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THE APPLICATION OF NAVSTAR DIFFERENTIAL GPS TO CIVIL HELICOPTER OPERATIONS

NASA CR 166169

F I N A L   R E P O R T

By

Jacques Beser and Bradford W. Parkinson

June 1981

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for

AMES RESEARCH CENTER
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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1 INTRODUCTION

The NAVSTAR Global Positioning System (GPS), currently being developed by the Department of Defense, is a space based navigation system that will provide the user with precise position, velocity and time information on a 24 hour basis, in all weather conditions and at any point on the globe. The system, as illustrated in Figure 1.1, consists of a space segment, a control segment and a user segment.

When fully deployed, the space segment will consist of 18 satellites in six 12 hour orbits of 3 satellites. Each satellite will continuously broadcast a message containing precise information relative to its own position (ephemeris) and clock accuracy and less precise information relative to the entire constellation position (almanac).

The control segment consists of monitor stations and a master control station. The monitor stations transmit satellite tracking data to the master control station, which determines the satellites' orbital parameters and communicates them to the satellites for retransmission to the users.

The user segment consists of the equipment necessary to derive position, velocity and time from the information received from the satellites.

The potential unauthorized use of this source of very precise navigational information has prompted the Department of Defense to intentionally contaminate the satellites' signals and to provide authorized users with the necessary information to recover the original signal. These methods, along with an anti-spoofing scheme, are known as Selective Availability and Anti-Spoofing techniques.

Since the baseline GPS system will provide guaranteed high accuracy to only a limited number of users, mostly the military, it became evident that the civilian community had to devise a variation of this system to allow for an assured, uninterrupted level of accuracy. Differential GPS provides such a capability.

Briefly, it consists of operating a receiver/transmitter at a fixed location, comparing its GPS derived position to its actual surveyed location and transmitting these errors to suitably equipped users. Different concepts can be implemented and are discussed later.

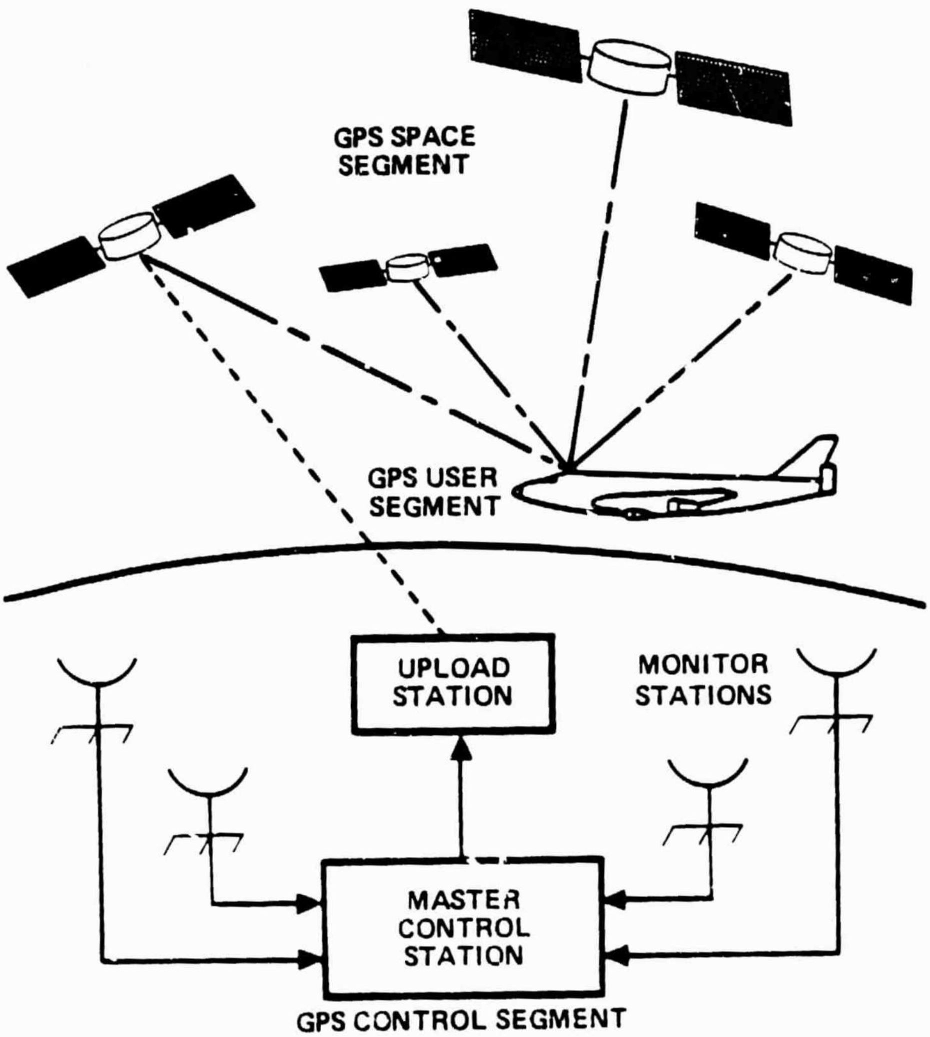


Figure 1.1. The Three Segments of the GPS

This study is intended to present the current thinking in the implementation of Selective Availability, its impact on the civilian use of GPS, and to assess the support in the civilian community for the development of Differential GPS and the potential market size for such a system, in particular for the helicopter. The probability of signal corruption and its possible relaxation with time are assessed and the justification for the development of Differential GPS are discussed for different cases of signal corruption.

Section 2 presents a brief description of the baseline Global Positioning System principles of operation. In Section 3, Selective Availability Issues are discussed, as viewed by the Department of Defense, the Department of Transportation, the helicopter community, and other possible users of the system. Probabilities and projections as to the implementation of such a system are presented. Section 4 describes different possible implementations of Differential GPS, including a discussion on performance. A justification for the development of such a system is presented. In Section 5, the potential civil support and market size for Differential GPS are assessed. This includes a review of existing radionavigation systems and a discussion of the operational requirements of the civilian community, in particular the helicopter community.

2 PRINCIPLES OF OPERATION OF THE GLOBAL POSITIONING SYSTEM

2.1 Pseudo Range and Delta Range

The user position is determined by measuring its range to four satellites. More precisely, the transmission time necessary for a satellite signal to reach the user is measured. This includes various propagation delays as well as satellite and user clock errors. The range corresponding to this transmission time is called pseudo range, since it is not quite the geometric ran . The satellite clock is very precise and its error can be determined with high accuracy and corrected accordingly. The user clock is far less elaborate and its error is considered to be an additional unknown. This is the reason why four rather than three satellites have to be used for a position fix. The user velocity and clock frequency offset are determined by measuring the rate of change of pseudo range (called delta range) to the four selected satellites.

2.2 Satellite Signal

The satellite signal uses 2 carrier frequencies in the L band, 1575.42 MHz (L_1) and 1227.6 MHz (L_2). Each of these two signals, L_1 and L_2, is modulated by either or both a 10.23 MHz precision (P) signal and/or by a 1.023 MHz clear/acquisition (C/A) signal. Each of these two binary signals is formed by a P-code or a C/A code which is modulo-2 added to 50 bps data. The P and C/A signals are modulo 2 added to L_1 and L_2 in phase quadrature. The P code is a pseudo random sequence reinitialized at the end of each 7 day period. The C/A code is a unique Gold code with a period of 1 msec. The user has the capability to duplicate both the P and C/A codes and the transmission time is determined by measuring the offset that has to be applied to the locally generated code to synchronize it with the code received from the satellite. Since the P code has a wider bandwidth, it will be more difficult to acquire than the C/A code, but it will provide better accuracy and additional anti-jam protection. This explains the names Precision and Coarse-Acquisition code. Operation with the P code can be expected to provide an unfiltered accuracy of about 16 m (1σ) while the C/A code will provide an unfiltered accuracy of about

32 m (1σ); (refer to Table 4.2).

3 ANALYSIS OF SELECTIVE AVAILABILITY ISSUES CONCERNING NAVSTAR-GPS

3.1 History

3.1.1 Conception and Approval

The NAVSTAR system was approved for concept validation in 1973. This initiation was based on tactical requirements, particularly in the area of weapon delivery. On 13 December 1973, DSARCI approval was given based in part on the results of the predecessor program. This program, 621-B, had achieved test results at Holloman AFB that proved both the concept of "3-Dimensional Navigation" and the concept of "Code Division Multiple Access"(1).

As a result of DSARC approval, a Joint Program Office was formed at the Space and Missile Systems Organization of the Air Force. The system which was to be validated was based on both Air Force test results, and also the Navy's ongoing Timation Program. In particular, the satellite orbits were selected to provide graceful degradation in the event of satellite outages. The 24 satellites in three rings of eight each also provided good geometric dilution of precision or GDOP. (The Space Segment of the GPS has recently been rebaselined to 18 satellites in 6 orbits of 3 satellites each.) The ground stations involved were prototypes of the operational ground stations, and a complete ensemble of user equipment was provided for testing at the Yuma Proving Ground in Arizona.

3.1.2 Initial System Goals

The initial system goals were principally to demonstrate the cost and feasibility of user equipment; to demonstrate the lifetime and stability of the satellite clocks; to demonstrate the ability to predict future satellite location; and, as the end result, to demonstrate the accuracy of the resulting navigation system.

3.1.3 Comparisons with Other Systems

Table 3.1, which has been extracted from the Institute of Navigation Bulletin, Volume 24, No. 1(2), shows a comparison of the GPS with other modern, radionavigation systems. Noteworthy are the global coverage for GPS combined with 3-dimensions of position and 3-dimensions of velocity. A more extensive discussion of these systems is presented in Section 5.

3.1.4 Test Results

Although NAVSTAR is in its infancy in terms of developing accurate ephemerides and sophisticated clock corrections or user equipment algorithms, the test results have been impressive. Example test results using a single channel set are shown in Figure 3.1, extracted from the Institute of Navigation Bulletin, Volume 26, No. 2(3).

In this example, the measured CEP of the static user was 6.2 meters against a systems spec for this single-channel set of 15 meters. GPS test results have generally met or exceeded all the requirements which were established in 1973.

In addition to these tests, a special Differential GPS test was run using the Texas Instruments High Dynamic User Set. These results are noteworthy because they provide evidence of the capability of Differential GPS, and may offer a solution for the civilian user with more stringent accuracy requirements than are currently expected to be available. More will be said about this in Section 4.

3.1.5 Low-Cost User Studies

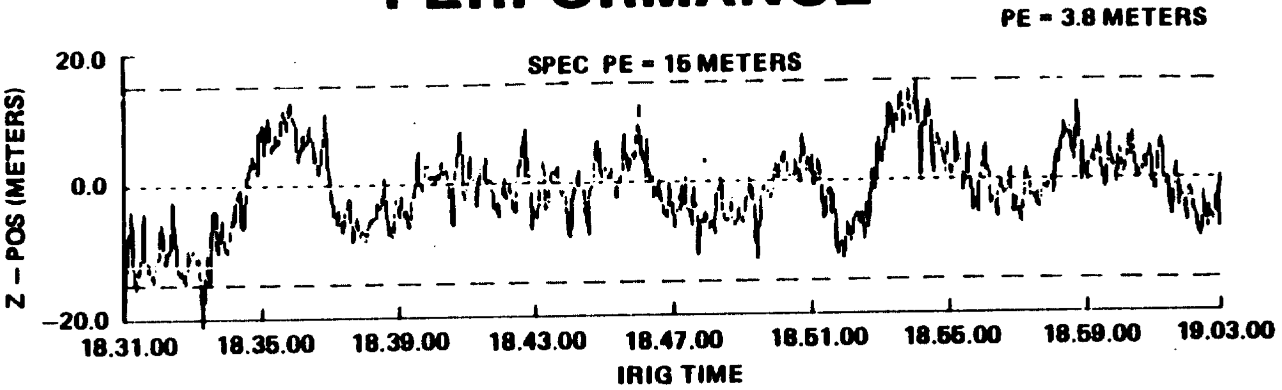
A number of studies were performed during the Phase I, Department of Defense Program. These aimed at the low-cost user equipment market. The projected prices ranged from approximately $1,000 up to $10,000, for a full, way point navigation equipment. For comparison, the single channel C/A tracking set (called Type Z), which had been developed for Phase I as a military low-cost prototype, had been targeted at a production cost of $10,000 (1973 $).

Table 3.1. Composite Performance Comparison of Modern Radio Navigation Systems

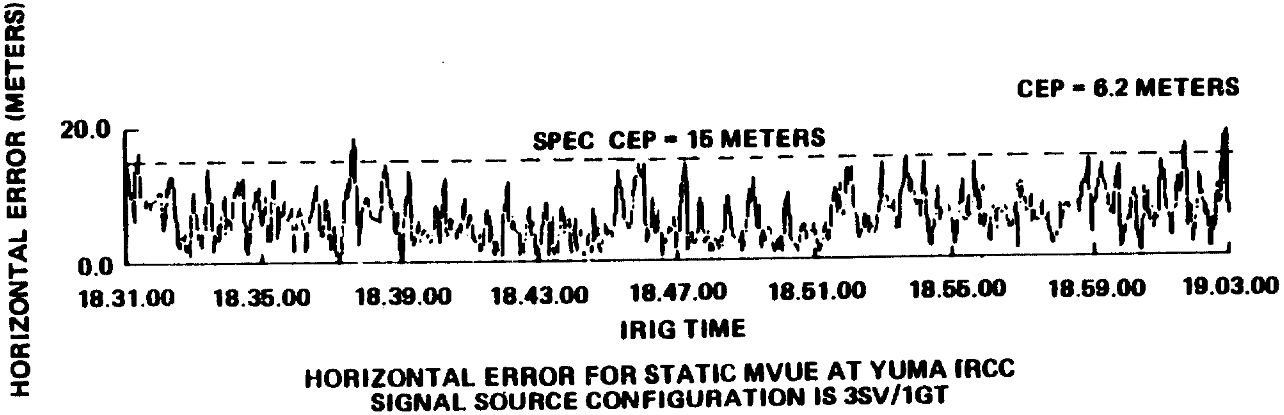
	Vortac	Loran-C	Omega	Differential Omega	Radar	Doppler	JTIDS RELNAV	NNSS	GPS
Volumetric coverage	Line-of-sight (100 NM)	1200 NM, to ground	Global, to ground	100-200 NM, to ground	Unlimited	Unlimited	Line-of-sight	Global, to ground (9)	Global, to ground
Signal reliability	High VHF, L-band	Fair 100 KHz	Fair (10-14 KHz)	Fair (10-14 KHz)	Moderate (5-16 GHz)	Moderate (13 GHz)	High (L-band)	High (150, 400 MHz)	High (1220, 1575 MHz)
Data content	Relative Rho/Theta 2D Pos	Absolute 2D Pos	Absolute 2D Pos	Relative 2D position	Relative Rho/Theta, 2D Pos	2D Position 3D Velocity	Relative 2D Pos; 3D Pos (1), 2D Vel Absol 2D Pos (2), time	Absolute 2D Pos	Absolute 3D Pos, 3D Vel time
Accuracy	±1°, 1σ ± 1 NM ±600 Ft, 1σ (DME)	1500 Ft, 95% Prob (predictability) 60-300 Ft (repeatability)	1-2 NM RMS	1100-1800 Ft	Variable	0.1-0.25% 1σ (Velocity) 0.5-1% CEP (Position)	(3)	270 Ft CEP (4) 420 Ft (5)	25 Ft Hor Pos (6) 36 Ft Vert Pos (6) 0.1 Knot Vel (6)
Application versatility	Air, short distance approach	Air, surface med dist Weap Del	Air, surface, underwater, long dist	Air, surface, underwater, short dist, terminal	Intermittent Pos Fix, Weap Del	Air, long dist, dead reckoning	Air, surface, med dist, Coll avoidance, weap del	Surface, intermittent Pos fix	Air, surface, space, long dist, terminal, weap del
User equipment cost	Low	Moderate	Low	Low	High	Moderate	Moderate (7)	Moderate	Moderate to high (8)

(1) 3D data available for favorable geometry of sources only
(2) If position references are available
(3) Under optimum conditions, 100 ft CEP considered likely
(4) Dual frequency receiver, exclusive of own velocity error effect
(5) Single frequency receiver, exclusive of own velocity error effect
(6) Predicted for highest performance receiver and full 24-satellites configuration
(7) RELNAV function is software addition only to basic communication terminal
(8) Different performance quality level equipment being developed
(9) Typically, fix obtainable every 90 minutes

SINGLE-CHANNEL/SINGLE-PROCESSOR GPS SET PERFORMANCE



VERTICAL ERROR FOR STATIC MVUE AT YUMA IRCC
SIGNAL SOURCE CONFIGURATION IS 3SV/1GT



HORIZONTAL ERROR FOR STATIC MVUE AT YUMA IRCC
SIGNAL SOURCE CONFIGURATION IS 3SV/1GT

Figure 3.1

(In report MX-TM-3212-76, Magnavox states a design to cost goal of less than $15,000 (CY78$). This is roughly equivalent to the $10,000 quote when allowing for a 10% inflation rate.) It is difficult to compare GPS User Equipment with most other varieties of navigation equipments. This is because the GPS equipment almost automatically provides such features as way point navigation in 3-dimensions.

3.1.6 Phase-In/Out Plan

An official plan has been adopted for Federal Radionavigation(4), which describes the phase-in/out of classes of equipments for the various users. This is shown in Figures 3.2 and 3.3. Although the phase-in/out times are only projections at this point, those phase points are important drivers for decisions regarding selective availability on GPS.

3.1.7 System Use and Recommendations

Figure 3.4 presents the schedule for GPS development, as well as for System Utilization as developed by the Federal Radionavigation Plan. It represents a blending of requirements and systems availability and cost.

3.2 Selective Availability (SA) Issues as Viewed by the Department of Defense (DOD)

3.2.1 Test Results Considered

As a result of the impressive test results for Phase I GPS, there is a clear concern over making GPS capabilities available to a potential enemy. This issue has been raised at each of the DSARC's and a great deal of time has been devoted to studying potential impacts and means to ensure that accuracy was denied to the enemy.

Appendix I contains an extract from a DOD statement on NAVSTAR availability by Dr. Gerald P. Dinneen.

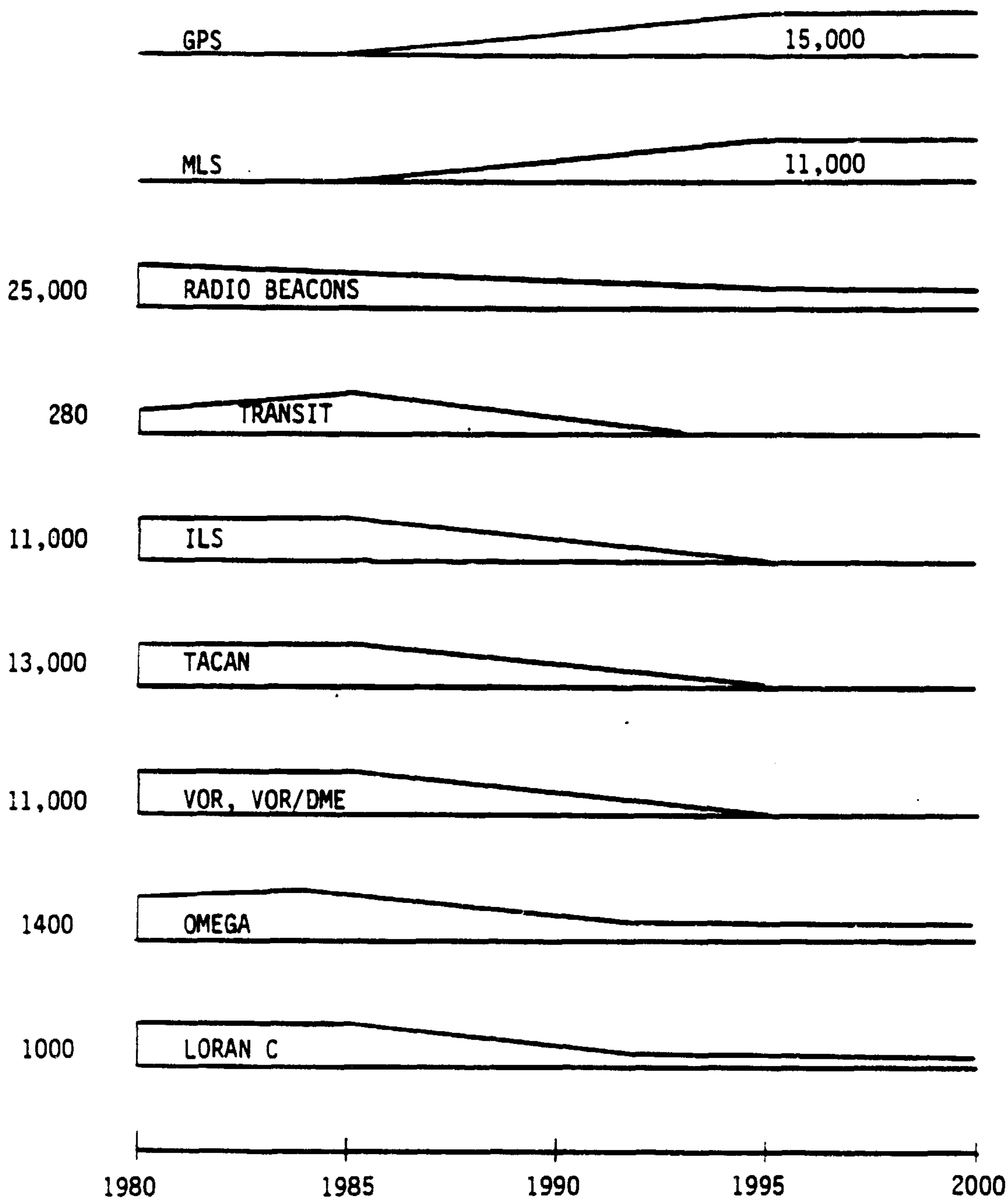


Figure 3.2. DOD Phase In/Out Schedule

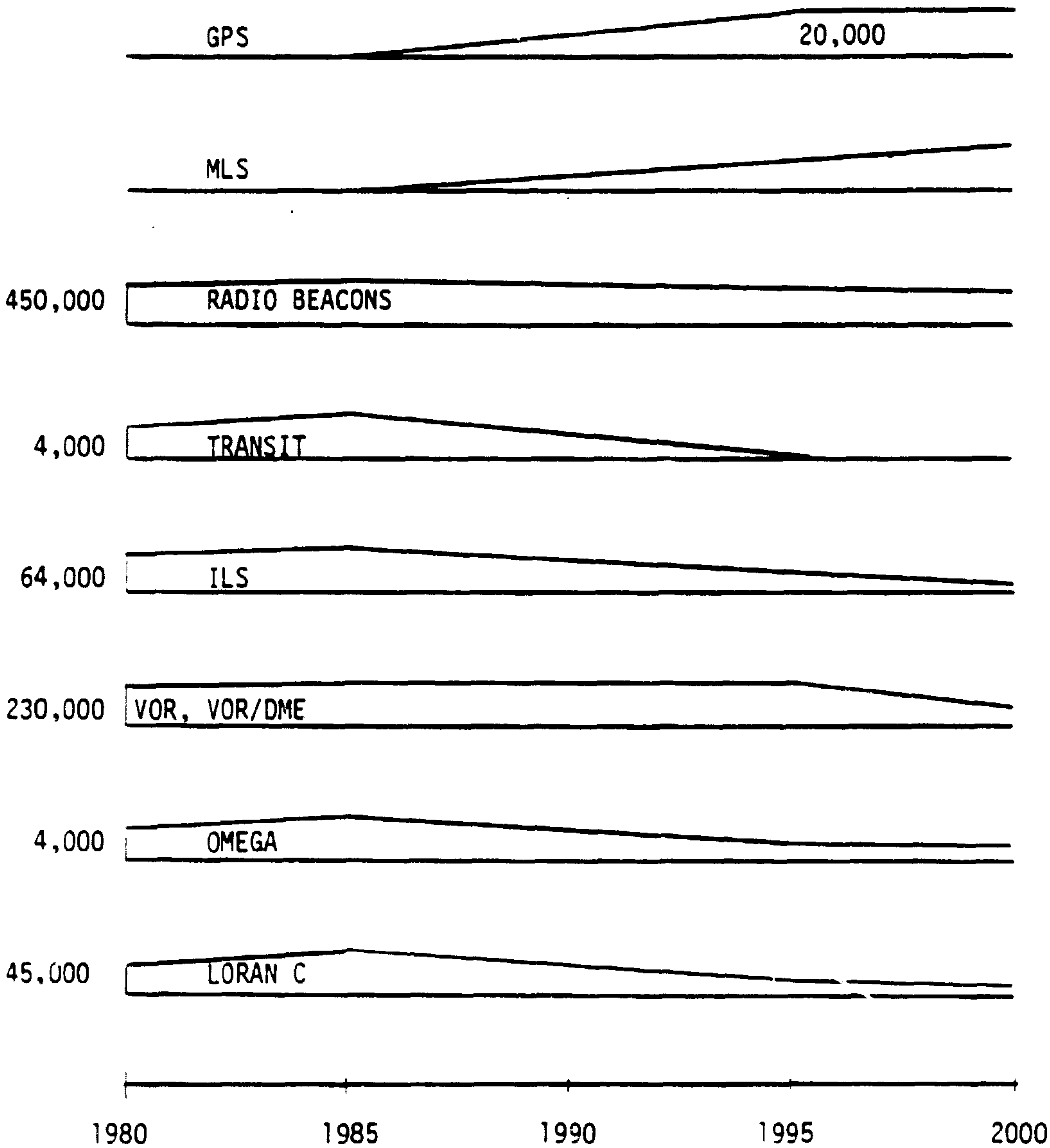


Figure 3.3. Civil Users Phase In/Out

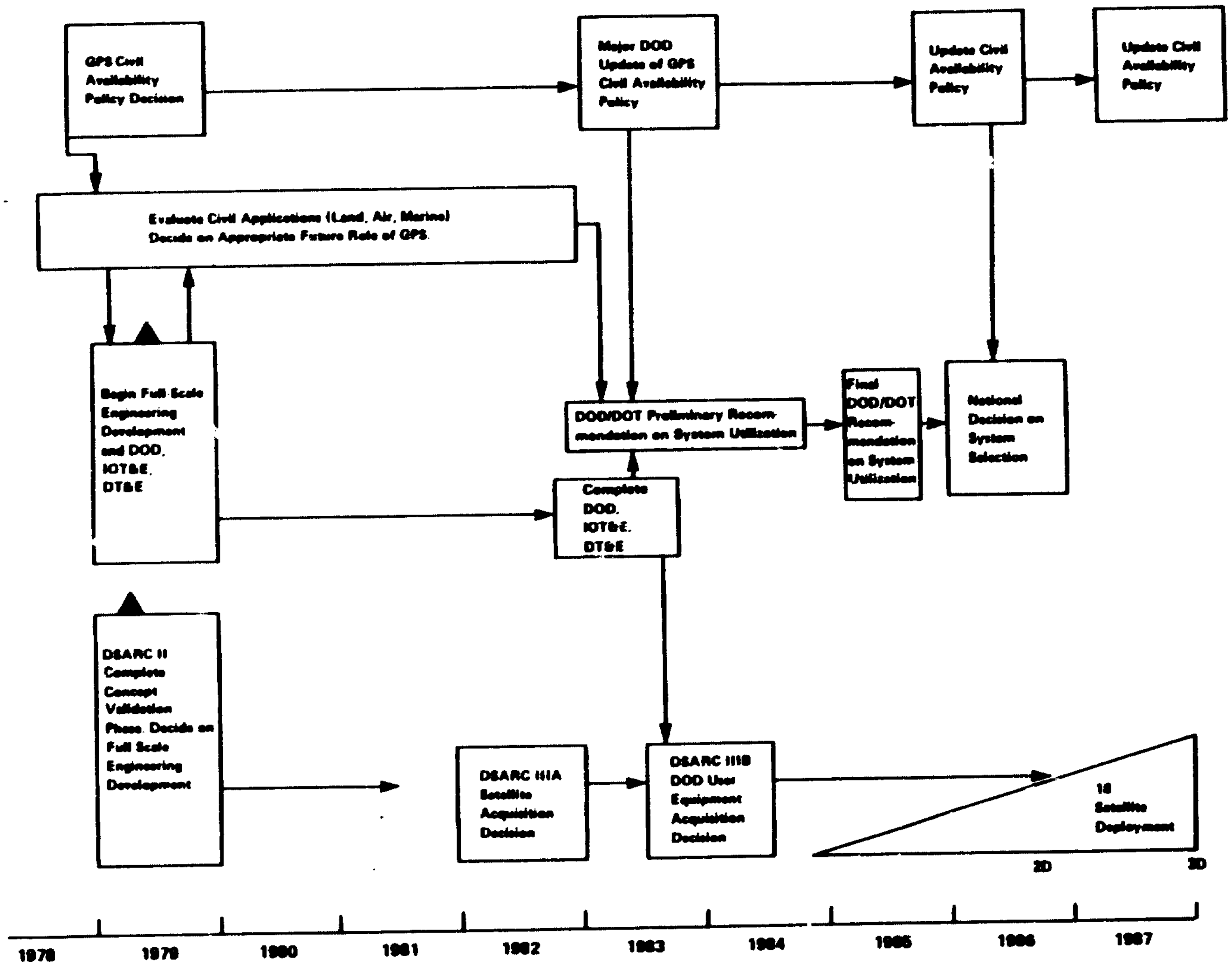


Figure 3.4. NAVSTAR Global Positioning System

The SA studies have included all cognizant members of the National Defense community. It has been generally recognized that the criteria for denying a navigation system are somewhat different than the criteria for securing a communications system. This is because a navigation system can potentially be gracefully degraded, whereas any access to certain communication systems is potentially severely damaging. In the process of studying the so-called denial of accuracy or selective availability issue, many different techniques have been considered. These will not be described in this study.

Generally speaking, the thrust in selective availability has been to have the following capabilities:

a) Totally deny the P channel or precise channel at times of national choosing, and

b) use various techniques to restrict the accuracy of the clear/acquisition channel (C/A) to some predetermined level based on national security considerations.

To more effectively examine the issues of selective availability, it is worthwhile to consider how a hypothetical enemy might exploit the non-degraded NAVSTAR signal. It should be noted at the outset that any general or extensive exploitation of GPS by a potential enemy will insure the very sizeable cost of developing, copying and equipping the enemy force in order to effect that exploitation. Table 3.2 summarizes enemy exploitation in each of five possible uses. We will now examine those uses one at a time.

3.2.1.1 Tactical

The use of the C/A code in a tactical environment is of little value to an enemy due to its susceptibility to spoofing and to jamming. As a result, it is not felt that the C/A code affords much help to an enemy in a tactical theater. The use of an unprotected P channel could be of considerable value. The issue is the cost of equipping an enemy force of sufficient size to take effective advantage of the common grid navigation system. Any potential enemy would be concerned that the P channel characteristics described in the open literature would no longer be available in time of national emergency.

Table 3.2. POTENTIAL ENEMY EXPLOITATION OF GPS

	HYPOTHETICAL NON-DEGRADED SIGNAL	
USE	C/A	P
Tactical	Not of value due to spoofing and jamming susceptibilities	Of considerable value Issue is cost of equipping enemy force if use can be denied
Strategic	Not of value due to spoofing and jamming susceptibilities	Missiles/fear of deception would make cost of equipping difficult to justify Aircraft/might be used as a backup system
Intelli-gence	Static user/little effective improvement over TRANSIT capability Dynamic user/some peacetime benefit	Static user/little effective improvement over TRANSIT Dynamic user/some benefit
Commercial	Value similar to U.S. civil use	Value similar to U.S. civil use
Peacetime Military Exercises	Little value since it would be an unlikely asset in wartime	If forces are equip-ped, it could be of considerable value

3.2.1.2 Strategic

The C/A code is not of value for the strategic environment for the same reasons that were described for the tactical environment. The P code is potentially of considerable value. There are two major areas where strategic forces might be so equipped. The first is for those applications involving intercontinental ballistic missiles. For this use, a fear of deception may make the cost of equipping difficult to justify. The second is the strategic aircraft; it is conceivable that selected vehicles be equipped with GPS receivers for use as a backup system.

3.2.1.3 Intelligence Gathering

The C/A code would afford little effective improvement over the position capability now given the static user through the TRANSIT receiver system. Therefore, locating specific geodetic bench marks can be carried out using either capability. The dynamic user in an intelligence-gathering mode may find some peacetime benefit from using the clear acquisition channel. This is because there is little likelihood of intentional spoofing or jamming during peacetime. The P channel for the static user would have little effective improvement over TRANSIT. The dynamic user would realize even greater benefits than the dynamic user of the clear acquisition code.

3.2.1.4 Commercial

The value matrix for the commercial users of a potential enemy would be similar to that for the U.S. civil users. There is one major exception; in time of national emergency, it is conceivable that certain selected U.S. civil users would continue to be granted full accuracy. For example, certain commercial airlines. Whether this might happen would be driven by considerations of the exposure of the encryption keys to the enemy access.

3.2.1.5 Peacetime Military Exercises

The C/A code is of little value since it would not be a likely asset in wartime. The P code could be of considerable value if the enemy decides it could afford to generally equip its forces.

3.2.2 Summary

In reviewing potential enemy use of the NAVSTAR signal, it is clear that there is an objective basis for concern. Whether the enemy would use the capability cannot be accurately assessed. The real issue is, would an enemy ever go to the effort and expense of generally equipping forces to use a navigation/positioning system which he did not control? The current military assessment is that such use is possible; therefore, it is necessary to implement a selective availability technical capability, as well as a policy. The currently preferred policy is one which would provide a variable guaranteed accuracy.

The issue of when S/A will be implemented is more difficult to answer. There is an official commitment that Selective Availability will be implemented. But, to our knowledge, there is no official statement of when and how frequently it will be used. It is, however, unlikely that S/A will be implemented continuously, but the DOD will probably be unwilling to give any written promise to that effect because this would defeat the S/A purpose.

3.3 The Issues as Viewed by the Department of Transportation (DOT)

3.3.1 History

The Department of Transportation has not been a part of the Phase I development program nor have they ever officially stated a requirement for the NAVSTAR Global Positioning System capabilities. They recognize it as a potential Department of Defense system. They had been urged by Congress to consider the NAVSTAR Global Positioning System in the context of the total navigation and positioning needs of the nation. As a result, a joint Federal Radionavigation Plan has been developed which goes into considerable detail in issues, requirements, technical capabilities, and long range projections. These are addressed in Section 4.

3.3.2 Specific DOT Issues

The specific issues which have arisen in DOT discussions of the NAVSTAR system have included the following:

a) Hasty Introduction. A concern by the Department of Transportation that events are moving too fast; that the promise of GPS had not yet been realized and that any conclusion which would cancel an ongoing DOT program was premature.

b) Impact of Selective Availability. The Department of Transportation has expressed concern that a system without continuous guaranteed accuracy was of little use to the civilian community. As a result of this concern and Congressional pressure, the Department of Defense has stated an official policy in the Federal Radionavigation Plan.

c) User Equipment Cost. The Department of Transportation has stated that potential NAVSTAR user equipment would be very expensive and not affordable by the general user community they service. There have been contrary opinions to this statement offered by a number of equipment manufacturers. However, at this point, there is no hard data on the actual user equipment costs compared to the cost of equipments of equivalent capability which navigate based on different systems. It is, however, generally accepted that in order to be competitive, a set suitable for general aviation should sell below $5,000.

d) Potential Requirements for Cost Sharing. From time to time the issue of sharing the system cost (i.e., satellite/ground station) cost with the users has been brought forward. Cost sharing has never been required for other federal radionavigation aids. To burden the Global Positioning System with such costs would create an unfair economic advantage to the alternatives. However, the fact that it is unfair does not preclude cost sharing and any civilian user must have a clearly stated policy regarding the cost which must be borne by the using community.

e) Lack of Civilian Control of the System. The Department of Transportation has been reluctant to consider a system which was not under civilian control. There have been joint use facilities such as search radars for some time. These are the exception rather than the rule. DOT feels the need for total control of any system of this magnitude.

f) Many Traditional Manufacturers Not Involved. The traditional radionavigation manufacturing community has not been involved in much of the development of the NAVSTAR system. As a result there are legitimate concerns on the part of DOT as to whether the equipments being developed truly address the needs of the user communities they serve.

f) Technical Adequacy of C/A. There has been a wide range of concerns over the technical adequacy of the C/A signal for commercial or civilian use. These range from multi-path to antenna shading and ionospheric group delay corrections. Generally, the test data for the so called Z set of Phase I has explored many of these issues; however, those tests were not under the control of the Department of Transportation. As a result, the Department of Transportation feels the need to independently verify the capabilities of the NAVSTAR system.

3.3.3 Summary

The Department of Transportation generally would like to go slow on the NAVSTAR GPS. It competes with certain DOT programs and its eventual deployment is not yet guaranteed by the Department of Defense. Active programs are now underway at the Department of Transportation to explore in greater depth some of the specific issues just described.

3.4 The Issues as Viewed by the Helicopter Community

There are now close to 10,000 civil helicopters in the United States and Canada. The projections and trends are very clear: their use will become more prevalent.

The helicopter is particularly attractive for service in the 30 to 300 mile range. There are three noteworthy attributes of rotor craft which make its navigation problems somewhat unique. These are:

1. Low Altitude Operations

   The helicopter performance is best at low altitudes where the existing navigation system availability is least.

2. Sparsely Equipped Terminal Areas

   The helicopter's ability to land and maneuver anywhere is one of its greatest benefits. However, most navigation aids are located for a region of maximum accuracy which is close to a fixed wing landing field. It would be economically prohibitive to use these same techniques for the range of helicopter terminal areas. There is an increased need for IFR rated helicopters, yet the improved NAV aids to provide them with the operational flexibility they need are not being planned.

3. Unstructured Routes

   Helicopters tend to operate over unstructured routes. Because they operate close to the ground, a 3-dimensional navigation capability is important to fly the so-called RNAV routes which are direct paths between the points they serve.

   One of the spokesmen for the helicopter community, Mr. Glen Gilbert, has frequently written and spoken in public concerning the need for the NAVSTAR Global Positioning System. He has stated, "I believe the U.S. Department of Defense satellite based NAVSTAR Global Positioning System (GPS) is the one system now in process of being implemented which offers the most likely potential for meeting the (helicopter community's) navigation goals. GPS provides seven dimensional information: 3 dimensions of position, 3 dimensions of velocity, as well as precise time." It is clear that the helicopter community represents a unique user. Mr. Gilbert feels the challenge is now with the U.S. Government to provide the helicopter community the services it needs. He has called for increased FAA R&D funding in the NAVSTAR Global Positioning System area.

3.5 The Issues as Viewed by Others

3.5.1 The Petroleum Industry

The petroleum industry has been the subject of numerous articles on Navigational Positioning, e.g., Johnson and Ward(3), Morgan(5). These describe the needs for the precise positioning offered by GPS for the offshore drilling community. Any delays in the operation tie up expensive pieces of capital equipment. As a result, these users would now gladly buy GPS, even though the receiver costs $100,000 to $150,000.

3.5.2 The International Community

Both military allies, such as NATO and other friendly countries such as Japan, have expressed interest in the NAVSTAR capability and potential availability. The NAVSTAR issue was explored in an earlier AGARD special report(6), which had been fostered by Prof. C.T. Leondes of UCLA. It would appear that the harsh winter weather characteristics of northern Europe have made GPS particularly appealing.

3.6 Current Official Selective Availability Status

The following paragraph is issued from Volume 1 of the Federal Radionavigation Plan(4).

"The availability of navigational signals of adequate accuracy at all times, including times of stress, is essential to reliance on a given system for safety of navigation. A preliminary evaluation of the proposed NAVSTAR GPS signals indicates that many civil requirements probably could be met with the coarse/acquisition signal Conversely, guaranteed availability of optimum performance may diminish national security objectives, so that a trade-off or mpromise is necessary. Hence, a proposed national policy is being developed on the criteria which will govern availability and accuracy. The Department of Defense proposes that NAVSTAR GPS coarse/acquisition (C/A) signal will be made continuously available on an international basis for civil and commercial use at the highest level of accuracy consistent with national security interests. It is presently projected that an accuracy of 200m CEP (500m 2 drms) will be available during the first year of full NAVSTAR GPS operation with accuracy available to civil users increasing as time passes. This policy is a key element in determining the non-military navigational services that can be based on use of NAVSTAR GPS signals."

3.7 Probability and Projections

3.7.1 Current Situation

The system is available and currently being used. Figures 3.5, 3.6 and 3.7, extracted from reference 3, show the coverage of the current GPS constellation. They show, for example, that there are four vehicle coverages over most of the oil exploration areas of the world on a daily basis. Figures 3.5 and 3.6 show the six satellite GDOP contours, and the near term GPS constellation time contours. Figure 3.7 shows the areas where 4 satellites are available. The point is that there is already a small user community who can be serviced and who is willing to pay 150 to 300,000 dollars for a GPS equipment, because the resulting navigation positioning capabilities so vastly improve their operations.

The currently planned operational date for the NAVSTAR System is not driven by technical development time, but rather by budget and cash flow considerations within the Department of Defense. As originally conceived, there would be a so-called worldwide 2-dimensional capability by 1982. Squeezes on the budget and modifications to the satellites' technical requirements have pushed that date out to 1986-87. If the military needs were sufficiently urgent, the final operational date would be accelerated considerably.

Because of the great costs in modifying the system configuration, it is unlikely that any substantial changes would be made. The selective availability feature is being implemented with its nominal accuracy set at about the 200 meter level.

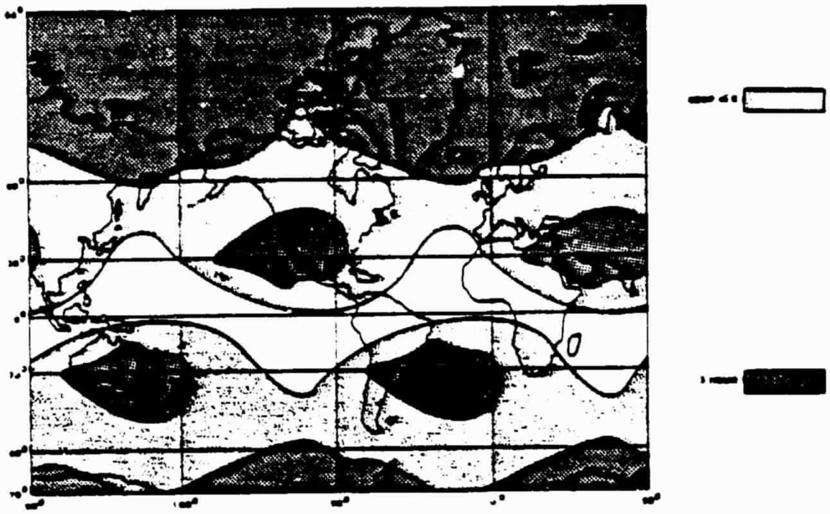


Figure 3.5. Near-Term GPS Constellation (Six-SV) GDOP Contours

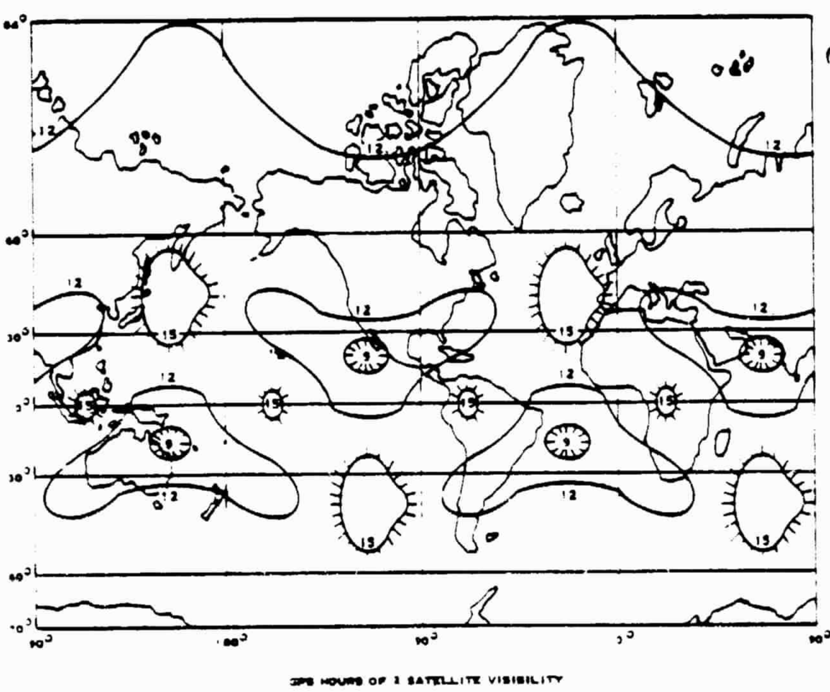


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Figure 3.6. Near-Term GPS Constellation Time Contours

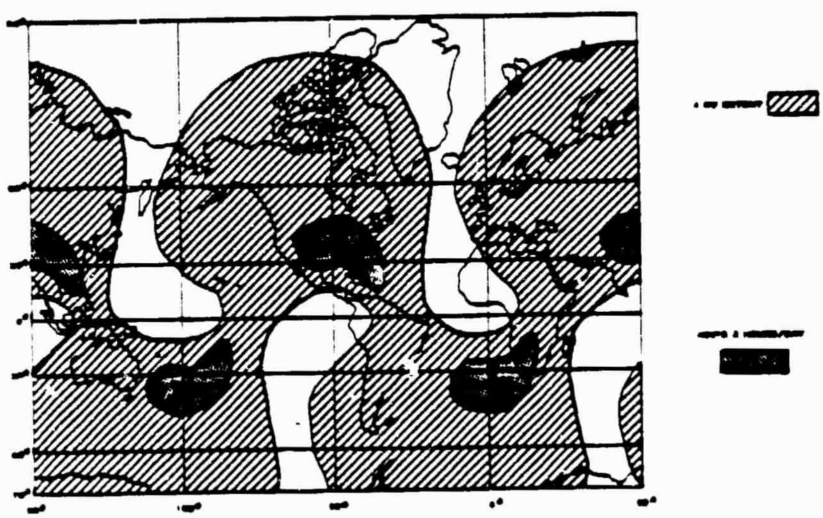


Figure 3.7. Current GPS Four SV Coverage Contours

3.7.2 Three Main Contending Factions

Predictions of future actions by the federal government are usually quite conjectural. The central question which involves both technical and political considerations is what guarantee of accuracy will be available to the civil users and how will that improve over time. The Department of Defense through their perception of enemy capability tends to limit the performance to a lower level. The users community which is driven by favorable cost performance trades tends to press for a guarantee for better accuracy. This is nowhere better evident than in the helicopter community. While the Department of Transportation has been unwilling to request greater accuracy of the Department of Defense at this time, their future actions might be somewhat different. This must depend on their understanding and assessment of true potential value to the users community whom they represent. These pressures are diagrammed in Figure 3.8.

The two central issues in the Department of Defense position are:

1. At what level of accuracy is there a material improvement in enemy capability?

2. Would an enemy equip its forces in the face of our selective availability capabilities?

The using community pressures can be summarized as follows: Many express a need for the system today. Whether that expands is a function of cost versus capability. Certainly as digital electronics drive down the cost curve, the potential for greater user interest is very real. The Department of Transportation, to this date, has concentrated on its largest volume of users. It can be expected that strong initial interest will principally come from special user groups such as the petrochemical or the helicopter community.

The Congressional position on NAVSTAR has been generally supportive to this date. In particular, Congress and the GAO have urged the Department of Transportation to give the system a fair hearing. If such pressures continue, it may hasten the date of GPS introduction into general use.

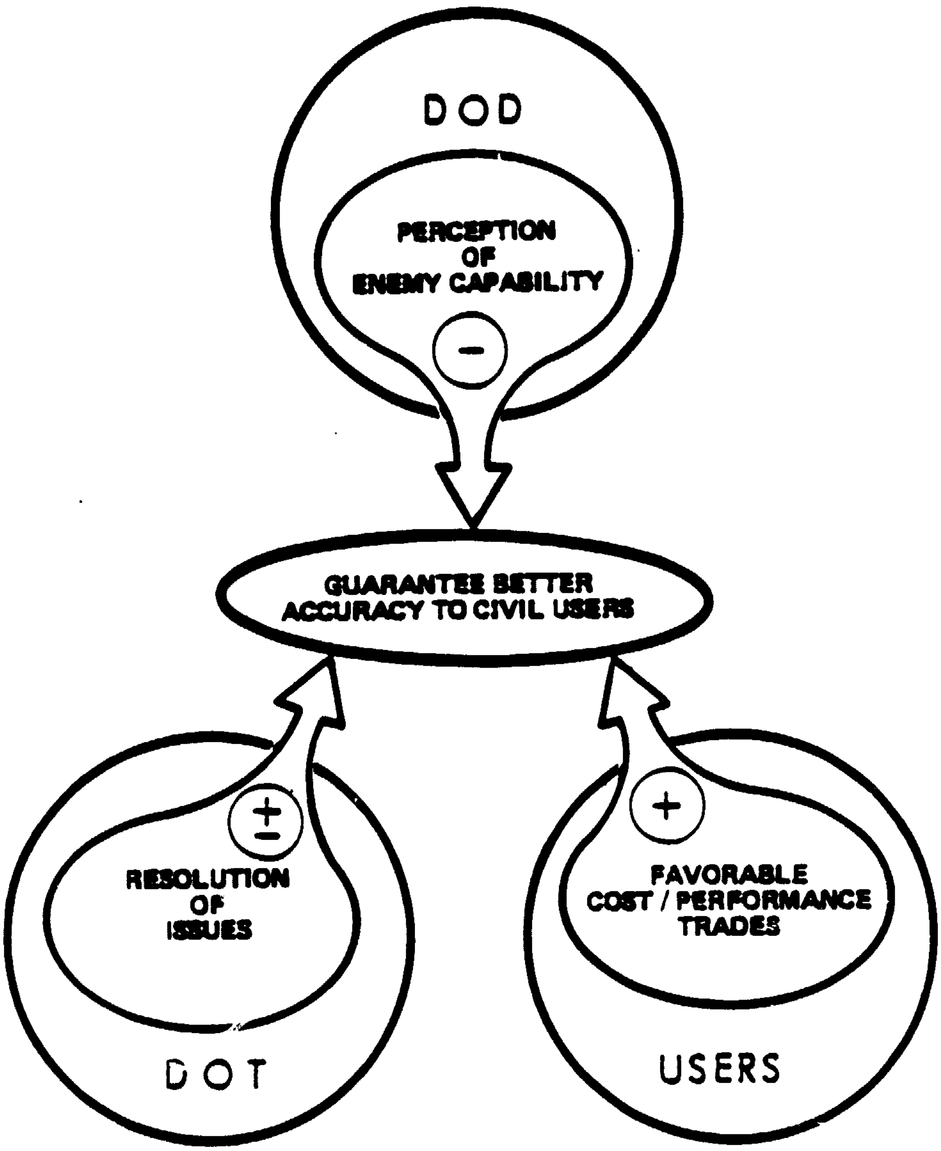


Figure 3.3. Pressures on Level of Guaranteed Accuracy

3.7.3 Past Examples

It is instructive to examine the history of certain of the current radionavigation aids as examples.

3.7.3.1 NNSS

The Navy Navigation Satellite System or Transit has been in use for over 10 years. It has not been officially declared available to the civilian community, but its use is prevalent. In particular, there is a small, but developing market for Transit receivers(5). The Navy has officially stated they expect the GPS system to eventually replace Transit.

3.7.3.2 OMEGA

The OMEGA system has been developed and is being implemented by the Navy with the assistance of the Coast Guard and the participation of several partner nations in an effort to assist in verifying system accuracy. Some commercial and private ships and aircraft are using the OMEGA system either as an update for their self-contained system or as a sole means of navigation when operating on oceanic routes. Because of OMEGA's extensive coverage, its use is expected to grow in the civilian community.

3.7.3.3 LORAN

LORAN was developed to provide the military with a long range radionavigation capability. It was subsequently selected as the U.S. Government-provided radionavigation system for civil marine use in the U.S. coastal areas. Its use has, however, been limited in the civilian community, by the lack of low-cost receivers and a lack of coverage. Technological advances are rapidly lowering user equipment costs and coverage limitations are being eliminated by an expansion and improvement program now underway.

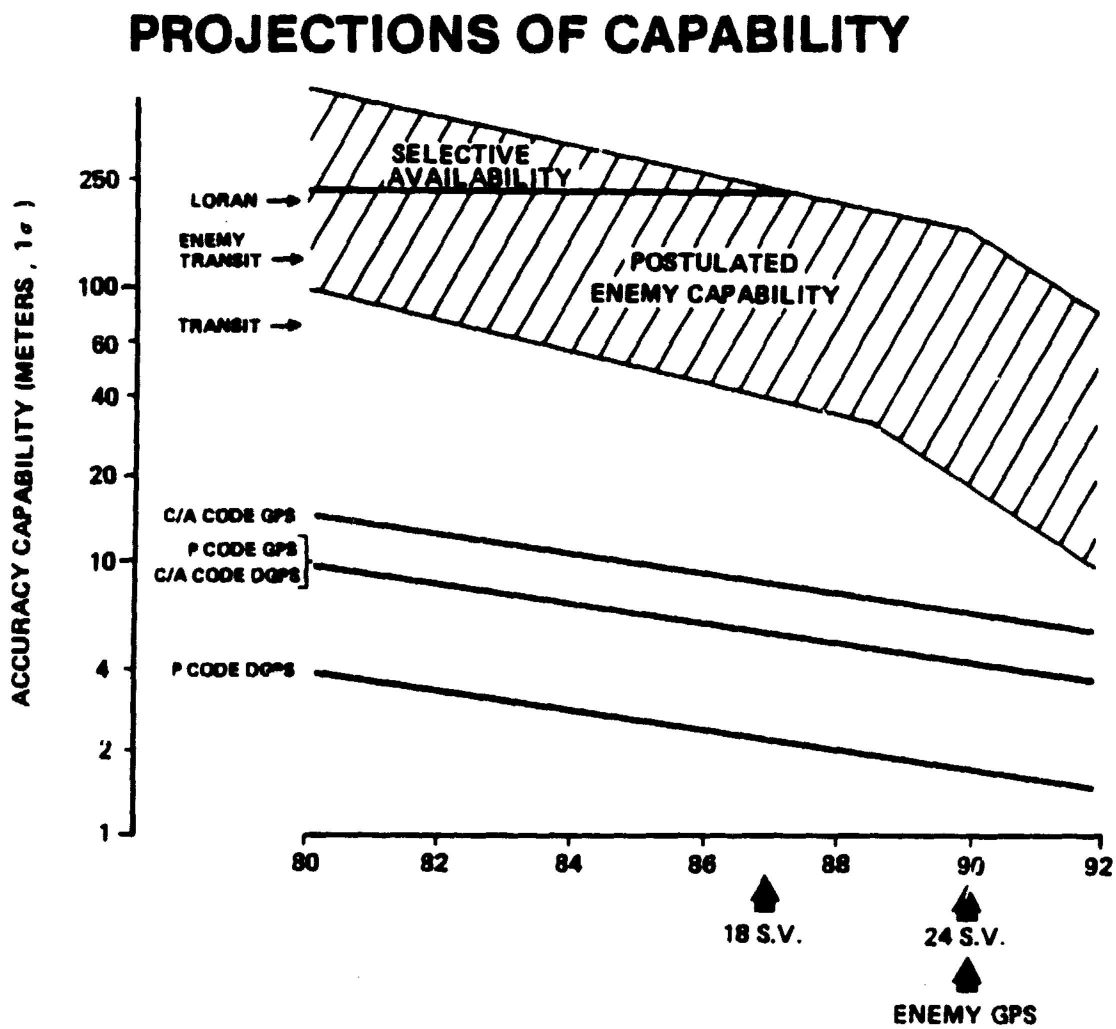
3.7.4 Projections

Figure 3.9 projects the GPS accuracy capability versus time. The accuracy capability of 1980 is taken from the open literature. The selective availability line is that taken from the Federal Radionavigation Plan. It is hypothesized that the enemy Transit capability is no worse than a factor of 2 below the capability of the U.S. Transit System. The 1980 data on the P code GPS is derived from Reference 7. Our Transit capability is derived from the Federal Radionavigation Plan. The P code Differential GPS is derived from Reference 8. The C/A code accuracies for GPS and Differential GPS were determined as described in Section 4.2.2. The enemy Global Positioning System capability hypothesized for 1990, suggests introduction 10 years subsequent to the frequency allocation approval for such a system. At that point, the enemy capability improves rapidly to a factor of approximately 2 worse than that of the U.S. P Code Global Positioning System. Based on that analysis, the need for a Selective Availability capability will extend out to at least 1990.

3.7.5 Conclusions

The Selective Availability concept will continue to be implemented by the Department of Defense. It is only prudent to insure that we have the capability to deny accuracy in time of national need.

If the enemy capability increases, as postulated by Figure 3.9, and the Department of Defense perceptions do not change, one would expect a 60 to 100 meters guaranteed CEP by about 1990. If the enemy were to deploy a Global Positioning system at an earlier date, it is likely that more accuracy would be available at an earlier date for the civilian community. At this time, there appears little likelihood of a guaranteed P channel prior to 1990. This is because the P Code GPS will continue to provide significant military assistance, particularly in such areas as blind bombing. Although P Code is not guaranteed, it may be available in usable form to special users. That is the situation now, and except for selective tests, there may be no need for a general policy for denial until, or unless, world tensions cause modifications to that policy. The fact that the P Code is usually available will not be of great assistance in obtaining ICAO sanctions for general use of the GPS P Code.



PROJECTIONS OF CAPABILITY
SELECTIVE AVAILABILITY
POSTULATED ENEMY CAPABILITY
LORAN
ENEMY TRANSIT
TRANSIT
C/A CODE GPS
P CODE GPS
C/A CODE DGPS
P CODE DGPS
ACCURACY CAPABILITY (METERS, 1σ)
250
100
60
40
20
10
4
2
1
80
82
84
86
88
90
92
18 S.V.
24 S.V.
ENEMY GPS

Figure 3.9

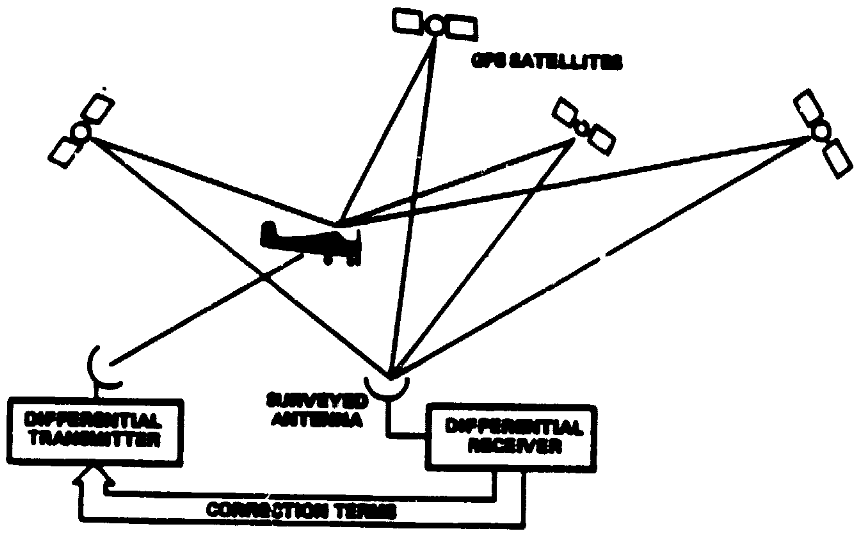


Figure 4.1. Differential GPS Operation

At least three Differential GPS concepts could be implemented:

A. A receiver is placed in a known location and the errors (Δx, Δy, Δz) in the solution derived from GPS satellites are measured. This information is then transmitted to the vehicle carrying the primary receiver. Issues here are the degradation of the validity of the correction terms as a function of the distance between the two receivers, and the fact that these correction terms are only valid if both receivers use the same set of satellites. The first issue will be discussed in the next section. The second issue is the fundamental drawback of this concept. However, with the 18 satellites constellation and the localized nature of Differential GPS, it is unlikely that the different constellations will be selected by the user and the ground station.

B. A receiver is placed in a known location and the errors in the pseudo range to all visible satellites are determined and transmitted to the user. With this technique, there is no need for the user to use the same constellation as the ground receiver, since he is getting the correction terms for all the satellites.

C. The ground station is acting as a pseudo-satellite. The biases in pseudo range for all the satellites are calculated and included in the navigation data message broadcast by the pseudo-satellite. The user can collect this information as part of the regular navigation message and correct his solution accordingly. This technique is especially attractive in areas where 4 satellites are not always available due either to terrain configuration or to constellation configuration.

4.2.1 Limiting Factors on Accuracy

All three techniques proposed for Differential GPS require the use of a data link between the ground reference point and the user. This limits Differential GPS to a localized area due to line of sight and propagation problems.

Another limiting factor is the degradation of accuracy as the distance from the ground reference increases. An upper bound for the ranging error introduced by using, at the user location, the pseudo range correction term calculated for the reference point is derived below.

Let us consider the situation, (see Figure 4.2), where the satellite S at location S_{true}, but believed to be at location $S_{assumed}$, transmits a message at time t believed to be t + Δt. These discrepancies can be due to genuine inaccuracies in ephemeris and clock error determinations or can be intentionally introduced as a Selective Availability technique.

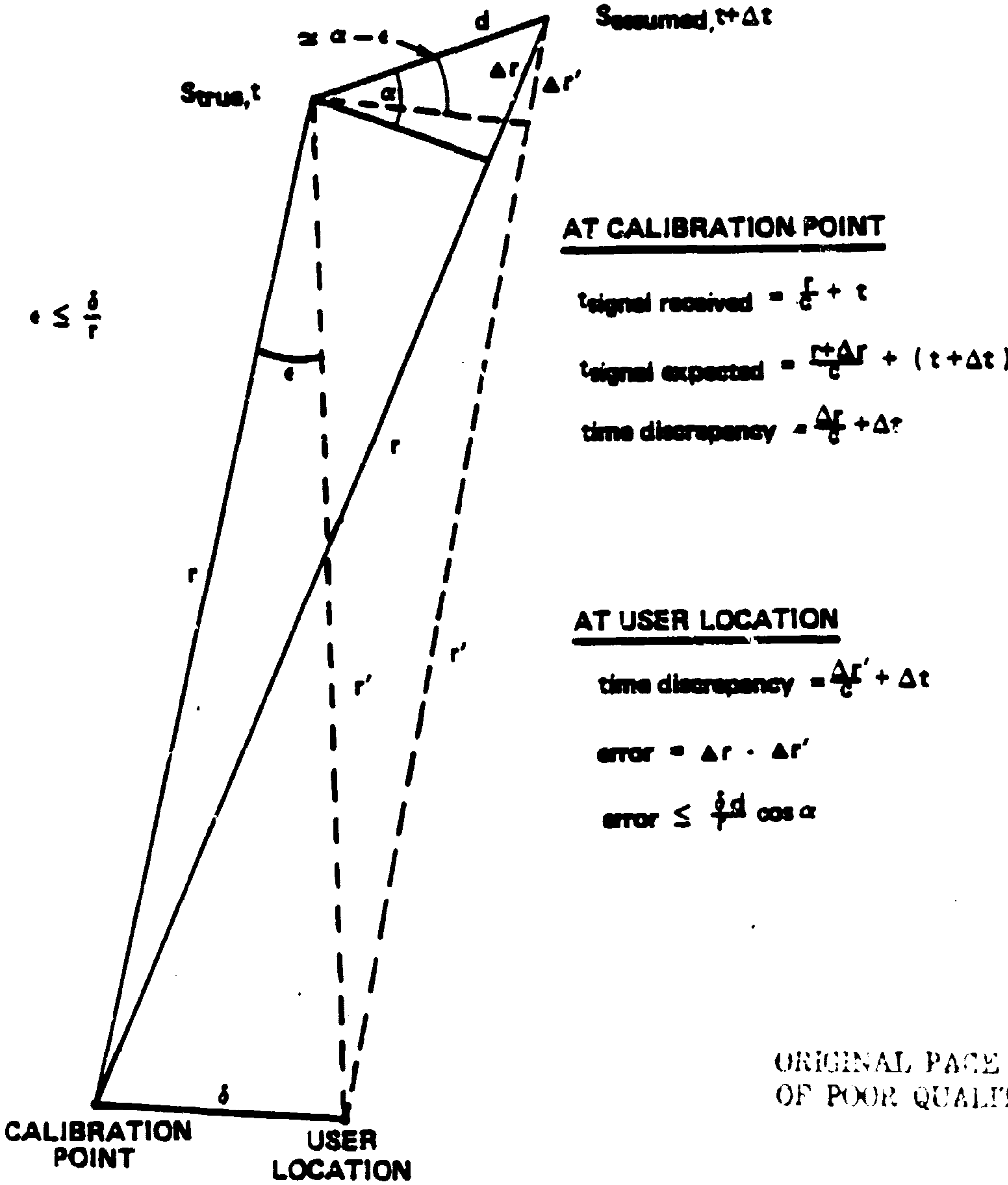


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Figure 4.2. Degradation of Accuracy With Distance From the Calibration Point

At the calibration point, the time at which the signal is received and the time at which it is expected are:

$$t_{signal\ recvd} = \frac{r_{true}}{c} + t$$

$$t_{signal\ expected} = \frac{r_{true} + \Delta r}{c} + t + \Delta t$$

The total time discrepancy is

$$\frac{\Delta r}{c} + \Delta t$$

Let us now consider a user, a distance δ away from the calibration point. For this user, the total time discrepancy will be

$$\frac{\Delta r'}{c} + \Delta t$$

Therefore, the range error introduced by using, at the user location, the discrepancy obtained for the calibration point is:

$$e = \Delta r - \Delta r'$$

or

$$e \simeq d \sin\alpha - d \sin(\alpha - \varepsilon)$$

$$e \simeq d(\sin\alpha - \sin\alpha \cos\varepsilon + \sin\varepsilon \cos\alpha)$$

Approximating to first order for small ε, we obtain

$$e \simeq \varepsilon d \cos\alpha$$

The value of ε can be bounded as

$$\varepsilon \leq \frac{\delta}{r}$$

which leads to

$$e \leq \frac{\delta d}{r} \cos\alpha$$

The worst case will be for

$\alpha = 0.$, i.e., an along track offset.

and $$|e| \leq \frac{\delta d}{r}$$

In Figure 4.3, these errors are plotted for various cases of user to calibration point separation. Obviously, one would not use Differential GPS if the ranging error is larger than the guaranteed accuracy of GPS. This is 83 m (1σ) (PDOP=3). If Selective Availability is not implemented, ranging errors can be expected to be about 5 m (P code) and 11 m (C/A code).

Example: for δ = 100 km and d = 1 km and
since r is approximately 20,000 km

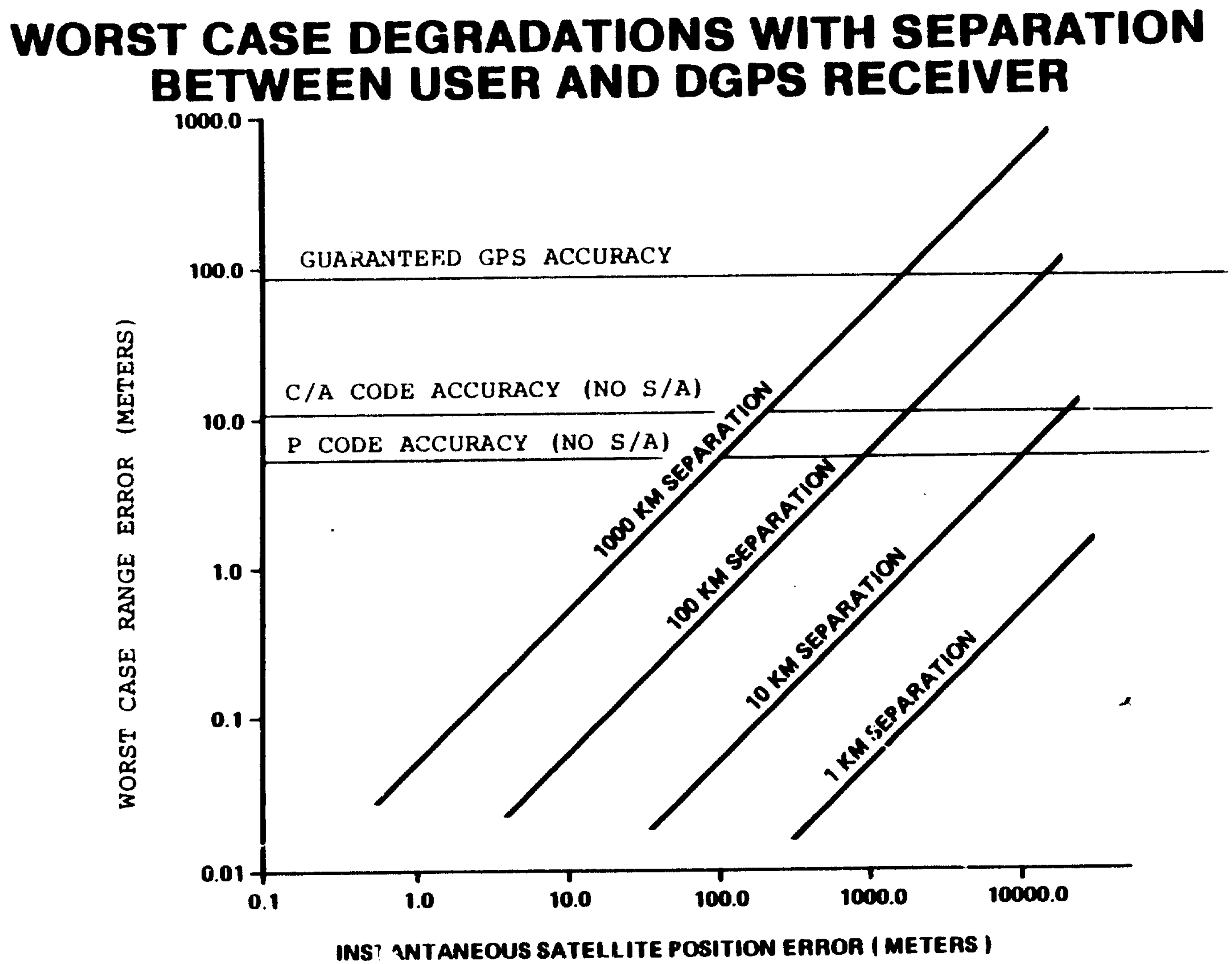
$$|e| \leq 5 \text{ meters}$$

The pseudo range correction at the calibration point is $\Delta r + c\Delta t$ and is obtained by taking the difference between the time at which the signal is expected and the time at which it is actually received. The time at which it is expected is determined by using the true calibration point location and the assumed satellite location. The difference will, therefore, include all propagation delays.

So, the ranging error introduced is linearly proportional to the distance from the ground reference point.

In the second and third techniques described above, pseudo range correction terms are actually sent to the user.

However, in the first technique, Earth Centered Earth Fixed (ECEF) coordinates correction terms (Δx, Δy, Δz) are broadcast by the ground reference station.



WORST CASE DEGRADATIONS WITH SEPARATION BETWEEN USER AND DGPS RECEIVER
1000.0
100.0
10.0
1.0
0.1
0.01
WORST CASE RANGE ERROR (METERS)
GUARANTEED GPS ACCURACY
C/A CODE ACCURACY (NO S/A)
P CODE ACCURACY (NO S/A)
1000 KM SEPARATION
100 KM SEPARATION
10 KM SEPARATION
1 KM SEPARATION
0.1
1.0
10.0
100.0
1000.0
10000.0
INSTANTANEOUS SATELLITE POSITION ERROR (METERS)

Figure 4.3

An error in position is related to a ranging error by the Position Dilution of Precision (PDOP); i.e.,

$$e_x = \text{PDOP}\ e_r$$

where

e_x and e_r are position and range errors, respectively.

PDOP is a function of the geometry between the user position and the satellite position. A PDOP of 3 is representative of GPS. For this value, a position error of 15 m would be obtained in the case of a 5 m ranging error. More on PDOP can be found in reference 11.

4.2.2 Differential GPS Performance

Table 4.1, borrowed from (8), presents the baseline GPS system error budget as well as the Differential GPS error budget (using the precision code P). This table, however, does not take into consideration the degradation of accuracy due to distance discussed above.

If we use the example of the previous section, i.e., a distance of 100 km between the two receivers and a 1 km alongtrack error in the satellite position, a 5 meters ranging error would result. The resulting User Equivalent Range Error (UERE) would be about 6.5 meters, which would correspond to a point solution accuracy of 19.5 meters without filtering or 15 meters with filtering, which does not compare favorably with the baseline GPS. A less extreme case would be a 100 km distance between the two receivers and a 200 meter alongtrack error in the satellite position. A 1 meter ranging error would result. This corresponds to a point solution accuracy of about 12 meters without filtering or 5 meters with filtering. These numbers compare more favorably with the baseline GPS. The sensitivity of Differential GPS to alongtrack errors is, however, noteworthy. The baseline GPS system, on the other hand, is pretty much insensitive to alongtrack errors, but very sensitive to line of sight errors. If a 1 km ranging error were added on in the GPS error budget, this error would dominate all other sources and the user would end up with a 1 km UERE, if the baseline GPS is used. Satellite clock errors are undistinguishable from the line of sight position errors and can therefore only be compensated by Differential GPS and not by the baseline system.

Table 4.1. P Code Receiver GPS Error Budget

Error Source	Absolute (meters)			Differential (meters)		
	Bias	Random	Total	Bias	Random	Total
Clock and navigation subsystem stability	0	2.7	2.7	0	2.7	2.7
Predictability of satellite perturbations	1.0	0	1.0	0	0	0
Other	0	0.866	0.866	0	0.866	0.866
Ephemeris and clock prediction	2.5	0	2.5	0	0	0
Ionospheric delay compensation	2.3	0	2.3	0	0	0
Tropospheric delay compensation	0	2.0	2.0	0	2.0	2.0
Receiver noise and resolution	0	1.5	1.5	0	1.5	1.5
Multipath	0	1.2	1.2	0	1.2	1.2
1σ system user equivalent range error (UERE)	3.54	3.97	5.3	0	3.97	3.97

Absolute:

Point solution accuracy = PDOP × ranging accuracy = 3 × 5.3 ≅ 16 meters

Filtered solution accuracy =

$$\sqrt{(3 \times 3.54)^2 + \left(\frac{3 \times 3.97}{3}\right)^2} \cong 11 \text{ meters}$$

Differential:

Point solution accuracy = PDOP × ranging accuracy = 3 × 3.97 ≅ 12 meters

Filtered solution accuracy =

$$\frac{3 \times 3.97}{3} \cong 4 \text{ meters}$$

Estimates of Differential GPS performance using the P and C/A codes are discussed next. Tables 4.2 and 4.3 present these results.

Table 4.2 addresses the performance of the baseline GPS and that of the three Differential GPS techniques assuming various scenarios of availability to the civilian community. Four satellites are available at all times.

Table 4.3 presents the same information as the first one with the exception that an overhead satellite outage is assumed, i.e., not satellite is available at a high elevation angle relative to the user. Use of the baseline GPS in this situation would provide a degraded vertical accuracy.

Differential GPS would provide a better accuracy. Techniques A and B provide an improved vertical solution, especially after filtering. Technique C, in which the ground station would act as a pseudolite, will give the best results when the ground station is directly below the user, thereby improving the Vertical Dilution of Precision (VDOP). The numbers presented in Tables 4.2 and 4.3 are only representative of the type of relative improvements one might expect from the use of Differential GPS. They were derived as follows:

I. <u>No Satellite Outages</u>

A. <u>C/A With S/A</u>

1. <u>Baseline GPS</u>

200 m (CEP) as indicated in the Federal Radionavigation Plan. This corresponds to about 250 m (1σ).

2. <u>Differential GPS</u>

The error budget of Table 4.1 was used, but the receiver noise and resolution error was assumed to be 10 meters rather than 1.5 meters since the C/A code is used.

DIFFERENTIAL GPS ACCURACY ESTIMATES IN THE CASE OF NO SATELLITE OUTAGE

CIVIL AVAILABILITY	NO OVERHEAD SATELLITE OUTAGE							
	ACCURACY WITHOUT DGPS (m 1σ)		ACCURACY WITH DGPS A (m 1σ)		ACCURACY WITH DGPS B (m 1σ)		ACCURACY WITH DGPS C (m 1σ)	
	HOR	VERT	HOR	VERT	HOR	VERT	HOR	VERT
C/A WITH S/A	250 / 250	250 / 250	16 / 5	27 / 9	16 / 5	27 / 9	16 / 5	21 / 7
C/A WITHOUT S/A	17 / 8	28 / 13	16 / 5	27 / 9	16 / 5	27 / 9	16 / 5	21 / 7
P WITHOUT S/A	8 / 6	13 / 9	6 / 2	10 / 3	6 / 2	10 / 3	6 / 2	8 / 3

NOTES: (1) FOR EVERY CASE, THE NUMBER ABOVE THE LINE IS THE ACCURACY WITH NO FILTERING; THE NUMBER BELOW THE LINE IS THE ACCURACY AFTER FILTERING

(2) HDOP = 1.5
VDOP = 2.5 (EXCEPT DGPS C) VDOP = 2.0 (DGPS C)

Table 4.2

DIFFERENTIAL GPS ACCURACY ESTIMATES IN THE CASE OF AN OVERHEAD SATELLITE OUTAGE

CIVIL AVAILABILITY	ONE OVERHEAD SATELLITE OUTAGE							
	ACCURACY WITHOUT DGPS (m 1σ)		ACCURACY WITH DGPS A (m 1σ)		ACCURACY WITH DGPS B (m 1σ)		ACCURACY WITH DGPS C (m 1σ)	
	HOR	VERT	HOR	VERT	HOR	VERT	HOR	VERT
C/A WITH S/A	250 / 250	400 / 400	16 / 5	43 / 14	16 / 5	43 / 14	16 / 5	21 / 7
C/A WITHOUT S/A	17 / 8	44 / 20	16 / 5	43 / 14	16 / 5	43 / 14	16 / 5	21 / 7
P WITHOUT S/A	8 / 6	21 / 15	6 / 2	16 / 5	6 / 2	16 / 5	6 / 2	8 / 3

NOTES: (1) FOR EVERY CASE, THE NUMBER ABOVE THE LINE IS THE ACCURACY WITH NO FILTERING; THE NUMBER BELOW THE LINE IS THE ACCURACY AFTER FILTERING

(2) HDOP = 1.5
VDOP = 4 (EXCEPT DGPS C) VDOP = 2.0 (DGPS C)

Table 4.3

This leads to a 1σ UERE of 10.65 meters. Any line of sight bias in the satellite position or any error in the satellite clock are cancelled out by Differential GPS. The error due to the distance between the user and the ground reference point was not included. Using a HDOP of 1.5 and a VDOP of 2.5 lead to horizontal and vertical position errors of about 16 meters and 27 meters, respectively, assuming no filtering. After filtering, and assuming that the random ranging error can be reduced by a factor of 3, the position errors are 5 meters (1 horizontal) and 9 meters (1σ vertical). Techniques A, B and C will provide the same ranging accuracy. The position accuracies could be different since there can be variations in the DOP values. A VDOP of 2.0 was assumed for DGPS-C since VDOP is improved by the pseudolite.

B. C/A Without S/A

1. Baseline GPS

The error budget of Table 4.1 is used, with 10 meters receiver noise error. The resulting 1σ UERE is about 11 meters. This corresponds to a horizontal and vertical position errors of 17 and 28 meters (HDOP = 1.5, VDOP = 2.5) before filtering and 8 and 13 meters after filtering.

2. Differential GPS

Since there is no Selective Availability, the satellite position error alongtrack can be assumed less than 1 km. A 200 meter error would induce a 0.1 meter error in range for a 10 km distance between the user and the ground reference point. This error can be neglected. The 1σ UERE would then be 10.65 meters. This corresponds to a horizontal position error (HDOP = 1.5) of 16 meters and 5 meters before and after filtering, respectively. The vertical errors (VDOP = 2.5) are 27 meters and 9 meters before and after filtering, respectively. Here again, possible DOP variations between Techniques A, B and C can occur. A VDOP of 2.0 was assumed for DGPS-C.

C. P Without S/A

1. Baseline GPS

The numbers from Table 4.1 are used with HDOP = 1.5 and VDOP = 2.5. This leads to horizontal errors of 8 and 6 meters before and after filtering and vertical errors of 13 and 9 meters before and after filtering.

2. Differential GPS

The numbers from Table 4.1 are used with HDOP = 1.5 and VDOP = 2.5. Horizontal and vertical errors are 6 and 10 meters before filtering and 2 and 3 meters after filtering. For DGPS-C a VDOP of 2.0 was used. This leads to slightly smaller errors.

II. One Overhead Satellite Outage

By an overhead satellite outage, we mean that all satellites available to the user are at relatively low elevations. This leads to an increased Vertical Dilution of Precision (VDOP), while the Horizontal Dilution of Precision (HDOP) is practically unchanged.

To illustrate this situation, a VDOP of 4 was assumed, while HDOP remained at 1.5. The horizontal accuracies obtained in the case of no overhead satellite outage are therefore the same in this case. The vertical errors are larger, except in the case of technique C of Differential GPS, where the ground station can be used as the fourth satellite in the constellation. For this case, VDOP would be conserved at 2.0 and the vertical accuracy would be much better. Table 4.3 presents these results.

III. Conclusions

From these tables, we can see that Differential GPS will, in most cases, greatly improve the accuracy. It is noteworthy that this is also true when no Selective Availability is implemented. The largest improvement provided by the differential approach is when an overhead outage occurs. Technique C provides the best accuracy, but it will require a fair amount of modification to the user equipment sets designed for the baseline GPS, since one satellite will now be on the ground, which, among other things, will require the use of multiple antennas. Techniques A and B also require a data link with the user but not at the rate required by Technique C.

Nevertheless, whatever the technique, Differential GPS is one sure way for the civilian community to have a guaranteed level of accuracy better than the 250 meters presently planned for GPS. Also, with an 18 satellites constellation, the probability of an outage is increased and the potential improvement of Differential GPS more apparent.

4.2.2.1 Ionospheric Compensation

Let us dwell just a little on the ionospheric delay compensation of Table 4.1. The ionospheric delay is dependent on both the character of the ionosphere at zenith and the elevation angle to the satellite. The effects of the elevation angle relative to the total ionospheric delay are illustrated in Figure 4.4 extracted from (12). The obliquity factor (multiplicative) gives the factor with which the ionospheric delay is increased relative to the delay for a ray to a satellite at zenith or

$$\mathrm{iono}_E = Q_E \, \mathrm{iono}_{90}$$

where iono_E is the ionospheric delay for an elevation E

iono_{90} is the ionospheric delay for an elevation of 90°

Q_E is the obliquity factor.

If we consider, as previously, a distance of 100 km between the ground reference point and the user, we obtain (see Figure 4.5).

$$\alpha \simeq \frac{100}{6400} \simeq 0.016 \text{ rad} \simeq 0.9 \text{ degree}$$

$$\beta \leq \frac{100}{20{,}000} \simeq 0.005 \text{ rad or } \beta \leq 0.3 \text{ degree}$$

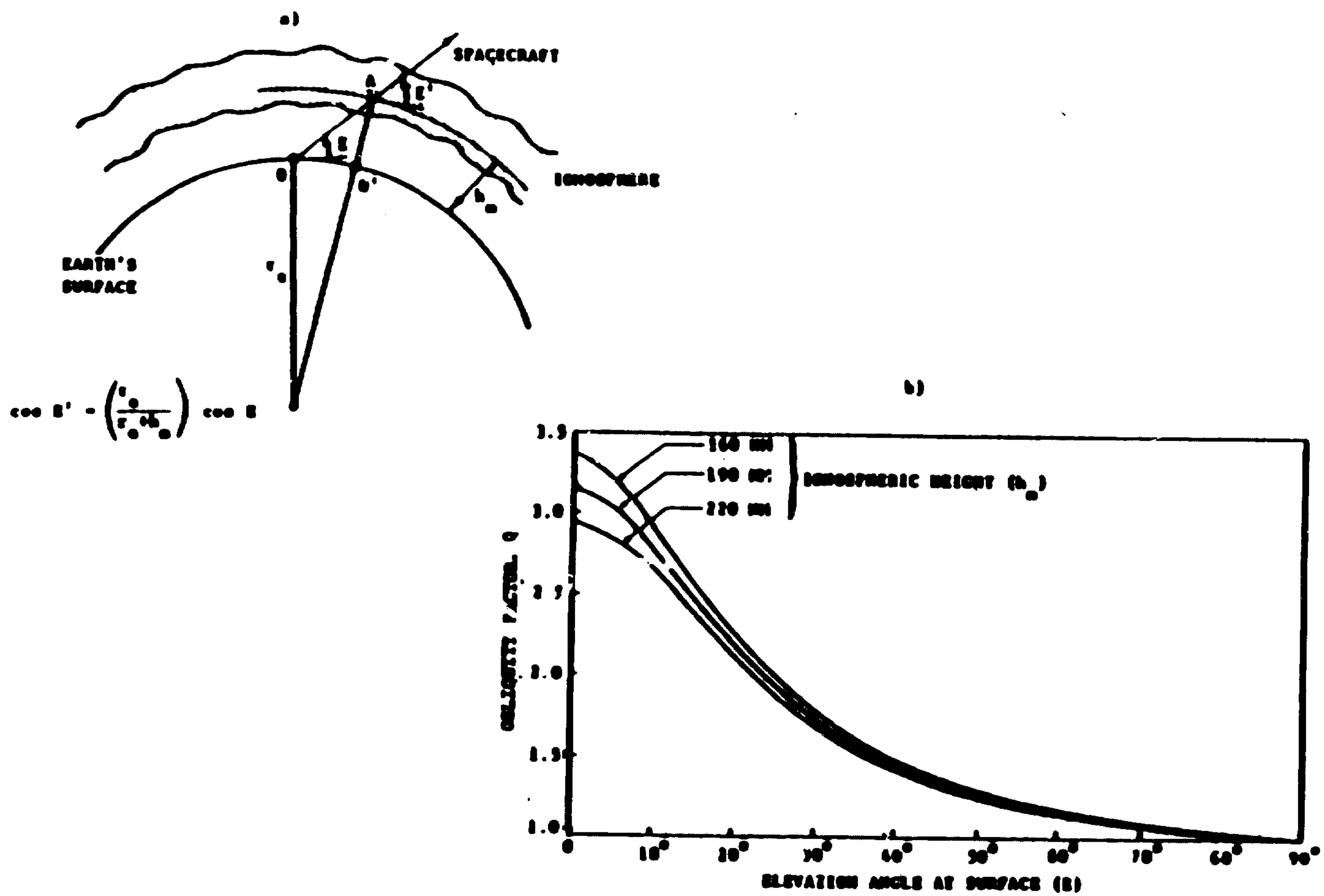


Figure 4.4

Oblique Ionospheric Path Geometry and the Relationship to Surface Elevation Angle

This limits the change in elevation to 1.2 degree.

The ionospheric delay for P and P' are, respectively,

$$Q_P \; iono_{90}$$

$$Q_{P'} \; iono_{90}$$

the difference is

$$|\Delta iono| = |Q_P - Q_{P'}| \; iono_{90}$$

From Figure 4.5, the maximum change of Q with elevation is about 0.06 for a 1.2° change or $|\Delta iono| \leq 0.06 \; iono_{90}$.

Replacing $iono_{90}$ by 2.3 m one obtains an upper bound on the difference of ionospheric delays between user and ground station

$$|\Delta iono| \leq 0.14 \text{ m}$$

So, for all practical purposes, the ionospheric delay compensation is the same at both points. It would therefore be advantageous to modify the user equipment software so as to inhibit the ionospheric delay correction. Two approaches are then possible.

For Differential GPS Technique A, where position corrections Δx, Δy, Δz are transmitted, either no ionospheric correction is made at the ground receiver, or the correction is made and transmitted to the user along with the position correction terms. In the former case, the position correction terms will include any ionospheric delay, and in the latter case, the same ionospheric correction will be made at both user and reference ground station. In any event, it is well known that ionospheric delay estimation is imprecise and requires a dual frequency receiver in the user set. The techniques above do away with this dual frequency requirement and provide for a more accurate ionospheric compensation.

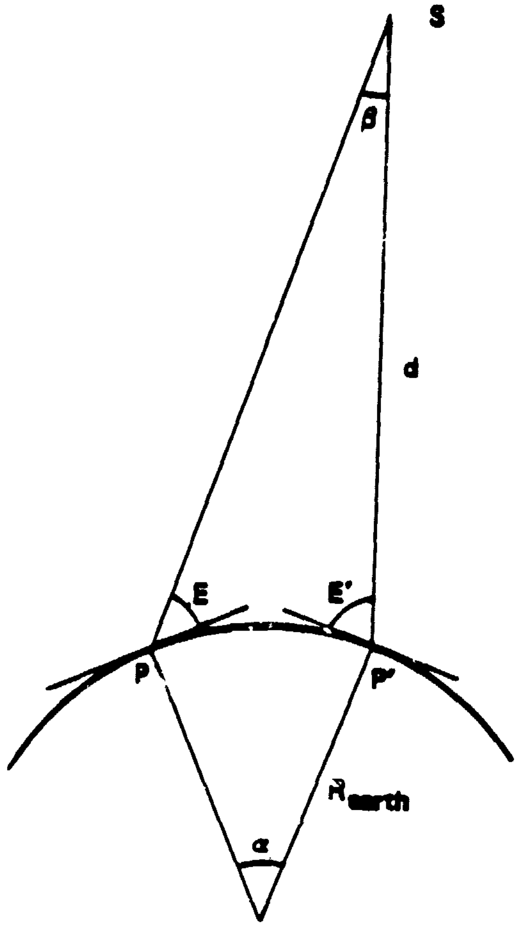


Figure 4.5. Change in Ionospheric Delay

For Differential GPS Techniques B and C, where pseudo range corrections are transmitted to the user, the same techniques can be used. If no ionospheric correction is made, this delay is included in the pseudo range correction terms broadcast, as indicated in Section 4.2.1. If the correction is made, it is transmitted to the user.

4.2.3 Field Test Results

Differential GPS Technique A described in Section 4.2 was tested by Texas Instruments (TI)(8) at the Yuma Proving Ground (YPG) test range. A TI 5 channel High Dynamics User Equipment (HDUE) receiver was used. The Inverted Range Control Center (IRCC) at YPG contains a multichannel receiver that provides continuous tracking of all GPS satellites being used by the user sets on the range. The IRCC provides "ground truth" data for post-mission analysis, and also controls four ground based GPS transmitters or pseudolites that can be used in conjunction with the satellites to obtain a "constellation" of four. These ground transmitters were used to transmit the Differential GPS information to the user (using the user equipment fifth channel), but they were never part of the constellation used for pseudorange measurements. The ionospheric delay was treated as indicated in 4.2.2.1. The differential correction terms were transmitted at a 50 Hz rate and had an update rate of 30 seconds.

The three items that were sent are:

1. Four satellite identifier codes.

2. Differential corrections in the earth-centered, earth fixed coordinate system.

3. Ionospheric delay compensation incorporated at the IRCC for each satellite.

Modifications were made to the HDUE software so as to add the following capabilities:

1. An interface established through the CDU allows the operator to select the differential mode and enter a ground transmitter number as the differential source. This action causes the HDUE to acquire and track this GT on its fifth channel. The satellite management function then inhibits the GT measurements from being incorporated into the navigation solution.

2. The data block processing function has been modified to recover the differential terms added to spare areas in the GT 50-Hz data frame.

3. All ionospheric measurement corrections are read from the differential data frame rather than being calculated from L2 measurements.

4. The navigation solution is corrected based on the received differential correction terms.

5. The corrected solution is then used for all normal HDUE navigation activities such as absolute position determination, relative navigation to a selected waypoint, and control of the steering display to maintain a desired approach.

The tests were conducted using a UH-1H helicopter. The course was a box pattern consisting of 4 legs of approximately 10 km each. Figures 4.6 and 4.7 present the results for a segment of such a flight. First the helicopter is operating in the non-differential mode, with horizontal and vertical errors of the order of 20 m and 40 m, respectively. When the differential mode is selected, errors immediately drop to about 5 m!

Noteworthy is that in this case the distance between the ground reference point and the user was probably of the order of 10-15 km and that, therefore, the degradation effect due to distance, as discussed earlier, was very small. Nevertheless, the dramatic improvement in accuracy achieved with Differential GPS makes it look very promising. Additional test results are provided in Table 4.4.

An additional point should be made here. The poor performance of the GPS set in its baseline configuration was due to aged ephemeris data and should not be attributed to the set itself. The ability of Differential GPS to handle such problems was clearly shown.

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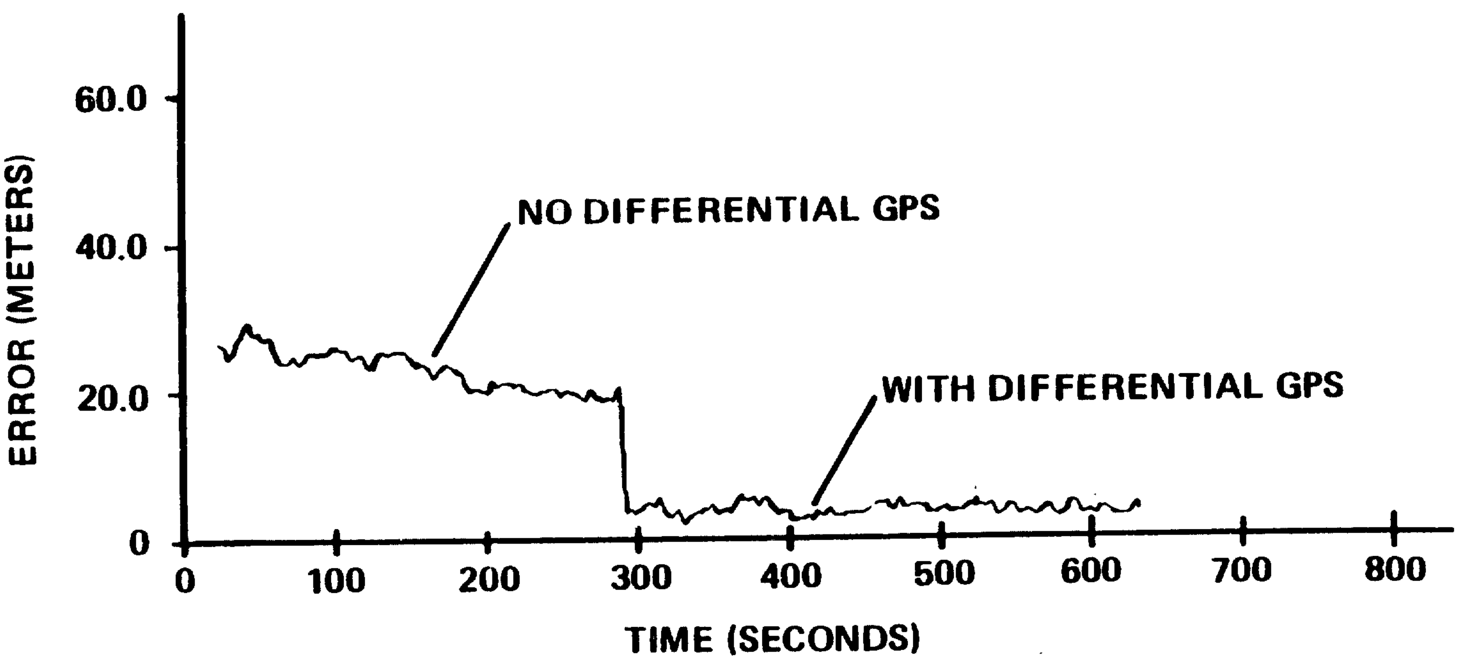
HORIZONTAL ACCURACY



(A) HORIZONTAL ERROR

Figure 4.6

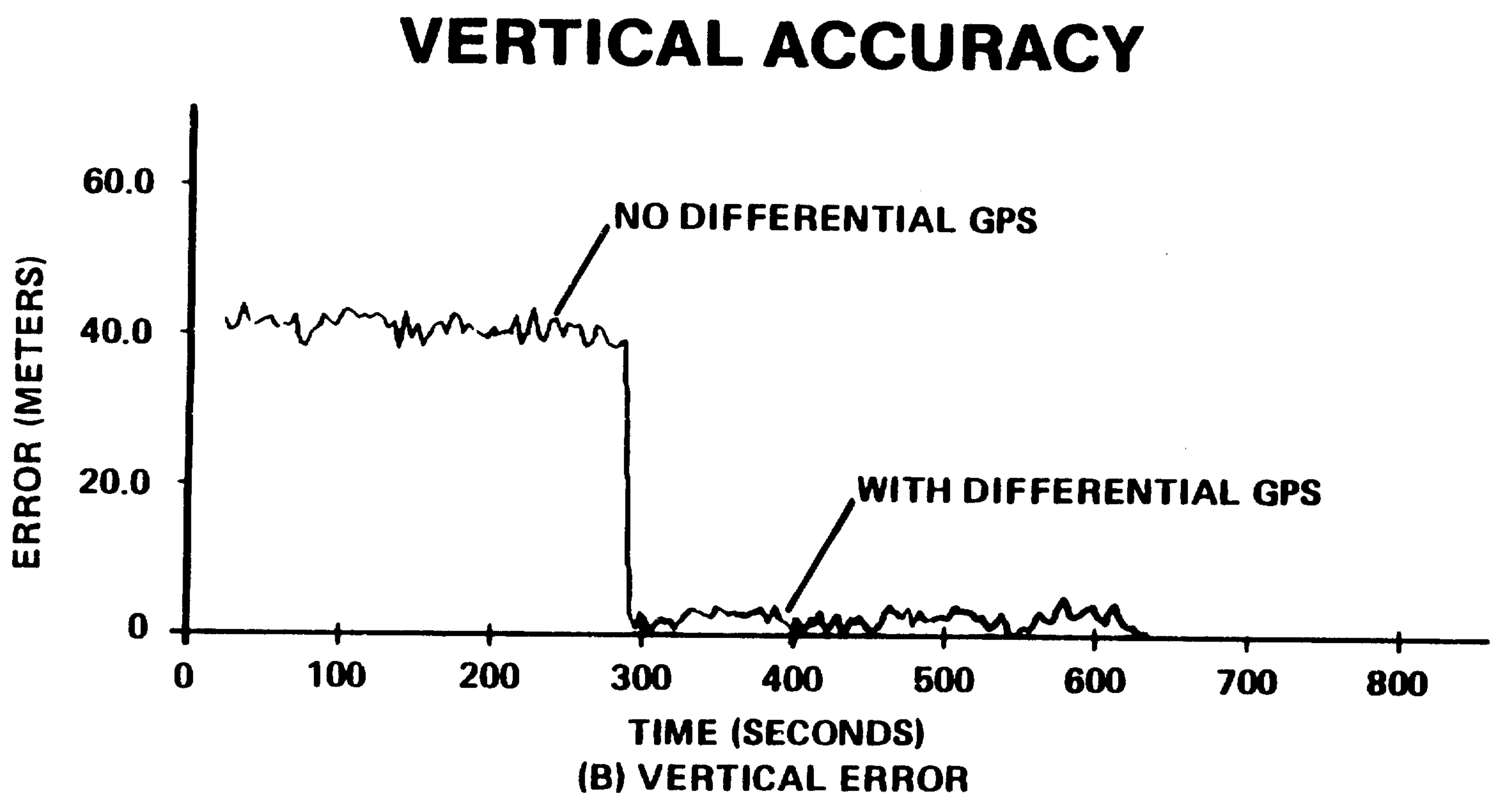

VERTICAL ACCURACY
ERROR (METERS)
60.0
40.0
20.0
0
NO DIFFERENTIAL GPS
WITH DIFFERENTIAL GPS
0
100
200
300
400
500
600
700
800
TIME (SECONDS)
(B) VERTICAL ERROR

Figure 4.7

Table 4.4. Representative Differential Performance

		ERROR (METERS)				
DATE		MEAN	RMS	STD DEV	CEP	PE
9 Jan 1980	Horiz	4.2	4.7	2.1	3.8	
	Vert	-5.2	5.5	1.9		5.2
10 Jan 1980	Horiz	5.0	5.3	1.8	5.0	
	Vert	3.9	4.5	2.2		4.0
11 Jan 1980	Horiz	3.8	3.8	0.8	3.7	
	Vert	1.4	2.0	1.5		1.5
16 Jan 1980	Horiz	3.6	3.8	1.5	3.4	
	Vert	2.1	2.6	1.5		2.1

4.2.4 Differential GPS Justification

The issues addressed in the previous sections relative to the performance of Differential GPS (with or without Selective Availability) are ample justification for its development.

Table 4.5 lists potential uses of Differential GPS. These are addressed one at a time.

Table 4.5

Potential Uses of Differential GPS

- Approach Instrumentation for Non-Instrumented Airfields
- All Weather Helicopter Resupply (Offshore)
- Narrow Channel Maritime Navigation
- Loss of Control Segment Due to Enemy Action
- All Weather Helicopter Rescue
- P-Code Performance at C/A Cost
- Seismic Geophysical Exploration
- Generally Improved VDOP
- GPS Accuracy Monitoring and Alert System
- Use of Space Vehicle Down to 0° Elevation
- Total Loss of Overhead Satellite Signal
- Less Than Four Satellites in View Due to Terrain Shading
- Unmodeled Atomic Clock Drift
- Atomic Clocks Failed/Use of Quartz Crystal
- Aged Ephemeris Data

A. Approach Instrumentation for Non-Instrumented Airfields

The non-precision approach accuracy requirement for controlled airspace is 50 m (1σ). This cannot generally be achieved with the baseline GPS if Selective Availability is implemented. However, even with S/A, Differential GPS should provide an accuracy of better than 10 m, which would allow for non-precision approaches.

If an overhead satellite outage occurs, the vertical accuracy will degrade, but Differential GPS would still meet the requirements.

B. All Weather Helicopter Resupply (Offshore)

The fast development of offshore oil exploration is creating a need for an all-weather helicopter resupply capability. While the baseline GPS would be sufficient for en route navigation, the terminal approach would require additional accuracy that could only be provided by Differential GPS. We have seen that distance between the ground reference station and the user induces errors in Differential GPS. If such a ground station was located on the oil rig, the accuracy of Differential GPS would improve as the helicopter is approaching, which is exactly what is needed.

C. Narrow Channel Maritime Navigation

The accuracy required for narrow channel navigation is very high, especially considering the size of today's ships and their inability to alter course or stop quickly. In the most restricted channels, accuracies of 4 to 10 m are required. From Table 4.2 it appears that Differential GPS using the C/A code could meet the 10 meters requirements. If no S/A is implemented, the P code accuracy obtained with Differential GPS would meet all the requirements.

D. Loss of Control Segment Due to Enemy Action

If the Control Segment is lost, the satellite navigation message will not get updated. This will, of course, lead to a slow degradation of the accuracy. The baseline GPS is helpless in this case; but Differential GPS can, as was discussed earlier, cancel out the resulting biases introduced by satellite and clock data errors.

E. All Weather Helicopter Rescue

This application is similar to the all-weather offshore resupply capability. The difference, however, is that there will be no ground station at the rescue point and therefore no improved accuracy with decreasing time to go. Nevertheless, precise localization of the rescue point and low repeatability errors are needed for a rescue operation and are provided by Differential GPS.

F. P Code Performance at C/A Cost

It is clear from Tables 4.2 and 4.3 that Differential GPS using the C/A code will provide accuracies comparable to that of the P-code for the baseline system. In fact, in the case of an overhead outage, technique C of Differential GPS using the C/A code will outperform the baseline P-code. The modifications the set needs to be able to operate in the differential mode are minor when compared to the additional cost of a P set. In addition, given that the P-code will most probably be de-' d to most users, this high accuracy capability take added significance.

G. Seismic Geophysical Exploration

The extremely high operating costs of geophysical exploration make it imperative to have a high positioning accuracy capability. Both marine and land surveys have stringent requirements in the areas of coverage and relative, reproducible and absolute accuracy. Even if this community is provided access to the P code, this accuracy can still be improved by differential techniques. There is, therefore, little doubt that strong financial support can be expected from this community for the development of Differential GPS.

H. Generally Improved VDOP

The Vertical Dilution of Precision (VDOP) relates vertical position accuracy to the ranging errors. If technique C of Differential GPS is used (the ground reference point is a pseudolite), very good vertical accuracy will be obtained when the user is directly above the pseudolite, which will be the case in a final approach, for example.

I. GPS Accuracy Monitoring and Alert System

Comparison of the GPS derived solution with the known surveyed location of the ground reference point would provide for an excellent accuracy monitoring system of the baseline GPS. When this error exceeds a maximum acceptable limit, a message could be broadcast to users to alert them to switch to the differential mode.

J. Use of Space Vehicle Down to 0° Elevation Without Serious Error

Due in part to visibility problems, but also to large ionospheric delays, space vehicles are not used below 5° elevation. The ability of Differential GPS to compensate for these ionospheric delays would allow the use of satellites down to the zero elevation level. This could, in some cases, be the difference between 3 or 4 available satellites and a considerable accuracy improvement.

K. Total Loss of Overhead Satellite Signal

The total loss of an overhead satellite signal would significantly degrade the solution. As already discussed earlier in this section, Differential GPS, especially Technique C, can greatly improve the accuracy in this situation.

L. Less Than Four Satellites in View Due to Terrain Shading

Temporary loss of a satellite due to terrain shading is very similar to the previous case. Of course, the loss is usually only temporary and the degradation is therefore less severe.

Differential GPS would be very well suited to handle such situations.

M. Unmodeled Atomic Clock Drift

As we saw earlier, unmodeled satellite clock errors can be easily corrected for, using Differential GPS.

N. Atomic Clocks Failed/Use of Quartz Crystal

In this case, the satellite clock error will be very large and this satellite will be of little use to the baseline GPS. However, Differential GPS can correct for large clock errors.

O. Aged Ephemeris Data

When ephemeris data grow old, the accuracy of the solution degrades due to the bias errors in the satellite position. As we have seen, Differential GPS is relatively insensitive to the line of sight errors, but fairly sensitive to alongtrack satellite errors. The reverse holds for the baseline GPS. Nevertheless, a 1 km alongtrack error leads to a 5 m ranging error at the user if it is 100 km away from the reference point. The sensitivity of the baseline GPS to a line of sight error is, of course, much stronger. The advantage of Differential GPS in the case of aged ephemeris is therefore apparent.

4.2.5 Advantages of Differential GPS Other Than Pure Navigation Accuracy Improvement

In the previous section, we have looked at Differential GPS as a system providing improved navigation accuracy. Let us now focus our attention on additional benefits that might be derived from the use of such a system.

4.2.5.1 Moving Bases Rendezvous

This is mainly a military application. In aircraft-to-aircraft, ship-to-ship, or aircraft-to-aircraft carrier rendezvous operations, absolute position determination is not as important as relative information. A data link would need to be established between the vehicles and each would transmit its position to all the others. Or, alternatively, one vehicle would be declared the master and would transmit its position to all the others.

4.2.5.2 Automatic Checking of Selective Availability (S/A) Corruption

Since the ground reference station is surveyed, it will provide an automatic indication of the amount of corruption introduced by S/A in that particular area. This information is essential if GPS is to be implemented in the ATC environment.

4.2.5.3 System Development May Have Elements in Common With Collision Avoidance

A collision avoidance system in which every aircraft would know where the other aircraft in the area are, where they are heading and at what speed, would be very effective. In such a system, each aircraft would compare its position, heading, and speed to that received from the nearby aircraft and take appropriate corrective action. The RELNAV function would by itself correct for all biases in the solution and has potentially many elements in common with a Differential GPS system. This type of collision avoidance would take some of the load away from Air Traffic Control -- certainly a welcome factor!

4.2.5.4 Cost

As was seen in Tables 4.2 and 4.3, the accuracy of a C/A set is often improved by Differential GPS. A user requiring a certain level of accuracy could therefore purchase a cheaper set (no P code capability) and still meet its requirements. This cost reduction is, of course, of paramount importance if GPS is to compete in the general aviation market.

5 CIVIL SUPPORT AND MARKET POTENTIAL FOR DIFFERENTIAL GPS

5.1 Review of Existing Radionavigation Systems

The multiplicity of radionavigation systems and the ensuing cost of maintaining and operating these systems has led the Department of Defense (DOD) and the Department of Transportation (DOT) to a Federal Radionavigation Plan(4). The goal is to select an optimal mix of radionavigation systems, either existing or in development, i.e., a combination that would provide for a high degree of common use (either military/civil or between the various transportation modes) by meeting diverse user requirements for accuracy, availability, reliability, operational utility, and cost. DOT and DOD expect to arrive at an initial selection of this mix by 1986. The systems being considered are:

LORAN-C

OMEGA

VOR, VOR/DME, VORTAC

ILS

TRANSIT

Radiobeacons

MLS

NAVSTAR GPS

The characteristics of these systems are addressed below.

1. LORAN-C

   LORAN-C has good accuracy but limited coverage. DOD phaseout of LORAN is scheduled to start as GPS becomes operational (1985). Characteristics and civil user schedule are provided in Table 5.1.

SYSTEM: LORAN-C (Civil User Totals)

DESCRIPTION: LORAN-C is a LF hyperbolic radionavigation system. The receiver computes lines of position based on time of arrival differences between two transmitters of a chain. The first chain was located along the U.S. coast in 1960. The Coast Guard will operate 12 chains throughout the world by 1980.

CHARACTERISTICS:

ACCURACY[1]			AVAILABILITY	COVERAGE	REL	FIX RATE	FIX DIM	CAPACITY	AMBIGUITY POTENTIAL
PREDICTABLE	REPEATABLE	RELATIVE							
460m	18-90m	18-60m	99+%	US Coastal, 2/3 CONUS Selected Overseas Areas	99+%	25 Fixes per Second	2D	Unlimited	Easily Resolved

		79	80	81	82	83	84	85
CIVIL USERS	AIR(2)	300	450	525	600	700	850	1000
	MARINE	32,600	44,900	54,000	57,800	62,000	66,500	71,500

(1) 2 drms
(2) Only CG Planes and Offshore Users

Table 5.1. LORAN-C System Characteristics and User Schedule

2. OMEGA

OMEGA has global coverage but limited accuracy. DOD phaseout is scheduled to start as GPS becomes operational (1985). Characteristics and civil user schedule are provided in Table 5.2.

Differential OMEGA, which is still in the development stages, is being studied in France, Canada, and the U.S. to determine to what extent its use can improve on the accuracy of the baseline OMEGA system.

3. VOR, VOR/DME, VORTAC

This system is extensively used today and is an integral part of ATC procedures. The heavy investment, both in user equipment and in ground stations, will provide for continued growth of this system until at least 1985 and its use probably into the next century.

The military phaseout is scheduled to start by 1985. Any replacement of VOR/DME by GPS should take at least 5 years. Characteristics and civil user schedule are provided in Table 5.3.

4. TACAN

DOD phaseout is scheduled to start by 1985. Characteristics and user schedule are provided in Table 5.4.

5. ILS

This system is widely used for instrumented approaches. It does not allow, however, for multiple approach paths. Its use is currently assured until at least 1995, by international agreement. Table 5.5 presents the user schedule for ILS.

6. TRANSIT

This system is used extensively in the maritime community for surveying. DOD phaseout is scheduled to start by 1985. Characteristics and user schedule are provided in Table 5.6.

SYSTEM: OMEGA (Civil User Totals)

DESCRIPTION: The OMEGA Navigation System is a VLF hyperbolic radionavigation system capable of use by ships, submarines, aircraft and units on land. The system has eight transmitting stations ~ 5000 miles apart. Position information is obtained by measuring relative phase of received signals.

CHARACTERISTICS:

ACCURACY[1]			AVAILABILITY	COVERAGE	REL	FIX RATE	FIX DIM	CAPACITY	AMBIGUITY POTENTIAL
PREDICTABLE	REPEATABLE	RELATIVE							
3.7-7.4km	3.7-7.4km	1.85-3.7km	99%	Near Global (over 90%)	99%	One FIX in 10 Seconds	2D	Unlimited	Requires Position Knowledge within 36 NM[2]

		79	80	81	82	83	84	85
CIVIL USER	(AIR)[3]	730	740	760	780	790	800	820
	MARINE (X000)	3.3	4	4.4	4.9	5	5.2	5.5

1. 2 drms
2. Assumes a three frequency receiver
3. Only oceanic users

Table 5.2. OMEGA Svstem Characteristics and User Schedule

SYSTEM: VOR, VOR/DME (Civil User Totals)

DESCRIPTION: VOR provides aircraft with bearing information relative to the VOR signal and magnetic north. Used for landing, terminal and enroute guidance. VOR transmitter operates in the VHF. DME provides a measurement of distance from the aircraft to the DME ground station. DME operates in the UHF.

CHARACTERISTICS:

	ACCURACY[1]			AVAILABILITY	COVERAGE	REL	FIX RATE	FIX DIM	CAPACITY	AMBIGUITY POTENTIAL
	PREDICTABLE	REPEATABLE	RELATIVE							
VOR	90m $(\pm 1.4°)^2$	23-282m $(\pm .35°)^2$	23-282m $(\pm .35°)^2$	Approaches 100%	Line of Sight	Approx. 100%	Continuous	Heading Angle Off Course	Unlimited	None
DME	185m (±0.1nm)	185m (±0.1nm)	185m (±0.1nm)	--	--	--	--	N.M. (slant range)	~100 users per site	--

		79	80	81	82	83	84	85
CIVIL USER (AIR)	VOR (X000)	158.5	168	176	182	185	190	196
	DME (X000)	54.3	57.3	61	64	65.3	67.5	70.3
	RNAV (X000)	9.6	10.1	10.7	11.3	11.3	11.6	12
TOTAL USER POPULATION		222.4	233.4	247.7	257.1	261.6	269.1	278.3
NUMBER OF EQUIPMENTS IN SERVICE	VOR (X000)	266.2	279	296	302	312	320.5	330.8
	DME (X000)	59.8	62.5	67	70.1	72	74.5	78
	RNAV (X000)	9.6	10.1	10.7	11.1	11.3	11.6	12
GOVT. STATION	VOR	927	927	927	927	927	927	927
	DME	847	847	847	847	847	847	847

1 2 drms
2 20NM from the transmitter, 2 Sigma

Table 5.3. VOR, VOR/DME System Characteristics and User Schedule

SYSTEM: TACAN (DOD Total)

DESCRIPTION: TACAN is a short range navigation system used primarily by the military. The system provides range, bearing and station identification. TACAN operates in the UHF band. When a TACAN transmitter is colocated with VOR it is denoted VORTAC – 15 such sites exist.

CHARACTERISTICS:

ACCURACY[1]			AVAILABILITY	COVERAGE	REL	FIX RATE	FIX DIM	CAPACITY	AMBIGUITY POTENTIAL
PREDICTABLE	REPEATABLE	RELATIVE							
63m ($\pm 1.0°$)[2,3]	63m ($\pm 1.0°$)[2,3]	63m ($\pm 1.0°$)[2,3]	Approaches 100%	Line of Sight	~100%	Continuous	Heading or Angle Off Course	~200 users per site	Slight
See Table I-4.8 For DME characteristics									

SCHEDULE:

		1980					1985					1990					1995				2000
PHASE IN/OUT:																					
DECISION PTS:							Review														
NUMBER OF USERS:	12,672	12,791	13,043	12,886	12,861	13,031	11,744	9,920	8,096	6,272	6,440	2,824	2,000	1,500	1,000	500	0				
EQUIP PURCH — USER SETS:	172	566	733	278	250	230	0														
EQUIP PURCH — GND STA.:	83	114	101	86	81	11	12	0													

1. 2 drms
2. 2NM from the transmitter
3. 2 Sigma

Table 5.4. TACAN System Characteristics and User Schedule

SYSTEM: ILS (Civil User Totals)

DESCRIPTION: The Instrument Landing System (ILS) is a precision approach system consisting of a localizer facility, a glide scope facility, and two or three VHF marker beacons. The VHF (108-112 MHz) localizer facility provides accurate, single path horizontal guidance information. The UHF (328.6-335.4 MHz) glide slope provides precise, single path, vertical guidance information to a landing aircraft.

	79	80	81	82	83	84	85
No. of Civil Users (x 1000)	60.6	63.8	68	70.7	72.4	75	77.5
No. of Equipments in Service (x 1000)	72.7	76.5	81.5	85	87	90	93
Ground Stations	816	816	816	816	816	816	816

Table 5.5. Instrument Landing System (ILS) User Schedule - Civil

SYSTEM: TRANSIT (DOD Total)

DESCRIPTION: TRANSIT nominally consists of four satellites in polar orbits. The satellites broadcast continuous information on 150 and 400 MHz. A receiver measures the apparent frequency shifts of the signals (doppler) as the satellite approaches or passes the user. The receiver then calculates the geographic position of the user, based on satellite position knowledge and corrections received from the transmitted signal. Vessel course, speed and time must be known accurately.

CHARACTERISTICS:

ACCURACY[1]			AVAILABILITY	COVERAGE	REL	FIX RATE	FIX DIM	CAPACITY	AMBIGUITY POTENTIAL
PREDICTABLE	REPEATABLE	RELATIVE							
500m	50m	38m	99+% When Satellite is in View	Worldwide, Non-Continuous	–	30 min. at 80° lat. to 110 min at Equator (Average)	2D	Unlimited	None

SCHEDULE:

		1980					1985					1990					1995					2000
PHASE IN/OUT																						
DECISION PTS:							Review		GPS FOC													
NUMBER OF USERS:																						
SHIPS/SUBS:	233	286	332	382	408	419	423	383	303	243	183	123	63	0								
NO OF EQUIP PURCH	50	52	47	50	26	11	4	0														

1. 2 drms

Note: The number of civil users was estimated to be 4500 in 1979 (Ref.13)

Table 5.6. TRANSIT System Characteristics and User Schedule

7. RADIOBEACONS

Continued use is assured for general aviation aircraft and pleasure boats until the year 2000, due to low cost of equipment. Characteristics and user schedule are provided in Table 5.7.

8. MLS

This system is scheduled to last well beyond the year 2025 and will probably be used in conjunction with an improved version of DME, the Precision DME (PDME). User schedule is provided in Table 5.8.

9. NAVSTAR GPS

The development schedule of GPS was presented in Figure 3.4. System characteristics and user schedule are presented in Table 5.9. For the system to be accepted by the civilian community, three main issues are to be worked out:

1) The cost of the user equipment must be competitive.

2) The management of the system by the military could create a reluctance to use it in the civilian community.

3) System availability and the probable implementation of Selective Availability must be clearly assessed.

The baseline system does not have the required accuracy to allow for precision landing, harbor approach, or harbor and inland navigation. Differential GPS, however, has this capability.

SYSTEM: Radiobeacon (NDB/RBN) (Civil User Totals)

DESCRIPTION: Aircraft nondirectional beacons (NDB) are used to supplement VOR-DME in the state of Alaska for transition from enroute to airport precision approach facilities and as a nonprecision approach aid at many airports. The beacons also relay transcribed weather broadcasts. Radio beacons are nondirectional radio transmitting stations which operate in the low frequency (LF) and medium frequency (MF) bands to provide ground wave signals to a receiver.

		79	80	81	82	83	84	85
CIVIL USER	AIR (NDB) (X000)	81.4	85.55	90.9	94.5	96.4	99.3	102.9
	MARINE (RBN) (X000)	370	386	404	423	442	462	484
GOVT GROUND STATION	NDB	629	629	629	629	629	629	629
	RBN	198	199	213	226	226	226	226

Table 5.7. Radiobeacon User Schedule - Civil

SYSTEM: MLS (DOD Total)

DESCRIPTION. The Microwave Landing System (MLS) has been developed by DOT, DOD, and NASA to provide a common civil/military landing sy tem to meet the full range of user operational requirements to the year 2000 and beyond. It is intended as a replacement for the Instrument Landing System (ILS) used by both civil and military aircraft and the Ground Controlled Approach system used primarily by military operators.

SCHEDULE:		1980					1985					1990					1995					2000
PHASE IN/OUT:																						
DECISION PTS:																						
NUMBER OF USERS: A/C RX:								1,090	2,180	3,270	4,360	5,450	6,540	7,630	8,720	9,810	10,900	10,900	10,900	10,900	10,900	10,900
GND/SHIP TX:							6	28	51	74	97	120	152	186	217	252	288	296	304	314	321	
EQUIP PURCH USER SETS:								1,306	1,306	1,306	1,306	1,306	1,306	1,306	1,306	1,306	1,306	636	636	636	636	
EQUIP PURCH GND STA:							6	23	24	24	23	23	33	33	33	33	23	9	8	9	7	

Table 5.8. Microwave Landing System (MLS) User Schedule

SYSTEM: GPS (DOD Total)

DESCRIPTION: The Global Positioning System is a space-based radio positioning navigation system that will provide extremely accurate three-dimensional position and velocity information together with system universal time to suitably equipped users anywhere on or near the Earth. The space segment will consist of 18 satellites in 12 hour orbits. Each satellite transmits navigation signals at frequencies of 1575.4 MHz and 1227.6 MHz.

CHARACTERISTICS:

ACCURACY 1/			AVAILABILITY	COVERAGE	REL	FIX RATE	FIX DIM	CAPACITY	AMBIGUITY POTENTIAL
PREDICTABLE	REPEATABLE	RELATIVE							
Horiz. 25m Vert. 30m	25m 30m	10m 8m	95%	Global, Continuous	99+%	Essentially Continuous	3D + Time and 3D Velocity	Unlimited	None

18 SATELLITE CONSTELLATION

SCHEDULE:	1980					1985					1990					1995					2000	
PHASE IN/OUT:																						
DECISION PTS.																						
NUMBER OF USERS:							838	2,718	4,300	8,420	11,222	12,960	13,823	14,433	14,886	15,383	15,814	15,814	15,814	15,814	15,814	15,814
EQUIP PURCH { USER SETS:						340	1,071	2,120	3,106	3,556	3,386	2,172	1,226	961	962	988	948	427	427	427	427	427
EQUIP PURCH { GND STA:																						

NOTE: Horizontal (2 drms) and vertical (2 sigma) accuracies are available to military and selected civil users. Accuracy available to other users is estimated at: 500m (2 drms) horizontal and 430m (2 sigma) vertical.

Table 5.9. Global Positioning System (GPS) Characteristics and User Schedule

5.2 Civilian Community Operational Requirements

The general requirements for the use of a Radionavigation System in the civilian community are:

1. Provide a service adequate for safety.

2. Provide good accuracy, flexibility and availability.

3. Be economically affordable (especially the user equipment).

Below are some specific requirements for different sectors of the civilian community as presented in the Federal Radionavigation Plan.

A. Aviation Requirements

1. The system must be safe, reliable, available and capable of providing global, all-weather, 24-hours-a-day service, regardless of terrain and propagation anomalies.

2. The system must be capable of being interpreted into the overall ATC, communications and navigation system.

3. The system should be capable of integration with all phases of flight, including the precision approach and landing system.

4. The frequency and accuracy of position determination must be such as to ensure that the operation minima can be maintained at all times and that holding and approach patterns can be executed accurately.

5. The system must be capable of providing the information necessary to permit maximum utilization of airports and airspace.

6. The system must be cost-effective to both government and users.

Current and projected future accuracy requirements for navigation in controlled airspace are provided in Tables 5.10 and 5.11.

Phase	Sub-Phase		Altitude (Flight Level)	Traffic Density	Route Width (NM)	Accuracy 2 drms (meters)
EnRoute/ Terminal	Oceanic		FL 275 to 400	Normal	60	12.6NM(1)
	Domestic		FL 180 to 600	Low	16	2000
				Normal	8	1000
			500 - 18,000 ft.*	High	8	1000
	Terminal		500 - 18,000 ft.*	High	4	500
	Remote		500 - 60,000 ft.*	Low	8 to 20	1000 to 4000
	Helicopter Operations		500 - 5000 ft.*	Low (Off-Shore)	Not Determined	1000 to 2000
			500 - 3000 ft.*	High (Land)	4	500
Approach and Landing	Non-Precision		250 to 3000 ft. above Surface	Normal	2	100
	Precision	Cat I	100 to 3000 ft. above Surface	Normal	$\pm$ 9.1 meters(2)	$\pm$ 3 meters(3)
					at 100 ft. above Surface	
		Cat II	50 to 3000 ft. above Surface	Normal	$\pm$ 4.6 meters	$\pm$ 1.4 meters
					at 50 ft. above Surface	
		Cat III	0 to 3000 ft. above Surface	Normal	$\pm$ 4.1 meters	$\pm$ 0.5 meters
					at Surface	

(1) The distribution of this error is detailed in the "Report of the Limited North Atlantic Regional Air Navigation Meeting," dated 1976; ICAO Montreal Canada

(2) This column is lateral position 2 sigma accuracy in meters for Precision Approach and Landing

(3) This column is vertical position 2 sigma accuracy in meters for Precision Approach and Landing

* feet above surface

Table 5.10. Controlled Airspace Navigation Accuracy to Meet Current Requirements

Phase	Sub-Phase		Altitude (Flight Level)	Traffic Density	Route Width (NM)	Accuracy (meters) 2 drms
EnRoute/ Terminal	Oceanic		FL 275 to 400	Normal	less than 60	better than 12.6nm
	Domestic		FL 180 to 600	Normal	8	1000
				High	8	1000
			500 ft to FL 180	Normal	8	1000
	Terminal		500 ft to FL 180	High	4	500
	Remote		500 ft to FL 600	Normal	8 to 20	1000 to 4000
	Helicopter Operations		500 ft to 5000 ft	Low (Off-Shore)	8	1000
			500 ft to 3000 ft	High (Land)	4	500
Approach and Landing	Non-Precision		250 to 3000 ft. above surface	Normal	1 to 2	100
	Precision	Cat I	100 to 3000 ft. above surface	Normal	± 9.1 meters(1)	± 3 meters(2)
					at 100 ft. above Surface	
		Cat II	50 to 3000 ft. above surface	Normal	± 4.6 meters	± 1.4 meters
					at 50 ft. above Surface	
		Cat III	0 to 3000 ft. above surface	Normal	± 4.1 meters	± 0.5 meters
					at Surface	

(1) This column is the 2 sigma lateral accuracy in meters
(2) This column is the 2 sigma vertical accuracy in meters

Table 5.11. Controlled Airspace Aviation Navigation Accuracy to Meet Projected Future Requirements

B. Marine Requirements

Safety considerations are of primary importance, but the operational and economic dimensions also need to be considered. For example, accurate worldwide navigation is important for the economy of large ships whose operating costs are very high. In fishing and oil exploration, the ability to locate precisely and return to productive or promising areas provides economic benefits.

The three phases of marine applications; the ocean phase, the coastal phase, and harbor approach and navigation have different requirements. These are addressed below.

1. Ocean Phase

a. Ability to avoid hazards (small islands, reefs, etc.).

b. Repeatability to locate and return to vicinity of maritime distress.

c. Provide accurate position fixes that enable the vessel to follow the shortest, safest route and thus minimize transit time, and therefore, cost.

Accuracy requirements are provided in Table 5.12.

The increasing use of relatively expensive satellite navigation (TRANSIT) by merchant ships and large fishing vessels is evidence of the perceived value attached to highly accurate ocean navigation by the vessel owners.

2. Coastal Phase

In general, the total navigational service in the coastal area must be of useful quality, be within economic reach of all classes of mariners, and sufficient to assure that no danger to a boat or ship or the environment is to be traced to the inability of the vessel to navigate safely with reasonable economic efficiency.

The accuracy requirements for this phase are provided in Table 5.13.

Requirements	Measures of Minimum Performance Criteria to Meet Requirements									
	Accuracy (2 drms)									
	Predictable	Repeatable	Relative	Coverage	Availability	Reliability	Fix Rate	Fix Dimension	Capacity	Ambiguity
Safety of Navigation – All Craft	2-4NM(3.7-7.4km) Minimum 1-2NM(1.8-3.7km) DESIRABLE	–	–	Worldwide	95% full cap. 99% Fix at least every 12 hours	(2)	15 Mins. or Less Desired; 2 hrs Maximum	Two	Unlimited	Resolvable with 99% Confidence

Benefits	Measures of Minimum Performance Criteria to Achieve Benefits									
Large Ships Maximum Efficiency	0.1-0.25NM (185-460M) (1)	–	–	Worldwide, except Polar Regions	99%	(2)	5 min.	Two	Unlimited	Resolvable with 99% Confidence
Hydrography Science, Resource Exploitation	0.1-0.25NM (185-460M)	Maximum Possible	–	Worldwide	95%	(2)	1 min.	Two	Unlimited	Resolvable with 99% Confidence
Search Operations	0.25NM (460M.)	0.25NM	185 M.	National Maritime SAR Region (NPAC, NWLAN)	99%	(2)	1 min.	Two	Unlimited	Resolvable with 99% Confidence

(1) Requirement subject to confirmation by additional study
(2) Dependent upon mission time

Table 5.12. Current Maritime User Requirements/Benefits for Purposes of System Planning and Development - Ocean Phase

Requirements	Measures of Minimum Performance Criteria to Meet Requirements									
	Accuracy (2 drms)			Coverage	Availability	Reliability	Fix Rate	Fix Dimension	Capacity	Ambiguity
	Predictable	Repeatable	Relative							
Safety of Navigation – All Ships	0.25NM (460M)	–	–	U.S. Coastal Waters	99.7% Minimum	(1)	2 Min.	Two	Unlimited	Resolvable with 99.9% Confidence
Safety of Navigation – Recreational Boats & Other Smaller Vessels	0.25NM-2NM (460-3700 M)	–	–	U.S. Coastal Waters	99% Minimum	(1)	5 Min.	Two	Unlimited	Resolvable with 99% Confidence

Benefits	Measures of Minimum Performance Criteria to Achieve Benefits									
Commercial Fishing (including Commercial Sport Fishing)	0.25NM (460 M.)	50-600 ft. (15-180M)	–	U.S. Coastal/ Fisheries Areas	99% Minimum	(1)	1 Min.	Two	Unlimited	Resolvable with 99.9% Confidence
Hydrography Science, Resource Exploitation	150 M.	20-600 ft. (15-180M)	–	U.S. Coastal Area	99% Minimum	(1)	1 Min.	Two	Unlimited	Resolvable with 99.9% Confidence
Search Operations, Law Enforcement	0.25NM (460 M.)	300-600 ft. (90-180M)	300 ft. (90M)	U.S. Coastal/ Fisheries Areas	99.7% Minimum	(1)	1 Min.	Two	Unlimited	Resolvable with 99% Confidence
Recreational Sports Fishing	0.25NM (460 M.)	100-600 ft. (30-180M)	–	U.S. Coastal Areas	99% Minimum	(1)	5 Min.	Two	Unlimited	Resolvable with 99.9% Confidence

(1) Dependent on mission time

Table 5.13. Current Maritime User Requirements/Benefits for Purposes of System Planning and Development - Coastal Phase

3. Harbor and Harbor Approach Phase

Given the inability for large vessels to maneuver quickly (stop, turn, etc.), the need for frequent and highly accurate position information is extremely important for navigation in congested areas.

The accuracy requirements for this phase are provided in Table 5.14.

C. Land Requirements

Use of radionavigation for Automatic Vehicle Monitoring (AVM) is being contemplated. The ability for a dispatcher to know where all the emergency vehicles are at any time would allow for quick rerouting. Tracking of a hazardous/valuable cargo transport are other possible applications for AVM.

5.3 Helicopter Community Requirements

The helicopter role in the civilian community has and will continue to increase in the foreseeable future. The high price of real estate, coupled with environmental groups' opposition to the development/expansion of airports show the way for the IFR helicopter. The key, however, is the integration of the helicopter in the ATC system without disturbing CTOL operations and increasing the risk of midair collisions. Therefore, the need for an all-weather, accurate, low altitude capability.

Helicopter missions that could greatly benefit from high accuracy are:

1. commuting to offshore oil platforms

2. city to airport commuting

3. business/corporate operations

4. police/firefighting

5. search and rescue operations

6. landing in remote areas

Requirements	Measures of Minimum Performance Criteria to Meet Requirements									
	Accuracy (2 drms)									
	Predictable	Repeatable	Relative	Coverage	Availability	Reliability	Fix Rate	Fix Dimension	Capacity	Ambiguity
Safety of Navigation – Large Ships & Tows	26-65 Ft (8-20 M) (1)	–	–	U.S. Harbor & Harbor Approaches	99.7% Minimum	(2)	6-10 Seconds	Two	Unlimited	Resolvable with 99.9% Confidence (Minimum)
Safety of Navigation – Smaller Ships	(1)	(1)		U.S. Harbors, & Harbor Approaches	99.7%	(2)	(1)	Two	Unlimited	Resolvable with 99.9% Confidence (Minimum)

Benefits	Measures of Minimum Performance Criteria to Achieve Benefits									
Fishing Recreational, and Other Small Vessels	(1)	(1)	–	U.S. Harbor, & Harbor Approaches	99.7%	(2)	(1)	Two	Unlimited	Resolvable with 99.9% Confidence

(1) Requirement under study; varies from one harbor to another
(2) Dependent on Mission time

Table 5.14. Current Maritime User Requirements/Benefits for Purposes of System Planning and Development - Harbor Approach and Harbor Phases

7. collision avoidance

8. service pipelines (Alaska)

In his paper "Helicopter and NAVSTAR/GPS"(14), Glen A. Gilbert lists the ideal navigation goals for the helicopter.

- Highly accurate three-dimensional (lateral, longitudinal, vertical) area navigation guidance.

- Four-dimensional (4-D) guidance adding time referenced navigational capability to 3-D guidance with extremely high time positioning accuracy.

- Sufficiently accurate approach and landing guidance by the airborne RNAV system so that reasonably low minimum descent altitude (MDA) for "no-precision" instrument approaches could be achieved by any pilot-selected point on the surface without the need to have an electronic landing aid at that location; also inherent capability to provide for "precision" instrument approaches with nominal external augmentation at the landing point.

- Ability to perform RNAV functions without line-of-sight (radio horizon) limitations from ground signal source facilities.

- Vertical velocity measurement accuracy in the order of 0.1 ft/second; horizontal velocity measurement accuracy in the order of 0.1 knots.

- Imperviousness to atmospheric conditions for non-interrupted operations.

- Non-saturable capacity.

- Service availability to all classes of airspace users on a world-wide basis.

- System outputs capable of inputting advanced multifunction cockpit displays, including displays of navigational and traffic situation information, as well as existing conventional cockpit displays.

- Data link capability to transmit x-y-z coordinates for automatic position reporting and air-to-air separation assurance.

- Cost effectiveness based on life cycle cost analysis with the system design such that it can have various levels of sophistication and thus will be affordable to all classes of airspace users.

The Federal Radionavigation Plan lists the following requirements for helicopter operations.

Helicopter operations occur in off-shore areas and on low-altitude domestic routes. For operations from U.S. coastline to off-shore points, the following requirements must be met:

1. Range from shore to 300 NM.

2. Minimum en route altitude of 500 feet above sea level or above obstructions.

3. Accuracy adequate to support routes ±4 NM wide or narrower with 95 percent confidence.

4. Minimum descent altitude to 100 feet in designated areas.

For helicopter operations over land, the following requirements must be met:

1. Accuracy adequate to support ±2 NM route widths in both en route and terminal areas with 95 percent confidence.

2. Minimum en route altitudes of 1200 feet.

3. Navigational signal coverage adequate to support approach procedures to minimums of 250 feet above obstruction altitudes at heliports and airports.

None of the currently implemented radionavigation systems can meet these goals. The Global Positioning System comes the closest.

The current thinking in the GPS community is that 200 meters (CEP) accuracy will be guaranteed at all times. This is sufficient for non-precision approaches and en route/terminal operations. However, Differential GPS is needed if precision approaches are to be executed.

5.4 Civil Support

From the above presentations of the capabilities of different radionavigation systems and the requirements of the civilian community, it is apparent that only GPS meets the requirements for availability, coverage and accuracy needed for most civilian applications. The only exceptions were precision landing, harbor approach and harbor and inland navigation. These applications are, however, localized and Differential GPS techniques as presented earlier can provide the required accuracy. It was also evident that Differential GPS would guarantee a high level of accuracy even when Selective Availability techniques were implemented.

A. Helicopter Community

Given the requirements of the civilian community presented above, and with a civil helicopter community expected to grow through 1986, and the need to go look for oil further at sea, there is little doubt that a strong financial backing can be expected for Differential GPS.

A recent article in Aviation Week and Space Technology(15) predicts a strong civil helicopter growth through 1986. A few points made in the article are presented below.

"There is a strong belief in the civil helicopter community that helicopter business will grow at a rate faster than that of the fixed-wing general aviation industry and that the civil helicopter industry will be less subject to economic stresses. This is due to the civil helicopter business geared almost completely to some aspect of business use, whether for energy development, corporate transportation or other growing industrial markets."

Figures 5.1 and 5.2 present helicopter population data in 1980 and projections for 1985.

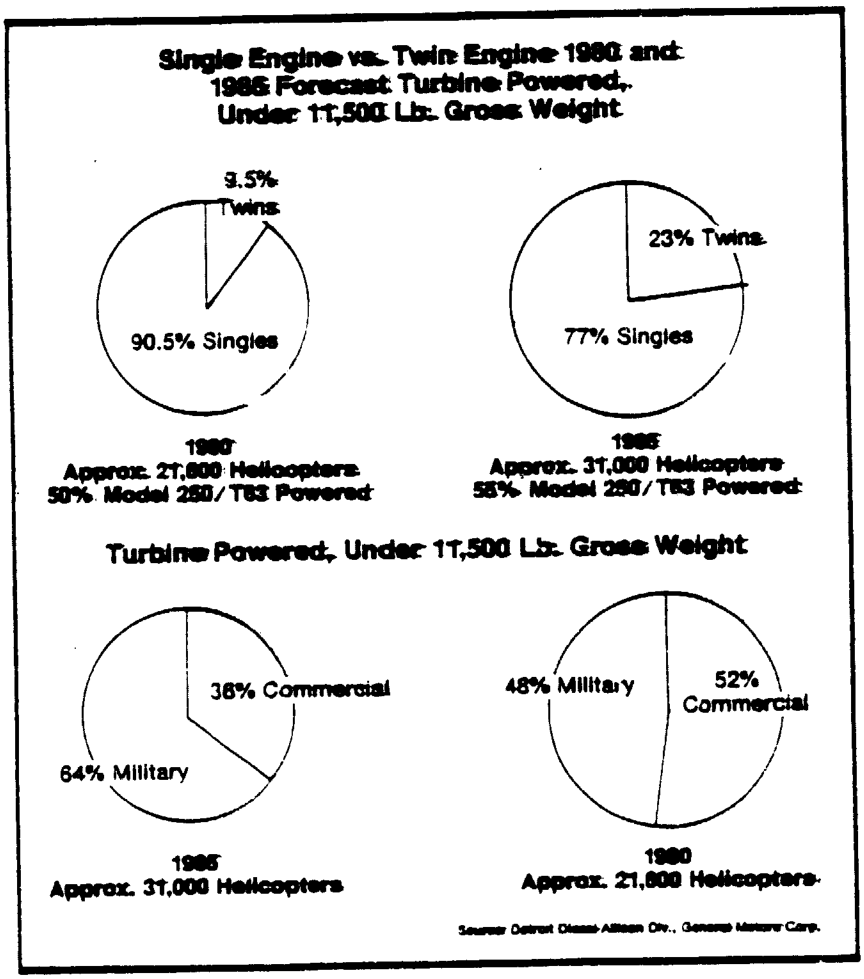


Figure 5.1

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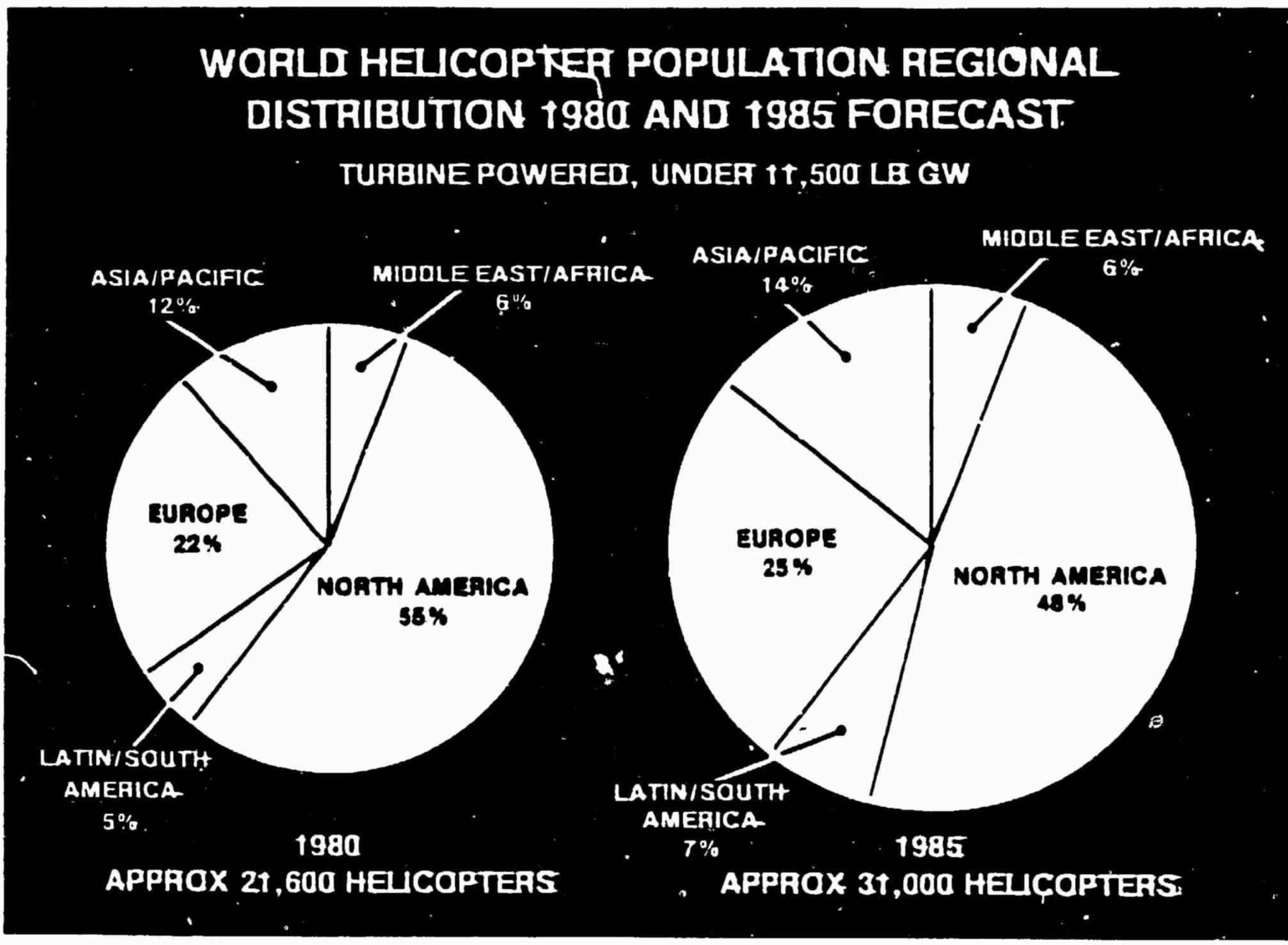

Figure 5.2

B. Other Civilian Support

The support outside of the helicopter community is expected to be just as strong, if not stronger. Marine applications look very promising. The projection that by the year 2000 the total marine trade will be 2 to 4 trillion tons, coupled with the requirements of perishable cargo, high demand products (oil) and ever-growing ship sizes, emphasize the critical nature of harbor approach navigation in all-weather conditions and the possibilities of Differential GPS look very attractive.

The use of Differential GPS for offshore oil exploration also looks very promising for both land surveying and drilling platform locations.

Morgan(5) studied the role of navigation satellites in oil exploration. He points out the extensive use of the TRANSIT system by this industry, the extremely high operating costs of seismic surveys, well site surveys, and actual drilling. Therefore, a very accurate positioning system is essential. Accuracies of the order of 5 m are the goal. This can only be achieved with Differential GPS. The very high savings that could be realized by such a system leave little doubt as to whether backing is to be expected from this industry. To support this point, the following projections were made for 1988 by oil industry experts(16): "By 1988, there will be approximately 9 billion barrels of new oil discovered each year. Dr. Jack Birks, Managing Director of British Petroleum, said that about half of the future oil discoveries would come from offshore exploration. It is estimated that, by 1988, 1/16th of the yearly discoveries would require accuracies of the order of 5 m. This corresponds to 0.6 billion barrels per year or about 10 billion dollars!!"

6 CONCLUSIONS

We have reviewed the existing radionavigation systems and their capabilities as well as the requirements of different sectors of the civilian community, with particular emphasis on the helicopter community. It was clear that the baseline GPS would provide the needed accuracy for many of the civilian applications if the P code was made available. However, the baseline GPS, even with the P code, would not fully satisfy the requirements of precision approach, harbor approach, inland navigation, and seismic surveys. Differential GPS would provide this capability. Three techniques were described. Two of them showed significant improvement over the baseline system in the case of an overhead satellite outage.

It was argued that the guaranteed availability of the P code to the civilian community is very much in doubt until at least 1990 and that it is likely that the C/A code accuracy will be degraded so as to provide 200 meters (CEP) of error. In this situation, the improvement derived from the use of Differential GPS could be dramatic and actually mean the difference between acceptance or rejection of the GPS system by many sectors of the civilian community.

The need for an IFR helicopter capability is clear and strong backing is expected from the Helicopter Association of America in an effort to develop Differential GPS. The oil industry and the shipping industry are also likely to back any such effort. The FAA might be more interested in GPS if it can control the system accuracy to some degree. Differential GPS will provide this capability in a local area. This would allow integration in the ATC procedures.

Highly successful field testing of Differential GPS was performed at the Yuma Proving Ground by Texas Instruments and is reported in this study. More such testing should be done with particular emphasis on the degradation of accuracy with distance from the ground reference point. In addition, the technique using the ground station as a pseudolite should be tested as well as C/A code operation. These tests would provide the evidence of the great potential of Differential GPS.

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APPENDIX I

STATEMENT BY HONORABLE GERALD P. DINNEEN

Assistant Secretary of Defense
Communications, Command, Control and Intelligence

Before the
Subcommittee on Transportation, Aviation and Communications
of the
Committee on Science and Technology
House of Representatives
58th Congress, Second Session

21 February 1980

EXTRACT

NAVSTAR AVAILABILITY

Turning now to a second area that I am sure is of interest to this Subcommittee, I would like to review our position with respect to civil availability of NAVSTAR. During even the formative stages of system development, the need for some form of denial or degraded capability was recognized to preclude the full potential of NAVSTAR being used militarily against the United States or its allies. Originally our concern was limited to the so-called "Precise" signals transmitted by each of the satellites. It was thought that the "Coarse/Acquisition" signal -- which is used as an aid to acquire the "Precise" signal and can be used for navigation -- would not be of sufficient accuracy to be militarily useful. However, tests performed with actual hardware have demonstrated that the "Coarse/Acquisition" signal accuracy is much better than we anticipated. Although it does not offer the jamming signal margins of the Precise signal, it could provide improved capabilities to an adversary.

As a result, we have carefully examined several techniques to not only deny the use of the Precise signal but to degrade the accuracy available from the Coarse/Acquisition signal as well. In establishing a level to which the system accuracy should be degraded, we asked the Organization of the Joint Chiefs of Staff to study the national security implications of such a global capability and to recommend an appropriate course of action. In addition, we worked closely with the Department of Transportation, the Federal Aviation Administration, the U.S. Coast Guard, NASA and other agencies of the Federal government to establish a range of capabilities _versus_ specific requirements for navigation service. In so doing, we have attempted to achieve an equitable balance between national security and national utility of the NAVSTAR system.

Our position is that NAVSTAR should be made available for civil use at an accuracy level that is consistent with national security. Consistent with the accuracy level we originally equated to the "Coarse" signal, we have concluded that an accuracy of approximately 200 meters (50 percent confidence level) would not seriously jeopardize national security in the mid-1980's. This figure, somewhat more accurate than the level originally recommended by the Joint Chiefs of Staff study, was selected since it represents a threshold level of accuracy for potentially widespread civil aviation and maritime use.

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I want to emphasize that the balance between national security and national utility and the resulting position on civil availability have been subject to considerable attention within the Department of Defense. We have developed, but not fully tested or evaluated several techniques to implement this capability in the operational system deployment. Further, we are still evaluating the operational procedures needed to provide adequate control and security of these techniques in all levels of conflict. We view this as the major issue remaining related to the development, acquisition and operation of the NAVSTAR system. We also recognize that the outcome may have some impact on future civil use of NAVSTAR. For this reason we will ensure that you and other interested parties are kept fully informed of our progress. It is our concern that a clear statement of policy and the ability to implement that policy must go hand-in-hand. Given our current situation with both the restructuring of the NAVSTAR program and the remaining work to be done to address the civil availability issue, we have been forced to delay finalizing the first Federal Radionavigation Plan.