PROJECT TRIDENT

TECHNICAL REPORT

REVIEW OF MARINE NAVIGATION SYSTEMS AND TECHNIQUES.

ARTHUR D. LITTLE, INC.
35 ACORN PARK   CAMBRIDGE, MASSACHUSETTS

DEPARTMENT OF THE NAVY
BUREAU OF SHIPS

NObsr-81564   SS-050

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by
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PREFACE

This is one of a series of Technical Reports being issued by Arthur D. Little, Inc., under contract NObsr-81564 with the Bureau of Ships as part of the TRIDENT Project.

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I. INTRODUCTION

Familiarity with navigation and ship-positioning problems is a pre-requisite for personnel concerned with ASW systems. Historically, celestial techniques and dead-reckoning methods have been used for marine navigation. During the past 20 years, however, various navigational aids and positional systems which permit the navigator to fix his position without regard to cloud or weather conditions have become available. Since World War II, but particularly since 1950, the trend in navigation equipment has been toward greater positional accuracy, continuous position-fixing capability, and longer-range operation. These improvements are being achieved by the use of more sophisticated electronic techniques, including celestial methods, electromagnetic and acoustical signals, and inertial systems. Automatic computation and display equipment has further simplified the work of the navigator. The more sophisticated navigation systems allow the computer to complete as many of the routine calculations as possible, thus reducing the time the navigator requires to fix his position accurately. Such methods also tend to reduce the incidence of human error.

The high positional accuracy of a sophisticated navigation system is expensive, and highly trained personnel are required to operate and maintain the equipment. Certain military and most oceanographic research and survey problems require positional accuracies of 0.1 - 0.5 nautical mile or better. This high precision may not be required or economically justified, however, for the vast majority of marine navigation problems, where a vessel is interested only in steaming from one port to another.

Navigation systems have been improved at the expense of greater equipment complexity, sophistication, variety and cost, compared to older navigation methods. System reliability and maintainability remain as problems, and precision coverage in all ocean areas using any one system is not yet available. The prudent marine navigator must use all navigation systems at his disposal and compare their results in order to plot his most probable position at a given point in time. A combination of systems is required to provide cross checking and to satisfy the differing requirements for precision, fix renewal period, and range.

We have divided marine navigation and ship-positioning systems into three classes: long range, mid range, and short range. The basic capabilities and limitations of the systems in each class are summarized in Section II. The fundamentals of electronic navigation, propagation phenomena, and range and accuracy considerations are discussed in Section III. In Sections IV - VI the important characteristics of the several classes of systems are described.

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These characteristics include useful range, positional accuracy, conditions of operation, ease and cost of operation, maintenance requirements, reliability, and geographical coverage. Important mechanical and electrical characteristics which affect the performance of each system are tabulated.

The sources of this information were the available literature, contractors' reports, and private communications. None of the material in this report is classified. Relevant reference material is cited following each system description.

II. SUMMARY

A. LONG-RANGE NAVIGATION SYSTEMS

Long-range navigation systems (Table II-1) are defined here as having a position fixing capability at ranges greater than about 400 miles. Celestial, azimuthal, pulse-time, and phase-measuring systems comprise the largest number of navigation systems in this group. Dependent upon requirements satellite systems may use combinations of these methods to yield accurate fixes. Inertial, and acoustic-doppler systems are essentially highly sophisticated dead-reckoning systems with potential world-wide coverage and position indicating capability. Of these only the inertial systems are completely passive and self-contained.

The inexpensive, hand-held sextant, tables, and chronometer are still the basic tools of the navigator and give him the possibility of a ± 3 mile position fix twice daily. Recently developed star tracker and sun and moon tracker equipment uses gyro-stabilized references, making a horizon unnecessary. Each of these celestial systems is limited by cloud cover or by the geometry of the sun-moon orbits. These factors limit the current world-wide availability of fix by celestial methods to below 50%. Because of their high cost, the automatic star and sun-moon tracker systems can usually be justified only for specialized applications.

Of the several azimuth measurement systems being used, the Consol/Consolan and the Radio Direction Finder (RDF) systems have gained the widest acceptance. Both systems require simple and inexpensive receiving equipment and have several stations along the coasts of North America and very good coverage throughout most of Europe. The precision of fix is not high by today's standards, and powerful ground stations and good operating conditions are required for the navigator to obtain a fix at ranges beyond about 300-600 miles.

Pulse-time measurement systems are capable of fixing a ship's position by the reception and identification of pulses received in a timed sequence from transmitting stations of known position. About 35% of the northern hemisphere is effectively covered by Loran-A. The more recent Loran-C equipment makes use of lower frequencies and uses both pulse-time and phase-measuring techniques. Although the coverage is not yet as great as that of the earlier Loran-A, the system is useful to ranges of 1000-2300 miles and is capable of high accuracy. With good operating conditions system accuracy can approach one foot per mile of range. The recent incorporation of microcircuitry into Loran-C receiving equipment will greatly reduce its size, weight, and eventual cost, and make it much more reliable than the present electromechanical equipment.

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TABLE II-1

LONG-RANGE NAVIGATION SYSTEMS

System	Estimated Useful Range	Estimated Accuracy	Frequency Range	Comments
Celestial	World-wide	± 3nm	--	Inexpensive equipment, easy to use; limited to 2 fixes/day, affected by clouds and bad weather, which also limits fix availability to <50%. Star Tracker equipment very expensive.
Star Tracker	World-wide	± 0.3nm		
Consol	700-1200nm	± 0.3-0.6°	190-194 kc 257-263 kc	Requires only a narrow-band communications receiver to establish LOP.
RDF	300-600nm	± 2-6°	200-415 kc 285-325 kc	World-wide coverage. U.S. coastal beacons. Capable of coarse fix only.
Decca	200-300nm	< 0.25-1.0	90-130 kc	Easy to use, insufficient coverage, limited to about 240 mile range at night because of sky wave interference.
Loran-A	700-900nm	± 0.5-3.0nm	1.75-2 mc	Easy to use, insufficient coverage, subject to sky wave interference. Less accuracy with sky wave.
Loran-C	1200-1500nm	± 0.2-0.5nm	90-110 kc	Accurate, easy to use, insufficient coverage, expensive installation. Less accuracy with sky wave.
Omega	5000nm	± 0.5-1.0nm	10-15 kc	World-wide coverage presently in advanced development. Will use three frequencies to yield both coarse and fine grids.
Satellite	World-wide	± 0.1-2.0nm	100-400 mc	World-wide coverage; Transit average fix renewal each 110 min., presently in advanced development, possibly operational in 1965-1970 period. Less sophisticated systems for commercial use now under study.

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TABLE II-1 (Continued)

System	Estimated Useful Range	Estimated Accuracy	Frequency Range	Comments
Inertial	3-12 hours	< 2.0 nm/hr	--	Must be checked with outside reference, accuracy decreases in a few hours at rapid rate, very expensive, requires expert maintenance.
Acoustic Doppler	< 300 ft water depth	$\leq 1\%$ of velocity $\leq 1\%$ of distance travelled	0.2-1 mc	Simple systems require a manual plotting board and complement standard dead reckoning procedures; sophisticated high-accuracy systems utilize gyro-compass, velocity input, and automatic track-plotting equipment.

The Decca Navigator phase measurement system can provide 2-4 mile positional information at maximum ranges of 200-500 nautical miles but is generally limited to ranges of the order of 250 nautical miles for the highest accuracy on a 24-hour/day basis. Coverage is available throughout Europe and the British Commonwealth. The Navy's developmental Omega system promises positional accuracies of 0.5-1 nautical mile for ranges as great as 5000 nautical miles. This system will probably use three frequencies to fix a course and a fine position. World-wide coverage by 8-10 ground stations is promised and could be available by the late 1960's or early 1970's.

World-wide coverage by a system of satellites and ground stations is also expected. The Navy's passive Transit program requires a minimum of four satellites in polar orbit and should yield positional information to better than ± 0.1 nautical mile. Several less sophisticated systems using larger numbers of satellites are currently being studied by other Governmental agencies for use by commercial and scientific groups. One system under consideration is the precision satellite tracking system, known as Secor, now in operation for the Army Map Service. It has demonstrated a positioning capability to geodetic accuracies of a few meters with base-line lengths greater than 2000 miles. Less sophisticated equipment of this type would be capable of positioning accuracies of 0.25-1 nautical mile when used for ship and aircraft navigation.

The inertial navigation systems in use by the Navy are passive, self-contained, and not directly subject to enemy action. Although these systems are highly sophisticated, they still accumulate a small error over a period of time and require recalibration, using an external source. The first commercially available inertial equipment is much less sophisticated. It will initially be used aboard high-speed, long-range, commercial aircraft and will generate an average error of less than two miles per hour of travel.

Acoustic Doppler navigation systems are not yet fully developed to the point where they can be used effectively in waters greater than a few hundred feet deep. These systems should help improve present dead-reckoning procedures and also appear to be attractive for use in shallow waters or aboard deep submersibles operating near the ocean floor. Navigation accuracies available with these systems are of the order of 1% of velocity and 1% of distance.

B. MID-RANGE NAVIGATION SYSTEMS

Mid-range navigation systems (Table II-2) are defined here as having ranging capabilities up to about 400 nautical miles. These systems are generally most useful for ship-positioning and survey applications where high accuracy and reproducibility are required. Because mid-range frequencies are used, the range and accuracy of these systems will be limited during evening hours

TABLE II-2

MID-RANGE NAVIGATION SYSTEMS

System	Estimated Useful Range	Estimated Accuracy	Frequency Range	Comments
Decca Two-Range	175nm	25-200 ft	110-170 kc	Circular geometry survey system. Night effect reduces range to 40 miles or less. Continuous tracking.
EPI	250nm	50-200 ft	1.85 mc	Circular geometry survey system used by USC and GS. Requires operators at 2 shore stations. Single-user system. Night effect reduces range.
Lorac	135 nm	25-100 ft	1.7 to 2.5 mc	Hyperbolic geometry portable survey system; requires 3 shore stations; used widely for offshore seismic work. Continuous-tracking, multi-user capability. Night effect reduces range.
Raydist DM	25-200nm	25-250 ft	1.6 to 5.0 mc	Circular geometry survey system; requires 2 shore sites. Low-power buoy equipment available. Continuous-tracking, multi-user capability. Night effect reduces range.

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by sky wave effects, and the survey activities are generally restricted to periods between sunrise and sunset. Lane ambiguity problems are also troublesome with phase comparison systems and require that the navigator know his initial checkpoint and keep an accurate track record. For most systems automatic track-plotting and recording equipment is available for this purpose.

The Decca Two-Range and the Raydist DM hydrographic survey systems use circular plot ranging methods which require two shore stations. Both systems use phase comparison techniques for establishing ranges from the receiver to each shore station. The Electronic Position Indicator (EPI) system is a pulsed-phase measuring system which sequentially measures the range from the survey vessel to each shore station. It was designed to work at ranges as great as 400 miles, while Decca and Raydist are limited to ranges of the order of 150-200 miles.

The Lorac (Long-Range-Accuracy) system was developed for oil exploration activities. It uses a cw phase comparison method which requires three shore stations. This system is used by both commercial and Government survey groups for near-shore control work. Working ranges are 100-150 nautical miles. Ranging accuracies of 1:50,000 are reported as being readily obtained with this system.

C. SHORT-RANGE NAVIGATION SYSTEMS

Short-range navigation systems (Table II-3) are defined here as being capable of achieving a very high order of positional accuracy at ranges from line of sight up to about 50 miles. Both pulse-time and phase comparison methods are used, at frequencies generally in the 3-10 cm band. Because of the high frequency and small size of the equipment in this class, most of the shore stations are small and highly portable. Where the highest accuracy is required, appropriate atmospheric measurements are made, and corrections for variations in the propagation velocity are calculated.

The Shoran system is a pulse-time ship-positioning system operating on radar principles. It has been in use for over 15 years and is a standard method of in-shore survey control. Transponders to shape and reinforce the return signal are placed at each of the two required shore stations and give the system a useful range of over 50 miles.

The Alpine-429 Precision Radar Ranging Unit was developed to be operated in conjunction with standard radar transmitting equipment. The unit is capable of a fixed operational accuracy of ± 80 feet at ranges to about 50 nautical miles. A remote Electrical Track Plotter increases the over-all accuracy and utility of the system.

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TABLE II-3

SHORT-RANGE NAVIGATION SYSTEMS

System	Estimated Useful Range	Estimated Accuracy	Frequency Range	Comments
Shoran	25-75 nm	100-250 ft	210-320 mc	A high-accuracy standard control method for near-shore surveys, used since 1945.
Alpine Precision Radar Ranging Unit	Dependent upon ship's radar being used	± 80 ft	3-cm band	System complements standard ship's radar. Includes accurate time base, digital readout and display, track-plotting and transponder equipment.
Radar	200 ft to 50 nm	1:2500	3- and 10-cm band	Moderate ranging accuracy. Used for general search, hazard warning, harbor control, etc.
Autotape	100 m to 100 km	±1 - 2 m	10-cm band	2 portable shore responders required. Automatic ranging and tracking capability. Digital output and track-plotting equipment available.
Hydrodist	40 km	± 1.5 m	10-cm band	2 portable shore responders required. Since automatic ranging, manual tracking, digital output and track-plotting equipment available.
Hi-Fix	50-100 nm	±2.5-40 ft	2 mc	2 or 3 portable shore stations required; both ranging and hyperbolic mode available. Decimal counter display; automatic plotting equipment available.

The Autotape system and the Hydrodist system operate in the 10-cm band and use cw phase comparison techniques. Two precisely positioned shore stations are used with each system; these can operate unattended. Automatic plotting equipment increases each system's utility and allows the survey vessel to be positioned with a potential accuracy of 1-3 meters at maximum ranges of 25-60 miles.

The Decca Hi-Fix system utilizes cw phase comparison techniques and ground wave transmission at frequencies in the 2-mc band. The system is portable and may be used in either the hyperbolic or ranging mode. Automatic track-plotting equipment is available. This system is in use for hydrographic and survey purposes in this country and in Europe.

III. FUNDAMENTALS REVIEW

A. GENERAL

Most electronic navigation and precise ship-positioning systems depend upon the measurement of the time it takes for radio frequency (rf) energy to travel from the transmitter to the receiver. The transmitted energy must be in the form of either short pulses or continuous waves (cw). Some systems measure pulse-time difference; a second group of systems measures phase differences, and a few systems use a combination of both techniques.

While the accuracy of the distance measurement is primarily a function of the time measurement, the characteristic velocity of the rf energy must also be known. For most distance measurements in ship-positioning or navigation applications, a standard value of propagation velocity is used. When measurements must be extremely accurate, the atmospheric index of refraction must be measured precisely so that the corrected velocity of transmission can be calculated. The distance as measured by the product of the velocity of propagation and the time may not be the same as the geometric distance, and further corrections for refraction and reflection may have to be made.

Rf energy may be propagated between transmitter and receiver (1) by direct path, (2) by reflection from the ionosphere, or (3) along the earth's surface. When radio waves are refracted or reflected from the ionosphere, they are called sky waves. Because of the instability of the ionospheric layer, corrections for sky-wave paths must be computed but at best are only approximations. When sky-wave transmission can be predicted with greater accuracy and reliable variations computed, they will be as valuable to long-range, precise ship positioning as they are now to communications and navigation. For the present, only the ground wave is used for the accurate ship positioning required for hydrographic surveys. Sky-wave transmission is used at great ranges for navigation purposes, but is less accurate and often is more of a hindrance than an aid.

A wide range of frequencies has been found necessary to satisfy the many precise ship-positioning and navigation requirements for accuracy and repeatability. Frequencies of 30 - 3000 mc and higher are most useful for line of sight and where precision is required. Frequencies in the range of 300 kc to 3 mc are used for systems operating out to distances of the order of 500 miles. Frequencies from 10 kc to 300 kc are used for those navigation systems requiring operation at ranges of several thousand miles.

For some measurements, only a range (distance) is required. However, in most navigation and near-shore hydrographic work, the direction from the transmitter to the receiver is also required, so that a position fix may be

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established. Figure III-1 identifies three of the more common methods of establishing a position fix.

In addition to these three techniques, doppler and inertial methods of navigation are becoming increasingly important. Both methods are capable of continuously plotting a vessel's position with respect to a fixed reference point.
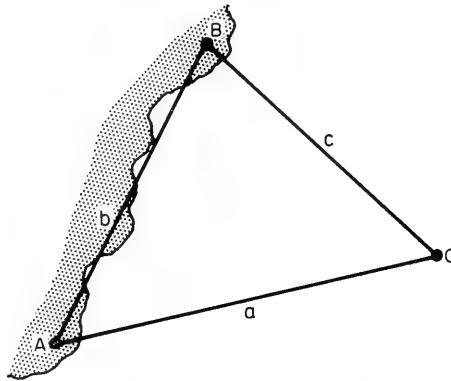
a. TWO ANGLES AND THE INCLUDED SIDE = TRIANGULATION OR DIRECTION FINDING.
b. TWO SIDES AND THE INCLUDED ANGLE = RADAR OR RHO-THETA METHOD.
c. THREE SIDES = TRILATERATION.

FIGURE III-1   POSITION FIX GEOMETRY

B. SYSTEM CLASSIFICATION

Navigation and ship-positioning systems are generally classified as hyperbolic, ranging, or azimuthal. This classification refers to the radiation patterns, which are illustrated in Figure III-2.

1. HYPERBOLIC POSITION-DETERMINING SYSTEMS

All hyperbolic position-determining systems define a hyperbolic line-of-position by measuring the difference in transmission time between signals transmitted simultaneously, or with a fixed delay, from two fixed stations; these stations represent the foci of the hyperbolic line of position. To generate a fix, two lines of position (LOP) must be generated, and a third station, which serves as a master to each of two slave stations, is required. The time-difference error makes the actual position line indeterminate between two adjacent position lines. This distance is called the lane width and corresponds to one-half wave length of the transmitted frequency. Either pulsed or continuous wave transmission is used. Some systems use a combination of the two.

The actual error of the position fix with such a system is proportional to the largest dimension of a diamond formed by the intersection of adjacent paired lines of position. The positional error increases as the distance from the stations is increased. Loran-A, Loran-C, Decca Navigator, and Omega are examples of hyperbolic navigation systems.

2. RANGING SYSTEMS

Distance-measuring (ranging) systems generate a circular pattern. The master interrogates the shore stations; these stations respond, and the round-trip time is measured at the master station. Either pulsed or continuous wave may be used. It is clear from Figure III-2b that this arrangement yields higher accuracy over a larger area than hyperbolic systems do. However, the systems required to generate circular patterns are usually more complex, and several frequencies are often required to generate and transfer the required information. Ranging systems such as Shoran and Raydist have found their greatest use in hydrographic work where the ranges are 200 nautical miles or less. Lower-frequency systems such as EPI have been found useful to ranges of 400 nautical miles.
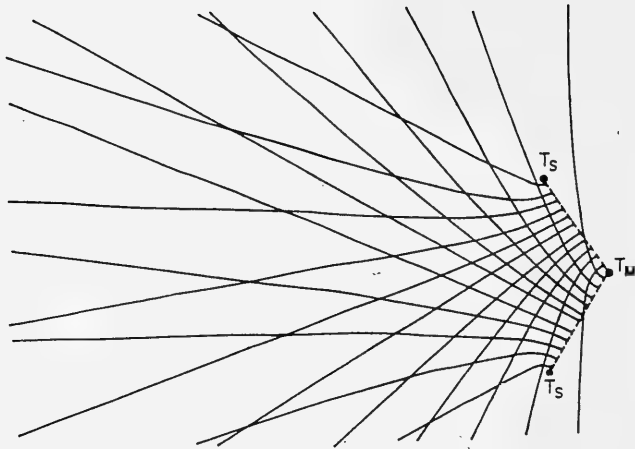
a) HYPERBOLIC SYSTEM GEOMETRY
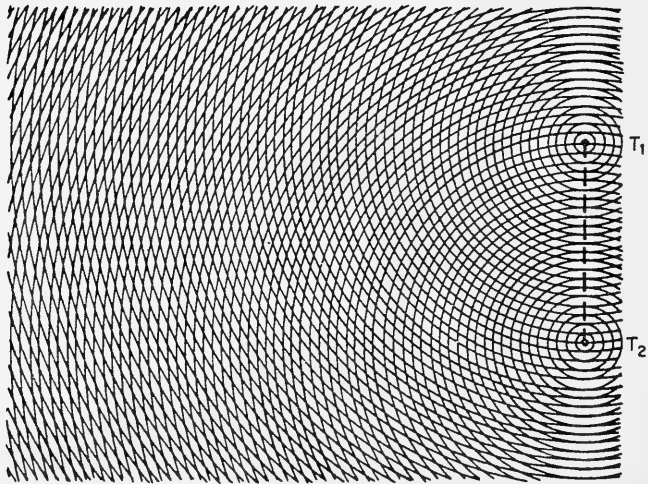
b) CIRCULAR SYSTEM GEOMETRY

FIGURE III-2   SYSTEM GEOMETRY

3. AZIMUTHAL SYSTEMS

Azimuthal systems (angle measurement systems) do not measure a range but measure an angle only. If the transmitter or the receiver position is known, a hyperbolic line of position can be established. Measurements of angle can be made either from shore stations or from a moving vessel. Thus, the azimuthal system requires a known base line and establishes a fix by measurement of two or more angles. This type of system is commonly known as radio direction finding (RDF). Another class of azimuthal system known as Consol (the U.S. version is known as Consolan) uses a rotating radiation pattern and provides identification signals which permit greater angular resolution than is possible with RDF.

Of the navigation systems in use, the angle measurement systems are the least complicated but also are the least accurate. The uncertainty of the azimuthal measurement of position is determined by the system geometry, the frequency of operation, the range, and other factors.

C. SYSTEM METHODS

1. PULSE-TIME SYSTEMS

For a pulse-time measurement two transmitters are precisely timed to transmit pulsed energy in a fixed sequence from transmitters located at end points on a base line. The receiver, C, may be located at some undetermined point, as shown in Figure III-3a. If the receiver C were placed nearer transmitter A on base line AB it would receive pulse A before receiving pulse B. If it were nearer B it would receive pulse B ahead of pulse A. In practice pulse B is transmitted after pulse A and separated from it with a fixed time delay, to eliminate ambiguity and help identify pulses A and B. A comparison of the time of arrival -- by equalizing amplitudes and matching the received pulses at the receiver C -- will locate the receiver on a hyperbola along which, by definition, all points have a certain constant distance-difference from two stations. The hyperbola thus forms a navigational line of position. Another pair of signals utilizing stations A and D could be precisely timed and identified in the same manner to form a second hyperbola intersecting the first at the receiver and fixing the receiver's position.

2. PHASE MEASUREMENT SYSTEMS

In the second method of position measurement a continuous wave signal is transmitted simultaneously from stations A and B, as in Figure III-3b.

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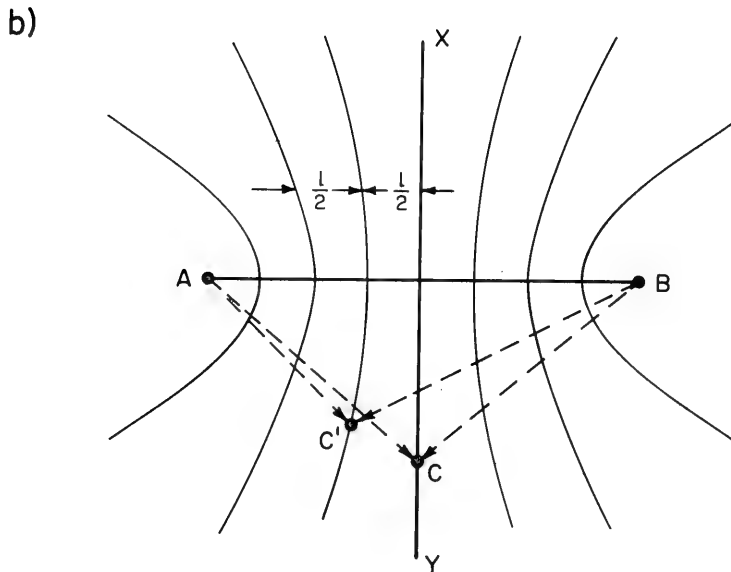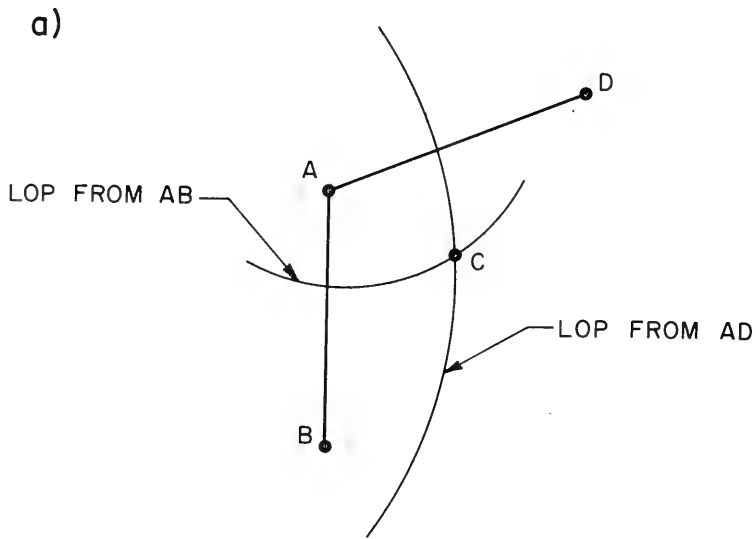
FIGURE III-3   RADIO FIX ILLUSTRATING BASIC HYPERBOLA
RADIO NAVIGATION PRINCIPLE

The phase of signal B is usually "phase-locked" to signal A. Thus, the phase difference of signals A and B at receiver C is a function of the position of the receiver with respect to each transmitter. For example, if line XY is the right bisector of the base line AB, it follows that at any point on line XY the signals from transmitters A and B will be in phase and a phase meter will read zero, as the signals will have traveled equal distances, assuming their velocity to be constant. Should receiver C be moved nearer transmitter A by a distance corresponding to one-half wave length of the transmitting frequency, the two signals from A and B would be 180 degrees out of phase and would have traversed one lane width. A second station, D, also phase-locked to station A operates in like manner and generates a second set of hyperbolic lines of position. The receiving and phase comparison devices are duplicated to work with the two sets of coordinates, and the observer fixes his position at any point in time by transferring the readings of the phase meters to a chart on which numbered lanes of the two patterns are printed. The proper reading of position is dependent upon initially setting the two phase meter dials and recording the reading when the receiver is at a known geographical position with respect to points A and B.

3. ANGLE MEASUREMENT

For this method only an angle is required to establish a line of position. Range is not measured. Two or more lines of position can establish a navigational fix.

Figure III-4 shows the geometry of the angle measurement system.
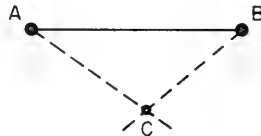
FIGURE III-4   ANGLE MEASURING SYSTEM GEOMETRY

In this figure, A and B represent the known locations and C represents the position to be determined by angle measurement. AC and BC are the lines of position. The position of C may be fixed by transmitting from C and determining

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the direction of the received signals at both A and B. A second method would be to transmit signals from A and B and to measure their direction of arrival at C.

D. RF PROPAGATION

The velocity of propagation of radio waves, in a perfect vacuum, is independent of frequency and is equal to the velocity of light. Recent experimental determinations have shown the values of free-space velocity to be in good agreement. A number of these values have been combined in a least squares determination which yields a value for this constant of C = 299,792.9 ± km/sec.

1. INDEX OF REFRACTION

Atmospheric conditions cause variations in the index of refraction and thus in the velocity of propagation in free space. Therefore, range measurements of high accuracy generally utilize a corrected velocity of propagation. Measurements may be made over a base line of known length or the atmospheric variables may be measured and the propagation velocity corrected with a computed index of refraction:

$$n = \frac{77.6}{T} \left[p + 4810 \left(\frac{w}{T} \right) \right] \tag{1}$$

where n is the index of refraction, T is the temperature in $^\circ$K, p is the air pressure in millibars, and w is the partial water vapor pressure, also in millibars.

The true velocity of propagation is then determined by the relationship:

$$v = \frac{299,793}{1 + N10^{-3}} \text{ km/sec} \tag{2}$$

where N = refractivity = $(n-1) 10^6$.

Atmospheric pressure, temperature, and humidity vary with location, time, and height. However, except for the most accurate range and ship-positioning measurements, a homogeneous atmosphere and a resulting constant propagation velocity are assumed. This assumption generally produces a negligible error.

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2. GROUND WAVE

    The ground wave travels over the transmission path near the earth's surface. Three types of ground waves may be propagated, as illustrated in Figure III-5.

                       a. DIRECT WAVE
                       b. GROUND-REFLECTED WAVE
                       c. SURFACE WAVE
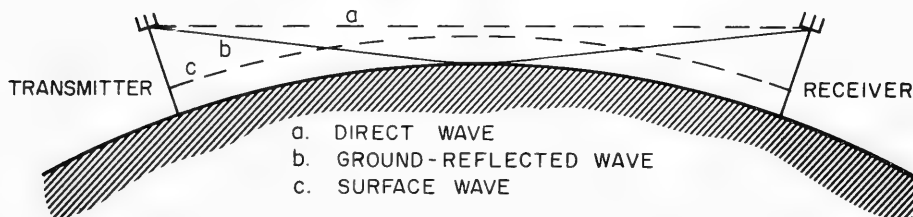
FIGURE III-5   GROUND-WAVE PROPAGATION

    Because of the curvature of the earth's surface, only the direct and the ground-reflected waves enter into consideration at frequencies above approximately 30 mc. At these frequencies the useful range is essentially line of sight. For the frequencies of interest here, surface waves are the most important of the ground waves.

    Surface waves are transmitted horizontally, and the earth's atmosphere and ground conductivity cause the propagated wave to remain near the earth's surfaces and follow its curvature. The rotation of the vertical plane of polarization of the wave front, due to the finite conductivity of the earth, gives rise to phase errors. This type of error is particularly important in long-range navigation problems where very low frequencies (VLF) are used.

    During propagation, the ground wave becomes more attenuated than in free space. Surface wave attenuation increases as the frequency is increased, until at a frequency of about 30 mc, the surface wave is almost totally absorbed. At frequencies above 30 mc, only sky-wave transmission remains for long-range navigation and communication purposes.

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3. SKY WAVES

The index of refraction does not vary linearly with height. In addition, ionized layers are always present in the upper atmosphere. As a result of these effects, rf energy when propagated at a sufficient angle to the earth's surface is refracted in the atmospheric layers and bent earthward. If conditions are favorable the rf wave will eventually return to earth at some distance from the point of origin. Upon reaching the earth the wave front may be reflected again toward the ionosphere and the process repeated until all the energy is finally attenuated. (See Figure III-6.)

Both the altitude and density of the three most important ionized layers vary as a function of the time of day, season, and year. Further variations occur each solar cycle of about 11 years.
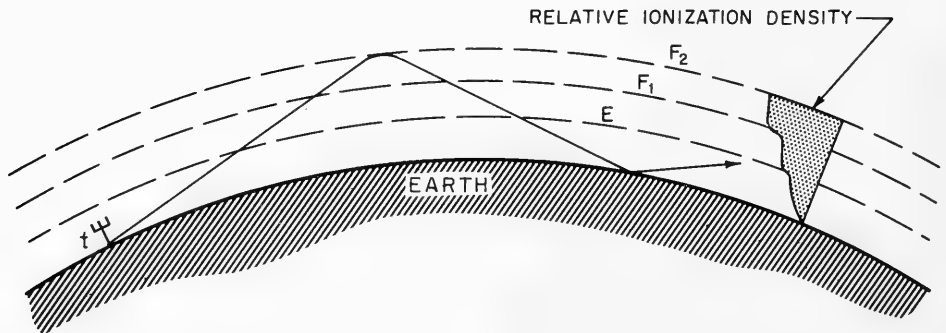
FIGURE III-6   SKY-WAVE PROPAGATION WITH REFLECTION FROM F_2 LAYER

a. Propagation at Frequencies of 30 - 300 kc

Frequencies in the range of 30 - 300 kc are known as low-frequency (LF) waves and are only slightly attenuated when propagated as a surface wave. With adequate amounts of power the surface wave can be propagated over distances of 500 nautical miles or more.

Because the frequency is low, the sky wave is heavily refracted by the ionosphere and is bent back toward earth after penetrating only a very short distance within the ionized layers; thus only a very small attenuation is incurred. The wave may be reflected at the earth's surface and redirected back toward the ionosphere. Because of the limited altitude of the layers and the curvature of the earth's surface, which limits the maximum skip distance, the sky waves propagated in this frequency range may travel over distances of 2000 miles or more.

A small energy loss occurs at each reflection. The path covered depends on the distribution of ionization. The field strength at the receiver shows both diurnal and seasonal variations. In general, propagation conditions are more favorable in winter than in summer.

b. Propagation at Frequencies of 300 kc - 3 mc

In the medium frequency (MF) range of 300 kc - 3 mc surface-wave propagation is less satisfactory; the wave becomes more attenuated than in the case of long-wave propagation. The range of effective coverage by powerful transmitters is generally less than 500 miles.

At the medium frequencies the sky wave is refracted less than at the lower frequencies, and a greater penetration into the ionosphere takes place. During daytime hours when the E-layer is low-lying, a large amount of absorption occurs because of the high density of this ionized layer. As a result the sky wave becomes highly attenuated and seldom reaches the ground to complete the first skip. During daylight hours, therefore, sky-wave transmission is not considered reliable, and surface-wave propagation must be used. At night, however, there generally is considerable sky-wave return in this frequency range because of the disappearance of ionization at the lower altitude. At sunset the absorption of the sky wave rapidly decreases, because the density of the low-altitude ionized layer decreases. A few hours after sunset ionospheric propagation as well as surface propagation takes place and continues until dawn.

During the evening hours this frequency range is characterized by three areas of reception. The surface wave predominates at the relatively short ranges, while at longer ranges the sky wave predominates. At the intermediate ranges both waves have nearly equal strength, and severe interference may result. The interference is in the form of phase distortion, because the sky wave travels varying distances as the height and strength of the ionospheric layers shift throughout the evening hours. Field strength also varies, and signal fading is common. Sky-wave reception is required beyond the intermediate area; reception is good but not as reliable as the surface-wave reception at the short ranges.

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c. Propagation at Frequencies of 3 - 30 mc

In the high frequency (HF) band, attenuation of the surface wave is more rapid than at lower frequencies, while the sky wave is attenuated less be-cause of the higher frequency. As the frequency is increased, the refractive index tends toward unity and the skip distance increases. Thus, for a given dis-tance between transmitter and receiver there is an optimum frequency. The frequency used is also determined by the state of the ionosphere. Statistical data is available which helps determine the maximum utilizable frequency for operation between two given points.

For long-distance communication and navigation, the sky wave may require more than one hop to cover the required distance. In this way it is pos-sible for the radio wave to complete one or more trips around the earth, thus giving rise to signal interference. However, transmitted frequencies in this range are generally less subject to atmospheric and local interference than the medium wave field. Fading is a problem in this high-frequency range and is often minimized by such means as automatic sensitivity control and diversity reception.

d. Propagation at Frequencies Greater than 30 mc

Rf energy, when radiated at the VHF and higher frequencies, behaves in the same manner as light rays. The surface wave follows an almost optically straight path from the transmitting antenna to the receiving antenna, with only small atmospheric refraction. Because of the high frequency, the index of re-fraction approaches unity, and wave fronts entering the ionosphere will not be bent sufficiently to return to earth. For this reason all communications at fre-quencies above about 30 mc operate within line-of-sight range.

Because of the inhomogeneities in the earth's atmosphere, some re-fraction does take place, and a direct wave can be directed to distances beyond the line-of-sight range. The probable range of transmission R is given by the expression:

$$R = k \left[\sqrt{h_1} + \sqrt{h_2} \right] \text{ in miles} \tag{3}$$

Antennas at the transmitter of height h_1 and the receiver h_2 are generally placed as high as possible, and a refraction factor k of 1.1 - 1.6 is used to ac-count for the increased range due to atmospheric refractivity.

Atmospheric ducts which may make even line-of-sight transmission within this frequency range impossible are sometimes formed. The ducts result

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from anomalies in the index of refraction and are commonly formed in seashore areas, where there may be large temperature and conductivity differentials, often attributed to the movement of warm, dry air out over the water.

Frequencies in the range of 100 - 10,000 mc are used for the measurement of ranges to geodetic accuracies. A corrected velocity of transmission is usually required for the most precise range determinations possible.

E. RANGE CONSIDERATIONS

Several factors have been shown to affect the useful range of a radio signal. These are the shape and electrical conductivity of the earth, the state of ionization and noise-producing qualities of the atmosphere, the bandwidth, and the signal frequency.

For ground-wave transmission, the ranges are essentially optical at the shortest wave length and depend upon antenna height and line-of-sight transmission. The effective operating range is greatest for the low and medium frequencies and is dependent almost entirely upon wave length. At the longer wave lengths effective antennas must be very large, and the radiation efficiency decreases to very low values, making it difficult to radiate large amounts of power.

Certain sky-wave factors must also be considered where high-quality ground wave transmission and reception is contemplated. At frequencies in the range of 30 kc to 10 mc, long-range transmission may be expected. Useful coverage is limited to a few miles during daylight and less than 2000 miles during evening hours at frequencies near 1 mc. For frequencies less than about 0.1 mc the stronger sky-wave component tends to invalidate the longer ground-wave ranges possible at these frequencies, and special circuit and statistical techniques are required to achieve these long ranges. These effects are shown in Figures III-7 and III-8.

As indicated in Figure III-8, the continuous wave systems take advantage of the characteristics of the predominating ground wave for ranges out to 400-500 miles. As distance from the transmitter increases, the ground-wave field intensity drops off more rapidly than the sky wave, so that sky-wave interference tends to predominate at ranges of a few hundred miles. Because the phase of the sky wave is random relative to the ground wave, the resultant signal fades. Under these conditions the indicated phase is made random and the readings bear little relation to the position of the navigator. The straight line of Figure III-8 indicates the maximum useful range for pure ground waves.

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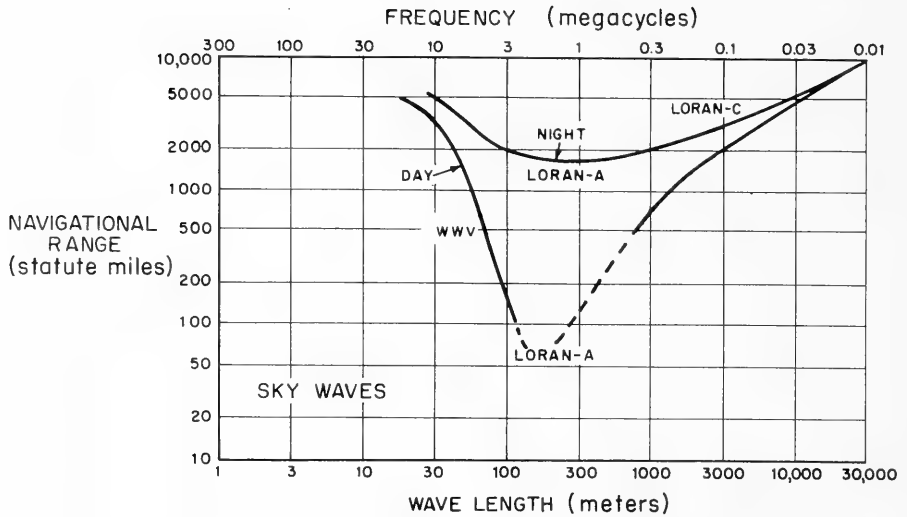
FIGURE III-7   AVERAGE SKY-WAVE TRANSMISSION
                    RANGES
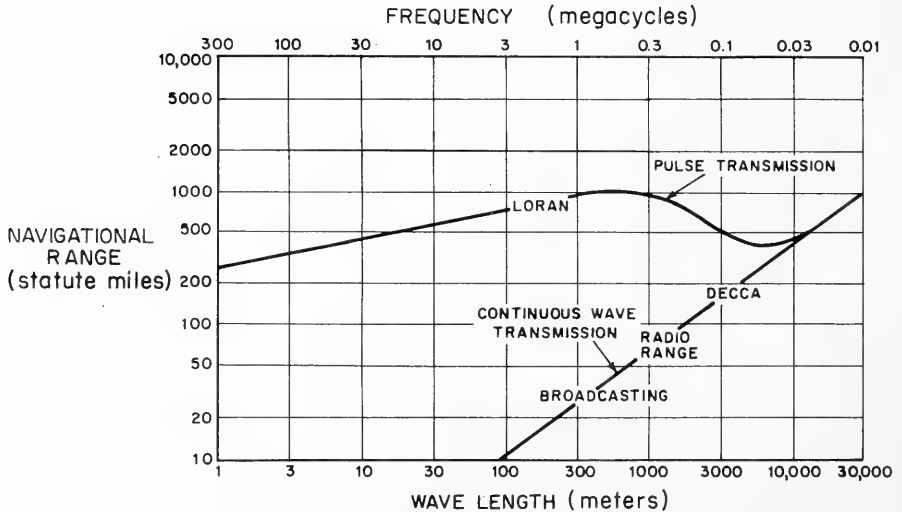
FIGURE III-8   MAXIMUM RANGE AT WHICH GROUND-
                    WAVE TRANSMISSION IS ESSENTIALLY
                    FREE FROM SKY-WAVE INTERFERENCE

Pulse systems in the high- and medium-frequency range have advantages because when short pulses are used the ground wave may be distinguished even with sky wave interference. However, at frequencies below about 100 kc, this advantage tends to disappear, as pulse generation and radiation become more difficult and pulse transmission approaches continuous-wave transmission, where phase-difference readings must be made. Figure III-8 shows that high-accuracy navigation systems dependent upon ground-wave transmission cannot operate effectively at ranges greater than a few hundred miles. Generally those systems using high-precision cw phase measurement techniques are restricted to daylight use to avoid sky-wave contamination. Combinations of pulse and continuous-wave techniques are used for the long-range low-frequency navigation systems such as Loran-C and Omega.

F. ACCURACY

The accuracy of a particular navigation system may be taken as a measure of its performance. However, the statistical terminology for describing accuracy is not well-standardized and for many systems is not generally available. In this report both the terms accuracy and precision are used in describing system performance. The accuracy of a system is taken to mean the deviation of a value from the true value. The term precision indicates the system's repeatability, expressed in suitable terms.

The accuracy of a navigation fix is a function of the accuracy and stability of each line of position and the angle at which these lines intersect. This stability is dependent upon a number of factors, many of which are variable with respect to time. These factors are often classed as systematic and random errors.

1. SYSTEMATIC ERRORS

The errors grouped as systematic errors are those which are the result of system design or alignment. This class of errors is of constant value and sign and adversely affects over-all system performance. Generally, these errors can be calculated or measured and then allowed for in the design of the equipment. In some cases they can be directly compensated for in the equipment's alignment or adjustment. Some systematic errors are calibrated out in the charts and tables provided.

2. RANDOM ERRORS

The random errors cannot be so easily accounted for because they are unpredictable and time-dependent and vary with changing radiation parameters.

propagation conditions, and operation error. Because of the random nature of
these events they must be averaged over a period of time and treated statistically.
In this manner it is possible to state the probability that the error of a given po-
sitional fix lies between zero and some upper limit. Much of the more recent
navigation literature makes use of the very important root-mean-square error of
repeatability which is discussed below.

In Figure III-9 point P is the apparent location of a navigational fix.
The individual position line errors are indicated as x and y.
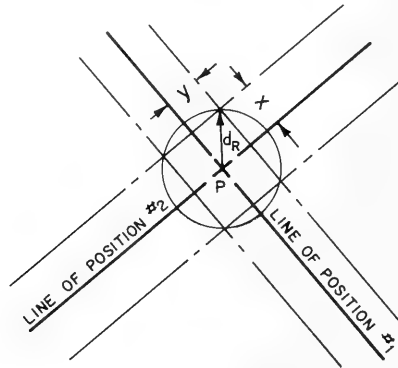
FIGURE III-9   LINE-OF-POSITION GEOMETRY

The radius d is taken as the radial error or the straight-line deviation of the
probable position from the true position. The root-mean-square error d_r is
often used to describe the random errors occurring in a navigation fix formed
by two intersecting lines of position. Measurement errors are calculated along
each of the two orthogonal axes, assuming they are uncorrelated and have a nor-
mal distribution. The error probability is found by first computing the standard
deviation σ from the errors of a large number of observations. With equal
standard deviations of $\sigma_x = \sigma_y$ a circle may be drawn with its center at the
mean value of its position coordinates. A circle of $d_r = \sigma \sqrt{2}$ is then defined
as the root-mean-square error. The circle defines the locus of points having
a constant probability density and encloses an area where a single measurement
will fall 63% of the time. For a circle of $2d_r$ the probability increases to 0.982.

For the case $\sigma_x \neq \sigma_y$ a parallelogram is formed which defines an
error ellipse. However, by a proper transformation of the axis the parameter d_r

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may again be used to represent the spread of individual position determinations. The error in using a circle instead of the appropriate ellipse is only a few percent, as indicated in Table III-1.

TABLE III-1

ERROR PROBABILITY CONTAINED IN CIRCLES OF VARYING RADIUS

Radius of Circle	Probability for $\sigma_x = \sigma_y$	Probability for $\sigma_y = 0$
$1\ d_r$	0.632	0.683
$2\ d_r$	0.982	0.954
$3\ d_r$	0.999	0.997

The use of d_r to describe the navigational fix radial error distribution is not standardized but is finding wider favor, especially among the newer systems being evaluated. However, other methods are sometimes used which are interrelated to the root-mean-square distribution d_r, as indicated in Table III-2. By using the conversion factors of Table III-2, one can intercompare systems using methods other than d_r error.

TABLE III-2

COMPARISON OF STATISTICS OF ERROR FOR $\sigma_x = \sigma_y$

	Statistical Measure	Value in Terms of σ	Normalized to d_r
Root-Mean-Square Error	d_r	$1.41\ \sigma$	1.00
Standard Deviation of d	σ_d	$0.65\ \sigma$	0.463
Variance of d	$\sigma_d^{\ 2}$	$0.43\ \sigma^2$	0.304
Circular Probable Error	CEP	$1.18\ \sigma$	0.833

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3. ESTIMATED SYSTEM ACCURACIES

The estimated accuracies achievable under the most favorable operating conditions for the common types of measurement methods are illustrated in Figure III-10. In this figure the curve on the left is calculated on the assumption that pulse comparison measurements may be made to about one-fifth of the pulse length. Since it is difficult to radiate a pulse whose length is less than 50 cycles of the carrier frequency, time-difference measurements between pulses can only be made at about one-fifth the pulse length. The measurement is therefore accurate to about 10 wave lengths in space. If we assume that two measurements are made and two lines of position which are at right angles to each other are established, the average error of fix will be about $\sqrt{2}$ times the least reading. This leads to the fix error shown.

If the two pulses to be compared are carefully made similar when radiated and are amplitude-equalized at the receiver, then visual superposition is accurate to within about 1% of pulse length. This makes possible a 20-fold improvement in the accuracy as shown by the center curve in the figure.

So far as is known, the final step in accuracy improvement is phase comparison, accurate to about 1 - 3 degrees of phase. Taking 1/200 wave length as an average figure, this represents an accuracy 100 times that of Loran-A, as the curve on the right in Figure III-10 indicates.

REFERENCES

J. A. Pierce, "Electronic Aids to Navigation," in Advances in Electronics, Academic Press, 1948, pp. 425 - 451.

FREQUENCY (megacycles)

WAVE LENGTH (meters)
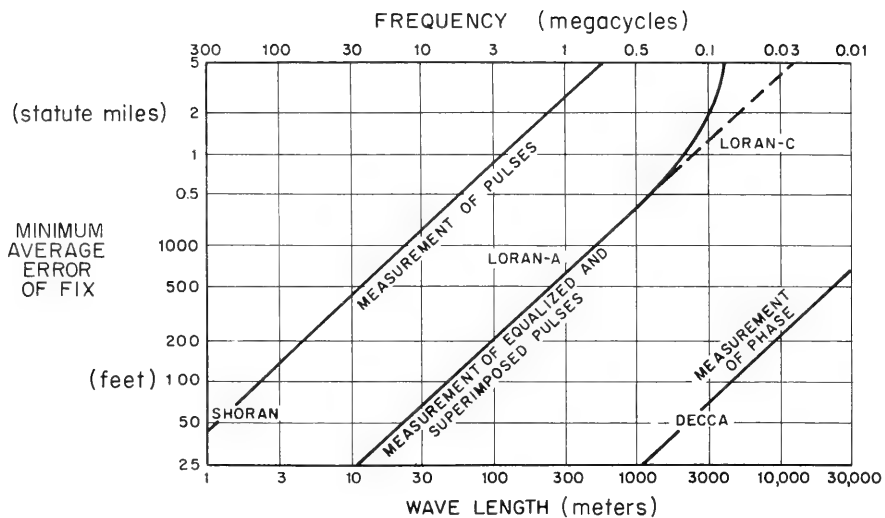
FIGURE III-10 THE MINIMUM ERRORS OF FIX
ATTAINABLE BY THREE STANDARD
MEASURING TECHNIQUES

IV. LONG-RANGE NAVIGATION SYSTEMS

A. CELESTIAL NAVIGATION

The hand-held sextant and tables, historically the basic tools of the navigator, are inexpensive and easy to use. With this equipment a navigational fix can be established to an accuracy of about ±3 nautical miles in most geographical areas throughout the world. The navigator's position can only be established to this precision, however, under the best of conditions at sunrise and at sunset, when the sun and horizon are clearly visible. The average usability of this method on a world-wide basis is less than 50%, and in some geographical areas many days may pass before a celestial sight can be taken and a fix established.

The Geon (Gyro Erected Optical Navigation System)[1] is a developmental high-accuracy celestial system which uses a Mark 19 gyrocompass to maintain the astronomical meridian and indicate the vertical. A small equatorial telescope is mounted on the system and sighted on a star. By setting the polar axis the navigator determines the altitude of the pole and the latitude is found directly. The longitude is calculated by noting the local hour angle and computing the Greenwich hour angle. The method makes use of celestial coordinates and avoids use of the visual horizon. The system requires manual setting and computation. About three minutes are needed to establish a fix. At the present state of development navigational accuracy is between 0.2 and 0.3 mile.

The recently developed Automatic Star Tracking equipment uses a very accurate inertial platform as a vertical reference system. It has the ability to lock on and continuously track a selected celestial body, thus producing position information continuously. Equipment of this type has been used successfully on a range ship for special applications. While the Geon and Automatic Star Tracking systems are passive and provide greater accuracy than the hand-held sextant, they have the same limitations with respect to cloud cover.

The Radiometric Sun and Moon Tracker is a celestial navigation system which uses only the sun and moon as celestial reference bodies. When only one body is available only lines of position may be plotted. Although cloud cover is not a limitation, the coverage is limited by the geometry of the moon-sun orbits, so that world-wide availability is again below 50%. Because of their complexity and high cost, this system and the Automatic Star Tracker system can usually be justified only for very special applications requiring a high degree of navigational accuracy.[2]

REFERENCES

1. W.S. Von Arx, "GEON: A New Navigation System," Journal of the Institute of Navigation, Vol. 9, No. 3, 1962.
2. B.J. Baecher, Naval Navigational Trends, paper presented at Institute of Navigation Meeting, June 1963.

B. CONSOL AND CONSOLAN

1. GENERAL

Consol is a radio navigational aid developed by the Germans (SONNE) during World War II and used and further developed by the British and their allies. There are seven stations in Europe and three in the United States, as indicated in Table IV-1. Figure IV-1 illustrates the European areas of coverage.

Consolan is an improved American version of Consol which uses two transmitting antennas instead of the three required in Consol. The identical pattern is generated in both versions. In Consolan higher power levels and lower frequencies are used and increase the coverage area. A three-tower system is located at Miami, and two-tower Consolan installations are operated by the Federal Aviation Agency at Nantucket and San Francisco. Charts are available from the U.S. Hydrographic Office.

The Consol system may be considered an improved version of the RDF radio range and is also an azimuthal system generating a hyperbolic grid. An operator using a standard communications receiver determines his LOP aurally as the courses sweep through his position. He must recognize and interpret the pattern (Figure IV-2) and plot his position on properly prepared charts. In addition he must use either a radio direction finder or dead-reckoning information to place himself in the proper sector. Thus, the Consol (or the Consolan) serves as a vernier adjustment to his RDF bearing, giving him an LOP to a fraction of 1° in most sectors of the pattern. These systems are useful at maximum ranges of 500-1400 nautical miles.

2. DESCRIPTION

a. Transmitter

A consol ground station has three antennas mounted in line with three-wave-length spacing. A transmitter feeds each antenna with energy of proper phase and amplitude, generating the field pattern of Figure IV-2. The phase in the center antenna B is taken as reference, and the currents in A and C are made to lead and to lag B by 90°, respectively. With a spacing of three wave lengths between antennas, the solid line curve of Figure IV-2 is generated. If the phases of antennas A and C were interchanged, the dotted curve would be generated.

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TABLE IV-1

CONSOL STATION CHARACTERISTICS

Station	Geographical Station	Frequency	Main Equisignal	Station Identification			Repetition Time and Number of the Bearing per 10 min
Bushmills (Ireland)	55° 12' 20" N 06° 28' 02" W	266 kc	130° 13'	T 30	D 4	R 2	W = 40 Z = 15
Ploneis (France)	48° 01' 06" .08 N 04° 12' 54" .16 W	257 kc	106° 12' 286° 12'	T 30	D	R 4	W = 40 Z = 15
Stavanger (Norway)	58° 37' 31" N 05° 37' 40" O	319 kc	067° 247°	T 30	D 19	R 4	W = 60 Z = 10
Lugo (Spain)	43° 14' 53" .29 N 07° 28' 53" .89 W	285 kc	088° 30' 268° 30'	T 30	D 18	R 4	W = 60 Z = 10
Sevilla (Spain)	37° 31' 17" .44 N 06° 01' 48" .06 W	315 kc	083° 263°	T 30	D 19	R 4	W = 60 Z = 10
Kanin (Russia)	68° 38' 18" N 43° 23' 30" O	269 kc	175.5°	T 30	D 10	R 6	W = 60 Z = 10
Rybacij (UdSSR)	69° 45' 12" N 32° 55' 0" 0	363 kc	25°	T 30	D 10	R 6	W = 60 Z = 10
Nantucket, Mass. (U.S.A.) CONSOLAN	41° 16' 07" N 70° 10' 50" W	194 kc	205°	T 30	D 0	R 7,5	W = 42.5 Z = 13
San Francisco, Cal. (U.S.A.) CONSOLAN	38° 12' 13" N 122° 34' 08" W	192 kc	50° 230°	T 30	D 0	R 7,5	W = 42.5 Z = 13
Miami, Fla. (U.S.A.) CONSOL		190 kc	90° 180°	T 30	D 0	R 2,5	W = 37.5 Z = 16

T = Keying cycle   D = Equisignal   R = Identification
W = Repetition time   Z = Number or bearing per 10 min
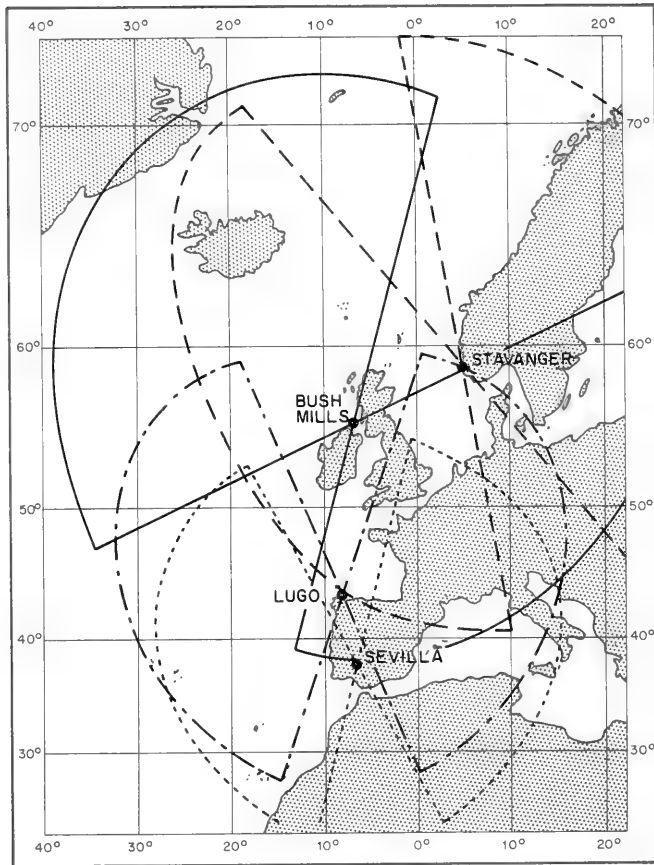
FIGURE IV-1   AREAS COVERED BY THE CONSOL STATIONS
BUSHMILLS, STAVANGER, LUGO, AND SEVILLE
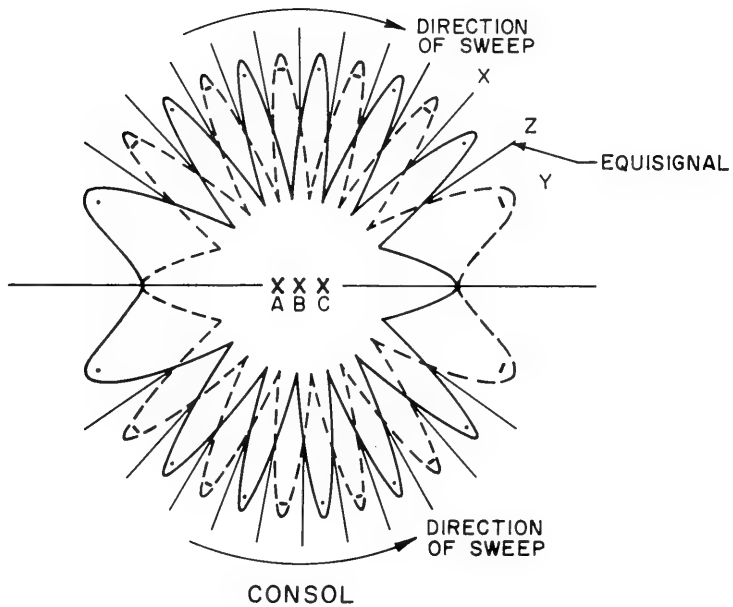
FIGURE IV-2   POLAR DIAGRAM OF ANTENNA SYSTEM
AT BEGINNING OF SWEEP

Each sector is of the order of 12° in width. Dot and dash signatures are radiated in alternate sectors. Smoothly varying the phase of antennas A and C with respect to B makes the equisignal lines rotate at an almost uniform rate through one sector during the keying cycle. Rotation ceases at the end of the cycle, and the pattern returns to its original position for the next cycle.

b. Receiver

The observer uses a standard communications receiver with an omni-directional antenna and hears the equisignal once during each keying cycle. The angular position in the pattern sector is determined by listening to the signal and counting the dots or the dashes before the equisignal, which always appears as a continuous tone. A continuous signal and an identification code are trans-mitted between the keying cycles.

At the end of each keying cycle all the equisignal lines momentarily disappear. They reappear in their initial positions at the beginning of the next cycle and resume rotation as described.

Each transmission cycle lasts for a time period whose length de-pends on whether the German or English cycle is being used. Some of the important transmission characteristics are listed in Table IV-2.

TABLE IV-2

TRANSMISSION CHARACTERISTICS

Transmitted Signal	Consol German Cycle Seconds	Consol English Cycle Seconds	Consolan American Cycle Seconds
Call Sign and DF Signal	55	26	7.5
Silent Interval	2.5	2	2.5
Directional Transmission (Dots or Dashes A n/sec)	n = 60	n = 30	30
Silent Interval	2.5	2	2.5

It is evident, for example, that with a sector width of 12° and a German keying cycle utilizing 60 dots or dashes per sector, the resolution per sector is of the order of 1/5°.

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Special charts are required for Consol fixes and are available from the hydrographic establishments of England, France, Germany, Denmark, and Spain. They are in mercator projection and contain the great circle bearings from each station. The lines are numbered and dot-dash characteristics are noted.

3. ACCURACY

The accuracy of Consol and Consolan fixes depends upon the distance of the receiver from the transmitter and upon its position in the field. It is generally felt that adequate fixes can be generated within a 70° sector either side of the normal to the line of transmitting antennas.

Receiver signal-to-noise (S/N) ratio will materially affect the useful over-all system range. Atmospheric static noise is proportional to the receiver $(B_W)^{\frac{1}{2}}$. Because the Consol signal is single frequency cw, a narrow-band filter can be used to improve the S/N ratio.

The polar diagrams plotted in Figure IV-2 tend to indicate reception to an infinite range. Application of a correction for reception at infinite range shows that the principal effect is a reduction in discrimination due to a poorer S/N ratio. The noise between dots and dashes builds up, thus making them more difficult to count.

Figure IV-3 indicates some typical signal strength curves for a 1-kw transmitter.[1] It should be noted that the sky wave is stronger than the ground wave during evening hours at all but short ranges of less than 200 miles. Lower frequencies are used in the U.S. version, and the useful range is thereby increased.

An area within which the reduction of the discrimination is 30% or more is bounded by a curve of which the radius vector is proportional to the sin of the azimuth. The maximum vector is at right angles to the line of the masts and is approximately equal to 12 times the mast spacing. Considering an antenna spacing of 3λ and utilizing a frequency of 300 kw, we find that within a circle of 15 - 25 miles the bearing taken with Consol will be inaccurate.

By utilizing antenna spacing of about 3λ, the narrowest sector generated is 10°, giving a theoretical bearing accuracy of 10/60 or 1/6° (using German cycles). Due to the form of the polar diagram, accurate vectors can be obtained over an arc of about 70° on each side of the bisector of the line of masts. Because the width of the sectors increases as the radius vector approaches the line of the masts, bearing accuracy deteriorates to about 1/3° at the extreme of the arc coverage.
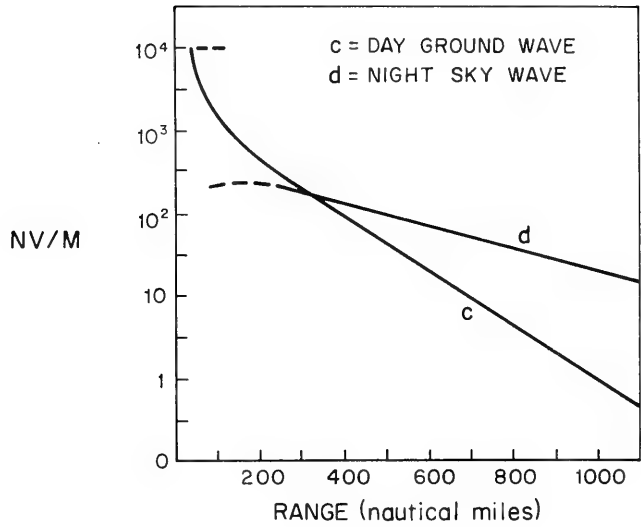
FIGURE IV-3   1 KW CONSOL FIELD STRENGTH
               CHARACTERISTIC AT F = 300 Kc

Sky wave-ground wave interference producing large LOP errors has been noted under some conditions of operation at ranges between 150 and 600 nautical miles. At ranges shorter than 150 miles, the ground wave predominates; at ranges greater than 600 miles, the sky wave predominates, and errors due to interference of the two modes of propagation become negligible. The errors are maximum when the two waves are of equal strength.

It is clear that the reliability of reception at a given range is dependent upon taking such data under standard conditions and in large groupings, so that statistical calculations can be made. The positional accuracy of Consol LOP have been determined with enough data to calculate statistical error information. The data include all random (equipment failure, etc.) as well as systematic (miscount of dots and dashes, etc.) errors. Table IV-3 shows the 95% confidence Consol LOP errors.

TABLE IV-3

CONSOL LOP ERRORS, 95% CONFIDENCE LEVEL

Angle from Normal	Error in Day Range Over Sea (nm)			Error in Night Range Over Sea (nm)		
	200	500	1000	100	300-1000	1500
On Normal	1.5	3	6	.5	10	18
60°	3	6 ·	12	1	20	36
75°	6	12	24	2	40	72

Operator errors also arise from faulty sector identification or poor counting accuracy resulting in lost counts. In practice, under less than maximum S/N conditions the equisignal line may appear broadened, with a resultant loss of both dots and dashes. The recommended method of counting dots and dashes is to count both dots and dashes, subtract the sum of the two from 60 (German cycle), and add half the difference to whichever is heard first. This method assumes an equal number of dots and dashes are lost.

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4. SUMMARY

a. Type of System

(1) Azimuthal.

(2) Base line length: 3 wave lengths.

(3) Dependence of relative amplitudes:

    (a) In transmission: the phase and amplitudes of transmission from two radiators must be maintained in order to hold the desired directivity pattern.

    (b) In reception: phase and amplitude measurements are not necessary. The receiver need only cover the proper frequency band and perform the standard detection and amplification functions.

(4) Type of modulation: keyed cw.

(5) Presentation:

    (a) Aural or visual: as normally used the presentation is aural; several visual dot-dash counting devices have been tried.

    (b) The Larkley Consol Indicator links dots and dashes on a teleprinter tape and provides a reading device for changing the equisignal value on the tape to a dot-dash count.

    (c) The Veedor counter utilizes three counters, one for dot count, one for dashes, one for equisignal divided by two.

    (d) Automatic or manual: manual operation is SOP.

    (e) Continuous or intermittent operation: continuous.

    (f) Time to procure data and plot fix: 4-5 min approximately.

(6) Ambiguities and how resolved: by RDF or dead-reckoning procedures

(7) Number of users: unlimited.

(8) Frequencies utilized:

    (a) Consol: 257kc, 266kc, 285kc, 315kc, and 319kc.

    (b) Consolan: 190kc, 192kc, 194kc.

(9) Bandwidth required: not more than 20 cps.

b. Reception Factors

(1) Adaptability to auto control: development appears to be practical but auto control not available at present.

(2) Fail-safe feature: system is fail-safe. A failure in transmission of the ground station is apparent at the receiver if it is properly monitored. No system error is introduced by a malfunctioning receiver.

(3) Circuit types employed and circuit peculiarities: Keyed cw transmissions. Character count at receiver determines LOP. Communications receiver only required. Specialized narrow-band equipment would increase reliability range and utility of the system.

(4) Uncertainty of LOP: 1/3 - 1° in the largest percentage of the coverage area.

(5) Special chart requirements: special charts which are relatively easy to prepare and use are required.

(6) Security: service cannot be denied and is useful to friend and foe alike.

(7) Adaptability to recording: strip chart recordings quite practical.

(8) Reliability: high; only a standard communication receiver is required.

(9) Range: 25 - 50 nautical miles minimum to 1000 - 1400 nautical miles maximum range.

c. Transmitting Factors

(1) Transmitter power: 1-3 kw used in each of the transmitters required per ground station.

(2) Antenna requirements: three top-loaded vertical antennas, 300-650 feet high.

(3) Complexity of ground equipment: transmitters are standard cw rigs. In addition, automatic keyer phase shifter and matching units are used.

(4) Reliability: high degree of reliability is apparent because of lack of complex equipment.

(5) Station operator requirement: automatic operation possible. Maintenance requirements similar to standard cw stations of this power.

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C. RADIO DIRECTION FINDING (RDF)

1. GENERAL

Radio direction-finding systems utilizing a non-directional transmitter and a direction-sensitive receiving antenna system have been in use for many years as navigational systems for both aircraft and ships at sea. The simple, low-cost equipment makes this system extremely useful where moderate LOP accuracy is satisfactory.

The RDF beacon system is an azimuthal system which measures direction rather than distance. In its most general use, it is composed of a fixed cw or amplitude-modulated transmitter with a non-directional antenna and a RDF receiver with tracking antenna which may be automatic. The output of the receiver is normally used in a feedback system to orient the receiving loop antenna so that its plane is at right angles to the direction of the arrival of the signal. The receiving instrumentation often includes a radio magnetic indicator (RMI). Controls are provided to select the following functions:

a. Automatic visual bearing indication of the direction of arrival of the rf signal and the simultaneous aural reception of modulated rf energy.

b. Aural reception of rf energy, using a non-directional antenna.

c. Aural reception of rf energy using a loop antenna.

2. DESCRIPTION

The system has a short-base-line, of the order of the ratio of the antenna loop diameter to the rf wave length. The system is useful in the allocated frequency range of 100 - 1750 kc, which includes the broadcast band. However, the quality of bearings decreases at frequencies above 500 kc because of polarization errors. A channel at 500 kc is reserved for international distress traffic. Maritime RDF traffic is assigned to a frequency band of 405 - 415 kc.

Transmitters installed at fixed sites are generally cw and operate at power levels of 0.4 - 10 kw. Antennas are typically 150 - 300 feet in height and are either wire or tower type. Transmission characteristics over sea water are excellent at frequencies used, and thus less power and antenna height are required when the transmitters are installed on surface vessels or buoys.

3. ACCURACY

Little data is available on the accuracy of non-directional beacons. A value widely used for σ is $\pm 3°$ when within the limits of ground-wave range. This indicates a $6°$ LOP error band 95% of the time. At distances less than 80 miles errors in LOP due to night effects are small, and errors of $2 - 3°$ can be expected.

Night effect occurs because a horizontal component of radio energy is generated when energy is reflected from the ionosphere and interferes with energy transmitted in the ground plane. The horizontal component results from the rotation of the vertical plane of polarization during propagation through the ionosphere.

The effects of terrain--reflections off mountains and irregularities in the coast line--decrease the accuracy by the ratio of direct to reflected energy. Refraction can take place and produce LOP errors which may exceed $5°$ when energy propagated crosses a sea-land mass obliquely.

4. SUMMARY

a. Type of System

(1) Azimuthal, measuring angles.

(2) Base line length: on the order of ratio of antenna loop diameter to rf wave length. LOP are obtained by use of relative bearing and magnetic compass information.

(3) Type of modulation: modulation of the carrier is used for station identification purposes.

(4) Presentation:

   (a) Visual or aural: presentation is visual for navigation, aural for identification.

   (b) Automatic or manual: fix information requires manual tuning and plotting. Presentation is continuous.

   (c) Time to establish position: approximately 2 minutes including plot time. Time to establish fix depends upon difference in angle between RDF needle position when resonance is first obtained and the final needle position when the needle is at rest on the bearing.

(5) Ambiguities: modern equipment utilizes antenna generating a cardioid field pattern with one maxima and one minima so that no ambiguity exists.

(6) Limitations on number of users: none.

(7) Frequency allocation: cw carrier in band between 100 kc and 1750 kc. Marine RDF stations are allocated frequencies in the 405 - 415 kc band, the standard frequency being 410 kc. U.S. Coast Guard radio beacons operate in the frequency range of 285 - 325 kc.

(8) Fail-safe feature: system is not fail-safe, although it has fail-safe features.

(9) Coverage: the coverage of a RDF is dependent upon:

    (a) radiated power

    (b) noise level

    (c) receiver bandwidth

    (d) terrain

    (e) magnitude of interfering sky wave.

b. S/N Ratio

A S/N level of 6 db is considered adequate for steady readings. A 1.2/1 ratio will give values that can be averaged. A daytime LOP range of 300 - 600 miles using the ground wave is typical for a 200-kc beacon radiating 1 kw of power. This range will decrease to about 350 miles at frequencies of the order of 1500 kc (considering over-water transmission).

c. Ground or Sky Wave

Beacons operate most reliably on ground wave. The sky wave produces stronger signal levels at greater distances than the surface wave, especially during the hours between sunset and sunrise and at the lower frequencies used during the day. Sky-wave field intensity is subject to diurnal, seasonal, and ionospheric variations. These effects decrease the reliability of the fix when using the sky wave.

d. Susceptibility to Tilt and Polarization Errors

The system is susceptible to tilt error when multiple antennas are used. The system is also susceptible to horizontal polarization, but this problem may be minimized by using vertical polarization. The Adcock antenna system is widely used to reduce the effects of horizontal polarization, although it is large for shipboard installation.

e. Susceptibility to Propagation Disturbances

The system is not susceptible to propagation disturbances in the pure ground-wave region but is highly susceptible in the sky-wave region.

f. Susceptibility to Atmospheric Noise

The system operation is degraded by noise, both man-made and static; thus greater field strengths are required for satisfactory operation. The generally accepted signal strength levels are 70 μv/M in noise zones under grade 4 and 120 μv/M in noise zones of grade 4 and above.

REFERENCES

1. Radio Direction Finding, Special Publication 39, International Hydrographic Bureau, Monaco.

2. P. C. Sandretto, Electronic Avigation Engineering, IT&T, 67 Broad St., New York, 1958.

D. DECCA

1. GENERAL

Standard Decca is a ship-positioning and navigation technique developed in Britain and introduced commercially in 1946 by the Decca Navigator Co., Ltd. It is now in extensive use throughout the British Commonwealth and in Greenland, Sweden, the Persian Gulf, and the eastern coast of Canada. (See Figures IV-4 and IV-5.)

Unmodulated continuous-wave transmissions occupying narrow frequency bands in the range 70-130 kcps are employed to generate hyperbolic lines of constant phase difference. Phase comparison circuits on a shipborne receiver utilize two or more of these lines to develop a position fix. Depending on conditions of season and time of day, useful maximum ranges vary between about 200 and 500 miles, while 95% rms radial errors are roughly 1/4 to 4 miles.

2. DESCRIPTION

Decca chains generally consist of a master station around which are disposed three slave stations at distances of 60-100 nautical miles. Thus, three intersecting hyperbolic patterns are generated, from which the user selects the two lines intersecting at the best angle for accurate cross-fix at his location.

Conceptually, the master station and a phase-locked slave station transmit unmodulated cw waves of the identical frequency. The shipborne receiving equipment then phase-compares the two signals to obtain a position line. In practice, two waves of equal frequency cannot be phase-compared, as they would combine at the receiver into a single wave. The desired effect is achieved by operating the two transmitters at two harmonics of a fundamental frequency f and then comparing phases at the receiver at a common multiplied-up frequency. (See Table IV-4.) The phase differences are displayed on three pointer-type phase meters, known as Decometers (one for each master/slave combination). On board ship the Decometer readings are usually plotted manually on a chart overprinted with correspondingly numbered Decca-grid lines. Airborne equipment generally provides a continuous automatic plot of the position fix.

The space between the two adjacent hyperbolic position lines having the same phase difference is known as a lane. In practice, interpolation of 0.01 lane can be achieved, corresponding to a position change of several meters along the base line where the lane is narrowest. Typical values of base-line lane width are given in Table IV-5.

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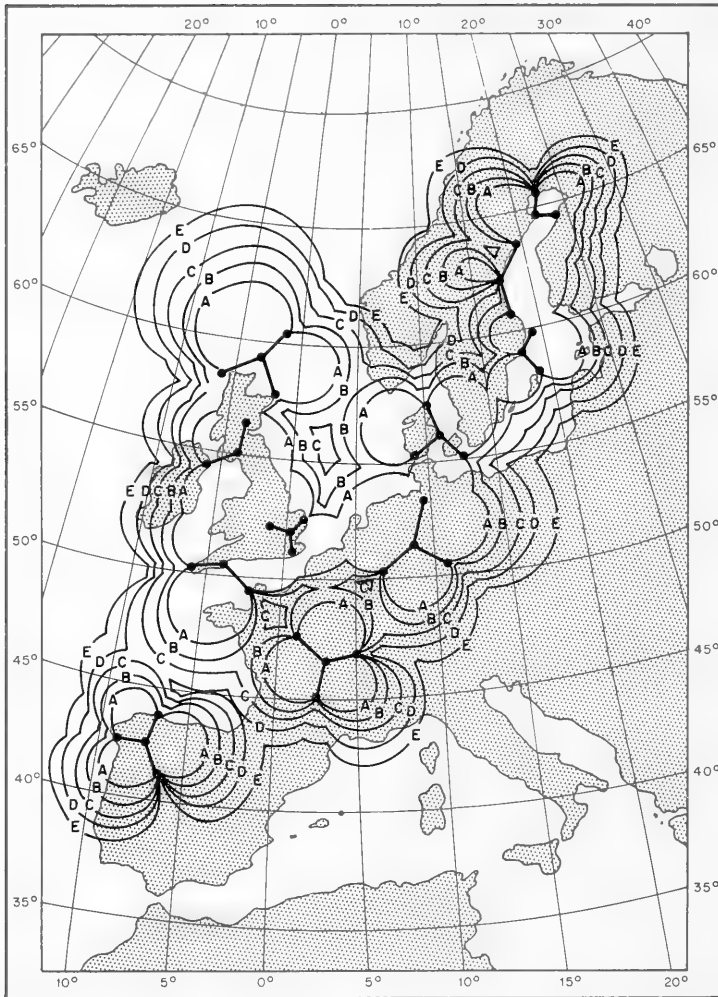
FIGURE IV-4   DECCA NAVIGATOR CHAINS IN EUROPE
QUASI-MAXIMUM 95% RANDOM FIXING
ERRORS AT SEA LEVEL IN NAUTICAL
MILES

When entering the region of coverage, a ship would have to know its position within half a lane; thereafter, a counter would record the number of lanes traversed. This system operates quite adequately in many cases, but is often inconvenient. The difficulty is avoided by superimposing a coarser-scale hyperbolic net over the basic Decca net. The transmitting stations radiate a coarse hyperbolic pattern confocally with each fine pattern sequentially, e.g., red, green, purple. The coarse pattern corresponds to the fundamental frequency f; hence, one of its lanes, called zones, corresponds to 18 green, 24 red, or 30 purple lanes. This effect is achieved in the case of the master by transmitting, together with the 6f signal, a 5f (purple) signal once a minute during the 1/2 sec period occupied by each identification transmission; simultaneously the normal purple slave is shut off. An f signal can thus be obtained by subtraction at the receiver. Similarly, momentary transmissions of 9f and 8f together from each slave provide a signal of frequency f at the receiver.

The lanes of the fine hyperbolic grid are numbered in a way that avoids confusion between the three patterns; the zones are identified by letters of the alphabet and are of uniform width (about 10 km on the base line). Figure IV-6 illustrates the lanes and zones of the English Decca chain.
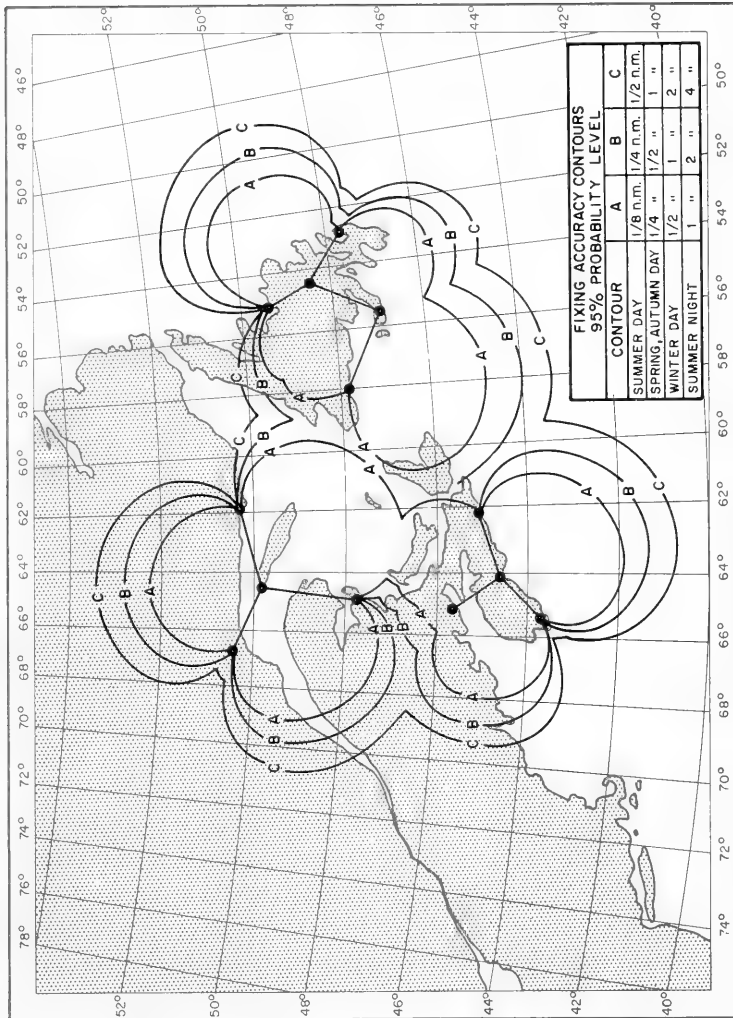
FIGURE IV-5   CANADIAN DECCA NAVIGATOR COVERAGE (WHEN QUEBEC CHAIN
RESIDED IN AREA OF ANTICOSI ISLAND) FIXING ACCURACY
CONTOURS 95% PROBABILITY LEVEL

FIXING ACCURACY CONTOURS 95% PROBABILITY LEVEL			
CONTOUR	A	B	C
SUMMER DAY	1/8 n.m.	1/4 n.m.	1/2 n.m.
SPRING, AUTUMN DAY	1/4 "	1/2 "	1 "
WINTER DAY	1/2 "	1 "	2 "
SUMMER NIGHT	1 "	2 "	4 "

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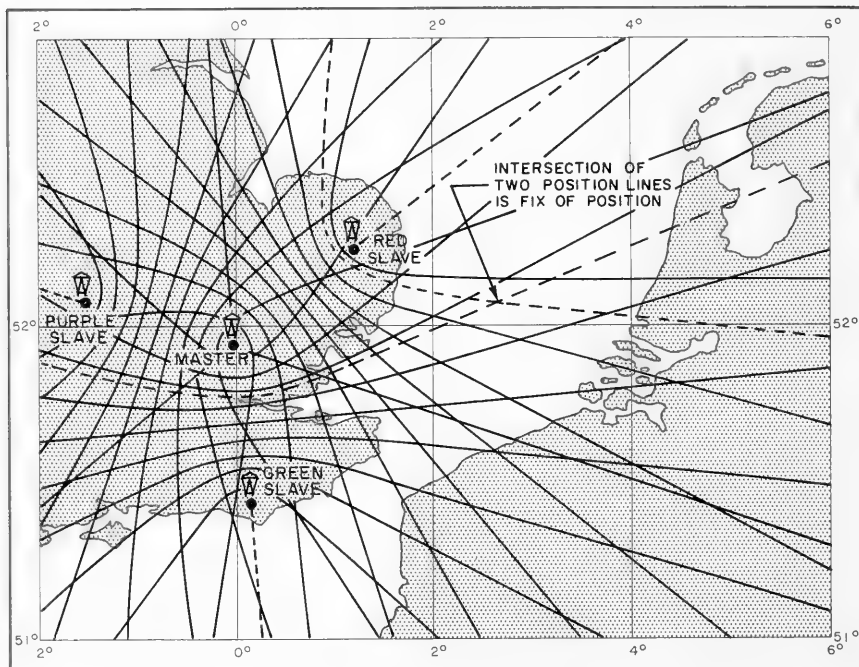
FIGURE IV-6   DECCA LATTICE OF THE ENGLISH CHAIN

TABLE IV-4

TYPICAL VALUES FOR RADIATED AND COMPARISON
FREQUENCIES AND WAVE LENGTHS
(f = 14.16 kcps)

Stations	Harmonic	Frequency (kcps)	Wave Length (m)
		Radiated Frequencies	
Master	6f	85,000	3521
Red Slave	8f	113,333	2640
Green Slave	9f	127,500	2347
Purple Slave	5f	70,833	4225
		Comparison Frequencies	
Red	24f	340,000	800
Green	18f	255,000	1174
Purple	30f	425,000	704

TABLE IV-5

LANE WIDTH ON BASE LINES ASSUMING
VELOCITY OF 299250 KM/S

	Meters	Yards
Red	440.074	481.28
Green	586.765	641.70
Purple	352.059	385.02

Since the transmissions are pure unmodulated cw, a very narrow receiver bandwidth may be used--typically ± 30 cps at half-amplitude. Furthermore, a large number of stations occupy only a small part of the frequency spectrum.

The maximum working range is generally set by the operating authority at 240 nautical miles from the master. The principal limiting factor is a tendency for the amplitude of the sky wave reflected from the ionosphere by night to reach equality with the ground wave at around 240 nautical miles. However, by day useful range may be extended by a factor of two or more, though accuracy at these larger ranges will be low due to the large lane width and small intersection angles.

3. ACCURACY

Random errors in the standard Decca system include errors in reading the phase meter, random changes in circuit parameters, and changes in local velocity of propagation. The standard deviation in phase readings from all such causes amounts to less than 0.01 mean lane; a mean lane being defined as one whose base-line width is 500 meters.

Systematic errors in Decca involve incorrect knowledge of the mean velocity of propagation and, more important, the tendency for the sky wave reflected from the ionosphere to reach equality with the ground wave at longer distances. When this situation obtains, ionospheric fluctuations will produce variations in phase-meter readings and lead to position errors. These errors increase with range and are more serious at night than at day, and in winter than in summer. The 95% radial errors to be expected under various conditions are reproduced in Figure IV-7. The tabulation in the figure lists the errors unlikely to be exceeded in one out of 20 readings.

The sky wave also has an important effect on lane identification errors. The probability of correct lane identification is a function of range, season, and time of day. Some typical results: During summer daylight over ground of conductivity 10^{-13} e.m.u., lane identification is about 95% successful at all working ranges; by night, the 95% probability contour extends out only some 150 miles, while the 67% probability level is at about 250 miles.

| 0 | 50 | 100 | 150 | 200 | 250 |

(nautical miles)
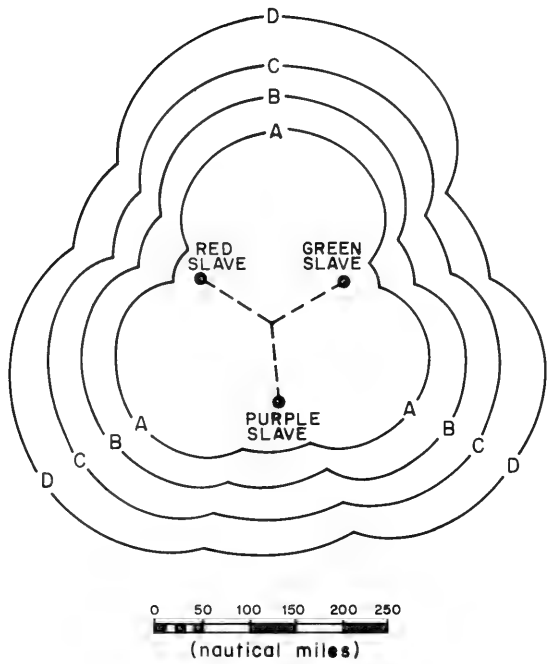
DECCA PERIOD	CURVE				
	A	B	C	D	E
WINTER NIGHT	1 1/2	3	X	X	X
SUMMER NIGHT	1	2	4	X	X
DUSK	1/2	1	2	4	X
HALF LIGHT	1/4	1/2	1	2	4
FULL DAYLIGHT	< 1/4	1/4	1/2	1	2

FIGURE IV-7   ERROR CONTOURS FOR DECCA NAVIGATOR

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4. SUMMARY

a. Type of System

(1) Hyperbolic phase comparison multi-user system.

(2) Number of shore stations required: master and three slave stations (red, green, and purple) are generally arranged in a star pattern.

(3) Length of base line; 60-100 nautical miles (nominal).

(4) Frequency range: 70-130 kcps.

(5) Transmitted power: 1200 watts for Decca Navigator 600 watts for mobile survey equipment.

(6) Transmitter power requirements: 2 kw for mobile survey equipment.

(7) Mobile antenna; 70 or 100 ft in tubular sections.

(8) Decca Navigator range:: 200-500 nautical miles.

(9) Receiver power requirements: 80-140 and 165-260 v, 47-63 cps, 22-30 v dc 250 watts

(10) Receiver readout: 3 dial (navigation); 2 dial (survey) Decometer Unit - Marine Automatic Track Plotter provides continuous position plot in rectilinear coordinates.

5. RANGE AND ACCURACY

		Daytime	Nighttime	
			Summer	Winter
(1)	Usable service distance (nautical miles)	500	240	200
(2)	Approx. 95% rms radial error at maximum range	2	4	3
(3)	Approx. 95% rms radial error at 150 nautical miles	1/4	1	1-1/2
(4)	Approx. 95% rms radial error at 40 nautical miles	1/20		

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1. Radio Aids to Maritime Navigation and Hydrography, Supplementary Paper No. 3 to S.P. No. 39. International Hydrographic Bureau, Monaco, 1961.

2. Radio Aids to Maritime Navigation and Hydrography, Supplementary Paper No. 4 to S.P. No. 32, 1962, International Hydrographic Bureau, Monaco, 1962.

Arthur D. Little, Inc.

E. LORAN-A

1. GENERAL

Standard Loran (Loran-A) was developed at M.I.T. Radiation Laboratories during World War II. Loran stations were established in the Atlantic and Pacific theaters and operated under security conditions as a navigational aid. Commercial equipment has been made available since the war and installed world-wide to increase the system's usefulness and coverage. (See Figure IV-8.) It now enables properly equipped ships and aircraft to plot their position with good accuracy out to 800 miles or more.

Loran-A uses a pulsed hyperbolic method of fixing a ship's position by the reception of pulsed radio signals in a timed sequence from transmitting stations of known position. The time difference of arrival of two or more pairs of signals is measured, and these measurements are transformed into radial distances from the transmitter. The Loran-A system does not require a knowledge of the ship's heading or dead-reckoning position and is independent of other mechanical devices, including the compass and chronometer.

2. DESCRIPTION

Loran-A operates in the frequency band from 1800 to 2000 kc. With present techniques the ground waves may be used to distances of 600-900 nautical miles in the daytime, and the sky waves are used out to 1400 nautical miles at night.

In this system, radio signals consist of short pulses which are transmitted in a precisely timed sequence from a pair of shore stations. The shore stations are carefully located on a base line of known length. The pulses are received on special receivers within the operating area of the transmitters, and the time difference of arrival of the pulses is displayed and measured on a cathode-ray-tube indicator. This measurement is used to determine from Loran-A tables or charts a line of position on the earth's surface. Two or more lines of position from two or more Loran station pairs are used to determine a position fix.

a. Ground Station Operation

A Loran position fix requires that the difference in time for pulses to arrive from a pair of transmitting stations be measured to a precision of ± 1 microsecond. One station of a Loran pair is a master station, and the
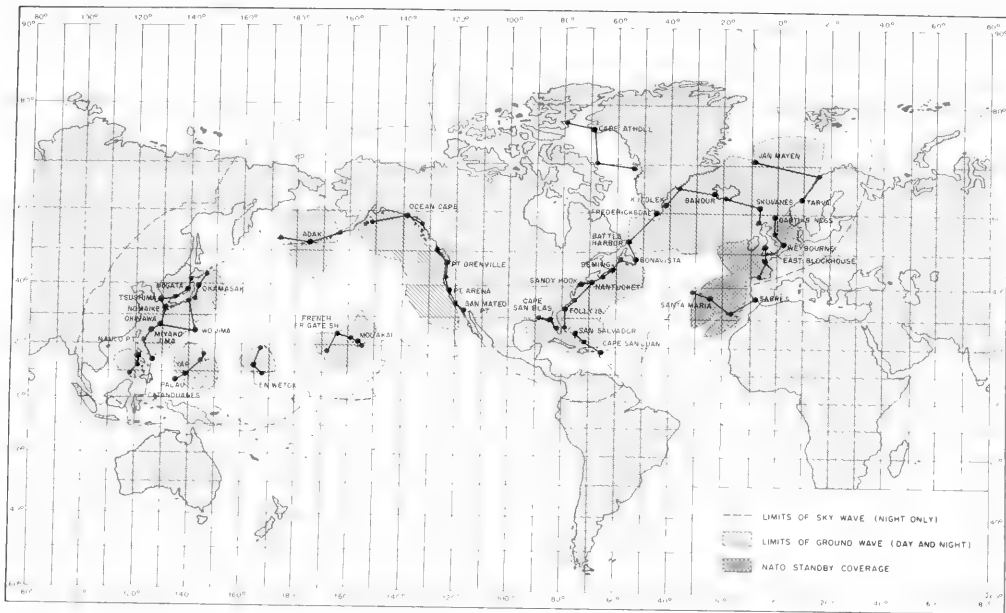
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FIGURE IV-8   LORAN A COVERAGE - JULY 1964

other is designated the slave station. In the system shown in Figure IV-9, the master station is a double-pulsed station common to two shore stations.

The accuracy of Loran-A is largely dependent upon the transmitting stations' keeping their signals correctly timed and synchronized. For this purpose, the master station utilizes a stabilized 100-kc crystal oscillator and precision timer to set the pulse recurrence rate. A precisely spaced series of pulses is thus transmitted. On reception of these pulses at the slave station, a corresponding series of pulses is transmitted.

The crystal oscillator also provides precise 1-microsecond timing pulses. Synchronization of the slave to the master is maintained by an operator at the slave station who monitors these radiated pulses and continuously makes the proper timing adjustments.

Loran signal pulses are approximately 40 microseconds in length. The number of pulses per second from each station is the recurrence rate. There are three basic rates, each of which is divided into seven specific rates differing by 100 microseconds. This system provides separation of signals from transmitters in the same area.

Figure IV-10 indicates the way in which the master and slave station pulses are spaced in time. The coding delay inserted at the slave station is a fixed value and insures that the time between reception of the master and slave pulses is always greater than one-half the recurrence interval at all receiver locations. An operator thus can distinguish between the master and slave station pulses and make a nonambiguous identification. The synchronization of slave to master station is presently ± 1 microsecond and is being reduced to ± 0.25 microsecond at U. S. operated stations.

When trouble occurs and the two stations are not properly synchronized, the operator "blinks" the signal by shifting the signal to the right and left at intervals of about 1 second. Blinking is a fail-safe feature of Loran and indicates to the navigator at a receiving station that the transmitter is malfunctioning and that readings should not be taken at that time.

b. Mobile Station Operation

Any mobile station having a Loran type A receiver can use the basic Loran navigation system. In this receiver, the pulses from the slave and master stations are displayed on a cathode-ray tube indicator. The display is divided into two equal horizontal segments one above the other, so that received pulses produce a vertical deflection on the screen. The operator matches the master
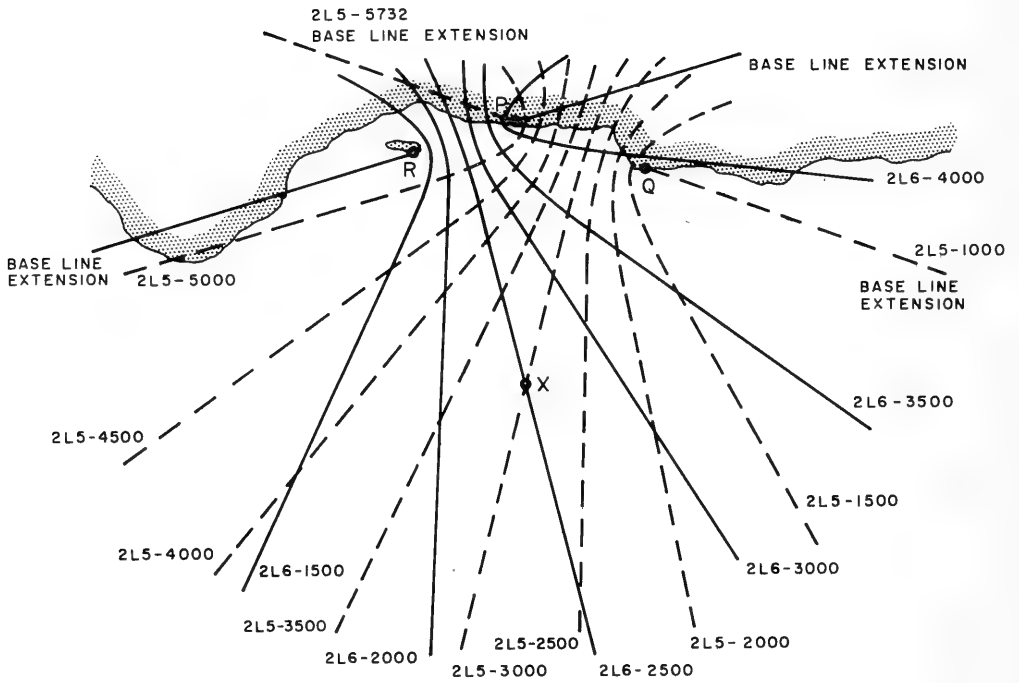
FIGURE IV-9   LORAN A GRID SYSTEM
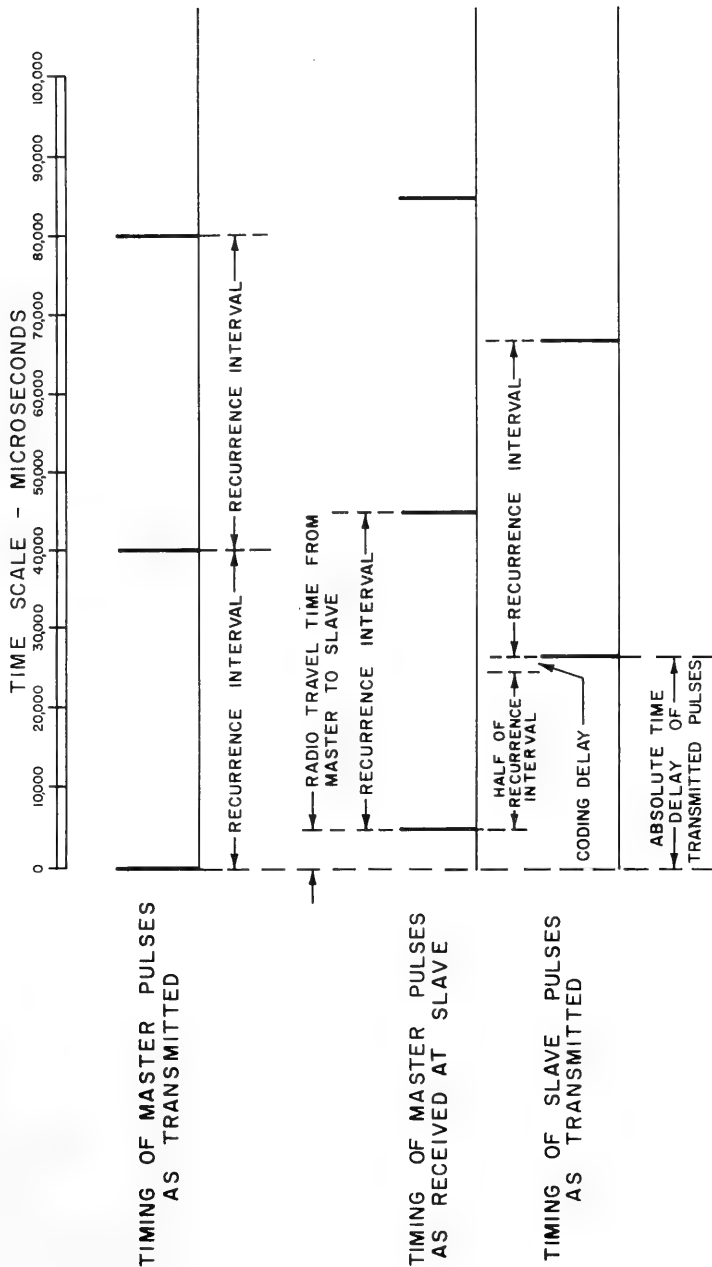
FIGURE IV-10   TIME RELATIONSHIP BETWEEN PULSES TRANSMITTED BY MASTER
AND SLAVE STATIONS IN AN ACTUAL LORAN STATION PAIR

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and slave pulses and reads the time delay on a dial and digital counter. Two such time-difference readings from two Loran pairs furnish the information required for a Loran position fix. Loran tables and charts must be used to establish a geographical position.

3. ACCURACY

The accuracy of a Loran-A fix is determined by the accuracy of the individual lines of position and by their angles of intersection. The accuracy of the individual lines of position is dependent upon the following:

a. Synchronization of transmitters

b. Operator skill in matching and identifying signals

c. Uncertainty of sky-wave correction (when sky waves are used)

d. Position of ship relative to transmitting stations

e. Accuracy of tables and charts

f. Timing and positional uncertainty.

With a reasonable signal-to-noise ratio, an operator can be expected to equalize the amplitude and match the leading edge of the received signals within 1 microsecond of the correct value.

Since the ionosphere does not maintain a constant height or angle with respect to the earth, these corrections vary slightly from tabulated values. Sky-wave reception is most reliable at distances greater than 800 miles from the transmitter, where readings, with proper correction, are generally correct to about ± 5 microseconds. At lesser distances, the uncertainty increases.

The relative accuracy of Loran over the coverage area is apparent from the spacing of the lines on the Loran charts. The most favorable position is on the base line between the transmitters. The most unfavorable positions are adjacent to the base line extensions, where the Loran line separations can be several miles per microsecond.

The accuracy of Loran tables and charts is of the order of a fraction of a microsecond. Inaccuracies do occur in those areas where insufficient survey data was available for positioning the transmitting stations. Where correction data is available, this is included in charts provided with the Loran-A tables. The timing uncertainty, in microseconds, results in a corresponding uncertainty

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in the location of the hyperbola, which is regarded not as a sharp line but as a band or zone.

The actual uncertainty in the location of the navigator's line of position is the product of the timing and positional uncertainties. If three-eights of a mile is considered a typical positional uncertainty and 2.5 microseconds a typical timing uncertainty for a hyperbola obtained by ground-wave reception from two Loran stations, then the actual position uncertainty for daytime operation is about 1 mile. If sky wave reception is used and three-fourths of a mile and 8 microseconds are the corresponding quantities, then the actual nighttime uncertainty would be about 6 miles. These figures are estimates only and not averages of a series. This margin of uncertainty is larger than found in practice and can be reduced by a factor of about 2 under favorable conditions. A Loran fix is normally expected to be compared to a good celestial observation.

Over large parts of the service areas of Loran, hyperbolic line crossing angles of 30° or better are obtained which allows a relatively good fix to be obtained. At the extreme limits of sky-wave coverage (approximately 1400 miles) crossing angles may be quite small if all stations are situated along one coast or in some similar arrangement. In this situation, positions are obtained with relatively good accuracy in a direction perpendicular to the lines of the position, but with relatively poor accuracy along the lines of position. Where crossing angles are small, the practice of averaging a number of readings should result in improved readings.

The uncertainty in plotting a position can be reduced by using three or more Loran lines of position or by combining Loran lines with those from another source. Careful consideration should be given to the relative accuracy of various Loran lines.

4. SUMMARY

a. Type of System

    (1) Pulsed time-difference hyperbolic plot

    (2) Length of base line:

        (a) average = 200 - 400 miles

        (b) long = 200-700 miles

(3) Pulse modulation: 45 microseconds length,
21 microseconds rise time

(4) Pulse repetition rate:

    (a) H rate = 33 - 34.11 pps in seven steps
Recurrence interval = 30,000 - 29,300 microseconds
in seven intervals

    (b) L rate = 25 - 25.44 pps in seven steps
Recurrence interval = 40,000 - 39,000 microseconds
in seven intervals

    (c) S rate = 20 - 20.28 pps in seven steps
Recurrence interval = 50,000 - 49,300 microseconds
in seven intervals

(5) Frequency channels:

Channel 1 = 1950 kc
Channel 2 = 1850 kc
Channel 3 = 1900 kc
Channel 4 = 1750 kc

(6) Bandwidth: 40 kc

(7) Radiated power: 160 kw peak, for older installations
1000 kw peak where high-power amplifiers
have been installed

(8) Number of Loran-A stations: 69 located throughout world

b. Accuracy and Range

	Daytime Ground Wave	Nighttime Sky Wave
(1) Usable service range	700-900 nm	approx. 1400 nm
(2) Approximate accuracy LOP	0.5 - 1.0 nm	3 - 6 nm
(3) Time required to obtain LOP: 2 - 3 minutes		

(4) Minimum usable S/N ratio: not less than 2/1
with a manual match. Automatic tracking receiver
will track to S/N ratio of about 1/2 or 1/3

(5) Number of users: Loran-A designed for multi-user application.

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1. Pierce, McKenzie, and Woodward, <u>Loran</u>, Rad Lab Series, Vol. IV, McGraw-Hill Book Co., 1948.

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3. Joe B. Stone, "Standard Loran - Technical and Operational Advances," U. S. Coast Guard, Sixth International Tech. Conf. on Lighthouses and Other Aids to Navigation, 1960, Paper 9/6/4.

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<u>F. LORAN-C</u>

<u>1. GENERAL</u>

Loran-C is a pulsed, low-frequency, long-range navigation system. It operates in a frequency band of 90-110 kc which was allocated on a world-wide basis for long-range radio navigation purposes by the ITU Conference of 1947. The first Loran-C installations were made and successfully tested in 1957. Coverage is now available for the greater part of the ocean areas of the northern hemisphere. (See Figure IV-11.)

Loran-C, like Loran-A, is a pulsed, hyperbolic navigational system which uses the time difference of arrival of rf signals from three shore-based stations of known location to establish a navigational fix. A phase-difference measurement system which provides a much higher degree of accuracy than is available by the pulse-difference method alone is also used. In addition, the Loran-C system uses a lower frequency than basic Loran, and this makes possible a large increase in range.

Under good conditions, position fixes to within 1500 feet and ranges of 1000-1400 nm can be expected 95% of the time when ground wave transmission is used. Ranges of 1800-2300 miles and fix accuracies of 2 nautical miles or better are generally available with sky wave reception.

<u>2. DESCRIPTION</u>

Loran-C stations are generally used in groups of three, a master and two slave stations. When 360° coverage is desired, a fourth station is added, and the system is called a star of "Y" configuration. Pulses are transmitted in a precisely timed sequence from the master and the slave stations, which are located on a base line of known length. The optimum base line is a compromise between geometry and signal strength considerations. Because of the low frequency (90-110 kc) used and the long range possible, base lines as long as 800 miles are used. (See Figure IV-12.)

Both the master and slave stations transmit on the same frequency on a shared time basis; i.e., the master station transmits its pulse group and is followed in succession by each of the slaves. A coding delay at each slave station eliminates ambiguity.
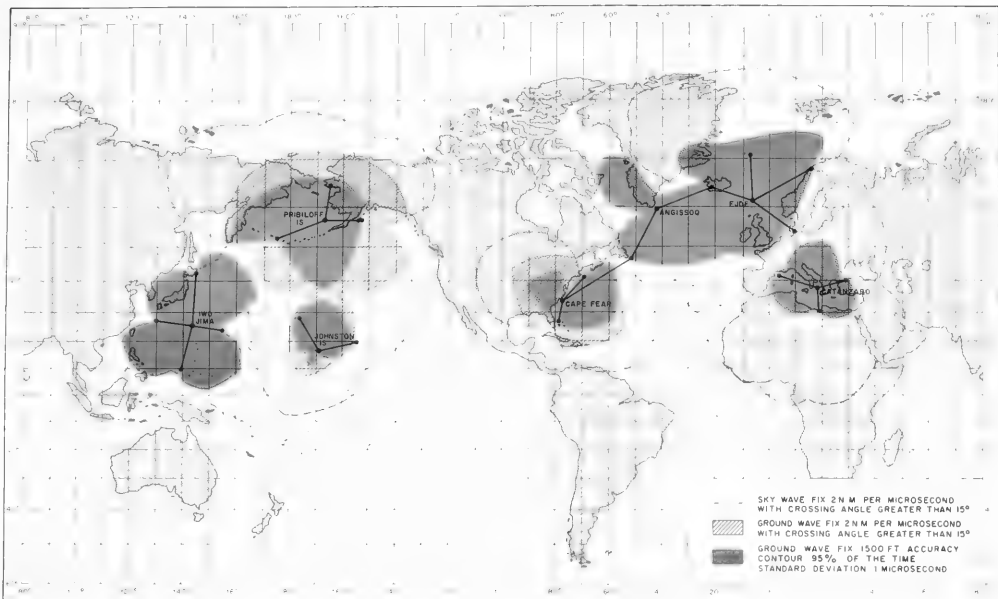
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FIGURE IV-11   LORAN C COVERAGE - JULY 1964

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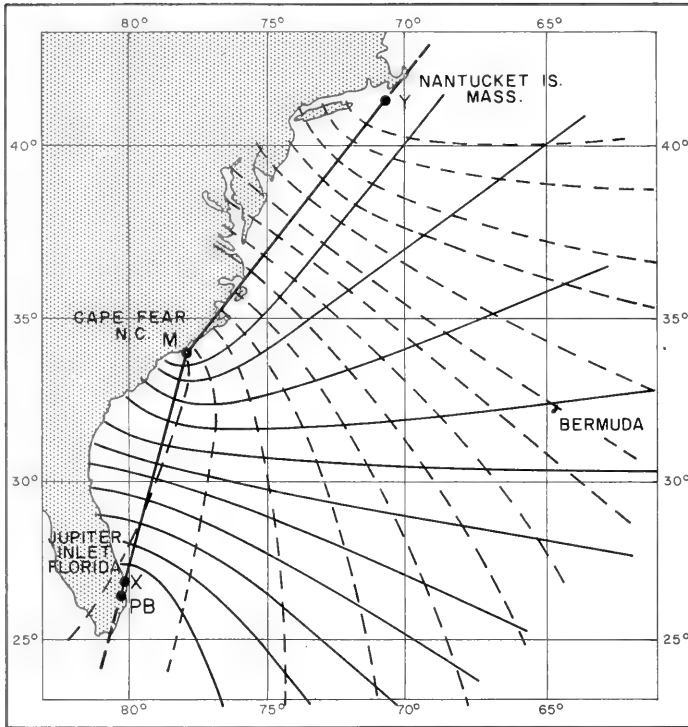
FIGURE IV-12   LORAN C EAST COAST CHAIN

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The pulses are received at stations within the operating area of the transmitters. Time-difference measurements are made by utilizing both the pulse envelope and the phase of the carrier cycles incorporated within the envelope. After the envelopes are matched to within ± 5 microseconds, a cycle match is made using the 100-kc sine waves that make up the pulse. In this manner, the pulse envelope match produces a coarse time-difference reading as in Loran-A, and the cycle match produces a fine time-difference reading. Thus, the time-difference readings of two or more master-slave combinations establish a Loran-C fix. Special tables and charts are required to help locate the geographic position of the mobile receiver.

a. Ground Station Operation

Loran-C transmitters utilize a peak pulse power of 250 kw - 1 mw and transmit a series of pulses in groups of eight with 1000 microsecond separation between pulses. Each pulse is about 200 microseconds long. The master station transmits a ninth pulse for identification purposes. The pulse groups are repeated at relatively long periods of time, such as 50,000 microseconds. When pulses are transmitted in groups the receiver integrates the pulses, thus adding together the signal from each pulse of the group and greatly increasing the signal-to-noise ratio. By increasing the S/N ratio at the receiver in this manner, one may use lower power at the transmitter and may increase the area of coverage.

To permit identification of master and slave station chains certain pulses within each pulse group are in phase opposition to others according to a predetermined code. Also, the transmission from different stations is very closely synchronized and a coding delay is used at each slave station as in Loran-A. Station coding is outlined in Loran-C tables and charts.

Each station in a chain of three or four stations transmits one pulse group per recurrence interval. Pulse groups are transmitted at six basic repetition rates. Seven additional specific rates can be generated for each basic rate, to provide a total of 48 different usable repetition rates. The master station transmits first, and is followed by the slave station. Signals are simultaneously displayed at the receiver as the envelope and phase-time difference readings for the two signal pairs, i.e., master and one slave, master and the other slave.

Each transmitter uses 100-kcps phase-coded signals from its timer synchronizer and in turn generates a 200-microsecond pulse of 100-kc sine waves. These pulses are amplitude-modulated, giving an envelope of the proper rise time and shape.

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In the event of improper transmitter operation, a standardized blinking procedure is used to notify receivers in the area. The blink consists of shifting the entire pulse group by a specified amount once each second. This operation is visible to the receiver operator and activates automatic alarms.

Master and slave station transmitters are similar, and both feed 625-foot antennas. Each station has a certain amount of redundancy in equipment to minimize downtime caused by equipment failure.

b. Receiving Equipment

Specialized receiving equipment is required to take full advantage of the Loran-C positional accuracy. A coarse position is obtained by the measurement of the time difference of the envelope signals from two master-slave pairs. This measurement is made to within ± 5 microseconds. A second measurement of the phase of the signals is made to within a few hundredths of a microsecond, thus making possible a very accurate line of position.

Sky-wave contamination is avoided by making the time-difference and phase-difference measurements before the sky wave arrives. Thus, these measurements are made automatically at the Loran-C receiver within the first 30 microseconds after receipt of the ground wave from the master station and each slave station.

The coarse position measurement is made automatically within the receiver. Only the leading edge of the envelope is used. By electronically processing the master and slave signals the receiver establishes a precise base line crossing at the 30 microsecond point of the leading edge for each signal and makes a time-difference measurement between them. A readout establishing a coarse line of position is automatically made on vernier dials to within 5 microseconds.

The fine measurement is made by comparing the phase of the individual sine waves contained in the pulse of the master and slave signals with the phase of a precisely controlled reference oscillator in the receiver. Electronically the receiver locks the frequency of the local oscillator to the frequency and phase of the incoming signal. A sampling gate allows the receiver to be turned on and to "look at" the signal at the 30-microsecond sampling point, thus avoiding sky-wave interference. The measurement is automatically presented on a vernier dial which reads from 0 to 10 microseconds in increments of 0.01 microsecond. The total time difference is the sum of the envelope and phase readings. For example, if the coarse (envelope) measurement were 19374.2 microseconds and the fine (phase) were 1.36 microseconds, the actual measurement would be

between 19369.2 and 19379.2 microseconds. The exact time difference measurement is therefore 19371.36 microseconds.

A method of statistical signal integration which helps extract the multi-pulse signal train from background noise is used. A series of sampling rates with a spacing corresponding to the 1000-microsecond spacing between transmitter pulses is used. In this manner only the coherent transmitter pulse train will integrate to a value other than zero. In many areas a signal-to-noise ratio of 1/10 can provide a useful output from the receiver.

A system of automatic signal research which makes use of the phase coding of the transmitter pulses is used in the Loran-C receiver. With this method of synchronous phase detection, the receiver yields an integrated output signal only when the received signal is of the same phase coding as contained in the receiver phase coder. The receiver searches and tracks the incoming signals automatically by maintaining the sampling gates in coincidence with the sampling points of the signals. The phase coding is determined when the operator selects the Loran-C stations to be used.

Sky-wave discrimination or selection is provided in the receiver by an additional sampling mechanism 30 microseconds ahead of the sampling gates. If the search results in the setting of the receiver at a sky-wave signal, this additional sampling mechanism causes a voltage to be generated through the integrator; to use the ground-wave signal the operator advances the position of the sampling mechanism.

The receiver may comprise a visual oscillographic display which facilitates signal search and allows checking to see if the signals are correctly followed by the receiver during its automatic operation. There are also provisions for manual operation. The receiver has protection and alarm circuitry which help the operator monitor proper operation.

3. ACCURACY

a. Ground Wave

The principal factors affecting radio-wave propagation, which in turn affects the range and accuracy of Loran-C, in the ground-wave areas are: the amplitude ratio of ground wave to sky wave and sky-wave delay, the S/N ratio, and the interference from other frequencies within the 90-110 kcps band. Interference from other frequencies is minimized by the synchronous detection and filtering techniques used in Loran-C. These tend to reduce the susceptibility to nonsynchronous interference caused by refractivity of the earth's atmosphere and by the conductivity of the earth.

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(1) Sky-Wave Interference

The first-hop sky wave limits the range of the useful ground wave. At ranges of about 1300 miles the signal strength of the sky wave exceeds that of the ground wave and varies with the time of day and season of the year. For example, at this range during the day the sky-wave-to-ground-wave-signal ratio is about 10/1 in winter and about 3/1 in summer. Sky waves do not affect ground-wave reception when they are less than about 10 times ground-wave amplitude. This is true during all seasons of the year. However, at night the ground wave is complicated by the very large sky-wave component at distances greater than 1000 miles during all seasons of the year.

The Loran-C receiver's ability to utilize the ground wave is largely dependent upon this component's arriving at the receiver slightly ahead of the sky wave. The nighttime sky-wave delay over sea is about 54 microseconds beyond 1300 nautical miles. This provides time for the ground-wave signal to be built up to a suitable S/N ratio before sampling. The sampling point is 30 microseconds after arrival.

(2) Atmospheric Noise Interference

The accuracy of the cycle-time-difference measurement is practically independent of atmospheric noise for a S/N ratio greater than 1 (0 db). At lower S/N ratios, the mean indicated cycle-time difference is little affected by noise, even though the short-term deviations from the mean increase in magnitude.

At low values of S/N ratio the cycle accuracy can be improved by averaging the indicated time difference for a few minutes. Reliable measurements of envelope-time difference require a S/N ratio of about 3 (10 db). However, for special applications such as surveying and mapping, satisfactory results are obtained with S/N ratios of -20 db.

(3) Factors Affecting Propagation

The pulse transmission time from transmitter to receiver depends upon the velocity of propagation. The factors affecting this are the conductivity of the earth's surface and the index of refraction of the atmosphere. An assumed constant propagation velocity is normally used. Some measurements of propagation time over the Bermuda base lines have been made. Variations no greater than a few hundredths of microseconds are expected over all seasons of the year.

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The conductivity of the earth has the greatest effect on the phase of the low-frequency ground wave. With a service area completely over water, conductivities can be predicted with good accuracy. Service areas over land, however, cause large variations in conductivity, which cause large distortions in the observed lines of position.

The greatest use of Loran-C equipment is for paths over water, where accurate prediction of conductivity can be made. Here the greatest cause of signal-phase variation is changes in the refractivity of the atmosphere.

b. Sky Wave

Many of the factors affecting ground waves also affect sky-wave propagation. A minimum S/N ratio is required for either mode of operation. There is also the possibility of contaminating by greater and lesser modes.

(1) Mode Interference

At times overlap by sky-hop pulses causes distortion of the pulse envelope at the receiver and malfunction of the time-difference-measuring circuits. Even small distortions will cause errors in phase measurement. The maximum phase error occurs when the (N-1) sky hop arrives at the receiver 90° out of phase with the Nth hop. The maximum phase error in this case would be 0.32 microsecond if the ratio of desired-to undesired signal were 20 db. For this reason, the amplitude of the Nth hop is required to be at least 10 db greater than the (N-1) hop before the Nth hop can be used.

Table IV-6 gives the minimum distance at which the amplitude of the Nth hop sky wave is 10 db greater than the next lower mode.

TABLE IV-6

SKY-WAVE RANGE DATA

	Nautical Miles			
	Winter		Summer	
No. of Hops	Day	Night	Day	Night
1	877	610	1300	610
2	2180	1900	3200	1900
3	3050	3200	4300	3200

(2) Sky-Wave Correction

The ability of sky waves to increase the area of coverage is dependent upon the stability and the predictability of the delay. In addition, the receiver must be able to identify the sky hop the receiver is using for each of the transmitters.

Many factors must be considered and special corrections applied to obtain good accuracy in Loran-C fixes using sine waves. Matching two one-hop sky waves is generally preferred to matching a sky wave with a ground wave. Sky-wave corrections can be computed or are available in tables and graphs.

c. Range

The maximum usable ground-wave range over water for 0 db S/N ratio for 100 kw of radiated power is about 1400 nautical miles in the daytime and about 900-1000 nautical miles at night. Increasing the radiated power to 1 mw increases the range an additional 260 miles. Line-of-position accuracy at these extreme distances should be to within 0.1 microsecond plus 0.1 microsecond for seasonal variations. Operationally the Loran-C system has recently demonstrated an ability to supply positional information to an accuracy of 0.1-0.5 nautical mile with ground-wave transmission in the North Pacific.

The nighttime sky-wave range under the same conditions should be about 1800 nautical miles for the first hop and 2300 nautical miles for the second hop. Increasing the power level to 1 mw radiated increases both figures approximately 300-400 nautical miles.

Position fixes with sky waves can be obtained with a probable error of 1-1.5 microseconds. About a 10% decrease in range can be expected for paths over land for both ground-wave and sky-wave operation.

4. SUMMARY

a. Type of System

(1) Pulsed time-difference hyperbolic plot plus phase-difference measurement for high accuracy.

(2) Length of base line: 500-800 miles

(3) Pulse modulation: 200 microseconds length,
70 microseconds rise time

(4) Pulse repetition rate:

    (a) 6 basic rates: 10 (SS), 12-1/2 (SL), 16-2/3 (SH), 20 (S), 25 (L), and 33-1/3 (H) groups per second.

    (b) 7 additional rates are available for each basic rate

(5) Frequency: 90-110 kc.

(6) Bandwidth: 99% of total pulse power contained in band of 90-110 kcps

(7) Radiated power: 250- 1000 kw

b. Accuracy and Range

(1) Usable service range at 100 kw at 50% sampling point and 0 db S/N ratio:

	Nautical Miles			
	Winter		Summer	
No. Hops	Day	Night	Day	Night
Ground Wave	1300	800	1400	800
1	1800	1700	1700	1700
2	2100	2300	- -	2300

(2) Usable service range at 1000 kw at 50% sampling point and 0 db S/N ratio: range increases approx. 15-20% over 100-kw range

(3) Approximate operational accuracy of fix in nautical miles

	Ground Wave		Sky Wave	
	Min	Max	Min	Max
	0.1	0.5	0.5	2

(4) Number of users: Loran C designed for single or multi-user applications.

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c. Receiver Characteristics

    (1) AN/APN - 145, transistorized, analog operation.

        (a) Size: 2.5 cubic feet.

        (b) Wt: 100 lb.

        (c) Power: 500 watts.

        (d) Controls: 26 manually operated.

        (e) Mtbf: approximately 500 hours.

    (2) AN/ARN-76 Microcircuit, digital operation, digital readout.

        (a) Size: 0.5 cubic foot, uses remote control indicator.

        (b) Wt: 20 lb.

        (c) Power: 155 watts.

        (d) Controls: 6 manually operated.

        (e) Mtbf: 1500 hours or more.

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G. OMEGA VLF NAVIGATION SYSTEM

1. GENERAL

The Omega VLF navigation system, undergoing evaluation tests, is an experimental system designed to provide long-range position fixes to ships and aircraft on a 24-hour basis. Omega presently utilizes four experimental stations, located at Summit, Canal Zone; Haiku, Hawaii; Forestport, New York; and Creggion, Wales. The final system, designed to cover the entire globe, will require 8-10 stations. Potential users are surface vessels and all types of aircraft, including those with speeds beyond Mach 1.

The assigned frequencies are in the 10-14 kc band now assigned for navigation. Omega is operating at a frequency of 10.2 kc. Hyperbolic lines of position are established by automatic phase-difference measurements of the carrier frequencies at the receiver. The phase-difference values are indicated on dials and strip charts. From these values the navigator determines his line of position from special charts.

Long base lines are practical at the low frequencies used. If base lines of the order of 3000-5000 miles are used, lines of position will approach parallel lines. By using three stations with base lines at near right angles, all lines of position in the coverage area cross at near 90°, the optimum crossing angle, giving the smallest fix error.

Coarse position measurement is not available with the developmental Omega equipment but will be added by the spring of 1965 to two of the transmitters now in use. Improved receivers, now under development, will also be available at that time. Position determinations to within 1 mile during daylight hours, 2 miles during evening hours, and 6 miles under worst-case conditions are possible with the present prototype equipment.

2. DESCRIPTION

An Omega experimental navigational chain is composed of three stations, a master and two synchronized slaves. At present these stations transmit sequentially on a frequency of 10.2 kcps. A pulse length of 1 second (approximately) is being used. The transmitted pattern is repeated every 4 seconds. The stations are identified at the receiver by the slight difference in pulse length characteristic at each station. After transmission the master station stands by while the other synchronized stations transmit their pulses.

At present, 100-kw transmitters are being used. The radiated power is dependent upon the antenna. Low antenna efficiency and lack of antenna gain at these frequencies permits use of only 2-3 kw of radiated power. Useful coverage of the area can be obtained at radiated power levels of about 2-10 kw. Automatic control at the antenna maintains the constant radiated wave phase characteristics required.

The system is designed as a hyperbolic network but may be used in the range-range mode. When operated in this mode a highly precise frequency standard must be carried aboard the navigating vessel but the system can establish a fix by receiving signals from only two shore stations.

Three types of receiving antenna are being used. A 35-foot whip is the most efficient unit for surface vessels. A 10- or 12-foot probe may also be used and can be mounted either vertically or horizontally as space permits. The same antenna coupler is used interchangeably. A loop antenna is used aboard submarines and requires a loop coupler.

The present Omega receivers indicate two phase-difference readings. Each reading is shown by two dial indications, one being the cycle (or lane) count from 0 to 99 cycles and the other the percent phase difference per cycle (100% = 360°). A strip-chart recorder is also provided to trace the two phase differences (neglecting the cycle count). Remote indication can also be provided.

The time differences as measured by the receiver are manually plotted on specially prepared charts. To plot a position to an accuracy of 2-6 nautical miles, the navigator must be able to plot to an accuracy of between 0.03 and 0.1° latitude. Allowances for diurnal and seasonal phase shift, taken from tables or charts, must be made by the operator before an accurate plot can be made.

Computers to utilize the required information and automatically track and plot a vessel's position in geographic coordinates are not yet available, but are in the early development stage. Such computers appear to be particularly necessary for use aboard high-speed aircraft, which cross one lane (7.9 nautical miles) in a very short time.

Equipment to resolve the problem of ambiguities of lane identification is not available with the early developmental Omega equipment. Other available navigation aids and dead-reckoning procedures must be used. The strip-chart recorder at the receiver helps to correct lane counts that have been lost and permits rapid recognition of anomalous propagation which might go unnoticed on a counter-type display.

In an effort to reduce the problem of position ambiguities, new transmitting equipment will be installed by early 1965. This equipment will be capable of generating three frequencies, 10.2, 12.75, and 13.6 kc, sequentially, as indicated in Table IV-7. New receivers using microelectronic circuitry will simultaneously track two of these frequencies and continuously indicate fine lines of position on 10.2 kc and coarse lines of position on the (13.6-10.2) difference frequency. The fine lane widths will be 8 nautical miles as before, but a new coarse lane width of 24 nautical miles will now be available to help reduce position ambiguity problems. The new receiver will weigh approximately 75 pounds and require about 1.5 cubic feet of space. Later versions of the receiver will also track the third frequency being generated and yield a third coarse lane width of 96 nautical miles.

TABLE IV-7

OMEGA SIGNAL FORMAT

Transmission Interval	0.9	1.0	1.1	1.2	1.1	0.9	1.2	1.0	0.9
Station 1	10.2	13.6	12.75	f1					
2	f2	10.2	13.6	12.75	f2				
3		f3	10.3	13.6	12.75	f3			
4			f4	10.2	13.6	12.75	f4		
5				f5	10.2	13.6	12.75	f5	
6					f6	10.2	13.6	12.75	f6
7						f7	10.2	13.6	12.75
8	12.75						f8	10.2	13.6

0.2 sec
→ ←

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3. ACCURACY

Extensive sea and land tests indicate that the Omega system's accuracy is better during the day than during the night or during transition periods. A statistical analysis of long-term tests at three of the fixed stations indicates a navigational accuracy of 0.5 and 0.9 nautical mile (circular probable error) in the daylight and the nighttime hours, respectively. Relative accuracy of vessels for station keeping should be of the order of 0.25 mile. At present, errors during transition periods (day/night and night/day) are less than 2 miles. Statistical studies at NEL indicate that inherently, transition period accuracies are capable of being intermediate between day and night values. To realize this capability, more numerous corrections computed by more elaborate methods may be required.

A recent analysis[4] indicates that the Omega system should be capable of an _operational_ fix accuracy of less than 6 nautical miles. More recent experimental data and improvements in equipment indicate this figure is conservative.

With present base lines NEL reports the operating range consistently reaches 6000 nautical miles. Some estimates indicate the present system cannot be made operational for world-wide use until the late 1960's or early 1970's. It must first be qualified by test and accepted for use by Federal authorities. Also the establishment of suitable transmitter sites on foreign soil requires considerable time and preparation. A recent report[5] describes the siting problem in some detail.

4. SUMMARY

a. Type of System

(1) Pulsed phase-difference hyperbolic plot

(2) Base line length: approximately 5000 miles

(3) Pulse duration: 1 sec (adjustable cw synchronized)

(4) Pulse repetition rate: 5 sec (adjustable up to 10 sec)

(5) Transmitter power: 1000 kw

(6) Radiated power: 2-3 kw

(7) Frequencies: 10.2 kc, 12.75 kc, 13.6 kc

(8) Receiver: 2 channel phase-difference measuring and indicating unit

(9) Receiver: phase-difference output indicated by

   (a) Front panel digital readout

   (b) Integral recorders

   (c) Provisions also for remote indication

(10) Receiver size: 8" high x 15" wide x 21" long (new versions available in spring 1965)

(11) Receiver power requirement: 115 v, 60 cps

(12) Receiver weight: 75 lb

b. Range and Accuracy

   (1) Usable service range: 6000 miles (approximately)

   (2) Approximate drms fix accuracy: 0.5 mile daytime
   1.0 mile nighttime
   2 miles at transition periods

   (3) Relative accuracy for station keeping or rendezvous: 0.25 nautical mile

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H. NAVIGATION SYSTEMS USING SATELLITES

1. GENERAL

A number of high-precision navigation networks using earth satellites are under study by the Navy, NASA, and FAA. To date, only the Navy's Transit program, being carried out by the Applied Physics Laboratory of Johns Hopkins University, under the cognizance of BuWeps, has been implemented. The more promising systems which have so far been investigated promise true global coverage, all-weather operation, relative immunity to interference, unlimited traffic-handling ability, the availability of frequent fixes, and very high positional accuracy. Mid-latitude positional accuracies exceeding 0.50 nautical miles are predicted on the basis of an early analysis of Transit 4A experimental data.

There is some commonality to all navigation systems which would utilize satellites. The satellite's position relative to fixed points on the earth's surface is communicated to the navigating vessel. The navigation system then determines the vessel's position with respect to the satellite at a given time. This information can then be combined with the known position of the satellite, and the vessel's longitude and latitude may be computed.

All satellite navigational systems will require precise orbital information so that the satellite's position at any point in time may be accurately predicted. A communication link for determining the position of the navigating vessel with respect to the satellite in all types of weather must be available. Also, in some cases, such as high-speed aircraft, the velocity and altitude will be required to obtain an accurate positional fix.

2. METHODS OF MEASUREMENT

A number of satellite navigational methods are possible and may be classified as to type of measurement made with the instantaneous position of the satellite as a reference. In all systems the satellite follows some orbital path around the earth. The satellite position is accurately computed in advance and corrections are made for perturbations which occur with time. The accuracy of the satellite position is then dependent upon how well the orbit is known and the accuracy of the time measurement. The position of a vessel relative to the satellite may then be found by measuring the:

1. altitude (elevation angle)
2. azimuth (bearing)
3. range to the satellite
4. rate of change of altitude, azimuth, or range.

To establish a navigational fix two intersecting lines of position are required. Where a single variable is being measured, such as the rate of change of range in the Transit system, for example, a number of successive measurements are required. Where two or more satellites are available simultaneously, a measurement of the vessel's position with respect to each satellite can generate the necessary lines of position to establish a fix. Orbital correction information is required of both satellites. In other systems which are designed to measure two variables simultaneously, only a single measurement is required to determine a fix.

A large number of possible combinations of range, angle, and Doppler measurements are possible for the determination of a navigational fix. However, evaluation studies have been made of only the more promising systems directed toward both military and civilian requirements.

3. MILITARY SATELLITE NAVIGATION SYSTEM

a. Description

The Navy's navigation requirements are quite different from those of the nonmilitary user. Since the navigator's position must not be betrayed, he must remain passive. For this reason the Navy's original Transit satellites were designed to give position information to vessels equipped with data-processing and accurate inertial guidance navigation equipment. An inertial guidance or similar system is required to supply the velocity information needed to compute navigational fixes of high accuracy by range-rate methods.

In the Transit system the satellite orbit is determined by ground stations and a parametric description is transferred to the satellite. (See Figure IV-13.) This information is stored in a memory and is updated at least once each 24 hours. It is continuously transmitted by the satellite and is repeated at precise two-minute intervals.

The relative motion between the satellite and the navigating vessel on a rotating earth produces the well-known Doppler frequency shift. These frequency variations are an accurate measure of the rate of change of the slant range between the satellite and the navigator. By measuring the Doppler shift one may obtain either of two results: (1) if the ground station position is known, the satellite orbit may be determined, or (2) if the orbit of the satellite is known, the position of the ground station may be calculated.
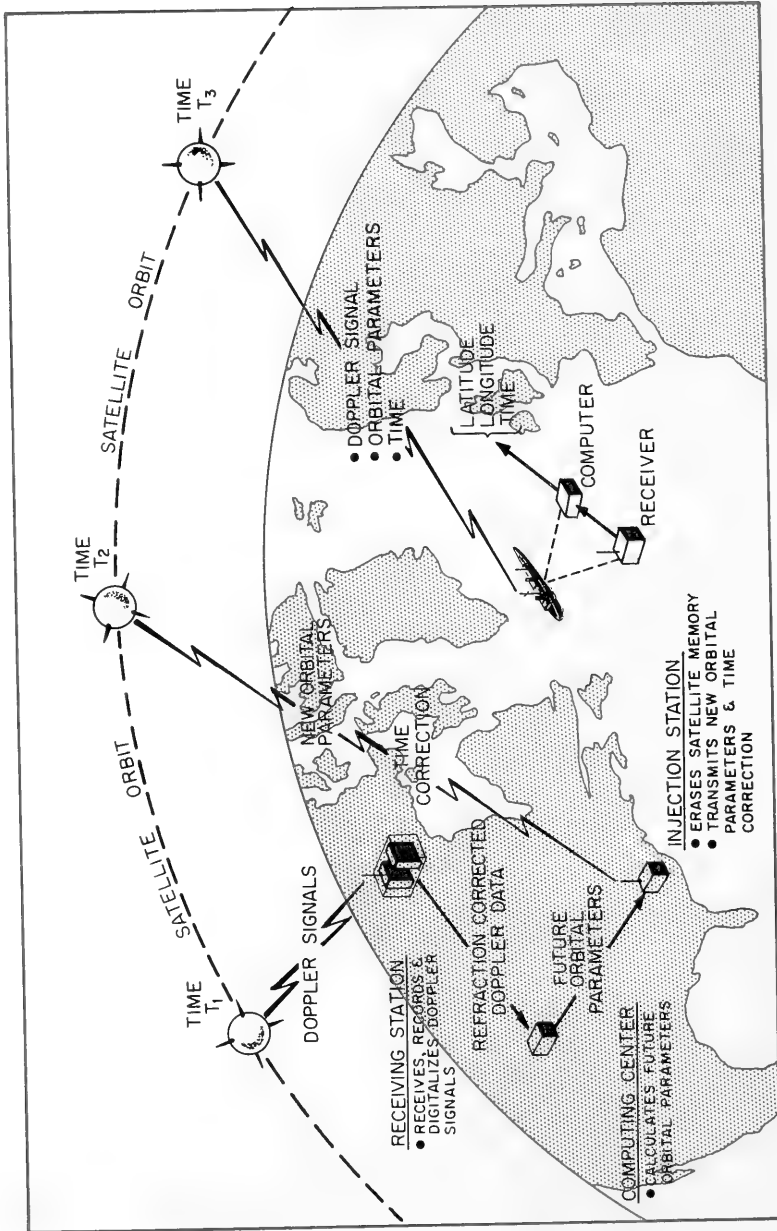
FIGURE IV-13   SCHEMATIC OF TRANSIT SYSTEM OPERATION

A navigator who wishes to establish a position fix using Transit during one of its passes overhead receives from the satellite:

(1) Correct time
(2) Updated orbital information
(3) Doppler frequency information.

Transit radiates two phase-modulated rf frequencies in the UHF region which are received by the navigating vessel with an apparent variation in each frequency. At the receiver a beat frequency is formed for each of the trans-mitted frequencies, which are then suitably combined in a manner which reduces errors due to atmospheric refraction.

The satellite transmits its position continuously during precisely timed two-minute intervals. A minimum of three intervals is required for an accurate position determination. From this information and the time that the Doppler frequency crosses through zero, the latitude can be determined. By measuring the rate of change of the Doppler frequency the longitude can be calculated. The satellite also transmits orbital and time reference information as phase modulation on the rf carrier during each interval.

A number of methods exist for computing the navigator's position once the Doppler frequency vs time has been measured and the orbital information received. To carry out the required calculations present plans require a specialized receiver and computing equipment with a pre-established program. By a precision analysis of all Doppler information the vessel can determine its position with respect to the satellite. Evaluation of the time and orbital information yields the vessel's position with respect to fixed references on the earth's surface.

b. Accuracy

Reliable figures of Transit system accuracy are classified and not readily available. However, the more important errors may be generally classified as follows:

(1) Inaccurate orbital information
(2) Lack of knowledge of the navigator's own velocity
(3) Errors in the received frequency from the satellite.

The principal orbital errors arise from unpredictable short-comings in the satellite period. Because of the earth's atmosphere and nonuniform gravitational field, the satellite may advance beyond or be retarded from its predicted position. An error in the assumed coordinates of the satellite will result in an

almost equal error in the computed position of a vessel. For navigation purposes, the position of the satellite is predicted up to 24 hours in advance. An analysis of test data from Transit 4A[1] indicates an error in satellite position not greater than 0.5 nautical mile for satellite coordinate predictions made 12 hours in advance. Errors increase rapidly for periods greater than 12 hours.

A second form of error arises from poor information about the navigator's own velocity. With a two-knot velocity error during a 15-minute pass of the satellite, the estimated positional error is 0.3 - 0.5 nautical mile.[2] This does not appear to be a severe limitation for surface ships and submarines, where accurate pit-log or inertial system information is normally available. This form of error could be of much greater importance in the case of high-speed aircraft, where a greater error in velocity might be expected.

Navigational errors of about 1 nautical mile could be produced if the satellite frequency or the local oscillator were to drift about one part in 10^8 cps. However, recent developments indicate stabilities of one part in 10^{10} per hour or better may be expected. Consequently the frequency stability of either oscillator should not make any significant contribution to the navigational error, if a constant frequency shift is monitored and corrected for in the computation.

Simplified methods of computing the navigator's position integrate the total number of cycles of Doppler shift over a minimum of three two-minute timing intervals. Some additional error over that experienced in the original method of using up to 50 data points can be expected. The error produced with data of this type, using refraction-corrected Doppler, should not exceed 1-2 nautical miles.[3]

It has been shown that position errors due to atmospheric refraction are reduced by the transmission of two frequencies from the satellite. With this technique navigational errors of about 0.5 nautical mile might be expected. By taking advantage of the higher precision (more digits) information being transmitted, one can reduce this error to less than 0.1 nautical mile. The higher accuracy requires more elaborate receiving and computing equipment. Currently such data is not available to the nonmilitary navigator, because it is coded and specialized receiving and computing equipment is required.

c. The Present Transit System

The Transit plan requires a minimum of four satellites in polar orbits of about 600 miles with the orbital planes separated by about 45°. An orbiting period of 108 minutes has been calculated for each satellite. To date a number of experimental Transit satellites have been built by Johns Hopkins University

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for the Navy Bureau of Weapons. Three of these are presently in orbit and have been operational since July 1964. Over this period some operational units of the fleet have made extensive use of Transit in all parts of the world and have reported navigational fixes accurate to ± 0.1 nautical mile. Transit is designed to provide this accuracy on an all-weather, 24-hour-a-day routine basis.

Westinghouse is responsible for the integration of the antenna, the data processor, the computer, and the new special-purpose receiver to form the "Navigational Shipboard Receiver" (AN/BRN-3). This receiver provides four basic outputs required for the navigation solution:

(1) Vacuum Doppler frequency (corrected for refraction)
(2) Digital data that furnish the navigator with satellite orbital information
(3) Timing pulses that provide accurate time information
(4) Imc reference and clock frequency, which through a frequency synthesizer provides all of the system conversion and reference frequencies.

The present Transit receiving and computing system requires several racks of equipment[5] which, because of size and power requirement, is probably unsuitable for most aircraft use. Certain simplifications have been suggested[4] which will decrease receiving equipment size and power requirements as well as initial cost, while decreasing the fix accuracy only a modest amount.

4. NONMILITARY SATELLITE NAVIGATION

Because of probable economic requirements, the nonmilitary satellite systems being studied will require only a minimum amount of equipment aboard the navigating vessel. The bulk of the complex and expensive computer equipment will be concentrated at properly positioned shore stations. For these systems the navigator would not need to be concerned with satellite orbit information and the corrections required for accurate computations. An additional advantage of the "cooperative" systems is that they permit traffic control, navigation hazard warning, and aids to vessels in distress; these are made possible by the positional information control available at the computer station.

Each vessel navigating in a given area would be assigned time slots for satellite transmission, the frequency of which would depend upon the vessel's requirements for position information. The satellite would be automatically interrogated by the ground station and navigating vessel. The satellite thus would serve as a retransmitting station to relay all measurement information to a ground station for computation and then relay the resulting positional information back to the vessel. In this manner one line of position could be established

by a range measurement from the shore station to the navigating vessel. This method would involve measuring the time difference in arrival of two signals, one being the vessel's automatic response via the satellite to the ground station's coded address signal and the second being the range signal from the vessel via the satellite to the ground station. From these measurements the distance from the satellite to the vessel is found and a line of position is established. A second line of position would be derived from a measurement of the elevation angle or bearing of the satellite with respect to the vessel. Other methods for finding the second line of position are also being considered.

Such a system using a single satellite per fix would require approximately eight station-keeping satellites at about a 6000-mile altitude. Each would require two or more microwave channels for relay purposes. A fix accuracy of about ±1 nautical mile is anticipated for general use, and a fix accuracy of ±0.1 nautical mile is predicted for special applications.

Another approach to the "cooperative" system which is under consideration would use two or more satellites to generate each individual fix. Positional information offering about the same accuracy achieved with the single satellite system would be somewhat easier to obtain. This system would require 16-24 nonstation-keeping satellites in 6400-mile circular orbits. Digital messages and ranging pulses would be transmitted to the two satellites within the user's view and relayed to the navigating vessel. The signals would be automatically retransmitted in reverse order via the same path to the computer station, where the range of the navigating vessel from the shore station would be determined and one line of position would be established. An identical measurement from a second satellite would generate an intersecting line of position, and thus a navigation fix would be established. This is called the active mode of operation.

Where the user did not wish to reveal his position, a passive mode might be selected and a general address code utilized. At periodic intervals the position and altitude of the satellites and then the required pulse information would be transmitted through the satellite to all passive users in the area. Each navigating vessel would then compute its own location. Each user would need pulse receiving, timing, and display equipment for passive mode operation.

Another suggested approach to using satellite systems for navigation and ship-positioning is a modification a geodetic survey system in use by the U.S. Army Map Service, Corps of Engineers. This system known as Secor (Sequential Collation of Range)[6] uses a single transponder-type satellite and three precisely positioned ground stations on base lines of 500-1000 miles in length. (See Figure IV-14.) Accurate positioning at ranges of several thousand miles is possible, depending on satellite altitude.
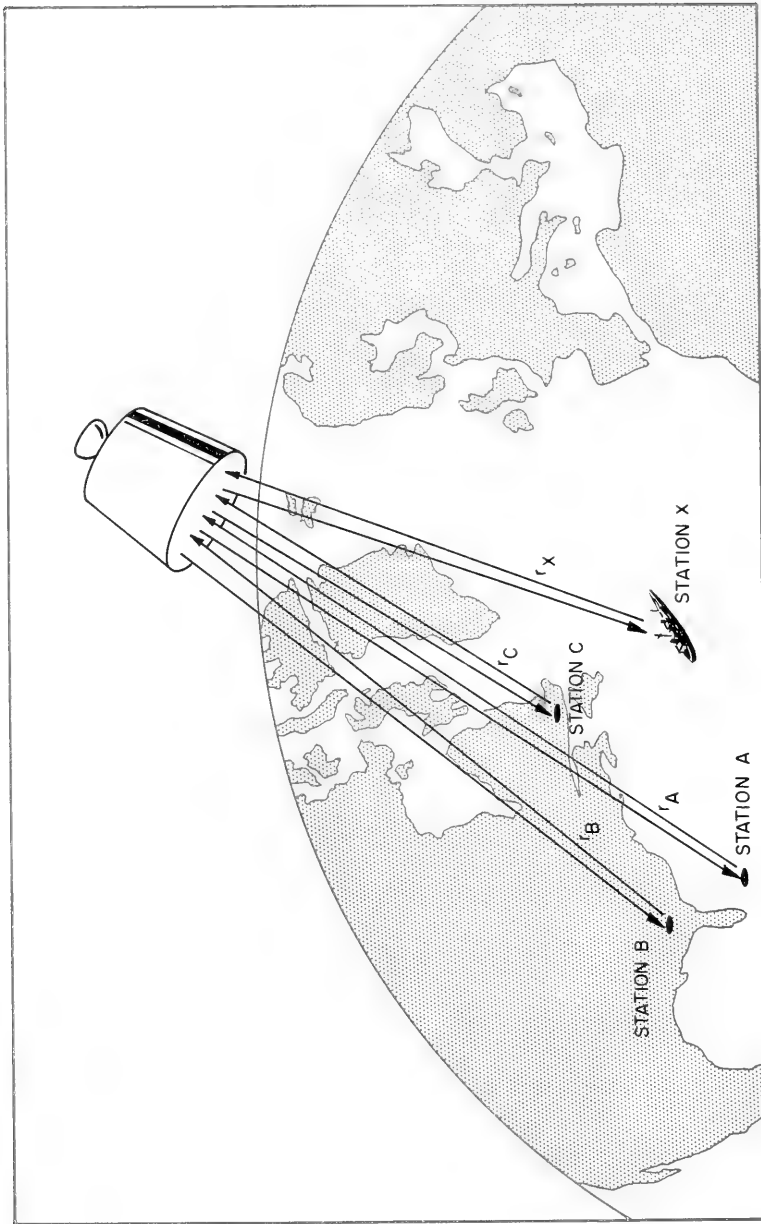
FIGURE IV-14   THE SECOR SATELLITE NAVIGATION SYSTEM

For the Secor-type system the distance from each ground station to the satellite is determined by phase comparison techniques. The master station transmits frequency-modulated cw signals in bursts which are repeated by the satellite transponder and transponded again by each of the other stations. Speed and course information from the navigating vessel would also be transmitted to the master station via the satellite. The resulting signals would be received back at the master station, where phase comparison measurements would be made and the satellite-to-ground ranges r_A, r_B, r_C, and r_X computed.

To obtain information to calculate the range error caused by ionospheric refraction, the satellite retransmits phase information on two or more frequencies. With this information and the range and speed information the coordinates of the navigating vessel would be computed at the master station and transmitted via the satellite to the vessel.

So far the most sophisticated form of Secor has achieved geodetic positioning accuracies of better than 10 ppm.[7] For navigational requirements and accuracies of 0.1-0.25 nautical mile less sophisticated equipment would be required.

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I. INERTIAL NAVIGATION SYSTEMS

1. GENERAL

Inertial navigation systems are ship-mounted and entirely self-contained. The vast majority of marine inertial navigation systems has been installed on Polaris submarines. (Until very recently each of these ships carried three identical systems, but the number is being reduced to two.) Similar inertial systems are carried on certain aircraft carriers and nuclear attack submarines and on range tracking ships. The systems are complex and expensive, but they offer unequalled accuracy in position-tracking and, being self-contained, are entirely independent of external sources of navigational information. They differ from other ship-mounted systems in their greatly superior ability to maintain a continuous track of the ship's position. They are not, of course, absolutely accurate; errors occur and, generally speaking, increase with time. The coupling of an inertial system with another system which is capable of correcting the inertially determined position by reference to some external object or signal produces a composite system having a degree of continuous accuracy unmatched by any other method of navigation.

2. DESCRIPTION

a. Typical Shipboard Inertial Navigation System

To determine the motion of a vehicle over the earth's surface an inertial navigation system first measures the vehicle's motion with respect to a reference system which has some known orientation with respect to the earth and then translates this motion into terms of earth coordinates. The reference system is provided by a device called a "stable platform," by a system of gyroscopes and by accelerometers mounted and interconnected in such a way that it maintains one of its orthogonal axes parallel to the local vertical and another pointed north, independent of vehicle movements. Accelerometers mounted upon this platform can then measure vehicle acceleration with respect to the platform. Accelerations are integrated to obtain velocity and distance traveled. These quantities are translated into earth coordinates to maintain position data and to correct platform orientation to correspond to the changing position.

To illustrate in more detail the technique of inertial navigation, we will consider a single typical shipboard system which uses as its reference system three orthogonal axes, one vertical, one north-south, and the third east-west. These axes are established by three single-degree-of-freedom gyros

orthogonally mounted to form the stable platform. The platform is supported within three gimbals to provide independence of vehicle roll, pitch, and heading. Means are provided to sense spurious precessions instantly and to eliminate them by rotation of the gimbals. Upon the platform the latitude accelerometer measures the north-south component of acceleration, and the longitude accelerometer measures the east-west component. Mounting the accelerometers in the level plane makes them insensitive to the influence of the earth's gravitational field (except for a small component resulting from the earth's "out-of-roundness," which is discussed later). The first integration of acceleration actually occurs within the "accelerometer" itself, so that the signal delivered is a measure of linear velocity. If the vehicle were moving along a fixed, flat surface, these velocities could obviously be integrated to give distances traveled.

The fact that the earth is rotating and has a rounded surface complicates the problem in two ways. First, the system must translate the measured horizontal motions into their corresponding curvilinear equivalents with respect to earth. The computer has two channels, latitude and longitude, for this purpose. In the latitude channel north-south velocity is converted from linear to angular terms to determine change of latitude. The longitude channel operates in the same way except that two additional complications are necessary. Because the relationship between longitudinal arc-length and arc-angle is a function of latitude, latitude must be inserted into the conversion from linear to angular velocity. Then the angular velocity must be corrected by adding the angular velocity of the earth, a known constant (for this purpose).

The second problem caused by the earth's shape and motion is that the platform, which would otherwise remain fixed with relation to space, must be constrained instead to remain fixed with respect to the earth, i.e., horizontal and indicating the north. Provision of this constraint is another function of the computer. In essence the computed values of ship's latitude and velocity and the known velocity of the earth's surface are used to determine the rate at which the platform should rotate about each of its three axes. These rates are converted to control signals which are sent to three torquing motors, one for each gyro; these motors in turn cause the gyros to precess at the proper rate. The platform is then erected to make its axes correspond to those of the gyros.

The computer must correct for three other factors: First, the earth is not actually a sphere but has, instead, a greater radius at the equator than at the poles. Because the orientation of the stable platform is controlled on the basis of calculations assuming a spherical earth, the latitude accelerometer tends to incline slightly away from a normal to the gravitational axis, i.e., the axis passing through the earth's center of mass, and thus to sense a small component of the earth's gravitational field. Second, the rotation of the earth about its polar axis produces a centripetal acceleration which has a component lying

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along the meridian and directed toward the equator. If not compensated, this component and the one resulting from the earth's ablateness would combine to produce a spurious acceleration signal from the latitude accelerometer. Therefore, the computer supplies a correction signal based on geographical position.

The remaining operation which the computer must perform is that of correcting for Coriolis acceleration, the phenomenon resulting when a vehicle moves in the direction of either pole and thus encounters variation in the linear velocity of the earth's surface. Corrections for this effect are computed and applied to the longitudinal accelerometer.

b. Alternate Arrangements

The stable platform of the system described above was maintained in a plane tangent to the earth's surface. Thus each of the gyros sensed a different component of the earth's rotational velocity. It was necessary for the computer to determine these components (as functions of latitude) and precisely to torque each gyro accordingly. To avoid the necessity for this demanding computation, some systems (typically not those used for ship navigation) incorporate a fourth gimbal, known as the latitude gimbal, and maintain the platform parallel to the equatorial plane. This orientation places the input axis of only one of the gyros parallel to the earth's spin axis; thus the other two are insensitive to earth rotation. The third gyro has its input axis parallel to the earth's spin axis. It therefore responds to total earth rate and can be compensated through the application of a fixed torque.

Systems have been built which employ five gimbals in such a way that the platform remains completely fixed with respect to space.

c. Composite Systems

The principal sources of errors in inertial systems are unbalance or bias in accelerometers and drifting of gyros. In the gravity-erected shipboard systems described above, a constant value of accelerometer bias will result in velocity and distance errors which vary sinusoidally with an 84-minute period. A constant value of gyro drift produces an oscillation of the platform about the vertical, and thus produces velocity and position errors varying sinusoidally with an 84-minute period. However, because of consequent errors in azimuth, a constant value of gyro drift will also bring about a distance error which increases monotonically.

The most common form of composite inertial system is one in which velocity, measured by some external source, such as an electromagnetic log, is used to damp platform oscillations and limit the amplitude of periodically varying errors. However, this measure is ineffective against the cumulative distance error caused by constant gyro drift or by random errors in velocity and distance caused by other phenomena. To eliminate these non-periodic errors--essentially to reset the inertial system--an additional system is required to obtain accurate navigational fixes. Such auxiliary systems can be designed to determine the ship's position either continuously or at discrete intervals. Use may be made of such navigational aids as Loran or Decca, of course, but of particular interest are systems which take advantage of the availability of the stable platform and which use celestial bodies for determining the ship's position. Composite systems such as these include a separate computer and an optical and/or radiometric sextant slaved to the stable platform. In effect the computer compares the actually observed altitude and azimuth of celestial bodies with those it has computed on the basis of the ship's position and heading as determined by the inertial navigator. Differences between the observed and computed values are used to provide corrective signals for latitude, longitude, and heading.

3. ACCURACY

Almost all inertial navigation systems for shipboard use have been installed on nuclear submarines and on missile range tracking ships, and data on their performance is classified. However, some notion of the accuracy obtainable can be derived from published information on airborne systems. For example, records of a large number of recent flights indicate that one system installed on jet airliners produces an error probability of 2.35 nautical miles per hour. It is likely that the accuracy demanded of inertial navigation systems (SINS) in Polaris submarines is considerably greater.

J. ACOUSTIC DOPPLER

1. INTRODUCTION

Both the Janus JN-400 and the Raytheon AN/SQS-12 acoustic Doppler navigation systems are self-contained active systems that operate on the Doppler or frequency-shift principle. In operational use, sound heads are positioned on the navigating vessel to transmit acoustic energy toward the ocean floor and to receive energy reflected from it. A precise measurement of the frequency shift of the reflected signal provides an accurate measure of the vessel's velocity over the bottom. An accurate magnetic or gyro compass is required for determining the heading reference.

These systems are capable of supplying the three basic quantities required for accurate navigation, i.e., speed relative to the bottom, distance traveled, and drift angle. In the Janus system, this information is displayed in digital form, and the course and position are manually plotted. Automatic track-following and plotting equipment has been developed for the more accurate Raytheon AN/SQS-12. Both systems are presently limited to operation in shallow waters of about 250-300 feet, where measurements of velocity and distance traveled have been demonstrated to be accurate to within 1%.

2. DESCRIPTION

a. Janus JN-400

The JN-400 equipment was developed for use on small craft in shoal waters less than 250 feet deep. The vessel's true speed over the bottom, the total distance traveled, and the drift angle with respect to a lubber line are displayed to the navigator in digital form. The true course over the bottom is found by adding the drift angle to the compass reading. The ship's relative position with respect to the point of departure is manually plotted by taking a digital reading (in miles) from the distance-traveled counter. This counter may be reset as required.

The basic track information is obtained by a fixed mounting of four transmitting transducers which are arranged to direct acoustic energy toward the ocean floor (see Figure IV-15). Energy striking the bottom is reflected and is received by four separate receiving elements. When the vessel is in motion, the received signal (Δf) is Doppler-shifted from the transmitted frequency (f) by an amount directly proportional to the velocity component (V) over the bottom and inversely proportional to the acoustic propagation velocity (C).
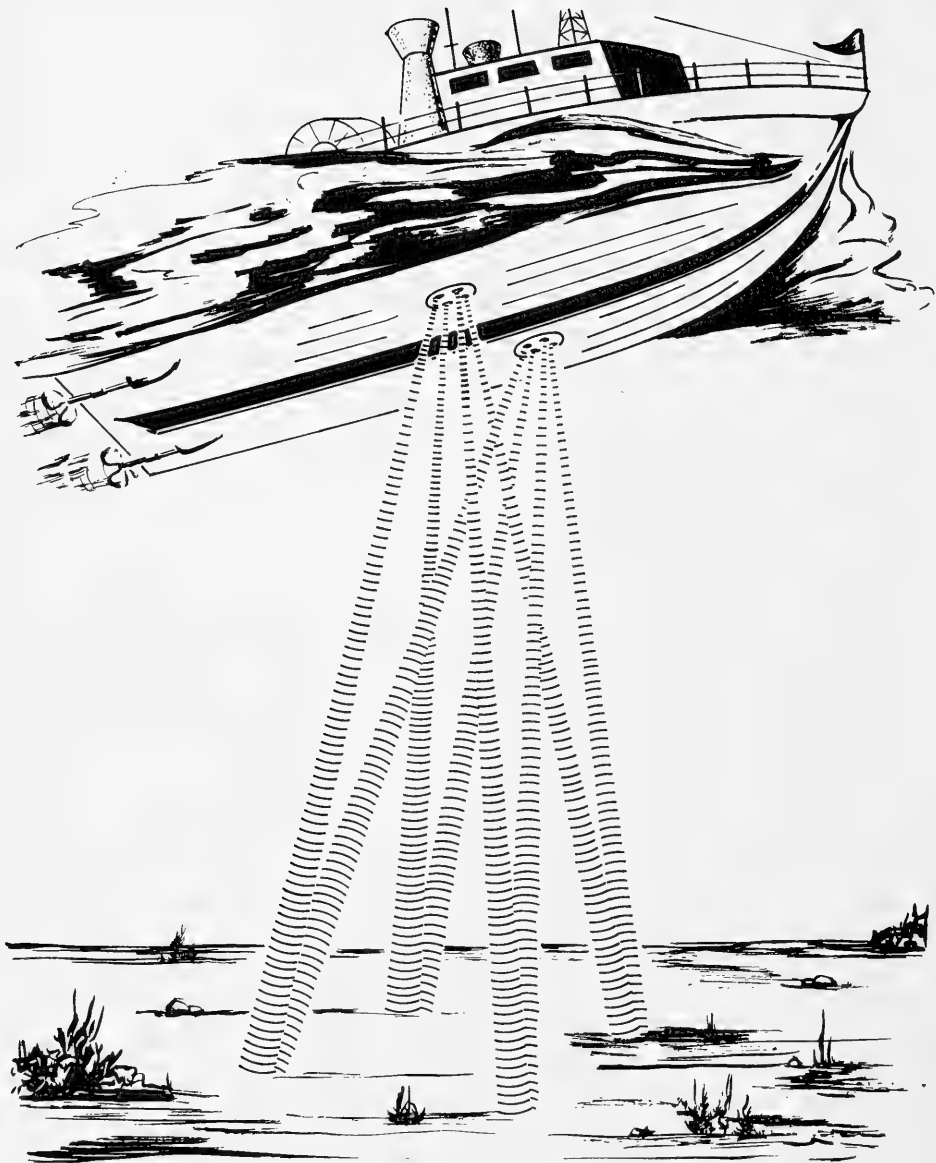
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FIGURE IV-15   JANUS JN-400 ACOUSTIC DOPPLER OPERATION

$$\text{(Doppler shift)} \quad \Delta f = \frac{V}{C} f \qquad (1)$$

Two pair of beams are used, one for the fore-aft and one for the port-starboard direction. This geometry tends to minimize the effects of vessel motion. Processing of the Doppler frequencies is performed in a small electronic console to yield the two velocity components and the resultant velocity over the bottom. The velocity is integrated once to obtain the distance traveled, and its phase relative to the fore-aft velocity components indicates the drift. Mechanical counters display both the drift and the distance traveled to six digits with a resolution of ± 0.001 nautical mile (± 6 feet).

The maximum depth where over-the-bottom information may be obtained is approximately 250 feet. This limit is set by limitations in power level and the high frequency used. At depths greater than 250 feet, sufficient return may be available from solid matter distributed within the water. However, velocity, in this case, is measured relative to subsurface currents. Although these generally have velocities between 0 and 0.5 knot, in some areas the velocity of subsurface currents may be considerably greater than this, and will produce an error in true velocity.

The system accuracy is 1-2% of the distance traveled. The $\pm 0.3°$ drift error specified for the equipment is considerably lower than the error in many of the heading references available. Velocity measurements have an accuracy of the order of 1% with a minimum threshold of about 0.1 knot.

b. Raytheon AN/SQS-12

The SQS-12 is a more sophisticated acoustic Doppler navigation system which is being developed for Navy use in shallow waters. Early tests of prototype equipment have indicated that this system can provide automatic dead-reckoning information with an error of less than 1%.

This developmental system uses an array mounted to a fixture on the bottom of the vessel in such a manner that the four transmitting-receiving pairs are arranged in two mutually perpendicular vertical planes. To increase the system accuracy, a stabilizing system can be employed to keep the 8-transducer transmitting and receiving array oriented in the true vertical direction and independent of small motions of the vessel. The array is also maintained in a north-south orientation by a servo mechanism which is referenced to a Mark 19 or the smaller, less accurate, Mark 26 gyro compass. It is the heading reference or compass error which limits the over-all accuracy of this system.

The distance traveled is displayed by four counters which record the distance traveled in each cardinal direction. Velocity over the bottom is also displayed digitally in the north-south and in the east-west directions. The ship's heading is indicated by a gyro repeater unit.

The vessel's track is traced on standard navigational charts by an x-y plotter to a resolution of 0.001 nautical mile on a chart scale of 1:10,000. The direction and scale factors are set by scaling circuits as required.

REFERENCE

Correspondent and data furnished by Janus Products, Inc., of Syosset, New York, and Raytheon Company, Submarine Signal Division, Portsmouth, Rhode Island.

V. MID-RANGE NAVIGATION SYSTEMS

A. DECCA TWO-RANGE SURVEY SYSTEM

1. GENERAL

The Decca Two-Range Survey system is a more recent development of the standard Decca Navigator system. It is used primarily for hydrographic surveying purposes where accuracy is important and a shorter range capability is acceptable. In this system the master transmitter is shipborne, as is the receiver, and the two shore-based slave stations are light in weight and mobile. Operational principles are the same as in standard Decca, but the geometry of the system leads to circular instead of hyperbolic patterns. Under favorable conditions, Two-Range Decca produces position fixes in error by only 25-60 feet.

2. DESCRIPTION

In 1950 there arose an operational requirement for radio navigation to aid in a marine survey in Antarctica, where only two suitable sites for shore stations were available. The Two-Range Decca system which was developed in response to this need has evolved into a useful survey tool which lends itself well to small, mobile equipment.

Figure V-1 illustrates the typical two-range layout. A master transmitter on the ship radiates a cw signal of frequency 12 f. The red slave station ashore receives this transmission and radiates a signal of frequency 8 f, in such a manner that the slave and master signals are phase-locked at the common multiplied-up frequency of 24 f. The lines of constant phase difference are now circles with a center at the red slave and a lane width of about 420 meters. Similarly, the master and green slave produce an intersecting circular net with a lane width of about 280 meters. Fixes are obtained through the intersection of a green and a red position line, as in standard Decca.

A notable characteristic of the system is that because the lane width is constant with increasing range, position accuracies of 1-2 meters are achievable. Furthermore, the angle of intersection of red and green position lines does not deteriorate with range. Thus accurate fixes are obtainable at ranges well in excess of 150 miles. A compensating disadvantage is the need for a transmitting station and receiver aboard each ship which desires to use the Two-Range Decca.

A more serious limitation is the high degree of pattern ambiguity. Before a fix can be obtained, ship position must be known to better than ±210 meters and ±140 meters from the red and green slaves, respectively.
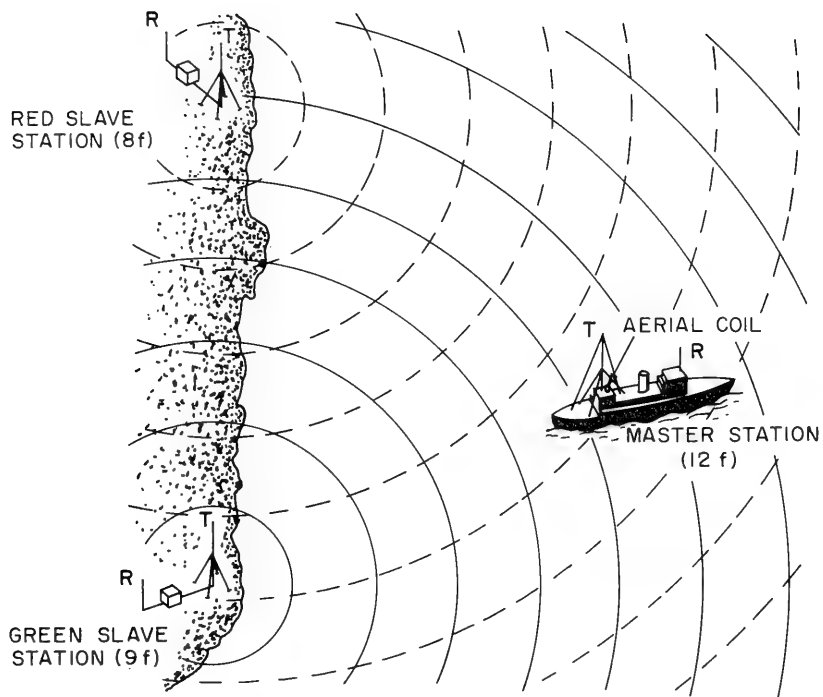
FIGURE V-1   DIAGRAM OF TYPICAL TWO-RANGE DECCA
HYDROGRAPHIC-SURVEY SYSTEM

The conventional Decca lane identification system does not lend itself to mobile equipment where light weight and compactness are desired, but a modified technique known as the Lambda method (Low Ambiguity Decca) which overcomes this difficulty has been evolved and is incorporated in a Decca survey system operating on the two-range principle. Lane identification is achieved as in standard Decca by superimposing on the fine grid a coarse circular pattern with a lane width of about 10 km.

3. ACCURACY

Errors in position as obtained with the Decca Two-Range Survey system are both systematic and random in nature. The systematic errors can generally be corrected to the degree required. More important are the random errors which may be caused by the instability of wave propagation and by instrumental variations.

Systematic errors usually involve incorrect knowledge of the mean velocity of propagation, and corrections must be made where the highest system accuracy is to be obtained. Corrections for variations in ground conductivity are usually applied in high precision work. This is especially important where part of the transmission path is over water and part over land. Figure V-2 illustrates the amount of phase correction required for the red and green stations for a typical seawater transmission path. With proper correction these errors can be reduced to about 1 or 2 parts in 10,000.

An additional phase shift caused by placing the receiver in close proximity to the transmitter must also be accounted for. This correction is usually determined experimentally.

Random errors often occur because of variations in skywave interference. This type of interference generally appears during the period from sunset to sunrise at all seasons of the year. It becomes detectable with this equipment at ranges beyond about 40 miles and increases in magnitude as the range increases. For this reason the survey activity is generally confined to daytime operation. During summer daylight, 95% rms radial errors run from 25 to 60 feet as the range increases. Typical random-error contours for daylight operation are illustrated in Figure V-3.

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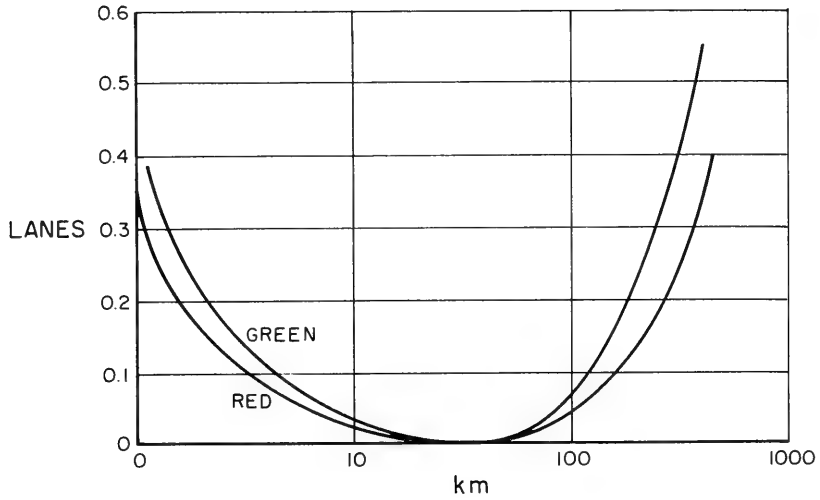
FIGURE V-2   PHASE CORRECTION VS RANGE FOR
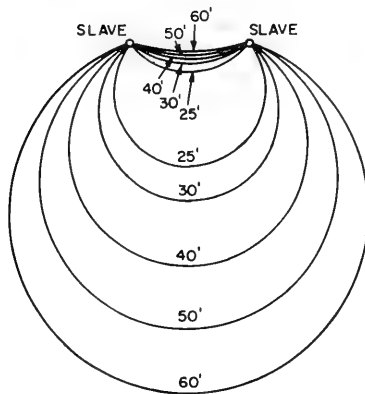   TYPICAL SEAWATER TRANSMISSION
              PATH

FIGURE V-3   FIXING ACCURACY CONTOURS FOR
              SUMMER DAYLIGHT OPERATION FOR
              A 0.01 LANE DEVIATION

4. SUMMARY

a. Type of System

 (1) Circular plot single-user system.

 (2) Number of shore stations required: master and two slaves (red and green).

 (3) Length of base line: 60 miles or less.

 (4) Frequency range: 112-180 kc (approximately).

 (5) Transmitted power: 350 watt cw shipboard-mounted transmitter.

 (6) Mobile antenna: 45-feet tubular sections.

 (7) Range: 6-175 nautical miles (approximately).

 (8) Receiver power requirements: 250 watts (approximately).

 (9) Shipboard and shore station power requirements: 2 kw.

 (10) Receiver readout: 4 dial Decometer Unit providing (Decca Mark 5 shipborne set) Lambda Identification System - Marine automatic track plotter provides continuous position plot in rectilinear coordinates.

b. Range and Accuracy

 (1) Usable service distance: 175 nautical miles.

 (2) Approximate 95% rms radial error at 40 nautical miles: 25 - 60 feet.

 (3) Approximate 60% rms radial error at 175 nautical miles: 300 feet.

REFERENCE

C. Powell, "Radio Aids to Hydrography," Wireless World, July, 1960.

B. ELECTRONIC POSITION INDICATOR (EPI)

1. GENERAL

The EPI electronic method of position control for use in hydrographic surveys was developed by the U.S. Coast & Geodetic Survey in the late 1940's. It was designed to complement the near-shore Shoran equipment (see Section VI E) and has a useful range of 200-500 miles, depending upon atmospheric conditions at the time of measurement. It operates at a frequency of 1.85 mc and is principally used for the control of a hydrographic survey on a scale of 1 : 100,000 and smaller.

Like Shoran, EPI is a pulse phase-measuring system which requires a minimum of two shore stations positioned at the ends of a fixed base line. In place of the automatic transponder-type shore stations found in Shoran, the EPI ship-positioning system uses interrogation and reply. It is a (rho-rho) system which measures the distance from the ship to each ground station. Periodic pulses are transmitted from the ship. The shore station operator observes the ship signals and his own shore station signal on a cathode-ray-tube display. He manually makes proper adjustment so that the two signals coincide. Delays of known size are incorporated in the circuits to prevent confusing one ground station with the other. Aboard ship, the signal pips are viewed on a similar cathode-ray tube and manually matched to the stationary ship signal pulse. The distance is displayed in digital form in units corresponding to microseconds of time. One unit on the dial equals about 150 meters, or 492 feet. Position fixes accurate from about 50 feet to 200 feet can be expected at ranges of 200-250 miles.

2. DESCRIPTION

The equipment consists of a shipborne transmitter which transmits precisely timed pulses toward the two shore stations positioned at either end of a base line. These stations, in turn, retransmit similar pulses accurately synchronized with those from the ship. A shipboard receiver-indicator unit (Figure V-4) receives the two ground station pulses and displays them simultaneously at a rate of about 20 times per second. Distance measurements to each ground station are then made by the shipboard operator.

Because of the low transmission frequency of 1850 kc the rise time of the pulse at the receiver is slow, i.e., 8-12 microseconds. For this reason, the received pulse is not used to retrigger the shore transmitter as in Shoran, because large errors would result if the pulse were noise-modulated. A synchronizing method is used in EPI which precisely sets the time at which the
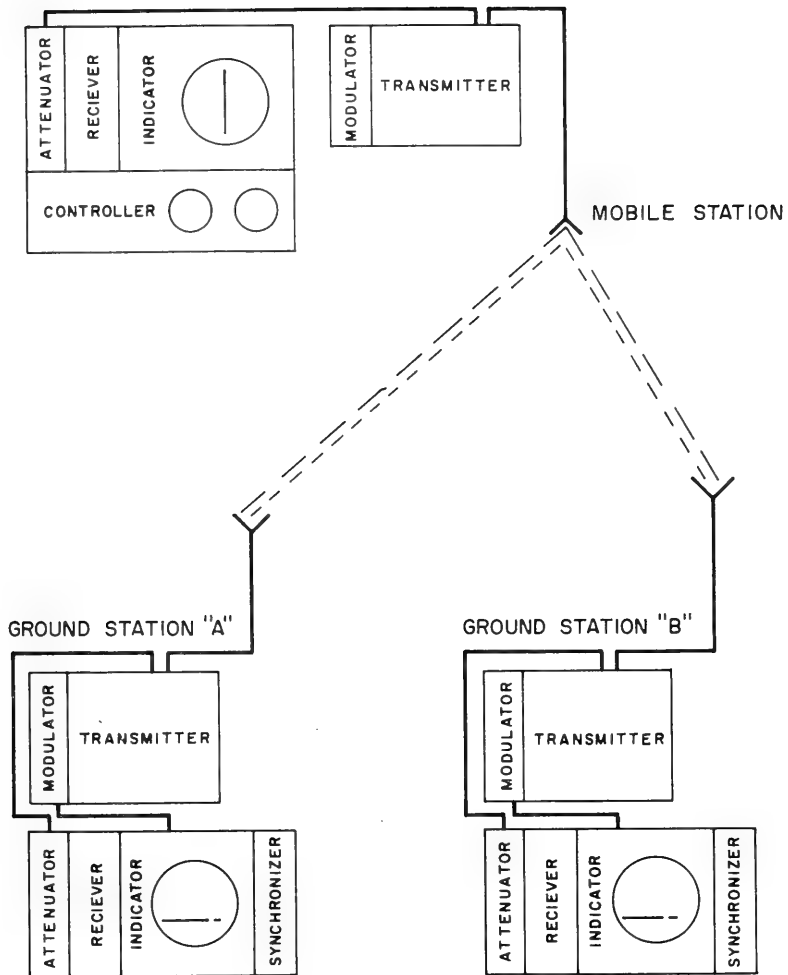
FIGURE V-4   BLOCK DIAGRAM FOR EPI SYSTEM

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ground station signal will be transmitted with respect to the time the ship station signal was received. A constant velocity of propagation is assumed and corrections are not normally made.

a. Shipboard Equipment

The timing of the entire system is controlled by a highly stable 100-kc crystal oscillator in the shipboard controller. Divider circuits are used to produce signals for driving the distance-measuring circuits, gating delay circuits and initiating pulses for the transmitter.

The 100-kc timing signal is also fed to three synchro-resolver circuits in the range units, along with the outputs of the appropriate dividers. The signals from the three resolver circuits (10, 100, and 1000 microseconds) are used to measure the distance between the ship and the ground stations.

A separate resolver system is used for each of the two ground stations, so that the distance to each shore station is measured simultaneously. The counting is done by a large vernier dial reading to 10 microseconds with a resolution of 0.1 microsecond. The dial is coupled to a counter which reads tens, hundreds, and thousands of microseconds, and thus indicates the distance to each ground station in microseconds.

Pulses from the range resolvers are directed to the indicator, where they initiate the cathode-ray-tube sweep. The sweep is positioned by operation of the ranger until it occurs simultaneously with the reception of the ground station signal. The pulse which triggers the transmitter also triggers a fixed, stationary sweep on which the transmitter signal is displayed. By adjusting each ranger so that its ground station signal is in coincidence with the ship pulse, one may read out the distance between ship and ground station on the vernier dial and counter in loop-microseconds.

The "A" ground station and "B" ground station signals are made to appear on the left and right sides of the vertical cathode-ray-tube sweep. The two signals are commutated at a high rate and thus appear continuously displayed to the operator.

Signals from both shore stations are received aboard ship on a single receiver and a common antenna quarter-wave flat-top antenna. The incoming signals are coupled to the receiver by an attenuator unit which amplifies the signals from weak ground stations and shorts out those from the transmitter. The receiver utilizes automatic gain control to equalize the strength of the signals from both ground stations.

The transmitter operates at a frequency of 1.85 mc and produces precisely spaced pulses at a peak power of 10 kw (average power about 25 watts). The pulse width is about 60 seconds and is produced with a repetition rate of 41-2/3 pulses per second. The peak power can be raised to 18 kw when ranges greater than 500 miles are required. The transmitter output is fed to a quarter-wave flat-top antenna.

b. Ground Station Equipment

The ground station equipment receives rf pulses from the ship and transmits a signal back to the ship after a definite time delay. All ground station equipment used for this purpose is similar in operation to the shipboard equipment except for the controller indicator.

The indicator contains a precision 100-kc oscillator which controls the timing functions of the shore station. It is closely synchronized to the ship crystal by appropriate AFC and synchronizer equipment and maintains a minimum timing accuracy of 0.1 microsecond. The degree of synchronization is continuously displayed for the operator.

A cathode-ray tube with horizontal sweeps is used to display the shipboard and ground station signal pulses. The operator continuously adjusts the shore station signal to match the time of arrival of the shipboard pulse.

A quarter-wave vertical radiator is used for both transmitting and receiving. A ground plane consisting of radial wires approximately 100 feet long is required for proper antenna operation.

The equipment requires about 5 kw of 115 v, 60 cps, single-phase, alternating current. This is sufficient for both equipment and station operation.

3. ACCURACY

Both systematic and random errors occur in the operation of EPI equipment.

a. Systematic Errors

Systematic errors include such factors as:

(1) Incorrect velocity of propagation

(2) Non-linearity of range circuits

(3) Initial zero correction.

A velocity of propagation of 299,690 km per second at a sea level pressure of 760 mm is assumed. The velocity is subject to change due to changes in barometric pressure, humidity, etc., but it is probable that the error caused by these assumptions is not greater than 5 parts in 200,000.

The non-linearity of the range circuits can be determined in the laboratory. Corrections can be applied if necessary. Generally they do not exceed 0.1 microsecond and can be neglected in hydrographic work if the scale is smaller than 1 : 100,000.

A small initial zero correction must be applied to all distance measurements. This error is caused by the difficulty of making the vernier read exactly zero to correspond to zero time. The error can be determined at the will of the operator and applied or corrected at any time. Daily calibration is necessary to correct for normal instrument drift.

b. Random Errors

The random errors are more serious, with no way of predicting their magnitude. They occur both in the shipboard equipment and shore station equipment and are caused mainly by human error.

At the ship they are:

(1) Misalignment of local and distance pulses

(2) Careless reading of the distance verniers and dials

(3) Poor alignment of pulses.

At the ground station they are:

(1) Poor synchronization of the time fix

(2) Incorrect setting of the balance gain.

The effect of all of these possible errors in the EPI system is to cause an uncertainty in position which is directly related to the magnitude of the error (algebraic summation) and the angle at which the distance arcs intersect. Experience has demonstrated that negligible error is introduced when the intersecting arcs are kept within the limits of 30° - 150°.

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Extensive field and laboratory tests have been performed by the USC & GS to determine the EPI system's accuracy and consistency. Table V-1 lists these data as a percentage of observations that come within the fraction of microsecond indicated. Accurately measured distances of 45, 90, 110, and 267 nautical miles were used. A total of 267 sets of observations were made. These tests also indicate there is little correction required to compensate for signal strength or distance between the ship and ground stations.

TABLE V-1

FIELD TEST DATA FOR EPI

Limits of Error ± Microseconds	% Observations Within Specified Limits	
	Field Tests 267 Observations	Laboratory Tests 21 Sets of Observations
0.1 (15 meters)	35	26
0.2 (30 meters)	53	53
0.3 (45 meters)	72	71
0.4 (60 meters)	83	82

4. SUMMARY

a. Type of System

(1) Pulsed phase-difference circular plot.

(2) Number of stations required: 2 shore stations, 1 shipboard station.

(3) Length of base line: 50-250 miles.

(4) Operators required: at ground stations and on shipboard.

(5) Transmitter pulse width: 60 microseconds.

(6) Transmitter pulse repetition rate: 41-2/3 per second.

(7) Shipboard transmitter frequency: 1.85 mc.

(8) Shore station transmitter frequency: 1.85 mc.

(9) Shipboard and ground station peak pulse power: 10-18 kw.

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(10) Shipboard antenna: one-quarter wave loaded flat top.

(11) Shore station antenna: one-quarter vertical dipole and ground plane.

(12) Ground station transmission: time separated by a controlled and precise delay.

(13) Number of ships handled by ground station: 1 ship or 2 ships (time sharing).

(14) Readout: pulse matching on shipboard cathode-ray tube. Distance is read on a vernier to 0.1 microsecond and digital counters to 9999.9 microseconds. Time is converted to distance using C = 299,690 km per second.

b. Range and Accuracy

(1) Usable service distance: 15-500 nautical miles.

(2) Approximate accuracy of distance measurement: 50-200 feet at distances out to 250 miles.

(3) Accuracy of LOP: dependent upon absolute magnitude of errors and angle at which distance arcs intersect. Area of uncertainty is negligible when angles of intersection are between 30 and 150°.

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C. LORAC

1. GENERAL

The LORAC (Long Range Accuracy) ship-positioning systems were developed by the Seismograph Service Corp. for survey work in the shelf area of the Gulf of Mexico. The LORAC system was designed to extend survey work beyond the line of sight distances of Shoran without sacrificing the accuracy of position determination.

LORAC is a hyperbolic cw phase comparison system using frequencies in the 1700-2500 kc band. At these medium frequencies rf energy tends to follow the curvature of the earth, permitting a high degree of accuracy.

However, both lower and higher frequencies have been used. At 2 mc the operating range is of the order of 135 miles during the day, but is limited to about 50 miles at night due to sky-wave interference. Over water, accuracy is of the order of ± 2.5 feet along the base line and is gradually degraded as the mobile receiver moves away from the base line.

Both LORAC A and LORAC B are position-fixing systems, and both supply a double hyperbolic grid. In both systems transmitting stations are set up at fixed shore sites. The basic receiving set displays grid coordinates in the form of dial and digital counter readings. Special indicating equipment including a course plotter, digital printer, tape punch, and distance-heading indicator is available.

2. DESCRIPTION

In the basic LORAC system, illustrated in Figure V-5, cw transmission is used and a phase difference measurement is made at the mobile receiver to obtain the coordinates of its position. Transmitters T_1 and T_2 are located at the ends of a base line and operate on frequencies f_1 and f_2 which differ by an audio frequency. A reference signal is established at T_3 by detecting the heterodyne beat between T_1 and T_2. This detection takes place at a fixed point and, therefore, has a constant phase angle. It is transmitted to the mobile receiver as amplitude modulation on a third rf frequency f_3.

The receiving station contains two separate receivers. The direct-heterodyne difference frequency when received at the mobile station has a phase angle dependent upon the station position relative to the base line. The difference in phase between the direct-heterodyne difference frequency and the

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reference-heterodyne frequency transmitted from T_3 is measured. The measured phase angle determines the location of the mobile station on one hyperbolic line of position.

To obtain a second line of position, the complete system of Figure V-6 is duplicated. A second base line which results in the second LOP is formed. The two patterns thus generated are conventionally known as the red and green patterns.

The phase meter at the mobile receiver is geared to a revolution counter which indicates the number of lanes traversed in both patterns. The readings can be transferred to charts of the area on which the equiphase contours are drawn, and a position fix can be established. Lane identification is not provided in the basic LORAC system.

The basic system requires six transmitters, six receivers, and four frequency channels to locate one mobile station. This is a multi-user system, and there are no limitations on the number of mobile receivers using the system simultaneously. However, the other LORAC systems provide the same capability and use less equipment.

a. LORAC Type "A" System

In the LORAC type "A" (Alpha) system the equipment required is reduced by the use of a time-sharing procedure. The system is similar to the basic system except that the T_1 and T_3 ground stations alternate as reference stations, as illustrated in Figure V-7. This system requires three transmitters and two receivers to establish a hyperbolic grid system. A receiver is required at both the red and the green ground stations. Each mobile station using the system requires two receivers and two phase meters along with the required frequency selective equipment.

The central shore station, T_2, alternately transmits two frequencies. The transmitter and receiver at both the red and the green ground stations are continuously energized. In this manner, a heterodyned reference signal is alternately transmitted as modulation on a carrier from each ground station and received at the mobile station. Simultaneously, a heterodyne position signal is received on a second receiver at the mobile station. These two signals are compared and displayed on an integrating-type phase meter. In this manner red and green lines-of-position are alternately established, with each phase meter operating for one-half of the complete cycle. The switching rate is sufficiently rapid to produce the effect of continuous transmission at the position indicators.
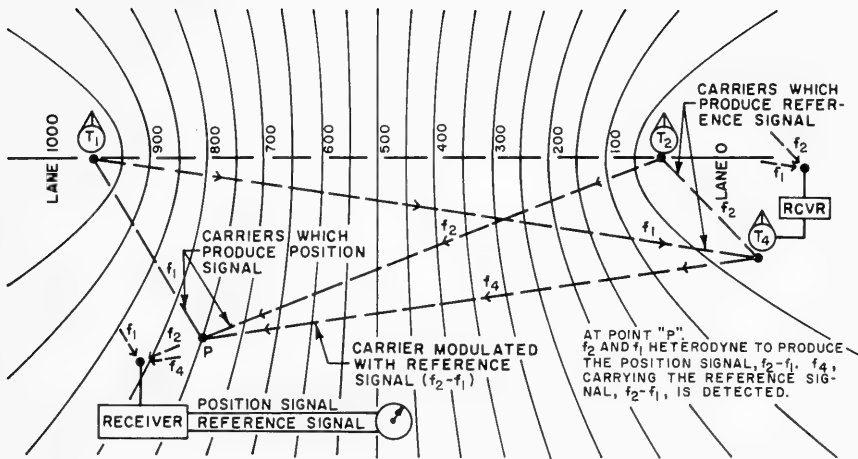
FIGURE V-5   BASIC LORAC SYSTEM REQUIRED FOR ONE
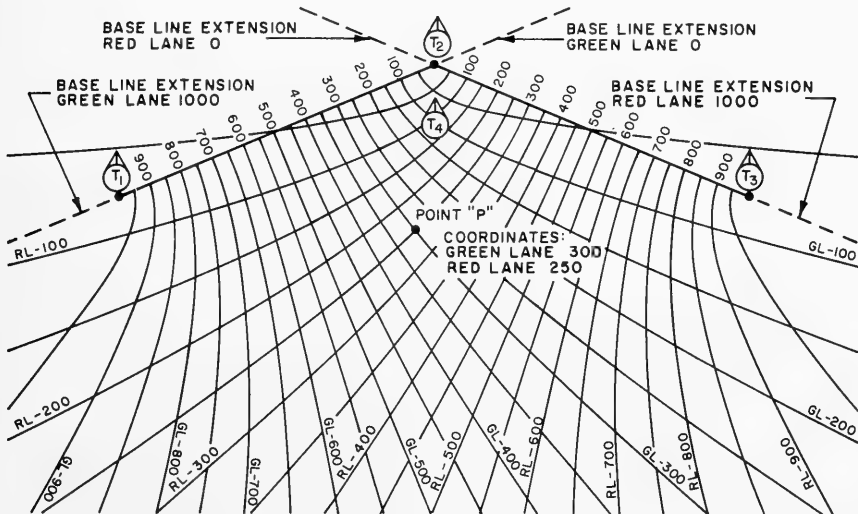   HYPERBOLIC LINE OF POSITION
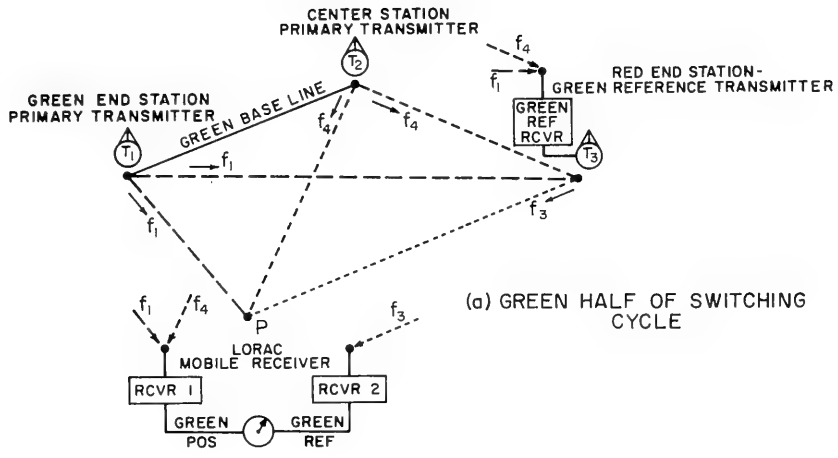

FIGURE V-6   HYPERBOLIC POSITION GRID

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(a) GREEN HALF OF SWITCHING CYCLE

FIGURE V-7   LORAC TYPE A (ALPHA) GREEN HALF
OF SWITCHING CYCLE

b. LORAC Type "B" System

The type "B" (Beta) system transmitters T_1, T_2, and T_4 establish one-half of the positioning grid and are called green lanes. The transmitters T_2, T_3, and T_4 establish the red lanes, as shown in Figure V-8. Transmitters T_1, T_2, and T_3 occupy precisely surveyed positions, while the receiver and transmitter of T_4 are placed at a convenient position within the grid system.

Figure V-8 indicates the frequency relationships of the complete Beta system. Mobile receiver No. 1 produces both the green position signal $(f_2 - f_1)$ and the red position signal $(f_4 - f_3)$. Receiver No. 2 receives both the red and green reference signals transmitted as amplitude modulation on carrier f_4.

The Beta system is less complex than the basic system. Beta requires four transmitters, one receiver, and four frequencies to establish a hyperbolic grid. Time sharing is not required. In addition, the Beta system has a somewhat greater area of coverage than Alpha.

c. Calibration

The LORAC equipment is a differential-distance-measuring system and for this reason must be calibrated for the particular grid system in which it is to operate. A hyperbolic position grid is drawn[1] when the location of transmitters T_1, T_2, and T_3 is precisely known.

The calibration is generally carried out by locating the mobile receiver at an accurately known geographic position within the grid system. The phase counters are then adjusted to the calculated lane settings and the phase meters set to the proper phase position within the lane. As the mobile receiver moves from this position, the phase meters and counters track and continuously indicate the ship's position on the grid system.

d. Transmitting and Receiving Equipment

LORAC transmitting and receiving equipment is of unitized construction, providing good portability and interchangeability. The transmitters are of two types, depending upon their function within the LORAC system used. They are adjustable over the frequency range of 1.7 to 2.5 mc and use a temperature-stabilized crystal master oscillator for close frequency control.
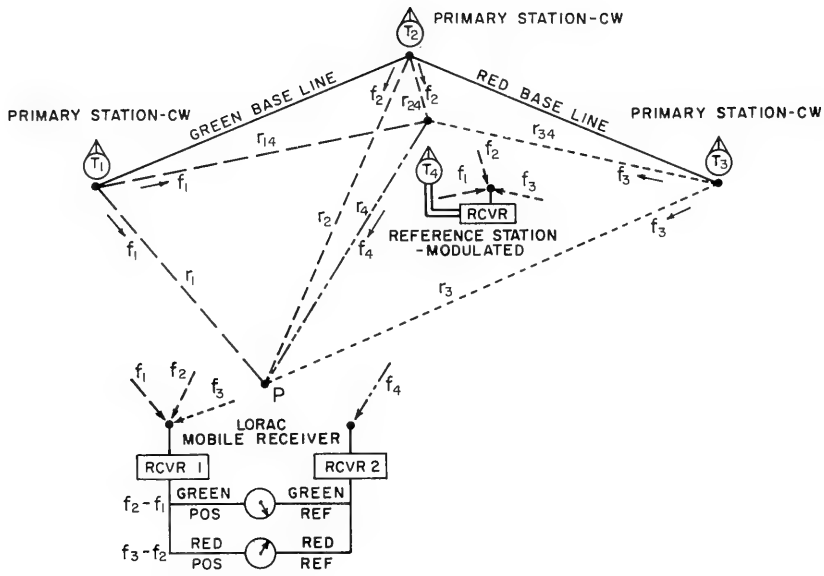
121

FIGURE V-8   LORAC TYPE B (BETA) OPERATION

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The basic radio receiver is also adjustable over the frequency range of 1.7 - 2.5 mc. The position indicators are part of the receiver and display the grid coordinates as dial and counter readings. The receiver also provides outputs to drive special indicating and course-plotting equipment.

e. Recording and Readout

The two phase meter indicators of both the Alpha and the Beta systems provide outputs for a digital printer and tape punch unit so that a ship's course can be recorded. Additionally, an Actrac course plotter may be used with the indicators to provide instantaneous position and track on preplotted charts; a distance-heading indicator also may be used to help navigate between preplotted points.

3. ACCURACY AND RANGE

In cw phase-measuring systems such as LORAC, the one-half wave lengths are counted and then a phase measurement is made of the remaining fractional one-half wave length. The accuracy is a function of the frequency employed. For a frequency of 2.0 mc, the wave length is approximately 492 feet. On the base line a lane (one-half wave length) is 246 feet, which constitutes a phase-difference reading of 360°. The phase meter is calibrated to 0.01 lane or ±3.6°, which is about ±2.5 feet on the base line. At distances farther from the base line, the lanes widen and the accuracy of the position fix is reduced. Field reports have indicated accuracies of 1 : 50,000 are achieved without difficulty.[2]

Over water, operating ranges up to 135 nautical miles during the day have been reported. At night, operation is restricted to base line lengths of less than 55 miles, because of sky-wave interference.

Propagation effects may produce other errors where part of the propagation path is across land masses. The magnitude of these errors has not been completely investigated, but an error of 0.1 lane would not be unusual. Larger errors can be expected where the propagation path is over rough terrain or where hills produce a shadow effect. A constant velocity of propagation is assumed for most LORAC navigational problems.

Because of the method of transferring a reference heterodyned signal to the mobile station, transmitter frequency synchronization is not needed in LORAC ship-positioning systems. However, in a cw positioning system of this type an ambiguity does exist. The two phase measurements which are required identify the position of the receiving station relative to the two intersecting pairs of

hyperbolic isophase lines, but they do not indicate the pairs of lines to which the readings are related. Thus, the geographic position of the receiving unit relative to the transmitting stations must be known at the start of the hydrographic survey. Each successive half-wave interval must then be tabulated as the receiving station is moved relative to the pattern of the hyperbolic grid. Digital counters mechanically coupled to the phase meters are provided for this purpose.

4. SUMMARY

a. Type of System

(1) Cw phase-difference hyperbolic plot multi-user system.

(2) Number of shore stations required:

Alpha: 3 (3 transmitters and 2 receivers required)

Beta: 4 (4 transmitters and 1 receiver required)

(3) Length of base line: 10 - 50 miles.

(4) Operators required: at ground station and on board ship.

(5) Transmitter frequency: 1.75 - 2.5 mc (crystal-controlled, adjustable).

(6) Shore station power level: 300 watts.

(7) Shore station transmitting antenna: one-quarter wave dipole.

(8) Shore station receiving antenna: directional loop.

(9) Shore station transmission: cw with no synchronization required.

(10) Shipboard receiving antennas: one-quarter wave dipoles (2).

(11) Mobile station readout: phase meters (2), red line and green line. Also provisions for driving automatic track plotter, tape punch, digital printer and distance-heading indicator.

(12) Lane identification: digital counter follows movement from lane to lane. Must be pre-set at known geographic position at the start of survey.

b. Range and Accuracy

    (1) Usable service range: 55 - 135 nautical miles.

    (2) Approximate accuracy of range measurement: 1 : 50,000 feet, depending upon the position of the mobile unit relative to the shore station transmitters.

    (3) Accuracy of LOP: dependent upon absolute magnitude of errors and angle at which hyperbolic arcs intersect. Area of uncertainty is negligible when angles of intersection are between 30 and 150°.

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1. LORAC - Seismograph Service Corp., Tulsa, Oklahoma - Radio Aids to Maritime Navigation and Hydrography. S.P. 39 - Article supplied, April 1960.

2. G. Leifson, "Hyperbolic Positioning Systems for Hydrographic Surveys," U.S. Hydrographic Office, International Hydrographic Review, May 1953.

3. Edward J. Crossland, "LORAC: What It is and How It Works," Seismograph Service Corp., Tulsa, Oklahoma. Reprinted from Philco Tech Rep Division Bulletin, March 1952.

1. GENERAL

Raydist is the generic name of a family of radio distance-measuring and navigation systems produced commercially by Hastings-Raydist, Inc., Hampton, Virginia. These systems are used extensively by the U.S. Coast and Geodetic Survey and by a number of commercial organizations and foreign governments.

All forms of Raydist operate on the same basic principle. Two cw transmitters are located on a base line and separated by a distance of up to 100 miles. They are operated at frequencies in the 1.6 - 5 mc range, the two transmissions differing by about 400 cps. The 400 cps beat note is obtained at each station and retransmitted to some convenient location where phase comparison is performed, yielding interstation distance. The frequency range used permits small efficient transmitters and operation to beyond line-of-sight.

Several geometric configurations are possible, depending upon the position of the stations, and include hyperbolic and elliptic coordinates, angle measurements, and circular or direct distance measurements. Because of the vast superiority of direct distance measurement, this system (DM) is replacing the others in all but a limited number of applications. It is illustrated in Figure V-9. Its major advantages are the requirement for only two stations, the simplified circular charts, and the much higher accuracy and area coverage inherent in the circular geometry.

All forms of Raydist are entirely automatic in operation, the position data being read directly from the phase meter dial or from the plot of an automatic position recorder. Accuracies of one part in 5000 can normally be expected, while one part in 50,000 or better is achievable in certain survey operations.

2. DESCRIPTION

a. DM Raydist

This system was developed for precise two-dimensional tracking of small cw transmitters for purposes of navigation, surveying, or position plotting. It gives the instantaneous position of a mobile transmitter with reference to two fixed receiving stations identified as the red and green stations. Mobile station equipment includes a cw transmitter, and the "Navigator," consisting of a special-purpose, dual-frequency receiver and a phase comparison unit (Fig. V-9).
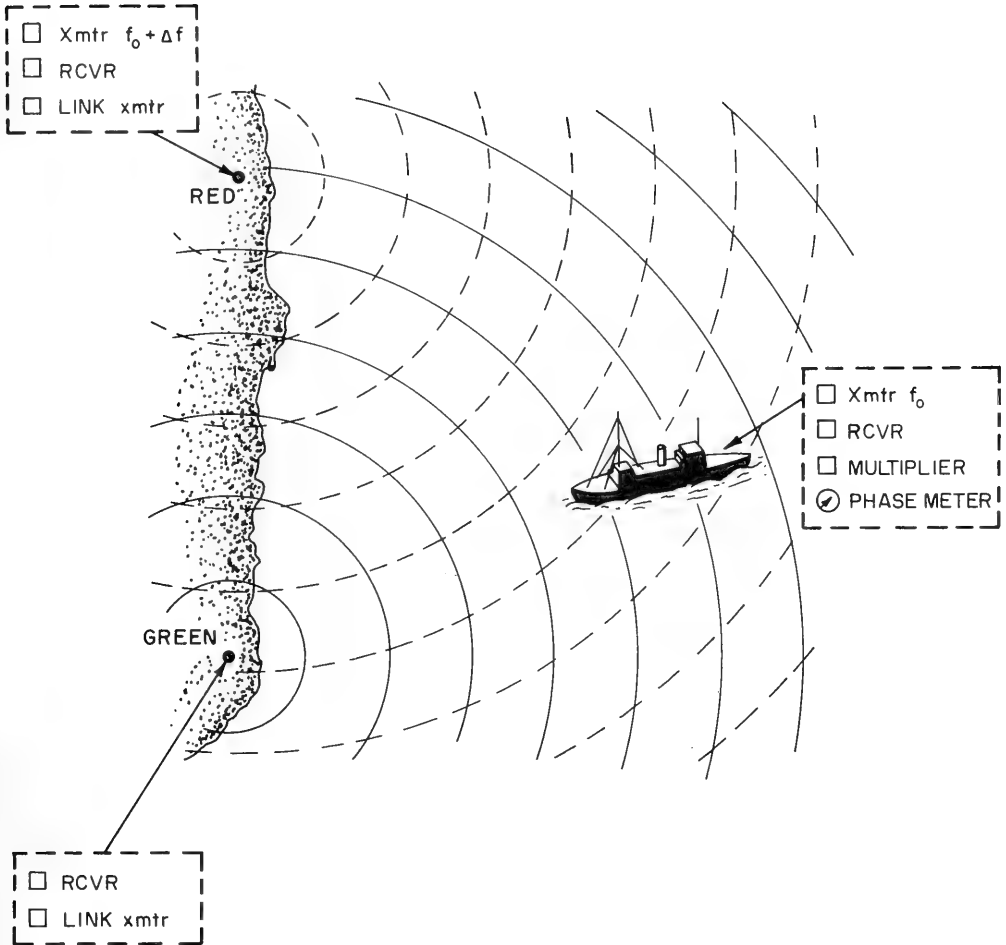
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RED

GREEN

- ☐ Xmtr $f_o + \Delta f$
- ☐ RCVR
- ☐ LINK xmtr

- ☐ Xmtr f_o
- ☐ RCVR
- ☐ MULTIPLIER
- ⊘ PHASE METER

- ☐ RCVR
- ☐ LINK xmtr

FIGURE V-9   DM RAYDIST LATTICE

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A cw transmitter located at the red station operates at a frequency 400 cps higher or lower than the mobile station frequency. A special-purpose, dual-frequency receiver is also used at both the red and green shore stations. The receiver at each shore station accepts the transmission from both the mobile station and the other shore station, doubles the lower frequency and heterodynes it with the higher frequency to generate the 400 cps audio beat note. Separate audio notes are then returned to the mobile station by the red and green stations as a modulation of two additional, completely independent frequencies. The Navigator phase-compares these signals with the beat note it produces locally. A comparison of the red signal with the local mobile frequency yields a reading on the phase meter of the distance to the red station. Comparing the green signal with the local signal yields a measurement in elliptic coordinates which the phase meter then converts into distance to the green station.

The system employed permits more than one user. A second Navigator-equipped vessel, for example, would transmit on a slightly different frequency, and produce therefore a slightly different beat note. A composite of both notes appears at the two shore stations and is returned to both Navigators. However, the local signal generated as the heterodyne of the vessel's own transmitter with the red transmitter will be a pure tone, since each shipboard transmitter is so close to its own receiver as to preclude reception of other transmissions on nearby frequencies. The mobile station phase meters respond only to the tone in the composite frequency corresponding to the pure tone and thus indicate the distance to the red and green stations.

b. Type DR Raydist

In this system, two independent DM systems are employed. Consequently, it is unnecessary to make transmissions from one shore station to another, an advantage when such transmissions are difficult because of a large interstation distance or rough terrain.

c. Type R Raydist

This system corresponds to DM Raydist but employs only the red shore station. As a consequence, two-dimensional fixes cannot be obtained; only direct distance to the red station can be obtained.

d. Type E Raydist

A group of stations are utilized to set up an intersecting net of hyperbolic coordinates. The shore station-Navigator combination of Type R is

duplicated at several points. The chief advantage of this system is that it can be designed so that heterodyning, phase comparison, and distance measurement are all performed at shore stations. The tracked object then requires a minimum of equipment, namely a small cw transmitter. For certain applications involving, say, expendable transmitters in buoys, the Type E system can prove quite practical. It is interesting to note that this form of Raydist was used for tracking the first satellites.

e. Other Systems

A number of other hyperbolic systems are in limited use, although they are being gradually superseded by the distance-measuring forms. Chief among these is the Type N Raydist, which is completely nonsaturable and finds application where the number of simultaneous users exceeds the capabilities of a DM system. The largest single Type N installation is a network covering the coastal waters of the Gulf of Mexico and used largely for offshore oil exploration.

3. RANGE AND ACCURACY

Because of the circular coordinates involved, DM Raydist has substantially greater potential for accurate position fixes than do the hyperbolic systems. DM Raydist is more accurate because lane width remains constant with increasing range in a circular system, while increasing very rapidly with range in hyperbolic coordinate systems. In addition, the angle of intersection of hyperbolic coordinate nets increases much more rapidly with range, so that two-dimensional fixes are subject to larger errors. Figure V-10 compares the accuracy of a circular and a hyperbolic system on the basis of these geometric considerations alone. It should be noted that other errors such as propagation velocity and ionospheric effects would also be greater in hyperbolic systems than in the distance-measuring system.

The frequencies (1.6 - 5 mc) employed by Raydist provide a lane width equivalent to a one-cycle change in phase. This is equivalent to distances of 30 and 100 meters. Since the phase meter can be read to 0.01 lane, readability of Raydist systems is 1/3 - 1 meter in the DM forms, and 1/3 - 1 meter difference in distance with the hyperbolic types.

Other accuracy considerations include the care with which shore stations are positioned and the system calibration. Experience has shown that accuracies of 1 : 5000 with a probable error of the order of 3 meters can be normally expected, and that accuracies to within 1 meter are achievable.

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10

30
20
10

HYPERBOLIC
SYSTEM

A   B

DM
RANGE
SYSTEM

IDENTICAL
BASE LINES
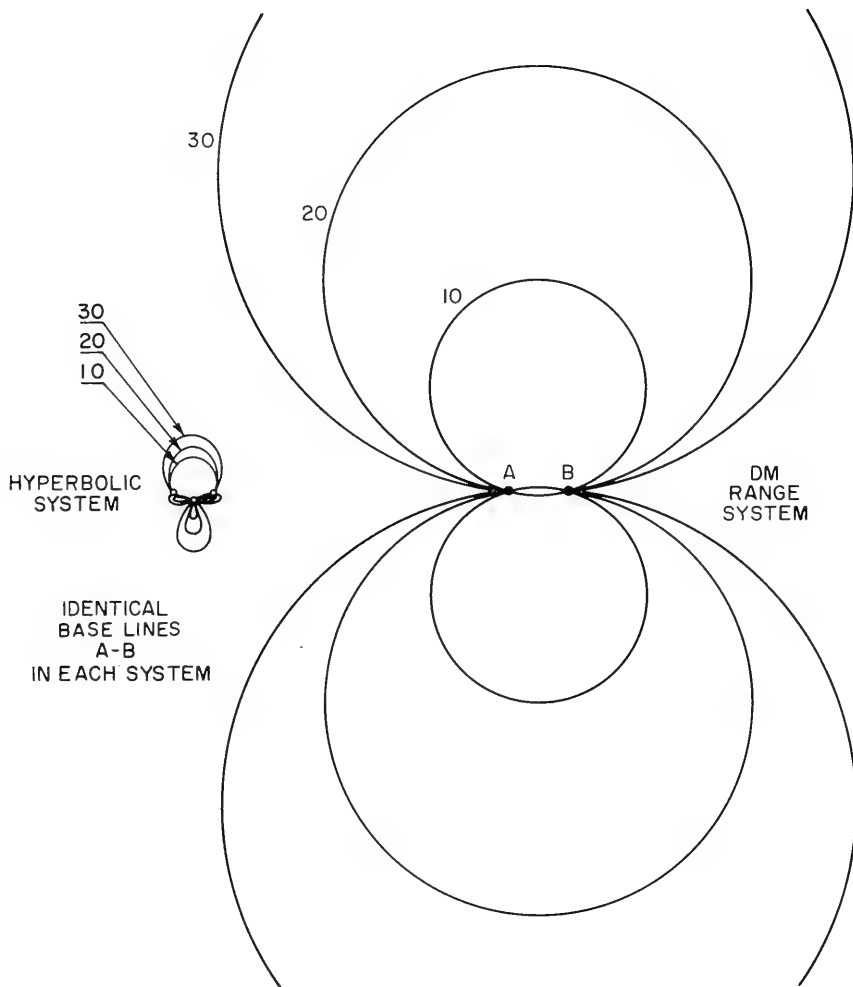A-B
IN EACH SYSTEM

FIGURE V-10   COMPARISON OF AREAS OF EQUAL ACCURACY
FOR CORRESPONDING RANGING AND HYPERBOLIC
SYSTEM

Operating ranges depend on the usual factors, including propagation path, ambient radio noise, sky-wave interference and its variations with season and time of day, receiver sensitivity, and transmitter power. Maximum ranges of 100-200 miles are usual under all but the most severe conditions. The newer miniaturized equipment is rated for 25 miles but has been operated at ranges in excess of 60 miles.

4. SUMMARY

a. Type of System

(1) Phase comparison of audio beat note.

(2) Direct-distance (circular) or hyperbolic coordinates.

(3) Operating frequency: 1.6 - 5.0 mc.

(4) Provision for lane identification possible but not usual.

(5) Operating ranges:

High-powered Raydist	100-200 nautical miles
Miniaturized (transistorized)	25- 60 nautical miles

(6) Accuracy of 1:5000 with a probable error of 1-3 meters.

b. Equipment Characteristics (DM Raydist only)

(1) High-Powered System

RED STATION

Receiver Unit	17 x 11 x 25 inches	63 pounds
AM Transmitter	17 x 11 x 25 inches	95 pounds
CW Transmitter	17 x 11 x 25 inches	95 pounds
Two Antenna Loading Boxes	6 x 12 x 25 inches	12 pounds
Power Required	950 w, 60 cps, 110 v, ac.	

GREEN STATION

Receiver Unit	17 x 11 x 25 inches	63 pounds
AM Transmitter	17 x 11 x 25 inches	95 pounds
Antenna Loading Box	6 x 12 x 12 inches	12 pounds
Antennas and Accessories		225 pounds
Power Required	700 w, 60 cps, 110 v ac.	

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MOBILE STATION

Navigator	17 x 8 x 25 inches	73 pounds
Position Indicator	9 x 12 x 12 inches	33 pounds
Power Supply	17 x 10 x 14 inches	90 pounds
Position Recorder	21 x 9 x 9 inches	18-1/2 pounds
Monitor	9 x 8 x 11 inches	22 pounds
Transmitter	17 x 11 x 25 inches	95 pounds
Antenna Loading Box	6 x 12 x 12 inches	12 pounds
Power Required	1.3 kw, 60 cps, 110 v, ac.	

(2) Miniaturized System

RED STATION

Relay Unit	18 x 10 x 11 inches	37 pounds
CW Transmitter	8,5 x 10 x 11 inches	19 pounds
Whip Antenna	35 feet extended (collapses to 6 feet)	12 pounds
Power Required	24 v, dc at 2 amps	

GREEN STATION

Relay Unit	18 x 10 x 11 inches	37 pounds
Whip Antenna	35 feet extended (collapses to 6 feet)	12 pounds
Power Required	24 v, dc at 2 amps	

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1. Raydist, Supplementary Paper 2 to S. P. 39, Radio Aids to Maritime Navigation and Hydrography, International Hydrographic Bureau, Monaco, November 1960.

2. Radio Distance Measurement and Position Fixing, Electronics Research Directorate, AFCRL, Publication No. AFCRC-TR-60-191, Bedford, Mass., pp. 48-51.

3. G. R. Fish, Raydist on Georges Bank, U.S. Coast and Geodetic Survey, Tech. Bull. No. 5, April 1959.

4. J. P. Comstock and C. E. Hastings, "Raydist Measures Speed of Ships," Marine Engineering, June 1953.

VI. SHORT-RANGE NAVIGATION SYSTEMS

A. RADAR

1. GENERAL

Radar as used for navigation and position fixing is a system of deter-mining distances by measuring the time-interval between the transmission of pulses and the return of the corresponding echoes from primary targets. In its use of the interrogation and reply method it is similar to such systems as Shoran.

Radar development began in England in the 1930's, and all of the more recent types of pulse measurement systems evolved from this early work. However, radar differs from the other pulse systems described herein in that the reply is the wave reflected from the target point, and transponding or re-transmitting equipment is not required to send back a reply. Thus, radar is an entirely self-contained system suitable for multi-user application. Ranges of from a few hundred feet to beyond the line of sight (200 feet-50 miles) and range resolution of the order of 1 part in 1000 or better can be expected with most classes of radar equipment.

2. DESCRIPTION

Radar systems consist of a transmitter, rotary antenna and switch, receiver, ranging unit, plan-position-indicator display unit (PPI), and associ-ated power supply. A typical system is diagrammed in Figure VI-1.
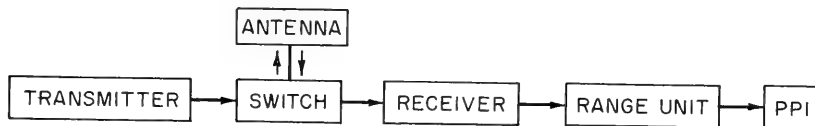

FIGURE VI-1   TYPICAL RADAR SYSTEM BLOCK DIAGRAM

The angular accuracy in radar is largely determined by the horizontal radiated beam width. The antenna beam width, i.e., half-power point, is inversely proportional to the horizontal dimensions of the antenna. It is this dimension and the transmitted pulse width which determine the horizontal target resolution of the system. Horizontal beam widths of $1-3^\circ$ are most common for marine radar equipment. Vertical beam widths of $15-40^\circ$ are quite common. The larger vertical widths are required where antenna stabilization is not used to prevent echoes from becoming lost because of rolling and pitching of the vessel.

Radar systems display both a range to the point of interest and a map of the surrounding area. The map is produced by coordinating the rotation of the sweep on the cathode-ray tube with the rotation of the antenna beam. The map type of display on the PPI is the equivalent of a large number of trilateration fixes if the prominent reflection points of the area are known. In this type of operation, a knowledge of the surroundings is used to fix the position of the radar.

The use of a meaningful PPI display requires high range resolution. The over-all pulse length is important because it determines the minimum spacing between discrete reflection points which is necessary to produce separated echoes on the screen. For PPI display purposes, radar pulses are made as short as the rise and fall time will permit. Thus, range resolution as well as angular resolution is important in the display of radar information on a radar PPI. This resolution is dependent not only on the pulse length and beam width but also on the minimum spot size on the PPI screen.

The limit of resolution attainable in radar systems depends on both the pulse length and beam width of the system. Fast-rise-time pulses require that the transmitter and receiver bandwidth, which is inversely proportional to the pulse rise time, be wide.

Experimental radars with pulse lengths of a small fraction of a microsecond, giving range resolutions of a few feet, have been built. In general, their useful range is reduced to line of sight or less. Similarly, antennas with beam widths of 0.1° which require an aperture of about 600 wave lengths have been built.

The navigational use of radar generally requires a comparison of the PPI display and an appropriate chart, whether supplemented or not by standard radar views or photographs. A superposition or chart overlay method is prob ably most effective in matching a chart to the screen. Generally the range rings of the PPI display are matched to those of the chart. Some matching of chart features to those of the PPI is also required.

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A second method of radar navigation and ship positioning requires the use of transponders (as in Shoran) and reflectors positioned at known geographical points. Standard methods of triangulation are then used.

Dead reckoning is an essential factor in positioning vessels by the use of radar, just as it is in conventional navigation.

3. ACCURACY

The accuracy of radar navigation is principally determined by the characteristics of the radar set and the interpretation of its display. Navigational aids in the form of either transponders or reflectors enhance the return signal, making possible better signal match and interpretation. Range accuracies of 1 part in 2500 or better can be measured with modern radar equipment at ranges out to about 50,000 yards. Decreasing accuracy can be expected at ranges greater than 50,000 yards. A range precision of ± 80 ft for 99.7% of the measurements out to the maximum range of the parent radar equipment is practical when a precision range unit is used.[3] Angular resolution of 1° can be expected with most equipment if the PPI is accurately centered, parallax is avoided, and the receiver gain is adjusted to give the narrowest bearing line.

Ranges of 10-15 miles can be expected with both 3 and 10 cm marine radar under most conditions of use. Higher power levels and antenna height can extend these surface ranges to 50 miles or more with some military equipment.

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2. L. N. Ridenour, Radar Systems Engineering, M.I.T. Radiation Laboratory Series, Vol. I, McGraw-Hill Book Co., 1947.

3. See Alpine Precision Navigation System Model 430, pp. 138-142.

B. ALPINE PRECISION NAVIGATION SYSTEM MODEL 430

1. GENERAL

The Alpine Geophysical Associates Precision Radar Ranging Unit, Remote Electrical Track Plotter, and X-band Radar Transponding Beacons were developed for short-range precision navigation and ship-positioning problems. This system utilizes, in conjunction with the standard shipboard radar transmitter and modulator system the Model 430 precision timing and digital readout equipment. The system is designed to operate with two or more fixed targets, which may be prominent land features, buildings, or markers of known position. Anchored reflector or transponder buoys may also be used. The precision ranging unit is capable of providing accurately timed trigger pulses to the radar transmitter and delay information to the radar PPI to provide for an expanded display. The equipment provides ranging accuracies of ± 80 ft with 99% probability at all ranges to the maximum range of the equipment.

2. DESCRIPTION

a. Precision Ranging Unit

The Alpine Model 428 Precision Radar Ranging Unit is operated in conjunction with standard marine radar equipment such as the Decca D-11 series. The Model 430 provides the precision timing required by utilizing a temperature-controlled crystal oscillator with a frequency accuracy of 1 part in 10^7. This is divided down to the repetition rate of the radar by using a series of high-stability multivibrator circuits and selection gates.

The outputs of the Model 430 are:

(1) A precision variable range marker fed to the radar display

(2) A digitally controlled step delay generating 1-mile increments for triggering the radar display

(3) A radar modulator trigger pulse

(4) Crystal-controlled markers for internal system calibration.

The Model 430 will function at ranges of standard radars from 0.75 mile to 50 miles. Its maximum accuracy is attained at the minimum ranges indicated on most marine radar equipment.

The total range to target is controlled by the number of one mile incre-ments set by switch positions on the range unit. This operation is initiated at the Precision Ranging Unit, which introduces a delayed sweep trigger on the radar display. For example, if the delay switch were set at 1 mile, the portion of the sweep around the target would be linearly expanded so that a one-mile range would cover the full radius of the radar display. This magnification reduces the error associated with visual alignment of the target and the variable range marker.

b. Remote Electrical Track Plotter

The Model 429 Precision Remote Electrical Plotter utilizes a pair of synchro-controlled ball bearing mount screw boxes which change the length and thus the position of the apex unit at the head of a set of precision lead screw rods. The apex unit is caused to follow and mark the hydrographic or navigational track by the operator as he follows target range changes at the ranging unit. The lead screw boxes are set over and pivoted around points on the area chart which are chosen as the operating targets. A solenoid-operated pointer automatically marks the chart at a preset rate or may be manually operated.

c. Radar Transponding Beacon

The Model 427 Radar Transponding Beacon is designed primarily for use as a precision radar target and operates in conjunction with a precision radar surveying system. Because of its small size and low power consumption, it is useful as a remote radar navigational beacon and aid, surface buoy trans-ponder, etc. The transponder is capable of operating with any single pulsed radar operating in the frequency band of 9300-9400 mc with a pulse repetition rate of up to 2000 pulses per second.

In the quiescent mode of operation, the transponder operates in a listening condition only. That is, the receiver is on and available to amplify signals. In this mode the receiver draws 1/4 watt from the 12-volt dc supply.

Upon receipt of an X-band signal from an interrogating radar, a relay circuit turns on the magnetron filaments. After a suitable warm-up time, coded pulses are transmitted at a preset rate. After radar interrogation ceases, a time delay holds the transponder in an active condition for approximately 2 minutes and then allows the transponder to return to the quiescent condition.

A horizontally polarized omnidirectional antenna is used for both the transmit and receive functions. A ferrite three-part circulator isolates the transmitting and the receiving circuits.

d. Radar Beacon Receiver

This separate receiver allows continuous viewing and variable mixing of the radar and video signal on the PPI display. With this unit, it is practical to operate the radar and obtain a picture of a target area and simultaneously obtain a brightened spot on the target indicating the position of a transponding beacon within the target area.

This system is adaptable to a standard radar. The electronic unit is close coupled to the radar transceiver and is tied into the wave guide. A control unit is mounted near the radar display. The control unit contains the necessary adjustments for setting to the beacon frequency and spot brightening as required.

3. ACCURACY

The equipment has a fundamental instrumental accuracy of $\pm$ 40 feet as a maximum incremental error due to crystal characteristics and performance. This standard of accuracy can be maintained up to maximum range, subject to a satisfactory target being available. A fixed operation accuracy of $\pm$ 80 feet for 99.7% of cases is reported as the result of operational tests.

For radar to beacon antenna heights of 45 feet and 10 feet respectively, strong contact can be maintained out to 10 n.m., steady response to 12 n.m. and occasional response to 15 n.m. Sea state and atmospheric conditions will modify these ranges.

Strong contacts to beyond 30 miles have been documented. These ranges have been repeated with no difficulty when the combined antenna heights were 1000 feet.

4. SUMMARY

a. Precision Ranging Unit

(1) Type of system: precision ship-positioning and ranging system utilizing ship radar equipment.

(2) Number of stations: two reflectors or transponding beacons placed at either end of base line.

(3) Range: out to normal ranges of radar being used.

(4) Accuracy (instrumental): $\pm$ 40 feet based on electronic specifications.

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(5) Accuracy (operational): $\pm$ 80 feet with 99% probability.

(6) Power required: 117 v, 50-1000 cps, 100 watts.

b. Remote Electrical Track Plotter Model 429

(1) Plotter scale: 1" = 4000' to 1" = 2000' or 1" = 8000"
by a simple gear change at the screw box. Special
ranges of 1" = 1000' are available.

(2) Accuracy of plot: $\pm$ 5 feet at any range.

(3) Method of track marking: sequential dot marking,
either automatic or manual.

(4) Cable and interconnections: Plotter to control unit
requires single 12-conductor cable.

(5) Power requirements: 117 v, 60 cps, 250 watts.

c. Radar Transponding Beacon Model 427

(1) Frequency band: X-band,
(a) receiver $\mp$ 9375 mc adj. $\pm$ 50 mc.
(b) transmit = adj. 9100-9400 mc.

(2) Maximum pulse repetition rate: 2000 pps.

(3) Return pulse spacing: adjustable (3-19 millisec).

(4) Maximum peak power output: 100 watts.

(5) Antenna polorization: horizontal omnidirectional with
8° vertical beam width.

(6) Power requirements: 12 v, dc.
(a) Receiver = 1/4 watt (normal quiescent state)
(b) Transmit = 16 watts (when interrogated at 2000 pps).

(7) Warm-up time (approx.): 30 sec.

d. Radar Beacon Receiver

(1) Frequency range: adjustable 9100-9400 mc to match
with transponder as required.

(2) Receiver mounting: close coupled to wave guide.

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(3) Control unit size and mounting: 8" x 8" x 6" mounted near radar display.

(4) Power requirements: 110 v, 60 cps, 100 watts.

REFERENCE

Data furnished by Walter C. Beckman, President, Alpine Geophysical Associates, Inc., Norwood, New Jersey.

C. AUTOTAPE

1. GENERAL

The Aeris II Autotape survey equipment was designed by the Cubic Corp. as an outgrowth of its high-precision, electrotape, distance-measuring equipment. The Autotape system is capable of automatic distance measuring for both fixed and mobile situations. It uses omnidirectional or directional antenna in determining distance from a mobile platform to two fixed responder positions on a known base line. Range information accurate to 1 meter + 10 ppm times the measured range over ranges of 100 meters to 100 kilometers (62 miles) is numerically displayed for visual monitoring by the operator. A voice communication mode of operation between the Interrogator and each transponder is used when initiating operations. A data output connection for external recording or processing of range information is available with a BCD output suitable for data processing. An Autotape plotter may be used at the Interrogator for a continuous plot of a moving platform in x-y coordinates.

2. DESCRIPTION

The Autotape system consists of a mobile interrogation unit and two remote transponders located at either end of a fixed base line. (See Figure VI-2.) In automatic operation a built-in program at the Interrogator controls the Autotape Responders, measures the range to each Responder, and sequentially presents each range on an integral digital display.

Separate carrier frequencies in the 10-cm (2900 - 3100 mc) band are used for the Interrogator and each Responder. A precisely regulated crystal oscillator located at the Interrogator serves as a basic clock controlling all frequencies. Responder transmissions are separated by frequency multiplexing techniques which require only one antenna and one transmitter at the two-range Interrogator which serves both Responders. This assures that both ranges are measured from a single focal point at the Interrogator and allows both ranges to be measured and displayed within 50 microseconds.

Distances are measured using electronic phase comparison techniques. Three basic modulation frequencies are automatically sequenced, and a phase comparison is made between transmitted and received frequencies at the Interrogator. By a unique use of modulation frequencies, the Responder electronic time delays are cancelled. The Autotape system then automatically measures the rf propagation time, utilizes a preset average value for the index of refraction to correct the velocity of propagation, and displays the resulting range to
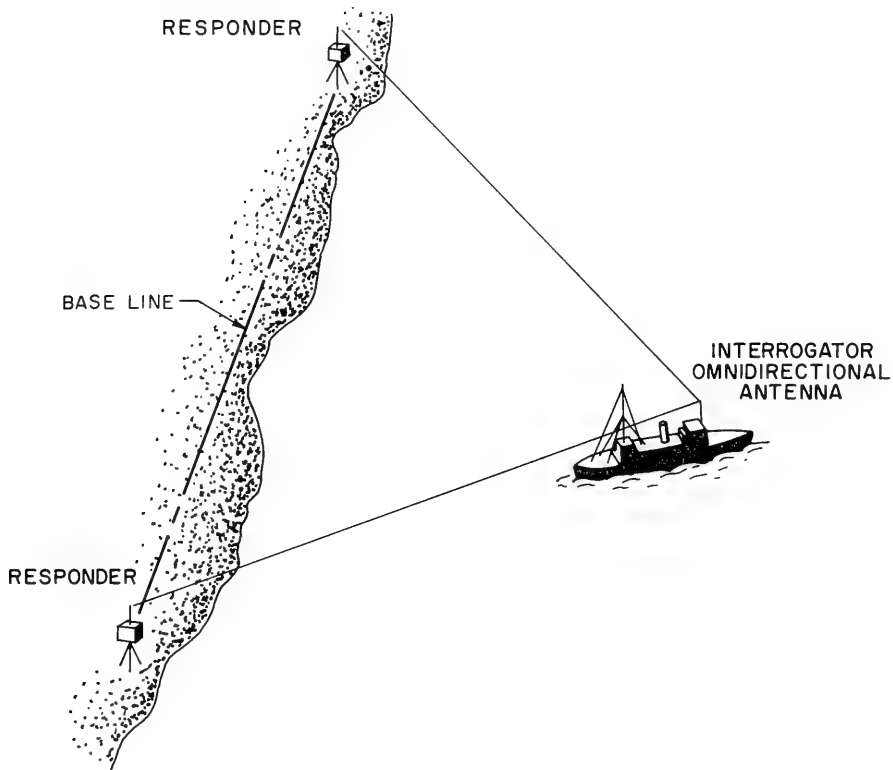
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FIGURE VI-2   AUTOTAPE RANGING DIAGRAM

each Responder station as a digital readout at the Interrogator. In this manner positional ambiguities are eliminated when the position is initially known to within 10,000 meters.

a. Modes of Operation

Two basic modes of ranging operation are available. In the Automatic trigger mode, the Autotape Interrogator utilizes a built-in program to measure the range to each Responder and display it automatically. A nonambiguous range is displayed on each of two digital readouts once each second. In the Fine, Intermediate, or Coarse method of operation, the ranges will be measured and displayed at a rate of three times each second. At this high rate of operation, only the last three digits of each range measured are presented:

(1) Fine = 0 to 100 meters with 10-cm resolution.

(2) Intermediate = 0 to 1000 meters with 1 meter resolution.

(3) Coarse = 0 to 10,000 meters with 10 meter resolution.

In the External mode of operation cycling times of less than one per second are under the control of the operator. A Hold position is also available where the display is locked to its last reading. Each of these modes has specific applications dependent upon the conditions of operation.

b. Antenna Requirements

To provide flexibility of operation in the selection of range and area of coverage both an omnidirectional antenna and a 60° beam horizontal horn have been designed for use with the Autotape equipment. Operational ranges of 25 - 100 km are predicted when these antennae are used in proper combination at the Interrogator and Responder stations.

An rf unit is mounted integral with the antenna, making it possible to position the antenna assembly away from the Interrogator or Responder by increasing the length of the connecting cables. Equipment calibration does not change with this arrangement.

c. Operation

All range measurements are initiated from the Interrogator unit after the Interrogator and Responder close the radio link using the Talk Mode of operation. The operator at the Responder then tunes to receive the Interrogator

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frequency. Automatic frequency control networks integral with the equipment maintain reception which gives continuous positional information at velocities up to about 80 knots. Less accuracy could be expected at higher velocities.

After completing the acquisition each operator switches his unit to the Measure Mode, where the internal program is used to range and display the data automatically. No further operator attention or calibration is required, as the measurement process is fully automatic. In the event of signal interruption the measurement process automatically resumes when the signals are again available.

d. Auxiliary Output

An auxiliary data output is provided as a 20-line binary coded decimal format which is compatible with standard data processing equipment. For in-shore operation, a special design accessory plotter is available. This plotter uses the two Interrogator ranges and converts them to an x-y plot for any pre-set base line. Intermediate equipment is required for conversion of BCD to an analog input to the plotter.

e. Power Requirements

The Autotape system is intended as a portable system. The Responders are tripod-mounted and require 36 watts at 12 v dc. The two-range Interrogators are table top-mounted and require 72 watts at 12 v dc. The radiated power output of the Interrogator and Responder is approximately 200 mw.

3. ACCURACY

Two classes of error are inherent in the Autotape system, systematic and random.

a. Systematic Errors

The systematic errors can be quite accurately determined and in many cases eliminated. Errors due to variations in the propagation velocity of rf energy and those due to reflection and refraction are in this group.

An instrumental accuracy of 50 cm is achieved with omnidirectional antennae at both the Interrogator and Responder sites at ranges out to 25 km, provided line-of-sight transmission is maintained. The phase measurements are converted directly to meters for an average index of refraction of 320N

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units, which is typical of most coastal areas. Using this value for the index, one can make ranging measurements in most coastal areas with good line-of-sight operation to an accuracy of ± 40 ppm. It is claimed that by making atmospheric measurements at all three stations and properly averaging the computed index of refraction, one can reduce the propagation velocity error to approximately ± 10 ppm. Thus the typical system accuracy achieved is ± 50 cm + 10 ppm times the measured range.

Errors can be caused by ground reflections and are governed by the modulation frequency, the antenna beam width, and the ground characteristics. Broad beam antennas increase the severity of ground reflections. The errors which may be introduced at the lower modulation frequencies will tend to be greater under certain conditions of high reflection. By using the more directive antennas at the stationary sites and by using data averaging techniques, one can reduce the errors due to reflection. For moving targets, computer data processing can provide accuracies approaching ± 10 cm + 10 ppm of range.

Data averaging should be particularly useful where a mobile station is hovering or fixed over one position for a period of time. With the Autotape equipment locked in the Fine channel, a hover of 10 seconds will provide 30 two-range Fine readings for averaging. This is said to be sufficient to approach a ±10 cm system accuracy prior to addition of the propagation error.

b. Random Errors

Because of the digital measurement techniques used, an increase in measurement accuracy and long-term stability can be expected in comparison with analog continuous display techniques. Some random errors such as operator error and instrument drift, may be minimized.

Ground reflection effects can cause readings to deviate by an amount which is a function of the excess length of the indirect ray, the strength of the ground reflection, and, most important, the relative phase of the microwave carrier over the two paths. The effect is a swing or variation of readings about the true reading, the amplitude of which is dependent upon the reflecting properties of the surface. Antenna heights of 200 ft or less should help to reduce the swing error by reducing the grazing angle of propagated energy with the surface of the terrain or water.

4. SUMMARY

a. Type of System

(1) Precision ship-positioning and ranging.

(2) Number of stations required for navigation: two remote transponder stations placed at either end of a base line. The mobile vehicle contains a single Interrogator station which automatically ranges to each transponder in sequential fashion.

(3) Carrier band: 3 cm (2900 - 3100 mc).

(4) Radiated power: 200 mw, all solid state circuitry.

(5) Antenna: omnidirectional or 60° beam width units integral with equipment. Antenna and rf unit may be mounted up to 100 ft distant.

(6) Modulation frequencies (automatically sequenced):

Fine = 1.5 mc, ambiguities each 100 m

Intermediate = 150 kc, ambiguities each 1 km

Coarse = 15 kc, ambiguities each 10 km.

(7) Number of simultaneous users: single (system may be expanded).

(8) Readout: illuminated five-digit display for each range displayed simultaneously.

(9) Auxiliary outputs: 20-line BCD suitable for data processing and x-y analog plotting equipment.

(10) Maximum range rate: 80 knots (for automatic operation).

(11) Integral voice transmit and receive facilities are provided for check and calibration purposes.

(12) Power requirements:

Interrogator = 72 watts 6a @ 12 v dc

Responder = 36 watts 3a @ 12 v dc

(13) Operating temperature: -10 to +60°C.

b. Range and Accuracy

    (1) Range: 100 m - 100 km with 60° coverage

                     100 m - 25 km with omnidirectional coverage.

    (2) Accuracy: ± 50 cm + 10 ppm x range with correction for the refractive index.

    (3) Resolution: ± 10 cm.

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D. 'TELLUROMETER' - HYDRODIST MODEL MRB/2

1. GENERAL

The 'Tellurometer' microwave system of distance measurement, introduced in 1957, provides distance measurements to geodetic accuracy from a relatively short range to line of sight (25 miles). These measurements can be made under proper conditions to an accuracy of 1 part in 30,000. The alignment of the radio beams need be only approximate, and operation from a single tower of minimum stability is practical where necessary. Problems in measurement brought about by reflected radio energy are minimized both by the relatively high frequency (10 cm band) and the specialized instrumentation techniques utilized.

A more recently developed 'Tellurometer' type system (termed Hydrodist) enables a fix for a moving vessel to be obtained as a function of two continuously measured ranges. The master station is located on the moving vessel and the remote stations are located at known points ashore. Accuracies of ± 1.5 meters at ranges out to 40,000 meters (25 miles) are obtained under optimum conditions.

2. DESCRIPTION

The basic 'Tellurometer' distance-measuring system was developed principally for the measurement of useful distances to geodetic accuracy between two fixed points, the master station and a remote station. Two operators are required, one at each instrument. The observations are made at the master station, while the operator at the remote station performs the various switching operations as instructed by the master station operator. A two-way voice communications link is built into the equipment for this purpose. An antenna with a parabolic reflector is located at each instrument and is directed toward the receiving instrument. A 12-volt storage battery provides the necessary power for portable equipment.

The Hydrodist system was developed from 'Tellurometer' for making position measurements from a moving vessel at sea. Two master stations, each with its own operator, are required aboard the moving vessel. Distance measurements are continually made to each shore station (or buoys) placed at known geographic positions within line-of-sight distances of the moving vessel. These remote stations may be left unattended if they include a remote-controlled, pattern-following auxiliary unit.

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The Hydrodist and the basic Tellurometer system utilize cw signals radiated from the master stations. The signal is modulated by a pattern frequency, received at the remote station, and reradiated as a similar wave with more complex modulation.

The return waves are received at the master stations and their phase modulations are compared with the outgoing phase. The phase is indicated on a cathode-ray tube in the form of a circular trace in which a small break marks the phase against a circular scale. A decimal scale with 10 major and 100 minor divisions is used and is read to the nearest small division, which has a value of one meter.

A cursor is attached to the cathode-ray-tube display and is manually rotated to follow the position of the gap as a function of range. The cursor is mechanically connected to a counter which, after being set to the initial range, will automatically follow the range in meters. A useful range of 20-25 miles may be expected with this equipment.

3. ACCURACY

Hydrodist operates in the 10-cm band. Because this system uses phase comparison methods to obtain the distances from the master to the remote operating points, ambiguities must be resolved. Pattern switching is used for this purpose. Three pattern or modulation frequencies are provided in Hydrodist. They are manually switched, and digital counter readings are tabulated. Vernier readings of transit time in millimicroseconds is quite practical.

The A pattern measures 100 meters for a complete rotation of the cathode-ray-tube display. A resolution of 1 meter is practical. The A-C and the A-D patterns have full scale ranges of 1,000 and 10,000 meters, respectively. No ambiguity resolution above 10,000 meters is provided, as it is regarded as certain that the vessel's position will be known within 10,000 meters (7 miles approximately). The automatic pattern-following device on the shore stations provides a rapid check on ambiguities.

The computed transit time is based on a mean value of 1.000325 for the refractive index of the atmosphere. A corrected value may be computed by taking meteorological observations at both the master and remote stations. With these corrections, the resultant accuracy of an individual line measurement is almost totally a function of the instrument error plus a scale reading error. After a number of fine readings have been taken and properly averaged it is probable that a measurement accurate to about 1/3 meter can be achieved.

For slow-moving systems of 20 knots or less manual switching of modulation frequencies controlled by the master is satisfactory, providing the remote switching keeps in step with the master. At higher speeds it is necessary for ambiguity resolution to be achieved on a continuous recording-chart system where the switching processes are automatically controlled from the master. Automatic timing permits the interrogation for ambiguity resolution to be repeated at regular adjustable time intervals and is useful to speeds in excess of 100 knots.

Errors can be caused by ground reflections and are governed by the modulation frequency, the antenna beam width, and the ground characteristics. Broad beam antennas increase the severity of ground reflections. Errors introduced by reflections at lower modulation frequencies will tend to be greater under certain conditions of high reflection.

Ground reflection effects can cause readings to deviate by an amount which is a function of the excess length of the indirect ray, the strength of the ground reflection, and most important, the relative phase of the microwave carrier over the two paths. The effect is a swing or variation of readings about the true reading, the amplitude of which is quite dependent upon the reflecting properties of the surface. Antenna heights of the order of 200 feet or less help reduce the swing error by reducing the grazing angle of propagated energy with the surface of the terrain or water.

4. SUMMARY

a. Hydrodist MRB/2

(1) Type of system: precision ship positioning and ranging.

(2) Number of stations required for navigation: two remote stations at either end of a base line. Two master stations placed side by side on the vessel, each of which continually ranges on its own remote station.

(3) Carrier band: 3 cm (2800 to 3200 mcps).

(4) Minimal frequency difference of master stations: 80 mcps.

(5) Length of base line: 10-20,000 meters (nominal).

(6) Radiated power: 100 mw.

(7) Power requirement: 12 v or 24 v dc.

(8) Range: 40,000 meters (25 miles).

(9) Range (minimal): 125 meters, limited by overloading.
     Accuracy: ± 0.33 - 0.50 meters with correction for
     refractive index.

(10) Antenna: 20° beam width conical (standard); others
      available.

(11) Pattern frequencies:

	Master	Remote
A pattern	1.49847 mcps	A-1.49947 mcps
		A+1.49747 mcps
C pattern	1.48349 mcps	1.48249 mcps
D pattern	1.34862 mcps	1.34762 mcps

(12) Readout: transit time in Nano seconds from master to
      remote station indicated as circular trace on cathode-
      ray tube and directly on mechanical or servo-driven
      digital counter. Readout is provided directly in meters
      and ambiguities are resolved in terms of 100, 1000, and
      10,000 meters. In the A pattern one scale graduation
      represents 1 meter of range and is readable to one-half
      a graduation.

(13) Auxiliary readout: digital display available (see below
      MRC/12).

(14) Integral voice transmit and receive facilities are sup-
      plied at the master and remote stations and are used
      as a functional part of the measurement process.

(15) Auxiliary plotter: The Alpine Geophysical Corp. Model
      429 Precision Remote Electrical Plotter may be used
      and has a plotting accuracy of ± 5 feet at any range.
      Unit consists of Apex Unit at head of two lead screw rods.
      As the operator follows the target range the screw
      length and thus the position of the Apex unit properly
      follows and indicates the track of the vessel. Gear

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changes allow the plotter scale to be changed at will from 1" = 8000' to 1" = 4000' or 1" = 2000'. Special gearing is available for 1" = 1000'. A solenoid pointer marks the chart automatically.

b. Hydrodist MRC/12

   (1) The MRC/12 is quite similar in function and operation to its predecessor the MRC/2 and has additional digital read-out and plotter equipment for automatic recording of transit time.

   (2) Digital Display Unit type DDU1: the unit is self-contained and provides a continuous integrated readout of the two ranges as a digital display. It is intended for table-top mounting and may be mounted remotely from the measuring instruments. Each of the Fine A readings is continuously displayed on a dial that is scaled 0 - 100. A counter continuously integrates the A pattern rotations and provides a direct readout of range.

      (a) Input: 1-kc amplitude modulated sine waves

      (b) Power: 1 amp at 24/27 v dc.

   (3) Recorder: the unit is two-channel thermal writing with a polarized event marker indicating ambiguous phase difference readings. The recorder pen moves from the bottom to the top of the chart as, for example, the A range changes from 0-50 meters. It moves from top to bottom as the range increases from 50 - 100 meters. An identical trace would be produced from top to bottom as the range decreased from 50-0 meters, thus producing an ambiguous reading.

   (4) Ambiguity is resolved by direction of the relay-operated event marker. Thus, the direction of the ambiguity pen deflection, in combination with the reading trace, determines whether the range is increasing or decreasing.

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2. "Hydrodist Model MRB2" Publication C-3, of Tellurometer Inc., 4435 Wisconsin Avenue, N.W., Washington, D. C.

3. Comm. J. K. Mallory, "Hydrodist, " Supplement to International Hydrographic Review, Vol. 1, October 1960, pp. 57-62.

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5. Private correspondence with Claire A. P. Duffie, Executive Vice President, Tellurometer, Inc., Washington, D. C.

6. Hugh B. Loving, "Airborne Control System, " Topographic Division, U. S. Geological Survey, August 13, 1962. (Report on Hydrodist Application in Airborne Control Survey Application.)

E. SHORAN

1. GENERAL

Shoran, a navigation and positioning system developed by RCA, uses radar principles for establishing an accurate fix. The original equipment was designed with the intent of controlling aircraft during a bombing mission.

The inherently high accuracy of the Shoran fix has made the system very useful as a control in hydrographic surveys at distances of 50 miles or more from shore. It has been used at minimum ranges of the order of 1 mile.

The accuracy of the system has been measured by assuming a constant velocity of signal propagation with a mean value of the refraction coefficient. Corrections in propagation velocity may be made by measuring the refractive index and computing a corrected velocity of propagation.

The Shoran system utilizes radar transponders placed at known shore sites at either end of a base line. Each transponder returns an amplified and reshaped signal to the ship's radar receiver. An accurate and stable time base converts the signal travel time to distance, which is read on a digital dial. Returns from two or more transponders on the base line establishes a fix.

2. DESCRIPTION

A shipborne transmitter transmits precisely timed pulses toward the shore stations. The signal is received at the shore stations, amplified, reshaped, and retransmitted. A shipboard receiver operating from the same directional antenna as the transmitter demodulates and amplifies the return signal. It is further processed in the indicator, and the elapsed time between transmit and receive pulses is measured and converted to a one-way distance. If the positions of the two ground stations are accurately known, then the position of the ship can be determined. Arcs are drawn whose radii are equal to the measured distances to the shore stations.

A single pair of intersecting arcs can give rise to ambiguity, as the fix can fall on either side of a line bisecting the base line between the shore stations. This ambiguity is resolved by following a known course and taking additional fixes.

a. Shipboard Equipment

Two distances measured simultaneously are required for a fix. The transmitter aboard ship alternately transmits a pulse on two frequencies, one for each ground station. The alternation rate between ground stations is about 10/second. The ground stations retransmit to the ship on a third frequency. The ship's receiver indicator provides simultaneous and continuous indications of the distances between the ship and the two ground stations.

The indicator unit contains circuitry for measuring the time of a round-trip pulse and for displaying the transmitted and received pulses on the circular sweep of a cathode-ray tube. The transmitted pulse appears as a fixed marker pulse, and the received pulses appear at points on the circular sweep dependent upon the distances from transmitter to receiver.

A phase-shifting method of pulse positioning is used as the measure of the distance between the ship and the ground station. The pulses are matched visually and read on a scale and vernier which are mechanically connected to the phase shifter. As the ship moves away from the ground station, the phase is advanced to permit coincidence of transmitted and received pulses. A phase advance of 360° corresponds to a distance between transmitter and ground station of 100 miles. Thus, the phase advance vernier repeats itself each 100 miles. It is, therefore, necessary that the observer know the ship's position within 100 miles or so, in order to fix its position accurately.

The trace shown on the cathode-ray tube screen is circular, with a reference pip at the top. The two shore station pips show elsewhere on the trace. In making distance measurements, one aligns the two distance pips with the marker pip. On the one-mile scale, for example, a circular sweep length of about 6 inches corresponds to a distance of 1 statute mile. A resolution of between 0.01 and 0.001 mile is possible using the scale and vernier. Indicator range scales are 1, 10, and 100 miles.

b. Ground Station Equipment

The ground station equipment is designed to handle up to 20 interrogations simultaneously and is, therefore, somewhat larger than the ship equipment. Crystals at both ground stations are used to provide a continuous mutual check on operations. These monitor crystals operate at a frequency of 93.109 kc, a cycle of which corresponds to a 1-mile loop time. Frequencies corresponding to 1, 10, and 100 miles are also derived from this crystal.

The ground station transmits a series of monitor crystal frequency pulses which the shipboard operator uses for adjusting the ship station oscillator. These pulses appear on the indicator circular sweep as stationary or slowly travelling pulses. The operator adjusts the pulses to a stationary position and thus calibrates his shipboard equipment. These pulses appear only on the time base during a calibration period as selected by a panel switch.

The Operate-Monitor switch is also used to check the zero adjustment of the ground station. Pulses originating at the ship station are received and amplified at the ground station. The signal is divided and sent through two delay lines, one of which is variable. By a matching process, the operator is able to adjust the leading edge of the two pulses to coincide and thus adjusts the ground station for the proper delay.

The transmitter at the ground station is similar to, but larger than the shipboard transmitter. It need be capable of transmitting on only one frequency (290-320 megacycles) and must be capable of answering to the pulses from as many as 20 ships. The transmitted peak power is over 15 kw.

The ground station antenna system consists of two dipoles--one for receiving and one for transmitting--mounted on a single 50 ft mast. Reflectors are used to give directivity and antenna gain. This system is necessary for working at distances greater than 50 miles.

Ground station power is normally supplied by two gasoline or diesel engine driven generator sets. One set acts as a back-up for the other in case of failure. The station requires 1500 watts of 400 to 2600 cycle 115-volt ac and 400 watts of 27-volt dc.

3. ACCURACY AND RANGE

Two types of errors are inherent in the Shoran system: systematic and random.

a. Systematic Errors

The systematic errors are those which can be precisely determined and include errors resulting from the difference between Shoran and map distance and from the assumed velocity of the radio wave. Because of atmosphere refraction and the elevation height of the antennas, the Shoran path is not a straight line, but approximates the arc of a circle. The elevation of the antenna is the dominating factor. Usually with elevations less than 100 ft and distances less than 100 miles the error is negligible.

A velocity of propagation is assumed to be 186,218 statute miles/ second at 29.92 inches Hg, which is probably correct to one part in 18,600. While the effects of changes in barometric pressure are calculable, they are negligible compared to other errors in Shoran equipment; a change of 1 inch in pressure will change the velocity of propagation about 2 miles/second, which is about 1 part in 100,000.

b. Random Errors

The random errors cannot be eliminated. They are tabulated below (in statute miles):

(1) Setting and reading mileage verniers: ± 0.002

(2) Nonlinearity of calibrated phase shift network: ± 0.005

(3) Zero adjustment in ground station: ± 0.002

(4) Nonalignment of pulses due to insufficient gain at long distances: ± 0.050

It is not probable that all the errors will be accumulative at the same time. The first and third listed are of variable sign and value and affect distance measurements within the line-of-sight distances from the ground stations. All four affect the results when greater than line-of-sight distances are measured. Errors in excess of 0.050 statute mile have been noted in lines as long as 100 miles. At the longer ranges the pulses are reduced in size and shape, so that the error will be dominated by nonalignment of pulses at long distances and the measured range will be too long.

The effects of the random errors is to give an uncertainty in position corresponding to the magnitude of the errors and the angle at which the distance arcs intersect. This uncertainty is illustrated in Figure VI-3.

Long experience indicates the areas of uncertainty to be negligible when the angles of intersection are between 30 and 150°. These limits are often exceeded in surveys which extend along both sides of the base line and its extension and at long range from shore.
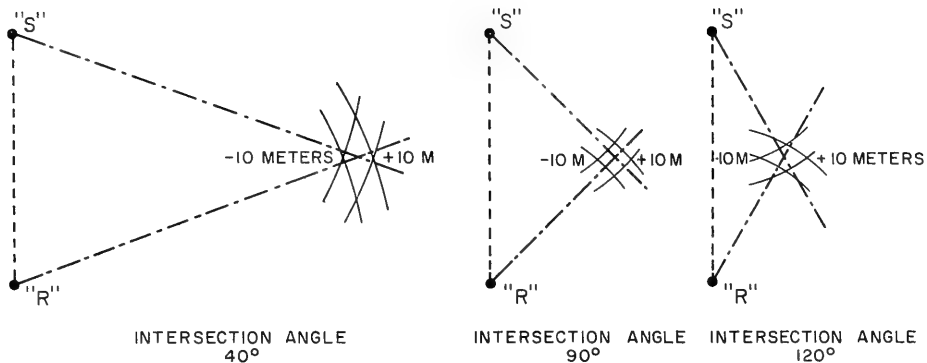
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FIGURE VI-3   POSITION UNCERTAINTY DUE TO RANDOM ERRORS

c. Range

The range of the equipment can be accurately computed from:

$$R = k \sqrt{h_1} + \sqrt{h_2} \tag{1}$$

where

R = range in statute miles

h = height of transmitting and receiving antennas

k = a constant between 1.8 and 2

The constant k has been determined from experience and can be applied for all practical purposes where the distances do not exceed 100 miles and the antenna heights do not exceed 2,000 feet.

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4. SUMMARY

a. Type of System

(1) Pulsed phase-difference circular plot.

(2) Number of stations required: 2 shore stations, 1 shipboard station.

(3) Length of base line: 10-50 miles.

(4) Operators required: at ground stations and on board ship.

(5) Transmitter pulse width: 1/4 microsec. rectangular.

(6) Transmitter pulse repetition rate: 930.09/second (time interval between two pulses thus corresponds to distance of 100 miles).

(7) Shipboard transmitter and antenna frequency range: 210-260 mc.

(8) Shipboard receiver and antenna frequency range: 290-320 mc.

(9) Ground station transmitter and antenna frequency range: 290-320 mc.

(10) Ground station receiver and antenna frequency range: 210-260 mc.

(11) Shipboard and ground station peak pulse power level: 12-15 kw.

(12) Antenna systems: separate receiving and transmitting dipoles required. Reflectors used on ground station equipment where distances are greater than 50 miles.

(13) Frequencies generally used: 230, 250, and 310 mc.

(14) Alternating transmission rate between the two ground stations: 10 times/second.

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(15) Number of ships handled by ground stations: up to 20 ships simultaneously per group of ground stations.

(16) Readout: cathode-ray tube with 6-inch circular sweep. Operator superimposes pulses and reads distance on a digital readout to a resolution of 0.01 to 0.001 statute mile.

(17) Power requirements for transmitter and receiver: 115 v ac, 400-2600 cps, at 1500 watts 27 v dc at 400 watts.

b. Range and Accuracy

(1) Usable service distance: 25-75 statute miles.

(2) Approximate accuracy of distance measurement: 30-60 feet except near extreme limits of range.

(3) Accuracy of LOP: dependent upon absolute magnitude of errors and angle at which distance arcs intersect. Area of uncertainty is negligible when angles of intersection are between 30 and 150°.

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3. Donald A. Rice, "Geodetic Application of Shoran," Journal of the Coast and Geodetic Survey, April 1950.

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F. HI-FIX

1. GENERAL

The Hi-Fix system was developed by the Decca Navigator Company, Ltd., as a high-precision, lightweight, portable, position-fixing system.[1] It is a single-user system designed for hydrographic, geophysical, and other surveying and tracking operations where an accuracy of a few feet is required at ranges as great as 100 nautical miles.

Hi-Fix is a phase-difference system and may be operated in either the hyperbolic mode, which requires three transmitting stations ashore (master and two slaves), or in the ranging mode, which uses two slave transmitters ashore and a master timing oscillator and transmitter aboard the navigating vessel. Time-multiplexing is used on a common carrier frequency of about 2 mc. The slave stations may operate unattended in the Hi-Fix system.

The position is displayed to the navigator in digital format on two counters. Supplementary display and automatic plotting equipment is available.

2. DESCRIPTION

This system utilizes closely synchronized, phase stable, cw frequency transmission from the master and the two slave stations. Each station transmits sequentially on the same frequency; the timing is controlled by the master oscillator and other associated circuitry. As illustrated in Figure VI-4, the slave 1 and slave 2 transmissions are keyed by the master trigger signal with a 0.3 and 0.6 second delay, respectively. Using a time-sharing system and a common frequency of operation makes it a simple matter to change the frequency of the Hi-Fix chain. Five operating frequencies are available, and a frequency selection is made by the operator at the master station.

a. Transmitter Unit

The master oscillator unit provides the drive signal for the master transmitter. At the slave stations the controlling receiver provides the input for the slave station transmitter, which is identical to the master station transmitter. The transmitters are portable, are rated at 25 watts, and are generally located close to the antenna. The antenna is a guyed portable mast approximately 30 feet in height. A ground plane is generally required for each shore station antenna to obtain stable and reliable transmission to ranges beyond line of sight.
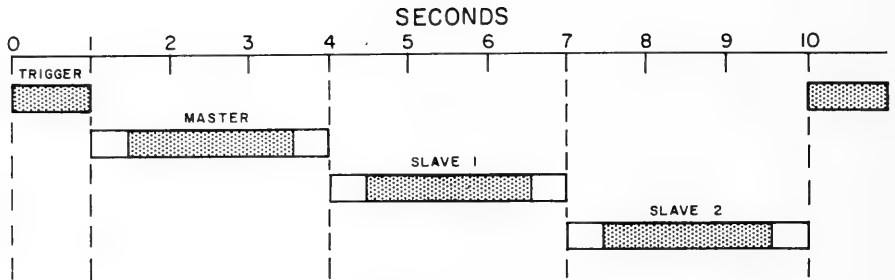
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SECONDS

FIGURE VI-4   HI-FIX TIME-SHARING OF MASTER AND
SLAVE TRANSMISSIONS

b. Receiver Unit

The receiver is used as a position-fixing instrument aboard the navigating vessel in the hyperbolic system, which places the master and the two slave stations ashore. In the ranging mode the master station and receiver are placed aboard the navigating vessel and each slave station is located at the end of a base line ashore. The slave station receiver is required to hold the phase of the slave transmission at a constant and predetermined relationship with respect to the master.

With the navigator's receiver in the operate mode, the incoming 1900 kc (approximately) signal from the master and the two slave stations is converted to an intermediate frequency of 132 kc. In addition to the phase-sensitive cw transmissions, the trigger signals from the master station are also received. These pulses are extracted from the intermediate frequency output to activate circuitry which gates the two digital display circuits. Using master timing pulses in this manner allows the digital display for each channel to be activated only during the proper slave transmission, as illustrated in Figure VI-4.

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The phase comparison system uses a phase discriminator to compare the phase of the master oscillator with that of each slave station and displays this difference on a goniometer dial in terms of lanes and fractions of lanes. Each of the two goniometers mounted on the receiver panel makes one revolution per lane or phase-difference cycle, and each is capable of driving various other displays. The goniometer has an accuracy of about 1 degree of phase, thus producing little error due to nonlinearity. The two lane counts are displayed on digital counters accommodating 999.99 lanes.

The use of an identical frequency of transmission by the master and both slave stations frees the system from differential phase errors due to thermal or other causes in the two halves of the phase-comparison circuit.

With Hi-Fix type A no means of coarse positioning is provided, and the navigator must keep track of lanes with respect to a known starting point. Lane identification can be provided by a system known as Hi-Fix type B. With this system additional receiver-transmitter units are placed at each station, and a second grid is generated. In this manner automatic and continuous lane identification is provided.

3. ACCURACY

The Hi-Fix system can generate either a hyperbolic or a circular pattern. The circular coordinate system has the advantage of a constant lane width with increasing range. The lane width of the system is about 250 feet, and the instrument accuracy corresponds to about 0.01 lane. The patterns generated are illustrated in Figure VI-5, where the relative accuracy of the system using the two patterns is indicated.

The working range is dependent largely upon the sight and the atmospheric noise level. Typical operating distances between Hi-Fix transmitters and receivers are 5 - 35 miles, but ranges of 100 - 130 miles can be obtained.

With Hi-Fix set up as a hyperbolic system, one series of tests[2] indicated system accuracy to be about ±0.05 lane, which is equivalent to between ±10 - 40 feet. For this case the transmission path was across both land and water. Rather large systematic errors can be expected for this situation where the propagation velocity is dependent upon the electrical conductivity of the terrain and proper corrections are not applied. When these measurements were repeated from the same stations for paths over water, the standard deviation for readings was of the order of ±0.01 - 0.02 lanes which is equivalent to a positional accuracy of between 2.5 and 7 feet.

The system can be calibrated at any time by using an internally generated phase datum contained in each receiver. Thus each operator can adjust his receiver at will to obtain the same fractional lane reading at a point of given location, without prior calibration at that point.
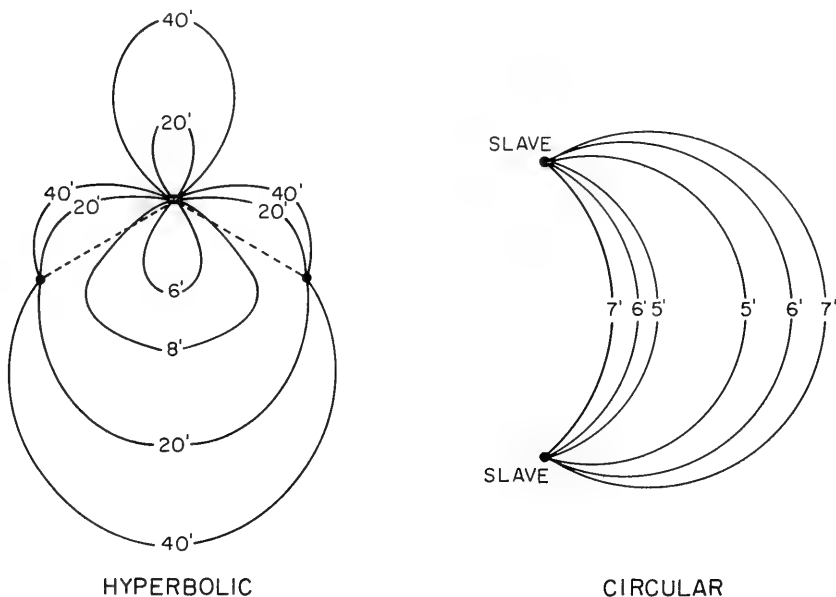

HYPERBOLIC   CIRCULAR

FIGURE VI-5   TYPICAL RELATIVE ACCURACY CONTOURS FOR
                HYPERBOLIC AND CIRCULAR PATTERNS

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4. SUMMARY

a. Type of System

(1) Mode of operation: hyperbolic or ranging.

(2) Frequency: one frequency per chain in 1.7 - 2.0 mc band.

(3) Operation: time-multiplexing of single frequency.

(4) Number of frequencies available: 5 in 1.7 - 2.0 mc band, selected by operator.

(5) Type of transmission: cw.

(6) Sampling rate: one/second.

(7) Time-multiplexing trigger signal: 60 cps in master transmission, lasting 0.1 second.

(8) Radiated power: 10 watts (approximately).

(9) Power required: 24 v @ 300 w (approximately).

(10) Personnel requirements: Master station can operate unattended, slave stations require one nontechnical attendant each.

b. Range and Accuracy

(1) Range: 40 - 100 miles, dependent upon ground conductivity.

(2) Accuracy: Over water, $\sigma = \pm 0.01 - 0.02$ lane, which is equivalent to about $\pm 2.5 - 7$ feet. Over combination land and water, $\sigma = \pm 0.05$ lane, which is equivalent to $\pm 10 - 40$ feet.

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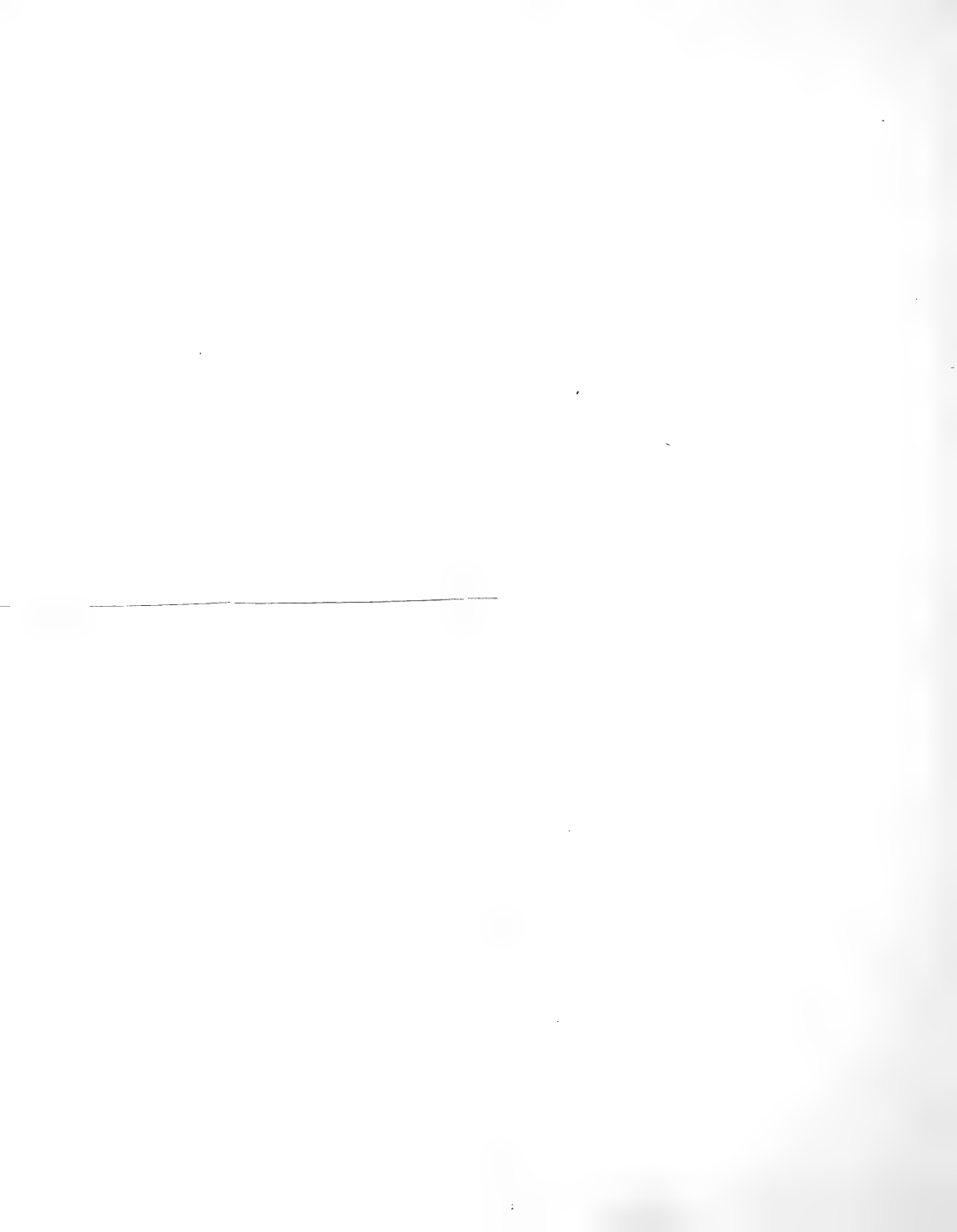REVIEW OF MARINE NAVIGATION SYSTEMS AND TECHNIQUES

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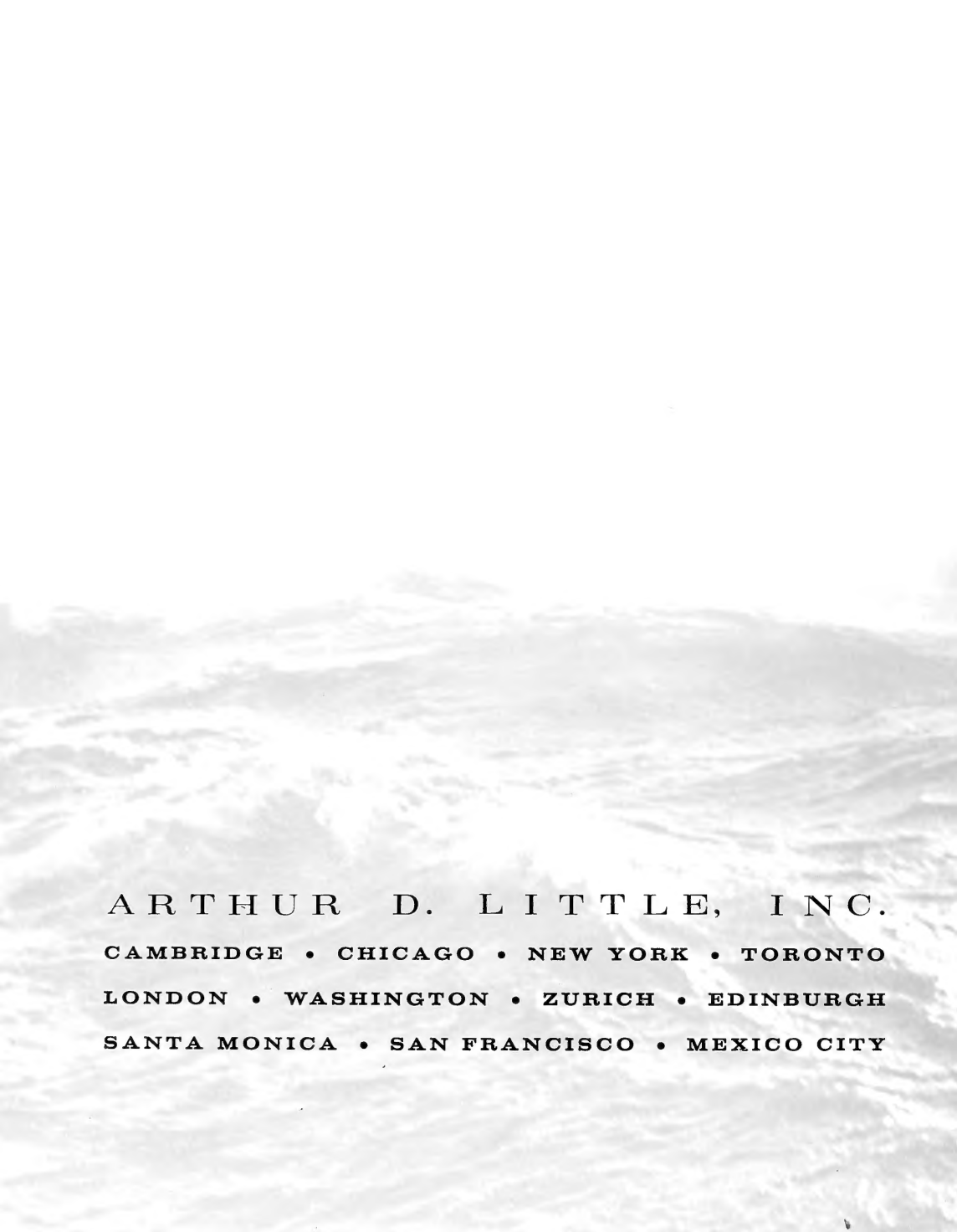
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