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POSITION-LOCATION/NAVIGATION SYSTEMS OVERVIEW FOR MILITARY LAND VEHICLES

CONTRACT NO. DAAK30-78-C-0091

29 JUNE 1979

by PAUL ROSENBERG

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RESEARCH AND DEVELOPMENT COMMAND
Warren, Michigan 48090

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Author: Paul Rosenberg

Final Technical Report
Contract DAAK30-78-C-0091
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Prepared for
UNITED STATES ARMY TANK-AUTOMOTIVE
RESEARCH AND DEVELOPMENT COMMAND
Warren, Michigan 48090

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PREFACE

The U. S. Army Tank-Automotive Research and Development Command is pleased to present this primer of position-location/navigation techniques and systems to those military and civilian parties interested in the application of such systems to military land vehicles.

Our intent, and subsequent instructions to Dr. Paul Rosenberg, the author, were to provide a succinct, readable, tutorial overview of position-location/navigation techniques and systems as an aid and reference to persons whose expertise may lie in other areas, or who have experienced only limited involvement in the technical aspects of navigation.

This document represents the completion of the first phase of an intended multiple-phase program. Each subsequent phase will provide increasingly specific comments (on the application of navigation techniques to land vehicles)

(Preface continued)

based on the supporting information provided by succeeding work efforts. These phases are presently planned:

1. Primer on position-location/navigation systems. (Completed)

2. Compilation/analysis of the various national plans for navigation.

3. Compilation of user requirements/operating scenarios.

4. Specific recommendations as to the navigation techniques/equipment appropriate to each user situation.

Comments on the program are solicited.

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ABSTRACT

Position-location/navigation systems are overviewed tutorially for possible application to military land vehicles. The overview includes position-location by celestial navigation, rho/theta systems, hyperbolic systems, radar, inertial systems and satellite systems. Potential advantages and disadvantages of applying various position-location systems to military land vehicles are suggested.

1. FOREWORD

1.1 The United States Army Tank-Automotive Research and Development Command (USATARADCOM), Warren, Michigan awarded study contract no. DAAK30-78-C-0091 to Paul Rosenberg Associates, Pelham, New York for a "Position-Location/Navigation Systems Application Analysis". This report is the Final Technical Report of the contract.

1.2 Dr. Paul Rosenberg was the principal investigator in this contract work, and is the author of this report.

1.3 Mr. Gordon J. McInnes was USATARADCOM's Technical Representative for this contract. Acknowledgement is made to Mr. McInnes for his excellent technical assistance and guidance to the contractor.

2. SCOPE AND OBJECTIVE

2.1 This report is an overview, analysis and discussion of position-location/navigation systems and equipment for civilian and military vehicles, including land, marine and aeronautical vehicles.

2.2 Position-location/navigation systems are treated in groups according to system types and technologies, in sections 4 through 10 herein. (See Table of Contents, page 4). In addition, the report contains: a section on definitions (section 3); a section on miscellaneous systems (section 11); and an index to selected systems, acronyms and definitions (section 12).

2.3 This report is tutorial in compliance with the following instruction in the scope of work of the contract:

> "Review the operating principles of the major navigation techniques, and describe the phenomena or physical principles used in these techniques. The review should be such as to enable an engineer or a layman with good technical background to understand the basics of each technique and its navigational application."

2.4 The report suggests advantages and disadvantages of each type of position-location/navigation system for possible application to military land vehicles in general. The scope of this contract work did not include study or consideration of the many different types of military land vehicles and the many different military environments, situations and missions in which the vehicles operate. The overview conducted under this contract prepares the foundation for future study, selection and development of optimum systems for the position-location/navigation of specific military land vehicles in specific military environments and mission roles.

3. DEFINITIONS

3.1.1 The practices of navigation and position-location have evolved from the applications of many scientific, engineering and technological disciplines, e.g. physics, astronomy, mathematics, electronics, optics, mechanics, and geodesy, as well as from the sailing arts through the ages. In this evolution, it is not surprising that acronyms and specialized terms have been devised. Some of these terms are used with different shades of meaning by different navigation practitioners, and some terms are used in navigation with meanings that differ from the strict meanings of these terms in the disciplines from which the terms were taken. In this study and report, every effort has been made to define specialized position-location/navigation terms as unambiguously as possible, in order to clearly describe, analyze and compare systems, methods and equipments.

3.1.2 Some of these terms are defined in paragraph 3.2 through 3.8.2 herein. Other terms, including acronyms and names of position-location/navigation systems, are defined in other sections of this report and are indexed alphabetically in Section 12. Each indexed term is usually underscored on the page to which the index refers.

3.1.3 The definitions formulated in this study and report are as consistent as possible with the terminology used in the position-location/navigation community and in related disciplines of science, engineering and mathematics. The following authoritative dictionaries, texts and glossaries are relevant:

"Navigation Dictionary"
H. O. Publication No. 220
NVPUB220
1969 Edition
Defense Mapping Agency, Washington, DC

"IEEE Standard Dictionary of Electrical and Electronics Terms"
Institute of Electrical & Electronics Engineers
ANSI/IEEE Standard 100-1977
Approved by American National Standards Institute, 1978
Wiley-Interscience, New York

"Mathematics Dictionary"
James & James
Multilingual Third Edition, 1968
D. Van Nostrand Company, Princeton, NJ

"Glossary of Mapping, Charting and Geodetic Terms"
Department of Defense, Washington, DC
June 1973
AD-775-778

(3.1.3 continued)

"American Practical Navigator"
Nathaniel Bowditch (1773-1838)
1977 Edition
2 volumes
Pub. No. 9
Defense Mapping Agency Hydrographic Center
Washington, DC 20390

"Dutton's Navigation and Piloting"
13th Edition, 1978
Elbert S. Mahoney
Naval Institute Press
Annapolis, Maryland

"Electronics Dictionary"
John Markus
4th Edition, 1978
McGraw-Hill Book Co., New York, NY
ISBN-0-07-040431-3

"Optical Terms and Definitions"
Department of Defense, Washington, DC
MIL-STD-1241A
31 March 1967

3.2 A <u>position</u> (or <u>point</u>) is a set of coordinate values in a spatial coordinate system. The system can be one, two or three dimensional. One-dimensional systems (such as, for example, the linear distance along a fixed railroad track) are not important for the purposes of this study. An example of a two-dimensional system is the latitude and longitude of a ship at sea, assuming the ocean surface is a sphere. An example of a three-dimensional system is a rectangular Cartesian system in which a position consists of a set of three values (x, y, z) corresponding respectively to values on three mutually perpendicular X, Y and Z axes. Another example of a three-dimensional coordinate system is an Earth geographic coordinate system in which a position consists of latitude, longitude, and altitude above the geoid; (see paragraphs 11.6.7.1 - 11.6.7.5).

3.3 <u>Position location</u> is the process of finding or measuring the position at which a vehicle (e.g. a tank, ship or aircraft) or a target is located at a given instant of time. The position thus determined is called a <u>fix.</u>

3.4.1 Navigation consists of the following four processes:

(a) Position location (defined above).

(b) Measuring the magnitude and direction of the vector that represents the instantaneous velocity of a vehicle.

(c) Planning and plotting a course (or path) of travel from one position to another position.

(d) Calculating the time and distance that will be required to traverse the course.

3.4.2 Processes (a) and (b) are the basic and critical processes of navigation. Compared to (a) and (b), processes (c) and (d) are simple and are readily performed after (a) and (b) have been accomplished. Processes (a) and (b) are the principal subjects of this study, analysis and overview. Therefore in this report, navigation shall mean processes (a) and (b), unless stated otherwise.

3.5.1 A line of position, abbreviated as LOP, is the locus of all positions (points) that correspond to a single measurement (not a fix) by a position-location system. Depending upon the system, the LOP can have a number of shapes, e.g. a straight line, a circle, a great circle of the

(3.5.1 continued)

earth's surface, or a hyperbola. The LOP can also be a bent straight line, or a distorted hyperbola, as a result of propagation anomalies in radio position-location systems. The intersection of two (or more) LOPs gives a position-location, i.e. a fix.

3.5.2 The accuracy of a fix is usually optimum if the two LOPs intersect each other at right angles. The accuracy of a fix usually degrades as the two LOPs approach parallelism at their intersection. Accuracy of the fix can be improved by using more than two intersecting LOPs. If three such LOPs do not intersect precisely at the same point, their three intersections form a triangle within which the fix is most probably located. If the three LOPs are considered to be equally reliable, the centroid of the triangle can be taken as the most probable fix.

3.6 Meaconing is a term derived from "measuring and confusing". It means measuring received radio navigation signals and transmitting confusing signals on the same frequency, for the purpose of giving enemy navigators a false indication of position. Meaconing is not synonymous with jamming or interference. Meaconing refers to radio navigation only; whereas jamming and interference refer to electronic systems in general, including radio navigation.

3.7.1 A position-location/navigation system is saturable if only a limited number of vehicles can use the system at one time. An example of a saturable system is DME (section 5.2.1) in which each ground-based transponder can respond to only a finite number of interrogations in a short time interval.

3.7.2 A non-saturable system is one that can accommodate an indefinitely large number of vehicles simultaneously. Examples of non-saturable systems are: hyperbolic radio systems (section 6); Transit (section 9.2); Navstar-GPS (section 9.3); and celestial navigation systems (section 4).

3.8.1 An active system for position-location/navigation of a vehicle is a system that deliberately transmits or emits signals or radiation from the vehicle. An active system breaches the electromagnetic security of the vehicle. Examples of active systems are DME (section 5.2.1) and radar (section 8.0).

3.8.2 A passive system for position-location/navigation of a vehicle is a system that does not deliberately transmit or emit signals or radiation from the vehicle. A passive system helps to keep the vehicle secure electromagnetically. Examples of passive systems are celestial navigation, hyperbolic radio systems, inertial systems and Navstar-GPS.

4. CELESTIAL NAVIGATION

4.1 Celestial navigation is navigation by optical measurements of the apparent angular locations of the sun, the earth's moon, the planets, and the major stars.

4.2.1 The apparent motions of these celestial bodies, as seen from earth, have been determined accurately by astronomical observations and are accurately predictable. The angular coordinates of these bodies with respect to earth as a function of time, are tabulated in almanacs for the use of navigators.

4.2.2 Two almanacs, the "Nautical Almanac" and the "Air Almanac", are used throughout the marine and aviation industries. They are published jointly by the United States Naval Observatory and H. M. Nautical Almanac Office, Royal Greenwich Observatory, England. Other nations re-publish the Nautical Almanac with minor modifications, using native languages for table headings, notes and text.

4.3.1 Celestial navigation assumes that all the celestial bodies are located on a sphere (the celestial sphere) with the earth at its center. The radius of the celestial sphere is assumed to be very large compared to the radius of the earth. The nearest fixed star is indeed at a distance that is more than 10^9 (a billion) times the earth's diameter, so that

(4.3.1 continued)

parallax due to sighting on the fixed stars from the two ends of an earth diameter is negligible for navigation purposes. However, parallax is appreciable when sighting on the sun, the earth's moon, and the planets, from different points on the earth's surface; and this parallax is taken into account in navigation almanacs when celestial bodies of the solar system are used.

4.3.2 Although the earth is actually an oblate spheroid, it is assumed to be a true sphere in celestial navigation. This assumption introduces no significant error in the practical navigation of aircraft and ships at sea. This assumption should likewise cause no significant error in the navigation of land vehicles by celestial navigation. (See paragraphs 11.4.7. - 11.4.11)

4.4.1 On the celestial sphere, "GHA" (Greenwich Hour Angle) is the equivalent of longitude on earth, and "declination" is the equivalent of latitude on the earth. The almanacs give the data for GHA and declination of all the celestial bodies commonly used in navigation for every 1^s (one second of time) throughout the year. The time is GMT (Greenwich Mean Time).

4.4.2 The Nautical Almanac gives the GHA and declination to the nearest 0.1' (one tenth of a minute of arc) in general. This almanac is published annually for marine use.

4.4.3 The Air Almanac gives the GHA and the declination to 1' (one minute of arc). This almanac is issued twice a year, and is tailored for the convenience of aircraft navigation. The Air Almanac is often used for marine navigation because the Air Almanac is more convenient to use than the Nautical Almanac, and because the 1' accuracy of the Air Almanac is often adequate for practical marine navigation.

4.4.4 One minute of arc (1') on any great circle on the earth's surface is equal approximately to one nautical mile or 1.85 kilometers.

4.5 In the actual practice of celestial navigation at sea and in the air, the accuracies of position-location are never as good as the accuracies of the almanac tables. An average error of plus or minus 2 (two) nautical miles is realistic for navigation at sea; and an average error of perhaps 4 (four) nautical miles is realistic for aircraft navigation. The same kinds of errors are likely if land vehicles are navigated by celestial navigation.

4.6.1 Celestial navigation instruments fall into two categories: first, sextants for visually sighting celestial bodies non-automatically (paragraphs 4.6.2 through 4.17); and second,

(4.6.1 continued)

automatic electro-optical tracking systems for sighting celestial bodies automatically (paragraphs 4.18 through 4.24).

4.6.2 The sextant is a hand-held opto-mechanical instrument that is used to measure the angle subtended, at the observor, by two distant objects. The objects can be two celestial bodies; or, more usually, the objects are a celestial body and the horizon.

4.6.3 In order to locate his position on the earth by celestial navigation, the navigator must find, in effect, the angles between his local vertical and the directions of two or more celestial bodies. He does this by a sextant that measures the angle between a celestial body and the horizon, assuming, as a first approximation, that his vertical is perpendicular to the line of sight between the sextant and the horizon. (His vertical or zenith direction is the direction of the line joining him with the center of the earth.)

4.6.4 The principal sources of error in the procedure of paragraph 4.6.3 are:

(a) The sextant is always at some appreciable altitude above the earth's surface; (otherwise no horizon would be visible). Therefore the plane of the horizon is below the plane that is perpendicular to the vertical at the observor's altitude; with the result that the line between the sextant and the horizon is not parallel to

(4.6.4 continued)

the aforesaid tangent plane. The resulting angular error is called the dip angle or dip. The navigation almanacs contain correction tables for dip as a function of the altitude of the observing sextant.

(b) The light ray from the celestial object is refracted (bent) as it enters the earth's atmosphere. The direction of the ray, as observed through the sextant, is therefore not the true direction of the object.

(c) The amount of the aforesaid refraction is a function of the density of the air at the time of observation, i.e. a function of temperature and barometric pressure.

4.6.5 The nautical almanacs and ephemeris provide correction tables and data for the errors listed in paragraph 4.6.4 and for other errors such as, for example: changes in the apparent semi-diameters of the sun and the moon; phases of the moon, Venus and Mars; parallax of the sun, moon and some planets, seen from different positions on the earth's surface.

4.7 In a military situation, it can be intolerable to have to wait for a conventional celestial navigator, in a land vehicle, to look up his declinations, GHA, and corrections in the almanac, and then compute the spherical triangles that finally give him a fix. Fortunately, small calculators, pocket-sized, can be programmed to perform the celestial navigator's computations in a matter of

(4.7 continued)

seconds or less; and much or all of the look-up information contained in the almanac can be stored in compact solid-state memory that is quickly accessible.

4.8 The sextant itself has instrumentation errors, but in a very good marine sextant the error does not exceed 0.1' (one tenth of a minute of arc), corresponding approximately to one-tenth of a nautical mile on the earth's surface. The U. S. Navy Mark II sextant has errors that lie within 35" (thirty-five seconds of arc) which is a little more than a half nautical mile.

4.9.1 The time at which a sextant observation of a celestial body is made must be measured with an accuracy that is comparable to the accuracy of the angle measurement. In the vicinity of the equator, an error of 1^s (one second of time) introduces an error of about 0.25 nautical mile of longitude (because of the diurnal rotation of the Earth). This longitude error, per second of time, decreases with increasing latitude. An accurate chronometer is an essential part of a celestial navigator's equipment.

4.9.2 The Hamilton ship chronometer, a mechanical chronometer, is widely used in the U. S. Navy. Because this chronometer cannot be carried topside each time that a celestial observation is

(4.9.2 continued)

made, the actual observations are timed by a hand-held watch, called a comparing watch, that is set to the chronometer. The chronometer in turn is set to, and periodically checked against, radio time signals that are broadcast by the U. S. Bureau of Standards, the U. S. Navy, and several foreign stations. The radio stations most commonly used by United States marine vessels are the Bureau of Standards stations WWV (Fort Collins, Colorado), NSS (Annapolis, Maryland) and WWVH (Kauai, Hawaii). The U. S. Navy also maintains time signal transmissions from stations in the United States, Australia and the Panama Canal Zone. Radio time signals usually are far more accurate than is needed for navigating marine vessels and aircraft.

4.9.3 Modern solid-state timepieces, with temperature-compensated crystal-controlled oscillators and digital displays, will eventually replace mechanical ships' chronometers and mechanical comparing watches.

4.10.1 The following spectrum allocations have been made by the WARC (World Administration Radio Council) for standard time signal broadcasting internationally:

(4.10.1 continued)

Name of Band	Band No.	Frequency Range
Very Low Frequency (VLF)	4	20.0 KHz ± 50 Hz
Medium Frequency (MF)	6	2.5 MHz ± 5 KHz
High Frequency (HF)	7	5.0 MHz ± 5 KHz
		10.0 MHz ± 5 KHz
		15.0 MHz ± 10 KHz
		20.0 MH_z ± 10 KHz
		25.0 MH_z ± 10 KHz
Ultra High Frequency (UHF)	9	400.1 MHz ± 25 KHz
Super High Frequency (SHF)	10	4.202 GHz ± 2 MHz
		6.427 GHz ± 2 MHz

4.10.2 The NBS (National Bureau of Standards) station WWV broadcasts from Fort Collins, Colorado at frequencies in bands 6 and 7. The NBS station WWVH broadcasts from Kauai, Hawaii at the same frequencies as WWV except at 25.0 MHz.

4.10.3 The most commonly used frequencies broadcast by WWV and WWVH are 2.5, 5.10 and 15 MHz. At 5, 10 and 15 MHz, the radiated power is 10 kilowatts for WWV and WWVH. At 2.5 MHz, the radiated power is 2.5 kilowatts for WWV, and 5 kilowatts for WWVH.

4.10.4 WWV and WWVH broadcast their time signals continuously. The Canadian station CHU likewise broadcasts time signals continuously. Other stations, such as the U. S. Navy station NAM in Norfolk, VA, broadcast their time signals on schedules, but not continuously.

4.10.5 The pulse, or "beep", at the end of each transmission from the Transit navigational satellite (section 9.2) can also be used as a time check. Accurate time checks can also be obtained from the pulsed signals of Loran-C (section 6.3) and Omega (section 6.6). Nevertheless, time checks from Transit, Loran-C and Omega are rarely used in celestial navigation.

4.11 One of the largest sources of inaccuracy in celestial navigation with a manually operated sextant is the motion and instability of the vehicle or platform on which the observor stands during his operation of the sextant. Seasoned marine navigators become expert in keeping themselves and their sextants steady during

(4.11 continued)

observations, but this requires long specialized experience and skill that crew members of a land vehicle are not likely to have.

4.12.1 Celestial navigation is not an all-weather navigation system. Atmospheric conditions must be good enough to allow sightings on celestial bodies and the horizon. The horizon is likely to be obscured (e.g. by haze) more often than the stars, planets, sun or moon. Consequently sextants that contain so-called artificial horizons have been developed to measure the elevations of celestial bodies without the necessity of sighting an horizon.

4.12.2 The most common form of artificial horizon is a bubble level vial. Sextants with these levels built in are called bubble sextants. The bubble level gives the instrument the direction of gravity, which is perpendicular to the plane of the horizon. Anomolies in the direction of the gravitational vector are insignificant compared to other errors in the celestial navigation procedure. Another form of artificial horizon is a pendulum which acts like a plumb line to give the direction of gravity. A third form of artificial horizon is gyroscopic; but a gyro attached to a sextant takes the sextant out of the class of relatively simple celestial navigational equipments and thrusts the instrument into a much more sophisticated class; (paragraphs 10.1.11, 10.1.12).

4.12.3 Artificial horizon sextants of the bubble or pendulum types have met with only limited success and acceptance. Accelerations of the vehicle, slow as well as rapid, give spurious artificial horizon indications because the bubble level or the pendulum indicates the direction of a vector that is the resultant of the gravity vector and the vehicle acceleration vector, not the direction of gravity alone. Artificial horizon sextants have been more successful in aircraft than in ships at sea, because the aircraft accelerations are less troublesome than ship accelerations.

4.13 Submersibles at periscope depth can perform celestial navigation by sextants that are built into the periscope. The observor remains below, in the hull, and takes sights on the horizon and the celestial bodies through the periscope. (See also section 11.5.)

4.14 An aircraft navigator can use a hand-held sextant if the craft is fitted with a transparent observation dome or if the cockpit canopy is opened. Neither of these situations is usual nowadays. An aircraft can be fitted with a periscopic sextant, which is similar in principle to a the periscope sextant used in submersibles. (The submersible device is called a periscope sextant; whereas the aircraft device is called a periscopic sextant.) Electronic navigation systems have completely replaced celestial navigation in commercial air transport operations. A few older military aircraft are still equipped with periscopic sextants.

4.15.1 The idea of a periscope (or periscopic) sextant could be applied to land vehicles that have closed roofs, e.g. tanks, trucks or troop carriers. The periscope sextant would extend out of the top of the closed vehicle; and the operator would remain inside the vehicle. In the case of a tank, the periscope sextant might be combined with the tank's other periscope or periscopes.

4.15.2 For use in a tank or other land vehicle, the sextant will require some form of artificial horizon, because surrounding topography and/or vegetation and/or cultural features will usually prevent the horizon from being visible from the relatively low altitude of the top of the land vehicle.

4.16 Advantages of celestial navigation (non-automatic) for use in military land vehicles are:

(a) The system is self-contained. No external equipment or installations are needed.

(b) The system (sextant, timepiece, almanac, pocket computer) is small and light-weight compared to other systems.

(c) The equipment is relatively reliable, and needs only infrequent maintenance.

(d) The equipment is not costly. The total cost of a high quality sextant, crystal-oscillator chronometer, programmable pocket computer and almanac is approximately $1,000.

(4.16 continued)

(e) The system is almost jam-proof. The only way to jam the system would be to generate an obscuring cloud above the vehicle.

(f) The system is not subject to meaconing. (par. 3.6).

(g) The system is passive (par. 3.8.2).

(h) The system is non-saturable (par. 3.7.2).

4.17 Disadvantages of celestial navigation (non-automatic) for use in military land vehicles are:

(a) The system can be used only in clear weather. It is not an all-weather system.

(b) The accuracy of position-location will probably be a circular probable error (CPE) of 5 (five) nautical miles if observations are made while the land vehicle is traveling over rough terrain. The accuracy will probably be a circular probable error(CPE) of 2 (two) nautical miles if observations are made while the vehicle is stationary.

(c) Skilled, experienced sextant operators will be needed. More operator training will be required for this system than for most electronic navigation systems. Position-location accuracy is likely to vary from operator to operator, and from hour to hour with the same operator.

4.18 A star tracker (also called star scanner, or astro tracker, or photoelectric sextant) is an electro-optical-mechanical instrument that automatically scans a field of view of the sky, senses and homes-in on the image of a celestial body, and measures the elevation and bearing (azimuthal) angles of the celestial body. This can be called automatic celestial navigation.

4.19 The essential components of a star tracker are a telescope mounted in servo-controlled gimbals, a radiation detector, and associated electronic circuitry. Photovoltaic, photoconductive and photoemissive detectors have been used. The photoemissive detectors include photomultipliers and image dissector tubes. Star-trackers that use solid-state array sensors, e.g. charge-coupled devices (CCD), are being developed.

4.20 The instantaneous field-of-view of the star-tracker's telescope is limited. Consequently a computer (or a manual input) must direct the star tracker to the approximate azimuth and elevation of the star to be found and tracked, so that the star image will fall within the telescope's field-of-view. The magnitude (a measure of brightness) of the desired star is also input to the star tracker so that it will ignore stars of lesser magnitude. The tracker can be programmed and instructed to scan its field-of-view to find and locate, in succession, all stars of the specified threshold magnitude. In aircraft, the field-of-view is usually less than one degree of arc. In spacecraft, it is sometimes 10 or as much as 24 degrees of arc.

4.21 A star tracker is usually combined with an inertial system, (section 10). The inertial system provides vertical and heading references to the star tracker. The star tracker periodically makes correction for the drift of the inertial system.

4.22 Aircraft star trackers can usually detect stars as dim as magnitude 2.1, e.g. Polaris. Other star trackers, for use in spacecraft, can detect stars as dim as magnitude 14. Aircraft star trackers have accuracies of about 2 to 6 arc minutes. Special spacecraft star trackers are said to have accuracies of about 2 arc seconds. The acquisition time for aircraft star trackers is in the range of 1/4 to 2 seconds. Weights of star trackers in aircraft systems vary from about 35 to 230 lbs. Lighter weight trackers are used in spacecraft.

4.23 Advantages of automatic celestial navigation for use in military land vehicles are the same as advantages (a), (e), (f), (g) and (h) of paragraph 4.16.

4.24 Disadvantages of automatic celestial navigation for use in military land vehicles are:

(a) The system can be used only in clear weather. It is not an all-weather system.

(b) The system is not as reliable as non-automatic celestial navigation.

(4.24 continued)

(c) Much more maintenance is needed for an automatic celestial navigation system than for a non-automatic celestial navigation system.

(d) Cost of an automatic celestial navigation system is in the order of 50 to 300 times as large as the cost of a non-automatic celestial navigation system.

5. RHO/THETA SYSTEMS

Contents of Section 5.

5.1 Introduction

5.1.1 In a system of polar coordinates, a point P is located by its distance ρ (rho) from a fixed point O, called the pole, and by the angle θ (theta) that the line OP makes with a fixed line ON called the polar axis. See Figure 5.1.1.

5.1.2 In navigation, the polar axis is usually tangent to the geographic meridian, i.e. the polar axis points North and South, and the pole of the coordinate system is at a known location.

Figure 5.1.1

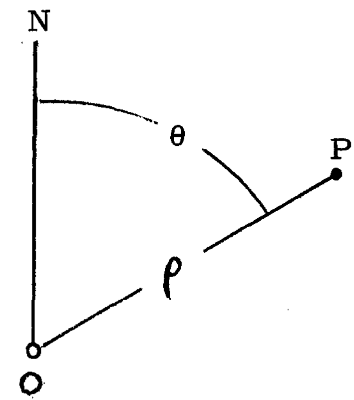
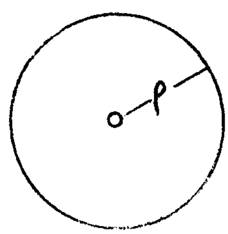


Figure 5.1.4.a



Circular LOP

Figure 5.1.4.b

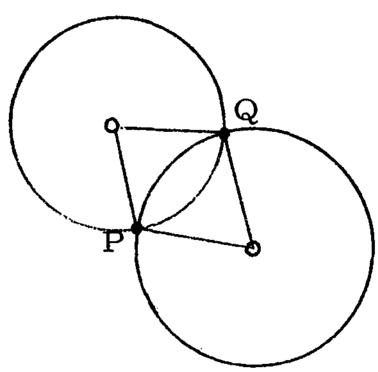
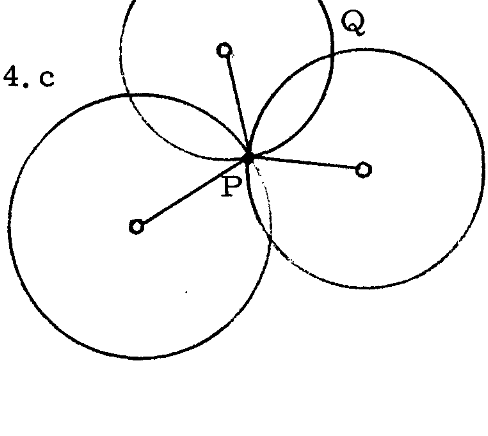


Figure 5.1.4.c



5.1.3 In position-location/navigation terminology and in this report, systems and equipments that measure only rho are called rho systems or rho-rho systems; systems and equipments that measure only theta are called theta systems or theta-theta systems; and systems and equipments that measure both rho and theta are called rho-theta systems.

5.1.4 In rho systems, measurement of a vehicle's rho with respect to one pole determines a LOP in the shape of a circle with its center at the pole and a radius equal to rho, as in Figure 5.1.4.a. Measurement of a second rho, with respect to a second pole, gives another LOP circle that intersects the first LOP circle in two points that constitute two ambiguous fixes P and Q, as in Figure 5.1.4.b. A third rho measurement, with respect to a third pole, gives a third LOP circle that eliminates the ambiguity of the fixes and can improve the accuracy of the final fix P, as in Figure 5.1.4.c.

5.1.5 In theta systems, measurement of a vehicle's theta with with respect to a single pole determines a LOP in the shape of a straight line that passes through the pole and subtends the angle theta with respect to the known polar axis. Measurement of theta with respect to another pole gives another straight-line LOP that intersects the first LOP in a point that constitutes an unambiguous fix. (Figure 5.1.5)

Figure 5. 1. 5

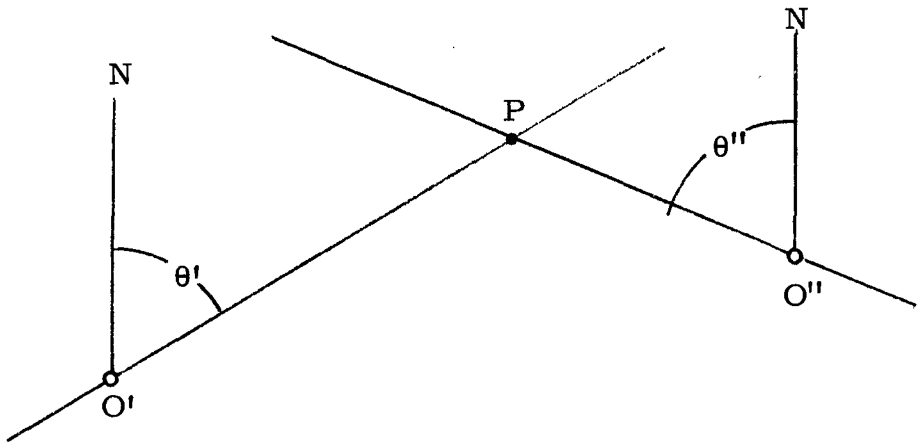


Figure 5. 1. 6. 1

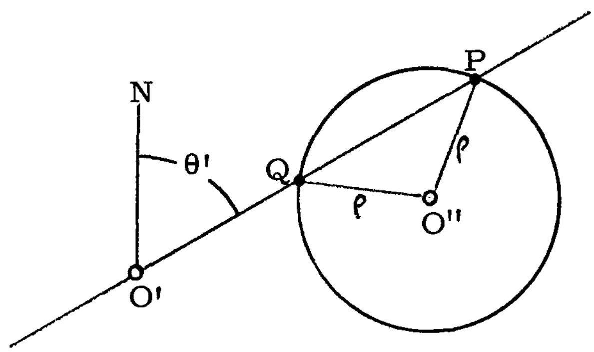
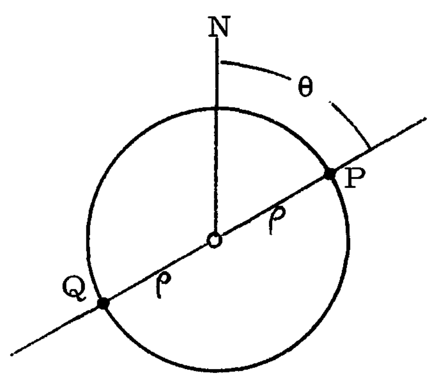
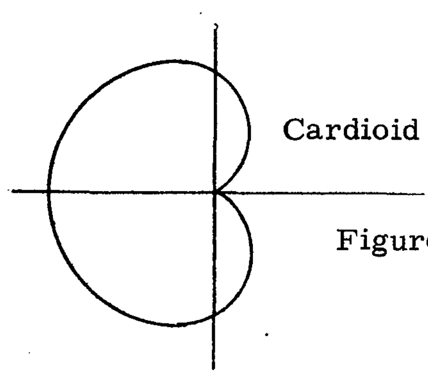


Figure 5. 1. 6. 2





Cardioid

Figure 5. 3. 2. 13 and 5. 3. 3. 3

5.1.6.1 In rho-theta systems, a rho measurement with respect to one pole, combined with a theta measurement with respect to another pole, can also be used for a fix. The LOP circle (determined by rho) intersects the LOP straight line (determined by theta) in two points that constitute an ambiguous fix. The ambiguity can be resolved either by knowledge of the vehicle's approximate location, or by measurement of rho or theta with respect to a third pole. (Figure 5.1.6.1)

5.1.6.2 The aforesaid rho-theta ambiguity (paragraph 5.1.6.1) can be resolved most conveniently and most accurately by measuring rho and theta both with respect to the same pole. In this case, the two intersections of the LOP circle and the LOP straight line lie on azimuths that are 180 degrees apart with respect to the pole; and the navigator should surely know which of these two fixes is correct from his general knowledge of his location. Furthermore, the two LOP's (circle and its straight-line diameter) intersect each other at right angles, thereby improving the accuracy of the fix. This type of rho-theta system (measuring rho and theta from the same pole) is the only type of rho-theta system used in actual practice, instead of rho-theta systems that measure rho and theta from separate poles. Rho-theta systems that measure rho and theta from the same pole are the systems described in section 5.4. (Figure 5.1.6.2)

5.1.7 It might be said pedantically that all position-location systems are either rho, theta or rho-theta systems, except inertial systems (section 10), piloting (section 7), and proximity systems (paragraph 11.4.4.). For example: celestial navigation (section 4) is a 3-dimensional theta system; hyperbolic systems (section 6) are 2-dimensional rho systems; radars (section 8) are rho-theta systems; and navigation satellite systems (section 9) are 3-dimensional rho systems. Pedantically, therefore, it might seem that almost all position-location/navigation systems should be placed and discussed under only three categories, namely rho, theta, and rho-theta systems. However, it turns out that the descriptions, analyses and comparisons of all the systems become more practical and clarified when the headings of "rho", "theta" and "rho-theta" are reserved for the systems described in sections 5.2, 5.3 and 5.4 respectively, while other systems are grouped under the other section headings of this report.

5.2. Rho Systems

5.2.1 DME

5.2.1.1 A rho system finds the distance (range) between a vehicle and a cooperating fixed station by measuring the time interval required for a round trip of a radio signal between the vehicle and the station. The distance is the product of half of the time interval multiplied by the speed of propagation of the signal, i. e. 3×10^{10} cm per second.

5.2.1.2 The most widely used rho system is DME, an abbreviation for Distance Measuring Equipment. In the Western World, an estimated 70,000 aircraft carry DME equipment, served by an estimated 2,000 DME ground stations. DME is rarely used in nautical navigation. DME had its origins in World War II when the British used a short-range pulse-ranging system called Rebecca-Eureka at a frequency of 200 megahertz.

5.2.1.3 The airborne equipment of the DME system is a transmitter-receiver, called an interrogator, that transmits an omnidirectional set of pulses that are received by the ground-based station called the transponder. After a fixed time delay of 50 microseconds, the transponder replies by transmitting a return set of pulses that are detected by the interrogator. The airborne DME then measures the

(5.2.1.3 continued)

elapsed time, taking account of the 50 microsecond delay, and calculates and displays the distance digitally in the aircraft.

5.2.1.4 A fixed operating frequency is assigned to each ground transponder. This frequency identifies the transponder to the interrogator. A typical interrogator can operate on as many as 250 frequency channels. The transponder also identifies itself by transmitting a coded signal at least once every 30 seconds. One transponder can handle as many as 100 airborne DME's almost simultaneously. The interrogator identifies its own response from the transponder by recognizing its own characteristic "jitter" that is deliberately put into its pulse repetition rate.

5.2.1.5 The International Civil Aviation Organization (ICAO) in its "Annex 10", promulgates the following specifications for airborne DME systems: range, up to 200 nautical miles; altitude, up to 75,000 feet; accuracy, plus or minus 3000 feet or 3 percent of slant range, whichever is greater. However, the better grades of commercial DME systems are capable of accuracies of plus or minus 600 feet. These are the accuracies of the over-all DME system, i.e. the accuracies that are usable by aircraft. The accuracies of DME interrogators alone are quoted by manufacturers to be much better, for example plus or minus 125 feet; but this is not the system accuracy.

5.2.1.6 An airborne DME interrogator can weigh as little as 4 kilograms. The cost is between approximately $2,000 and $10,000, depending upon quality and features.

5.2.1.7 At DME frequencies (960 to 1215 MHz, corresponding to wavelengths of 30 to 25 cm) radio propagation is line-of-sight. Ground waves and sky wave effects are not observed. This makes DME very useful for aircraft that fly at altitudes that permit direct line-of-sight to DME ground stations. However, for a DME interrogator aboard a land vehicle, transmission and reception would be seriously hampered by terrain features, cultural features, (e.g. buildings) and by other land vehicles that block the direct line-of-sight between the land vehicle and the DME ground station. Some non-line-of-sight DME reception can be observed, caused by diffraction around obstacles and by scattering; but this reception is weak, unreliable, and error-ridden. Consequently, DME is not judged to be useful for land vehicles.

5.2.2. Other Rho Systems

5.2.2.1 OBOE is an acronym for "Observing Bombing Of the Enemy". It was a World War II pulsed rho-rho system devised by the British to locate and guide the positions of bomber aircraft. Two ground-based stations interrogated a beacon transponder in the aircraft. Accuracy was about plus or minus 100 meters at distances of about 300 km. OBOE was not operable beyond the optical horizon, and could handle only one aircraft at a time.

5.2.2.2 The British "H" system was another rho-rho pulsed system used by the British in World War II for position-location of bombing aircraft. The interrogation and display equipment was in the aircraft. Beacon transponders on the ground at two separate locations could handle more than one aircraft at a time. Gee-H was a British modification of the H system, used as an aid to photogrammetric mapping after World War II, operating at 30 MHz.

5.2.2.3 SHORAN is an acronym for "short range navigation". It is a pulsed rho-rho system, based on the same principle as the British H system. SHORAN was developed by the United States Air Force for military applications in World War II. A SHORAN interrogator-receiver-indicator is mounted in an aircraft, and fixed transponders are placed at fixed stations on the ground.

(5.2.2.3 continued)

SHORAN was used also for position-location in aerial mapping and surveying. In surveying, the interrogator was sometimes placed on a fixed tower. The original SHORAN airborne interrogator set was denoted as AN/APN-3, and the ground responder beacons were denoted as AN/CPN-2. The system operated on frequencies of 210, 260 and 320 MHz. Modern, improved versions of SHORAN, variously called Digital SHORAN, Long-Distance SHORAN, and Long-Range SHORAN, use frequencies of 220-320 MHz and 420-450 MHz. The maximum measurable distance is about 320 km with an accuracy of $\pm$4 m.

5.2.2.4 HIRAN is a "high accuracy SHORAN" that has been used in intercontinental survey work. HIRAN operates at 300 MHz. HIRAN is pulsed (as are OBOE, H, Gee-H, and SHORAN and SHIRAN).

5.2.2.5 SHIRAN ("S-band HIRAN"), also called the "Microwave Geodetic Survey System" was developed under U. S. Air Force contract beginning in 1963. SHIRAN operates at about 3GHz, (10 cm). The SHIRAN interrogator is in an aircraft (as is the case in HIRAN, SHORAN, Gee-H and H); but SHIRAN uses transponders at four instead of two ground stations. Accuracy of SHIRAN is in the neighborhood of $\pm$ 3 m over distances of about 400 km. Maximum measurable distance is about 1400 km, with two 700 km legs. SHIRAN, like HIRAN, is intended for aerial geodetic survey and photogrammetry.

5.2.2.6 AERIS (acronym for airborne electronic ranging instrumentation system) is a predecessor of SHIRAN (paragraph 5.2.2.5). AERIS uses rho geometry, and phase comparison in the UHF band, with four ground transponders, an interrogator in an aircraft vehicle and a data reduction station on the ground. It is claimed that AERIS gave 3-dimensional position-location with a resolution (not necessarily accuracy) of ± 1 meter over a range of 250 km.

5.2.2.7 EPI (acronym for electronic position indicator) combines some features of SHORAN (paragraph 5.2.2.5) with Loran (section 6.0) pulse techniques. It was developed by the U. S. Coast and Geodetic Survey in its Radiosonic Laboratory about 1945. Frequency is 1850 kHz. Range is 500 km. Accuracy is ± 50 meters.

5.2.2.8 Some of the Raydist systems are rho systems. See section 6.10.

5.2.2.9 "Distance-finding-stations", used in marine navigation, are stations that simultaneously transmit a radio signal and an acoustic (sound) signal. The latter signal may be transmitted through either air or water or both. The time of travel of the radio signal is negligible compared to the time of travel of the sound signal. The navigator aboard the vessel uses a stopwatch to count the time interval in seconds,

(5.2.2.9 continued)

between reception of the radio signal and reception of the sound signal. He multiplies this time interval by the assumed speed of propagation of sound, in air or water as the case may be, to give rho. In practice, this method for measuring rho can be relied upon only to an accuracy of 10 (ten) percent. This poor accuracy results partly from human error in sensing and measuring the time of arrival of the sound signal, and partly from the effects of temperature and other conditions upon the actual speeds of travel of the sound signals in air and water.

5.3 Theta Systems

5.3.1 Introduction

5.3.1.1 Theta systems are position-location systems that measure only direction (bearing); (section 5.1). The two principal types of theta systems are: DF/RDF/ADF (direction finders, section 5.3.2); and VOR (section 5.3.3). Other theta systems are mentioned in section 5.3.4.

5.3.1.2 In addition to the differences between the two types of theta systems described in sections 5.3.2 and 5.3.3, the following difference should be noted: DF/RDF/ADF systems need a compass aboard the vehicle in order to determine theta (see paragraphs 5.3.2.2); whereas VOR does not need a compass to determine theta.

5.3.1.3 This difference between VOR and DF/RDF/ADF is academic for most vehicles because they almost always carry a magnetic or gyro compass. However, the difference can be significant in the case of some military land vehicles that carry magnetic compasses. For example, in a tank with a rotatable steel turret, the compass deviation usually changes when the turret is rotated.

5.3.2 Radio Direction Finders

5.3.2.1 A radio direction finder (abbreviated as RDF or DF) is a theta system consisting of a radio receiver and a directional antenna that sense the direction (i.e. bearing) in which radiation is received from a radio transmitter. Paragraphs 5.3.2.2 through 5.3.2.20.2, and paragraphs 5.3.2.26 and 5.3.2.27, consider the usual case in which the RDF receiver and receiving antenna are aboard the mobile vehicle (e.g. ship, aircraft, or land vehicle), and the transmitter is at a fixed station of known location. Paragraphs 5.3.2.21 through 5.3.2.25 consider the relatively unusual case in which the RDF receiver and receiving antenna are at a fixed station of known location, and the transmitter is aboard the mobile vehicle.

5.3.2.2 When DF/RDF/ADF receiving equipment aboard a vehicle finds the direction (i.e. bearing) from which radiation is received from a transmitting station of known location, this is the direction only with respect to the vehicle itself. Without any other information, this line of direction could have any orientation with respect to the earth. A compass heading (magnetic or gyroscopic) is needed to orient the RDF direction and to convert it into theta and into a LOP. The vehicle's position-location/navigation system must therefore include some form of compass if the system relies on RDF to obtain theta and LOP.

5.3.2.3 RDF equipment can be used to "home in" on a beacon or fixed transmitter, without knowing compass heading and theta, and without establishing a LOP on a map. In this mode of operation, the vehicle follows the direction from which the radio signals are received until the vehicle arrives at the location of the transmitter. The vehicle can then proceed to navigate the next leg of the journey by homing on another conveniently located fixed transmitter. The path of the vehicle thus becomes a series of straight lines in a "dog-leg" journey. This navigation method was used by aircraft in the early days of aviation.

5.3.2.4 When RDF receiving equipment aboard a vehicle (assisted by a compass) finds the direction to a fixed transmitting station of known position, one LOP has been determined (subject to the propogation errors discussed below). Another LOP to another fixed transmitter must be determined in order to locate the position of the vehicle. The intersection of the two LOPs locates the position of the vehicle. (Figure 5.1.5)

5.3.2.5 RDF is the oldest practical type of radio aid to navigation. It is widely used for navigation by aircraft, ships and boats of all sizes. There are more than 10,000 broadcasting stations in the world that can be used for radio direction finding (by RDF receivers aboard vehicles).

(5. 3. 2. 5 continued)

In addition, many nations maintain special radio beacons (transmitters) along their coastlines to aid maritime navigation. For example, the U. S. Coast Guard maintains approximately 200 marine radio beacons in the 285 to 325 kilohertz frequency band. There are also radio beacons established for aviation, called aeronautical beacons. Other radio beacons, sometimes called aeromarine beacons, are maintained for use by mariners and aviators.

5. 3. 2. 6 The basic method of RDF is to compare the arrival times of a radio signal at two known points in the receiving antenna system. The simplest type of such an antenna is a loop antenna lying in a vertical plane, rotatable about the loop's vertical axis of symmetry. A typical such loop would have a diameter of 2 feet. The vertical arms of the loop are the two points at which the arrival times are compared. When the loop is rotated so that its plane is perpendicular to the direction of propagation of the received plane wave front, the signal is received simultaneously by both arms of the antenna, and the resulting voltage across the antenna output terminals is zero or a minimum. The detection of this null position of the loop is more sensitive than the detection of the position of maximum signal received when the direction of propagation of the received signal lies in the plane of the loop.

5.3.2.7 However, the foregoing statement regarding voltage is accurate only if the wave is plane polarized and is polarized vertically (i.e. with the electric vector of the electromagnetic wave vertical, and the magnetic vector horizontal). The antenna system responds differently to other types of polarization (e.g. circular, elliptical, or non-vertical plane polarization) which give different direction readings. Various types of antennae have been developed to minimize the direction errors resulting from non-optimum polarization. Examples of such antennae are the spaced-loop antenna, the Adcock antenna, and the buried-U Adcock antenna.

5.3.2.8 Direction finding is subject to the following errors:

a. Polarization errors (paragraph 5.3.2.7) which usually are a maximum at sunrise and sunset, when changes (called the "night effect") occur in the reflective layers of the ionosphere.

b. Sky waves that do not always travel in the vertical plane between the transmitter and receiver, because of tilts in the ionosphere layers.

c. Reflections from non-horizontal terrain surfaces such as mountains.

d. Reflections from cultural structures such as buildings.

e. Change of direction of the radio wave as it crosses a coastline at an oblique angle; caused by refraction due to differences in propagation characteristics of water and land; (sometimes called the "land effect" in marine navigation).

(5.3.2.8 continued)

f. Reflections and re-radiations from the vehicle itself, e.g. from the superstructure and hull of a marine vessel, or from the body of an aircraft, or from the body of an armored land vehicle.

5.3.2.9 This last mentioned error f. is often called the "quadrantal" error, a term borrowed from the quadrantal deviation of a magnetic compass, because the error is likely to change its sign approximately every 90 degrees of azimuth. The quadrantal error can be calibrated for each individual vehicle, and the RDF indications can be corrected accordingly. This is done routinely for marine vessels, and could likewise be done for an armored land vehicle.

5.3.2.10 The variable, unpredictable errors, described above, make it difficult to specify the accuracy of RDF measurements. Under favorable conditions, a well-calibrated well-designed ship-board RDF will have an accuracy of ± 1 deg to ± 2 deg.

5.3.2.11 Accuracy is affected also by the field strength of the received signal. An accuracy of ± 1 deg requires a field strength of approximately 50 microvolts per meter. At a field strength of 20 microvolts per meter, the ± 1 deg accuracy degrades to ± 5 deg.

5.3.2.12 Reflections from mountain sides (5.3.2.8.c) can cause bearing errors of 20 deg. Reflections from a nearby large building (5.3.2.8.d) can cause bearing errors of 45 deg.

5.3.2.13 Determination of a line of direction by means of a simple loop antenna has a 180 degree ambiguity because the signal could be coming from either direction along the line. To resolve this ambiguity, a simple omni-directional antenna called a "sense antenna", usually consisting of a vertical dipole, is added to the loop antenna (or to other types of symmetrical antennas) to convert the antenna pattern into a cardioid shape that has only one minimum. Figure 5.3.2.13, page 33. (Also see paragraph 5.3.3.3, page 56.)

5.3.2.14 In addition to loop antennas, direction finders use Adcock DF antennas, yagi antennas, and ferrite core antennas. A ferrite core antenna can be mounted in an aircraft in a shallow pan almost flush with the skin of the aircraft.

5.3.2.15 In manually operated direction finders, the operator first tunes in to a transmitting station that he identifies by its frequency and by its audio signals. He then mechanically turns the loop antenna (or other directional antenna) until the signal is a minimum, as detected either audibly or with the aid of a meter. In shipborne installations, the rotatable antenna can be mounted remotely from the radio receiving console, and can be turned by electromechanical remote control.

5.3.2.16 There are types of automatic direction finders (ADF) which use continuously rotating antennas. The intensity of the received signals is monitored and displayed as a function of the angle of rotation of the antenna. These types of ADF are now rarely used.

5.3.2.17 The RDF antenna need not be rotated. The antenna can be a fixed array that has two mutually perpendicular antenna patterns. One such fixed antenna system (the Belli-Tosi system), widely used, consists of two fixed vertical loop antennas with their planes mutually perpendicular. This combination is called a cross loop antenna. Another system consists of two fixed Adcock dipole arrays. The two mutually perpendicular antennas and antenna patterns resolve incoming radio waves into two components in mutually perpendicular directions. The two components are recombined, in an instrument called a radiogoniometer, to determine the direction of the received radio wave.

5.3.2.18 Fixed antenna arrays and radiogoniometers are the basis for modern automatic direction finders (ADF). The operator simply tunes in the transmitting station, and the ADF then automatically indicates the direction (bearing) of the station with respect to the heading of the ship or aircraft, and/or with respect to a compass heading (because the vehicle is almost always equipped with some type of compass). The indicator is either a heading dial or a cathode ray tube. The tuning range of an ADF is usually 200 KHz to 1,600 KHz.

5.3.2.19 ADF electronic receiver/indicator consoles usually provide convenient dialing and tuning, indications of magnetic and/or gyro compass headings, course headings, etc. Console sizes are approximately in the range from 6" x 6" x 12" to 14" x 14" x 16". Console weights are approximately 10 kg to 20 kg. Prices are approximately in the $1,000 to $2,500 range.

5.3.2.20.1 Small, portable non-automatic DF's are available with a compact ferrite antenna built in a shallow compartment directly on top of a portable, battery-powered radio receiver, so that the antenna can be turned simply and easily by hand. Claimed accuracies are ± 3 deg on broadcast frequencies, ± 4 deg on marine bands, and ± 5 deg on radio beacons. Approximate dimensions of this type of DF, including the ferrite antenna, are: 11 inches wide, 12 inches deep, and 7 inches high with the simple sense antenna retracted. Weight is approximately 9 lbs. The DF operates on 4 or 6 "D" size flashlight-type batteries, or with an AC power supply. Price is approximately $210. Other portable DF's are available with yagi antennas that are less compact than the ferrite core antennas, but are in the same approximate price class.

5.3.2.20.2 There is also a "pocket-size" RDF, approximately 6"x3"x2.5", weighing 13 ounces, operating on four 1.5 volt type AA penlight batteries. The antenna is a 4.5 inch long ferrite rod inside the case. The output is audio, through a stethescope-type headset. The price is $100. It is intended for small motor boats or sailboats, or as an emergency RDF to be carried by vessels equipped with larger RDF's.

5.3.2.21 Paragraphs 5.3.2.2 through 5.3.2.20.2 considered cases in which the RDF receiving equipment was aboard the vehicle (e.g. the marine vessel, aircraft or land vehicle). The unpredictable errors caused by reflections from objects near the vehicle can be reduced if the RDF receiving equipment is at a fixed station of known position, and an omni-directional transmitter is aboard the vehicle. The bearing of the vehicle, with respect to the fixed station, is then measured at the fixed station, and the result is communicated by radio from the station to the vehicle. (In this system, the vehicle need not carry a compass to determine a LOP; but this is hardly an advantage, because a knowledge of compass direction is essential for other navigation operations of the vehicle.) These fixed ground stations are called radio direction finding stations, and are listed in U.S. DMAHC Publications Nos. 117A and 117B.

5.3.2.22 The RDF receiver and antenna at the fixed station employ many of the same techniques that are used in the vehicle-mounted RDF receiver and antenna, except that the aperture of the antenna at the fixed station is wide, without ambiguity, in order to reduce site errors. One type of such receiving antenna at the fixed station consists of a 12-foot diameter circle of individual UHF or VHF antennas, commutated to give the electrical effect of a single antenna rotating around the circle. This results in a Doppler effect, similar to Doppler-VOR (paragraph 5.3.3.6), except that the antenna in the D-VOR is transmitting instead of receiving.

5.3.2.23 Another type of RDF receiving set-up at a fixed station is called the Wullenweber System. The receiver is connected by a mechanically rotating commutator to a circle of antennas, 1,000 feet in diameter. Accuracy of this RDF is said to be plus or minus 1 degree, except for propagation errors caused by reflection of the HF by the ionosphere. The Wullenweber System was first used by Germany in World War II. Since then, systems of this type have been used for non-navigational purposes. CADF (Commutated Antenna DF) is a British version of the Wullenweber System.

5.3.2.24 For convenience in the discussions in paragraphs 5.3.2.25 through 5.3.2.27, let system A denote a RDF/ADF system with receiving equipment in the vehicle and an omni-directional transmitter at a fixed station; and let system B denote a RDF/ADF system with receiving equipment at a fixed station and an omni-directional transmitter aboard the vehicle.

5.3.2.25 System A (paragraph 5.3.2.24) is much more desirable than system B for military land vehicles for the following reasons:

a. System A is passive whereas system B is active, as far as the vehicle is concerned. (Paragraphs 3.8.1, 3.8.2)

b. System A can use non-cooperating fixed stations that are more numerous (e.g. by a factor of 50) than cooperating fixed stations.

c. As a result of item b above, special cooperating fixed stations might have to be deployed if system B is used in a military situation.

d. In system B, the vehicle's transmitter must be finely tuned to the RDF receiver at the fixed station, because the latter must operate on a set of fixed frequencies if the station is to serve many vehicles; whereas in system A the vehicle's operator can easily tune his receiver to any one of a large number of fixed transmitting stations.

e. If the receiver of one fixed station of system B is jammed, all vehicles within range will be affected; whereas jamming the receiver of one vehicle of system B affects only that vehicle.

f. The vehicle must supply more power to an on-board transmitter in system B than to an on-board receiver in system A.

5.3.2.26 System A (paragraph 5.3.2.24) has the following advantages for military land vehicles:

a. The system aboard the vehicle is passive. (Paragraph 3.8.1)

b. There are a multitude of radio transmitting and broadcasting stations, and radio beacons, throughout the world, that can be used by RDF/ADF receivers aboard a vehicle.

c. System A is a reliable simple back-up to other radio position-location systems that require more elaborate equipments.

d. The equipment is convenient in size and weight, and is reasonably priced. (Paragraphs 5.3.2.19, 5.3.2.20.1, 5.3.2.20.2)

5.3.2.27 System A (paragraph 5.3.2.24) has the following disadvantages for military land vehicles:

a. Site errors (paragraphs 5.3.2.8.c, 5.3.2.8.d, 5.3.2.12) can be large near buildings or other large structures, and in the vicinity of other armored vehicles.

b. The system is subject to all the other errors in paragraph 5.3.2.8.

c. The receivers can be jammed.

5.3.3 VOR

5.3.3.1 VOR is the widely used abbreviation for "Very-high-frequency Omni-directional Range". This name can be misleading because VOR gives bearing (direction) information, not range (distance). VOR is sometimes called "omni-range" or "omni". VOR is a theta system, not a rho system. VOR is usually combined with DME (distance measuring equipment) which is a rho system. The combination, called VOR/DME, is a rho-theta system (section 5.4.1).

5.3.3.2 Development of VOR began in the 1930-1940 decade when aircraft began to use VHF for voice communication, and it seemed desirable to use the same frequency band for aircraft position-location/navigation. Furthermore, VHF avoided the propagation problems of the LF and MF bands. In 1946 VOR became standard in the United States; and in 1949 VOR was standardized internationally. About 175,000 VOR receivers are probably now in use in all types of aircraft throughout the world, served by about 2,500 VOR ground stations.

5.3.3.3 The VOR ground station radiates a cardioid-like pattern that rotates in azimuth at 30 revolutions per second. (A cardioid is a heart-shaped closed curve, generated by a fixed point on a circle that rolls on an equal but fixed circle; i.e. a cardioid is an epicycloid of one loop.) The rotation of the cardioid beam pattern (Figure 5.3.3.3, page 33; & paragraph 5.3.2.13, page 49) generates a

(5.3.3.3 continued)

30 Hz amplitude modulated signal at the airborne receiver. Simultaneously the ground station radiates an omni-directional signal that is frequency modulated with a fixed 30 Hz reference tone. The airborne VOR equipment measures the phase difference between the two 30 Hz tones. This phase is determined by, and is a measure of, theta of the aircraft with respect to the pole at the ground station. The ground station keeps the two 30 Hz signals exactly in phase in the direction of North. The measured theta, or azimuth, is usually presented automatically to the pilot in a visual readout.

5.3.3.4 VOR operates in the frequency band of 108 to 118 MHz. Channels are spaced at 100 KHz intervals. Polarization is horizontal. The CW omni-directional radiation carries a Morse-code identifying signal, and can be voice-modulated for communication.

5.3.3.5 Propagation of the VHF frequencies, at which VOR operates, is line-of-sight. Site errors at the ground stations, due to reflections from obstructions, are serious; e.g. 15 degree errors in aircraft navigation can be caused by neighboring hills, structures, and even trees. These errors can be alleviated by an improved type of VOR, namely Doppler VOR, described in paragraph 5.3.3.6.

5.3.3.6 Doppler VOR, also called D-VOR, operates in the same way as VOR with the following differences: the ground-based D-VOR antenna is a wide (44 feet diameter) circular array of Alford loops; this antenna circle is rotated electrically, simulating the rotation of a single antenna on a 22 foot radius at 30 revolutions per second; this generates a Doppler-VOR frequency-modulated theta-dependent signal, instead of the amplitude-modulated azimuth dependent signal in VOR. The reference signal in D-VOR is amplitude-modulated instead of frequency-modulated as in VOR. The normal VOR receiver in the aircraft operates equally well with either VOR or D-VOR transmissions, because the receiver measures only the phase difference between the reference signal and the theta-dependent signal.

5.3.3.7 Using a VOR at a favorable ground station site, an aircraft can measure theta with an accuracy of about ± 3.0 degrees. Using a D-VOR at an equally favorable site, accuracy of theta is about ± 1.5 degrees. Using a VOR at an average ground station site, accuracy of theta is about ± 4.5 degrees, 95 percent, RMS.

5.3.3.8 All aircraft operating under IFR (Instrument Flight Rules) in U. S. airspace are required to be equippped with VOR. At least one VOR is aboard approximately 80 percent of all U. S. general aviation aircraft. VOR is the internationally accepted standard for radio navigation, over land and in continental approach, for aircraft IFR operations.

5.3.3.9 VOR is very widely used in aviation. An estimated 280,000 civilian aircraft, and 13,000 military aircraft carry VOR throughout the world. In United States registry, about 136,000 private aircraft, 2,500 commercial transport, and 8,000 military aircraft use VOR.

5.3.3.10 The U. S. Army has VOR receivers on approximately 3,500 helicopters, which is about 40 percent of all U. S. Army helicopters. Plans are to have VOR on 6,000 U.S. Army helicopters by the late 1980's.

5.3.3.11 Prices of airborne VOR receivers vary from about $16,000 for a military receiver to about $1,200 for a simple civilian receiver. VOR transmitters are priced at about $50,000 each.

5.3.4 Other Theta Systems

5.3.4.1 A system that is analogous to VOR is the rotating loop radiobeacon used for marine navigation in Japanese waters. A directional loop antenna, at a fixed land station, rotates and transmits a radio beam of signals as though it were a rotating beam of light sent out by a lighthouse. The navigator aboard the vessel uses a stop-watch to measure the interval between the time he detects a minimum intensity of the rotating beacon signals and the time he receives an omni-directional signal that is broadcast from the land station when the minimum is pointed North. His theta is then easily calculated, using the known speed of rotation of the radiobeacon. The advantage of this system is that any radio receiving set, tunable to the radiobeam's frequency, can be used aboard the vehicle to determine theta.

5.3.4.2 Consol, Consolan and BPM5 can be classed as theta systems as well as hyperbolic systems. See 6.11, 6.12.7, and 6.12.8.

5.4. Rho-Theta Systems

5.4.1 VOR-DME

5.4.1.1 VOR-DME (a rho-theta system, paragraph 5.1.6.2) consists of a VOR and a DME colocated at the same station. VOR is described in section 5.3.3. DME is decribed in section 5.2.1.

5.4.1.2 VOR-DME is used extensively for aircraft position-location. See paragraphs 5.3.3.8, 5.3.3.9, 5.3.3.10 and 5.2.1.2. VOR-DME is not used by marine or land vehicles.

5.4.1.3 For accuracies of VOR-DME, see paragraphs 5.3.3.5, 5.3.3.7 and 5.2.1.5. For equipment costs, see paragraphs 5.3.3.11 and 5.2.1.6.

5.4.1.4 VOR-DME, Tacan (section 5.4.2) and Vortac (section 5.4.3) provide the basic guidance for enroute air navigation in the United States.

5.4.2 Tacan

5.4.2.1 Tacan (tactical air navigation) is a rho-theta system consisting of a DME (section 5.2.1) combined with a special theta system. Tacan is used for position-location of aircraft, not marine vessels. Tacan was introduced in 1945 as a military system, but it is used by civil as well as military aircraft in the United States and Europe.

5.4.2.2 The rho part of Tacan is the same as, and is compatible with, civil DME, operating in the frequency band of 960 to 1215 MHz. Tacan's DME is the same as the DME in VOR-DME. Thus all civil DME interrogation/receivers can use Tacan's DME; and any airborne Tacan equipment can obtain rho from any DME ground-based beacon-transponder.

5.4.2.3 The theta part of Tacan is different from, and not compatible with VOR. The theta part of Tacan operates in the same frequency band as DME. This gives Tacan at least two advantages over VOR-DME: (1) The Tacan theta transmitting antenna is about one-tenth the size of the VOR antenna, because the Tacan frequency band (960 to 1215 MHz) is about ten times the VOR frequency band (108 to 118 MHz);

(5.4.2.3 continued)

the Tacan transmitting antenna thereby becomes transportable and suitable for mounting on a vehicle such as a ship or large land vehicle.

(2) In Tacan, rho and theta are both obtained in the same radio frequency band, thereby allowing some economies in equipment.

5.4.2.4 The Tacan "ground" beacon antenna consists of: a fixed central broad-band (960 to 1215 MHz) antenna that handles all Tacan transmission and reception; a single parasitic antenna element rotating around the central antenna at a speed of 15 Hz at a radius of about 3 inches; nine parasitic antenna elements rotating around the central antenna at the same speed of 15 Hz at a radius of about 18 inches.

5.4.2.5 The single rotating parasitic antenna element generates a rotating single-lobe radiation pattern. This rotating pattern is used by the Tacan receiver (aboard the aircraft) to determine theta in the same way as a VOR receiver uses the VOR rotating cardioid-like pattern (paragraph 5.3.3.3). The nine rotating parasitic elements generate a rotating nine-lobe radiation pattern that is used by the Tacan receiver to improve the accuracy of theta.

5.4.2.6 A typical Tacan "ground" beacon antenna, for installation aboard a ship or aircraft carrier, weighs 125 lbs and is 36 inches high by 41 inches diameter. Three chassis that complete the Tacan station add about 360 lbs and about 12 cubic feet of space.

5.4.2.7 A Tacan ground station is available also in a portable shelter that is suitable for mounting on a M-715 truck. The shelter and its complete Tacan equipment weigh 2,000 lbs and is about 6 x 7 x 7 feet in size.

5.4.2.8 AN/TRN-41 is a light weight Tacan ground station, designed to be air-dropped or man-packed into forward combat zones. The station weighs about 100 lbs, and can be operated from batteries or a power supply. It is said that this Tacan station can be set up and be operating in 10 minutes by non-technical personnel.

5.4.2.9 Tacan "ground" stations cost from about $60,000 for a portable station, to $200,000 for a permanent ground station, to about $500,000 for a gyro-stabilized shipboard station. Tacan airborne receivers cost from about $10,000 to $30,000 each. Tacan airborne receivers can weigh less than 40 lbs and occupy a space less than one cubic foot.

5.4.2.10 Theta accuracy of Tacan, for position-location of aircraft, is affected by reflecting objects or terrain in the vicinity of the Tacan ground station, because Tacan frequencies are high (1 GHz, or a wavelength of 30 cm). With the Tacan ground station at an "ideal" site, theta accuracies of $\pm$ 0.2 degrees have been demonstrated. In actual practice, Tacan system accuracy is more like $\pm$ 2 degrees.

5.4.2.11 The rho accuracy of Tacan is the same as the accuracy of DME (paragraph 5.2.1.5). The useful range of Tacan, for rho and theta, is about 200 nautical miles, depending upon the power of the Tacan transmitter/antenna, among other factors.

5.4.2.12 Advantages of Tacan, for military vehicles, are:

a. The Tacan equipment aboard the vehicle can be small and light in weight.

b. The Tacan ground station can be compact and light in weight. (Paragraphs 5.4.2.6, 5.4.2.7).

c. A tacan ground station can be set up quickly in the field. (Paragraph 5.4.2.8).

5.4.2.13 Disadvantages of Tacan, for military land vehicles, are:

a. Tacan reception is likely to be seriously affected by obstacles and terrain in the line-of-sight between the ground station and the vehicle.

b. Accuracy is adversely affected by reflections from objects near the ground station and the vehicle.

c. The ground station and the equipment aboard the vehicle are active systems; (paragraph 3.8.1).

5.4.3 Vortac

5.4.3 Vortac (VOR-Tacan) is a system that combines Tacan and VOR, colocated at the same ground station. This enables military and civil aircraft to fit into the same ATC (air traffic control) network. Military aircraft use the Tacan part of Vortac to measure rho and theta. Civil aircraft use the DME part of the Tacan to measure rho, and the VOR part of Vortac to measure theta.

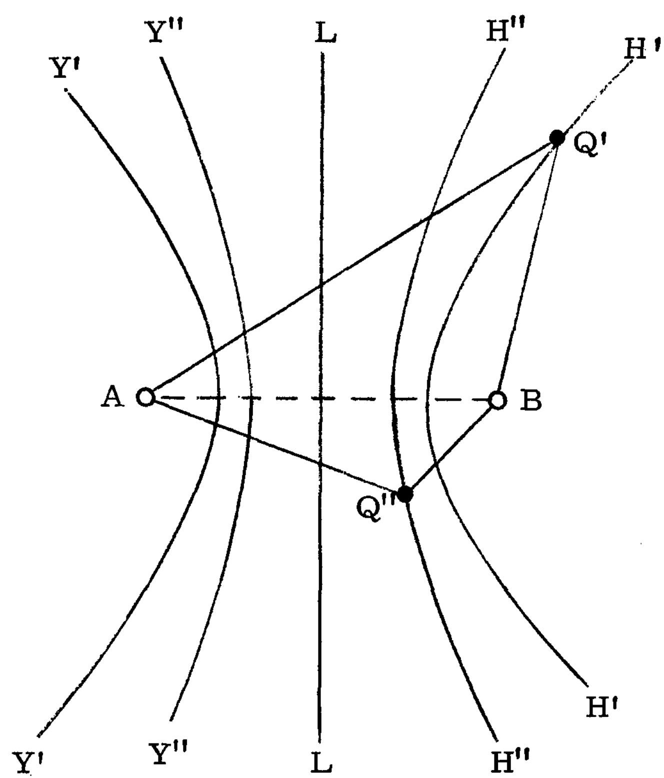
6. HYPERBOLIC SYSTEMS

Contents of Section 6

6.1. Hyperbolic Systems in General

6.1.1 Hyperbolic position-location systems are called hyperbolic because they give fixes by the intersections of hyperbolic LOP's. A hyperbola may be defined as the locus of a point whose distances from two fixed points have a constant difference. In Figure 6.1.1, A and B are the two fixed points, called the foci of the hyperbola. Q'A is the distance from a point Q' to A; and Q'B is the distance from Q' to B. The hyperbola H'H' is the locus of all points Q' such that Q'A-Q'B = a constant K'. The hyperbola H"H", in Figure 6.1.1, is the locus of all points Q" such that Q"A-Q"B = a constant K", where $K'' < K'$. Each value of the constant K defines a different hyperbola in a family of hyperbolas belonging to the foci A and B.

Figure 6.1.1

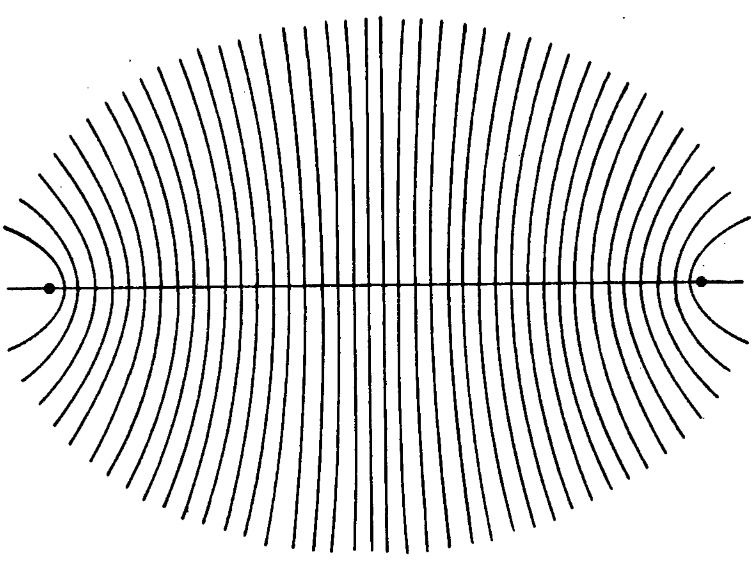


(6.1.1 continued)

When the constant K is zero, the hyperbola becomes the straight line LL that is the perpendicular bisector of the baseline AB, in Figure 6.1.1. The curves Y'Y' and Y"Y", in the same figure, are examples of other hyperbolas in the same family, with negative values of K.

6.1.2 In a hyperbolic radio position-location system, two fixed radio transmitting stations are the foci of a family of hyperbolic LOPs such as shown in Figure 6.1.2. Each station transmits signals that are timed or phased with respect to similar signals transmitted from the other station. The vehicle carries a receiver and electronic circuitry that measure the difference in time or phase between the arrivals of the radio signals from the two fixed transmitters. This time difference (multiplied by the speed of radio propagation) gives the distance difference (QA-QB) which determines the hyperbolic LOP.

Figure 6.1.2



6.1.3 One pair of fixed transmitters gives the vehicle one hyperbolic LOP. Another pair of fixed transmitters gives another hyperbolic LOP. In general, the pairs can share stations, so that three fixed transmitting stations can give two or three LOPs. The intersection of two hyperbolic LOPs is usually sufficient for a fix. The intersections of three LOPs are sometimes necessary.

6.1.4 Accuracy of a fix in a hyperbolic position-location system depends upon the geometric configuration of the receiver and the transmitting stations that are used to get the fix, i.e. upon the geometry of the particular hyperbolas that determine that particular fix.

6.1.5 Compared to rho systems and rho-theta systems, hyperbolic systems have the advantage that the vehicle's equipment does not need to measure the absolute distance from the vehicle to any station.

6.1.6 Hyperbolic radio position-location sytems are non-saturable (paragraph 3.7.2), and passive (paragraph 3.8.2).

6.2 Loran-A

6.2.1 The name Loran is derived from "Long-range navigation".

6.2.2 Loran-A is a hyperbolic radio system operating in the frequency band between 1,800 and 2,000 kHz. A fixed station, called the "master", emits a series of pulses that are 50 microseconds long each, with a peak power of 100 kilowatts. Another fixed station, formerly called a "slave", but now called a "secondary" station, receives the pulses and, after a fixed time delay, emits similar pulses. The receiving equipment aboard the vehicle measures the time differential between reception of corresponding pulses from the two stations, and takes into account the known, fixed time for propagation of the pulse from the master station to the secondary station, and the known fixed time delay in the secondary's equipment. Loran-A uses pulse envelope matching techniques.

6.2.3 A system of one master station and two or more secondaries is called a "chain". Over land, the maxiumum baseline length between Loran-A stations is about 200 km. Over seawater, the maximum baseline is about 500 km.

6.2.4 Loran-A transmission over seawater by the ground wave gives a range between 600 and 800 nautical miles. At night, this range can increase to 1,500 nautical miles by using sky waves, i.e. waves reflected from the E and F layers of the ionosphere.

6.2.5 Accuracy of position-location can be between 1 and 2 nautical miles using the ground wave. Using sky waves, accuracy can vary from 7 to 40 nautical miles, depending upon conditions.

6.2.6 Loran-A was called "Standard Loran" until the middle 1960's. Loran-A was the first long-range position-location system. It was first proposed in 1940 in the USA; and the first full-scale test was conducted in 1942. The first airborne Loran-A receiver, designated AN/APN-4, was interchangeable with the British Gee VHF hyperbolic system. Loran-A was used extensively in World War II by trans-Atlantic merchant ship convoys and by military ships and aircraft. After World War II, Loran-A was used widely for navigation of civil and military aircraft. The peak usage of Loran-A was probably in the early and mid 1970's, when there were tens of thousands of Loran-A receivers in use in marine and air vehicles throughout the world. At that time, chains of about 80 Loran-A transmitters were operating in coastal areas of many parts of the world, including the East and West coats of continental United States, the East and West coasts of Canada, the Gulf of

(6.2.6 continued)

Mexico, the Aleutian Islands, the Southwest coast of Asia, and the West coast of Europe. In 1977, the United States Loran-A system, operated by the U. S. Coast Guard, covered about 15 percent of the Northern hemisphere.

6.2.7 The entire United States Loran-A system, including all Loran-A transmitting stations, is in process of being discontinued. The system is expected to terminate its operations approximately in 1980. Loran-C is being phased in, to replace Loran-A.

6.2.8 Loran-A should not be considered for use with military land vehicles because the system will be non-existent after 1980, and because Loran-C is superior to Loran-A.

6.3 Loran-C

6.3.1 During World War II, it was recognized that the coverage and accuracy of Loran-A could be improved by operating the system at lower frequencies. Therefore an experimental system called LF-Loran (low frequency Loran) was initiated and put into operation at a frequency of 180 kHz in 1945. LF-Loran was terminated at the close of World War II, and was succeeded by Cyclan, a hyperbolic 160 and 180 kHz pulsed system with the added feature of automatic cycle matching in the pulse envelope. Cyclan in turn was terminated in 1947. A similar hyperbolic system called Cytac, in the 90 to 110 kHz band, was developed between 1952 and 1955 for long-range bombing, and then set aside. In 1957, the Cytac concept was reactivated for military use, and was re-named Loran-C. In 1974, the U. S. Department of Transportation adopted Loran-C for navigation in the U. S. Coastal Confluence Zone, to be available to all commercial, public and government users, domestic as well as foreign.

6.3.2 Loran-C is a hyperbolic radio position-location system similar to Loran-A. The following are the principal differences between the systems.

(a) Loran-C operates in the 90 to 110 kHz band (compared to Loran-A at 2,000 kHz).

(6.3.2 continued)

(b) In order to measure the time difference (TD) between arrivals of pulses, the Loran-A receiver compares (matches) envelopes of pulses; whereas the Loran-C receiver compares phases of individual pulses.

(c) Peak powers of Loran-C stations are approximately between 400 kw and 2,000 kw, compared with about 100 kw for Loran-A.

6.3.3 As a result of Loran-C's lower frequency and higher peak power, the ground-wave range of Loran-C is typically 600 to 1,400 nautical miles over seawater. Loran-C is primarily a ground-wave system. The time difference measurement is made in the Loran-C receiver by comparing a zero crossing of a specified early RF cycle in each pulse; thereby making the measurement before the corresponding sky waves arrive. This Loran-C phase measurement results in better accuracy than is possible by matching envelopes of the signals as is done in Loran-A.

6.3.4 Position accuracy of Loran-C is usually better than 0.25 nautical mile (1500 feet), 2-drms. (2-drms means that 95 percent of the

(6.3.4 continued)

measured fixes, at a given point, will probably fall within a circle with a radius of the cited accuracy, assuming a gaussian (normal) distribution of errors.) The precision with which a vehicle can return to the same position, using Loran-C, is between 60 and 300 feet, 2-drms, depending upon location.

6.3.5 Loran-C charts are nautical and aeronautical charts that are overprinted with sets of hyperbolic LOPs. Each LOP is customarily labeled with its chain, its secondary station and its TD (time difference). The printed LOPs are usually separated by 5 or 10 microseconds, between which the navigator interpolates. Scales of Loran-C charts may range from 1:2500 (e.g. Boston Harbor) to 1:2,000,000 (e.g. Gulf of Mexico) to 1:5,000,000 (global chart). Loran-C charts are available for many localities and areas in the world, published by: U. S. National Ocean Survey; U. S. Defense Mapping Agency (Hydrographic Center & Topographic Center); Canadian Hydrographic Center; Icelandic Hydrographic Service; Norweigan Hydrographic Office; and the German Hydrographic Institute.

6.3.6 Simple Loran-C receivers require that the operators match phases of the received pulse signals on a cathode ray tube display in order to measure TDs (time differences). Sophisticated Loran-C receivers perform this matching automatically, and automatically display the TD in microseconds. Still more sophisticated Loran-C receivers automatically measure two TD's from two hyperbolic LOPs, and then compute and display the latitude and longitude of the fix. One such Loran-C system of the last mentioned type demonstrated a mean position error of less than 900 feet and a circular error probability of less than 400 feet; ("An Operational Flight Test Evaluation of a Loran-C Navigator, Final Report, March 1977", Report No. CG-D-9-77, U. S. Dept. of Transportation, U. S. Coast Guard, Office of Research & Development, Wash., DC 20590.)

6.3.7 Loran-C receivers for civilian use cost between $1,000 and $5,000, depending upon their features and quality. The most sophisticated Loran-C receivers (e.g. with automatic conversion to latitude and longitude and with other navigation features) cost up to $25,000.

6.3.8 It is estimated that there are 3,000 to 4,000 civilian and military users of Loran-C. The number of civilian users is expected to increase as Loran-C receivers replace the rapidly obsolescent Loran-A receivers.

6.3.9 Until recently, the Department of Defense (DOD) has been the major user of Loran-C. Indeed the initial chains of 27 Loran-C transmitters were established for the DOD (approximately in 1976). Loran-C is used principally for marine navigation in the CCZ (Coastal and Confluence Zone), and secondarily for aeronautical navigation. At present there are no actual operational users of Loran-C for land vehicles.

6.3.10 In the last two years, there has been considerable interest in the potential application of Loran-C to position-location of land vehicles in the non-military sector. This interest has been stimulated by, and is being fostered by the U. S. Department of Transportation (DOT). This stems from the following facts:

(a) By about 1980, the inland Loran-C transmitters operated by the U. S. Coast Guard (of the DOT) for marine services in the Great Lakes and CCZs of continental United States, will cover 63 percent of the contiguous land areas of the 48 United States and 92 percent of its population.

(b) It is estimated that only five additional transmitting stations in the mid-continent would extend the Loran-C coverage to the entire 48 states.

(6.3.10 continued)

(c) DOT cost-benefit studies of the use of Loran-C for land and air vehicles over continental United States seem to be favorable.

6.3.11 Some of the non-military land-vehicles that have been suggested and are being considered for possible applications of Loran-C are: trucks, buses, taxicabs, police cars, ambulances, fire engines and other public service vehicles. See section 11.4.

6.3.12 A number of demonstration and test projects and programs are being conducted to assess the practicality, usefulness, accuracy and reliability of Loran-C for non-military land-vehicle use. Projects of this type are being conducted or planned in the states of Tennessee, New York and Vermont, and in the cities of Los Angeles, CA and Philadelphia, PA.

6.3.13 Some of the problems in using Loran-C for land vehicles are: propagation anomalies caused by topography and by variations in the electrical impedance of the ground between the vehicle and the transmitting stations; obstructions and reflections by building and other man-made structures; radiofrequency interference (RFI), particularly near power lines and in cities where RFI can be in or near Loran-C's LF 100kc band.

6.3.14.1 AN/PSN-6 is a manpack Loran receiver, consisting of a receiver unit and a control-indicator unit. The receiver can be carried on a man's back; and the control-indicator can be carried on the man's web belt. The complete manpack weighs about 9 pounds. The AN/PSN-6 is powered by NiCd batteries with a useful life of 8 to 12 hours between chargings. The Loran TD (time difference) coordinates are converted automatically into 8-digit UTM (Universal Transverse Mercator) coordinates, and displayed in the AN/PSN-6 receiver unit.

6.3.14.2 The U. S. Army Materiel Command began the development of the Loran Manpack Receiver in 1967. The first models, designated AN/PSN-1 and AN/PSN-2, were succeeded by AN/PSN-4 which was tested in 1971 by the U. S. Army Infantry Board. The latest model, AN/PSN-6, was developed in 1972, and was first tested in 1973 and 1975. More recent field tests of AN/PSN-6 were conducted from November 1977 to February 1978 at the U. S. Army Infantry Center, Fort Benning, Georgia.

6.4 D-Loran-C

6.4.1 Over seawater up to a distance of about 2,000 km from each transmitter, the Loran-C waves are propagated under approximately ideal conditions; i.e., under conditions of ground waves traveling on the surface of a perfect sphere of uniform conductivity. Under these conditions, the time differences between arrivals of the signals can be calculated with good accuracy. However, propagation in paths that are partially or completely over land, particularly over inhomogeneous or irregular terrain, can distort the hyperbolic grid and can introduce errors as large as hundreds of meters in the calculated location of position, especially in mountainous regions. These errors are caused partly by non-uniform soil conductivities.

6.4.2 D-Loran-C (Differential-Loran-C) can correct most of these errors over selected areas of navigation, as follows. Loran-C signals are received at fixed sites of known location in each area. The errors between the actual TDs (time differences) and the theoretically calculated TDs are monitored, and corrections are then broadcast to Loran-C users in that area.

6.4.3 The method of D-Loran-C can be useful in applications of Loran-C to land vehicles, particularly in urban areas where man-made structures may further distort the hyperbolic grid.

6.5 Loran-D

6.5.1 Loran-D is a military version of Loran-C with transmitting stations that are transportable for tactical mobility. The entire station, designated AN/TRN-21A, including shelters and equipment on pallets, is transportable by helicopter.

6.5.2 The usual Loran-C antenna is a permanently installed tower, 625 feet high, with a concrete foundation and concrete guy anchors. By constrast, the Loran-D tower is 400 feet high, and its soil bearing does not require concrete foundation or anchors. This reduction in weight is achieved partly by using a scaffold-type construction with high-strength aluminum tubing, and partly by using epoxy-bonded fiberglass rope in place of metallic guys and separate tower insulators. Some parts of the Loran-D tower snap together during erection. The tower can be erected in the field in one day.

6.5.3 Loran-D transmits groups of 16 pulses with a separation of 500 microseconds, instead of Loran-C's groups of 8 pulses with a separation of 1,000 microseconds. Loran-D thereby radiates higher average power than Loran-C for the same peak power. Loran-D receivers take advantage of this pulse pattern. Loran-C receivers can operate with Loran-D transmitters, but Loran-C receivers can not take

(6.5.3 continued)

advantage of the Loran-D pulse pattern. Loran-D receivers can operate with Loran-C and Loran-D transmissions.

6.5.4 Early Loran-D transmitters, completely transistorized, radiated 7 kilowatts peak power. Later Loran-D transmitters use SCR's (silicon control rectifiers) and are said to radiate 40 kilowatts peak power.

6.5.5 The range of Loran-D is about one-half the range of Loran-C under comparable site conditions and comparable propagation paths. The accuracy of Loran-D is said to be equal to or better than the best accuracy of Loran-C, namely plus or minus 0.04 microseconds RMS.

6.5.6 Loran-D is a good candidate system for position-location of military land vehicles. Advantages of Loran-D for this application are:

(a) Transportability of the transmitting station.

(b) Potential accuracy of plus or minus 12 meters.

(6.5.6 continued)

(c) Loran-D receivers (and transmitters) have already been developed and tested in military exercises.

(d) Cost of a Loran-D receiver should not be much more than the cost of a Loran-C receiver. (Paragraph 6.3.7.)

(e) Loran-D is passive. (Paragraph 3.8.2.)

6.5.7 Disadvantages of Loran-D for application to military land vehicles are:

(a) Loran-D presents the same problems that are faced by Loran-C applied to land vehicles; e.g. propagation anomalies, obstructions and reflections by man-made structures, and RFI (radio frequency interference). (See paragraph 6.3.13.)

(b) Loran-D can be jammed.

(c) Loran-D might be susceptible to meaconing.

6.6 Omega

6.6.1 Omega is a hyperbolic radio-position-location system. It is a phase-comparison CW (continuous wave) system operating in the VLF (very low frequency) band (10 kHz to 30 kHz). Omega signals are usable over about 90 percent of the world.

6.6.2 Omega had its origins in 1947 when John A. Pierce of Harvard University proposed a hyperbolic phase-difference system called Radux, intended to operate in the LF band at about 50 kHz with a sine wave modulation of 200 Hz. At about 1955, Radux was modified by adding a VLF 10.2 kHz signal, and the modified system was re-named Radux-Omega. After testing, Radux-Omega was further modified by omitting the LF signal and adding transmissions at 11.33 kHz and 13.6 kHz, and the resulting three-frequency system is now called Omega.

6.6.3 There will be a total of eight transmitting stations in the Omega system. Seven of these stations were in operation in 1978 at the following locations: Aldra, Norway; Monrovia, Liberia; Haiku, Hawaii; La Moure, North Dakota, USA; La Reunion Island (East of Madagascar); Golfo Nuevo, Argentina; and Tsushima, Japan. The eighth station, in Australia, is expected to go into operation in 1979 or 1980, when it will replace a low-power station operating on an interim basis in Trinidad.

6.6.4 Loran-C and Omega are similar in that both systems are hyperbolic and both systems measure the differences in phase angle. The two systems differ in the following two major respects: Omega operates at a lower frequency than Loran-C (paragraph 6.6.5); Omega and Loran-C use different methods for synchronizing their transmissions (paragraph 6.6.11.)

6.6.5 Omega frequencies lie between 10.2 and 13.6 kHz; (wavelengths between 16 and 12 nautical miles approximately). One result of these low frequencies (about ten times lower than Loran-C frequencies) is that the range of Omega signals is large enough to cover all the world with the aforementioned eight transmitting stations; whereas other systems, such as Loran, require many more stations for only limited coverage. A second result of Omega's low frequencies is that the phase of an Omega signal is more predictable and more nearly stable over longer paths than is the case with Loran.

6.6.6 To a useful approximation, Omega signals propagate as though they are in a waveguide, the boundaries of which are the D-layer of the ionosphere and the surface of the earth. Usually in a waveguide, a higher mode is attenuated at a higher rate than a lower mode; and at Omega frequencies the attenuations of the second and higher modes are so large that only the first mode would be expected to have practical

(6.6.6 continued)

importance at long distances. However, the types of transmitters used in the Omega system excite the second mode more strongly than the first mode, so that both modes must be considered at intermediate distances from the transmitter. Furthermore, the phase velocity of mode 2 is higher than that of mode 1. The result is that Omega is not generally reliable within about 450 nautical miles of a transmitter. Fortunately it should be possible for an Omega receiver, anywhere on Earth, to use four or more transmitting stations, no one of which is closer than 450 miles.

6.6.7 The boundaries of the natural waveguide, that carries Omega transmissions, are complex, variable and non-uniform. The height of the ionosphere varies with: the time of day and night; the seasons; solar activity; latitude; and solar zenith angle. Ground conductivity varies from place to place, especially at boundaries between land and water. Nevertheless, it appears that the phases of the Omega signals can be predicted and mapped with sufficient accuracy to permit position-location to within 1 to 2 nautical miles drms.

6.6.8 "Omega Propagation Correction Tables" (H. O. Publication No. 224) are issued by the U. S. Defense Mapping Agency Hydrographic Center (DMAHC), Washington, DC. These tables give the data for correcting Omega readouts from the prevailing propagation conditions to the standard conditions on which the published DMAHC Omega hyperbolic charts and lattice tables are based. The U. S. Coast Guard Omega Navigation System Operation Detail (ONSOD) collects data for improving the prediction of spatial and temporal variations of Omega phase propagation.

6.6.9 Each of the eight Omega stations transmits time-shared signals at 10.2 kHz for 0.9 seconds, at 13.6 kHz for 1.0 seconds, and at 11.33 kHz for 1.1 seconds, followed by silence for the balance of a repeated period of 10 seconds. The stations stagger these sequences of transmissions so that the Omega receiver can use combinations of the three frequencies from different Omega stations.
A fourth frequency, 11.05 kHz, has been added recently.

6.6.10 The Omega receiver compares and measures the difference in the phases of signals received from a pair of transmitting stations. Each such phase measurement determines one hyperbolic LOP. However, a given phase value repeats itself in distance at every integral number of wavelengths. Therefore the comparison of phases from each pair of

(6.6.10 continued)

stations is ambiguous as to the lane of isophase contours in which the LOP lies. Along the baseline joining two stations, this ambiguity is equal to one wavelength, e.g. 16 nautical miles. The ambiguity is resolved either by knowledge of the gross position of the vehicle, or by keeping count of the lanes that have been traversed, or by using several pairs of stations. The ambiguity would not pose a problem for a land vehicle which should know its approximate location within a lane width without aid from Omega.

6.6.11 In a hyperbolic radio position-location system, the transmitters must be synchronized with each other, or they must transmit with a known phase relation to each other. In a Loran chain, synchronizing signals are transmitted from the master station to the secondary stations. However, in Omega the transmitters keep in synchronism by means of very accurate cesium frequency standards (atomic clocks), four of which are kept in each transmitting station.

6.6.12 Therefore in Omega there are no master stations and no secondary stations. Any two stations in the Omega system can be used to give a LOP. The vehicle can thereby select pairs of Omega stations that provide LOP's that intersect at angles that are closer to right angles

(6.6.12 continued)

than might otherwise be possible. This reduces the geometric dilution of precision, and improves the accuracy of the fix.

6.6.13 A further advantage of the fact that any two Omega stations can be used to give a LOP, is that multiple LOPs can be obtained by using any three or more stations. Thus three stations give three LOPs; four stations give six LOPs; five stations give ten LOPs; - all for the same fix. Multiple LOPs for the same fix obviously improve the accuracy of the fix.

6.6.14 Omega transmitting stations are large, expensive installations. It was a major challenge to design and construct transmitters and antennas capable of radiating 10 kw at 10 kHz. The Omega antennas in Norway and Hawaii consist of cables suspended between elevated land masses. The other antennas are top-loaded vertical monopoles on high towers (e.g. 1,500 ft. high in Liberia). The cost for design, site preparation and construction of each transmitting station and tower is estimated to be about 7 to 10 million dollars.

6.6.15 The Omega system is designed to achieve a position-location accuracy of 2 to 4 nautical miles, 2-drms. Accuracies of 1 nautical mile

(6.6.15 continued)

may be possible when the system is fully calibrated and improved correction tables are available. Monitoring and calibration of Omega signals is continuing, and must continue for some time before the system is considered fully operational.

6.6.16 Nevertheless, Omega is now usable, and is being used by the U. S. Navy, the U. S. Coast Guard, the merchant marine and commercial fishermen. It is estimated that more than 2,500 vessels are now using Omega receivers. There are also several hundred Omega receivers in use on aircraft of the U. S. Air Force and the U. S. Navy. Use of Omega on U.S. commercial airlines is limited at the present time.

6.6.17 Prices of Omega receivers cover a wide range. Single-frequency receivers are as low as $3,500. Three-frequency receivers start at about $4,200. Other Omega receivers can cost several times these prices, even up to $50,000, depending upon the degree of automation in the receiver, e.g. continuous automatic display of latitude and longitude, and depending upon the capability of the Omega receiver to interface automatically with other navigation systems.

6.6.18 A typical Omega reciver, not including the receiving antenna, occupies a space that is usually about one cubic foot, and weighs between 20 and 40 lbs. depending upon the complexity of its features.

(6.6.18 continued)

Power consumptions of receivers with displays, etc. are typically between 12 and 80 watts, depending upon the complexity of the receivers and displays.

6.6.19 Omega receiving antennas are relatively simple. One type of receiving antenna is a whip between 8 and 15 feet in length. Another type is a crossed pair of orthogonal loops occupying a space of about 8 x 10 x 2 inches.

6.6.20 The U. S. (United States of America) built the Omega system described above, and maintains and operates the system through the U. S. Coast Guard and the U. S. Navy. The U.S.S.R. (United States of Soviet Russia) has its own VLF position-location system operating in the same 10 to 14 kHz band as Omega. The Soviet system has a network of four transmitting stations, all in the U.S.S.R. The locations of the Soviet stations seem to provide coverage primarily in the Indian and Arctic Oceans. The radiated power of the Soviet stations is estimated to be an order of magnitude greater than that of any of the Omega stations.

6.6.21 Advantages of Omega for application to military land vehicles are:

(a) The system is world-wide (covers about 90 percent of the world).

(b) Omega reception is not likely to be affected by obstructions such as buildings, other vehicles, or topographic features.

(c) Omega is passive. (Paragraph 3.8.2.)

(d) Size and weight of the receiver and receiving antenna are reasonable.

(e) Receiver operation and display of position-location information can be automatic and continuous (in the more costly models of equipment).

6.6.22 Disadvantages of Omega for application to military land vehicles are:

(a) Accuracy of position-location is only about 2 nautical miles, or possibly 1 nautical mile.

(b) The Omega system could become inoperative for a long period, if hostile action should destroy or seriously damage more than 3 or 4 Omega transmitting stations. An Omega station can not be rebuilt quickly.

(c) Costs of automatic Omega receivers are relatively high. (Paragraph 6.6.17.)

6.7 D-Omega

6.7.1 Differential Omega (abbreviated as D-Omega) is a technique for using the Omega system with enhanced accuracy in limited geographic areas. In each such area, a monitor station, at a known location, receives the Omega signals and measures the differences between the receiver readings and the values on the published Omega charts. Via an ordinary radio communications link, the monitor station broadcasts these differences to be used as correction factors by marine vessels and aircraft in the area.

6.7.2 The causes of errors in D-Omega are essentially the same as the causes of errors in Omega itself (see 6.6.7); but the monitoring technique reduces the errors in the vicinity of the monitor station. Estimates of the useful range of D-Omega vary from about 370 to 1,000 km from the monitor station, depending upon location of the monitor station and propagation conditions. Examples of reported accuracies of D-Omega fixes are: 0.5 km at 93 km from the monitor station; 0.9 km at 370 km; 1.1 km at 555 km; 0.74 km at 1110 km.

6.7.3 The relation of D-Omega to Omega is analogous to the relation of D-Loran-C to Loran C. (See 6.4).

6.7.4 D-Omega was introduced about 1965, and has been tested by U. S. and foreign manufacturers and navy research laboratories.

6.7.5 Advantages of D-Omega for application to military land vehicles are the same as stated in sub-paragraphs 6.6.21 (b), (c) and (d) for Omega, with the important added advantage that the fix accuracies of D-Omega (paragraph 6.7.2) are better than those of Omega.

6.7.6 The disadvantages of D-Omega for application to military land vehicles are the same as stated in sub-paragraphs 6.6.22 (b) and (c) for Omega, plus the following two disadvantages:

(1) A D-Omega monitor station must be deployed in the D-Omega operating area; whereupon the presence and location of the monitor station is disclosed by its radio transmissions.

(2) Operation of D-Omega aboard the vehicle is not fully automatic even though a fully automatic Omega receiver is used, because the broadcasted D-Omega corrections must be used manually to correct the chart readings.

6.8 Micro Omega

6.8.1 Micro Omega is an automated D-Omega. In D-Omega the monitor station broadcasts correction factors by voice to be used aboard the vehicle. In Micro Omega, the monitor station broadcasts audio tones on a single sideband HF carrier. The tones contain the phase correction information. The Micro Omega receiver aboard the vehicle automatically uses this information to correct the phase of the signal received simultaneously from the Omega station.

6.8.2 Micro Omega accuracies of ± 100 meters have been reported at distances as large as 370 km from the monitor station. The weight and size of a Micro Omega receiver and antenna on board the vehicle is not much greater than the weight and size of a fully automated Omega receiver and antenna, (paragraphs 6.6.18, 6.6.19).

6.8.3 The advantages and disadvantages of Micro Omega for application to military land vehicles are the same as the advantages and disadvantages of D-Omega (paragraphs 6.7.5, 6.7.6), except that Micro Omega has the following advantages compared to D-Omega:

(a) Micro-Omega fix accuracy is better than D-Omega fix accuracy.

(b) The Micro Omega receiver, aboard the vehicle, can be completely automatic.

6.9 Decca

6.9.1 Decca, also called the Decca Navigation System, is a hyperbolic radio position-location system in the LF band, using phase-difference measurements. A Decca chain consists of one master transmitting station and three slave transmitting stations placed symmetrically around the master station at distances of 130 to 200 km from the master station. Ideally, the slave stations should be spaced equally around the circumference of a circle centered on the master station.

6.9.2 The master station transmits continuous unmodulated waves at 85.000 kHz. The three slaves transmit continuous unmodulated waves at 113.333, 127.500, and 70.833 kHz respectively. The aforesaid four frequencies are respectively 6, 8, 9 and 5 times a basic Decca frequency of 14.1666 kHz which is internal to Decca but not transmitted. The phase relationships between the stations are controlled by transmissions from the master to the slaves.

6.9.3 Aboard the vehicle, the Decca receiver converts the signals from the master and each slave to a common frequency, and measures

(6.9.3 continued)

the phase differences between the master signal and each slave signal. Each such difference gives a hyperbolic LOP. The two slave stations that give the best intersection angle of the LOPs are selected to determine the fix. The third slave station and its LOP can be used to improve the accuracy of the fix.

6.9.4 The three phase differences (between master and each of the three slaves) are automatically measured and displayed on three dials called "Decometers". The readings of the Decometers are then plotted on published Decca charts that show the Decca hyperbolas printed in colors (red, green, purple) that identify the three slave stations and the three Decometers. Auxiliary equipment is available to plot and display fixes and courses automatically.

6.9.5 The useful maximum range of a Decca chain varies with different chain locations and propagation conditions in different parts of the world, but the range is of the order of 440 km (240 nautical miles) from the master station. A typical chain covers a service area of about 180,000 square miles.

6.9.6 On a direct baseline between a master station and a slave station, the accuracy of a fix can be as good as ± 5 meters. In other parts of the covered area, accuracies of ± 25 meters at the 68% probability level are quoted. At maximum range, not on a baseline, accuracies are said to be about ± 30 to ± 50 meters.

6.9.7 The Decca transmitting antennas are masts approximately 100 meters high. Radiated power is about 800 to 1,000 watts.

6.9.8 A typical Decca receiver for shipboard use (the Mark 21, solid-state) weighs 55 lbs and is about 17 x 16 x 19 inches in size.

6.9.9. Decca is almost unique in the following respects. The receivers are usually not sold. They are usually available on lease only, at approximately $2,500 per year. Furthermore, in many areas, the Decca ground transmitting stations are privately owned and operated, supported by the lease (and sale) of the receivers. In the case of almost all other radionavigation systems, the fixed ground stations are owned and operated by a government, and the equipment carried by the vehicle is owned by the vehicle.

6.9.10 Decca receivers are said to be in use on 23,000 ships that include 10,000 merchant ships of 50 nations, 2,000 ships of 14 navies, and 11, 500 fishing vessels. Decca receivers are employed also in a variety of aircraft, but not in the quantities quoted above for marine vessels.

6.9.11 Decca was first used in the D-day landings in France in 1944. The first Decca chain became operational in 1946. Forty-nine Decca chains are now in operation or are under construction as follows: 25 in Europe; 5 in South Africa; 4 in Canada; 4 in Nigeria; 3 in Japan; 3 in India; 2 in Australia; 2 in the Persian Gulf; 1 in Bagladdesh.

6.9.12 The aforesaid 49 Decca chains cover only perhaps 3 or 4 percent of the Earth's surface, because each chain covers only about 180,000 square miles and because there is overlap between some Decca chains. Decca coverage is therefore very small compared to Omega coverage which encompasses more than 90 percent of the Earth. Decca coverage is principally in areas of heavy traffic.

6.9.13 For application to military land vehicles, Decca has about the same advantages and disadvantages as Loran-C and the Omega systems except that Decca has the advantage of better accuracy

(6.9.13 continued)

than Loran-C, D-Omega and Micro-Omega; and Decca has the disadvantage that present Decca coverage is not as extensive as Loran-C and Omega.

6.9.14 There was a manpack Decca receiver, denoted as Minidec Mark 2. Maximum range from the Decca master station was 150 miles by night, and 300 miles by day.

6.9.15 A Decca receiver (Mark 23) has been developed specifically for military land vehicles. It is housed in a military-type container, and is said to be capable of the full performance of Decca marine or air receivers.

6.10 Raydist

6.10.1 Raydist is a name that has been applied to a series of position-location systems developed after World War II for over-water surveying, principally for geophysical and hydrographic exploration. Most of the Raydist systems were hyperbolic. Some were rho systems (5.1.3, 5.1.4); and some were, and are, combinations of hyperbolic and rho systems. The two latest Raydist systems are designated as Raydist DRS-H and Raydist "T".

6.10.2 The basic DRS-H system is a rho system consisting of two fixed base stations (on land) and a mobile station on the vehicle. The mobile station transmits CW at about 3 MHz to both base stations, and receives CW at about 1.5 MHz from both base stations, using heterodyne methods and SSB (single-side-band) techniques. Up to four vehicles can use the Raydist DRS-H in this rho mode.

6.10.3 The Raydist DRS-H becomes a hyperbolic system by installing the mobile transmitter at a third fixed base station, and equipping the vehicle with a receiver only.

6.10.4 The Raydist "T" system is basically the DRS-H system with four fixed base stations, used principally as a hyperbolic system.

6.10.5 Over seawater, with the fixed base stations on the shore, the Raydist DRS-H and "T" systems have a range of about 250 miles during the day, and about 150 miles at night. Over seawater, accuracy of position-location is about ± 1 meter on the baseline, and about ± 3 meters in other areas of favorable geometry; and sensitivity is said to be about one-half meter. Over land, Raydist is considerably less accurate and less predictable than over water.

6.10.6 The size of the Raydist mobile receiver is 16 x 14 x 5 inches. It weighs 16 lbs. The position indicator that is part of the mobile installation is 16 x 14 x 4 inches, and weighs 15 lbs. The Raydist CW transmitter, that also is aboard the vehicle in the DRH-S system, is an additional 18 x 15 x 12 inches, weighing 37 lbs. The antenna on the vehicle can be a relatively simple 22-inch "voltage probe".

6.10.7 The solid-state electronic chassis for each base station is in a single weatherproof unit, about 18 x 15 x 12 inches, weighing 45 lbs. The chassis can be powered by two automobile storage batteries delivering 24 volts.

6.10.8 The antenna of Raydist "T", for medium range operation , is telescopic, 47 feet high, weighing 30 lbs. including guys and ground system. For long range operation, the antenna is sectional, 100 feet high, weighing 205 lbs. including the ground system.

6.10.9 The least expensive Raydist system is the basic single-user DRS-H rho system. It sells for approximately $66,000; and the lease price is $6,300 for the first month, and lesser amounts for succeeding months. Selling and rental prices are higher for 4-user DRS-H systems, hyperbolic DRS-H systems, and "T" systems.

6.10.10 For application to military land vehicles, the advantages of Raydist are:

(a) Possibility of good accuracy. (6.10.5)

(b) Relative portability of each fixed base station and its antenna. (6.9.7, 6.9.8)

(c) The "T" system, operated in the hyperbolic mode, is non-saturable (3.7.2), and passive (3.8.2).

6.10.11 The disadvantages of Raydist, for application to military land vehicles, are:

(a) High cost.

(b) The system is saturable and active when operated in the rho mode.

(c) Relative complexity of the electronic equipment.

6.11 Consol

6.11.1 Consol is a hyperbolic radio position-location system that uses the following geometric property of a family of hyperbolas. At large distances from the foci (paragraph 6.1.1), each hyperbola asymptotically becomes a straight line, and each such straight line passes through the midpoint of the baseline between the foci. Thus, at distances greater than about 12 times the baseline, the hyperbolic LOPs may be considered to be straight lines radiating from the midpoint of the baseline.

6.11.2 Consol uses a very short baseline. Each Consol fixed transmitting station consists of three transmitting antennas placed in a straight line and spaced at equal intervals of about three wavelengths. The two outer antennas generate a hyperbolic pattern. The system is sometimes called a "collapsed" hyperbolic system because the baseline is short and the system uses the pseudo straight-line segments of the hyperbolas.

6.11.3 Consol stations transmit signals in the frequency band from 190 to 370 kHz. These signals can be received on most ordinary LF/MF radio communication receivers. No other equipment is needed in order for the vehicle to use Consol! This is Consol's feature which is

(6.11.3 continued)

taken advantage of by small boats and fishing vessels. Their regular inexpensive communications receivers or simple DF receivers (section 5.3.2) are all that are required to receive and use Consol position-location signals. The signals are as follows (6.11.4, 6.11.5).

6.11.4 By alternately changing phase angles and amplitudes in the transmitting antennas, the Consol station sends out a multilobe rotating radiation pattern consisting of alternate sectors of dot and dash signals. Each lobe subtends about 15 degrees of arc. The operator aboard the vehicle (vessel) counts the numbers of these dots and dashes that he hears aurally through his radio communication receiver, in between keying signals (called equisignals) that are also transmitted by the Consol station about every 60 seconds. (The call sign of the Consol station is also transmitted during each 60 second cycle).

6.11.5 The operator's count of dots/dashes tells him his position within his lobe of the pattern, and thereby gives him a straight-line LOP (passing through the Consol station) on a Consol chart. (He must know which lobe he is in, from a gross knowledge of his position.) He then uses a second Consol station, counts its dots/dashes/equisignal, and thereby obtains a second LOP. The intersection of these LOPs

(6.11.5 continued)

gives him a fix. Bearings for various dot/dash counts, with respect to Consol stations, are published in DMAHC Publication No. 117A; and charts showing Consol lines overprinted for various dot/dash counts are published by the British Admirality Hydrographic Service.

6.11.6 The maximum useful range of Consol, over water, is about 1,850 km by day and 2,200 km by night, to be expected about 90 percent of the time. Consol can not be used closer than 50 km from a Consol station because the hyperbolas are too curved to be used as straight lines in this range.

6.11.7 Consol is, in effect, an azimuthal or theta system (section 5.3.1). Best angular accuracy is obtained for LOPs near the perpendicular bisector of the baseline (as is the case in all hyperbolic systems). If reception is by "ground" waves over water, accuracy is about one-third of a degree in the approximate direction of the perpendicular bisector, and about two-thirds of a degree at other angles. Useful angular coverage is limited to about 60 degrees on either side of the perpendicular bisector because of degraded accuracy at these angles.

6.11.8 Converting the angular accuracy to linear accuracy, the error is about 1 nautical mile (1.85 km) for each 180 nautical miles (333 km) from the Consol station along the perpendicular bisector of the baseline, and about 1 nautical mile (1.85 km) for each 90 miles (167 km) in either direction 60 degrees away from the perpendicular bisector. At the maximum useful range of approximately 2,000 km, this means an accuracy of 6 km for a ship on the perpendicular bisector, and an accuracy of 12 km for a ship lying on a radial line that is 60 degrees away from the perpendicular bisector.

6.11.9 There are Consol stations in Norway, Ireland, France and Spain. There are none in North America.

6.11.10 Advantages of Consol, for possible application to military land vehicles, would be:

(a) Simplicity of the equipment (a conventional radio receiver) aboard the vehicle. (See 6.11.3)

(b) Reliability of the equipment aboard the vehicle.

(c) Low cost of the equipment aboard the vehicle; e.g. less than $100.

(d) The system is passive. (3.8.2)

(e) The system is non-saturable. (3.7.2)

6.11.11 Disadvantages of Consol, for application to military land vehicles:

(a) The Consol operator, aboard the vehicle, must perform time-consuming operations to obtain a fix; i.e. tune to a Consol station, count dots/dashes/ equisignals, plot a LOP on a Consol chart, and repeat these operations for another Consol station. (See 6.11.4, 6.11.5)

(b) Fix accuracy is poor. (See 6.11.8)

(c) Consol can not be used closer than 50 km from a Consol station. (6.11.6)

(d) Acoustic noise aboard some military land vehicles, e.g tanks, may make it difficult for the operator to count the aural dots/dashes/equisignals, especially if the Consol signals are weak at long ranges.

6.12 Other Hyperbolic Systems

6.12.1 Loran-B was an intermediate step in the development from Loran-A to Loran-C. Loran-B used frequencies of 1850 to 1950 kHz, in the same band as Loran-A; but Loran-B used pulse/phase-matching techniques like Loran-C. Loran-B was never operational.

6.12.2 "Survey Decca" is a variation of Decca using two instead of three slave stations. Historically, Survey Decca was first tested in the early 1940's, before Decca.

6.12.3 Delrac (acronym for Decca long range area coverage) was a VLF experimental hyperbolic radio position-location system developed in the late 1950's, intended for use over very long ranges by ionospheric reflection. Delrac was similar to Decca except that the Delrac stations worked in pairs, one slave to each master, with baselines as long as 1600 km. Delrac was never operational.

6.12.4 Lorac (acronym for long range accuracy) is a group of position-location systems used principally for accurate off-shore survey. Lorac operates in the 1.6 to 2.5 MHz band. Lorac and Raydist systems share some similarities. Type "A" Lorac uses three ground base stations. Type "B" Lorac uses four ground base stations. Over water, ranges are 400 km in daytime, and 160 km at night; and accuracy on the

(6.12.4 continued)

baseline is about ± 1 meter. Some Lorac systems are combinations of rho and hyperbolic systems. Some Lorac systems are integrated with Loran receivers.

6.12.5 Toran is a French system similar to Lorac Type B, using frequencies between 1.6 and 3.0 MHz, with a claimed range of 700 meters and an accuracy of ± 1 meter on the baseline. Toran "O" is a later version of the basic Toran system. Toran "O" uses atomic frequency standards in the base transmitting stations and in the receivers aboard survey vessels. Toran "O" is a non-saturable rho system with a range of 1000 km and a resolution of ± 1 meter.

6.12.6 Rana is a hyperbolic system using four transmission frequencies in the 1600 to 2000 kHz band. Phase comparison is performed by audio tones, using heterodyning. Maximum range is about 160 km. Accuracy is about ± 15 meters. Rana was developed for the French Hydrographic Service and was used for surveying in North Africa in the 1960's.

6.12.7 Consolan was a Consol-type system developed by the United States. Consolan is no longer in use. It used only two transmitting antennas at each station, instead of three as in Consol.

6.12.8 BPM5 is a Soviet version of Consol. The U.S.S.R. system uses five transmitting antennas in the form of a cross at each station. The dot/dash lobes are narrower in BPM5 than in Consol.

7. PILOTING

7.1 Piloting is the oldest form of marine navigation. In marine terminology, piloting means the continuous or very frequent determination of LOPs and/or positions and/or headings by means of one or more of the following: visual observations of land and sea marks such as buoys, lighthouses, shorelines, rocks, hills, docks, buildings and bridges; depth soundings; aural signal from sound buoys; and sonar (underwater acoustic directional echo ranging). Ship-borne radar (section 8) is an additional aid to modern marine piloting.

7.2.1 Pilotage is the air navigation term analogous to piloting in marine navigation. Pilotage is the determination of an aircraft's LOP and/or position and/or heading by means of visual observation of natural and cultural features on the ground, and by means of airborne radar (section 8).

7.2.2 Visual pilotage is used in military and civil aviation whenever visibility permits. Pilotage by radar is used in many military and civil aircraft. Infrared viewing devices are not usual in civil aviation, but such devices could be used in civil pilotage, particularly at night.

7.3 The driver of a land vehicle ordinarily uses visual observation of his surroundings for steering and guidance, when visibility and illumination permit. This obvious and common procedure may be called <u>land piloting</u>. Infrared viewing devices and radar (section 8) are potential aids to land piloting under conditions of low visibility, e.g. at night or in fog.

7.4 Two characteristics that distinguish piloting, pilotage and land piloting, as a group, from other types of position-location/navigation are:

(1) In piloting, pilotage and land piloting, the LOPs and/or positions and/or headings are determined continuously or very frequently; whereas these parameters are determined only periodically in most other forms of position-location/navigation.

(7.4 continued)

(2) In piloting, pilotage and land piloting, positions and headings are determined in coordinate systems that need be only informal local systems limited to the immediate neighborhood of the vehicle. These local coordinate systems can change frequently as the vehicle travels; and the local systems need not necessarily be tied to state-wide or country-wide or world-wide coordinate systems (e.g. Earth latitude and longitude).

By contrast, most other forms of navigation demand that LOPs, positions and headings be determined in formal, established coordinate systems that are world-wide, country-wide or state-wide.

8. RADAR

8.1 The term "radar" is an acronym for "radio direction and range". Radar systems use radio propagation to measure simultaneously the direction and range (distance) of objects (called targets). Radar does not include systems that measure direction only, such as radio direction finders (section 5.3.2); nor does radar include systems that measure range only, such as DME (section 5.2.1). Radar is an active system when the radar equipment is aboard the vehicle; (paragraph 3.8.1).

8.2 The origins of radar can be traced back to Heinrich R. Hertz (1857-1894) who showed that solid objects could reflect radio waves. In 1904 a patent was granted to a German engineer, Hulsmeyer, for detecting obstacles and aiding ship navigation by the reflection of radiowaves. In 1922 Guglielmo Marconi suggested that short radio waves be used for detection. In 1925, Breit and Tuve, of the Carnegie Institution of Washington, measured the height of the ionosphere by a radio-pulse method. However radar development received its greatest impetus during World War II. More funds were spent for research, development and procurement of radar equipment and radar systems, from 1941 through 1944, than were spent for the development of the atomic bomb. Since then, radar techniques have become highly sophisticated and effective.

8.3 The term "radio" in the acronym "radar" has come to mean the portion of the electromagnetic spectrum between 3×10^8 Hz and 3×10^{11} Hz, (between wavelengths of 1 meter and 1 millimeter). In radar terminology, this portion of the spectrum is divided into the bands listed in Table 8.3 below.

TABLE 8.3

Radar Band Designations

Based on "Standard Letter Designations for Radar-Frequency Bands," Institute of Electrical and Electronics Engineers, Standard 521-1976, Nov. 30, 1976.

Band	Frequency (GHz) *	Wavelength (cm)
UHF**	0.3 - 1.0	30.0 - 100.0
L	1.0 - 2.0	15.0 - 30.0
S	2.0 - 4.0	7.5 - 15.0
C	4.0 - 8.0	3.75 - 7.5
X	8.0 - 12.0	2.5 - 3.75
Ku	12.0 - 18.0	1.67 - 2.5
K	18.0 - 27.0	1.11 - 1.67
Ka	27.0 - 40.0	0.75 - 1.11
mm***	40.0 - 300.0	0.10 - 0.75

* 1 GHz (Gigahertz) = 10^9 cycles per second

** 0.42 - 0.45 GHz is occasionally called the P band.

*** 46 - 56 GHz is occasionally called the V band.

8.4 Radar uses short pulses or bursts of radiation emitted from a directional antenna. Some experimental radars have used frequency-modulated continuous-wave radiation (FM-CW); but operational radars today are pulsed. Radar has become synonymous with pulsed radar; and the term radar hereinafter means pulsed radar.

8.5 If a target lies in the path of the emitted pulse, some of the electromagnetic energy in the pulse is reflected or scattered from the target back to the same directional antenna that emitted the pulse. This electromagnetic "echo" is collected by the antenna and detected by the radar equipment.

8.6.1 The radar equipment measures the elapsed time between the emission of the pulse from the antenna and the reception of the reflected echo by the antenna. This elapsed time gives the range of the target (distance between antenna and target) by using the known speed of propagation of the electromagnetic pulse.

8.6.2 Electromagnetic waves in vacuo travel with a speed c that is close to 2.9998×10^{10} cm per second. In vacuo, this speed is independent of frequency (or wavelength). In the atmosphere, the speed is $v = c/n$

(8.6.2 continued)

where n is the refractive index of the atmosphere. The refractive index is a function of the frequency of the radiation and a function of the density and water vapor content of the air.

8.6.3 However, in the radar portion of the spectrum, the refractive index of air is practically constant with frequency (except for two narrow bands of frequencies near 22 GHz and 60 GHz). For radar frequencies, the refractive index of the atmosphere is 1.0003 at sea level, and approaches unity with increasing altitude. Consequently, for all practical navigation, piloting, pilotage and land piloting, the refractive index of the atmosphere may be assumed to be exactly unity, and the speed of propagation of the radar pulse may be assumed to be exactly 3×10^{10} cm per second. (As a rough rule of thumb, this can be taken to be a speed of one foot per nanosecond, a nanosecond being 10^{-9} second.)

8.7 One microsecond (1 u sec) of delay between emission of the pulse and reception of the echo corresponds to a range of 150 meters, because the pulse travels the range distance on the way out to the target and the echo travels the same range distance on its way back to the antenna. A range measurement accuracy of one meter, for example,

(8.7 continued)

requires that the time delay be measured with an accuracy of 0.0067 microseconds. Fortunately, time can be measured more precisely and accurately than any other physical quantity.

8.8 After each emitted pulse, multiple echoes may be received from multiple targets that are "seen" by the antenna while pointed essentially in a single direction. These multiple targets can be resolved from each other on the time base if the pulse length is shorter than the range separation of discrete targets. The pulse length also sets a limit to the minimum range at which the radar can operate. Typical pulse lengths for nautical piloting and navigation radars are 0.6 to 2.0 microseconds. In the discussion of radar in this report, parameters are given principally for nautical radar because this is the type of radar that is most likely to be adaptable to the navigation/position-location of land vehicles.

8.9 The radar antenna scans the area that contains targets of interest. Scanning patterns vary, depending upon the application of the radar. The most usual scanning pattern, for piloting, pilotage, and navigation, is a 360 degree horizontal scan around a vertical axis. This scanning pattern is typical of shipborne radars, airborne navigation radars, air traffic control radars, and military surveillance

(8.9 continued)

radars. In marine radar, typical scanning speeds for this type of scanning pattern are 15 to 25 rpm. Another typical antenna scanning pattern is an horizontal sector scan, scanning back and forth in azimuth through an angle that is less than 180 degrees, e.g. 90 degrees, pointed ahead of the vehicle. Scanning patterns that are used for search and location of target aircraft include: a spiral scan; and a raster scan, analogous to a television scan, covering a sector of view in azimuth and in elevation.

8.10 The direction of the target is the direction in which the directional antenna is pointed when the target's echo was detected. The angular precision, accuracy and resolution with which the target's direction is measured, (sometimes called the cross-range precision, accuracy and resolution), depend upon the shape and width of the antenna beam pattern. (As in all radio antenna patterns, the beam shape of a given antenna is the same for transmission as it is for reception.) The larger the antenna aperture and the shorter the wavelength of the radiation, the narrower is the antenna beam shape, and hence the finer is the cross-range resolution and precision. The beam width, e.g. the width of the beam at half its maximum power, is inversely proportional to the size of the antenna aperture, and directly proportional to the wavelength. For marine radars, typical half power

(8.10 continued)

beam widths are 0.5 to 2.0 degrees horizontally, and 15 to 30 degrees vertically. Airborne radars that are used for pilotage, navigation, mapping or earth resources surveys, have vertical beam patterns that extend from a little below the horizon to near vertical downward. The antenna patterns that are used in raster scans and spiral scans are narrow in azimuth and elevation.

8.11 For mapping and resources survey, aircraft also use side-looking radars, the antenna patterns of which are narrow in the cross-range direction, pointing out from both sides of the craft at right angles to the plane's longitudinal axis. These antennae and their patterns remained fixed in position with respect to the aircraft, and the scanning is accomplished by the motion of the plane along its flight path. Side-looking radar is excellent for mapping and resources survey, in which the recorded radar information is used on the ground after the aerial flight is concluded. Side-looking radar is not useful for real-time operations of piloting, pilotage or navigation, because this radar gives no information of what is ahead of the vehicle in a 180 degrees sector of azimuth.

8.12 High speed aircraft and spacecraft can use synthetic aperture radar (SAR) which simulates a large imaginary antenna aperture by

(8.12 continued)

storing coherent radar echoes as the actual antenna moves with the craft. The radar then synthesizes the signals as though they were received by a large antenna. Synthetic aperture radar is not applicable to land piloting or to land vehicle navigation because the speeds of land vehicles are too slow.

8.13 In almost all radar systems for piloting, pilotage and navigation, the radar information is presented on a cathode-ray tube (CRT) display to the pilot or navigator of the vehicle. Various display patterns have been used in the past to meet specialized requirements. The most widely used display pattern, and the one that is most useful for piloting, pilotage and navigation, is the plan position indicator, abbreviated as PPI, used with antennae that scan in azimuth. The PPI pattern is generated by a flying spot that starts at the center of the CRT face, sweeps radially outward to the circumference of the pattern, blanks out, returns to the center, sweeps radially outward again along a closely adjacent radius, and repeats the process so as to produce a full set of overlapping spokes of a wheel. The start of each spoke, at the center of the PPI pattern, is synchronized with the emission of the radar pulse from the radar antenna. The rotation of the radial spoke of the PPI pattern is synchronized with the azimuthal rotation of the radar antenna. The intensity of the flying spot is modulated by the

(8.13 continued)

intensity of the radar echo, in real time. The result is a display or plan "view" with the vehicle in the center and all the surrounding radar targets indicated by spots in their proper azimuth and range. In some radar sets, the operator can expand the PPI pattern radially, or he can expand a sector of the pattern, in order to display more detail of a portion of the pattern. If the antenna is scanning through an azimuthal sector of less than 360 degrees, e.g. 120 degrees, the radial sweeps of the PPI move only through a corresponding angular sector on the CRT. The PPI would undoubtedly be the preferred display pattern for a radar mounted on a land vehicle.

8.14 In designing and engineering a radar system, an optimum combination of many parameter values must be selected to suit the particular application of the radar. The most important of these parameters (not necessarily listed in order of importance) are: frequency (wavelength); antenna size and shape, and beam shape; antenna scanning pattern; antenna scanning speed; pulse length; pulse power; pulse repetition rate; minimum and maximum ranges; size and pattern of the CRT display; total size, weight and power consumption of the radar equipment.

8.15 The radar image of a target, presented on a CRT, is gross compared to the image of the target seen by the human eye. The radar image can not be as detailed as the image by direct vision because the radar wavelengths are at least 2,000 times as long as the wavelengths in the visible portion of the electromagnetic spectrum. Radar usually provides only the outline shape of a target. This often makes target recognition and identification by radar difficult.

8.16.1 The relative intensities of radar echoes from targets are important clues to recognizing and identifying the targets. The relative intensities (or radar "cross sections") depend, among other factors, upon the radar wavelength and upon the shapes and sizes of the targets and upon their materials and surfaces. For example, materials and surfaces with high electrical conductivity, such as metals, give stronger radar reflections than materials with high electrical impedance, such as wood and plastics. The relative intensities of the radar echoes are indicated by the relative brightness of the spots on the CRT face. The dynamic range of intensities on a black-and-white CRT display is limited, but the operator can partly overcome this limitation by varying a gain control in some radar sets. Color CRT's can provide additional display discrimination between intensities of the radar signals returned from the targets; but color CRT's are not widely used in radar.

8.16.2 Considerable work has been done, through the years, to determine the radar cross-sections of cultural and natural targets of various sizes, shapes, materials, and surfaces, at various radar-observed aspect angles, and at various radar frequencies. This work has been done principally for airborne radar; but the results should be applicable in part, to radar mounted on land vehicles.

8.17 In marine piloting and aeronautical pilotage, radar has an unobstructed view of surrounding targets of interest. In the case of marine ship-borne radar, the view is unobstructed because the antenna can be mounted on a mast sufficiently above normal wave heights, and because all targets of interest are above the wave level. In the case of airborne radar, the view is obviously unobstructed because of the elevation of the antenna. However, in land piloting, with a radar antenna mounted on the roof of a land vehicle, the radar view could be obstructed by nearby buildings, trees or hills; and a slope of ground, rising from the vehicle's position, could fill the radar scope display with continuous echoes called "ground clutter" that can mask the presence of small targets of interest.

8.18.1 The prime advantage of radar for use on marine, aeronautical and land vehicles is that radar can operate at night and during conditions of reduced visibility such as fog and smoke.

8.18.2 Other principal advantages of radar are:

(a) radar is a self-contained system aboard a vehicle; i.e. no equipment or cooperation is required external to the vehicle;

(b) range and direction are measured simultaneously with one equipment;

(c) range is measured with a high degree of accuracy;

(d) the PPI gives a chart-like presentation of the surroundings, without distortions of perspective.

(e) a vehicle's position can be located by a single radar reading of the range and direction of a single target of known position, if the vehicle also has a compass (magnetic or gyro compass).

8.19 Potential disadvantages of radar for use on land vehicles are:

(a) obstruction of the radar view (paragraph 8.17);

(b) ground clutter (paragraph 8.17);

(c) difficulty (described above) of recognizing and identifying targets from their radar images displayed on the CRT;

(d) size, weight and power consumption that might be too large for small land vehicles;

(e) radars carried by two or more friendly land vehicles in the same general area might unavoidably jam each other by transmitting unwanted pulses into each other's antennae;

(f) radars are susceptible to unfriendly jamming;

(g) radar, mounted on a vehicle, is a very active system (paragraph 3.8.1).

8.20 Doppler Radar

8.20.1 Doppler radar is a navigation aid for aircraft. The equipment is airborne and self-contained. It sends at least three, and usually four radar beams toward the Earth's surface. The beams intersect the Earth at spots that lie fore, aft, left, and right of the aircraft position. Motions of the aircraft produce doppler shifts of frequency in the radar returns. From the doppler shifts, the aircraft equipment continuously derives the aircraft's heading velocity, cross-heading velocity (drift), and vertical velocity.

8.20.2 Doppler radar systems operate in the X and Ku bands (Table in paragraph 8.3). A typical frequency is 13.25 GHz.

8.20.3 Other typical characteristics of doppler radar are: ground speeds, 70 to 1,000 knots, with an accuracy of ± 0.2 percent; maximum drift angle, 40 degrees left or right; altitude, 50 to 50,000 ft; equipment weight, 15 kg; volume, 1 cu. ft.

8.20.4 By itself, doppler radar is neither a navigation system nor a position-location system. Doppler radar is a part, but only a part, of a dead-reckoning system. In order to perform dead-reckoning navigation, the doppler radar must be combined with a direction indicator or direction sensor, e.g. a gryrocompass.

8.20.5 Doppler radar is applicable to aircraft (including helicopter) navigation. Doppler radar is not applicable to marine vessels or to land vehicles.

8.21 Radar Beacons

8.21.1 Radar beacons are transmitters placed at known marine radar targets to identify the targets by distinctive indications on the radar scopes.

8.21.2 Racon is a radar beacon consisting of a transponder that emits a characteristic signal when triggered by a radar. The Racon signal on the radarscope provides range and bearing.

8.21.3 Ramark is a radar beacon that provides bearing information only, not range. Ramark transmits either continuously or at intervals. The purpose of transmitting at intervals is to avoid cluttering the radarscope with Ramark signals continuously.

9. NAVIGATION SATELLITES

Contents of Section 9

9.1 Introduction

9.1.1 When man constructed and launched his own satellites orbiting the Earth, he added new celestial bodies to the natural celestial bodies (stars, planets, the Moon and the Sun) that are used for position-location/navigation. Two important differences between position-location by means of natural celestial bodies and position-location by means of man-made Earth-orbiting satellites are: (1) Light is used to sense the natural celestial bodies, whereas radio is used to sense the man-made satellites. (2) Only angular positions of the natural celestial bodies are measured in traditional celestial navigation, whereas only distances (or rates of change of distances) to man-made satellites are measured; i.e., traditional celestial navigation

(9.1.1 continued)

may be considered to be a theta system, whereas position-location by man-made satellites might be considered to be a rho system (paragraph 5.1.3).

9.1.2 Systems using man-made earth-orbiting satellites have one unique and undisputed advantage over other radio position-location systems, namely: each satellite has direct line-of-sight with vehicles and ground stations over a large area of the globe. This line-of-sight is unhindered by terrain and cultural objects that obstruct some ground-based systems. Satellites can be tracked and their orbits determined so accurately that the satellites can be used as reference points for determining the positions of vehicles on the Earth.

9.1.3 Many systems have been proposed for utilizing satellites for position-location of marine vessels, aircraft and land vehicles, using radio techniques to link satellites with the vehicles. (Reference: "Useful Applications of Earth-Oriented Satellites: Panel 11, Navigation and Traffic Control"; Paul Rosenberg, Panel Chairman; 1967-1968 Summer Study on Space Applications, National Academy of Sciences, Washington, DC, 1969.) Nevertheless there is now only one operational satellite system for position-location, namely Transit (section 9.2); and there are only two satellite systems for position-location that are actively under development or test, namely Navstar-GPS (section 9.3) and ATS Ranging (section 9.4).

9.2 Transit

9.2.1 The U. S. Navy Navigation Satellite System is sometimes called NNSS or Navsat, but is more usually called Transit. It is the only U. S. operational satellite navigation system. Presumably the Soviet Union has its own classified operational satellite navigation system.

9.2.2 The Transit concept originated at the Applied Physics Laboratory of Johns Hopkins University in 1958 when a doppler effect was observed while monitoring the radio "beeps" emitted by the first Sputnik. It was found that all the orbital parameters of a passing satellite could be determined by doppler observations from a single fixed ground station. Inversely, if the satellite's orbit was known, doppler shift measurements could be used for position-location on the Earth.

9.2.3 The Transit satellites travel in nominally circular polar orbits, at altitudes of about 1075 kilometers. The orbits are spaced from each other to form a bird-cage like pattern.* There are usually five Transit satellites in orbit at one time. Four are the minimum necessary to provide world-wide coverage. The fifth satellite is for redundancy, and for allowing time to prepare and launch a replacement satellite when necessary. Each satellite circles the Earth in approximately 108 minutes, and weighs about 64 kilograms.

*Figure 9.2.3, page134.

9.2.4 Each Transit satellite transmits at very stable frequencies of 150 and 400 MHz. The signals include accurate time synchronization signals, identification signals, and exact information concerning the satellite's orbit. The orbital information is updated every 12 to 16 hours, from tracking data acquired by four fixed ground stations located in Hawaii, California, Minnesota and Maine.

9.2.5 Position-location by Transit requires that doppler measurements be made at approximately five sequential positions of a passing Transit satellite. This requires 10 to 16 minutes, during which the satellite has traveled 4,400 to 7,000 km to give a good baseline for position-location. Transit doppler measurements made aboard fast moving aircraft must be corrected for the doppler effect of the motion of the aircraft itself.

9.2.6 If a vehicle carrying Transit receiving equipment stands still, a single-frequency Transit receiver can determine a fix with an accuracy of about 90 meters, and a dual-frequency Transit receiver can give a fix accuracy of about 50 meters. If the vehicle moves during the 10 to 16 minutes required for a fix, the fix accuracy depends upon precise knowledge of the vehicle's movements during this time interval. The typical accuracy of a Transit fix of a moving marine vessel at sea is 0.1 nautical mile.

9.2.7 A position fix can be made by Transit only when one of the satellites is within radio sight. At 70 degrees of latitude, with 5 Transit satellites in orbit, a vehicle has to wait about 30 minutes between fixes. At the equator, the vehicle has to wait more than 1.5 hours between fixes.

9.2.8 Transit became operational on U. S. Polaris submarines in 1964, and was released for civilian use in 1967. Transit is used by almost all U. S. Navy submarines, many U. S. Navy ships, and an estimated several hundred commercial ships worldwide. The cost of Transit receivers varies from about $6,000 for simple models to about $100,000 for military models.

9.2.9 Advantages of Transit for use by all types of vehicles are:

(a) Coverage is world-wide.

(b) Transit equipment aboard the vehicle is passive; (par. 3.7.2).

(c) The system is non-saturable; (par. 3.7.2).

9.2.10 Disadvantages of Transit for use by military land vehicles are:

(a) The vehicle has to wait 30 minutes to 1.5 hours between fixes, depending upon latitude; (par. 9.2.7).

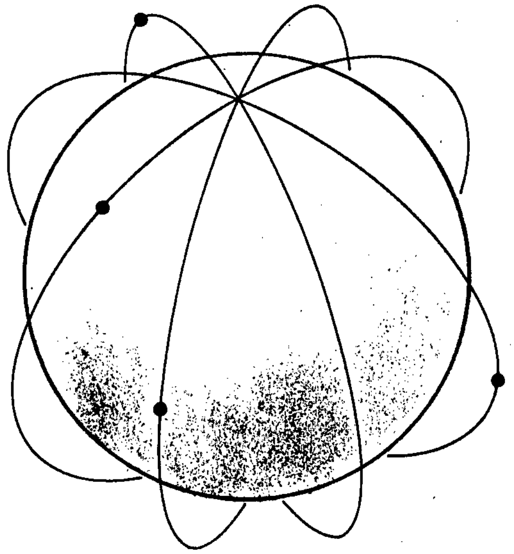
(b) Each fix (determination of a position-location) takes 10 to 16 minutes; (par. 9.2.5).

(c) If the vehicle moves during this 10 to 16 minutes, the vehicle navigator must have a means, independent of Transit, for knowing his track during the period; (par. 9.2.6).

9.2.11 The Transit Improvement Program (TIP) is a program to insert satellites with improved onboard hardware into the Transit system. The operational improved satellite is called Nova. The improvements aboard the satellite are a general-purpose mini-computer, high precision clock, orbit adjustment system and drag compensation system. Tip and Nova do not require any changes in the user equipment on the vehicle or in the vehicle's method of using Transit.

Figure 9.2.3

"Bird-cage" configuration of four Transit satellites



9.3 Navstar-GPS

9.3.1 The following names and abbreviations are currently used synonymously and interchangeably in the navigation community:

Navstar Global Positioning System
Navstar-GPS
Global Positioning System
GPS
GPS-Navstar
Navstar

For the sake of brevity, the abbreviation GPS is used herein.

9.3.2 When fully developed and deployed, GPS will consist of a constellation of 24 satellites orbiting the Earth in 12-hour circular orbits at an altitude of about 10,900 nautical miles (20,198 km). Eight satellites will orbit in each of 3 planes, at angles of inclination of 63 degrees, so that any user of the system, anywhere in the world, will have direct radio-line-of-sight with 6 to 11 satellites, at 5 or more degrees above the horizon, at all times. The user, or his automatic equipment, will select the 4 satellites that offer the best accuracy each time a fix is to be made.

9.3.3 GPS may be regarded as a type of ranging system, or as a 3-dimensional rho-rho-rho system (paragraph 5.1.3), in which the user determines his distance simultaneously from two or more GPS

(9.3.3 continued)

satellites. Each satellite transmits data that gives the time at which the satellite sends out radio signals; and the user's receiver makes measurements of the time of arrival of the signals. The elapsed time interval for the one-way transmission from satellite to receiver, multiplied by the speed of radio propagation, gives the distance (rho) from the receiver to the satellite. The satellite transmits also its orbital position data which, together with its time data, is updated daily by a master ground station in the United States, aided by passive monitor stations in U. S. territory.

9.3.4 The measured distance from a receiver to one satellite tells the receiver that it lies on the surface of a sphere, the center of which is the satellite, and the radius of which is the measured distance. A simultaneously measured distance from the receiver to a second satellite determines a second such sphere. The intersection of the two spheres is a LOP in the form of a circle in space. If the vehicle knows its elevation with respect to the geoid, e.g. if the vehicle is a marine vessel or a land vehicle, the last mentioned circular LOP is sufficient for a fix. If the vehicle is an aircraft at an uncertain altitude, simultaneous measurement from a third satellite gives a third sphere of position: and the intersection of the three spheres is a point in space, i.e. a 3-dimensional fix. For accuracy, the 3-dimensional fix will probably be used by marine and land vehicles as well as by aircraft.

9.3.5 Determining the distances between a user vehicle and each of three GPS satellites would require that the vehicle carry a prohibitively expensive clock that is highly accurate and highly synchronized with the satellites' clocks. However, this stringent requirement on the vehicle's clock is reduced to a practical level if measurements are made simultaneously with one additional satellite, i.e. with four GPS satellites. It is therefore planned to use four GPS satellites for each 3-dimensional fix.

9.3.6 GPS satellites will transmit on two L-band frequencies: 1575 MHz, called L1; and 1227 MHz, called L2. The two frequencies will permit corrections to be made for ionospheric effects on propagation times.

9.3.7 GPS modulates its signals by a pseudo-noise (PN) coding method that prevents jamming, reduces multi-path effects, and improves accuracy. Two types of PN code are planned. The P (precise) code is a long sequence that does not repeat for days, and is difficult to acquire for synchronization. The second PN code is the C/A (coarse acquisition) code that repeates every millisecond, and assists in locking into the P code. The P code will be carried on both L1 and L2 frequencies. The C/A code will be carried on L1 only.

9.3.8 Horizontal accuracies of 5 to 10 meters are predicted for the fully developed GPS, using the P code on both L1 and L2 frequencies. This prediction is supported by preliminary tests. With the C/A code alone, the accuracy may be degraded by a factor of perhaps 10 to 50 from the P accuracy. The U. S. Dept. of Defense will maintain control of the codes and their resultant fix accuracies, so that the DOD can deny P code accurate position-location information to unauthorized users in certain situations, while permitting civil users to continue to use the less accurate C/A code. It takes from tens of seconds to several minutes to make a GPS fix, depending upon the sophistication of the receiving equipment.

9.3.9 GPS is primarily a military system, being developed by the U. S. Department of Defense for the use of military vehicles of all types (air, marine, subsurface and land) and for missiles. The proponents of GPS propose GPS as a system that will eventually replace all, or almost all, navigation/position-location systems, civil as well as military. This proposal is highly controversial at the present time. Many civil navigation users object to the adoption of GPS as a universal civil system, principally because: (a) This would obsolete present user equipment that represents large capital investment. (b) GPS receiving equipment is likely to be costly. (c) In times of hostility, the GPS accuracy available to civil users would be degraded; (see paragraph 9.3.8).

(9.3.9 continued)

(d) Existing non-GPS systems are adequate for many users.

(e) Some civil users require, and now have, fix accuracies that are higher than those that GPS will give to civil users.

9.3.10 A central point in the aforesaid controversy is the eventual cost of the civil user's receiving equipment aboard his vehicle. Estimates of future cost of the civil equipment vary widely, e.g. from $1,600 to $25,000 per vehicle, depending upon the sophistication of the receiver and predictions of the quantities that will be produced and sold. Costs of military GPS receivers will probably range from $15,000 to $50,000, depending upon accuracy, ruggedness, resistance to jamming, mobility, etc.

9.3.11.1 In the 1960's, the U.S Navy began a project called Timation, and the U. S. Air Force began a project denoted as 621B. The objective of both projects was to develop a position-location/navigation system that uses ranging from Earth-orbiting satellites. In 1973, Timation and 621B were merged into a joint project, out of which GPS was born.

9.3.11.2 Figure 9.3.11 is a chart of the schedule of GPS development from 1974 to 1987. DSARC is the acronym for Defense Systems Acquisition Review Council. The DSARC II decision point on the chart was reached in June 1979, at which time DSARC approved the continuation of the GPS development program into Phase II, full scale development and system test.

9.3.12 Successful tests of GPS were performed in 1978 by SAMSO (Space and Missile Systems Organization) at the Yuma Proving Grounds. The tests included "manpack" GPS receivers mounted in a 2.5 ton Army M-35 truck, a jeep, and an armored personnel carrier. The tests also included GPS receivers aboard aircraft and helicopters.

9.3.13 Advantages of GPS for use in military land vehicles are:

(a) GPS coverage is world-wide.

(b) GPS equipment aboard the vehicle is passive. (Paragraph 3.8.2)

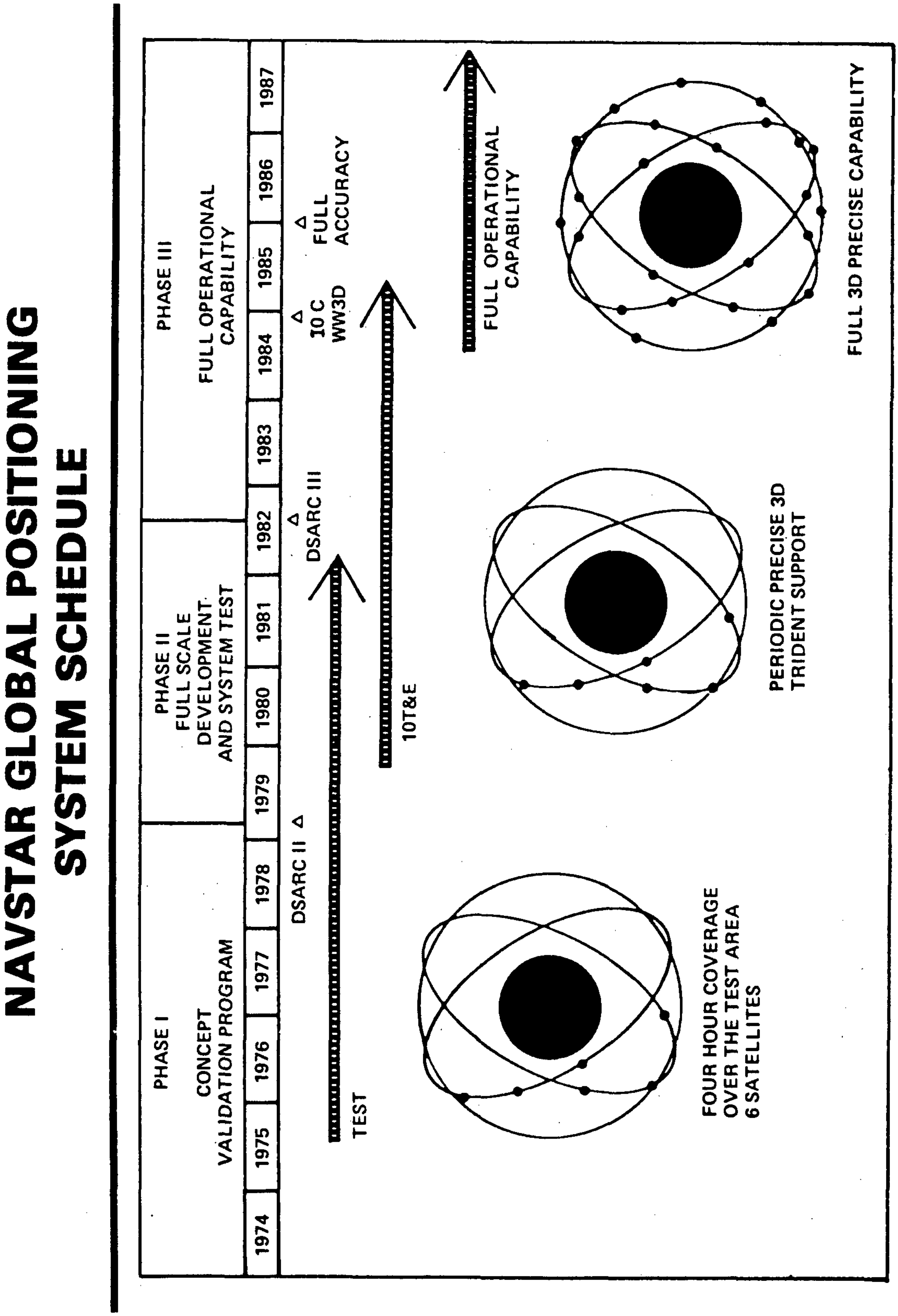
(c) GPS is non-saturable.

(d) GPS receivers can probably be made resistant to jamming.

(e) GPS fix accuracy is potentially of the order of 10 meters.

(f) GPS receivers of manpack size and weight seem feasible, depending upon accuracy desired.

Figure 9.3.11


NAVSTAR GLOBAL POSITIONING
SYSTEM SCHEDULE
PHASE I
CONCEPT
VALIDATION PROGRAM
PHASE II
FULL SCALE
DEVELOPMENT
AND SYSTEM TEST
PHASE III
FULL OPERATIONAL
CAPABILITY
1974
1975
1976
1977
1978
1979
1980
1981
1982
1983
1984
1985
1986
1987
DSARC II
DSARC III
IO C
WW3D
FULL
ACCURACY
TEST
IOT&E
FULL OPERATIONAL
CAPABILITY
FOUR HOUR COVERAGE
OVER THE TEST AREA
6 SATELLITES
PERIODIC PRECISE 3D
TRIDENT SUPPORT
FULL 3D PRECISE CAPABILITY

9.3.14 Disadvantages of GPS for use in military land vehicles are:

(a) Cost of a military GPS receiver may be high, especially if high accuracy and rapid fixes are required for the vehicle.

(b) GPS will not be fully operational until the middle or late 1980's.

(c) Reliability of GPS satellites and receiving equipment is not yet demonstrated, although it is expected to be high.

(d) GPS reception aboard land vehicles may face multi-path problems in some situations (i.e. problems arising from GPS signals reflected by topography and by man-made structures).

9.4 ATS Ranging

9.4.1 NASA (National Aeronautics and Space Administration) of the United States has a program of Application Technology Satellites (ATS) for the broad mission of flight testing advanced components and techniques for application to future communication, meteorological, earth sciences and navigation satellites. Each ATS is a geosynchronous satellite, i.e. a satellite in a circular equatorial orbit at a nominal altitude of 35,780 km. The satellite has a 24-hour period and maintains a nominally stationary position with respect to the rotating Earth. The successfully launched ATS and their respective launch dates are: ATS-1, Dec. 1966; ATS-3, Nov. 1967; ATS-5, Aug. 1969; and ATS-6, May 1974. ATS-6 has the most powerful and complex communications system of any communications satellite to date.

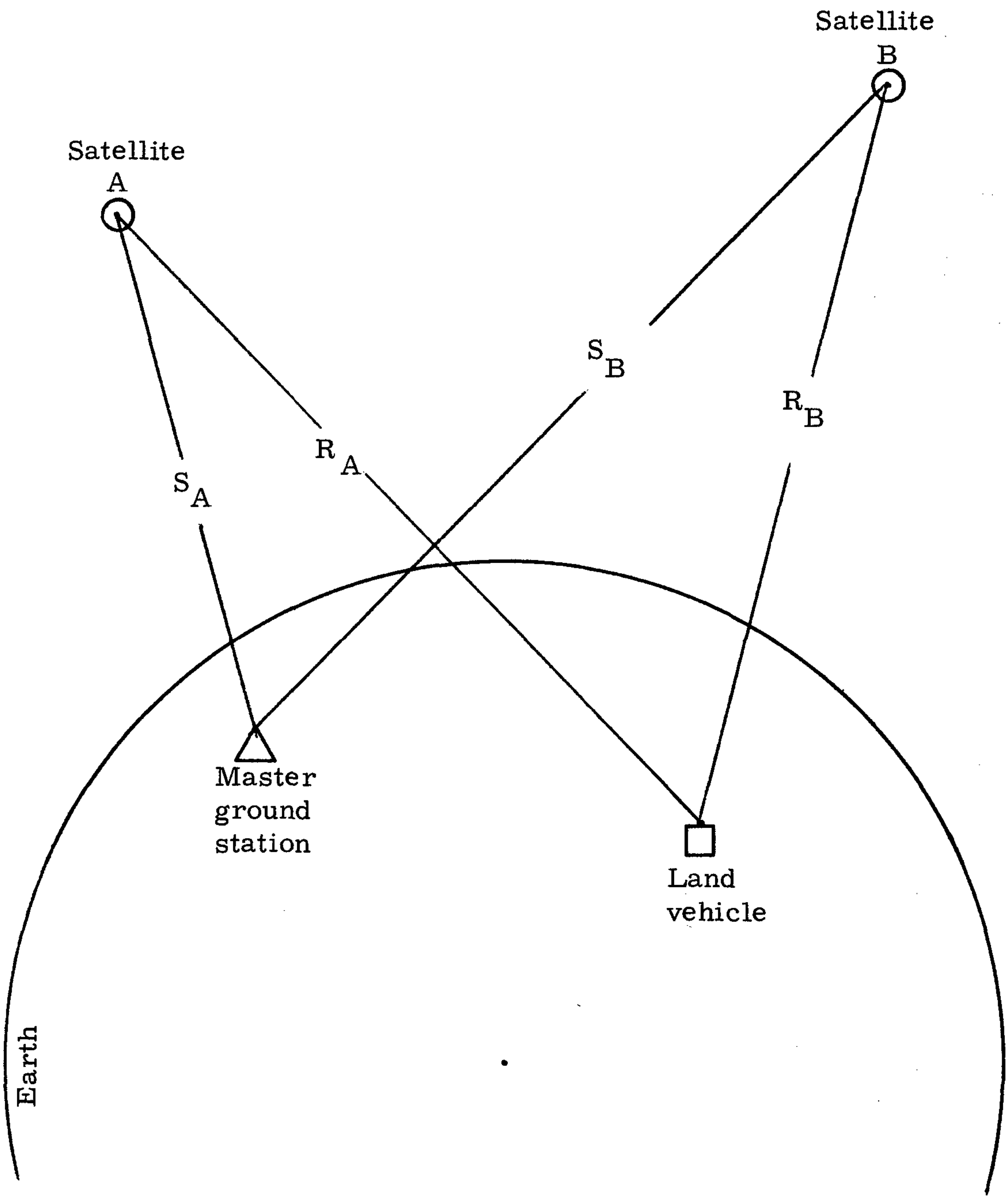
9.4.2 One of the uses of ATS since 1968 has been to test certain proposed methods for position-location of vehicles, including land vehicles, by ranging with satellites. These methods are called ATS ranging herein. They are rho methods, (paragraph 5.1.3). As discussed in paragraph 9.3.4, simultaneous range measurements from only two satellites of known position can determine a fix of a land vehicle, the elevation of which is known.

9.4.3.1 A typical ATS ranging method of position-location may be summarized as follows, referring to Figure 9.4.3. A master ground station automatically sends a coded VHF radio signal to a vehicle via a transponder in satellite A. Another transponder in the vehicle then automatically returns a coded VHF signal to the master ground station via a transponder in the same satellite. The sum of the distances $S_A + R_A$ is calculated at the master ground station from the measured elapsed time for this round trip of the signals, taking into account the known fixed delays in the transponders, and using the speed of propagation of the radio signals corrected for propagation delays in the ionosphere. S_A is determined by round-trip ranging between the ground station and the satellite. This gives R_A.

9.4.3.2 Almost simultaneously, a similar round-trip is taken by VHF signals between the master ground station and another satellite B, resulting in the value of R_B. The master ground station then uses R_A, R_B, and the known positions of satellites A and B, to calculate a fix for the land vehicle. The coordinates of this fix are finally transmitted to the vehicle automatically via one of the satellites. The positions of the satellites are determined periodically by ranging from transponders at other ground stations of known location.

Figure 9.4.3

ATS Ranging



9.4.4 The ATS ranging concept has been tested successfully in several experiments, e.g.: the ATS-6/ATS-5 Position Location and Communication Experiment (PLACE) of NASA and MARAD in 1973-1975; and a demonstration test of ATS-ranging applied to a land vehicle in 1976. In this last mentioned test, real-time position-location accuracies on the order of one quarter mile were demonstrated in a moving station wagon across continental United States, using ATS-1 and ATS-3. Post-experiment data processing showed fix accuracies of several hundred feet under most circumstances. At the present writing, further land vehicle tests are being conducted, under NASA sponsorship, with the L-band transponder of ATS-6.

9.4.5 The ATS ranging type of system for position-location has potential for application to civil land vehicles. However, for application to military land vehicles, this type of system has these disadvantages:

(a) The system can be jammed.

(b) The system is probably susceptible to meaconing. (Paragraph 3.6)

(c) The system is active. (Paragraph 3.8.1)

(d) The system is saturable. (Paragraph 3.7.1)

10. INERTIAL NAVIGATION

Contents of Section 10

10.1 Definition, Description, Discussion, History

10.1.1 Inertial navigation is the measurement of a vehicle's position relative to an assumed or known initial position, and the measurement of the vehicle's velocity vector relative to an assumed or known initial velocity vector, by means of on-board inertial sensors that continuously measure the vehicle's acceleration vectors. Inertial navigation is a form of dead-reckoning. ("Inertial navigation" and "inertial navigation system" are abbreviated as IN and INS respectively.)

10.1.2 Inertial navigation relies upon Newton's laws of motion and the fundamental property of inertia that resists changes in linear and angular momentum; hence the name inertial navigation. Changes in linear momentum are accompanied by forces that are sensed and

(10.1.2 continued)

measured by instruments called accelerometers. Changes in angular momentum are accompanied by torques that are sensed and measured with the aid of gyroscopes.

10.1.3 The concept of an accelerometer is diagrammed in Figure 10.1.3, in which a mass M rides with negligible friction on a guide rod B which is fastened rigidly to a vehicle. The axis of the rod is here assumed to be perpendicular to the direction of gravity. The mass M is constrained by two equal springs S1 and S2, the outer ends of which are fastened to the guide rod. When the rod (and the vehicle) are at rest or are moving with constant velocity, the mass M remains at the mid-point of the rod as shown in Figure 10.1.3 (a), with the two springs exerting equal and opposite forces on the mass. When the rod is subjected to an acceleration A to the right, the mass M is displaced toward the left end of the rod as shown in Figure 10.1.3 (b), until the net sum of the forces exerted by the two springs upon the mass is equal to the inertial force MA of the accelerated mass. In other words, $F = MA$ which is an expression of Newton's second law of motion. The displacement of the mass is a measure of the force F, from which the acceleration is calculated as $A = F/M$. If the rod (and vehicle) are accelerated to the left, the mass M is displaced to the right and the acceleration is calculated from the displacement as before.

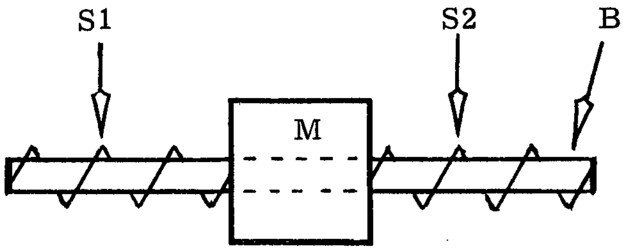


Figure 10.1.3 (a)

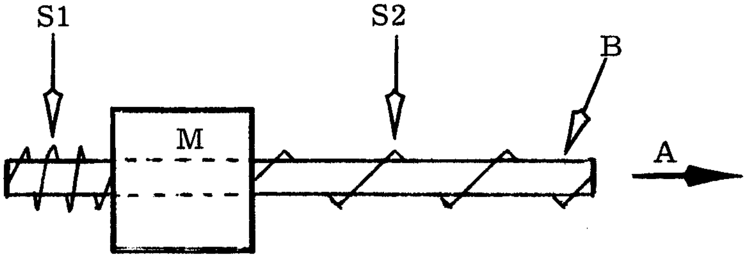


Figure 10.1.3 (b)

10.1.4 If the acceleration A is continuously measured and recorded as a function of time beginning with time T_o when the velocity was V_o, then the velocity at any time T is obtained by the integration:

$$V = V_o + \int_{T_o}^{T} A \, dt$$

(10.1.4 continued)

and the distance S, traversed in the time $T - T_o$, is obtained by a double integration:

$$S = S_o + \int_{T_o}^{T}\int A \, dt \, dt$$

10.1.5 Now assume that the vehicle carries three such accelerometers that are always oriented respectively along three mutually orthogonal directions that are East-West, North-South, and vertical. The integrations in paragraph 10.1.4 can then be combined vectorially to give the position and velocity of the vehicle in three dimensions, regardless of changes in speed and direction experienced by the vehicle.

10.1.6 Inertial navigation makes severe demands on the accuracy, sensitivity and stability of accelerometers. Examples of these demands (not all of which are necessarily imposed on one type of accelerometer) are: acceleration range, $\pm$ 40 g; threshold sensitivity, .0005 g; linearity, .01 percent. Consequently the accelerometers actually used in inertial navigation systems are far more sophisticated in design and construction than the conceptual accelerometer described in paragraph 10.1.3 and Figures 10.1.3(a), 10.1.3(b). Examples of actual types

(10.1.6 continued)

of accelerometers are: a pendulum suspended on a flexural hinge, restored automatically to its null position by an electromagnet that is controlled by a sensitive position pick-up and a servo-amplifier; a pendulum floated in a liquid, jewel-pivoted about an axis through the pendulum's center of buoyancy, electromagnetically restrained to the null position; a vibrating string, the frequency of which is a function of tension which is designed to vary with acceleration; a vibrating beam, the frequency of which depends upon compression which is made to vary with acceleration; the "pendulous integrating gyro accelerometer" which is a single-axis stabilized platform with an intentionally unbalanced gyro, the precession torque of which serves as the restoring force to null the accelerometer.

10.1.7 In paragraph 10.1.3 it was postulated that the axis of the accelerometer rod B was perpendicular to the direction of gravity. If the axis of the rod is not perpendicular to the gravity vector, a component of the force of gravity will act in the direction of the axis of the rod to produce a displacement of the mass M in addition to the displacement caused by inertia and the acceleration of the vehicle. Accelerometers can not distinguish between gravitational force and inertial force, because gravitational and inertial forces are physically equivalent.

10.1.8 A consequence of paragraph 10.1.7 is that the three accelerometers, postulated in paragraph 10.1.5, should be stabilized so that the East-West and North-South accelerometers remain in a horizontal plane regardless of the vehicle's pitch and roll. Furthermore, the accelerometers should be stabilized to maintain their E-W and N-S directions regardless of the vehicle's heading. This stabilization can be effected by mounting the accelerometers on a stable platform held in a set of gimbals. The orientation of the platform is controlled by sensing gyros (see paragraphs, 10.1.10 and 10.1.11), servo loops and torque motors. However, simple gyro stabilization would stabilize the platform in inertial space (with respect to the fixed stars); whereas the platform must be stabilized with respect to the local vertical (i.e. with respect to the direction of the local force of gravity). The problem is that the local vertical moves with respect to the fixed stars because the Earth rotates on its axis and the vehicle rotates with the Earth.

10.1.9 The problem of determining the local vertical in a moving vehicle was solved by the principle of the Schuler pendulum; (Maxmilian Schuler, Journal of Physics, Vol. XXIV, July 1923, Kiel, Germany). This is a theoretical pendulum with a period of oscillation

$$P = 2\pi \sqrt{R/g}$$

(10.1.9 continued)

where R is the distance from the center of the Earth to the pivot of the pendulum, and g is the acceleration of gravity. At the surface of the Earth, the period of the pendulum is 84.4 minutes; hence it is often called the 84 minute pendulum. It has the property that it remains vertical under all accelerations of the vehicle on the Earth's surface. A simple pendulum with this period can not be built because it would have its "bob" at the center of the Earth and the support for the "string" at the surface of the Earth. It is also impractical to build a compound pendulum with distributed mass, with an 84 minute period, because, for example: if the radius of gyration is one inch, the distance between the pivot and the center of mass would have to be 4×10^{-9} inch. However, a gyro-stabilized servo-controlled accelerometer platform can be "tuned" to an 84-minute period; and such a Schuler pendulum is invaluable in this type of inertial navigation system.

10.1.10 A gyro (more properly called a gyroscope) is a spinning body. In simple form, a gyro is a well-balanced wheel spinning around its axis of symmetry. The angular momentum $\overline{H}$ of a gyro is a vector quantity, the direction of which is the direction of the axis of rotation. The magnitude of the vector $\overline{H}$ is the product of the rate of spin S and the moment of inertia I of the gyro. A torque (a couple)

(10. 1. 10 continued)

applied around the spin axis will change the magnitude of S, but will not change the direction of $\overline{H}$. A torque $\overline{T}$ applied to the gyro around an axis other than the spin axis changes the direction of the spin axis, and changes the angular momentum of the gyro to the vector cross-product $\overline{H}x\overline{T}$. This change is called precession of the gyro.

10. 1. 11 In accordance with the laws of motion, the angular momentum vector $\overline{H}$ maintains a constant direction in space (with respect to the fixed stars) unless acted upon by an external torque around an axis other than the spin axis of the gyro. This inertial property of a gyro enables it to provide a fixed direction in space, independent of the motions of a vehicle and independent of the rotation of the Earth, provided no torque is applied around any axis other than the spin axis. This proviso is difficult to meet in actual practice. In order to reduce or eliminate unwanted torques, some gyro rotors are supported in liquids, other gyros are suspended on gas bearings, and other gyros (electrostatic gyros) are suspended by electric fields in vacuum. Magnetic suspension, in vacuum, has been used also. In some cases of magnetic suspension, gyro rotors have been cooled down to extremely low superconducting temperatures so that an external applied magnetic field suspends the rotor by inducing in it a counter-electromagnetic field.

10.1.12 Despite the best efforts of gyro designers, unwanted torques arise, for example, from: asymmetric friction in the rotor suspensions; mass shifts in the rotor itself; ambient magnetic fields; asymmetry in the electromagnetic forces of the motor that drives the rotor; thermal convection currents in the liquid that suspends a rotor. The result is that even the best gyros will precess (see 10.1.10). In inertial navigation, this unwanted precession is called drift. The drift rates of gyros vary greatly with their design and complexity; for example from 15 degrees of arc per hour for small gyros, to less than .001 degree per hour random drift for high-performance gyros.

10.1.13.1 Paragraphs 10.1.5 through 10.1.12 have discussed stable-platform or gimballed inertial navigation (IN) systems. Another class of IN systems are strapdown systems, in which the accelerometers are rigidly fastened (strapped down) to the vehicle so that they pitch, roll and turn with the vehicle. The vehicle accelerations are therefore sensed and measured with respect to the vehicle axes. Gyros simultaneously measure the orientation of the vehicle axes with respect to inertial space. A dedicated digital computer performs the rather complicated coordinate system transformations and integrations to perform the dead reckoning that is inherent in all inertial navigation.

10.1.13.2 Strapdown IN systems do not contain the stable platforms (including the gimbals, gyro-gimbals-sensors, servos and associated electronic circuits) that complicate and raise the cost of gimballed IN systems. On the other hand, the strapdown systems require computers and computer programs that are not needed by gimballed systems. However, as computers become smaller, more reliable and less costly, the strapdown systems become more reliable and less costly than the gimballed systems. Consequently strapdown systems are replacing gimballed systems in many applications; and this trend is likely to accelerate in the future.

10.1.14 Historical Notes.

10.1.14.1 Inertial navigation had its origins in attempts to use a spinning top to provide an artificial horizon for a sextant (Mr. Serson, England, 1743) (Admiral Fleuriais, France, 1885) and in the classic work of Foucault who, in 1851 in France, demonstrated the rotation of the Earth inertially by his well-known Foucault pendulum. A gyro device for steering a torpedo was patented by Obry, an Austrian engineer in 1898. The most prominent names and dates in the development of the gyrocompass are Max Schuler (1908) and Elmer Sperry (1911). See also paragraph 10.1.9 regarding Schuler's pendulum. Sperry built the first gyroscopic automatic pilot for aircraft in 1909. The first gyroscopic automatic pilot for ships was built in Kiel, Germany

(10.1.14.1 continued)

for a Danish passenger ship in 1916. The navigation system in the V-2 rocket, developed by the Peenemunde group in Germany in World War II and first flown in 1942, can be said to be the first operating inertial system. In the U.S.A., intensive development of inertial navigation systems began after World War II, seeded by an Army-sponsored group that was part of the Peenemunde group under Werner von Braun. This group developed successful inertial guidance systems for such missiles as the Redstone, Jupiter, and Pershing.

10.1.14.2 The M.I.T. Instrumentation Laboratory, now called the Charles Stark Draper Laboratory after its eminent leader, has been the main spearhead in the U.S.A. in the modern development of inertial navigation systems and components for ships, aircraft, missiles and spacecraft. A number of large industrial firms in the U.S.A., with high technical capabilities, have been actively engaged in the development of inertial systems and components. Noteworthy U.S.A. inertial systems have been developed in: Snark and Navaho cruise missiles; Nautilus nuclear submarine, in an under-the-ice crossing of the North Pole; SINS (Ship's Inertial Navigation System) for the Minuteman ICBM (Intercontinental Ballistic Missile) and for Polaris submarines; Thor, Atlas, Titan and Poseiden missiles; and the Apollo manned lunar space vehicles.

10.1.15 Inertial navigation systems (INS) are now carried by almost all U. S. Navy submarines, by some Navy ships, and by an estimated 4,000 U. S. military aircraft. Many commercial air carriers use INS as the primary navigation aid for transcontinental and oceanic routes. For reliability by redundancy, some of these aircraft carry three INS. The commercial airlines are experimenting with a combined Omega-INS to replace the three-INS installations. Some business aircraft also carry INS.

10.1.16 The cost of a typical INS for military aircraft and commercial airliners is about $100,000. This cost may go down to about $50,000. These systems usually have a drift error of about one nautical mile per hour of flight. Aircraft carriers and submarines use INS that cost as much as $1,000,000 per system, with an accuracy much better than one nautical mile per hour. (See also paragraph 10.3.8.) One manufacturer projects a system cost of only $20,000 in the near future, with unspecified accuracy.

10.2 Land Vehicle INS

10.2.1 In the early 1960's, the U. S. Department of the Army began studies of a vehicular mounted inertial navigation system (INS) that used a gimballed gyro-stabilized platform and an on-board general purpose digital computer. These studies showed that such a system was a feasible technical approach to the survey problems of field artillery. Accordingly, in 1965 the U. S. Army Engineer Topographic Laboratories (USAETL), Fort Belvoir, VA began development of an inertial system entitled "Position and Azimuth Determining System", or "PADS". The basic system components of PADS were adapted from AN/ASN-92, the Carrier Aircraft Inertial Navigation System (CAIRNS).

10.2.2 PADS, designated AN/USQ-70( ) can be mounted in jeeps (e.g. CH-47), in light observation helicopters (LOH) (e.g. OH-58A), and in a 1/4 ton truck (e.g. M151, M151A1, M151A2). One intended use of PADS is for artillery survey parties to extend survey control to artillery elements in the field army areas of operation and influence. PADS is now a U. S. Army type classified standard; and 99 (ninety-nine) units are scheduled for production in the next 3 (three) years.

10.2.3 As in all inertial navigation systems, the initial coordinates of the vehicle, including altitude, must be set into the system at the beginning of the mission. Initial azimuthal information (bearing) can be inserted into the system by an external theodolite and porro prism, or the gyrocompass in the system can determine true North by self-alignment if it is given about one hour of warm-up time. PADS then continuously calculates position, elevation and azimuth in any one of seven earth-spheroid reference systems, and displays these parameters upon command.

10.2.4 All inertial navigation systems suffer from drift (paragraph 10.1.12), the errors of which are cumulative with time. PADS is no exception. Every 10 (ten) minutes or so, the PADS vehicle (jeep, truck or helicopter) must come to a complete stop, with respect to the ground, for about 20 (twenty) seconds during which the vehicle's zero velocity is used to correct the inertial system's drift. This repeated calibration procedure is called Zero Velocity Update or "ZUPT".

10.2.5 Various field tests of PADS have yielded various accuracy results as follows:

Horizontal position:	10.4 to 12.1 meters, circular probable error.
Vertical position:	5.9 to 9.7 meters, root mean square error.
Azimuth direction:	0.22 to 0.32 mil, root mean square error.

10.2.6 USAETL is developing a more accurate inertial navigation system for land vehicles, called the Rapid Geodetic Survey System (RGSS). Elevation accuracies of RGSS are said to be 5 cm; and latitude and longitude accuracies are said to be 30 cm.

10.2.7 In discussing PADS, USAETL states (in Tech Tran, Spring 1979, Vol. 4, No. 1) that "the expected cost of this system may prevent its being purchased in numbers sufficient for deployment to the lowest echelons". ETL is evaluating an auxiliary system to be used in conjunction with PADS at a cost of one-tenth of the cost of PADS.

10.2.8 One commercial company, serving the surveying industry, operates a land vehicle equipped with a PADS-type inertial system. This system is reported to obtain surveying accuracies of 1:10,000 ± 10 cm (one sigma) relative to the nearest control point.

10.2.9 At least three government agencies, in addition to USAETL, are using inertial navigation systems in land vehicles for surveying, mapping and similar purposes. All of these systems are essentially the same as USAETL's PADS or RGSS, with minor changes in software and operational procedures. These agencies, with the name and acronym that each agency applies to its own system, are: U. S. Defense Mapping Agency, Inertial Positioning System, (IPS); U. S. Bureau of Land Management, Auto Surveyor; Canadian Department of Energy, Mines & Resources, Inertial Survey System (ISS).

10.2.10 The FNA 4-15 is a navigation system developed in Heidelberg, West Germany, for military land vehicles. The system is not completely inertial. The only inertial parts of the FNA 41-15 are a directional gyro that senses changes in heading of the vehicle, and a north-seeking gyro that is used periodically to calibrate and correct the directional gyro. The vehicle must come to a stop for this calibration and correction. There are no accelerometers in the system. An electrical odometer, connected to the vehicle's driving mechanism, measures distance traversed. This distance data is continuously integrated with data from the directional gyro to derive position coordinates by dead reckoning. The FNA 41-15 has been used in West Germany's Army GEPARD 420 AA tank, and in vehicles in Belgium, Holland, England and Canada. Soviet combat units are said to use large numbers of similar navigation systems.

10.3 Laser Gyro

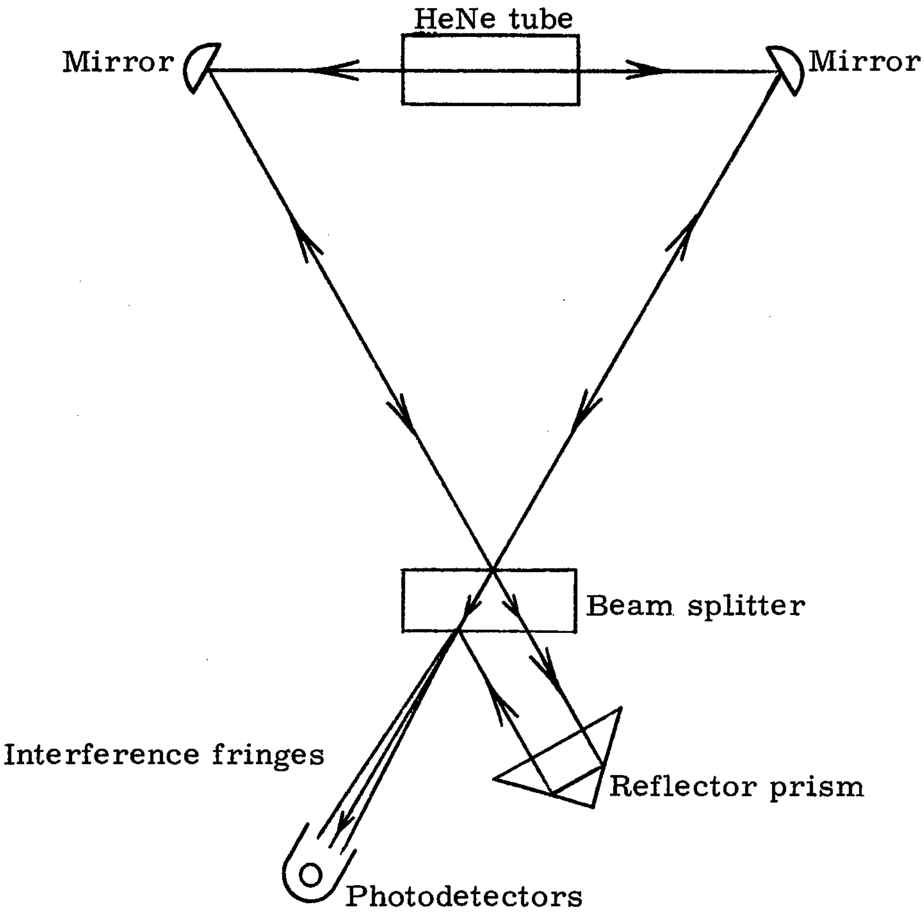
10.3.1 The laser gyro, often called the ring laser gyro (RLG), is not a gyro or gyroscope, strictly speaking, because the RLG has no mechanically rotating part and does not utilize or sense rotational inertia. The RLG is a "gyro" only in the sense that the RLG serves the same end purpose as a mechanical gyroscope in a strapdown inertial navigation system, namely the purpose of sensing rotation of the vehicle.

10.3.2 The operating principle of a laser gyro is diagrammed in Figure 10.3.2. The HeNe gas discharge tube (laser tube) sends two coherent beams of light continuously in opposite directions around the same closed triangular optical path. The beams are monochromatic because dielectric coatings on the mirrors reflect only a very narrow band of frequencies corresponding to the particular HeNe transition that is used. A small fraction of the light from each beam is allowed to pass through the output mirror to form a set of interference fringes.

10.3.3 As long as the RLG (and the vehicle to which the RLG is fastened) do not rotate, the aforesaid fringes are stationery. When the RLG rotates, the net optical path around the triangle lengthens in the direction of rotation, and shortens in the opposite

Figure 10.3.2

Laser Gyro



(10.3.3 continued)

direction. This moves the fringe pattern at a rate that is proportional to the angular speed of rotation of the RLG and its vehicle. The fringe pattern movements are detected and measured automatically by a photodetector, the output of which is fed into the strapdown inertial navigation computer.

10.3.4 The RLG is usually built out of a monolithic block of ceramic material with a low temperature coefficient of expansion, typically Cervit. Construction, assembly and alignment are costly.

10.3.5 A major source of trouble in RLGs is frequency lock-in that results in no shift, or insufficient shift, of the interference pattern at low rotation rates. Methods for minimizing or eliminating lock-in include mechanical dithering and the use of magneto-optical effects, e.g. the Faraday effect. Another method for eliminating lock-in and frequency bias drift is to employ, in effect, two laser gyros in the same triangular cavity path, the two beams of one gyro being right circularly polarized, and the two beams of the other gyro being left circularly polarized. This device is called a Differential Laser Gyro or DILAG.

10.3.6 The sensitivity of the RLG is directly proportional to the area of the ring, and inversely proportional to the perimeter of the ring. Early RLGs were square. Modern RLGs are in the shape of an equilateral triangle. Another development uses a long interferometer path through multiple turns of a fiber-optical guide coiled in a circle.

10.3.7 Random drift rates of good laser gyros are less than 0.01 degree of arc per hour. This is adequate for many strapdown inertial navigation systems, and is as good as many mechanical gyros; but not as good as very high performance mechanical gyros that have random drift rates less than 0.001 degrees per hour.

10.3.8 The proponents of RLG predict that the use of RLG will lead to lower costs for future strapdown inertial navigation systems.

10.4 Advantages, Disadvantages

10.4.1 The advantages of inertial navigation systems (INS) for application to military land vehicles are:

(a) INS is completely self-contained.

(b) INS operates anywhere in the world, independently of environment (e.g. meteorological conditions and terrain).

(c) INS is passive (paragraph 3.8.2).

(d) INS is immune to jamming.

(e) INS is immune to meaconing (paragraph 3.6).

(f) INS is a non-saturable system (paragraph 3.7.2).

(g) Relatively little skill is needed to operate INS.

10.4.2 The disadvantages of INS for application to military land vehicles are:

(a) The present cost of available INS equipment is higher than the present cost of any other type of on-board navigation/position-location equipment. (Paragraphs 10.1.16, 10.3.8.)

(b) The land vehicle must stop periodically to calibrate and correct the INS, if reasonable accuracy of position-location is to be maintained. (Paragraphs 10.2.4, 10.2.10.)

(c) INS position-location errors diverge with elapsed time of travel.

(10.4.2 continued)

(d) As in other dead-reckoning systems, INS position accuracy is no more accurate than the accuracy of the initial position-location.

(e) Maintenance and repair costs are high. Skilled maintenance and repair personnel are required.

11. MISCELLANEOUS

Contents of Section 11

11.1 PLRS

11.1.1 PLRS (Position Location Reporting System) is a communications navigation and identification (CNI) battlefield system, planned by the U. S. Army and Marine Corps for use in land combat areas. Receipt of the system is scheduled for the early 1980's.

11.1.2 PLRS is a rho system (paragraphs 5.1.3, 5.1.4). Each PLRS consists of a ground-based master control unit and up to 370 user units to be carried by vehicles and by individual manpacks. In order to learn his position, a user turns on his PLRS which

(11.1.2 continued)

automatically transmits radio bursts of data several times a minute. The transmissions are received by the master unit and by all user units within range. These user units measure the times of arrival of the bursts, and relay this time information to the master unit.

11.1.3 The time intervals between the transmissions and receptions of the bursts are converted to distances. The master unit then uses multilateration to calculate the relative positions of the user units with respect to each other and to the master unit. Multilateration, also called trilateration, is a rho method for determining the relative positions of three or more points, by measuring the distances between the points. The master unit sends all the position information to all the users, and displays all the positions on a large plot board for the information of the commander in the control station.

11.1.4 The frequency band of PLRS is 420 to 450 MHz. PLRS is a line-of-sight system that can cover a diameter of about 50 miles for ground units, and about 250 miles for aircraft. Accuracy is expected to be within 15 meters for moving troops, 5 meters for stationary units, and 25 meters for helicopters in flight; although preliminary tests did not give these high accuracies.

11.1.5 A manpack user unit of PLRS weighs 17 pounds, and can be carried by an infantryman or adapted for mounting in ground vehicles. Hundred of users can be tracked simultaneously by the master unit.

11.2 RMS/SCORE

11.2.1 RMS/SCORE is an acronym for Range Measurement System/Simulated Combat Operations Range Equipment. It is a U. S. system for position-location and data communications for use in field training the armed forces and for operational testing and evaluation of military tactics and weapons. The DOD has deployed the system in seven or more series of tests since 1972.

11.2.2 A number of stationary radio stations, called A stations, at known positions in the field of operations, interrogate portable transponders, called B stations, carried by participants (e.g. infantrymen, land vehicles, aircraft). The time intervals for round trips of the signals between the A and B stations are communicated by radio to a central station. At the central station, the time intervals are converted to ranges and the positions of the B stations are calculated by multilateration and displayed in practically real time. The same radio network provides communication between stations and participants.

11.2.3 Each B station transponder weighs 1.3 kilograms, and is about 4 x 12 x 21 cm in size. Operating frequency is 918 MHz. Operation is line-of-sight. Area coverage is a diameter of about 200 km. Accuracy is said to be ± 3 meters. The system can be expanded to handle up to 1,000 transponders.

11.3 JTIDS

11.3.1 JTIDS (Joint Tactical Information Distribution System, is an integrated communications, position-location and identification system for U. S. military air, marine and land vehicles. JTIDS is designed to give tactical forces a system for cryptographically-secure communications and identification, and position-location, with low detectability and with resistance to jamming. JTIDS resulted from the merger of a U. S. Air Force program called Seek Bus and the U. S. Navy's ITNS (Integrated Tactical Navigation System).

11.3.2 The JTIDS radio communications network operates in the frequency band of 960 to 1215 MHz. The participants in the network are vehicle users, and terminals. One of the terminals is a command-and-control terminal. The terminals are not necessarily at fixed ground stations. The terminals can be on moving ships, aircraft carriers,

(11.3.2 continued)

aircraft, and land vehicles. The users likewise can be marine, air or land vehicles. The JTIDS equipments of all participants operate on a common time base, using stable oscillator clocks that are periodically corrected and synchronized by communication throughout the net.

11.3.3 Participants in the JTIDS net can measure the distances between each other by measuring the transmission times between each other, using the common network time base. This can be done either by two-way (round trip) ranging using a transponder in one unit, or it can be one-way ranging from a terminal to a user vehicle. In the latter case, the vehicle remains passive and secure. In either case, position-location by JTIDS is a rho system; (paragraph 5.1.4).

11.3.4 If the absolute positions of the terminals are known accurately, (e.g. in latitude and longitude), then the user vehicle can determine his own absolute position. If the absolute positions of the terminals are not known accurately enough, then the user determines his position only relative to the terminals and hence relative to all other participants in the JTIDS network. This is called Relnar (relative navigation).

11.3.5 In general, JTIDS broadcasts a large amount of its position and identification data routinely without knowing which participants in the net will extract which information from the continuously broadcast data base. Some data or messages are inserted into the data base for general dissemination; other data and messages may be coded and addressed to one or more discrete participants. Data processing is digital.

11.4 Maps/Charts

11.4.1 A map is a graphic representation of the Earth's surface or a part thereof, displaying the positions and sizes of features and objects relevant to the purpose of the map. Planimetric maps show horizontal positions only. Topographic maps show vertical as well as horizontal positions. There are many kinds of maps, serving different purposes or themes. For example, there are thematic maps for agriculture, city planning, demography, forestry, geology, highway planning, irrigation, and mining. No one map serves all purposes.

11.4.2 A chart is a map intended primarily for the purpose of navigation. There are many kinds of charts, for example: marine charts; aeronautical charts; magnetic charts; charts designed for

(11.4.2 continued)

use with a particular position-location or navigation system, e.g. Loran charts (paragraph 6.3.5), Omega charts, Decca charts, Consol charts, radar charts. Strictly speaking, an automobile road map is a chart. Charts (and maps) are issued in a wide range of scales; for example, nautical charts are issued in scales from 1:2,500 to 1:14,000,000 (and even smaller scales for some world charts).

11.4.3 A variety of projections are used to represent the curved surface of the Earth on a flat chart or map. The most common types of projections and grids are: plane projections, e.g. the Universal Polar Stereographic (UPS) grid; cylindrical projections, e.g. the Universal Transverse Mercator (UTM) grid, and the oblique Mercator grid; cone projections, e.g. the Lambert grid; the Military Grid Reference System (MGRS); and the World Geographic Reference System (GEOREF).

11.4.4 There is no single set of accuracy standards that cover the many kinds of maps and charts, their many scales, and their many projections, (paragraphs 11.4.1 - 11.4.3) in addition to the fact that maps and charts are issued by many governments and non-government publishers throughout the world. Indeed, indication of a chart's accuracy is rarely stated on a chart, with the exception that some maps issued by some U. S. Government agencies carry the legend "This map complies with the National Map Accuracy Standards"; (paragraph 11.4.5).

11.4.5 The "United States National Map Accuracy Standards", issued by the Bureau of the Budget in 1941, and revised in 1947, are still in effect. Regarding horizontal accuracy, these Standards state: "For maps on publication scales larger than 1:20,000, not more than 10 percent of the points tested shall be in error by more than 1/30 inch, measured on the publication scale; for maps on publication scales of 1:20,000 or smaller, 1/50 inch. These limits of accuracy shall apply in all cases to positions of well defined points only". The Standards state also: "Vertical accuracy, as applied to contour maps on all publication scales, shall be such that not more than 10 percent of the elevations tested shall be in error more than one-half the contour interval".

11.4.6 The National Map Accuracy Standards are not necessarily applied to charts commonly used for position-location/navigation. In the United States, there is no requirement, other than that imposed by an individual producing agency, that charts meet these Standards. In any case, there are unavoidable limitations on the accuracy of any practical chart or map, namely: distortion of the paper or plastic on which the chart/map is printed, due to changes in temperature and humidity; thickness of lines on the chart/map; difficulty of interpolating between grid lines because the projection distorts distances and/or directions on the chart/map.

11.4.7 Accurate mapping and charting must take account of the shape of the Earth. A first approximation to this shape is a sphere; but since the Earth is not a perfect sphere, it is called a "spheroid" which is an inexact term meaning a surface that is close to a sphere, but not a perfect sphere. The Earth is also called an "oblate spheroid" which is another non-quantified term meaning a sphere that is flattened at the poles and bulged at the equator. Obviously none of the aforementioned terms accurately describes the shape of the Earth. The shape that is most significant for geodetic, mapping and charting purposes is the geoid.

11.4.8 The geoid is the imaginary surface representing the mean sea-level of the undisturbed oceans of the world, extended through the continents, such that the geoid surface is perpendicular to the gravity vector (perpendicular to the plumb line) at every point on the geoid. The geoid is therefore a gravitational equipotential surface. This is what is usually meant by the shape of the Earth.

11.4.9 The geoid is an irregular undulating surface that tends to dip over ocean depths and to rise under high land masses. There is no completely accurate mathematical expression for the geoid. Instead, it is approximated by an ellipsoid of revolution, generated by rotating an ellipse about its minor axis. The minor axis of the ellipsoid coincides with the polar axis of the Earth.

11.4.10 More than a dozen different ellipsoids have been promulgated and used at different times for different geodetic, astronomical and mapping purposes. One of the oldest and most frequently mentioned is the Clarke spheroid of 1866. A recent one is the 1972 World Geodetic System (WGS) ellipsoid. The Fischer ellipsoids of 1960 (Mercury Datum) and 1968 are used for calculating satellite orbits.

11.4.11 In the 14 (fourteen) best known ellipsoids, the values of the respective equatorial radii all fall within .017 percent of each other; and the values of the respective polar radii all fall within .013 percent of each other. These differences are insignificant for many position-location/navigation systems; for example, in practical celestial navigation. Nevertheless, the differences between the various ellipsoids can be significant for purposes of astronomy, satellite orbit calculations, long range ballistic missile trajectories, and world cartography and mapping.

11.5 Subsurface Navigation

11.5.1 When a submersible vessel (submarine) is on the surface, the submersible can use the same position-location/navigation systems that are available to surface marine vessels, e.g.: celestial navigation, rho-theta systems, hyperbolic systems, radar, and navigation satellites. When a submarine is submerged and it is permissible to raise a periscope above the surface, celestial navigation can be practised with a periscope sextant (paragraphs 4.13, 4.14). Submerged submarines sometimes use Loran-C (section 6.3) by trailing a long buoyant wire as an antenna or by towing an antenna mounted on a buoy. The last mentioned type of antenna can be used for other radio position-location systems and for some satellite position-location systems, although this is awkward.

11.5.2 All of the position-location/navigation systems mentioned in paragraph 11.5.1 are denied to a completely submerged submarine in tactical situations in which no periscope or antenna is permitted above the surface. In such cases, inertial navigation (section 10) is the best solution to the problem of position-location. See paragraphs 10.1.14.2 and 10.1.15. It may be noted that even a INS as sophisticated as SINS experiences drift, and the inertial dead reckoning must be corrected periodically by an independent fix.

11.5.3 Less sophisticated dead reckoning instruments, relied upon by completely submerged submarines before the advent of INS, are: magnetic compass; gyrocompass; pitot-static log; electro-magnetic log.

11.5.4 Sonar (acronym for sound navigation ranging) is a class of underwater systems for measuring the distance and direction of an underwater object by measuring the time interval between the transmission of an underwater sonic or ultrasonic signal and the return of its echo. Sonar is the underwater analog of radar. Doppler sonar is analogous to doppler sonar. Sonar can be used for underwater piloting of submersibles in which a cathode-ray-tube display of the sonar echoes gives a "picture" of the surrounding underwater terrain.
An acoustic fathometer is a related device that displays a profile of the ocean bottom beneath the submarine. An acoustic transponder is the underwater analog of a radio beacon.

11.6 AVM/SR

11.6.1 Automatic position-location can benefit fleets of land vehicles such as trucks, buses, taxicabs, police vehicles, ambulances and other emergency vehicles. In each fleet, a central dispatch station can monitor the positions of its vehicles in real time, automatically, without requiring any action by the drivers or occupants of the vehicles. The central station can thereby control its vehicles at all times. The station can be alerted automatically if any emergency or unusual situation diverts a vehicle from its assigned route. This application of automatic position-location is called Automatic Vehicle Monitoring or AVM.

11.6.2 Site Registration (SR) is an application of position-location that is closely related to AVM. SR is the position-location of the sites of highway accidents, police-related incidents, etc. for purposes of official records and statistics.

11.6.3 Proximity systems, also called sign-post systems, are AVM systems in which vehicles communicate automatically by VHF or UHF radio, or by microwaves, with transmitters or receivers that are placed in fixed positions at selected sites, i.e. "sign-posts".

(11.6.3 continued)

For example, coded radio transmitters are placed at intervals along a bus route, and the buses are equipped with radio receivers that select the nearest transmitter by the strength of its signal; and the coded selected signal is automatically broadcast by the bus to its central control station. Conversely, the transmitters can be carried by the buses, and the receivers can then be placed at the "sign-posts". A sign-post system is being tested in the Southern California Rapid Transit District.

11.6.4 Several position-location systems described in this report are potentially applicable to AVM/SR. These systems include ATS Ranging (section 9.4), GPS (section 9.3), and especially Loran-C (paragraphs 6.3.10 through 6.3.13, and paragraph 6.4.3).

12. INDEX

This section 12 is an alphabetical index of selected position-location/navigation terms used in this report, including acronyms and system names. The index lists the number of the page on which each term is defined or explained or introduced. The term is usually underscored on the page to which the index refers. (See also paragraphs 3.1.1 - 3.1.3.)

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See Page 188.

20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

Position-location/navigation systems are overviewed tutorially for possible application to military land vehicles. The overview includes position-location by celestial navigation, rho/theta systems, hyperbolic systems, radar, inertial systems and satellite systems. Potential advantages and disadvantages of applying various position-location systems to military land vehicles are suggested.

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19. KEY WORDS

Position Location

Navigation
- Celestial Navigation
- Dead Reckoning
- Doppler Navigation
- Inertial Navigation
- Navigational Aids
  - Radar Beacons
  - Radio Beacons
  - Gyro Compasses
  - Radio Compasses
  - Ground Position Indicators
  - Navigation Charts
  - Sextants
- Navigation Satellites
- Radar Navigation
- Radio Navigation
  - Hyperbolic Navigation
    - Loran
    - Omega
    - Shoran
  - Radio Ranges
  - Tacan

Global Positioning System

Ring Lasers
Ring Laser Gyro

Ground Vehicles
Land Vehicles
Military Vehicles