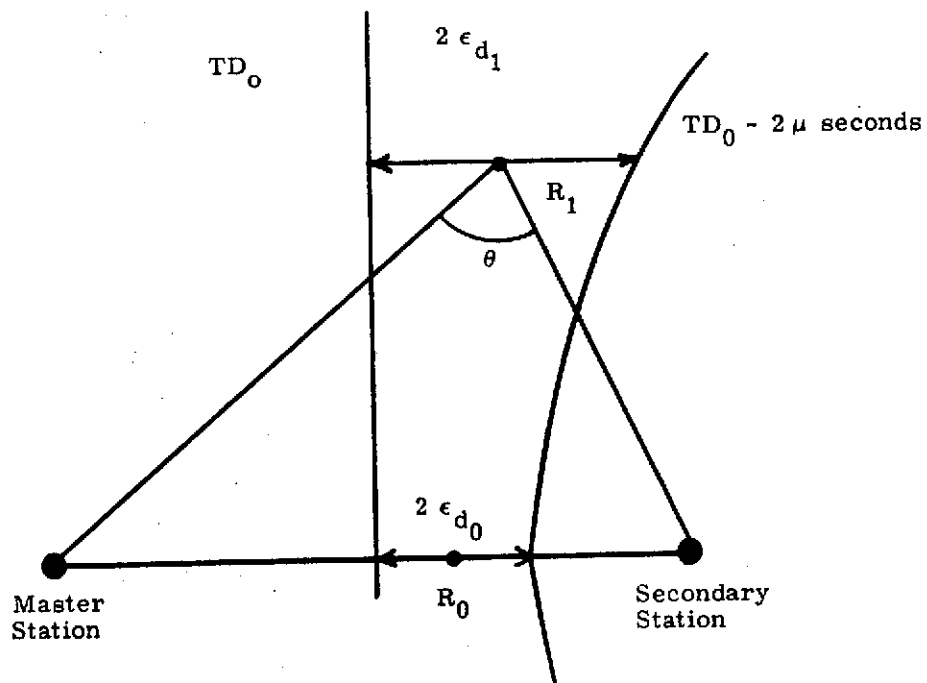
For $\epsilon_{td} = \pm 1 \, \mu$ second,

at receiver R_0, $\epsilon_{d_0} = 492$ feet

at receiver R_1, $\epsilon_{d_1} = CSC \, (\frac{\theta}{2}) \times 492$ feet

Figure 3-10. Effect of Hyperbolic Divergence

ϵ_{td} = the error in time difference measurement;

w = conversion constant: 0.5 times the speed of light; and

θ = the subtended angle between the master and secondary station as measured at the receiver.

In a hyperbolic navigation system reception from three stations is required to establish a fix. Geometrical errors result not only from the divergence of the second set of hyperbolae, but also from the effect of a nonorthogonal crossing angle of the lines of position. In order to account for the geometrical error that resulted from a triad configuration, and hence determine contours of constant accuracy for that station layout, the U.S. Coast Guard developed the nomogram illustrated in Figure 3-11. An example will assist in understanding the nomogram. This is shown in Figure 3-12. The receiver R is located at a point in the service area such that the angle subtended at R between the master and secondary station A is 60 degrees, and the angle subtended between the master and secondary station B is also 60 degrees. If one plots θ_A = 60 degrees and θ_B = 60 degrees on the nomogram, one generates a K factor of approximately 3.3. This is the value of the GDOP multiplier. Equation 3.2 enables one to relate time difference error to position error once the GDOP multiplier, K, has been determined.

$$\epsilon_d = K \times w \times \epsilon_{td} \qquad\qquad \text{Eqn. 3.2}$$

where

ϵ_d = the error in position;

K = factor for geometrical dilution of precision;

w = conversion constant: 0.5 times the speed of light; and

ϵ_{td} = the error in time difference measurement.

A time difference error of ± 0.1 μ seconds at receiver R would result in a position error of 160 feet:

$$3.3 \times 492 \text{ feet}/\mu \text{ second} \times 0.1\,\mu \text{ second} = 160 \text{ feet} \qquad \text{Eqn. 3.3}$$

The importance of the GDOP factor is readily apparent. At certain positions within the service area small time difference errors can generate quite large errors in position. Figure 3-13 illustrates the contours of constant GDOP multiplier for a typical Loran-C chain.

When planning navigation coverage for a designated area, various station layouts must be considered. Each possible configuration has advantages and disadvantages in terms of system accuracy and coverage.

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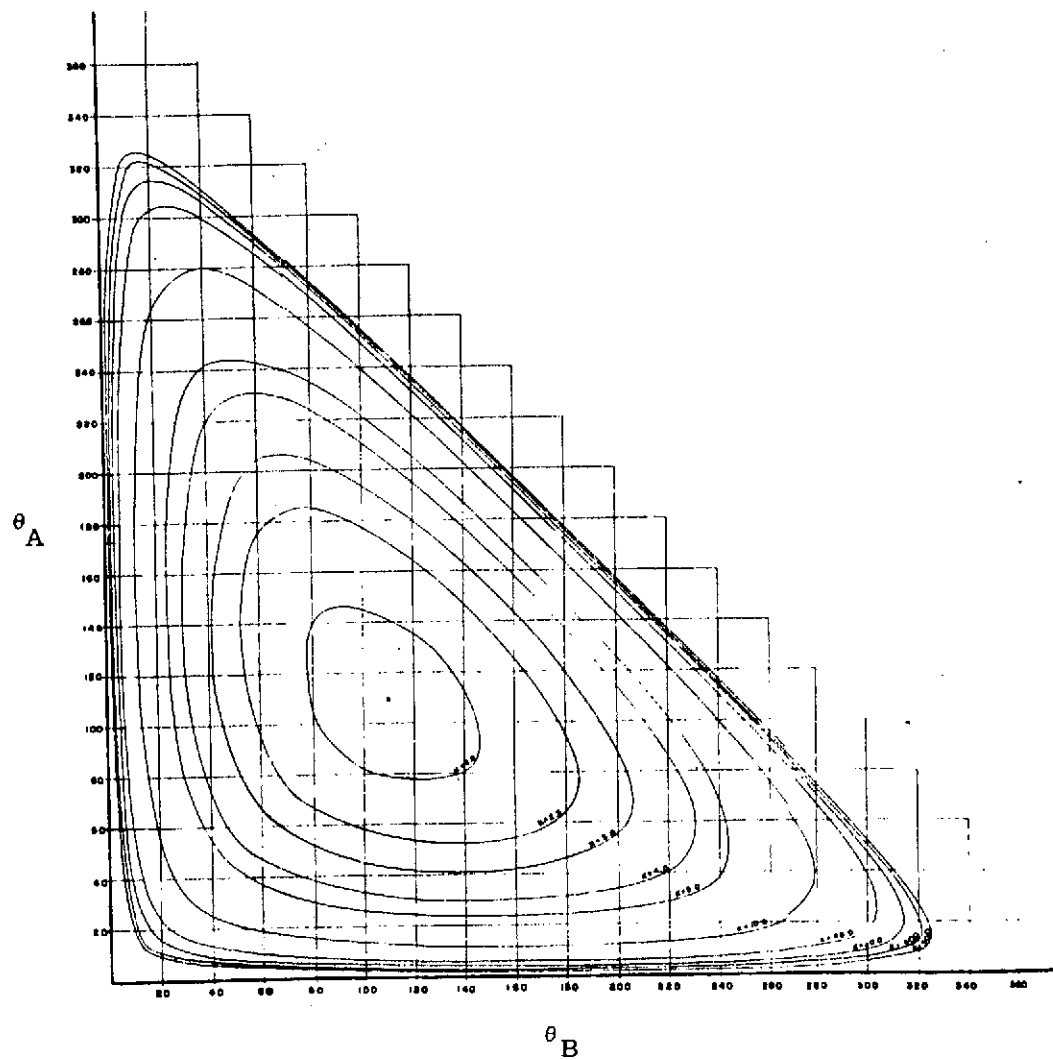
Figure 3-11. Nomogram for Computing Contours of Constant Geometric Accuracy

Source: Jansky and Bailey, The Loran-C System of Navigation, p. 130.

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$\theta_A = 60^O$, $\theta_B = 60^O$
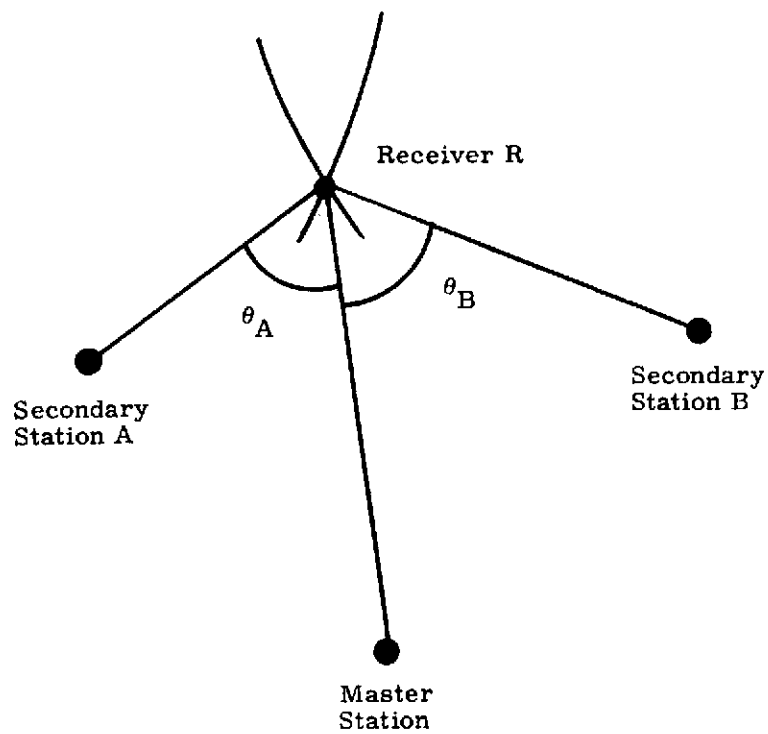
From Figure 3-11, $K \approx 3.3$

$\epsilon_p = K \times 492 \text{ ft}/\mu \text{ second} \times \epsilon_{td}$

For $\epsilon_{td} = \pm 0.1 \mu \text{ seconds}$,

$\epsilon_p = \pm 160 \text{ feet}$

Figure 3-12. Example Problem: Use of Nomogram
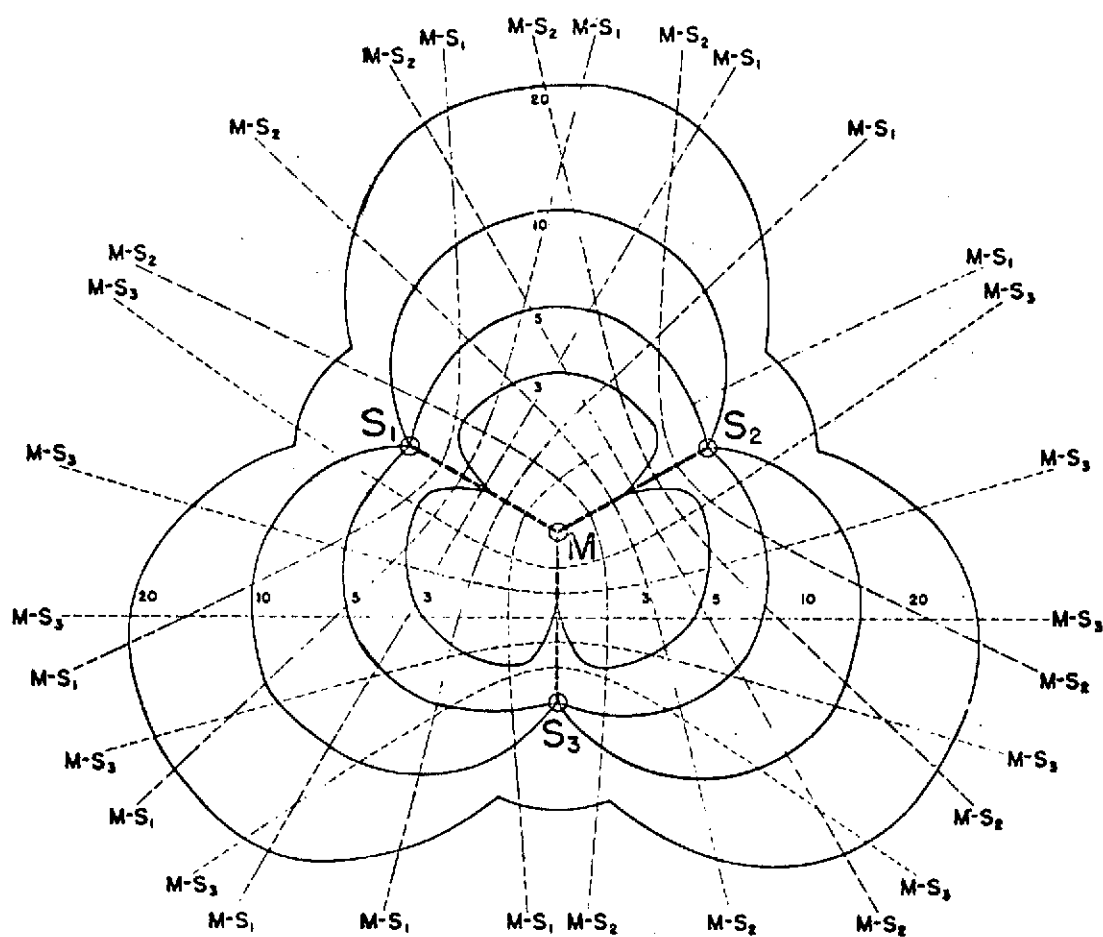
M • Master Station

S_1, S_2, S_3 = Secondary Stations

Dashed lines indicate hyperbolic lines of position.

Figure 3-13. Contours of Constant Geometric Dilution of Precision for a Typical Loran-C Chain

Adapted from Jansky and Bailey, The Loran-C System of Navigation, p. 48.

Each of the factors in the accuracy analysis is important. The instrumental and noise errors contribute to the uncertainty in the time difference measurement; and the geometry of the configuration provides the multiplier to convert time difference uncertainty into position uncertainty, which is one of the results most needed for the analysis of navigation systems.

3.6.2 Coverage

When the Loran-C navigation system is being used to provide position location information, coverage is furnished everywhere within the service area. There are no line-of-sight problems or similar occurrences of no reception. The service is spatially continuous throughout the coverage area and is available from the ground to high altitudes, providing information for high and low flying aircraft as well as the many types of surface vehicles. Because no round-trip radio measurement is required, the radiated power is limited only by the facilities at the ground station. Consequently, long range can generally be achieved.

It is very difficult to define exactly the area of coverage for a radio navigation system since many variables are involved. The radiated power, propagation conditions, atmospheric noise conditions, local noise and interference, and receiver sensitivity all have an effect on the useful range of the Loran-C system.

The accuracy of the Loran-C receiver is dependent on the relative strength of the received signal and the level of interfering noise. As the signal to noise ratio decreases, the accuracy of the time difference measurement made by the receiver also decreases. Since reception from three stations is required to fix one's position in the hyperbolic mode, the system service area is also a function of the geometry. For these reasons the dimensions of the service area for the Loran-C system need to be specified as that area within which reliable groundwave accuracies will result. In general, one can assume a groundwave range of 800 - 1200 nautical miles from each station, and each specific implementation plan will have a different service area resulting from these transmissions.

3.6.3 Availability of Signal

The availability of the signal is defined as the percentage of time that the system can provide information of the required accuracy to the user. When one analyzes the availability of the Loran-C signals, attention must be directed to two major areas: the reliability of transmitter station operation and the influence of propagation effects on the reception of accurate signals.

The importance of transmitter station reliability cannot be overstated. If a master station fails, one experiences a loss of coverage over the entire area not duplicated by another chain. The failure of a secondary station is less severe, but does result in the degradation of service for the coverage area of that one station.

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Increasing the reliability of transmitter station equipment is a major goal in the U.S. Coast Guard "Loran - 70's Program". One of the elements in the "Loran-C Improvement Program" is the development of a solid state transmitter. The transmitters are designed to be operated as multiple units in parallel in order to provide the station output. In the parallel configuration failure of a unit will cause only a partial reduction in the output power. The station transmissions will continue in this "gracefully degraded" mode. The construction is modular, and repair can be accomplished by module replacement.

Development of new timing equipment and a monitor and control group is underway at the Electronics Engineering Center of the Coast Guard. These are the electronic elements that produce the pulse and monitor the other station equipment. The goal of this project is to furnish hardware that will provide for unmanned operation with an availability of output of 99.99%. This equipment will have remote control capability and will also be modular for ease of repair. Other research and development efforts have been directed toward antenna design, development of the system communications net, and toward advanced power source provision.

Each of the efforts is aimed at increasing the transmitter station reliability. A recent analysis yielded a 95% probable per station reliability of 0.997, and the probability of failure of two or more stations in a chain is negligible. [43]

Atmospheric noise has an effect on the propagation characteristics of Loran-C signals and, therefore, an effect on their availability. In the 20 kHz bandwidth centered on 100 kHz, atmospheric noise is characterized by very sharp impulses with relatively quiet periods in between. Because of this, censoring techniques can be employed in the Loran-C receiver that discard signals during high noise bursts and, hence, are very effective against real-world noise. Resistance to precipitation static effects can be accomplished by the use of dischargers on the aircraft and recognition of the importance of proper antenna location in receiver installations. An additional tolerance to p-static can be provided by applying known techniques in the receiver. It is anticipated that with the proper station configuration, i.e., one capable of providing high power signals to the service area, and with attention directed to aircraft precipitation static control, the atmospheric noise and other propagation effects will not have a large influence on the availability of signals in the coverage area.

3.6.4 Additional Capabilities

When the Loran-C receiver is operated in the time difference or hyperbolic mode, reception from at least three stations is required to accomplish a fix. At present a good deal of effort is being directed toward development of Loran-C avionics which will operate in the rho-rho or direct ranging (circular) mode. In this manner of operation reception from only two stations is required to determine

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position. The required reception from fewer stations results in a larger service area, and at longer ranges the geometry of the direct ranging system is far better than that of the hyperbolic. Specifically, the hyperbolic divergence error does not exist, and the error due to non-orthogonal crossing angles is greatly reduced. Direct ranging allows for interchain operation and removes the user's dependence on the master station transmissions. Subsequent increases in system availability are a natural consequence of this development. The primary problem in the effort is the need for a high precision, short-term clock that can be initialized at some instant that is directly related to the start of the Loran interval. Once this has been accomplished the advantages of rho-rho operation are available to the user.

Along with providing the navigation service in its coverage area, Loran-C can be employed for numerous other tasks. One of the most important of these is the dissemination of precise time and frequency information. As the Loran-C chains are synchronized with the Universal Time from the U.S. Naval Observatory, the system acquires the capability to provide this information to within ± 1 μ second to all users within the groundwave reception area. At the present time Loran-C is being used to provide timing information to many diverse interests, e.g., satellite tracking stations, aerial mapping operations, power companies, and international bureaus and observatories for the intercomparison and maintenance of atomic time scales. Future applications of this provision appear to be limitless. [44, 45]

3.7   Implementation Plans/Costs of the System

In order to achieve the performance that has been outlined an appropriate network of ground stations must be in operation. The U.S. Coast Guard has been tasked by the Department of Transportation with the development of implementation plans for a Loran-C system to provide navigation information intended primarily for marine users in the U.S. coastal/confluence region. Figure 3-14 illustrates the proposed Loran-C coverage to provide service in the coastal waters. Eight stations of the proposed system are in existence. Of these, four would require modification in order to operate with the capabilities of the new system. The costs of the station modifications vary from 100 thousand to 3 million dollars. Eleven new stations would have to be constructed. While the expense of electronic installation and construction of an individual station is dependent on local conditions and, therefore, highly variable, a conservative figure of 4.5 million dollars per station has been assigned. For the Alaskan stations an estimate of 6.0 million dollars is required to cover the additional expenses of remote area construction. Table 3-4 outlines the construction and electronic installation costs and the costs of modifications to existing equipment for the Coast Guard implementation program.

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The new station names represent approximate geographic areas, not specific locations and these areas are subject to change.

The construction of new stations and modification of existing stations is subject to congressional appropriation of the necessary funds.

LEGEND

●   EXISTING STATIONS
◆   NEW STATIONS
(M) MASTER STATIONS
(S)   SECONDARY STATIONS
(DS) DOUBLE SECONDARY STATIONS
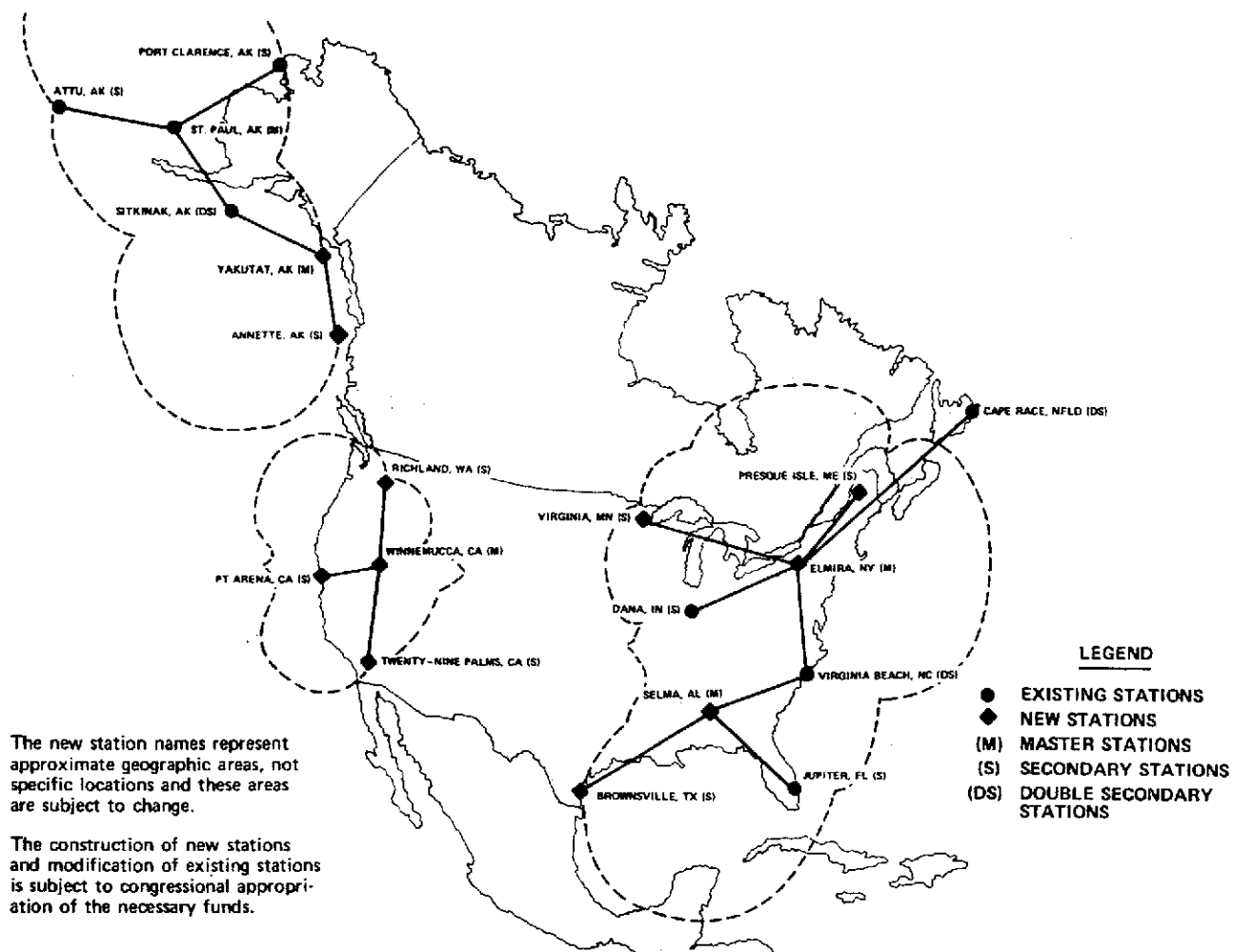
Figure 3-14. Proposed Loran-C Coverage of U.S. Coast Guard Implementation Program

Table 3-4

APPROXIMATE COSTS OF THE U.S. COAST GUARD
LORAN-C IMPLEMENTATION PROGRAM

Chain	Cost (millions)
East Coast and Great Lakes	$16.1
Gulf of Mexico	$11.5
West Coast	$18.0
Alaska	$15.0
Total	$60.6

In order to meet the requirements set forth in this study, coverage must be continuous over the coterminous U.S. and Alaska. The system proposed by the Coast Guard does not suffice. Additional stations are required. Figure 3-15 illustrates a system that could satisfy the coverage requirement. This configuration requires the construction of five additional stations in the continental U.S. and one in Alaska. At the assigned station construction expense of 4.5 and 6.0 million dollars respectively the incremental cost to provide complete coverage is:

$$5 \text{ stations} \times \$4.5 \text{ million/station} + 1 \text{ station} \times \$6 \text{ million/station} = \$28.5 \text{ million} \qquad \text{Eqn. 3.4}$$

The annual operations and maintenance costs of a station in the coterminous U.S. have been estimated to be 250 thousand dollars decreasing to 150 thousand dollars after fully automatic operation has been implemented. 150 thousand dollars per year per station has been assumed as the operations and maintenance costs for this analysis. For the Alaskan stations an annual cost of 350 thousand dollars per year per station has been assigned. These values result in a total annual operations and maintenance cost of 5.15 million dollars of which 1.1 million dollars represents the incremental cost for complete air coverage.

The level of performance that would be provided by the proposed system can be calculated. The coverage is complete; the signal availability is 0.997; and everywhere within the service area the signal to noise ratio is at least 1:3. This results in timing accuracies of better than $\pm 0.20 \mu$ seconds in the calibrated areas and $\pm 0.40 \mu$ seconds in the areas which have not been calibrated. The geometrical dilution of precision for this configuration has a maximum value of approximately 6.

The new station names represent
approximate geographic areas, not
specific locations and these areas
are subject to change.

The construction of new stations
and modification of existing stations
is subject to congressional appropri-
ation of the necessary funds.

LEGEND

● U.S. COAST GUARD
STATIONS (EXISTING
AND PROPOSED)

◉ ADDITIONAL STATIONS
REQUIRED FOR
COMPLETE COVERAGE

M MASTER STATIONS

S SECONDARY STATIONS

DS DOUBLE SECONDARY
STATIONS

Figure 3-15. Proposed Loran-C System for Complete Coverage of Conterminous
United States and Alaska

Therefore, positional accuracies of better than ± 600 feet exist in the calibrated areas, and accuracies of better than ± 0.2 nautical miles exist everywhere else within the service area.

Table 3-5 summarizes the performance and costs of the proposed Loran-C system.

Table 3-5

LORAN-C PERFORMANCE AND COSTS

Performance

System Accuracy:	
Terminal and Approach Areas	± 600 feet
Enroute Areas	± 0.2 nautical miles
System Coverage:	Continuous
System Availability:	0.997

Costs

Total Cost for Loran-C Coverage:	
Facilities and Equipment	$89.1 million
Operations and Maintenance/year	$5.15 million
Incremental Cost for Air Service:	
Facilities and Equipment	$28.5 million
Operations and Maintenance/year	$1.1 million
Cost of Airborne Equipment:	$4 thousand

CHAPTER 4

THE OMEGA RADIONAVIGATION SYSTEM

Omega is a long range, continuous wave, hyperbolic radio navigation system. It operates in the internationally allocated very low frequency (VLF) navigation band of 10-14 kHz. Position location using Omega is based on the premise that signals arriving at a given location from two widely separated, phase synchronized transmitters will bear a fixed phase relationship to one another. Each of the stations in the system broadcasts for a period of approximately one second at a predetermined time on precisely the same radio frequency as all the other stations. A family of hyperbolic lines of position is defined by the relative radio frequency phase between the time shared transmissions of two Omega facilities. A fix is obtained from the intersection of two lines of position. Therefore, reception from at least three stations is required to position locate oneself with the Omega system. By taking full advantage of the high phase stability and low attenuation rate of the VLF signals, system designers are able to provide global coverage with a network of only eight stations. Each station, when operating at its full rated power of ten kilowatts, will have a range of approximately 6,000 nautical miles. Together these stations can provide continuous, redundant coverage anywhere in the world. At present (Spring 1973) the Omega system is partially implemented and in limited use. There are four stations operating at reduced power providing coverage for the northern half of the western hemisphere. By 1975 the complete network of eight stations, operating at full power, will be providing global coverage. The development of the Omega system, sponsored initially by the U.S. Navy and later in cooperation with several other nations, has been directed with "the intent to embrace the earth in a permanent network of identifiable grid lines, part or all of which can be measured in any of several ways at the pleasure of the navigator". [46] In order to understand how the "pleasure of the navigator" is to be satisfied, and how the techniques can be applied to the operations of general aviation, one must examine the characteristics of the Omega navigation system itself.

## 4.1   Omega Continuous Wave Transmissions

Omega navigation signals are broadcast in the very low frequency band between 10-14 kHz. The basic measurement in Omega is the phase of the 10.2 kHz

signal transmitted from each of several ground stations. The use of low duty cycle pulsed signals similar to those emitted in the Loran-C system has been precluded due to the radio spectrum restrictions and the narrow band width characteristics of the transmitting antennae. Instead, relatively long bursts of continuous wave signal are transmitted. The 10.2 kHz emission from each station lasts approximately one second and is repeated every ten seconds. Each burst of signal has a duration of roughly 10^4 carrier periods and is, therefore, a substantially steady state continuous wave broadcast. Figure 4-1 illustrates a continuous wave signal that would be received by a fixed observer monitoring the 10.2 kHz transmission from a particular Omega station. Because of the excellent phase stability of VLF signals there is a nearly linear relationship between signal phase and distance from the transmitter. The different lines of 0° phase relative to the transmitter are separated by one wavelength or approximately 16 nautical miles.

If the receiver could measure the phase angle of the incoming signal in relation to a reference oscillator that was synchronized with the transmitter station, a family of circular lines of position would be generated as possible receiver locations. Figure 4-2 illustrates an example. If the navigator is able to determine that the phase relationship between the received signal and the reference signal is 180°, then he knows that he is located somewhere on a family of circles with radii of $n\lambda/2$, where n is an odd number, and λ is the wavelength of the 10.2 kHz signal. To undertake this method of navigation it is necessary to keep the reference signal synchronized with the transmitting station. A very accurate clock would have to be installed in the receiver, and this is expensive. To avoid the clock installation requirement, a different method of operation has been implemented.

4.1.1 Phase Difference Measurements

The broadcasts from all of the ground transmitting stations are synchronized to each other in a ten second commutation pattern. This system design requires accurate clock installations only at the transmitters. The receiver requirements are to identify the broadcast from each station and compare the phases of the received signals. The signal identification can be accomplished by equipping the receiver with a commutator which, when properly set initially, can identify the unique time shared pattern of the Omega transmissions. Because the broadcast from a particular station occurs in the same time slot every ten seconds, the receiver is able to make the identification. The relative phase measurement is performed by comparing each signal with an internal reference which oscillates at the 10.2 kHz frequency. The phase relationships between the reference oscillator and the temporally unique broadcasts are stored, and later the characteristics of the two signal transmissions can be compared. Since the transmissions are phase synchronized, the relative phase angle of a particular pair of signals that is received at a fixed location is a constant and

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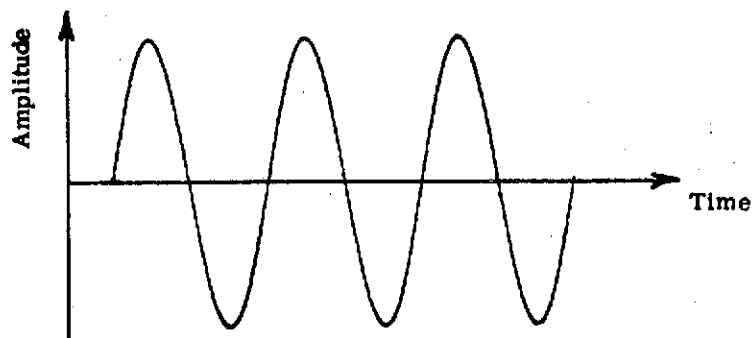
Frequency = 10.2 kHz
Wavelength = Approx. 16 nautical miles

Figure 4-1. Continuous Wave Signal

Navigator has determined that the phase relationship between the received signal and the reference signal is 180°. He therefore knows that he is located somewhere on a family of circles (the dashed ones in this illustration) with radii $n\lambda/2$, where n is an odd number.
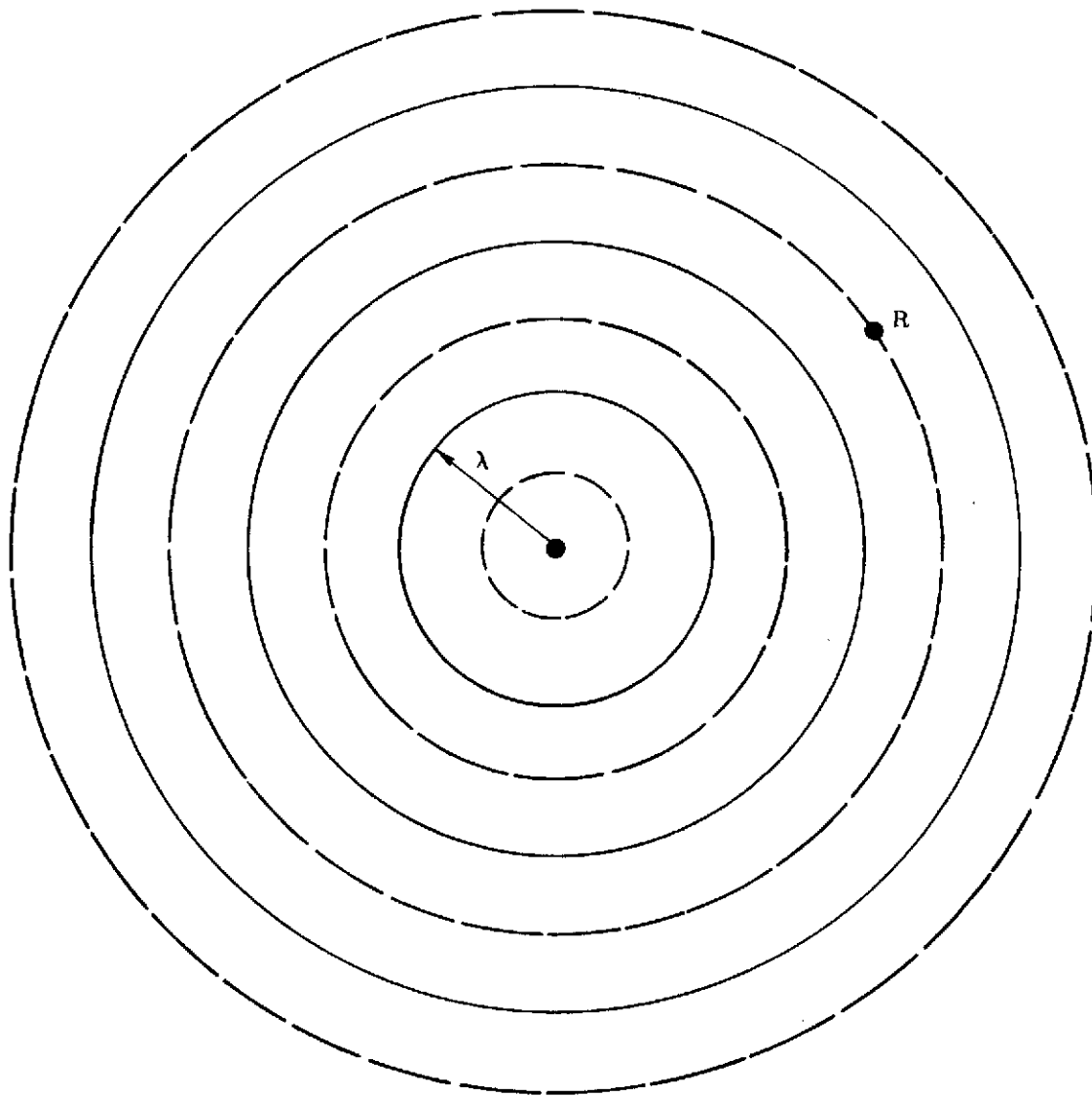

Figure 4-2. Circular Lines of Position

is dependent only on how much further it is to one of the transmitting stations than the other. The same phase angle difference will be observed at all points having the same difference in distance to the two stations.

A hyperbola is defined as the locus of all points whose difference in distance from two foci is constant. A measurement at the receiver of the phase difference between transmissions from any two Omega stations yields a family of hyperbolic lines of constant phase relationship whose foci are at the two transmitting station locations. The loci of constant phase relationship are referred to as lines of position. An observer measuring a given phase relationship between two signals knows that he is located on a resultant line of position. If the navigator compares the received phase from at least three transmitting stations, two or more lines of position can be determined and a fix realized.

There are some advantages gained by the phase differencing method of operation. Economic spectrum utility is achieved because the signals appear as time shared bursts of the same radio frequency. No internal ambiguity due to divider shifts within the receiver can arise, and a hyperbolic or phase difference receiver has no specification for absence of internal phase shifts since shifts common to all signals will be removed in the differencing. There is, however, a major problem that does arise. The system has an inherent physical ambiguity in that phase can only be measured in modulo 2π. Adjacent carrier cycles cannot be distinguished, and so total phase cannot be measured. This results in a lane ambiguity.

4.1.2 Omega Lane Ambiguity

Adjacent carrier cycles cannot be distinguished by the receiver, and so the lines of position are not unique. In Omega the relative phase between any pair of stations defines not one contour, but an entire family of contours. Figure 4-3 illustrates the numerous receiver phase contours that exist when the signals from transmitter stations A and B are compared. The phase space is divided into lanes which are bound by the cross-over points of the two signals representing the zero phase difference contours of the pair. The width of each of these lanes is a function of the transmitted signal frequency and the subtended angle between the transmitters as measured at the receiver location. On the baseline between the transmitters the lane width is one-half the wavelength of the transmitted signal or approximately eight nautical miles. In order for Omega to operate as a functional navigation system, some method of lane identification is required.

The resolution of this lane ambiguity involves the process of selecting, from among the lanes in which the receiver may be located, the particular lane which does contain its position. The lane identification process requires establishing the receiver position to within ± one-half lane.
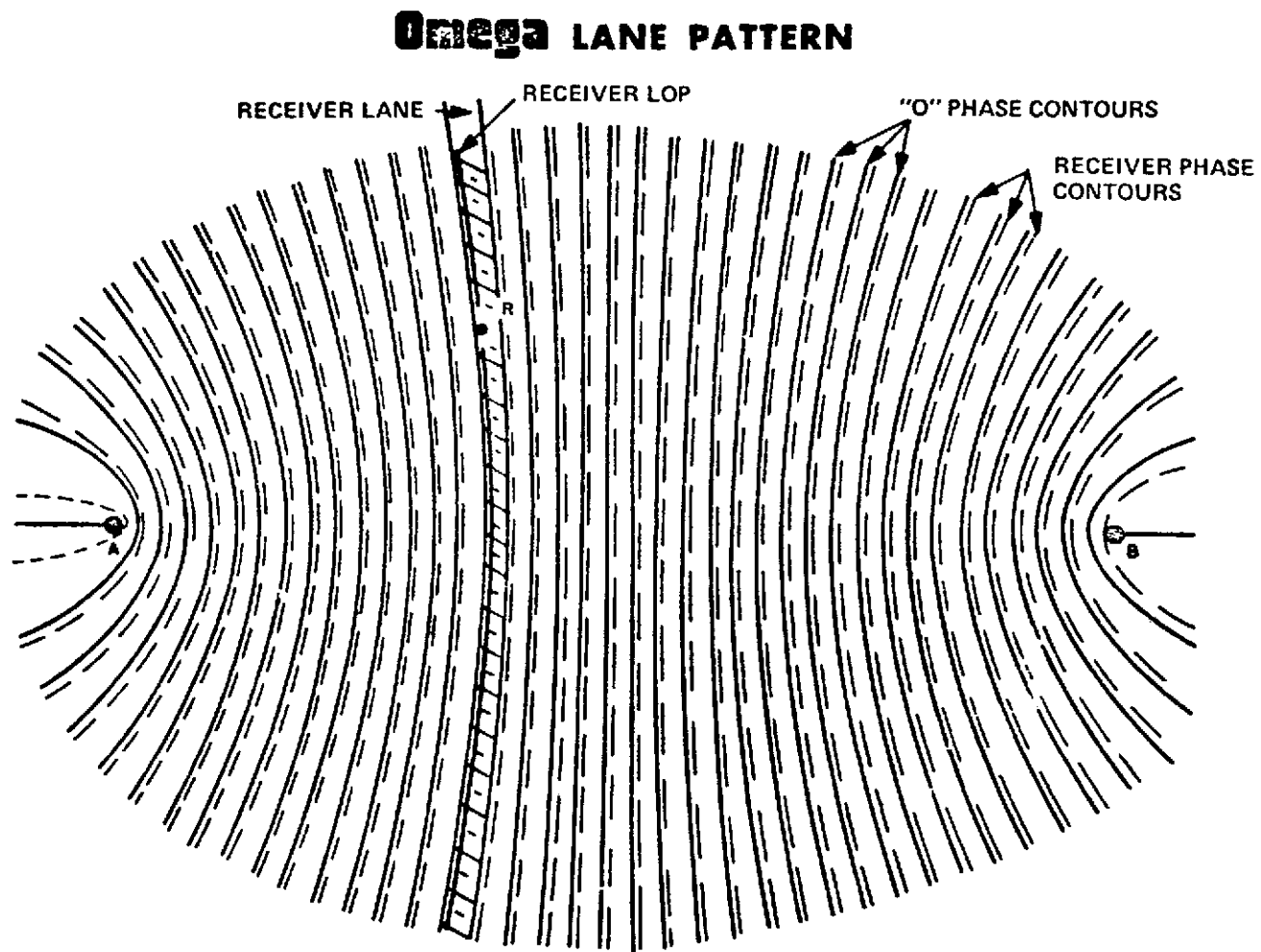
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Omega LANE PATTERN

Figure 4-3. Omega Family of Contours

There is very little difficulty in resolving lane ambiguity at the commencement of a flight. It is assumed that the coordinates of the initial takeoff point would be available to the pilot and his navigation equipment so initial lane identification could be made. However, all information necessary for lane identification during the trip would have to be derived from the received signals.

Numerous methods have been proposed as solutions to the lane identification problem. This study will focus on two of the methods which have been applied in general aviation receivers.

The first method is based on the use of multiple frequency transmissions from the Omega ground stations. Lane ambiguity can be reduced by transmitting additional signals that are fractionally related to the original 10.2 kHz signal. A transmission at 3400 Hz is such a signal. A set of contours for a signal at 3400 Hz would coincide with one of every three 10.2 kHz contours. However, experiments have determined that this 3400 Hz signal cannot be radiated successfully from an Omega antenna. A solution to this problem is available by broadcasting signals at 13.6 kHz in addition to those at 10.2 kHz. The application of frequency differencing methods to these transmissions results in the expanded lanes. If the phase synchronization between all the signals is adjusted so that a contour of the 13.6 kHz signal coincides with one of the 10.2 kHz signal, a Moire pattern is obtained in which every third contour of the lower frequency will coincide with every fourth contour of the upper one. The coincidental contours define a pattern of broader lanes extending over three lanes of the basic 10.2 kHz pattern. Figure 4-4 illustrates the multi-frequency patterns.

Further expansion of the unambiguous lane width can be obtained by additional transmissions at other related frequencies. For example, transmissions at 11.33 kHz define a pattern of contours with a spacing nine-tenths that of the basic 10.2 kHz pattern. There is a triple coincidence every seventy-two miles between the contours of the frequencies 10.2, 11.33, and 13.6 kHz. The present Omega signal format includes transmissions at these three frequencies. The seventy-two mile wide, unambiguous lane is thought to be sufficient for general aviation operations. For other applications additional methods of further increasing the unambiguous lane width have been proposed. Pierce et al. [47] recommended applying an amplitude modulated signal to each of the three basic frequencies. This could result in unambiguous lanes as wide as 7200 nautical miles. It was found, however, that it would be more advantageous to accomplish the lane widening by transmitting additional carrier frequencies. The high cost for the coupling network required for the modulation scheme reduces its appeal. The U.S. Navy has a research program underway presently to investigate the use of additional frequencies in its air-sea search and rescue operations. The results of that study could have a significant impact on future

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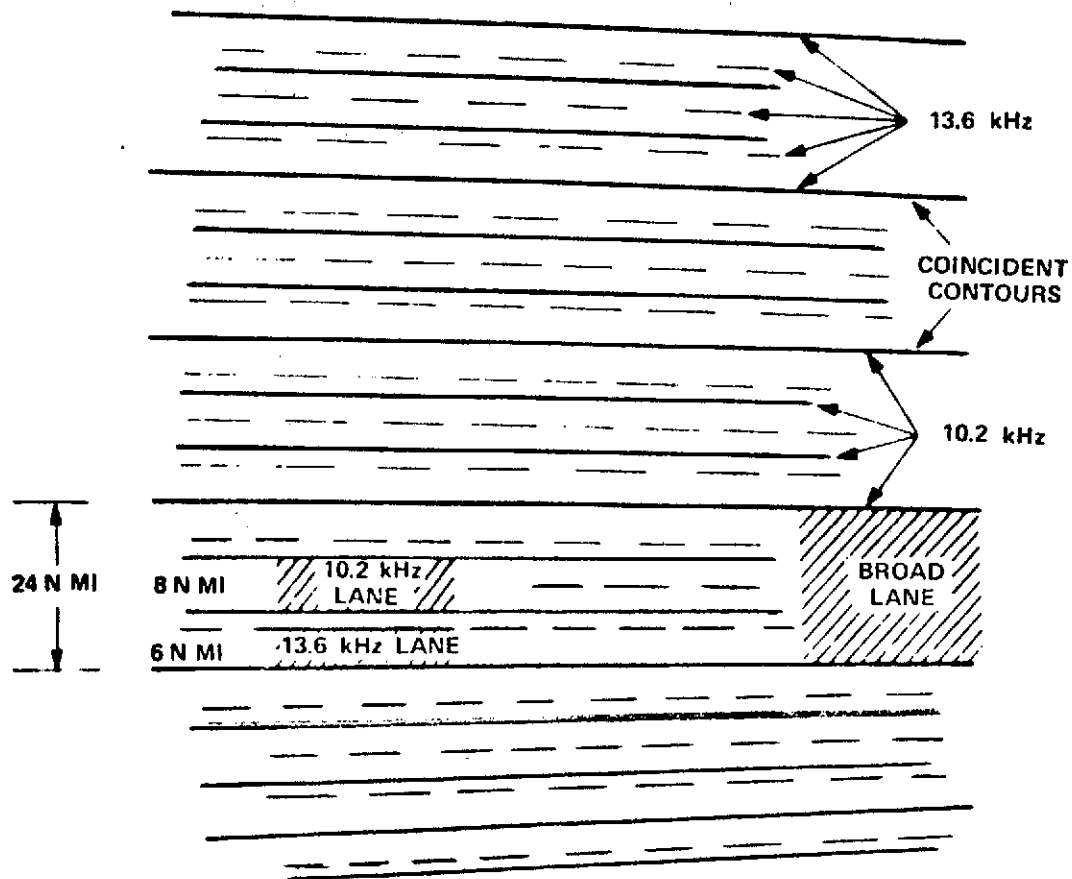
Omega PRINCIPLES OF LANE RESOLUTION

Figure 4-4. Omega Multi-Frequency Patterns

Source: Northrop Corporation, Electronics Division, Omega Navigation System,
February, 1973.

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receiver design and Omega signal format. The intention of all these methods is to
increase the unambiguous lane width and reduce the requirement of accuracy from
an independent means. For general aviation applications only the most basic lane
widening is necessary. The initial 10.2 kHz signal requires independent fix accuracy
of at least ± 4 nautical miles; the implementation of the two frequencies at 11.33 and
13.6 kHz lessens the requirement to ± 36 nautical miles.

The second method of lane identification involves tracking from a known
position. If the receiver is equipped with an automatic lane counter that can record
the number of lanes traversed, no ambiguity will exist. Position can be determined
by noting the integral number of lanes crossed from the initial position and adding
the fractional lane count for the particular lane of location. Problems can arise,
nevertheless, if lane slippage or signal loss should occur. When the phase indicator
is caused to retard or advance by one or more full cycles, the navigator has no way
of determining the correct lane count, and position location information must be
reacquired by another means. Simple techniques can be applied in the receiver to
generate a position fix with the lane counters. The multiple frequency receivers
require slightly more signal processing. Both methods have been adopted for general
aviation applications.

4.1.3 Omega Signal Format

The Omega signal format is designed so that the eight stations transmit a
sequence of three continuous wave pulses — the first pulse on 10.2 kHz, the second
on 13.6 kHz, and the final pulse on 11.33 kHz. The duration of each signal burst is
about one second, and the total time required for the commutation pattern is ten
seconds. Specifically, the total time span of each burst varies from 0.9 to 1.2
seconds with a non-transmission time between signals of 0.2 second. After the
third burst the station will not transmit Omega navigation fix information for about
6.5 seconds or the remainder of the ten second pattern. The repetitive pattern
allows a position fix to be determined every ten seconds, and the uniqueness of the
burst duration pattern enables the receiver to identify each of the transmitting
stations. Figure 4-5 illustrates the Omega navigation signal format. The eight
transmitting stations are designated A-H. The individual pulse lengths in seconds
are given across the top of the table. It should be noted that any point in time (except
the 0.2 second non-transmission times) there are three bursts being transmitted:
one signal from each of three stations and one burst on each of the three frequencies.
To acquire the simultaneous bursts on each of the three frequencies, the Omega
navigation receiver uses three separate hard-wired receivers each tuned to a parti-
cular Omega frequency. Any one of these frequencies can be used for navigation
purposes. Of the three, 10.2 kHz has the longest period and the greatest spacing
between the lines of position; and, therefore, presents the least problem from the
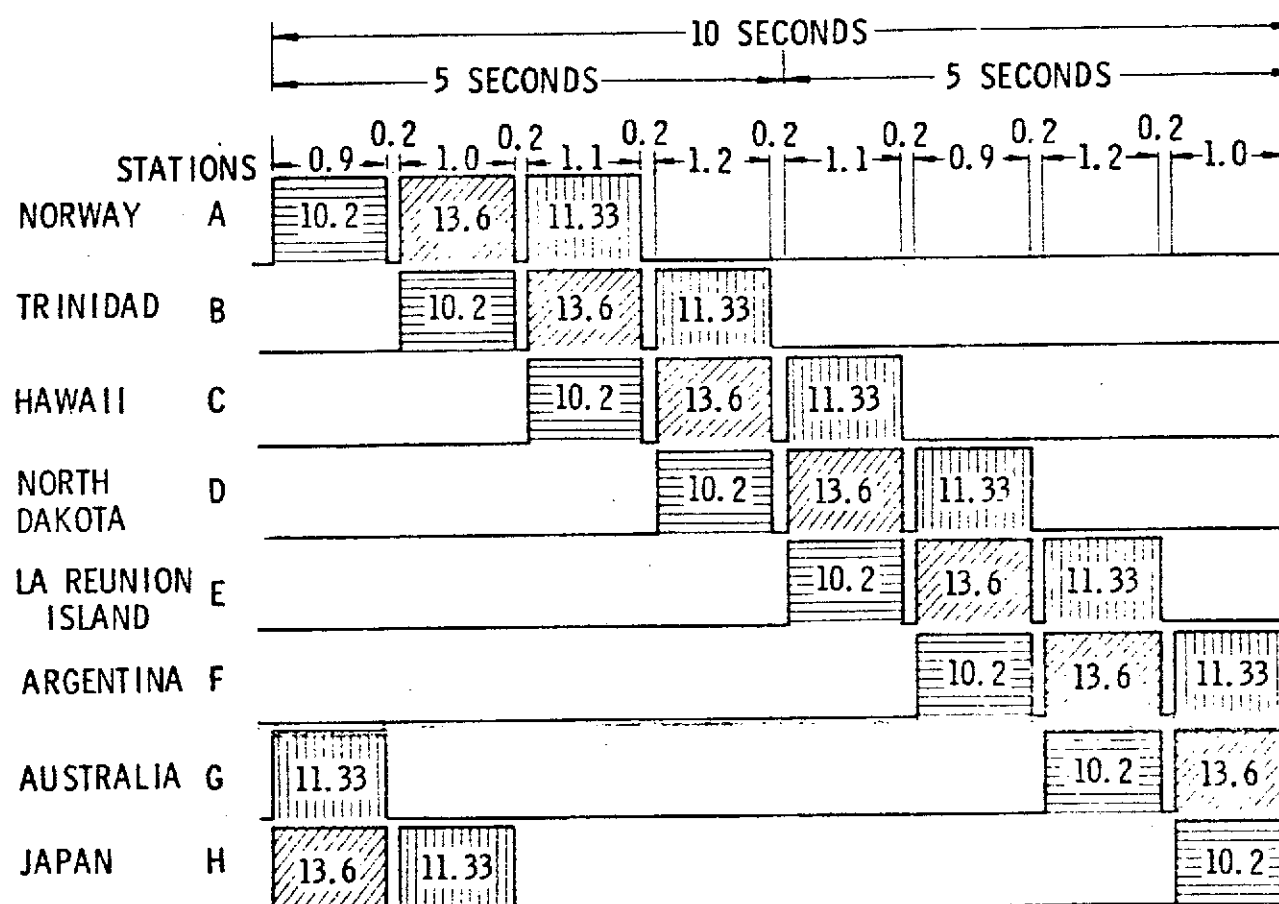
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Omega TRANSMISSION FORMAT

Figure 4-5. Omega Navigation Signal Format

viewpoint of possible navigation lane ambiguity. 10.2 kHz is also the best calibrated of the Omega frequencies. However, 13.6 kHz will generally have the best signal to noise ratio and the greatest repeatability.[48] Each frequency is time and phase synchronized with Universal Time and, therefore, to every other Omega signal. In the Omega system there is no master-secondary relationship. All stations are equal and, in a sense, secondary to Universal Time.

A good deal of consideration has been directed toward developing uses for the 6.5 second "dead time" in each station's broadcast pattern. One scheme calls for the transmission of two additional frequencies which are unique for each station. [49] They would be used for station identification and intrasystem communication of synchronization control information. Another plan calls for a unique frequency from each station to be broadcast so that it can be used for navigation based on distance difference values. [50] And in other efforts, the U.S. Navy search and rescue research group would like to use the time segments for the transmission of additional common frequencies to expand the unambiguous lane widths so important for their operations.[51] The Omega signal format was deliberately designed to allow as much flexibility as possible. The potential for satisfying so many diverse users lends a great deal of credit to this forethought.

4.2 Very Low Frequency Propagation

One of the outstanding characteristics of the Omega navigation system is the vast coverage area which is provided service by the transmissions from any particular station. The long range propagation of Omega information not only provides signals to users in widely scattered locations, but also contributes a major economic advantage in that global service can be furnished with a limited number of the costly transmitter stations. System designers have implemented a configuration which, while using only eight strategically located transmitter sites, can cover the world with Omega signals. This enormous coverage is a consequence of the characteristics of very low frequency propagation.

To furnish a complete description of VLF propagation is a monumental task. Various aspects of the subject have been described in numerous works.[52, 53, 54] The reader is referred to other publications for a more complete treatment of the subject than is offered here. In this analysis the primary interest in propagation is how it affects general aviation operations. The present description will be simple and brief.

A convenient analytical model for the propagation of VLF signals is that of a spherical waveguide whose boundaries are formed by the surface of the earth and the D layer of the ionosphere. In this model individual rays or hops of signal are not considered explicitly. Instead, the natural resonant modes of the waveguide are examined.

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Many modes will propagate in such a waveguide. Each has a different characteristic velocity, attenuation, and excitation factor. A vertical electric field antenna, which is situated on the surface of the earth and radiating VLF signals, excites transverse magnetic (TM) modes in the waveguide. The modes are designated by a number which indicates the relative amount of attenuation they incur. For example, TM_1 is propagated with less attenuation than TM_2. TM_1 and TM_2 are the two most important modes for Omega operations. It would be nice if one of these modes predominated over the other in terms of field strength at all distances. The higher resultant field intensity of the signal would enable the exclusive use of that mode for navigation; the signal phase and amplitude would vary regularly as a function of distance from the transmitter without fluctuation due to interference with other modes. However, this is not the case. The field intensities of the TM_1 and the TM_2 modes are functions of the attenuation rates and the excitation factors. At 10.2 kHz the excitation factor is about equal for both resonant modes. At higher frequencies the waveguide is excited more by the TM_2 mode. However, the TM_2 mode attenuates more rapidly than TM_1. At considerable distances the TM_1 mode will come to dominate because of its lower attenuation. In regions where the field strengths of the two modes are essentially equal, there exists a large amount of interference due to the fact that the TM_2 mode is propagated with a higher phase velocity than TM_1. Phase perturbations are a natural result. In the frequency range above 10-14 kHz the TM_2 mode remains approximately equal in strength to the TM_1 mode for a very great distance. This results in large areas that cannot be used for navigation due to the phase irregularities. Below the 10 kHz mark the signals begin to approach the waveguide cutoff point. This results in high attenuation and a large reduction in phase velocity which makes it too hard to predict phase observations. These considerations were all taken into account when the 10-14 kHz range was selected for the navigation frequencies of Omega.

There are two factors which weigh heavily in the evaluation of the potential of certain signals for navigation. The first is that the field strength of the signal must be great enough to overcome the background noise; and the second is that the phase versus distance pattern must be nearly constant in time.

The strength of the Omega signals is sufficient to overcome environmental noise. The attenuation of very low frequency transmissions is dependent on a large number of parameters. Several of the more important are: the signal frequency, the height of the ionosphere, the direction of propagation relative to the magnetic field of the earth, and the earth surface conductivity. Figure 4-6 illustrates the effect of ionospheric height and direction of propagation on the attenuation of the TM_1 mode of a 10.2 kHz signal. Two consequences are apparent. The first is that as the effective height of the ionosphere varies from 70 kilometers during the day to
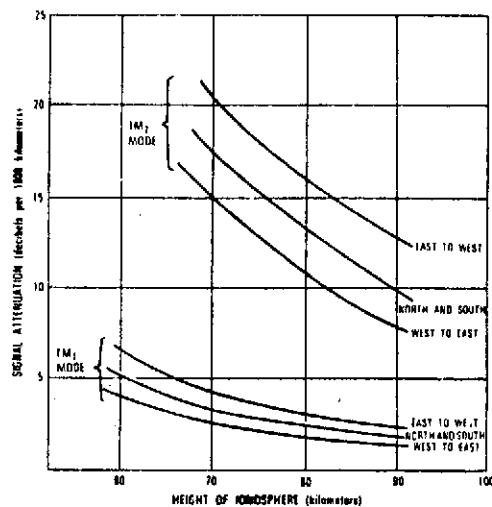
Figure 4-6. Attenuation of the 10.2-kHz Omega signal as a function of
ionosphere height. The curves show the effect of the earth's
magnetic field. Ground conductivity is assumed to be infinite.

Source: Van Etten, J.P., "Navigation Systems: Fundamentals of Low- and
Very-Low-Frequency Hyperbolic Techniques," Electrical Communi-
cation, Vol. 45, No. 3, 1970, p. 11.

90 kilometers during the night, the signal attenuation will decrease. The second is due to the effect of the horizontal component of the earth's magnetic field: the signals are attenuated less when propagated from west to east than when propagated from east to west. Figures 4-7, 4-8, and 4-9 indicate the field strength of the Omega signals that would be received at various distances from the transmitter site for 1 kilowatt of radiated power. Figure 4-7 illustrates field strength for signals which are propagated north to south or south to north. The close hatched area indicates the strength of the short path signal. The wide hatched area indicates the strength of the signal which has been propagated the long way around the earth. At 15 megameters (8000 nautical miles) the two signals are both so strong that they interfere with each other. This makes phase measurement impossible; and, therefore, sets the effective range of the system. Figures 4-8 and 4-9 are for the propagation of signals from west to east and east to west respectively. The resultant effective ranges are 21 megameters (11300 nautical miles) and 9 megameters (4900 nautical miles). After careful consideration of these signal strengths, atmospheric noise levels, and receiver characteristics, it has been determined that the planned 10 kilowatt transmitter power levels will furnish the power required to provide service. [55]

When considering the temporal stability of the Omega phase versus distance pattern, one of the most important parameters is the height of the ionosphere. The D layer of the ionosphere acts as a moving boundary for the waveguide. This motion produces changes in the phase velocity of the Omega transmissions, and the degree to which these variations can be predicted is a prime determinant of the accuracy of the system. The height of the D layer of the ionosphere varies with the time of day, the season, and with any disturbances in solar conditions. Some of the variations are predictable; some are not. The largest regular variation in the phase of the Omega signals is related to daily changes in the ionosphere. These changes are a function of the solar zenith angle along the propagation path. As the sun reaches a higher angle, the degree of ionization of the particles in the ionosphere increases, and this lowers the effective height of the upper surface of the waveguide. As the reflecting surface is lowered, the phase velocity of the signals increases, and there will be a dilation in the spacing of the resultant lines of position.

In addition to the diurnal effect there are smaller regular changes resulting from solar zenith angle variations. They fluctuate with the season of the year and the latitude of the receiver position. All the effects of ionospheric variation due to changes in solar zenith angle can be predicted quite accurately. Numerous methods have been developed to forecast these changes and present the information to the user. The regular fluctuation of observed signal phase does not pose a significant problem to Omega users. There are, however, large unpredictable variations that can be trouble.

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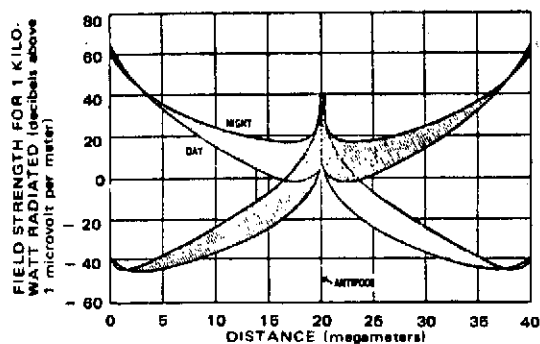
Figure 4-7. Variation of the field strength of the 10.2-kHz Omega signal with distance for transmission from north to south or south to north. The close-shaded area shows the range of field strengths to be expected at the distances indicated on the abscissa. The open-shaded area represents the signal propagated in the opposite direction around the world. The vertical bar represents the extreme range of usefulness of the system as limited by excessive interference from the around-the-world signal.

Figure 4-8. Variation of the field strength of the 10.2-kHz Omega signal with distance near the equator. The figure is drawn for transmission from west to east.

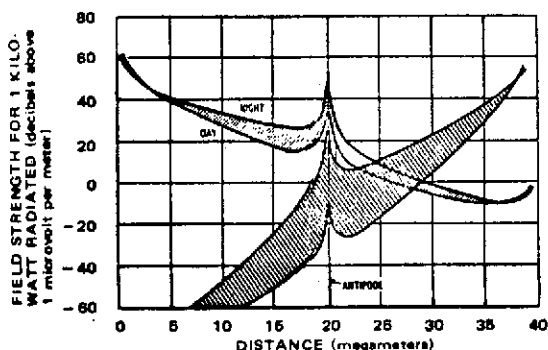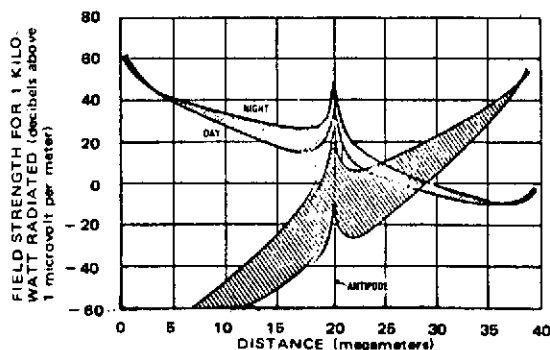Figure 4.9. Variation of the field strength of the 10.2-kHz Omega signal with distance near the equator. The figure is drawn for transmission from east to west.

Source: Van Etten, J. P., "Navigation Systems: Fundamentals of Low- and Very-Low-Frequency Hyperbolic Techniques," Electrical Communication, Vol. 45, No. 3, 1970, p. 13.

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There are two sudden phase anomalies that are most common. The first occurs as a result of X-ray radiation emitted from the sun during solar flare activity. This radiation increases the ionization of the D layer of the ionosphere. This lowers the effective height of the upper boundary of the waveguide and causes a sharp phase advance along the sunlit paths. Recovery from this type disturbance usually takes from one-half to three hours. During periods of high solar activity this disturbance can occur numerous times a day. Likewise, during periods of relative quiet in the sunspot cycle, they will occur very infrequently. The year 1968, which was a period of maximum solar activity for the present sunspot cycle, produced sudden ionospheric disturbances 3.6% of the time. It should be noted that the two largest disturbances indicated maximum phase changes of 70 μ seconds, and only 0.3% of the time showed a phase change in excess of 20 μ seconds. [56]

The second sudden phase anomaly is called polar cap absorption. It is the result of solar protons entering the magnetosphere around the earth and being guided to the geomagnetic poles. This lowers the effective height of the ionosphere in the auroral zone by approximately ten kilometers. There is a resultant decrease in phase delay, and it, too, must be interpreted in terms of line of position variations.

The accuracy of the Omega navigation system is primarily determined by the degree to which regular phase changes can be predicted and the degree to which irregular phase changes can be accomodated. "Differential Omega" is one scheme that has been proposed to meet the requirements of prediction and accomodation.

4.3   Differential Omega

A major limitation on the accuracy of the Omega navigation system is the lack of real time propagation information. A great deal of effort has been expended to develop very complex prediction techniques for VLF signals. However, the propagation of Omega information is not only subject to predictable variations, but also to unpredictable occurences. Any two receiver sites in the same area are affected by the same unpredictable phase perturbations of the Omega signal. The signals traverse the same propagation paths and are subject to the same disturbances. This phenomenon provides the rationale for the implementation of a Differential Omega network.

Differential Omega requires the installation of fixed ground monitor sites. These monitor sites are essentially high quality Omega receivers which have the capability to receive the Omega transmissions, compare the Omega readings with the actual value for its location, and broadcast a correction factor which can be used by other receivers in the area to adjust their readings for the propagation fluctuations of a particular moment. The propagation disturbances will be cancelled to the extent that they are spatially correlated at the fixed monitor and the mobile receiver location. This correlation should be very high at short distances

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from the monitor and decreases as the separation distance grows. The useful limit is reached when the accuracy of the system is equal to that of regular Omega. This range can be as high as 300 nautical miles.

It is anticipated that the Differential Omega sites would be installed throughout the coverage area. The requirement for each site is that it measure the Omega signals accurately and then disseminate the correction information in a manner which is reliable, convenient, and inexpensive. For airborne operations the FAA Flight Service Station facilities provide excellent locations for Differential Omega installations. These stations have the communications and information processing capability necessary to handle the requirements. A quality installation at one of the government facilities is expected to cost approximately $25,000. This price includes two receivers, an antenna system, and installation costs. Additional sites would be available, perhaps at lower cost, wherever private individuals or organizations wish to install one themselves. There are a large number of "unicom" type facilities which would provide a natural base for such an installation.

After the implementation of a Differential Omega network the accuracy of the system is determined by the spatial correlation between the propagation effects at the two receiver sites and the resolution and measurement accuracy of the receivers under the existing signal and noise environment. Extensive test data [57] indicate that the spatial correlation of errors is considerably lower at night and during the transition period from day to night. This apparently is due to the irregular nature of the ionosphere during these periods and the resultant multiple propagation paths. Figure 4-10, which can be found on page 137 of this report, demonstrates this effect and the accuracy that can be achieved with the Differential Omega operation. To take full advantage of the accuracy offered by Differential Omega, it is very important to minimize receiver measurement errors. As the correlation increases, the receiver accuracy is the limiting factor in the system.

4.4 Omega Receiver Characteristics

There is a large number of Omega receivers available on the market today. The designs and methods of operation are as varied as the companies that produce them. Some are manual, single-frequency, analog receivers that display only line of position information to the navigator, and some are fully automatic, multi-frequency, digital receivers with numerous display capabilities including date and time, groundspeed and estimated time enroute, and position, which can be displayed in any one of numerous coordinate frames. In order to realize the maximum benefit from the Omega navigation system, it is believed that a fully automatic, three-frequency, digital receiver would be necessary for general aviation applications. This fully automatic receiver must perform four basic types of functions:
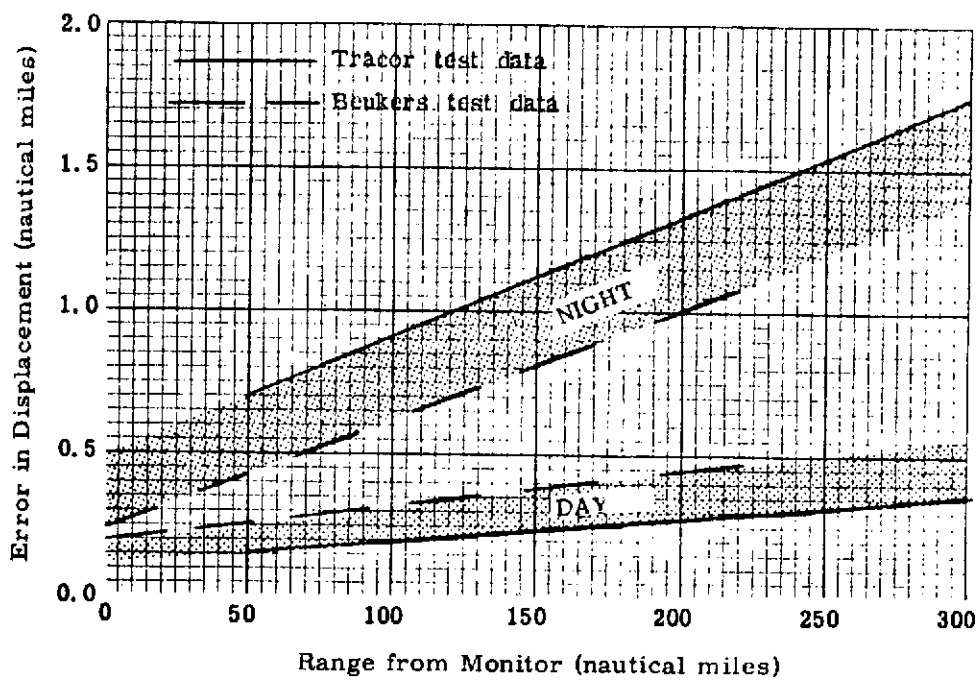
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Figure 4-10. Differential Omega Position Fix Accuracy

Source: Polhemus Navigation Sciences, Inc., Radio Aids to Navigation for the U.S. Coastal Confluence Region, Interim Report No. 2, Systems Evaluation, June 1972, p. 4-21.

(1) alignment of the receiver commutating function with the signal multiplex sequence so as to identify the particular signals it is desired to measure;

(2) determination of the signal relative phase at all frequencies incorporated in the signal format;

(3) resolution of the lane ambiguity; and

(4) presentation of the signal timing in a form suitable for further processing. [58]

The alignment of the receiver commutation pattern with the Omega multiplex sequence is necessary to identify the received signals. Each station broadcasts on a particular frequency for a particular duration of time. These transmission lengths vary from 0.9 seconds to 1.2 seconds and are present in a unique combinatorial pattern. The signal processing section of the receiver has a program which includes the multiplex sequence scheme. By sampling the incoming signals at short time intervals and comparing them with this standard sequence, it is possible to align the two by maximum correlation techniques.

The relative phase determination of the incoming signals is made by comparing the phase of each signal with an internal reference oscillator and then storing that information. Once all the samples are taken for a given sequence, these stored phase differences are combined to yield the resultant relative phases of importance.

Enough information to resolve the lane ambiguity is included in the multi-frequency signal inputs. It is a receiver requirement to process this information so as to take advantage of its ambiguity resolution capability. The 10.2 kHz signal will generate a phase contour pattern with an 8 nautical mile lane spacing. When this is combined with the 3400 Hz contour pattern that results after differencing the received signals at 10.2 and 13.6 kHz, a lane spacing of 24 nautical miles is produced. Similar differencing methods applied to the third frequency which is received result in lane widths of 72 nautical miles. These are sufficient for general aviation operations.

Finally, the signal timing needs to be processed so as to display the information most helpful to the user. Some user requirements call for display in terms of hyperbolic lines of position. This, however, is not the most useful for the applications of interest in this analysis. For general aviation the most useful method of presenting the information is that of distance to go to a waypoint and cross-track error from a predetermined route. This display is somewhat more expensive, but it is considered a worthwhile investment. Receivers that perform the functions that have been outlined are expected to be available to general aviation users for approximately $4000.

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4.5   Differential Omega Performance

The performance of the Omega navigation system in this analysis is determined by that which will be realized with the implementation of a Differential Omega network. The performance of the Omega system without the differential compensation is unable to meet the requirements as set forth in Chapter One. As in VORTAC and Loran-C, three major criteria will be used to evaluate the performance of the Differential Omega system. They are accuracy, coverage, and availability of signal. None of these measures is completely independent of the others. All are a function of the transmitting station characteristics, the configuration of the differential compensation stations, and the environmental conditions. In this analysis, however, they will be examined separately and then, in the end, combined to generate the performance characteristics of the proposed Differential Omega system.

4.5.1 System Accuracy

The accuracy of the Differential Omega system is primarily a function of three parameters:

(1)   the user equipment accuracy and resolution;

(2)   the reduction in the correlation of the phase variations observed at both the monitor site and the aircraft receiver as the separation distance between these two increases; and

(3)   the geometrical configuration of the stations contributing to the position fix.

Receiver error or user measurement error refers to the uncertainty in the relative phase measurements due to characteristics of the user's equipment. Timing accuracy, phase measurement, band limiting, and receiver display resolution all contribute to this error. Instrumental errors of 1 centilane (1/100 of a lane) are standard in quality Omega receivers. There is an additional user measurement error that can arise in some propagation correction schemes. Tests by TRACOR, Inc. of Austin, Texas [59] have indicated that there is an improvement in the accuracy that results from Differential Omega operations if the receiver is able to compensate for the fact that the geographical separation between the monitor and the aircraft introduces predictable propagation errors that can be removed by incremental skywave corrections. This method is referred to as "skywave corrected Differential Omega". The skywave correction tables that are available from the U.S. Navy are printed with the corrections quantized to 1 centilane. When these tables are implemented to correct Differential Omega readings, this coarseness of quantization introduces an rms error of 0.58 centilanes. [60]

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The largest error in the accuracy analysis is that due to a reduction in the correlation of the phase variations as observed at the fixed monitor site and the mobile receiver as the separation distance between the two increases. Very near the monitor site the correlation is high, and the accuracy should approach that of the instrumental value listed above. Conversely, as the separation distance increases, the accuracy decreases and eventually approaches that of regular Omega. A quantitative description of this spatial correlation has not yet been presented. Some statistical analysis techniques have been applied[61] and two well-known field tests have been undertaken [62, 63]. The results of these field tests are shown in Figure 4-10. Before a final evaluation of Differential Omega accuracy can be accomplished, additional testing of this nature is required. For the present the most conservative values that resulted from the TRACOR and Beukers Laboratories tests will be assumed to be the most appropriate for this study. The accuracy illustrated in Figure 4-10 is expressed in terms of nautical miles of distance and not in centilanes of phase measurement. A conversion factor to account for the geometry of the particular situation has been applied.

The geometry of station configuration has less effect on Differential Omega accuracy than it did on Loran-C accuracy. Like Loran-C, Differential Omega is a hyperbolic navigation system, and the position accuracy is a function of the hyperbolic divergence and the crossing angle of the lines of position at the fix. However, due to the very long baseline lengths of the Omega network the hyperbolic divergence is not very much of a factor at all. Equation 4.1 relates position errors to observed relative phase measurement errors.

$$\epsilon_d = \gamma \times \csc (\theta/2) \times \epsilon_\phi \qquad \text{Eqn. 4.1}$$

where

ϵ_d = the error in position;

ϵ_ϕ = the error in relative phase measurement;

γ = conversion factor relating phase measurement error to distance on the baseline between the stations; and

θ = the subtended angle between the two Omega transmitter stations as measured at the receiver.

The $\csc (\theta/2)$ term in Equation 4.1 is the factor which relates to the amount of hyperbolic divergence that is present at the receiver site. For very long baseline lengths this subtended angle gets large and the divergence decreases. Figure 4-11 illustrates the comparison of hyperbolic divergence for short and long baseline navigation systems. The maximum divergence that will be experienced at most places within the required coverage area for this study is less than 2.5.

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Short Baseline System
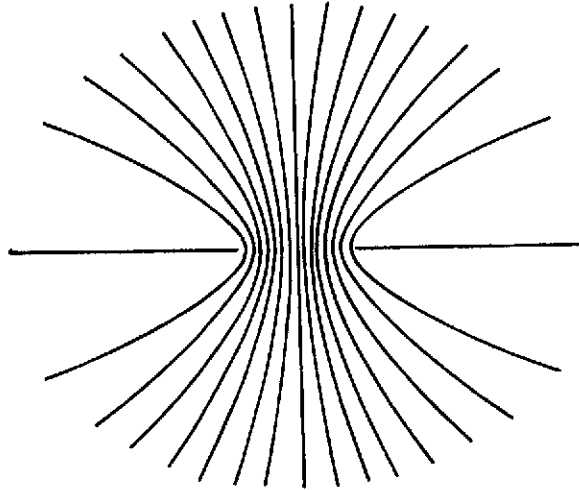
Long Baseline System
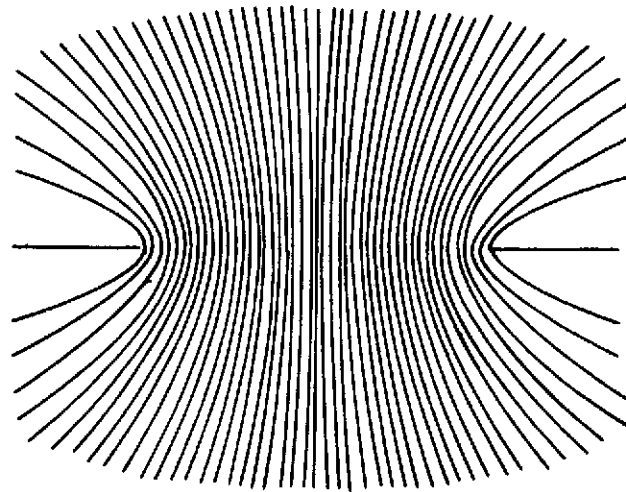
Figure 4-11. Comparison of Hyperbolic Divergence for Short and Long
Baseline Systems

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The crossing angle of the lines of position at the fix is also an important factor. The errors that result from a non-orthogonal crossing angle increase as the cosecant of the crossing angle. For the Omega transmitter station configuration as it is now being implemented the navigator can choose from a number of lines of position, and it is possible to use lines with crossing angles of at least 60°. The error dilation factor from a 60° crossing angle is only 1.15. There is a very definite geometrical effect on the accuracy of the Omega system. However, because of the advantages of very long baselines and large signal coverage areas, this adverse factor can be minimized.

When the implementation of the Differential Omega system is begun, the designers will need to consider the service requirements and the accuracy values of Figure 4-10. Many possible configurations and station locations will have to be examined. It is interesting to note that in the error budget for Differential Omega operations, the technology related errors are very small. Improvements in the technology will not greatly improve the accuracy of the system as the main error comes from the inherent propagation phenomenon of VLF signals. Table 4-1 lists the accuracy that can be expected from the Differential Omega system as the separation distance between the aircraft and the fixed monitor increases. These figures are derived from the most conservative accuracy values indicated in Figure 4-10.

TABLE 4-1

DIFFERENTIAL OMEGA POSITION FIX ACCURACY

(from Figure 4-10)

Range from Monitor Station (nautical miles)	Position Fix Accuracy (nautical miles)
50	0.7
100	0.9
150	1.1
200	1.35
250	1.55

4.5.2 Coverage

When the coverage of the Differential Omega navigation system is being evaluated, two specific aspects need to be considered. The first is the coverage provided by the basic Omega navigation signals, and the second is any limitation on coverage imposed by the choice of communications methods used for dissemination of the differential correction information.

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When the complete implementation of the Omega navigation system is accomplished, it will provide a continuous electromagnetic environment around the globe. The very long range propagation characteristics of the Omega signals result in complete global coverage. It is anticipated that five of the eight Omega stations will be received at any one point on the earth. This wide area coverage will result in multiple line of position redundancy and give navigators the ability to choose lines of position pairs for good accuracy and maximum crossing angles. Like Loran-C, there are no line-of-sight problems or similar occurrences of no reception. The service is spatially continuous everywhere and is available from the surface to high altitudes, thereby providing signals to surface vehicles as well as aircraft at any altitude.

It has been recommended that the differential correction information be passed on to the pilots in much the same way as the altimeter setting information is handled today. [64] This requires the use of very high frequency radio transmissions. The limiting factor in the coverage of a Differential Omega network is the line-of-sight restriction for this kind of broadcast. The approximate range of very high frequency transmissions over flat terrain can be calculated by the following simple formula.

$$r = 1.23 \sqrt{h_T} + 1.23 \sqrt{h_R} \qquad \text{Eqn. 4.2}$$

where

r = range of transmission in nautical miles;

h_T = height of transmitting antenna in feet; and

h_R = height of receiving antenna in feet.

Table 4-2 illustrates the effective range for the Differential Omega correction information for h_T = 0 and various values of h_R.

Table 4-2

EFFECTIVE RANGE OF
DIFFERENTIAL OMEGA CORRECTION TRANSMISSIONS

Aircraft Altitude (ft)	Range (n. mi.)	Aircraft Altitude (ft)	Range (n. mi.)
500	28	10000	122
1000	39	15000	152
1500	48	20000	174
2000	55	30000	213
3000	69	40000	246
5000	87		

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The coverage requirement for this study, as specified in Chapter One, is that the system must provide service everywhere within the conterminous United States and Alaska from an altitude of 1,500 feet above ground level to 45,000 feet. The lower altitude limit determines the service area for each differential correction communications site. From Table 4-2 the effective range of the differential correction transmissions for aircraft flying at 1,500 feet is 48 nautical miles. By assuming a circular service area with radius of 48 nautical miles, it can be calculated that the total service area for each differential correction communications site is 7,235 square nautical miles. This is a very important figure and will be used later to determine the number of facilities required for service.

4.5.3 Availability of Signal

The signal availability of the Differential Omega navigation system is the percentage of time that it can provide information of the required accuracy to the user. Presently there are no Differential Omega installations, and any assessment of the availability of signals must be based on projection. In this analysis attention will be directed to three areas:

(1) the reliability of the Omega transmitter station equipment;

(2) the reliability of the Differential Omega monitor site equipment; and

(3) the influence of propagation effects on the reception of accurate signals.

The Omega transmitter stations have been designed for maximum reliability. A great deal of redundancy has been installed throughout the system in the form of dual transmitters, four Cesium beam frequency standards, and duplicate timing equipment for every Omega station. It is expected that the reliability of this configuration will be very close to 100%.

The reliability of the Differential Omega monitor station equipment will probably be the primary factor in determining system availability. The monitor station installation that was described earlier in this study and priced at $25,000 provides for dual Omega receivers to furnish redundant operation. In the event of monitor station communications failure the correction information may be available on another channel, or the information from an adjacent Differential Omega correction site may have to be used, resulting in only a slight decrease in accuracy. Consequently, it is expected that the reliability of the Differential Omega operation will also be very near 100%.

The final factor that needs to be considered is the influence of propagation effects on the reception of accurate signals. The performance of a Differential Omega operation during sudden phase anomaly occurrences has been investigated, but additional research needs to be accomplished before definitive performance measures can be presented. The Differential Omega tests conducted by TRACOR, Inc.,

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demonstrated that the resultant accuracy of the system during anomalies was nearly as high as that during regular operations. [65] The correction process removes most of the effect of the anomaly. In this analysis it will be assumed that propagation anomalies have no effect on Differential Omega accuracy; however, the need for further research in this field must be recognized. A propagation effect in the form of precipitation static can arise in Omega operations, just as it could in Loran-C. Resistance to this effect can be accomplished by the installation of dischargers and the recognition of the importance of proper antenna location on the aircraft. If the level of p-static that occurs during the general aviation operations is determined to be so strong that it cannot be controlled by these techniques, an orthogonal loop antenna can be installed. This antenna greatly improves the p-static resistance, but adds an increment to the airborne equipment cost.

Each of these factors is important when assessing the availability of the signals of the Differential Omega system. However, at this time, because of the lack of facilities and definitive research, a final value cannot be given to the availability of Differential Omega signals. An availability of approximately 100% is expected, but it cannot be assigned until further development is accomplished.

4.5.4 Additional Capabilities

The global coverage of the Omega navigation signals enables that system to provide service to many diverse interests. In addition to serving the aviation community, Omega also furnishes navigation signals to submarines, ships, and many other different types of surface vehicles. The earlier description of system capabilities was focused primarily on Differential Omega. This same level of performance can be realized anywhere in the world for rendezvous operations. Because of common phase variations in the same local area vehicles are able to locate one another quite accurately. Due to the long range of VLF propagation the same navigation system can be used to provide guidance from Santiago to Sao Paulo as readily as from Bangor to Boston. Omega's world-wide coverage is unique among radionavigation systems.

The position errors present in the Omega navigation system are bounded and independent of the duration of a trip. These properties have generated a good deal of interest toward using Omega in a hybrid configuration with self-contained airborne navaids.[66] This results in a very synergistic operation. The most common self-contained aids have good short term accuracy, but have errors that are unbounded over a long period of time. Omega provides a limit for this error and also fulfills the blunder protection requirement. Some air carriers have undertaken investigations to determine if the Omega navigation system can satisfy the same requirements for the triply redundant inertial systems. If it can, and if an inertial unit can be replaced with an Omega installation, large cost reductions will result.

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Omega navigation can be accomplished in the rho-rho or circular mode. As in Loran-C, the receiver needs to be equipped with a very accurate short-term clock. A receiver so configured can count the beats between the receiver signal and the identical frequency derived internally and then use the beats between the received signal and the identical frequency derived internally and then use the beats to furnish a figure for the changes in distance from the transmitter. This operation requires starting from a known point, but has some distinct advantages:

(1) navigation can be accomplished with signals from only two stations;

(2) the geometry is better than that of the hyperbolic lines of position; and

(3) the lanes of ambiguity are a full wavelength wide. If the cost of the internal clocks can be reduced, rho-rho operation offers a great deal of promise.

The timing provision capabilities of Omega are quite remarkable. It can be used to provide precise time and frequency information to users throughout the world. Because of technological improvements to the timing of Omega transmissions and improvements in administrative control to maintain service within precise tolerances, the Omega system has the capability to provide Universal Time globally to within a few μ-seconds.[61] This information can be used in satellite tracking operations, aerial mapping, television control, and a number of other widely varied applications.

4.6 Implementation Plans/Costs of the System

The implementation of the Differential Omega navigation system will occur in two distinct steps: first, all Omega transmitting stations will be prepared to operate with their full capability; and second, the Differential Omega monitor sites will be constructed and placed in operation. The construction of the Omega transmitting stations is continuing. Under the present schedule all eight transmitting stations will be operating at full power by mid-1975. Table 4-3 describes the present status and future plans for each station.

The U.S. Coast Guard will be responsible for the operations and maintenance of the U.S. Omega stations, and they also will satisfy the U.S. management commitmen for the entire Omega system. As the stations are completed and normal operations are undertaken, it is foreseen that an International Omega Policy Committee will be formed, and this body will be responsible for the overall policy governing the international aspects of the Omega system.

The construction and equipment costs of the Omega transmitting stations are very high. Estimates of the total system cost range from 100 to 120 million dollars, and the operations and maintenance costs are estimated at 600 thousand dollars per station per year.[68, 69] For the particular area of interest in this study these costs are not applicable. In accounting parlance they are considered to be "sunk" costs.

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Table 4-3

STATUS OF THE OMEGA TRANSMITTING STATIONS

Station-Location	Present Status	Future Plans
A - Norway	Semi-operational; 3 kw power	Fully operational-end 1973
B - Trinidad	Semi-operational; 0.6 kw power	Fully operational-mid 1975
C - Hawaii	Semi-operational; 2 kw power	Fully operational-early 1973
D - North Dakota	Fully operational; 10 kw power	--------------------
E - La Reunion	--------------	Fully operational-end 1974
F - Argentina	--------------	Fully operational-end 1974
G - Australia	--------------	Fully operational-mid 1975
H - Japan	--------------	Fully operational-early 1974

The transmitting stations will be built whether or not differential monitor sites are established; and, therefore, the costs of the transmitting stations are not an item for consideration in the present comparative analysis between VORTAC, Loran-C, and Differential Omega.

On the other hand, the cost of the Differential Omega monitor sites is an important aspect of the present analysis and deserves a good deal of attention. An estimate of the facilities and equipment costs for a single station has been mentioned previously as 25 thousand dollars. The number of these Differential Omega monitor sites that are needed is dependent on decisions as to what performance will be required and how the differential correction information is to be communicated to the user.

The requirements as specified in Chapter One include:

(1) coverage over the complete area of the conterminous United States and Alaska (2.75 million square nautical miles) from 1,500 feet above ground level to 45,000 feet; and

(2) accuracy of the total system, including allowances for computer and flight technical error, of ± 2.5 nautical miles for the enroute case and ± 1.5 nautical miles for the terminal area. This specification leads to a

requirement of Omega navigation system accuracy of ± 1.09 nautical miles. The method used to derive this value will be outlined in Chapter Five.

By reference to Figure 4-10, the requirement of ±1.09 nautical mile accuracy determines a maximum range from the differential monitor site of 142 nautical miles. The maximum service area for a single monitor site is then:

$$A^1_{max} = \pi \, (r_{max})^2 = 64,000 \text{ sq. n. mi.} \qquad \text{Eqn. 4.3}$$

where

A^1_{max} = the maximum service area for a single monitor site; and

r_{max} = the maximum effective range of the monitor site, i.e., 142 nautical miles for the present requirements.

To meet the coverage requirement of Chapter One, the number of monitor stations needed is:

$$n = \frac{K_2 A_T}{A^1_{max}} = \frac{1.57 \times 2,750,000}{64,000} = 68 \text{ stations} \qquad \text{Eqn. 4.4}$$

where

n = the number of monitor stations required to serve the total area;

A_T = the total area to be served, i.e., 2.75 million square nautical miles;

A^1_{max} = the maximum service area for a single monitor site, i.e., 64,000 square nautical miles for the present requirements; and

K_2 = a multiplier to account for service area overlap = 1.57 as discussed in Chapter Two.

The cost of implementation for these sixty-eight stations is 1.7 million dollars (68 stations at a unit cost of $25,000), and this represents the minimum expenditure for a Differential Omega network. The terminal area accuracy requirement is satisfied, but only marginally. If greater accuracy is desired, more facilities would have to be constructed. Chapter Five will contain an analysis of the sensitivity of system cost to changes in the accuracy requirement.

Once this network of Differential Omega monitor stations has been constructed, it is necessary to provide a communications network whereby the correction information

can be disseminated to the users. The configuration of the communications network can be a constraint to the performance of the Differential Omega navigation system. The means of communications that is adopted must be consistent with general aviation equipment, and this can lead to a requirement for a far greater number of communications outlets than monitor sites. Very high frequency radio transmissions will probably be used to relay the correction information. The line-of-site characteristics of these transmissions limit their effective range. Reference to Table 4-2 indicates that to provide service at 1,5000 feet above ground level, over flat terrain, the transmitting station must be within 48 nautical miles of the user. The service area for such a transmitter is 7,235 square nautical miles:

$$A_{comm} = \pi \, (r_{comm})^2 = 7,235 \text{ sq. n. mi.} \qquad \text{Eqn. 4.5}$$

where

A_{comm} = the communications service area for a VHF transmitter; and

r_{comm} = the effective range of VHF transmissions at a specified altitude, i.e., 48 nautical miles for reception at 1,500 feet.

To meet the coverage requirement of Chapter One, 656 communications outlets are required:

$$N_{comm} = K_1 \times K_2 \times \frac{A_T}{A_{comm}} = 1.1 \times 1.57 \times \frac{2,750,000}{7,235} = 656 \text{ outlets} \qquad \text{Eqn. 4.6}$$

where

N_{comm} = the number of communications outlets required to serve the total area;

A_T = the total area to be served = 2.75 million square nautical miles;

A_{comm} = the communications service area for a VHF transmitter at a specified altitude;

K_1 = multiplier to account for non-flat terrain, as was discussed in Chapter Two, = 1.1; and

K_2 = multiplier to account for service area overlap, as was also discussed in Chapter Two, = 1.57.

This number of communications outlets can be provided by the proposed configuration of Flight Service Stations and air/ground communications facilities. The National Aviation System Plan [70] prepared by the Federal Aviation Administration indicates that the future system layout in 1982 will consist of approximately 100 manned

Flight Service Stations and approximately 600 remote air/ground communications outlets. Each of these facilities could be used to relay the Differential Omega correction data. If additional manpower and equipment are necessary at the facilities to effect these communications, the costs of such will have to be charged against the Differential Omega system.

A likely estimate of the annual operations and maintenance costs of a Differential Omega monitor station is taken as 10 percent of the facilities and equipment costs. This amounts to $2500 per station per year. If it is found that the presence of the monitor sites or communications outlets leads to an increase in workload that results in additional manning for the flight service facilities, then these costs will also have to be assessed to the Differential Omega operation. The minimum installation of 68 stations will require an annual expenditure of $170,000 for operations and maintenance functions.

The level of performance that would be provided by this minimum configuration of 68 stations satisfies the requirements as presently stated. The coverage is complete; the accuracy is such that when combined with the computer and flight technical errors, it still is within the ± 1.5 nautical mile requirement for the terminal area tolerance; and the availability is estimated to be approximately 100 percent. The accuracy can be improved with the installation of additional monitor stations. In the immediate area of a Differential Omega monitor site the accuracy can be ± 0.5 nautical miles or better. Table 4-4 summarizes the performance and costs for a Differential Omega navigation system.

Table 4-4

DIFFERENTIAL OMEGA PERFORMANCE AND COSTS

Performance

System Accuracy:	± 0.5 – ± 1.09 nautical miles
System Coverage:	Continuous, except for some communications outages in mountainous areas
System Availability:	Approximately 100%

Costs

Facilities and Equipment:	$1.7 million minimum
Operations and Maintenance/year:	$170 thousand minimum
Cost of Airborne Equipment:	$4 thousand

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CHAPTER 5

A COMPARATIVE ANALYSIS OF CANDIDATE

AREA NAVIGATION SYSTEMS

Within the next decade area navigation is to become the primary method of
air navigation within the United States. The adoption of this mode of navigation
offers a great deal of benefit to general aviation operations. As the number
of general aviation aircraft operations grows, a more efficient method of navigation
is required in order to make optimum use of the appropriate airspace, aircraft, and
airports. Area navigation offers one important element in the approach to this
optimization.

There are numerous radionavigation systems that offer the potential of area
navigation available to general aviation enthusiasts. The purpose of this particular
analysis has been to examine a representative group of those radionavigation systems
and compare them with respect to performance specifications in terms of accuracy,
coverage, and availability. In addition to the performance comparison a cost-
effectiveness assessment has been undertaken. This assessment evaluates each
candidate system with respect to the economic aspects required to satisfy a given
set of performance constraints.

The author has examined three radionavigation systems: (1) the VORTAC
system; (2) the Loran-C system; and (3) the Differential Omega system. After
a description of system parameters and operation, an analysis was accomplished
where-by that particular system was examined in light of its ability to satisfy the
following performance specifications:

(1) coverage - the area of coverage is the area within which the system
    delivers navigation signals that can be received and processed resulting
    in navigation accuracies within the specified limits - the system must
    provide service everywhere within the conterminous United States and
    Alaska from an altitude of 1, 500 feet above ground level to 45, 000 feet;
(2) availability - the signal availability is a measure of the ability of the
    system to provide a signal within the coverage area to the accuracy
    tolerance specified - a goal of 100% is ideal; and
(3) accuracy - the system accuracy is the repeatable accuracy that the system
    provides with a 95% (2 σ) probability of error less than the stated value -
    the enroute tolerance will be ± 2. 5 nautical miles, and the accuracy in the

terminal area will be ± 1.5 nautical miles. This accuracy is for total navigation system performance and includes error contributions from the radionavigation system, the area navigation computers, and the flight technical performance.

The three performance measures, coverage, availability, and accuracy are highly interrelated. None can be treated independent of the others. In the preceding system analyses the author has investigated each separately and then combined the performance measures to generate an overall evaluation of the system. An economic analysis was then undertaken, and the results of these analyses are presented in this chapter for final comparison.

5.1 Navigation System Error Budget

The author has specified minimum accuracy tolerances to be met by the candidate navigation systems. The total aircraft navigation system accuracy is dependent not only on the performance of the radionavigation system, but also on the performance of the airborne area navigation computer and the pilot. Some of these error elements can be measured quantitatively, and some have to be judged primarily on the basis of experience.

The area navigation computer error includes error components contributed by any input, output, or signal conversion equipment used, by any computing element employed, by the display as it presents either aircraft position or guidance commands, and by any course definition entry devices employed. [71] With the adoption of improved digital computing techniques and refinement in the input and output processing, it has been estimated that the airborne area navigation equipment error will be approximately ± 0.25 nautical miles. [72]

The flight technical error refers to the accuracy to which the pilot controls the aircraft as measured by his success in causing the indicated aircraft position to match the indicated command or desired position on the display. [73] This error is one which is extremely difficult to quantify. It is dependent on such widely diverse factors as pilot experience, cockpit workload, fatigue, motivation, and the manner in which the guidance information is displayed to the pilot. In the past, the value given to this error has been specified in terms of angular deviation rather than linear displacement. Area navigation devices are expected to present their information in linear rather than angular terms, and it is anticipated that the flight technical error may be reduced somewhat when this display is utilized. The effects of aircraft control dynamics, air turbulence, etc., greatly influence the performance of the pilot. Some signal processing is used to minimize their contribution, and it is expected that future processing and displays will further reduce this error source. A value of ± 1.0 nautical miles has been assigned for the enroute and terminal performance measures for flight technical error. [74]

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The errors that result from the utilization of a particular radionavigation system have been discussed in detail in the earlier chapters of this study. Each radionavigation system contributed errors to the total system performance, and this performance must meet the specific accuracy requirements.

If one assumes that the errors from the various sources are normally distributed and independent, they may be combined in a root sum squares fashion. The combination by this method allows the analyst to determine the allowable error contribution from the radionavigation system in order to satisfy certain total system performance constraints. The enroute accuracy specification of ± 2.5 nautical miles determines that the radionavigation system error must be less than or equal to ± 2.28 nautical miles:

$$\epsilon_{total} = \left[\epsilon^2_{computer} + \epsilon^2_{pilot} + \epsilon^2_{radio} \right]^{\frac{1}{2}}$$ Eqn. 5.1

$$\pm 2.5 \text{ n. mi.} = \left[(0.25)^2 + (1.0)^2 + \epsilon^2_{radio} \right]^{\frac{1}{2}}$$ Eqn. 5.2

$$\epsilon^2_{radio} = 5.1875 \text{ (n. mi.)}^2$$ Eqn. 5.3

$$\epsilon_{radio} = \pm 2.28 \text{ n. mi.}$$ Eqn. 5.4

The terminal area accuracy specification of ± 1.5 nautical miles determines that the radionavigation system used for terminal area operations must have an error less than or equal to ± 1.09 nautical miles:

$$\pm 1.5 \text{ n. mi.} = \left[(0.25)^2 + (1.0)^2 + (\epsilon_{radio})^2 \right]^{\frac{1}{2}}$$ Eqn. 5.5

$$\epsilon^2_{radio} = 1.1875 \text{ (n. mi.)}^2$$ Eqn. 5.6

$$\epsilon_{radio} = \pm 1.09 \text{ n. mi.}$$ Eqn. 5.7

where

ϵ_{total} = the total navigation system error;

$\epsilon_{computer}$ = the error of the airborne area navigation computer;

ϵ_{pilot} = the flight technical error; and

ϵ_{radio} = the error from the radionavigation system.

Radionavigation system performance that exceeds these levels is required in order to meet the total system performance specifications. Each system under study in this analysis is capable of meeting these performance levels. The costs of doing so, however, are widely divergent, and their comparison provides a fruitful area for further analysis.

5.2 Comparative System Analysis for Specified Operational Performance

With full consideration for the operational requirements as specified above, the author investigated each radionavigation system to determine the cost requirements for such a provision.

For the purposes of this analysis the radionavigation system costs are divided into two main categories: (1) facilities and equipment costs; and (2) operations and maintenance costs. The facilities and equipment costs are those costs which can be defined as one-time-only expenditures for the installation of new equipment and/or the establishment of new facilities. These costs include land costs, facility engineering costs, the costs of the construction material and labor, the costs of the electronic equipment and its installation, and the associated transportation costs. The operations and maintenance costs are the annual costs required to operate and maintain the particular type of facility in the FAA/DOT inventory. In addition to the annual costs, a twenty-year operations and maintenance cost has been assessed. It is computed by compounding the annual operations and maintenance costs by 1.06 per year to reflect increases in costs for necessary material and labor. This six percent inflation factor is maintained throughout the twenty-year period. A total system cost is given also. This is simply the sum of the initial facilities and equipment costs plus the operations and maintenance costs accrued over the twenty-year utilization period. The cost of the user equipment has also been determined, and it is enumerated in the comparative analysis.

The VORTAC radionavigation system is in use today. In fact, it broadcasts the signals which furnish the present method of short-range air navigation in the United States. There are approximately 900 VOR facilities installed, with slightly over 700 of them having colocated TACAN or DME equipment. The costs of implementation reflect the necessity to upgrade the VOR's without DME equipment to fully

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functioning VORTAC's. Table 2-8 enumerates the approximate implementation costs for the VORTAC system.

The VORTAC radionavigation system has been examined for three separate phases of its development. The first is the ground navigation stations configured as they are today, used in conjunction with present day general aviation type equipment; the second is the ground navigation stations configured as they are today, used in conjunction with improved airborne equipment; and the third is the implementation of Post-1982 ground stations (Doppler or precision VORTAC's), used in conjunction with advanced airborne equipment. Each of these systems is able to satisfy the binding terminal area accuracy requirement with a reasonably high level of availability. However, the requirement for complete coverage is not met due to the line-of-sight propagation limitations of VHF/UHF transmissions. A multiplier is included in the equations to compensate somewhat for this shortcoming, but areas of no coverage continue to exist. Table 5-1 displays the performance assessment of the different VORTAC configurations and specifies the approximate costs associated with their implementation to satisfy the stated requirements of coverage, accuracy, and availability.

The Loran-C radionavigation system is partially implemented today. The U.S. Coast Guard operates a Loran-C chain on the east coast of the United States and another in Alaska. To achieve complete coverage of the conterminous United States and Alaska additional stations have to be implemented. At present the Coast Guard has presented a proposed Loran-70's program in which the implementation of west coast, Gulf coast, and additional Alaskan chains would be accomplished. The author has proposed a configuration which combines the Coast Guard program with six additional stations to generate a complete coverage system. Since the Loran-C system operates in the low-frequency band and is not hampered by line-of-sight limitations, the highly accurate signal is provided everywhere within the service area. Table 5-1 displays the performance assessment of the proposed Loran-C system and specifies the approximate costs associated with the implementation plan.

The implementation of the Differential Omega system follows essentially two tracks. The first is the establishment of the Omega transmitting stations. This has been underway for a good while and will continue with an approximate system completion date of mid-1975. The Omega transmitting stations are very expensive installations; however, for the purposes of the present analysis, this cost is not applicable. In accounting parlance it is considered a "sunk" cost. The second element of the Differential Omega implementation is the establishment of the differential correction monitor sites, and and the costs of this aspect of the implementation are very much applicable to the present analysis. The accuracy of the Omega system is primarily a function of the degree to which regular phase changes can be predicted and the degree to which irregular

Table 5-1

COMPARATIVE SYSTEM ANALYSIS FOR SPECIFIED OPERATIONAL PERFORMANCE

	Accuracy	Coverage	Availability	No. of Facilities Required	Total Facilities & Equipment Cost
Conventional VORTAC Ground Stations					
with present day airborne equipment	±1.09 n. mi.	Continuous, except in some areas	0.992	5,690	$1,522,450,000
with improved airborne equipment	±1.09 n. mi.	Continuous, except in some areas	0.992	2,934	$ 654,310,000
Post-1982 VORTAC Radio-navigation Facilities	±1.09 n. mi.	Continuous, except in some areas	0.992	780	$ 112,000,000
Loran-C Radionavigation System	±0.1-0.2 n. mi.	Continuous	0.997		
Total System				25	$ 89,100,000
Incremental System dedicated to aviation				6	$ 28,500,000
Differential Omega Radio-navigation System	±1.09 n. mi.	Continuous	approx. 1.000		
Differential Omega Monitor Sites				68	$ 1,700,000
Communications Outlets				656	

Table 5-1 (Cont.)

COMPARATIVE SYSTEM ANALYSIS FOR SPECIFIED OPERATIONAL PERFORMANCE

	Total Annual Operations & Maintenance Cost	Twenty-Year Operations & Maintenance Cost	Total System Cost	Airborne Equipment Cost
Conventional VORTAC Ground Stations				
with present day airborne equipment	$136,560,000	$5,023,500,000	$6,545,900,000	$3,000-4,000
with improved airborne equipment	$ 70,416,000	$2,590,300,000	$3,244,600,000	$3,000-4,000
Post-1982 VORTAC Radionavigation Facilities	$ 21,840,000	$ 803,400,000	$ 915,400,000	$3,000-4,000
Loran-C Radionavigation System				
Total System	$ 5,150,000	$ 189,400,000	$ 278,500,000	$4,000
Incremental System dedicated to aviation	$ 1,100,000	$ 40,500,000	$ 69,000,000	
Differential Omega Radionavigation System				
Differential Omega Monitor Sites	$ 170,000	$ 6,250,000	$ 7,950,000	$4,000
Communications Outlets				

phase changes can be accommodated. The differential correction monitor sites aid in the prediction and accommodation and allow the resultant accuracy of the system to be such that it is a candidate for nation-wide implementation of area navigation signal provision.

The Omega navigation signals are broadcast in the VLF band and are not subject to the line-of-signt limitations of higher frequency systems. This ensures coverage throughout the service area. The method of disseminating the differential correction information, however, can be subject to these limitations. Air-to-ground VHF communication is a natural method for the dissemination of the correction information, and these transmissions are subject to line-of-sight propagation. Table 5-1 displays the performance assessment of the Differential Omega radionavigation system and specifies the approximate costs associated with the implementation to satisfy the performance requirements.

An analysis of Table 5-1 leads to the following conclusions relating to the radionavigation system performance with respect to the specified performance constraints:

(1) All systems are capable of satisfying the performance constraints with the exceptions relating to line-of-sight propagation in mountainous areas;

(2) The Loran-C radionavigation system provides the highest degree of accuracy;

(3) The Loran-C system requires the fewest ground facilities, followed by the Differential Omega system, and then by the various configurations of the VORTAC system;

(4) The number of facilities required by the conventional VORTAC system, when utilizing present day general aviation receivers, is so great as to remove it from reasonable consideration, i.e., there is just no possible way that 5,690 facilities could be implemented;

(5) The number of facilities required by the conventional VORTAC system, when utilizing improved airborne equipment, is so great as to present a question of its reasonable consideration;

(6) The Differential Omega system requires the least expenditure for facilities and equipment, operations and maintenance, and total system utilization, followed by Loran-C, and then by the various configurations of the VORTAC system; and

(7) The airborne equipment cost of all three systems is essentially equal.

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5.3 Sensitivity Analyses of the Radionavigation System Cost Elements to Changes in Performance Specification

In the previous section the author was able to produce a table that allowed a comparative analysis of candidate navigation system with respect to the satisfaction of specific performance requirements. The designation of the specific requirements is always somewhat arbitrary, and in this section the author will develop techniques whereby an analyst can determine the sensitivity of each radionavigation system cost element with respect to a change in performance specifications.

The analysis for the various configurations of the VORTAC radionavigation system will be the first undertaken. In order to satisfy reasonable future accuracy requirements, the conventional VORTAC system, used in conjunction with present day receivers, requires so many facilities as to be totally impractical. For this reason its sensitivity will not be developed.

The conventional VORTAC facilities, used in conjunction with improved airborne equipment, require a large number of facilities to satisfy reasonable accuracy requirements. However, unlike the previous configuration, the number of facilities is not completely out of the question, and a sensitivity analysis is to be undertaken.

From Equation 2.10, one can ascertain that the total system error is approximately $\pm 0.048d$, where d is the distance separating the aircraft and the ground facility.

$$\epsilon_d = \pm 0.048d \qquad \text{Eqn. 5.8}$$

therefore,

$$d = \frac{\epsilon_d}{0.048} \qquad \text{Eqn. 5.9}$$

where

ϵ_d = the error in position; and

d = the distance between the aircraft and the ground station.

The service area for a given VORTAC station, A_s, can be defined in terms of the resultant error in position, ϵ_d:

$$A_s = \pi d^2 = \pi \left(\frac{\epsilon_d}{0.048}\right)^2 = 1364 \, \epsilon_d^2 \qquad \text{Eqn. 5.10}$$

The total number of facilities required, n, was determined in Equation 2.40 to be:

$$n = K_1 \times K_2 \times \frac{A_T}{A_s} \qquad \text{Eqn. 5.11}$$

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where

n = the number of conventional VORTAC radionavigation facilities required;

K_1 = a multiplier to account for non-flat terrain = 1.1;

K_2 = a multiplier to account for service area overlap = 1.57;

A_T = the area of the conterminous United States and Alaska, i.e., approximately 2,750,000 square nautical miles; and

A_s = the radionavigation facility service area.

Therefore,

$$n = 1.1 \times 1.57 \times \frac{2,750,000}{1364\ \epsilon_d^2} = \frac{3,482}{\epsilon_d^2} \qquad \text{Eqn. 5.12}$$

A graphical presentation of this result is illustrated in Figure 5-1.

From the information as to the number of facilities required, one can determine the numerous cost elements. The facilities and equipment cost is simply the number of new facilities multiplied by the appropriate unit price plus the modification cost to the 200 VOR's that were not equipped with TACAN or DME. Table 2-7 outlines the approximate unit costs for VORTAC facilities. For the present configuration of interest, the $315,000 figure for the new VORTAC stations and the $68,000 figure for a DME conversion yield the results illustrated in Figure 5-2. This chart allows the analyst to determine the facilities and equipment expenditure required to produce radionavigation system accuracy of a given tolerance.

The twenty-year operations and maintenance expenditure can be computed by simply multiplying the required number of facilities by the annual operations and maintenance cost per facility ($24,000 in the present analysis) and then applying the 6% inflation factor over the twenty-year period. Figure 5-3 depicts this result.

Finally, the total radionavigation system cost can be determined by summing the facilities and equipment expenditures and the twenty-year operations and maintenance cost. Figure 5-4 illustrates the final result. This figure relates total radionavigation system cost to the accuracy required of that radionavigation system.

Similar curves can be constructed for the Post-1982 VORTAC, utilizing advanced airborne equipment.

From Equation 2.11

$$\epsilon_d = \pm \left[0.000576\ d^2 + 0.0729 \right]^{\frac{1}{2}} \qquad \text{Eqn. 5.13}$$
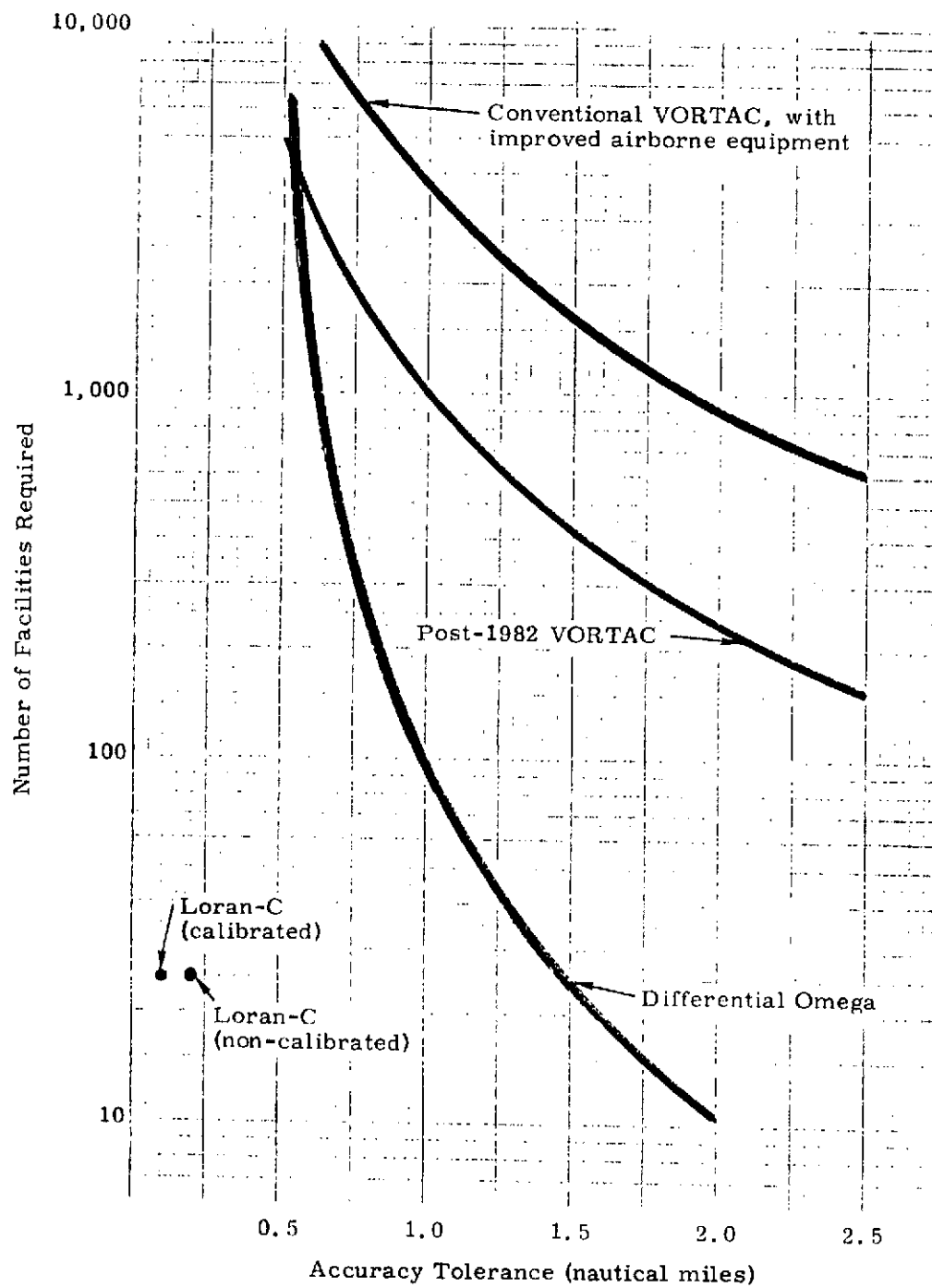
Figure 5-1. Number of Facilities Required vs Accuracy Tolerance
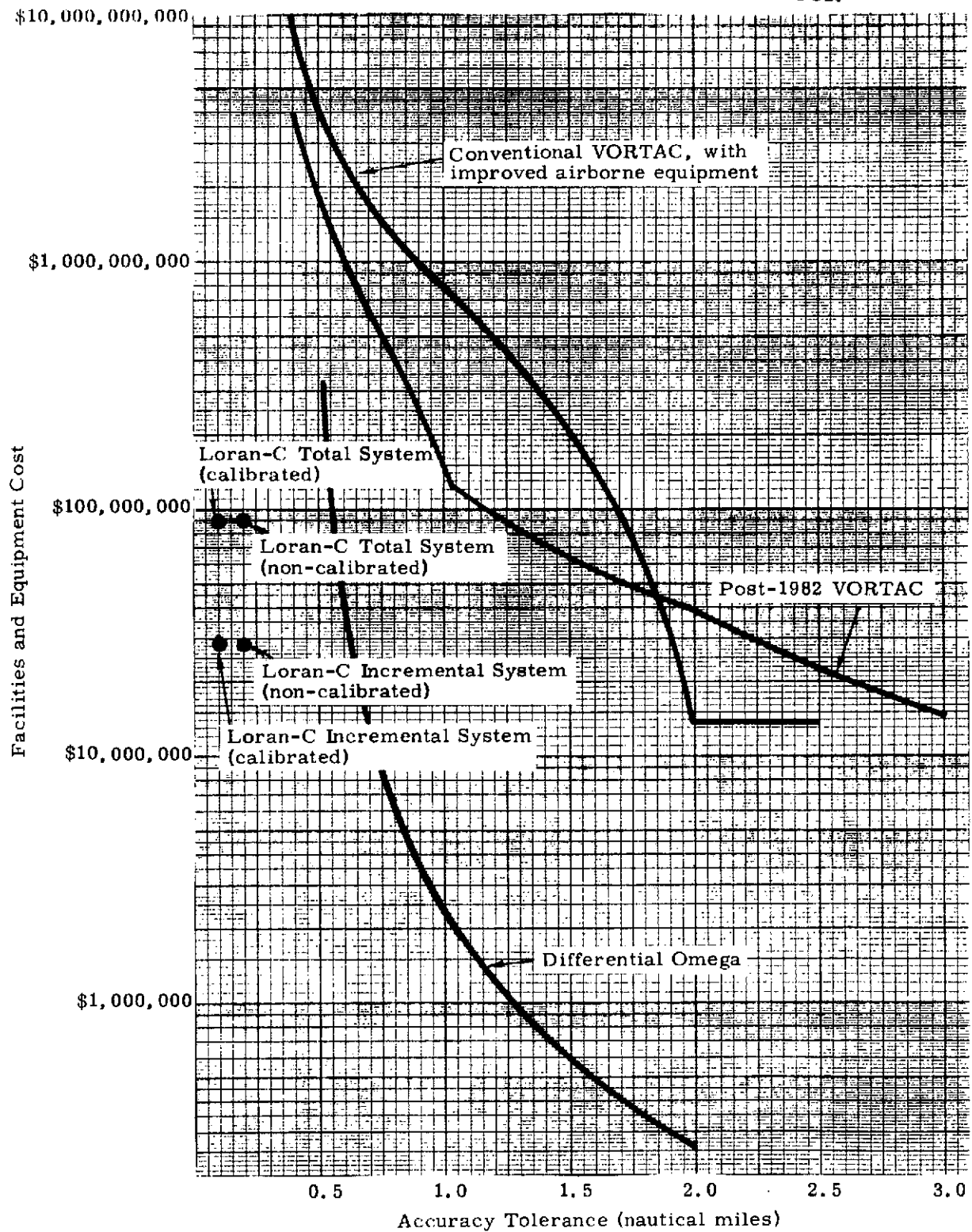
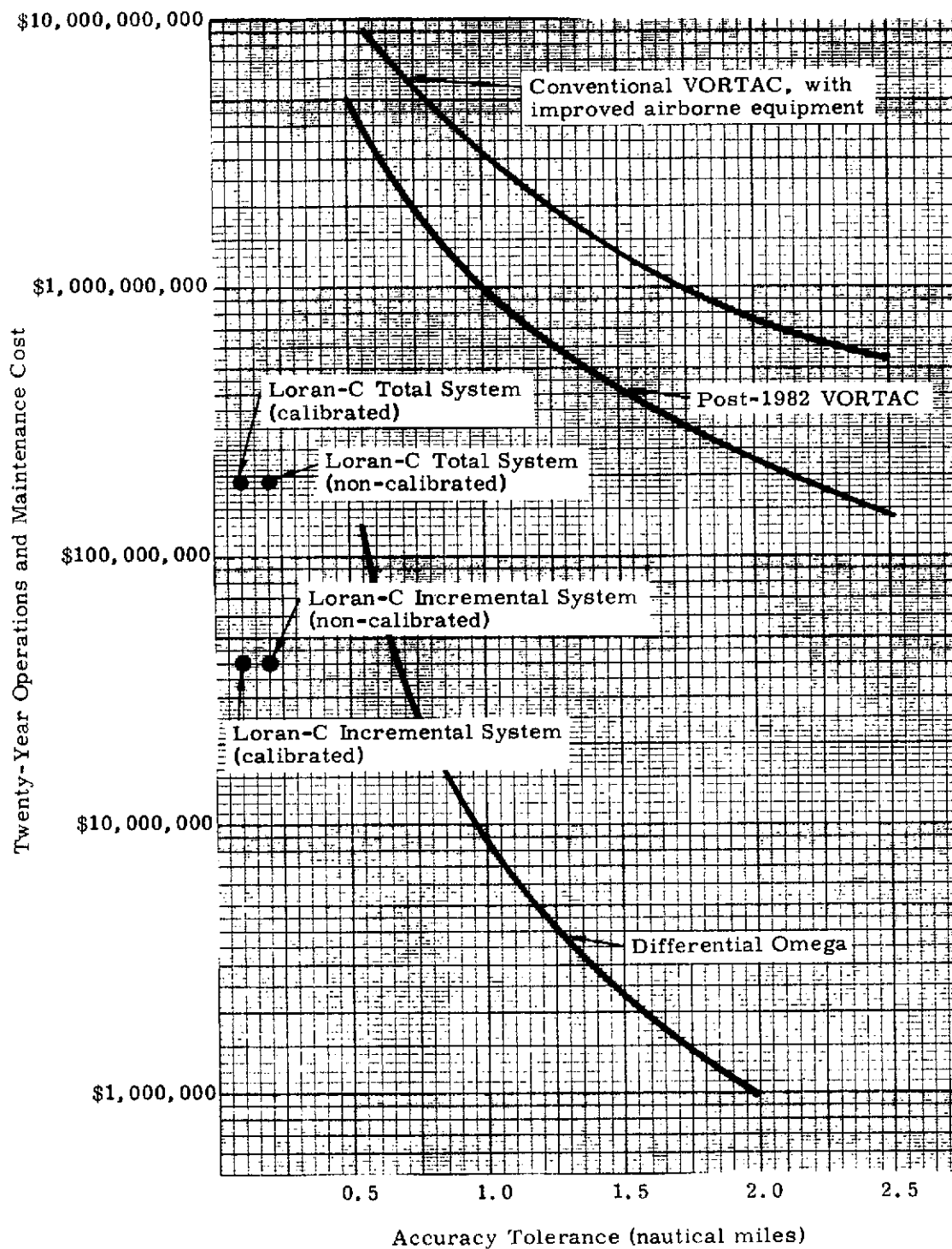Figure 5-2.   Facilities and Equipment Costs vs Accuracy Tolerance

Figure 5-3. Twenty-Year Operations and Maintenance Cost vs Accuracy Tolerance

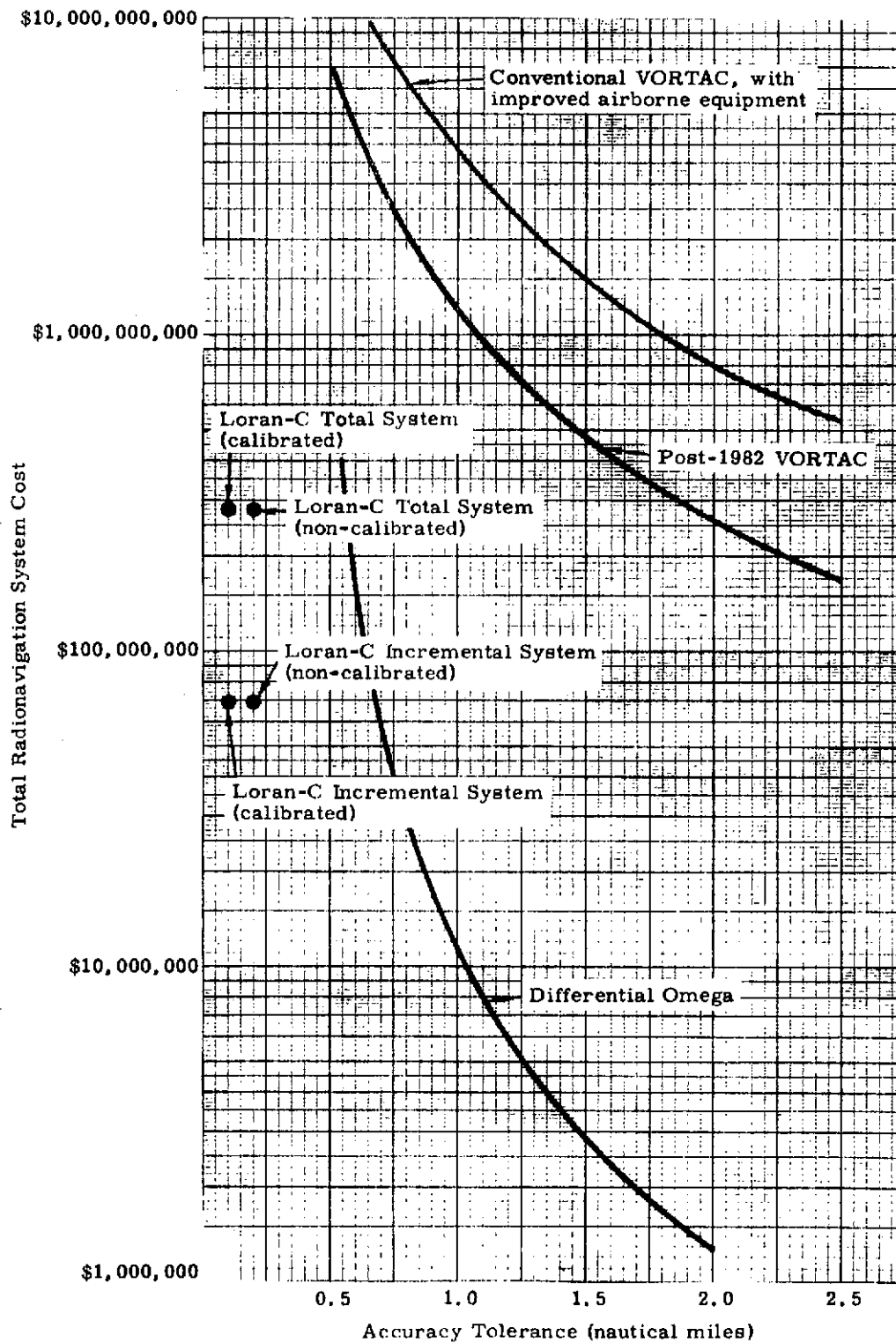Figure 5-4. Total Radionavigation System Cost vs Accuracy Tolerance

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then,

$$\epsilon_d^2 = 0.000576\,d^2 + 0.0729 \qquad\qquad \text{Eqn. 5.14}$$

and therefore,

$$d^2 = \frac{\epsilon_d^2 - 0.0729}{0.000576} \qquad\qquad \text{Eqn. 5.15}$$

The facility service area, A_s, is

$$A_s = \pi\,d^2 = \pi\left[\frac{\epsilon_d^2 - 0.0729}{0.000576}\right] \qquad\qquad \text{Eqn. 5.16}$$

Applying this to Equation 2.38 generates the required number of facilities, n

$$n = K_1 \times K_2 \times \frac{A_T}{A_s} \qquad\qquad \text{Eqn. 5.17}$$

where K_1, K_2, A_T, and A_s are as defined in Equation 5.11.

$$n = \frac{4,749,250}{\pi\left[\dfrac{\epsilon_d^2 - 0.0729}{0.000576}\right]} \qquad\qquad \text{Eqn. 5.18}$$

This equation is plotted on Figure 5-1. It relates the total number of facilities required in order to realize a Post-1982 VORTAC radionavigation system with a specified accuracy.

The facilities and equipment costs incurred to realize a given accuracy of the Post-1982 VORTAC radionavigation system can be determined from Figure 5-2. The appropriate values were computed by applying the following logic: if more than 900 facilities are required, the new ones will be installed at a unit cost of $426,000 (see Table 4-7). This is the cost for a precision VORTAC with single DME. The older facilities will be modified to enhance their operations:

(1) The Doppler VORTAC's will be modified to precision VORTAC's at a unit cost of $30,000;

(2) The VOR's will have TACAN or DME equipment installed and be modified to operate as precision VORTAC's at a unit cost of $198,000 ($130,000 + $68,000); and

(3) The conventional VORTAC's will be modified to precision VORTAC's at a unit cost of $130,000.

The modifications of existing equipment will be performed in the order specified in the previous sentence.

The twenty-year operations and maintenance costs of the Post-1982 VORTAC system are illustrated in Figure 5-3. These costs are determined by multiplying the number of facilities required by the annual cost per facility and then applying the 6% inflation factor. When this cost is summed with the facilities and equipment cost of Figure 5-2, the total radionavigation system cost is derived. Figure 5-4 depicts the total system cost for the Post-1982 VORTAC radionavigation system as a function of the desired accuracy tolerance.

Another interesting sensitivity analysis can be conducted for the VORTAC radionavigation systems. The transmission of signals from these facilities is subject to the limitations of line-of-sight propagation. The range that a facility can be received is a direct function of the altitude of the receiver. Equation 5.19 relates this phenomenon for an assumed transmitting antenna height of zero feet.

$$r = 1.23 \sqrt{h_R} \qquad \text{Eqn. 5.19}$$

where

r = maximum reception range, in nautical miles; and

h_R = the height of the receiving antenna, in feet above ground level.

The number of stations required, n, can be determined from Equation 5.11.

$$n = K_1 \times K_2 \times \frac{A_T}{A_s} \qquad \text{Eqn. 5.20}$$

where all parameters are as defined in Equation 5.11.
If

$$r = 1.23 \sqrt{h_R} \qquad \text{as in Equation 5.19,}$$

then

$$r^2 = 1.513 \, h_R \qquad \text{Eqn. 5.21}$$

and since

$$\pi r^2 = A_s \qquad \text{as in Equation 5.16,}$$

then

$$n = K_1 \times K_2 \times \frac{A_T}{\pi (1.513 \, h_R)} = \frac{999,211}{h_R} \qquad \text{Eqn. 5.22}$$

Table 5-2 enumerates this result.

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Table 5-2

NUMBER OF FACILITIES REQUIRED FOR VHF/UHF
RADIO RECEPTION AT SPECIFIED ALTITUDES

Altitude (feet)	Number of Facilities
250	3997
500	1998
1000	999
1200	833
1500	666
1800	555
2000	500
2200	454
2500	400
2800	357
3000	333

If an analyst plots these numbers of facilities on the earlier figure which relates the number of facilities required to the specified accuracy (Figure 5-1) a very interesting result becomes apparent. Figure 5-5 illustrates the result. Once the analyst has specified a lower altitude performance requirement, such as reception assured everywhere at 1,500 feet above ground level, a maximum radionavigation system error is determined. As an example, on Figure 5-5, if a Post-1982 VORTAC radionavigation system is being evaluated, and if reception is required everywhere from 2,000 feet above ground level up to 45,000 feet, the maximum radionavigation system error that could be present would be ± 1.37 nautical miles. This is determined by following the horizontal line specified for 2,000 feet reception altitude across until it intersects the "Number of Facilities" curve for the Post-1982 VORTAC radionavigation system. Dropping vertically to the abscissa allows the analyst to determine the specified maximum system error.

The Loran-C radionavigation system does not lend itself to the simple sensitivity analysis characteristic of the VORTAC or the Differential Omega systems. The accuracy is not just a function of distance from the ground facility, but also a function of chain configuration, environmental conditions, and system calibration. This system offers the greatest accuracy available from any of the candidate configurations and its major limitations, as related to accuracy, are imposed by geometric dilution of precision and signal to noise ratio. In this analysis the representative values for the Loran-C system are plotted of Figure 5-1, 5-2, 5-3, and 5-4 to illustrate their position in relation to the other navigation systems.
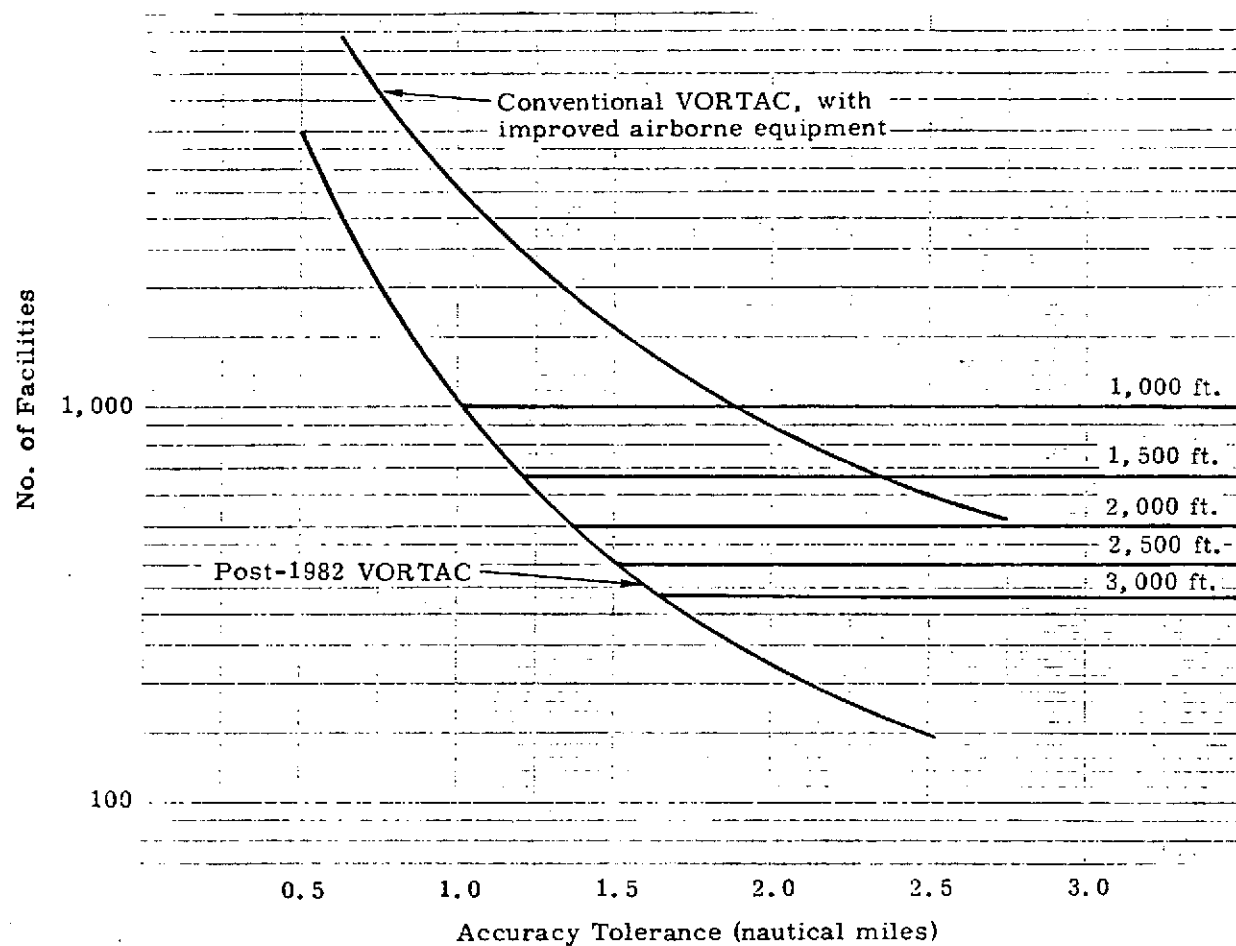
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Figure 5-5. Relationship Between Coverage Area Specification and Maximum Accuracy Tolerance

Four points have been indicated for the Loran-C system. They are used to indicate the accuracy differences between calibrated points (± 0.1 nautical miles) and non-calibrated points (± 0.2 nautical miles) within the service area; and they are used to distinguish between the costs incurred for the total Loran-C radionavigation system implementation and those incurred just as a result of the addition of incremental facilities to support the aircraft operations. Any further sensitivity analysis of the Loran-C system will be reserved until a later time.

The sensitivity analysis of the Differential Omega radionavigation system provides an interesting comparison between that system and the various configurations of the VORTAC radionavigation system. Determinations can be made with respect to the costs associated with the implementation of systems having equivalent accuracy tolerances.

After an analysis of Figure 4-10, which illustrates four cases of Differential Omega radionavigation system accuracy, one can determine that for the worst case, i.e., the reported TRACOR, Inc. night data, there is a linear equation that relates the resultant radionavigation system error with distance from the differential correction monitor site. Equation 5.23 specifies this relation.

$$\epsilon_d = 0.0042\,d + 0.5 \qquad\qquad \text{Eqn. 5.23}$$

where

ϵ_d = the resultant error in position; and

d = the separation distance between the receiver and the Differential Omega correction site.

If

$$\epsilon_d = 0.0042\,d + 0.5 \qquad\qquad \text{as in Eqn. 5.23,}$$

then

$$d = \frac{\epsilon_d - 0.5}{0.0042} \qquad\qquad \text{Eqn. 5.24}$$

And since

$$A_s = \pi\,d^2 \qquad\qquad \text{as in Eqn. 4.3,}$$

then

$$A_s = \pi\left(\frac{\epsilon_d - 0.5}{0.0042}\right)^2 \qquad\qquad \text{Eqn. 5.25}$$

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The total number of facilities required, n, is introduced by Equation 4.4:

$$n = K_2 \text{ x } \frac{A_T}{A_s} \qquad \text{Eqn. 5.26}$$

where

n = the number of Differential Omega correction sites required;

K_2 = G multiplier to account for service area overlap = 1.57;

A_T = the area of the conterminous United States and Alaska, i.e., approximately 2,750,000 square nautical miles; and

A_s = the service area for a single Differential Omega correction site.

Therefore,

$$n = 1.57 \text{ x } \frac{2,750,000}{\pi \left(\frac{\epsilon_d - 0.5}{0.0042} \right)^2} \qquad \text{Eqn. 5.27}$$

This relationship is illustrated in Figure 5-1.

The facilities and equipment cost can be determined by simply multiplying the number of facilities required by the unit cost per facility ($25,000). Figure 5-2 relates the facilities and equipment cost for the implementation of a Differential Omega radionavigation system.

The twenty-year operations and maintenance cost can be determined in a similar manner. The required number of facilities multiplied by the annual operations and maintenance cost per facility and then compounded by 6% over the twenty-year period produces the results illustrated in Figure 5-3.

The final total system cost is determined by summing the facilities and equipment cost of implementation along with the twenty-year operations and maintenance expenditure. This result is displayed in Figure 5-4. Here again, the analyst can relate total system cost for the Differential Omega radionavigation system to a specified accuracy tolerance.

The final comparative analyses between the candidate radionavigation systems can now be accomplished. By reference to Figure 5-1, the following conclusions can be derived:

(1) For radionavigation system errors of less than ±1.5 nautical miles, the Loran-C system requires the fewest ground facilities. If the errors are allowed to exceed ±1.5 nautical miles, the Differential Omega system requires the fewest sites. The number of facilities required for both configurations of

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the VORTAC system far exceeds the requirements for the Loran-C or Differential Omega systems for any reasonable accuracy assignments.

Reference to Figures 5-2, 5-3, and 5-4 leads to the following conclusions:

(1) Over the proposed twenty-year utilization period for the candidate radionavigation systems, the operations and maintenance costs form the primary contribution to total system cost.

(2) The Differential Omega system entails the least expenditure in facilities and equipment and also the least operations and maintenance costs for all but the most restrictive accuracies.

(3) The total expenditure required for a Loran-C system which would result in $\pm 0.1 - 0.2$ nautical mile radionavigation accuracy everywhere within the conterminous United States and Alaska would be $278 million. A similar investment in an advanced VORTAC system would result in a radionavigation system accuracy of ± 1.94 nautical miles. If these two radionavigation system errors are combined with the flight technical error and the airborne area navigation computer error, total navigation system accuracies of ± 1.05 nautical miles for the Loran-C system and ± 2.2 nautical miles for the Post-1982 VORTAC system would result.

(4) The generation of a total navigation system accuracy of ± 1.5 nautical miles requires a radionavigation system accuracy of ± 1.09 nautical miles. The total cost for the Differential Omega system for such performance is approximately $8 million; for the Loran-C system it is approximately $278 million; for the Post-1982 VORTAC it is approximately $915 million; and for the conventional VORTAC, with improved airborne equipment, it is approximately $3.2 billion. The VORTAC radionavigation system configurations do not demonstrate any measure of cost-effectiveness when compared with the Loran-C or Differential Omega radionavigation systems.

(5) The cost-effectiveness assessment between the Differential Omega configuration and the Loran-C system is more difficult. The Differential Omega system is so very inexpensive that it will probably be implemented no matter what direction the main thrust of attention proceeds. The Loran-C implementation plan requires a considerable financial commitment, but the potential benefits are immense. Additional study is necessary to determine the tradeoff between the highly accurate potential of the moderately expensive Loran-C system and the very inexpensive but less accurate Differential Omega system.

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CHAPTER 6

CONCLUSIONS

1. Area Navigation implementation offers a great deal of benefit for general aviation operations.

2. There are numerous radionavigation systems that are capable of providing general aviation customers with area navigation service.

3. The three primary performance parameters for evaluation are accuracy, coverage, and signal availability.

4. Of the candidate systems in this analysis, Loran-C offers the highest performance with respect to accuracy.

5. There is a clearly demonstrated necessity to improve the airborne receiving equipment for the VORTAC system.

6. The signal coverage and availability are primarily affected by signal propagation characteristics. The line-of-sight limitations of the VHF/UHF signals of the VORTAC system can significantly decrease the signal availability in certain areas.

7. The low frequency and very low frequency transmissions of Loran-C and Omega respectively are not limited by line-of-sight propagation; consequently, they can provide navigation signals over a wider area and serve more diverse customers than the VORTAC system.

8. In the cost-effectiveness assessment throughout a considerable length of time, e.g., twenty years, the operations and maintenance costs predominate over those of the initial facilities and equipment expenditures.

9. The Loran-C system requires the smallest number of ground station facilities, Differential Omega is next, followed by the various configurations of the VORTAC system.

10. The Differential Omega system requires the lowest expenditure for facilities and equipment and also for the operations and maintenance functions. Loran-C and the various configurations of the VORTAC system follow in their respective order.

11. The cost-effectiveness assessment of the VORTAC system falls considerably short of those assessments for the Loran-C and the Differential Omega systems.

12. Additional research is necessary to evaluate the cost sensitivity of the Loran-C system to changes in accuracy or coverage specifications. Once this is accomplished, the construction of curves similar to those for the VORTAC and Differential Omega systems will greatly facilitate additional comparative analysis.

13. Further research is necessary to determine the effect of additional system capabilities on the total evaluation of the system potential for general aviation operations.

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