R and D CENTER LABORATORY TECHNICAL REPORT

NO. 12686

NAVIGATION: NATIONAL PLANS; NAVSTAR-GPS; LASER GYROS

CONTRACT NO. DAAK30-80-C-0073

31 AUGUST 1982

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Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER 12686	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Navigation: National Plans; Navstar-GPS; Laser Gyros.		5. TYPE OF REPORT & PERIOD COVERED Final Technical Report 3 Sept 1980 - 31 Aug 1982
		6. PERFORMING ORG. REPORT NUMBER PRA-8049
7. AUTHOR(s) Paul Rosenberg		8. CONTRACT OR GRANT NUMBER(s) DAAK30-80-C-0073
9. PERFORMING ORGANIZATION NAME AND ADDRESS Paul Rosenberg Associates 330 Fifth Avenue, Pelham, New York 10803		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 1L162601AH91
11. CONTROLLING OFFICE NAME AND ADDRESS U. S. Army Tank-Automotive Command Warren, Michigan 48090		12. REPORT DATE 31 August 1982
		13. NUMBER OF PAGES v + 153
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release. Distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Navigation	Navigation Satellites	Laser Gyros
Position-Location	NAVSTAR-GPS	Fiberoptic Gyros
Planning	Global Positioning System	Sagnac Interferometer
National Plans for Navigation		Inertial Navigation

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

Three navigation topics are reviewed, analyzed and summarized: (1) United States national plans for navigation; (2) the NAVSTAR-Global Positioning System; (3) laser gyros including Sagnac interferometer laser gyros and fiberoptic laser gyros. This study is a sequel to USATARADCOM Technical Report No. 12496, "Position-Location/Navigation Systems Overview for Military Land Vehicles", (AD-A088070).

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

PREFACE

1.1 This is the Final Technical Report of Contract DAAK30-80-C-0073, awarded by the United States Army Tank-Automotive Command (USATACOM), Warren, Michigan to Paul Rosenberg Associates (PRA), Pelham, New York for a review and analysis of selected navigation/position-location topics.

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

1.3 Acknowledgement is made appreciatively to the following members of USATACOM's staff (listed alphabetically) for their excellent cooperation and guidance in the technical work of this contract:

CPT Roger C. Braxton, Jr., USA, DRSTA-ZS
Technical monitor of this contract
from April 1981 to June 1982.

Gordon J. McInnes, DRSTA-ZSC
Technical monitor of this contract
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Donald Rees, DRSTA-ZSC
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Dr. Douglas W. Templeton, DRSTA-ZSC
Technical monitor of this contract
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1.4 This report is a follow-on to TARADCOM Technical Report No. 12496, AD-A088070, prepared previously by Paul Rosenberg Associates for the U. S. Army Tank-Automotive Research and Development Command, Warren, Michigan, under Contract DAAK30-79-C-0091.

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1. INTRODUCTION and OBJECTIVE

1.1 This report and the previous report, TARADCOM Technical Report No. 12496, are tutorial reviews of POS/NAV (position-location/navigation) systems, methods and concepts.

1.2 The objective of these reviews is to provide a background of POS/NAV information to assist future selections of POS/NAV systems for military land vehicles.

1.3 It is unlikely that one POS/NAV system will be found to meet the needs of all types of military land vehicles in all mission roles in all military environments. A broad spectrum of POS/NAV systems, methods and concepts should be considered when selecting an optimum system for each combination of vehicle type, mission and environment. The purpose of this report and the previous report is to describe this spectrum.

2. SCOPE

2.1 This review and report treats three navigation topics in three separate sections:

Section 4: United States national plans for navigation.

Section 5: NAVSTAR-GPS (Global Positioning System).

Section 6: Laser gyros, including Sagnac interferometer laser gyros and fiberoptic laser gyros.

2.2 The U. S. national plans for navigation are included in this review and report because plans for navigation systems for military land vehicles must take into account national plans for navigation.

2.3 NAVSTAR-GPS is included because this system has been proposed as an universal navigation/position-location system suitable for almost all types of vehicles, civil as well as military, and because NAVSTAR-GPS has a major role in recent national plans for navigation.

2.4 Laser gyros are included because:

(1) Inertial (self-contained) systems are highly advantageous for navigation/position-location of military vehicles, including military land vehicles.

(2) Gyros are critical components of inertial systems.

(3) Laser gyros may eventually replace mechanical rotating gyros in inertial systems, particularly for military land vehicles.

2.5 Preparation of this report has been guided by the following precept, quoted from the Preface, page 1, of TARADCOM Technical Report No. 12496, and paraphrased from paragraph 2.3, page 5, of Report 12496:

> " . . . . 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."
>
> . . . . Review the operating principles of the relevant navigational techniques, and describe the phenomena or physical principles used in these techniques. The review should enable a non-specialist in navigation to understand the basics of each technique and its navigational application.

3. DEFINITIONS

3.1 This report uses navigation/position-location terms, system names and acronyms as they are defined and/or described in TARADCOM Technical Report No. 12496*. In Report 12496, see Section 3, pages 7-13, and Section 12, pages 183-186.

3.2 Other navigation/position-location terms, acronyms and system names that appear in the present report are defined where they are introduced in the text herein.

3.3 The term "navigation system(s)" is used in the present report to mean "navigation and/or position-location system(s) and/or aid(s)", unless otherwise specifically stated. (Cf paragraphs 3.3, 3.4.1, 3.4.2, pages 10-11, in Report 12496).

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*TARADCOM Technical Report No. 12496, "Position-Location/Navigation Systems Overview for Military Land Vehicles", June 1979, Accession Number AD-A088070, unclassified, is available from the U. S. Dept. of Commerce, National Technical Information Service, 5285 Port Royal Road, Springfield, Virginia 22161, and from the Defense Technical Information Center, Cameron Station, Alexandria, Virginia 22314.

3.4 "Self-contained" navigation systems are navigation systems that use only equipment or devices carried in or on the vehicle. Examples of such systems are: inertial navigation systems (INS); celestial navigation devices; radar equipment aboard the vehicle, without the use of radar beacons or transponders; sonar without the use of sonar transponders; marine dead-reckoning (DR) with log and magnetic compass; land vehicle DR with odometer and magnetic compass.

3.5 "Station-referenced" or "externally-referenced" navigation systems are navigation systems that depend upon, or are referenced to, equipment or devices that are not in or on the vehicle. The synonyms "station-referenced" and "externally-referenced" are antonyms to "self-contained".

3.6 "Radionavigation" systems are navigation systems that use electromagnetic transmission/reception in the radio/microwave portions of the spectrum. All station-referenced and externally-referenced navigation systems, except acoustic systems, are radionavigation systems. Hence, radionavigation systems are practically synonymous with station-referenced and externally-referenced navigation systems.

3.7 Drms is the abbreviation for "distance root mean squared". It is used in navigation to describe the probable accuracy or statistical error of a position-location or "fix", assuming a normal (gaussian) distribution of errors. An accuracy of X drms indicates the probability that a circle of radius X contains 63.2 percent of all data points. An accuracy of X 2-drms indicates the probability that a circle of radius X contains 95 percent of all data points.

4. U. S. NATIONAL PLANS FOR NAVIGATION

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4.1 Introduction to Section 4

4.1.1 Many competing navigation systems (defined in paragraph 3.3) have been developed since the beginning of World War II, in the civil and military sectors. These systems vie with each other for use with many types of vehicles on land, on water, under water, in the air and in space. The proliferation of these navigation systems has been accelerated by the growth of air and marine traffic, and by the development of spacecraft.

4.1.2 Since World War II, it has been recognized that navigation systems should be coordinated, standardized and reduced in number, for the sake of safety, efficiency and economy of transportation, and for national security, in the United States and abroad. Beginning in the late 1940's, and continuing to the present, these matters have been addressed by many individuals and organizations in industry, in government and in the engineering professions.

4.1.3 Examples of these organizations that had official or semi-official status in these matters in the United States prior to the establishment of the Department of Transporation in 1967 (paragraph 4.1.5) are: the Air Coordinating Committee, an interdepartmental group sponsored by the President of the United States to coordinate the policies of Federal agencies that were interested principally in aviation; the Air Navigation Development Board (established in 1948); the Congressional Aviation Policy Board; the President's Air Policy Commission; the Radio Technical Commission for Marine, including its Special Committee 60; the Radio Technical Commission for Aeronautics, including its Special Committee 31; and the Department of Transportation Air-Traffic Control Advisory Committee.

4.1.4 Each organization, such as those listed in paragraph 4.1.3 above, was specialized in that the organization concentrated upon either air navigation, or air traffic control (ATC), or marine navigation; and each organization rendered significant service in advancing the safety, efficiency and economy of its own specialized field of navigation; but prior to 1970 no organization produced a comprehensive plan that could deservedly be called a national plan for navigation. Furthermore, prior to 1977, no official or semi-official group planned significantly for the navigation of land vehicles.

4.1.5 In 1967, Public Law 89-670 established the United States Department of Transportation (DOT), and gave the DOT the statutory function of planning and coordinating civil navigation, both air and marine. The DOT was designated as a centralized authority with the responsibility for development of a comprehensive navigation plan on a national scale. The result was the first truly national and official plan for navigation, issued by the DOT in 1970 and discussed in section 4.2.1 herein.

4.1.6 The navigation plans that can properly be called U. S. national plans for navigation are reviewed and analyzed in section 4.2. in chronological order, beginning with the 1970 DOT National Plan for Navigation, and culminating with the Federal Radionavigation Plan (section 4.2.6) and the Joint Chiefs of Staff (JCS) Master Navigation Plan (MNP) (section 4.2.7).

4.1.7 Two additional documents are reviewed in Section 4.3, Addenda.

4.1.8 All documents cited or referenced in Section 4 are unclassified, except the 1978 and 1980 JCS MNPs (References 4.4.7, 4.4.8). (See paragraph 4.2.7.1.)

4.2 National Plans for Navigation

(See paragraph 4.1.6)

4.2.1 1970 DOT NPN

4.2.1.1 The DOT issued a "Department of Transportation National Plan for Navigation", dated May 1970, abbreviated as the "1970 DOT NPN" herein. (Ref 4.4.1). This Plan was prepared by the Federal Aviation Administration (FAA) and the U. S. Coast Guard (USCG), and was promulgated by the Secretary of Transportation on 5 June 1970. (See paragraph 4.1.5.)

4.2.1.2 The 1970 DOT NPN was a plan for civil navigation only. Nevertheless, the Department of Defense (DOD) provided assistance to the DOT in the preparation of the Plan, and the Secretary of Defense concurred with the contents of the Plan (as was disclosed later in the 1977 DOT NPN). This DOT-DOD cooperation is additional reason for properly calling the 1970 DOT NPN the first U. S. national plan for navigation. DOT-DOD cooperation continued in a series of NPNs (subsections 4.2.2, 4.2.3, 4.2.4) that culminated in the Federal Radionavigation Plan of 1980 (subsection 2.5).

4.2.1.3 The purpose of the 1970 DOT NPN was: "... to provide for the orderly and efficient development, implementation and operation of aids to navigation responsive to both current and future needs of civil air and marine interests in the United States . . ." In developing this plan, consideration was given to military navigation systems that were being used, or could be used, by the civil community; but navigation needs that were exclusively military were not considered.

4.2.1.4 Civil air requirements for long distance navigation, and maritime navigation requirements on the high seas, received the major attention of the 1970 DOT NPN. Secondary attention was given to civil marine requirements for navigation in coastal/confluence, harbor, estuary and marine terminal areas.

4.2.1.5 A new statement of United States policy regarding navigation was proposed in the 1970 DOT NPN, to replace the policy regarding long distance navigation adopted by the Air Coordinating Committee(ACC 58/12.1B) on 23 December 1958. A significant difference between the old policy and the new policy is that the new policy omits a principal goal of the old policy, namely the national and international standardization of a single type of ground-based long-distance radio aid to navigation to meet the needs of all air, surface and subsurface users. Both policies promote minimizing the the number of standardized navigational aids. The new policy contains the statement, not in the old policy: "To require users of federally operated aids and services to bear their fair share of the costs".

The new policy does not specifically mention self-contained aids, as does the old policy; indeed the 1970 DOT NPN gives plans for station-referenced (paragraphs 3.5, 3.6) navigation systems only.

4.2.1.6 Figure 4.2.1.6 shows the operating plan of the 1970 DOT NPN for six-station-referenced navigation systems, namely Loran-A, Loran-C, Omega, a civil navigation satellite (e.g., TRANSIT), Consol/Consolan, and Decca. Other station-referenced navigation systems are discussed in the 1970 DOT NPN, but the document makes no definite plans for these systems. These systems are: air terminal navigation systems such as ILS (Instrument Landing Systems) and approach radars; marine radio/visual aids; and systems for navigation of land vehicles.

4.2.1.7 The 1970 DOT NPN specified a requirement for a complete navigation system for marine use throughout the U. S. coastal/confluence zone (CCZ) with a repeatable accuracy of 1/4 nautical mile rms. The CCZ was taken as extending out to 50 nautical miles offshore. Three candidate systems were nominated by the 1970 DOT NPN to meet this CCZ requirement: Loran-A, Loran-C, and Decca. The operating plan for alternative selections of these three systems is shown in Figure 4.2.1.7.

OPERATING PLAN
STATION REFERENCED NAVIGATION SYSTEMS

LORAN-A

	1974 ▼	1980 ▼
Military requirement. Marine requirement. Civil air requirement.	No military requirements. Continued marine requirement. Continued civil air requirement.	Possible phase out if marine requirement is not validated.

LORAN-C

	1972 ▼
Military requirement. No requirement for civil air or marine; Requires evaluation.	Continued military use. Possible application for marine use. Civil air use depends on special applications.

OMEGA

	1975 ▼
U.S. Navy use. No civil air or marine requirement; Requires evaluation.	Continued U.S. Navy use. Possible application for civil air/marine in combination or as alternative to satellite system.

CIVIL NAVIGATION SATELLITE

	1975 ▼
No firm requirement; Requires development and evaluation for all users.	Potential operational use by civil air/marine if found superior to Omega.

CONSOL/CONSOLAN

	1970 ▼
Military use of San Francisco station only. No marine or civil air requirements.	Begin phase out and complete when DOD requirement terminates.

DECCA

Limited air use as a non-federal aid. Requires evaluation for marine use in U.S. coastal/confluence zone.

▼= END OF INDICATED CALENDAR YEAR.

Figure 4.2.1.6

1970 DOT NPN

MARITIME COASTAL/CONFLUENCE ENVIRONMENT OPERATING PLAN.

<table>
<tr><th>TIME
SYSTEM</th><th colspan="2">1972</th><th colspan="2">1975</th><th>1980</th></tr>
<tr><td rowspan="3">LORAN A</td><td rowspan="3">Develop improved accuracy station equipment</td><td rowspan="7">Select System for Coastal/ Confluence</td><td>Selected</td><td>Augument existing stations</td><td>Continue operations indefinitely</td></tr>
<tr><td rowspan="2">Not selected</td><td colspan="2">Stations required by FAA-continue operation</td></tr>
<tr><td colspan="2">Stations not required by FAA- continue operations thru 1985</td></tr>
<tr><td rowspan="2">LORAN C</td><td rowspan="2">Develop reliable low cost receiver</td><td>Selected</td><td>Augument existing stations</td><td>Continue operations indefinitely</td></tr>
<tr><td>Not selected</td><td colspan="2">Continue operations to meet DOD requirements</td></tr>
<tr><td rowspan="2">DECCA</td><td rowspan="2">Monitor developments</td><td>Selected</td><td>Implement system</td><td>Continue operation indefinitely</td></tr>
<tr><td>Not selected</td><td colspan="2">Allow installations as Non-Federal aids</td></tr>
</table>

Figure 4.2.1.7

1970 DOT NPN

4.2.1.8 In the light of navigation systems developments in the decade following this 1970 plan, three aspects of the 1970 DOT NPN are especially interesting: (1) The Plan left open the question of whether Loran-C would eventually replace Loran-A (this did occur later). (2) The Plan stated that there was no general civil requirement for a navigation system that used satellites. (3) Navigation of land vehicles was not included in the Plan.

4.2.1.9 The Plan stated that research and development should be directed principally toward these civil applications: long distance air navigation; maritime high seas navigation; maritime harbor, estuary and marine terminal systems.

4.2.1.10 The 1970 DOT NPN contained, as background material, discussions of requirements for air and marine navigation, and descriptions of characteristics of navigation systems. In a discussion of the Federal Government's costs of furnishing navigation services, the NPN pointed out that there are Government imposed user charges on airline and general aviation aircraft, but there are no corresponding maritime user charges.

4.2.2 1972 DOT NPN

4.2.2.1 The May 1970 DOT NPN had stated that the Plan would be maintained current on an annual basis as of 1 November each year. Nevertheless the next published plan was the "Department of Transportation National Plan for Navigation" dated 28 April 1972, (Reference 4.4.2), abbreviated as the "1972 DOT NPN" herein. This gap in time between the two published plans is understandable because navigation systems were developing slowly (although steadily) during this two-year period. Like the 1970 DOT NPN, the 1972 DOT NPN was prepared by the FAA and the USCG (paragraph 4.2.1.1), with the cooperation of the DOD (paragraph 4.2.1.2).

4.2.2.2 The 1972 DOT NPN is similar to the 1970 DOT NPN in many respects. The purposes of the two Plans were the same (paragraph 4.2.1.3). Paragraphs 4.2.1.4 and 4.2.1.5 regarding the 1970 DOT NPN apply also to the 1972 DOT NPN. The research and development plans are almost alike in both Plans (paragraph 4.2.1.9). The discussions of requirements for air and marine navigation, the descriptions of navigation systems, and the discussions of user charges are substantially the same in both NPNs (paragraph 4.2.1.10).

4.2.2.3 A comparison of civil air and marine long distance navigation requirements, according to the 1972 DOT NPN, is given in Figure 4.2.2.3. The 1970 DOT NPN had presented an almost identical comparison.

4.2.2.4 The 1972 DOT NPN planned timetable of station-referenced navigation systems is shown in Figure 4.2.2.4. This timetable should be compared with the operating plan of the 1970 DOT NPN shown in Figure 4.2.1.6. The differences between Figure 4.2.2.4 and Figure 4.2.1.6 represent the principal differences between the 1972 DOT NPN and the 1970 DOT NPN.

4.2.2.5 The 1970 DOT NPN had considered three candidate systems for the coastal/confluence zone (CCZ) requirement, namely Loran-A, Loran-C, and Decca (paragraph 4.2.1.7). The 1972 DOT NPN added D-Omega (differential Omega) as a fourth candidate system. The 1972 NPN did not answer the significant question: Which of the four systems will be selected as the U. S. Government sponsored radionavigation system for the CCZ?

COMPARISON OF CIVIL AIR AND MARINE LONG DISTANCE NAVIGATION REQUIREMENTS

Feature	*Air Requirements*	*Marine Requirements*	*Difference*
Coverage area capability	Worldwide	Worldwide water area	Land area only
Time limitations	None	None	None
Weather limitations	None	None	None
Propagation	No limitation	No limitation	None
Reliability/Integrity	100%	100%	None
Warning	Cockpit	Navigation Bridge	None
Ambiguity	Free from those of operational significance	Free from those of operational significance	None
Accuracy	Remain within half separation distance 99.95% of time	Error not greater than 2 NM 95% of time	Marine more stringent at present
Blunders	Protection required	Protection required	None
Capacity	Sufficient to handle all craft requiring access	Sufficient to handle all craft requiring access	None
Presentation	Present position, steering information	Present position	Steering information
Interval	Continuous	Two hours	Less frequent
Lag	Speed dependent	5 min.	Greater lag allowable for marine
Compatibility	Smooth integration with other phases of flight	Smooth integration with other phases of voyage	None

Figure 4.2.2.3

1972 DOT NPN

TIMETABLE OF STATION-REFERENCED NAVIGATION SYSTEMS

SYSTEM \ End of CY	1972	1974	1975	1980	1982	
LORAN-A (U.S. stations only)	Maintain status quo		Terminate stations outside 50 states as user demands allow			Terminate stations within 50 states if not selected as coastal/confluence system
U.S. Maritime Coastal/Confluence System	System Selection	System Procurement		System Implementation	Continue full operation until rendered obsolescent	
LORAN-C (DOD System)	Continue present system with coverage as required by DOD					Continued operation based on demand civil and/or military
OMEGA	Implementation Worldwide		Continue operation worldwide			Continued operation dependent upon demand and international agreement
CONSOLAN	Nantucket Discontinued—1971; discontinue San Francisco when DOD requirement ceases					
CIVIL SATELLITE	Potential use if found superior to other systems					

Figure 4.2.2.4

1972 DOT NPN

4.2.2.6 The maritime coastal/confluence environment plan in the 1972 DOT NPN is the same as the 1970 DOT NPN shown in Figure 4.2.1.7, except that a new row, at the bottom of the 1972 diagram, adds the following to the 1970 Plan: determine the system parameters of D-Omega in 1972; select a system for the CCZ in the 1972-73-74 period; if D-Omega is selected, then implement the system beginning in 1975, and continue operation beyond 1980; if D-Omega is not selected, then allow its installation as non-Federal aids beginning in 1975.

4.2.3 1974 DOT NPN Annex

4.2.3.1 The selection of a radionavigation system for the coastal/confluence environment was announced by the DOT in a "Department of Transportation National Plan for Navigation Annex", 15 July 1974 (ref 4.4.3), abbreviated as the "1974 DOT NPN Annex" herein. The selected system was Loran-C. See paragraphs 4.2.2.5, 4.2.2.6.

4.2.3.2 The 1974 DOT NPN Annex was the result of a U. S. Coast Guard study in which the four candidate systems (Loran-A, Loran-C, D-Omega and Decca) were compared on the bases of: capability to meet the technical requirements and costs including system installation, operating expenses, present investment, and user equipment. The needs of commercial fishermen and the scientific community were considered in addition to general navigation requirements.

4.2.3.3 The study redefined the CCZ (paragraph 4.2.1.7) to have an inner boundary at the harbor entrance, and an outer boundary at 50 nautical miles offshore or at the edge of the continental shelf (100 fathom curve) whichever is greater. The required navigation accuracy was revised to provide 95 percent assurance that a vessel could be navigated, with a tolerance of 1/4 nautical mile, along a track to its designated destination or within its designated shipping lane. Lane widths varied from 1 nautical mile at harbor entrances and in the Gulf of Mexico fairways to 5 nautical miles at the edge of the high seas zone.

4.2.3.4 The plan in the 1974 DOT NPN Annex was to terminate the U. S. operated domestic Loran-A chains in 1979 and 1980. Overseas chains were to be terminated in 1975 and 1977.

4.2.3.5 The same plan called for the Loran-C system to be upgraded and expanded to cover the entire U. S. CCZ and the Great Lakes beginning in 1977, with complete coverage by 1980. This provided dual Loran-A Loran-C coverage for about 24 months. The U. S. Coast Guard planned to continue operating Loran-C overseas stations in response to requirements of the Department of Defense.

4.2.4 1977 DOT NPN

4.2.4.1 A revised, reorganized and enlarged plan, "Department of Transportation National Plan for Navigation", (ref 4.4.4) called the "1977 DOT NPN" herein, was issued by the DOT and promulgated by the Secretary of Transportation on 14 November 1977. The Department of Defense, the Department of Commerce, and the National Aeronautics and Space Administration assisted the DOT in preparing this Plan, and concurred with the Plan.

4.2.4.2 Civil air and marine navigation requirements were discussed in greater detail in the 1977 DOT NPN than in the 1970 and 1972 DOT NPNs. In addition, the 1977 DOT NPN included land navigation, i.e., position-location and surveillance of land vehicles, a subject that was not treated in the earlier NPNs.

4.2.4.3 The 1977 DOT NPN centered its Plan around six externally-referenced navigation systems (paragraphs 3.5, 3.6) that the Plan considered to be operating systems (operated principally by the U. S. Coast Guard and the Federal Aviation Administration), and around two externally-referenced navigation systems that the Plan considered to be developmental systems.

The operating systems were:

(1) Loran-A

(2) Loran-C

(3) Omega

(4) Radiobeacons

(5) VOR-DME/TACAN

(6) ILS (Instrument Landing System)

The developmental systems were:

(7) NAVSTAR-GPS

(8) MLS (Microwave Landing System)

4.2.4.4 Loran-A, Loran-C, Omega, and Radiobeacons were to serve aircraft and marine vessels. Loran-C was potentially to serve land vehicles also. NAVSTAR-GPS was planned tentatively to serve aircraft and marine vessels and land vehicles. MLS was planned tentatively for aircraft terminal navigation.

4.2.4.5 The planned system phasing schedule for the eight principal navigation systems of the 1977 DOT NPN is shown in Figure 4.2.4.5 for the years from 1977 to beyond 2000.

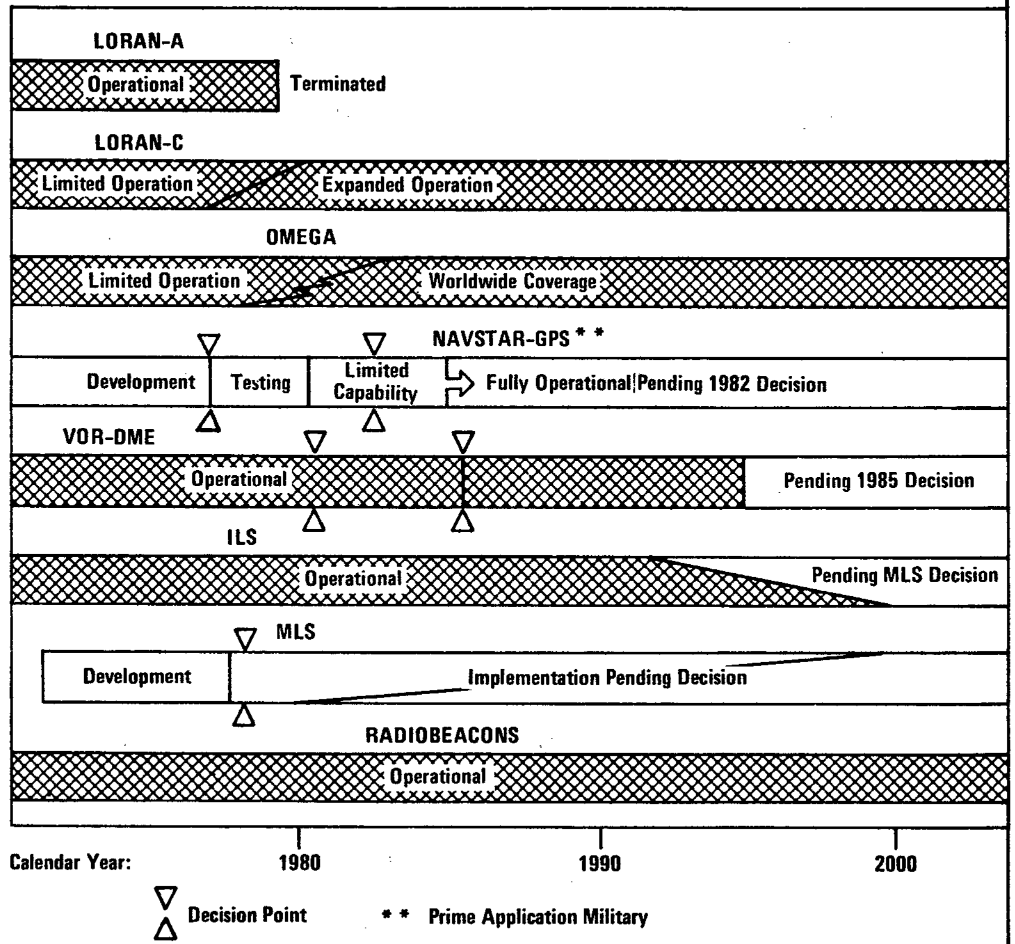
4.2.4.6 The decision in the 1974 DOT NPN Annex regarding the phase-out of Loran-A (paragraphs 4.2.3.4, 4.2.3.5) was reaffirmed in the 1977 DOT NPN. During the 1974-1977 period, Loran-C was being implemented to replace Loran-A in the CCZ of continetal United States (including Alaska). The plan was to cease all U. S.-operated Loran-A

PRINCIPAL SYSTEMS OF THE NATIONAL PLAN FOR NAVIGATION

APPLICABILITY TO NEEDS

MARINE			AERONAUTICAL				LAND
High Seas	Coast and Confluence	Inland Waterways	Oceanic	Continental En Route	Approach	Landing	
★			●				
●	★	●	●	P	P		P
★			●	P			P
P	P	P	P	P	P		P
				★	●		
						★	
						★	
	★	●		●	★		

★ Prime Application
● Secondary Application
P Potential to be Evaluated
▒ Inapplicable



MAJOR FEDERALLY PROVIDED SYSTEMS AVAILABLE FOR CIVIL NAVIGATION

Figure 4.2.4.5. 1977 DOT NPN

chains in mid 1980. This gave civil users of Loran-A at least 5 years (from 1974 to 1980) to substitute Loran-C equipment for their Loran-A equipment, thereby minimizing the economic impact of the change upon the users.

4.2.4.7 Loran-C, combined with Omega, was to replace Loran-A according to the 1977 DOT NPN. There were several contributing reasons for this decision. The Loran-A system was more than 30 years old in 1977. Loran-A no longer met the increased accuracy requirements of the CCZ. It would cost as much, or more, to upgrade the performance of the Loran-A system, as it would to replace it with a superior system, namely Loran-C. Furthermore, Loran-A signals (in the 1800 to 2000 kHz band) do not propagate over land as well as Loran-C signals (in the 90 to 110 kHz band). Finally, all Department of Defense requirements for Loran-A were scheduled to terminate on 31 December 1977.

4.2.4.8 Omega had seven permanent stations, in 1977, providing basic coverage over all the Northern Hemisphere and over more than 90 percent of the Earth's surface. An eighth Omega station was planned to be completed in 1980 to make the system fully operational worldwide. Omega's designed accuracy of 2 to 4 nautical miles, 2-drms*, sufficed for oceanic/high seas navigation, but was not accurate enough for maritime use in the CCZ or for aircraft in some parts of U. S. airspace. Hence, Loran-C and Omega were planned to complement each other to form a complete navigation system.

4.2.4.9 D-Omega (Differential Omega), which had appeared tentatively in the 1972 DOT NPN (paragraph 4.2.2.6), was not definitely included in the 1977 DOT NPN. The 1977 Plan described D-Omega as being still in the developmental stage, with only tentative prospective users in the United States.

4.2.4.10 Self-contained navigation systems (paragraph 4.2.1.5) were discussed in the 1977 DOT NPN, but no plans were made for these systems because they did not need Government services. These self-contained systems included: INS (Inertial Navigation Systems); radar carried aboard aircraft and marine vessels; Doppler systems;

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*Defined in paragraph 3.7, page 6.

Air Data Systems, i.e. DR (Dead Reckoning) air navigation systems using aids such as magnetic compasses, gyro compasses, altimeters, and airspeed indicators; marine DR systems using aids such as compasses, the log and depth finders.

4.2.4.11 The DOT did not have a specific responsibility, under law, to provide navigation facilities for land vehicles. Nevertheless, land navigation was included in the 1977 DOT NPN (paragraph 4.2.4.2) under the DOT's general responsibility for improving safety and efficiency of transportation.

4.2.4.12 Navigation surveillance systems for fleets of land vehicles, and position-location (location identification) on land, were only in a development stage when the 1979 DOT NPN was issued. Consequently, this NPN did not adopt a specific policy regarding land navigation service, and did not propose a specific land navigation system to be established and maintained by the Government. Only general requirements were mentioned in the NPN. Applications that were mentioned included: Automatic Vehicle Location (AVL) and surveillance of fleets of land vehicles (e.g. buses, trucks, public safety vehicles); and accurate position-location for randomly selected sites over large land areas, e.g., rural site location for census takers.

4.2.4.13 Three navigation systems were listed in the 1977 DOT NPN as having potential, to be evaluated, for land navigation: Loran-C, Omega, and NAVSTAR-GPS. The Plan did not actually recommend or designate one of these three potential systems for land navigation in the future , but discussions in the text of the NPN document appeared to favor Loran-C.

4.2.4.14 Consol/Consolan and Decca, that appeared in the 1970 and 1972 DOT NPNs, did not appear in the 1977 DOT NPN. Indeed, the 1977 DOT NPN did not even mention these systems. The last two Consolan stations in the United States were the East Coast station (at Nantucket) that was terminated in 1971, and the West Coast station (at San Francisco) that was decommisioned before the 1977 DOT NPN was issued. Prior to the 1977 NPN, Decca had failed to be selected as a U. S. Government operated system for the coastal/confluence environment plan.

4.2.4.15 TRANSIT, the U. S. Navy Navigation Satellite (NNSS), was considered in the 1977 DOT NPN, but was not included as a planned system. Although TRANSIT coverage is worldwide, its signals, at any given location, are unavailable at intervals that can be as long as 110 minutes. The 1977 DOT NPN judged NAVSTAR-GPS to be a more promising candidate satellite system than TRANSIT.

4.2.5 1978 GAO Nav Report

4.2.5.1 "Navigation Planning--Need for a New Direction", (ref 4.4.5) is the title of a provocative report issued by the U. S. General Accounting Office (GAO) in March 1978, denoted as the "1978 GAO Nav Report" herein.

4.2.5.2.1 The 1978 GAO Nav Report criticized U. S. civil and military departments and agencies for lack of progress in inter-agency navigation planning. The Report recommended that a single manager be assigned, within one of the Executive Offices of the President, to direct the development and implementation of a Government-wide navigation plan, including budgetary controls. As of June 1981, this recommendation had never been carried out. The Report stated also that Congress may have to decide whether a civil or military agency should eventually manage the NAVSTAR-GPS system. Cf section 4.3.1 herein.

4.2.5.2.2 The 1978 GAO Nav Report presented its own national plan for navigation as an alternative to the 1977 DOT NPN. The GAO Report was probably partly responsible for stimulating action that led to the 1979 DOD POS/NAV Plan (section 4.3.2) and to the 1980 Federal Radionavigation Plan (FRP) (section 4.2.6 herein). Nevertheless the FRP did not adopt the plan presented in the 1978 GAO Nav Report.

4.2.5.3 Thirteen (13) station-referenced navigation systems were reviewed by the 1978 GAO Nav Report: VOR, TACAN, Loran-A, Loran-C, Loran-D, Omega, TRANSIT, INS, Doppler Radar, D-Omega, PLRS, NAVSTAR-GPS, and non-directional radio beacons (NDB/DF/ADF). The report's estimates of the uses of navigation systems by the U. S. military services and by civil users are given in Figures 4.2.5.3A and 4.2.5.3B.

4.2.5.4 The 1978 GAO Nav Report expressed the belief that future civil and military navigation requirements can be met with only four of the aforesaid thirteen systems:

(1) NAVSTAR-GPS as the primary navigation system for most land, sea and air-users.

(2) INS and (3) Doppler radar; for military operations, and as back-up systems for some civil aviation.

(4) Marine non-directional beacons (NDB/DF/ADF) for small watercraft.

4.2.5.5 Planned spending was justified, according to the plan of the 1978 GAO Nav Report, only for the four systems listed in paragraph 4.2.5.4 above. The report considered the remaining nine systems of paragraph 4.2.5.3 to be unneeded because NAVSTAR-GPS has the potential for replacing them. The recommended plan was to

TYPICAL CURRENT AND PLANNED USES OF NAVIGATION SYSTEMS BY THE MILITARY SERVICES

	Direction finders	VOR	TACAN	Loran-A	Loran-C/D	Omega	Transit	Inertial	Doppler radar	PLRS	NAVSTAR
Land											
Vehicles										*	*
Personnel										*	*
Ships											
Aircraft carriers				C		C F	C	C F			F
Cruisers				C		C F	(C)	F			F
Destroyers and frigates				C		C F	(C)	F			F
Strategic submarines					C F		C F	C F			
Attack submarines				C		C F	C	C F			F
Aircraft											
AF fighters	C		C		(C)			C F	(C)		F
Navy fighters	C F		C					(C)	(C)		
AF attack	C		C					C (F)	C		F
Navy attack	C F		C					(C) F	C F		F
AF bombers	C	C	C					C F	C (F)		F
AF cargo	C	C	C	C	(C)			(C) F	C (F)		F
Navy cargo	C F	C	C	(C)	(C)	(C) F		(C)	(C)		F
Army helicopters	C F	(C) F							(F)	*	*
Navy helicopters	C F	(C)	C			(F)			C F	*	*

Notes: C=currently used by more than 50 percent.
(C)=currently used by some (less than 50 percent).
F=1990 planned use by more than 50 percent.
(F)=1990 planned use by some (less than 50 percent).
*=1990 likely use but plans are incomplete.

Figure 4.2.5.3-A GAO Nav Report

CURRENT USE OF NAVIGATION SYSTEMS BY CIVIL USERS

	Direction finders	VOR	Loran-A	Loran-C	Omega	Transit	Inertial	Doppler radar
Civil ships and boats:								
Ocean-going	C		(C)	(C)	(C)	(C)		
Coastal waters	(C)		(C)	(C)				
Pleasure craft	(C)		(C)	(C)				
Civil aircraft:								
Commercial	C	C	(C)				(C)	(C)
General aviation	(C)	C						

Notes: C=currently used by more than 50 percent.
(C)=currently used by some (less than 50 percent).

Figure 4.2.5.3-B

GAO Nav Report

minimize Government spending for development, modernization and expansion of VOR, TACAN, Loran-C, Loran-D, TRANSIT, the navigation part of PLRS, and DOD's non-directional beacons. The U.S. Navy's development of D-Omega had been terminated just prior to the GAO report; and Loran-A was scheduled to be phased out.

4.2.5.6 The 1978 GAO Nav Report stated that U. S. Government departments and agencies planned to spend $277 million over the ensuing 3 or 4 years for equipment and development of the nine "unneeded" navigation systems, excluding maintenance that could equal equipment costs. The GAO report recommended that much of this planned expenditure should be deferred as long as NAVSTAR-GPS remains a potential replacement for the nine "unneeded" systems. It may be noted that the 1978 GAO Nav Report is one of the few national plans for navigation that presents or discusses costs in actual dollar figures.

4.2.5.7 The 1978 GAO Nav Report favored NAVSTAR-GPS strongly. The GAO report was optimistic about the future success of NAVSTAR-GPS. The GAO report seemed to plan on world-wide two-dimensional Navstar-GPS coverage by 1982, and world-wide three-dimensional coverage by 1985. At the present writing, these dates do not appear to be feasible.

4.2.6 FRP

4.2.6.1 The "Federal Radionavigation Plan" (FRP) is a comprehensive national plan for navigation, developed and promulgated jointly by the U. S. Department of Defense, OUSDRE*, and by the U. S. Department of Transportation, DPB-22. The first edition of the FRP is dated July 1980, but the document was not released until January 1981. This 1980 edition is denoted as "1980 FRP" or sometimes simply as "FRP" herein. (Ref 4.4.6). The 1980 FRP updated the 1977 DOT NPN and those sections of the 1978 edition of the DOD Joint Chiefs of Staff Master Navigation Plan dealing with common-user (paragraph 4.2.6.7) systems. See section 4.3.1 herein for historical background of the 1980 FRP. See also paragrpah 4.2.7.2.

4.2.6.2 The 1980 FRP sets forth an official United States national radionavigation policy consisting of 18 policy statements that concern transportation safety, economy, avoidance of unnecessary duplication of systems and services, commonality/interoperability between military and civil users, national and international standarization, international cooperation, and optimum use of the electromagnetic spectrum. The following two of the eighteen statements of policy are especially relevant to military navigation:

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*Office of the Under Secretary of Defense for Research & Engineering.

K. Develop, implement, and operate the minimum special navigational aids and services necessary to accomplish military operations.

L. Operate radionavigation systems only as long as the United States and its allies accrue greater military benefit than potential adversaries; otherwise, cease operations or change the operating characteristics and signal formats of special purpose DOD systems. Non-DOD users who choose to use these systems do so at their own risk. Incorporate selective availability techniques into radionavigation systems to deny service to non-allied military users should denial be in the interest of national security.

4.2.6.3 Policy statement L in paragraph 4.2.6.2 is directed toward NAVSTAR-GPS; see Section 5 herein. Indeed, the 1980 FRP espouses NAVSTAR-GPS and almost takes for granted the eventual success of NAVSTAR-GPS. For example, statement N of the U. S. national radionavigation policy, as given in the 1980 FRP, reads:

N. Make NAVSTAR-GPS continuously available on an international basis for civil and commercial use at the highest level of accuracy consistent with national security interests. It is presently projected that an accuracy of 200M Circular Error Probable (CEP) (500M 2 drms) will be made available during the first year of full NAVSTAR-GPS operation with accuracy available to civil users improving as time passes.

4.2.6.4 The DOD internal management structure for navigational coordination, as reported in the FRP, is shown in Figure 4.2.6.4.

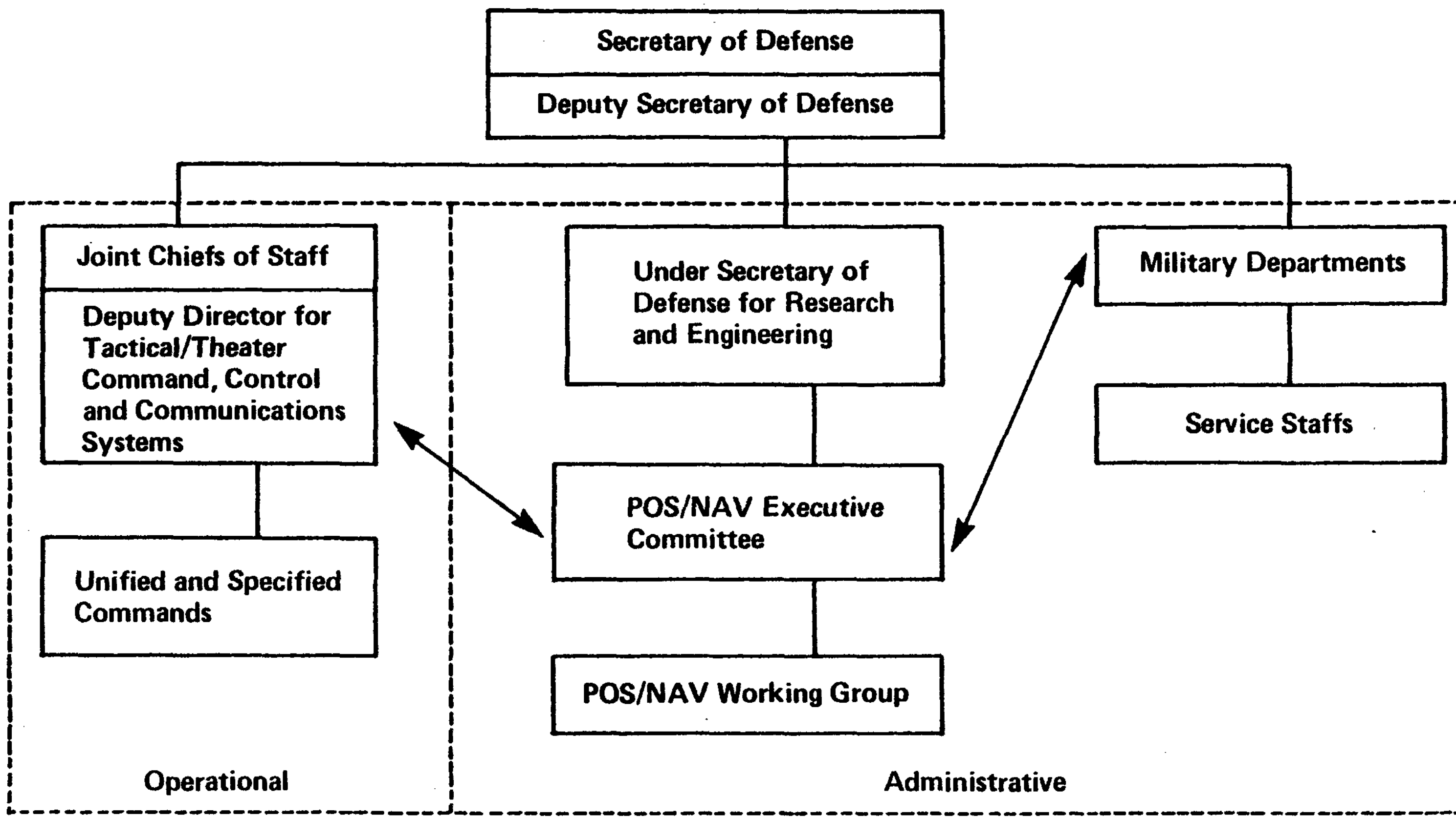


Figure 4.2.6.4 DOD Navigation Structure

4.2.6.5 The DOT internal management structure for civil navigational systems planning, as given in the FRP, is shown in Figure 4.2.6.5. This structure was set up by DOT Order 1120.32 in April 1979; (ref 4.4.11). In addition, three DOT agencies, not listed in Figure 4.2.6.5, relate to navigation: The Federal Highway Administration (FHWA); the National Highway Traffic Safety Administration (NHTSA); and the Urban Mass Transportation Administration (UMTA).

4.2.6.6 In addition to the agencies listed in Figure 4.2.6.5 and in paragraph 4.2.6.5, the following agencies participated in the development of DOT radionavigation plans: the U. S. Maritime Administration (MARAD) of the Department of Commerce (DOC); the National Oceanic and Atmospheric Administration of the DOC; and the National Aeronautics and Space Administration (NASA).

4.2.6.7 Thus the FRP can be considered to represent the consensus of all U. S. Federal agencies that provide or are concerned with services for common-user radionavigation systems. A common-user navigation system is a navigation system that is used by both the civil and military services. Common-user navigation systems are available to anyone who has properly designed equipment that is obtainable without restriction.

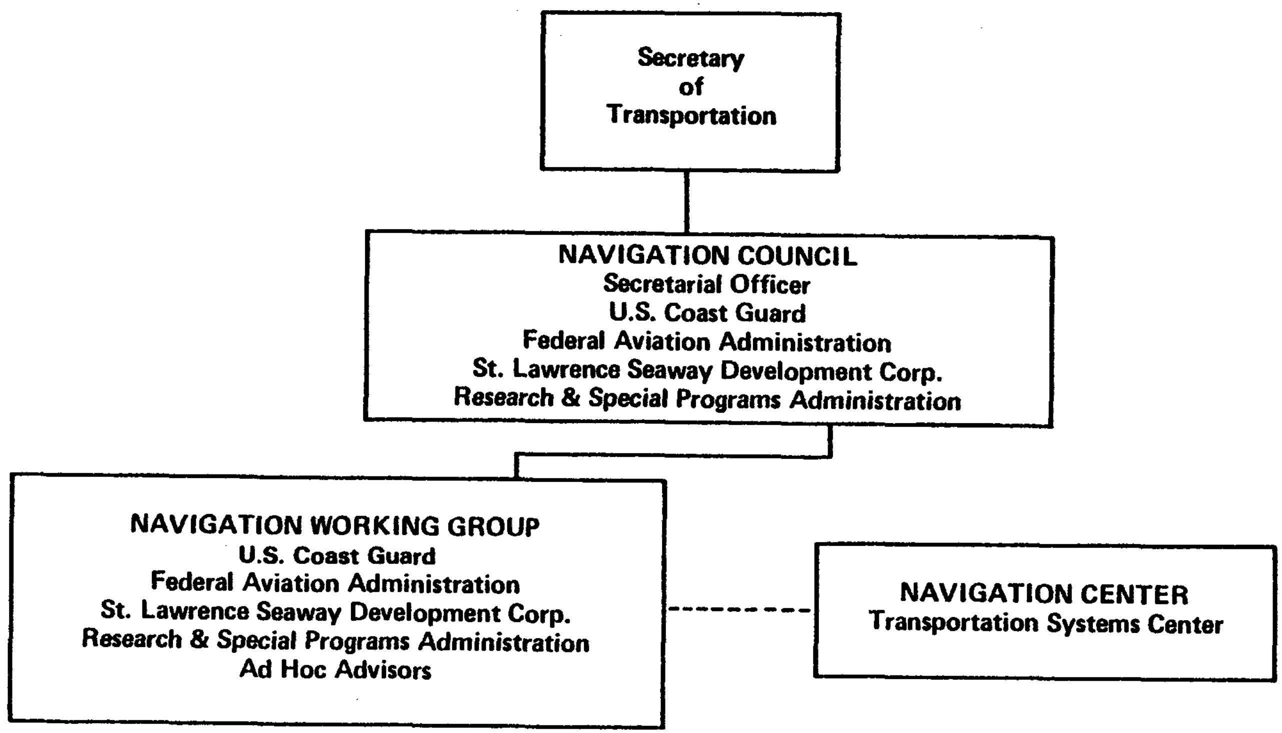


Figure 4.2.6.5 DOT Navigation Structure

4.2.6.8 These ten categories of current common-user radio-navigations systems are covered in the planning of the FRP:

Loran-A
Loran-C
Omega
VOR, VOR/DME, VORTAC
TACAN
ILS
TRANSIT
Radiobeacons
MLS
NAVSTAR-GPS

This list may be compared with the eight system categories considered in the 1977 DOT NPN; cf paragraph 4.2.4.3. The FRP does not cover systems that function mainly for surveying, surveillance and communications. The FRP includes changes to the 1977 DOT NPN and the U. S. Department of Defense (DOD) Joint Chiefs of Staff (JCS) Master Navigation Plan (MNP) of 1978.

4.2.6.9 Applications of the navigation systems listed in paragraph 4.2.6.8 are shown in Figure 4.2.6.9 according to the FRP. In this figure, ILS and MLS are combined; and VORTAC is presumably included under the heading of either VOR/DME or TACAN, both of which are shown as having the same applications and the same categorizations. Each application in Figure 4.2.6.9 is categorized as either a primary (P) system, or a secondary/supplemental (S) system, or a system in evaluation (E).

SYSTEM	VOR/DME	TACAN	LORAN-A***	OMEGA	LORAN-C	RADIO-BEACON (NDB/RBN)	ILS/MLS	TRANSIT	NAVSTAR GPS
Phase of Navigation									
AIR									
ENROUTE/TERMINAL									
*Remote Area	E	E	—	E	E	S	—	—	E
*Helicopter	E	E	—	E	E	S	—	—	E
Oceanic En route	—	—	—	P	—	—	—	—	E
Domestic En route	P	P	—	S	E	S	—	—	E
Terminal	P	P	—	—	E	S	—	—	E
APPROACH/LANDING									
Non Precision	P	P	—	—	E	S	—	—	E
Precision	—	—	—	—	—	—	P	—	—
MARINE									
Oceanic	—	—	—	P	S	S	—	P	E
Coastal	—	—	—	—	P	S	—	—	E
*Harbor & Harbor Approaches	—	—	—	—	E	—	—	—	E
*Inland Waterways	—	—	—	—	—	—	—	—	—
LAND**									
AVM/AVL	—	—	—	—	E	—	—	—	E
Site Registration	—	—	—	—	E	—	—	S	E
SPACE									E

LEGEND
P — Primary System
S — Secondary/Supplemental System
E — System in Evaluation
*New Requirement
**This area is under assessment
***All US LORAN-A service is being terminated no later than December 31, 1980

Figure 4.2.6.9 Radionavigation System Applications

4.2.6.10 Loran-C, TRANSIT, and NAVSTAR-GPS are the only systems listed as applicable to land navigation (in Figure 4.2.6.9); but none of these three systems is categorized as a primary system for land navigation. TRANSIT is categorized as a secondary/supplemental system for site registration. TRANSIT may be acceptable by the civil sector for site registration; but TRANSIT is not acceptable for navigation/position-location of military land vehicles in a combat environment because the time interval between available TRANSIT fixes (paragraph 4.2.4.15) is too long.

4.2.6.11 Loran-C and NAVSTAR-GPS, which are the only other systems in Figure 4.2.6.9 applicable to land navigation, are listed only as systems in evaluation. The FRP does not specify a primary system for any type of land navigation.

4.2.6.12 Some of the common-user radionavigation systems shown in Figure 4.2.6.9 are adequate for some, but not all, military missions. The FRP lists which common-user systems serve, or do not serve, the missions of the U. S. Air Force, the U.S. Navy, the Defense Mapping Agency (DMA), and the U.S. Army. The list for the Army is given in Figure 4.2.6.12, from which Loran-A is omitted because the system is terminated.

MISSION	SYSTEM							
	GPS	LORAN-C	OMEGA	TACAN	TRANSIT	VOR/DME	RADIO-BEACONS	MLS/ILS
General Aerial Navigation	E			P		P	P	P
General Land Navigation of Wheeled Vehicles	E							
General Land Navigation of Tracked Vehicles	E							
General Navigation of Troop Units	E							
General Navigation of Marine Assault Patrol	E							
General Navigation of Sea Transport Vessels	E							
Aircraft Approach	E			S		S	S	P
Position Location of Aerial/Ground Sensors	E			S		P	S	E
Position Location of SIGINT/COMINT/DF Systems	E			P				
Position Location of COMINT Collection Systems	E							
SURVEYING								
Tube Artillery	E							
Missile Artillery	E							
Air Defense Artillery	E							
Mapping	E							
Mine/Counter mine (LAND)	E							
Special Projects	E							
Position/Navigation System Calibration	E							
Common POS/NAV Calibration	E							

LEGEND

P – Primary System
S – Secondary System
E – System in evaluation

*Special purpose systems are not reflected in this table.

Figure 4.2.6.12

U.S. Army Missions vs Selected Common-User Radionavigation Systems*

4.2.6.13 NAVSTAR-GPS is listed as a system in evaluation for every one of the 18 Army missions in Figure 4.2.6.12. This is a reflection of the FRP's optimistic viewpoint regarding the future success and universal applicability of NAVSTAR-GPS.

4.2.6.14 Aside from NAVSTAR-GPS, only 4 of the 18 Army missions in Figure 4.2.6.12 are listed as served by common-user navigation systems; and these 4 missions are served by only 4 of the systems, namely TACAN, VOR/DME, radiobeacons and MLS/ILS.

4.2.6.15 Three important Army missions in Figure 4.2.6.12 are: general land navigation of wheeled vehicles; general land navigation of tracked vehicles; and general navigation of troop units. NAVSTAR-GPS, as a system in evaluation, is the only one of the common-user systems that is shown as being applicable to these three important Army missions. Loran-D, the military version of Loran-C, is applicable to a number of the 18 Army missions in Figure 4.2.6.12; but the figure does not list Loran-D because it is not a common-user system and is therefore not in the scope of the FRP.

4.2.6.16 A well-prepared 5-year plan of Research, Engineering and Development (R, E&D) is presented by the DOT in the FRP, to assess the potential land applications of common-user radionavigation systems. The DOT Research and Special Programs Adminstration

(RSPA) has the responsibility for the R&D activities in this land navigation program. The program will evaluate Loran-C, NAVSTAR-GPS and proximity systems for use with civil land vehicles. Initially, emphasis will be on Loran-C. Potential land users include trucks, transit vehicles (e.g. busses), taxis, police cars, fire engines, ambulances, vehicles carrying dangerous or very valuable cargoes, highway maintenance departments, traffic records bureaus, and census bureaus. (Reference 4.4.21) (Also see Taradcom Technical Report 12496, paragraphs 6.3.10 through 6.3.13, and subsection 11.6 AVM/SR.)

4.2.6.17 The aforesaid R, E&D plans for land navigation (paragraph 4.2.6.16) are part of a broader plan, in the FRP, for selecting common-user radionavigation systems to be used in the future. This selection will be a coordinated DOD/DOT effort to recommend, by the year 1996, a system or mix of systems that will be optimum for the national interest. The flow diagram and timetable for this effort is shown in Figure 4.2.6.17, in which the year zero can be assumed to represent the year 1980.

4.2.6.18 The two most critical decision points in the flow diagram of Figure 4.2.6.17 are: the 1983 preliminary DOD/DOT recommendation on the selection of navigation systems; and the 1986 national decision on the final selection of navigation systems for the future .

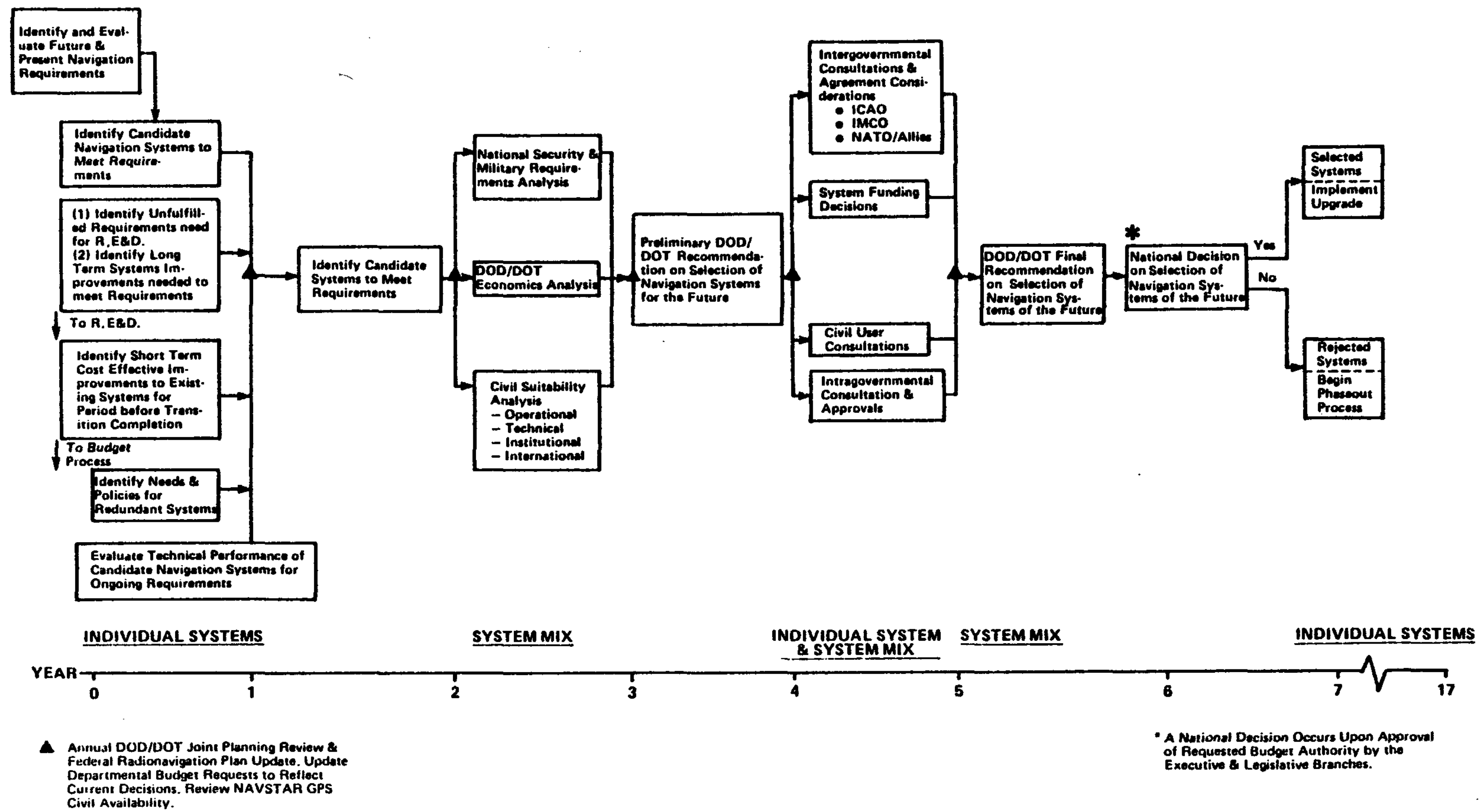


Figure 4.2.6.17

Selection of Initial Radionavigation Systems Mix

4.2.7 JCS MNP

4.2.7.1 The U. S. DOD Joint Chiefs of Staff (JCS) issued a revised "Master Navigation Plan" (MNP) in December 1980; (ref 4.4.7). This plan is denoted as the "1980 JCS MNP" or "1980 MNP" herein. Parts of the 1980 JCS MNP are classified Secret or Confidential, and parts are unclassified. The unclassified parts of the 1980 JCS MNP are the only parts of the 1980 JCS MNP used in preparing the present report.

4.2.7.2 The December 1980 JCS MNP and the July 1980 FRP were developed cooperatively in the same time frame of 1979-1980. This is indicated by: (1) the historical background described in section 4.3.1 herein; (2) a statement in the 1980 JCS MNP that "the MNP provides an information base for preparation of the DOD position for the FRP"; (3) a statement in the 1980 JCS MNP that it supercedes the 1978 JCS MNP (ref 4.4.8); (4) a statement in the FRP that it incorporates the latest changes in the 1978 JCS MNP; and (5) the fact that the 1980 JCS MNP described each navigation system using the basic performance parameters developed by the DOD-DOT working group for use in the FRP.

4.2.7.3 The 1980 FRP addressed common-user (paragraph 4.2.6.7) navigation systems. The 1980 JCS MNP supplemented the 1980 FRP, in effect, by addressing the uniquely military requirements for navigation. At the same time, special effort was taken, in preparing the 1980 MNP, to consider the needs of U. S. civil users of navigation systems. Consideration was given also to the NATO (North Atlantic Treaty Organization) military navigation requirements, in the preparation of the 1980 JCS MNP.

4.2.7.4 The 1980 JCS MNP is a broad plan, but it does not purport to cover every possible topic of navigation. For example, no significant reference is made to celestial or visual navigation (piloting). The was the case also in the DOT national plans for navigation.

4.2.7.5 The 1980 JCS MNP lists service and DOD agency requirements for navigation according to originator, mission to be accomplished, and accuracy required. Each navigation system is described by its basic performance parameters. The systems are further categorized by their primary function and method of operation.

4.2.7.6 A feature of the 1980 JCS MNP is that it presents the first DOD-wide 25-year navigation systems plan, projecting system deployments and system replacements. The plan, from the year 1980 through and beyond the year 2000, is summarized graphically in the six Figures described below.

4.2.7.7 The Figures give the planned phase-in/phase out of specific navigation systems. The phase-in plan for a developing system is shown at the top of each Figure, followed by the phase-out plan for existing systems. The Figures show also those systems that are not to be replaced.

4.2.7.8 Figures 4.2.7.8-A, -B, and -C show the 25-year phase-in/phaseout plan for cooperative, i.e. station-referenced (paragraph 3.4.2)systems.

4.2.7.9 Figure 4.2.7.9 gives the phase-in/phase-out plan for JTIDS and PLRS.

4.2.7.10 Figure 4.2.7.10 displays the phase-in/phase-out schedule for self-contained systems.

4.2.7.11 Figure 4.2.7.11 shows systems that are planned to continue beyond the year 2000.

4.2.7.12 In preparing the 25-year plans shown in Figures 4.2.7.8-A, 4.2.7.8-B, 4.2.7.8-C, 4.2.7.9, 4.2.7.10 and 4.2.7.11, the following major assumptions were used:

(U)
PHASE-IN/PHASE-OUT 1/
COOPERATIVE SYSTEMS
UNCLASSIFIED

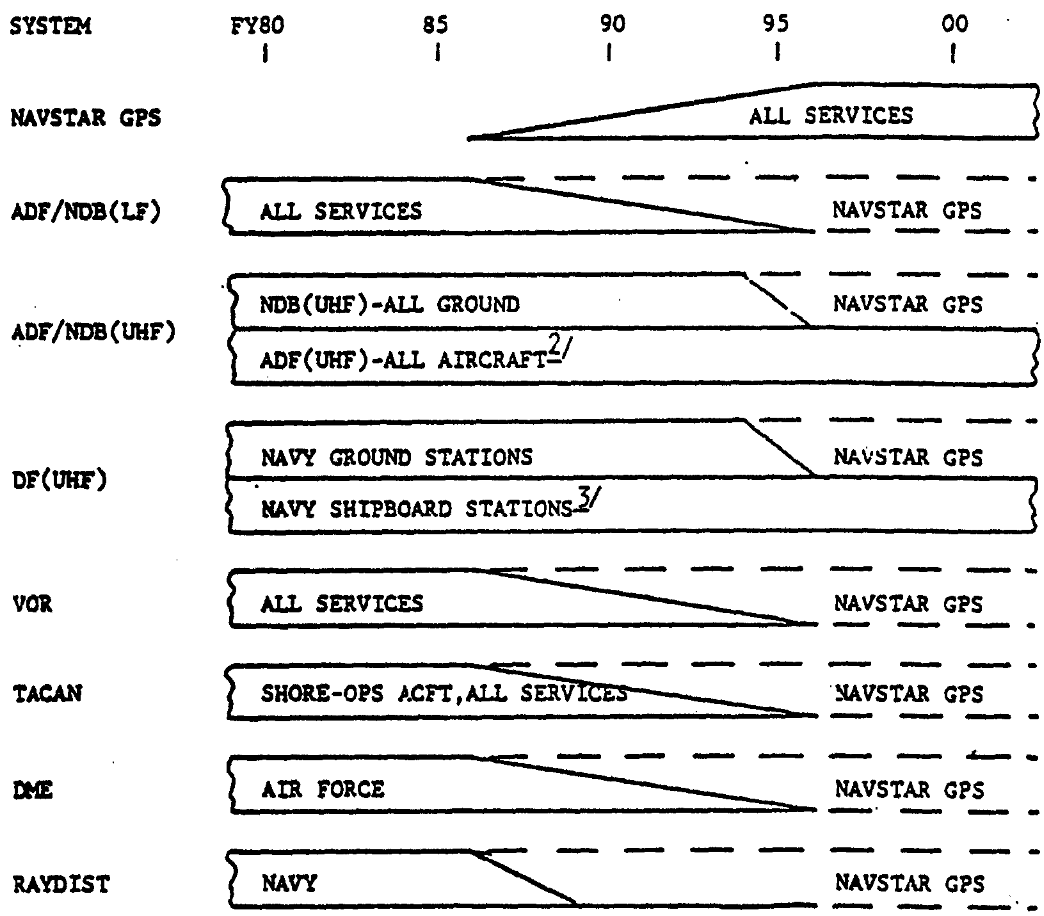


Figure 4.2.7.8-A
JCS MNP 25-Year Plan
Cooperative Systems

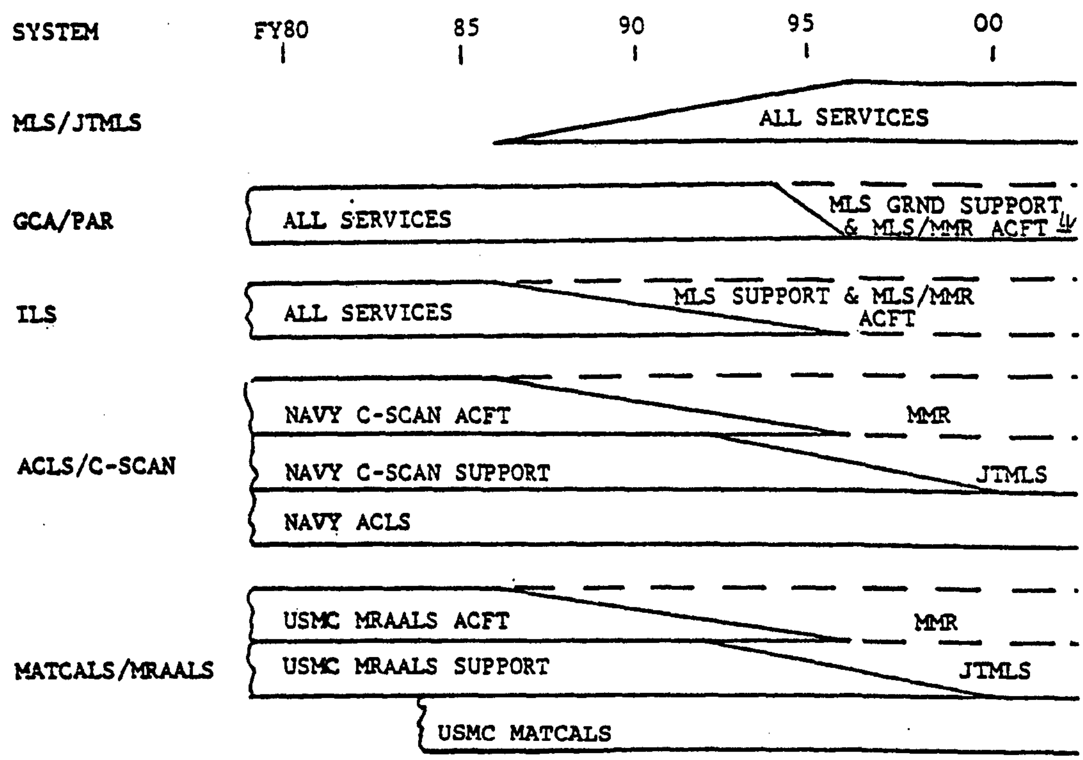
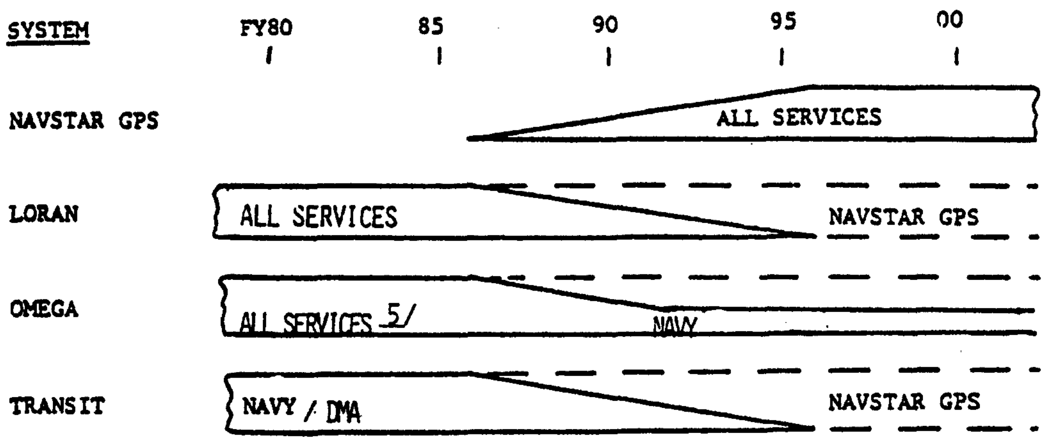


Figure 4.2.7.8-B

JCS MNP 25-Year Plan

Cooperative Systems



1/ SYSTEM SUPPORT IS ASSUMED TO BE AVAILABLE AT THE IOC OF THE USER EQUIPMENT AND REMAINS IN SERVICE UNTIL ALL SIGNIFICANT USE HAS ENDED.

2/ RETAIN AIRCRAFT ADF (UHF) FOR RENDEZVOUS AND SEARCH AND RESCUE.

3/ RETAIN DF (UHF) FOR SEARCH AND RESCUE.

4/ MULTIMODE RECEIVER.

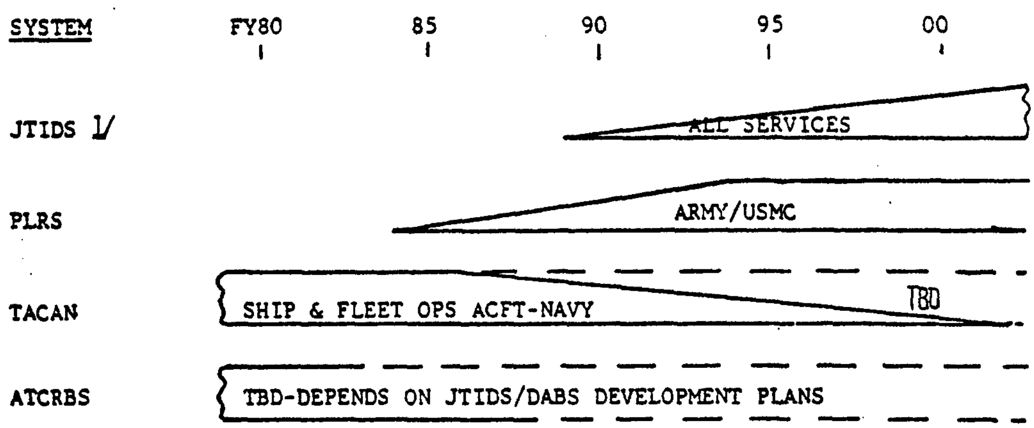
5/ CRITICAL MISSIONS PERFORMED BY SUBMARINES AND OTHER MAJOR UNITS REQUIRE NAVIGATION SUPPORT WITHOUT EXPOSURE OF ANTENNAS OR AS A BACKUP MEANS OF NAVIGATION. THIS REQUIREMENT MUST BE SATISFIED OR WAIVED PRIOR TO PHASE-OUT.

Figure 4.2.7.8-C

JCS MNP 25-Year Plan

Cooperative Systems

(U)
PHASE-IN/PHASE-OUT
JTIDS/PLRS
UNCLASSIFIED



1/ SELECTED PLATFORMS ONLY.

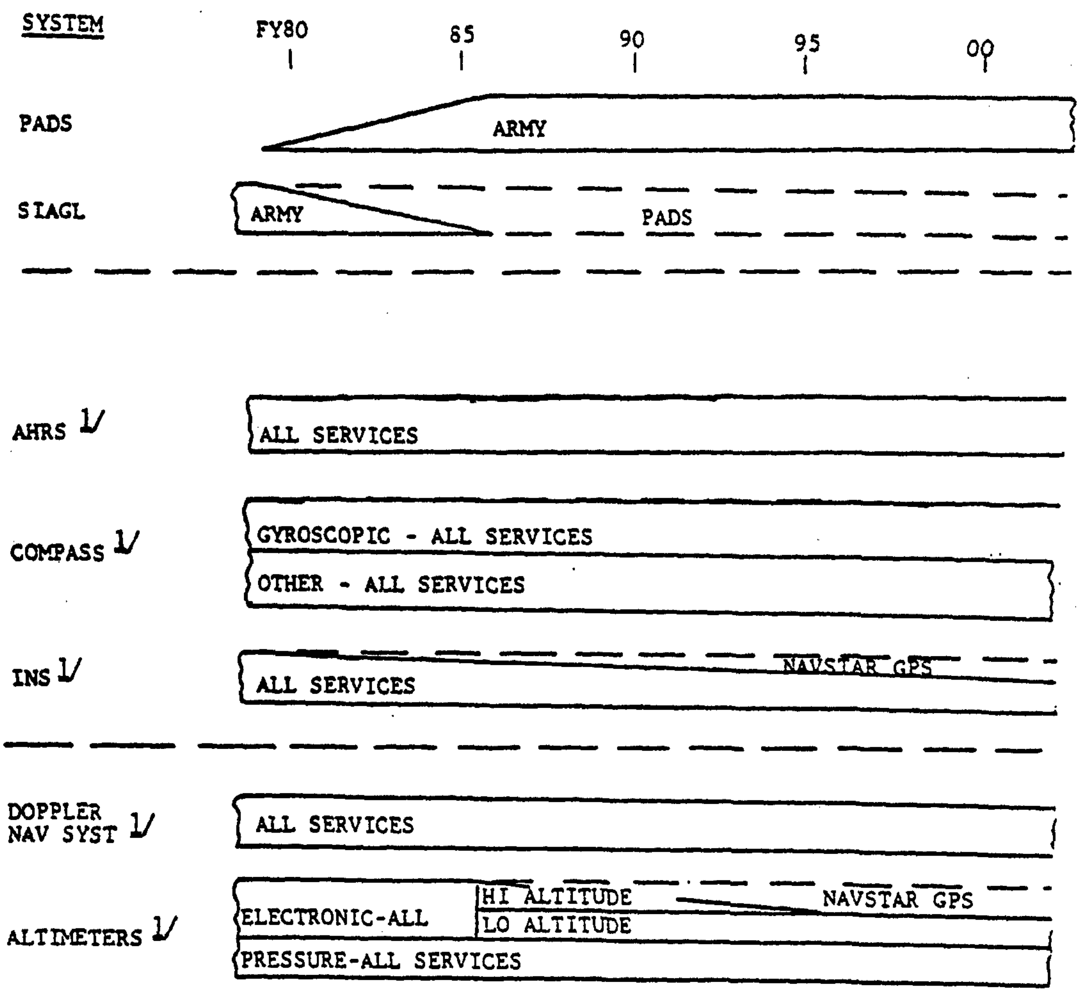
Figure 4.2.7.9

JCS MNP 25-Year Plan

JTIDS/PLRS

(U)
PHASE-IN/PHASE-OUT
SELF-CONTAINED SYSTEMS

UNCLASSIFIED



1/ REPLACE WITH IMPROVED SYSTEMS AS REQUIRED.

Figure 4.2.7.10
JCS MNP 25-Year Plan
Self-Contained Systems

(U)
CONTINUING SYSTEMS
UNCLASSIFIED

SYSTEM	FY80 — 85 — 90 — 95 — 00
SURFACE NAV RADAR	ARMY/NAVY
ATC RADAR	ALL SERVICES
DEPTH FINDER/ DETECTORS	NAVY
TERCOM	AIR FORCE/NAVY
BOTTOM CONTOUR	NAVY (SUBMARINE)

NOTE: REPLACE WITH IMPROVED SYSTEMS AS REQUIRED.

Figure 4.2.7.11
JCS MNP 25-Year Plan
Continuing Systems

(a) NAVSTAR-GPS will be accepted for use by NATO and for national/international civil use.

(b) NAVSTAR and/or JTIDS can satisfy relative navigation requirements on platforms equipped with both systems.

(c) MLS/MMR is required for most military aircraft by FY 1995.

(d) JTMLS will satisfy accuracy, space and weight requirements for military tactical systems.

(e) All cooperative type POS/NAV systems can be jammed or meaconed.

(f) Self-contained navigation systems are required for position and velocity in hostile environments.

(g) MLS will replace ILS for fixed-base operations.

4.2.7.13 In the foregoing list of assumptions, the following are definitions of abbreviations that are not defined in TARADCOM Technical Report No. 12496:

MLS = Microwave Landing System

MMR = Multimode Receiver

JTMLS = Joint Tactical Microwave Landing System

ILS = Instrument Landing System

4.2.7.14 The 1980 JCS MNP mentions that DOD is developing a computer model for DOD navigation systems planning.

4.2.7.15 NAVSTAR-GPS is the keystone of the 1980 JCS MNP 25-year plan. The plan relies upon a successful NAVSTAR-GPS program with an 18-satellite system achieved in the late 1980s. This will depend upon adequate budget support for NAVSTAR-GPS, as well as upon the technical performance of the system.

4.2.7.16 NAVSTAR-GPS was the keystone also in three other major national plans for navigation, namely: the 1978 GAO Nav Report (section 4.2.5); the 1979 DOD POS/NAV Plan (section 4.3.2); and the 1980 FRP (section 4.2.6). If NAVSTAR-GPS should fail to meet the expectations of these four national plans for navigation, as regards accuracy, coverage, reliability, user equipment cost, or system funding, then national plans for navigation will have to be redrawn drastically.

4.3 Addenda

4.3.1 DOD-DOT Interagency Agreement

4.3.1.1 When the U. S. Congress passed the INMARSAT (International Maritime Satellite) legislation in late 1978, Congress requested the executive branch of the Government to make a complete review of all navigation systems and services provided or used by the Government. Principal objectives of this review were to reduce Government costs and minimize duplication. This Congressional action may have been stimulated partly by the 1978 GAO Nav Report (Section 4.2.5 herein).

4.3.1.2 In response to the Congressional requirement, an interagency working group was set up in late 1978 to study planning among various United States Government agencies responsible for radionavigation services for both civil and military users. The group was co-chaired by the Office of Management and Budget (OMB) and by the National Telecommunications & Information Administration (NTIA) and was composed of representatives from the DOT, DOD, National Aeronautics and Space Administration (NASA), Department of Commerce (DOC), Department of State (DOS) and the Central Intelligence Agency (CIA).

4.3.1.3 The interagency working group recommended that management of navigation systems within the Federal Government be accomplished jointly by the Department of Defense and the Department of Transportation, and that these two agencies should prepare a Federal navigation plan. As a result of this recommendation the DOD and DOT executed an Interagency Agreement entitled "Coordination of Radionavigation Planning", April 1979, (Reference 4.4.9), denoted as the "DOD-DOT Interagency Agreement" herein.

4.3.1.4 The DOD-DOT Interagency Agreement established procedures and policies for working relationships between DOD and DOT for coordination of radionavigation planning. The DOD and DOT agreed to prepare and publish jointly the 1980 FRP (section 4.2.6 herein), and to consider only common-user radionavigation systems in the FRP. Systems unique to the DOD were to be described and discussed in a revised edition (1980) of the JCS MNP (section 4.2.7 herein).

4.3.2 1979 DOD POS/NAV Plan

4.3.2.1 A "POS/NAV Systems Plan for DOD" (ref 4.4.10), denoted as the "1979 DOD POS/NAV Plan" herein, was prepared in the Pentagon in November 1979. This document identified itself as a first iteration of a comprehensive plan for improving POS/NAV systems capabilities while reducing duplication and costs where possible. The Plan was expected to be important to future budget reviews, in view of the fact that OMB and the Congress were encouraging DOD and DOT to improve planning for navigation systems. (Paragraphs 4.2.5.2.1 and 4.2.5.2.2) The 1979 DOD POS/NAV Plan was a precursor to the 1980 JCS MNP.

4.3.2.2 Seven major assumptions were made in the 1979 DOD POS/NAV Plan. With one exception, these assumptions were identical to the seven major assumptions used to prepare the 25-year plan in the 1980 JCS MNP, as listed in paragraph 4.2.7.12 herein. The exception was that the 1980 JCS MNP deleted an assumption from the 1979 DOD POS/NAV Plan, reading "NAVSTAR will meet or exceed predicted position and velocity accuracies", and added assumption (g), "MLS will replace ILS for fixed-base operation".

4.3.2.3 As stated in paragraph 4.2.7.15, the 1979 DOD POS/NAV Plan relied heavily upon the success of NAVSTAR-GPS. Assuming that NAVSTAR-GPS will meet or exceed predicted position and velocity accuracies, the 1979 DOD POS/NAV document planned to have NAVSTAR-GPS replace the following existing twelve systems:

- LORAN C, D, C/D
- OMEGA
- TRANSIT
- ADF/NDB (Non-Directional Beacon) (LF)
- ADF/NDB (Non-Directional Beacon) (UHF)
- DF (UHF)
- VOR
- TACAN/DME
- RAYDIST "T"
- Altimeter (Electronic-High Altitude)
- Doppler Navigation (Remove only from INS-equipped aircarft when NAVSTAR-GPS is installed)
- INS (Remove one system from triple-redundent INS platforms when NAVSTAR-GPS is installed)

4.3.2.4 Schedules and costs for phase-in/phase-out of all U. S. Army, Navy and Air Force navigation systems are given in three detailed appendices to the 1979 DOD POS/NAV Plan.

4.4 References and Bibliography for National Plans for Navigation

4.4.1 "Department of Transportation National Plan for Navigation".
Federal Aviation Administration & U. S. Coast Guard.
U. S. Dept. of Transportation.
May 1970. 32 pages. Washington, DC.
AD-706965

4.4.2 "Department of Transportation National Plan for Navigation".
Federal Aviation Administration & U.S. Coast Guard.
U. S. Dept. of Transportation.
28 April 1972. 34 pages. Washington, DC.
AD-741944

4.4.3 "Annex to the Department of Transporation National Plan for Navigation".
U. S. Dept. of Transporation.
15 July 1974. 4 pages. Washington, DC.
Also published as FR Doc. 74-16557 in the Federal Register, Vol 39, No 140, page 26468, 19 July 1974.

4.4.4 "Department of Transporation National Plan for Navigation".
Arthur Goldsmith, Editor
U. S. Dept. of Transportation (DPB-22).
Report DOT-TST-78-4
14 Nov 1977. 116 pages. Washington, DC.
AD-A052269.
U. S. Government Printing Office: 1978-721-108/699

4.4.5 "Navigation Planning -- Need For A New Direction".
Report to the Congress by the Comptoller General of the United States.
U. S. General Accounting Office.
GAO Code 941100. LCD-77-109. B-180715.
21 March 1978. 107 pages.

4.4.6 "Federal Radionavigation Plan".
U. S. Dept. of Defense (OUSDRE) & U. S. Dept. of Transportation (DPB-22).
DOD Report No 4650.4-P.
DOT Report No DOT-TSC-RSPA-80-16.
July 1980. Washington, DC.

Volume	I,	90 pages,	AD-A093774
Volume	II	50 pages,	AD-A093775
Volume	III	46 pages,	AD-A093776
Volume	IV,	124 pages,	AD-A093777

4.4.7 "Joint Chiefs of Staff, Master Navigation Plan" (U).
The Joint Chiefs of Staff
U. S. Dept. of Defense.
SM-686-80
3 December 1980.
The Pentagon, Washington, DC 20301.
Secret document. See paragraph 4.2.7.1

4.4.8 "Joint Chiefs of Staff, Master Navigation Plan" (U).
The Joint Chiefs of Staff
U. S. Dept. of Defense.
SM-551-78.
6 July 1978.
The Pentagon, Washington, DC 20301.
Secret document. Not reviewed for this report.

4.4.9 "Coordination of Radionavigation Planning"
Interagency Agreement between DOD and DOT.
U. S. Dept. of Defense & U. S. Dept. of Transportation.
17 April 1979. 4 pages.

4.4.10 "POS/NAV Systems Plan for DOD".
U. S. Dept. of Defense.
1 November 1979.
42 pages plus 83 pages of Appendix.
The Pentagon, Washington, DC 20301.

4.4.11 "Navigation Coordination and Planning".
Office of the Secretary,
U. S. Dept. of Transportation.
Order DOT-1120.32.
27 April 1979. 6 pages. Washington, DC

4.4.12 "Annual Reports of the Technical Committees for the
12-Month Period Ending 30 May 1949".
Paul Rosenberg, Coordinator.
Institute of Navigation.
Revised & enlarged edition, 16 August 1949.
96 pages. Washington, DC.

4.4.13 "Report on Electronic Systems of Air Navigation".
Report of Special Working Group Nine.
Air Traffic Control & Navigation Panel,
Air Coordinating Committee.
Report PB-111344.
March 1954. 52 pages.
DOC Office of Technical Services. Washington, DC.

4.4.14 "Electronic Aids to Navigation"
Report of Special Committee No. 60,
Radio Technical Commission for Marine Services.
RTCM Report 157-68/DO-44
17 October 1968. 58 pages. Washington, DC.

4.4.15 "Report of the Department of Transportation Air Traffic
Control Advisory Committee".
U. S. Dept. of Transportation.
December 1969.
Volume 1: 105 pages. Volume 2: 483 pages.
U. S. Government Printing Office, 1970:
O-375-448, 375-449.
Washington, DC

4.4.16 "Information on Management and Use of the Radio Frequency
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and the Office of Telecommunications Policy.
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4.4.17 "Radio Navigation Study".
Computer Sciences Corp.
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Executive Office of the President.
Final Report. February 1975.
Volume 1, Summary, 50 pages, AD-A010114.
Volume 2, Appendices A & B, 143 pages, AD-A010115.

4.4.18 "Radio Navigation Systems Economic and Planning Analysis".
Computer Sciences Corp.
Prepared for the Office of Telecommunications Policy,
Executive Office of the President.
Final Report. July 1977.
3 volumes. CSC/SD-77/3582.

4.4.19 "An Overview of Enroute Radio Navigation Services".
Carlo Yulo.
U. S. Dept. of Transportation,
Federal Aviation Administration,
Systems Research & Development Service.
Report No. FAA-RD-76-187.
August 1976. 22 pages. Washington, DC.

4.4.20 "FAA Activities in Support of the Federal Radionavigation Plan"
J. C. Heurtley & J. W. Bradley.
Proceedings of the National Aerospace Symposium.
11-13 March 1980, Dayton, Ohio.
Pages 72-84.
Institute of Navigation, Washington, DC.

4.4.21 "Proceedings of the Civil Radionavigation Users' Workshop"
Department of Transportation, DOT-RSPA-80-7, & Institute of Navigation.
9-11 October 1979.
DOT Report No. DOT-RSPA-DPB-20-80-3.
198 pages.
For land navigation, see pages 19-32; 40-41; 62-83.

5. NAVSTAR-GPS

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5.1 Introduction

5.1.1 The system that is the subject of Section 5 of this report is denoted by one or more of the following synonyms in the literature and in other reports and documents: NAVSTAR Global Positioning System; NAVSTAR-GPS; GPS; GPS-NAVSTAR; NAVSTAR; Global Positioning System. For conciseness, GPS is used in the text of Section 5 to denote all of the synonyms.

5.1.2 GPS is a system for position-location/navigation (POS/NAV) by means of satellites (other than the Moon) orbiting the Earth. These satellites are extra-terrestrial bodies that man has added to the natural extra-terrestrial celestial bodies (the Moon, Sun, planets and stars) that he has used for position-location (celestial navigation) through the ages, (Reference 5.10.1). POS/NAV by means of GPS differs from position-location by means of natural celestial bodies in these basic respects:

(a) POS/NAV by GPS uses the radio portion of the electromagnetic spectrum, whereas traditional celestial navigation uses the visible spectrum.

(b) Distance and velocities are measured in POS/NAV by GPS, whereas angular positions are measured in traditional celestial navigation; i.e. GPS is a rho system, whereas celestial navigation is a theta system.

(c) GPS gives the user his position-location in three dimensions, but traditional celestial navigation gives position-location in two dimensions only.

(d) GPS provides precise time to the user, but the celestial navigator must obtain the time by means that are independent of his celestial observations, e.g. by a chronometer.

(e) The GPS user can derive his velocity from GPS signals almost instantaneously, whereas the celestial navigator can only calculate his average velocity in an appreciable time interval by determining his position-locations at the beginning and end of the time interval.

5.2 Program History and Schedule

5.2.1 The following is a chronology of the POS/NAV satellite projects that preceded and led up to GPS.

1950-1958:
U. S. Naval Research Laboratory conducts experiments with radio frequency methods for tracking early satellites; e.g. Minitrack and the Naval Space Surveillance System, using interferometry.

1958:
TRANSIT (also called Navy Navigation Satellite System or NNSS or NAVSAT) development program is initiated by the U. S. Navy for the particular purpose of furnishing navigation to the Fleet Ballistic Missile submarine. References: 5.10.2; 5.10.14; 5.10.15; 6.6.1, pages 131-134.

January 1964:
TRANSIT becomes operational on U. S. Polaris submarines.

1964:

U. S. Air Force conducts preliminary concept formulations and system design studies for "System 621B", a highly accurate three-dimensional POS/NAV system. The concept and system techniques are subsequently verified in a series of tests and experiments at Holloman Air Force Base and the White Sands Missile Range.

September 1964:

TIMATION (TIMenavigATION) satellite development project begins at U. S. Naval Research Laboratory with a task from the Bureau of Naval Weapons.

31 May 1967:

TIMATION I satellite is launched by U. S. Navy. TIMATION I is the first demonstration of range measurements from a time synchronized satellite.

29 July 1967:

TRANSIT is made available to non-military users.

1968:

First non-military commercial TRANSIT receiving sets become available.

30 September 1969:

TIMATION II is launched by the U. S. Navy with a two-frequency ranging system to compensate for ionospheric refraction.

17 April 1973:

The Deputy Secretary of Defense issues a Memorandum titled "Defense Navigation Satellite Development Program", designating the Air Force as the Executive Service to coalesce the POS/NAV satellite concepts that were being developed by the Navy and the Air Force into a Defense Navigation Satellite System (DNSS).

26 November 1973:
U. S. Air Force prepares Development Concept Paper #133 for a DNSS.

13 December 1973:
Development Concept Paper #133 is briefed to the DSARC (Defense Systems Acquisition Review Council).

22 December 1973:
Secretary of Defense approves the DNSS proposed by the Air Force in Paper #133, and renames the program the NAVSTAR Global Positioning System.

5.2.2 The history of the development program of GPS from 1973, and the planned schedule of the program through 1987, are given in Figure 5.2.2.A (Reference 4.4.6, Vol. I, page I-60) and Figure 5.2.2.B (Reference 5.10.3). In these figures, DSARC is the abbreviation for the Defense Systems Acquisition Review Council of the U. S. Department of Defense. See also Reference 5.10.4.

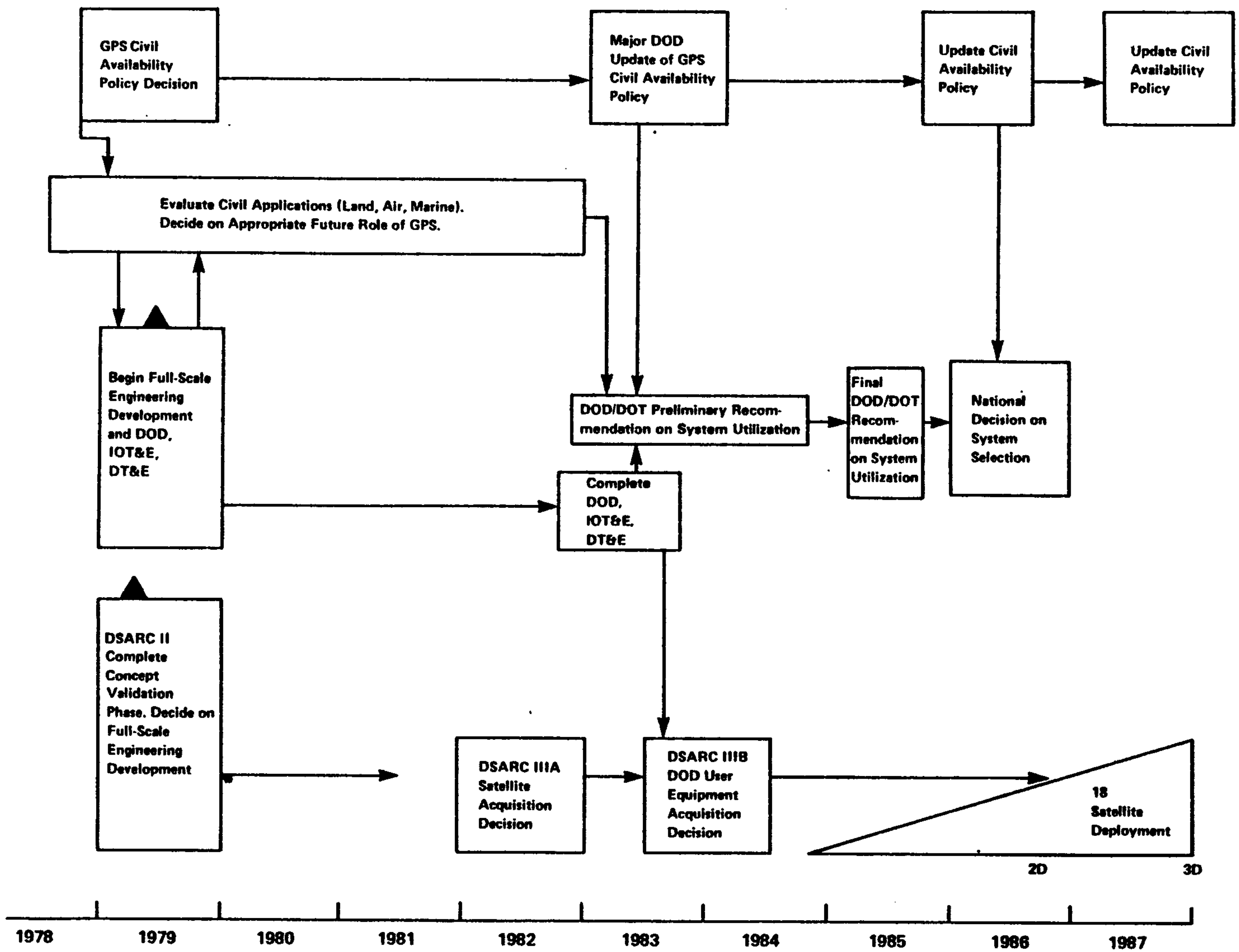

Figure 5.2.2.A. GPS Program

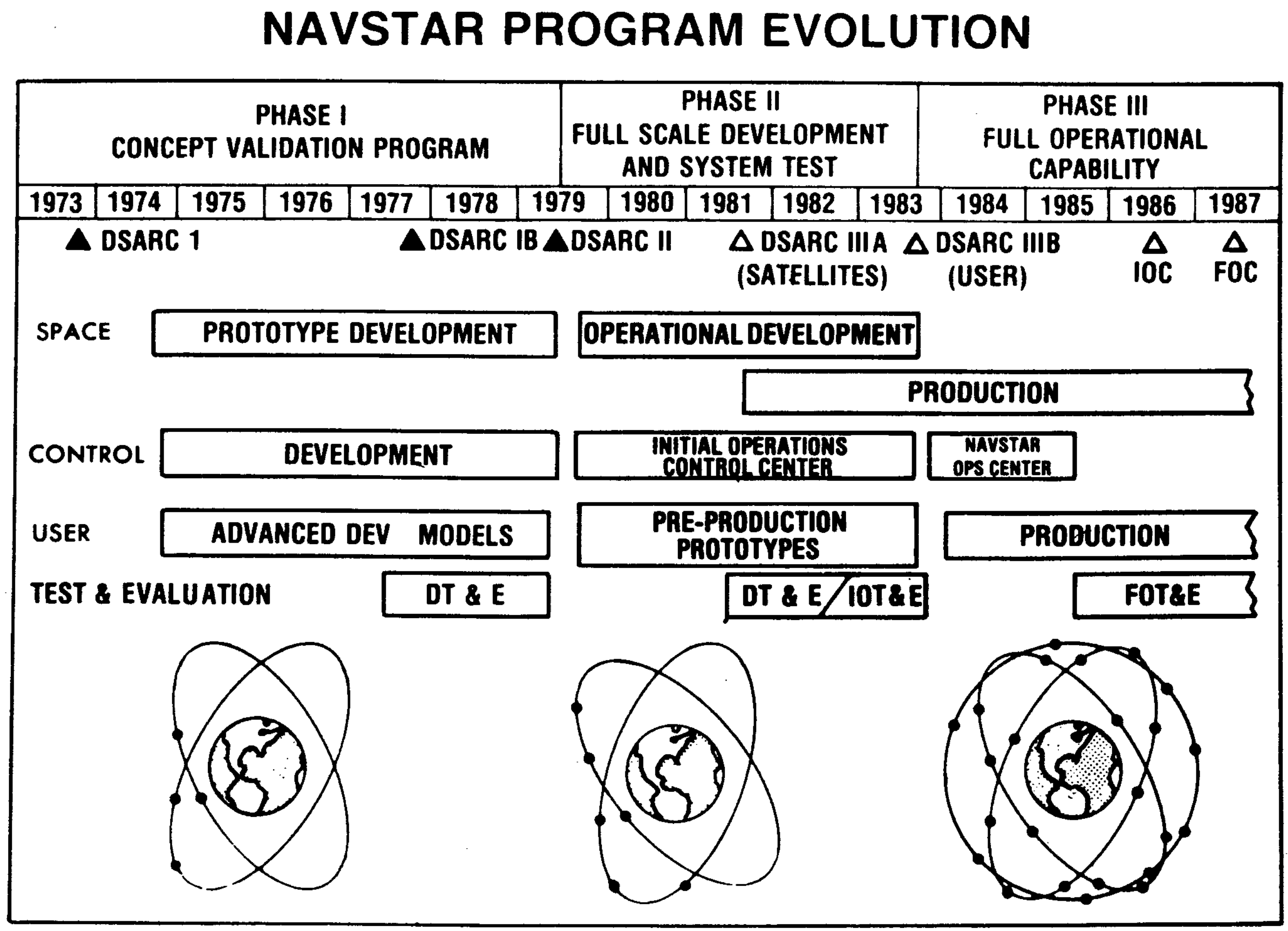
NAVSTAR PROGRAM EVOLUTION
PHASE I
CONCEPT VALIDATION PROGRAM
PHASE II
FULL SCALE DEVELOPMENT
AND SYSTEM TEST
PHASE III
FULL OPERATIONAL
CAPABILITY
1973
1974
1975
1976
1977
1978
1979
1980
1981
1982
1983
1984
1985
1986
1987
DSARC 1
DSARC IB
DSARC II
DSARC IIIA
(SATELLITES)
DSARC IIIB
(USER)
IOC
FOC
SPACE
PROTOTYPE DEVELOPMENT
OPERATIONAL DEVELOPMENT
PRODUCTION
CONTROL
DEVELOPMENT
INITIAL OPERATIONS
CONTROL CENTER
NAVSTAR
OPS CENTER
USER
ADVANCED DEV MODELS
PRE-PRODUCTION
PROTOTYPES
PRODUCTION
TEST & EVALUATION
DT & E
DT & E
IOT&E
FOT&E

Figure 5.2.2.B

5.3 GPS Objectives

5.3.1 The military requirements for an ideal POS/NAV system for air, marine and land vehicles are:

(a) World-wide coverage (with no terrain-shadowed dead spots).

(b) User equipment must be passive.

(c) Use can be denied to an enemy.

(d) Non-saturable.

(e) Resistant to MIJI (meaconing, interference, jamming and intrusion).

(f) Resistant to natural disturbances and to hostile attack.

(g) Continuously available for fix information.

(h) Effective real-time response.

(i) Available for combined military operations with allies.

(j) Provide a common grid for all users.

(k) Position-location accuracy not degraded by changes in altitude.

(l) Accuracy retained during high energy maneuvers.

(m) Maintainable at the operating level.

(n) No frequency allocation problem.

(o) Self-contained in the user vehicle.

5.3.2 The requirements listed in paragraph 5.3.1 above are slightly re-worded from the requirements issued by the Joint Chiefs of Staff (JCS) in the 1978 Master Navigation Plan. The JCS MNP requirements have appeared, since 1978, in several unclassified publications. References: 4.4.6, Volume II, pages II-36, II-37; 4.4.8; 5.10.5; 5.10.6, pages 4-5.

5.3.3 No existing POS/NAV system meets all the requirements listed in 5.3.1. The objective of GPS is to meet all the aforesaid requirements except (o) the requirement for the system to be self-contained aboard the user vehicle.

5.3.4 However, the self-contained requirement is partially satisfied by combining GPS with an inertial system that is carried aboard the vehicle. GPS can be used periodically to correct for the inevitable drift of the inertial system. The inertial system provides the self-containment feature for periods of time between GPS fixes. GPS provides long term accuracy. The inertial navigation system (INS) can provide navigation during GPS outages when GPS signals might not be available or usable; and the INS can shorten the time needed to re-acquire the GPS signals when they again become usable. Reference 5.10.25. A combined GPS-INS system is sometimes called aided-GPS.

5.4 Space Segment

5.4.1 GPS is composed of three system segments: the space segment (also called the satellite segment); the control segment; and the user segment. These segments of the system are the subjects of Sections 5.4, 5.5 and 5.6 herein respectively. References 5.10.3 through 5.10.13.

5.4.2.1 GPS is basically a ranging system. The user's equipment receives a radio signal from a GPS satellite, measures the time of travel from the satellite to the user, and multiplies this travel time by the speed of radio propagation (the speed of light) to obtain the distance from the satellite to the user. The user lies somewhere on the surface of a sphere, centered on the satellite, with a radius equal to the distance from the satellite to the user. By the same method, the user measures his distances from two other GPS satellites. Each such distance is the radius of another sphere, on the surface of which the user lies, with each sphere centered on the satellite. The point of intersection of the three spherical surfaces is the position-location (a "fix" in navigation terminology) of the user in three dimensions.

5.4.2.2 The signal received by the user equipment from each satellite includes data that tells the user equipment the time, on the satellite's clock, when the signal left the satellite. In order to measure the time interval between transmission and reception, the user equipment must have its own clock that is synchronized with the satellite's clock. If the user's clock and its synchronization with the satellite's clock were accurate enough, the point of intersection of the three spherical surfaces (paragraph 5.4.2.1) would be an accurate fix; and each fix would require ranging to only three satellites.

5.4.2.3 At the speed of light, 3×10^{10} cm/sec, a ranging accuracy of one meter requires a timing accuracy of 3 nanoseconds (3×10^{-9} second). In order to maintain this accuracy for a period of one day, a clock would need an accuracy of the order of 10^{-13} second. Only atomic clocks (e.g. rubidium or cesium) give this accuracy; and atomic clocks are too costly to put one into every user equipment.

5.4.2.4 The alternative to an atomic clock in each user equipment is to range with four (instead of three) satellites. Each such range, or range estimate, made by the user equipment with a clock that is not sufficiently precise and/or not sufficiently well synchronized with the satellite's clock, is called a pseudo-range. Four simultaneous equations are set up in the user's equipment, using four pseudo-ranges to four GPS satellites. A computer in the user's equipment solves the equations to yield four unknown quantities, namely: the error between the user's clock and the satellite's clock; and the three dimensions of the user's position-location. Thus ranging measurements to four GPS satellites are necessary and sufficient to give an accurate fix with an imprecise clock in the user's equipment.

5.4.3 A constellation of 24 satellites was originally planned for the space segment of the operational GPS with these nominal orbital parameters for each satellite:

Period: 12 hours.

Eccentricity: zero (Circular orbit).

Altitude: 10,900 nautical miles (20,200 Km).

Inclination: 55 degrees.

Argument of perigee: zero degrees.

3 orbital planes, each containing 8 satellites.

120 degrees between the 3 planes.

45 degree separation between the satellites in each plane.

5.4.4 The 24-satellite constellation would give complete world-wide coverage. At least 6, and as many as 11 satellites would be visible electronically at 5 degrees or more above the horizon at any time anywhere in the world. This constellation would more than meet the requirement (paragraph 5.4.2.4) that ranging be available to four satellites simultaneously. The user's receiver can select, either manually or automatically, the four of the visible satellites that offer the lowest value of GDOP (geometric dilution of precision), i.e. the best accuracy. (GDOP is a measure of accuracy of a fix, taking into account only the geometry of the situation; in this case taking into account only the relative 3-dimensional angles of the satellites with respect to the user equipment.)

5.4.5 For purposes of economy, the Air Force was directed in 1979-1980 to develop GPS with a constellation of only 18 satellites planned to be operational in 1987. The 18-satellite constellation was expected to have the same orbital parameters listed in paragraph 5.4.3 except that each orbital plane would contain 6 satellites with a 60 degree separation between the satellites in each plane. (See paragraph 5.4.7.)

5.4.6 With this 18-satellite constellation, a user anywhere in the world will almost always be able to receive GPS signals from four or more satellites that are 5 degrees or more above the horizon. The disadvantage of the 18-satellite configuration, is that the user in the 18-satellite system will not always have as many visible satellites as he would have in a 24-satellite system, from which to select 4 satellites with a favorable geometry for accuracy. This could result in occasional outages of the 18-satellite system for some GPS users in some geographic locations at some times.

5.4.7 Studies have therefore been made of alternative 18-satellite constellations that might minimize such outages; e.g. spacing the satellites non-uniformly in each orbital plane instead of the 60-degree spacing, or placing the 18 satellites each in 18 separate orbital planes. The latest plan for the Operational Navigation Satellites (ONS) is to deploy 18 satellites in six orbital planes, 60 degrees apart, each plane containing three equally spaced satellites. Inclination of the ONS will be 55 degrees as in the original 24-satellite plan (paragraph 5.4.3).

5.4.8 In the meanwhile, six Navigational Development Satellites (NDS) were launched between 22 February 1978 and 26 April 1980 for GPS system development and testing. Five of these NDS are functioning. The NDS (which will not be part of the ONS) are deployed in two planes, 120 degrees apart, at 63 degrees inclination. Each NDS weighs about 1000 lb. Atlas was the launch vehicle for NDS. The NDS is powered by solar panels with a total area of about 54 sq. ft., generating about 400 watts. Nickel-cadmium batteries aboard the spacecraft provide power when the spacecraft is in the Earth's shadow. The satellite's antennas are controlled to point toward the Earth.

5.4.9 The latest design for the ONS, as of approximately May 1982, is denoted as the Block 2 model. It is scheduled for launch in 1986, and for operation in 1987. The Block 2 ONS will weigh about 1735 lb., and will be correspondingly larger than the NDS in order to provide for increased capabilities and future growth needs. The Block 2 ONS will be powered by about 78 sq. ft. of solar cells, generating about 700 watts. The spacecraft's panels have room for additional solar cells that can be mounted in the future to increase the available solar cell power to 1000 watts. The ONS spacecraft will probably be deployed from a space shuttle orbiter.

5.5 Control Segment

5.5 1 The control segment of GPS is a complex of ground stations that monitor and support the satellites. The segment consists of: Monitor Stations; a Master Control Station; and an Upload Station.

5.5.2 The Monitor Stations are widely separated data-collection stations. In the development and test phase of the GPS program, four unmanned Monitor-Stations have been located in U. S. controlled territories: Vandenberg Air Force Base, California; Alaska; Hawaii; and Guam. Each Monitor Station contains a receiver, somewhat similar to a GPS user receiver, to acquire signals from the GPS satellites. Each Monitor Station contains also a cesium frequency standard, a computer, and an environmental sensor package. The environmental sensor package acquires local meteorological data from which corrections for tropospheric signal delays can be made subsequently. Data acquired by each Monitor Station is stored there until it is relayed to the Master Control Station upon the latter's demand.

5.5.3 The Master Control Station processes the information received from the Monitor Stations to obtain ephemerides of the satellites, signal data errors, clock errors, and status of the system. The Master Control Station is tied in with the Naval Surface Weapons Center (NSWC) at Dahlgren, Virginia, which provides ephemeris references used by the

Master Control Station to predict ephemerides. The Master Control Station produces messages to correct for satellite position errors and data errors, and generates corresponding messages to the Upload Station to be relayed by transmitter to the satellites. The messages can include instructions to the satellites to alter or encrypt the signals broadcast by the satellites, in order to degrade the system performance to unauthorized users.

5.5.4 Vandenberg Air Force Base, California is currently the location of the Master Control Station, the Upload Station, and one of the Monitor Stations. It is expected that the Master Control Station will eventually be moved to a location in Central CONUS (Continental United States).

5.5.5 The Satellite Control Facility at Sunnyvale, California, is also tied in with the Master Control Station. The Satellite Control Facility furnishes telemetry and command information to the GPS spacecraft. This can serve as a back-up for uploading in case the Upload Station should fail. An S-Band Command Control Link is used to send data to the spacecraft.

5.6 User Segment

5.6.1 Each user vehicle carries a set of equipment containing: an antenna; a receiver; a quartz crystal oscillator clock; a computer/micro-processor; I/O (input/output) devices (e.g., keyboard/CRT or digital display); and a power source. A preamplifier may be included between the antenna and the receiver.

5.6.2 The antenna should have approximately isotropic gain from the zenith to 5 degrees above the horizon, in order to cover all of this reception volume uniformly. A conical spiral antenna is used preferably because the signals from the GPS satellites are circularly polarized. It is contemplated that a directional antenna, electronically steered by a null-steering adaptive array, might be used to avoid strong jamming.

5.6.3 Receivers of various degrees of complexity have been under development. The simplest receivers have only one channel to accept only the C/A or P code (section 5.7) from only one satellite at a time. More complex receivers have five channels capable of accepting and processing C/A and P signals from at least four satellites in a short period.

5.6.4 In the more complex receivers, the computer/micro-processor automatically selects satellites and signals, controls the receiver, makes corrections for propagation effects, computes correct three-dimensional coordinates and velocities, and feeds the resulting data to the output display devices.

5.6.5 GPS uses the DOD WGS (World Geodetic System) 72 system of coordinates. This is a world-wide single grid that is readily processed by high speed digital computation. The user's computer/micro-processor will first compute the fix and the velocity in the WGS-72 coordinate system; and will then instantly convert to any other coordinate system and set of units for which the user's computer has been programmed. The resulting position coordinates (for example latitude, longitude and altitude) and velocity are displayed on the output device and/or recorded.

5.6.6 All vehicles, military and civil, are potential hosts for GPS user equipment. These include: manpacks; land vehicles (including tanks, troop carriers, weapon carriers, jeeps, etc.); amphibians; surface ships; submarines; aircraft (including helicopters, fighters, bombers, transports, cargo carriers and reconnaissance craft); spacecraft; and missiles.

5.6.7 The GPS user equipment is being designed and developed with the objective of maximum commonality between host vehicles and between the elements of the user equipment. Three general types of user equipment sets are being developed:

> Sets for low dynamic (LD) vehicles, e.g. man and land vehicles. Sometimes called MP for "Manpack", or MVUE for "Manpack/Vehicular User Equipment". Usually one receiver channel in each set.

Sets for medium dynamic (MD) vehicles, e.g. helicopters and surface ships. Sometimes called MD sets, or MBRS for "Missile Borne Receiver Set". Four receiver channels in each set.

Sets for high dynamic (HD) vehicles, e.g. high performance aircraft and submarines. Sometimes called HDUE for "High Dynamic User Equipment". Five receiver channels in each set.

5.6.8 GPS user equipment sets were tested in LD, MD and HD host vehicles during Phase I of the GPS development program (Figure 5.2.2.B). (Reference 5.10.16.). These vehicles included: M-35 Truck; C-141, and F-4J, and P-3B aircraft; LCU, FF vessels; mobile test van; and manpack. 775 test missions were performed between March 1977 and May 1979, by the U. S. Army and the U. S. Air Force at the U. S. Army Yuma Proving Ground, Arizona, and by the U. S. Navy in the North Pacific Ocean.

5.6.9 The U. S. Army tested manpack vehicular receiver equipment in a number of scenarios: reconnaissance, survey, night operation, and foliage. In addition to being man-transportable, the GPS manpack receiver is intended for use on jeeps, tanks, personnel carriers and other land vehicles. One GPS manpack receiver is said to weigh only 25 lb and occupy a volume of less than 0.5 ft^3, not including batteries, with a power consumption of less than 30 watts. It is predicted that the weight of the GPS manpack receiver will ultimately be reduced to about 10 lb.

5.6.10 GPS user equipments are being designed for about 30 different host vehicles in Phase II of the GPS development program. Phase II user equipment will be installed in these 8 host vehicles:

M60 Tank
UH60 Helicopter
A6E Attack Aircraft
F16A Fighter Aircraft
P3C Maritime Aircraft
B52D Bomber Aircraft
CV64 Aircraft Carrier
SSN Submarine

5.6.11 In the development of GPS, the United States Navstar Joint Program Office (JPO), that manages the GPS program, takes account of the operational, technical and logistic requirements and problems of the NATO nations. Nine of these nations (Belgium, Canada, Denmark, France, Germany, Italy, Netherlands, Norway, & the United Kingdom)sent a multinational liaison team to the JPO in 1978. The team's liaison mission concerns the development of user equipment in particular.

5.7 Signal Structure

5.7.1 The GPS space vehicle clock frequency is nominally 10.23 MHz (megahertz). Actually this clock frequency is offset to a center frequency of 10.22999999545 MHz to allow for relativity effects. This is the basic frequency standard from which all frequencies in the space vehicle are derived, and with which all space vehicle frequencies are synchronized. This 10.23 MHz is maintained by an atomic (e, g, rubidium or cesium) clock in each satellite. The maximum allowable error in this clock frequency is 10^{-12} per day. If necessary, the Master Control Station can use uplink commands to adjust the clock frequency and phase.

5.7.2 Each GPS space vehicle transmits on two L-band frequencies:

$$L1 = 154 \times 10.23 \text{ MHz} = 1575.42 \text{ MHz}$$

$$L2 = 120 \times 10.23 \text{ MHz} = 1227.6 \text{ MHz}$$

L1 is sometimes called the primary frequency, and L2 the secondary frequency.

5.7.3 The speed of propagation of radio signals in the ionosphere (through which the GPS signals travel) fluctuates as the ion density fluctuates. These propagation anomolies can add significant errors to the measurements of ranges from GPS satellites to a user. Fortunately, the propagation speed through the ionosphere is frequency dependent.

Simultaneous range measurements at the two GPS frequencies, L1 and L2, enable the receiving equipment to calculate and make corrections for the ionospheric delay errors. This is the reason for the two different transmission frequencies.

5.7.4 The L1 signal is modulated by two codes, called the P (Precision) code and the C/A (Clear Acquisition) code. The L2 signal is modulated by either the P code or the C/A code. The user's receiving equipment measures the phase shift required to match each code pattern in a received signal with a like pattern in the user's receiver. This phase shift is a measure of the time of travel of the signal from the satellite to the user; (cf paragraph 5.4.2.1).

5.7.5 The codes are synchronized with GPS space vehicle time, and are kept within about 1000 microseconds of so-called GPS system time which is maintained by a set of highly accurate cesium clocks in the Master Control Station. Time accuracy is critical in GPS because the ranges from each user to the GPS satellites are determined by time measurements, and because the signals travel at the speed of light. (Cf paragraph 5.4.2.3)

5.7.6 The P code is a pseudo-noise chip sequence, generated by the 10.23 MHz clock at 10.23 megabits per second. The P code is made up of seven-day segments and does not repeat for 267 days. All GPS satellites use the same P code generator, but each satellite generates its own assigned seven-day segment of the 267-day code.

5.7.7 The C/A code also is a pseudo-noise chip sequence, but the C/A code is generated at only 1.023 megabits per second, and the C/A code has only 1023 bits. The C/A code repeats every millisecond, in contrast to the 267-day P code. Each GPS satellite has its own assigned unique C/A code that enables the user's receiver equipment to identify the satellite by matching its C/A code pattern with one of the 18 code patterns generated in the receiver.

5.7.8 The user's receiver cannot match and lock on to the P code directly, because the P code bit rate is so high and the P code does not repeat for a long time (paragraph 5.7.6). It is estimated that it would take several hours for a typical receiver, operating at a search rate of 60 bits per second, to search only one second of the seven-day P code. The receiver can, however, match and lock on to the C/A code directly, because the receiver need search only a one millisecond interval of the C/A code instead of searching through a seven-day segment of the 267 day P code, and because the C/A code chip rate is ten times slower than the P code chip rate. When the receiver locks on to the C/A code, the C/A code and HOW transfer the receiver over to the P code so that the receiver locks on to the P code in less than 6 seconds. HOW is a "Hand Over Word" that appears in the data stream of the "Navigation Message" (paragraph 5.7.10) every 6 seconds. HOW is time synchronization information, and gives GPS system time to all users.

5.7.9 From the numbers in paragraphs 5.7.6 and 5.7.7, it is evident that the P code provides ten times as many bits per second as the C/A code provides. Matching the P code can therefore be ten times as precise as matching the C/A code; and the P code can provide a fix accuracy that is theoretically about ten times better than the accuracy of a fix by means of the C/A code above. (When the symbol C/A was coined in the early stages of GPS development, it stood for "Coarse Acquisition". This was subsequently changed to "Clear Access" in order to avoid giving the impression that GPS was a coarse system.)

5.7.10 A so-called navigation message is transmitted by each GPS satellite for reception by the user on the L1 and L2 frequencies. The message is in a data frame that is 30 seconds long and contains 1500 bits sent at 50 bits per second. The data frame has five subframes, each of which starts with a telemetry word and HOW including GPS system time. In addition, the contents of the five frames are respectively:

Frame 1: Correction parameters for the space vehicle's clock; and parameters for the ionospheric propagation delay model.

Frame 2 and 3: Ephemeris of the space vehicle.

Frame 4: Alphanumerics for special messages.

Frame 5: Almanacs of all the GPS space vehicles, cycled at one vehicle per frame, giving ephemerides, satellites' health status, and clock correction parameters. The almanacs enable the user to acquire other GPS space vehicles.

5.8 Accuracy

5.8.1 Principal sources of error in GPS measurements of three-dimensional position-location and velocity are:

Uncertainties in the ephemerides of the satellites.

Unpredictability of satellite perturbations.

Satellite clock drifts.

Ionospheric delays.

Tropospheric delays.

Receiver resolution.

Receiver noise.

Geometric Dilution of Precision (GDOP).

Multipath effects.

User vehicle dynamics.

5.8.2 No single number can be stated for the accuracy of position-location or velocity measurement by GPS at all times, in all locations, with all types of receivers in all kinds of host vehicles, under all conditions. This is true also with many other electronic POS/NAV systems such as, for example, Loran, Omega, Transit, Decca, Consol and Tacan.

5.8.3 In designing GPS and embarking on its development, it was anticipated that the P code would provide three-dimensional position-location accuracy on the order of 10 (ten) meters. Tests during Phase I and II of the GPS development program confirm this order of accuracy. This is remarkable, considering the high precision that GPS demands in its clocks and time measurements; (paragraphs 5.4.2.3, 5.7.1, 5.7.5). GPS is made possible not only by space technology, but also by modern electronic techniques for precise time measurement.

5.8.4.1 The 10 (ten) meter accuracy stated in paragraph 5.8.3 is the most frequently mentioned accuracy figure for GPS. However, various reports and authorities give other estimates of GPS accuracy. Examples are given in paragraphs 5.8.4.2 through 5.8.4.5 below.

5.8.4.2 A GPS Program Final User Field Test Report (Reference 5.10.16) gives the following error distribution for GPS:

Percent	Position Error in Meters
50	11.5
90	23
95	27

5.8.4.3 The Federal Radionavigation Plan (Reference 4.4.6) Vol. III, Page III-33, states that the best predictable positioning accuracy, with the most sophisticated user equipment, will be 25 meters (2 drms) horizontally, and 30 meters (2 sigma) vertically; with a velocity accuracy of 0.1 meters per second (1 sigma) in 3 dimensions; and timing accuracy of thirty nanoseconds (30×10^{-9} seconds). This reference states that repeatable accuracy will be the same as predictable accuracy, and that the best relative accuracy will be 13 meters (2 drms) horizontally, and 15 meters (2 sigma) vertically.

5.8.4.4 A GAO report (Reference 5.10.19) states that GPS can provide horizontal and vertical accuracies of 11 meters or better, 50 percent of the time; and that GPS measured the velocity of a test vehicle to within 0.12 meters per second.

5.8.4.5 Another GAO report (Reference 5.10.20) states that GPS "will provide a highly accurate (less than 20 meters) worldwide navigation capability", and that "accuracies of approximately 1 quarter nautical mile or better will be available to civil users when GPS becomes operational".

5.8.5.1 The P code accuracy of position-location is intended to be better than the C/A code accuracy by approximately one order of magnitude; (paragraph 5.7.9). In times of peace, both codes will be available to civil as well as military users. In times of international stress or hostilities, the United States can deny the use of the P code to hostile users by selective availability, i.e. by changing or encrypting the P code (via the Master Control Station and the Upload Station) and disclosing the new P code only to U. S. military vehicles and to U. S. allies. In that event, civil users could not use the P code, and they would have to resort to the less accurate C/A code.

5.8.5.2 The accuracy of the C/A code (and the accuracy of the P code) can be degraded intentionally by degrading the accuracy of the information carried in the navigation message (paragraph 5.7.10). It is difficult to decide on a C/A accuracy that will satisfy the needs of civil users during selective availability without being useful to unfriendly military users. Accuracies between 50 and 500 meters have been discussed for the C/A code. See paragraph 4.2.6.3 herein. A final decision on the C/A code accuracy has not yet been announced.

5.9 Addenda

5.9.1 The U. S. Department of Defense promulgated GPS for civil as well as military use, with the expectation that GPS will eventually replace many existing POS/NAV systems, civil as well as military. Some civil users of existing systems have been concerned about this replacement, principally because:

a. New capital investment will be required to replace existing POS/NAV receiving equipment (e.g. Loran, Omega) by GPS receiving equipment.

b. The C/A code accuracy might not be adequate for civil use when the U. S. exercises selective availability to deny the P code to unauthorized users.

c. GPS satellites might be vulnerable to enemy attack that could paralyze civil POS/NAV.

5.9.2.1 General acceptance of GPS by the community of civil POS/NAV users will help to justify the cost of developing, implementing and maintaining the GPS. Otherwise the DOD would have to justify the cost for military purposes only. The GAO has estimated that it will cost 8.6 billion dollars to acquire and maintain GPS through the year 2000; (Reference 5.10.19).

5.9.2.2 In order to help defray the costs of establishing and maintaining POS/NAV systems and services, (such as Loran and Omega), that are provided by the U. S. Government, it has been suggested for many years that the Government should require civil and foreign users to pay user charges; (e.g. paragraphs 4.2.1.10 and 4.2.2.2 herein). This suggestion has often been made for GPS (e.g. Reference 5.10.20).

5.9.3 The U. S. General Accounting Office issued a report to the Secretary of Transportation in September 1981, the thesis and recommendation of which is stated in the title of the report: "DOT Should Terminate Further LORAN-C Development And Modernization, And Exploit The Potential Of The NAVSTAR/GLOBAL Positioning System". Reference 5.10.21.

5.9.4 If the GPS user receiver is stationary while GPS position-location observations are made repeatedly over a few hours, it is said that accuracies of better than 2 meters can be obtained for use in geodetic positioning and in mapping and charting. Reference 5.10.22

predicts that this geodetic use of a stationary GPS receiver will eventually yield point positioning accuracies of less than 1 meter and distance measurements of about 2 to 5 centimeters.

5.9.5 GPS could be used as a differential system, analogous to D-Loran-C and Omega (Reference 6.6.1). Differential-GPS would use a stationary GPS receiver at a position that was accurately determined by non-GPS means. Differences between this accurate position and positions of the fixed receiver as measured by GPS would be transmitted to GPS users in the vicinity to enable them to correct their GPS derived positions. Reference 5.10.23. Differential-GPS would require a data link between the fixed reference receiver and the users, with attendant line-of-sight and propagation problems. Each fixed differential-GPS receiver could serve users only in a limited localized area.

5.9.6 Soviet Glonass. The USSR notified the International Telecommunications Union in February 1982 that the Soviets were planning a navigation satellite system that would be very similar to GPS. The USSR has named their system Glonass, an acronym standing for global navigation satellite system. Glonass would transmit at approximately the same two frequencies as GPS, and would use satellites at approximately the same altitude and orbital period as GPS. As of August 1982, no Glonass satellite had yet been observed in orbit. Reference 5.10.24.

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6. LASER GYROS

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6.1 Introduction to Section 6

6.1.1 A laser gyro is a self-contained navigation device that senses and measures the rotation of a vehicle, using the principle of the Sagnac effect, (Section 6.2), aided by a laser.

6.1.2 The useful properties of a convential gyroscope derive from the rotational inertia and angular momentum of the gyroscope's spinning mass. Unlike conventional gyroscopes, laser gyros have no spinning masses. Rotational inertia and angular momentum play no role in the operation of laser gyros.

6.1.3 Despite the fact that a laser gyro is not a gyro in the sense of a spinning mass, the laser gyro is so-called because: (1) it rivals the spinning-mass gyroscope (gyro) in strapped-down inertial navigation systems; (2) in a laser gyro, light travels around a closed path that can be considered as a ring or circle for which the Greek word is "gyros"; (3) all modern laser gyros employ lasers, although the original Sagnac interferometer did not.

6.1.4 A set of three mutually perpendicular laser gyros, combined with a set of three mutually perpendicular accelerometers, can serve as the sensors for a 3-dimensional strapped-down inertial navigation system (INS). For a review of the basic principles of inertial navigation, see Section 10 in Reference 6.6.1, or Chapter XLVI in Reference 6.6.2.

6.2 Sagnac Effect

6.2.1 All laser gyros are applications of the Sagnac effect. This phenomenon was predicted by A. A. Michelson in 1904 (Reference 6.6.3) and was first demonstrated in 1913 by G. Sagnac (Reference 6.6.4). He constructed an interferometer, the conceptual design of which is diagrammed schematically in Figure 6.2.1. In this figure, a light beam from a source S is divided by the beamsplitter B into two beams, one of which is reflected by the mirrors M_1, M_2, M_3 in the clockwise direction around the loop $BM_1M_2M_3B$; while the other beam is reflected by the same mirrors in the counterclockwise direction around the loop $BM_3M_2M_1B$. After traversing the loop in these contra-rotating directions, the two beams recombine at B and form a pattern of interference fringes at F.

6.2.2 When the entire Sagnac interferometer is rotated such that the rotational velocity has a component that is perpendicular to the plane represented by Figure 6.2.1, the interference fringes at F shift away from the positions that they occupied when the interferometer was not rotating. The fringe shift changes its direction when the direction of rotation is reversed.

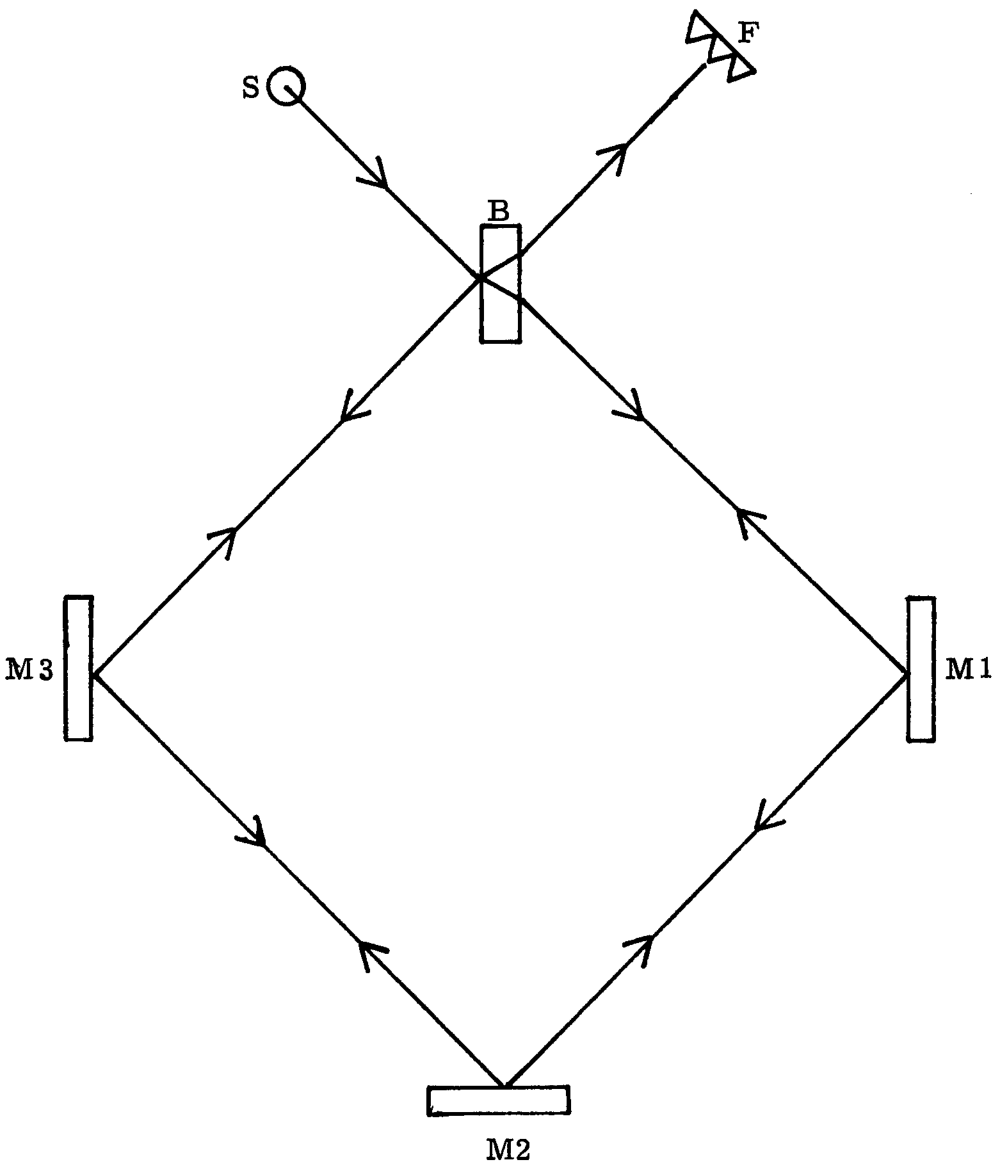


Figure 6.2.1

Sagnac Interferometer

6.2.3 The following is an explanation for the fringe shift. Let L be the total length of the loop $BM_1M_2M_3B$ when the interferometer is not rotating. When the interferometer rotates, the beam that goes around the loop in the direction of the rotation travels a path $L_1 > L$ before the beam returns to B because B is moving around the loop in the same direction as the beam. Conversely, the contrarotating beam travels a path $L_2 < L$ before the beam returns to B because B is moving around the loop in the direction opposite to this beam. (When the interferometer rotates, one beam "chases" the beamsplitter B around the loop, so to speak; while the other beam travels "head-on" toward B around the loop.) The difference $L_1 - L_2 = \Delta L$ results in a phase difference between the two beams when they reunite at B. This phase difference is evidenced as a fractional fringe shift ΔF in the interference pattern at F. The phase difference may be considered also as a result of the difference ΔT between the travel times of the two contrarotating beams.

6.2.4.1 Let

A be the area enclosed by the optical loop path.

Ω be the angular speed (radians per second) of the component of the rotational velocity perpendicular to the plane of the optical loop.

c be the velocity of light in free space.

λ be the wavelength of the light used in the interferometer.

R be the radius of a circle that circumscribes the optical loop.

6.2.4.2 $\Omega R \ll c$ in all practical applications of Sagnac interferometers and laser gyros. With this condition, actual measurements and theoretical studies show that the following approximate equations apply with excellent accuracy:

$$\Delta T = 4A\,\Omega / c^2$$
$$\Delta L = 4A\,\Omega / c$$
$$\Delta F = 4A\,\Omega / c\lambda$$

Derivations of these equations appear in References 6.6.5, 6.6.6, 6.6.7.1, 6.6.7.2, 6.6.8.

6.2.5 The explanation in paragraph 6.2.3, and the derivations referred to in paragraph 6.2.4.2, utilize a tenet of Einstein's special theory of relativity; i.e. the fact that the phase velocity of light in free space is independent of the velocity of the source. This applies to all laser gyros as well as to the Sagnac interferometer.

6.2.6.1 The Sagnac effect and the relations in paragraph 6.2.4.2 are independent of:

(a) The shape of the area A.

(b) The location of the center of rotation of the interferometer.

(c) Rectilinear motion and linear acceleration of the interferometer; i.e. translatory motion.

(d) The presence of a refracting medium in the path of the contrarotating light beams, (in all practical applications).

6.2.6.2 The statements in paragraphs 6.2.4.2 and 6.2.6.1 are valid not only for Sagnac interferometers, but also for all types of laser gyros. This means that:

(a) The optical path in a laser gyro can be square, rectangular, triangular, circular, hexagonal, etc.

(b) A set of laser gyros can detect and measure any change of orientation of a vehicle, including rotations around axes that are outside the vehicle; e.g. an army tank traveling around a wide curve.

(c) The laser gyro's measurement of rotation is not affected by linear velocities or linear accelerations; (provided that mechanical shock and vibration do not disturb optical alignments or the value of the area A).

(d) The optical path in the laser group may contain air, helium, neon, glass, cervit, plastic, etc.

6.2.7 In any practical application, ΔL, ΔF, and ΔT are small. For example, in one of Sagnac's experiments, he observed a fringe shift (ΔF) of only 0.07 fringe, when A was 866 cm^2, and Ω was 4π radians per second. For these values of A and Ω, the formulas in paragraph 6.2.4.2 give ΔL = 14,5 nanometers, and ΔT = 450 nanoseconds.

6.2.8.1 Michelson and Gale, in 1925, (reference 6.6.9) constructed a Sagnac-type interferometer, fixed to the Earth, to demonstrate and measure the diurnal rotation of the Earth. The area A had to be large, to compensate for the small value of Ω in this experiment. The contrarotating beams were sent, in vacuo, around a rectangle with sides of approximately 1100 and 2000 feet. ΔL was appoximately 1300 nanometers, a value that agreed with the known speed of diurnal rotation of the Earth. This agreement was highly significant as additional confirmation of the fact that, if the historically postulated all-pervading ether existed, it did not rotate with the Earth, thereby adding strength to the theory of relativity.

6.2.8.2 The aforesaid Michelson-Gale experiment differed from the famous 1886-1887 Michelson-Morley ether-drift experiment (ref. 6.6.10) because the interferometer in the Michelson-Morley experiment did not enclose a finite area, even though the Michelson-Morley interferometer was mounted on a turntable. Consequently, the Michelson-Morley experiment did not demonstrate the Sagnac effect.

6.2.9 Although Sagnac's original interferometer (and the equation for ΔF in paragraph 6.2.4.2) provided a means for determining Ω by measuring ΔF, the interferometer could not serve as a practical navigation device until the invention and development of lasers augmented the capabilities of interferometers in general and Sagnac-type interferometers in particular. When a laser is used as the light source S in Figure 6.2.1, the coherence, collimation, high intensity, and monochromaticity of the laser beam substantially improve the resolution, sensitivity, precision, and signal-to-noise ratio of the interferometer; and the instrument is then called the Sagnac Interferometer Laser Gyro (SILG).

6.2.10 It should be emphasized that the laser in a laser gyro plays no part in the basic phenomenon (the Sagnac effect) that detects and measures rotation. The laser is an adjunct, albeit an important adjunct, used to improve sensitivity and resolution.

6.3 Fiberoptic Laser Gyros

6.3.1 The equations of paragraph 6.2.4.2 apply to the SILG (paragraph 6.2.9). For a given Ω, ΔF is proportional to A. The resolution and sensitivity of the SILG could therefore be improved by building a large interferometer with a large area A, (e.g. the Michelson-Gale interferometer, paragraph 6.2.8.1). Alternatively, mirrors could reflect the contrarotating beams many times around a small area, thereby increasing the effective area A without increasing the over-all size of the interferometer. This was tried, but it did not lead to a practical gyro device.

6.3.2 In 1968, R. B. Brown (page 21 of reference 6.6.11) suggested that a fiberoptic light guide be used to enclose a large effective area in a small instrument. However, very long optical fibers, e.g. 1000 meters, would be needed for the fiberoptic instrument to approach the sensitivity of the ring laser gyro (Section 6.4), and at that time the attenuation in optical fibers was too high to implement the suggestion. This obstacle was removed, in the ensuing decade, by the advent of single-mode optic fibers with low attenuation, e.g. 15 to 5 dB/km.

6.3.3.1 These low-loss fibers made it possible in 1976 for V. Vali and R. W. Shorthill (References 6.6.12, 6.6.13, 6.6.14) to construct an experimental fiber ring interferometer. The fiber was 950 meters long, was wound on a cylinder about 37 cm in diameter, and had an attenuation of 13.7 dB/km at 6328 Angstroms, the principal wavelength of light emitted by HeNe gas lasers.

6.3.3.2 The Vali-Shorthill laser interferometer is diagrammed in Figure 6.3.3.2. Light from the laser is divided by the beam-splitter B into two beams, one of which is focused into one end of the coiled optical fiber by the lens L1, while the other beam is focused into the other end of the fiber by the lens L2. When the two contra-rotating beams emerge from the ends of the fiber, the beams are expanded by the lenses L1 and L2, and the beams are combined by the beamsplitter to form interferometric fringes at F. The similitude between the fiberoptic laser gyro of Figure 6.3.3.2 and the Sagnac interferometer of Figure 6.2.1 is obvious. However, even with long low-loss fibers, the fiberoptic laser gyro is beset by problems such as those of paragraphs 6.3.4, 6.3.5 and 6.3.6.

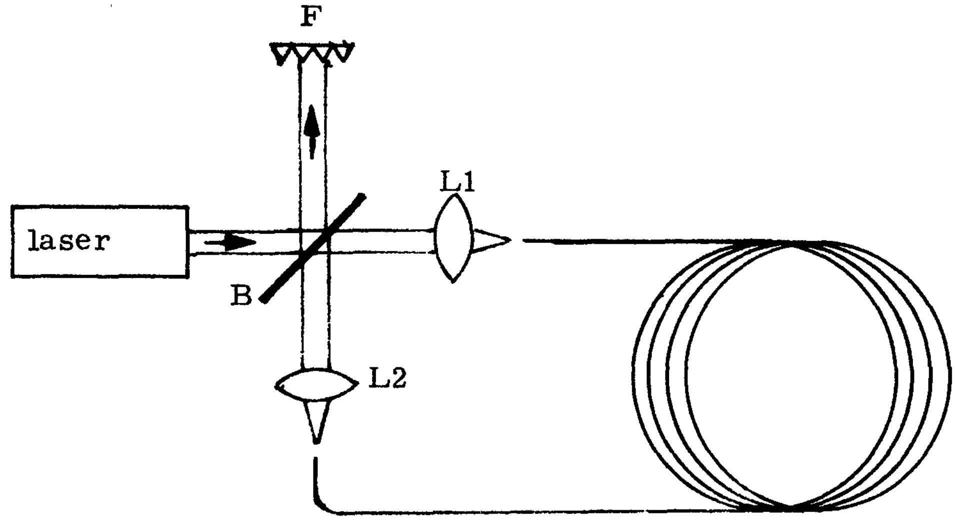


Figure 6.3.3.2

Fiberoptic Laser Interferometer

6.3.4 Birefringence in the optical fiber changes the polarization of the laser beam as it propagates through the fiber. Speed of propagation varies with polarization, resulting in noise in the output fringes. Approaches to control or stabilize the polarization include: using a fiber core with an elliptical cross section instead of the more usual circular cross section; stressing the circular core of the fiber with a cladding so as to produce a strain that controls the birefringence; twisting the optical fibers; shielding the optical fiber from magnetic fields that effect polarization.

6.3.5 Temperature variations also effect polarization in some optical fibers. Indeed, if the two contrarotating laser beams are not of equal power, more heat will be generated in the optical fiber by one beam than by the other, thereby affecting reciprocity. To appreciate the magnitude of this effect, consider that one (1) milliwatt of laser power injected into an optic fiber core of 3 (three) micron diameter, is equivalent to a power density of 10 (ten) kilowatts per cm^2.

6.3.6 Other fiberoptic laser gyro problems are: means for efficiently coupling the laser output into the ends of the fiber without affecting the monochromicity of the beams; selection of the type of laser, e.g. HeNe gas laser or GaAs light-emitting diode (LED); minimizing the effects of shock and vibration, to which fiberoptic laser gyros, in general, are surprisingly susceptable.

6.3.7 Research and development of fiberoptic laser gyros is widespread in industry and universities in the United States of America and abroad. This includes approximately a dozen large electronic/aerospace companies in the U.S.A.

6.3.8 Fiberoptic laser gyros, suitable in size and ruggedness for military use, demonstrate drift rates of 35 to 100 degrees per hour. Experimental fiberoptic laser gyros have demonstrated drift rates that approach 0.1 degrees per hour; but these experimental units are, as yet, too fragile and too large for practical applications. The performance of these gyros is still not equal to the performance of current conventional spinning-mass gyros that typically show drift rates of 0.01 degrees per hour. Nevertheless it is reasonable to expect that improved fiberoptic laser gyros will compare favorably with spinning-mass gyros by the end of the 1980's. (References 6.6.15 through 6.6.25)

6.3.9 The laser in a fiberoptic laser gyro (Figure 6.3.3.2) can be a solid-state laser diode, whereas the laser in a ring laser gyro (RLG) (Section 6.4) must be a gas laser. Consequently, compared to a RLG, the fiberoptic laser gyro has the potential advantages of all-solid-state construction, and elimination of lock-in (paragraph 6.4.13).

6.4 Ring Laser Gyros

6.4.1 The laser is placed outside of the Sagnac optical ring in the SILG (paragraph 6.2.9) and in the fiberoptic laser gyros described in Section 6.3. Laser gyros, such as these, with the lasers lying outside the ring, are called passive laser gyros.

6.4.2 Active laser gyros are those in which the laser discharge tube lies inside the laser optical ring with the ring serving as part of the laser resonator. Active laser gyros are called ring laser gyros, or RLG. In these lasers, the electromagnetic waves circulate around the ring continually, with the result that Sagnac-effect phase differences between the contrarotating beams increase by an additional ΔL for each transit around the ring.

6.4.3 In active laser gyros, the ring becomes a resonator. When there is no rotation, i.e. when $\Omega = 0$, the two contrarotating laser beams resonate at the same frequency. When Ω is not zero, the two beams resonate at different frequencies because the effective path lengths are different for each beam. When the two frequencies are combined at the output of the ring, they heterodyne, in effect, and produce a beat frequency that is the difference of the two laser frequencies. This beat frequency is a measure of Ω.

6.4.4 The basic optical components of a typical triangular ring laser are diagrammed in Figure 6.4.4. The rectangle 4 symbolizes the gas discharge tube of a laser (usually a helium-neon laser). The laser's customary end mirrors are replaced by the three mirrors 1, 2 and 3 that are part of the triangular closed optical ring. The mirrors are usually dielectric coated to selectively reflect a principal wavelength of the lasing population, for example the 6328 Angstroms line of a HeNe laser. Mirror 3 reflects almost all (e.g. 99 percent) of the contra-rotating beams in the closed optical ring, and transmits a small amount (e.g. 0.1 percent) of each beam into the output sensing system 5, 6 and 7. The transparent block 5 and the corner reflector prism 6 bring the 0.1 percent outputs of the contrarotating beams together to form an interference pattern at the photodiode detectors 7.

6.4.5 The gas discharge tube 4 (Figure 6.4.4) and the closed optical Sagnac-like ring 1-2-3 act like a laser. Macek and Davis (Reference 6.6.26) demonstrated that stable oscillations could be maintained in both directions around such a ring laser. The Macek and Davis experimental device, built in 1963 in the Sperry Rand laboratory, was the first ring laser gyro.

6.4.6 For lasing, i.e. for reinforcement of the light waves in the lowest order transverse mode, the optical path length L around the ring

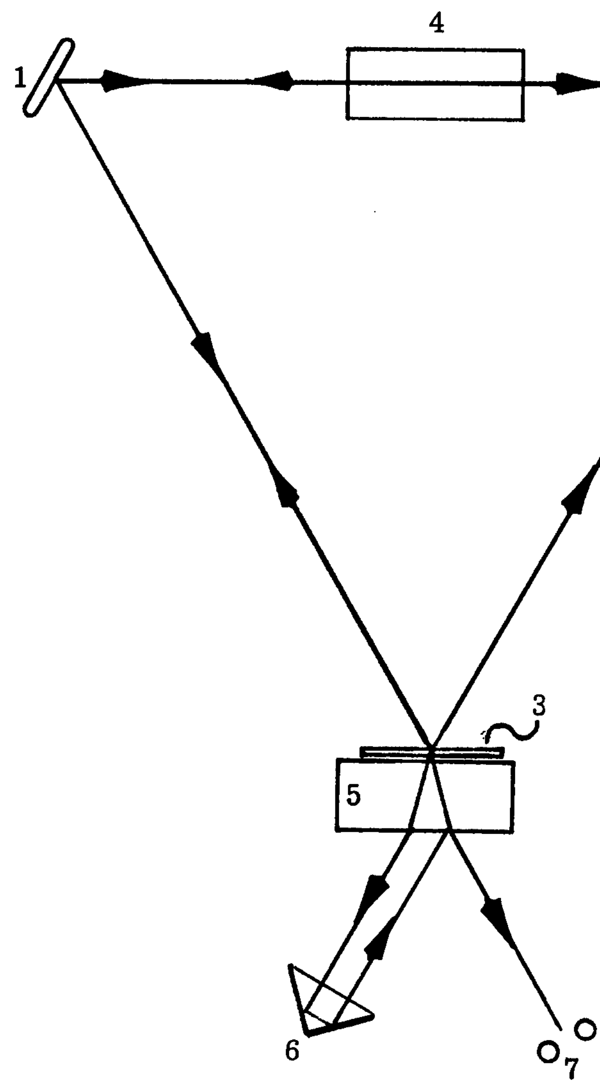


Figure 6.4.4

Basic optical components of a ring laser gyro must be equal to an integer number N of wavelenghts; $L = N\lambda$. The number N is large. For example, for L = 30 cm, and $\lambda = 6328 \times 10^{-8}$ cm, N = 474, 000. Small changes in L produce small changes in the resonant optical frequency of the ring laser oscillations. See paragraph 6. 4. 18.

6. 4. 7 The difference in frequency Δf between the two contra-rotating beams is called the beat frequency and is given by

$$\Delta f = 4A\Omega / L\lambda$$

In any practical application, Δf is small compared to the resonant optical frequency which is usually of the order of 5×10^{14} Hertz. For example, the above equation gives $\Delta f = 1.3$ Hertz for a rotation rate Ω of one degree per hour, with a ring in the shape of an equilateral triangle that is 10 cm on a side, using the HeNe laser wavelength $\lambda = 6328$ Angstroms. Small beat frequencies such as this can be measured with relative ease by heterodyne techniques. This makes the RLG much more sensitive than the interferometric gyro (Sagnac) for measuring the low rotation rates of vehicles encountered in navigation.

6. 4. 8. 1 Each of the two photodiode detectors 7 in Figure 6. 4. 4 is smaller than the spacing between the maxima of the fringes in the interference pattern. As each fringe moves across one of the detectors, a pulse is generated. Each pulse corresponds to an incremental angle through which the gyro has turned. A count of the pulses gives the total

angle through which the gyro has turned, independent of changes in the rate of rotation Ω during the time that the count was made. This digital output makes the RLG an integrating rate gyro, in effect.

6.4.8.2 The two photodiode detectors are separated from each other by the distance of approximately one quarter of a fringe, i.e. 90 degrees apart. From the two detector outputs, a logic circuit determines the direction of motion of the fringe pattern, thereby sensing the direction of the gyro's rotation and keeping account of positive and negative pulse counts.

6.4.9.1 The scale factor SF of an RLG is the instrument's calibration factor. The SF relates the output, namely the number of counts, to the input, namely the angle through which the gyro has rotated. SF is expressed either as angle per count, or as the number of counts per unit angle. An example of an SF is 137,000 counts per radian, or 1.5 arcseconds per count.

6.4.9.2 SF is the factor that converts the observed number of counts into angle of rotation. Consequently, the linearity (variation of SF with Ω) and the stability of the SF are important performance and reliability characteristics of an RLG. Examples of good SF stability are: 0.25 ppm (parts per million) for a monolithic construction two-wave RLG; and 5 ppm for a modular construction RLG. The theoretical limit for SF stability is 0.015 ppm. An example of good

SF linearity is less than 20 ppm from 5 to 160 degrees, clockwise and counterclockwise. Stability and linearity values depend upon the design and construction of the RLG, and upon the manufacturer.

6.4.10 Changes in the length of the resonant ring caused by temperature changes and vibration must be minimized in an RLG. For this reason, the gyro is usually fabricated out of a single block of quartz or glass-ceramic with a low temperature-coefficient of expansion, e.g. Cer-Vit. There are two general types of construction: modular, described in paragraph 6.4.11; and monolithic, described in paragraph 6.4.12.

6.4.11 A modular type of RLG is diagrammed in Figure 6.4.11. The broken lines indicate the path of the contrarotating waves around the "ring" of the RLG. The path is partly through a vacuum-sealed gas discharge tube 4 containing its own cathode 8 and anodes 9, 10; and partly through cavities in the Cer-Vit block B. The cavities are not vacuum-sealed, enabling the discharge tube 4, the mirrors 1 and 2, and the subassembly 3, 4, 5, 6 to be demounted from the RLG assembly. Mirror 3 is the same as the mirror 3 described in paragraph 6.4.4. The boxes 5, 6 and 7 in Figure 6.4.11 denote correspondingly numbered components in Figure 6.4.4 as described in paragraph 6.4.4. Paragraph 6.4.17.2 explains the reason why the gas discharge tube 4 is equipped with two symmetrically located anodes. The modular RLG is

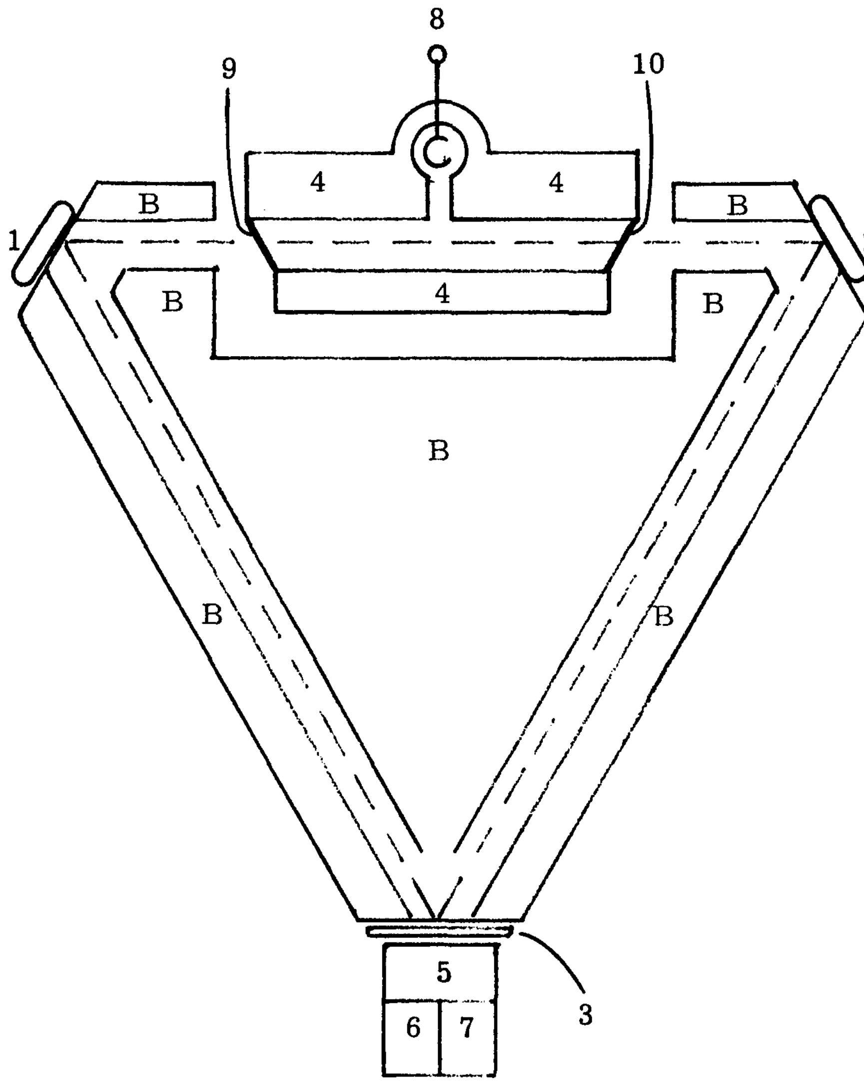


Figure 6.4.11

Modular RLG

perhaps simpler than the monolithic RLG to manufacture and repair; but the monolithic RLG is more stable than the modular RLG mechanically and thermally.

6.4.12 A monolithic type of RLG is diagrammed in Figure 6.4.12. Broken lines indicate the path of the waves through cavities in the Cer-Vit block B. Unlike the modular RLG, the cavities in the monolithic RLG are vacuum-sealed and contain the gas discharge. The mirrors 1, 2, 3 are vacuum-sealed to the block B and are not demountable from the RLG assembly. The mirror 3 and the boxes 5, 6, 7 in Figure 6.4.12 denote the correspondingly numbered components of paragraphs 6.4.4 and 6.4.11. The cathode 8 and the anodes 9, 10 in Figure 6.4.12 lie within the cavities of block B. Two symmetrically located anodes 9, 10 are used for the reason given in paragraph 6.4.17.2.

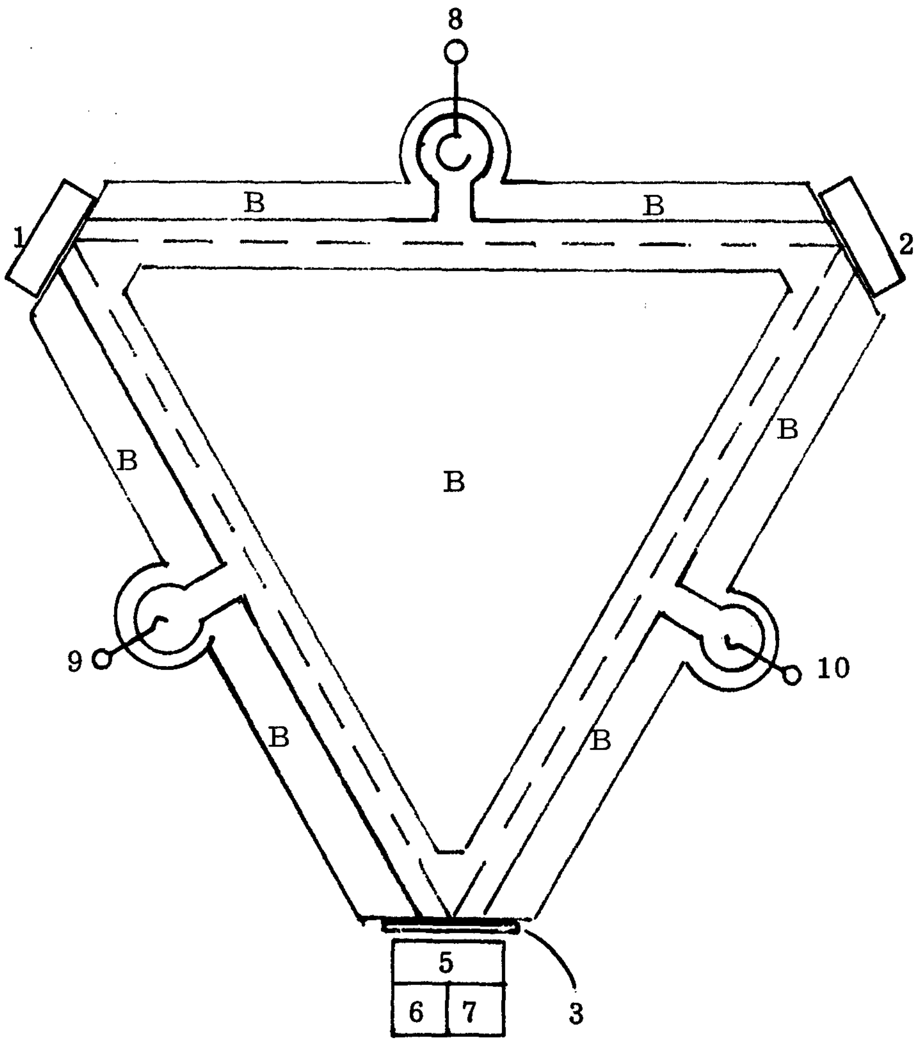


Figure 6.4.12

Monolithic RLG

6.4.13 At low rotation rates of the order of less than 0.1 degree per second, the RLG suffers from the phenomenon of lock-in. This phenomenon is a mutual coupling of the two laser oscillations in the optical ring, triggered principally by backscattering from unavoidable minute imperfections in the mirrors. Lock-in of electromagnetic oscillations in circuits other than laser gyros has been known for many decades. Lock-in of the RLG reduces the SF to zero pulse counts per arcsecond in the lock-in range centered around $\Omega = 0$, as shown in Figure 6.4.13. A great deal of research and development effort has gone into the lock-in problem, in the evolution of laser gyros.

6.4.14 Lock-in could be overcome by applying a fixed DC bias to keep the RLG operating outside of the lock-in range. The bias could be either mechanical or electro-optical. However, the fixed DC bias has to be stable, mechanically or electro-optically, to the order of one part in a million. This is difficult to achieve.

6.4.15 Alternating bias methods circumvent the stability problems of DC bias methods. With alternating (oscillating) bias, the RLG is kept out of the lock-in range most of the time, particularly if the alternating bias is a square wave. Under these conditions, with the RLG operated as an integrating rate gyro, (counting pulses and taking account of signs), the output contains only net rotation angles.

Figure 6.4.13

Laser Gyro Lock-in

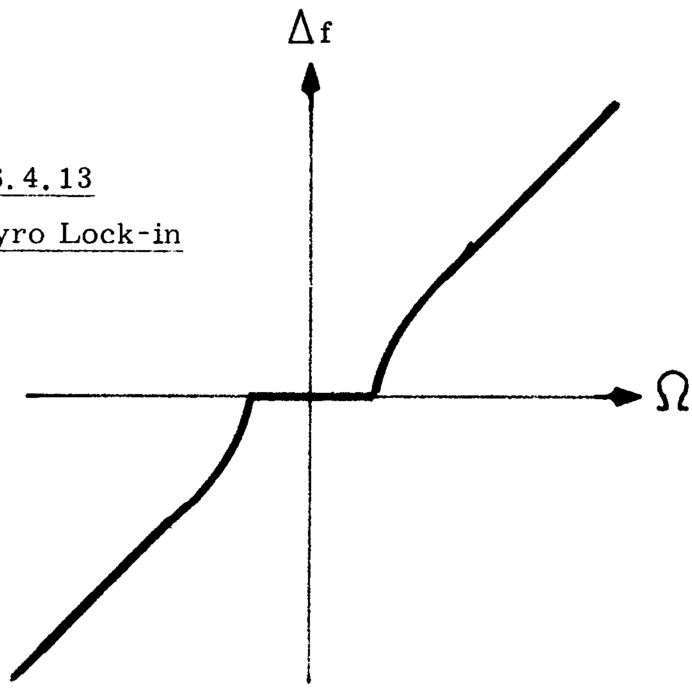
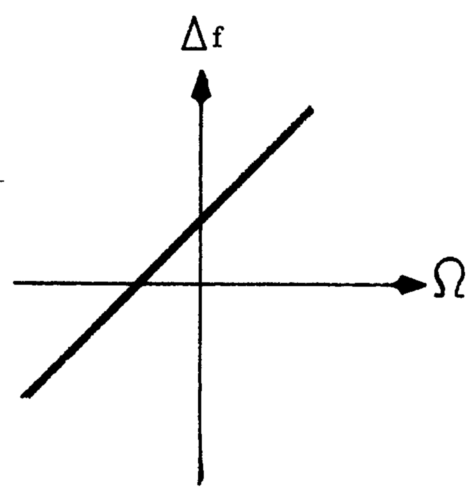


Figure 6.4.17.1

RLG Null Shift



6.4.16.1 There are three principal methods for producing alternating bias to overcome lock-in: mechanical dither (also called body dither); Faraday cell; and magnetic mirror. Mechanical dithering consists of mechanically oscillating the entire RLG about its input axis, with a small amplitude, at a frequency in the range of about 100 Hz to 500 Hz, driven torsionally by piezoelectric transducers.

6.4.16.2 For Faraday cell biasing, a Faraday magneto-optical-effect cell is placed in one leg of the optical path of the RLG ring, and square wave alternating control fields are applied to the cell. The cell introduces alternating differences in the effective path lengths of the two contrarotating beams. Magnetic shielding minimizes the effects of stray magnetic fields.

6.4.16.3 For magnetic mirror biasing, a magnetic mirror replaces either mirror 1 or mirror 2 in Figures 6.4.11 and 6.4.12. The magnetic mirror consists of a multilayer dielectric film deposited on a layer of material, e.g. iron garnet, that exhibits strong magneto-Kerr optical effects. An alternating magnetic field, e.g. 1 Hz, is applied to the garnet to give a dither effect. Susceptibility to stray magnetic fields is minimized by operating the mirror in a saturated state.

6.4.16.4 With Faraday cell biasing or magnetic mirror biasing, symmetry of the alternating bias is important in order to prevent a DC drift. The advantage of mechanical dithering is that it avoids long term accumulation of drift because the dither is mechanically bounded. Mechanical dithering is also insensitive to temperature variations and stray magnetic fields.

6.4.17.1 A shift of the output null, e.g. as diagrammed in Figure 6.4.17.1, is another RLG problem. A null shift can result from anisotropy in the optical cavity, making the effective path length for the laser wave traveling in one direction around the ring different from the path length for the wave in the opposite direction. This path length difference makes the two waves oscillate at different frequencies when $\Omega = 0$, resulting in the null shift. The anisotropy can result from gas circulation produced in the RLG cavity by the DC current that sustains the laser gas discharge. The gas circulation usually consists of a gas flow toward the cathode in the center of the discharge where the laser energy is concentrated, and a return flow close to the walls back to the anode. The gas flow in the center of the discharge shifts the effective refractive indices for the two contrarotating waves, thus producing the null shift.

6.4.17.2 The null shift that results from the gas flow is considerably reduced by using two anodes and one cathode in a symmetric configuration as shown in Figures 6.4.11 and 6.4.12. The path length differences caused by the gas circulation between the cathode and one anode are balanced by the path length differences caused by the gas circulation between the cathode and the symmetrically placed other anode. Residual unbalances are reduced by electrically adjusting the anode currents.

6.4.18 Either mirror 1 or mirror 2, in Figures 6.4.11 and 6.4.12, is typically fastened to a piezoelectric (PZT) transducer to control the optical path length to an integral number of wavelengths to obtain maximum average power. (See paragraph 6.4.6.) A photodiode, mounted usually on one of the mirrors, detects and measures a small portion of both contrarotating beams, and controls the transducer through a closed-loop circuit. This is called PLC or path length control.

6.4.19 Laser mode pulling in the HeNe gain medium can cause bias instability and produce noise in the output. An aperture is therefore usually built into the laser cavity of an RLG to keep the lasing to a single optical mode. The RLG then becomes susceptible to mechanical shock and vibration, and to thermal instabilities, that produce relative motion between the aperture and the cavity. The resulting bias instabilities are usually second order effects, and fortunately are minimized by using short wavelengths (e.g. 6328 Angstroms) and large apertures.

6.5 Addenda

6.5.1 A list of impressive advantages, some actual and some as yet only theoretical, can be compiled for laser gyros compared to spinning-mass gyros. These advantages are listed in subparagraphs (a) through (i) below.

(a) Linear accelerations do not affect the performance of laser gyros.

(b) Laser gyros can respond very rapidly and operate over a wide dynamic range of input rates.

(c) Digital outputs are generated directly by laser gyros.

(d) No appreciable warm-up time is needed for the laser gyro. It becomes fully operational within a few seconds after it is turned on; whereas the spinning-mass gyro requires several minutes for warm-up.

(e) Laser gyros are mechanically simpler and more rugged than spinning-mass gyros; e.g. laser gyros have no spinning components, slip rings, gimbals or gimbal servos.

(f) As a result of item (e) above, reliability (MTBF) of laser gyros should be better than that of spinning-mass gyros.

(g) As a further result of item (e), maintenance of laser gyros should be relatively simple.

(h) The input axis of a laser gyro is stable and accurately determined because the axis is perpendicular to the plane of the laser ring. Therefore alignment stability and alignment accuracy of the laser gyro are excellent.

(i) Mechanical shock and vibration are less likely to affect the performance of laser gyros than spinning-mass gyros. Laser gyros are therefore more adaptable than spinning-mass gyros for use in tanks and other military land vehicles.

6.5.2 On the other hand, spinning-mass gyros have these advantages over laser gyros at the present time:

(a) Spinning-mass gyros can be used for gimballed systems as well as for strapdown systems; whereas laser gyros are adaptable to strapdown systems only.

(b) The technology of spinning-mass gyros is more mature than the technology of laser gyros.

(c) There is more operational experience with spinning-mass gyros than with laser gyros. Performance and reliability have been more fully demonstrated for spinning-mass gyros than for laser gyros.

(d) Smaller drift rates have been demonstrated for high-performance spinning-mass gyros than for laser gyros.

6.5.3.1 Every ring laser gyro (RLG) described in Section 6.4 is a two-wave (or two-mode) RLG, i.e. a RLG with one pair of contrarotating waves. There is a class of laser gyros, under development, called multi-oscillator laser gyros, with four waves (or four modes), i.e. two pairs of contrarotating waves, all operating in the same optical cavity. References 6.6.27, 6.6.28, 6.6.29.

6.5.3.2 The best known multi-oscillator laser gyro is DILAG (DIfferential LAser Gyro). (Reference 6.6.30) A polarizing crystal in the DILAG cavity produces one pair of contrarotating waves that are right circularly polarized, and a second pair of contrarotating waves that are left circularly polarized. A Faraday cell in the cavity biases the outputs of each pair of waves oppositely because their circular polarizations are opposite in sense. A polarizing filter at the output distinguishes one pair of waves from the other pair. By subtracting the output frequency of one pair of waves from the output frequency of the other pair of waves, instabilities in the Faraday bias are cancelled out; and furthermore the scale factor SF of the DILAG becomes twice the scale factor of the comparable two-wave RLG. In other words, lock-in is avoided in the DILAG without the disturbances of unstable bias, and the sensitivity and resolution of DILAG is improved twofold compared to a two-wave RLG.

6.5.3.3 The DILAG optical "ring" path is in the shape of a quadrilateral with four mirrors, one at each corner, because the circular polarization of each wave is reversed at each reflection from a mirror, and an even number of reversals is required in each circuit around the ring in order to provide constructive interference.

6.5.3.4 ZLAG (Zeeman LAser Gyro) is another type of multi-oscillator laser gyro under development. ZLAG is a DILAG with a magnetic field applied to the laser medium. ZLAG utilizes the Zeeman effect, i.e. the splitting of the spectroscopic lines of radiation when the source is placed in a moderately intense magnetic field. (References 6.6.28, 6.6.29.) The objectives of the developments of ZLAG, like those of DILAG, are to avoid lock-in, to improve stability of output, and to improve sensitivity in the measurement of Ω .

6.5.4 There is no theoretical restriction on the shape of the optical ring path in a laser gyro, as stated in paragraph 6.2.6.2.(a). Fiberoptic laser gyros (Section 6.3) use circular paths. Early experimenters (e.g. paragraphs 6.2.1 and 6.4.5) used square or rectangular ring paths. The DILAG and other multi-oscillator laser gyros must use a square or rectangular or other quadrilateral configuration, for the reason given in paragraph 6.5.3.3. However, most laser gyros now in actual use have a triangular configuration, usually an equilateral triangle. The triangular shape is preferred to a quadrilateral shape because: (1) The triangle requires only 3 instead of 4 mirrors, with corresponding reduction of alignment problems, savings in cost, and reduction in mirror backscattering (paragraph 6.4.13); (2) The plane of the optical ring, and hence the direction of the input rotation axis, is accurately determined by the vertices of the triangle (see paragraph 6.5.1.h); and

(3) The triangular shape is more rigid and rugged than the quadrilateral shape.

6.5.5 Three triangle-shaped laser gyros mounted separately with their planes (and input axes) mutually perpendicular can occupy more instrument space than an equivalent conventional spinning-mass gyro. In order to reduce the over-all space required for the three mutually orthogonal triangular laser gyros, they can be interleaved, resulting in a 50 percent reduction in overall size. Three such laser gyros, each with a 7.5 inch equilateral triangular perimeter can be built into a single block of Cer-Vit with an over-all size of approximately 3 x 3 x 3 inches. Reference 6.6.31.

6.5.6 Laser gyros have been constructed with the laser outside the optical cavity, but with the cavity resonant. These gyros are passive according to paragraph 6.4.1, but they are also resonant. They are called passive ring resonator laser gyros, and the optical ring is in the shape of a square in one such type of gyro. (References 6.6.32, 6.6.33, 6.3.34.) In effect, the resonant ring optical cavity houses two Fabry-Perot interferometers, one operating in a clockwise direction, and one in the counter-clockwise direction. Another version of the passive ring resonator laser gyro has a complete laser inside one arm of a triangular optical ring, but the gyro is nevertheless called passive because the laser is said to be used only to furnish a pair of contrarotating beams, one out of each end of the laser, for the two Fabry-Perot interferometers; Reference 6.6.35. A principal objective of passive ring resonator laser gyros is to avoid the lock-in that plagues ring laser gyros.

6.5.7 Three distinctively different basic phenomena can be used by self-contained instruments to detect and measure rotation. These phenomena are: (1) the rotational inertia (and precession) of macroscopic spinning-masses; (2) the nuclear magnetic resonance (NMR) of atomic nuclei; and (3) the Sagnac effect. The first of these phenomena is the basis for the widely used conventional spinning-mass gyroscopes. The second phenomenon is used in NMR gyros, also called MRG (Magnetic Resonance Gyros), that are in a relatively early stage of development; (References 6.6.36, 6.6.37, 6.6.38, 6.6.39.) The third phenomenon, the Sagnac effect, is the basis for all laser gyros. These three kinds of gyros have very little in common except their end purpose which is to detect and measure rotation by self-contained means.

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Each of the three separate topics in this report (paragraph 2.1, page 3) has its own set of specialized references and bibliography. The set of references and bibliography for each topic is at the end of the section that treats that topic, as follows:

21 references and bibliography for National Plans for Navigation (Section 4) are in Section 4.4, pages 63-66.

49 references and bibliography for GPS (Section 5) are in Section 5.10, pages 97 - 102.

62 references and bibliography for Laser Gyros (Section 6) are in Section 6.6, pages 137 - 143.

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