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WSEG REPORT 289 ✓

IMPACT OF NAVSTAR GLOBAL POSITIONING SYSTEM ON MILITARY PLANS FOR NAVIGATION AND POSITION FIXING SYSTEMS

Including
IDA Report R-217 ✓

October 1975

H. A. Cheilek
Project Leader

Colonel W. R. Seymour, USAF
WSEG Project Officer

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IDA
INSTITUTE FOR DEFENSE ANALYSES
SYSTEMS EVALUATION DIVISION

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WEAPONS SYSTEMS EVALUATION GROUP
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WEAPONS SYSTEMS EVALUATION GROUP
400 ARMY NAVY DRIVE
ARLINGTON, VIRGINIA 22202

9 APR 1976

MEMORANDUM FOR DIRECTOR OF DEFENSE RESEARCH AND ENGINEERING

SUBJECT: Impact of NAVSTAR Global Positioning System (GPS) on Military Plans for Navigation and Position Fixing Systems

1. This report, WSEG No. 289, is the response to a request by the Deputy Director (Strategic and Space Systems), Office of the Director of Defense Research and Engineering to the Director, Weapons Systems Evaluation Group (WSEG).

2. The focus of this study was toward three principal objectives: (a) an examination of the wide variety of existing and developmental navigation and position techniques, the identification of those potentially replaceable by GPS and the attendant cost advantages; (b) the identification and description of operational demonstrations that illustrate the applicability and utility of GPS to military operations; and (c) the identification of system test opportunities wherein GPS early availability would find useful application as test range instrumentation.

3. Cost uncertainties were such that the range between the minimum and maximum periods for recovery of the cost of GPS is quite large. There are however significant factors evident in the study, but not amenable to fiscal quantification that provide impetus for employment of GPS. They are: simplification of navigation logistics, improvements in effectiveness, and provision of capabilities not now available.

ECWaller

E. C. WALLER
Vice Admiral, USN
Director

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~~REPORT~~ R-217

(6)

IMPACT OF NAVSTAR GLOBAL POSITIONING SYSTEM ON MILITARY PLANS FOR NAVIGATION AND POSITION FIXING SYSTEMS,

(10)
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This report has been prepared by the Systems Evaluation Division of the Institute for Defense Analyses ~~in response to the Weapons~~ Systems Evaluation Group Task ~~Order~~ DAHC 15 73-C-~~0200~~ -238, dated 23 January 1975.

(15)

(18) WSEG, IDA/HQ

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PREFACE

This study has been conducted by the Systems Evaluation Division of IDA in response to WSEG Task Order T-238 (dated 23 January 1975), which was assigned to IDA by the Director, Weapons Systems Evaluation Group. The study group was assisted in the conduct of the project by Col. Loren T. Erickson (USMC), Capt. Kyle H. Woodbury (USN), and Col. William C. Stephens (USA) from WSEG. The authors are pleased to acknowledge the valuable guidance and review provided by the IDA Technical Review Committee.

The planning and programming data cited in this study reflect the status as of mid-July 1975. At that time the major study effort was directed toward the analysis of data and preparation of the report. Because of the considerable current activity in the development and procurement of navigation systems, there may have been changes in status since July. The authors do not know of any such changes that would have a material impact on the general results of this study.

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Part 3–Analyses

Appendices

Part 1

INTRODUCTION

INTRODUCTION

and

A. OBJECTIVES

The purpose of this study is to provide analytical support for a continuing DDR&E review of all operational and developmental navigation and position fixing systems. A primary concern of this review is the identification of cost saving actions relative to navigation systems whose utility is questionable in view of the potential capabilities of the NAVSTAR Global Positioning System (GPS).

This study addresses three specific objectives:

Task 1 – To compare existing and proposed military navigation systems, including GPS, and to estimate the potential cost avoidance that would result from the phasing out of current systems as a result of GPS becoming operational.

Task 2 – To identify and describe operational demonstrations using contemporary weapon systems that could display the utility of GPS for military application.

Task 3 – To identify weapon systems currently under development that could benefit from the early availability of GPS test range instrumentation.

B. APPROACH AND SCOPE

The general approach adopted for the analysis of the above three tasks was as follows:

Task 1

- The navigation suites of all current and future platforms were reviewed to determine which systems could be removed, if GPS were installed, without compromising mission capabilities.
- RDT&E, procurement, and operations costs for GPS and for the equipments selected for replacement were estimated.
- The implications of phasing out certain existing and programmed navigation systems on future operational capabilities were assessed, and associated cost savings were identified.

Task 2

- Discussions were held with senior members of the Services in order to (1) determine which military mission areas were in need of improved navigation, position fixing and timing capabilities, and (2) examine the potential application of GPS to these problem areas.
- The mission areas that appeared most suitable for demonstrating the utility of GPS were identified, and appropriate concepts for operational demonstrations were formulated.
- The concepts for operational demonstrations were reviewed, with cognizant Service agencies having doctrinal responsibility for the mission areas, and were revised to incorporate their suggestions.

Task 3

- The weapon system development programs that have a significant amount of testing scheduled after November 1977 (GPS availability date) and that have test data needs including position, velocity, and time, were identified.
- Discussions were held with appropriate personnel from each of the programs to determine if the project could benefit from the use of the planned GPS capability for test range instrumentation.
- Programs having testing needs that will potentially require the acquisition of additional test range instrumentation and that could be satisfied by GPS test range instrumentation were identified, and their specific testing needs were listed.

C. ORGANIZATION OF THE REPORT

A brief summary and discussion of this study are presented in Part 2. The supporting analyses are contained in Part 3, in which Chapters I and II relate to Task 1, Chapter III to Task 2, and Chapter IV to Task 3. Supporting data for the NAVSTAR GPS program, the computerized model used to determine cost avoidance, the cost detail for the current and advanced technology GPS user equipment analysis, and a Glossary and indexes of tables and figures are contained in the appendices. This study is also supported by the following IDA reports:

- IDA Report R-173, *Comparison of Satellite and Conventional Military Navigation Systems Programs,* May 1971, SECRET.
- IDA Study S-409, *Sensitivity of Mission Performance to Position Fixing Accuracy,* January 1973, SECRET.
- IDA CAG-TM-2, *Life Cycle Cost Estimates for Three Position Fixing Systems,* July 1973, SECRET.

- WSEG Report 216/IDA Report R-190, *Defense Navigation Satellite System Study*, July 1973, SECRET.
- IDA Report R-204, *Study of a Functional Area Summary for Navigation*, November 1974, SECRET.
- IDA Note N-834, *Force Structure Supplement to IDA Report R 217*, October 1975, SECRET.

Part 2

SUMMARY & DISCUSSION

SUMMARY

The results of the study in each of the three areas investigated are summarized and briefly discussed in this section and are examined in detail in Part 3.

A. TASK 1: CANDIDATE SYSTEMS FOR REPLACEMENT BY GPS

The current navigation and position fixing systems potentially replaceable by NAVSTAR GPS are (1) the enroute radio systems (i.e., LORAN, TACAN, VOR/DME, OMEGA, DF, and TRANSIT[1] systems); (2) the self-contained airborne Doppler navigators used in single, dual, or hybrid inertial installations; (3) precision landing aids, consisting of the Instrument Landing System (ILS), its developmental counterpart, the Microwave Landing System (MLS), and Precision Approach Radars (PARs); and (4) a small number of airborne radars used exclusively for weapon delivery and navigation (bomb/nav radars). Inertial systems are not considered replaceable by GPS because of (1) the operational need for having a truly self-contained system in the event external radio aids are jammed or destroyed, and (2) the mutual augmentation provided by a GPS/inertial hybrid to significantly improve both the resistance of GPS to ECM and the unaided performance of the inertial system.

The development plan established by the GPS Joint Program Office (JPO) envisages the deployment of space vehicles in three phases. The space segment for Phase I will be available in 1977 and will consist of 6 satellites, which will allow 1 to 3 hours of daily testing over CONUS (and adjacent ocean areas). This constellation will provide three-dimensional, high accuracy position and velocity data during each test period. For Phase II, the constellation will consist of 9 satellites[2] (in 1981), which will provide an interim worldwide two-dimensional capability with navigation accuracies of 100 to 200 meters. For the purpose of this study, it has been assumed that an additional 3 satellites, a total of 12, will be necessary to retain the high accuracy testing capability of Phase I and also provide the two-dimensional global capability. The plan for Phase III is to establish the full operational capability of GPS in 1984. The space segment will consist of a 24-satellite constellation providing worldwide three-dimensional coverage and estimated accuracies on the order of 10 meters. A summary of the JPO development plan is contained in Appendix A.

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[1] Although TRANSIT is not truly an enroute navigation system, it would certainly be phased out with the advent of GPS.

[2] Recent GPS program information indicates 9 to 11 satellites for Phase II.

The GPS JPO plans to develop several types of user equipment capable of satisfying a broad spectrum of military applications. The equipment concepts range from high performance units (designated Classes A and B) for aircraft needing the highest accuracy and jam resistance, to moderate performance units (Class C) for transport aircraft, ships, and helicopters, to lightweight, battery-operated manpacks (Class D) for one-man operation.

A major motivation for the development of GPS is its potential for high accuracy weapon delivery. The use of GPS in such a role is not sufficiently well proven either on a cost or an effectiveness basis that defendable cost avoidances could be identified, therefore, these costs are not included in this study. Given the uncertainty of the utility of GPS for weapon delivery, the study has identified two sequential courses of action that would minimize the risk of deploying a GPS system of unproven value to precision weapon delivery and yet retain the cost avoidance potential and navigation capability of a GPS system having lesser accuracy. The first course of action would provide a worldwide GPS of Limited Operational Capability (LOC) for enroute navigation to replace the above-mentioned enroute and Doppler systems. The second course of action would provide a worldwide GPS of Full Operational Capability (FOC) potentially capable of satisfying the needs of many additional military applications. These sequential options and their implications are summarized below and elaborated further in the Discussion.

1. Limited Operational Capability Option

The key steps in implementing the LOC option are:

(1) Provision of a sufficient number of satellites (~12) to ensure a global two-dimensional navigation capability on the order of 200 meters and a daily "window" (1 to 3 hours) for the testing of new GPS applications and weapon systems requiring high accuracy and three-dimensional information.

(2) Development of low cost user equipment (~$10,000 for Class C) to replace the enroute (LORAN, TACAN, VOR/DME, OMEGA, DF, and TRANSIT) and Doppler navigation systems in the vast majority of military platforms.

(3) Planning the efficient removal of current enroute systems when GPS space and user equipment segments are available. An annual avoidance[3] of about $130 million per year in reprocurement and O&M would result if the enroute systems and some Dopplers (primarily those paired with an inertial system) were phased out.[4] If all Dopplers were phased out, this avoidance would increase to about $155 million per year.

(4) Closely monitoring the progress of GPS space and user equipment development in order to maximize the potential cost avoidance of R&D and procurement of new versions of current systems. If GPS capabilities and availability were

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[3] A short discussion of the methods and assumptions used in deriving the cost avoidance potential for current systems is given in Section A.1.e, page 23, and summarized in Table 8, page 24, of the Discussion.

[4] Cost figures in Part 2 are usually rounded to the nearest $5 million; also, all costs in this report have been adjusted to 1975 levels.

demonstrated soon enough, all or part of the planned $340 million in new R&D and procurement of current enroute and Doppler systems might be avoided. In some cases, such cancellations could result in a gap of 3 to 5 years before improved navigation capabilities would become available. Alternatively, a 2-year delay in the decision to halt programs may negate most of the potential savings.

(5) Continue the study, development, and testing of GPS user equipment for high accuracy applications such as coordinate bombing, midcourse guidance of tactical and strategic weapons, instrument landing of aircraft, etc. These weapon delivery and aircraft landing applications will need a long lead time for development and subsequent acceptance by the user commands.

The potential cost avoidances cited above assume that *every* present user of the current navigation systems (23,000 aircraft and ships) would be provided a GPS receiver of limited accuracy (Class C set). This class of receiver should provide essentially the same capability as the systems it would replace at the expense of somewhat less redundancy in the number of reference (signal transmitting) systems. The estimated costs (in 1975 dollars) for the GPS user equipment and the 12-satellite space segment of the LOC option are shown below (see Part 3, Chapter II, for further discussion).[5] These GPS costs are to be compared with the costs of the conventional systems that would be avoided given in the preceding paragraphs.

Space and Control Segments	
Initial Investment	$530 million
Annual Costs	$70-85 million
User Equipment	
Initial Investment	$315-630 million
Annual Costs	$20-46 million

For each range of values shown, the lower figure is derived from cost data provided by the GPS JPO, while the higher figure results from cost increase factors assumed in this study. (For summary of these factors, see Section A.2.a, page 25, in the Discussion.)

These ranges of GPS cost, as well as the corresponding costs for the current systems, may be used to determine the number of years required to amortize the initial cost of GPS. If the lower goals for GPS costs are met and enroute plus *all* Dopplers are removed, the initial cost of GPS would be amortized (without discounting) in 8 to 13 years, depending on the fraction of new procurements of current systems that would be avoided. If only the Dopplers in dual and hybrid installations are removed, this break-even range shifts to a range of 12 to 20 years. If, however, the GPS costs were to shift to the upper range of values indicated above, all break-even points become unreasonably large (i.e., much greater

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[5] The estimates of GPS costs presented herein are in terms of program functional requirements (i.e., initial RDT&E and procurement of hardware, and subsequent annual operating costs). Since these estimates are not time phased and some GPS program parameters have been varied, they will differ in composition and vary somewhat in magnitude from current JPO estimates.

than 20 years). These estimates are based on the assumption that the current enroute and Doppler systems would not be phased out until the GPS (12-satellite system) becomes operational. The sensitivity of the results to reasonable changes in costs emphasizes the importance of achieving the low cost goals for GPS equipment if future savings are to result. (See Figure 1, page 29, and Table 20, page 65.)

2. Full Operational Capability Option

The FOC option includes all the steps previously listed for the LOC option; the major additional steps are:

(1) The establishment of the full 24-satellite constellation soon after the 12-satellite constellation of the LOC option is attained (see Table 9, page 26, for space segment and user equipment costs.)

(2) Development and production of both enroute and high accuracy GPS user equipment for a large number of new applications and users. The JPO estimate for the unit cost of the high accuracy (Class A) user equipment is about $25,000.

(3) Removal of current landing aids[6] and about 10 percent of the current weapon delivery radars. Note that the application of GPS in precision landing and weapon delivery techniques needs to be demonstrated. In the case of landing aids, the accuracy of the FOC GPS is marginal (see Part 3, Chapter I). In the case of radar weapon delivery systems, the accuracy of GPS is adequate; however, this does not provide sufficient basis for replacing most (90 percent) of the bomb/nav radars in the inventory, since these radars also perform other functions, such as air-to-air search, weapon delivery, and terrain avoidance. The potential cost savings for these additional removals of equipment are given in Table 8, page 24.

(4) Cancellation of the R&D and new procurements for landing aids and ground-based radars identified in Tables 7 and 8, pages 21 and 24.

Under the most optimistic assumptions (i.e., lowest GPS costs and the saving of all identified sources of cost avoidance), the break-even time for the FOC option is significantly greater (about 25 years) than for the LOC option. This difference results from the much higher GPS costs and the relatively small additional cost avoidance from the landing aids and bomb/nav radars. If the high end of the GPS cost ranges were to apply, then GPS operations costs would become greater than the potential savings in the operations costs of current systems, and break-even points would cease to exist. Thus, it is apparent that the FOC option will probably not save any money in the navigation area.

The significant advantage that would accrue from the FOC option is the potential application of GPS (1) to new weapon systems to increase operational effectiveness, and (2)

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[6] Assuming the acceptance by the FAA of GPS as a landing aid at civil airports.

to combined operations of large task forces to improve the command and control functions. The operational demonstrations described in the following Discussion provide examples of these potential applications of GPS. Additional examples of GPS application to the guidance of tactical and strategic missiles (although not covered in this report) have been suggested in other studies,[7] wherein substantial improvements in missile effectiveness have been predicted.

In conclusion, the LOC option represents the least risk since (1) the impact of unforeseen development problems in the satellites (e.g., the space clocks) would be reduced by the smaller constellation, (2) the current enroute and Doppler systems represent the bulk of the potential cost avoidance, and (3) the applications of GPS to other military missions may proceed at a pace consistent with efficient use of RDT&E resources and acceptance by the user commands.

In contrast, the risks of going very quickly to the FOC option appear appreciably greater. The more rapid development of GPS user equipment required for this plan runs the risk of increasing the costs[8] and creating problems of acceptability with the users. Most of the interesting new applications for GPS are in an embryo stage at present, and it may take 10 to 15 years to bring them to fruition and to gain their acceptance by the user commands. In the interim, it should not be necessary to carry the added cost of the additional satellites needed to achieve the FOC.

B. TASK 2: OPERATIONAL DEMONSTRATIONS

Seven demonstrations have been identified to illustrate the operational utility of GPS for military applications. These demonstrations are in the mission areas of *air assault, aircraft approach and landing, amphibious operations, attack helicopter operations, close air support forward observer and artillery operations,* and *photoreconnaissance and coordinate bombing.* Descriptions of each of these proposed demonstrations have been developed. The general concepts of these demonstrations have been reviewed with the Service agencies having the doctinal responsibility for the position fixing and navigation problem areas forming the bases for the demonstrations. The concepts have been exposted to include their comments. Each of these demonstrations is examined in the Discussion (and in Part 3, Chapter III), along with the current problems and the potential benefits of using GPS.

C. TASK 3: PROGRAMS THAT COULD BENEFIT FROM EARLY AVAILABILITY OF GPS TEST RANGE INSTRUMENTATION

Seven programs were identified as potentially benefiting from the early availability of GPS test range instrumentation. These include two aircraft developments (B-1 and F-16),

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[7] For example, *Impact of the Instrumental Globe on Military Forces in the 1980s: Strategic Forces–A Briefing,* Rand Working Note WN-8941-PR, January 1975, SECRET.

[8] See page 31 for potential impact of advanced technology on user equipment costs.

two cruise missiles programs (ALCM and SLCM), a strategic missile development (MX), and two air defense systems (SAM-D and SHORAD). Each of these programs has range testing needs that will probably require acquisition of additional (i.e., over and above those currently available) instrumentation systems. The potential benefits that GPS may bring to these weapon programs are high accuracy position, velocity, and time measurements; greater mobility/flightpath freedom for the test vehicle; and the ability to quickly establish test ranges on a worldwide basis. The specific [illegible] objectives of each of these programs that GPS may be able to satisfy are examined [illegible] owing and in Part 3, Chapter IV.

DISCUSSION

This portion of the report is divided into three major sections. Section A examines the most likely candidate systems for replacement by GPS, and the technical, operational, and cost implications resulting from such replacements; Section B examines seven candidate demonstrations for displaying the operational utility of GPS; and Section C examines the current development programs that could benefit from the availability of GPS for range instrumentation.

A. TASK 1: CANDIDATE SYSTEMS FOR REPLACEMENT BY GPS

The major issues and questions posed by this task, assuming that GPS will perform as predicted,[1] are (1) which current navigation systems are potential candidates for being phased out, (2) which should be retained to be used in conjunction with GPS, (3) what are the orders of magnitude of the cost avoidances implied by phasing out systems, and (4) what are the technical and operational aspects, both positive and negative, that would result.

The general approach adopted to answer these questions was to assign GPS equipment to all user platforms and then review the navigation suite of each platform type for equipment that could be removed without compromising its mission capabilities. The rationale for equipment removal also considered the vulnerability of GPS to both physical and electronic countermeasures by electing to remove equipment in stages; that is, the first systems chosen for removal would probably create the least incentive for an enemy to attack GPS satellites or ground control stations, and subsequent removals would create increasingly higher incentives. The specific cases used in this removal process are:

Case 1: Remove all enroute radio navigation equipment (i.e., equipment whose primary function is point-to-point navigation).

Case 2: Remove the self-contained Doppler systems. Two subcases are analyzed: (a) removal of one Doppler in dual and hybrid installations and (b) removal of all Dopplers.

Case 3: Remove all military landing systems.

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[1] See Appendix A for discussion of the NAVSTAR GPS program.

Case 4: Remove all radar sensors whose prime function is weapon delivery, navigation, and mapping.

In the first two cases, the navigation requirements are such that a two-dimensional, relatively low accuracy GPS system is an adequate replacement. For the next two cases, the full three-dimensional, high accuracy GPS system is necessary. These cases are summarized in Table 1 in terms of the specific generic navigation systems now employed by military users.

Table 1. Generic Types of Equipment Removed From Aircraft

Case 1:	Enroute Radio NAVAIDS – LORAN – TACAN – VOR/DME – OMEGA – Direction Finders (DFs)
Case 2:	Doppler Systems
Case 3:	Landing Aids – Instrument Landing System (ILS) – Precision Approach Radars (PARs)
Case 4:	Bombing/Navigation Radars

Not all of the systems listed in Table 1 are important from a potential cost avoidance point of view. Table 2 summarizes the user equipment inventory and the order-of-magnitude investment in military navigation systems, and indicates which systems are the major candidates for cost avoidance, since annual operations costs are typically proportional to equipment investment. It is evident from Table 2 that the dominant users of current navigation equipment are aircraft. Ship users are far less numerous (1.5 percent of total inventory), and the ground forces have virtually no equipment of the types listed.

The inertial systems are not considered replaceable by GPS because they provide (1) the best self-contained performance available today, and (2) the needed backup in case GPS is jammed or physically attacked. Of the remaining systems in Table 2, the important ones for this study are the enroute LORAN, TACAN, VOR/DME, OMEGA, and DF systems and the Doppler systems. These systems represent an investment of approximately $670 million, which is almost 60 percent of the estimated total investment of $1.2 billion.

1. Operational Considerations and Cost Avoidance Potential

Each of the aforementioned four cases of navigation system removal has its own special set of technical and operational consequences, as well as cost avoidance potentials. These are discussed in the following sections.

a. Case 1: Enroute Radio Navaids

The enroute radio navigation aids (navaids) are those employed primarily in navigating from point A to point B over considerable distances. The accuracy needed for enroute navigation is relatively low: several hundred meters may be required near congested terminal areas, while 1 to 5 miles sufficient for the "cruise" portions of most missions.

The present radio systems are of three general types: (1) hyperbolic systems such as LORAN and OMEGA, which require a minimum of three ground stations for position

Table 2. Estimated Total User Equipment Investment Costs for Navigation Systems Currently in Use by the U.S. Military Services (Costs in 1975 Dollars)*

	Aircraft Users			Ship Users		
System Type	Total Inventory	Average Cost† per Unit ($)	Total Investment ($M)	Total Inventory	Average Cost† per Unit ($)	Total Investment ($M)
LORAN	4,200	50,000	210	500	15,000	7.5
TACAN	14,000	10,000	140			
VOR/DME	8,000	4,000	32			
OMEGA/VLF	400	25,000	10	300	25,000	7.5
DF	20,000	2,500	50			
ILF	5,000	3,500	18			
Doppler (Single)‡	4,000	37,000	148			
Doppler (Redundant)‡	1,700		63			
Inertials	4,000	80,000	320	200	500,000	100.0
Bombing/Navigation Radars	600§	150,000	90			
Satellite				100	25,000	2.5
Total			1,081	Total		117.5

*Land users have been omitted from the table since currently they have few high value systems in the inventory.

†Average costs quoted here are approximate and are for scoping purposes only. Detailed cost estimates for specific systems are given in Chapter II.

‡Single Dopplers are installations in which only one Doppler is used as a means of navigation beyond the range of radio navigation aids. Redundant Dopplers are those which are paired with an inertial system or another Doppler.

§The 600 radars listed here are those which have only an air-to-ground weapon delivery or navigation capability. There are about 6,000 radars which have functions in addition to air-to-ground weapon delivery and navigation, i.e., search, air-to-air, intercept, etc.

fixing; (2) "rho/theta" systems such as TACAN, which require only one ground station for a position fix; and (3) direction finding (DF) systems, which give only a line of position and are seldom considered a primary navigation aid except on minimally equipped platforms (some helicopters and small boats).

These navaids are characterized by extensive networks of ground stations to provide coverage of most or all of the populated areas of the world, as well as almost universal use by both military and civil aircraft and ships of both the Free World and Red Bloc nations. Table 2 estimates the current U.S. military inventory of user equipment for aircraft and ship platforms.

From a technical point of view, a simplified, low cost GPS receiver, using only the clear/acquisition signal,[2] could fulfill most of the navigation functions of the current enroute systems. Furthermore, only about half of the currently planned 24 satellites would be needed to provide a two-dimensional capability equivalent to the present systems.

There are a number of technical and collateral aspects, both positive and negative, which may influence a decision to phase out any of the enroute systems considered. These are discussed below.

LORAN. LORAN is a long range radio navigation system of the hyperbolic type in widespread use by military and civil users. LORAN A is scheduled to be phased out by 1980 insofar as U.S. support is concerned. LORAN C has been selected (by DOT) as the primary system for the U.S. coastal/confluence waters and the Great Lakes. This net is scheduled to have 21 stations, of which 8 are operating (4 in Alaska and 4 on the east coast). The positive and negative aspects of the use of GPS for the LORAN function are:

Positive Aspects

- GPS would be worldwide, whereas LORAN coverage is presently limited to heavily traveled ocean areas. Broad ocean coverage by LORAN does not appear practical.
- The potential accuracy of a 12-satellite GPS space segment and low cost user equipment would meet most of the requirements fulfilled by LORAN. The full 24-satellite space segment and high accuracy user sets are predicted to exceed LORAN performance.
- The phaseout of LORAN A by 1980 would provide GPS with a potential civil market if the low cost goals for GPS user equipment were achieved.

Negative Aspects

- Cancellation of the Air Force Tactical LORAN (ARN-101), the Army low cost LORAN (ARN-114), and the corresponding LORAN D ground chain (see Table 5); and substitution of equivalent GPS user equipment would result in a gap of 3 to 5 years before improved navigation capability could become available.
- The two-dimensional GPS capability would have to be available by 1979 (or shortly thereafter) to service the U.S. coastal/confluence zones (in particular, the west coast and Gulf of Alaska areas) to replace LORAN A.

In general, the substitution of GPS for the LORAN function is attractive from the standpoint of both equal or improved capabilities and cost avoidance potential. The inhibiting factor is primarily timing of the availability of GPS to fulfill specialized needs for both civil and military users.

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[2] See Appendix A for discussion of GPS operation.

TACAN and VOR/DME. TACAN and VOR/DME are treated together since they provide nearly identical navigation service. In large measure, the two ground reference systems are collocated for civil operations and are called VORTACs. The DME component of the collocated systems is common to both TACAN and VOR/DME. TACAN is primarily a military system, and VOR/DME is the Free World civil system. The nominal accuracies of both systems are similar (3.5 degrees in azimuth and 0.5 nmi or 3 percent of range, whichever is greater, 1 sigma). Techniques for improving the accuracy for both systems by almost a factor of 10 exist and have been employed in special situations. The locations of the fixed VORTAC sites determine, in large measure, the overland route structure for aircraft in the Free World.

VOR/DME is installed in some military aircraft (primarily cargo types) to enable use of the civil airspace structure in the absence of TACAN ground stations. Assuming that GPS will be approved for IFR navigation in the civil airspace, VOR/DME user sets would no longer be required by these military aircraft.

Abandonment of the civil reference system is an FAA/ICAO matter and has little cost avoidance potential for the DOD. The broad implications of GPS to civil navigation suggest that the development of GPS be coordinated with the FAA and ICAO, and be made available for civil use. These implications are:

(1) Eventual elimination of the civil network of VOR/DME ground stations, and provision of a suitable replacement.

(2) Availability of IFR navigation capability in areas not presently served.

(3) Facilitation of the area navigation concept.

(4) The impact of a large number of additional users on user system cost through high-volume production and more competition.

In addition to the obvious enroute navigation function, the VORTAC system provides additional services to both military and civil aircraft. The most important of these is its use as an aid for nonprecision approaches to landing. In the military case, this includes approaches to aircraft carriers and forward unimproved airstrips (using portable TACAN beacons). An operational demonstration to confirm the potential capability of GPS as a nonprecision and Category I approach aid is discussed on page 35 and in Part 3, Chapter III.

In an analogous way, TACAN is used as a means for aircraft-to-ship and aircraft-to-aircraft rendezvous. The rendezvous function requires positioning relative to a moving target. This relative navigation source is automatically provided by the TACAN beacon. The use of GPS would require a data link to establish relative position and headings. While this might be done by voice for slowly moving platforms, it would probably require a narrow-band data link and computer (for distance and bearing computations) for an aerial refueling operation.

The positive and negative aspects of the use of GPS for the TACAN function are:

Positive Aspects

GPS would be worldwide, while TACAN is primarily an overland system.

The accuracy of a 12-satellite space segment and low cost user equipment would potentially equal or exceed the performance of TACAN.

GPS would have greater resistance to ECM.

GPS would provide an area navigation capability, whereas TACAN requires the addition of a computer to provide this capability.

Users of GPS would be passive, whereas TACAN users must radiate.

GPS could not be saturated, whereas the DME portion of TACAN ground stations are saturable.

Negative Aspects

- The GPS reference system would provide less redundancy than TACAN.
- A GPS user would require a data link when performing a rendezvous with another moving platform.
- GPS would require approval by FAA and ICAO if it is to be used as a substitute for VORTAC IFR navigation in the civil route structure.
- Abandonment of the ground reference system may be objected to by friendly foreign forces that have adopted TACAN as principal means of navigation.

As is indicated above, GPS generally fulfills the function of TACAN. The only exception is rendezvous. The negative aspects are in large measure administrative. There is little question that GPS should meet the FAA standards set forth in Circular 90-45A and thus should be approved by the FAA and the ICAO. The attitudes of the foreign friendly forces are unknown. It is worth noting, however, that they could share in the cost avoidance potential in proportion to the isze of their aircraft fleet without a concomitant investment in R&D and the space segment.

Direction Finding Systems. DF systems consist of a series of nondirectional beacons (NDBs) and a user receiver with an antenna that senses the direction from which the NDB radiation comes. Automatic direction finding (ADF) receivers display the direction of the received signal relative to the longitudinal axis of the platform (aircraft or ship). The system has the advantages of being comparatively cheap and easy to maintain. Its limited accuracy under good atmospheric conditions (about 5 degrees), coupled with added sensing errors in electrical storms and pilotage errors in high winds, makes it unsuitable for use in high density traffic. Nevertheless, the low cost of DFs has resulted in their use as a primary navigation aid on "low cost" platforms (e.g., helicopters) and as a backup system on virtually everything else–military and civil. In spite of its deficiencies, the NDB/ADF continues in use as a means of conducting nonprecision approaches at many airports and as an aid in making the initial approach to a precision instrument landing. The cost avoidance potential of military DF systems is significant because of the large number in use (see Table 4).

Although GPS can provide much more capability than the ADFs, it may still be desirable to retain them as a low cost backup for a "get home" capability rather than provide dual GPS receivers.

OMEGA. The only truly global radio navigation systems other than GPS are the VLF hyperbolic systems. The best known of these is OMEGA. The military usage of OMEGA is increasing, as indicated in Table 3.

Table 3. Military Usage of OMEGA

	1974	*Future Increase*
Navy		
Ships	278	54
Aircraft*	127	177
Air Force	0	690

Source: OPNAV Instruction S3530.1B.

*P-3 and S-3 aircraft only.

†For C130 MOD.

Its use, for the period covered by this study, is confined to high value platforms that routinely operate over the ocean beyond the range of other systems. The individual system costs, both user and ground reference, are relatively high. However, their limited usage makes the overall cost avoidance potential small. Since OMEGA is the only reliable worldwide alternative to GPS, and since there is little cost to be saved by its abandonment, it is reasonable to retain it as a backup system for broad ocean navigation.

Costs of Enroute Systems. The two major cost segments for the enroute radio navigation systems are the user equipment and the reference equipment. The estimated average annual operations and recurring acquisition costs for the enroute user systems considered in Case 1 are summarized in Table 4. The methodology and cumulative cost data on which the 15-year averages in Table 4 are based are given in Part 3, Chapters I and II. The user system costs shown in Table 4 do not include the procurement of new designs of equipments that either provide a new capability for existing platforms or replace aging or otherwise unsatisfactory older equipment. The specific programs of this type are listed in Table 5.

The new equipments listed in Table 5 would probably be installed by the earliest time at which a two-dimensional GPS capability could exist as an alternative. Realization of any cost avoidance would entail some delay in the scheduled upgrading of enroute navigation equipment capabilities. The magnitude of realized cost avoidance will depend on early cancellation of these R&D procurement programs. However, such cancellation decisions would depend critically on the early demonstration of satisfactory GFS performance.

b. Case 2: Self-Contained Doppler Systems

Self-contained systems are utilized in military platforms either because the enroute radio navaids (previously discussed) are unavailable in the areas of use or because it is expected that these radio systems will be jammed or otherwise compromised. A common

Table 4. Estimated Average Annual Costs for Military Enroute User Equipment*
(Costs in Millions of 1975 Dollars)

System	Number of Sets	Recurring Acquisition Cost	O&M Cost	Total Cost
LORAN	4,900	24.3	35.0	59.3
TACAN	12,500	4.1	24.5	28.6
VOR/DME	7,200	1.1	2.3	3.4
OMEGA	300	0.5	0.4	0.9
ADF	20,900	3.1	8.4	11.5
Total	45,800	33.1	70.6	103.7

*Quantities and costs are averaged over the 15-year period covered by this study (see Part 3, Chapter I).

*Table 5. New Enroute Equipment Procurement**

System	Type	Time Span	Quantity Planned	Average Unit Cost (dollars, 1975)	Total ($ millions, 1975)
Air Force					
ARN-118	TACAN	1976-	10,000†	12,000	120.0
ARN-101	LORAN	1978-1979	242	150,000‡	36.3
Unknown	OMEGA	Thru FY 1978	690	15,000	10.4
TRN-35	LORAN (Ref)	1976-1977	- 3 chains -		15.6
Army					
ARN-114	LORAN	1975-	2,100	28,000 §	59.0
ARN-123	VOR/ILS	1975-	7,100⊕	1,540 ☆	11.0
PSN-6	LORAN	1976-1978	1,740	18,000	30.0
Total					282.3

*Note that quantities and costs are planning figures and do not represent firm contract data.

†Contract has been let for initial 1,100 units.

‡Contract price does not include inertial measurement unit (IMU).

§Army cost target.

⊕Contract let for initial 864 units plus 100 percent option.

☆Includes 4-year failure free warranty.

form of self-contained navigation equipment is the dead-reckoning system, which integrates velocity to derive position change. All systems of this type require initialization to provide the position in geographic coordinates. The velocity vector required for the dead-reckoning systems can be obtained in a variety of ways. The most accurate systems using direct measurement of velocity are based on Doppler radar measurements of platform speed relative to the ground and employ a gyrocompass measurement of heading relative to true north. Accuracies of 1 to 5 percent of distance traveled are typical for Doppler systems. All self-contained systems are characterized by an unbounded position error that grows with time. Thus, periodic position updates are required to control the errors on long missions.

The Doppler systems are frequently used in dual or hybrid installations both for redundancy and to improve the overall accuracy. Of 5,370 platforms containing Doppler systems, 3,700 have a single Doppler, 1,300 have Doppler/Inertial hybrids, and 370 have dual Doppler installations. Substitution of GPS receivers for these Doppler sensors is technically feasible, since the predicted velocity accuracy for GPS (see Appendix A), is equal to, or better than, the performance of present-day Dopplers. Furthermore, an inertial/GPS hybrid would be more accurate than any of the current dual self-contained systems, since the errors would be bounded by the GPS system. The potential cost avoidances arising from the substitution of GPS for the Doppler component of the redundant (i.e., dual or Doppler/Inertial) self-contained systems or for all Dopplers in the inventory are presented in the next section. The positive and negative aspects of these subsitutions are:

Positive Aspects

- GPS/Inertial systems provide better accuracy for long range enroute navigation than Doppler/Inertial combinations.
- Unlike Doppler systems, GPS is unaffected by terrain reflectance characteristics. Under some conditions Doppler is unusable over water.
- GPS users are passive, whereas the radiation from Doppler systems is detectable.

Negative Aspects

- GPS is not self-contained and is thus vulnerable to physical countermeasures against the satellites and ground stations.

GPS would generally fulfill the functions performed by the Doppler systems. The vulnerability of GPS satellites and ground stations to physical and electronic countermeasures would necessitate the retention, and perhaps greater use, of inertial systems on military platforms.

Costs of Doppler Systems. The average annual expenditure for all Doppler systems is about $35 million, of which $10 million is for procurement and $25 million is for O&M. Since approximately 30 percent of the total number of Dopplers in the inventory are one of a pair in a dual or hybrid system, 30 percent of the costs cited above could be avoided by removing one Doppler from each of these systems. The corresponding average annual rate is $10 million, of which $3 million is for procurement and $7 million for O&M. In addition, approximately $55 million is planned (by the Army) for future procurement of new Doppler systems.

The potential cost implications of other hybrid systems using the Air Data System or the Airborne Heading and Attitude Reference System (AHARS) with GPS have not been examined in this study. However, they may be a major factor in the feasibility of eliminating the single Doppler, which would be a significant added cost avoidance.

c. Case 3: Landing Aids

The ability to approach and land under reduced ceiling and visibility conditions is vital to the operation of virtually all military aircraft. The primary approach and landing aid in current use by the military is the Precision Approach Radar (PAR), which requires only a communications capability by the user. The standard civil landing aid is the Instrument Landing System (ILS). ILS is also used extensively in those military aircraft which routinely land at civil airfields–about 5,000 of the total inventory of 23,000. This includes primarily the cargo aircraft. In addition, many of the Air Force tactical aircraft are being equipped with ILS. A microwave landing system is being developed by the FAA (with DOD participation) that is expected to become the common system for both military and civil use.

There are four classes of approach and landing requirements: nonprecision approaches, and Category I, II, and III approaches and landings (see Part 3, Chapter I). Comparison of the accuracy requirements with the expected performance of GPS indicates that GPS could easily fulfill the requirement for the nonprecision approach. In addition, there appears to be a potential for the use of GPS as a landing aid for Category I, if a local differential system is implemented. This would consist of a GPS receiver precisely located relative to the approach path and a data link provided to the aircraft. However, it appears doubtful that a differential system would provide sufficient accuracy in the vertical coordinate to allow Category II and III approaches. A proposed operational demonstration of the capabilities of GPS for the approach and landing function is discussed in Section B.2 of this Discussion and in Part 3, Chapter III.

Aside from the accuracy issues, a major advantage offered by GPS as a landing aid would be its worldwide availability. In the case of nonprecision approaches, it would eliminate the need for ground systems; in the case of the higher precision approaches, the ground installation may be somewhat simpler than ILS or the developmental Microwave Landing System (MLS). As will be seen in the next section, the tactical flexibility that these characteristics offer is probably more important than the modest cost savings that they potentially provide.

Costs of Landing Systems. The present inventory of both Precision Approach Radar and ILS reference systems is given in Table 6 along with the approximate annual O&M costs of $11 million for ILS and $14 million for PAR. The average annual cost for ILS user

Table 6. Inventory and Annual Operation and Maintenance Costs of Precision Military Landing Aid Reference Systems

System Type	Inventory	O&M ($M, 1975)
PAR	101*	14.2†
ILS	189	11.3

*Does not include any Army systems—data not in ECAC data base.

†Includes military controller costs based on six controller years per set at $15,000 pay and allowances.

Table 7. Planned Total Expenditures for New Military Landing Aids 1975-1980

User Equipment	$M-1975
R&D	
Military Share of National MLS Development	38
ILS Modernization Program	35
Ground Reference Systems	
R&D*	0
Procurement	
GRN-27	15
TPN-19	46
Product Improvement	13
Total	147

*MLS ground reference R&D included in $38 million for user R&D.

equipment is $12 million, comprising about $2 million for procurement and $10 million for O&M. Thus, the total annual cost for landing aids is $37 million.

The Air Force is planning to upgrade the ILS and PAR installations at its bases during the period covered by this study. Other than this interim program, the expenditure for landing aids is expected to be small until MLS becomes available in the mid-1980s.

The planned expenditures for new landing aids is summarized in Table 7.

d. Case 4: Bombing/Navigation Radars

The use of GPS as an aid in the delivery of airborne weapon systems is probably the role most likely to elicit an enemy attack against GPS. Nevertheless, given that GPS will perform as predicted, it appears to be a viable alternative for radar bombing as it is currently done.

The capabilities of the current radar systems are such that the ability of the aircrew to acquire and strike targets of opportunity is, for all practical purposes, nonexistent. Strikes are preplanned using prior photo or radar reconnaissance. Release points are determined by offset beacons or, if the target is distinctive enough, by matching radar scope photographs (actual or simulated). In either case, the measured impact errors are quite large. This entire procedure can, in principle, be done using GPS in a coordinate bombing mode (see p. 39 and Part 3, Chapter III). The resulting accuracy has been predicted to be better by as much as an order of magnitude.[3] GPS alone, however, has no potential to strike targets of opportunity, either moving or stationary, unless a FAC or other target acquisition

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[3] WSEG Report 216/IDA Report 190, *Defense Navigation Satellite System (DNSS) Study*, July 1973, SECRET.

system could determine the coordinates of the target and hand off its GPS coordinates to a strike aircraft also using GPS.

The development of a new strike radar system such as the Electronically Agile Radar (EAR), and capitalization of the Forward Looking Advanced Multimode Radar (FLAMR) technology, are underway and are expected to lead to a capability to acquire and accurately strike targets of opportunity such as tanks and trucks. The cost of such systems will be high–probably approaching $1 million each. The conservative approach at this time would appear to be a continued development of the technology of precision radar weapon delivery to the point of tactical demonstration and concurrently to develop the techniques for blind bombing using GPS. This approach would also yield better estimates of costs of the advanced radars as well as the subsidiary equipment required to utilize GPS for striking targets of opportunity. If both developments are successful, GPS could serve as a backup system for the advanced radar. In any case, because of the poor performance of current weapon delivery radars, consideration should be given to the practicality of phasing out some of the current radar systems as GPS becomes available and is proven effective for coordinate bombing.

There are currently about 5,500 airborne radars in the inventory that have at least an air-to-ground weapon delivery, navigation, or mapping capability. In 90 percent of the cases, these radars have additional capabilities such as air-to-air intercept that cannot be supplied by GPS. The remaining fraction (about 580 radars) have only a bombing/navigation or mapping capability. These are the only radars that could be replaced by a proven GPS alternative without a marked degradation in the capabilities of the aircraft. The functions that would be lost if the other radars were phased out are primarily air-to-air search and weapon delivery on air superiority fighters, terrain following and avoidance on attack aircraft, and surface search on naval patrol and attack aircraft. Although innovative use of GPS in conjunction with other target acquisition systems might fulfill some of these radar functions, there have been no studies to determine the efficacy of such new approaches.

It is conceivable that more than 580 of the current radars could be phased out. The factors that would influence such a decision include the development of the new radar systems as noted before and the changing role of the F-4 with the advent of the F-14, F-15, and F-16 aircraft and their air superiority role. If the air-to-air role of the F-4 is downgraded, then approximately 600 additional radars might be phased out.

The Air Force is currently conducting a study of these and other issues surrounding the needs for, and use of, radars in aircraft. This study should shed more light on the potential cost avoidance resulting from the use of GPS rather than radars for weapon delivery.

In addition to the airborne radars, there is a ground-based radar bombing system currently under development by the Air Force–Ground Directed Bombing/Radar Bomb Scoring (GDB/RBS) system. This system would be used to vector aircraft to the target and to score the results. These functions are potentially accomplished more effectively with GPS.

The positive and negative aspects of the use of GPS for the weapon delivery function are:

Positive Aspects

- The weapon delivery accuracy of GPS is potentially better than present radars for preplanned strikes against targets accurately located in a GPS-based coordinate system.
- GPS is designed to be relatively immune to decoying or spoofing countermeasures.
- GPS is passive, whereas radar is detectable by enemy defenses.
- The radars are among the most costly avionics systems to acquire and maintain; thus, potential removal of a small fraction of them is not insignificant.

Negative Aspects

- A strike aircraft using GPS has no capability (without continuous target updating) against targets of opportunity; advanced radars of the future may have such a capability.
- The payoff for physical or electronic attacks against GPS would be increased if GPS is the primary navaid for weapon delivery.

Costs of Bombing/Navigation Radars. The cost to operate and maintain all of the airborne radars with a weapon delivery capability is approximately $70 million per year. Roughly 10 percent of this is avoidable if the two current radars (APQ-102 and ASB-16) that are used only for weapon delivery are phased out. These estimates are believed to be conservatively low. As noted above, a more detailed investigation of the demonstrated value of the additional capabilities of multipurpose radars may indicate that the additional functions alone do not justify their continued use in view of the cost. If this is found to be true, the potential cost avoidances would increase accordingly The APQ-120 on the F-4E alone would provide an additional 10 percent in cost avoidance.

The cost data are based on continued use of the current designs in future aircraft at $100,000 to $150,000 per system. However, the development of EAR and the use of FLAMR technology will result in systems that approach $1 million in cost. If the technology and related tactics are successfully developed, these systems will have a capability against targets of opportunity that cannot be duplicated by GPS. Thus, the high cost systems *would not* be potential sources of cost avoidance. Neither the R&D nor the procurement costs of these advanced systems have been included in the analysis. However, the GDB/RBS procurement and support costs are included. The estimates for the GDB/RBS costs are $60 million for procurement and $3 million for annual support.

e. Analysis of Cost Avoidance Potential

Table 8 summarizes the estimated costs of continuing the use of the various current navigation systems discussed in the previous sections. The estimates are based on a military

Table 8. Summary of the Cost of Continued Use of Current Navigation Systems (Costs in Millions of 1975 Dollars)

System	*User Equipment (per year)*	*Reference System (per year)*	*Additional R&D and Procurement**
Enroute			
LORAN	59.3	10.0	141.2
TACAN	28.6	1.9	120.0
VOR/DME	3.3	2.1†	11.0
DF	11.5	3.1	
OMEGA	0.9	unknown	10.4
Total Enroute	103.6	17.1	282.6
Dopplers			
Redundant Dopplers	10.0	–	55.0
Remaining Dopplers	23.5	–	
Total Dopplers	33.5		55.0
Landing Aids			
ILS	12.0	11.3	147.0
PAR	–	14.2	
Total Landing Aids	12.0	25.5	147.0
Radars			
Bomb/Nav Only (APQ-102 & ASB-16)	7.0	–	–
Bomb/Nav Plus Other Functions	62.0	–	–
GDB/RBS‡	–	3.3	60.0
Total Radars	69.0	3.3	60.0

*Total planned expenditures for new "AN" systems prior to 1980.
†Includes $600,000 for VORTAC.
‡Ground Directed Bombing/Radar Bomb Scoring Systems.

aircraft and ship force structure through 1989, developed from Service planning documents,[4] and the known or planned navigation suites of each specific platform in the force. The navigation suites of new aircraft were postulated by analogy with similar current aircraft. The acquisition and annual operating costs of over 350 currently installed AN navigation systems were based on specific data obtained for about 100 of these systems, the latter figure representing a major fraction of all installations (see Part 3, Chapter II).

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[4] IDA Note N-834, *Force Structure Supplement to IDA Report R-217,* October 1975, SECRET.

Table 8 presents the average values of annual operating costs for the user and reference system segments, and the planned new R&D and procurements for current systems that can potentially be replaced by GPS. The cost avoidance potential represented in Table 8 totals about $170 to $255 million per year for annual operating cost (depending on whether the single Dopplers and all radars are included or not) and $545 million of future R&D and procurement of current systems. The enroute systems account for a significant fraction of the totals, or about $120 million per year for annual operations and $285 million for R&D and procurement. Removal of redundant Doppler systems would avoid costs at the rate of $10 million per year; if all Dopplers were removed, this rate would increase to about $35 million per year. The annual recurring costs for the landing aids are approximately $40 million per year plus about $145 million for procurement. In the case of the radars that are used only for bombing, navigation, and mapping, the recurring costs are approximately $7 million per year, or 10 percent of the total operations cost for all radars in this category.

For the most part, the $545 million of future equipment expenditures represents replacements for, or alternatives to, equipment already available whose functions are also potentially satisfied by GPS. The major questionable cases are the new landing aids that have been discussed earlier and the advanced radars for which no cost avoidance potential is credited. The motivation lies in the need for improvements in performance or operating cost over current operational systems. If the procurement of any of these systems were halted in the anticipation of GPS, then an additional period of dissatisfaction on the part of the user would result unless the GPS IOC is about the same. The IOCs for these systems are no later than 1980 (except for MLS, whose IOC date has not been set), and the IOCs for GPS are 1981 and 1984 for the two-dimensional and three-dimensional global systems, respectively. This indicates that an approximate parallelism in schedule exists. Realistic acceleration of the GPS schedule would engender some confidence in the user that his needs will be fulfilled. Conversely, the always present possibility of slippage in the GPS schedule will result in a hesitancy to halt procurement. Unfortunately most of the programs are in the early procurement stages, and any delay in the decision to halt reduces the avoidable expenditures. Although the planning for these programs is in a continuously changing state, it appears that a 2-year delay in the decision could negate most of the potential savings.

2. GPS Costs

The cost of providing the space and user segments of GPS has been computed in a manner similar to that described in the previous section. In general, the input data to the cost model for GPS are based on information obtained from the GPS JPO. The development of these cost estimates is described in detail in Part 3, Chapter II.

a. Cost of Equipping Aircraft and Ships

Table 9 summarizes the initial procurement and annual recurring cost estimates of the GPS space and control segments, and the user equipment installed on approximately 23,000 military aircraft and ships. The cost range shown for some of the entries in the table

Table 9. Summary of GPS System Costs To Equip 23,000 Military Aircraft and Naval Ships (Costs in Millions of 1975 Dollars)

	12-Satellite System (Cases 1 and 2)	*24-Satellite System (Cases 3 and 4)*	
Space and Control Segments			
RDT&E	260	260	
Initial Costs	270	503	
Annual Costs*	71 - 87	127 - 159	
User Equipment		*Case 3*	*Case 4*
Initial Costs†	315 - 630	598 - 1196	656 - 1332
Annual Costs*	18 - 36	40 - 80	44 - 88

*O&M and equipment replacement.

†Initial procurement and installation of hardware, spares and spare parts.

Note: Lower values of the ranges are based on data provided by the JPO. Higher values represent possible increased costs as noted in the text.

indicates the potential impact of uncertainties in two key cost estimating parameters. The lower values of the cost ranges (and the fixed cost entries) are based on cost parameter information obtained from the GPS JPO. The upper values of annual costs for the space and control segments reflect the uncertainty in the satellite lifetime (e.g., the space clocks) and is based on varying the satellite MTBF from 5.5 to 4 years. The range of uncertainty associated with the user segment represents an arbitrary doubling of the estimated unit equipment costs–not an unusual occurrence in system development programs.

All GPS costs are identical for Cases 1 and 2. The space segment costs of $530 million for RDT&E and initial procurement, and about $70 to $85 million per year for operations (primarily satellite replacement), are based on a 12-satellite constellation. This constellation is expected to be adequate for the two-dimensional worldwide enroute navigation needs postulated for Cases 1 and 2. It will also provide a daily window (1 to 3 hours) over CONUS (and adjacent ocean areas) for testing new applications requiring the high accuracy, three-dimensional capability of GPS. The ranges of user costs to outfit 23,000 platforms with low cost user equipment are $315 to $630 million for initial procurement, and $18 to $36 million per year for operations.

Cases 3 and 4 assume the Full Operational Capability (FOC) of the projected 24-satellite constellation to obtain the higher accuracy and the three-dimensional capability needed for landing and weapon delivery operations. This is reflected by the higher space segment costs–about $765 million for initial procurement and $125 to $160 million per year for operations. User equipment costs (23,000 users) are also higher than for Cases 1 and 2 since receivers capable of providing the higher accuracy position estimates are more expensive. In addition, the user equipment costs for Case 4 are higher than Case 3 because of the necessity to provide higher antijam margin receivers to the weapon delivery platforms in Case 4 (about 5,500 platforms). The ranges of user costs for the 23,000 users are: $600 to $1,200 million initial procurement and $40 to $80 million per year operations for Case 3, and $665 to $1,330 million initial procurement and $44 to $88 million per year operations for Case 4.

In summary, the total initial cost for Cases 1 and 2 is about $0.85 to $1.16 billion; for Cases 3 and 4, $1.4 to $2.1 billion (about 70 percent higher). The total operations costs are approximately $90 to $125 million per year for Cases 1 and 2, and about $170 to $245 million per year for Cases 3 and 4 (about 100 percent higher).

b. Costs To Equip Ground Forces With GPS

Since the ground forces are not traditional users of sophisticated positioning systems, there is no historical basis for determining the number of GPS equipment needed. The most recent analysis of this question is the Army POS/NAV Study.[5] Updating this study to reflect the projected FY 1982 active ground force structure (1975 FYDP) leads to a total issue of 8,600 sets for use as manpacks and for mounting on vehicles. This quantity of equipment is somewhat higher than that developed in the POS/NAV Study and reflects the inclusion of nondivisional elements and an increase of three in the number of active Army divisions. The estimated cost for the 8,600 manpacks is about $150 million for initial procurement and $14 million per year for operations (see Part 3, Chapter II, for further discussion).

3. Assessment of Options and Net Cost Avoidance

This section discusses the more favorable options among the four cases previously presented from the point of view of *net cost avoidance*. Net cost avoidance, as defined in this study, is the cost of continuing to use and support the current navigation systems (Table 8) less the costs of providing the global services of GPS (Table 9).

Two sequential courses of action for the GPS program appear open at this time. The first would combine the cost avoidance potentials of Cases 1 and 2 and provide a worldwide GPS of Limited Operational Capability (LOC) for enroute navigation; the second would avoid all current systems costs (Cases 1 through 4) and provide a worldwide GPS of Full Operational Capability (FOC) potentially capable of satisfying many additional military applications. These options and their implications are discussed below.

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[5] Army POS/NAV Systems Special Task Force, *Positioning and Navigation Systems Cost Effectiveness Study*. August 1973, CONFIDENTIAL.

a. LOC Option

The provision of a two-dimensional worldwide GPS would allow the phasing out by the military of systems discussed in Cases 1 and 2 (i.e., LORAN, TACAN, VOR/DME, DF, OMEGA, TRANSIT,[6] and Doppler navigators). The key steps in implementing this option are:

(1) Provision of a sufficient number of satellites (12 to 15) to ensure a global two-dimensional navigation capability on the order of 200 meters and a daily "window" (1 to 3 hours) for the testing of new applications and systems requiring high accuracy and three-dimensional information.

(2) Development of low cost user equipment ($10,000) to replace the above listed navigation systems in the vast majority of military platforms.

(3) Planning the efficient removal of current enroute systems when GPS space and user equipment segments are available.

(4) Closely monitoring the progress of GPS user equipment development in order to maximize the potential cost avoidance of new R&D and procurement of current systems.

(5) Continuing the study, development, and testing of GPS user equipment for high accuracy applications such as coordinate bombing, midcourse guidance of tactical and strategic weapons, instrument landing of aircraft, etc. These weapon delivery and aircraft landing applications will need long lead time for development, and subsequent acceptance by the user commands.

This course of action represents the least risk since (1) the impact of unforeseen development problems in the satellites (e.g., the space clocks) would be reduced by the smaller constellation, (2) the current enroute systems represent the bulk of the potential cost avoidance, and (3) the applications of GPS to other military missions may proceed at a pace consistent with efficient use of RDT&E resources and acceptance by the user commands.

The net cost avoidance potential for this option may be determined from the cost estimates presented in Tables 8 and 9. If the enroute and self-contained Dopplers are removed, the cost avoidance potential is $131 million per year for the redundant Doppler case and $154 million per year if all Dopplers are removed. In addition, a potential of avoiding $338 million of new R&D and procurement exists for these systems. The estimates of GPS costs for space and control segments and user equipment are: $850 to $1,200 million for RDT&E and initial investment, and $90 to $125 million per year for operations (where the previously discussed ranges of GPS cost uncertainties are used).

These ranges of GPS cost, as well as the corresponding costs for the current systems, are shown in Figure 1 as a function of years after IOC. If the present goals for GPS costs

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[6] Although TRANSIT is not truly an enroute navigation system by itself, it would certainly be phased out with the advent of GPS.

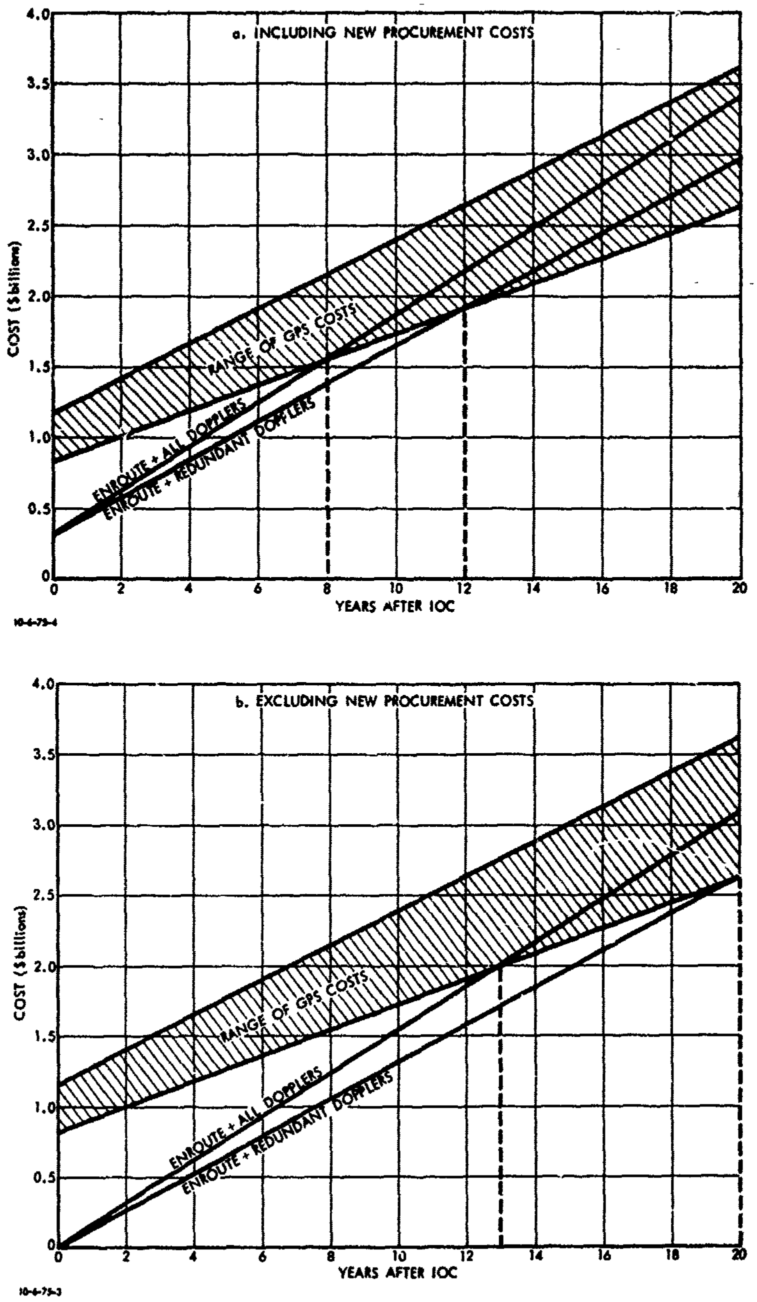

Figure 1. Comparative Cost of Providing Two-Dimensional GPS Capabilities With Enroute and Doppler Systems

are met (lower edge of GPS cost range in Figure 1) and enroute plus all Dopplers are removed, the initial cost of GPS would be amortized in 8 to 13 years depending on the fraction of new procurements of current systems that would be avoided. If only the redundant Dopplers are removed, this break-even range shifts to 12 to 20 years. However, if the GPS costs were to shift to the upper range of values, all break-even points would become unreasonably large (i.e., much greater than 20 years). The sensitivity of these results to reasonable changes in costs emphasizes the importance of achieving the low cost goals for GPS equipment if future cost savings are to result.

b. FOC Option

This option includes all the potential cost avoidances of the previous option, plus four additional steps:

(1) The need for early establishment of the full 24-satellite constellation.

(2) Development and production of both enroute and high accuracy GPS user equipment for a large number of applications and users.

(3) Removal of current landing aids and about 10 percent of the current weapon delivery radars.

(4) Cancellation of programs for landing aids and the GDB/RBS radars.

The cost estimates for this option may be obtained from Table 8 by summing the cost avoidance potentials for the four cases and from Table 9 for the 24-satellite configuration (Case 4).

Realistically, one can only plan on removing the bombing/navigation radars that are used exclusively for bombing at this time. In this case, the estimate of cost avoidance for operations is $200 million per year if all Dopplers are phased out (only about 30 percent higher than the LOC option). The total potential for avoidance of new R&D and procurement costs for current systems is $545 million (or 60 percent higher than the LOC option). The ranges of GPS costs for this option are $1.4 to $2.1 billion for R&D and initial investment (about 70 percent higher than the corresponding LOC costs), and $170 to $245 million per year for operations (about 100 percent higher).

It would take about 25 years to amortize the much higher initial GPS investment for the lower end of the GPS cost estimates for this option. If the high end of the GPS cost ranges were to apply, then GPS operations costs would become greater than the potential savings in the operations costs of current systems, and break-even points would cease to exist.

The risks for this option appear appreciably greater than those for the option previously discussed. First, the more rapid development of new applications and user equipments required for this plan runs the risk of increasing the costs and reducing the acceptability of the developed systems to the users. Second, the potential real payoff for this option does not accrue from cost avoidance, but rather from the future applications of GPS to new weapon systems to increase operational effectiveness, and to combined operations of large task forces to improve the command and control functions. However, these new applications of GPS are in an embryo stage at present, and it may take 10 to 15 years to bring them to fruition and gain their acceptance by the user commands. In the interim, therefore, it should not be necessary to carry the added cost of the additional satellites needed to achieve the FOC.

4. Potential Impact of Advances in Digital Large Scale Integration (LSI) Technology on User Equipment Costs

The stringent size, weight, and power specifications of manpack user equipment drive its design to extensive use of micro-electronics. The further considerations of modularity and commonality across all user equipment imply a similar use of micro-electronics for all mission equipment. Micro-electronics is currently experiencing a rapid rate of technological advance centered on increasing densities and digital clock rates attainable through the use of bipolar LSI devices. In order to estimate the cost impact of these advances, the study group adopted a manpack design concept, formulated by the current user equipment development contractor, which employs extensive current technology micro-circuitry. The study group then formulated modifications to this design concept based on the potential capabilities of future LSI devices.

Both design concepts are at a functional diagram level and consist of little more than counts of major components (e.g., thin-film boxes, LSI chips) and identification of their functions (e.g., frequency multiplier, IF switch). The significant design difference is the extent of digital signal processing; the significant cost difference lies in the decrease in receiver complexity and component count associated with early signal digitalization. These estimates, however gross, establish a high probability of significant cost advantages accruing from the advancing technology. Further discussion of the design concepts and cost estimates are contained in Part 3, Chapter II, and in Appendix C.

Figure 2 displays the reduction of user equipment cost with increasing quantities of production for both the current and advanced technology designs. The crossover point is the result of higher nonrecurring and lower recurring production costs associated with the advanced system. Past the crossover, the curves diverge continuously as the result of assumptions regarding rates of cost reduction for the several types of components and subsystems composing the receivers.

In the range of interest (20,000 to 60,000 units), the average cost of installed hardware for the advanced system is roughly one-half that of the near-future system. If a buy of 50,000 units were anticipated, the estimated difference in procurement cost of installed equipment would be close to $0.5 billion.

Granting that definitive designs do not exist and that there is a high degree of uncertainty surrounding the capabilities of high density/high speed LSI, this difference appears to be significant, and a small fraction of this would support an extensive development and evaluation effort. It suggests a potentially large payoff to an early and thorough investigation of high density LSI capabilities in GPS-type applications. Further, early investigation and development of the technology would remove a significant degree of

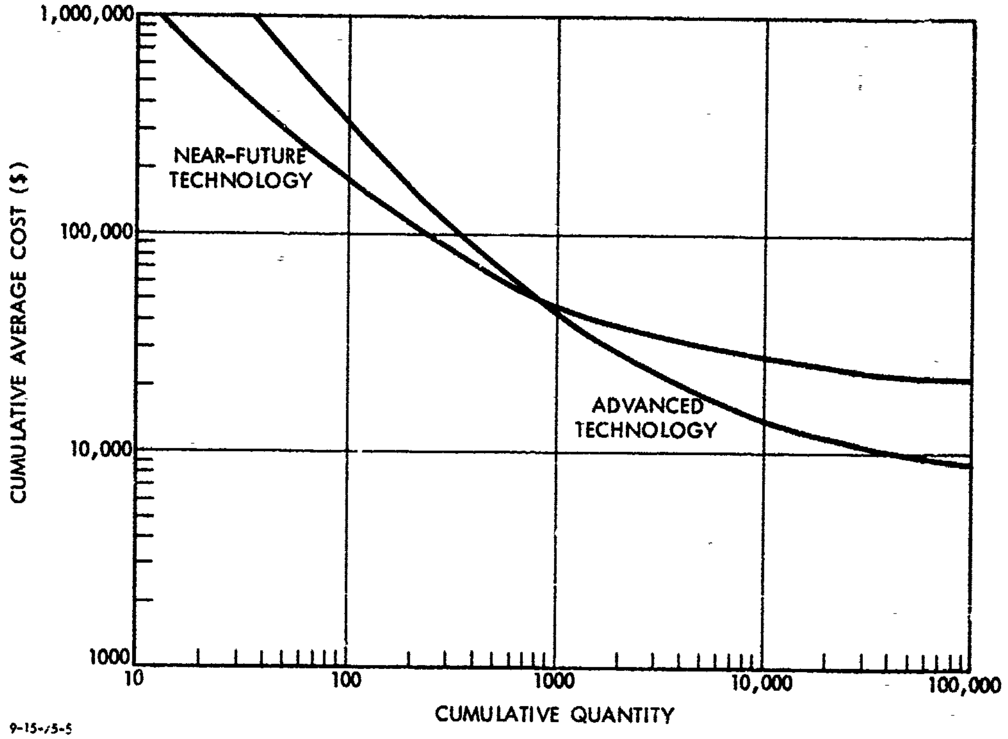

Figure 2. Average Total Hardware Costs

uncertainty in the program and offer additional savings of costs associated with the development of competitive navigation equipments. It should be recognized that the scope of such a thorough investigation is broad and encompasses questions of efficient production methods and quantities; rational policies regarding the tradeoffs between reliability standards, maintenance philosophies, and costs; and contracting procedures. The recent JPO awards of alternative user equipment development contracts carry a significant potential for reducing a wide range of the uncertainties surrounding both user equipment capabilities and costs.

5. Other New Position Fixing Systems

In addition to GPS, the Services are developing three new systems that have a potential for providing a navigation and position fixing service: the Precision Emitter Location and Strike System (PELSS), the Joint Tactical Information Distribution System (JTIDS), and the Position Location and Reporting System (PLRS). The primary purposes of these systems are only indirectly related to navigation. PELSS is designed to locate electronic emitters and guide strike weapons to these emitters; JTIDS, to provide secure communications; and PLRS, to provide the locations of combat elements to the force commanders for command and control. Because of the way in which these primary functions are accomplished, all three systems would also be used for navigation and position fixing over limited distances (up to roughly 300 miles).

In the case of PELSS and JTIDS, additional equipment would be required to provide navigation service. For PLRS, the navigation function is included in the basic design. The functions that stimulated these developments cannot be performed by GPS. For this reason none of the systems are considered in detail in this study. Nevertheless, there are potential interactions between GPS on one hand and PELSS, JTIDS, and PLRS on the other. The most obvious one arises from each of these being a *relative* navigation system—that is, all position information is relative to some arbitrary and possibly moving origin. The availability of GPS would permit referencing these "nets" to the fixed GPS origin, thus facilitating interoperability. Other less obvious interactions may exist. As an example, GPS could serve as an alternative to the DME guidance system currently proposed in PELSS for tracking the airborne platforms and guiding the weapons. The PELSS Project Office is considering GPS as the positioning system for the platforms. At the present time, DME is the favored weapon guidance technique, primarily because of the greater expected jam resistance of DME (however, JTIDS is also being considered). Coordination of these development programs with GPS is necessary to help ensure that the interactions are accounted for and that the benefits of combined use are recognized and utilized.

B. TASK 2: OPERATIONAL DEMONSTRATIONS

Seven operational demonstrations to illustrate the utility of GPS for military applications have been identified.[7] A description of each of these demonstrations has been developed and reviewed with the Service agency having doctrinal responsibility for the position fixing or navigation problem area being addressed. The proposed demonstrations and the reviewing Service agencies are shown in Table 10.

Each of the operational demonstrations is discussed below. The discussions include a description of the position fixing and/or navigation problems forming the basis for the demonstration, a summary of the scenario describing the proposed demonstration (with emphasis on the areas where GPS would be used) and the major measures that could be used to determine the improvement brought about by the use of GPS. It should be emphasized that the proposed demonstrations are not operational tests but rather vehicles to illustrate the utility of GPS for military applications. Furthermore, the descriptions have been developed to present the concepts of the demonstrations rather than detailed plans.

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7. Recently received data indicate that GPS might be used to significantly improve the effectiveness of certain ASW operations. However, these data were received too late to be used in this study.

Table 10. Proposed Operational Demonstrations

Operational Demonstration	*Reviewing Service Agency*
Aerial Assault	Infantry School, Ft. Benning
Aircraft Approach and Landing	Tactical Air Command, Langley AFB
Amphibious Operations	Commander Amphibious Group—Two, USS Mount Whitney
Attack Helicopter Operations	Armor School, Ft. Knox
Close Air Support	Tactical Air Command, Langley AFB
Forward Observer and Artillery Operations	Artillery School, Ft. Sill
Photoreconnaissance and Coordinate Bombing	Tactical Air Command, Langley AFB; and Marine Tactical Reconnaissance Squadron Three, MCAS, El Toro

1. Air Assault

A basic aim of an air assault operation is to land troop-carrying helicopters at assigned landing zones in the objective area, at the appointed times, with appropriate artillery and air cover. Aerial assaults are usually large operations, and several different routes are used by the helicopters to reach the objective area. A number of helicopter flights may be spaced along each route. Artillery support and air cover must be provided for each of these flights.

In an air assault operation, the scout helicopters, troop-carrying helicopters, and close air support aircraft rely on maps and compasses for navigation. This method is very difficult to employ, especially while flying nap-of-the-earth (as current doctrine requires when in the forward area of the division or in hostile territory). In addition, the coordination of the helicopter flights, air cover and artillery support, and the landing of troops in the objective area is a major problem. The coordination problem becomes even worse with reduced visibility, when enemy forces are discovered along any of the routes to the objective area, or when the ground forces must be disengaged and redeployed against a subsequent objective. Furthermore, current procedure requires that pathfinders be inserted into the objective area ahead of the main assault to guide the troop-carrying helicopters to the landing zones. This may provide the enemy with an early warning of an impending assault.

In the proposed air assault demonstration, an infantry force would be assigned the task of taking an objective in enemy territory. The force would be moved by helicopter from the assembly area to the landing zones in the objective area. GPS equipment would be used for position fixing and navigation throughout the operation, as described in the following paragraphs.

The lead helicopter of each flight would be equipped with a GPS set, which would contain the waypoints defining the route to be used to reach the objective area. These waypoints would be used to guide the troop-carrying helicopters (which maintain visual contact with the lead helicopter) over the route and to the assigned landing zone. The current doctrine of flying nap-of-the-earth when in the forward area of the division or in hostile territory would be followed.

The aircraft providing air cover and the batteries providing artillery support for the enroute assault force would use GPS sets and coordinates provided by the GPS-equipped helicopters to furnish fire support. If enemy resistance could not be neutralized within the allotted time, the assault force flights would be rerouted around the enemy areas. Waypoints, defined in GPS coordinates, would be used to coordinate the new routes with both the assault force and support teams.

Once landed in the objective area, troops from the assault force would use their GPS manpacks to navigate to their assigned objective. They would also use their GPS equipment to help determine the coordinates of enemy areas for which the assault force requires fire support from the air cover or artillery teams. The support aircraft and artillery batteries would use these coordinates in providing the desired fire support.

To determine the improvement in the performance of aerial assault operations using GPS as compared to operations using the current means of position fixing and navigation, certain measures of effectiveness have been established. These include the improved ability of the air assault force to navigate while flying nap-of-the-earth and the improved ability to locate the designated landing zones in the objective area.

Another measure of effectiveness would be the reduction in the susceptibility of the helicopters to enemy fire. This reduction would be brought about by selecting terrain that would facilitate nap-of-the-earth flying and enhance the ability to provide effective artillery and air support. (With current navigation and position fixing methods, the selection is determined chiefly by "how good" the terrain is for visual navigation.)

A third measure would be the time and effort required to coordinate the fire support for the assault force while it is enroute to the objective area and while it is engaged with the enemy. Finally, the measures would include the reduction in the time and effort required to reroute the assault force around enemy concentrations that could not be suppressed and to coordinate this rerouting with the fire support teams.

2. Aircraft Approach and Landing

There is no method currently available or under development that will allow an aircraft to make an instrument approach to an airfield that is not equipped with extensive ground-based equipment. Furthermore, present procedures require a considerable amount of ground survey work and ground equipment setup time to provide an instrument approach capability at a new airfield.

In the proposed aircraft approach and landing demonstration, aerial surveys of the approach and landing areas would be made by an aircraft equipped with a GPS receiver. These aerial surveys would be used to develop IFR approach procedures. Then aircraft equipped with GPS sets could conduct nonprecision approaches without the aid of any ground support equipment.[8]

Category I precision approaches would be performed by using a differential system.[9] In this system, a second GPS set would be placed near the desired touchdown position on the runway. Position data from this set would be sent to the approaching aircraft so that the difference between the two readings could be determined. This should provide the increase in accuracy required for a Category I precision approach (see Part 3, Chapter I).

The measures of effectiveness of GPS over current instrument landing systems include the reduction in the time and effort required to develop instrument approach procedures and to prepare an airfield to support nonprecision and Category I precision approaches.

3. Amphibious Operations

In an amphibious operation, the objective is to land the assault force in such a way that each element reaches its assigned objective at the specified time. Each wave of landing craft or amphibious vehicles is guided to shore by a launch or control ship.[10] Even in good weather, coordination of the landing and deployment of an assault force on unfamiliar terrain under enemy fire are major problems; these problems are greatly increased by adverse weather, darkness, or smoke. Weather and darkness also adversely affect the ability of (1) the task force to locate the Amphibious Objective Area and (2) the mine sweepers to locate and clear the designated channels.

In the proposed demonstration, the amphibious task force would use GPS receivers to navigate to the Amphibious Objective Area and to define all channels, landmarks, etc., in the area. For example, channels for moving the troops and supplies ashore would be defined in GPS coordinates. These coordinates would be used by minesweepers to clear the channels and by ships to navigate through the cleared channels to their assigned launch or landing areas. Each wave of landing craft or amphibious vehicles would also be equipped with GPS receivers, which would be used to guide the wave ashore in all types of weather or under the cover of smoke. The launch or control ships that currently guide the waves ashore could be eliminated. Once ashore, the amphibious vehicles and ground troops would use their GPS receivers to navigate to their assigned positions.

The measures of effectivensss of GPS in amphibious operations would include the reduction in the susceptibility of the landing force to enemy fire through the use of smoke,

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[8] The most stringent position fixing requirement for nonprecision approaches, as shown in Part 3, Chapter I, Table 11, is the 40-meter (2σ) vertical accuracy required at the outer marker. This is well within the GPS capability.

[9] The most stringent position fixing requirement for Category I approaches, as shown in Part 3, Chapter I, Table 11, is the 5-meter (2σ) vertical accuracy required at the middle marker.

[10] Landing craft and amphibious vehicles have no navigational capability except for maps and compasses.

darkness, and weather to cover the assault. Other measures include the reduction in the effort required to coordinate the elements of the assault in such a manner that the attack develops as planned, the reduction in the effort required by the task force to locate the Amphibious Objective Area and prespecified points within the area, and the reduction in the effort required to define and clear the mines from the channels.

4. Attack Helicopter Operations

In conducting attack helicopter operations, the helicopter crews currently rely on maps and compasses for navigation. This is a difficult method with which to navigate while flying nap-of-the-earth—the procedure helicopters must adhere to when flying in the forward area of the division and while in hostile territory. With this procedure, the crew of the scout helicopter must be very familiar with both map and terrain. In addition, once the enemy targets have been located, the scout helicopter must fly back to the attack helicopter holding area and lead the attack helicopters to their attack positions. This is a time-consuming procedure and causes the scout helicopter crew to lose contact with the enemy.

In the proposed attack helicopter demonstration, both the scout and the attack helicopters would fly nap-of-the-earth using GPS as their primary navigation aid. The scout helicopter crew would use GPS to help determine the coordinates of the targets and the pop-up points from which they should be attacked. The scout helicopter would also determine the GPS coordinates defining the route that the attack helicopters should use to move from their holding area to the pop-up points. Attack helicopters would use these data to move to the pop-up points and to engage the targets. The scout helicopter would be free to remain in the attack area to provide local fire support for the attack helicopters or to search for additional targets.

The measures of effectiveness of the improvement provided by GPS include the increased ability to navigate while flying nap-of-the-earth, the reduction in the exposure time of the scout helicopter brought about by the decrease in the time required to locate targets and hand them off to the attack helicopters, and the reduction in time required for the attack helicopters to respond to the attack request (this last measure is possible because the time currently required for the scout helicopter to fly back and locate the rendezvous area would be eliminated).

5. Close Air Support

One of the major problems in close air support (CAS) is the handoff of the target from the ground-based Forward Air Controller (FAC) to the attack aircraft. The source of the problem is the lack of a satisfactory method to cue the target acquisition sensor (electro-optical or eye) in the CAS aircraft to the target area.

In the proposed demonstration, both the FAC and the attack aircraft (using either ballistic or guided weapons) would be equipped with GPS receivers. The FAC would use his GPS equipment to help determine the GPS coordinates of the target (either fixed or slowly moving).[11] These coordinates would then be provided to the attack aircraft and entered into its GPS equipment. The aircraft's GPS equipment and inertial system would then provide steering signals to the electro-optical target acquisition sensor, if available, or to the Heads Up Display (HUD) if visual acquisition were being used. These steering signals would be used to drive the sensor's field of view (or the HUD's cursor) toward the target area. The pilot, therefore, would need to search only the area within the cockpit display. He would take advantage of any magnification capability of the target acquisition system to provide standoff against enemy antiaircraft capability. Upon acquisition of the target, the pilot would center it in the display. The GPS equipment would use these new angles to refine its target coordinate data.

The pilot would then select the position from which to begin the attack and fly toward the target. As he approached the range of the enemy antiaircraft weapons, the pilot would begin to execute evasive maneuvers. These maneuvers would include jinking and low level flying. GPS would continue to provide steering signals to hold the electro-optical target acquisition sensor or HUD cursor in the direction of the target even if intervisibility were lost. Once the pilot reached the selected position, he would turn the aircraft to begin the attack run. If the pilot could not see the target from this position (e.g., if he is flying too low), he would align the aircraft's line of flight with the sensor or HUD cursor. Just prior to weapon release, the pilot would make last-minute corrections by placing the cursor in the display on the intended target impact point. The GPS receiver would use this information to update the coordinate data to be used by the weapon release computer to determine the weapon release point.

The measures of effectiveness of GPS in close air support operations would include the reduction in the susceptibility of the aircraft to antiaircraft fire. This potential reduction in susceptibility is brought about by four individually measurable factors: (1) the increase in the range at which the pilot can acquire the ground target, (2) the decrease in the time the aircraft is within range of enemy weapons, (3) the improvement in the ability to maneuver to avoid the antiaircraft fire when flying within its range, and (4) the increased probability of executing a one-pass attack. Other potential measures are the reduction of the pilot's workload during the target acquisition and attack phases of the mission, and the reduction in the prebriefing and target area knowledge necessary for the pilot to operate effectively in a CAS environment.

6. Forward Observer and Artillery Operations

In this type of operation, the Forward Observer (FO) determines the coordinates of the targets and provides them to the artillery battery via the Fire Direction Center. The FO needs to know his location, the range from his position to the target, and the bearing of the

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[11] The FAC would use his GPS equipment to determine the bearing to a visible landmark the coordinates of which had previously been entered into his user set. This bearing line would be entered into a device (such as the GVS-5 laser rangefinder) with an azimuth scale to determine the bearing from the FAC's position to the target. The FAC would use a laser rangefinder to determine the range to the target. Provided with these data, the GPS equipment could determine the GPS coordinates of the target.

target with respect to some reference. Currently the primary means for obtaining these data are a map of the area and a magnetic compass.

The artillery battery also needs to know its position as well as a reference line of bearing. This is currently provided by ground surveys. However, the survey teams may lag several hours behind the Army's current mobile artillery capability. This tends to reduce the effectiveness of the mobile artillery, since several rounds may have to be fired and successively corrected by the FO before the target is effectively engaged.

In the proposed demonstration, the FO would use his GPS equipment to help determine the GPS coordinates of the targets in a manner similar to that described for the FAC in the CAS demonstration. These coordinates would be provided to the Fire Direction Center for relay to the artillery battery. Upon receiving the fire mission, the artillery battery would select a firing position and, using their GPS equipment, lay the battery. Using the target coordinates provided by the FO, the battery would determine its firing data and commence firing.

The reduced time required for a mobile artillery battery to engage targets effectively would be the principal measure of effectiveness of the improvement that GPS would provide over the current means of position fixing used in FO and artillery operations.

7. Photoreconnaissance and Coordinate Bombing

Previous studies have shown that coordinate bombing with conventional bombs can be improved if position fixing accuracies that are better than those attainable with LORAN can be provided.[12,13] Furthermore, the accuracy with which targets are located by the reconnaissance system must be commensurate with that of the system used to strike the targets. That is, if a photoreconnaissance aircraft is to be used to collect target imagery from which target coordinates are to be determined, then the position fixing system in the reconnaissance aircraft should be at least as accurate as that in the strike aircraft.

Another matter of concern is that the effort required by the photointerpreters to determine the coordinates of targets increases as the navigation accuracy of the photoreconnaissance system decreases.

In the proposed photoreconnaissance and coordinate bombing demonstration, both the photoreconnaissance aircraft and the strike aircraft would be equipped with GPS receivers integrated with inertial systems. The pilot in the photoreconnaissance aircraft would use his GPS equipment to navigate to the target area. As the photographs of the target area are being taken, aircraft position data from the onboard GPS equipment would be recorded on the film. These data would then be used by the photointerpreter to determine the GPS coordinates of the targets recorded on the film. These coordinates would be entered into the GPS equipment onboard the strike aircraft, along with waypoints defining the route to and from the target areas. Using these data together with the weapon characteristics, the strike aircraft would bomb the targets.

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[12] IDA Study S-409, *Sensitivity of Mission Performance to Position Fixing Accuracy*, January 1973, SECRET.

[13] *DNSS Study*, op. cit.

The primary measure of effectiveness of GPS for this mission would be the increase in bombing accuracy that could be achieved compared to that provided by LORAN and airborne radar. An additional measure would be the reduction in the time required for the photointerpreters to derive the target coordinates from the film.

C. TASK 3: PROGRAMS THAT COULD BENEFIT FROM EARLY AVAILABILITY OF GPS TEST RANGE INSTRUMENTATION

Seven programs have been identified as potentially benefiting from the early availability of the GPS test range instrumentation: two aircraft programs (B-1 and F-16), two cruise missile programs (Air-Launched Cruise Missile and Sea-Launched Cruise Missile), one strategic missile program (MINUTEMAN X), and two air defense system programs (SAM-D and SHORAD). Each of these programs has range testing needs that will probably require the acquisition of additional instrumentation systems (over and above those currently programmed). The specific testing needs that GPS may be able to satisfy for each of these programs are discussed below.

1. Aircraft Programs

B-1. Low altitude, over-water flights are scheduled to be conducted at Vandenberg Air Force Base. However, the Space and Missile Test Center at Vandenberg considers the current range instrumentation (radars) to be inadequate for this test. An onboard GPS receiver could be used to compute the position and velocity of the aircraft for onboard recording or relay to a ground or airborne control/monitor station. In addition, the current concept for the evaluation of the onboard navigation system requires the aircraft to fly over specific points on the ground (checkpoints). This limits the flight paths that are available to test the aircraft's navigation system. An onboard GPS receiver could alleviate this limitation. Furthermore, the onboard GPS system would provide continuous position and velocity profiles against which the B-1 navigation system could be evaluated. This could reduce the number of flights required.

F-16. There is no instrumented range capability in the areas to be used to conduct the F-16 climatic tests. An onboard GPS receiver could be used to provide the range instrumentation for these tests. As noted for the B-1, onboard GPS equipment would provide the necessary data to evaluate the F-16 navigation system. It could also provide improved flightpath freedom, especially to test the F-16s low-level capability. Furthermore, an onboard GPS system could provide (in Phase II or Phase III of the GPS Program) mobile instrumentation to support foreign sales by facilitating demonstrations and tests to be conducted in the potential buyer's own country.

2. Antiaircraft Programs

SAM-D and SHORAD. These air defense systems have multiple target tracking capabilities that must be evaluated in tactical environments at a number of different test sites.

These sites do not currently have adequate range instrumentation. Currently available instrumentation that could be used to equip each site or be moved from site to site to support the tests has already been judged to be too expensive. Instrumentation pods, each containing a GPS receiver and a recorder, which could be mounted on the test aircraft, could potentially satisfy this need for a mobile test range with a multiple target tracking capability.

3. Missile Programs

Air-Launched Cruise Missile (ALCM). ALCM, a long-range cruise missile, uses TERCOM as part of its guidance system and therefore must be tested over land. At the present time, however, there is no sufficiently instrumented test range that is long enough to test the maximum range capability of the ALCM. The current concept is to fly the missile in a racetrack or circular pattern. However, AFTEC feels that this may not be a sufficient test since the potential exists for some error sources to remain masked. An alternative approach would be to use an onboard GPS receiver to provide real-time position and velocity information to an airborne or ground control center. This approach might provide sufficient data such that the missile could be allowed to fly beyond the current limits of the range or between ranges. In addition, the GPS receiver may allow the missiles to be flown over a larger variety of flightpaths, which could add to the completeness of the evaluation.

MINUTEMAN X (MX). The present MINUTEMAN flight tests are being conducted at Vandenberg Air Force Base. The impacts are normally in the Kwajalein area, with the evaluation of the missile accuracy being based on data from the metric tracking systems available along the flight trajectory. The increased range potential of the MX and the desire to test the missile along more than one launch azimuth may necessitate the acquisition of additional test range instrumentation. The use of onboard GPS equipment to continuously determine the location and velocity of the missile for transmission to a land or shipboard control station could provide the instrumentation with which to test the missile at various ranges and azimuths.

Sea-Launched Cruise Missile (SLCM). The requirement exists to fly these missiles over land to test their guidance system, which includes TERCOM. The current approach is to have test flights originate at the Pacific Missile Range and go inland to one of the air bases (e.g., Dugway AFB, Utah, or Mountain Home AFB, Idaho). The flightpaths currently selected for use in these tests do not have adequate radar coverage. One possibility for closing the gaps in the radar coverage is to place a GPS receiver and a transmitter onboard the missile. The GPS receiver could continuously determine the position and velocity of the missile. The onboard transmitter could relay these data to an airborne or ground control/monitor station, where the data could be analyzed to determine if the missile is following its prespecified track.

Part 3

ANALYSES

Chapter I

ANALYSIS OF OPERATIONAL AND COST FACTORS AFFECTING SELECTION OF NAVIGATION SYSTEMS

Preliminary design studies and tests indicate that GPS would be capable of providing most, if not all, of the navigation and positioning functions now being provided by several different systems.

Given that the GPS will perform as well as these preliminary design studies and tests indicate, and that the development and implementation schedule is reasonable, the natural question is "which current navigation systems can be phased out and which should be retained to be used in conjunction with GPS?" A further question "what is the cost avoidance that could be realized from the phasing out of the current systems?"

The general approach adopted to answer these questions was to give GPS receivers to all user platforms and then review the navigation suite of each platform type for equipment which could be removed without compromising its mission capabilities.

These aspects and the costs of current systems are discussed in Section A. Section B summarizes the cost of the GPS systems which would replace the current navigation systems and develops the net cost avoidance for the various options considered.

An important question, the complete answer to which was beyond the scope of this study, is what benefits GPS might provide in improving military operations. An earlier IDA study[1] analyzed some very specific applications and estimates; for example, the effect of GPS accuracy on weapons required to destroy various targets. In terms of cost savings, it was concluded that, on the average, the cost of GPS was not much less than the cost of continuing to use current systems. It is, however, more difficult to determine the benefits in terms of military effectiveness (that is, probability of winning an engagement) as a result of doctrine changes made possible by GPS. Quantitative answers to this question are not possible at this time; however, Chapter III discusses several key operational demonstrations of GPS which are expected to lead eventually to operational concepts and tests which would provide such answers.

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[1] IDA Study S-409, *Sensitivity of Mission Performance to Position Fixing Accuracy*, January 1973, SECRET.

A. EVALUATION OF CURRENT NAVIGATION SYSTEMS

1. Approach

The rationale for removing equipment had to consider the vulnerability of GPS to both physical and electronic countermeasures. Both of these depend in part on the desirability or value of GPS as a target, which in turn depends on its use. At present, there is no quantitative analytical method with which to sort out the interdependencies of vulnerability, target value, and use of GPS. Therefore, the study group elected to remove navigation equipment in stages.

The first systems removed are those which are believed to create the least incentive to attack GPS. Subsequent additional removals create a higher incentive. The following specific steps or cases are used in this removal process:

Case 1: Remove all radio referenced, enroute navigation equipment; that is, equipment whose primary function is a long distance navigation from Point A to Point B, exclusive of the terminal area portions of the path.

Case 2: In addition to Case 1, remove one part of any dual self-contained systems. In the case of Doppler/inertial systems, the Doppler was removed since GPS could fulfill the same function as Doppler in a GPS/inertial hybrid.

In the above two cases, the requirements are such that a two-dimensional, relatively low accuracy GPS system would be an adequate replacement. For the next two cases, the full three-dimensional, high accuracy GPS system is necessary.

Case 3: In addition to Cases 1 and 2, remove all landing systems.

Case 4: In addition to Cases 1, 2, and 3, remove all radars whose prime function is weapon delivery.

These cases are summarized in terms of the generic systems in Table 11.

Table 11. General Types of Equipment Removed from Aircraft

Case 1:	Enroute Radio Navaids	Case 3:	Landing Aids
	– LORAN		– ILS
	– TACAN		– MLS
	– VOR/DME		– CLS
	– OMEGA		– GCA
	– DF		
Case 2:	Dual Self-Contained	Case 4:	Air-to-Ground Weapon Delivery or Navigation Radars
	– One of two Dopplers		
	– One of two inertials		
	– Doppler of Doppler/Inertial		

The analysis of current navigation systems consists of two basic elements. The first is a discussion of the technical pros and cons of the capabilities of GPS to fulfill the functions lost when the various types of equipment are removed. The second is the gross costs that could be avoided if the systems were removed. These cost considerations include, where appropriate, the corresponding ground reference systems. The feasibility of decommissioning major segments of the ground reference "establishment" is discussed in terms of its use and ownership by non-DoD and foreign agencies.

Because of the intermingling of civilian and military users, the inventory of civilian systems is estimated, both to provide a feel for the size of the civilian market and to gauge the impact of a U.S. abandonment of common military/civilian systems. It is emphasized, however, that the cost avoidance data include only those systems owned by the U.S. military Services.

As will be shown, the gross analysis is dominated by aircraft. Ship users are neither as numerous nor do they have the variety of equipment used by aircraft.

2. Scoping Considerations

From a potential cost avoidance point of view, certain systems dominate the analysis. In order to isolate these dominant systems, the investment in the generic types of systems (user equipment only) has been summarized in Table 12. Since O&M costs tend to be roughly proportional to investment costs, the relative ranking of the systems would not be altered significantly by including O&M costs.

Comparison of the totals for aircraft and ship users indicates that as a whole the ships are relatively minor "consumers" of navigation systems and thus the potential cost avoidance resulting from substitution by GPS would be small. This observation is reinforced by the fact that the ship navigation costs are dominated by inertial systems primarily on nuclear submarines for which GPS has no potential for substitution.

At the present time there is little sophisticated navigation and positioning equipment for ground users, and none in widespread use. Thus cost avoidance attributable to current equipment of the ground forces is negligible. There are, however, some new systems in the R&D and early procurement phases whose functions could be fulfilled by GPS, thus avoiding their future procurement costs. These systems are considered in the appropriate sections.

Inertial and radar systems dominate the inventory value (accounting for almost 70 percent if all radars with a weapon delivery capability are included). However, because of their function in military operations, the possibility of substituting GPS even in part requires specific attention. Inertial systems, because they are the only completely passive self-contained system available, have not been considered for replacement by GPS. Radar weapon delivery systems as they have been employed in the past may be replaceable by GPS. This possibility is discussed further in Section A-7. Only those radars which are used solely for air-to-ground weapon delivery or navigation are included in the totals in Table 12.

Of the remaining systems used by aircraft, the important ones for this study appear to be LORAN, TACAN, VOR/DME and Doppler. Of these, the first three involve a ground reference system "establishment," and LORAN and VOR/DME are part of the worldwide civil navigation system.

Table 12. Estimate of Total Investment Costs for Navigation Systems Currently in Use by the U.S. Military Services*

System Type	Aircraft Users			Ship Users		
	Total Inventory	*Average Cost† Per Unit ($ 1975)*	*Total Investment ($M, 1975)*	*Total Inventory*	*Average Cost† Per Unit ($ 1975)*	*Total Investment ($M, 1975)*
LORAN	4,200	50,000	210	500	15,000	7.5
TACAN	14,000	10,000	140			
VOR/DME	8,000	4,000	32			
OMEGA/VLF	400	25,000	10	300	25,000	7.5
DF	20,000	2,500	50			
ILS	5,000	3,500	18			
DOPPLER (Single)‡	4,000	37,000	148			
DOPPLER (Redundant)‡	1,700		63			
Inertial	4,000	80,000	320	200	500,000	100.0
Air-to-Ground Weapon Delivery Radars	600§	150,000	90			
Satellite				100	25,000	2.5
	TOTAL*		1,081	TOTAL		117.5

*Land users have been omitted from the table since currently they have few high value systems in the inventory.

†Average costs quoted here are approximate and are for scoping purposes only. Detailed cost estimates for specific systems are given in Chapter II.

‡Single Dopplers are installations in which only one Doppler is used as a means of navigation beyond the range of radio navigation aids. Redundant Dopplers are those which are paired with an inertial system or another Doppler.

§The 600 radars listed here are those which have only an air-to-ground weapon delivery or navigation capability. There are about 6,000 radars which have functions in addition to air-to-ground weapon delivery and navigation, i.e., search, air-to-air intercept, etc.

The total investment cost from Table 12 is about $2 billion.[2] The FASNAV Study[3] estimates that the annual O&M costs of a somewhat larger set of avionics equipments (including IFF, all radars and ground reference systems) to be about $0.4 billion per year. This is consistent with the 0.1 to 0.2 ratio of annual O&M to investment observed on a large number of systems.

Table 11 summarized the four generic cases constructed for use in the analysis. Each of these cases has its own peculiar set of ramifications and exceptions. These are discussed in the following sections in the order shown on the table.

3. Case 1: Enroute Radio Navaids

As the name implies, enroute radio navigation aids are those employed primarily in navigating from Point A to Point B over considerable distances. The accuracy needed for enroute navigation is relatively low. Several hundred meters may be required near congested terminal areas, while 1 to 5 miles is sufficient for the "cruise" portions of most missions.

Radio systems are of two general types: hyperbolic systems such as LORAN and OMEGA, which require a minimum of three ground stations for position fixing, and "rho/theta" systems such as TACAN, which require only one ground station for a position fix. The existing hyperbolic systems operate at low (10-100 Hz) frequencies and are not limited by line of sight. The rho/theta systems are at VHF and L-band frequencies and thus are line-of-sight limited.

Direction finding (DF) systems give a line of position only and are seldom considered as primary navigation systems except on minimally equipped platforms (helicopters and small boats).

These navigation aids have extensive networks of ground stations to provide coverage of most or all of the populated areas of the world; and almost universal use by both military and civilian aircraft and ships of both the Free World and Red Bloc nations. Table 13 presents an estimate of the worldwide inventory of both the ground stations and user equipments of the systems considered.

From a technical point of view, a simplified GPS receiver using about half the complement of satellites currently planned could fulfill most of the navigation functions of these systems. The reduced number of satellites follows because only a two-dimensional capability is required. Furthermore, only the clear/acquisition signal , needed because of the lesser accuracy requirements.

The widespread use of the systems listed in Table 13 gives some insight into both the benefits and the problems associated with replacing them with GPS. The major advantages are the avoidance of the costs of R&D, new procurement of conventional systems, and operation and maintenance. Estimates of these costs are given later.

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[2] If all 6,000 radars are included. See last footnote on Table 12.

[3] IDA Report R-204, *Study of Functional Area Summary for Navigation*, December 1974 SECRET.

Table 13. Current Installed Inventory of Enroute Radio Navigation Systems

System	U.S.				Free World (less U.S.)			Red Bloc	
	User		Reference		User				
	Military	Civil	Military	Civil	Military*	Civil	Ref.	User†	Ref.
LORAN	4,235‡	72,000§	73	75	2,200		38		
TACAN	15,011‡,⊕	negligible	239☆	4☆	8,000		70		
VOR & VOR/DME	8,279‡	225,000□	55☆	243☆	5,000	56,000○			45△
VORTAC	not applicable		25	997					
OMEGA/VLF	405	1,000◇	2/9				6✱/0		3■
DF/NDB	21,148‡	64,000●	279☆	2,189☆	12,000	56,000○			279△

*The composition of the free world military aircraft navigation systems were not considered in any detail in this study. However, the active NATO fleet (not including U.S.) is approximately 2,500 aircraft of all types. Non-NATO forces comprise several thousand additional aircraft. The basic enroute navigation equipment of the free world aircraft is not believed to be grossly different from comparable USAF aircraft. Thus, estimates given in the table are based on 5,000 aircraft with an average navigation suite similar to USAF aircraft.

†No data is available on Red Bloc user equipment inventories.

‡Based on data base developed for this study (See Section A3a).

§Derived from data presented in Hearings before the Subcommittee on Coast Guard and Navigation 93rd Congress, Second Session on HR 13695, March-April 1974, pp. 270-271. All documented (over 5-ton) civil ships and between 12,000 and 26,000 of the pleasure boat fleet are assumed to be users. Aircraft users represent a small part, about 200.

⊕Includes 3,183 CNI sets for which TACAN is the navigation component.

☆Based on ECAC data derived from worldwide IFR supplement.

□As reported in 1973 to the FAA on annual inspection questionnaire. Actual number is higher. Comprised of approximately 53,000 single VOR installations, 86,000 dual VOR installations and 28,000 DME. DMEs are not added into total since a VOR/DME is considered as a single positioning system.

○Based on approximately 56,000 civil aircraft assuming an average of one VOR and one ADF set per aircraft. Source: IAOPA fact card for end of 1973.

△From Jeppeson Airway Manual (civil facilities only).

◇Based on sales reported by manufacturers of VLF navigation systems for aircraft. Use of OMEGA for aircraft is believed by the FAA to be negligible at this time; however, Pan American and TWA are planning about 150 OMEGA installations for their fleet.

✱Site of South Pacific station not yet established.

■Equivalent of OMEGA.

●As Reported in 1973 to the FAA on annual inspection questionnaire.

At the present time, most of the systems that could be replaced have been accepted as domestic and international standard for route definitions. For instance, the VOR-TACAN (VORTAC) system is the primary enroute navigation system for domestic and international use by aircraft. The abandonment of the VORTAC systems (and the route structure defined by them) and the substitution of point-to-point (area) navigation requires new agreements and methods of traffic control which are just now being developed.

It is unlikely that there would ever be an abrupt, large-scale transition from, for example, a VORTAC system to GPS. It is worth emphasizing, however, that GPS becomes a worldwide system the moment that the satellites are in place and approved for navigation. Thus, any user could convert to GPS and abandon the present equipment; and users who travel to various parts of the world need not carry multiple types of equipment to accommodate different kinds of facilities.

a. LORAN

The estimated number and cost of LORAN C systems for aircraft, ship, and ground users in the 1975-1989 time period are shown in Figure 3. As stated previously, aircraft are by far the largest military users of these navigation systems. The fractional number and cost contributed by ship and ground users are discussed in Sections b and c below.

The LORAN A ground reference system is scheduled to be phased out about 1980 insofar as U.S. support is concerned. LORAN C has been selected as the primary system for the U.S. coastal confluence and the Great Lakes. This net is scheduled to have 21 stations, of which 8 are now operating (4 in Alaska and 4 on the east coast). Worldwide, LORAN C forms a major means of over-ocean radio navigation and time transfer. The Soviet LORAN C system is identical to the Free World system, is synchronized with it, and thus the chains[4] are fully interoperable.

LORAN C coverage, exclusive of the Soviet element, is shown in Figure 4.

The dominant requirements which led to the selection of LORAN C over other candidates for the coastal confluence (OMEGA, Differential OMEGA, LORAN A, Decca, Hastings Raydist, etc.) were the accuracy needed in harbors and estuaries and ship routes in the Gulf of Mexico (¼ mile-2-sigma geodetic) and the usable offshore distance (more than 50 miles).

For certain other applications—e.g., fishing and oil exploration—50-foot repeatable accuracy (2-sigma) is desirable. These requirements strain the capabilities of GPS C/A signal accuracy for single fix. However, most of the users are slow moving or stationary which would permit integration time to improve the performance.

The most numerous long range radio navigation system used aboard ships[5] is LORAN. As noted in the introduction to this chapter, however, there are considerably

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[4] A chain is a series of at least three synchronized transmitters which provide hyperbolic coordinate systems.

[5] In addition to LORAN, the Navy navigation satellite "Transit" currently is providing precise position information to a limited class of ships (mostly submarines). The major disadvantages of Transit for aircraft use is the time to derive a fix (a few minutes) and that a precise fix requires knowledge of the users velocity. The repeatable accuracy of Transit for stationary users who have time to integrate several fixes is very high (on the order of 1 meter). However, the precise ephemeris is classified and the ultimate precision of Transit is not available to commercial users. GPS is in part an outgrowth of Transit and can provide all of the services of Transit as well as the other radio navigation aids used by ships.

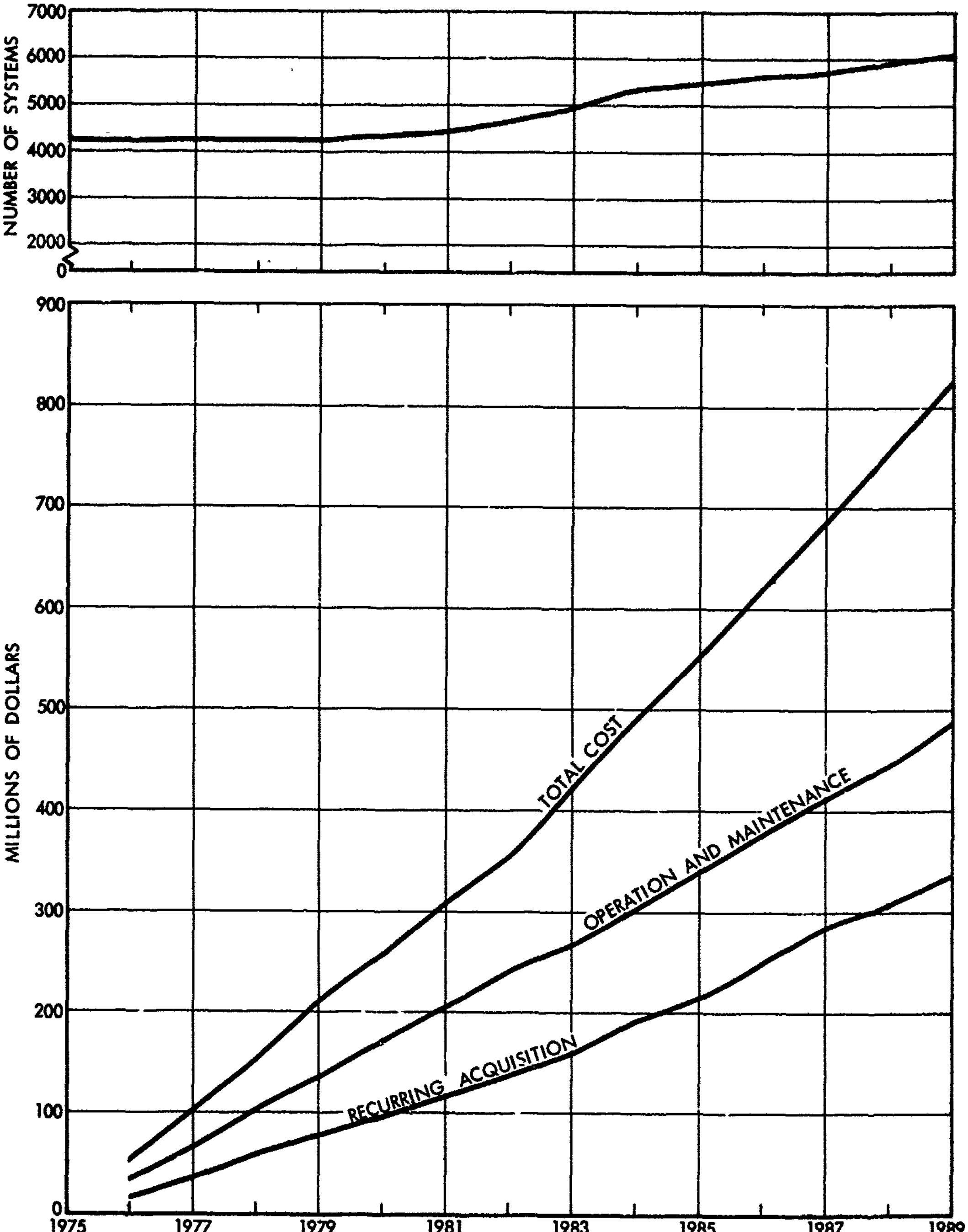

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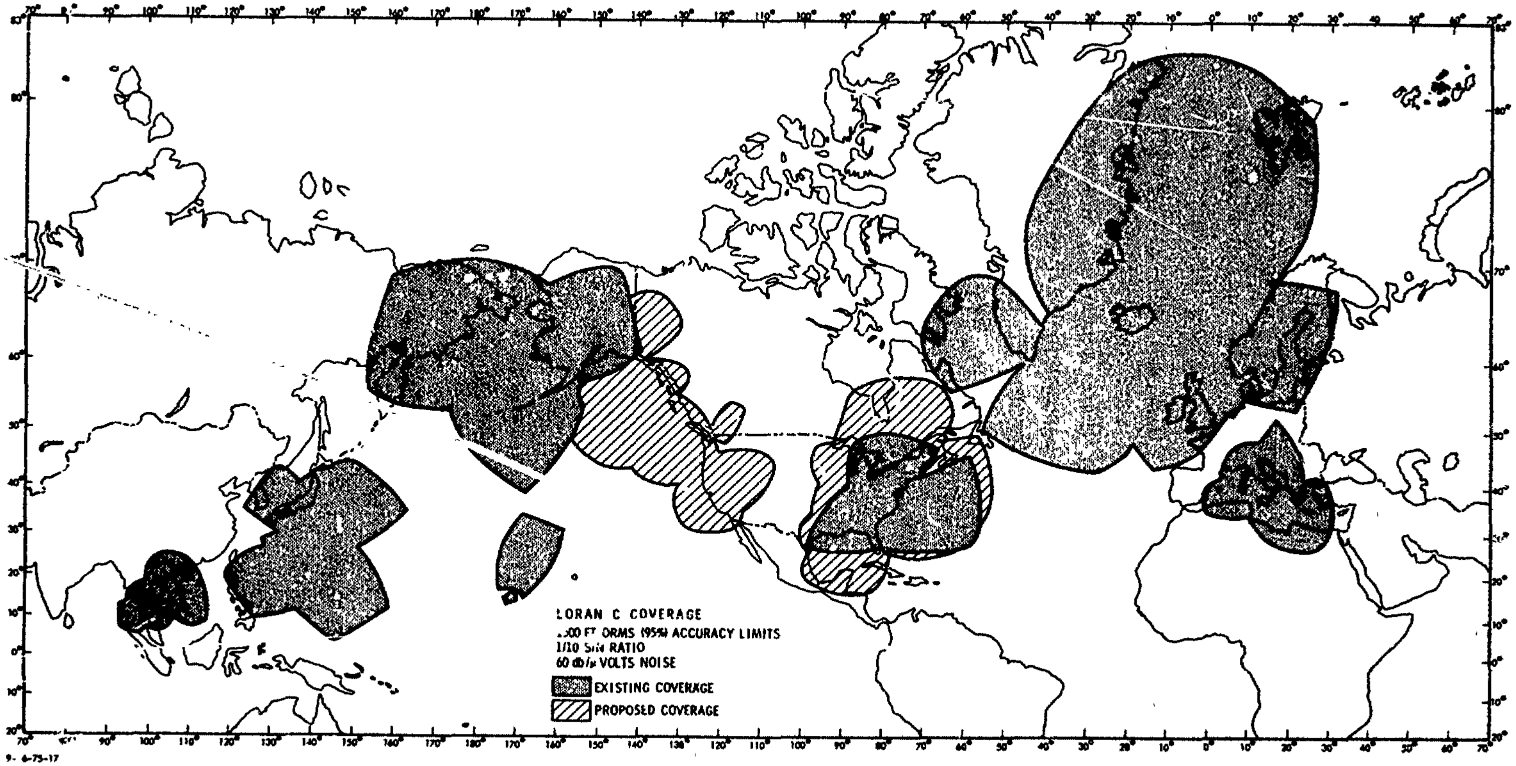
Figure 3. Number and Cumulative Costs of Military LORAN User Systems



Source: "Hearing" HR-13595, March-April 1974.

Figure 4. World Wide LORAN C Coverage *

fewer ships than aircraft in the military inventory. Thus, the cost avoidance that might be realized from a substitution of GPS is limited. The estimated average annual costs of shipboard LORAN receivers are $6 million for acquisition and $3.8 million for O&M. These estimates were included in Table 12 and in Figure 3.

For the most part, the navigation equipment used aboard ships is less sophisticated than that on aircraft. Notable exceptions to this observation are the inertial systems aboard submarines and aircraft carriers. However, the mission of these ships does not permit substitution of a radio navigation system for a high precision self-contained system.

As shown in Figure 3, LORAN C coverage is far from worldwide. OMEGA, when it becomes fully operational, will fill this gap as could the VLF system if desired.

Ground users of positioning systems are considered as part of Case 1. They have little to lose and much to gain from GPS. There is currently nothing in the Army or Marine Corps inventory beyond compasses, conventional survey instruments, and topographical charts to provide position of ground forces. An Army system that is at the end of its development cycle and expected to enter the inventory soon is the LORAN Manpack (AN/PSN-6). The latter is dependent upon the fielding of the LORAN D net by the Air Force. The Army is also examining a commercially available LORAN transmitter as a backup to the Air Force TRN-35. The commercial system is van-mounted with a shorter 150-foot antenna; hence, its range is less than the TRN-35. It is probably adequate, however, for Field Army operation.

b. TACAN and VOR/DME

TACAN and VOR/DME are treated together since they provide almost identical navigation service (rho/theta positioning to line-of-sight distances) and in large measure the two systems are collocated (called VORTACS). The numbers and cumulative costs of military TACAN and VOR/DME systems are shown in Figures 5 and 6. The DME (or "rho") component of the collocated systems is common to both TACAN and VOR/DME. The "theta" component of TACAN operates at L-band whereas the VOR operates at VHF. Thus, the antenna of the TACAN is considerably smaller (~2 feet) than the VOR (~20 feet). Because of their smaller size, TACAN beacons are much more readily installed on ships and aircraft and made man-portable. For these reasons, TACAN is primarily a military system and VOR/DME is the civilian system (worldwide-Free World). The nominal accuracies of both systems are similar (3.5 degrees in azimuth and 0.5 nmi or 3 percent of range, whichever is greater, 1 sigma). Techniques for improving the accuracy of both systems by almost a factor of 10 exist and have been used in special situations. The location of the fixed VORTAC sites in large measure determines the overland route structure for aircraft in the Free World. (In some areas, notably Africa and Australia, the nondirectional beacons and four-course ranges are still the predominant navaids.)

In addition to its obvious enroute navigation function, the VORTAC system provides additional services to both military and civilian aircraft. The most important additional

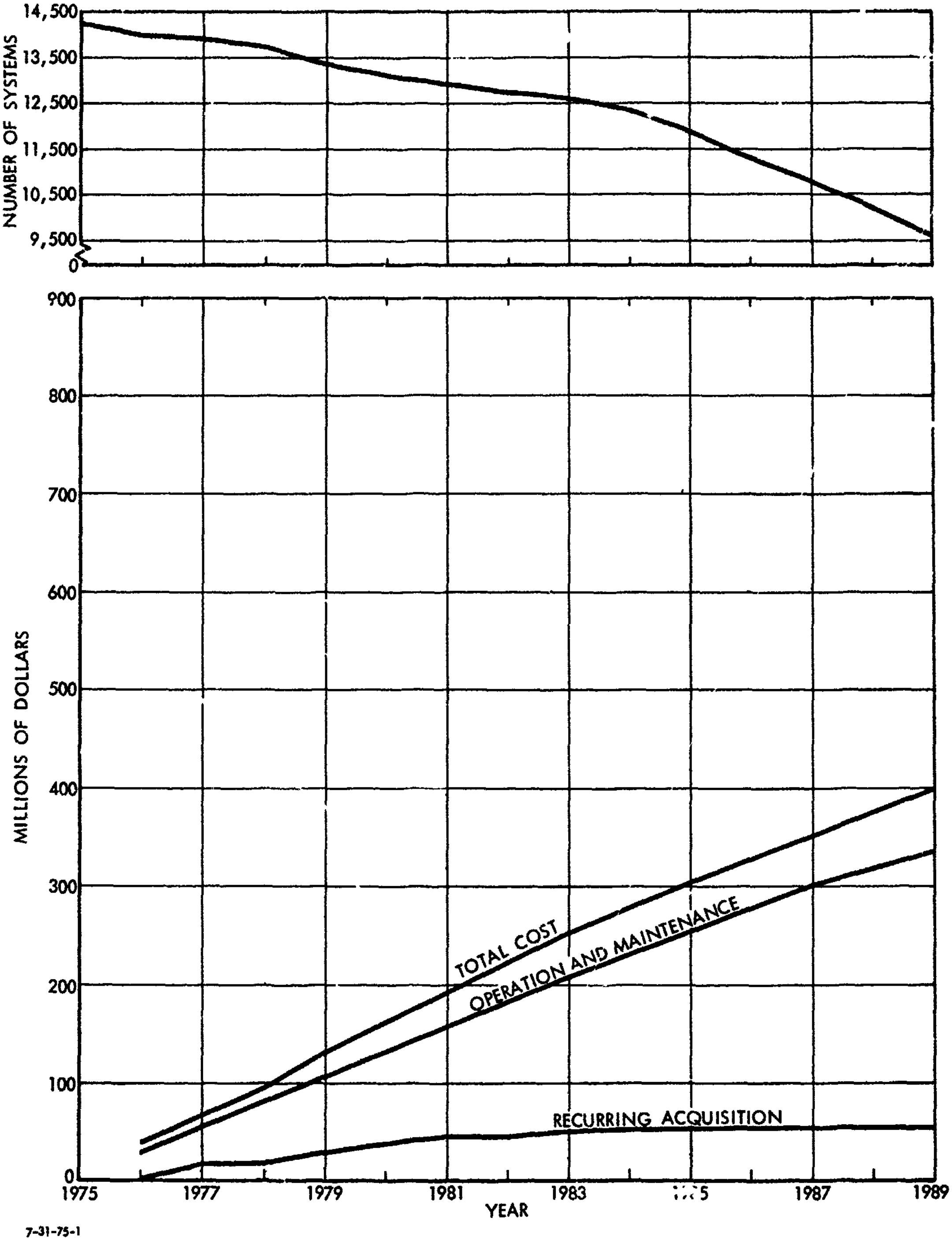


Figure 5. Number and Cumulative Costs of Military TACAN User Systems

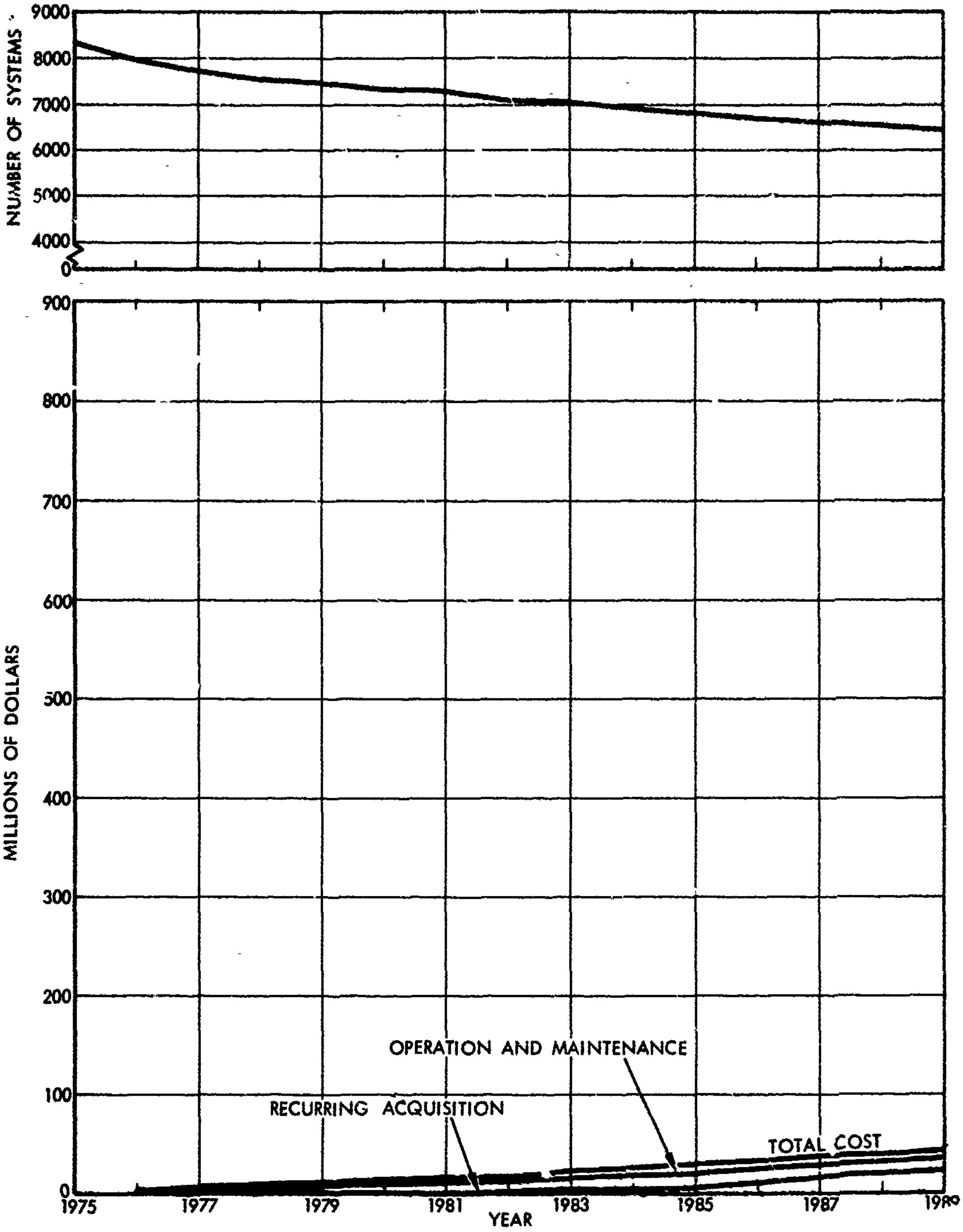


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Figure 6. Number and Cumulative Costs of Military VOR/DME User Systems

service is as an aid to nonprecision approach to landing. In the military case, this includes approaches to aircraft carriers and unimproved air strips (using portable TACAN beacons).

In an analogous way to landing, TACAN is used as a means for aircraft-to-ship and aircraft-to-aircraft rendezvous. If the substitution of GPS for TACAN should be considered seriously, an alternative to this relative positioning capability would be needed. The use of voice transmission to exchange position coordinates is a possibility; however, the need for a pilot to compute steering commands manually is a significant task in an aircraft. A more acceptable solution is a narrow-band data link and computer to generate a display analogous to TACAN. Potentially, such a function could be incorporated in the JTIDS (Joint Tactical Information Distribution System) being developed jointly by the Navy and the Air Force. Significantly, the Navy adaptation of JTIDS (formerly called ITNS–Integrated Tactical Navigation System) provides precision relative navigation and also provides a local backup GPS. This is desirable because of the uncertain vulnerability of GPS.

The VORTAC system as it exists today can be saturated. The DME portion is a two-way ranging system in which the aircraft transmits an interrogation pulse and the beacon replies after a fixed delay. This allows the airborne system to compute its slant range to the beacon. The signal structure is such that approximately 100 aircraft can use any given beacon before mutual interference[6] overcomes the beacon.

An adaptation of the VORTAC system which is being used increasingly is "Area Navigation" or R-NAV. Until recently, the technique for navigating the VORTAC route structure was simply to fly VORTAC-to-VORTAC in straight line segments. Deviation from the desired course was indicated by the right-left deflection of the "omni-bearing" indicator needle. Along-course position is given by the DME reading (in the case of VOR-only users, along-course position is obtained from a bearing from an adjacent off-course VORTAC– "theta/theta" navigation). The VORTAC-to-VORTAC procedure is strictly for convenience since the system is intrinsically capable of providing position anywhere within range. For courses not directly between two stations, however, the pilot is faced with computing the desired bearing and distance to a station as a function of time along a route and attempting to make good these estimates. The task is difficult to perform manually in spite of the rather simple trigonometry involved. Small computers have been integrated into the VOR/DME/TACAN user equipment that makes the computation and provides the pilot the familiar right-left, distance to go display or, in some cases, a stylized pictorial display called a horizontal situation indicator (HSI). This added capability of R-NAV (which has always been available in other systems such as inertial and hyperbolic systems) converts what was essentially a 2-degree-of-freedom navigational system (along track and vertical) to a true 3-degree-of-freedom system. The added horizontal degree of freedom (for flight planning purposes) creates problems for air traffic control. The

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[6] It is estimated that in certain high density areas (e.g., LaGuardia) the average (busy hour) traffic is approaching 50 percent of saturation. Traffic growth projections indicate that the saturation limit might be reached in some high density areas within the timeframe of this study (1990). This estimation is according to S.A. Meer, "Study of the VORTAC System and Its Growth Potential," MTR-6547, Mitre Corporation, November 1973.

primary difficulty is conflict prediction in three dimensions rather than two. At the present time, techniques for accepting R-NAV flight plans and flight following (including conflict prediction) are being developed. Full implementation of R-NAV Air Traffic Control is planned for the early 1980s. The few R-NAV routes that have already been established are little more than extensions of the present two-dimensional system.

An important feature of R-NAV is that it is possible to develop nonprecision approach procedures at airports that would otherwise require additional ground facilities. The practicality of this application of R-NAV is still limited, however, by the proximity of the nearest VORTAC since the accuracy of R-NAV is limited by that of the basic VORTAC accuracy which is range dependent.

The basic enroute function of the VORTAC system can easily be furnished by GPS using the Clear Acquisition signal, since the nominal lane widths are currently 8 nautical miles. The nonprecision approach functions to a fixed base can also be fulfilled by GPS. (The landing application of GPS is discussed further in Section A6.)

c. OMEGA/VLF

The only truly global radio navigation systems, other than GPS, are the VLF hyperbolic systems. The best known of these is OMEGA. Figure 7 indicates that military use of OMEGA is increasing somewhat. However, in comparison to other systems (e.g., LORAN or TACAN in Figure 5), use is small.

A less well known VLF system uses the Navy VLF communication net. This net is time synchronized and stable to within one part in 10^{+11} and, therefore, can be used for navigation in a manner similar to OMEGA. In fact, VLF receivers use OMEGA transmissions as well as the VLF communication signals. However, the converse is not true.

Commercial user systems are available (e.g., the GNS-500 from Global Navigation, Inc., Torrance, California). The navigation accuracies of the OMEGA and VLF communications systems are similar (1 to 2 nmi during daylight hours). Approval of the VLF navigation system for IFR navigation rests in part on whether the Navy will assure that the transmitters will either remain on continuously or that the users will receive advance notification of scheduled outages. For security reasons, the Navy has declined to provide such assurances. OPNAV Instruction 53530.1B indicates that the Navy prefers OMEGA as the radio navigation backup to GPS. However, the VLF communications/navigation system provides services equivalent to OMEGA.

d. Direction Finding Systems

Direction finding systems consist of a series of isotropically radiating ground stations (nondirectional beacons or NDBs) and a user receiver with an antenna that senses the direction from which the radiation comes. Automatic Direction Finding (ADF) receivers display the direction of the receiver relative to the longitudinal axis of the platform (aircraft or ship). The system has the advantages of being comparatively inexpensive and easy to maintain. Its accuracy under good atmospheric conditions is poor (about 5 degrees). Since it

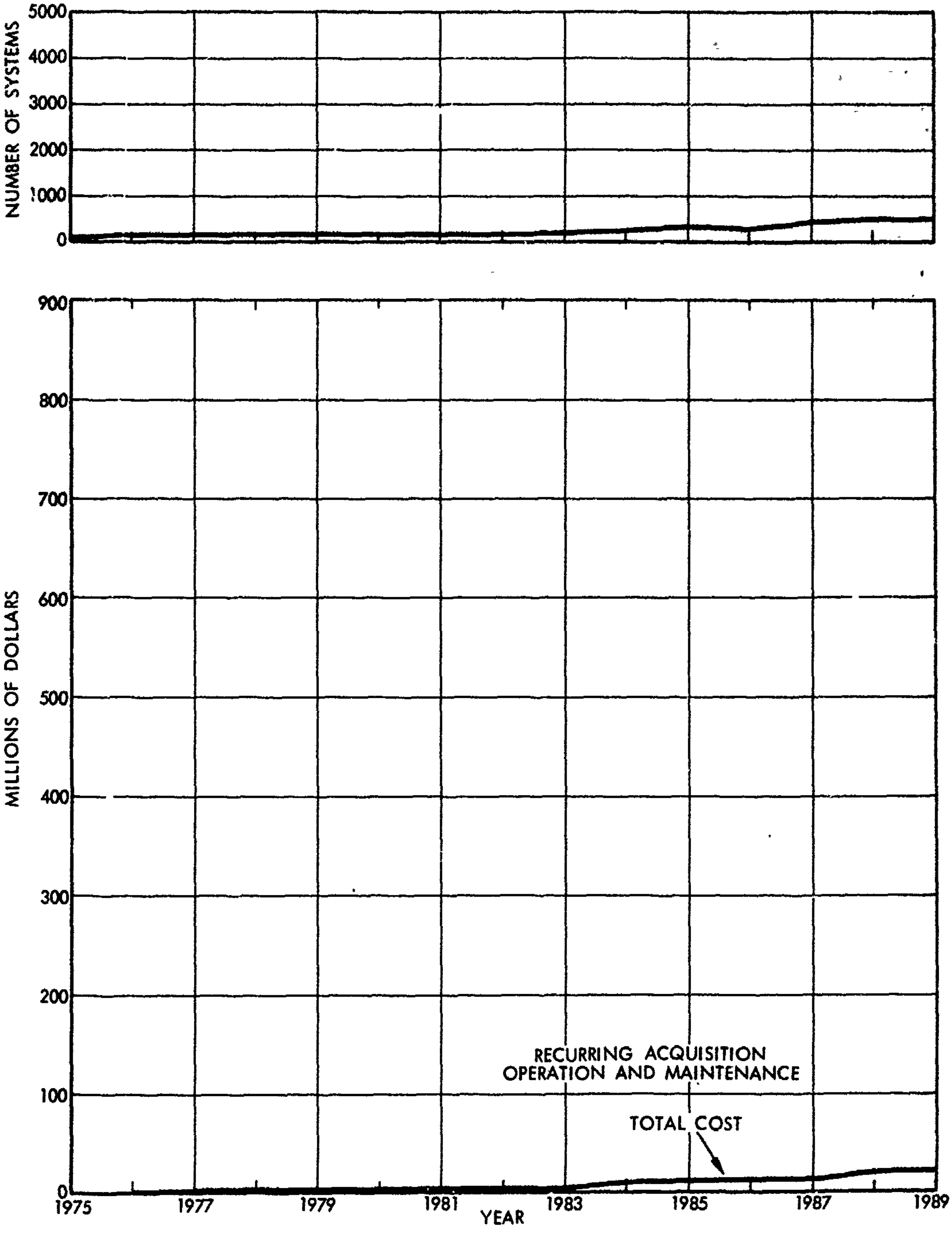

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Figure 7. Number and Cumulative Costs of Military OMEGA User Systems

is also subject to sensing errors during electrical storms and pilotage errors in high winds, it is unsuitable for use in high density traffic. Nevertheless, its low cost has resulted in its continued use as a primary navigation aid in most of the world outside of the U.S. and Western Europe. Even in these areas, the NDB/ADF continues to be used as a means of conducting non-precision approaches at many airports and as an aid in making the initial approach to a precision instrument landing. The cost avoidance potential of direction finding systems is significant only because of the large number in use (see Figure 8).

Paradoxically, although GPS can provide much more capability than ADF, it may be desirable to retain ADF as a low cost backup for a "get home" capability rather than provide dual GPS receivers.

e. Summary of Case 1

For the enroute radio navigation systems the two major cost segments are the user equipment and the reference equipment.

The estimated average annual costs for the enroute user systems considered in Case 1 are summarized in Table 14. The recurring acquisition costs are shown separately from the operation and maintenance costs.

Table 14. Estimated Average Annual Costs for Military Enroute User Equipment (millions of 1975 dollars)

System	Average Number of Sets	Recurring Acquisition Costs	O&M Costs	Total Costs
LORAN	4,900	24.3	35.0	59.3
TACAN	12,500	4.1	24.5	28.6
VOR/DME	7,200	1	2.3	3.4
OMEGA	300	.5	.4	.9
ADF	20,900	3.1	8.4	11.5
Total	45,800	33.1	70.6	103.7

The cumulative data on which the averages in Table 14 are based are shown in Figures 3 and 5 through 8. The averages are based on the entire period of 1975 through 1989. For the most part, the functions are reasonably linear and the averages are reasonable approximations for any period within the total span. The uncertainties in fleet composition and navigation suites outweighs any error in using the average annual cost.

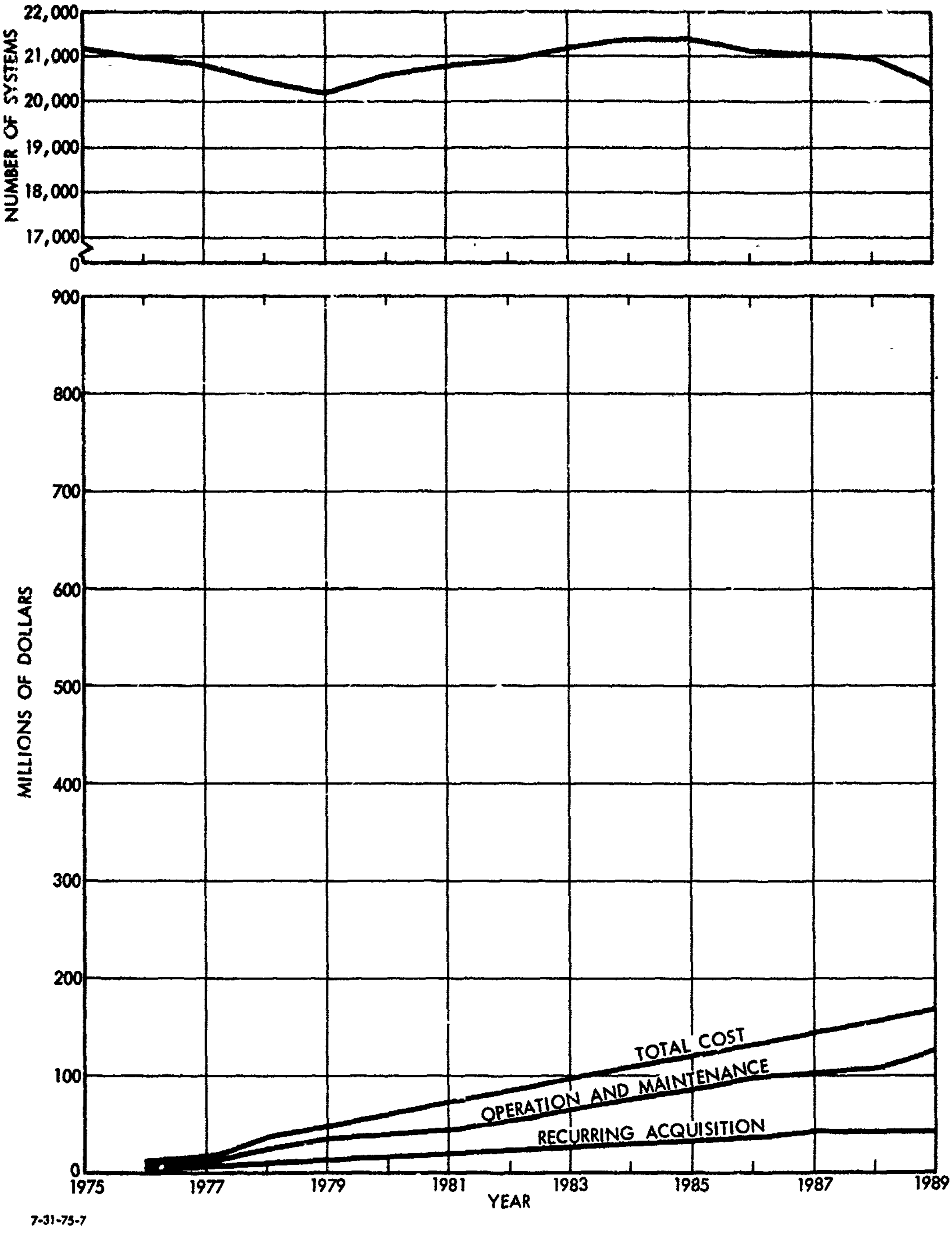

Figure 8. Number and Costs of Military User Direction Finding Equipment

Table 15: Estimated Average Annual Operating and Maintenance Costs for Enroute Radio Reference Equipment (millions of 1975 dollars)*

Equipment	*U.S. Military*	*U.S. Civilian*
LORAN	10.0	10.0
TACAN	1.9	Neg.
VOR and VOR/DME	1.5	6.5
VORTAC	.6	25.0
OMEGA	Unknown	Unknown
NDB	3.1	19.6
Total	17.1	61.2

*Estimated as approximately 10 percent of current acquisition costs.

Because of the joint military-civilian use of major portions of the systems there are constraints on the decommissioning of military reference equipment which is used extensively for civilian navigation. Obviously, there are no such constraints on equipment used exclusively by the military. There are, however, few reference systems which can be considered as solely military. The estimated annual operation and maintenance costs for the various elements of the reference system complex are shown in Table 15.

It is apparent from Table 15 that most of the operation and maintenance costs of the reference equipment are borne by the civilian sector. Only the TACAN stations are supported by the military, and a considerable number of these are ship and airborne beacons that are used for rendezvous. As noted previously, an alternative system must be provided (not GPS) for rendezvous if TACAN is to be phased out.

The system costs shown in Tables 14 and 15 do not include the procurement of new designs of certain equipment that either provide a new capability for existing platforms or replace aging or otherwise unsatisfactory older equipment. The specific programs of this type are listed in Table 16.

The new equipment listed in Table 16 would be installed in a time period roughly corresponding to the time when a two-dimensional GPS capability could exist as an alternative. However, Chapter II indicates that a significant cost advantage may result from GPS user equipment designs based on advanced digital LSI technologies. This may cause a delay in the GPS IOC. If it is desired to accept the delay to gain the cost advantage, then the costs of the new conventional enroute systems could not be entirely avoided. Some undetermined part of the production would have to be completed to fulfill interim requirements for new aircraft, or alternatively, more of the current systems could be procured for this purpose.

*Table 16. New Enroute Equipment Procurements**

System	Type	Time Span	Quantity Planned	Average Unit Cost ($, 1975)	Total ($M, 1975)
Air Force					
ARN-118	TACAN	1976-	10,000†	12,000	120.0
ARN-101	LORAN	1978-1979	242	150,000‡	36.3
Unknown	OMEGA	Thru FY 1978	690	15,000	10.4
TRN-35	LORAN (Ref)	1976-1977	- 3 chains -		15.6
Army					
ARN-114	LORAN	1975-	2,100	28,000§	59.0
ARN-123	VOR/ILS	1975-	7,100⊕	1,540☆	11.0
PSN-6	LORAN	1976-1978	1,740	18,000	30.0
TOTAL					282.3

*Note that quantities and costs are planning figures and do not represent firm contract data.

†Contract has been let for initial 1,100 units.

‡Contract price does not include inertial measurement unit (IMU).

§Army cost target.

●Initial contract let for 864 units plus 100 percent option

☆Includes 4-year Failure Free Warranty.

f. Other Considerations

Effects of Civilian Users on GPS. Because of the extensive intermingling of military and civilian air traffic in the enroute phase of navigation, any discussion of substituting GPS for current systems must consider the interaction between the civilian and military usage.

A necessary condition for the use of GPS in the civilian route structure is the approval by the FAA (in the U.S.) and the ICAO (in the rest of the world). Such approval is generally contingent on the ability of the system to provide sufficient accuracy to maintain track accuracy within established standards and reliability and availability adequate to ensure safe completion of the flight. The nominal capabilities required are described in FAA Advisory Circular 90-45A and are summarized in Table 17.

All of the variants of the GPS system cited in Table 22, page 70, are capable of the accuracies cited in Table 17, including the terminal and nonprecision approach accuracies specified.

A recent FAA-sponsored study[7] examined both the accuracy requirements and operational requirements of Area Navigation (R-NAV) in detail. The study presumed that R-NAV will be based largely on the VOR/DME facilities. However, GPS can provide

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[7] "Applications of Area Navigation in the Airspace System," FAA/Industry RNAV Task Force, DOT/FAA, February 1973.

essentially the same service without incurring some of the same problems and expenses as a VOR/DME based system. In brief, these avoidable problems and expenses are:

(1) Insufficient coverage by VOR/DME in certain areas, notably the mountain states and Alaska. Stations would have to be added or relocated.

(2) VOR accuracies would have to be improved to meet the post-1982 requirements. This would require installation of P-VOR (Precision VOR) stations in high density terminal areas at an added cost to both the FAA and user aircraft.

(3) Inaccuracies in altimetry used for slant range corrections inhibit the implementation of three dimensional R-NAV based on VOR/DME.

Table 17. Minimum Accuracy Requirements for Three Dimensional Area Navigation Systems (2 Sigma Limits)*

Flight Phase	Cross Track (nmi)	Along Track (nmi)	Vertical (feet)
Enroute	1.5	1.5	230
Terminal	1.1	1.1	230
Approach (nonprecision)	0.3	0.3	130

*Not including pilot errors.

Other problems with R-NAV are operational in nature and are common to all such systems. The least understood have to do with pilot and controller workload and consequently its acceptance by them. The workload problems occur primarily in terminal areas. This subject is discussed in more detail in Section A6.

Red Bloc Radio Navigation. The Red Bloc radio navigation system was omitted from the foregoing accounting primarily because of considerable uncertainty as to how extensive it is and because of consideration of the potential benefit of GPS to the Red Bloc countries, which merits a separate discussion.

The defined route structure within the Red Bloc countries (Eastern Europe, USSR, and The Peoples Republic of China) is most striking in its sparsity. Table 18 shows the total

Table 18. Published Route Mileage and Navigation Aids in Red Bloc Countries

	Route Miles	VOR	NDB*	ILS/KGSP†
Eastern Europe	7,230	39	112	22
USSR	24,200	6	134	52
Peoples Republic of China	4,100	2	33	5
Totals	33,830	47	279	79

*Nondirectional beacons.

†KGSP is the Russian variant of ILS; it uses the same frequency assignments but is not usable by ILS-equipped aircraft without additional equipment.

mileage and navigation aids of the defined air route (both high and low altitude) within the Red Bloc countries. The data are taken from the navigation charts prepared by Jeppeson[8] based on data supplied by the various countries. Since these charts are primarily for international air carrier operations into the various countries they may not contain data used exclusively by in-country air traffic.

The comparable number of route miles for the U.S (contiguous U.S., Alaska, and Hawaii) is 406,905 nautical miles. The radio navigation aids upon which the published route structure for Red Bloc areas is based consist largely of nondirectional beacons (NDB), of which 279 are listed. In addition, there are 45 VOR installations, primarily in Eastern Europe.

The route structure as defined on the available navigation charts is clearly inadequate for IFR navigation in the central regions of the USSR and China. Two alternative conclusions are possible from the data available—the more likely one is that there is a much more extensive route structure that is not available or known to the outside world at large; the other is that the available charts do, in fact, represent the actual route structure. [If the latter is correct, implementation of GPS and making it available to everybody (as the U.S. has done with Transit) would provide, free of charge, a major asset with considerable potential impact on the economic development of the central regions.]

4. Case 2: Dual Self-Contained Systems

a. System Description

Self-contained systems are used for two major reasons: either externally referenced systems are unavailable in the areas of use, or it is expected that radio reference systems will be jammed or otherwise compromised. The two most common forms of self-contained systems are (1) Dead-Reckoning Systems that integrate velocity to derive position change and (2) Inertial Systems that integrate acceleration twice to derive the position change. All of these systems require initialization to provide the position in geographic coordinates. The velocity vector required for the dead-reckoning systems can be obtained in a variety of ways. The most accurate systems in use are based on Doppler radar measurements of speed relative to the ground and a gyrocompass measurement of heading relative to true north. Accuracies of 1 to 5 percent of distance traveled are typical. Air data systems are also used which derive ground speed from calibrated air speed with corrections for air density and wind velocity. The wind corrections contribute the largest errors. Air data systems are of little use for precision navigation without current and accurate wind data which are seldom available.

All of the self-contained systems are characterized by an unbounded position error which increases with time. Thus, on long missions, periodic position updates are required to control the errors.

Dual self-contained systems are frequently used, both to provide higher reliability and to control the error growth.

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[8] *Airway Manual, Eastern Europe and China*, Jeppeson Company, Denver Col., June 1975, UNCLASSIFIED.

Dual self-contained installations are commonly Doppler-inertial. Dual inertials are least common because of their high cost. Air data dead-reckoning is a universally available backup since it can be accomplished manually as well as by the navigation computer. However, it is never acceptable for routine extended IFR flight.

The major motivations for the use of dual self-contained systems rather than single installation—overall reliability and accuracy—could be fulfilled by GPS as a substitute for at least one of the pair of self-contained systems.

Table 19. Current Usage of Self-Contained Systems in Aircraft

Type of Self-Contained System	*Number of Users*	*Percent of Total*
Dual Doppler Installation	371	22
Dual Inertial Installation	17	1
Doppler/Inertial Installation	1,311	77
Total	1,699	

The current usage of self-contained systems is summarized in Table 19.

In addition to dual and self-contained systems, there are 3,726 single Doppler installations. These represent a large potential cost avoidance that is dependent on the operational feasibility of doing without any self-contained capability.

In addition to the current aircraft usage summarized in Table 19, there are substantial numbers of military aircraft under development that will enter the inventory in the time frame of this study. Although their specific navigation suites have not been selected by the Services, some of these aircraft would contain dual self-contained systems.

In order to approximate the effect in the out years of removing one of the self-contained systems from these aircraft, the study developed representative navigation suites for them. This was done largely by analogy to current aircraft with similar missions. Those new aircraft having dual self-contained navigation systems are listed in Table 20. The inventory values are the maximum numbers foreseen during the time frame of the study.

The C-141 modification listed in Table 20 consists of the installation of dual inertials. A major stimulus for this modification is to provide acceptable navigation accuracy for the high density North Atlantic routes. Currently these aircraft are unable to maintain cross track errors within acceptable limits set by ICAO and must fly at uneconomical low altitudes or use circuitous routes.

b. Technical and Performance Considerations

As noted earlier, the major motivations for dual self-contained systems are to provide higher reliability and to improve accuracy. It is for the latter reason that most of the dual installations are Doppler/inertial in which the primary function of the Doppler is to provide long period damping for the inertial systems, and the inertial systems provide the heading reference required by the Doppler radar. The velocity damping function of the Doppler systems can be fulfilled by GPS. Both the Doppler and GPS are susceptible to electronic countermeasures; however, it is not possible to make any conclusive statements about their relative vulnerability. The GPS may have some advantages since the user is passive whereas the Doppler is an active system.

In any event, aside from vulnerability considerations, the Inertial/GPS hybrid would be at least as accurate as any of the dual self-contained systems since, in the case of Inertial/GPS systems the errors would be bounded by the GPS component.[9]

The potential cost avoidance is arising from the substitution of GPS for one of the components of the dual self-contained systems (primarily the Doppler of Doppler/Inertial hybrids) is estimated in the next section.

An attractive feature of the GPS/Inertial hybrid is the added jamming margin of the GPS component provided by the inertial system. The benefits arise in two ways. Assuming that the satellite signal has been acquired, the velocity of the user platform is accurately measured by the inertial system. This allows the Doppler shift induced by the vehicle motion to be corrected for. This permits a narrow width of the code tracking loop and increases the antijamming margin. In addition, if acquisition is lost for any reason, the inertial system continuously determines the position of the platform. This allows the adjustment of the "position" of the internal code so as to minimize the scanning time to reacquire (correlate) the satellite code signal.

Table 20. New Installations of Dual Self-Contained Navigation Systems

Aircraft	*Maximum Aircraft Inventory*
Doppler/Inertial	
RF-X	155
AMST	354
AC-X	16
KC-X	108
E-3A	32
E-4A	13
ER-111A	42
VAMX	120
VAWX	39
KAX	63
COD	23
Dual/Inertial	
C-141 (Modification)	279

The cost avoidance estimate shown for the case of the dual self-contained systems does not give any credit for the enhanced capabilities of those navigation suites for which GPS is added to an existing single self-contained system. Assuming that the necessary integration functions are performed, these systems will have the same qualitative performance as those that have had one of the self-contained units removed. The major differences would be in the quality of the inertial system. This suggests that this type of inertial system or, even more generally, the type of "aiding" sensor to be used with GPS (if any) should be examined in the light of the mission requirements of the platform. The NAVSTAR GPS program office is part of the Phase I effort and is examining a number of possible aiding sensors. A General Dynamics Corporation study[10] considers four integrated systems in a preliminary way. They are:

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[9] *A Treatise on Anti-Jamming Margin of an IMU/Computer aided Global Positioning Navigation System*, Aerospace Corp., May 1974 (Unpublished Draft).

[10] Harrington, R., "Auxiliary Sensor Study," General Dynamics Corp., 1975 (Draft).

(1) LDNS[11]/AHARS[12]/GPS
(2) Air Data/GPS
(3) Strapdown Inertial/GPS
(4) Gimbaled Inertial/GPS

This preliminary study indicates that all of these systems have some potential for aiding acquisition or reacquisition–and possibly for code loop velocity aiding. Only the inertial systems have the necessary technical characteristics to provide carrier loop aiding. At this time the results are too preliminary to develop firm system design characteristics and costs.

The current trend appears to be toward the Inertial/GPS hybrid combination because of the added antijam margin. However, it is not clear what the optimum inertial system performance (and hence cost) levels are. Since the system accuracies are bounded by the GPS accuracies when both systems are functioning, selection of the inertial system performance should be based primarily on the expected length of time GPS is not available and on required terminal position accuracies.

The AHARS and the Air Data Systems, although considerably less accurate than the inertial systems, are installed in most aircraft whether or not GPS is included. Thus, since some benefit could be derived from hybridizing them with GPS, they have a potential for low cost platforms. The primary design uncertainty of this application is what added computer capabilities would be required to integrate the system. If provisions are made for air data inputs in the design of the GPS computer, the added cost may be very small.

c. Cost Analysis

As noted in the foregoing discussion, operational considerations restrict removal of self-contained systems to the Doppler systems. The average annual expenditure for all Doppler systems is $33.5 million of which $11 million is for procurement and $22.5 million is for O&M. The cumulative data for the period of 1976 through 1979 are given in Figure 9. Approximately 30 percent of the total number of Dopplers in the inventory is one of a pair in a dual self-contained system (dual Dopplers are counted only once). Thus, approximately 30 percent of the costs cited above could be avoided by removing dual self-contained systems. (The dual inertials presently are a small portion of the total.) The 30 percent portion of dual systems is shown on Figure 9. The corresponding average annual rates are $3.3 million for procurement and $6.75 million for O&M for a total of $10 million. The only new Doppler system identified is the ASN-128 being developed by the Army. Procurement plans call for 800 sets. The total future cost, including R&D, is about $55 million. Provisions are included for hybridizing the ASN-128 and the LORAN ARN-114.

The study has not examined the potential cost implication of the other hybrid systems using the Air Data System or the AHARS with GPS. However, they may be a

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[11] Lightweight Doppler Navigation System.

[12] Airborne Heading and Attitude Reference System.

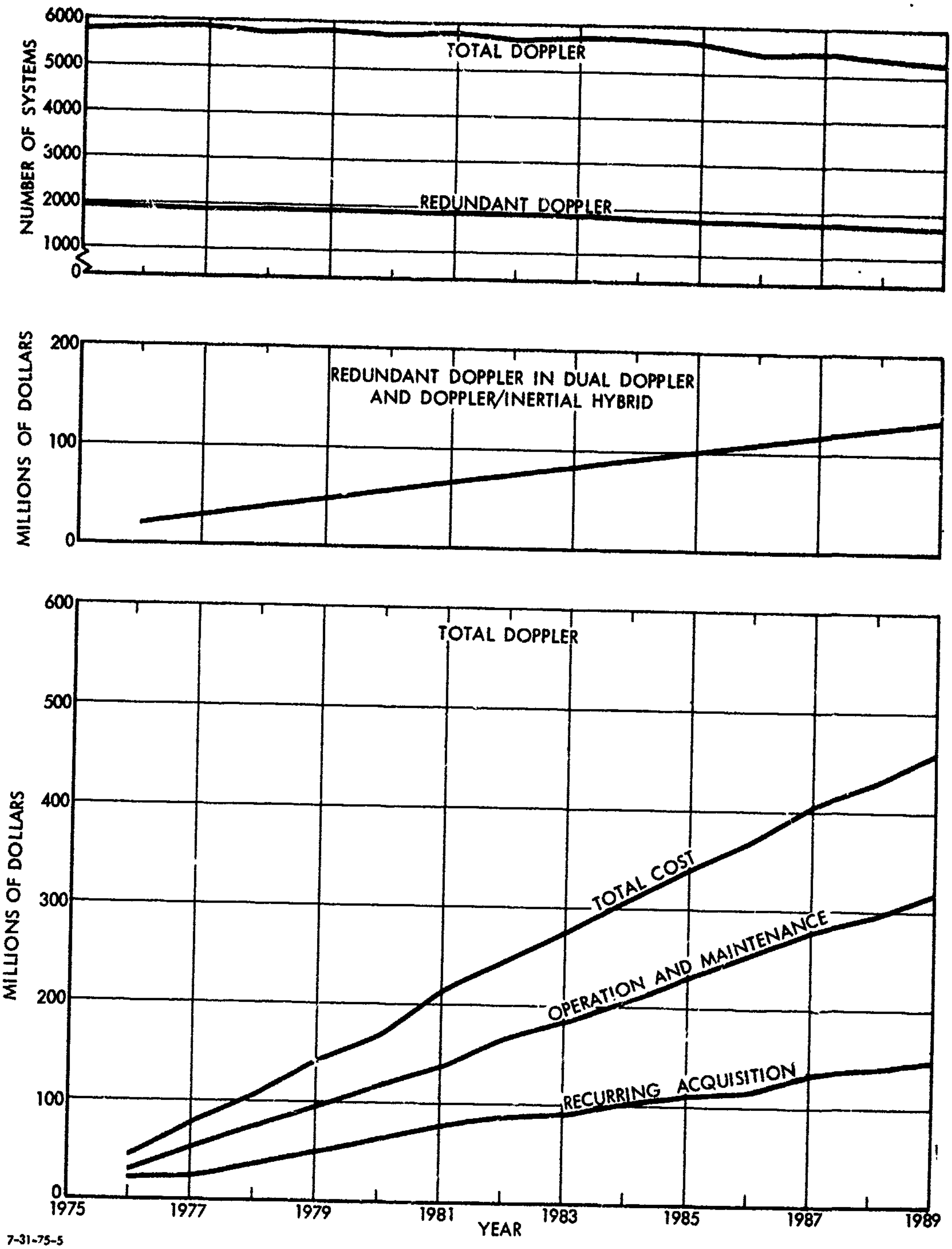

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Figure 9. Number and Costs of Military Doppler Systems

major factor in the feasibility of eliminating the single Doppler, which would be a significant added cost avoidance.

5. Case 3: Landing Systems

a. System Description

Of the routine functions performed by aircraft, the one requiring the most precise aids to navigation is landing under instrument meteorological conditions (IMC). Because of the precision required and the catastrophic effect of undetected failures, landing procedures based on GPS would be among the most demanding on the system. All military aircraft and a large fraction of all civil aircraft have some form of instrument landing or approach aid. The primary military instrument landing system is the 3-D Precision Approach Radar (PAR) System. The user equipment required is minimal--a voice radio. However, the ground equipment is substantial. The radar system and associated vans or structures are expensive and must be manned by highly specialized controllers who essentially talk down the pilot. Civil landing systems are largely "air derived"; that is, the navigation commands are generated in the aircraft with reference to some fixed path generated by a ground radio reference system. "ILS" is the most prevalent of these systems and it is the ICAO standard system. Because of the high cost and inflexibility of the "ground derived" radar systems, the military Services initiated the development of various microwave landing systems. These systems are operationally similar to ILS. The various concepts developed differ in how the flight path data (glide slope, localizer, and distance) are generated. The FAA has been designated as the executive agent for microwave landing systems to select the standard technique and complete development for both military and civil use.

b. Technical and Performance Characteristics

There are four generic classes of landing approach and landing aids; they are summarized in Table 21. Comparison of the accuracy requirements shown in Table 21 with the expected performance of GPS shown in Table 22 indicates that GPS could easily fulfill the requirement for the nonprecision approach.

For Category I, II, and III landing requirements, given in Table 21, GPS accuracies do not appear to be adequate. The primary concern is with the vertical error since the requirements are most stringent. Use of GPS for landing systems may require selection of satellites to minimize the vertical GDOP at the expense of increased horizontal errors. However, a significant portion of errors shown are due to factors which can be avoided if differential techniques are used. Table 23 shows the expected error budget for the Phase III GPS system along with the corresponding budget for a differential system.

As before, there appears to be a potential for the use of GPS as a landing aid, in this case for Category I. However, to implement the differential system, a receiver must be precisely located on the approach path and a data link provided to the aircraft. The need for the ground based receiver may be some constraint on tactical utilization for remote

Table 21. *Summary of Accuracy* Requirements of Approach and Landing Systems (meters)*

Category of Approach and Landing System	Ceiling	Visibility (meters)	Current Radio Aids in Use	Outer Marker (~Threshold Minus 10,000 Meters)			Middle Marker (~Threshold Minus 1,600 Meters)			Inner Marker (Threshold Minus 400 Meters)			Threshold 0			Flare (~Threshold Plus 300 Meters)		
				Lat.	Long.	Vert.	Lat.	Long.	Vert.	Lat.	Long.	Vert.	Lat.	Long.	Vert.	Lat.	Long.	Vert.
Non-Precision	130	2,000	VOR, TACAN NDB, ASR	500	500	40		(Visual)			(Visual)			(Visual)			(Visual)	
Precision																		
Category I	60	920	ILS, PAR	70	180	27	24	180	5		(Visual)			(Visual)			(Visual)	
Category II	30	460	ILS, PAR	36	180	17	15	180	3	12	12	1.2		(Visual)			(Visual)	
Category IIIA	None	200	ILS	17	180	17	7	180	3	5.5	12	1.2	4.8	12	0.6		(Visual)	
Category IIIB	None	45	None Avail.	17	180	17	7	180	3	5.5	12	1.2	4.8	12	1.0	4.8	12	0.6
Category IIIC	None	None	None Avail.	17	180	17	7	180	3	5.5	12	1.2	4.8	12	1.0	4.8	12	0.6

*2-sigma limits, including ground and airborne components, but not including pilot error.

†Taxi Guidance Required—(Navigation to Ramp) in addition to Category IIIB capabilities.

Table 22. *Preliminary Design Goals for GPS User Equipment Applicable to Approach and Landing (Phase III)**

	Equipment Class and Application			
	A	*B*	*C*	*S*
Design Parameters	*High Performance Aircraft With High Antijam*	*High Performance Aircraft*	*Mission Support Vehicles*	*Spartan Very Low Cost*
x, y, & z† (meters)	8-14	8-14	30-40	30
x, y, & z† (knots)	0.1	0.1	0.4	No Requirement
Time†	30-50 nsec	36-50 nsec	18-25 nsec	1 sec (Displayed)
Time to First Fix‡	80-180 sec	30-150 sec	200-300 sec	10 min
Antijam Margin (dB)	44	44	30	30

*Data for all user systems are given in Appendix A.

†Two sigma limits.

‡90 percent probability.

Table 23. Range Error in GPS Error Budget (meters)

	Phase III(2σ)	*Phase III diff(2σ)*
Space Vehicle Ephemeris	6	0
Atmosphere	4.8-10.4	0
Group Delay	2	0
Receiver Noise	3.0	3.0
Multipath	2.4-5.4	2.4-5.4
Total RSS	8.8-13.6	3.8-6.2

unattended bases; however, it is unlikely that a "first landing" Category I approach would ever be required into an unimproved base.

Aside from the accuracy issues, a major advantage offered by GPS as a landing aid is its worldwide availability. In the case of non-precision approaches it eliminates the need for ground systems and, in the case of the higher precision category approaches, the ground installation may be somewhat simpler than ILS or MLS. These characteristics are probably more important because of the tactical flexibility that they offer than for the potential cost savings. As will be seen in the next section, the cost savings are small compared to other opportunities.

The operational demonstrations considered in Chapter III include a demonstration of approach and landing. The emphasis of the demonstration is the use of GPS as a landing aid into unprepared bases without use of a ground reference system (nonprecision approach). Additional demonstrations and tests are desirable to shed some light on the practicality of using differential GPS for precision approaches, particularly Category II.

In addition to accuracy considerations, the use of GPS as a landing aid requires the development of an "approach procedure" for each landing site. Such procedures are published for pilot use in the form of charts (Figure 10 is a sample). Such procedures are established after considerable survey of surrounding terrain, cultural features, electromagnetic anomalies, etc. For unimproved sites, the establishment of an approach procedure on short notice requires somewhat different techniques than those currently used. It is expected that precise (2-3 meter elevation error) stereophoto maps of the site and surrounding area (about a 10-mile radius) would be the primary data base for development of such approach procedures.

The pilot workload and opportunity for gross errors associated with the present ILS landing systems are relatively low. It is only necessary to dial in the correct frequency and fly the aircraft to center the glide slope (altitude) and localizer (heading) needles and note passage of the marker beacons. For experienced pilots, the procedure is instinctive and gross errors are immediately apparent.

Workload problems occur primarily in terminal areas where navigation to final approach course defined by the ILS usually involves a series of short legs, large changes in heading, and simultaneous changes in altitude. Currently, this is done by "radar vectoring" which imposes minimum workload on the pilot but considerable workload on the controller. R-NAV based on GPS on the other hand, would transfer the load to the pilot who would have to fly to a series of 3-dimensional "waypoints" inserted into the GPS computer. Unless some very simple way is found to program the entire sequence into the system, it is doubtful that pilot acceptance will be obtained, particularly for single-pilot IFR operations. All of the present R-NAV systems allow for the manual insertion and storage of waypoint coordinates, one by one. However, gross insertion errors which are highly improbable with VOR, TACAN, or ILS systems are possible with R-NAV. Furthermore, impromptu changes in desired flight profile caused by traffic and/or weather would be difficult to keep up with manually. In such cases, the system would most likely fall back on the radar vectoring

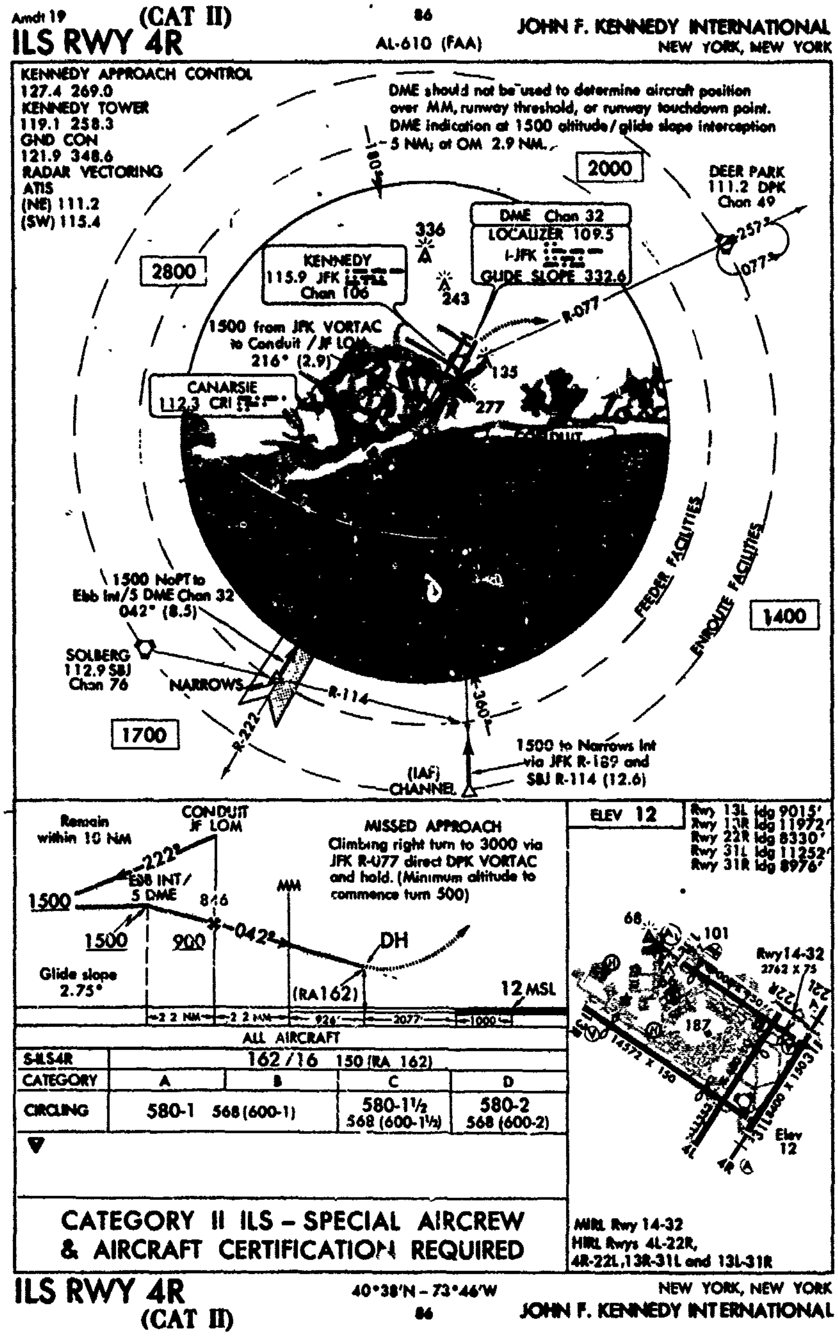

Figure 10. ILS Approach Plots

mode. Recent simulations[13] by the FAA with live controllers have indicated that controller work load as measured by frequency of voice contacts could decrease considerably. Whether this observation can be translated into fewer controllers is not known. Equivalent simulations with live pilots have not yet been conducted, and the extent of the increase in pilot workload is not clear.

c. Cost Analysis

Currently, the military Services do not routinely install ILS equipment in all aircraft since the primary instrument approach aid is the Precision Approach Radar (PAR). However, military aircraft that are expected to use civil airfields in the course of normal operations are equipped with ILS. These include primarily the cargo aircraft. In addition, many Air Force tactical aircraft are being equipped with ILS. Figure 11 summarizes the inventory of aircraft and costs associated with ILS user equipment in military aircraft. The average annual cost for ILS user equipment for the Services is $12 million comprised of $2.5 million for procurement and $9.5 million for O&M.

In addition to the PAR system, many military airfields are equipped with ILS to support the operation of civilian aircraft into military bases as well as equipped military aircraft. The present inventory of reference systems for both PAR and ILS is given in Table 24 along with the approximate annual O&M costs for these systems. The total annual costs for ILS for both user equipment and reference systems for the U.S. military is $23.3 million. For the PAR, the annual costs (the $14.2 million shown in Table 24) are for the reference systems only since no special user equipment is required.

Table 24. Inventory and Annual Operation and Maintenance Costs of Precision Landing Aid Reference Systems

	U.S. Military		*U.S. Civilian*	
System Type	*Inventory*	*O&M ($M,1975)*	*Inventory*	*O&M ($M,1975)*
PAR	101*	14.2†	6	1.38‡
ILS	189	11.3	1,081	65.0

*Does not include any Army systems—data not in ECAC data base.

†Includes military controller costs based on 6 controller years per set at $15,000 pay and allowances.

‡Includes civilian controller costs based on 6 controller years per set at $30,000 pay and allowances

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[13] *Preliminary Two-Dimensional Area Navigation Terminal Simulations*, FAA-RD-74-209, FAA/DOT, Washington, D.C., February 1975, UNCLASSIFIED.

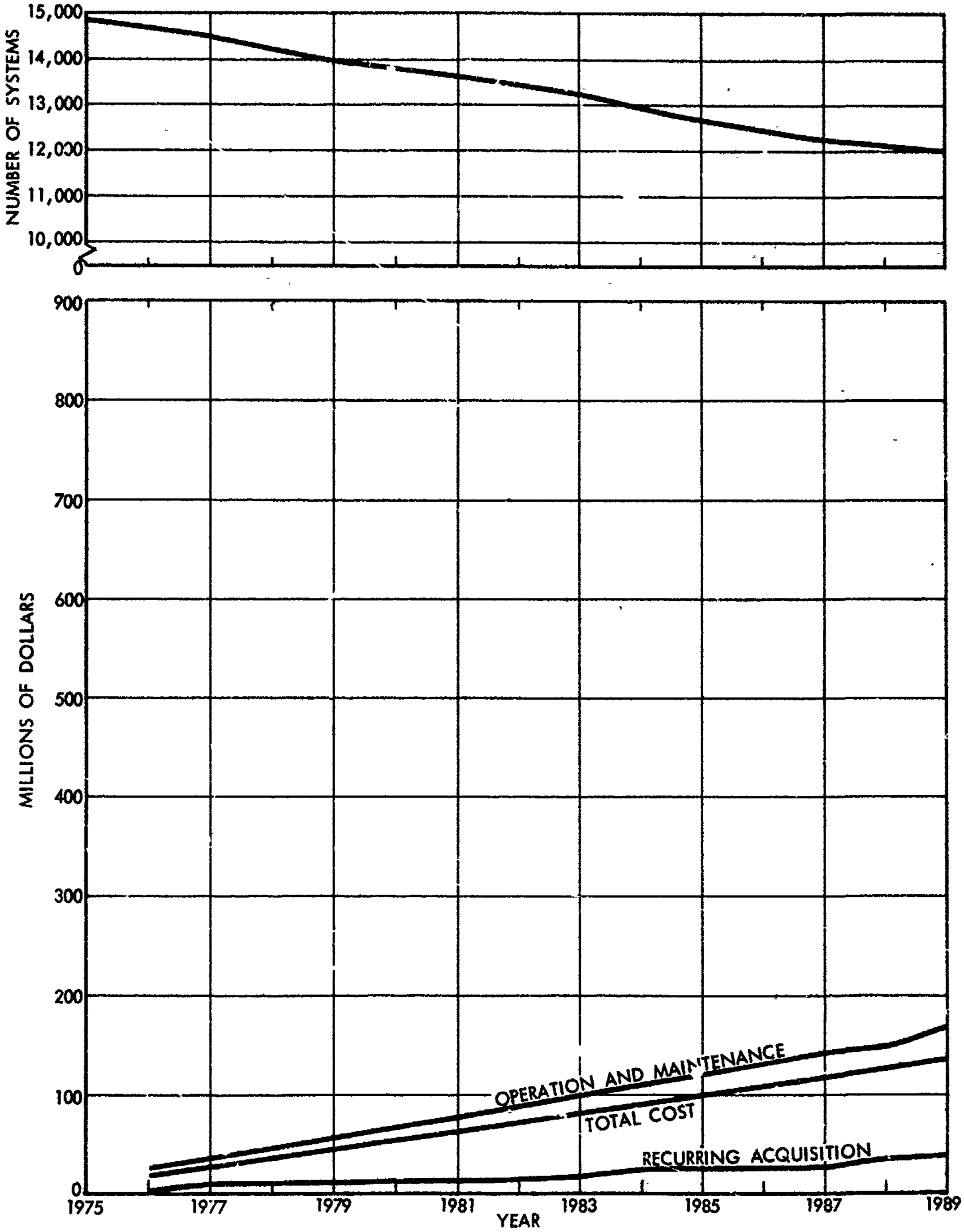

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Figure 11. Quantity and Costs for Military Landing Aid User Equipment

The Air Force is planning to upgrade the ILS installations at its bases during the period covered by this study. The total expected cost of this program is $15 million. Other than this interim program the expenditures for landing aids are expected to be small until MLS becomes available in the mid-1980s.

The planned expenditures for new landing aids are summarized in Table 25.

Table 25. Planned Total Expenditures for New Military Landing Aids, 1978-1980

User Equipment	*$M (1975)*
R&D	
Military Share of National MLS Development	38
ILS Mod Program	35
Ground Reference Systems	
R&D*	0
Procurement	
GRN 27	15
TPN 19	46
Product Improvement	13
Total	147

*MLS ground reference R&D included in $38 million for user R&D.

6. Case 4: Air-to-Ground Weapon Delivery or Navigation Radars

The positioning systems which, if supplanted by GPS, are believed to *create the most incentive for the enemy to attack GPS* are the radar systems used in air-to-ground weapon delivery. Thus, such a substitution is the least desirable from the standpoint of assurance of completing a bombing mission. Nevertheless, given that GPS is available, it appears to be a viable substitute for radar bombing as currently done.

The capabilities of the current weapon delivery radar systems are such that the ability of the aircrew to acquire and strike targets of opportunity is for practical purposes nonexistent. Strikes are preplanned using prior photographic or radar reconnaissance. Release points are determined by offset beacons or, if the target is distinctive enough, by matching radar scope photography (actual or simulated). In either case, impact errors are intolerably large for hard targets. This entire procedure can, in principle, be performed with GPS. The resulting accuracy would probably be better by as much as an order of magnitude (not including weapon dispersion). GPS alone, however, has no potential to strike targets of opportunity, either moving or stationary.

The development of new strike radar systems (i.e., Electronically Agile Radar (EAR) and exploitation of the FLAMR technology is underway and is expected to lead to a capability to acquire and effectively strike targets of opportunity, including hard targets with homing weapons. The cost of such systems would be high, on the order of $800 thousand each. The most conservative approach at this time would appear to be a continued development of the technology of precision radar weapon delivery to the point of tactical demonstration and a more solid definition of costs and concurrent development of the techniques for blind bombing using GPS as a backup system to the advanced radar. In addition, because of their approximate equivalence in performance, some consideration should be given to the practicality of phasing out current radar systems as GPS becomes available.

The radar systems considered by this study as candidates for phase-out are given in Table 26 along with the aircraft on which they are installed and the approximate inventory

Table 26. Radar Systems Used for Weapon Delivery, Navigation, or Mapping

Radar System	*Installed On*	*Average Quantity*	*Replaceable By GPS*
APD-7	RA-5C*	14	
APQ-83	RF-4B	2[illegible]	
APQ-99	RF-4B, C	350	
APQ-100	R-4C	120	
APQ-102	RF-4B, C	350	Yes
APQ-109	F-1D	327	
APQ-112	TC-4C, A-6E	205	
APQ-113	F-111A, E	150	
APQ-114	FB-111A	70	
APQ-116	A-7A/B	55	
APQ-120	F-4E	631	
APQ-122	T-43A	17	
APQ-124	F-8J*	7	
APQ-126	A7C/D/E	740	
APQ-129	EA-6B	50	
APQ-130	F-111D	82	
APQ-144	F-111F	206	
APQ-146	F-111F	206	
APQ-148	A-6E	195	
APN-59	Cargo & Tankers	1,550	
APS-42	C-97 C-118, C-121, C-131*	55	
APS-116	S-3A	136	
ASB-16	B-52G/H	230	Yes
TOTAL		5,449	580

Note: Aircraft indicated with an * are expected to be phased out by the early 1980s.

of each system. All of the radars listed have at least an air-to-ground weapon delivery or a navigation or a mapping capability. As noted, they number about 5,500. In most cases these radars have additional capabilities–such as air-to-air intercept–which cannot be supplied by GPS. The radars that have only an air-to-ground weapon delivery, or navigation or a mapping function replaceable by GPS, are indicated in the table. There are about 580 of such radars. These are the only radars which could be replaced by GPS without a marked degradation in the capabilities of the aircraft. The functions that would be lost if the other radars were phased out are primarily air-to-air search and weapon delivery on air superiority fighters, terrain following and avoidance on attack aircraft, and surface search on Navy patrol and attack aircraft.

It is conceivable that some greater number than 580 of the current radars could be phased out. The factors that would influence such a decision include the development of new radar systems as noted before and the changing role of the F-4 with the advent of the F-14, F-15 and F-16 aircraft and their air superiority role. If the air-to-air role of the F-4 is downgraded, then approximately 600 additional radars might be phased out.

The Air Force is currently conducting a study of these and other issues concerning the needs for and use of radars in aircraft. When completed, this study should shed more light on the potential cost avoidance resulting from the use of GPS rather than radars for weapon delivery.

In addition to the airborne radars, a ground-based radar bombing system is currently under development by the Air Force (Ground Directed Bombing/Radar Bomb Scoring (GDB/RBS) system). This system would be used to vector aircraft to the target and to score the results. These functions could be readily accomplished with GPS.

Cost Analysis. The cost to operate and maintain all of the airborne radars with a weapon delivery capability is approximately $69.3 million per year. Roughly 10 percent of this, or $7 million, is avoidable if the two current radars (APQ-102 and ASB-16), which are used only for weapon delivery, are phased out.

These estimates are believed to be conservatively low. As noted above, a more detailed investigation of the demonstrated value of the additional capabilities of multipurpose radars may indicate that these additional functions alone do not justify their continued use in view of the cost. If this is found to be true, the potential cost avoidances increase accordingly. Eliminating the APQ-120 from the F-4E alone would provide an additional 10 percent in cost avoidance.

The cost analysis is based on continuing to use the listed systems in future aircraft at approximately $100,000 to $150,000 per system. However, the development of EAR and the use of FLAMR technology will result in systems that will cost on the order of $800,000 or more. If the technology and related tactics are successfully developed, these systems will have a target of opportunity capability which cannot be duplicated by GPS. Thus, the high cost systems are not potential sources of cost avoidance. Neither the R&D nor the procurement of these systems has been included in the analysis. The GDB/RBS procurement and support costs are included, however. The estimates for the GDB/RBS costs are $60 million for procurement and $3.3 million annually for O&M.

B. SUMMARY AND ANALYSIS OF COST AVOIDANCE

This section collects the cost data on conventional systems presented in the previous sections to summarize the potential gross cost avoidance that could result from a phase-out of current systems. Additionally the costs of GPS developed in Chapter II are summarized in a similar format. Together, these two sets of data make it possible to estimate net cost avoidance and a breakeven period for each case of interest.

To provide an appreciation of the effect of uncertainty on the net cost avoidance, the GPS costs as developed from data supplied by the Joint Program Office were used directly as a lower estimate and increased by arbitrary but reasonable factors to obtain an upper estimate.

In all of the explicit calculations, the effective discount rate (discount rate less inflation rate) is assumed to be zero and costs are in terms of 1975 dollars. The effect of a finite discount rate is to increase the breakeven period. The effect is small for short breakeven periods and large for periods greater than 10 to 15 years.

It is emphasized that the breakeven periods have meaning only if GPS and the conventional systems provide equivalent capabilities. If GPS provides an added capability, then there may be an implicit operational cost advantage of GPS that is presently unmeasurable in dollars, as noted in the beginning of this chapter. With this caveat, the breakeven period is useful as a figure of merit to aid in rating the various alternative cases. Obviously, the shorter the breakeven period the better, all other things being equal

The major cost parameters used in the summary are

Conventional Equipment

- The average annual cost of operating and maintaining the conventional user equipment plus new procurements of conventional equipment for new user platforms.
- Cost of R&D and procurements of new designs of conventional equipments that would be needed in the absence of GPS.

GPS

- Initial investment in the space and control segment to deploy the initial complement of satellites.
- The average annual cost of supporting this space and control segment.
- The initial investment in user equipment to retrofit the fleet. This includes the cost of equipment plus costs of installation.
- The average annual cost of operating and maintaining the user equipment plus procedures for new user platforms.

Strictly speaking, the annual costs referred to above are variable year to year and a rigorous treatment should consider this variation. However, in view of the uncertainties in all of the cost data and the rather small variation in the annual costs as displayed by the graphs in the previous sections, it is judged that average values produce acceptable accuracy. This approximation greatly simplifies the arithmetic and provides results that are more readily understood and verified. The various average annual costs are derived from the detailed annual calculations using the computer model described in Appendix B, which takes into account the projected variation in force levels and suite compositions. The basis and sources for the costs analyses are summarized below.

1. Cost of Conventional Navigation Systems

The costs of conventional systems shown in Table 27 and individually in preceding sections, are based on a buildup of detailed cost of equipment and user platform data with projections into the future using the computer model.

The basic data needed for the computations are of three kinds: Force Structure, Navigation Suite Composition, and Cost of Specific Navigation Systems. The sources used for these data and the adjustments made are summarized below.

Force Structure. The quantity of each type of user platform, e.g., number of A-7Cs, was derived from various sources described in IDA Note 834.[14] Since these sources are changing almost continuously and do not always agree either in quantity or in platform designation, some adjustments were necessary to derive a consistent force structure for the time period encompassed by the study. It is emphasized that the results are used to develop approximate quantities of equipments required and do not represent formal DoD long range planning.

Navigation Suites. The navigation suites of the various specific user platforms were obtained from the computer files of the Electromagnetic Compatibility Analysis Center (ECAC). A previous IDA study[15] had compiled an extensive suite composition data base from the ECAC data. This data base was used for current platforms without change. The force structure identifies platforms that have not yet progressed to the point of having a designated navigation suite. For these cases the study group assigned a suite by analogy with current platforms with similar missions. The detailed data base is voluminous and of limited interest and is thus not reproduced in this report. It is available to interested parties.

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[14] IDA Note 834, *Force Structure Supplement to IDA Report R-217* SECRET. Sources cited in this note are:

USAF, DCS/Programs and Resources: *USAF Program, Aerospace Vehicles and Flying Hours, Vol. 1, Aircraft and Flying Hours by M/D/S (PA 77-1, Vol. 1);* 6 January 1975, SECRET.

Department of the Navy, *Five Year Program–Ships and Aircraft Supplemental Data Tables (SASDT),* 24 January 1975, SECRET.

August, Joseph, et al; *1974 Extended Planning Annex;* Center for Naval Analysis, CNA 1211-74, 26 July 1974, SECRET.

Department of the Army, Office of the Director of Program Analysis and Evaluation; Chief of Staff, Army; *FY1969-82 Five Year Defense Program, Program 2, General Purpose Forces;* 24 January 1975, SECRET.

U.S. Army, DCS for Research Development, and Acquisition, *Procurement Programs, Summary Item Readiness Studies (Exhibit P-20), FY77/81 Program Objective Memorandum (POM), Annex B;* 9 May 1975, CONFIDENTIAL.

U.S. Army, Office of the Chief of Research, Development, and Acquisition. machine listing of Army aircraft inventory projections by model and supplementary listing of inventory as of 31 March 1975 by model, series

[15] "Study of A Functional Area Summary For Navigation" IDA Report R-204, November 1974, SECRET.

Table 27. Summary of the Gross Annual Average Cost Avoidance Potential for the Systems Considered in this Study

(millions of 1975 dollars)

System	User Equipment (per year)	Reference System (per year)	Additional R&D and Procurement*
Enroute			
LORAN	59.3	10.0	141.2
TACAN	28.6	1.9	120.0
VOR/DME	3.3	2.1†	11.0
DF	11.5	3.1	
OMEGA	0.9	unknown	10.4
Total Enroute	103.6	17.1	282.6
DOPPLERS			
Redundant Dopplers	10.0	–	55.0
Remaining Dopplers	23.5	–	
Total Dopplers	33.5		55.0
Landing Aids			
ILS	12.0	11.3	147.0
PAR	–	14.2	
Total Landing Aids	12.0	25.5	147.0
Radars			
Bomb/Nav Only (APQ-102 & ASB-16)	7.0	–	
Bomb/Nav plus other functions	62.0	–	–
GDB/RBS‡	–	3.3	60.0
Total Radars	69.0	3.3	60.0

*Total planned expenditures for new "AN" systems prior to 1980.

†Includes $600,000 for VORTAC.

‡Ground Directed Bombing/Radar Bomb Scoring Systems.

Equipment Costs. Approximately 300 distance navigation systems have been identified as being currently in use. Cost data of varying quality and completeness have been obtained on about 100 of these systems. The detailed cost data used in this analysis are given in Chapter II. The systems listed in Chapter II comprise over 90 percent of all of the current installations. For those systems for which cost data could not be obtained, a "generalized" system cost was used that is the average of the available data. For LORAN there are two categories of generalized systems that are defined herein as "low cost" and "high cost." Typically the distinction arises in the degree to which the signal acquisition process is automated and the type of user platform. The high cost systems are highly automated and are used on aircraft. Low cost systems require more manual intervention and interpretation and are most often found on ships. Operations and maintenance costs were applied as factors on the corrected acquisition costs. Again historical data were used when available to derive the factors and averages used to fill gaps in the data.

The force structure, navigation suites and cost data were combined in a straightforward way to obtain annual inventory levels, new procurement requirements and annual support. In some instances, user platforms phased out of service generated a surplus of equipment that was usable as spares and as new installations for those platforms which were increasing in number. For any given AN number, this surplus was credited against new requirements. Exchanges between types were not considered, i.e., ARN-52 TACAN was substituted for an AN-84 TACAN.

The final output of the computation is the annual costs of a given system type[16] (i.e., TACAN). The annual costs are in two categories–new installations and operations and maintenance costs. From these outputs, the cumulative cost curves in the preceding sections and the average values of system costs shown in Table 27 were developed. The reference system costs in Table 27 were derived from the inventories shown in Tables 13 and 24 combined with operational test data from the DOT.[17] DOT data were used here under the assumption that for similar systems there would be no appreciable difference between military and civilian system costs.

Included in Table 27 (last column) is a summary of costs associated with the introduction of new conventional equipments. For the most part, these equipments are placements for or alternatives to equipment already available. In most cases, their functions can be satisfied by GPS. The principal questionable cases are the new precision landing aids that have been discussed earlier and the advanced radars for which no cost avoidance potential is credited. The motivation for the development of these new systems in the first place was dissatisfaction either with the operating costs or the performance of both of the systems then available. If the procurement of any of these systems is halted in the anticipation of GPS then an additional period of dissatisfaction on the part of the user will result unless the GPS IOC is roughly the same. For all of the systems, the IOC is no later than 1980 except for MLS whose IOC data has not been set. This indicates that schedules

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[16] Other aggregations are possible in the program as described in Appendix B.

[17] Aviation Cost Allocation Study, Department of Transportation, 1972.

are approximately parallel. Realistic acceleration of the GPS schedule would engender some confidence in the user that his needs will be fulfilled. Conversely, the ever present possibility of slippage in the GPS schedule will result in a hesitancy to halt procurement. Unfortunately, most of the programs are already in the early procurement stages and any delay in the decision to halt reduces the avoidable expenditures. Although no detailed study has been made of the planning of these programs, it is clear that a 2-year delay in the decision would eliminate most of the potential savings.

2. GPS Costs

a. User Systems

The aggregate costs of GPS user equipments shown in Table 28 were developed using the force model in the same way as the conventional equipments. The basic unit cost data, however, are necessarily predictions. The most authoritative cost estimates available for GPS user equipment are those developed by the GPS Joint Program Office at SAMSO. They are, nevertheless, highly speculative since they have no historical basis and they are based on design details and a state of the art that is not well defined. For these reasons, it appeared desirable to use a range of GPS user system costs to estimate the sensitivity of any conclusions to cost uncertainty. Historically, estimates of future costs have been biased on

Table 28. Summary of GPS System Costs To Equip All Military Aircraft and Naval Ships (millions of 1975 dollars)

	12 Satellite System (Cases 1 & 2)	*24 Satellite System (Cases 3 & 4)*	
Space & Control Segments			
RDT&E	260	260	
Initial Costs	270	503	
Annual Costs†	71 - 87	127 - 159	
User Equipment		Case 3	Case 4
Initial Costs*	315 - 630	598 - 1196	666 - 1332
Annual Costs†	18 - 36	40 - 80	44 - 88

*O&M and equipment replacement.

†Initial procurement of installed hardware, spares, and spare parts.

Note: Lower values of the ranges are based on data provided by the JPO. Higher values represent possible increased costs assumed by this study.

the low side. This result is understandable given the optimism of management and the pervasiveness of unforeseeable problems. In view of the complexity of GPS receivers and the nature of the technology, a factor of two range of uncertainty in user costs is not unreasonable. This factor was applied to the JPO unit costs estimates to obtain the higher values shown in Table 28.

The aggregate estimates shown in Table 28 are proportional to the quantities procured (on the order of 23,000) since cost-quantity relationships were not assumed by the JPS. This is consistent with the current procurement practices. Cost reductions might be obtainable by larger quantity, multi-year production contracts, but this procurement method for avionics equipment is rare. Retrofit costs were applied to the basic receiver costs in the computation of Table 28 as a factor on the basic cost. A factor of 1.2 was applied for the Class C sets used in Cases 2 and 3 and a factor of 1.3 for the Class A and B sets used in Cases 3 and 4. These retrofit costs were applied only to the initial installation in existing platforms as *added* costs to GPS. Installation costs for new aircraft are assumed to be the same for conventional and GPS equipment and it thus does not affect the net cost avoidance.

Interface modules which permit the navigation receivers to be connected to other user equipment, such as displays, are not included in the cost analysis. It was not possible to determine the extent that such items have been included in the historical cost of conventional equipment. It is believed to be small and if so the assumption would have no effect on net cost avoidance.

b. Space and Control Segment

The costs of the space and control segments were derived directly from the detailed data supplied by the JPO. These data were aggregated into two categories. The first is "initial investment" and includes all of the costs incurred up to and including the initial complement of satellites. The second is the average annual operating costs required to maintain the space and control segment in its required configuration. These operating costs include satellite launches to replace those reaching the end of their expected life. The advantage of this division is that it avoids the need to deal with detailed time phased cost estimates in the net cost avoidance analysis. The costs of the space and control segment are summarized in this way in Table 28 along with the user equipment costs.

The uncertainty in the costs of the space and control segment were treated in a somewhat different fashion than that of the receivers. There are considerable historical data on the costs to conduct satellite operations. Thus, the strictly operational aspect of launching satellites and subsequent orbital operations and monitoring should be reasonably well determined and the cost known. The uncertainty lies in the satellite lifetime and with the clocks in particular. At this time, no space-qualified atomic clock is available. In addition, the earth-bound technique for achieving continuous availability of precise time (e.g., at the Naval Observatory) is to use a much higher level of redundancy (tens of clocks rather than the two planned for GPS). For these reasons, the 5.5-year satellite lifetime currently assumed may be optimistic. The higher space and control segment costs shown in Table 28 are based on a launch schedule that assumes a 4-year satellite lifetime. The reduction in expected life time may be due to any cause. However, at this time it appears that the clock will be the controlling factor. Excess consumption of consumables and unforeseen component stresses are the other posibilities; however, the design standards appear to be conservative.

3. Net Cost Avoidance

The net cost avoidance as defined in this study is the cost of continuing to use and to support the cost of the conventional systems considered in the four cases less the cost of providing equivalent GPS services. The major cost parameters have been summarized in the preceding section.

At this time there are a number of alternative courses of action for the GPS program. These courses of action interact with the feasibility of removal of conventional equipment and have a marked effect on net cost avoidance. Table 29 summarizes the parameters and levels which are included in the development of net cost avoidance and breakeven period.

Ground forces were handled separately since the various "cases" did not apply to these systems. Currently the ground forces do not use navigation systems of the type considered in this study. Thus, they have no current operating costs which might be avoided. The Army does have one program that will result in substantial future procurement, the PSN-6 Manpack Loran described earlier. PSN-6 is included in the breakeven computation.

Table 28 summarized the cost of the various GPS alternatives. Note that Cases 1 and 2 are identical insofar as GPS costs are concerned. The differences arise from the equipment removed. The space segment for Cases 1 and 2 is a 12-satellite system that is expected to be adequate for 2-D worldwide navigation and a limited 3-D capability over CONUS for test purposes.

Cases 3 and 4 differ only in the respect that in Case 4 some platforms are given Class A GPS sets having a high antijam capability.

The results of the net cost avoidance computations are shown in Table 30. The net differences in initial investment and in annual operating costs are shown separately and the quotient, net initial investment divided by net annual operation costs, yields the time to amortize the initial investment.

To the approximation used in the study, the effect on GPS costs of varying the IOC date of a given GPS alternative is negligible. The effect of IOC date arises only in the ability or desirability of avoiding R&D procurement of new conventional systems. Thus there are in reality only two kinds of IOC dates "early" and "late". Early IOC is defined as early enough to avoid the R&D and procurement and a representative date is 1980, late IOC is defined as too late to avoid procurement of these systems.

All of the variety of GPS "plans" using the "low" GPS cost estimate are self-amortizing; that is, the costs of operating GPS are sufficiently less than that of current systems that the initial investment in GPS will be recouped. However, the amortization

Table 29. Parameters and Levels Used in the Estimation of Net Cost Avoidance

GPS PARAMETERS

1. GPS Cost Range
    - a. Lower: Based on JPO data
    - b. Higher: 2 times receiver costs and reduced satellite lifetime
2. GPS System Type
    - a. High dynamics, high antijam, high accuracy
    - b. High dynamics, high accuracy
    - c. Moderate accuracy
3. Space and Control Segment
    - a. Sufficient satellites for 2-D positioning and navigation
    - b. Full complement of satellites
4. Year of IOC
    - a. Early—New procurements of conventional systems can be avoided.
    - b. Late—New procurements of conventional systems cannot be avoided.

CURRENT SYSTEM PARAMETERS

1. Case 1: Remove enroute systems
2. Case 2: Remove enroute systems and Doppler systems
    - a. Redundant Dopplers
    - b. All Dopplers
3. Case 3: Remove enroute systems, dual self-contained capability, and landing systems
4. Case 4: All of the above plus remove weapon delivery radars
    - a. Radars with only air-to-ground weapon delivery or navigation capability.
    - b. Radars with air-to-ground weapon delivery or navigation and other capabilities.

periods vary considerably and in Case 3 are impractically long. The cost computations have assumed constant 1975 dollars and a discount rate has not been applied. If the latter factor is introduced the slow payoff alternatives become even less attractive from the point of view of being self-amortizing.

The greatest potential payoff is given by Case 2. Breakeven could be achieved in approximately 20 years. An eight year breakeven period could be realized if all Dopplers were removed. Removal of all Dopplers requires further detailed examination to determine the effect, if any, on mission capability.

Implementation of the full 3-D GPS capability (Cases 3 and 4) pays off only if it is possible to remove most of the high cost radar systems. The potential of GPS as a precision

Table 30. *Net Cost Avoidance Summary*
(millions of 1975 dollars)

Cases	Net Initial Investment [GPS minus Base Case]		Net Recurring Procurement + O&M [Base Case minus GPS]	Years to Breakeven	
	New Procurement Included in Base Case	New Procurement Not Included in Base Case		New Procurement Included in Base Case	New Procurement Not Included in Base Case
Case 1 (Remove Enroute Systems)					
Nominal (JPO)	558	844	31.2	18	27
High (IDA)	877	1,160	-2.7	–	–
Case 2 (Case 1 and remove redundant Doppler)					
Nominal (JPO)	506	844	41.2	12	20
High (IDA)	822	1,160	7.3	112	160
Case 2A (Case 1 and remove all Doppler)					
Nominal (JPO)	506	844	64.7	8	13
High (IDA)	822	1,160	30.8	27	38
Case 3 (Case 2 and removing landing aids)					
Nominal (JPO)	827	1,361	0.7	1,200	2,000
High (IDA)	1,470	1,959	-71.0	–	–
Case 3A (Case 2A and remove landing aids)					
Nominal (JPO)	827	1,361	24.1	36	56
High (IDA)	1,470	1,959	-47.6	–	–
Case 4 (Case 3 and limited removal of bomb/nav radars)					
Nominal (JPO)	880	1,429	11.0	80	130
High (IDA)	1,556	2,095	-60.7	–	–
Case 4A (Case 3A and limited removal of bomb/nav radars)					
Nominal (JPO)	880	1,429	34.5	26	41
High (IDA)	1,556	2,095	-37.3	–	–
Case 4B (Case 3 and remove bomb/nav radars)					
Nominal (JPO)	880	1,429	69.3	13	22
High (IDA)	1,556	2,095	94.6	–	–
Case 4C (Case 3A and remove bomb/nav radars)					
Nominal (JPO)	880	1,429	92.8	9	16
High (IDA)	1,556	2,095	17.0	92	156

landing aid is too problematical at this time and the avoidance potential too small to offset alone the higher cost of the additional satellites.

As noted in the discussion of weapon delivery radars, there is considerable uncertainty as to the feasibility of removing all or even most of the weapon delivery radars that are installed in aircraft. This situation results in a cost avoidance potential that is conservatively low, if only the radars which are exclusively for weapon delivery are removed.

The "high cost" GPS assumption rather dramatically highlights Case 2 as the only one that would be self-amortizing in a reasonable period of time and then only if all Dopplers were removed. This observation plus the operational reasonableness of Case 2 indicate that it is the most feasible of the alternatives considered.

Chapter II examines the GPS costs in detail and derives an independent estimate of user systems costs. An analysis is made of the potential costs of such systems if the next generation of technology is employed. These costs, if they are achievable would have a substantial effect on breakeven period. The relative position of the cases on a scale of breakeven period would not be changed, however.

The net cost avoidance shown in the Tables was based on eliminating reference equipment under the ownership and control of the military Services. A similar calculation considering the potential civil use of GPS is not presently possible because of large uncertainties in user system costs. However, such a computation can be expected to show a much more favorable amortization rate than for military use only. However, the more favorable amortization rate would be realized only after the complete phase out of the present civilian systems. Such a phase out could be expected to take 10-20 years if the historical phase out of the low frequency four-course ranges in favor of the VOR is any guide.

Chapter II

COSTS OF GPS AND OTHER NAVIGATION EQUIPMENT

A. INTRODUCTION

1. Objective

This chapter addresses four topics relevant to estimating either GPS system costs or its cost avoidance potential: (1) procurement and O&M costs of conventional navigation equipments that are candidates for replacement by GPS, (2) GPS system procurement and operations costs employed in the cost avoidance estimates of Chapter I, (3) the incremental costs associated with equipping ground combat forces at alternative bases of issue (BOI), and (4) the impact on user equipment costs of the rapidly advancing technology of digital microcircuitry.

2. Uncertainties Associated With Cost Estimates

The approach to estimating costs was dominated by two considerations: (1) the paucity of available data for both GPS and other navigation equipment costs, and (2) the high levels of uncertainty associated with almost all aspects of the GPS program. A parametric approach was adopted with modest objectives for both the level of detail and the confidence that could be placed in the estimates. Emphasis was placed on comparability of estimates rather than accuracy in their absolute levels. Input parameters were limited to those having major cost impacts, with estimates being developed at a gross level. The sensitivity analysis was limited to relative changes in input and output values. All estimates have been generated in terms of current (1975) dollars to facilitate comparisons.

a. Conventional Navigation Equipment

Over 200 models (by AN number) of conventional navigation equipment were identified as candidates for replacement by GPS and, hence, the basis of cost avoidance. Both procurement and O&M costs for any equipment model are highly uncertain. With few exceptions the Services' management and recordkeeping of electronic equipment occurs at the subsystem or black box level, and it is a formidable task to construct AN number costs from their constituent subsystems. In addition, replacement costs are seldom accurately mirrored by historical procurement costs, and maintenance cost data are collected in a consistent format for depot actions. These considerations are reflected in the manner that data on existing navigation systems have been collected and reduced, and limit the confidence that can be placed in the estimates.

b. GPS System

A principal uncertainty in the NAVSTAR program is attainable system performance (i.e., whether the system can provide position information within the accuracies required by the various military missions). Phase I of the development program is keyed to demonstrating this capability and requires a relatively extensive effort to develop and deploy space and control segments that closely resemble the operational configuration. The Joint Program Office (JPO) has organized the program on this basis and allowed the pace of user equipment development to lag behind that of the space segment. As a result, design and unit cost uncertainties for the space segment are small relative to those of user equipment. However, large uncertainty lies in the lifespan of the satellite clock. A period of 5.5 years was assumed by the JPO life cycle cost model (LCCM) for the cesium clock proposed for the operational satellite. The uncertainty surrounding this assumption is significant since such clocks have never been tested in a space environment, and attained lifespan has a major impact on space systems costs.

The LCCM also contains estimates of user equipment costs by mission employment. The technology applicable to this equipment is advancing at a rapid rate with significant cost implications, and the study group was unable to obtain sufficiently detailed design backup to determine the technological basis for the JPO estimates. To gauge the impact of projected technological advances, an independent estimate of user equipment initial costs was prepared based on a recent Magnavox design concept for manpack equipment employing current circuit technology. Differences between the JPO and IDA estimates vary with the scope of initial costs considered and the cost avoidance case.[1] In light of its early stage of development and relative impact on system cost, the unit cost of user equipment must be considered highly uncertain.

c. Use of GPS by Ground Forces

Since ground combat forces possess little in the way of position fixing equipment, they are insignificant in estimating the cost avoidance aspect of GPS. However, use of the system capabilities has been proposed for a number of applications representing increased capabilities to perform current missions as well as new missions. To date, neither the Army nor Marine Corps has formalized requirements into a BOI or procurement program plan, and a wide range of alternatives appears open. This uncertainty could have a large impact on incremental program costs; at the extreme it could range from 10 to 75 percent of the costs of establishing the space segment and outfitting the aircraft and ship fleets. Further, ground force usage introduces stringent design constraints that will impact on costs and availability of all user equipment.

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[1] When only costs of procuring installed hardware are considered, the IDA estimate ranges between 60 percent higher for Case 1 and 15 percent higher for Case 4. When other initial costs are included (especially initial spares and spare parts) the IDA estimate varies between 100 percent and 40 percent higher (Case 1 and Case 4, respectively).

d. Advancing Technology

Performance specifications of manpack equipment—particularly size, weight, and power—can only be satisfied by extensive use of microelectronics. Once adopted for this application, the custom nature and the general advantages of microcircuitry (along with its relatively high nonrecurring cost) imply its use in user equipments for all missions with a maximum of common componentry.

Digital LSI is experiencing a rapid rate of technological advance, resulting in increasing capabilities and decreasing costs. These advances are associated with increasing component densities and digital clock rates. The next major step will raise frequency response rates to a level permitting digital conversion at roughly 200 MHz. The prime impact on GPS user equipment is twofold: (1) a several-times reduction in the number of components per set and (2) a corresponding decrease in cost.

There is little doubt that significant cost benefits would accrue from the advancing technology. However, quantifying the level of benefit has considerable uncertainty. In addition to uncertainties inherent in estimating costs of systems not yet built, the benefits realized will depend on (unknown) quantities to be procured and, heavily, on military standards applied in qualifying the equipment.

Projections of historical trends imply availability of the required technology in 1977 or 1978. However, projections of this sort are subject to error, and a modest deviation could push this date to 1980. Considering the lead times associated with design and normal military qualification procedures of both the chips and user equipments, a 1- or 2-year delay in availability would cast strong doubts on having advanced technology user equipments available for an IOC of 1982.

B. COSTS OF CURRENT NAVIGATION EQUIPMENT

In all, several hundred different models of navigation systems were identified with the navigation equipment suites of the weapons in the proposed force structure. Of these several hundred, more than 200 are associated with aircraft and more than 100 with ships. Within these two broad categories, the systems were grouped into the classes shown in Table 31. The original list was reduced to 88 airborne and 20 shipborne navigation systems. For these 108 selected systems, procurement and maintenance costs were sought; the results are summarized in Tables 32 and 33.

A general ground rule used in selecting the final list of systems was to include those with the largest number of units deployed and to have at least one representative from each class of system. Beyond these general criteria, a system was included if it possessed interesting or unusual characteristics in the regimens of electronic or mission performance or if it was expected to be deployed in large quantities in the future.

1. Sources of Data

In all, nine major sources were used in developing the cost data base used in deriving the unit cost estimates that appear on Tables 32 and 33. These sources are identified in the

Table 31. Classes of Navigation Equipment

Airborne	*Shipborne*
Enroute Radio Reference	Enroute Radio Reference
LORAN	LORAN
TACAN	OMEGA
VOR/DME	Direction Finder
ADF	Satellite
Inertial	Inertial
Doppler	Aircraft Navigation Ref.
Landing Aids/CLS	TACAN
Traffic Control	ACLS
Beacons	
Radar	

list of reference codes that support the two tables. The first three sources reflect data obtained from prior studies; sources four through seven reflect responses by Navy and Air Force offices to requests for cost data for equipment in their custody; the final two sources reflect unit procurement cost data derived by the study team from supply catalog-type records available at military installations.

In addition, IDA/WSEG prepared and sent to Air Force and Navy offices a questionnaire requesting data concerning quantities procured, spares requirements, and retrofit costs, in addition to unit procurement and maintenance costs for each navigation system. Unfortunately only a few responses were received in time to be incorporated into the data base.

2. Derivation of Cost Parameters

From the assembled data, two "generalized average" values for each class of equipment were calculated: (1) a unit procurement cost and (2) a ratio of maintenance to procurement cost. Generally these two values were calculated as a simple average of the values for the systems in each class. In a number of cases, however, the computed average value for a class was adjusted based on other information gathered in the course of the study, or based on a subjective evaluation of the validity of the data used in computing the average (Table 32, footnote □). In the several cases where no maintenance cost data could be found for any of the sets in a class, a generalized average for that class was assigned, based on the averages observed for classes of equipment with related operational and mission characteristics.

The generalized average values shown on Tables 32 and 33 were used to calculate the costs of all sets of equipment in that class not included in the data base.

3. Evaluation of Data Compiled

The Services do not normally maintain cost records aggregated by AN number. Instead, the records are maintained at the black box level. As a result, cost data by AN number generally are available only for systems still in procurement or as the result of special studies. (See source references 1, 2, and 3, identified following Tables 32 and 33.) In cases where a unique federal stock number (FSN) was assigned to the navigation system,

Table 32. Cost Data Base of Airborne Navigation Equipment

Hardware Category/ Designation/Descriptor		Holding Service*	Unit Procurement Cost		Annual Unit Maintenance Cost		Ratio of Maintenance to Procurement
			1975 Dollars (thousands)	Source Reference	1975 Dollars (thousands)	Source Reference	
LORAN		A N F					
AN/APN-9	LORAN A	F	–	–	–	–	–
AN/ARN-157	LORAN C/D	F	$ 30.0	1,8	$ 2.71	1,3	.09
AN/ARN-81	LORAN A/C	N	–	–	–	–	–
AN/ARN-85	LORAN D		130.0	8	–	–	–
AN/ARN-92	LORAN C/D		122.0	3	5 17	3	.04
Generalized Average (LORAN)			75.0†	–	–	–	.1
TACAN‡							
AN/ANS-905	TACAN	N F	–	–	6.25	4	4
AN/ARN-21	TACAN	N F	5.5	1,2,8	2.75	1,4,3	.50
AN/ARN-52	TACAN	A N F	11.0	1,2,8	1.25	1,4,3	.11
AN/ARN-62	TACAN		9.3	1	–	–	–
AN/ARN-65	TACAN	F	10.7	1,8	2.78	4	.26
AN/ARN-72	TACAN	F	8.5	1,8	1.18	1	.14
AN/ARN-84	TACAN	N	15.2	8	–	–	–
AN/ARN-86	TACAN	N	–	–	–	–	–
AN/ARN-96	TACAN	F	–	–	2.28	1,4	–
RT-1045 ARN	TACAN (For F-15)	F	–	–	–	–	–
Generalized Average (TACAN)			10.0	–	–	–	.15
VOR/DME							
AN/ARN-6	Radio Compass	N F	1.2	8	.18	1	.15
AN/ARN-14	VOR	N F	6.0	1.2,8	.30	1,3,4	.05
AN/ARN-30	VOR	A N F	3.0	1,6	.10	1	.03
AN/ARN-87	VOR	F	–	-	–	–	–
AN/AVQ-75	DME	F	3.1	8	–	–	–
AN/NVA-22A	VOR		–	–	–	–	–
VOR-101	VOR	F	8.0	1,2	.50	1,3,4	.06
51R-3	VOR	N F	2.6	1	.39	1	.15
51R-6	VOR	N F	2 8	1	.39	1	.10
806-C	VOR	F	4.0	–	2.03	8	.1 §
Generalized Average (VOR/DME)			4.0§				.1
ADF							
AN/ARA-25	Direction Finder	N F	3.4	1,6,8	.85	1,4	.25
AN/ARA-50	Direction Finder	N F	1.0	1,8	.03	1,4	.02
AN/ARN-59	Direction Finder	A N F	1.5	1,8	.10	1	.07
AN/ARN-83	Direction Finder	A N F	3.0	1,8	.85	1	.22
AN/ARN-89	Direction Finder	A N	2.0	8	-	–	–
Generalized Average (ADF)			2.5				.15
INERTIAL							
AN/ASN-31	In. Nav. Sys.	N	143.0	6	–	–	–
AN/ASN-42	In. Nav. Sys.	N	169.0	6	–	–	–
AN/ASN-48	In. Nav. Sys.	F	70.4	5	–	–	–
AN/ASN-56	In. Nav. Sys.	N F	94 0	5,6	–	–	–
AN/ASN-63	In. Nav. Sys.	F	82.5	5	–	–	–
AN/ASN-86	In. Nav. Sys.	A	–	–	–	–	–
AN/ASN-90	In. Meas. Set	N F	90.0	6	–	–	–
AN/ASN-92	In. Nav. Sys.	N	160.0	6	–	–	–
AN/ASN-109	In. Nav. Set	F	146.9	5	–	–	–
AN/HAN-17	In. Nav. Sys.	F	69.3	5	–	–	–
Comm. LTN-51	In. Nav. Set		114.0	5	–	–	–
Generalized Average (INERTIAL)			80.0 ⊕	–	–	–	.2
DOPPLER		A N F					
AN/APN-82	Doppler Nav.	F	25.0	1,8	–	–	–
AN/APN-89	Doppler Nav.	F	22.7	1,8	3.3	1	.15
AN/APN-108	Doppler Nav.	F	25.0	1,8	9.9	1	.33
AN/APN-131	Doppler Nav.	F	91.0	1,8	17.6	1	.13
AN/APN-147	Doppler Nav.	F	23.0	1,8	4.0	1,3,4	.12
AN/APN-153	Doppler Nav.	N F	35.0	1,8	2 0	1,4	.10
AN/APN-182	Doppler Nav.	N	31.0	6	–	–	–
AN/APN-185	Doppler Nav.	F	32.0	8	2.4	4	.08
AN/APN-190	Doppler Nav.	N F	50.0	8	1.9	4	.05
AN/ASN-64	Doppler Nav.	A	–	–	–	–	–
Generalized Average (Doppler)			37.0	–	–	–	.15

Table 32. *(Continued)*

Hardware Category/ Designation/Descriptor		Holding Service*	Unit Procurement Cost		Annual Unit Maintenance Cost		Ratio of Maintenance to Procurement
			1975 Dollars (thousands)	Source Reference	1975 Dollars (thousands)	Source Reference	
LANDING AIDS/CLS☆							
Glide Slope							
AN/ARA-54	Glide Slope	A F	1.4	1,8	1.18	1	.66
AN/ARN-18	Glide Slope	A N F	1.0	1,8	.15	1,3	.20
AN/ARN-31	Glide Slope & LOC	N F	1.0	1,3,8	07	1,3	.10
ARN/ARN-67	Glide Slope	N F	.9	1,8	.06	1,3	.03
R-844	Glide Slope	A	–	–	–	–	–
51-V-2	Glide Slope	N F	1.1	1	.17	1	.16
Generalized Average (Glide Slope)			1.1				.23
Marker Beacon							
AN/ARN-12	Marker Beacon	F	2.0	1,8	1 11	1,3	.05
AN/ARN-32	Marker Beacon	A N F	1.1	1,8	.10	1,3	.10
R-1041	Marker Beacon	A N F	–	–	–	–	–
51Z-4	Marker Beacon	A N F	.5	1,6	.10	1,3	.22
MN-61B	Marker Beacon	N F	.9	1	.31	1	.34
Generalized Average (Marker Beacon)			1.1				.18
Localizer Average—Estimated			1.0§	–	–	–	.2 §
CLS/ILS Systems							
AN/ARN-58	ILS	N F	2.7	1,8	–	–	–
AN/ARN-61	ILS	F	5.1	1,8	1.9	1	.45
AN/ARN-82	ILS		2.6	1	–	–	–
AN/ARA-63□	CLS	N	4.0	6	–	–	–
Generalized Average (CLS/ILS) Sys.			3.6				.45
Generalized Average (Landing Aids)			3.5	–	–	–	.2
TRAFFIC CONTROL BEACON							
AN/APN-69	Beacon Rendezvous	F	2.7	1,8	1.27	1	–
AN/APN-134	Beacon Rendezvous	F	5.0	1,8	–	–	–
AN/APN-154	Beacon	F	4.3	1,8	–	–	–
Generalized Average (T.C. Beacon)			4.0				.25
RADAR							
AN/APN-59	Search Weather	N F	43.0	1,6,8	8.6	1	.19
AN/APN-158	Search Weather	A F	15.2	1,8	4.2	1	.25
AN/APQ-83	Multi-Purpose	N	–	–	–	–	–
AN/APQ-99	Ground Map & Ter.	F	100 0	1,8	7.5	1	.08
AN/APQ-100	Multi-Purpose	F	115.0○	–	–	–	–
AN/APQ-109	Multi-Purpose	F	109.0○	–	–	–	–
AN/APQ-110	Terrain Following	F	112.0	1,8	1.3	1	.02
AN/APQ-112	Multi-Purpose	N	–	–	–	–	–
AN/APQ-113	Ground Mapping	F	255.0○	1,8	6.3	1	.02
AN/APQ-114	Radar Set	N	200.0	1,8	6 3	1	.02
AN/APQ-116	Terrain Following	N	–	–	–	–	–
AN/APQ-120	Multi-Purpose	F	295 0○	–	–	–	–
AN/APQ-126	Multi-Purpose FLR	F	100.0○	1,8	–	–	–
AN/APQ-146	Terrain Following	F	52.0	8	–	–	–
AN/APQ-148	Multi-Purpose	N	–	–	–	–	–
AN/APS-42	Search	N F	17 0	1,8	2.1	1	.16
AN/APS-80	Radar Set		–	–	–	–	–
AN/APS-115	Search	N	136.0	8	–	–	–
AN/APS-116	Terrain Following	N	200 0	6	–	–	–
AN/ASB-16	Bomb Navigation		–	–	–	–	–
AN/ADP-7	Multi-Purpose	N	–	–	–	–	–
Generalized Average (Radar)			100.0	–	–	–	.1

*A, N, and F Service codes designate Army, Navy, and Air Force, respectively.

†The Generalized Average unit procurement cost of $75K attempts to reflect a judgmentally derived weighted average of two categories of LORAN, i.e., a high-cost LORAN costing about $130K and a low-cost category of LORAN at about $30K each. The high-cost-type LORAN generally is more sophisticated, includes more automatic features, and generates steering data.

‡In addition to TACAN systems shown here, three CNI systems (AN/ASQ-19, ASQ-88, ASQ-57) were also included in the original list of systems requiring costing. Because their TACAN portion of cost could not be isolated, their cost was excluded in calculating the general average for TACAN.

§Amount estimated, based on generalized average.

●The arithmetical average of the inertial systems in this group is $114K, but $80K is used here as the generalized average because it is reported to reflect a more representative estimate of the cost of future inertial systems, based on a conversation with inertial specialists at the Oklahoma City ALC.

☆Landing aid systems generally consist of a Glide Scope, Marker Beacon, and Locator for which seperate subtotals were developed.

□The ARA-63 Carrier Landing System was originally treated as a seperate equipment class but later combined with Land Aids Although cost data received from NAVAIR indicated a unit procurement cost of $4.1K, this was rounded for use here to $4K.

○The USAF Avionics Laboratory supplied (after the cut-off date for this study) unit acquisition cost data for five radars as follows: AN/APQ-100 at $115K, AN/APQ-109 at $109K, AN/APQ-113 at $192K, AN/APQ-120 at $295K, and AN/APQ-126 at $175K.

Table 33. Cost Data Base of Ship Navigation Equipment

Hardware Category/ Designation/Descriptor	Holding Service	Unit Procurement Cost		Annual Unit Maintenance Cost		Ratio of Maintenance Procurement
		1975 Dollars (thousands)	Source Reference	1975 Dollars (thousands)	Source Reference	
LORAN						
AN/WPN-5	N	39.7	7	–	–	.1
AN/WPN-4	N	49.9	7	–	–	–
AN/UPN-12	N	4.2	7	–	–	–
AN/SPN-40	N	3.5	7	–	–	–
AN/SPN-38	N	35.3	7	–	–	–
AN/SPN-32	N	53.8	7	–	–	–
Generalized Average (LORAN)		30.0				.15
OMEGA						
AN/BRN-7	N	55.3	7	6.0	–	.09
AN/SRN-12	N	10.3	7	0.3	–	.03
Generalized Average (OMEGA)		30.0				.15
DIRECTION FINDER						
AN/URD-4	N	33.0	7	0.1	–	–
Generalized Average (DF)		30.0				.01
SATELLITE						
AN/SRN-9	N	76.0	7	–	–	.03
AN/WRN-5*	N	108.0	7	–	–	.48
Generalized Average (Satellite)		100.0				.15
INERTIAL						
AN/WSN-1	N	564.0	7	20.0	6	.04
MK-3 SINS	N	1,410.0	7	100.0	–	.07
MK-2 SINS	N	960.0	7	100.0	–	.10
ESGN	N	500.0	7	25.0	–	.05
Generalized Average (Inertial)		1,000.0				.06
TACAN						
AN/URN-20	N	234.0	7	–	–	–
AN/URN-3	N	100.0	7	–	–	–
AN/SRN-6	N	–	7	–	–	–
Generalized Average (TACAN)		150.0				.15
ACLS						
AN/ARA-63 CLS (Receiver/Decoder)	N	11.0	7	–	–	–
AN/SPN-42 ACLS	N	2,583.0	7	–	–	–
Generalized Average (ACLS)		250.0				.15

*Not on request list; substituted by NAVELEX.

SOURCE REFERENCE CODES USED ON TABLES 32 AND 33

Studies

Source Code 1: *Communications/Navigation/Identification/Cost Development Study,* RAD-043, three volumes, 15 June 1970, RCS:HAF-H-63 (OT). This AFLC-prepared report, reflecting a compendium of forms completed by cognizant USAF AMAs, shows various types of cost data in a standardized format for the several hundred AN designations covered. This report supplied the largest number of entries to the cost data base.

Source Code 2: *Cost Analysis of a Proposed Defense Navigation Satellite System Receiver,* ARINC Research Corporation, ARC 1041-01-1-1259, (sponsor: USAF Space and Missile Systems Organization (SAMSO)). Applicable unit procurement cost data appearing in Table B-1 were incorporated into the cost data base.

Source Code 3: *Cost Study of Selected Communications, Navigation and Identification Equipments* by ARINC Research Corporation, June 1972 (sponsor: HQ ESD, AFSC). Table 32 supplies unit procurement cost data of USAF Navigation Avionics Equipment incorporated into the data base. That table cites the sources for the presented data as being the Consolidated Aerospace Equipment List (CAEL), RAD-043, WRAMA D-041 Factors Printout, and ADS GFAE Impact Listing.

Service Response to Requested Cost Data

Source Code 4: Attachment to Letter of Transmittal dated 12 February 1975 from HQ AFLC (Deputy Director, Integrated Logistics Management; Office of DCS/Acquisition Logistics, to Mr. J. String, IDA). Attachment is letter from AFLC to AFSC (XRP dated 20 January 1975; subject: Global Positioning System Accelerated Operational Capability). Briefly this letter supplies a copy of an analysis AFLC had done earlier showing the annual logistics support cost (no procurement cost data) for the navigation systems/equipments *identified by AFSC* as candidates for replacement by GPS. AFLC extracted its cost data from the Logistics Support Cost Ranking Report (K051PN3L, RCS: LOG-MM) (Q) 7213-(2).

Source Code 5: Oklahoma City ALC (ALC/MMR), replying to a telecon request, supplied the unit procurement cost on nine USAF inertial systems. These unit-procurement costs were built up from unit component costs extracted from *Compendium of Inertial Systems,* published by HQ AFLC/MMA/EA. The supplied cost data were reported to reflect "then-year" dollars and apply to the most recent lot. Though the year of the dollars is not identified by the authors, it is assumed that all the reported costs reflect 1974 dollars.

NAVAIR and NAVELEX Response to Requested Cost Data

Source Code 6: Replying to a telecon request, the Naval Air Systems Command (Office 506-2) supplied unit procurement cost data for 15 navigation systems under Navy cognizance. NAVAIR suggested that the cost data they supplied reflects actual contract data.

Source Code 7: Attachment to letter dated 8 July 1975 from Commander NAVELEX to Director WSEG, Attention Colonel Erickson; Ident. Code: 520C: TT: MM Ser 26-520. Responding to a questionnaire, Navy Electronics Systems Command supplied their estimates of the unit procurement cost and annual operating costs for 15 Navy ship systems. The cost data for the several shipborne inertial platforms were actually supplied by the NAVSEA office.

Supply Catalog-Type Sources

Source Code 8: (USAF) Management List (ML). This item management listing of USAF supply catalog equipment includes unit procurement costs for Federal Stock Number (FSN) equipment items. The Master Equipment Management Index (MEMI) was used to translate AN designations to FSN numbers used in the ML.

Source Code 9: Navy Management Data Listing (NMDL). This catalog-type document, which is comparable to the Air Force ML, supplies unit procurement cost for Navy shipboard equipment. (Records are not maintained at the AN or system level for airborne equipment.) The Marine Base Supply office at Andrews AFB supplied the catalog prices in the NMDL for shipboard equipment.

procurement cost data could be traced to a stock catalog. Cost data obtained from such FSNs, however, are less than ideal in that the user cannot determine certain important information (e.g., the year of the dollars, applicable lot size, and application of price escalation factors). Further, the stock catalog identification supplied for a specific FSN number was often found to be quite vague, employing descriptors such as "subsystem-component-set" or "bench-set." In fact, the FSN being cited may be describing and presenting the cost of a brassboard system bought for maintenance shop use, the cost of which may vary considerably from that for an operational system.

Whatever their sources, costs compiled would be subject to adjustment to reflect current prices. Costs obtained from supply catalogs were adjusted for the year prior to the last recorded transaction date in the catalog record. Costs obtained from special studies were adjusted from the year prior to the publication date of the study, unless supplementary information suggested use of an earlier year. In all cases the index used is an unpublished update of the "Electronics Materials Index" contained in RAND Corporation Report R-568-PR.

C. GPS SYSTEM COSTS

The Joint Program Office *Global Positioning System Life Cycle Cost Model* (YEN-73-289), dated 1 October 1974, contains estimates of costs and other characteristics of the various elements of the control, space, and user equipment segments. With the exceptions noted below, these values were accepted in estimating cost avoidance.

1. Space and Control Segments

Costs of the space and control segments presented below were developed from estimating parameters contained in the JPO life cycle cost model publication. The values contained in the model represent 1974 estimates and have been adjusted to reflect 1975 costs.

The estimates are summarized in Table 34 for both the limited and full operational capability cases. Three categories of costs have been defined. The first represents those required for development and test of the space segment and includes procurement, launch, and operation of the six test satellites. The second category represents all other nonrecurring costs associated with establishing IOC, including a complete constellation of operational satellites. The third describes the costs required to operate and maintain the system for a 1-year period, including average requirements for satellite replacement. These values were derived from the detailed estimates contained in Tables 35, 36, 37, and 38. The JPO publication does not provide definitions of the various line items in these tables, but, with the exception of satellite and launch vehicle hardware, all costs can be attributed to requirements for ground support of the satellite system.

Note that a calculation of life cycle costs (initial and annual for a given number of years) would not necessarily be equal ~~to~~ a calculation of expenditures required over the

Table 34. Summary of Estimated Space and Control Segment Costs (Millions of 1975 Dollars)

Costs	*Limited Operational Capability (12 Satellites)*	*Full Operational Capability (24 Satellites)*
Development and Nonrecurring Costs		
Developmental Satellites	108.7	108.7
Orbital Operations	.2	.2
Space Segment Initial Costs	34.7	34.7
Space Segment Operations	8.7	8.7
Control Segment Initial Costs	61.3	61.3
Control Segment Operations	46.1	46.1
Total	259.7	259.7
Initial Operational Capability Cost		
Initial Satellites	233.5	467.0
Space Segment Initial Costs	35.9	35.9
Total	269.4	502.9
Annual Costs		
Satellite Replacement	42.5	84.9
Orbital Operations	13.6	27.1
Space Segment Operations	6.1	6.1
Control Segment Operations	9.2	9.2
Total	71.4	127.3

Source: Tables 35, 36, 37, and 38.

same number of years. Determination of expenditure requirements involves assumptions of an IOC date and definitive launch schedule. At the end of the assumed periods of operation, satellites would be in orbit with remaining useful lifetimes less than the full period assumed (5.5 years). The costs shown in Table 34, on the other hand, carry the implicit assumption that all satellites in orbit at any point in time have remaining lifetimes of the full 5.5 years.

The most striking cost uncertainty in the space segment is that of the satellite clock and its impact on annual operating costs. Figure 12 shows the magnitude of cost sensitivity to this assumption for the operational satellites. Since clocks of this type have yet to be employed in a space environment, the 5.5 years assumed by the JPO is highly uncertain. Should actual lifetimes prove significantly less, the effect on system cost will be dramatic, while small deviations or increases significantly greater than 5 years will have a relatively small effect.

Table 35. Estimated Control Segment Costs
(Millions of 1975 Dollars)

Costs	Control Stations	Monitor Stations	Upload Stations	Total
Nonrecurring Costs				
Costs per Station				
Acquisition	22.47	.43	6.31	–
Installation	.11	.05	.32	–
Total per Station	22.58	.48	6.63	–
Number of Stations	2	6	2	
Total Initial Nonrecurring Costs	45.16	2.88	13.26	61.30
Annual Costs				
Logistics Support Cost per Station	3.21	.11	1.07	–
Number of Stations	2	6	2	–
Annual Logistics Support Cost	6.42	.66	2.14	9.22

Source: *Global Positioning System Life Cycle Cost Model,* (YEN-73-289), Joint Program Office, 1 October 1974.

Table 36. Estimated Space Segment
Nonrecurring Costs
(Millions of 1975 Dollars)

Costs	RDT&E Program	Operational Program
DT&E	1.13	–
Peculiar Support Equipment	2.71	2.26
Data	.53	.68
Satellite Nonrecurring	27.46	26.74
Launch Vehicle Nonrecurring	2.88	6.22
Total	34.71	35.90

Source: *Global Positioning System Life Cycle Cost Model,* (YEN-73-289), Joint Program Office, 1 October 1974.

Table 37. Estimated Space Segment Annual Ground Installations Operating Costs (Millions of 1975 Dollars)

Costs	RDT&E Program	Operational Program
Logistics Support, Spares, Storage	.03	5.65
Ground Communications and Control	.15	.11
Training	.11	.23
Program Management	1.45	.14
Total	1.74	6.13

Source: *Global Positioning System Life Cycle Cost Model,* (YEN-73-289), Joint Program Office, 1 October 1974.

Table 38. Space Segment· Estimated Cost per Satellite in Orbit (Millions of 1975 Dollars)

Costs	RDT&E Vehicles	Operational Vehicles
Initial Cost		
Satellite Unit Cost	7.35	6.22
Launch Vehicle Unit Cost	4.29	4.29
Satellite Launch Operations	0.19	1.41
Launch Vehicle Operations	1.86	1.41
Other Launch Operations	0.28	1.41
Satellite Checkout	1.20	1.36
Launch Vehicle Checkout	0.23	1.41
Cost per Launch	15.40	17.51
Successful Launch Probability (÷)	0.85	0.90
Cost per Successful Launch	18.12	19.46
Mean Mission Duration, years (÷)	4.0	5.5
Annual Cost per Satellite in Orbit	4.53	3.54
Orbital Operations per Satellite	0.01	1.13

Source: *Global Positioning System Life Cycle Cost Model,* (YEN-73-289), Joint Program Office, 1 October 1974.

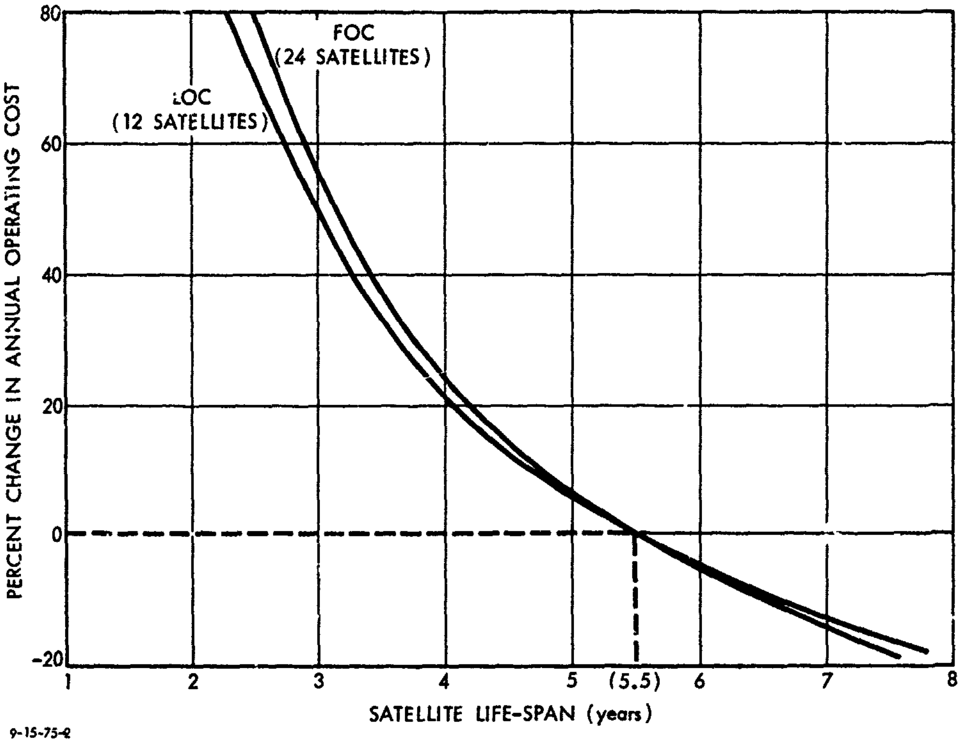

Figure 12. Sensitivity of Estimated Annual Operating Costs to Satellite Life-Span

A second area where costs are particularly sensitive is the procurement of satellites and launch vehicles as well as the costs of the launches. A high degree of uncertainty cannot be assigned to these elements since there is considerable history in building and launching satellites and this history may explain the current satellite contractor's willingness to operate on a fixed price contract. However, should these estimates prove low (along with that of the probability of successful launch), the impact on program costs is close to proportional, as shown in Figure 13.

2. User Equipment Segment

The JPO life cycle cost model publication does not contain descriptive material to supplement the estimates of user equipment costs, and the study group was unable to obtain these backup data from other sources. The JPO has recently revised the estimating parameters; the current values are shown in Table 39. As with the earlier estimates, the study group was unable to discover backup materials.

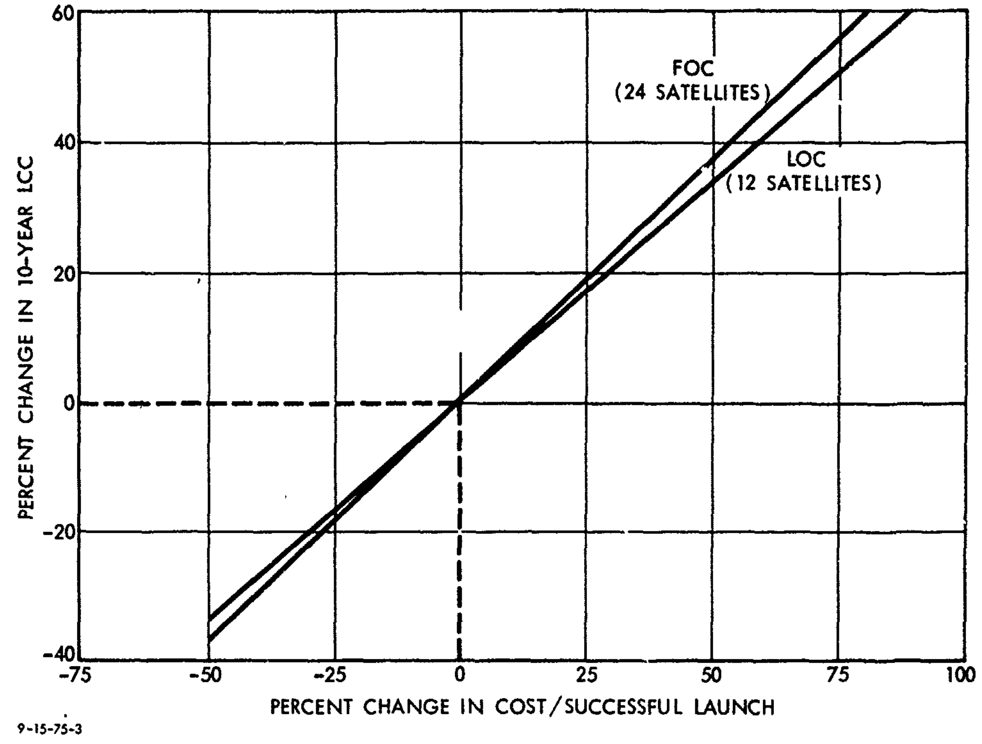

Figure 13. Sensitivity of Estimated Post-DSARC II 10-Year Costs to Cost of Successful Satellite Launch

Table 40 presents initial and annual cost estimates of user equipment for the four cost avoidance cases described in Chapter I. These estimates are based on the parameters shown in Table 39, with the modifications described below (where necessary, data were modified to be consistent with the time-phased force model employed to estimate cost avoidance):

(1) Costs of procurement and O&M of integration modules were not included. Integration equipment would, in fact, vary by platform type as a partial function of other installed equipments and the extent of mutual sensor aiding desired. This is an open question currently under study and beyond the scope of this study.

(2) Initial support and O&M requirements were converted to the percentage rates shown in Table 39.

(3) Costs of retrofit were charged only for those aircraft and ships contained in the fleets at the time of IOC. Retrofit costs were charged at rates of 30 percent of procurement cost for A, B, and F mission equipments and 20 percent for C mission equipment.

(4) Use of a time-phased model permitted consideration of the cost impact of user equipment losses and resulting replacement requirements. An annual factor of 5 percent of the value of installed equipment was applied to all mission groups.

With the limited specifications of user equipment given, little can be done in the way of identifying factors that have a significant impact on system costs. One area that can be examined is the cost of system support (spares and spare parts and annual O&M). An allowance of roughly 15 percent has been allowed for spares. By historical standards this is little more than sufficient for the initial pipeline. Thus, all annual costs (both materials and labor) must be covered by the annual O&M estimate, and the 4 percent and 6 percent allowed appear overly optimistic. The impact on life cycle costs of higher support rates is not insignificant. Over a 10-year period, a total support rate of 50 to 100 percent higher appears more reasonable; its impact is shown in Figure 14.

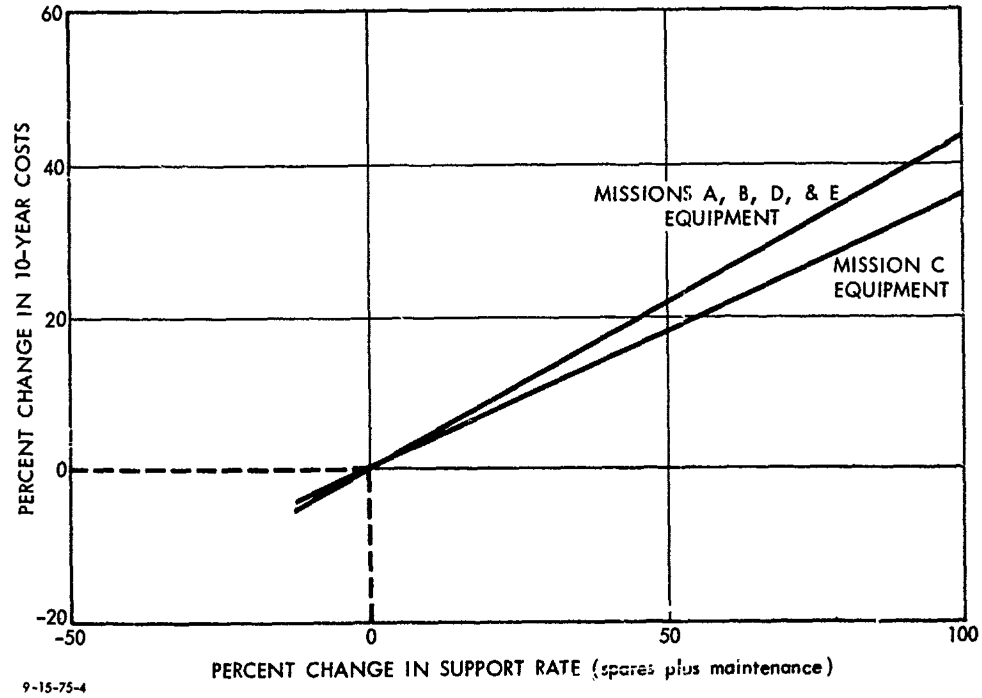

Figure 14. Sensitivity of Estimated 10-Year Costs to Support Rates

Table 39. Cost Parameters for User Equipment, by Mission
(1975 Dollars)

	*Equipment Class**				
	A	*B*	*C*	*D/E*	*F*
Unit Cost†	25,000	18,000	10,000	15,000	25,000
Retrofit (A kits plus labor)	9,000	5,000	2,000	–	9,000
Integration Module	10,000	5,000	3,000	–	–
Initial Support (spares, data, TE, facilities, management)	3,300	3,000	1,600	2,500	3,300
Spares Rate (percent)	13	17	16	17	13
O&M–GPS (annual spares, on and off maintenance, labor, training, supply operations, data, etc.)	1,520	1,000	420	910	1,520
O&M Rate (percent)	6	6	4	6	6
O&M–Integration Module	690	300	130	–	–

*See Appendix A, Table A-1, for a description of the equipment class.

†Cumulative average cost in lots of 3,000 or more.

Note: Spares and O&M rates are derived values based on the ratio of spares and O&M to unit cost.

Source: *Global Positioning System Life Cycle Cost Model* (YEN-73-289), unpublished update to Joint Program Office, 1 October 1974.

Table 40. Summary of Estimated User Equipment Costs To Equip Military Aircraft Fleets and Naval Ships
(Millions of 1975 Dollars)

Costs	*Case 1: Enroute*	*Case 2: Dopplers*	*Case 3: Landing Aids*	*Case 4: Radars*
Initial Costs				
Procurement of Hardware	229.7		407.0	452.9
Installation	45.9		122.1	135.9
Spares and Spare Parts	39.0		69.2	77.0
Total	314.6		598.3	665.8
Annual Costs				
O&M	9.4		24.0	27.0
Replacement of Equipment	8.9		15.5	16.9
Total	18.3		39.5	43.9

D. ESTIMATED COSTS OF GPS ISSUES TO GROUND COMBAT FORCES

Issues of GPS user equipment to ground combat forces (Army and Marine Corps) were not addressed in Chapter I. They have little in the way of navigation/position fixing capability for which GPS could be substituted; therefore, the potential for cost avoidance is insignificant. However, GPS can provide better ways of performing some current missions as well as offer a potential for new mission functions.

While there is no direct effect on cost avoidance resulting from the use of GPS by the ground forces, there may be an indirect effect arising from the constraints of size, weight, and power that define the manpack GPS. These constraints are most readily satisfied by the advanced microcircuit technology. Thus, the exploitation of the advanced technology to meet the manpack requirements should result in the availability of lower cost (common) components for airborne and shipborne user systems. Additional cost reductions may also result from the additional quantities of common components procured for the ground user.

The issues of user equipment to aircraft and ships described in Chapter I represent roughly the maximum quantities that can be anticipated for these types of weapons. Any significant increase in procurement levels would have to come from ground force users. To date, neither the Army nor the Marine Corps has developed a BOI, nor have they formalized requirements into a procurement program plan. The range of possible procurement quantities is wide. A number of BOI alternatives have been investigated with the intent of providing a range sufficiently wide to bracket any procurement option that might be adopted. Total procurement quantities, by mission application and cost avoidance case, for each of the ground forces alternatives are shown in Table 41.

1. Full Operational Capability

Four alternative levels of issue for ground forces were assumed for the 24-satellite cases. Only Alternative 1 has a basis in past Army studies. It is several years old and assumes equipping only active Army forces. The three other alternatives are based on equipping both the active and reserve forces at successively higher levels.

Quantities for Alternative 1 result from applying the BOI described in the Army Pos/Nav Study[2] to the projected FY 1982 active Army organizational structure contained in the Department of Army FYDP (dated 24 January 1975). The total issue of approximately 8,600 is some 1,400 higher than that developed in the Pos/Nav Study and reflects the inclusion of nondivisional elements in the force structure and the addition of three divisions to the number of Active Army divisions. Alternative 2 (18,300 user sets) accounts for equipping National Guard and Army Reserve units at the same BOI.

Alternatives 3 and 4 result from a BOI based on both organizational structure and inventories[3] of wheeled and tracked vehicles. Alternative 3 is based on a BOI to active and

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[2] *Positioning and Navigation System Cost Effectiveness Study,* Part IV, Appendix B, "Requirements and Force Structure," August 1973.

[3] Army FY 77/81 POM, 9 May 1975.

Table 41. GPS User Equipment Alternative Total Force Quantities and Composition-Installed Inventory Year After IOC

Capability	*Requirements for Aircraft and Ships*	*Total Requirements, Including Ground Forces, at Alternative Levels*			
		1	*2*	*3*	*4*
Full Operational Capability – Case 4					
Total	22,573	31,173	40,873	57,373	93,373
A Configuration	7,451	7,451	7,451	7,451	7,451
B Configuration	14,986	14,986	14,986	14,986	14,986
C Configuration	–	–	–	–	–
D/E Configuration	–	8,600	18,300	34,800	70,800
F Configuration	136	136	136	136	136
Full Operational Capability – Case 3					
Total	22,573	31,173	40,873	57,373	93,373
A Configuration	–	–	–	–	–
B Configuration	22,437	22,437	22,437	22,437	22,437
C Configuration	–	–	–	–	–
D/E Configuration	–	8,600	18,300	34,800	70[illegible]0
F Configuration	136	136	136	136	136
Limited Operational Capability – Case 1/2					
Total	22,773	27,073	31,873	–	–
A Configuration	200	200	200	–	–
B Configuration	494	494	494	–	–
C Configuration	21,943	21,943	21,943	–	–
D/E Configuration	–	4,300	9,100	–	–
F Configuration	136	136	136	–	–

reserve organizations at roughly the same level as Alternatives 1 and 2, with the following exceptions:

(1) Artillery and tank battalions receive no issue.
(2) Mechanized battalions receive a 60 percent issue.
(3) Infantry battalions receive a 150 percent issue.

Additional GPS user sets are then issued to approximately 50 percent of all full-tracked, gun-mounting vehicles; 25 percent of all other full-tracked vehicles; 15 percent of towed artillery pieces; and 1 percent of wheeled vehicles. In the case of Alternative 4, the BOIs of organizational units were increased by approximately 50 percent over Alternative 3, and those of vehicles were doubled (except for wheeled vehicles, where the level of issue went to 5 percent). Estimated incremental program costs associated with each alternative are shown in Table 42.

Table 42. Estimated Incremental Costs To Equip Ground Combat Forces With GPS User Sets at Four Levels: Cases 3 and 4 (Millions of 1975 Dollars)

Costs	Number of User Sets Alternative 1 (8,600 Units)	Alternative 2 (18,300 Units)	Alternative 3 (34,800 Units)	Alternative 4 (70,800 Units)
Initial Costs				
Procurement of Hardware	129.0	245.5	522.0	1,062.0
Spares and Spare Parts	21.9	46.7	88.7	180.5
Total	150.9	321.2	610.7	1,242.5
Annual Costs				
O&M	7.7	16.5	31.3	63.7
Replacement of Equipment	6.5	13.7	26.1	53.1
Total	14.2	30.2	57.4	116.8

2. Limited Operational Capability

For the limited operational capability (12 satellites), only two levels of issue have been assumed. One can infer a requirement from the Army consideration of developing a backpack LORAN system providing position fixing capabilities no better than those attainable for the limited GPS system. However, the Army has not addressed itself to using the GPS LOC system, nor has it formulated a BOI for the LORAN backpack. As a result, there is no reference on which to base a GPS issue, and the study has arbitrarily assumed it equal to one-half that described in the Pos/Nav Study. For the equipping of active forces only, a level of 4,300 has been assumed; for equipping both active and reserve forces, a level of 9,100 has been assumed. Estimated incremental program costs associated with each alternative are shown in Table 43.

E. COST IMPACT OF ADVANCES IN DIGITAL LSI TECHNOLOGY

Mission performance requirements are shown in Appendix A. The stringent size, weight, and power requirements of the manpack system leads to a definitive conclusion that the specifications can only be met by extensive use of microelectronics. The relatively high nonrecurring costs associated with its use leads to a further conclusion that modularity and commonality should be a major design goal. A corollary is that without a requirement for manpack equipment the use of microcircuitry would not be necessary, but, even in the absence of such a requirement, the apparent cost advantages for large quantity buys is sufficient reason for its use.

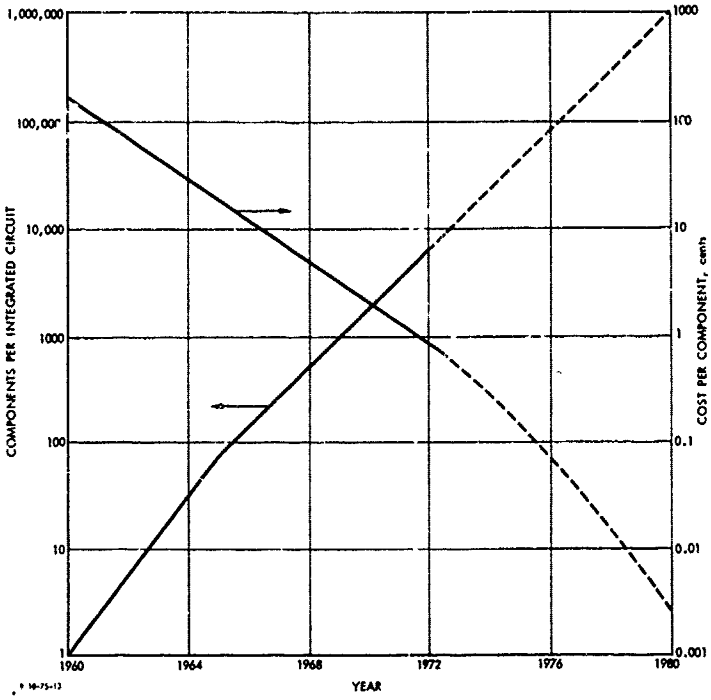
Table 43. Estimated Incremental Costs To Equip Ground Combat Forces at Two Levels: Cases 1 and 2 (Millions of 1975 Dollars)

Costs	Number of User Sets	
	Alternative 1 (4,300 Units)	Alternative 2 (9,100 Units)
Initial Costs		
Procurement of Hardware	64.5	136.5
Spares and Spare Parts	11.0	23.2
Total	75.5	159.7
Annual Costs		
O&M	3.9	8.2
Replacement of Equipment	3.2	6.8
Total	7.1	15.0

Microelectronics is currently experiencing a rapid rate of technological advance centering on increasing densities attainable in bipolar LSI chips. Devices such as integrated injection logic (I^2L) may become available in production quantities in time to be incorporated into the design of GPS user equipment. Realization of this possibility would have a substantial impact on systems costs. Figure 15 displays the historical trend (solid line) of densities and costs of digital devices–primarily the metal oxide semiconductor (MOS) type. The average increases in densities have been an order of magnitude each 3 to 4 years. This has combined with increasing yield rates (the ratio of "good" obtained to the total number produced) to reduce per-element costs an average of an order of magnitude each 5 years.

The data in Figure 15 has been extrapolated (dotted lines) on the basis of continued similar increases in density with an accelerating rate of cost decrease. The density projection indicates a level of 200,000 near mid-1977. This should be sufficient for digital clock rates that allow digitalization of the GPS signal regarded close to the receiver front end and result in user equipment requiring only one IF stage of linear signal processing. The impact is dramatic on the size, weight, complexity, and cost of user equipment designed for an IOC of 1982.

Discussions with industry and laboratory personnel indicate that technology is advancing at roughly the rate projected in Figure 15. Considering the conservatism of the Services in adapting to new technologies in this area and the period required between design acceptance and fielding of equipment, a lag of 2 to 4 years between completion of the development of LSI chips and the start of full-scale production is indicated. This would result in an IOC date of 1979 to 1981. Prediction of the time of availability of new



SOURCE: Hittinger, William C., "Metal-Oxide-Semiconductor Technology," *Scientific American*, August 1973, Vol. 229, No. 2, p. 28.

Figure 15. Estimated Density and Cost per Component as a Function of Time for LSI Devices

technology in the form of usable hardware is always risky and unusually optimistic. Thus, consideration of the new LSI technology for a 1982 IOC of GPS must be as a high-risk option. Clearly the risk is reduced if more time is allowed for the development of the advanced technology. However, if the development period is extended more than 1 or 2 years, the IOC must be delayed correspondingly.

This is a large element of uncertainty, and the cost of over-optimism could be great in terms of both program expenditures and system availability.

Ultimately realizing the cost and other advantages of high density LSI in the GPS program depends on military acceptance of these devices and the changes in procurement and qualification procedures that they imply. The relative level of nonrecurring costs that they entail is higher than any other type of available circuitry, and once designed and tooled they are practically impossible to modify. As a result, the cost benefit can only be realized by accepting the design adopted and procuring it in large (and guaranteed) quantities. The low recurring costs imply changes in screening and maintenance concepts.

The application of traditional military standards and repair of failures may not be nearly as appropriate as concurrent procurement of lifetime spares and throw-away of failing modules. Early tradeoff studies can establish ranges of module costs and associated optimal procurement/maintenance policies, but the military must be able to modify procurement practices accordingly.[4]

1. User Equipment Design Adopted

Investigation of impact of advanced high density LSI required a comparison with user equipment designed around current technology components and, preferably, one employing extensive microelectronics. With no backup materials available, the configurations described in the JPO life cycle cost model could not serve the function of a benchmark for comparison, and the demonstration hardware currently under contract to Magnavox will be too far from an operational configuration. However, Magnavox has published a design study for the manpack system that recognizes the requirement for extensive microcomponents[5] It contains a sufficiently detailed block diagram of a receiver and was adopted as the benchmark for comparison.

The Magnavox concept provides little in the way of digital processing. The L-band amplifiers and significant portions of the synthesizer and calibration circuitry are composed of discrete circuitry. The majority of microcircuit elements are hybrid or thin-film "cans," and digitalization does not occur until signal frequencies have been stepped down to below 1 MHz through a number of IF stages.

The advanced technology system assumed that digitalization could occur at a frequency near 200 MHz, thus requiring linear processing only for the L-band and first IF stages, and prior to signal correlation. Feasibility of this early conversion with advanced LSI chips was confirmed by conversations with laboratory personnel and manufacturers' representatives. The concept is also contained in an earlier Magnavox study.[6]

The manpack specification for time-to-first-fix led Magnavox to propose a two-channel receiver. Four channels is the maximum that has been considered by the JPO for high dynamic and high antijam applications. Since commonality of modules and minimization of the number of configurations appear desirable, these two configurations were assumed to satisfy all mission applications. The impact of early digitalization can be seen in the count of microcircuit components required for current and advanced technology (Table 44). The relation between receiver costs is roughly in proportion to the count of elements. Further specifications of the current and advanced technology designs, including gross block diagrams, are contained in Appendix C.

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[4] The user equipment development contracts recently awarded to Texas Instruments, as well as work proposed and under way by the Air Force Avionics Laboratory, should provide valuable insights into these questions. Hopefully, substantive results will emerge sufficiently early to have maximum impacts on equipment design and procurement procedures.

[5] *Design Development Study for Phase I NAVSTAR Global Positioning System Manpack/Vehicular Set–Set Description, Performance and Trade-Off Analysis,* Magnavox Company, Advanced Products Division, 23 May 1975.

[6] *NAVSTAR Global Positioning System Manpack Study Program, Receiver Micro-Circuit Analysis Design Review Bulletin C-1063B-5,* Magnavox Company, Advanced Products Division, 1 April 1975.

Table 44. Quantities of Microcircuit Elements per Receiver

Type of Microcircuit Element	Number of Unique Mircocircuit Elements	Total Quantity of Microcircuit Elements per Receiver	
		2 Channel	4 Channel
Current Technology			
Strip-Line Boxes	5	9	15
Thin Film/Hybrid Boxes	13	37	59
LSI Chips – Receiver	12	45	75
LSI Chips – Computer	3	6	6
Total	33	97	155
Advanced Technology			
Strip-Line Boxes	12	15	24
Thin Film/Hybrid Boxes	2	5	5
LSI – Receiver	9	19	27
LSI – Computer	3	6	6
Total	26	45	62

2. Costs of Microcircuit Components

Data sources proved to be very limited and frequently conflicting. Microcircuitry is sufficiently new, and the number of manufacturers so limited, that no general body of historical data has been compiled. Current supply prices to buyers fail to provide a reliable guide to production cost since they are based on diverse considerations, such as producers' price policies regarding amortization of nonrecurring costs, anticipation of market size and design obsolescence, and anticipated general market conditions and competitors' behavior.

In addition, there are several types of circuitry for both linear and digital processing,[7] and differences in the inherent complexity of the manufacturing process of the several types may or may not be the dominant factor in observed price differences. A number of these circuit types have only been produced under laboratory conditions or in small quantities. In all, experience is too scanty to permit isolation of the impact of complexity from other factors or the formulation of generalized costs for each type.

A further complication is the rate of change in cost shown in Figure 15. If a comprehensive study of component costs were undertaken, the chances are good that it would be out of date before publication. For example, LSI chip manufacturers frequently fall behind in providing customers with current price lists, forcing buyers to manually update their suppliers' catalogs.

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[7] There are two basic groups of LSI devices—bipolar and MOS Within each group are several particular types of devices. In linear microcircuits, the situation is similar.

The approach adopted for this study was to contact microcircuit industry (both producing and buying companies) and laboratory personnel to solicit opinion on recurring and nonrecurring costs of current and future componentry for those types of microcircuits that are candidates for use in GPS user equipment. These opinions were supplemented by a limited number of printed articles containing microcircuit cost and cost trend information and manufacturers' brochures. This information was then melded to formulate a consensus opinion of component costs.

Table 45 summarizes the estimating parameters for all components of both the current and advanced technology system. The derivation of individual values in the table is given in Appendix B. All parameters are based on the assumption of large-volume, large-lot production. Efficient production methods vary with lot sizes and ultimate planned volume. For large-scale production, one would expect manufacturers to incur large nonrecurring costs (capital expenditures) for smaller recurring production costs in such a way as to minimize total program cost. As a result, the estimates shown in Table 45 are close to the high end of information obtained on nonrecurring costs and close to the low end for recurring costs. The values shown were used directly in the equipment cost estimates.

3. Equipment and Program Cost Estimates[8]

a. Estimated Costs

Chapter I identified approximately 22,000 potential installations of user equipment to outfit aircraft and ships. Alternative issues to ground forces, described in Section D, may account for an additional 10,000 to 70,000 users. The mixes of equipment according to ground force use are shown in Table 46. Figure 16 shows estimated cumulative average hardware costs, as a function of quantity.[9] Issues to ground forces were assumed to occur only after the 22,000 aircraft and ship users were outfitted. At this quantity, the curves show inflation points reflecting the mix of equipment changing in favor of the lower cost two-channel equipment.

Figure 17 shows estimated 10-year LCC for these system concepts. The LCC estimates are based on assumptions of concurrent procurement of lifetime spares (taken at 50 percent of hardware cost) and an annual maintenance rate of 5 percent. Over the 10-year period, this averages to 10 percent per year—close to that experienced in current equipments. Failure rates of microcircuitry are purported to be significantly lower than those of discrete circuits, and the 10 percent level seems conservative. Since the relative use of microcircuits is higher in the advanced technology system, the difference in lifetime costs between the two would be understated to some extent.

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[8] The equipment design concept adopted envisions deployment of the 24-satellite constellation. As a result, the quantities and mixes of equipment used in this analysis are based on cost avoidance Cases 3 and 4

[9] These estimates do not include allowances for installation of the equipment in aircraft and ships. If the installation cost factors employed in Chapter I were adopted, the impact would be to increase the costs of the first 22,000 user sets by 30 percent

Table 45. Cost Estimating Parameter Values (Costs in Thousands of 1975 Dollars)

Type of Circuit (or Receiver Subsystem)	*Nonrecurring Cost*	*Recurring Cost (Cumulative Average at Quantity 1,000)*	*Cost Quantity Slope (percent)*	*Remarks*
LSI				MOS chips with densities up to 20,000 elements.
Current Technology	150	60	0	Includes linear monolithic as well as digital.
Advanced Technology	1,500	100	0	High-density devices up to 200,000 elements (such as I^2L).
Linear Microcircuits	10	200	90	Single substrate in hermetic "brass cans." Includes strip-line, thin film, hybrid (except monolithic portions) etc.
"MIC" Boxed Linear Microcircuits	40	700	90	Multiple substrates in hermetic cast boxes. Typically perform three times the functions of single-substrate cans.
Data Processor (LSI)				Microcomputer.
Current Technology	600	2,000	0	
Advanced Technology	4,500	625	0	
Quartz Crystal	50	2,000	90	Complete assembly including heater, assumed to be "off-the-shelf" with minor nonrecurring modification and integration cost.
Discrete Components				Purchased parts cost only at $20 per microcircuit element.
Current Technology System				
Two Channel	0	2,100	0	
Four Channel	0	3,500	0	
Advanced Technology System				
Two Channel	0	1,100	0	
Four Channel	0	800	0	
Assembly, Test, Rework (as a percent of manufacturing cost)	10,000			Includes nonrecurring manufacturing cost for the integrated system and those costs that cannot be associated with specific elements of the system.
Discrete Circuitry		65%	80	
Linear Microcircuitry		20%	80	
Digital and Linear LSI		6.5%	80	
Other and Packaging				Does not include installation labor or materials.
Two Channel	100			
Antenna		100	90	
Case		100	90	
Display/Keyboard		50	90	
Four Channel	500			
Antenna		500	90	
Case		250	90	
Display/Keyboard		250	90	

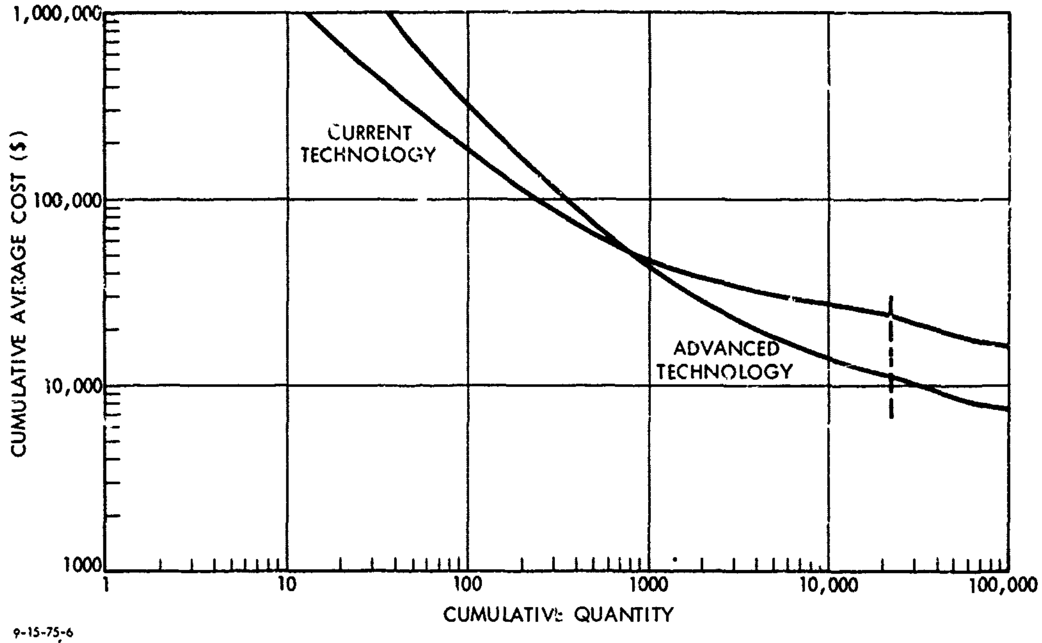

Figure 16. Estimated Average Total Hardware Costs

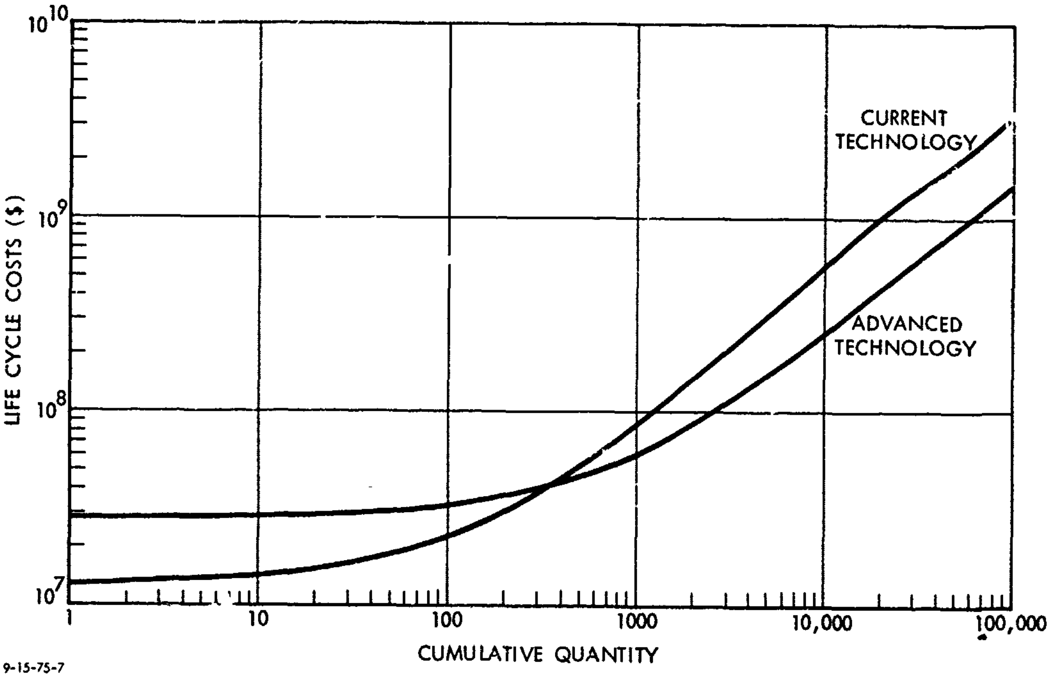

Figure 17. Estimated 10-Year Life Cycle Costs

Table 46. GPS User Equipment–Alternative Quantities and Composition of Installed Inventory, Year After IOC

Current and Advanced Technology Systems: Full Operational Capability (Case 3/4)	*Requirements for Aircraft and Ships*	*Total Requirements, Including Ground Forces, at Alternative Levels*			
		1	*2*	*3*	*4*
Two-Channel Configuration	–	8,600	18,300	34,800	70,800
Four-Channel Configuration	22,573	22,573	22,573	22,573	22,573
Total	22,573	31,173	40,873	57,373	93,373

b. Analysis

In the range of interesting quantities (30,000 to 60,000), the average cost of the advanced technology system is roughly one-half that of the current system. Recognizing that definitive designs do not exist, this difference still appears to be significant. The only real difference between the two is the assumed difference in capabilities of current and future digital LSI elements, and its main impact is to reduce the component count of the system. Considering the rate of advance recently experienced in the field, it appears highly unlikely that technological development will stop short of the requirements of the GPS system. This leaves cost of the high-density devices as the principal uncertainty in the difference in system costs.

A rough measure of the cost sensitivity of any type of circuit element is the percent of total cost embodied in that element. As shown in Table 47, no one type of element, including LSI, dominates equipment cost for either system within any relevant range of quantities. With a procurement of 50,000 sets, the recurring production cost of high-density chips would have to increase three and one-half times before the cost advantage of the advanced system disappeared (see Figure 18).

At this level of cost, the high-density devices would not be competitive with MOS technology, and the whole question of their development would be in doubt. Manufacturers, however, are continuing to push their development with company funds, and the probability of their costs being significantly higher than current devices must be judged as slight.

These program cost estimates, including the slopes of the cost/quantity curves, are based on an implicit assumption of large contract or lot procurements. Multiple source, or small contract procurements, can be expected to result in replication of nonrecurring costs, less than optimum scales of production, and higher levels of cost. Estimates of their impact are beyond the scope of this paper, but they can be neither neglected nor minimized. This is particularly relevant for the advanced technology system. The best estimate of

Table 47. Percentage Distribution of Estimated Recurring Costs by Type of Receiver Element

Type of Receiver Element	*Installed Quantity* 1	10	100	1,000	10,000	100,000
Current Technology						
LSI Elements	5.3	8.6	13.1	18.5	24.3	30.6
Discrete Elements	4.8	7.8	11.9	16.9	22.1	25.5
Micro-Linear Elements	28.6	32.9	35.4	35.2	32.5	27.4
Other	7.1	8.2	8.8	8.7	8.1	7.5
Assembly	54.3	42.5	30.8	20.8	13.0	9.0
Advanced Technology						
LSI Elements	6.9	10.8	15.9	22.2	29.3	36.7
Discrete Elements	1.7	2.6	3.8	5.4	7.1	8.6
Micro-Linear Elements	34.7	38.1	39.6	38.9	36.3	31.6
Other	18.0	19.7	20.5	20.1	18.8	17.1
Assembly	38.7	28.8	20.2	13.4	8.5	6.1

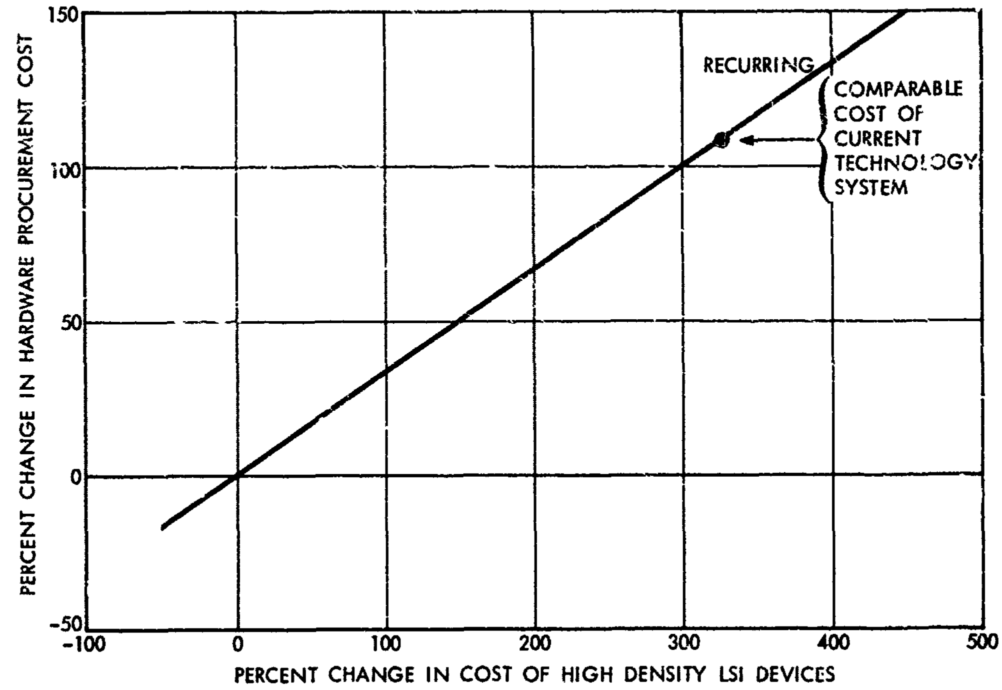

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Figure 18. Sensitivity of Estimated Hardware Procurement Costs to Recurring Cost of High-Density LSI Devices (Quantity = 50,000)

nonrecurring costs of high-density chips is 10 times that of current MOS technology, and close to half of the total estimates of nonrecurring cost of the advanced system is associated with the chips. Manufacturers express the opinion that efficient production quantities for custom MOS LSI begin around 50,000 units with continuous production, and testify to the relatively high nonrecurring and tool setup costs. At this rate, efficient production quantities of high-density devices must run well over 100,000. Typically, a single type of chip will be used at a number of places throughout a receiver, and lifetime spares can be procured concurrently. Thus, the quantity required can be several times the number of receivers produced. Still, efficient production quantities may be difficult to achieve in the GPS program, even when supplied by a single contractor in a single sustained production run.

Table 48 shows the nonrecurring cost as a percent of total cost for varying production quantities. Should multiple source or small lot contracting result in the repetition of nonrecurring costs, the impact on program costs could be significant. In addition, small lot contracting, by itself, could result in less than optimum production techniques and higher recurring production costs.

Table 48. Nonrecurring Cost as a Percentage of Total Cost for Custom MOS and Advanced Technology Chips

Chips	Nonrecurring Cost	Unit Recurring Cost	Nonrecurring Cost as a Percent of Total Cost at Quantities of				
			10,000	50,000	100,000	500,000	1,000,000
Custom MOS Technology Chips	150,000	60	20	5	2.5	.5	–
Advanced Technology Chips	1,500,000	100	60	23	13	3	1.5

Chapter I has shown a significant cost avoidance potential for GPS IOC in 1982 (or earlier) compared with 1984. In addition, the savings in GPS system cost for employing the most advanced technology appear significantly greater and on solid ground. The problem is that timely availability of the high-density digital devices presents the greatest risk in the advanced technology system, but the major part of this risk can be avoided at a relatively low cost.

An option that has not been investigated thus far is parallel development of user equipment employing current and advanced technology. Parallel development serves as a hedge against two eventualities. The first is late availability of the advanced system. The second is the chance that high-density LSI simply cannot be incorporated into the GPS system. The probability of the first is not insignificant, while that of the second must be judged very slight. Parallel developments should nearly eliminate the cost associated with either eventuality.

Figure 19 shows the total procurement cost of 50,000 user equipments according to the percentage of the advanced system in the buy. The horizontal lines represent the costs estimated for each technology, assuming a single development program. The only increment of program cost that can be quantified is the nonrecurring estimate for each program individually, and this may understate the true increment for parallel development. In addition, 50,000 equipments may be a high number over which to amortize nonrecurring cost. In any case, though, the cost increment should prove small relative to that associated with late availability of the system.

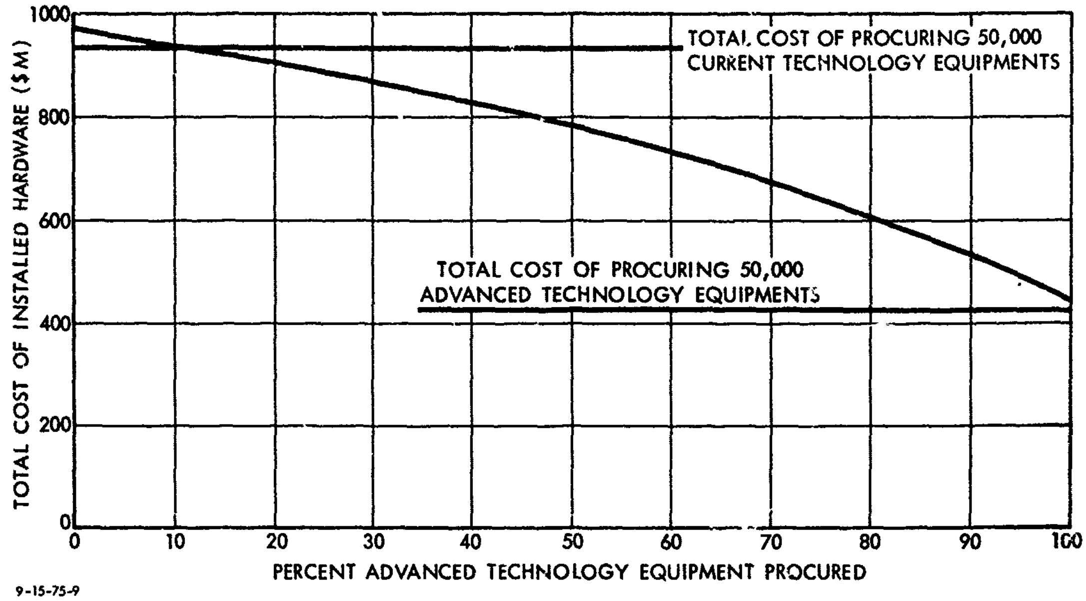

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Figure 19. Total Cost of Procurement of 50,000 User Equipments (Millions of 1975 Dollars)

These considerations suggest a potentially large payoff to an early and thorough investigation of high-density LSI capabilities in GPS-type applications. For procurement quantities near 50,000 user equipments, differences in procurement costs of installed equipment (over MOS technology systems) are estimated to approach several hundred million dollars. A small fraction of this amount would constitute a many-fold increase in funds devoted to technology development. Further, early investigation and development of the technology would remove a significant degree of uncertainty in the program and offer additional savings of costs associated with the development of competitive navigation equipments. It should be recognized that the scope of a thorough investigation is very broad and encompasses questions of efficient production methods and quantities; rational policies regarding the tradeoffs between reliability standards, maintenance philosophies, and costs; and contracting procedures. Manufacturers cannot be expected to incur the sizable and sunk expenditures seemingly required for efficient (low-cost) production of high-density LSI devices without guarantees that large quantities will, in fact, be procured.

Chapter III

TASK 2: OPERATIONAL DEMONSTRATIONS

A. INTRODUCTION

The objective of this task was to identify and describe operational demonstrations using contemporary weapon systems that will illustrate the utility of GPS for military applications. The approach used was to:

- Discuss position fixing, navigation, and time problems, and the application of GPS to these problems, with senior members of all the Services.
- Identify those problem areas that appear suitable for demonstrating the utility of GPS.
- Develop initial concepts for operational demonstrations around the problem areas identified.
- Review these operational demonstrations with the schools or commands having the doctrinal responsibility for the problem areas. Incorporate inputs from these sources into the demonstrations.

B. POSITION, NAVIGATION, AND TIME PROBLEM AREAS CONSIDERED AS CANDIDATES

Discussions with the Services revealed many significant position fixing, navigation, and time problems. As these problem areas were uncovered, they were assessed as to their suitability for a demonstration. This assessment was based on:

(1) The difficulty of the position fixing or navigation problem and the potential payoff of using GPS to help solve the problem.

(2) The number of applications of GPS user equipment that the demonstration could illustrate.

(3) The potential difficulty of conducting the demonstration.

(4) The apparent Service interest in such a demonstration.

(5) The degree to which such a demonstration would exercise the accuracy of GPS.

Using the criteria above the following problem areas were considered for development into operational demonstrations.

Aerial Assault
Aerial Refueling
Air Cavalry Operations
Aircraft Approach and Landing
Aircraft/Carrier Rendezvous and Landing
Amphibious Operations
Antisubmarine Warfare
Artillery Operations
Attack Helicopter Operations
Close Air Support
Coordinate Bombing
Forward Observer
Ground Patrols
Helicopter Rendezvous
Missile Guidance
Photo Reconnaissance
Satellite Position Fixing

C. OPERATIONAL DEMONSTRATIONS IDENTIFIED

In the development of the operational demonstrations, it was felt that some problem areas should be combined. As a result, the Forward Observer and Artillery Operations were combined into one demonstration while Photo Reconnaissance and Coordinate Bombing were put together in another. Ground Patrol and Helicopter Rendezvous were considered separately and as a combined demonstration. However, they were dropped when the Infantry School indicated a strong preference for the Aerial Assault demonstration over that of Ground Patrol and/or Helicopter Rendezvous.

The Aircraft/Carrier Rendezvous and Landing demonstration was rejected since most of its features are contained in the Aircraft Approach and Landing demonstration.

Missile Guidance and Satellite Position Fixing demonstrations were not pursued since both of these areas already have sufficient interest that funding exists outside of the Joint Program Office for the development and testing of GPS hardware for these applications.

The Air Cavalry demonstration was not pursued since the position/velocity/time problems associated with it are similar to those in aerial assault and attack helicopter operations. The aerial refueling demonstration was dropped after it was determined that GPS alone could not provide a covert means with which to rendezvous and, therefore, did not appear to provide a significant payoff in this type of operation.

Thus, seven problem areas were assessed as suitable for operational demonstrations to illustrate the utility of GPS for military applications.[1] Scenarios describing each of these demonstrations have been developed and reviewed with the Service agency having doctrinal responsibility for the position fixing or navigation problem areas forming the basis for the demonstration. The Service interest in these demonstrations, especially by the agencies which reviewed them, was found to be very high. This is important since these same agencies would probably be involved in conducting the demonstrations. The proposed demonstrations and reviewing agencies are shown in Table 49.

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[1] Recently received data indicate that GPS might be used to significantly improve the effectiveness of certain antisubmarine warfare operations. However, these data were received too late to be used in this study.

Table 49. Proposed Operational Demonstrations

Operational Demonstration	*Reviewing Service Agency*
Aerial Assault	Infantry School, Ft. Benning
Aircraft Approach and Landing	Tactical Air Command, Langley AFB
Amphibious Operations	Commander Amphibious Group–Two, USS Mount Whitney
Attack Helicopter Operations	Armor School, Ft. Knox
Close Air Support	Tactical Air Command, Langley AFB
Forward Observer and Artillery Operations	Artillery School, Ft. Sill
Photo Reconnaissance and Coordinate Bombing	Tactical Air Command, Langley AFB; and Marine Tactical Reconnaissance Squadron Three, MCAS, El Toro

D. DISCUSSION OF THE PROPOSED OPERATIONAL DEMONSTRATIONS

Each of the operational demonstrations is discussed below. The discussions include a description of the position fixing or navigation problems forming the bases for the demonstration, the applications of GPS to the problems, a scenario describing the proposed demonstration and the measures that could be used to determine the improvement brought about by the use of GPS. It should be emphasized that the proposed demonstrations are not operational tests but vehicles to illustrate the utility of GPS for military applications and that the scenarios have been developed to present the concepts for conducting the demonstrations rather than detailed test plans.

1. Air Assault

A basic aim of the air assault operation is to land the troop-carrying helicopters at their assigned landing zones in the objective area, at the appointed times, with appropriate artillery and air cover so that the attack on the objective can develop as planned. Aerial assaults are usually large operations with several different routes being used by the helicopters to reach the objective area. A number of flights of helicopters may be spaced along each route. Artillery support and air cover must be provided for each of these flights as they progress along their assigned routes.

Most of the elements in an air assault operation (e.g., scout helicopters, troop-carrying helicopters, and close air support aircraft) currently rely on maps and compasses for navigation. This is very difficult, especially for helicopters flying nap-of-the-earth, as current doctrine requires when the helicopters are flying in the forward area of the division or in hostile territory. In addition, coordinating helicopter flights along the attack routes, air cover and artillery support along these routes and in the objective area, and landing of troops in the objective area, are major problems. The coordination problems become even worse with reduced visibility, when enemy forces are discovered along a route to the objective area, or when the ground forces must be disengaged and redeployed against a subsequent objective. Furthermore, current procedure requires that pathfinders be inserted into the objective area ahead of the main assault to guide the troop-carrying helicopters to the landing zones. This may provide the enemy with an early warning of an impending assault.

a. Applications of GPS

In the proposed air assault demonstration, an infantry force would be assigned the task of taking an objective in enemy territory. The force would be moved by helicopter from the assembly area to the landing zones in the objective area. GPS user equipment would be used for position fixing and navigation throughout the operation as described in the following.

The lead helicopter of each flight would be equipped with a GPS receiver which contains the waypoints defining the route the flight is to take to the objective area. These waypoints would be used to guide the group of troop-carrying helicopters over the route and to the landing zone assigned to it in the objective area. The current doctrine of flying nap-of-the-earth when in the forward area of the division or in hostile territory would be followed.

The aircraft providing air cover and the batteries providing artillery support would use GPS receivers and coordinates provided by the GPS equipped helicopters in the flights to furnish fire support for the assault force while it is enroute to the objective area. When enemy resistance could not be neutralized within the time allotted, the flights would be rerouted around the enemy areas. Waypoints, defined in GPS coordinates, would be used to coordinate the new routes with both the assault force and support teams.

Once landed in the objective area, the assault force would use their GPS manpacks to navigate to their assigned positions and to help determine the coordinates of enemy areas for which the assault force requires fire support from the air cover or artillery teams. The aircraft and artillery batteries would use these coordinates to provide the desired fire support.

b. The Scenario

In this demonstration, which is illustrated in Figure 20, a GPS equipped infantry force will be assigned the task of taking an objective using an air assault operation. A GPS equipped helicopter force will be assigned to pick up the infantry force at designated pick-up zones (PZs) which will be defined by GPS coordinates. Each flight of helicopters will be given arrival and departure times so that these areas do not become unduly congested.

Flight paths from the PZs to the landing zones (LZs) will be chosen to best avoid areas of known or suspected enemy concentrations, areas within enemy antiaircraft coverage

Figure 20. Air Assault

and areas containing undesirable terrain. The routes selected should afford good artillery and air coverage, and should facilitate nap-of-the-earth flying.

While enroute the helicopters will be required to (1) call upon artillery and air cover to neutralize suspected areas of enemy concentrations and (2) deviate from their assigned flight paths to avoid enemy strong points discovered by the scout helicopters in the lead. These deviations must be coordinated with all other forces involved including artillery support, friendly ground troops to be overflown, fixed wing air cover and attack helicopters flying escort.

LZs and waypoints, all of which will be designated in GPS coordinates, will be used to define the air corridors for each of the helicopter forces. The helicopters will fly nap-of-the-earth from the PZs to the LZs. Each flight of helicopters will also be given a time to land at its assigned LZ.

Prior to the helicopters landing at the LZs, artillery, attack helicopters and fixed wing aircraft will place fire on designated points in the objective area. These points will be defined by the GPS coordinates. In addition, these elements will provide supporting fire during the landing phase of the assault.

Following the landing, the infantry elements will disembark and begin the ground phase of taking the objective. Using GPS coordinates to define attack routes and target positions, the ground element will call for artillery and air support to neutralize enemy resistance.

After the ground attack has progressed far enough to show the major benefits of GPS in this phase, an order will be issued for the infantry to withdraw by air and redeploy to secure a second objective. The only difference between this phase and the previous phase is that it is not preplanned; that is, the planning is to be done in the field under field conditions.

c. Measures of Effectiveness

The *major* measures of effectiveness of GPS over current means of position fixing and navigation used in aerial assault operations are the degrees to which GPS would

- Reduce the effort required to coordinate the landing and fire support operation in the objective area with the precision, timing, and flexibility required to insure success.
- Reduce the planning and effort required for pilots to navigate from the PZs to the LZs while flying nap-of-the-earth.
- Increase the speed with which routes around enemy forces can be defined and coordinated.
- Increase the speed and accuracy with which disengagement and redeployment plans can be drawn up and executed.

- Facilitate changes in attack plans and their coordination with resupply forces, medevac teams, artillery and air cover.
- Reduce the susceptibility of the helicopters to enemy fire by facilitating the use of routes that provide superior concealment and protection (current methods require the use of routes that provide good visual navigation).

Additional measures of the improvement brought about by the use of GPS are

- The reduction in communication requirements.
- The improvement in the effectiveness of ground and air fire support while the helicopters are enroute to the LZs.
- The reduction in the effort required to execute the loading phase.
- The increase in the element of surprise due to the elimination of the need for pathfinders.

2. Aircraft Approach and Landing

There is no method, currently available or under development, which will allow an aircraft to make an instrument approach to a non-radiating airfield. Furthermore, a considerable amount of ground survey work and ground equipment set-up time is required to provide an instrument approach capability at a new airfield.

a. Applications of GPS

In the proposed aircraft approach and landing demonstration, aerial surveys of the approach and landing areas of a number of airports would be made by an aircraft equipped with a GPS receiver. These aerial surveys would then be used to develop IFR approach procedures for the airports. Then, using these approach procedures, aircraft equipped with GPS receivers would conduct nonprecision approaches[2] to these airfields without the aid of any ground support equipment. Category I precision approaches[3] would be performed by using a differential system. In this system a second GPS receiver would be placed near the desired touchdown position on the runway. The position data from this receiver would be sent to the approaching aircraft so that the difference between the two readings could be determined. This should provide the increase in accuracy required for a Category I approach.

b. The Scenario

A number of airfields will be selected for use in this demonstration. For each airfield selected, instrument approach and departure procedures, based on GPS, will be developed. This can be done by flying or driving a GPS receiver to each terrain point of interest and

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[2] The most stringent position fixing requirement for non-precision approaches, as shown in Chapter I, Table 21, is the 40-meter (2σ) vertical accuracy required at the outer marker. This is well within the GPS capability.

[3] The most stringent position fixing requirement for Category I approach, as shown in Chapter I, Table 21, is the 5-meter (2σ) vertical accuracy required at the middle marker.

noting its GPS coordinates or by employing a GPS equipped photo reconnaissance aircraft to obtain stereo photographs of the area. The approach and departure routes from each airport will be defined as a series of legs, each end of which is designed by a GPS waypoint. An illustration of the scenario is given in Figure 21.

In conducting the demonstration, each pilot will make an instrumented approach and departure from each of the selected airports. Prior to that approach, the pilot will insert the following data into his onboard GPS user equipment: the GPS coordinates of the approach end of the runway, the waypoints defining the legs to be flown to reach the runway, the waypoints defining the legs to be flown in case of a missed approach, and the GPS coordinates for any other prominent waypoint, beacon or marker in the area. When turning onto the course to fly to the first waypoint in the approach, the pilot will set the controls of the GPS receiver such that it provides a continuous readout of the range and bearing to the waypoint. These data will be used to fly to the vicinity of the waypoint at which time the GPS receiver will be switched to the next waypoint. This procedure will be followed and a landing attempt made. If a landing is made, data will be inserted for the departure. If the landing attempt is unsuccessful, the pilot will switch the GPS receiver to the first abort waypoint and execute the missed approach procedure.

c. Measures of Effectiveness

The measures of the effectiveness of GPS over current instrument landing systems include the reduction in the time and effort required to develop instrument approach procedures, and to prepare an airfield to support nonprecision and Category I precision approaches. Another measure is the reduction in the time and effort required for pilots to locate and land at airfields which are not transmitting or are uncontrolled.

3. Amphibious Operations

One of the basic aims of the amphibious operation is to land the assault force in such a way that each element of the force can reach its assigned objective at the specified time. Currently each wave of landing craft and/or amphibious vehicles used to land the assault force is guided to shore by a launch or control ship. The landing craft and amphibious vehicles have no navigational capability of their own except for maps and compasses. Thus, the coordination of the landing and engagement of an assault size force on unfamiliar terrain is a major problem. However, the problems are greatly increased by adverse weather, darkness and smoke. Weather and darkness also adversely affect the ability of the amphibious task force to locate the Amphibious Objective Area, and of the minesweepers to locate and clear the designated channels.

a. Applications of GPS

In the proposed demonstration the amphibious task force would use GPS in navigating to the Amphibious Objective Area. GPS coordinates would be used to fix all areas, landmarks, etc., in the objective area. For example, the channels to be used to move the

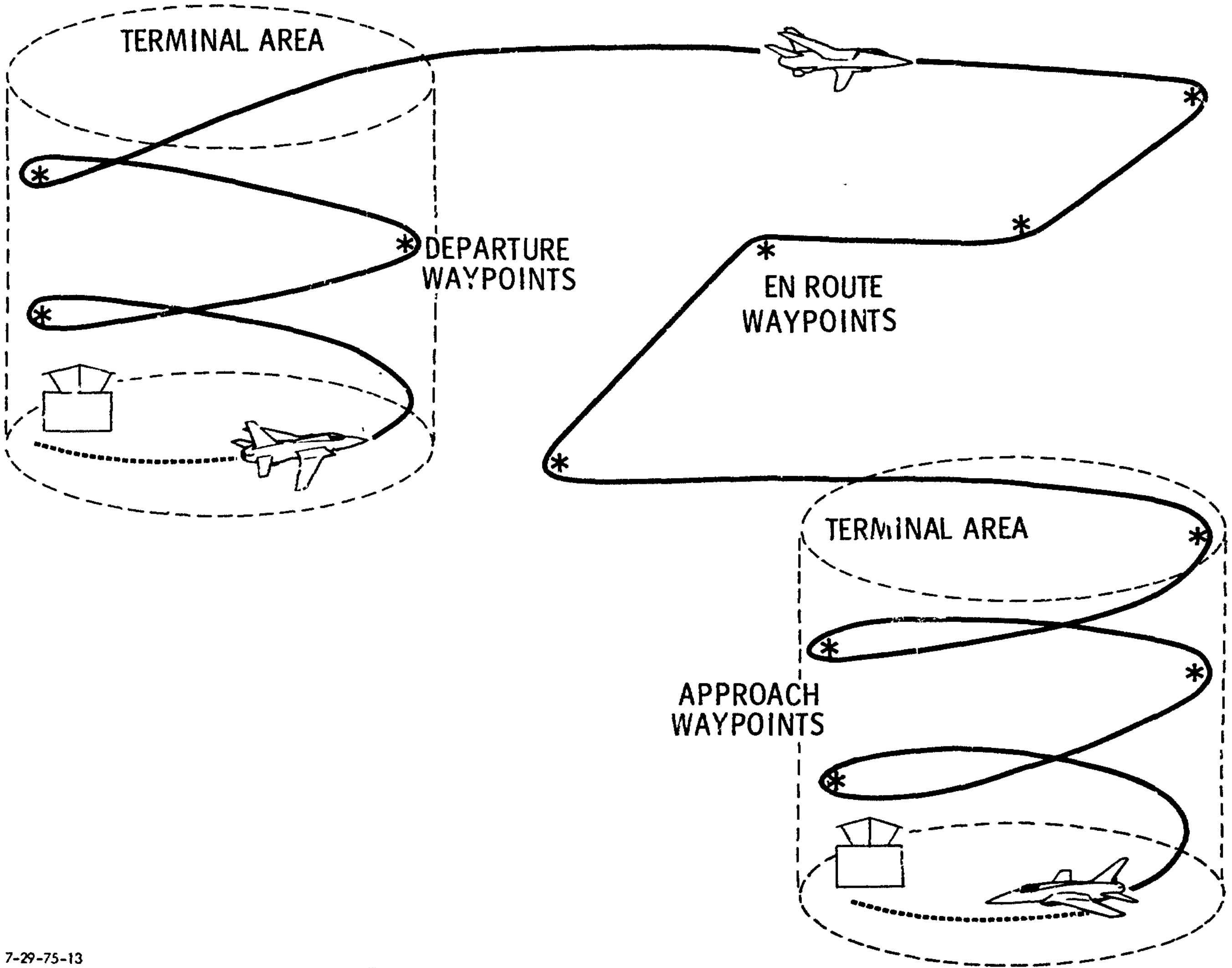

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Figure 21. Aircraft Approach and Landing

troops and supplies ashore would be defined in GPS coordinates. The minesweepers would use these coordinates to clear channels of mines. The ships would use these coordinates to navigate through the cleared channels to their assigned launch or landing area.

Each wave of landing craft and/or amphibious vehicles would also be equipped with GPS receivers. This equipment would be used to guide the wave ashore in all types of weather as well as under the cover of smoke. The launch or control ships currently used to guide the waves ashore would be eliminated. Once ashore, the amphibious vehicles and ground troops would use their GPS receivers to navigate to their assigned positions.

b. The Scenario

In this demonstration, which is illustrated in Figure 22, a GPS equipped task force would sail to the Amphibious Objective Area which would be defined in GPS coordinates. Channels to and from the underway launch area would be swept clear of mines as would the launch area itself. Landing points would also be described in GPS coordinates, and the minesweepers would clear approaches to these designated points. Using GPS coordinates to avoid uncleared and shallow water areas, patrol craft would provide a blanket of smoke in the area between the shore and the launch area. The smoke would permit the GPS equipped amphibious ships to remain masked from visual view of the enemy ashore while moving to the launch area, launching their landing craft and amphibious vehicles, and returning to the sea echelon area. Using GPS equipment, and without the benefit of the currently used launch or control ships and flares, the landing craft and amphibious vehicles would move to their assigned positions behind the smoke-filled area and remain on station until the first wave is assembled. On command, they would move out toward their individual, GPS defined, landing areas. Waypoints, whose coordinates were inserted into the GPS receivers prior to the launch phase, would be used to permit the landing craft and amphibious vehicles to navigate around obstacles, avoid dangerous or uncleared areas, avoid shallow water, etc., as they proceed from the assembly area to the individual landing areas. Upon reaching the shore they would switch their GPS equipment to indicate the range and direction to their assigned positions.

In the airborne or vertical assault phase, GPS equipped helicopters would move an infantry force from the ships to their designated LZs. The LZs and the routes to be used to reach the LZs would be defined in GPS coordinates. Flight paths from the ships to the LZs would be chosen to best avoid areas of known or suspected enemy concentrations and areas within enemy antiaircraft coverage. The routes selected should afford good artillery and air coverage, and should facilitate nap-of-the-earth flying.

While enroute the helicopters would be required to (1) call upon artillery and air cover to neutralize suspected areas of enemy concentrations and (2) deviate from their assigned flight paths to avoid enemy strong points discovered by the lead aircraft. These deviations would be coordinated with all other forces involved including naval gunfire support, friendly ground troops to be overflown, fixed wing air cover and attack helicopters flying escort.

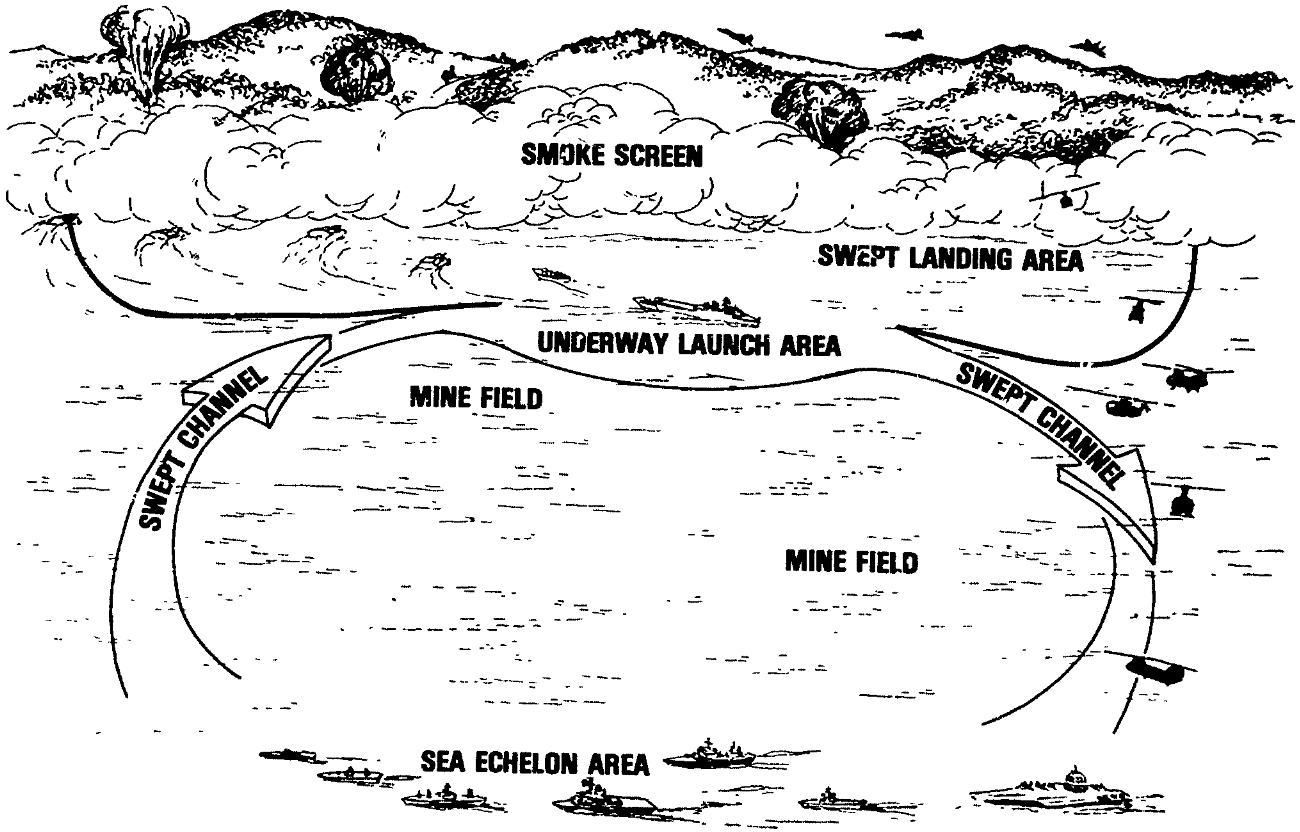

Figure 22. Amphibious Operations

Following the movement of the troops ashore, locations requiring resupply would be designated in GPS coordinates. These coordinates would be given to the helicopters along with the waypoints defining the routes to the area requiring the resupply.

c. Measures of Effectiveness

The primary measures of effectiveness of GPS over the current methods of position fixing and navigation used in amphibious operations are the degrees to which GPS would:

- Reduce the susceptibility of the landing force to enemy fire and improve the tactical advantage afforded the assault force through the elimination of the launch or control ships and the ability to use smoke, darkness, or weather to cover the assault.
- Reduce the effort required to coordinate all elements of the assault such that the attack develops as planned.
- Reduce the effort required to locate the Amphibious Objective Area and prespecified points within the area.
- Reduce the effort required to define and clear the sea lanes, launch area, and landing areas.

Other measures are the:

- Reduction in the size of the channels that must be cleared.
- Improvement in the ability of ships and landing craft to maneuver around hazardous areas.
- Improvement in the ability of the elements to quickly adjust their plans to account for changes in enemy location or strength.
- Improvement in the ability to support the elements ashore with gunfire and supplies based on improved knowledge of the location of the ships and shore elements.
- Reduction in the communications required to coordinate the assault.

4. Attack Helicopter Operations

In conducting attack helicopter operations the helicopter crews currently rely on maps and compasses for navigation. This is a very difficult method with which to navigate while flying nap-of-the-earth, as current doctrine requires when flying in the forward area of the division or in hostile territory. Thus, to conduct the search operation, the crew of the scout helicopter must be very familiar with the map and the terrain. In addition, once the enemy targets have been located, the scout helicopter must fly back to the attack helicopter holding area and lead the attack helicopters to their attack positions. This is time consuming and causes the scout helicopter to lose contact with the enemy.

a. Applications of GPS

In the proposed attack helicopter demonstration both the scout and the attack helicopters would fly nap-of-the-earth and use GPS as their primary navigation aid. The scout helicopter crew would use GPS to help determine the coordinates of the targets and the pop-up points from which they should be attacked. The scout helicopter would also determine the GPS coordinates defining the route the attack helicopters are to use to move from their holding areas to the pop-up points. The attack helicopters would use these data to move to the pop-up points and to engage the targets without additional guidance. The scout helicopter would be free to remain in the attack area to continue to observe the enemy and to provide local fire support for the attack helicopters when they arrive or to continue the search for additional targets.

b. The Scenario

In this demonstration, which is illustrated in Figure 23, the crew of a GPS equipped scout helicopter would be given an area to search with approximate target locations indicated in GPS coordinates. They would also be given the type of target in each location, and navigation routes to and from the search area, defined by waypoints in GPS coordinates.

The scout helicopter would conduct a normal search for each target, and upon locating each one, would establish a pop-up point for the attack helicopter as well as fixing the exact location of the target. After completing its search, the scout helicopter would determine a route that the attack helicopter could use to fly from its base to the target areas, attack each of the targets in turn and return to its base. Waypoints would be provided along the route to aid the attack helicopter in navigating to the firing positions. The routes selected should facilitate nap-of-the-earth flying and minimize exposure to enemy fire. Following the completion of this portion of the mission, in the case of stationary targets, the scout helicopter would leave the area to continue the search or remain to provide local security (fire coverage) for the attack helicopter, if required. In the case of moving targets, the scout helicopter would remain to continue to observe the targets. The attack helicopter would then attempt to follow the suggested route, pop up at the designated locations, and fix and fire on each target. The mission would be carried out in a near covert manner; that is, no information beyond that noted above would be communicated between the scout and attack helicopter crews.

In the demonstration the helicopters are to fly nap-of-the-earth. It is anticipated that the crews would use the GPS generated data on the direction and distance to the next waypoint or pop up point to do course navigation while visually navigating around vegetation, hills, etc. As the demonstration progresses and the helicopters need additional fuel or ammunition, they would be given the GPS coordinates of a Forward Area Rearm/ Refuel Point (FARRP). Different locations for the FARRP can be used to show its mobility which would reduce its vulnerability to enemy attack.

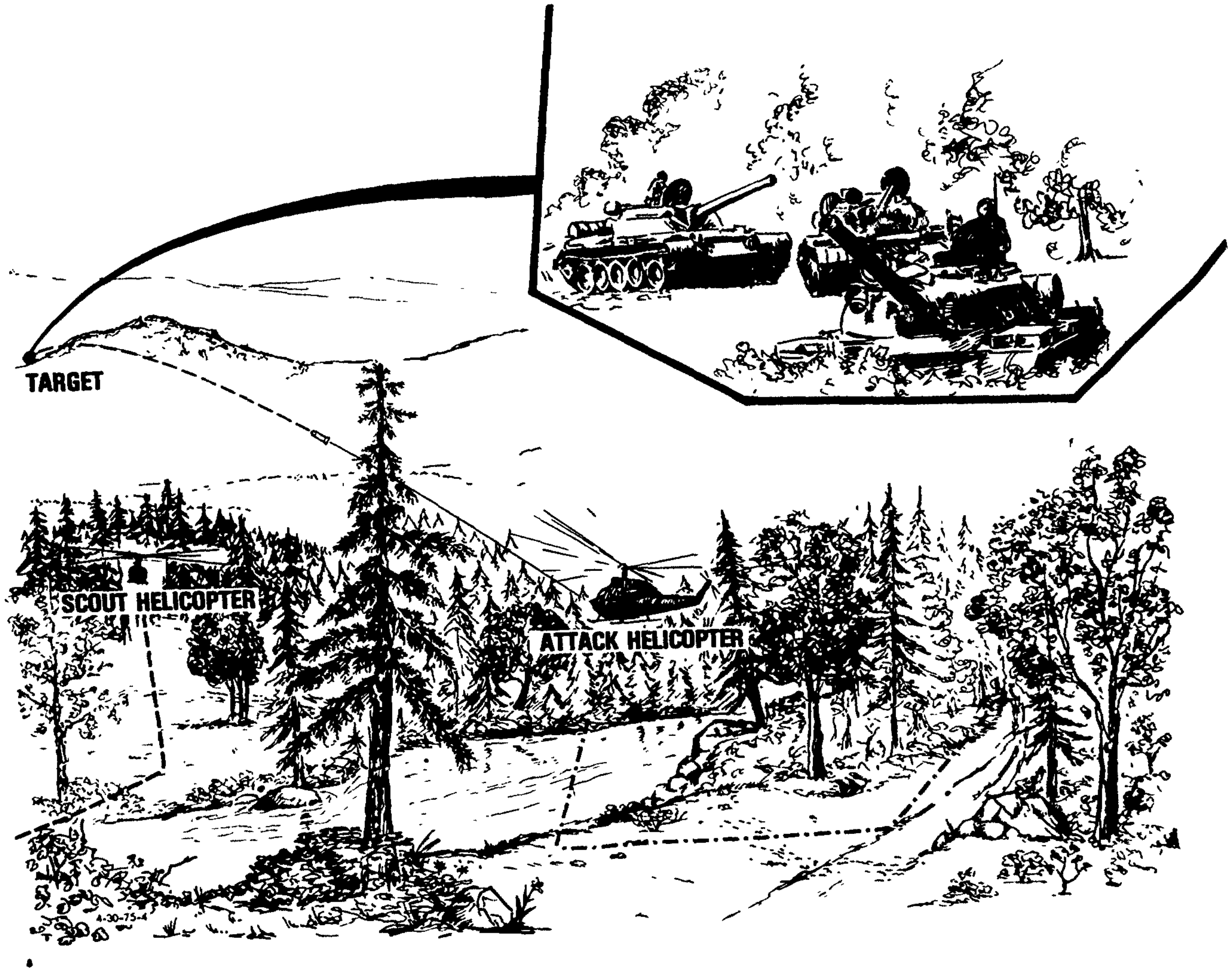

Figure 23. Attack Helicopter Operations

c. Measures of Effectiveness

The measures of the effectiveness of GPS over the current means of position fixing and navigation used in attack helicopter operations are the degrees to which GPS would:

- Reduce the time and effort required for the scout helicopter crew to plan and execute the search mission, locate targets and hand the targets off to the attack helicopters.
- Reduce the time and effort required to get the attack helicopters from the holding area to the pop-up locations, and for them to locate and engage the targets.
- Increase the speed and accuracy of navigating from one point to another while flying nap-of-the-earth.
- Increase the operational window by being able to operate during periods of reduced visibility.
- Reduce the susceptibility of the FARRP to enemy attack brought about by its freedom to move during the attack since the helicopters can readily locate its current position by GPS coordinates.

5. Close Air Support

In Close Air Support (CAS), one of the major problems is the hand-off of the target from the Forward Air Controller (FAC) on the ground to the attack aircraft. The source of the problem is the lack of a satisfactory method to cue the target acquisition sensor (electro-optical or eye) in the CAS aircraft to the target area. With the exception of the laser designator[4] current techniques require the CAS aircraft to fly to within the range of the enemy antiaircraft capability before the pilot can acquire the ground target. In addition, while conducting the search for the target the pilot would usually not be able to maneuver (jink) the aircraft to avoid the antiaircraft fire. Further, the potential to acquire and attack the target on the first pass is small. These problems become even more difficult during periods of reduced visibility

a. Applications of GPS

In the proposed Close Air Support demonstration both the FAC and the attack aircraft would be equipped with GPS receivers. The FAC would use his GPS receiver to aid in determining the GPS coordinates of the target. The pilot would enter these coordinates in the aircraft's GPS receiver to direct the target acquisition sensor or heads-up-display (HUD) cursor toward the target area. Once the pilot has visually acquired the target, the sensor or cursor pointing angles would be used to update the target's coordinate in the GPS receiver. Steering signals from the receiver would then be used to hold the sensor or cursor on the target as the pilot maneuvers into position and makes the attack run.

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[4] Laser designation allows the aircraft to stand off from the target. However, it requires the FAC to illuminate the target with a light beam during the target acquisition phase, which may give away his position.

b. The Scenario

In this demonstration, which is illustrated in Figure 24, a ground FAC would use a GPS manpack, an azimuth scale and a laser rangefinder to determine the GPS coordinates of the targets in the following manner. First, he would use his manpack to determine the bearing to a landmark visible in the distance. The GPS coordinates of this landmark could be provided from intelligence prior to the advance or the FAC himself could obtain them as he moves to his position. This bearing line would be entered into a device (such as the GVS-5 laser rangefinder) with an azimuth scale. Then by rotating the line-of-sight onto the target, the target's azimuth relative to the FAC's position would be read directly from the scale. This bearing along with the range from the FAC's position to the target, which the FAC would determine with a laser rangefinder, would be used by the GPS manpack to determine the GPS coordinates of the target. The FAC would provide these coordinates to the Direct Air Support Center for relay to the CAS aircraft.[5]

The CAS aircraft would be equipped with a TISEO[6] and an inertial measurement system in addition to a GPS receiver. Upon receiving the attack mission, the crew of the CAS aircraft would enter the GPS target coordinates into the GPS receiver. The receiver would then provide the pilot with the range and bearing of the target relative to the aircraft. The receiver and the inertial system would also provide steering signals to the TISEO system to bring the target area into the field of view. The pilot would center the TISEO cursor on the intended target. Using these new pointing angles the receiver would update the location of the target in its memory. This target acquisition phase would be done with the CAS aircraft at the greatest possible range from the target area, since one of the objectives of the demonstration is to show the ability to acquire targets beyond the range of enemy antiaircraft capability.

Once the target has been acquired and its coordinates updated in the GPS receiver, the pilot would select a point from which to make his attack run and fly to it, maneuvering along the way to avoid enemy antiaircraft fire. During this period the GPS system would continue to provide the pilot with range and bearing to the target and, with the aid of the inertial system, steering signals to the TISEO to keep it pointed toward the target's location even though the view of the target may be obstructed by hills, trees, etc., since the pilot may very well elect to avoid line-of-sight with the target area as he is maneuvering into a position from which to begin the attack run.

As the pilot begins to make the attack run, if he cannot see the target, he would fly so as to align the cursor with the aircraft's line-of-flight since this provides the direction to the target and the best potential for a one pass attack. When the target comes into view the

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[5] In some cases the FAC might prefer to provide the GPS coordinates of his position, and target range and bearing relative to his position. However, for security reasons, it would seem preferable for the FAC not to announce the location of his position. Since the computer in the GPS receiver will be programmed to provide the GPS coordinates of the targets based on the range and bearing from its current position (which the FAC could easily input), the increased effort required by the FAC should be insignificant.

[6] Target Identification System, Electro-Optical. However, other systems such as PAVE SPIKE, PAVE TACK, LATAR, or HUD could be used.

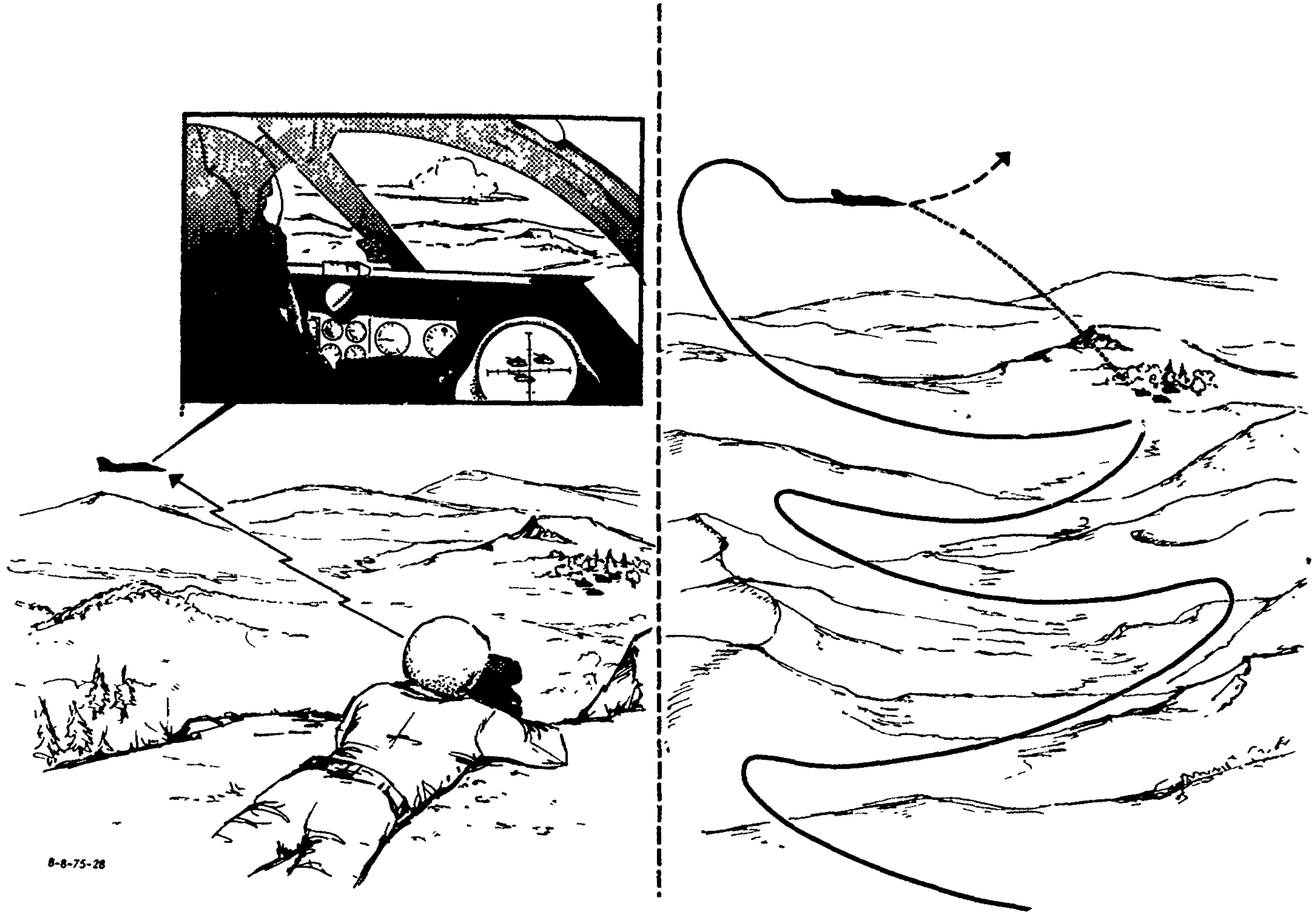

Figure 24. Close Air Support

pilot would position the cursor in the display on the intended impact point. The appropriate target location data would be fed into the weapon release computer which would select the weapon release point. The pilot would release the weapon at the time indicated by the computer.

During the attack run, the pilot would continue jinking to reduce his susceptibility to antiaircraft fire except for any settling time required by the weapon release computer.

c. Measures of Effectiveness

The measures of the effectiveness of GPS over the current means of position fixing and navigation used in the CAS operations include the reduction in the susceptibility of the aircraft to antiaircraft fire. This is brought about by four factors that are individually measurable. The first is the increase in the range at which the pilot can acquire the ground targets. The second is the decrease in the time the aircraft is within the range of the enemy weapons. The third is the improvement in the ability to maneuver to avoid the antiaircraft fire when flying within its range. This includes the breaking of the line-of-sight with the target once it has been acquired. The fourth factor is the increased probability of executing a one pass attack. Other measures are the reduction of the pilot's workload during the target acquisition and attack phases of the mission, the reduction in the prebriefing and target area knowledge necessary for the pilot to operate effectively in a CAS environment, and the decrease in the FAC's susceptibility to enemy fire brought about by the reduction in the communications necessary to specify the target's location to the pilot.

6. Forward Observer and Artillery Operations

In this type of operation the Forward Observer (FO) determines the coordinates of the targets and provides them to the artillery battery via the Fire Direction Center. To determine the coordinates of a target the FO needs to know his location, the range from his position to the target and the bearing of the target with respect to some reference. Currently, the primary equipment available to him with which to determine these data is a map of the area and a magnetic compass. The artillery battery also requires an accurate knowledge of its position as well as a reference line of bearing. This is currently provided by ground surveys. However, the survey teams may lag several hours behind the Army's current mobile artillery capability. This tends to reduce the effectiveness of the mobile artillery, since several rounds may have to be fired and successively corrected by the FO before the target is effectively engaged.

a. Application of GPS

In the proposed demonstration, both the FO and the artillery battery would use GPS receivers to locate their positions. The FO would also use his receiver to determine a reference bearing which would then be used in determining the bearing from the FO's position to the target.

b. The Scenario

In this demonstration, which is illustrated in Figure 25, a test umpire would designate each of the targets to an FO. The FO would use his GPS manpack to help determine the GPS coordinates of the target.[7] These coordinates would be provided to the Fire Direction Center for subsequent transmittal to the artillery battery.

Upon receiving the fire mission the artillery battery, which would be moving, would select a firing position and lay the battery using their GPS receiver and azimuth/bearing indicator equipment. Using the target coordinates provided by the FO, the battery would determine its firing data and commence firing. The FO would conduct subsequent adjustments.

c. Measures of Effectiveness

The measures of effectiveness of GPS over the current means of position fixing used in the Forward Observer and artillery operations include the degrees to which GPS would:

- Reduce the time required for the FO to determine his location.
- Improve the accuracy with which the target can be located.
- Improve the first round accuracy as shown by the actual impact locations of the artillery rounds.
- Reduce the time and effort required to lay the battery and effectively engage the target as indicated by the time necessary to place sufficient rounds within the lethal range of the target so as to destroy it.
- Reduce the necessity to rely on registration rounds that may be obscured by weather, smoke, etc.

7. Photo Reconnaissance and Coordinate Bombing

Previous studies have shown that coordinate bombing with conventional bombs can be improved if position fixing accuracies which are better than those attainable with LORAN can be provided.[8,9] Furthermore, the accuracy with which the targets are to be located by the reconnaissance system must be commensurate with that of the system that is to be used to strike the targets. That is, if a photo reconnaissance aircraft is used to collect target imagery from which target coordinates are to be determined, then the position fixing system in the reconnaissance aircraft should be at least as accurate as that in the strike aircraft. In addition, the effort required by the photo interpreters to determine the coordinates of target increases as the accuracy of the photo reconnaissance system decreases.

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[7] See Section 5.b for details.

[8] *Sensitivity of Mission Performance to Position Fixing Accuracy*, IDA Study S-409, January 1973, SECRET.

[9] *Defense Navigation Satellite System Study*, IDA Report R-190, July 1973, SECRET.

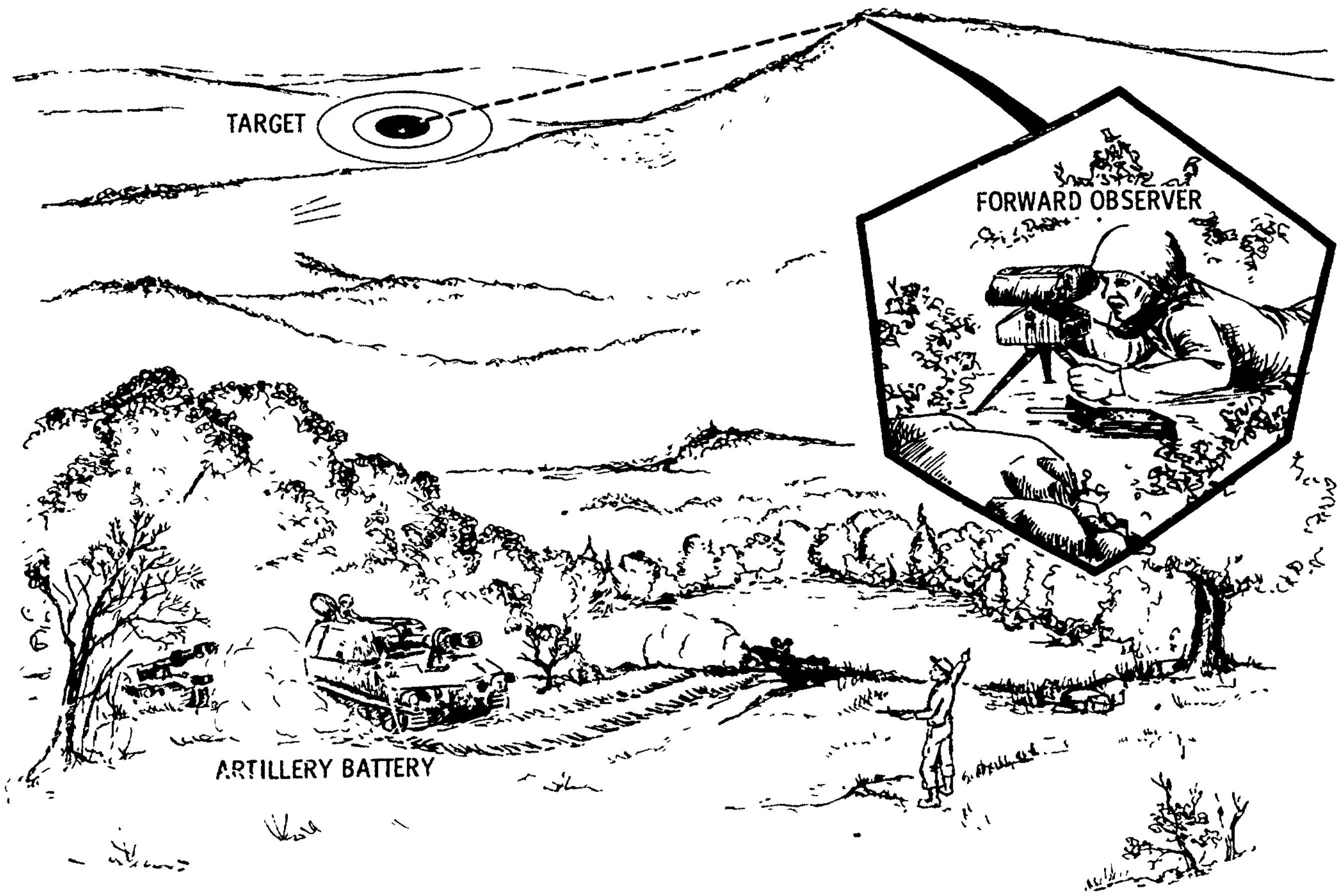

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Figure 25. Forward Observer and Artillery Operations

a. Applications of GPS

In the proposed photo reconnaissance and coordinate bombing demonstration, both the photo reconnaissance aircraft and the strike aircraft would be equipped with a GPS receiver integrated with an inertial system. The pilot in the photo reconnaissance aircraft would use his GPS equipment to navigate to the target area. As the photographs of the target area are being taken, aircraft position data from this receiver would be recorded on the film. These data would then be used by the photo interpreters to determine GPS coordinates of the targets recorded on the film. These coordinates, along with waypoints defining the route to and from the target areas, would be used by the strike aircraft to attack the targets.

b. The Scenario

In the photo reconnaissance mission, the pilot would be given the GPS coordinates of the area to be photographed as well as the information on the target type and photo requirements currently provided. He would enter the coordinate into his GPS receiver along with those of the waypoints defining the route to the target area. He would then use the GPS equipment to navigate to the area and take the desired photographs. Position data from the receiver would be recorded on the film as the photographs are being taken. This part of the demonstration could be conducted at night or against camouflaged targets (e.g., using photo flash or IR film) to show the additional improvement GPS provides for these types of missions.

Ground checkpoints, recorded on the film, would be used to determine how well the reconnaissance aircraft was able to fly the photo mission using the given coordinates. These ground checkpoints would be surveyed in with a GPS receiver on the ground.

The photo interpreter, using the position data recorded on the film, would determine the GPS coordinates of the targets. These coordinates would be provided to the pilot of the strike aircraft who would enter them into his GPS receiver along with the waypoints defining the route the strike mission is to follow. Using these navigation data the pilot would fly the strike aircraft over the target. The GPS receiver would provide the weapon release computer with navigation data so that it could compute the release point and release the bombs. The scenario is illustrated in Figure 26.

c. Measures of Effectiveness

The measures of effectiveness of GPS over LORAN for position fixing and navigation in photo reconnaissance and coordinate bombing missions include the degrees to which GPS would:

- Reduce the time required by the pilot of the photo reconnaissance aircraft to plan the mission.
- Reduce the susceptibility of the photo reconnaissance aircraft to enemy fire due to decreased time in the target area.

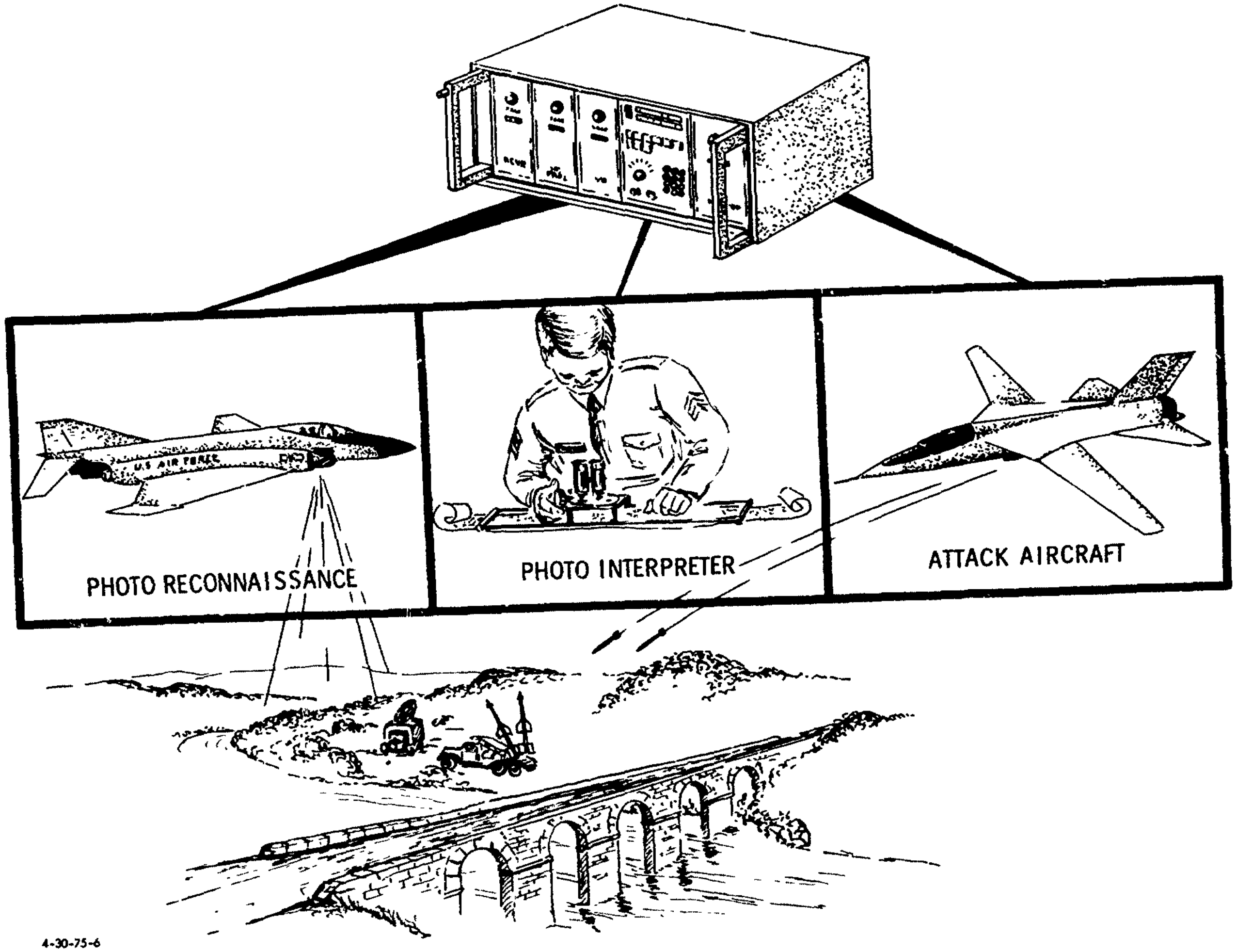

Figure 26. *Photo Reconnaissance and Coordinate Bombing*

- Reduce the time required for the photo interpreter to derive the target coordinates.
- Increase the bombing accuracy of the strike aircraft.

8. GPS Applications Illustrated by the Operational Demonstrations

The potential applications of the GPS receivers that each operational demonstration will illustrate are shown in Table 50a and 50b.

9. Additional Considerations

The research done for this report indicates that the Service agencies having doctrinal responsibility for the areas covered by the demonstrations proposed in this report have not been tasked, at the time of this writing, to design, develop, conduct or support any GPS demonstrations. In addition, it is expected that additional user equipment, or at least a reallocation of the equipment currently on order, would be required to accomplish the proposed demonstrations. Thus, it can be seen that a considerable amount of coordination between DDR&E, the Service agencies involved, the GPS JPO, and the user equipment vendors would be required to successfully conduct the demonstrations proposed in this report.

Table 50a. Applications vs Operational Demonstrations

Applications of GPS	Operational Demonstrations		
	Aerial Assault	Aircraft Approach and Landing	Amphibious Operation
Target Acquisition and Weapon System Standoff			
Photo (Airborne) Reconnaissance		P	
Forward Observer or FAC (Air and Ground)	X		X
Weapon Delivery			
Coordinate Bombing	P	P	P
Field Artillery	X		P
Shore Bombardment	P		X
Weapon Acquisition Basket			
Coordinated Operations			
Amphibious Assault			X
Airmobile Operations	X		X
Armor Operations			P
Close Air Support	P	P	P
Search and Rescue	P	P	P
Antisubmarine Warfare		P	
Naval Task Force Operations			X
Navigation			
Helicopter NOE	X		X
Aircraft Approach and Landing	P	X	
Long Range Patrols	X		X
Riverine Operations			P
Buoy and Mine Placement		P	
Rendezvous			
Combat Resupply	X	X	X
Air Cargo Release		P	
Aircraft Carrier Landings		P	
Extraction of Troops	X		X
Medevac	X		X
Surveys			
Military Land Maps	X	P	X
Artillery			
Test Range Instrumentation	X	X	X

X-Complete P-Partial Demonstration

Table 30b. GPS Applications vs Operational Demonstrations

Applications of GPS	Operational Demonstrations			
	Close Air Support	Forward Observer and Artillery Operation	Photo-Reconnaissance and Coordinate Bombing	Attack Helicopter Operations
Target Acquisition and Weapon System Handoff				
Photo (Airborne) Reconnaissance	P		X	
Forward Observer or FAC (Air or Ground)	X	X		X
Weapon Delivery				
Coordinate Bombing	P		X	
Field Artillery		X	P	
Shore Bombardment		P	P	
Weapon Acquisition Basket	X		P	
Coordinated Operations				
Amphibious Assault				P
Airmobile Operations		P		P
Armor Operations				
Close Air Support	X	P	P	P
Search and Rescue	P	P	P	P
Antisubmarine Warfare			P	
Naval Task Force Operations				
Navigation				
Helicopter NOE				X
Aircraft Approach and Landing				
Long Range Patrols				P
Riverine Operations				
Buoy and Mine Placement	X		X	P
Rendezvous				
Combat Resupply	X		X	X
Air Cargo Release	X		X	
Aircraft Carrier Landings				
Extraction of Troops				P
Medevac				P
Surveys				
Military Land Maps		P	P	P
Artillery		X		
Test Range Instrumentation	X	X	X	X

X-Complete P-Partial Demonstration

Chapter IV

TASK 3: PROGRAMS THAT MAY BENEFIT FROM THE EARLY AVAILABILITY OF GPS TEST RANGE INSTRUMENTATION

A. INTRODUCTION

One potential use of GPS is its application in test range instrumentation. As an example, a GPS receiver could be placed aboard the test vehicle and any of the data available within the receiver (e.g., x, y, z $\dot{x}$, $\dot{y}$, $\dot{z}$, t) could be recorded on tape. Thus, a complete time history of the vehicle's position and velocity during the test or exercise would be available for direct comparison with similar tapes from other vehicles or with the output of onboard position and velocity equipment under test.

Another approach is to use a translator onboard the test vehicle to modify the carrier of the GPS satellite signals received at the antenna and retransmit them to an off-vehicle location for processing to determine the vehicle's position and velocity.

The Navy Trident Program plans to use GPS as an instrumentation system to provide data for post-flight accuracy evaluation. The approach selected is to place a translator in the Trident missile to retransmit the satellite signals to a control ship below. The control ship will record these signals. A post-flight processing method will be used to develop refined position and velocity profiles for the launches.

As noted in Appendix A, the last of the six GPS satellites in Phase I is scheduled to be launched in November 1977. These six satellites will provide position, velocity, and time data over CONUS and regions in the Atlantic and Pacific Oceans adjacent to CONUS. These data will be available at locations within this area from 1 to 3 hours daily. Although the time period at any particular location may vary from day to day, it is expected that the time period and the GDOPs available for any day at any location will be predictable well in advance.

The projected precision of the GPS system during the three phases of development is contained in Appendix A. The system, although very precise by current standards for navigation systems, may not be sufficiently accurate for some applications of range instrumentation. However, improved accuracy can be obtained from the GPS equipment by using transmitters on the ground rather than in the satellites (e.g., to eliminate atmospheric effects). The more ground transmitters used, the greater the improvement in precision. Furthermore, transmitters on the ground might also be used to provide extended time and area coverage during the early phases of the GPS program.

B. APPROACH

The objective of this task was to "identify those user systems currently under development which could benefit from the early availability of the GPS Test Range Instrumentation." Since there is no direct way to locate the potential programs among the very large number of programs being worked on in the Services, the planned approach was to:

- Identify major programs having
  - (1) A significant amount of testing scheduled after November 1977, and
  - (2) Data requirements which include position, velocity, and time

  by reviewing
  - (1) The latest available RDT&E descriptive summaries,
  - (2) Test range schedules, and
  - (3) Plans and schedules of the Service operational test agencies; OTEA, MCDEC, OPTEVFOR and AFTEC.
- Discuss the programs identified above with the appropriate program offices, test managers, and program monitors to determine if the project's requirements exceed current range instrumentation capability and if there would be any benefit in using the GPS test range instrumentation capability.
- Identify those programs having testing needs that will potentially require the acquisition of additional test range instrumentation and that could be satisfied by GPS test range instrumentation. For each program identified, list its specific testing needs.

The planned approach was followed to the extent time allowed except that the only RDT&E descriptive summaries available were the Army and Air Force summaries for FY 1975. However, the major difficulty encountered was that requirements for tests to be conducted after November 1977 were found to be incomplete or nonexistent. Furthermore, most requirements that did exist seemed to reflect current range capability. That is, the philosophy appeared to be one of requesting what could currently be obtained rather than requesting data that might require an advance in the state-of-the-art. Thus, the potential benefits that have been identified can be considered only as such since to date no test requirements appear to have been written that require the use of GPS other than those for Trident I. In addition, cost implications and test schedule constraints imposed by the necessity to use current range instrumentation could not be ascertained at this early date.

C. PROGRAMS IDENTIFIED AS HAVING A POTENTIAL BENEFIT

From the available documentation, scheduled briefings and discussions, approximately 70 programs were noted as potentially having a significant amount of testing after November 1977 that would require the recording of position, velocity, and/or time data. About 26 of these programs were selected for review with their respective program offices, test managers, or program monitors. From these discussions, seven programs have been identified as potentially benefiting from the early availability of the GPS test range instrumentation. Included are the B-1 and F-16 aircraft, the Air-Launched and Sea-Launched Cruise Missiles, the MINUTEMAN X strategic missile, and the SAM-D and SHORAD air defense systems. Each of these programs has range testing needs that probably require the acquisition of additional instrumentation. The specific testing needs which GPS may be able to satisfy for each of these programs are discussed below. A summary of the discussion is contained in Table 51.

Table 51. Summary of Program Testing Needs Potentially Satisfied by GPS

Program	*Testing Needs Potentially Satisfied by GPS*
Aircraft	
B-1	• Improved flight path freedom. • Position and velocity data for low-altitude flights over water. • Continuous position and velocity data against which to evaluate onboard systems.
F-16	• Improved flight path freedom. • Continuous position and velocity data against which to evaluate onboard systems. • Mobile test range capability to support operational climatic tests and future foreign sales.
Antiaircraft Systems	
SAM-D and SHORAD	• Mobile test range capability to support operational tests. • Improved capability to monitor multiple target tracks.
Missiles	
Air-Launched Cruise Missile	• Instrumentation to support longer flight paths.
MINUTEMAN X	• Data to evaluate range capability. • Increased azimuth launch freedom.
Sea-Launched Cruise Missile	• Instrumentation to fill gaps in radar coverage.

1. Aircraft

B-1. Low altitude, over-water flights are scheduled to be conducted at Vandenberg Air Force Base. However, the Space and Missile Test Center at Vandenberg considers the current range instrumentation (radars) to be inadequate for this test. An onboard GPS receiver could be used to compute the position and velocity of the aircraft for onboard recording or relay to a ground or airborne control/monitor station. In addition, the current concept for onboard navigation system evaluation requires the aircraft to fly over specific points on the ground (navigation check points). This limits the flight paths that are available to test the aircraft's navigation system. An onboard GPS receiver could alleviate this limitation. Furthermore, the onboard GPS system would provide continuous position and velocity profiles against which the B-1 navigation system could be evaluated. This could reduce the number of flights required.

F-16. There is no instrumented range capability in the areas to be used to conduct the climatic tests. An onboard GPS receiver could be used to provide the range instrumentation for this test. In addition, onboard GPS equipment would provide continuous position and velocity profiles against which the F-16 navigation system could be evaluated. This could reduce the number of flights required to obtain the necessary data. It could also provide improved flight path freedom, especially to test the F-16's low-level capability. Furthermore, an onboard GPS system could provide (in Phase II or Phase III of the GPS Program) mobile instrumentation to support foreign sales.

2. SAM-D and SHORAD Air Defense Systems

These air defense systems have multiple target tracking capabilities that must be evaluated in tactical environments at a number of different test sites. These sites do not currently have adequate range instrumentation. Currently available instrumentation that could be used to equip each site or be moved from site to site to support the tests has already been judged as too expensive. Pods, each containing a GPS receiver and a recorder, which could be mounted on the aircraft designated to support the test and removed after the test, could potentially satisfy this need for a mobile test range with a multiple target tracking capability.

3. Missiles

Air-Launched Cruise Missile (ALCM). At the present time there is no sufficiently instrumented test range which is long enough to test the long range capability of ALCM's guidance system, which includes TERCOM and therefore must be tested over land. The current concept is to fly the missile in a racetrack or circular pattern. However, this may not be a sufficient test. An alternate approach would be to use an onboard GPS receiver to provide real-time position and velocity information to an airborne or ground control center. This approach might provide sufficient data such that the missile could be allowed to fly beyond the current limits of the range or between ranges. In addition, the GPS receiver may allow the missiles to be flown over a larger variety of flight paths that could add to the completeness of the evaluation.

MINUTEMAN X (MX). MINUTEMAN flight tests are being conducted at Vandenberg Air Force Base. The impacts are nominally in the Kwajalein area with the evaluation of the missile accuracy being based on data from the metric tracking systems available along the flight trajectory. The increased range potential of the MX and the desire to test the missile along more than one launch azimuth may require range instrumentation beyond that currently available. The use of an onboard GPS receiver to continuously determine the location and velocity of the missile for transmission to a land or shipboard control station could provide the range instrumentation required to exercise the range and azimuth capabilities of the missile.

Sea-Launched Cruise Missile (SLCM). The requirement exists to fly these missiles over land to test their guidance system which includes TERCOM. The current approach is to have test flights originate at the Pacific Missile Range and go inland to one of the air bases (e.g., Dugway AFB, Utah, or Mountain Home AFB, Idaho). The flight paths currently selected for use in these tests do not have adequate radar coverage. One possibility for closing the gaps in the radar coverage is to place a GPS receiver and a transmitter onboard the missile. The GPS receiver could continuously determine the position and velocity of the missile. The onboard transmitter could relay the data to an airborne or ground control/monitor station where it could be analyzed to determine if the missile is following its prespecified track.

D. ADDITIONAL CONSIDERATIONS

The utility of GPS as range [illegible]tation will be inversely related to the weight, cost, size, external drag, and install[illegible]ts of the GPS equipment. Furthermore, it is expected that user equipment in [illegible] that currently being purchased (and perhaps with some modifications) will be req[illegible]r the programs identified to take advantage of early availability of the GPS test range instrumentation capability. In addition, it can be seen that considerable coordination between DDR&E, the programs, the GPS JPO and the user equipment vendors would be required to successfully take advantage of this range instrumentation capability on a significant basis.

Finally, to keep the cost of using the GPS approach down, consideration should be given to developing an arrangement whereby each project could obtain the GPS equipment (with maintenance) required to accomplish its range instrumentation task, return the equipment after completing the task and pay only its prorated share of the equipment's cost and maintenance. For example, for aircraft applications a standard pod (containing a GPS receiver with recorder) could be developed that could be attached to many different types of aircraft. To use the pod, it would only be necessary for the user to set controls indicating the parameters to be recorded and the sampling frequency, insert a blank tape cartridge and attach the pod to the aircraft. A similar set could be provided for land and sea based test vehicles.

APPENDIX A

SUMMARY OF NAVSTAR GPS PROGRAM

Appendix A

SUMMARY OF NAVSTAR GPS PROGRAM

A. BACKGROUND

The first satellite navigation system (TRANSIT) was developed by the Navy to provide a worldwide, two-dimensional positioning capability—primarily to support submarines. The first satellites were launched in the mid-60s and the system is currently operational. Concurrent with the development of TRANSIT, the Navy and Air Force pursued extensive studies, experiments, and hardware developments to devise a satellite navigation system which would overcome some of the deficiencies of TRANSIT and thus be potentially more useful to a larger spectrum of military users. The Navy sponsored the TIMATION program which emphasized the development of high stability oscillators, accurate time transfers and three-dimenstional navigation. The Air Force also performed concept and system design studies for a very accurate three-dimensional navigation system called 621B, which culminated in a series of experiments at Holloman Air Force Base and the White Sands Missile Range. The integration of these separate activities was initiated by a memorandum issued by the Deputy Secretary of Defense on 17 April 1973. This memo designated the Air Force as the lead Service to coalesce the best concepts into a single system that would satisfy the needs of all the military Services. This exercise resulted in a proposal to develop NAVSTAR GPS and the establishment of a Joint Program Office (JPO) with active participation by the Army, Navy, Marines and Air Force. The jointly proposed GPS program was briefed to DSARC 1 on 13 December 1973, and was approved by the Deputy Secretary of Defense in a memo to the Secretaries of the Military Departments on 22 December 1973.

B. NAVSTAR SYSTEM DESCRIPTION

NAVSTAR GPS is a space-based radio position fixing and navigation system that has the potential for providing, on a global basis, highly accurate three-dimensional position, velocity, and system time information to users equipped with suitable (passive) receivers. As illustrated in Figure A-1, NAVSTAR GPS consists of three major segments; namely, the space system, the control system, and the user system segments. These are briefly discussed below.

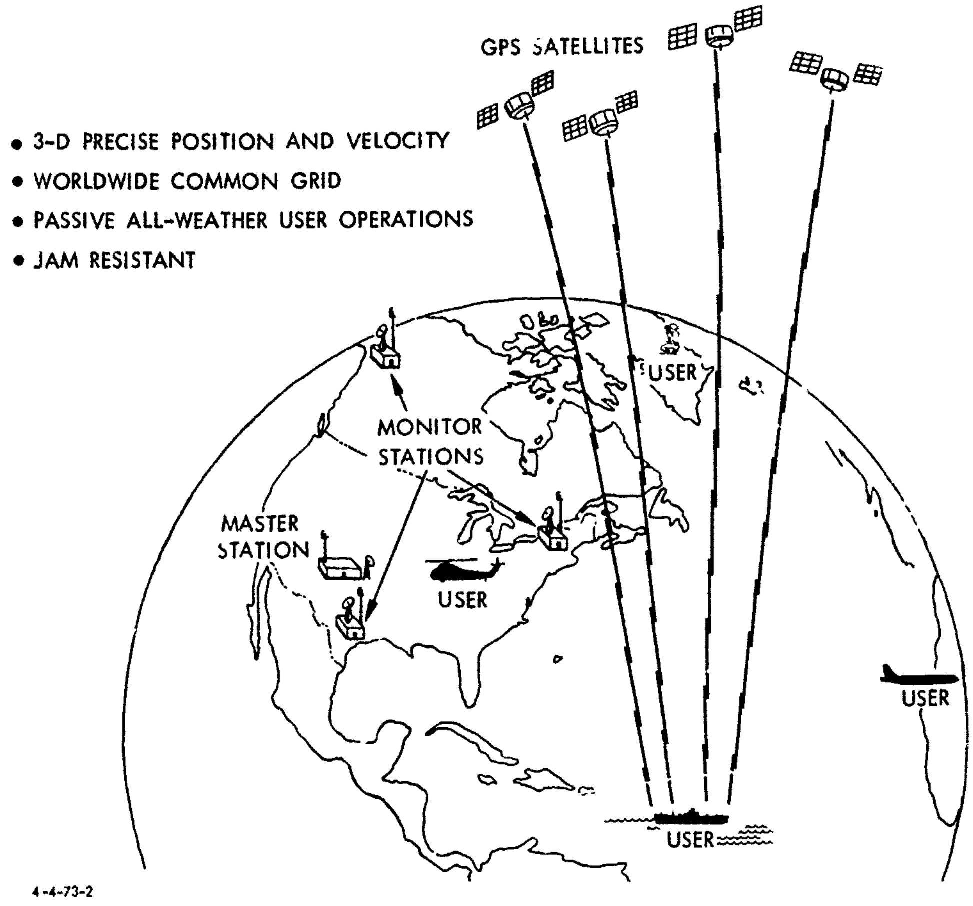

Figure A-1. NAVSTAR GPS Concept

1. Space System Segment

It is planned that the operational space segment will consist of three equi-spaced planes of satellites in circular, 12-hour[1] (~10,000 nmi) orbits, with an inclination of 63 degrees. Each orbital plane is to contain eight suitably phased satellites, for a total of 24. Each satellite will transmit a composite waveform consisting of a Protected (P) Signal and a Clear/Acquisition (C/A) Signal in phase quadrature. The P Signal will be used by the precision military user and is being designed to resist jamming, spoofing, and multipath and also be deniable to unauthorized users by employing transmission security (TRANSEC) devices. The C/A Signal will serve as an aid to the acquisition of the P Signal, and will also provide an uncoded (clear) navigation signal to both the military and civil user.

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[1] The desired period is one-half of a sidereal day (approximately 11 hrs. 58 min.). This synchronizes the satellites to the earth in that the ground tracks are repeated every two orbits (or about once a day).

Both the P and C/A Signals are Pseudo Noise Biphase Shift Keyed (PN/BPSK) continuous sinusoidal carriers and both signals carry system data. System data will consist of such information as satellite ephemeris, ionospheric propagation corrections, and satellite clock biases. Each space vehicle will be assigned a unique set of pseudo noise codes of seven days' length for the P signal and one msec length for the C/A signal.

It is planned the navigation signals will be transmitted on two channels; L_1 and L_2. Channel L_1, the Primary Navigation Channel will be 1575.4 MHz and will carry both the P and the C/A Signals. Channel L_2, the Secondary Navigation Channel, will be 1227.6 MHz and will carry the P and the C/A Signal, but not simultaneously. System data will always be carried on both channels. The additional L_2 signal will permit the high accuracy user to more accurately determine the ionospheric group delay.

The signal waveform is being specifically designed to allow system time to be conveniently and directly extracted in terms of standard units of days, hours, minutes, and integer multiples and submultiples of the second.

2. Control System Segment

Four widely separated Monitor Stations will passively measure range and velocity time histories of all satellites in view. This information will be processed at the Master Control Station (possibly collocated with a Monitor Station) to use in determining satellite ephemerides, clock drifts, electronic delays, etc. An upload station located in CONUS will transmit the necessary system data via a secure link to the satellites.

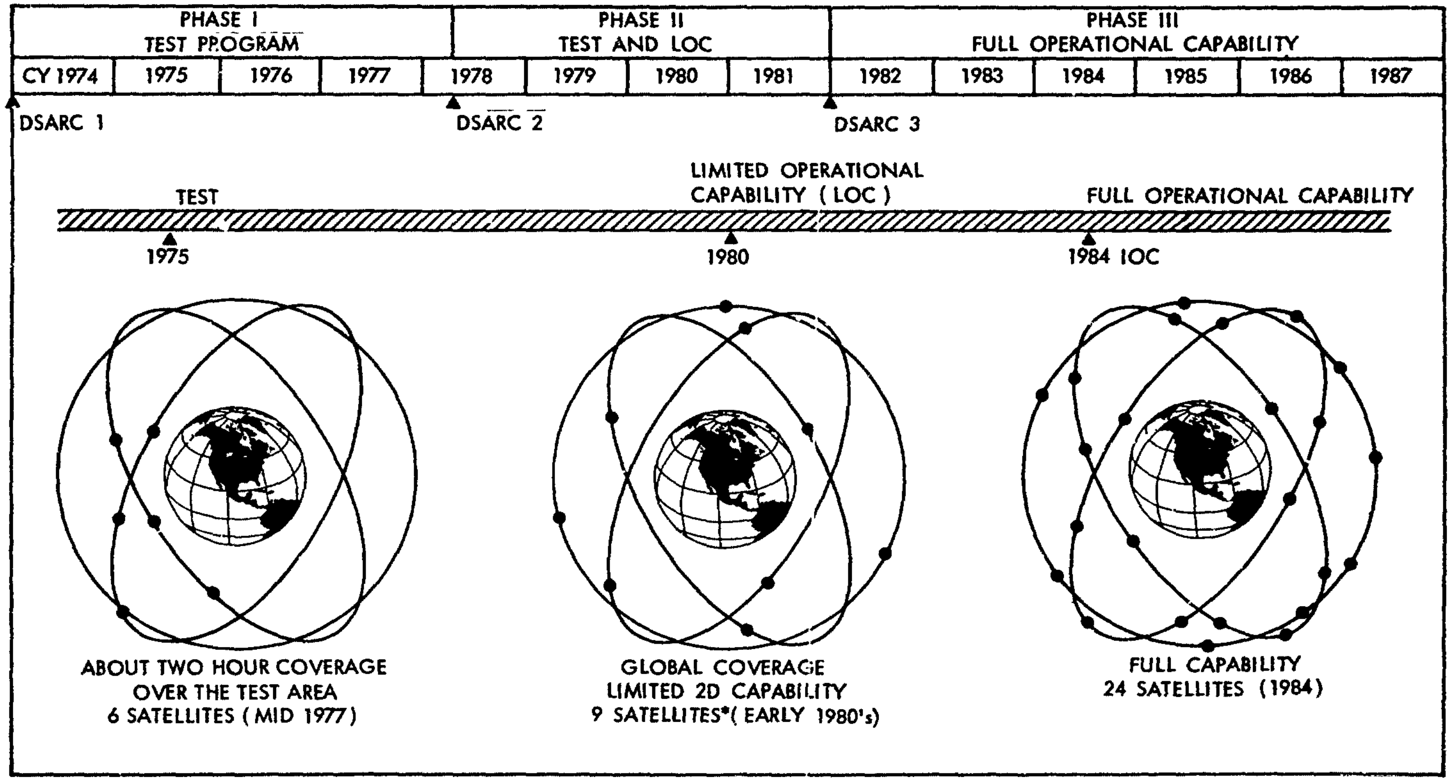
3. User System Segment

The user equipment will in general consist of a receiver, antenna, data processor, and control and display unit. Some user systems will have the capability of being integrated with auxiliary sensors such as inertial and air data systems. The receiver will process the signals from four suitably chosen satellites and will measure four independent pseudo-ranges and pseudo-range rates. The processor will then convert these eight independent measurements into three-dimensional position and velocity of the user, and phase and frequency corrections for the user's clock. The process of solving for position would be carried out in an earth centered coordinate frame, which would then be converted for display to either geographic coordinates (Lat., Long.), UTM grid coordinates, or any other grid convenient for the user. The user equipment will also have the capability of accepting waypoint or destination coordinates in the geographic or UTM grids and providing the user with range, bearing, and cross track error to any of these points.

C. GPS DEVELOPMENT PROGRAM

1. Overview

The development plan for NAVSTAR GPS has three distinct phases as indicated in Figure A-2. The decision at DSARC 1 was to proceed with Phase I, which concentrates on validation of system design concepts, DT&E of user equipments, and limited operational



*Recent GPS program information indicates a range of 9 to 11 satellites

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Figure A-2. NAVSTAR Development Program demonstrations (see Chapter III of this report). A six satellite constellation will be available late in 1977 which will provide about a 2-hour window every day for conducting tests (see Chapter IV of this report) or demonstrations over CONUS and adjacent Pacific and Atlantic ocean areas. Follow-on efforts in Phase II, System Validation, are scheduled to complete the IOT&E of user equipment and lead to an early two-dimensional Limited Operational Capability (LOC) in 1981. The early LOC would be provided by three uniformly spaced satellites in each of three orbits.[1] In order to continue providing high accuracy and three-dimensional capability (as in the Phase I program) for testing or range instrumentation, the satellite constellation for LOC will have to be augmented by at least three satellites for a total of twelve satellites in orbit. Finally Phase III, Full Operational Capability (FOC), is currently scheduled to provide the full (24 satellite) capability in 1984, proceed with major production of user equipment, and verify the operational effectiveness of the system.

a. User Equipment Development

Phase I will start the first of three design-build-test cycles to develop user equipment configurations and to establish firmer estimates of user equipment life cycle costs. During this phase a number of developmental models of user equipment will be designed, fabricated, and tested. Each of these models is being designed to simulate a restricted set of functional requirements so that in total a large variety of user applications will be satisfied. Table A-1 lists the potential equipment classes for a large spectrum of applications and indicates the driving functional requirements for each class of equipment. Final selection of user equipment classes will depend on the results of development model tests, and further review and inputs from the user commands on operational needs. It is intended that the user equipment classes will incorporate a high degree of subassembly commonality in order to minimize equipment life cycle costs.

Final determination of user equipment classes will be accomplished during Phase II, as well as initial production of the low cost Class C set. Production procurement of all other user system classes will be accomplished during Phase III.

The design goals for the major NAVSTAR GPS user equipment characteristics are shown for each of the three program phases in Tables A-2 to A-4. This information was prepared by the NAVSTAR JPO and only slightly modified for this report. The data in Table A-2 for Phase I are based, in the main, on present equipment specifications. The design goals shown in Tables A-3 and A-4 are speculative at this time and represent normal developmental improvements in the first generation sets as well as potential improvements due to new technology.

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[1] Recent GPS program information indicates a range of 9 to 11 satellites for the LOC phase.

Table A-1. Development Plan for NAVSTAR User Equipment

Equipment Class	*Applications*	*Driving Functional Requirements*
A	High Performance Aircraft	High Accuracy* High Dynamics of User High Immunity to Jamming
B	High Performance Aircraft	High Accuracy* High Dynamics of User Medium Immunity to Jamming
C	Mission Support Vehicles (Air, Land, and Sea)	Medium Accuracy† Medium Dynamics of User Low Cost
D	Land and Sea Vehicles	High Accuracy* Low Dynamics of User High Immunity to Jamming
E	Manpack	High Accuracy* Low Dynamics of User High Immunity to Jamming Low Weight and Power
F	Submarines	High Accuracy* Low Dynamics of User Fast Acquisition
M	Missiles	High Accuracy* High Dynamics of User High Immunity to Jamming
S‡	Civil Ships, Boats, and General Aviation	Medium Accuracy Consistent With Very Low Cost

*Better than 10 m for all axes.

†Accuracy (in the range of 15-150 m) will be traded for cost.

‡This application, though not funded by DoD, is being actively pursued by user equipment manufacturers.

Table A-2. Design Goals for NAVSTAR User Equipment (Phase I)

Design Parameters	Equipment Class and Application							
	A	B	C	D	E	F	M*	S*
	High Performance Aircraft With High Antijam	*High Performance Aircraft*	*Mission Support Vehicles*	*Land and Sea Vehicles With High Antijam*	*Manpack*	*Submarine*	*Space Missile*	*SPARTAN, Very Low Cost*
$\sigma_x, \sigma_y, \sigma_z$†	6-9 m	6-9 m	15-20 m	18-25 m	18-25 m	6-9 m	16 m	30-100 m CEP
$\sigma_{\dot{x}}, \sigma_{\dot{y}}, \sigma_{\dot{z}}$†	0.1 kt	0.1 kt	0.5 kt	No Requirement	No Requirement	0.1 kt	0.024 kt	No Requirement
System Time (1 sigma)	18-25 ns	18-25 ns	18-25 ns	1 sec (Displayed)	1 sec (Displayed)	18-25 ns	To Be Determined	1 sec (Displayed)
Time to First Fix ‡§ (90% Probability)	80-180 sec	80-180 sec	200-300 sec	100 sec	100 sec	80-180 sec	400	600 sec
Antijam Margin	44 dB⊕	44 dB⊕	30 dB☆	44 dB⊕	44 dB⊕	44 dB⊕	To Be Determined	30 dB☆
Size	12,200 in^3	12,200 in^3	6,700 in^3	1,100 in^3	1,100 in^3	12,200 in^3	12,200 in^3	2,440 in^3
Weight	123 lb	123 lb	50 lb	23 lb	23 lb	123 lb	66 lb	40 lb
Power	632 W	632 W	151 W	30 W	30 W	623 W	80 W	30 W
MTBF	500 hr	500 hr	500 hr	500 hr	500 hr	500 hr	To Be Determined	

*No JPO-sponsored development programs at present.

†Includes all system errors; without GDOP correction. Accuracies shown are for single fix.

‡Add 4-8 minutes (depending on equipment class) for equipment warm-up from 0°C start. (From Phase I specification)

§Simultaneous conditions of Table II in the User Equipment Specifications—SS US 101B.

⊕Unaided P signal -Code Track Threshold.

☆Unaided C signal—Code Track Threshold.

Table A-3. Design Goals for NAVSTAR User Equipment (Phase II)

Design Parameters	Equipment Class and Application							
	A	*B*	*C*	*D*	*E*	*F*	*M**	*S**
	High Performance Aircraft With High Antijam	*High Performance Aircraft*	*Mission Support Vehicles*	*Land and Sea Vehicles With High Antijam*	*Manpack*	*Submarine*	*Space Missile*	*SPARTAN, Very Low Cost*
σ_x, σ_y† σ_z†	5-8 m	5-8 m	15-20 m	5 m CEP 10 m PE	5 m CEP 10 m PE	5-8 m	15 m	30-50 m CEP
$\sigma_{\dot{x}}, \sigma_{\dot{y}}, \sigma_{\dot{z}}$†	0.08 kt	0.08 kt	0.4 kt	No Requirement	No Requirement	0.08 kt	0.024 kt	No Requirement
System Time (1 sigma)	15-25 ns	15-25 ns	45-60 ns	1 sec (Displayed)	1 sec	15-25 ns	To Be Determined	1 sec (Displayed)
Time to First Fix‡§(90% Probability)	80-100 sec	80-100 sec	200-300 sec	60 sec	60 sec	80-100 sec	60 sec	400 sec
Antijam Margin	44 dB⊕	44 dB⊕	30 dB☆	44 dB⊕	44 dB⊕	44 dB⊕	To Be Determined	30 dB☆
Size	To Be Determined		6,700 in^3	1,000 in^3	1,000 in^3	To Be Determined	400 in^3	800 in^3
Weight			50 lb	20 lb	20 lb		16 lb	36 lb
Power			151 W	20 W	20 W		12-16 W	14-18 W
MTBF			500 hr	1,000 hr	1,000 hr		1,000 hr	To Be Determined

*No JPO-sponsored development programs at present.

†Includes all system errors; without GDOP correction. Accuracies shown are for single fix.

‡Add 4-8 minutes (depending on equipment class) for equipment warm-up from 0°C start. (From Phase I specifications)

§Simultaneous conditions of Table II in the User Equipment Specifications—SS US 101B.

⊕Unaided P signal—Code Track Threshold.

☆Unaided C signal—Code Track Threshold.

Table A-4. Design Goals for NAVSTAR User Equipment (Phase III)

Design Parameters	Equipment Class and Application							
	A	B	C	D	E	F	M*	S*
	High Performance Aircraft With High Antijam	*High Performance Aircraft*	*Mission Support Vehicles*	*Land and Sea Vehicles With High Antijam*	*Manpack*	*Submarine*	*Space Missile*	*SPARTAN, Very Low Cost*
σ_x, σ_y † σ_z †	4-7 m	4-7 m	15-20 m	3 m CEP 3 m PE	3 m CEP 3 m PE	4-7 m	10 m	30 m CEP
$\sigma_{\dot{x}}$, $\sigma_{\dot{y}}$, $\sigma_{\dot{z}}$ †	0.05 kt	0.05 kt	0.02 kt	No Requirement	No Requirement	0.05 kt	0.024 kt	No Requirement
System Time (1 sigma)	12-21 ns	12-21 ns	45-60 ns	1 sec (Displayed)	1 sec (Displayed)	12-21 ns	To Be Determined	1 sec (Displayed)
Time to First Fix‡§(90% Probability)	80-180 sec	80-180 sec	200-300 sec	30 sec	30 sec	80-180 sec	60 sec	300 sec
Antijam Margin	44 dB⊕	44 dB⊕	30 dB☆	44 dB⊕	44 dB⊕	44 dB⊕	To Be Determined	30 dB☆
Size Weight Power MTBF	To Be Determined			500 in^3 8-12 lb 10 W 2,000 hr	500 in^3 8-12 lb 10 W 2,000 hr	To Be Determined	250 in^3 10 lb 8-12 W 2,000 hr	800 in^3 To Be Determined

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*No JPO-sponsored development programs at present.

† Includes all system errors; without GDOP correction. Accuracies shown are for single fix.

‡Add 4-8 minutes (depending on equipment class) for equipment warm-up from 0°C start. (From Phase I specification)

§Simultaneous conditions of Table II in the User Equipment Specifications—SS US 101B.

⊕Unaided P signal—Code Track Threshold.

☆Unaided C signal—Code Track Threshold.

APPENDIX B

MODEL FOR DETERMINATION OF COST AVOIDANCE

Appendix B

MODEL FOR DETERMINATION OF COST AVOIDANCE

The cost avoidance values shown in Chapter II are determined by a formal model programmed for EDP. This appendix describes the broad outlines of the model.

The model calculates procurement and maintenance costs of positioning and navigation equipment by individual AN number and for selected groups of AN numbers (current and future, including the GPS system). Costs are determined in a three-step process. The first step calculates total required inventories for each individual AN number across all prime mission equipment (PME) specified by a force structure. The second estimates procurement and maintenance costs associated with the required inventories. The third aggregates the estimated costs or forms totals for equipment with related characteristics, mission, etc. (e.g., TACAN, enroute radio reference) according to predetermined specifications.

A. DETERMINATION OF REQUIRED INVENTORIES

Two basic inputs are employed in determining inventory requirements. The first is a time phased (15 year) force structure by PME. (In Chapter II the force structure PME consisted of all aircraft in Army, Navy, and Air Force inventories, by model and series, and Naval ships, by class.) The second input consists of time phased suites (AN numbers and associated quantities per unit of PME) of navigation equipments for each PME identified in the force structure.

For each PME, total installed inventory requirements are determined for each AN number contained in its suite for each year (the product of the quantity of that PME in the force structure and the quantity of the AN number in the suite). For each AN number and for each year, inventories are summed across all PME to yield a schedule of aggregate installed inventory requirements. Yearly requirements for spares are then determined according to a multiplitive spares factor associated with the AN number. The yearly totals of installed and spare equipment comprise the schedule of total required inventory. Thus, the installed inventory requirement for a single AN number generated by one PME in a single year is

$$P_{i,j,k} \cdot Q_{i,j,k}$$

where

P = the number of units of the PME (e.g., the number of aircraft of a given model/series) contained in the force structure

Q = the quantity of the AN number (generally one) contained in the suite of the PME

i = value of the index identifying an AN number

j = value of the index identifying a year

k = value of the index identifying a PME.

The total requirement for installed inventory is

$$I_{i,j} = \sum_{k=1}^{n} \left(P_{k,j,k} \cdot Q_{i,j,k}\right)$$

where

I = the total installed inventory requirement across all PME

P and Q are defined as above

and the total inventory requirement is

$$R_{i,j} = (1\text{-}s_i)(I_{i,j})$$

where

R = the total inventory requirement

s = spares percentage associated with the AN number

I is defined as above.

B. ESTIMATION OF PROCUREMENT AND MAINTENANCE COSTS

Except for non-recurring costs associated with development and production start-up, estimated costs are concerned only with procurement of new equipment[1] and maintenance of presently installed equipments. Maintenance costs are estimated for each AN number based on a maintenance rate for that equipment stated as a percentage of average or final procurement cost. The percentage rate is applied to the average value of installed inventory for each year, i.e.,

$$M_{i,j} = m_i \left[\frac{V_{i,j} + V_{i,j-1}}{2}\right] \text{, and}$$

---

[1] New equipment is defined to include both new production of current AN number equipment and production of new models of electronic equipment. Equipments are procured for a number of purposes, including outfitting of new PME, replacement of existing installed equipment, and retrofit of existing PME with new types of equipment.

$$V_{i,j} = C_{i,j} \cdot \sum_{k=1}^{n} \left(P_{i,j,k} \cdot Q_{i,j,k} \right)$$

where

M = annual maintenance cost associated with the AN number

V = value (or historical procurement cost) of the installed inventory of the AN number

m = percentage maintenance rate associated with the AN number

C = average or current unit procurement cost of the AN number

P and Q are the same as defined above.

As the force structure and suite compositions of PME vary from year to year, so will the level of total required inventories of different AN numbers. For any one the quantities of equipment that must be newly procured in any year depends upon three values: the installed inventory required in that year, the change in installed inventory required over the prior year, and the pattern of all past years' requirements and procurements.

Two sources of potential requirements for new procurement are treated by the model. The first, and most obvious, arises from changes in the level of installed inventory requirements from one year to the next. This requirement is either positive or negative as inventory requirements increase or decrease (thereby freeing existing equipment). The second source is always positive and arises from wear-out or unintentional loss of equipments (accidents, cannibalization, etc.) requiring replacement. Equipment losses, or replacements, for each year are estimated as a percentage of the average installed inventory of that year,

$$F_{i,j} = f_i \left(\frac{I_{i,j} + I_{i,j-1}}{2} \right)$$

where

F = inventory losses or replacements

f_i = inventory loss rate associated with an AN number

I is defined as above.

The sum effect of these, denoted as net requirements, is expressed as follows

$$N_{i,j} = R_{i,j} - R_{i,j-1} + F_{i,j}$$

where

N = net requirement for an AN number

R and F are defined as above.

Two potential sources are available for satisfying the net requirement. The obvious, procurement of equipment, is treated as a secondary source. The primary source springs from recognition by the model that electronic equipment can be transferred between PME and across time. That is, should net requirements in any year (N_{ij}) be negative, surplus or excess equipments result that can be stored to offset positive net requirements of a future period. The size of the available surplus at the end of any year is the net result of the pattern of prior years' inventory requirements and procurements. New equipments are procured only after the surplus of the prior year is exhausted. Thus

if $N_{i,j} \geqslant E_{k,j-1}$ then $E_{i,j} = 0$, and

$$A_{i,j} = N_{i,j} - E_{i,j-1} \ ;$$

if $N_{i,j} < E_{i,j-1}$ then $E_{i,j} = E_{i,j-1} - N_{i,j}$, and

$$A_{i,j} = 0$$

where

E = available surplus of an AN number

A = quantity to be procured

N is defined as above,

and

$$B_{i,j} = C_{i,j} \cdot A_{i,j}$$

where

B = cost associated with the quantity to be procured

C and A are defined as above.

C. AGGREGATION OF ESTIMATED COSTS AND QUANTITIES

The final processing step of the model requires little explanation. Once individual equipment totals have been determined (15-year) schedules of quantities and costs) they can be aggregated in any combination(s) specified.

APPENDIX C

DESIGN AND COST DETAIL OF THE CURRENT AND ADVANCE TECHNOLOGY USER EQUIPMENTS

Appendix C

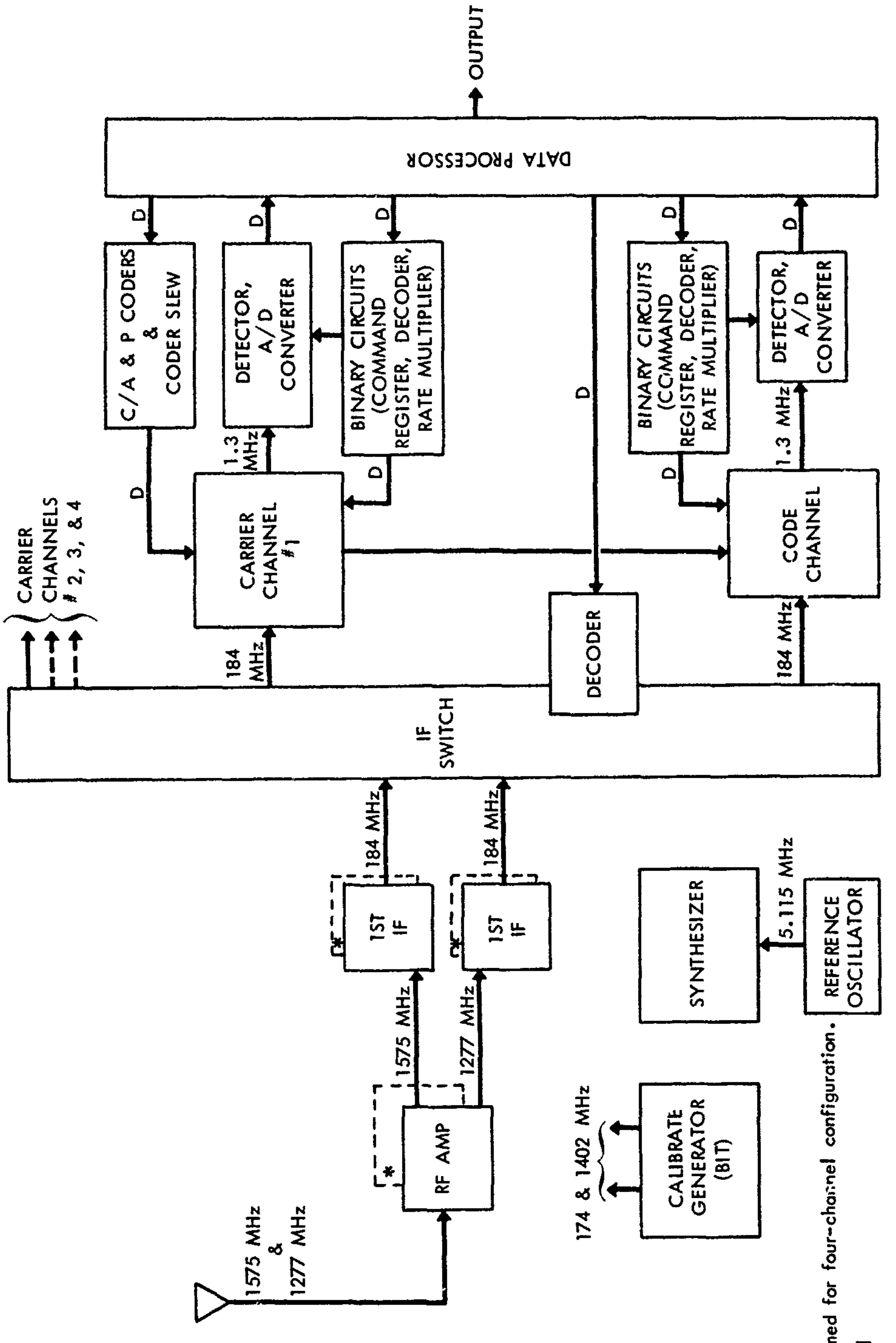
DESIGN AND COST DETAIL OF THE CURRENT AND ADVANCE TECHNOLOGY USER EQUIPMENTS

The purpose of this appendix is to provide backup detail for the comparisons of current and advanced technology user equipment presented in Section E of Chapter II. The design concept formulated by Magnavox was defined by subsystem and the electronic (signal and data processing) subsystems further defined in terms of function performed. Each function was then analyzed to obtain quantities of micro-circuit elements, of different types, it would contain. Quantity requirements, by type, were aggregated across all functions to develop the total quantities, by type of user equipment, shown in Table 14 of Chapter II. Cost estimating parameters were then developed for each type of micro-circuit and non-electronic subsystem as shown in Table 15 of Chapter II. Section 1, below, describes the compositions of the user equipment. Section 2, below, explains the derivations of the cost parameter values.

A. COMPOSITION OF EQUIPMENT

Figure C-1 illustrates the block diagram of the near technology design. Table C-1 describes the composition of each of the major functions of the receiver. Identification of types and quantities of circuit elements follows the Magnavox manpack concept.

Figure C-2 illustrates the block diagram of the advanced technology design assumed and the description of each major function is given in Table C-2. The difference between the near and advanced systems results from maximum use of digital LSI, employment of strip-line linear micro-circuits, and for L-band processing minimization of discrete components. With the projections of the growth in LSI densities and capabilities it will be possible to convert to digital processing at frequencies up to 200 mega-hertz. (Conversion frequencies are limited to a few mega-hertz with currently available devices.) As a result the linear signal processing may be limited to L-band and first I.F. frequencies and to the higher frequency ranges of the synthesizer and calibrate generator. Given the anticipated low cost of LSI chips it could be efficient to convert the reference oscillator signal to digital before processing by the synthesizer and to convert back to analog above the mega-hertz constraint.



*Two assumed for four-channel configuration.

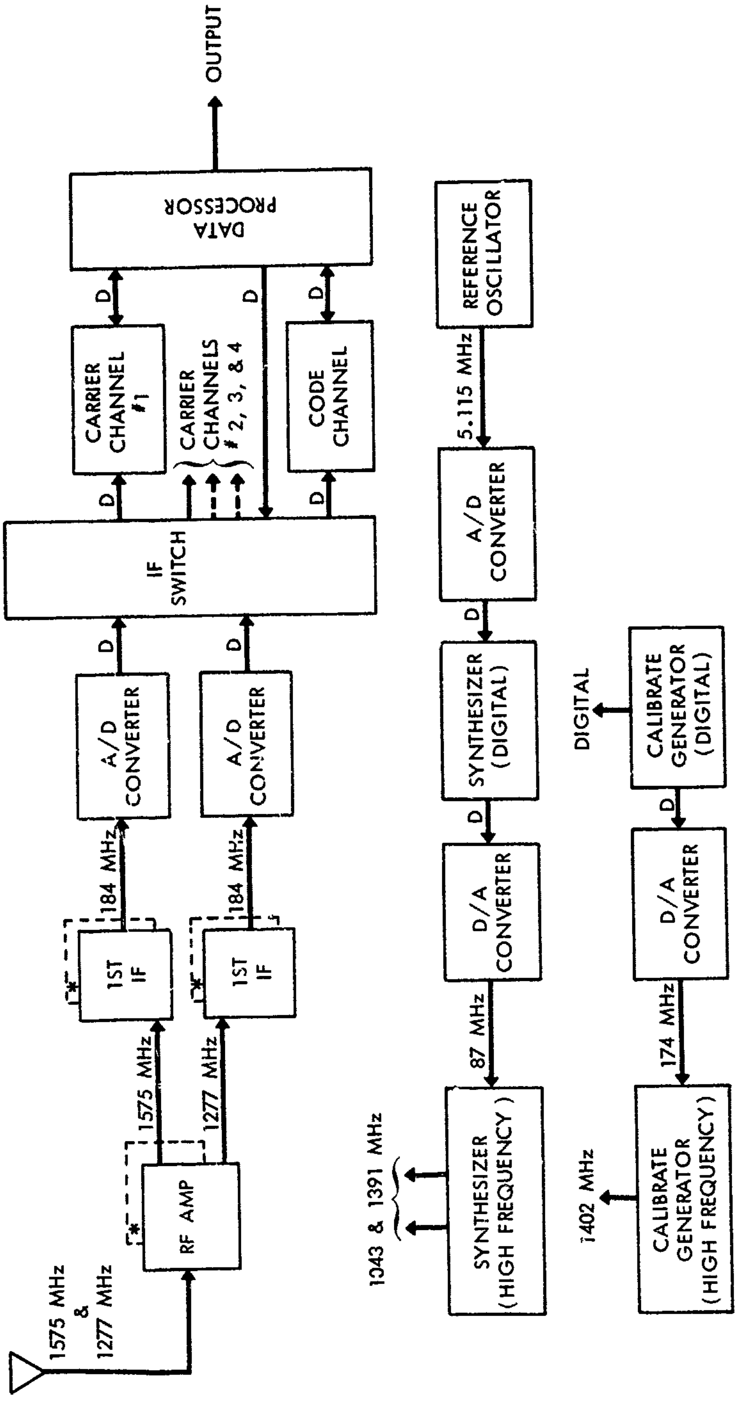
D - Digital

10-22-75-21

Figure C-1. Block Diagram of Near Future Technology Receiver

Table C-1. Composition of Current Technology Receiver

Function (or LRU)	Type of Processing	Type of Circuitry	Quantity of Elements per Functions (Boxes, Chips)	Quantity of Functions per Receiver	
				2 Channel	4 Channel
RF Amplifier	Linear	Discrete	–	1	2
1st IF Amplifier	Linear	Strip-Line	3	2	4
IF Switch - Switch - Decoder	Linear Digital	Thin Film LSI	1 1	1 1	1 1
Carrier Channel	Linear	Thin Film Hybrid } Thin Film LSI	6 3 6	2	4
Code Channel	Linear/Digital	Thin Film Hybrid } Thin Film LSI	6 2 6	1	1
"C/A" and "P" Channel Coders and Slew	Digital	LSI	4	2	4
A/D Converter and Detector	Linear/Digital	Hybrid } Thin Film LSI	2 2	3	5
Binary Circuits	Digital	LSI	3	3	5
Synthesizer	Linear	Strip-Line Thin Film	2 3	1	1
Code Generator/BIT	Linear	Strip-Line Thin Film	1 1	1	1
Data Processor	Digital	LSI	9	1	1
Summary			Number of Unique Micro-Circuit Elements	Total Quantity of Micro-Circuit Elements per Receiver	
				2 Channel	4 Channel
		Strip-Line Boxes	5	9	15
		Thin Film/Hybrid Boxes	13	37	59
		LSI Chips - Receiver	12	45	75
		LSI Chips - Computer	3	6	6



*Two assumed for four-channel configuration.

D - Digital

10-22-75-22

Figure C-2. Block Diagram of Advanced Technology Receiver

Table C-2. Composition of Advanced Technology Receiver

Function (or LRU)	*Type of Processing*	*Type of Circuitry*	*Quantity of Elements per Function (Boxes, Chips)*	*Quantity of Functions per Receiver*	
				2 Channel	*4 Channel*
RF Amplifier	Linear	Strip-Line	3	1	2
1st IF Amplifier	Linear	Strip-Line	3	2	4
A/D Converter	Linear/Digital	Hybrid } Thin Film Hybrid } LSI	1 1	3	3
IF Switch	Digital	LSI	1	1	1
Carrier Channel	Digital	LSI	4	2	4
Code Channel	Digital	LSI	3	1	1
Synthesizer (low frequency)	Digital	LSI	1	1	1
Synthesizer (high frequency)	Linear	Strip-Line	3	1	1
Calibrate Generator/BIT (low frequency)	Linear	LSI	1	1	1
Calibrate Generator/BIT (high frequency)	Linear	Strip-Line	3	1	1
D/A Converter	Digital/Linear	Hybrid } LSI Hybrid } Thin Film	1 1	2	2
Data Processor	Digital	LSI	6	1	1
Summary			*Number of Unique Micro-Circuit Elements*	*Total Quantity of Micro-Circuit Elements per Receiver*	
				2 Channel	*4 Channel*
		Strip-Line Boxes	12	15	24
		Thin Film/Hybrid Boxes	2	5	5
		LSI - Receiver	9	19	27
		LSI - Computer	3	6	6

B. DERIVATION OF ESTIMATING PARAMETERS

Due to the nature of available data, costs of different types of components were estimated in several ways. This section lists the cost assumptions employed and discusses the manner they were derived Where possible data sources are described or cited. Table 15 of Chapter II summarized the parameters used to estimate nominal costs of user equipment for each receiver technology. (In all cases the parameter values are assumed to apply at quantity 1000.)

All parameters are based on large volume, large lot production. Except for the commerical pocket calculator and electronic watch markets experience with micro-circuit production has been predominantly with small quantities and in relatively small lot sizes. This has three implications for interpretation of available data and formulation of the estimating parameters. First, a considerable portion of the average cost of current micro-circuits for military and scientific uses is composed of non-recurring costs for initial design and tooling and batch setup costs (for both processing and screening). Available cost data reflect this non-recurring cost component, with no backup data to allow its separation. Second, the impact of the typically small lot buys by the military can be argued as a major factor in the relatively high cost increment associated with military screening. With large buys one can expect the use of automated screening and an attendant reduction in costs. The values derived assume a minimum increment for this screening on the basis of the large lot and volume assumption. Third, efficient production methods vary with lot sizes and volume. Capital expenditures (non-recurring costs) can be, and will be, traded for smaller recurring production costs for larger planned production runs in such a way as to minimize total cost. As a result the estimates shown in Table 15 of Chapter II close to the high end of information obtained on non-recurring costs and close to the low end for recurring costs.

Cost/quantity relationships in electronic production do not appear to be well understood, verified, or accepted (as in industries where complex assembly dominates production costs, like airframe). Of the several dimensions of the cost/quantity phenomenon those concerned with lot size and cumulative production (learning) have received the greatest attention and, on logical grounds, should have impacts large enough to be significant under volume production conditions. Unfortunately there are no data available today to verify the impact of either or to permit their separation. For the various elements of the user equipment rates of cost decrease with rising cumulative production (learning) have been assumed in proportion to subjective judgments of the amount of assembly labor they entail.

The remainder of this section discusses the derivation of the individual parameter values.

1. LSI- Digital and Linear Monolithic

Costs of current generation chips (primarily MOS technology) were developed after conversations with a number of representatives of both manufacturing and using companies and laboratory personnel. Four parameters have been estimated; the recurring and non-recurring costs of both near-future and advanced technology devices.

a. Non-Recurring Costs

The near future parameter is based on current MOS devices. Estimates ranging from $50,000 to $150,000 were obtained with manufacturers generally quoting in the lower range (between $50,000 and $100,000) and user industries talking in terms of over $100,000 with statements similar to, "they quote 50 or 75 thousand until you get down to specifics and then it goes up." No doubt there is a wide range of chip complexities other considerations that impact on non-recurring cost and the range of actual cost may wider than these limits. There was no way to judge the relative complexity or other relevant considerations for devices suitable for the GPS system and the higher level of $150,000 has been assumed as the nominal value.

When one moves into the area of high density advanced devices there appears to be a general agreement that non-recurring cost will increase in direct proportion to the increase in density. Thus for a density of 200,000 components (such as is advertised to be available within a few years) non-recurring costs could be expected to rise an order of magnitude over the "typical" 20.000 component MOS device. Given the increased complexity of circuitry that can be designed and the tighter manufacturing tolerances required the order of magnitude increase appears reasonable.

b. Recurring Costs

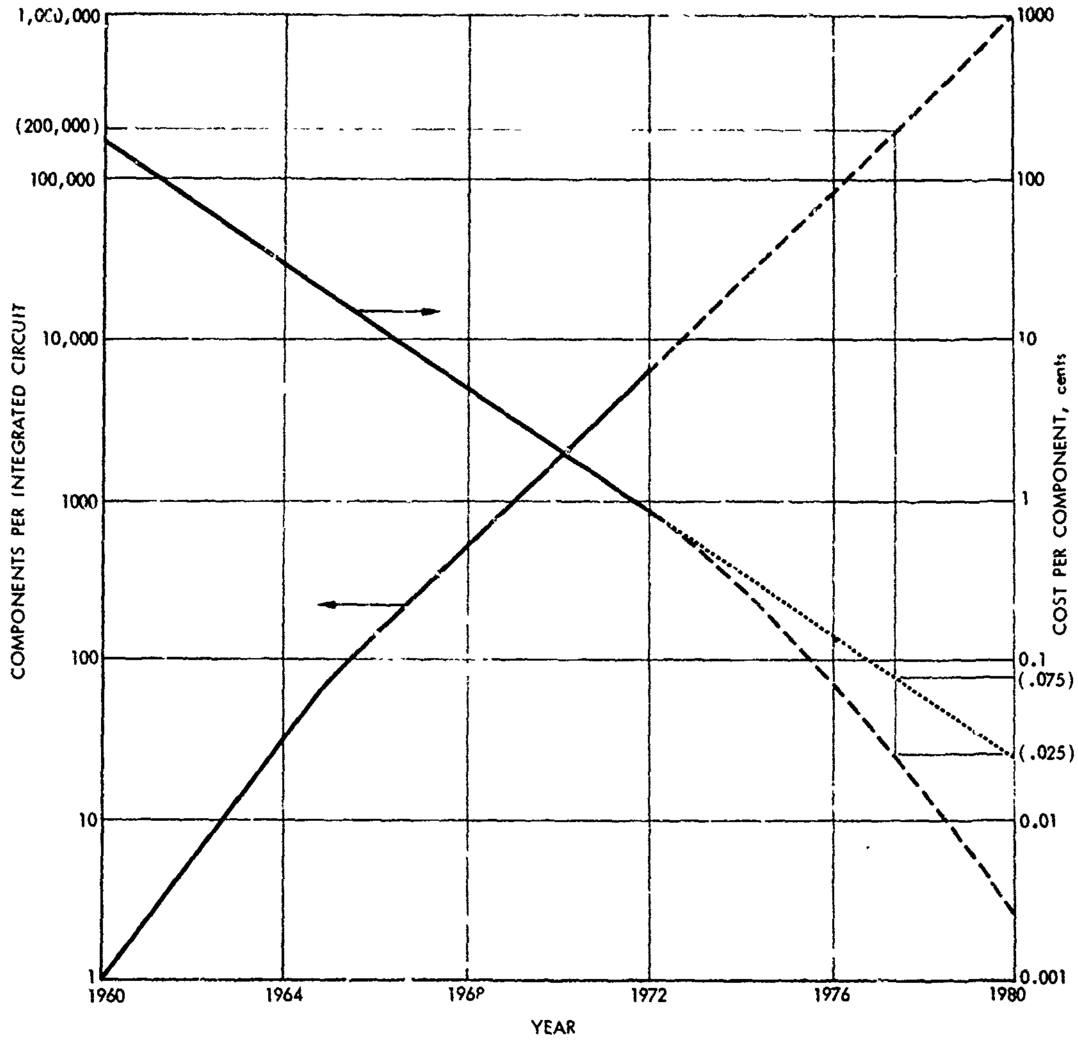
Observed differences in market prices of presently marketed MOS chips exceed ten times without obvious reasons. Manufacturers' price lists are available, but such catalogue prices contain unknown amounts of non-recurring costs and may reflect widely different and unknown competitive market conditions. In the absence of further information the nominal recurring chip cost was derived as shown in Table C-3. A representative range of an uncut 50-chip wafer is $3.00 to $5.00, and assuming the yield rate of military screened chips is close to ½ percent, the range of final costs narrows to between $50 and $80. This is in rough agreement with the assertion that "between 99 percent and 99.86 percent of final cost is represented by reject and screening costs"–implying a range of $10 to $71. While the assumed increment for military screening (two times) is smaller than current industry experience, it appears reasonable with the assumption of high volume and automated screening. A nominal cost of $60 per chip has been assumed.

Table C-3. Derivation of LSI Device Recurring Cost (dollars - 1975)

Material and Initial Processing Cost of a Wafer Containing 50 Chips		*5.00*
Cost per Chip From Uncut Wafer		*0.1*
For Yield Rates of	*2%*	*1/2%*
Material cost of a "good" chip	5	20
Double cost for commercial screening	10	40
Double cost again for military screening	20	80

Turning consideration toward high density chips of the future there is no reason to assume material and initial processing costs to differ from MOS technology. Due to the increased number of components per chip one could expect both higher reject rates and screening costs. However, one can also anticipate technological advances in manufacturing and screening machinery and processes that will serve as partial offset.

Figure C-3 shows the same density/cost projections as Figure 4 of Chapter II. Decreases in cost per component have accompanied both increasing densities and the



Source: Hittinger, William C., "Metal-Oxide-Semiconductor Technology, 'Scientific American, August 1973, Vol. 229, No. 2, p. 28.

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Figure C-3. Estimates Density and Cost per Component as Functions of Time for LSI Devices passage of time, and it has been assumed that density is dominant in predicting cost to permit projections of cost based on density without reference to a time frame. The author presented no rationale for the decreasing slope of the cost-trend line. A continuation of the linear trend is also shown here, and the two are assumed to bracket the range of recurring costs of future devices. The mid-point of this range implies a recurring cost of $100 for a density of 200,000 components, and this value has been adopted for estimating user equipment costs.

2. Other Linear Micro-Circuits (Thin Film, Hybrids, etc.)

Information on linear circuits was obtained from only one manufacturer and one using company. As a result the data are sketchy yet show inconsistencies similar to those obtained for LSI chips. The user company data consisted of costs on one contract for a custom thick film device containing 10 to 12 ICs and are summarized below.

Non-recurring cost	$4,000
Recurring cost (lots of 25)	$ 150

Part of the information obtained from the manufacturer is summarized in Table C-4. Over the range of quantities shown the rate of cost reduction is roughly 85 percent for the complete package and 82 percent for the labor component. The source of these figures ventured the opinion that one might expect a continual 90 percent rate of progress over a large production run. Non-recurring costs were estimated to range between $2,000 and $10,000 with an average of $4,000.

A somewhat different estimate was given by another person from the same organization. In this case a recurring cost of $500 was estimated for a design of a dual channel L-band amplifier and mixer suitable for use in the GPS front end. The package consisted of six or seven brass cans of strip-line circuitry mounted on a mother board with all required external connections. This estimate was not related to any lot size and did not include military screening. The cost increment for military qualification was estimated at three to four times that of the unqualified cost.

Table C-4. Recurring Cost of Linear Micro-Circuits (dollars - 1975)

	Recurring Cost	
	Including Material	*Excluding Material*
Lots of 10		
Simple Device	300	200
Complex Device	800	500
Lots of 1,000		
Simple Device	100	50
Complex Device	300	150

In formulating the nominal estimating parameters (non-recurring of $10,000, recurring of $200, and 90 percent rate of cost reduction) no distinctions have been made between the various types of circuits (thin film, strip-line, etc.), and with one exception these values were applied to all linear circuitry. The one exception involves hybrids containing large scale linear monolithics. Here costs were considered not to include chip costs which were estimated as a separate LSI component.

Linear micro-circuits are frequently designed for packaging in cast metal containers called "MIC" boxes. A principal advantage is providing a rigid support for the circuit substrates. A typical MIC box is nearly 1 inch thick, contains several substrates, and performs roughly three times the number of electronic functions as a substrate mounted in a conventional brass can. MIC packaging does not appear to contribute to recurring costs on a per function performed basis. Non-recurring costs were estimated to range between $10,000 and $35,000, with an average of $15,000–roughly three times that of conventionally packaged circuits. The nominal estimating parameters reflect these equivalences between MIC and brass can circuits–recurring of $700 including a $100 increment for MIC packaging and non-recurring of $40,000 including an increment of $10,000 for packaging.

No anticipations of significant technological advances in linear micro-circuits were expressed by anyone contacted. As a result the same costs and capabilities were assumed for both the near and advanced technology concepts.

3. Micro-Computer Costs

Several companies market complete micro-computers for the commercial market, and military qualified units have also been produced. In addition a number of companies manufacture LSI components. As a consequence more data are available and recurring costs have been estimated in a slightly different fashion.

Initial estimates, based on the parameters adopted for MOS chips, produced a seemingly low estimate of $1,200, and a more conservative approach yielded the estimates shown in Table C-5. This estimate is approximately double the price of three recently introduced MOS technology commerical micro-computers. More exact comparisons between

Table C-5. Estimated Recurring Cost of Representative Current Generation Micro-Computer

Element	*Quantity*	*Unit*	*Unit Cost, Commercial (dollars - 1975)*	*Military Screening Multiple*	*Unit Cost, Military (dollars - 1975)*
Micro-Processor	1	each	250	4	1,000
Input/Output Control	2	each	50	4	400
Memory*	65,000	bits	.001	4	260
Case, Assembly, etc., at 25 percent of chip costs					415
Total					2,075

*2^{13} words at 8 bits per word.

the commercial computers and one suitable for GPS are not possible since insufficient data are available on the commercial systems and detail specifications for the GPS system have not been formulated. What is known of the commercial systems is listed below.

(1) Digital Equipment Corp., PDP-8A KIT consisting of a main frame and 4,000 words of storage–$1,195.

(2) Digital Equipment Corp., LSI 11 (newer than the PDP-8A KIT) contains 110,000 transistors–less than $1,000.

(3) Motorola product (model number not known) contains 60,000 transistors (in a micro-processor, 2 input/output control units, and 7 memory packages) with a 10 microsecond add time–$975.

For the advanced technology system the linear extrapolation of the cost trend in Figure C-3 would estimate the 1980 cost of comparable equipment at 20 percent or $415. This apparently low figure was arbitrarily increased by 50 percent.

Nominal non-recurring cost values are based on the estimate of development cost of custom MOS chips–$150,000. In the near technology case four different chips were assumed (micro-processor, input/output control, random access memory, and read only memory). In the advanced technology case three chip developments were assumed at $1.5 million each. The assumption of development of custom chips for the GPS system is open to question since a ready availability of suitable chips can probably be assumed. However, the impact on average user equipment cost is negligible. Should the total procurement quantity be as low as 25,000 the impact is less than $200 for the advanced system.

4. Other User Equipment Components

a. Reference Oscillator

Estimates of single and dual quartz crystal assemblies (with heaters) range generally between $1,000 and $3,000. In the absence of a more definitive specification for the GPS system an average recurring cost of $2,000 was assumed with a 90 percent cost/quantity factor. It was further assumed that the crystal assembly could be "off-the-shelf," but a nominal $50,000 non-recurring cost has been assumed for modification and integration into the system.

b. Discrete Components

Efforts to obtain specifications and reliable counts of discrete components contained in the Magnavox manpack design concept were not successful, nor were efforts to obtain generalized cost estimates for classes of discrete components. The values shown in Table 15 of Chapter II are based on a rule-of-thumb estimate of $20 of purchases parts per micro-circuit element. For the near-future system an allowance is also included to account for discrete circuit RF amplifiers.

c. Assembly, Test, and Rework

The ratio of parts to labor for automated line production of discrete component circuits has been estimated to fall between 2:1 and 3:2. Considering the nature of military quality circuits it was assumed that labor content would be near the high end of this range and a value of 65 percent was assumed

Unpublished data compiled by Pye TMC Ltd of London indicate that the labor content of LSI telephone switching circuitry is roughly one-tenth that of discrete and electromechanical versions, and a rate of 6.5 percent was assumed.

For linear micro-circuits one could expect the ratio of labor to material to be closer to that of LSI than discrete circuits, and a value of 20 percent was assumed.

These factors were applied to the cumulative average materials bill for each type of circuitry at the thousandth unit. Since it consists wholly of assembly labor a cost/quantity factor of 80 percent has been assumed.

d. Packaging and Other

This element includes the three items; antenna, cases, and display/keyboard. In fact, there are no data on which to base the values and they are given only for completeness. The wide differential between the two and four channel missions arises from the minimal requirements imposed by the manpack and land vehicle applications that constitute the major share of two channel uses. Note that these estimates include no allowances for installation in user vehicles.

APPENDIX D

GLOSSARY
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GLOSSARY

ACLS	All-weather carrier landing system
ADF	Automatic direction finding
AFTEC	Air Force Test and Evaluation Center
AHARS	Airborne heading and attitude reference system
ALCM	Air-launched cruise missile
ASW	Antisubmarine warfare
ATC	Air traffic control
BOI	Basis of issue
bomb/nav	Bombing/navigation
C/A	Clear/acquisition
CAEL	Consolidated aerospace equipment list
CAS	Close air support
CONUS	Continental United States
DF	Direction finding
DSARC	Defense Systems Acquisition Review Council
EAR	Electronically agile radar
ECAC	Electromagnetic Compatibility Analysis Center
EDP	Electronic data processing
FAA	Federal Aviation Agency
FAC	Forward air controller
FARRP	Forward area rearm/refuel point
FLAMR	Forward looking advanced multi-mode radar
FO	Forward observer
FOC	Full operational capability
FSN	Federal stock number
FYDP	Five-Year Defense Plan
GCA	Ground-controlled approach
GDB/RBS	Ground-directed bombing/radar bomb scoring
GPS	Global positioning system
HSI	Horizontal situation indicator
HUD	Heads-up display
ICAO	International Civil Aviation Organization
I^2L	Integrated injection logic
IF	Intermediate frequency
IFF	Identification, friend or foe
IFR	Instrument flight rules

ILS	Instrument landing system
IMC	Instrument meteorological conditions
IMU	Inertial measurement unit
INS	Inertial navigation system
IOC	Initial operational capability
IR	Infrared
ITNS	Integrated tactical navigation system
JPO	Joint Program Office
JTIDS	Joint Tactical Information Distribution System
LATAR	Laser tracking and ranging
LCCM	Life cycle cost model
LDNS	Lightweight Doppler navigation system
LOC	Limited operational capability
LORAN	Long-range aid to navigation
LSI	Large scale integration
LZ	Loading zone
MCDEC	Marine Corps Development and Education Center
MEMI	Master equipment management index
MIC	Microwave integrated circuitry
ML	Management list
MLS	Microwave landing system
MOS	Metal-oxide semiconductor
MTBF	Mean time between failure
MX	MINUTEMAN X
NDB	Nondirectional beacon
NMDL	Navy management data listing
O&M	Operation and maintenance
OMEGA	Global VLF navigation system
OTEA	Operational Test and Evaluation Agency
OPTEVFOR	Operational Test and Evaluation Force
P	Protected (signal)
PAR	Precision approach radar
PAVE SPIKE	Laser pod with low light level TV
PAVE TACK	Laser pod with FLIR (forward looking infrared)
PELSS	Precision emitter location and strike system
PLRS	Position location and reporting system
PME	Prime mission equipment
PN/BPSK	Pseudo noise/biphase shift keying
P-VOR	Precision VOR
PZ	Pickup zone
RDT&E	Research, development, test and evaluation
R-NAV	Area navigation
SAMSO	USAF Space and Missile Systems Organization
SLCM	Sea-launched cruise missile

TACAN	Tactical air navigation
TERCOM	Terrain contour matching
TISEO	Target identification system, electro-optical
TRANSEC	Transmission security
UTM	Universal Transverse Mercator
VLF	Very low frequency
VOR/DME	Visual omni-range/distance measuring equipment
VORTAC	Collocated VOR and TACAN systems

TABLES

FIGURES