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CONTINUED STUDY OF NAVSTAR/GPS FOR GENERAL AVIATION

Final Report

Prepared for

NASA

National Aeronautics and Space Administration
Langley Research Center
Hampton, Virginia

R E S E A R C H   T R I A N G L E   P A R K ,   N O R T H   C A R O L I N A   27709

CONTINUED STUDY OF NAVSTAR/GPS FOR GENERAL AVIATION

Final Report

Prepared Under Contract NAS1-14719

by

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ABSTRACT

This report describes the activities conducted to provide systems engineering and planning support for examining the full potential of GPS for the general aviation community. The report presents a conceptual approach to this goal and discusses aspects of an experimental program to demonstrate these concepts. The report concludes with the observation that the true potential of GPS can only be exploited by utilization in concert with a data link. The capability afforded by the combination of position location and reporting stimulates the concept of GPS providing the auxiliary functions of collision avoidance, and approach and landing guidance. A series of general recommendations for future NASA and civil community efforts in order to continue to support GPS for general aviation are included.

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1.0 INTRODUCTION

The Research Triangle Institute, previously, under contract NAS1-14302 entitled "Preliminary Study of NAVSTAR/GPS for General Aviation" conducted a planning effort to focus attention on the applicability of the Global Positioning System for General Aviation. During that study, Department of Defense literature was reviewed and a description of the GPS concept, system definition, and implementation program was formulated. Comparative costs and achievable performances were examined for GPS and for conventional avionics suites. It was projected that it was realistic to provide GPS to the general aviation community at a reasonable cost in a 1985 time frame.

As a part of the previous study, recommendations were made for subsequent activities which would continue to define the nature of NASA participation in developing GPS technology for general aviation.

A major theme implicit in these recommendations is the concept of an integrated Communications Navigation and Identification capability for general aviation to be implemented over the next two decades. A low-cost navigation system as derived from GPS in concert with a low-cost data link also derived from existing military programs provides the cornerstone from which such a capability can be achieved.

The current study continues to support this theme. Its general objective is to provide systems engineering and planning support for a low-cost, satellite-based communication/navigation capability to general aviation and to other NASA programs. Major tasks performed as a part of this study include the analysis of GPS navigation capability with ground augmentation, a cursory survey of data link systems for application to general aviation, and a comparison of various generic candidate navigation system concepts. In the performance of these tasks, the interplay between navigation concept and data link requirements has become evident, in that promising approaches to ground augmented navigation include systems requiring data link to the user aircraft.

A major conclusion of this study is that the high accuracy available with GPS is not a requirement for enroute navigation; thus, GPS provides very little capability over conventional systems in this flight segment.

It is in the terminal area environment, where advantage of GPS precision can be taken, that a distinction occurs. It is the availability of the precision position that provides the advocacy of incorporating a data link with GPS. This results in the ability of the integrated system to provide auxiliary functions which normally would not be available to General Aviation at a nominal cost. These functions include collision avoidance and guidance for approach and landing. Significant in this light is that to whatever degree is practical, these functions can be self-contained.

The following sections of this report will develop the idea that operation of GPS in a differential mode presents a strategy for expanding the role of GPS for general aviation to that of providing auxiliary functions such as approach and landing guidance and collision avoidance. The feasibility of this strategy is to be the subject of a future study.

2.0 STUDY OBJECTIVES

The basic objectives of this study were two: first, to determine the ultimate potential of GPS in serving the general aviation community, and second, to identify and define the research and development activities required to realize this potential. It will be discussed in subsequent sections that the potential for GPS in general aviation lies in the auxiliary application directed system functions which develop through integration with a data link. It will be recommended that this potential be demonstrated through the conduct of an experimental program including flight test.

3.0 CONCEPTS

3.1 Introduction

The definition of concepts is based on drawing from conventional systems and then configuring in such a way as to support basic communications and navigation functions. The extrapolation to considering the capability available when both functions are integrated leads to several innovative ideas. This section presents the background for these considerations. Included are brief system descriptions of basic navaids and data links followed by the definition of candidate system configurations. Detailed description of these basic systems are included as appendices. It should be noted that the system descriptive information has been extracted from the literature as referred to at the end of this report.

Reference 3-1 presents a survey of present and forecasted navigation technology through 1980. This discussion has been condensed and included here in that it tends to focus on generic capabilities and limitations as they relate to candidate avionics suites. While the referenced study was conditioned on military mission scenarios, it is felt that the carry-over to the general aviation requirements of enroute, terminal area, and landing is easily accomplished. For example, the military aircraft essentially has point "A" to point "B" navigation requirements with intervening way points as does general aviation; further, while in the target area, the military aircraft has weapon and material delivery guidance requirements similar to terminal area navigation for general aviation; finally, the military aircraft has similar or possibly more stringent landing guidance requirements if carrier landing and/or severely adverse climatological conditions are considered. The following discussion addresses the LORAN, OMEGA, and GPS navaids as well as addressing a hypothetical satellite-based system directed at civil application. This discussion serves as the technology overview required to integrate the navigation side of a combined communications/navigation system with the goal of increased functional application.

3.2 System Attributes

3.2.1 Loran [3-1]

Loran-C is a low-frequency, long-range, all-weather, pulsed-hyperbolic radio navigation system which is capable of providing horizontal position fixes of very high repeatable accuracy, but only moderate absolute accuracy. Loran-C is presently operational in several parts of the world and an extensive expansion program is currently underway. The military has been using Loran-C for the past 10 to 15 years; thus, numerous Loran-C user equipments are available. Normal operation of Loran-C is as a hyperbolic navigation system, although Loran-C can also be used in a direct ranging mode at the expense of increased complexity of user equipment. This direct ranging mode is capable of providing increased accuracy through a reduction in user/Loran transmitter geometry dependency errors.

Loran-C service in a region is provided by a chain of transmitting stations consisting of a master and three or more secondaries. Each chain can provide service to an area within 2500 km from the chain baselines. The U.S. Coast Guard is currently responsible for the operation of seven Loran-C chains throughout the world. Fourteen additional stations are planned to complete the coverage of the U.S. coastal Confluence Zone and a large portion of the northern hemisphere.

Loran-D is similar to and compatible with Loran-C but designed for military tactical use. There are presently three Loran-D chains in the U.S. and one in Europe.

Performance Capabilities

The Loran-C navigation system is capable of providing absolute navigation (horizontal position) accuracies of 0.5 km rms or better and repeatable navigation accuracies of 15 - 90 m rms. The absolute accuracy can be improved by a factor of 2 or 3 using sophisticated user equipment and prior calibration of propagation abnormalities.

The Loran-C system does not inherently provide for velocity measurements. However, the Loran-C time difference (TD) measurements can be differentiated to provide velocity estimates, although the resultant accuracy will likely be poor as well as noisy.

The Loran-C user equipment can potentially be integrated with an inertial navigation system (INS) to provide velocity estimates with an

accuracy set by the INS (typically 0.5 to 1.0 mps rms). This is, however, beyond the cost capability of most general aviation users.

Performance Limitations

The Loran-C navigation system is currently usable only within the designated coverage areas, and does not provide CONUS coverage.

3.2.2 Omega [3-1]

OMEGA is a terrestrial-based radio navigation system with global all weather coverage that is capable of providing moderately accurate position fixes. The system operates with eight very low frequency (VLF) transmitter stations located around the world. The eighth permanent transmitter, to be located in Australia, is scheduled to become operative in late 1979. However, the present operational system provides coverage for most of the globe.

Performance Capabilities

The Air Force OMEGA navigation equipment specification requires accuracies of 4km or better, 50th percentile and 8km or better, 95th percentile. Such performance was indeed demonstrated on Air Force conducted performance tests. While the OMEGA system does not inherently provide for velocity measurements, the (military) airborne equipment should internally implement dead reckoning for velocity aiding of signal tracking and for minimizing of lane-jump probabilities during temporary loss of the OMEGA signal. The dead reckoning capability is enhanced by automatic compass heading and true airspeed inputs. System velocity errors commensurate with dead reckoning navigation from these devices are to be expected if they are installed in the aircraft. Maneuvering susceptibility of current system design is restricted to sustained high bank angle conditions and is not expected to be an operational problem.

To increase the airborne navigation accuracy available with OMEGA (especially in high performance aircraft) an inertial navigation system (INS) can be integrated with the OMEGA navigation equipment. According to reference 3-1, OMEGA navigation equipment integrated with a 0.5 mps (CEP rate) inertial navigation system, position estimates can be obtained with an accuracy of 2km CEP. Also, since an INS is employed, velocity estimates are available with an rms accuracy of 0.5 - 1.0 mps.

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Performance Limitations

Although OMEGA is a long-range, moderate accuracy global navigation system, it cannot be considered for (Military) use as a primary, autonomous navigation system in either strategic or close tactical operations. Its absolute accuracy is limited by sudden phase distortions due to ionospheric disturbances and by polar cap absorption effects, both of which though infrequent, can lead to temporary errors as large as 15km without special mechanizations. The civil OMEGA system should be regarded as a system for enroute navigation to a way point with transition required to other navaids such as GPS, Loran, and/or other routine terminal aids (TACAN, VOR, or PAR) when in the vicinity of the terminal area.

3.2.3 Global Positioning System (GPS)

GPS is a satellite-based radio navigation system designed to provide highly accurate navigation fixes to properly equipped users. This system is presently in development stage, but limited operation is scheduled to commence in the mid 1980's with full operation in the late 1980's. Several types of GPS user equipment are being designed to satisfy various user requirements. Preliminary designs are to emphasize commonality of equipments as much as possible in order to reduce costs.

Performance Capabilities

The accuracy with which a GPS user can determine his position and velocity depends upon the measurement accuracy of his user equipment as well as the error in the satellites ephemeris and clock data received from the satellites. The measurement accuracy of the military user equipment depends upon the equipment type. The Air Force has identified three types of user equipment for the various Air Force aircraft missions. The Type X user equipment is designed for the tactical high dynamics mission, Type Y for the strategic mission, and Type Z for the benign transport mission. The user equipment makes pseudorange and pseudorange-rate measurements to the GPS satellites. These are not true range and range-rate measurements since the time the signals were initiated by the satellite is not known accurately. However, with four sets of these measurements, the user is able to estimate his position and velocity as well as the GPS system time.

The pseudorange and pseudorange-rate measurement accuracies of the three types of user equipment as specified by the Air Force [3-2] are summarized in Table 3.4-1.

Table 3.4-1 GPS User Equipment Measurement Accuracies

Type Set	Pseudo-Range (meters)		Pseudo-Range Rate (mps)	Smoothing Times (sec)	Remarks
	P-Signal	C/A-Signal			
X	1.5	15.0	0.006	≥ 0.1	High Performance
Y	1.5	15.0	0.006	≥ 0.1	Medium Performance
Z	-	15.0	0.006	≥ 0.1	Low Cost

The other major influence on the accuracy of position and velocity estimates are the errors in the satellite ephemeris and clock data. This data is required by the user in the solution of the GPS navigation equations. These (pseudorange, ephemeris, and clock) errors tend to be the dominate source of errors and thus determine the overall system accuracy limits.

These pseudorange errors translate into equivalent position errors through standard geometrical translation. The Aerospace Corporation has indicated [3-3] that 99.9% of the time the error magnification effects of geometry are less than a factor of about four and that 99% of the time the magnification is less than a factor of three. The pseudorange accuracies shown in Table 3.4-1 then translate to position accuracies of about 5 meters for the X and Y sets and 50 meters for the Z set.

The accuracies as discussed above represent user equipment specification numbers and the extention of these based on geometrical analyses. It is of interest to compare these with actual results being obtained using the Yuma Proving Ground inverted range in conjunction with one or both of the first two satellites in orbit. Figure 3-1 shows representative data [3-4] indicating actual performance being attained with GPS. The results

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GPS POSITION ERROR
(GPS — RTE)
C·141, 20 SEP 77

● 1ST RESULT
● REAL TIME COMPARISON
● ONE SPACE VEHICLE CLOCK

X ERROR (m) $\sigma_x = 3.36$ (m)

Y ERROR (m) $\sigma_y = 4.18$ (m)

Z ERROR (m) $\sigma_z = 3.60$ (m)

TIME (MINUTES)
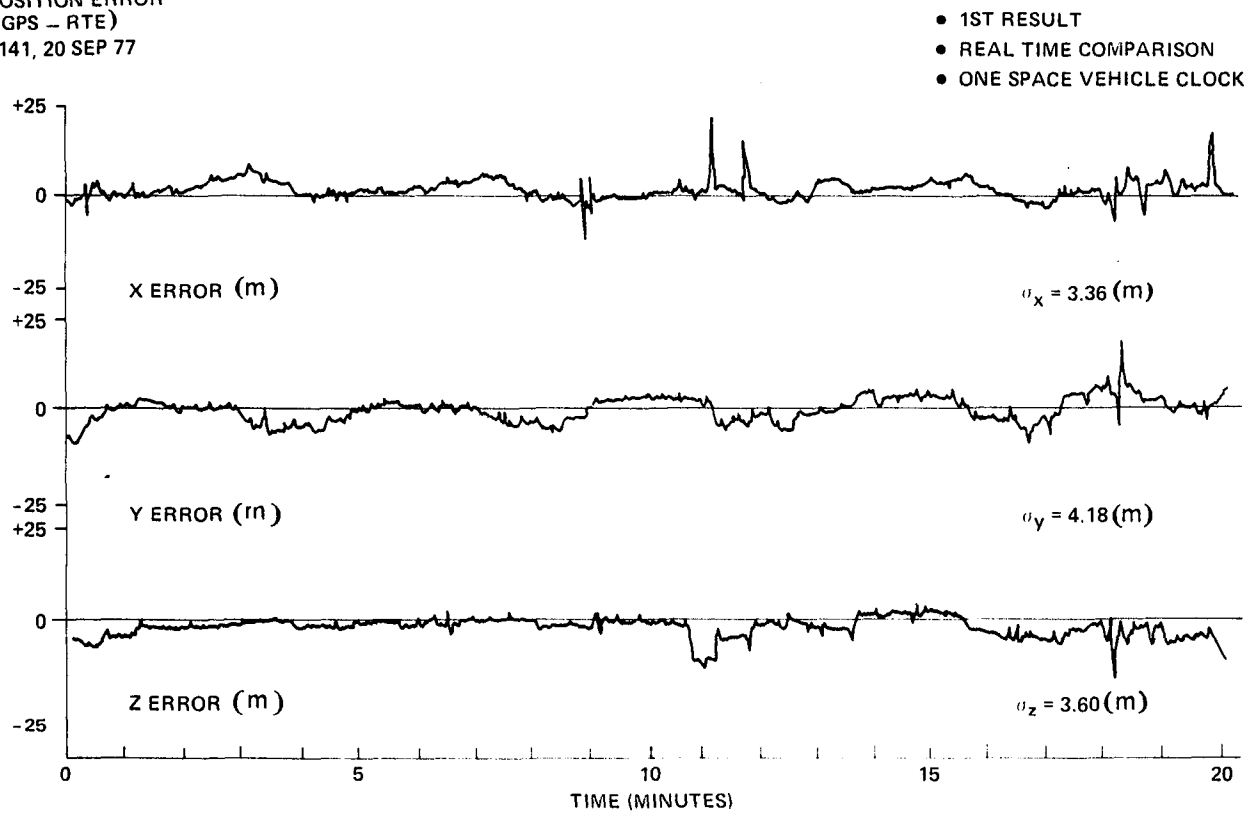
Figure 3-1. Typical GPS Performance Over Inverted Range [3-4]

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are from a C-141 flying at an altitude of 6km. Presented are the observed differences between the GPS position estimates and the Real-Time Estimate (RTE) of trajectory. The author identifies the several spikes as resulting from tracking instrumentation performance degradation during turns. The author states that these transients disappeared on subsequent flights utilizing the Best Estimate Trajectory (BET).

Performance Limitations

GPS is, by comparative measure, remarkably free of obvious performance limitations. The major limitation envisioned for the military is stated to be interference by jamming. For the civil user this translates to inter- ference by such sources as multipath and/or locally interferring systems such as VORTAC, TACAN, DABS, and ATCRBS. The GPS signal structure provides some degree of immunity, but susceptibility nonetheless remains. The evaluation of these effects is an aspect of the experimental program discussed in subsequent sections. The military has posed a solution of utilizing highly directional steerable receiving antennas to avoid this occurrence. This is not viable for the civil community in that antenna placement, even ommidirectional coverage, is problematical and increased complexity simply complicates the problem at increased cost.

3.2.4 Continental Positioning System

This system is a hypothetical system which is configured, here rather arbitrarily, to address the general aviation navigation requirements from a satellite-based navigation system perspective. The system is predicated both on providing coverage for the CONUS and Coastal Confluence Region (CCR) only and on relaxing the anti-jam requirement while retaining the pseudorandom code ranging signal structure. The implication of CONUS and CCR is that coverage may be obtained with a single satellite constellation. If this were to be at geostationary altitude, the number of satellites to provide the necessary coverage is minimized (i.e., a total of four). This implies loss of satellite redundancy as well as the negation of improved accuracy through the smoothing available with an overspecified system employing more than four satellites such as GPS.

Performance Capabilities

Since the Continental Positioning System is a hypothetical system, no true performance estimates are available. However, since the CONUS coverage assumption alluded to a single satellite constellation, it is of interest to compare this system concept to the NAVSTAR/GPS predecessor, that is, the Air Force sponsored 621B system. This system is described in further detail in the Appendix C. 621B was designed for simultaneous high precision and anti-jam capability which is reflected in the complex signal structure and as in GPS is overly sophisticated for general aviation. The point made here is that 621B demonstrates that a small number of satellites at geosynchronous altitude does provide the geometrical aspects of a viable system. The extension of this approach is therefore applicable to general aviation.

The 621B system has also been tested at the Yuma inverted range [3-5]. The basic objective of these tests was to validate the theoretical predictions of receiver bias and noise errors. These tests consisted of flying two receivers (Hazeltine and Magnavox) and performing non-real-time navigation by recording range and range-rate to the ground transmitters and then reconstructing a navigation solution post-flight. No attempt was made to compare the two receivers. Sample results of these tests are shown in Tables 3-1 and 3-2. These data indicate that GPS equivalent performance can be achieved from the CONUS/geostationary approach to satellite navigation system.

Performance Limitations

This approach to satellite-based navigation has several disadvantages above and beyond those addressed for GPS. Essentially, all of the limitations are geometry related. For example, there is no inherent constellation redundancy, capability for constellation optimization for GDOP, or potential for improved accuracy through the use of more than four satellites for a smoothed solution. Further, the increased range to geosynchronous orbit places heavier requirements on transmitter power and/or impacts the received signal margin. The other limitations discussed for GPS such as multipath, interference, etc. also affect the Continental Positioning System to some extent dependent on system parameters such as carrier frequency, signal structure, etc.

Table 3-1   621B Enroute Navigation System Accuracy Summary [3-5]

POSITION		MEAN (m)	1 σ	RATE		MEAN (mps)	1 σ
X				X			
	HC	-0.30	1.77		HC	0.03	0.18
	MRL	-0.70	1.86		MRL	0.03	0.15
Y				Y			
	HC	0.12	3.14		HC	-0.03	0.18
	MRL	0.40	2.50		MRL	0.06	0.21
Z				Z			
	HC	-1.25	3.66		HC	0.09	0.18
	MRL	0.49	2.59		MRL	-0.15	0.27

Table 3-2.   621B ILS Navigation Accuracy Summary [3-5]

POSITION		MEAN (m)	1 σ	RATE		MEAN (mps)	1 σ
X				X			
	HC	0.09	1.01		HC	0.06	0.34
	MRL	-0.34	2.23		MRL	0.06	0.43
Y				Y			
	HC	-0.82	3.47		HC	-0.15	0.52
	MRL	0.67	3.75		MRL	-0.06	0.67
Z				Z			
	HC	-0.40	4.05		HC	-0.06	0.70
	MRL	-0.40	2.53		MRL	-0.12	0.61

HC - Hazeltine Receiver
MRL - Magnavox Receiver

3.3 Comparative Attributes

In attempting to compare relative navigation systems, it is convenient to simply examine the matrix shown in Table 3-3 in rather general terms. Table 3-4 presents a system comparison in considerable detail. Both LORAN-C and GPS possess

Table 3-3. Navaid Matrix

	land-based systems	satellite-based systems
precision systems	LORAN-C	GPS
medium-accuracy systems	OMEGA	Continental Positioning System*

*postulated medium accuracy

sufficient accuracy to provide precision navigation for general aviation while the hypothetical Continental Positioning System could also be upgraded to this category. All systems could conceivably be operated in a differential mode to further improve accuracy. It is not likely that any system, with the exception of GPS, and then in a differential mode, could address the requirements of navigation during approach and landing due to lack of vertical position as well as accuracy considerations.

All systems, with the exception of LORAN-C provide at least CONUS coverage. LORAN-C presently does not provide interior CONUS coverage although the addition of five stations to accomplish this has been proposed. GPS and OMEGA provide global coverage and as such are supportive of ICAO requirements.

Another interesting comparative feature among systems over and above that of accuracy is the degree of inherent redundancy contained in the GPS system concept.

Table 3-4 Candidate Ground Based Navigation Systems [3-6]

	LORAN-C	OMEGA	DIFF. OMEGA
FREQUENCY	90 to 110 KHz	10.2, 11.3, 13.6 KHz	10.2,11.3,13.6 KHz FOR STATIONS, MONITOR NOT DETERMINED
COVERAGE	1500-2250 KM GROUND 5500 KM SKYWAVE	15000 KM PER STATION WORLDWIDE BY 8 STATIONS	20-200 KM FROM MONITOR STATION
ACCURACY	20-90 M	5-10 KM DAY 4 KM NIGHT	1-2 KM AT 20-200 KM
READOUT	15 SEC FOR MANUAL CONT. FOR AUTOMATIC	POSITION UPDATE 2 MIN. TO CONTINUOUS	CONTINUOUS
WEIGHT (KG)	<100	<100	<100
SIZE (CM^3)	<1,000,000	<1,000,000	<100,000
COST ($)	<10,000	<10,000	<10,000
EASE OF OPERATION	SKILLED/LIMITED TRNG	SKILLED/LIMITED TRNG	SKILLED/LIMITED TRNG
SECURE USAGE	NO REQUIREMENT	NO REQUIREMENT	REQUIREMENT
COMMUNICATION	NOT REQUIRED	NOT REQUIRED	NOT REQUIRED
SPEED (MPS)	25-850	25-85	25-85
FUNCTION	LONG-RANGE NAV OCEANIC	LONG-RANGE NAV CONUS AND OCEANIC	MEDIUM TO SHORT-RANGE NAVIGATION IN AREAS WHERE HIGHER ACCURACY IS REQUIRED THAN OMEGA
USERS	CIVILIAN = 4000	SHIPS AND AIRCRAFT US AND FOREIGN	VESSELS IN COASTAL CONFLUENCE REGION AIRCRAFT IN CONUS
REMARKS	GEOGRAPHICAL COVERAGE LIMITED TO NORTH ATLANTIC AND COASTAL CONFLUENCE AREA	LANE AMBIGUITY	EXPERIMENTAL

Candidate Satellite Based Navigation Systems

	GPS	621B	CPS[4]
FREQUENCY	L-BAND	L-BAND	L-BAND
COVERAGE	WORLDWIDE	WORLDWIDE	CONUS
ACCURACY	10 M (HDUE)[1]	10-25 M	100-250 M
READOUT	10 PER SEC (MAX)[2]	(NOT AVAILABLE)	SECONDS
WEIGHT (KG)	11 (MRL/MP)[3]	(NOT AVAILABLE)	GA COMPATIBLE
SIZE (CM^3)	200,000 (MRL/MP)[3]	(NOT AVAILABLE)	GA COMPATIBLE
COST ($)	5000	(NOT AVAILABLE)	~2500
EASE OF OPERATION	SKILLED/LIMITED TRNG	SKILLED/LIMITED TRNG	SKILLED/LIMITED TRNG
SECURE USAGE	REQUIRED	REQUIRED	NOT REQUIRED
COMMUNICATION	NOT REQUIRED	NOT REQUIRED	NOT REQUIRED
SPEED (MPS)	TACTICAL REQ.	TACTIAL REQ.	GA COMPATIBLE
FUNCTION	MILITARY	MILITARY	CONUS NAVIGATION
USERS	MILITARY, CIVIL MARINE	MILITARY	CIVIL/GENERAL AVIATION
REMARKS	UNDER DEVELOPMENT	CANCELLED	HYPOTHETICAL

1) High Dynamic User Equipment
2) Depends on User Equipment
3) Magnavox Research Laboratory Manpack
4) Hypothetical Parameters

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For LORAN and OMEGA a station failure may be overcome by selection of a new station, the resulting degraded geometry provides poorer accuracy while a user equipment failure results in lack of solution. For the Continental Positioning System, the loss of a satellite results in loss of navigation solution unless a dimension such as vertical may be derived from an alternate system. This then results in degraded performance. Simultaneous tracking using one of a variety of multi-channel user equipments results in gracefully degraded performance when other lower accuracy position information is available and only one channel fails. GPS contains redundancy both in the satellite constellation and in multi-channel user equipment providing graceful degradation in performance for either mode of failure. The total system redundancy afforded by GPS elevates it above the competing systems. It is this feature, in concert with the accuracy and coverage afforded, which develops the advocacy for the GPS as a general aviation navaid.

3.4 Data Link Advocacy

The obvious conclusion of the preceding section is that GPS provides superior coverage and accuracy for enroute navigation. However, GPS provides very little additional useful enroute capability over that provided by OMEGA and LORAN-C. It is in the terminal area environment, where advantage of GPS precision can be taken, that a distinction occurs. It is in the availability of the precision position that provides the advocacy of incorporating a data link with GPS. This results in the ability of the integrated system to provide auxiliary functions which normally would not be available to General Aviation at a nominal or perhaps any cost. These functions include collision avoidance and guidance for approach and landing. Significant in this light is that to whatever degree is practical, these functions can be self-contained. There is no theoretical requirement for extensive ground instrumentation facilities (other than the monitor station in the case of differential GPS).

These functions are supported through the concept of position reporting for collision avoidance and through the operation in a differential mode for approach and landing. This latter point is discussed further in subsequent sections. The explicit point to be made here is that it is

through the integration of a data link with GPS that the full potential of
GPS for general aviation can be realized. GPS and a data link can provide
precision four-dimensional guidance and control globally as well as in the
airspace environment which is notably characteristic of general aviation.
This environment includes those enroute and terminal areas which possess
limited or in some instances no ground instrumentation for terminal area
control and approach guidance.

3.5 Clock Impact

Recalling that, to achieve time synchronization, each user has a semi-
accurate clock which is calibrated against the system master clock by 1)
inserting satellite clock offset (with respect to the master clock) into
the telemetry data stream and 2) by using a fourth satellite to solve a
four-dimensional geometry where the fourth dimension is user clock offset
(with respect to the satellite clock), the user is afforded the avail-
ability of a very precise estimate of system time.

Addressing the accuracy to which this estimate can be provided, con-
sider that the user bias is essentially computed to the range equivalent
accuracy of the pseudorange measurement magnified by the time-dilution-of-
precision (TDOP). Magnovox [3-7] has indicated an error budget allocating
an RMS error of about 4 meters to the ranging measurement for the two fre-
quency receiver. Further, Aerospace [3-3] has indicated a maximum percent
probable TDOP of about two for a 5° elevation mask for the Phase III fullup
satellite configuration. This predicts that the range equivalent time
accuracy available to the user is on the order of the position error and
for the specification goal of 10 meters this translates to about 30 nano-
seconds.

The impact of clock availability is coupled with the data link
advocacy of the preceding section. In order to support self-contained
functions such as collision avoidance and landing guidance, an interrogate
and reply link concept is negated. An alternative which is applicable is
the use of a Time-Division-Multiple-Access link. The GPS can provide the
synchronization to support such a link inherently.

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3.6 Comparative Concepts (Realization Potential)

In order to assess the extent to which GPS may potentially provide capabilities above and beyond conventional area navigation systems, various navigation concepts may be compared. The development of this comparison will be seen to point toward a single concept which should be explored in depth.

Candidate approaches to area navigation are categorized into three generic classes. These are: hyperbolic systems such as LORAN and Omega, satellite systems such as GPS, and hybrid systems which represent combinations or innovative systems. Representative of the latter are: hyperbolic systems with GPS for altitude and time only, hyperbolic systems with a low cost altimeter for altitude, and ground augmented GPS for increased position accuracy.

Conventional Approaches -

Hyperbolic systems such as LORAN and Omega are quite limited in the potential they offer general aviation for capabilities beyond conventional enroute navigation. They are essentially horizontal position finding systems with no capability for altitude determination or time measurement. They are medium to high accuracy systems (1.5 - 3 km for Omega and 150 - 300 m for LORAN). Omega is global but susceptible to ionospheric variation, while LORAN operates primarily in the ground wave propagation mode thus having limited coverage capability. The systems are ground station dependent with a very low level of redundancy for station outages. There is essentially no inherent user redundancy with accompanying degraded operation except that potential exists for Omega to resort to single frequency operation with the associated introduction of lane ambiguity which is potential degradation in quantum steps. Omega does offer the potential of increased accuracy by taking advantage of the spatial correlation property of ionospheric variation and operating in a differential mode.

Satellite systems, on the other hand, offer expanded performance in the sense that altitude and possibly time are available as well as increased precision in the position estimate. This, however, is at the expense of system cost - both to the user and facility (i.e., satellite constellation and ground monitor stations). Conceivably, user costs can be reduced through technology development, probably at the expense of position

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accuracy. The system is satellite dependent although a high level of re-
dundancy is offered by the GPS concept in that alternate satellites may be
acquired, at the expense of GDOP degradation, in case of satellite outage.

The user equipment in satellite systems can provide inherent redun-
dancy by receiver design at a cost. For example, the four or five channel
high performance GPS receiver could conceivably be operated with one or
more channels failed if coarse position or time were available from alter-
nate sources, or if the receiver were reconfigured to operate sequentially.
This advances the idea of an integrated system with graceful degradation as
opposed to a dual redundant approach where redundancy is a cost-non-
effective feature until the occurrence of a failure. Further, if the
four-channel graceful degradation approach is implemented, the user can
acquire the additional features of the four channel receiver over a sequen-
tial version essentially at no cost.

Hybrid system concepts may be divided into two categories. The first
consists of conventional two-dimensional systems augmented to provide alti-
tude information. The second consists of GPS with ground augmentation to
improve accuracy. The motivation here is to examine system concepts which
could extend the enroute capability of RNAV systems to the terminal area
environment by adding altitude measurement and improving accuracy.

Two concepts have been explored to augment conventional navaid systems
such as Omega and LORAN with altitude in order to upgrade their performance
capabilities. These consisted, one, of adding a low-cost radar altimeter
and, two, adding a dual channel GPS receiver for altitude and time only.
Both concepts were discounted very quickly in that the horizontal accuracy
for both systems, and Omega in particular, is marginal with respect to
other than enroute applications. LORAN has been observed to have repeat-
able position accuracy of about 15 m but for self-contained navigation and
guidance, absolute accuracy is required. Further, a survey of current
altimeters as shown in Table 3-5 indicates that while the required altitude
accuracy is achievable, cost (even anticipating a two-to-four-to-one reduc-
tion with technology development) is prohibitive. Utilization of a dual
channel GPS receiver to provide altitude and time was also quickly
dismissed when it was observed that in effecting a four-dimensional solu-
tion to the GPS algorithm using position from a conventional navaid, the

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Table 3-5. Radar Altimeter Survey

MANUFACTURER	MODEL	RANGE(m)	ACCURACY	FREQUENCY	PWR OUT	WT(kg)	V_{in}	I_{in}	COST
BONZER	MARK-10X (PULSE)	15- 30 30-150 150-750	+2m +5% +7%	4300 MHz	16 W PK	2	12-30 VDC	1.5A MAX	2295
	MINI-MARK (PULSE)	30-300	+7%	4300 MHz	3 W PK	1	14 or 28 VDC	0.6 A	995
COLLINS	ALT 50 (FM/CW)	0 to +30 30-150 150-600	+2m +5% +7%	4300 MHz	-	4	28 VDC	(24 W NOM)	5535
	ALT 55 (FM/CW)	0 to +30 30-150 150-750	+5% +5% +7%	4300 MHz	-	4	28 VDC	(30 W NOM)	6635
HOFFMAN	HRA-100 (PULSE DOPPLER)	0-30 30-150 150-750	+1m +2% +5%	4300 MHz	50 MW	3	14 or 28 VDC	0.8 A	3995
KING	KRA 10 (-)	< 30 30-150 >150	+2m +5% +7%	-	-	2	28 VDC	0.2 A	2095
	KRA 405 (FM/CW)	0-150 150-600	+2m or +5% +7%	4300 MHz	150 MW	5	28 VDC	0.85 A	4800
KOLLSMAN	AHV-10 (FM/CW)	-	Typical +(10cm+2%) Maximum +(20+5%)	4300 MHz	50 MW	1	28 VDC	(10W)	5500
	KS 250 (FM/CW)	0-30 0-1500 0-7.5km 0-20km	5%+0.3m 3%+1m 1%+0.3m 1/2%+0.3m	4300 MHz	50 MW	4	-	-	-
SPERRY	AA-100 (SHORT PULSE)	15-150 150-600 600-750	3m or +5% +7% +9%	4300 MHz	-	3	14 VDC (or) 28 VDC	1 A 0.5 A	2990
	AA-215 (SHORT PULSE)	0-30 30-150 150-750	+1m +3% +4%	4300 MHz	70 W	4	28 VDC	1.5 A	6350

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conventional navaid errors mapped directly into the altitude and time measurements. The net result is that augmented hyperbolic systems are not considered capable of supporting terminal area navigation or approach and landing guidance.

Ground Augmented Approach -

Special attention has been given the development of GPS with ground augmentation to improve accuracy. One approach here was to look at GPS with a satellite transceiver located on the ground (i.e., a "pseudolite"), probably near the end of the runway. This approach was felt to afford increased accuracy on two fronts. First, the location of a transceiver on the ground was felt to significantly reduce the error in pseudorange for that satellite. As an example, Table 3-6 shows the anticipated error reduction of a pseudolite (satellite-on-the-ground) over a satellite. The net improvement indicated is a ten-to-one improvement in RMS error in pseudorange. Second, the location of the satellite beneath the aircraft was felt to significantly improve the geometry, especially in the z-dimension. A detailed simulation was conducted to demonstrate the effects of a pseudolite augmented system and are included as Appendix B. Various combinations of up to four satellites overhead and one on the ground as shown in Figure 3-2 were examined as a function of constellation geometry (i.e., elevation angle) and for a simulated landing profile. The net results of the simulation were, however, not encouraging. For cases where the aircraft was directly overhead, improvement of about two was evidenced from the increased accuracy of the pseudolite and a further improvement of again two was observed with the improved geometry. The discouraging results were obtained when the aircraft was permitted to maneuver within the geometry. Figure 3-3 shows an example of the dilution-of-precision in the vertical plane as an aircraft is allowed to fly an approach pattern to a runway threshold located at the center of the y-axis. Notice that the geometry improves accuracy to the touchdown point, but thereafter quickly degrades as the aircraft is now "outside" the tetrahedron formed by the connecting lines between the three overhead satellites and the pseudolite. Another geometry where the aircraft is not allowed to exit the geometry is shown in Figure 3-4 and does not produce this effect.

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Table 3-6. Ground Transceiver Accuracy - Rationale

ERROR SOURCE (1σ)	Satellite	Pseudolite
EPHEMERIS ERROR	1.5m	none
SATELLITE CLOCK ERROR	0.9m	0.45m
TROPOSPHERIC DELAY ERROR	1.5m	none
SPACE VEHICLE GROUP DELAY ERROR	3m	1.5m
MULTIPATH ERROR	1.8m	none
IONOSPHERIC CORRECTION · INDUCED ERROR	15m	none
TOTAL ERROR RMS	15.57 meter	1.57 meter

$$\frac{\sigma \ \text{PSEUDOLITE}}{\sigma \ \text{SATELLITE}} \approx \frac{1}{10}$$

SATELLITE CLUSTER

Ranging Error: σ
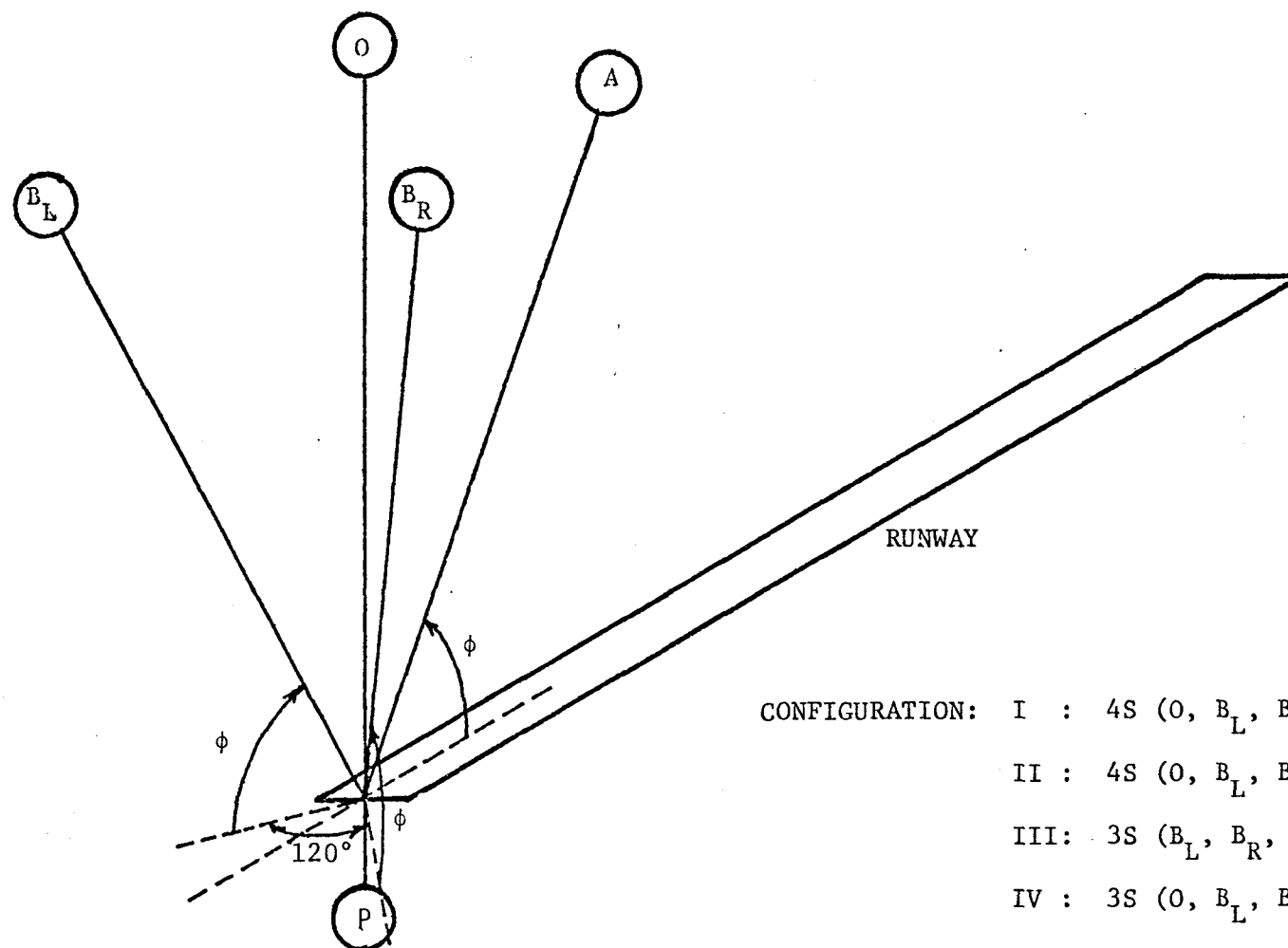
RUNWAY

CONFIGURATION: I : 4S (O, B_L, B_R, A)

II : 4S (O, B_L, B_R, A) and P

III: 3S (B_L, B_R, A) and P

IV : 3S (O, B_L, B_R) and P

PSEUDOLITE

Ranging Error: $k\sigma$

Figure 3-2. Ground Augmentation Geometry
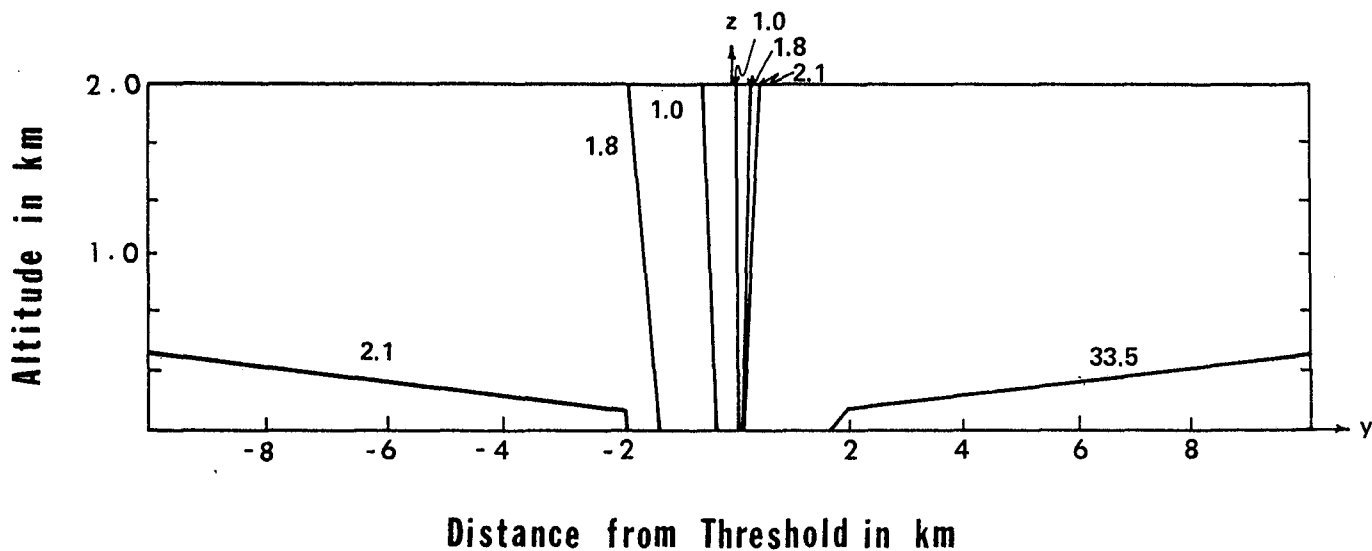
Figure 3-3. VDOP Contours in Vertical Runway Plane for
Configuration IV:3S $(0, B_L, B_R)$ and P (k=1.0)
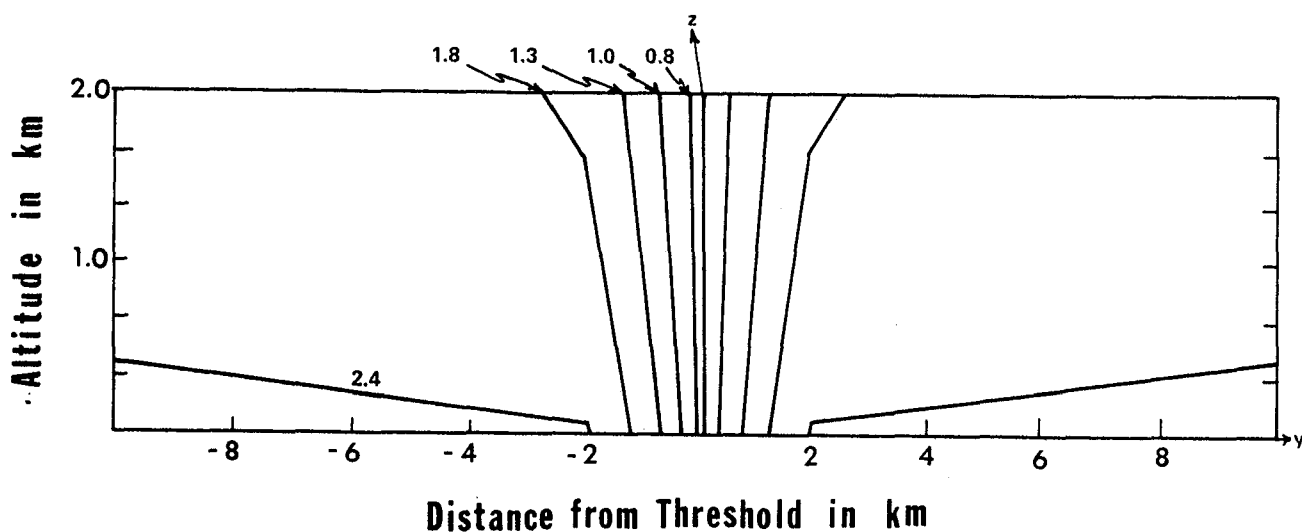
Figure 3-4. VDOP Contours in Vertical Runway Plane for
Configuration III:3S (B_L, B_R, A) and P (k=1.0)

In addition, the negative system aspects of pseudolite augmentation should be mentioned. The obvious dissident factor in pseudolite augmentation is, of course, cost. It is not inconceivable that ground-based satellite equivalent transmitters could be in the cost range of tens to hundreds of thousands of dollars--a probably prohibitive cost to be associated with the majority of small airports. Further, a significant technical problem exists with the deployment of a large number of additional GPS transmitters. Each transmitter is assigned a satellite identification code: this code is of sufficient length to accommodate only a limited number of transmitters (thirty-two). The system impact (on signal structure) of a larger number of transmitters could be significant if each airport was to have a unique code. However, airports with sufficient separation could conceivably use the same identification code.

Summarizing the pseudolite performance, then, the concept appears to be susceptible to rapid geometry effects while providing only modest improvement in accuracy with attendant technology constraints.

Differential GPS -

The second approach for ground augmentation considered was drawn from observing the improvement obtained by operating Omega in a differential mode. The basic theme of differential GPS is to note, see Table 3-7, that the significant error sources in pseudorange measurement occur as bias errors associated with the satellite and tropospheric propagation, and correlated errors associated with the ionospheric group delay error correction process. The total RSS error computed from Table 3-7 is 4.04 meters. If a differential mode is implemented as shown in Figure 3-5 where a monitor station is established to measure and correct a major portion of these errors, there is potential to reduce this to 1.75 meters. This potential is dependent on the assumption that the error sources are correlated over spatial dimensions comparable to the spacing between the monitor station and the user position. It also assumes temporal correlation over time intervals on the order of the delay in computing the correction factor at the monitor and data linking this to the user aircraft. The requirement for this data link is significant to the concept, for through it resides the capability of extending the auxiliary functional capability to include guidance for approach and landing and for collision avoidance.

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Table 3-7. GPS Navigation Error Summary [3-8]

Error Contributor	Pseudorange	Statistics	Notes
Satellite Ephemeris	1.5 meter	Bias	Uncorrelated between Satellites
Satellite Group and Clock	1.0 meter	Bias	Uncorrelated between Satellites
Pseudorange Noise	1.0 meter	Markov	Evaluated at $C/N_0 = 30$ db for P-Code
Range Quantization	0.226 meter	White Noise	
Range Mechanization Error	1.0 meter	White Noise	
Ionospheric Dual Frequency	3.0 meter	Markov	Evaluated at $C/N_0 = 30$ db for P-Code. No Averaging
Tropospheric Residual	1.0 meter	Bias	Evaluated at 5° elevation and zero altitude
Multipath Error	1.0 meter	White Noise	
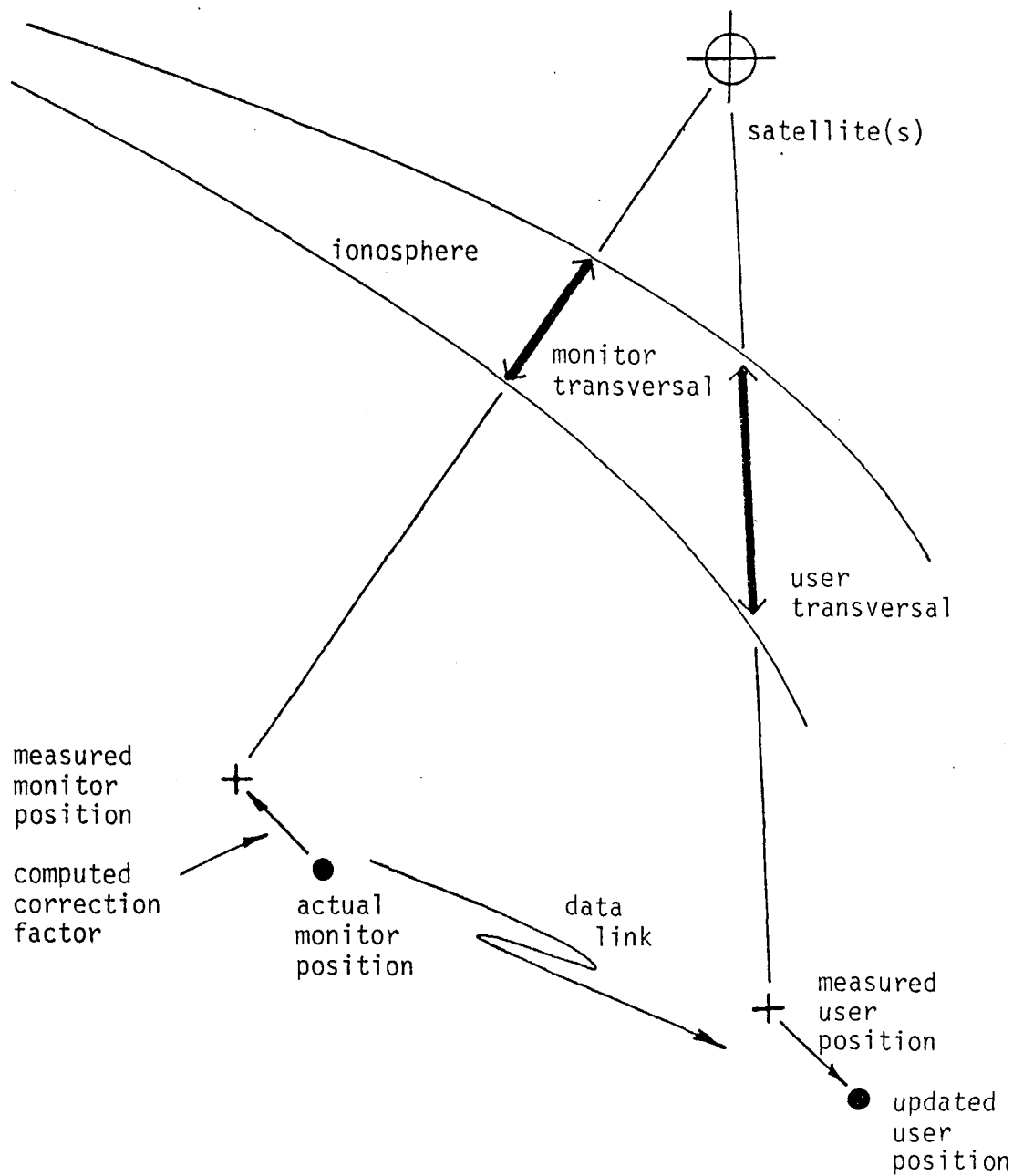
Figure 3-5. Differential GPS Geometry

GPS in a differential mode offers distinct performance improvements in several different ways. It essentially removes the major portion of ionospheric group delay correction and other bias type errors. It is very likely much less expensive to implement a user receiver and data link than a ground-based satellite-equivalent transceiver (i.e., the pseudolite would require the expensive clock carried on board the satellite). It would allow the user to be single frequency in that ionospheric correction would not be required. It would overcome the rapidly changing local geometry effects discussed previously.

In summary then, a single frequency GPS receiver operated in differential mode can conceivably provide performance equal to or better than a two-frequency receiver at the expense of a monitor station and a data link. The concept is further supportive of increased functional capability through designing the data link to also implement guidance for approach and landing and collision avoidance. The recommendations in Section 5.0 will indicate the desirability of developing further the feasibility of differential GPS and experimentally demonstrating the increased functional capability resulting from this concept.

3.7 Economic Considerations

The economic considerations here emphasize the user segment of alternate navigation aids. Two general categories are discussed: one, the total system costs for current, satellite, and area navigation systems, excluding facility acquisition costs; and two, the relative cost of single user equipment, again for the three categories. Facility acquisition costs are not included as the current system is just that, current. Land-based systems are in the implementation stages and GPS is soon to be an important national resource.

Relative Total System Costs-

Table 3-8 [3-6] indicates the user system cost comparison for the three alternatives. The "current-base system" includes a majority of known or planned navigational components which are now in use or planned for use to satisfy global civilian and military navigational requirements during the 1975-1995 time frame. The "satellite-based system" incorporates

Table 3-8. User System Cost Comparison ($1,000) [3-6]

Alternative	New User Equipment Costs	Maintenance Costs (20 Yrs.)		Equipment** Replacement		Total Costs (20 Yrs)
		New Systems	Current System*	Cost***	Maint. of Replacement Equipment	
Current Based System	3,753,165	2,075,000	1,457,000	2,801,000	1,040,000	11,126,165
Satellite Based System	3,588,225	2,084,000	1,457,000	600,00	---	7,726,225
Ground Based System	3,665,444	2,133,000	1,457,000	720,000	---	7,975,444

*Cost of maintaining the current system during phase-in of alternative system.

**For the current system, existing equipment is assumed to be replaced at least once over the next 20 years.

***Includes satellite replacement costs (every 7 years).

existing naviads such as DABS and MLS for short-range requirements and includes a satellite subcomponent for the long-range requirements. The "ground-based radio system" is similar to the satellite-based system except that systems such as LORAN or OMEGA support the long-range requirement. The costs here include new user equipment acquisition costs, equipment replacement costs for the current base system, and ongoing maintenance for all three alternatives.

Notice that overall, the satellite system cost is 40% less than the current system and on an equal with ground-based area navigation. In a cost-effective sense this weights the satellite system in a much more favorable position due to the increased performance at comparable cost.

Relative User Equipment Costs-

The FAA [3-9] has indicated a receiver design cost allocation as shown in Figure 3-6. This results in an anticipated GPS receiver cost of about $2800. This is slightly high with respect to the predicted costs of on the order of $2000 contained in reference [C-1]. Although the correct order of magnitude, technology developments in the area of microelectronics can certainly impact these costs for the 1985 time frame; although on a relative basis, it can be argued that other navaid costs will similarly be affected. It should be pointed out, however, that to a certain extent there may be a lack of motivation to force a new non-GPS microelectronic technology design when GPS is available and offers increased performance. Thus, technology may actually drive GPS costs down, while not affecting other navaids.

In order to maintain perspective, relative costs for comparative navaids are shown in Table 3-9 [3-9]. The comparison is again slightly unbalanced in that the relative performance of the systems has not been weighted. Nonetheless, it does indicate that anticipated GPS user costs place it in a favorable candidacy for the general aviation user.

Table 3-9. Estimated Cost of GA Avionics [3-9]

GENERAL AVIATION	LIST PRICE
VOR	$ 900
DME	1,800
RNAV Computer for VOR/DME	1,000
LORAN Receiver/Navigator	2,050
GPS Receiver/Navigator	2,800
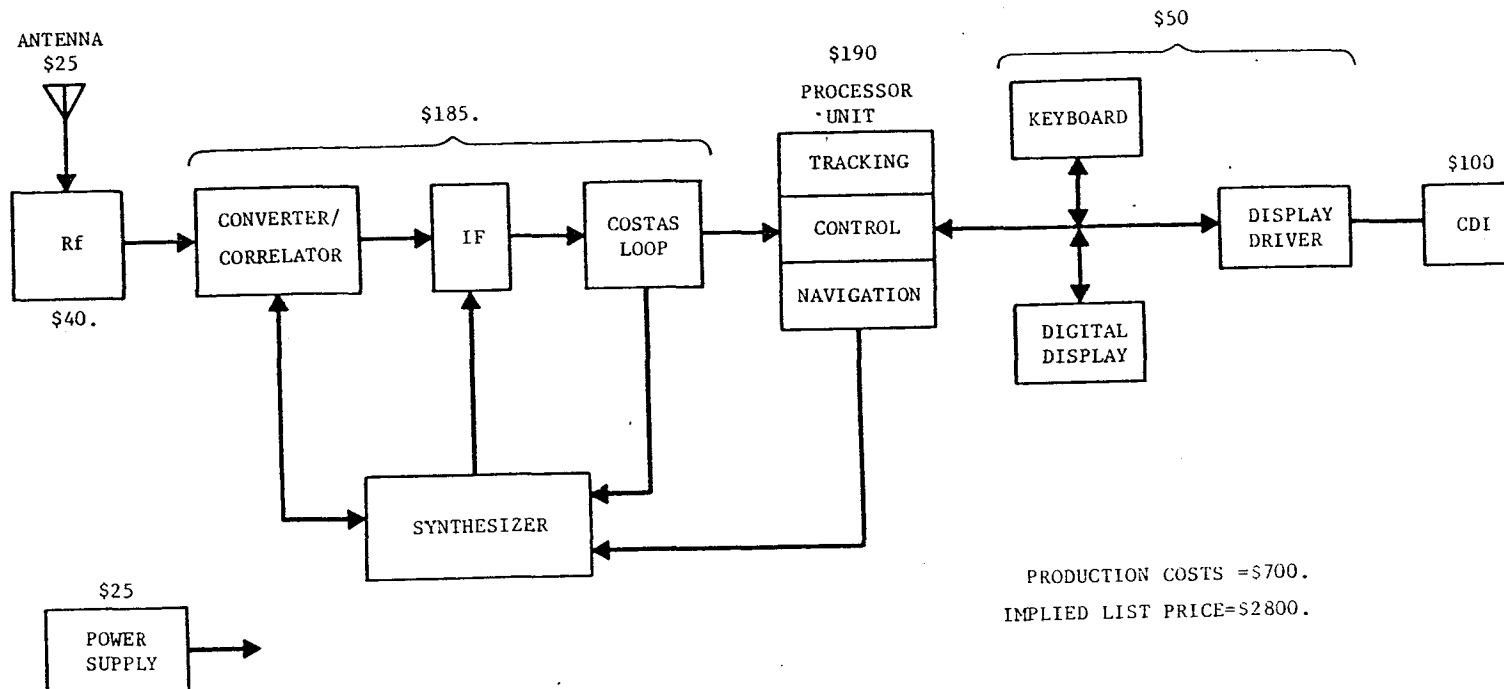
Figure 3-6. Low Cost GPS Receiver Block Diagram [3-6]

4.0 EXPERIMENTAL PROGRAM OBJECTIVES

This section presents the objectives of an overall program to establish
an optimum user equipment configuration through experimental evaluation.
The task definition is directed at evaluation via flight test as had been
the case for predecessor systems (i.e., 621B); however, during the develop-
ment of these objectives, it became apparent that laboratory and/or
"hot-bench" testing could provide valuable data without the expense (and for
Phase I GPS coverage, the inconvenience) of flight test. It is with regard
to overall test and evaluation that these objectives have been defined.

The development of the objectives begins with evaluation concept
definition, proceeds to establish experiment guidelines, provides a state-
ment of general objectives supported by specific identified performance
evaluation areas, and concludes with representative architectures for
experiment definition.

4.1 Concept

The concepts addressed in the definition of an evaluation plan should
focus on proving system worth and on demonstrating the unique capabilities
provided to a given user group. Thus, the experiments should verify those
quantitative measurables which demonstrate navigation performance and limi-
tations specific to General Aviation requirements and utilization and
further, demonstrate the increased scope of functional utilization available
to the General Aviation pilot through unique features of GPS. As an example
of the first category, the evaluation program should demonstrate the achiev-
able relative and absolute accuracies for a variety of flight conditions.
It should further explore those contributing factors such as multipath,
shading, etc., which constrain or otherwise influence the general aviation
pilot's ability to use the system and should specifically address the advan-
tages available over alternate navigation equipments. Examples of the
second category include increased scope of utilization such as collision
avoidance (when used with a data link), guidance for approach and landing,
etc. Also considered in the second category is the redundancy availabiity
inherent in multichannel mechanized user equipment.

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4.2 Evaluation Definition Guidelines

The following guidelines have been defined for the specification of evaluation procedures:

1) The experiment objective will establish criteria whereby existing system requirements or procedures can be augmented or replaced. An example here is the use of GPS to provide position data in the terminal area, thus modifying (or replacing) the surveillance radar function.

2) The experiment(s) will begin with the minimum configuration of a single channel receiver and reconfigure toward four channels to demonstrate the increased capability, performance, and redundancy. This is shown graphically in Figure 4-1. Incremental reconfiguration to upgrade system complexity is noted to increment user scope as well as cost simultaneously.

3) The experiments will separately address the flight profile segments. These include enroute, terminal, approach, and landing as well as segment transitions. The role of GPS in general aviation operations is considered particularly directed at the terminal area and approach segments. Enroute does not exercise GPS capability over more conventional techniques, while landing probably requires augmentation to some degree. Thus, the latter two segments are prioritized differently. The overall priority of flight segment in an evaluation program is then projected as:

    a) terminal area and approach
    b) landing (augmented)
    c) transitioning
    d) enroute

4) The experiments will specifically address general aviation requirements, but will also emphasize the potential available to the commercial fleet and thus address total civil aviation.

$

COMMERCIAL
ENROUTE

CAT III
COMM & GA

APPROACH

△

COMMERCIAL
AND GA TMA

△

CAT II

MINIMUM
CONFIG-
URATION

△

Configuration
Complexity*

GA ENROUTE
(SINGLE CHANNEL
SEQUENTIAL)

AUGMENTED RNAV

MLS/ILS TRANSITION

SELF CONTAINED
LANDING
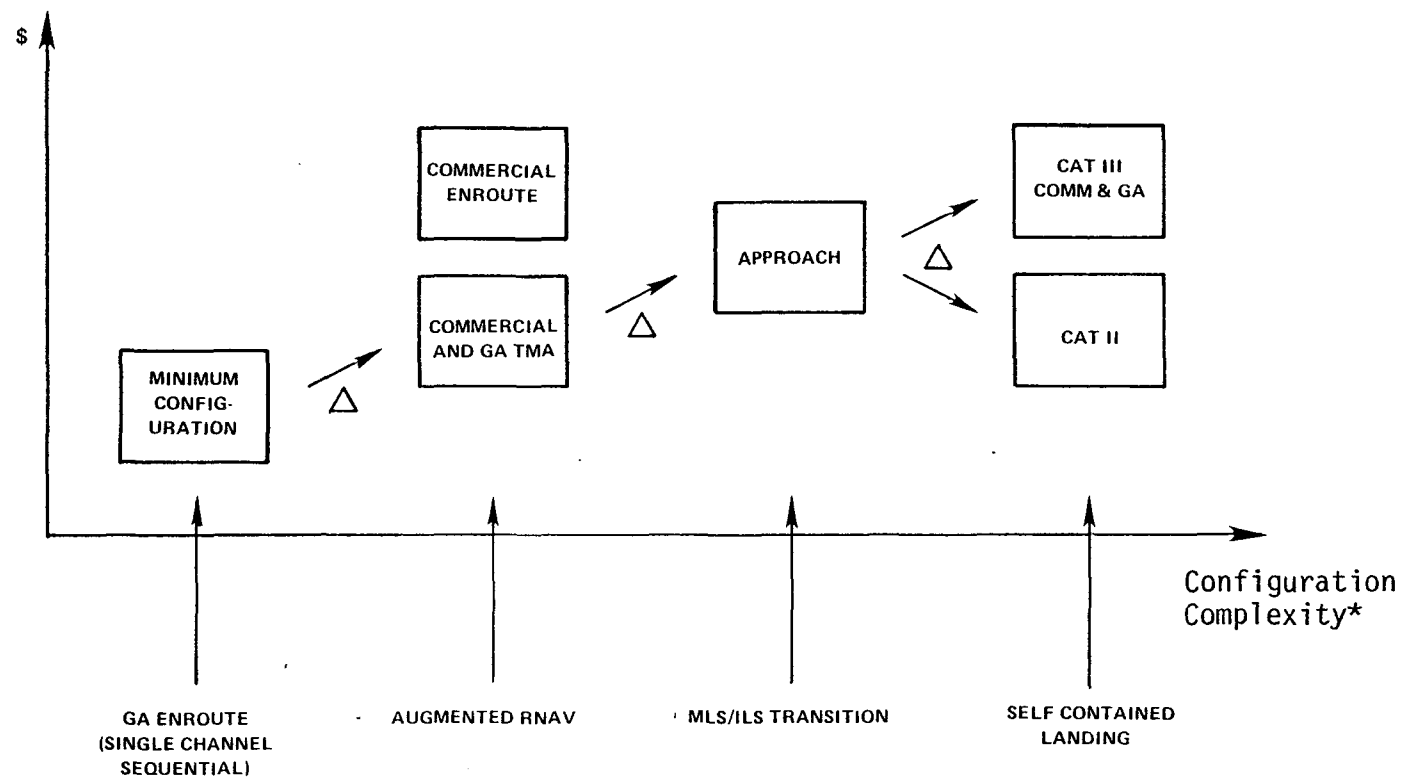
*Redundancy/Accuracy Requirements and Management

Figure 4-1.   Experimental Program Philosophy

4.3 General Objectives

The general objectives of an evaluation program for satellite naviga-
tion systems include the demonstration/evaluation of those features specific
to navaids in the GA environment as well as the determination/demonstration
of the redundancy management features. The demonstration/evaluation objec-
tives may be conveniently partitioned into three categories representing
enroute, terminal area, and approach and landing flight segments. Represen-
tative investigation areas include:

1) Enroute - The potential resident within a GPS configured system to
replace and/or augment VOR/DME functions with RNAV capability,

2) Terminal Area - Potential available for replacing the ground sur-
veillance function with position reporting, and

3) Approach and Landing - Potential for and feasibility of providing
precision approach guidance and self-contained landing to the general avia-
tion fleet.

4.4 Specific Performance Evaluation Areas

Table 4-1 lists specific performance evaluation areas of significant
impact to the general aviation user. The primary objective of these evalua-
tion areas is to quantify performance and system requirements as directed to
general aviation.

Table 4-1. Specific Performance Evaluation Areas

- POSITION AND VELOCITY ACCURACY (RELATIVE & ABSOLUTE)
- ACQUISITION/REACQUISITION TIME
- DROPOUTS
- CONSTELLATION REVISION TIME
- INPUT SIGNAL DYNAMIC RANGE
- MULTIPATH/SHADING
- L_1/L_2 CONSIDERATION
- UPDATE RATE
- CA/P CODE PERFORMANCE

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Accuracy

Of obvious importance in the achievement of a performance evaluation is the demonstration of system accuracy as a means of establishing a baseline from which comparisons may be made. These comparisons span the ensemble of quantitative parameters of interest as well as being a means of evaluating the absolute accuracy of a given system.

Acquisition/Reacquisition Time

The time to acquire and more especially the time required to reacquire in the event of track loss is an important consideration over the general aviation flight profile. Dependent on the flight segment, lengthy reacquisition time could represent a serious problem. This is especially important since preceding sections have alluded to GPS in the role of landing guidance and collision avoidance. It is also important to demonstrate that enroute navigation is not degraded by lengthy acquisition times.

Dropouts

Dropouts are perhaps not different in impact from reacquisition time except in a cause and effect respect. That is, signal dropouts cause the concern for reacquisition time. What is unique with respect to dropouts is the effect of the length of time signal is lost on the ability to reestablish track. For long signal outages, the initial conditions may degrade to the point of increasing the difficulty of their acquisition process.

Constellation Revision Time

Constellation revision results from the need to overcome geometrical dilution of precision as the satellites progress in orbit and to replace satellites which have dropped below 5° elevation. This requires that the interplay between time to access the current geometry, time to predict the new geometry, and the time to acquire the new satellite or satellites, if required, be demonstrated. The performance of GPS is dependent on the data rate of this assessment as well as the total time to revise and the degree of degradation which can occur in these time frames.

Input Signal Dynamic Range

This area of evaluation simply demonstrates the levels at which dropout occurs and the effects of saturation in the event of strong signals.

Multipath [4-1]

Significant range errors can result when the line-of-sight signal and a delayed multipath signal are of comparable amplitude. The purpose of this specific evaluation area is to explore the multipath problem and its effects in ranging error. While emphasis is on effects at the user equipment, results are also applicable to the monitor station(s).

Operational environments typically encountered with GPS type equipment can cause satellite signals to be received over multiple paths and result in delayed signals having amplitudes comparable in amplitude to the line-of-sight signal. Delay of the indirect path may vary from a few nanoseconds to several microseconds. A PRN ranging system can track the direct and delayed signals independently, given sufficient delay of the multipath signal. However, when the delay is less than about 1.5 code chip intervals, the delayed signal can cause errors in the signal tracking loop. Also, severe fading can occur when comparable amplitudes and very small delays are experienced. For delays on the order of one-two chip intervals, error performance is a function of the signal-to-interference ratio, the multipath signal delay, and the relative phasing of the direct and delayed path carriers. The interference ratio is further a function of the receiving antenna pattern and its orientation, the transmission paths for the direct and reflected signals, and the characteristics of the signal reflecting surfaces.

Multipath analyses have predicted GPS performance for selected situation environments. This evaluation will provide supportive test data for these limited scope analyses and will extend performance evaluation to include the effects of multipath from multi-specular and distributed diffuse scatterers.

Dual Frequency Considerations [4-2, 4-3]

The general aviation receiver will likely receive on only one frequency. As a result ionospheric refraction correction capability and choice of frequency are important issues. The correction capability consideration is obvious in that it ultimately impacts system accuracy (and is

likely the single largest error source). The choice of frequency is an important consideration in that it impacts signal margin, which affects initial acquisition, threshold performance, and bit error rate.

Ionospheric group delay is compensated for in one of two ways: either two precisely known frequencies are transmitted and the true pseudorange calculated as:

$$R = R_1 - (R_1 - R_2) \left(\frac{F_2^2}{F_2^2 - F_1^2} \right)$$

where the R_i are the measured pseudoranges and the F_i are the transmitted frequencies, or an ionospheric model is used to calculate delay. The thrust of this evaluation area is then to determine the achievable accuracy using a model at either frequency with respect to the two-frequency approach as well as the ultimate accuracy achievable with the two-frequency technique in a realistic environment.

With regard to signal-margin dependence on frequency, assume the C/A could be transmitted on either transmitted frequency, then it becomes important to evaluate in a realistic environment, the actual effect on signal margin and subsequent performance of frequency selection. This two-point check together with theoretical predictions can be used to predict the appropriate frequency selection for general aviation if GPS is to be deviated from, as well as the performance available with the current GPS configuration.

4.5 Example Experiment Definition

A more specific evaluation of GPS potential, discussed here in somewhat more detail than in the previous sections, is the demonstration of the user equipment redundancy features inherent in the GPS system concept. The multichannel receiver implementation allows a performance/redundancy exploitation which raises the issue of the optimum receiver configuration for general aviation. Table 4-2 shows the evolution of capability available

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Table 4-2.   <u>FIVE CHANNEL RECEIVER - REDUNDANCY/ACCURACY</u>

- FIVE CHANNEL CONTINUOUS

    WITH LOW COST INERTIAL AUGMENTATION

    WITHOUT LOW COST INERTIAL AUGMENTATION

- FOUR CHANNEL CONTINUOUS

    x,y,z,t WITH NO ACQUISITION CHANNEL

- THREE CHANNEL CONTINUOUS

    x,y,t WITH z FROM ALTIMETER

- THREE CHANNEL SEQUENTIAL

- TWO CHANNEL SEQUENTIAL

    "A" ACQUIRES THEN HANDS TO "B"

    "A" ACQUIRES & TRACKS THEN
    "B" ACQUIRES & TRACKS

    "A" FOR DATA ACQUISITION

    "B" ACQUIRES & TRACKS

- SINGLE CHANNEL SEQUENTIAL

REDUNDANCY
GRACEFUL
DEGRADATION

ACCURACY
UPDATE
RATE

<u>OBJECTIVE</u> - DETERMINE OPTIMUM CONFIGURATION

with various GPS configurations. The objective of the demonstration would be to evaluate the relative weight of redundancy/graceful degradation versus accuracy/update rate. The basic procedure is to examine the previously discussed performance evaluation areas under the parameter of redundancy management.

The basic approach employed in the demonstration assumes a flight experiment. However, static hot-bench testing is an appropriate subset of this and may be desirable as a precursor to the expense and complexity of a flight demonstration program.

The experimental concept is that of allowing the test bed to perform normal general aviation flight profiles consisting of enroute, terminal area, approach and landing maneuvers. This affords an evaluation of general performance as well as susceptibility to multipath, dropouts in turns, etc. It is anticipated that the test-bed would consist of a general aviation type aircraft and that the terminal area and landing phases of test would be staged from the Wallops Flight Center so as to take advantage of the tracking capability and the runway instrumentation available there. The enroute aspects of testing could be performed in areas of convenience.

A sketch of the test-bed configuration is as shown in Figure 4-2. The approach postulates a five-channel receiver from which the pseudoranges may be interfaced directly with a minicomputer. Auxiliary systems are anticipated from which a best-estimate-trajectory (BET) may be derived and compared in real time with the GPS solution. The GPS solution is derived from the pseudoranges by the minicomputer, compared with the BET and statistics generated. The results are displayed in real time via CRT and/or strip chart media. The data are also recorded on digital magnetic media for post-flight data analyses. The post-flight analyses are anticipated to use the Wallops tracking radar and runway instrumentation generated BET for improved accuracy.

The general experiment procedure is to examine each of the candidate configurations shown in Table 4-2 under similar flight profiles and to establish from the results the redundancy/accuracy trade-off for the various flight segments.

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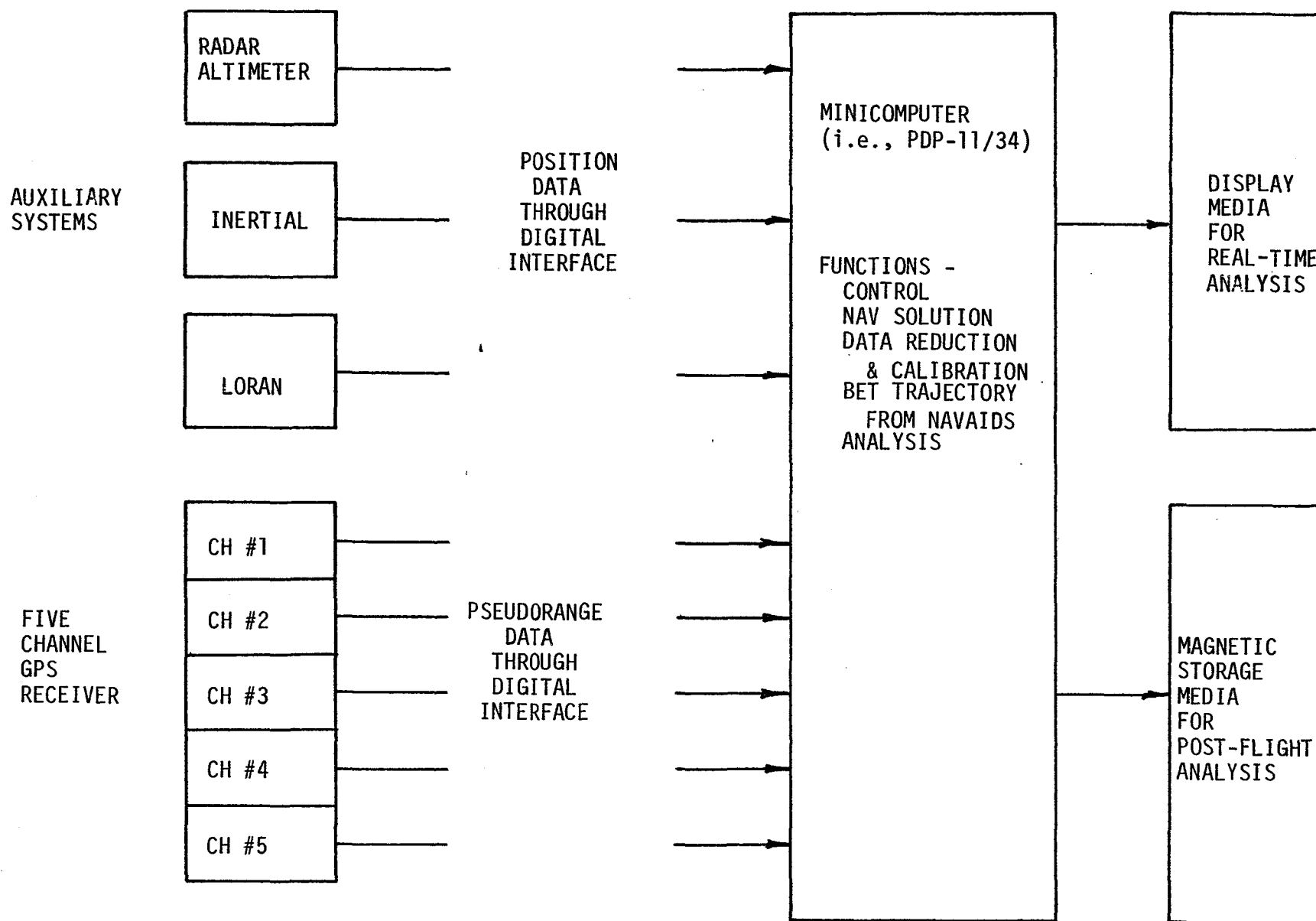
Figure 4-2. On-Board Test Bed Configuration

4.6 GPS/Data Link Research Facility Considerations

This section presents the functional design of a research facility
with the objective of supporting the demonstration of the full potential of
GPS integrated with a data link for general aviation. This demonstration
will focus on performance evaluation as well as integration and optimiza-
tion of various conceptual approaches to GPS integrated with a data link.
Functional requirements of such a facility include real-time interface with
satellites, satellite simulator, and the capability of incorporation of
actual equipments in a hot-bench environment. Capability is required for
dedicated command, control, and display as well as for general purpose data
acquisition, reduction, and analysis. The facility is anticipated to be
highly interactive and reconfigurable to accommodate a broad scope approach
to avionic concept evaluation. Figure 4-3 shows a functional organization
of the facility to support these requirements. The salient features of
this organization as indicated are: 1) real-time evaluation of equipments
in aircraft and/or hot-bench test beds through a roof-top antenna facility,
2) a modularized computer complex to achieve control functions and to per-
form data acquisition and analyses, and 3) appropriate display and documen-
tation capability.

Figure 4-4 indicates a flow diagram of the suggested facility. Notice
again that capability is provided for either hot-bench or aircraft testing
as well as the use of real satellites as they become available or the use
of a satellite simulator in the interim. The interactive and real-time
aspects of the facility are supported by a moderately sized minicomputer
which accepts operator commands and interfaces the display information.
This computer complex is recommended to contain 64K words of memory, CACHE
for improved throughput, on-line mass storage and a real-time operating
system. The bulk processing for analyses is handled by a more sophistica-
ted, but still of minicomputer proportion, general purpose analysis module.
Within this module, preprocessing, editing, data reduction, and data analy-
sis functions are performed. Mass data busses provide the "ground truth"
and auxiliary data required. The analysis module essentially performs a
post-experiment function. Almost real-time "quick look" analyses are
hosted in the command and control computer.

43
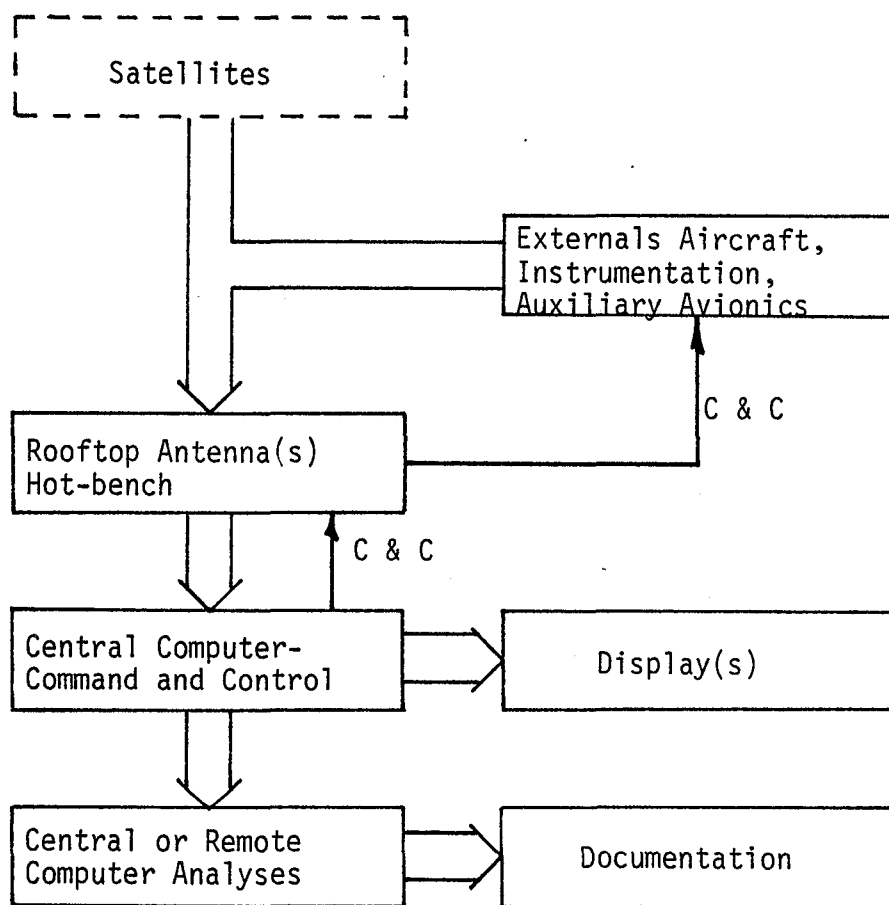
Figure 4-3. Evaluation Facility Functional Organization

Test Bed-A/C

Satellite(s)

Voice/data Communications

Rooftop Antenna UHF/VHF

Satellite Simulator → data → Rooftop Antenna L-Band

Command

data

UHF/VHF Communications System

Command and Control-low memory requirement → Command → Test Bed-Hot-bench

Command

synchronization and data

Navigation Instrumentation, and auxiliary Avionics data

Operator Console/ Display (CRT) → Command → Situation Display

GPS Navigation Data

Analysis Module* (CPU and peripheral)

Ground Instrumentation-Best Estimate Trajectory, etc.

Figure 4-4. Detailed Functional Flow Diagram
*See Figure 4-5 for more detail

The general philosophy of data handling is to provide limited data to the central computer for operator interface and "quick look" while logging an extensive data set in the analysis module for later processing. In the case of aircraft tests, substantial on-board data logging is performed for expediency and for redundancy.

Rooftop antenna complex - The rooftop antenna complex interfaces the facility with test aircraft, differential mode monitor stations, and with the satellites themselves. Included are the data and voice communications to support flight test activities. Obvious frequency coverage includes the L-band GPS frequencies and UHF/VHF frequencies for voice and data links. Growth to a high performance antenna with steerable beams is a very desirable feature for evaluation of aircraft antenna configurations for general aviation aircraft.

Satellite simulator - The satellite simulator provides real-time rf signals to the user equipment, either in the aircraft through the rooftop antenna or directly to the hot-bench, by means of a digital simulation driven programmable transmitter array. The simulation implements satellite dynamics as well as providing for constellation selection and updating. General functional capability of the simulator includes software development, receiver strategy evaluation, and test and integration facility.

Command and control/user interface module - This module provides for initial configuration, test procedure programming, real-time data display, and operator interface. It is recommended as a minicomputer hosted system with the requirement of compatibility with the GPS user equipment microprocessor. Display capability will include real-time data display as well as cockpit representative displays such as the horizontal situation display. Operator interface is through CRT terminal as well as cockpit representative controls. An actual cockpit simulator is not presently envisioned but could be a future development.

Data acquisition and distribution - Provision for relevant parameter monitoring and communication to either archival or processing machinery is included. The concept is that of large data bussing for local functions. In the cases where remote facilities need be in communication with the evaluation facility, medium to high speed (4800 to 9600 baud) synchronous telephone links are recommended. Aircraft-to-ground communication is via the data link discussed elsewhere.

Data analysis module - An almost antonomous module is recommended to perform the extensive data reduction and analysis functions inherent in evaluation and demonstration. A detailed diagram of the analysis module is shown in Figure 4-5. This module is basically configured as a general purpose computational facility so as to support current requirements while providing to flexibility to accommodate future programs.

A recommended analysis module configuration includes 256K bytes of main memory, two 50 megabyte removable cartridge disk drives, two CRT stations, two tape drives, a medium speed (300 LPM) line printer, and a graphics terminal with hardcopy capability.

As discussed elsewhere in this report, one of the promising concepts resulting from the integration of a data link is that of operating GPS in a differential mode. This provides the specific requirement that the facility be capable of data transfer from the monitor station required in differential mode. This is anticipated to be accommodated by the UHF/VHF communications link shown in Figure 4.4. Whether the monitor receiver and data transmitter is considered part of the facility is to be decided at a later date.

DATA BUSSES

```
         ┌──────┐     ┌─────────────────────┐     ┌──────────┐
         │ TAPE │─────│                     │─────│   CRT    │
         │DRIVE │     │                     │     └──────────┘
         └──────┘     │        CPU          │
         ┌──────┐     │   256K BYTE MEMORY  │     ┌──────────┐
         │ TAPE │─────│                     │─────│   CRT    │
         │DRIVE │     │                     │     └──────────┘
         └──────┘     └─────────────────────┘
         ┌──────┐                                 ┌──────────┐
         │ DISK │────────────┐         ┌──────────│  LINE    │
         │DRIVE │                                 │ PRINTER  │
         └──────┘                                 └──────────┘
         ┌──────┐                                 ┌──────────┐
         │ DISK │────────────┘         └──────────│GRAPHICS  │
         │DRIVE │                                 │TERMINAL  │
         └──────┘                                 └──────────┘
                                                  ┌──────────┐
                                                  │  HARD-   │
                                                  │  COPY    │
                                                  └──────────┘
```
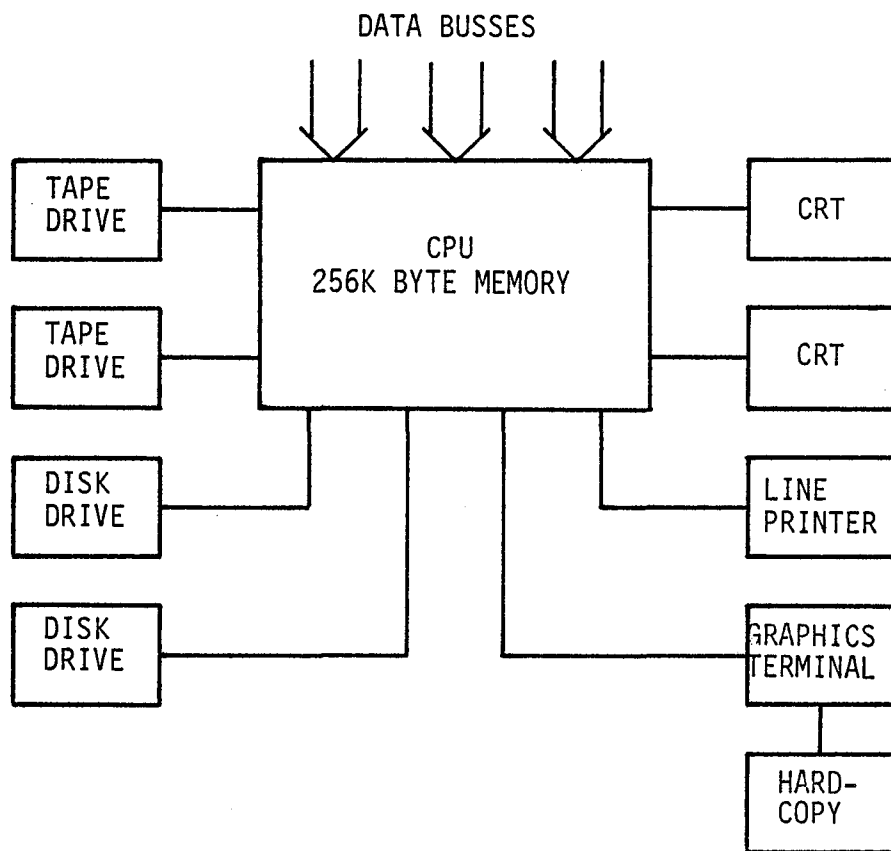
Figure 4-5. Analysis Module Description

5.0 RECOMMENDATIONS

The preceding discussion has indicated that the true potential of GPS for GA lies in the enhanced capability which appears available through integration with a data link. The hand-in-hand ability to provide position reporting and operation in a differential mode by means of data transfer offers significant functional extension of the GPS concept to the general aviation user. Operation in a differential mode may allow the GA user to achieve position accuracies of less than two meters. The implication of this degree of accuracy is that, with the data link, GPS can be used for landing and collision avoidance, and that new concepts in air traffic management may be considered. In order to fully explore the extent to which GPS in a differential mode can be used to implement auxiliary functions such as landing guidance and collision avoidance, RTI recommends that NASA implement a feasibility/demonstration program which would begin with a theoretical/simulation verification of the feasibility and culminate in an experimental demonstration of performance.

Further, pursuant to the total potential of GPS for the civil community, RTI recommends that NASA, with other government agencies as well as members of the civil community:

1. Assign responsibility for developing the civil use of GPS and fund development on an increasing basis.
2. Procure user equipment and embark on an experimental program to demonstrate the potential of GPS and to define critical issues.
3. Based on current developments in VLSI, VHSI and solid-state microwave device development, implement a program to develop a low-cost high performance user equipment.
4. Continue to plan system alternatives, develop their advocies, and demonstrate them through experimental programs in case of non-availability of GPS.
5. Develop the strategy for an orderly, cost-effective transition from existing systems to advanced systems.

6. Accelerate GPS to provide worldwide two dimensional coverage by 1981 in order to further stimulate low-cost user equipment development by the general aviation avionics manufacturers.
7. Influence the Department of Defense to include GPS and JTIDS user equipment equipment under the VLSI/VHSI demonstration program and then participate in this demonstration.

APPENDIX A - DATA LINK SURVEY

A.1 INTRODUCTION

The intent of this aspect of the study was to investigate various military data link system concepts for applicability (of concept) to civil systems. Unfortunately, the security aspects of this class of military systems is such that access to technical data is for all intent not possible. The strategy employed, then, for this study is to look at that military system for which data is available, namely the Joint Tactical Information Distribution System (JTIDS) and to contrast this with the foremost civil system being developed for the ATC environment (DABS). This then brackets other data links between a TDMA system at one extreme and an interrogate-and-reply system at the other extreme.

A.2 JOINT TACTICAL INFORMATION DISTRIBUTION SYSTEM (JTIDS)

A.2.1 Introduction

This section presents a preliminary system description of the Joint Tactical Information Distribution System (JTIDS) for Command and Control being developed by the Department of Defense. The purpose of this section is to provide documentation of JTIDS with the goal of acquainting the civil aviation community with data link developments currently residing within or being developed by military agencies. As a result, emphasis may be shifted in some instances toward the low-cost, low-user dynamics version of the JTIDS terminal. Areas discussed include system concept, signal structure, system characteristics, and concludes with a description of the JTIDS terminal.

A.2.2 JTIDS System Concept [A-1]

General Description - JTIDS is the digital information distribution system specifically tailored for the battlefield command structure. It will be used for ground-to-ground, ground-to-air, and air-to-air communication necessary to support air defense, close air support and other tactical battlefield operations; e.g., artillery fire support, battlefield surveillance, target acquisition and helicopter nap-of-the-earth operations. It provides connectivity among its subscribers by its use of a time division multiple access (TDMA) or distributed TDMA organization and omnidirectional signal transmission. Each subscriber terminal is programmed in time for transmitting information on a non-interfering basis. A subscriber may transmit in his time intervals and will listen at all other times. Receivers are tuned to receive all transmitted signals on the net or channel and thus have access to all transmitted information. Each subscriber maintains synchronism with system time and controls his transmission to occur at the appropriate time. Figure A-1 depicts the general system concept. A summary of JTIDS user classes and system characteristics is included in Tables A-1 and A-2.

Each subscriber employs digital data processing techniques to selectively access only that portion of the total system information that he requires to perform his mission. Information filtering is accomplished

MISSION AIRCRAFT
SUBSCRIBERS

INFORMATION
DISTRIBUTION
SYSTEM

GROUND
SUBSCRIBERS

SEA BASED
SUBSCRIBERS

12.8 MINUTE EPOCH = 64 CYCLES

0	1	2		29		63

12-SECOND CYCLE = 1536 TIME SLOTS

0A	0B	0C	1A	1B	1C		511A	511B	511C

PREAMBLE	SYNC REFINE	DATA	PROPAGATION AND GUARD TIME

7.8125 MILLISECOND TIME SLOT
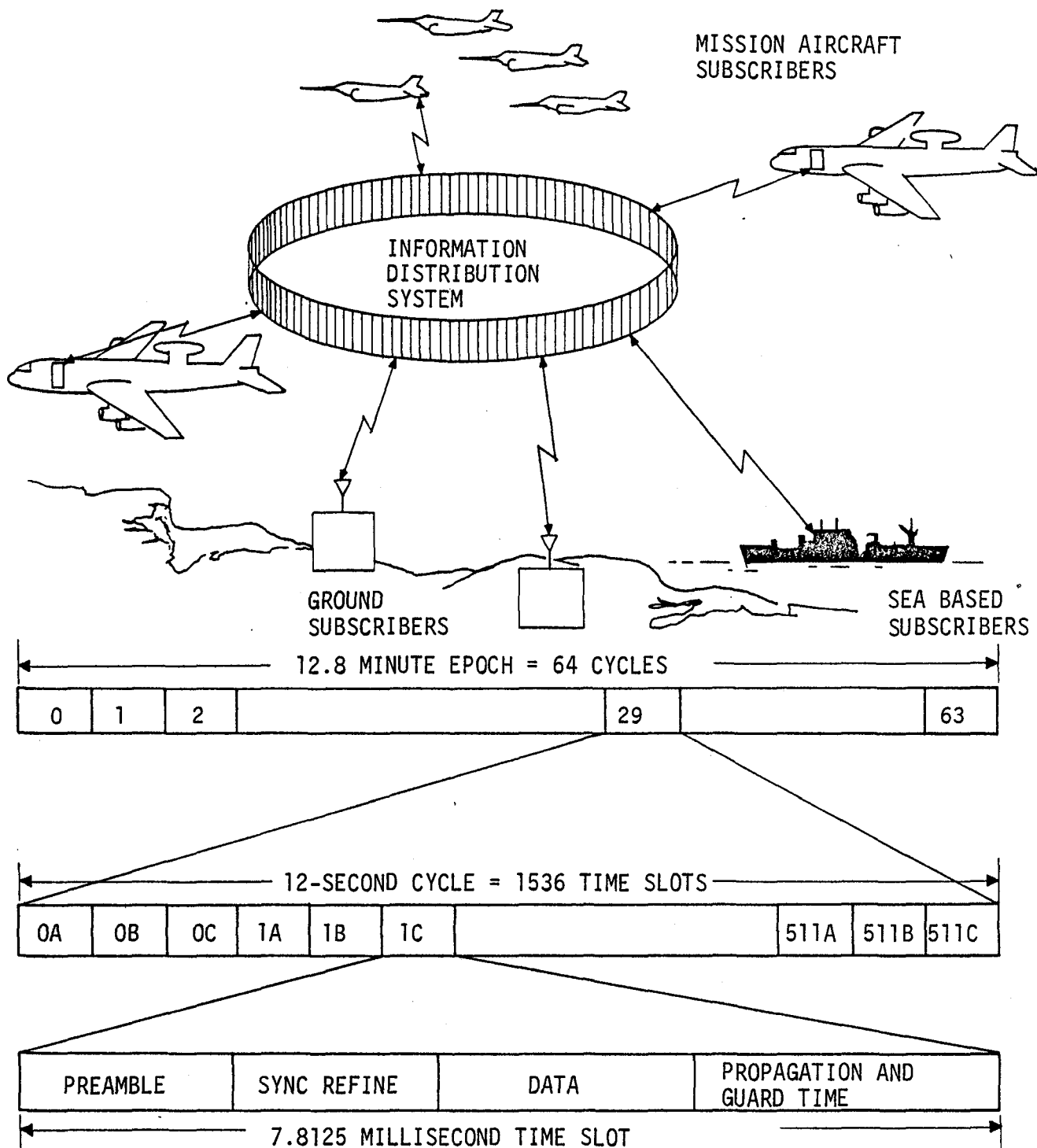
Figure A-1. JTIDS TDMA System Concept [A-2]

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Table A-1. JTIDS User Classes

TERMINAL CLASS	USER CHARACTERISTICS	NOMENCLATURE
I	LARGE VEHICLES (E3A/AWACS), AIRBORNE/ SURFACE COMMAND AND CONTROL (INITIAL TESTING 77-78, OPERATIONAL AVAILABILITY FY79)	AN/ARC-181
II	CLASS I MINIATURIZED (OPERATIONAL AVAILABILITY FY82)	AN/ARQ-40
III	VERY LOW COST, COMPACT, TRANSPORTABLE (RPV, MANPACK, MISSILE GUIDANCE, LIGHT AIRCRAFT)	CURRENTLY IN CONCEPT DEFI- NITION PHASE

Table A-2. JTIDS System Characteristics

CONCEPT   -   TDMA COMMUNICATIONS
                     960-1215 MHz TACAN BAND
                     1980 TACTICAL ENVIRONMENT

ARCHITECTURE -   MULTIPLE USER/PRE-ASSIGNED TIME SLOT
                     ALL TERMINALS IN NET MAY LISTEN TO
                         ALL TIME SLOTS
                     PROVIDES COVERAGE FOR OVERLAPPING NETWORKS
                     TERMINAL CAN SELECT AMONG MULTIPLE NETWORKS
                         ON TIME-SLOT BY TIME-SLOT BASIS
                     ANY USER CAN BE SELECTED TO SERVE AS
                         MASTER CONTROL

PARAMETERS   -   DATA RATE - 100KB/S
                     TIME SLOTS/CYCLE - 1000
                     INFORMATION BITS/MESSAGE - 208
                     CHANNEL BANDWIDTH - 20 MHz
                     MODULATION TECHNIQUE - DIFFERENTIALLY
                         COHERENT BIPHASE, PSEUDO-NOISE

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by specifying criteria related to message type and content. Generally, the filtering criteria will be operator-selectable to allow flexibility in information retrieval; however, the filtering scheme provides for both the mandatory acceptance of orders and other critical information, and for the restricted distribution of certain information.

The network will provide for jamming resistance to enemy electronic countermeasures and security against eavesdropping and spoofing. Performance against an enemy's EW technique will be determined after the final selection of a waveform.

Normally, JTIDS subscriber terminals transmit information during certain assigned transmit periods and receive information transmitted during other time periods. However, JTIDS subscribers can operate in two other states -- radio-silent and on-demand. In the radio-silent state, a terminal never transmits but continues to receive information and maintain synchronism with system time. The radio silent state is maintained until a positive action is taken by an operator to assume one of the other states of operation. In the on-demand state, information is received and synchronism maintained as in the radio-silent state, but information is transmitted only upon the receipt of a special request message.

Operation of the system is at microwave frequencies. The terminals will provide range capabilities dependent on the power capabilities of the terminal's platform. For the manpack (i.e., low-cost) this will be 5 to 15 km for ground-to-ground and 100 km for ground-to-air. Radio coverage may be extended among elements not in line-of-sight through the use of relay stations. Any subscriber terminal can be operated as a radio relay.

The JTIDS provides a relative navigation capability which allows appropriately equipped subscribers to navigate with respect to each other within a common grid. This is accomplished by automatic interchange of relative navigation and position data between subscribers, combined with radio range measurements between the subscribers. The radio range measurements are derived through measurement of the time of arrival of JTIDS messages with the synchronized clocks possessed by each terminal.

The security features of the JTIDS provide a built-in identification of friend capablity. The identification function is enhanced by the

ability of the System to distribute secure information on the location, identity, status, and disposition of non-equipped friendly and hostile force elements.

Missions - The (low-cost) terminal network will provide the digital communications links necessary to connect the tactical elements performing the following major tactical operations:

> Air Defense - SHORAD
> Reconnaissance/Surveillance
> Close Air Support
> Fire Support, and
> Land Combat

In support of these operations, the (low-cost) terminals will be designed to operate in manpack, jeep, tank, helicopter, and light aircraft configurations.

The network will provide information transfer for combat management and monitoring, and will permit equipped units to accurately locate themselves on a common grid. Supporting operations, e.g., search and rescue, reconnaissance, fire support, etc., will be able to coordinate actions for maximum effectiveness through use of the JTIDS network. The network thus provides the media for exchanging coordination information necessary for combined arms battlefield operations.

System Functional Diagram - Figure A-2 depicts the system-level functional diagram of JTIDS and indicates the four major functional areas:

1. Information Distribution Function
2. Relative Navigation Function
3. Identification Function
4. Subscriber Function

These functional areas are highly interrelated. The first three functional areas are both system-level functions as well as allocatable to the Subscriber Function.

A.2.3 Signal Structure

JTIDS transmission time is Time Division Multiple Access (TDMA) divided into time slots, cycles, and epochs. Time slot assignments for

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SYSTEM LEVEL FUNCTIONS

INFORMATION DISTRIBUTION

RELATIVE NAVIGATION

IDENTIFICATION

SUBSCRIBER FUNCTIONS

TERMINAL

INTERFACE

UNIT TO BE EQUIPPED
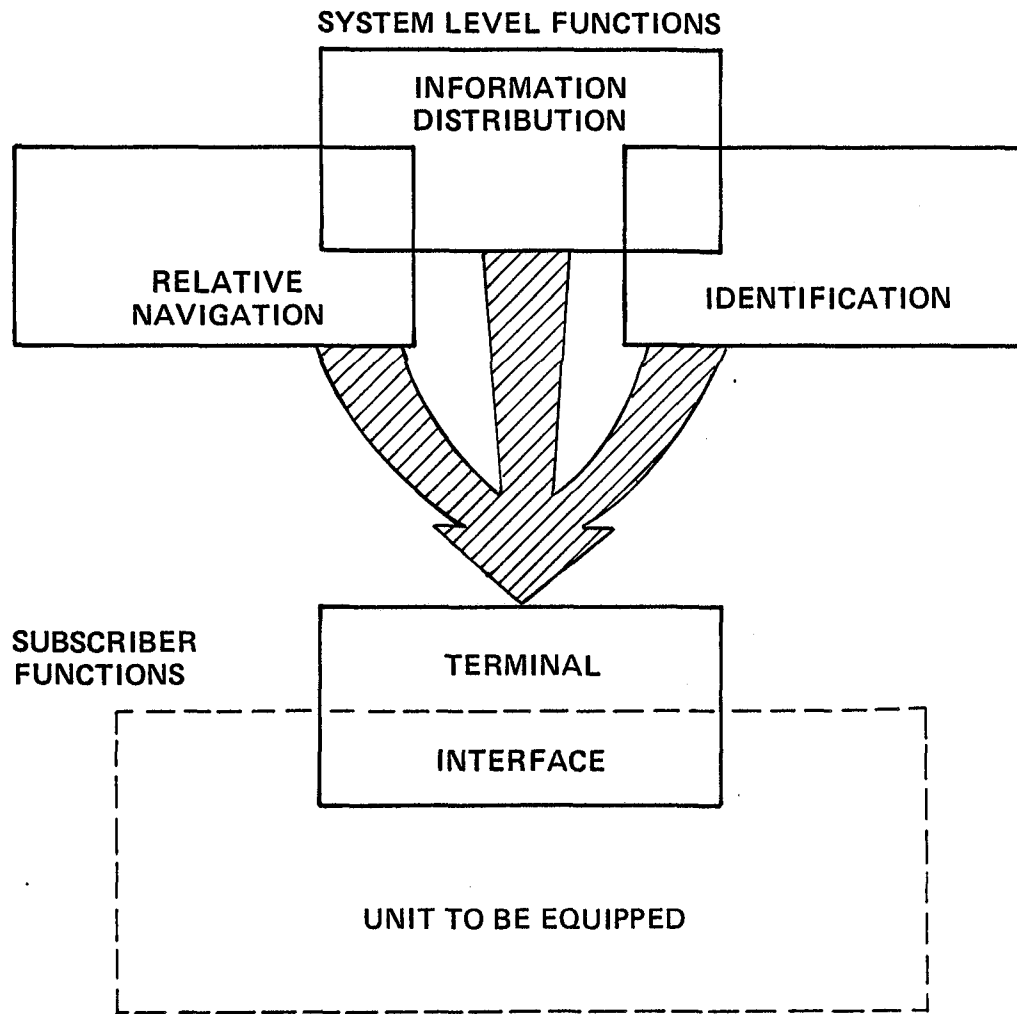
Figure A-2. JTIDS Functional Requirements [A-1]

transmission are generally made on the basis of 2^N time slots per 12.8 minute epoch where N can vary from 0 to 15 (i.e., from 1 to 32,768 time slots per epoch). The repetition rate of time slots is compatible with the 75×2^N bits/second standard transmission rates for TTY instruments. The 7.8125 millisecond time slot is partitioned among preamble, synchronization refinement, and data transmission functions and the propagation/guard times.

The principal characteristics of the JTIDS waveform are summarized in Table A-3 while signal-timing and waveform structure are shown in Figure A-3. The waveform consists of 16 preamble signals, 4 synchronization refinement symbols, and 109 data symbols. Each symbol can be transmitted as one (higher TACAN compatibility) or two (better communications and A/J performance) 32 chip pulses. The chip rate is 5 megachips per second (each pulse thus has a duration of 6.4 microseconds). The one pulse per symbol waveform has a 6.4/19.6 µs on/off time while the two pulse per symbol waveform has two 6.4/6.6 µs on/off bursts.

The modulation method employed is MSK (minimum shift keying) which minimizes the spectral width of transmission. The spectrum of the 32 chip pulse falls off very rapidly and is a significant factor in achieving operational compatibility with TACAN.

Table A-3. Waveform Characteristics

Direct Sequence Spreading	- 5 megachips/second
Pulses (one or two per symbol)	- 32 chips per pusle
Block Data Transmission	- 5 bits per 32-ary symbol
Forward Error Correction Coding on Coded Messages	- Reed Solomon 32-ary coding
Pulse pairs are interleaved for burst error detection	
Residual Error Detection Coding	

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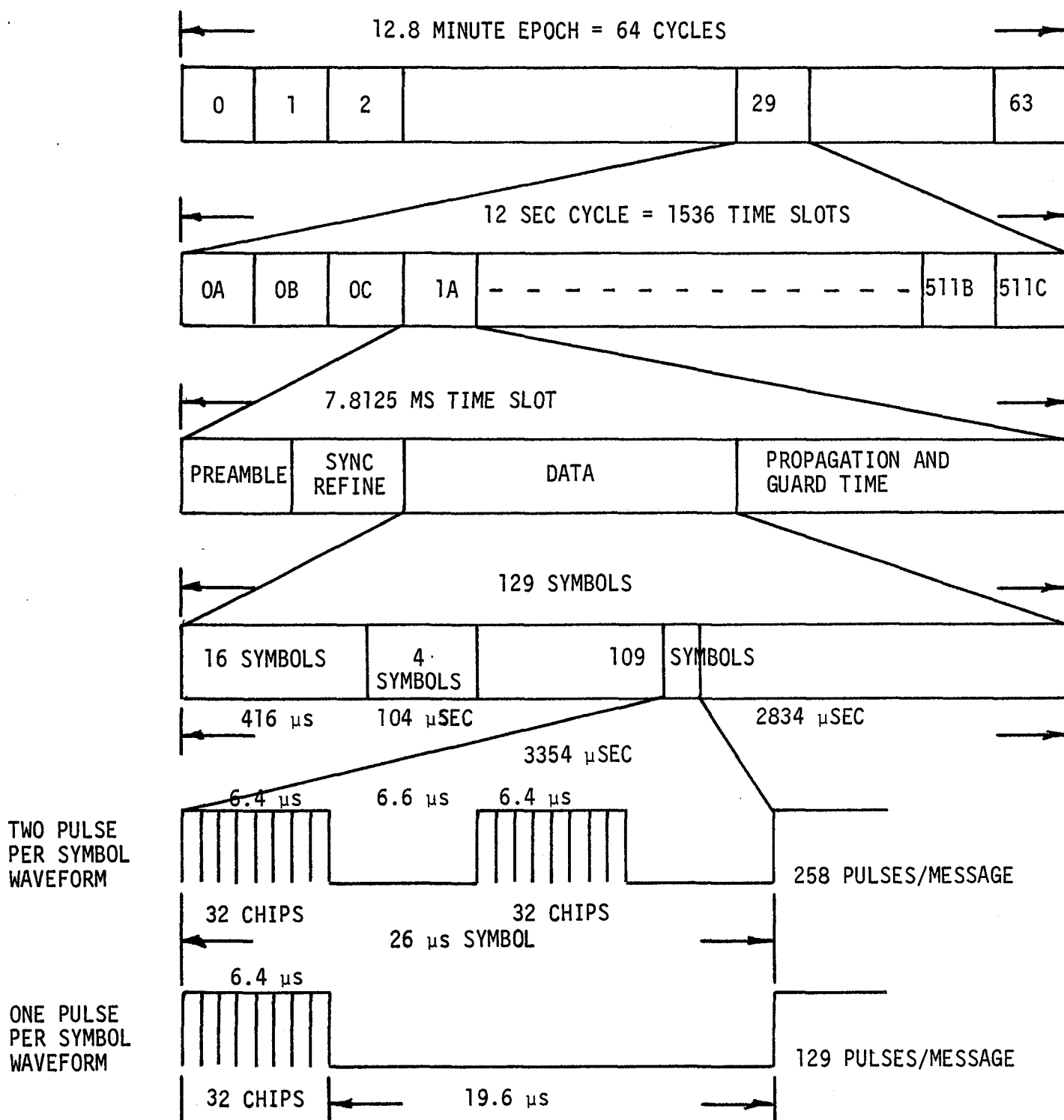
Figure A-3. JTIDS Signal Timing and Waveform Structure [A-2]

In the data field, each symbol is encoded into one of 32 orthogonal 32 chip waveforms representing 5 bits. These waveforms are the 32 cyclic shifts of a particular 32 chip sequence. Detection of which of the 32 cyclic shifts was transmitted is accomplished in a single digital matched filer in which the 32 chip reference pattern is cyclically shifted through each of the 32 possible states.

Reed Solomon coding is used in the 109 symbol data field of coded messages (i.e., formatted and coded free text) to eliminate transmission errors. There are three 31 symbol Reed Solomon code words and one 16 symbol Reed Solomon code word. Each 31 symbol word contains 15 information symbols and 16 parity symbols. The (31, 15) code word can correct up to eight errors in a block of 31 symbols or up to 16 erasures (no symbol decision) or any combination of errors and erasures in which

$$2x \text{ erasures } + \text{ errors } = 16$$

To avoid saturation of the error correcting capability of any single Reed Solomon word, the 109 symbols are interleaved by a fixed permutation pattern. An inverse operation is applied at the receiver prior to decoding.

In addition to error correction in formatted messages, there is a 12 bit error detection code used for identifying formatted messages with uncorrected errors. This code reduces the probability of a formatted message containing undetected residual errors to less than 10^{-6}.

These properties apply to all transmission modes, secure and non-secure. The narrow hand transmission modes use a fixed frequency of 969 MHz. In the maximum jamming resistant mode, the transmission uses frequency hopping over the 960-1215 MHz band with gaps about the 1030 and 1090 MHz IFF bands.

A.2.4 System Characteristics

The characteristics presented here have been extracted from the USAF RFP for the Class 3 terminal conceptual phase procurement [A-1]. Part of the motivation for using this material instead of Class 1 or 2 published data is that the Class 3 terminal represents the low-cost version of the JTIDS terminal and is therefore appropriate to considerations for the general aviation application.

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The JTIDS class 3 terminal is anticipated to have performance bounds as shown in Table A-4 and as discussed in the following paragraphs:

Connectivity - The information distribution system will provide participants in combat operations with access to all essential information in time to effectively use it. Users will be capable of selecting messages on the basis of content since it is unnecessary for everyone to receive all of the information that exists in a combat area. It is desirable for the system to provide privacy for a selectable subset of users. The system will permit messages to be addressed to any particular recipient or to multiple elements. Users will have the option of entering a radio-silent mode and will be able to maintain system synchronization time, and will have the capability to immediately revert to the active mode. The candidate system will permit preemptive priority for command messages to override normal messages if required.

Survivability and Reconstruction - The system will be as survivable as the force elements themselves and will be free of dependence on system nodes which if destroyed would eliminate the entire capability. So long as any force elements remain, the system will be capable of the three major system functions: namely, information distribution, position location, and identification.

Crypto Security - The system will be crypto secure to deny the enemy access to the message content and to deny an intelligent jammer the spreading sequence.

Message Error Probability - The probability of any message being in error will be as low as practicable. The anticipated rate of acceptable messages is 99 out of 100 messages without error; i.e., the probability of a digital message being in error at any receiver's message processor is less than 10^{-2}. Additionally, the error detection technique used in the messages will not allow the undetected message error rate to exceed 10^{-6}. Those criteria are established for the case where jamming and noise are present. In the absence of jamming, 10^{-5} bit error rate and a 10^{-7} terminal bit error rate will be maintained.

Jam Resistance - Classified.

Low Probability of Intercept (LPI) - As practical as possible, within

Table A-4. JTIDS (Class 3) Bands of
Performance Characteristics [A-1]

Characteristic	Minimum	Maximum
Connectivity	Total	Total
Survivability	Nodeless	Nodeless
Crypto Security	Total	Total
Message Errors	5×10^{-2}	5×10^{-2}
Unrecognized Errors	10^{-6}	10^{-6}
AJ	(CLASSIFIED)	(CLASSIFIED)
Intercept Probability	LPI	LPI
Throughput (Free Text)	9.6 kbpsec	200 kbpsec
Throughput (Formatted)	9.6 kbps	28.8 kb/sec
Throughput (Voice)	16 kbps	32 kbps
Message Rate & Size	42 msg/sec & 245 bits	128 msg/sec & 245 bits
Number of Users	350	2,000
Range Direct		
manpack-to-manpack	5 km	15 km
manpack-to-50 ft. antenna	12 km	15 km
ground-to-air	100 km	300 km
Relay	Any unit	Any unit
ID dissemination	Any source	Any source
Message Formats	JTIDS IJMS* + growth	IJMS + growth
Compatibility	TACAN, IFF	TACAN, IFF
Interoperability	Class 3	Class 1, 2 & 3
Multiple nets	15	128
Modularity	Modular	Modular
Power Options	3 to 100 watts	High/Low
Relative Navigation	(CLASSIFIED)	(CLASSIFIED)
Net Entry	<2 min	<1 min
Secure Voice Channels per net	1	8

*Interim JTIDS Message Standards

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the other design constraints, the system will limit the enemy's capability to exploit the radio transmissions to determine the presence, position, numbers, and intent of a user group.

Capacity - The Class 3 JTIDS network will provide the capability of transmitting at least 42 messages per second at a minimum rate of 9.6 kilobits per second on each net. The formatted messages are equal in length to those of the Class 1 and Class 2 JTIDS networks.

Range - The manpack Class 3 JTIDS terminal has a minimum operating range of 5 km on manpack-to-manpack ground links, 12 km for manpack-to-50 ft. antenna, and 100 km for ground-to-air links.

The vehicle mounted terminal is capable of 12 km ground-to-ground links under conditions similar to those for the manpack, and 300 km for the ground-to-air links.

Relay Capability - The system will also provide a relay capability. Each terminal will have the potential of acting as a relay without degrading its availability to a user. Relays will be used to extend communications in the network beyond the limitations of terrain masking or other discontinuities in the LOS between elements of a network.

Identification - The system will have the capability to distribute information on the location, identity, status, and disposition of non-equipped friendly and hostile force elements as observed by friendly surveillance elements as well as reporting identity, status, and position of equipped elements.

Message Format - The Class 3 terminals will be capable of transmitting and receiving two types of messages: Formatted and Unformatted. The information portions of the formatted messages directly correspond to that used by Class 1 and Class 2 JTIDS networks and conform to the field structures defined in the Interim JTIDS Message Standards (IJMS). Thus, using TDMA the preamble will be followed by 245 data bits organized into: 12 parity bits for an internal error detection code: 8 header bits defining message type and classification; and 225 message bits divided into message fields appropriate for the type message being exchanged.

The unformatted messages are defined according to the chosen waveform structure to allow more flexible use of the message time-bandwidth product.

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These unformatted messages support voice transmission or special applications for existing systems.

Compatibility With Other Systems - The system permits simultaneous operation with the following systems: UHF AM voice, TACAN, MARK X and MARK XII, IFF, ATCRBS, Global Positioning Systems (GPS), Position Location Reporting System (PLRS), radars, and other tactical data information links, and navigational systems existing and programmed for in the 960 to 1,215 MHz frequency band.

Joint Operations - The system provides for and enhances interoperability among the various military services and nations deployed in combined and joint operations.

Multiple Netting - The system has the potential of operating several networks in the same tactical area. The need is for 4 with growth to 15 independent simultaneous networks.

Modularity - The equipment design includes modularity to accommodate the varied user performance needs and cost limitations. Modularity in transmitter power output and terminal power supply is provided to convert the manpack configuration to a vehicle mount configuration. Modularity in the message processor and man-machine interfaces is provided to permit more sophisticated functional capabilities on Class 3 terminals mounted on vehicles than provided for the weight and size conscious manpack design. The partitioning is arranged to facilitate the implementation of built-in-test equipment (BITE) in the hardware design.

Power Options - The Class 3 terminal power supplies are provided with the modularity features described above. The manpack version derives its power from a battery pack whose size is determined by the weight limitations on a manpack terminal. The battery life supports continuous operation in a radio-silent mode and with 1 transmission per 12 seconds.

Relative Position Location and Navigation - Classified.

Net Entry - The system permits a new subscriber to enter a net or change nets by a simple automatic procedure. In particular, the synchronization mechanism and technique permit a new user to establish synchronization with the net in either an active or passive mode. A user is able to establish synchronization in less than two minutes, and if synchronized to

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one net, may switch nets in less than 15 seconds if a common time among nets has been established.

Secure Voice - The Class 3 system design includes the capability of using the unformatted mode of operation for the exchange of digitized voice. The voice information is not processed within the JTIDS terminal other than to accept and present the buffered voice data stream through one of the terminal's I/O parts; i.e., voice data sampling or coding decoding and buffering is performed by an external piece of hardware. The ability to operate at least one voice channel simultaneously with data is provided where the data message rate has been reduced by one-half. This channel is capable of handling 16 kbps CVSD voice.

Physical Characteristics - One of the principle design goals of the Class 3 terminal was to arrive at a system architecture and terminal design that is effective in applications with stringent size and weight limitations. The manpack terminal is projected to not be larger than 20,000 cc nor its weight to exceed 15 kg. including battery and display. The design goals are 10,000 cc and 7 kg. The weight and size goals are relaxed when the terminal platform is a ground or airborne vehicle. The size and weight goals will depend on the sophistication of the terminal.

A.2.5 JTIDS Terminal Description

A precise discussion of the JTIDS terminal at this time is confounded by the variety of terminal classes, user requirements, and overall JTIDS program evolution. It is, however, appropriate to include a representative discussion to attempt to show the major elements which comprise the user equipment. Figure A-4 shows a functional description of a Hughes prototype Class I terminal which was flown in a F-102 for system evaluation. As shown, each terminal configuration is partitioned into a signal processor, central processor, and a control unit. This partitioning is supported by transceiver and interface elements.

The signal processor provides the translation from the digital base-band messages to the RF waveform. The processes of encryption, modulation, demodulation, and decryption occur in the SP. It also contains the master oscillator/system clock which is the source of all carrier frequencies and all terminal timing data.

```
                    ┌─────────────────┐
                    │  CONTROL AND    │
                    │ DISPLAY PANEL   │
                    │     (CDU)       │
                    └─────────────────┘
```

```
                          ┌──────────────────┐    ┌──────────────────┐
ANTENNA          ┌─────┐  │     SIGNAL       │    │  COMMUNICATIONS  │  INTERFACE
INTERFACE  <==>  │ T/R │  │  PROCESSOR (SP)  │<==>│  PROCESSOR (CP)  │  COMPUTER
UNIT             └─────┘  │ REED-│SEC │      │    │     4π AP-1A     │
                          │ SLMN │DATA│ UME  │    │                  │
                          │ ENCDR│UNIT│ CONT │    │                  │
                          └──────────────────┘    └──────────────────┘
```
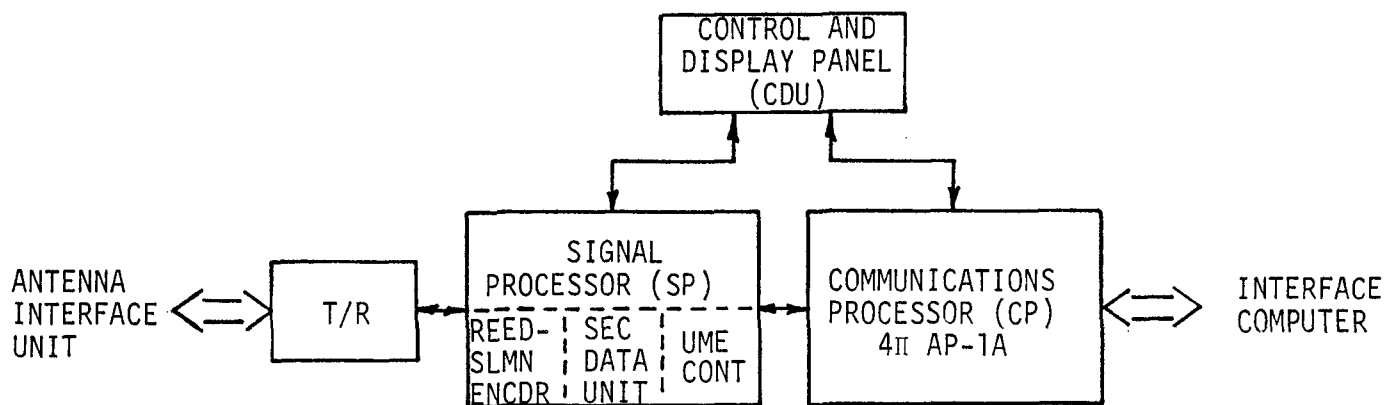
FUNCTIONAL ELEMENTS--

    T/R - UP/DOWN CONV
           FREQ SYNTHESIS
           POWER AMPLIFICATION

    SP - MOD/DEMOD
           PREAMBLE AND DATA CORRELATION
           ERROR ENCODE/DECODE
           TIME BASE
           SECURE DATA UNIT
           TOA MEASUREMENT
           BITE/DATA INTERFACES

    CP - TERMINAL CONTROL
           TADIL MESSAGE PROC
           EXEC FUNCTIONS
           TIME DRIFT MODEL
           SELF TEST/BITE CONTROL

    CDP - TERMINAL CONTROL ENTRY
           TERM. INITIALIZE
           BITE INDICATIONS
           TEST CONTROL
           FAULT INDICATIONS

Figure A-4. JTIDS Terminal Configuration [A-2]

The communications processor is an IBM supplied 4π computer which is the source of all formatted and relayed messages. It provides communications with other user computers, performs coordinate conversions, controls synchronization and provides the control of overall terminal operations.

The control and display unit provides the means to set operating parameters and to initialize the terminal computer. The computer interface portion of the CDU logic provides the multiplexing, buffer storage, and control functions necessary to implement two-way digital communication between the 4π computer and the radio interface of the CDU logic. The radio interface of the CDU logic interfaces the computer with the transmitter/receiver and maintains precise determination of message transmit and receive times.

A.3 DISCRETE ADDRESS BEACON SYSTEM (DABS) [A-3]

The objective of the DABS development is to provide the basis for
Intermittent Positive Control, as recommended by the ATCAC, [A-6], through
improved surveillance and accuracy, plus an integral data link between the
ground and the aircraft. This IPC is to be completely automatic, based on
computer processing of surveillance data, detection of impending conflicts,
and generation of necessary data link messengers. The following paragraphs
describe this system in more detail. As the thrust of this section is to
be descriptive of data link options, this aspect of DABS is given
particular attention.

A secondary objective of DABS is to eliminate the synchronous garble
that occurs when two aircraft at the same range and azimuth but at differ-
ent altitudes try to respond to an Air Traffic Control Radar Beacon System
(ATCRBS) interrogation. In order to achieve this, DABS uses a single-coded
interrogation for each aircraft. Since only the interrogated aircraft
would respond, garble is overcome. This further prevents saturation caused
by all transponders within line-of-sight responding since only the trans-
ponders for which a given DABS ground station has surveillance responsi-
bility would be interrogated and thus would reply.

A high degree of compatibility exists between DABS and ATCRBS. The
same interrogate and reply frequencies are used by both systems and signal
format compatibility provides substantial hardware commonality. Thus,
since DABS interrogation can provide surveillance for ATCRBS equipped
aircraft and DABS transponders can reply to ATCRBS interrogation, a gradual
and orderly transition can be provided.

Table A-5 provides a summary comparison of DABS and ATCRBS systems
characteristics and performance parameters. Figure A-5 shows a block
diagram of a typical DABS transponder.

A.3.1 Link Characteristics - [A-5]

DABS signal formats are shown in Figure A-6. As stated previously,
DABS uses the same frequencies as ATCRBS (1030 and 1090 MHz for interroga-
tion and reply, respectively), uses differential phase shift keying at a

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Table A-5. Comparison of DABS vs. ATCRBS Characteristics [A-3]

PARAMETERS	DABS	ATCRBS
Frequency Up	1030 MHz	1030 MHz
Frequency Down	1090 MHz	1090 MHz
Range Accuracy (3σ)	30 m	30 m
Azimuth Accuracy (3σ)	0.1°	0.75°
Altitude Accuracy (3σ)	40 m	40 m
Addresses	16 Million (2^{24})	4096
Uplink Message Length	32.5 μsec 112 bits	8 to 21 μsec 3 bits
Downlink Message Length	120 μsec 112 bits	20.3 μsec 15 bits
Data Link Messages	Unlmited Ground-Air-Ground	Limited to Aircraft I.D. and Altitude Downlink Only
Surveillance Capacity	2000 A/C Per Sensor	Garble Limited
Coverage	ATC Facility can draw on any sensor in its airspace	ATC Facilities use only their own sensors
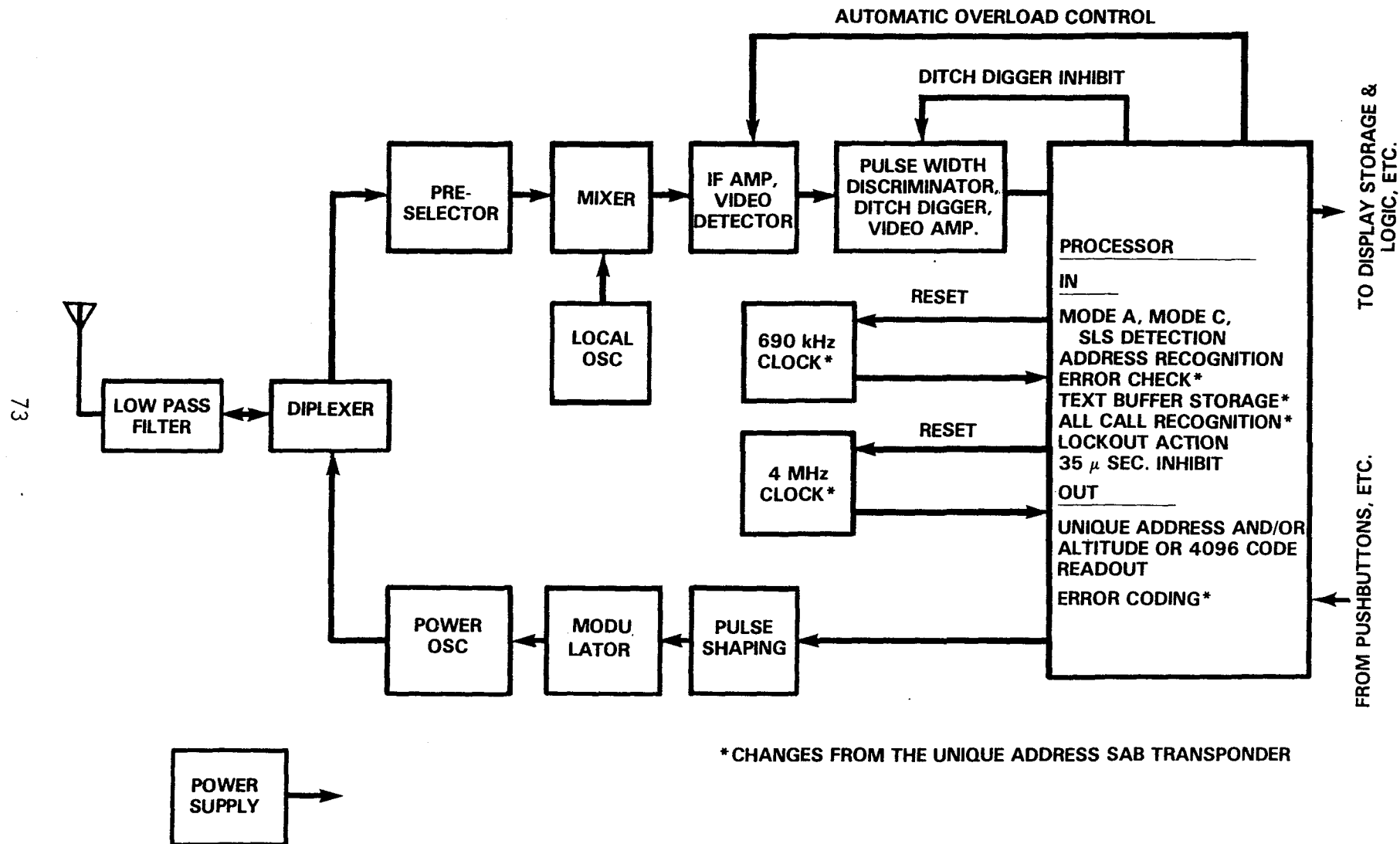
Figure A-5. DABS Transponder [A-6]

a) Interrogation

b) Reply

Figure A-6. DABS Interrogation and Reply Formats [A-5]

4MBPS rate on interrogate and uses pulse position modulation (PPM) at a 1 MBPS rate on reply. The message format consists of either 56 or 112 bits including the 24 bit address which is overlayed on the 24 bit parity field. The preamble for interrogation consists of a pair of pulses spaced 2.0 μs apart while on reply the preamble consists of a pair of pulse pairs spaced 3.5 μs apart.

The choice of the two-pulse preamble on interrogate is designed to appear as an ATCRBS sidelobe suppression, thus avoiding having ATCRBS transponders replying sporadically as a result of the DABS data block transmission. The choice of 4 MBPS data rate provides for the transmission of the 112 bit message within the ACTRBS suppression interval. DPSK provides additional performance margin for the environment in terms of interference immunity, fade margin, and multipath immunity as compared with pulse amplitude modulation.

On reply, the four-pulse preamble is designed to distinguish it from ATCRBS replies and used as a source of timing in case of an overlapping ATCRBS reply. PPM provides for reliable bit detection in the presence of ATCRBS interference and since it results in the same number of pulses for each reply assuring sufficient energy for a monopulse position estimate. Data rate on the downlink is 1 MBPS and a 24 bit parity code permits error correction of errors which result from simultaneous ATCRBS replies.

Since the parity field is overlayed on the address field, an error anywhere in the reception of an interrogation or reply will result in an error in the decoded address. On the uplink, the transponder will not reply as it does not think the message was intended for it. On the down-link, the ground station knows the address expected from a discrete interrogation and can thus perform a limited amount of error correction. Most errors resulting from simultaneous reception of ATCRBS replies can be corrected.

Acknowledgment of an interrogation is provided by the transponder reply while acknowledgment of a reply is provided by a bit set in a sub-sequent interrogation. Provision for requesting and receiving separate

pilot acknowledgment when desired is included. On interrogate, if an error occurs and no reply is received, the message is repeated.

A.3.2 Formats

The DABS 112 bit data block formats, as shown in Figure A-7, provide for the functions of link control, message transmission (both surveillance data link data), and, as mentioned previously, combined address/parity.

The link control field (16 bits for standard, 80 bits for extended length messages) identifies the type transmission, controls transponder backout, and controls data link transmissions and acknowledgments.

Each routine DABS interrogation and reply contains a 16 bit field to provide ATCRBS Mode C altitude reporting or a Mode A emergency condition report. Also, provision is included for transmission of altitude echo data which provides a pilot with his altitude report adjusted for local baro-metric pressure and thus serves as a loop check on the accuracy of his altitude report.

Typical DABS messages occur as 56 bit standard message fields. Ground-to-air message can include IPC/PWI commands, ATC instruction etc., while air-to-ground messages can be pilot initiated or can be automatically ground initiated for readout of aircraft data such as rate-of-turn, etc. The standard message field is deleted when there are no data to be trans-mitted. Each standard message interrogate/reply must be acknowledged prior to transmission of the next message; thus, messages longer than a single field can be transmitted sequentially but at lowered efficiency.

In order to provide more efficient transmission of longer messages, an extended length message field can be adopted. Here a sequence of up to 16 80 bit message segments can be transmitted in either direction on the link and acknowledged with a single interrogation/reply.

A.3.3 Interrogation Scheduling

Interrogation protocol is nominally contingent upon whether the antenna is mechanically or electronically scanned. For a mechanical system, the following ground rules apply:

LINK CONTROL FIELD 16 BITS	SURVEILLANCE DATA FIELD 16 BITS	STANDARD MESSAGE FIELD 56 BITS	ADDRESS/PARITY FIELD 24 BITS

a) Normal

LINK CONTROL FIELD 8 BITS	EXTENDED LENGTH MESSAGE FIELD 80 BITS	ADDRESS/PARITY FIELD 24 BITS

b) Extended Length

Figure A-7. DABS Data Block Formats [A-5]

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1. Interrogations are addressed only to targets with the antenna beam.
2. Channel time is allocated based on a prediction of radar range.
3. System must be able to reinterrogate an aircraft while it remains in the beam.

Those targets within the antenna beam comprise an active target list through which repeated passes are made to schedule interrogations/replys on a nonconflicting basis. Interrogations are timed so that nonoverlapping blocks of channel time are assigned to each individual transmission. In the case of list saturation, time is allocated based on a preassigned transaction priority.

Roll-call scheduling begins with the first (longest range) target on the list, scheduling an interrogation time at the beginning of the cycle and computing an expected reply time of arrival. Subsequent targets are scheduled by placing their reply listening periods in a queue and computing the corresponding interrogate times. A cycle is completed when the next interrogation (if actually scheduled) would overlap the first reply. This interrogation will be the first in the next cycle.

Utilization of an electronically scanned antenna impacts protocol only in that the same target list can consist of targets at widely different azimuth angles. Handling of lists would then allow flexibility for re-interrogation or for concentrating on high-priority targets.

A.3.4 Data Interfaces

Data interfaces range from the standard message interface designed to handle single segment messages (most ATC-related messages) to transponders equipped for extended length messages utilizing an interface which provides a standard I/O part for available data terminals.

The standard message interface provides serial connection between the transponder and data I/O devices. After an uplink transmission has been received and verified, the data (less parity and address) are shifted out of the interface to the peripherals. When this is complete the transponder

is ready for reply and any downlink data available are shifted onto the line for insertion in the transmission. The I/O line is operated full duplex with clocking transferred on an independent line. Observe that activity occurs on the standard message interface only between interrogation and reply of the transponder. The signal on the clock line is differentially encoded and consists of a qualifier pulse followed by a series of strobe pulses occurring at the 1 MBPS downlink transmission rate.

The message line is again differentially encoded three state line to permit control by either the transponder or the peripherals. The peripherals are addressed one-at-a-time by uplink content or interrogation protocol. On input each device holds the data line HIGH or LOW during its assigned time slot and leaves the lines OFF otherwise. A standard message interface timing diagram is shown in Figure A-8. Notice that at time of downlink transmission the data are shifted in the date line ahead of actual transmission so as to be compatible with transponder timing.

Extended length messages may be sent to aircraft with compatible transponders in a burst of up to 16 segments which is acknowledged with a single reply. Messages requiring more than 16 segments are accommodated by concentration and using a message continuation indicator contained in the 16th segment. The minimum length ground-to-air extended message is 2 segments. Transfer of all segments without an intervening downlink transmission can occur at up to a 50 sec rate which accommodates ATCRBS resuppression by the DABS preamble code.

This message transaction is begun by a "dial up" interrogation with a special initialization link control code to which the transponder does not reply. The initial call delivers the final message segment and its segment's number to inform the transponder of the message length. Successive segments are then delivered and properly ordered by segment number.

The interrogator identifies the final segment of the transmitted set with a finalization link control which prompts the transponder to issue an acknowledgement reply containing a data block which indicates the segments it has received. The interrogator, having ascertained that all segments

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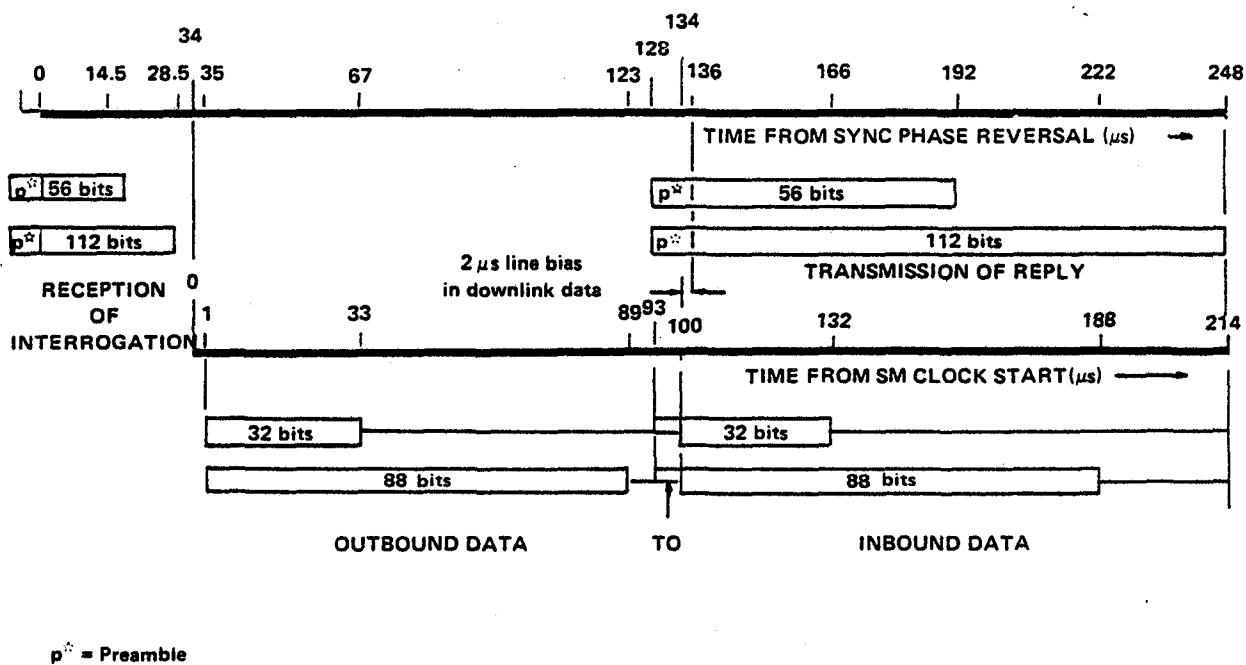
Figure A-8. SM Interface Timing Diagram for DABS Transactions [A-5]

sent were received, closes out the transaction by sending a special clearance interrogation which prompts a single clearance acknowledgement reponse from the transponder.

Air-to-ground transfer is similar in protocol with minor exceptions resulting from the facts that all channel activity is ground initiated and that a transponder reply with the longer format occurs only with the specific permission of the ground interrogator.

The transfer again is initiated by setting a bit in the transponder reply link control field; the link control field, however, here contains a subfield used to designate message length. The interrogator then requests the transponder to send the segments comprising the downlink message by a single uplink message which contains a special segment request field and to which the transponder replies with the designated segments. The interrogator checks the ground-received segments and asks for retransmission of those not received or received in error. When all segments have been received properly, the transaction is concluded with a special clearance interrogation and reply.

Transponders equipped to receive extended messages store the entire message before transferring to peripheral I/O devices. The interface to peripherals is serial full duplex and multiported to handle several peripherals. EIA Standard RS-232C is the recommended configuration. Data transfer is transponder clock controlled at 2400 bps.

A.3.5 Data Link Capacity

Factors which principally determine capacity for single-segment standard messages (for a rotating antenna sensor) are:

a) target distribution in range and azimuth within the coverage area,
b) mix of message lengths, and
c) design of interrogation scheduling algorithms.

Since the downlink messages are generally shorter than the uplink messages (i.e., they usually consist of routine identification, altitude readout, or

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acknowledgement), the four-field increase in capacity of the uplink over the downlink due to the difference in data rate is easily accommodated.

A favorable range/azimuth distribution coupled with 112 bit interrogate/56 bit reply accommodates about 100 transactions per 40ms beam dwell. Utilization of the 112 bit reply format cuts the number of transactions possible by about half. This capability will support approximately 1250 targets (with about 8 messages available per target) per DABS ground terminal assuming a 4 second scan and standard message (short reply) format. Utilization of the long reply format reduces the number of messages available per target by about a factor of two. Use of the extended length message, as would be expected, compromises capacity. In equipment now being developed, capacity is limited to about one 16 segment ELM to a very small percentage of targets in the beam. In principle, however, based on 4 degree beam width and a 4 sec scan, as many as 4 ELM's could be directed to or from a target while still providing some support for other DABS and/or ATCRBS targets.

Replacement of the mechanically scanned antenna by an electronically agile or an omnidirectional antenna provides a significant increase in system capacity and flexibility. It has been postulated [A-5] that such a system could handle as many as 400 aircraft with virtually any azimuth distribution and have approximately 2 msec for each target after ATCRBS interrogation. This would allow scheduling several single-segment transactions per target and approximately one extended length message per second to about 200 targets.

Decreased link reliability due to link interference adversely affects link capacity. Since each required reinterrogation reduces channel availability, both uplink and downlink signal formats have been designed to provide a reasonable amount of interference immunity. Sources of link interference include ATCRBS interrogations, multipath, and terrain and/or airframe shadowing. Interference from ATCRBS is only considered problematic in the initial phase of DABS implementation while multipath and shadowing are specific to local geography and may be addressed by multiple sensor coverage or readjustment at sensor coverage boundaries. Summarizing link reliability, Drouilet [A-7] states "reliable link operation is

possible in a severe interference environment--the level of reliability being set primarily by fade statistics. The resulting performance depends on the location of the aircraft and on whether or not the aircraft is maneuvering". He further asserts that a useful reliability (performance) level can be maintained out to about 300 km from the DABS sensor. At these ranges his calculations show link reliability to be less than 90% requiring more than ten percent of the messages to be retransmitted. This is likely adequate for IPC/PWI and other CAS functions potentially affiliated with the DABS system.

APPENDIX B - GROUND AUGMENTED GPS - PSEUDOLITE ANALYSIS

B.1 AUGMENTED GPS

The purpose of this section is to analyze the performance improvement realized by augmenting the GPS satellite configuration with strategically located ground-based pseudolites.* It is assumed that the pseudolites are integrated into GPS in such a way that they not only resemble satellites with respect to signal structures and data formats but also are capable of synchronizing their clocks with those of the satellites. The ultimate aim of the analysis is to support the use of such an augmented system in providing navigation and guidance to an aircraft during the final landing phases.

To provide a consistent framework for the analysis, it is assumed that the user (aircraft) is equipped with a multi-channel GPS receiver with which at least four beacons** may be monitored simultaneously. Thus, the user has available on virtually a continuous basis current range and range-rate measurements with respect to four or more beacons. At any point in time, these measurements may be processed to obtain updated estimates of position and velocity in a (rectangular) coordinate system of interest. Although a multi-channel receiver represents overly sophisticated equipment for much of the aviation community, its use in the present analysis is justified in two ways. First, attention may be effectively restricted to the "static" multilateration problem and the more complicated problem of trajectory estimation avoided. Second, since the analysis proceeds strictly on a comparative basis, the results should carry over to alternative receiver designs which do not employ parallel channels.

As a baseline for comparison, a cluster of four satellites is employed in which the satellites are arranged in some predetermined orientation with respect to a ground reference point.

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 * As discussed in Section 3.6, a pseudolite is a satellite transmitter located on the ground.
** The generic term "beacon" refers to either satellites or pseudolites.

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Although the range between a given satellite and the reference point is calculated on the basis of a circular, twelve-hour orbit, satellite azimuth and elevation are specified arbitrarily. It is possible, therefore, that some of the geometrics considered may not be consistent with the proposed twenty-four satellite GPS constellation. For present purposes, this lack of realism is thought not to be detrimental, although it represents a problem which should be pursued further.

The primary failing of a four-satellite cluster in providing navigation information sufficiently accurate to enable an aircraft to land involves imprecise altitude determination, a situation pseudo-lites are to remedy, if possible. Given an emphasis on altitude determination, the analysis which follows focuses, for the most part, on that aspect of the multilateration problem concerned with position fixing alone. Although the general theoretical development presented treats both position and velocity estimation, numerical results pertain only to the former. This restricted scope allows another significant simplification: satellite kinematics need not be modelled numerically.

Section B.1.1 which follows examines rigorously the static multilateration problem. B.1.2 treats a number of numerical examples. On the basis of these examples, one can draw the following tentative conclusion: An overall factor of about four improvement in accuracy can be derived from the combination of improved geometry and higher ranging precision available with the ground transmitter. However, in situations where user-transmitter geometry is marginal, the performance can degrade seriously and rapidly.

B.1.1 Theoretical Analysis

In this section, a mathematical analysis of the GPS multilateration problem is presented. The GPS model employed is quite standard and can be found described, for example, in references B-1 and B-2. Given the mathematical model, which is, as might be expected, nonlinear, customary techniques are invoked to obtain "best" estimates of the navigation variables of interest (see ref. B-3 pp. 54-81, for a general development of these techniques). Numerical examination of these estimates and their properties is deferred to the following Section B.1.2.

More complete discussions of multilateration systems can be found in references B-4 and B-5, and the development here parallels to some extent these references. Although the latter reference proceeds somewhat differently, it can be shown that the results obtained there and those presented here are consistent with one another.* This reference, moreover, gives a novel mechanical interpretation of the problem which provides insight into the positioning accuracy which can be obtained with a multilateration system.

Mathematical Model

The range and range rate of a user relative to the ith beacon of a GPS cluster are given by

$$d_i = |\vec{r} - \vec{r}_i| \qquad \text{(B-1)}$$

and

$$\dot{d}_i = \frac{(\vec{r} - \vec{r}_i) \cdot (\dot{\vec{r}} - \dot{\vec{r}}_i)}{d_i} , \qquad \text{(B-2)}$$

respectively. Here $\vec{r}$ denotes the (unknown) user position vector

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*Reference B-5 effectively eliminates from consideration user clock bias, an important quantity in the present analysis.

and $\vec{r}_i$ the (known) beacon position vector, both with respect to an inertial coordinate system. The over-dot signifies time differentiation, so that $\dot{\vec{r}}$ is the (unknown) user velocity vector and $\dot{\vec{r}}_i$ the (known) beacon velocity vector. The numerator in (B-2) is the usual dot product of the relative position and velocity vectors.

With respect to the given beacon, the user measures the transit time and the doppler shift of the pseudorandom-coded, L-band signal transmitted by the beacon. The measured quantities, however, differ from the true quantities for two reasons: systematic errors in the user's clock and, to a lesser extent, in the beacon clock; and random errors arising from a number of noise sources in the communication link. Thus, if it is assumed temporarily that the beacon clock is perfect, the measured transit time, t_i°, is related to the true transit time, t_i, by the formula

$$t_i^{\circ} = t_i + \tau + \tau_i \, , \tag{B-3}$$

where τ represents the bias of the user's clock and τ_i accounts for all noise terms. Similarly, the measured doppler shift, f_i°, and the true doppler shift, f_i, are related by

$$f_i^{\circ} = f_i + \nu + \nu_i \, , \tag{B-4}$$

where ν represents drift in the user's clock and ν_i accounts for all noise terms.

Now the true transit time, t_i, is related to range, d_i, by the usual formula:

$$t_i = \frac{1}{c} d_i \, , \tag{B-5}$$

where c is the speed of propagation. Likewise, the true doppler shift, f_i, is related to range rate, $\dot{d}_i$, according to

$$f_i = - \frac{2}{\lambda} \dot{d}_i \, , \tag{B-6}$$

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where λ is the propagation wavelength (corresponding to L-band).

Analogous to (B-5) and (B-6), one defines the pseudorange to be the quantity

$$d_i{}^o = ct_i{}^o \qquad\qquad (B-7)$$

and the pseudorange rate to be the quantity

$$\dot{d}_i{}^o = -\frac{\lambda}{2} f_i{}^o \ . \qquad\qquad (B-8)$$

The prefix pseudo- refers to the presence of the bias terms τ and ν which, even in the absence of noise, offset $d_i{}^o$ and $\dot{d}_i{}^o$ from d_i and $\dot{d}_i$, respectively.

Combining the equations above gives

$$|\vec{r} - \vec{r}_i| + c\tau = d_i{}^o - c\tau_i \qquad\qquad (B-9)$$

and

$$\frac{(\vec{r} - \vec{r}_i) \cdot (\dot{\vec{r}} - \dot{\vec{r}}_i)}{|\vec{r} - \vec{r}_i|} + \frac{\lambda}{2} \nu = \dot{d}_i{}^o - \frac{\lambda}{2} \nu_i \ . \qquad\qquad (B-10)$$

In the GPS multilateration problem considered here, the user effectively obtains the pseudoranges, $d_1{}^o$, ..., $d_4{}^o$, and the pseudo-range rates, $\dot{d}_1{}^o$, ..., $\dot{d}_4{}^o$, simultaneously from four beacons.* He then solves the set of equations (B-9) and (B-10), where $i = 1, ..., 4$, for his position, $\vec{r}$; clock bias, τ; velocity, $\dot{\vec{r}}$; and clock drift rate, ν.

As it stands, however, the problem is ill-posed because of the presence of the τ_i and ν_i. That is, one has effectively eight

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*More generally, one can admit more than four beacons, say, N beacons, in which case the index i varies from one to N. This possibility, which entails an N-channel GPS receiver, is considered below.

equations in sixteen unknowns. To see this explicitly, let x, y, z denote the rectangular components of $\vec{r}$ and x_i, y_i, z_i those of $\vec{r}_i$. Then (B-9) and (B-10) take the form

$$\left((x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2\right)^{1/2} + \delta$$
$$= d_i{}^\circ - \delta_i \tag{B-11}$$

$$\frac{(x - x_i)(\dot{x} - \dot{x}_i) + (y - y_i)(\dot{y} - \dot{y}_i) + (z - z_i)(\dot{z} - \dot{z}_i)}{\left((x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2\right)^{1/2}} + \dot{\delta}$$
$$= \dot{d}_i{}^\circ - \dot{\delta}_i \; , \tag{B-12}$$

where, for convenience,

$$\delta \triangleq c\tau \qquad\qquad \delta_i \triangleq c\tau_i$$
$$\dot{\delta} \triangleq \frac{\lambda}{2} \nu \qquad\qquad \dot{\delta}_i \triangleq \frac{\lambda}{2} \nu_i \; . \tag{B-13}$$

The sixteen unknowns are seen to be x, y, z, and δ; $\dot{x}$, $\dot{y}$, $\dot{z}$, and $\dot{\delta}$; and δ_1, ..., δ_4 and $\dot{\delta}_1$, ..., $\dot{\delta}_4$. Since an infinity of values for these variables can be found which satisfy (B-11) and (B-12), it is clear that statistical considerations must be used to choose which of these solutions should be preferred. The technique next described for finding the preferred solution leads naturally to a description of its accuracy.

Analysis

Of the many algorithms proposed for solving (B-11) and (B-12), that described here is perhaps the most convenient from a theoretical standpoint. Whether it is equally good from a practical standpoint, however, is a moot question and beyond the scope of the present discussion.* Stated briefly, the technique begins with a determination

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*A more complete discussion is given in reference B-4.

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of initial estimates of the variables of interest, namely x, y, z, δ, $\dot{x}$, $\dot{y}$, $\dot{z}$, and $\dot{\delta}$. The origin of these initial estimates, denoted $\hat{x}_o$, $\hat{y}_o$, $\hat{z}_o$, $\hat{\delta}_o$, $\hat{\dot{x}}_o$, $\hat{\dot{y}}_o$, $\hat{\dot{z}}_o$, and $\hat{\dot{\delta}}_o$, is not critical; it is only required that they be reasonably accurate. Thus, for example, the initial estimates could represent merely informed guesses; they could be predictions produced by a navigation filter; or they could, in fact, themselves be a solution of some sort of the given equations (B-11) and (B-12). **The last alternative is** explored more fully in **Attachment A** to this Appendix.

Whatever the case, the initial estimates are used as a reference point about which to linearize equations (B-11) and (B-12). Linearization allows application of the standard least-squares linear estimation methodology to the problem to obtain new esti**mates,** denoted $\hat{x}$, $\hat{y}$, $\hat{z}$, $\hat{\delta}$, $\hat{\dot{x}}$, $\hat{\dot{y}}$, $\hat{\dot{z}}$, and $\hat{\dot{\delta}}$, together with their variances and covariances. The last quantities are of particular importance to the present discussion because they give immediately the customary accuracy measures with which to characterize the performance of multilateration systems.

To review quickly the process of least-squares linear estimation, suppose first that one uses N beacons instead of four, where N is greater than or equal to four always. Denote the left-hand side of (B-11), for i = 1, ..., N, by

$$\phi_i(x, y, z, \delta, \dot{x}, \dot{y}, \dot{z}, \dot{\delta}) = \qquad \qquad \text{(B-14)}$$

$$\left((x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2\right)^{1/2} + \delta \; ;$$

similarly, denote the left-hand side of (12), for i = 1, ..., N, by

$$\psi_i(x, y, z, \delta, \dot{x}, \dot{y}, \dot{z}, \dot{\delta}) = \qquad \qquad \text{(B-15)}$$

$$\frac{(x - x_i)(\dot{x} - \dot{x}_i) + (y - y_i)(\dot{y} - \dot{y}_i) + (z - z_i)(\dot{z} - \dot{z}_i)}{\left((x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2\right)^{1/2}} + \dot{\delta} \; .$$

Then, to first-order accuracy,

$$\phi_i(x, \ldots, \dot{\delta}) \simeq \phi_i(\hat{x}_0, \ldots, \hat{\dot{\delta}}_0)$$

$$+ \frac{\partial \phi_i}{\partial x}(\hat{x}_0, \ldots, \hat{\dot{\delta}}_0)(x - \hat{x}_0) + \ldots + \frac{\partial \phi_i}{\partial \dot{\delta}}(\hat{x}_0, \ldots, \hat{\dot{\delta}}_0)(\dot{\delta} - \hat{\dot{\delta}}_0)$$

$$\triangleq \hat{d}_{i0} + \hat{\delta}_0 \qquad\qquad (B\text{-}16)$$

$$+ \Phi_{i1}(x - \hat{x}_0) + \ldots + \Phi_{i4}(\delta - \hat{\delta}_0)$$

$$+ \dot{\Phi}_{i1}(\dot{x} - \hat{\dot{x}}_0) + \ldots + \dot{\Phi}_{i4}(\dot{\delta} - \hat{\dot{\delta}}_0) \ .$$

Here $\hat{d}_{i0}$ is the range between $(\hat{x}_0, \hat{y}_0, \hat{z}_0)$ and the ith beacon, while $\Phi_{i1}, \ldots, \Phi_{i4}$ and $\dot{\Phi}_{i1}, \ldots, \dot{\Phi}_{i4}$ correspond to the various partial derivatives of ϕ_i evaluated at the reference point. Similarly

$$\psi_i(x, \ldots, \dot{\delta}) \simeq \hat{d}_{i0} + \hat{\delta}_0$$

$$+ \Psi_{i1}(x - \hat{x}_0) + \ldots + \Psi_{i4}(\delta - \hat{\delta}_0) \qquad (B\text{-}17)$$

$$+ \dot{\Psi}_{i1}(\dot{x} - \hat{\dot{x}}_0) + \ldots + \dot{\Psi}_{i4}(\dot{\delta} - \hat{\dot{\delta}}_0) \ .$$

Substituting these expressions in (B-11) and (B-12) and writing the result in matrix form give

$$\begin{bmatrix} \Phi & \dot{\Phi} \\ \Psi & \dot{\Psi} \end{bmatrix} \left(\begin{bmatrix} X \\ \dot{X} \end{bmatrix} - \begin{bmatrix} \hat{X}_0 \\ \hat{\dot{X}}_0 \end{bmatrix} \right) =$$

$$\begin{bmatrix} D^\circ \\ \dot{D}^\circ \end{bmatrix} - \begin{bmatrix} \hat{D}_0 \\ \hat{\dot{D}}_0 \end{bmatrix} - \begin{bmatrix} \hat{\delta}_0 J \\ \hat{\dot{\delta}}_0 J \end{bmatrix} - \begin{bmatrix} \Delta \\ \dot{\Delta} \end{bmatrix} \ , \qquad (B\text{-}18)$$

where, with various affixes,

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$$X = \begin{bmatrix} x \\ y \\ z \\ \delta \end{bmatrix} \;, \quad \dot{X} = \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \\ \dot{\delta} \end{bmatrix} \;; \tag{B-19}$$

and

$$D^\circ = \begin{bmatrix} d_1{}^\circ \\ \cdot \\ \cdot \\ \cdot \\ d_N{}^\circ \end{bmatrix} \;, \quad \dot{D}^\circ = \begin{bmatrix} \dot{d}_1{}^\circ \\ \cdot \\ \cdot \\ \cdot \\ \dot{d}_N{}^\circ \end{bmatrix} \;, \tag{B-20}$$

$$\hat{D}_0 = \begin{bmatrix} d_{10} \\ \cdot \\ \cdot \\ \cdot \\ d_{N0} \end{bmatrix} \;, \quad \hat{\dot{D}}_0 = \begin{bmatrix} \hat{\dot{d}}_{10} \\ \cdot \\ \cdot \\ \cdot \\ \hat{\dot{d}}_{N0} \end{bmatrix} \;, \tag{B-21}$$

$$\Delta = \begin{bmatrix} \delta_1 \\ \cdot \\ \cdot \\ \cdot \\ \delta_N \end{bmatrix} \;, \quad \dot{\Delta} = \begin{bmatrix} \dot{\delta}_1 \\ \cdot \\ \cdot \\ \cdot \\ \dot{\delta}_N \end{bmatrix} \;; \tag{B-22}$$

and J is a column matrix of ones:

$$J = \begin{bmatrix} 1 \\ \cdot \\ \cdot \\ \cdot \\ 1 \end{bmatrix} . \tag{B-23}$$

Before proceeding further, several points should be made concerning the linearized model (B-18). In the first place, it is observed that the notation used to define the functions ϕ_i and ψ_i in (B-14) and (B-15), respectively, suppresses any dependence on the quantities x_i, y_i, z_i, $\dot{x}_i$, $\dot{y}_i$, and $\dot{z}_i$ which describe the position and velocity of

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the ith beacon. This procedure is consistent with the earlier assumption that these quantities are known to the user. Unfortunately such is not strictly the case; beacon kinematics can rarely be ascertained exactly by the user.* To avoid complicating the analysis, however, the original assumption is formally retained and the incumbent errors accounted for in the noise vectors Δ, $\dot{\Delta}$ under the general classification of "equivalent" range and range-rate errors, respectively.

Secondly, it is assumed that the relevant statistics of the noise vectors Δ, $\dot{\Delta}$ are known to the user. More precisely, if the N-vectors

$$\bar{\Delta} = E(\Delta) \ , \quad \bar{\dot{\Delta}} = E(\dot{\Delta}) \tag{B-24}$$

denote the expected values of Δ and $\dot{\Delta}$ and if the 2N x 2N matrix

$$R = \begin{bmatrix} R_{11} & R_{12} \\ R_{21} & R_{22} \end{bmatrix} \tag{B-25**}$$

$$\triangleq \begin{bmatrix} E((\Delta - \bar{\Delta})(\Delta - \bar{\Delta})^T) & E((\Delta - \bar{\Delta})(\dot{\Delta} - \bar{\dot{\Delta}})^T) \\ E((\dot{\Delta} - \bar{\dot{\Delta}})(\Delta - \bar{\Delta})^T) & E((\dot{\Delta} - \bar{\dot{\Delta}})(\dot{\Delta} - \bar{\dot{\Delta}})^T) \end{bmatrix}$$

denotes their covariance matrix, then $\bar{\Delta}$, $\bar{\dot{\Delta}}$ and R are to be known quantities. The assumption that $\bar{\Delta}$ and $\bar{\dot{\Delta}}$ are known has two important ramifications: that no beacon clock contributes a systematic error to the measurement of the corresponding t_i° and f_i°; and that mean propagation anomalies can be accounted for either through an atmospheric model or through direct measurement $(L_1|L_2)$. To the extent that neither of these assertions is valid, systematic errors will be introduced in the estimates of user position, clock bias,

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*An exception to this statement might be granted to a pseudolite; whether it should or not, however, is not clear.
**The superscript T denotes transpose.

velocity, and clock drift which cannot be removed without the use
of alternative navaids. On the other hand, the possibility that
R may not be known exactly carries with it less severe penalties.
Indeed, the major drawback to using an incorrect covariance matrix
is that one may not weight the observations (pseudoranges and
pseudorange rates) in the optimal fashion in forming estimates of
x, y, etc. As a result, the estimates will display somewhat more
variation than they might otherwise, but they will not exhibit
systematic errors.

In view of the assumptions just made, (B-18) is written in the
form

$$
\begin{bmatrix} \Phi & \dot{\Phi} \\ \Psi & \dot{\Psi} \end{bmatrix}
\begin{bmatrix} X - \hat{X}_0 \\ \dot{X} - \hat{\dot{X}}_0 \end{bmatrix} =
$$

$$
\begin{bmatrix} D^\circ - \hat{D}_0 - \hat{\delta}_0 J - \bar{\Delta} \\ \dot{D}^\circ - \hat{\dot{D}}_0 - \hat{\dot{\delta}}_0 J - \bar{\dot{\Delta}} \end{bmatrix}
- \begin{bmatrix} \Delta - \bar{\Delta} \\ \dot{\Delta} - \bar{\dot{\Delta}} \end{bmatrix}
\tag{B-26}
$$

or, more compactly, as

$$
A Z = Y - V . \tag{B-27}
$$

In the language of estimation theory, Y denotes observations; AZ,
the mean value of Y; and V, noise. Note that the expected value of
V is zero and that its covariance matrix is R. It follows that the
minimum least-squares estimate of Z is given by

$$
(A^T R^{-1} A)^{-1} A^T R^{-1} Y \tag{B-28}
$$

and that the covariance matrix of this estimate is

$$
(A^T R^{-1} A)^{-1} . \tag{B-29}
$$

Translated into the original quantities, (B-28) becomes

$$\begin{bmatrix} \hat{X} \\ \hat{\dot{X}} \end{bmatrix} = \begin{bmatrix} \hat{X}_0 \\ \hat{\dot{X}}_0 \end{bmatrix} + (A^T R^{-1} A)^{-1} A^T R^{-1} \begin{bmatrix} D^\circ - \hat{D}_0 - \hat{\delta}_0 J - \bar{\Delta} \\ \dot{D}^\circ - \hat{\dot{D}}_0 - \hat{\dot{\delta}}_0 J - \dot{\bar{\Delta}} \end{bmatrix} , \quad (B\text{-}30)$$

which expresses the final estimate as the sum of the initial estimate and a correction factor.

In what follows, attention is focussed on $\hat{X}$ alone, it being surmised that consideration of the "position" coordinates - x, y, z, and δ - suffices to assess the performance improvement brought about by pseudolites. To this end, one can imagine that only pseudorange measurements are made by the GPS receiver, in which case

$$\hat{X} = \hat{X}_0 + (\Phi^T R_{11}^{-1} \Phi)^{-1} \Phi^T R_{11}^{-1} (D^\circ - \hat{D}_0 - \hat{\delta}_0 J - \bar{\Delta}) \qquad (B\text{-}31)*$$

and the covariance matrix of the error vector $\hat{X}$ - X is

$$P = (\Phi^T R_{11}^{-1} \Phi)^{-1} . \qquad (B\text{-}32)$$

Application

Note that the procedure described above is of an operational nature. That is, it prescribes a sequence of steps a user might follow in estimating his position and clock bias. In the process, the user has little interest in the covariance matrix P defined by (B-32) beyond its appearance as an intermediate quantity in the formula (B-31) for the position estimate $\hat{X}$. In the analysis here, however, which is concerned only with questions of accuracy, the user's position can be assumed known, and it is the covariance matrix P, and not the position estimate $\hat{X}$, which is of interest. Stated another way, the problem here is that of determining how well a user, at some known location and with a known clock bias,

---

*Since $\dot{\Phi} = 0$, it can be shown alternatively that (B-30) and (B-31) give identical results for X whenever $R_{12} = R_{21} = 0$, i.e., whenever the errors associated with pseudorange measurements and those associated with pseudorange rate measurements are uncorrelated.

can reproduce this information on the basis of noisy pseudorange measurements to a number of beacons.

It follows, therefore, that proper procedure requires at the outset that the matrix Φ appearing in (B-32) be evaluated at the user's position, X, and not at the user's initial position estimate, $\hat{X}_o$. In the remainder of the discussion, it is implicitly assumed that such is always done. In this case, the diagonal terms of P indicate the variance of the errors committed in attempting to estimate x, y, z, and δ from the pseudorange measurements d_i°, ..., d_N°. Properly interpreted, these variance terms produce the various accuracy measures of interest.

To carry out the interpretation, it is necessary first to translate the results just obtained to a user-oriented coordinate system, a coordinate transformation which can always be accomplished through translation and rotation of axes. The effect of this transformation on the covariance matrix P can be evaluated by noting that this matrix is geometry-dependent only through the matrix Φ and that Φ is an N x 4 matrix of the form

$$\Phi = [Q \quad J] , \tag{B-33}$$

where

$$Q = \begin{bmatrix} \dfrac{x - x_1}{d_1} & \dfrac{y - y_1}{d_1} & \dfrac{z - z_1}{d_1} \\ \vdots & \vdots & \vdots \\ \dfrac{x - x_N}{d_N} & \dfrac{y - y_N}{d_N} & \dfrac{z - z_N}{d_N} \end{bmatrix} \tag{B-34}$$

and J is defined by (B-23). The ith row of Q is seen to consist simply of the direction cosines of the user position with respect to the ith beacon position. The indicated coordinate transformation, therefore, replaces Q with the product $Q\Omega$, where Ω is the 3 x 3 orthogonal matrix describing the rotation of axes whose elements,

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like those of Q itself, are direction cosines. (Note that Q is invariant under translation.) It is assumed that the matrix $Q\Omega$ is of the form

$$Q\Omega = \begin{bmatrix} \dfrac{x' - x_1'}{d_1} & \dfrac{y' - y_1'}{d_1} & \dfrac{z' - z_1'}{d_1} \\ \vdots & \vdots & \vdots \\ \dfrac{x' - x_N'}{d_N} & \dfrac{y' - y_N'}{d_N} & \dfrac{z' - z_N'}{d_N} \end{bmatrix} \quad , \tag{B-35}$$

where x' and y' refer to horizontal axes and z' to the vertical axis of the user coordinate system. To avoid burdening the notation, however, it is henceforth assumed that the rotation matrix Ω is implicit in Q and the form (B-34) used instead of (B-35).

For concreteness, suppose now that beacons $i = 1, \ldots, N_s$ are satellites and that beacons $i = N_s + 1, \ldots, N_s + N_p$ are pseudolites. Suppose, moreover, that R_{11} is a diagonal matrix,

$$R_{11} = \begin{bmatrix} \sigma_1^2 & & 0 \\ & \ddots & \\ 0 & & \sigma_N^2 \end{bmatrix} \quad , \tag{B-36}$$

in which $N = N_s + N_p$ and

$$\begin{aligned} \sigma_i^2 &= \sigma^2 , & i = 1, \ldots, N_s \\ &= k^2 \sigma^2 , & i = N_s + 1, \ldots, N_s + N_p \end{aligned} \tag{B-37}$$

The parameter k is to relate the accuracy of the pseudolites to that of the satellites; typically $k \leq 1$, implying the former are at least as accurate as the latter. It follows that

$$R_{11} = \sigma^2 S_{N_s,N_p}(k) \ , \tag{B-38}$$

in which $S_{N_s,N_p}(k)$ is a diagonal matrix, N_s of whose elements are unity and N_p of which are k^2. If (B-38) is substituted in (B-32), then

$$P = \frac{1}{\sigma^2} P = (\Phi^T S_{N_s,N_p}(k)^{-1} \Phi)^{-1} \tag{B-39}$$

represents a normalized version of P. Indeed, the elements of $\tilde{P}$ are solely a function of the following factors:

. beacon/user geometry as reflected in the matrix Φ;
. the number of satellites and pseudolites (N_s, N_p);
. the relative accuracy of satellites and pseudolites (k).

On the basis of the observation just made and (B-39), it is reasonable to define

$$HDOP^2 \triangleq \tilde{P}_{11} + \tilde{P}_{22} \tag{B-40}$$

$$VDOP^2 \triangleq \tilde{P}_{33} \tag{B-41}$$

$$PDOP^2 \triangleq \tilde{P}_{11} + \tilde{P}_{22} + \tilde{P}_{33} \tag{B-42}$$

$$TDOP^2 \triangleq \tilde{P}_{44} \tag{B-43}$$

and

$$GDOP^2 \triangleq \tilde{P}_{11} + \tilde{P}_{22} + \tilde{P}_{33} + \tilde{P}_{44} \ , \tag{B-44}$$

where DOP abbreviates "dilution of precision" and the prefixes H, V, P, T, and G denote horizontal, vertical, position, time, and geometric, respectively. (See ref. B-6). In the next section, the behavior of these quantities with respect to the factors listed is examined.

To close the present section, it is pertinent to point out that, because of the form of Φ given by (B-33) and (B-34), the measures HDOP, VDOP, etc., depend geometrically only on the angular orientation of the user with respect to a beacon cluster and not on the individual user/beacon ranges. The conclusion to be drawn is that any geometrical improvement to be realized with pseudolites must arise because their proximity to the user creates a more favorable orientation than could otherwise be obtained with satellites alone. If a favorable angular geometry is not obtained, then one should anticipate no significant improvement simply due to the proximity of pseudolites.*

B.1.2 Numerical Analysis

To explore the potential of pseudolite augmentation, the situation depicted in Figure B.1 is considered, namely an aircraft flying a three degree glide slope to touchdown. For concreteness, a runway heading of ninety degrees is assumed. Therefore, with respect to the coordinate axes shown in the figure, the aircraft flight path is assumed to be given by

$$x = 0$$
$$y \leq 0$$
$$z = -(y \tan(w) + 1), \qquad \qquad (B-45)**$$

where w is the glide angle. In what follows, the accuracy measures listed earlier in (B-40) through (B-44) are evaluated for points along the glide path defined by (B-45). The particular point (0, 0, -1) is referred to as the touchdown point.

---

*The conclusion addresses geometry alone and not other factors such as calibration, ionosphere error, etc.
**At y=0, z=-1 m so that the glide path does not pass through the origin. The purpose of this artiface is to prevent the position of the aircraft from coinciding with that of a pseudolite to be located at the origin.
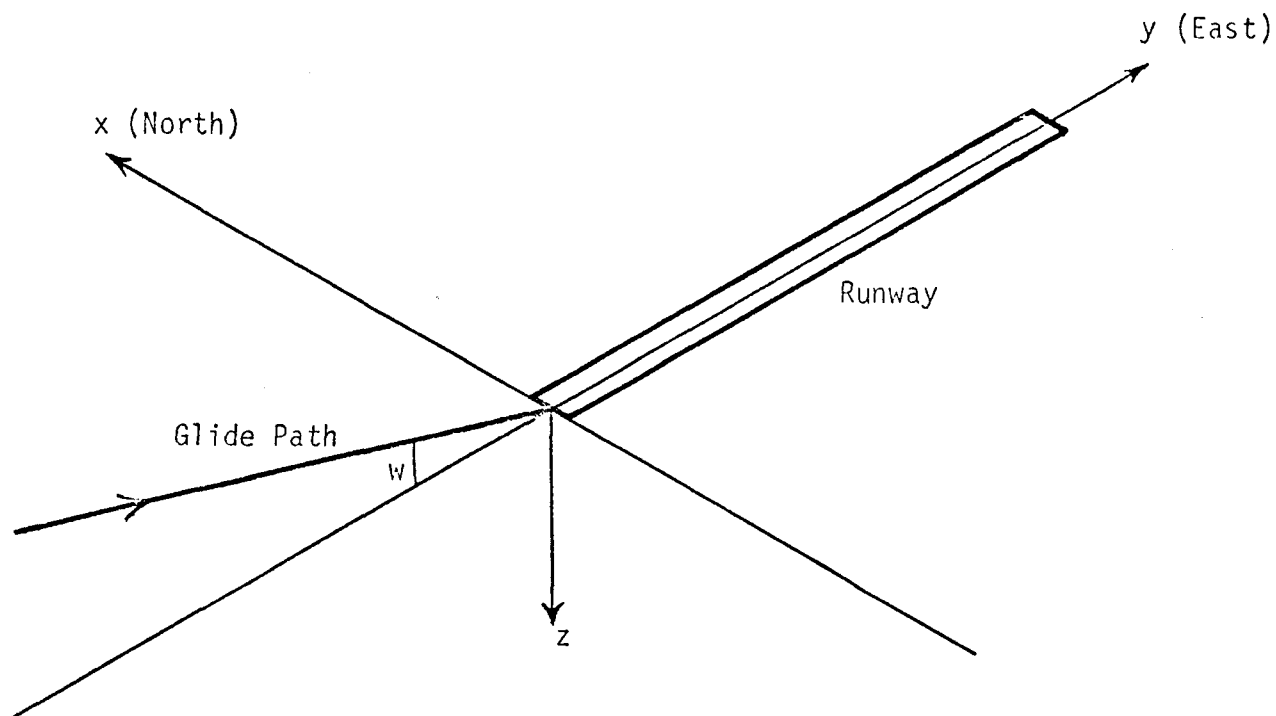
Figure B-1.   Illustration of Landing Geometry Used to Evaluate
Pseudolite Augmentation.   The glide angle w is taken
to be three degrees.

Baseline Configuration

A basis for comparison is provided by the four-satellite cluster shown in Figure B-2, in which the coordinate axes coincide with those of Figure B-1. The symmetrical satellite geometry shown in Figure B-2 places one satellite directly over the touchdown point (or origin) and three others in a conical arrangement with respect to this point. Thus the azimuths of the latter three satellites are taken as 90, 210, and 330 degrees, respectively; and their common elevation, as a variable parameter, γ. Since the GPS satellites follow circular orbits of radius R, the distance of a satellite from the origin is

$$d(\gamma) = (R^2 - R_e^2 \cos(\gamma)^2)^{1/2} - R_e \sin(\gamma) \quad , \qquad (B-46)$$

where γ is the elevation of the satellite and R_e is the radius of the earth. For R = 20,000 km and R_e/R = 0.32, $d(\gamma)$ varies from approximately 19,000 km to 13,600 as γ varies from 0 to 90 degrees. The rectangular coordinates of the respective satellites in Figure 2 are given as follows:

$$x_1 = 0$$
$$y_1 = 0$$
$$z_1 = -d(90°) = -(R - R_e) \quad ;$$

$$x_2 = 0$$
$$y_2 = d(\gamma) \cos(\gamma)$$
$$z_2 = -d(\gamma) \sin(\gamma) \quad ;$$

$$x_3 = d(\gamma) \cos(\gamma) \cos(210°)$$
$$y_3 = d(\gamma) \cos(\gamma) \sin(210°)$$
$$z_3 = -d(\gamma) \sin(\gamma) \quad ;$$

$$x_4 = d(\gamma) \cos(\gamma) \cos(330°)$$
$$y_4 = d(\gamma) \cos(\gamma) \sin(330°)$$
$$z_4 = -d(\gamma) \sin(\gamma) \quad .$$

(B-47)
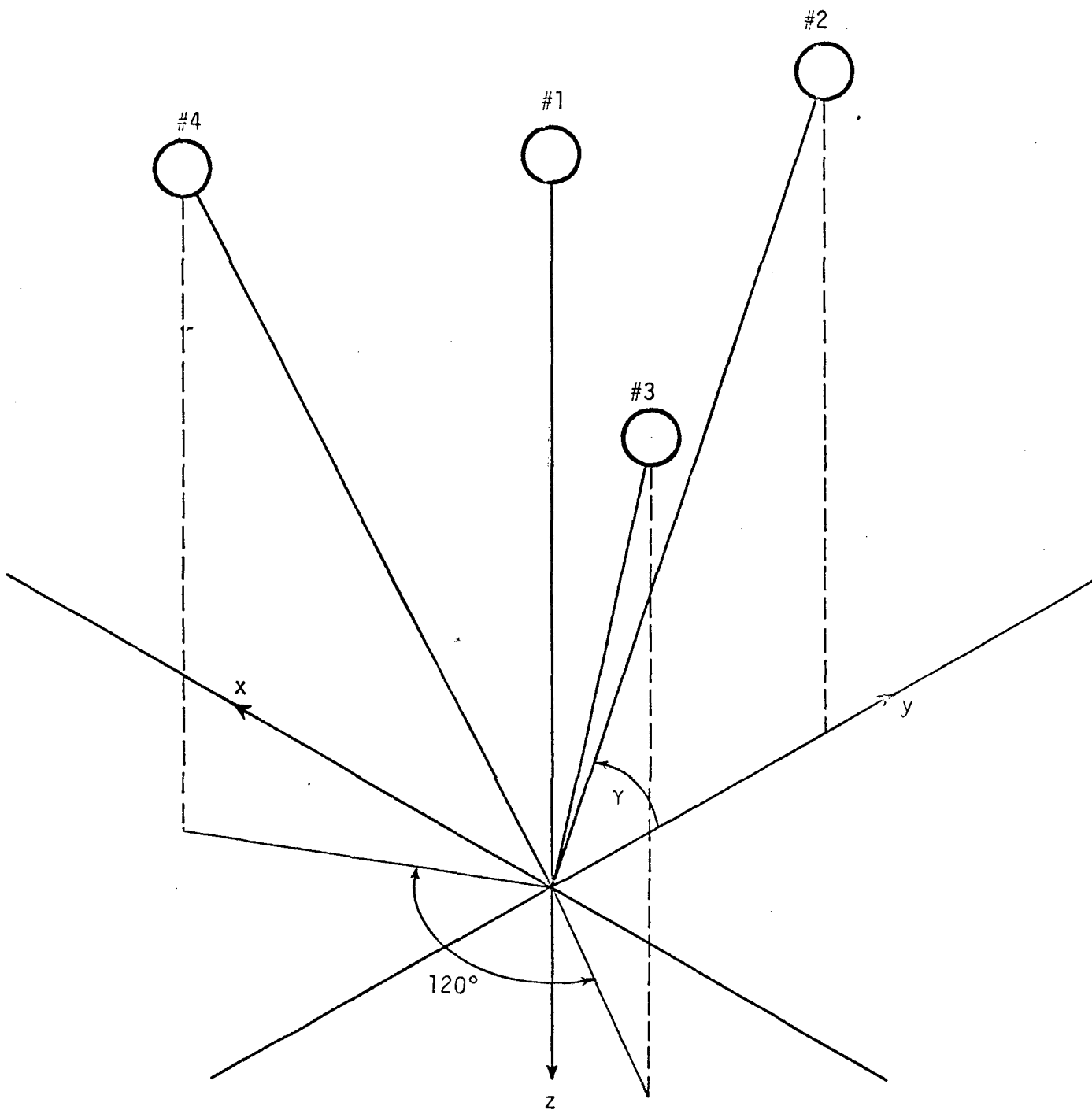
Figure B-2. Four-Satellite Cluster Serving as Baseline Configuration.
Coordinate axes coincide with those of Figure B-1.

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The question of whether the baseline geometry of Figure B-2.
is truly representative of what might be obtained with the twenty-
four satellite GPS at latitudes typical of CONUS is not considered
here. The assumption is made, rather, that this configuration is,
through variation of the elevation angle γ, capable of providing
a realistic setting in which to evaluate the benefits of pseudolite
augmentation. In particular, the case in which γ is forty-five
degrees is taken to define a median baseline geometry.

The analysis begins with an evaluation of HDOP, VDOP, etc.,
for the baseline configuration. The calculations, performed using
the computer program listed in Appendix B, trace the following
sequence:

- determine the basic error covariance matrix $S_{N_s, N_p}(k)$;
- determine the direction - cosine matrix Q and S_{N_s, N_p} from it
  the transformation matrix Φ;
- calculate the matrix $\widetilde{P}^{-1} = \Phi^T S_{N_s, N_p}(k)^{-1} \Phi$;
- invert $\widetilde{P}^{-1}$ to obtain the normalized covariance matrix $\widetilde{P}$;
- use the diagonal elements of $\widetilde{P}$ to compute HDOP, VDOP, etc.

As might be expected, the various accuracy measures for the
baseline configuration vary insignificantly from one point to the
next along the glide path (45).* They do, however, vary considerably
as a function of the cone angle γ as Figure B-3 indicates. Indeed,
VDOP and TDOP are seen to increase rapidly as soon as the elevation
of the "cone satellites" exceeds fifty degrees. Stated another way,
VDOP and TDOP approach infinity as the satellites are brought toward
a uniform elevation. Another manifestation of this behavior is
displayed in Figure B-4, in which the cone satellites are now held
at the median elevation of 45 degrees while the "overhead satellite"
is lowered in a westerly direction (azimuth, 270 degrees) from its

---

*Attention is restricted to values of y between -10 and 0 km.
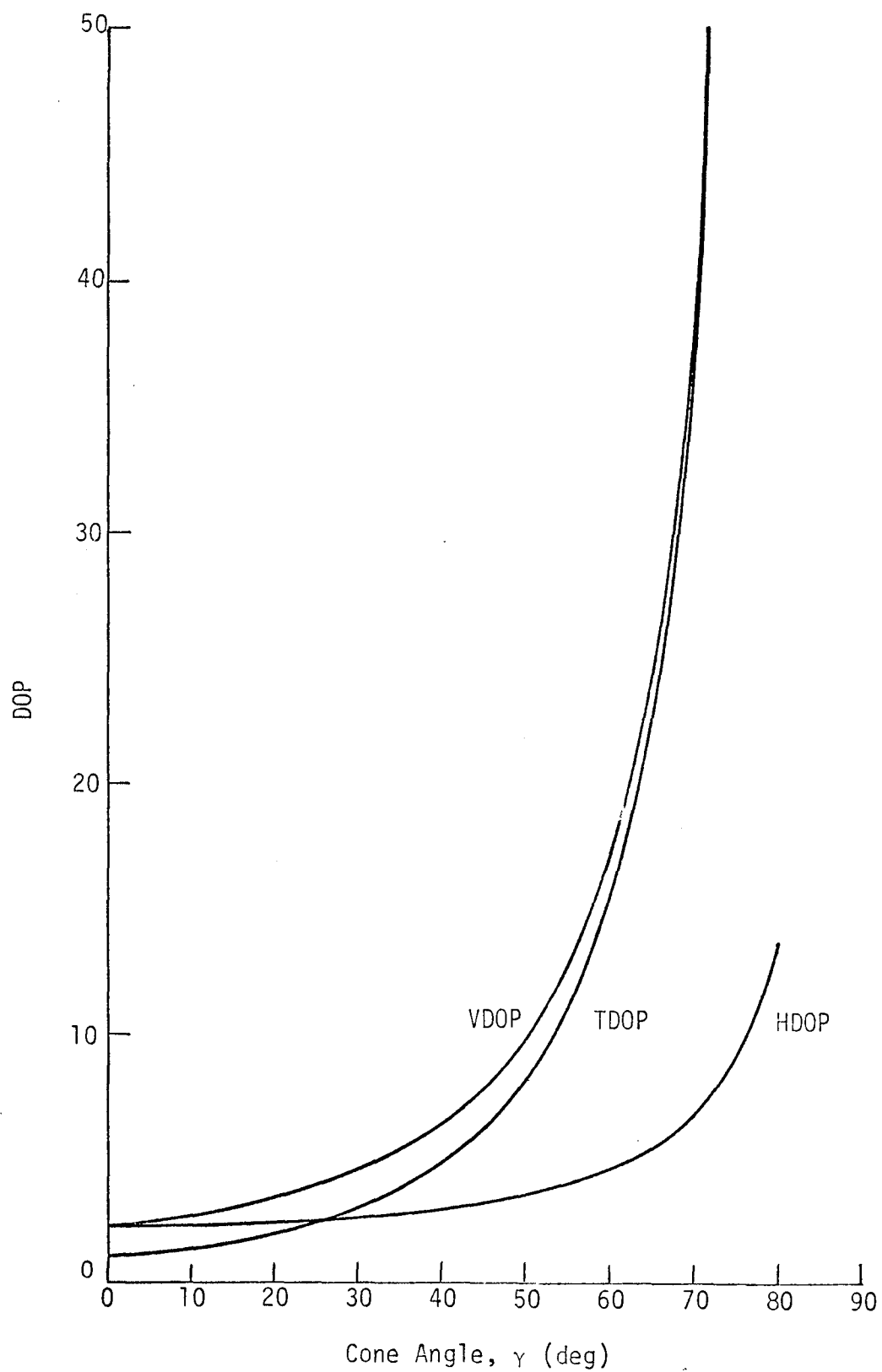
Figure B-3.   Variation of HDOP, VDOP, and TDOP with Cone
Angle for Baseline Configuration

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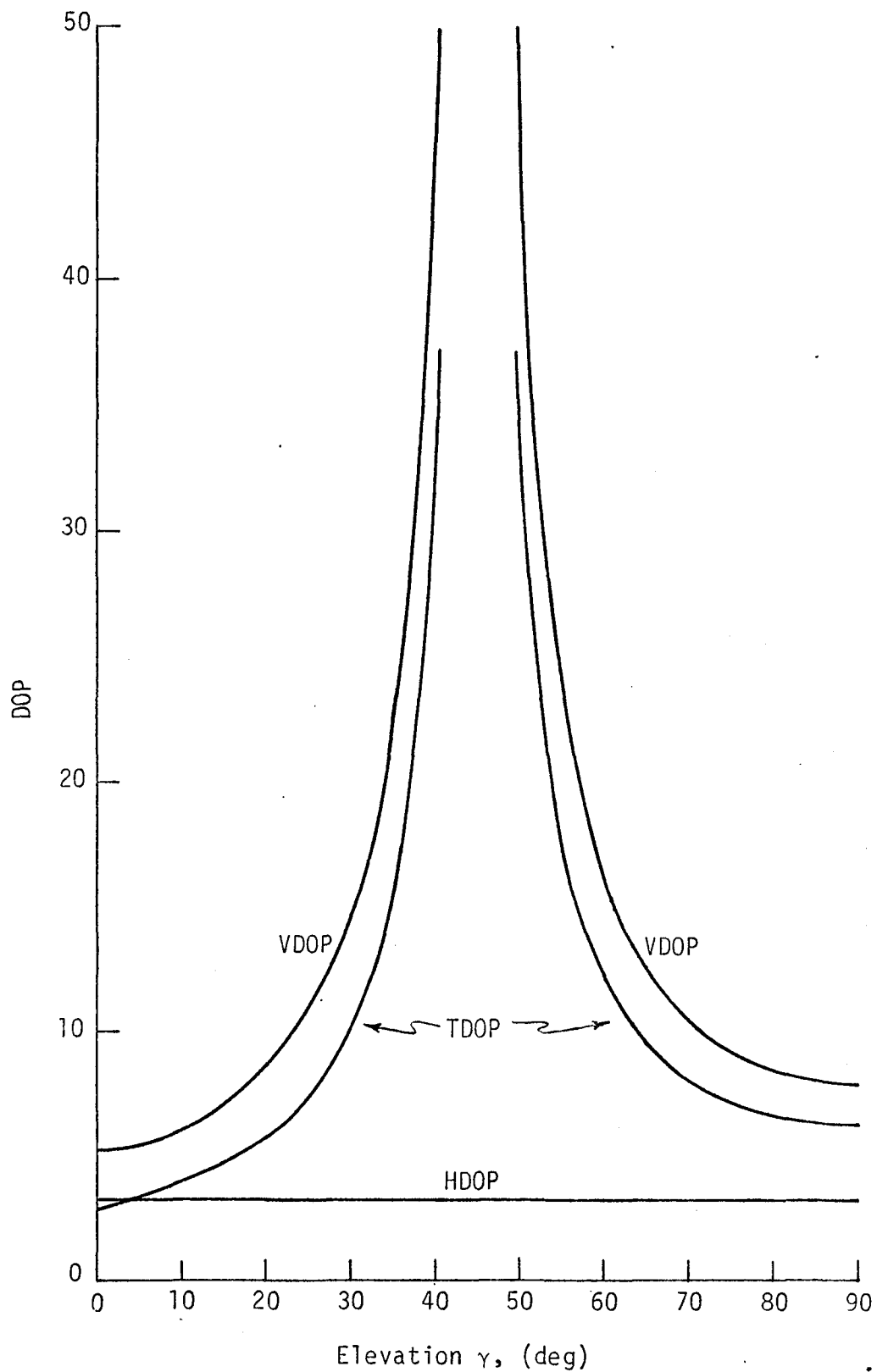
Figure. B-4. Variation of HDOP, VDOP, and TDOP with Elevation
of Satellite #1 for Baseline Configuration.
Constant azimuth of #1 is 270°; cone angle is
45°.

initial elevation of $\gamma_1 = 90$ degrees to a position on the horizon
at an elevation of $\gamma = 0$ degrees. Again it is seen that, as γ_1
approaches $\gamma = 45$ degrees, both VDOP and TDOP grow without bound.
This behavior is explained by the obvious failure of the matrix
$\phi^T S_{N_s,N_p}(k)^{-1}\phi$ to possess an inverse for the value $\gamma_1 = 45$ degrees.
Now an inverse of this matrix exists if and only if the four columns
of the matrix ϕ form a linearly independent set of vectors. ' Con-
sider, then, in the present case, a user located at the origin; in
this case

$$\Phi = \begin{bmatrix} 0 & -\cos(\gamma_1) & -\sin(\gamma_1) & 1 \\ 0 & \cos(\gamma) & -\sin(\gamma) & 1 \\ -\frac{\sqrt{3}}{2}\cos(\gamma) & \frac{1}{2}\cos(\gamma) & -\sin(\gamma) & 1 \\ \frac{\sqrt{3}}{2}\cos(\gamma) & -\frac{1}{2}\cos(\gamma) & -\sin(\gamma) & 1 \end{bmatrix} \quad \text{(B-48)}$$

Examination of the last two columns of this matrix shows one to be,
for $\gamma_1 = \gamma$, a scalar multiple of the other. Thus the columns of
ϕ are not linearly independent and the indicated matrix inverse
does not exist. This behavior, or something very close to it,
persists for all points on the glide path because the elements of
ϕ are barely perturbed by these relatively minor changes in user
position.

A geometrical criteria for detecting when the columns of ϕ
are approaching a state of linear dependence is obtained as follows.
Construct a sphere centered at the user position, outside of which
are located all the beacons (satellites and pseudolites). Draw
an extended radius to each of the beacons, noting the point at which
it pierces the sphere. To the extent, then, that these intersection
points lie in a plane, so will the accuracy with which the user can
determine his position be compromised.

Pseudolite Augmentation

Figures B-3 and B-4 support the general observation that a satellite-based navigation system tends to give poor performance with respect to altitude determination as compared to horizontal position determination. They also support the observation that such a system gives equally poor performance with respect to the determination of clock bias as well. To explore the possibility that these deficiencies can be corrected by pseudolites, it is imagined that a single pseudolite is placed at the origin in Figure B-2 (or B-1). Two separate cases are considered, the first of which involves straight augmentation of the baseline configuration and uses, therefore, five beacons: the four satellites and the pseudolite. The second case uses four beacons: the three cone satellites and the pseudolite. Thus, the first case effectively requires the use of an additional GPS receiver channel, while the second can use, in principal, the same four-channel receiver as that employed for the baseline configuration.

It is noted above that the baseline configuration exhibits almost no variation in the accuracy measures of different points along the glide path, simply because the satellites are so far removed from the aircraft that the direction-cosine matrix is essentially constant. Such is not the case, however, when the pseudolite is employed. Thus, Figures B-5 and B-6 depict the variation in VDOP and TDOP, respectively, for each of the three configurations in the case in which γ = 45 degrees and K = 1, i.e., for the median cone angle and a pseudolite of equal accuracy to the satellites. It is seen that VDOP and TDOP for each of the two pseudolite configurations degrade rapidly at points only slightly removed from the touchdown point, but then level off to essentially constant values which are maintained (as can be shown) for distances of tens of kilometers. In view of this behavior, therefore, it is reasonable in comparing the various configurations to examine their performance at two distinct points: the touchdown point and a
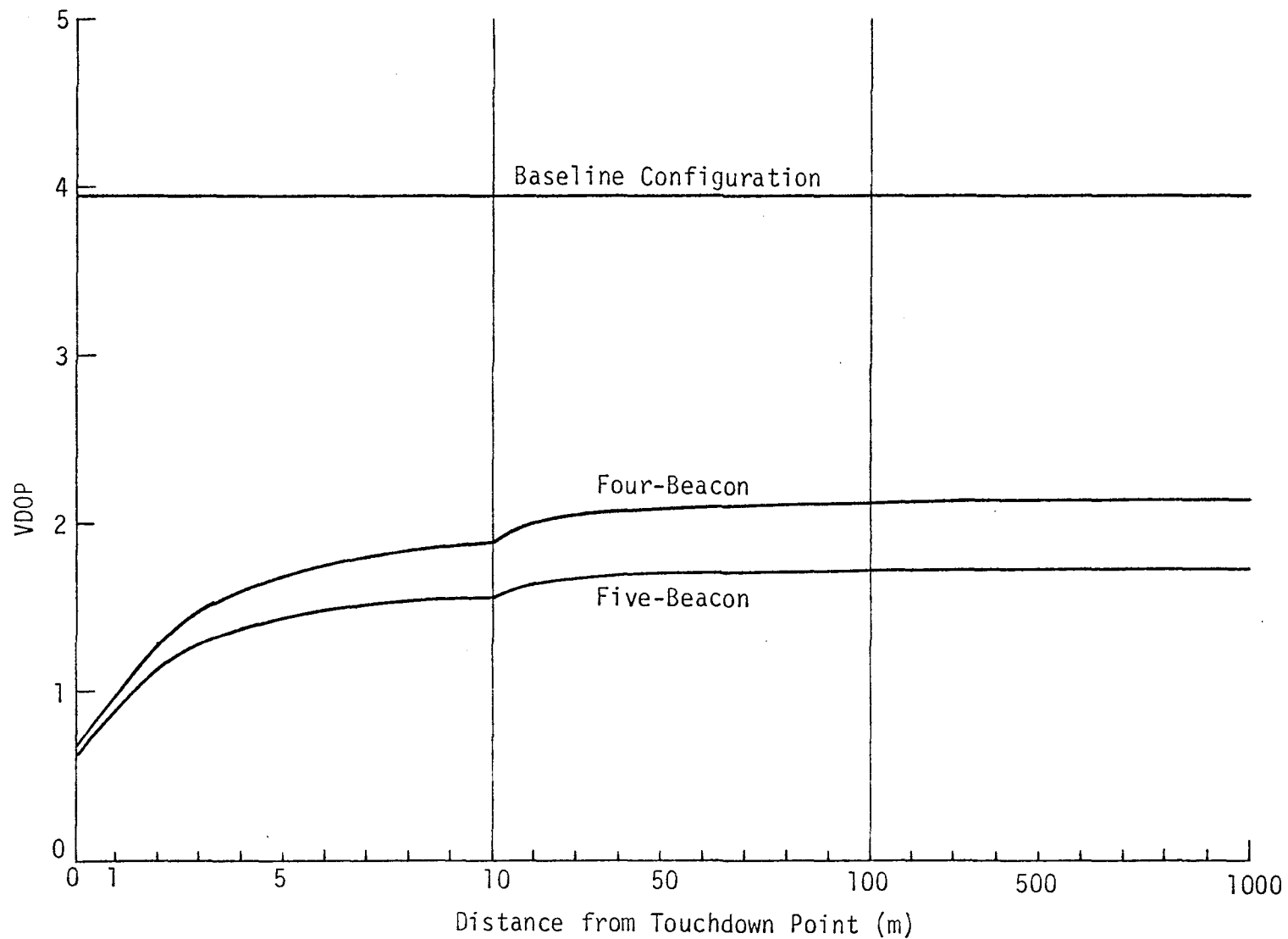
Figure B-5. Variation of VDOP Along Glide Path for Three Alternative Beacon Configurations. Cone angle is 45 degrees. (Note distorted abscissa.)
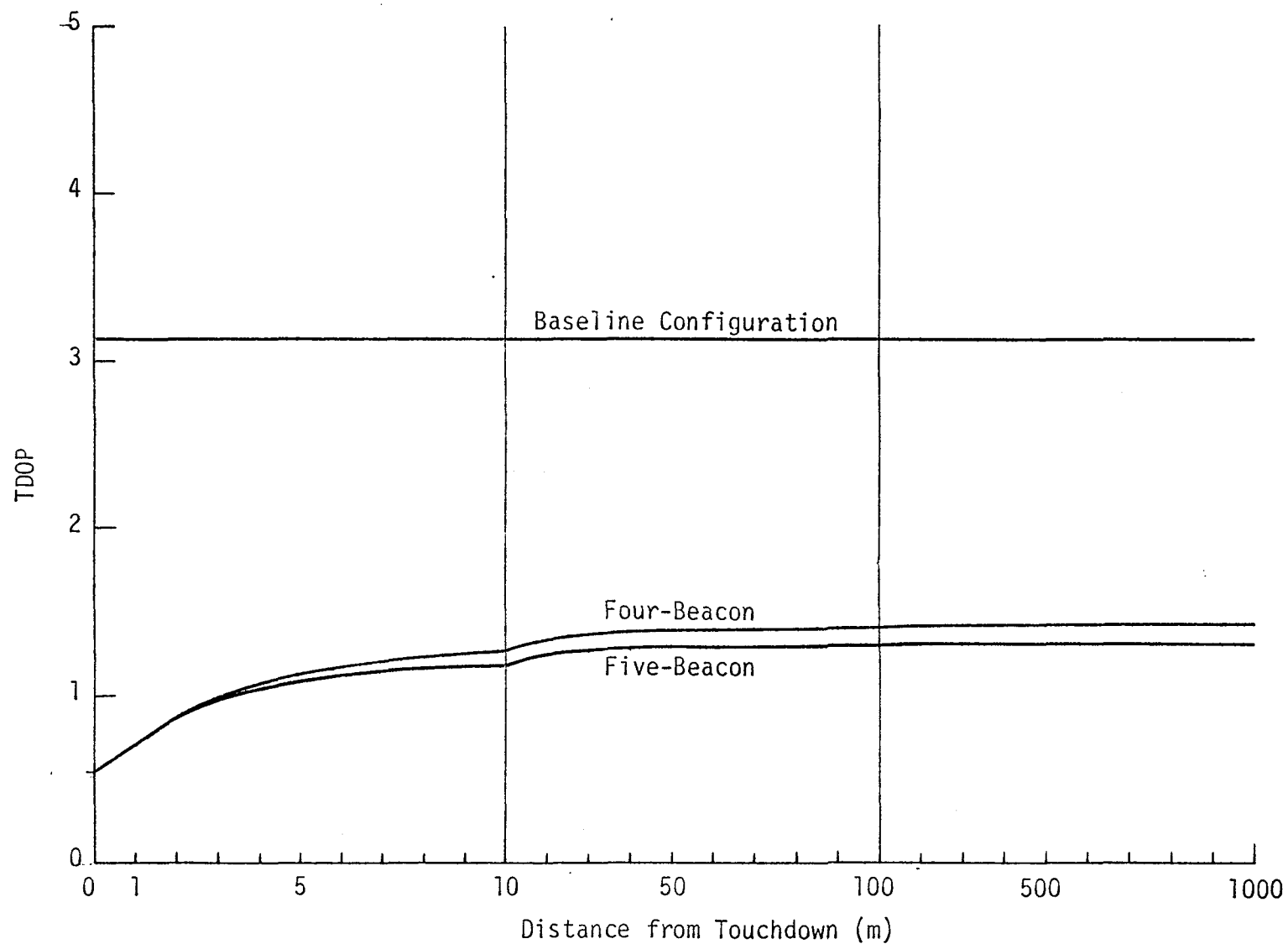
Figure B-6. Variation of TDOP Along Glide Path for Three Alternative Beacon Configurations. (Companion figure to Figure 5)

second "approach point" somewhat removed from the first, say one kilometer distant. As Figures B-5 and B-6 imply, the various accuracy measures have become essentially constant at the approach point.

Figures B-7 through B-12 display, the HDOP, VDOP and TDOP for the three configurations as functions of cone angle γ at each of the two points mentioned. As before, it is assumed that the pseudolite provides a ranging accuracy equal to that of a satellite. The first three of these figures indicate that either of the pseudolite configurations outperforms the baseline configuration at the touchdown point. Thus, HDOP performance is not compromised and, at the same time, both VDOP and TDOP performance are improved significantly. Indeed, use of the pseudolite maintains both of the latter measures at values less than one for the full range of cone angles.

Although the situation is somewhat more complicated at the approach point according to Figures B-10 through B-12; nevertheless, it can be asserted that even the four-beacon configuration continues to display an improvement over the baseline configuration. The obvious difference between these figures and those for the touchdown point is that now the advantages of the pseudolite do not appear until the cone angle exceeds 40 degrees.

Figures B-8 and B-11 are translated into a more pertinent form for the accuracy measure of primary interest here; namely, VDOP, in Figures B-13 and B-14. The new figures plot the ratio of VDOP for the baseline configuration to that for the respective pseudolite configurations, a quantity which might be termed an improvement factor. Figure B-13 pertains to the touchdown point and clearly displays results more favorable to the pseudolite than Figure B-14, which pertains to the approach point.

Also shown in these figures are the analogous curves for the case in which the pseudolite is assumed to provide a ranging accuracy ten times better than a satellite ($k = 0.1$). Such a superior accuracy might be justified, for example, by observing that a pseudolite signal need not cope with the propagation difficulties facing a

113
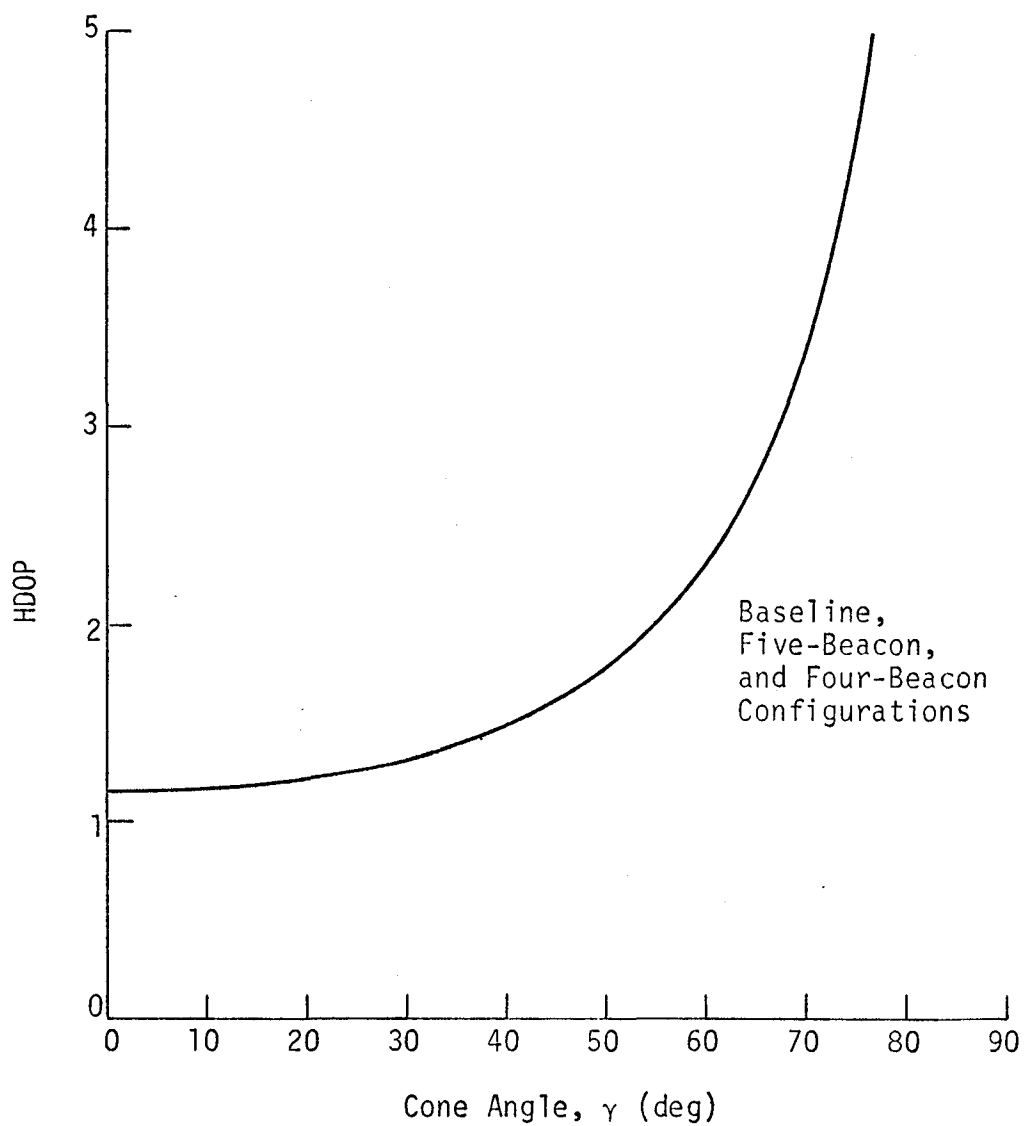
Figure B-7. Variation of HDOP with Cone Angle for Three Alternative Beacon Configurations at Touchdown Point

114
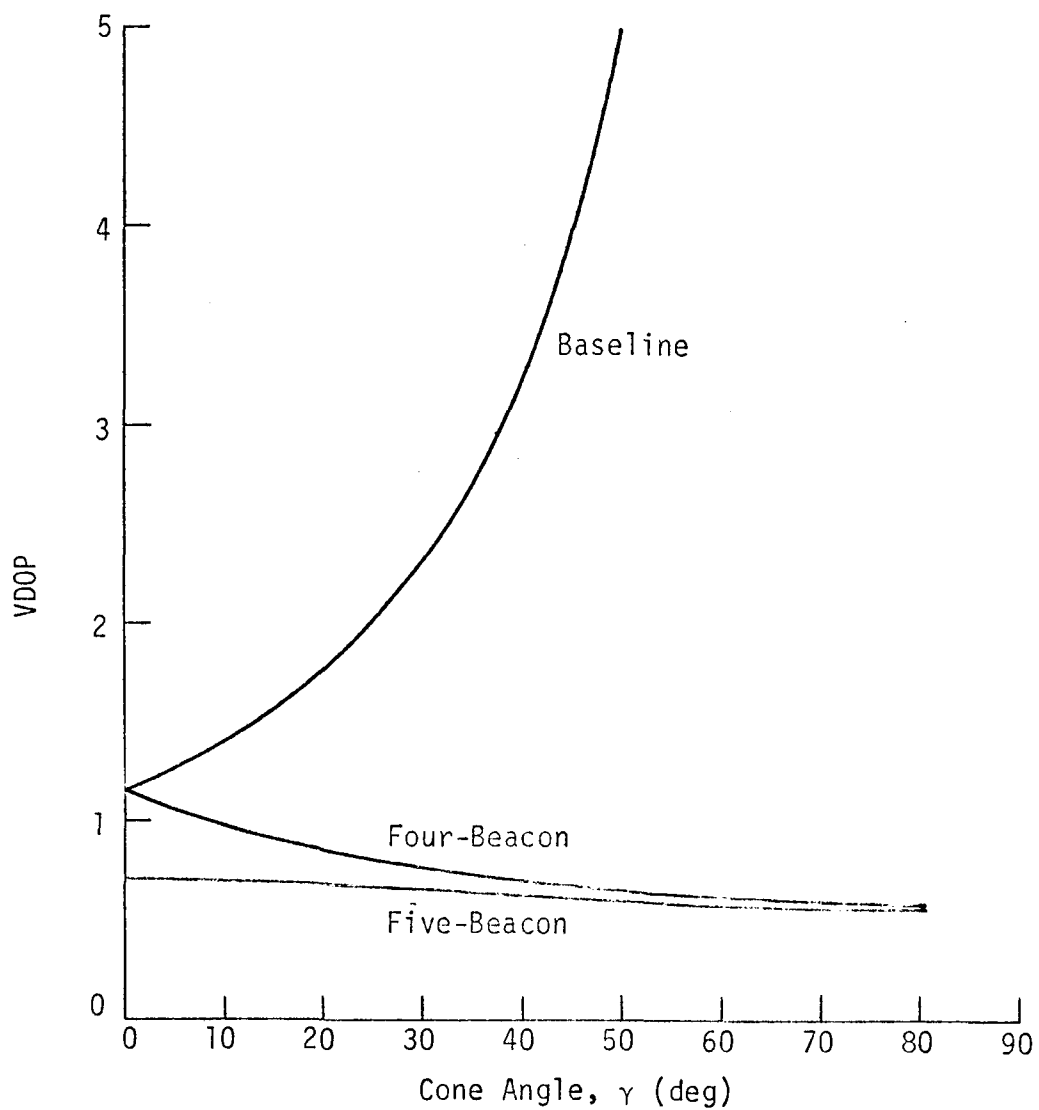
Figure B-8. Variation of VDOP with Cone Angle for Three
Alternative Beacon Configurations at Touchdown
Point (Companion figure to Figure B-7)

115
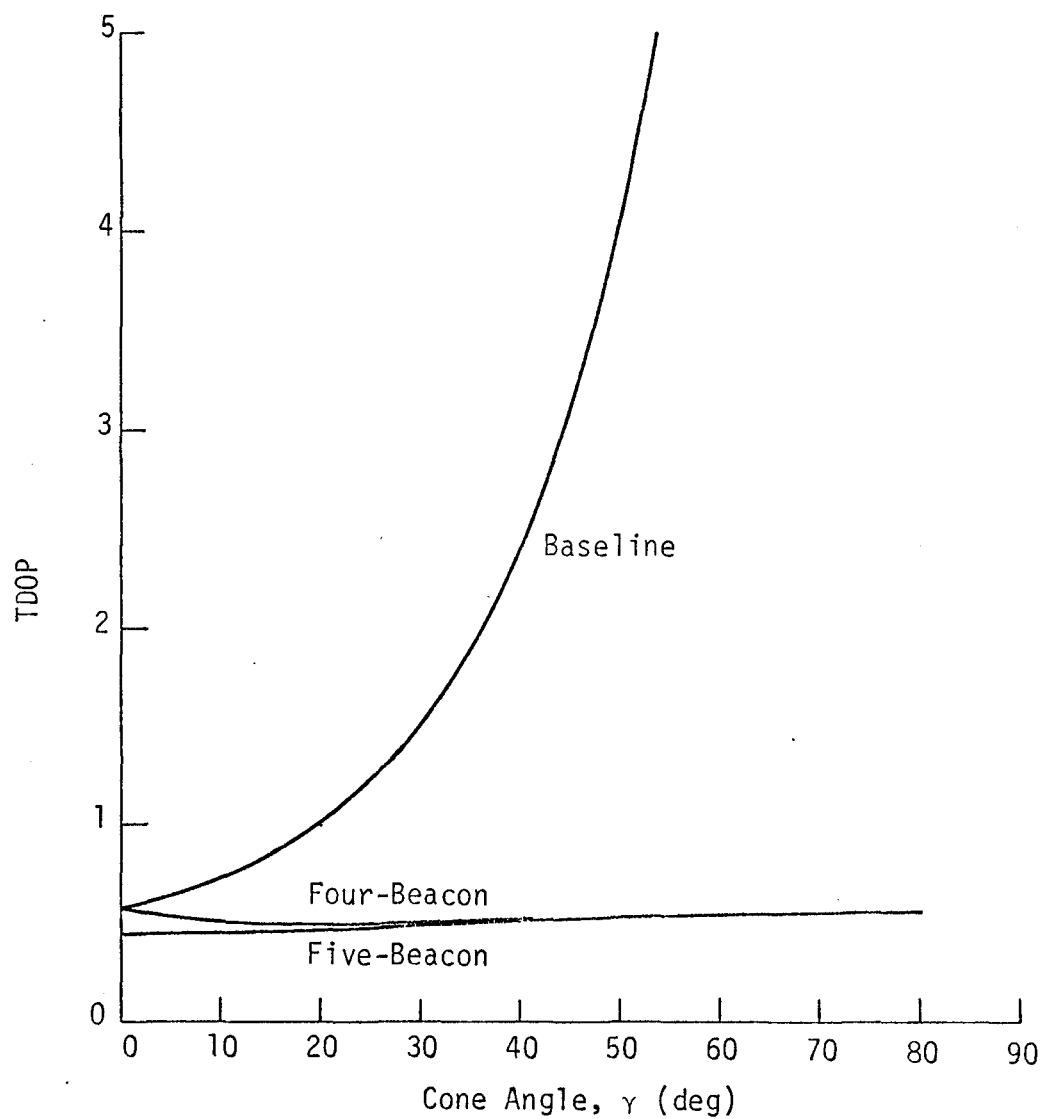
Figure B-9. Variation of TDOP with Cone Angle for Three Alternative Beacon Configurations at Touchdown Point (Companion figure to Figure B-7)

116
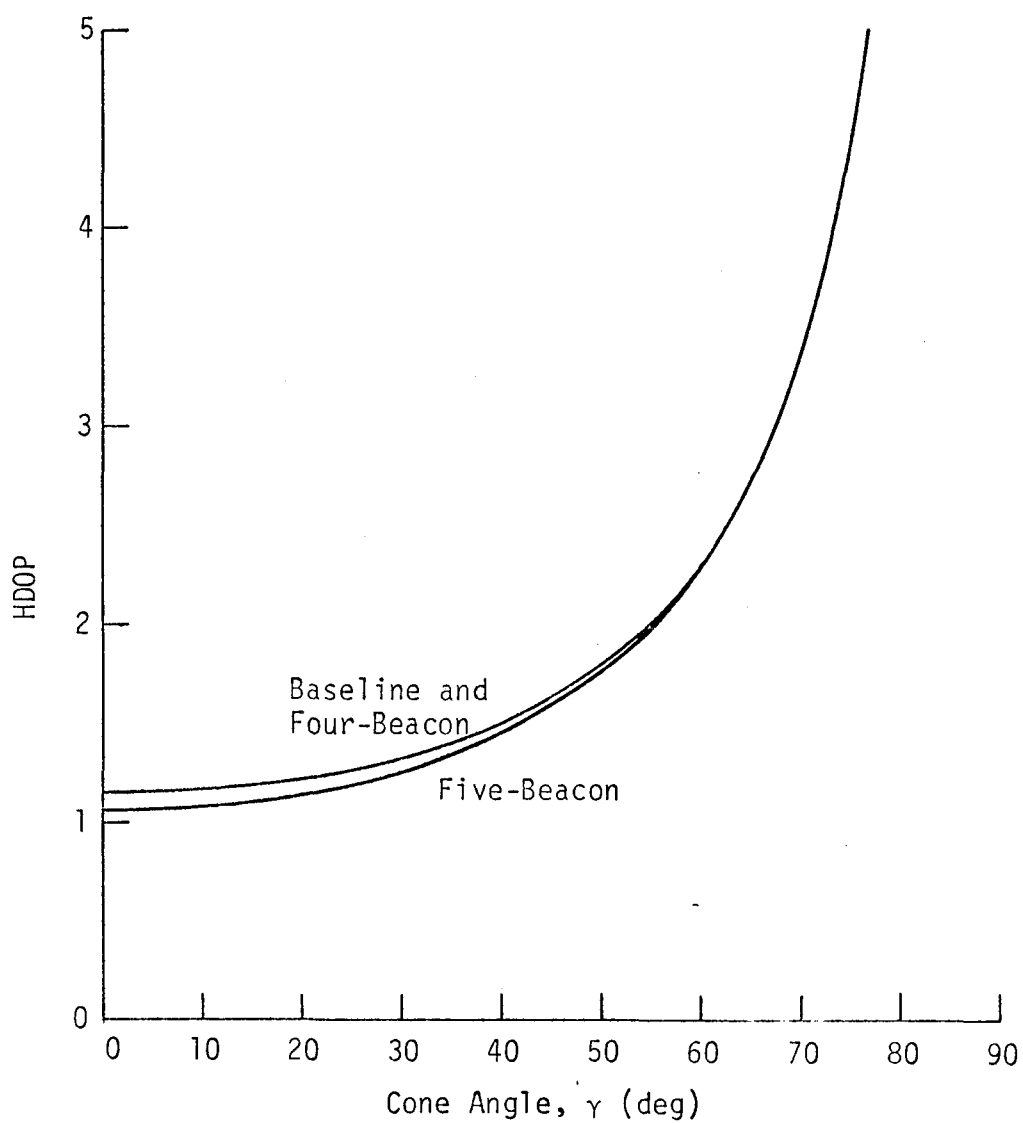
Figure B-10. Variation of HDOP with Cone Angle for Three Alternative Beacon Configurations at Approach Point

117
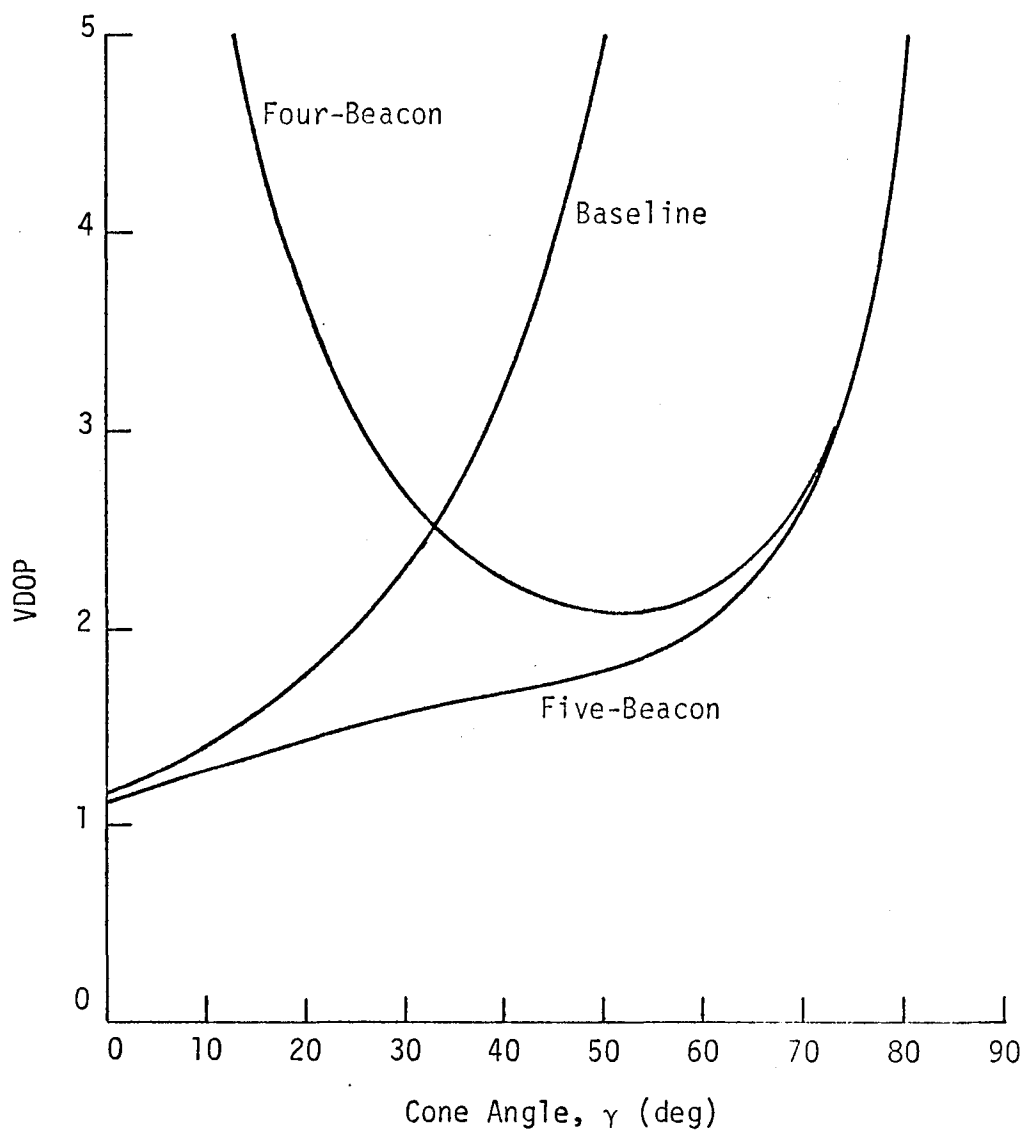
Figure B-11. Variation of VDOP with Cone Angle for Three Alternative Beacon Configurations at Approach Point (Companion figure to Figure B-10)

118
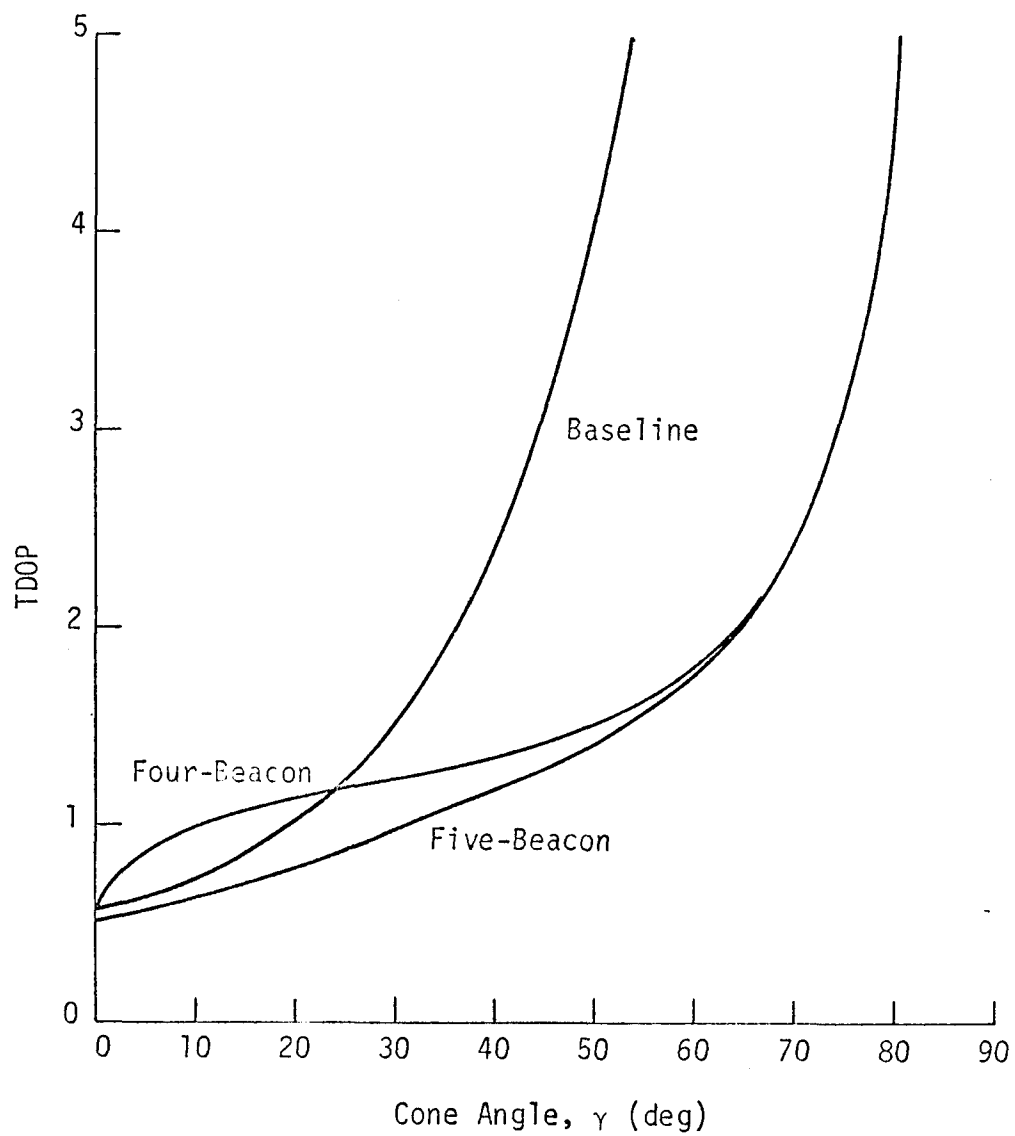
Figure B-12. Variation of TDOP with Cone Angle for Three Alternative Beacon Configurations at Approach Point (Companion figure to Figure B-10)

119
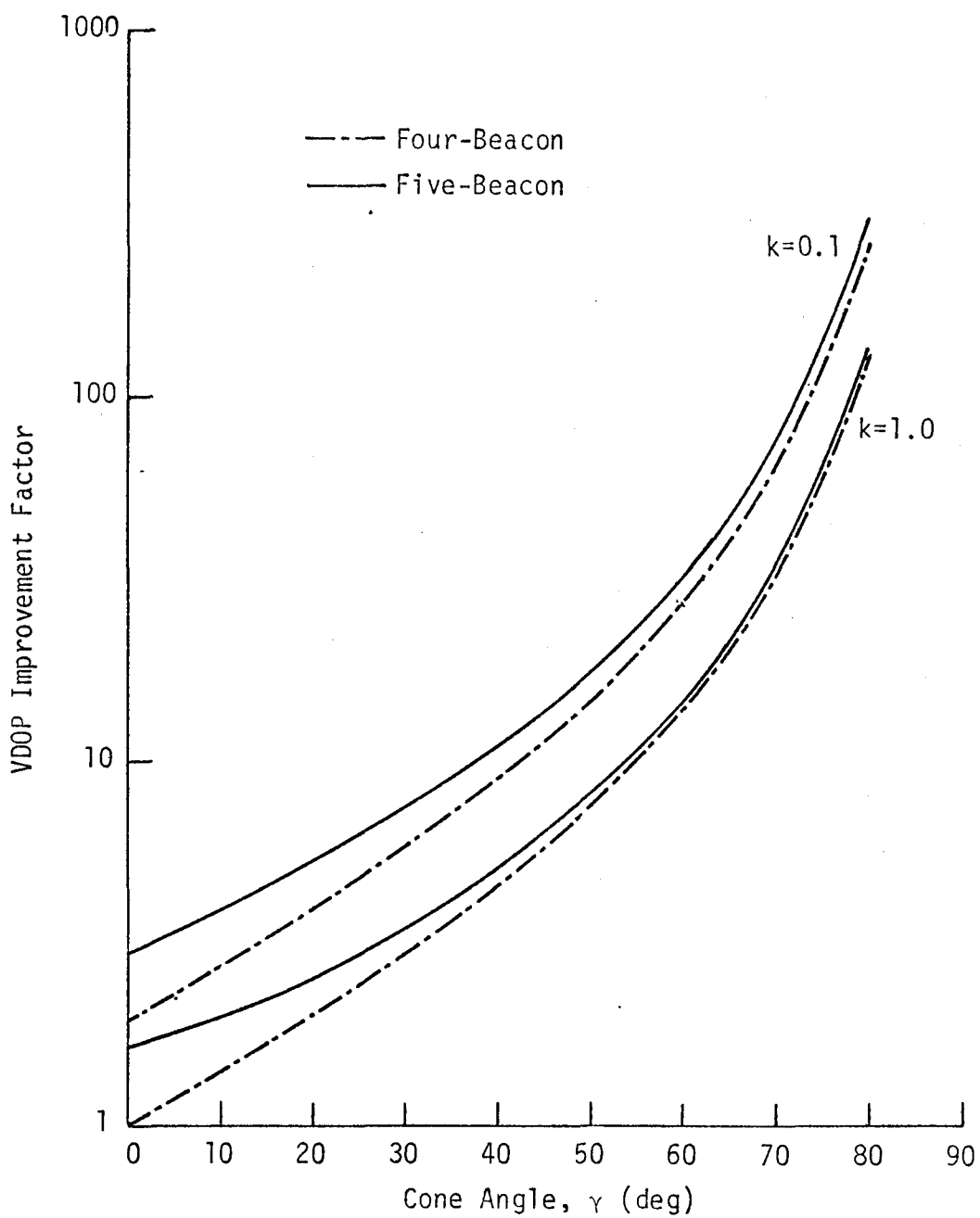
Figure B-13. Variation of VDOP Improvement Factor with Cone Angle for Two Pseudolite Configurations at Touchdown Point. The figure depicts behavior for two different pseudolite ranging accuracies.

120
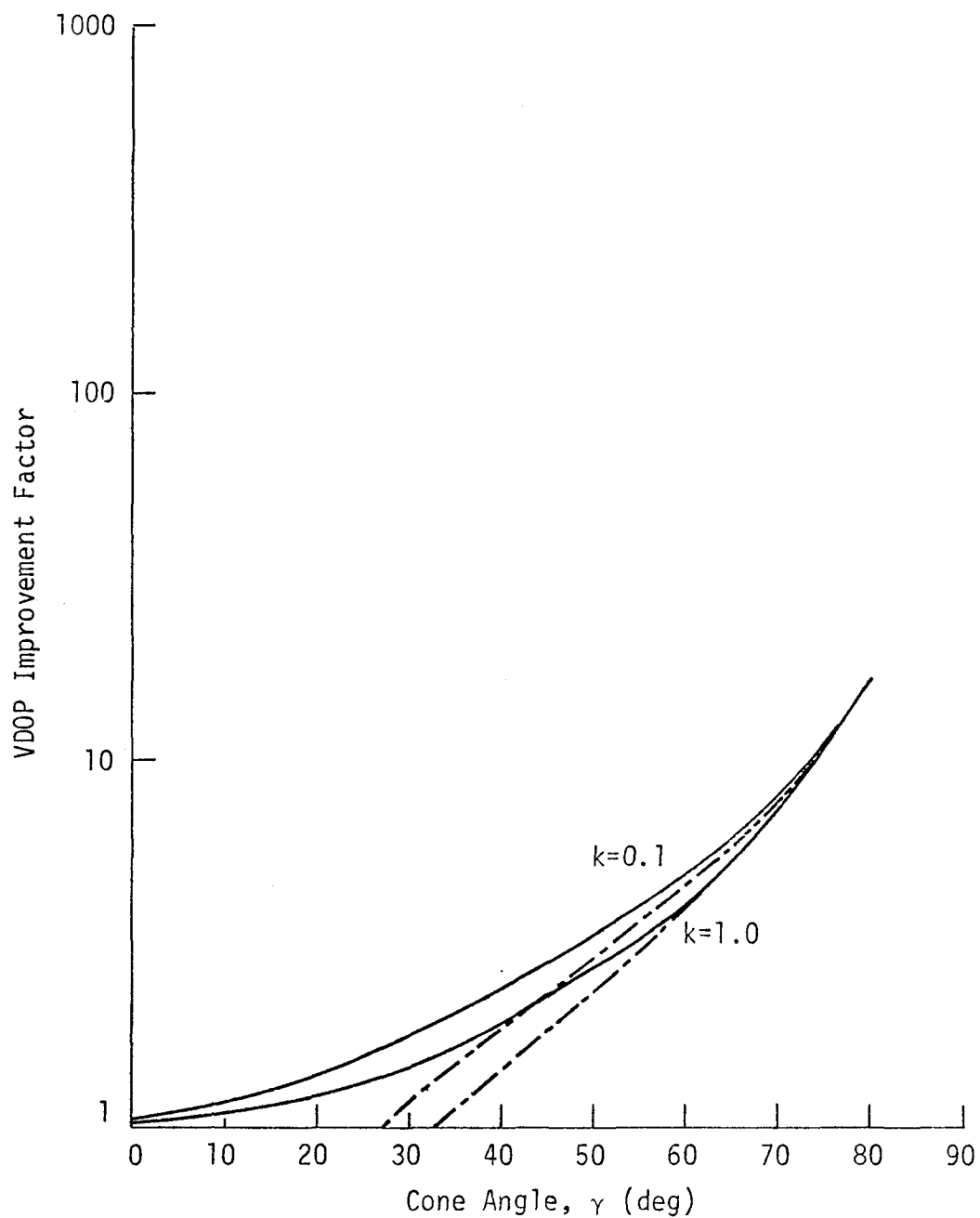
Figure B-14. Variation of VDOP Improvement Factor with
Cone Angle for Two Pseudolite Configurations
at Approach Point. Again, behavior is
depicted for two different pseudolite
ranging accuracies.

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satellite signal. It is noted, however, that the factor of ten does not appear in VDOP primarily because the pseudolite is simply one of four or five beacons. Rather, an additional improvement factor of two occurs at the touchdown point; at the approach point, the corresponding factor is more variable but does not exceed one and a half.

The preceding Figures B-7 through B-14 underscore an observation made earlier: use of a pseudolite does not automatically produce a dramatic improvement in the performance of GPS. Indeed, a simple example serves to show that quite the opposite can occur. With reference to the four-beacon configuration just considered, suppose that it is satellite #2 and not satellite #1 which is replaced by the pseudolite (see Figure B-2). Assume a cone angle, γ, of 45 degrees and a pseudolite accuracy factor, k, of unity. Then a user at the touchdown point sees

$$HDOP = 3.366$$
$$VDOP = 0.707$$
$$PDOP = 3.440$$
$$TDOP = 0.707$$
$$GDOP = 3.512,$$

while a second user, located at the same altitude (one meter) but 100 m west of the first, sees

$$HDOP - 1.990$$
$$VDOP = 2.412$$
$$PDOP = 3.127$$
$$TDOP = 1.620$$
$$GDOP = 3.525.$$

Both of these sets of values are reminiscent of the original four-beacon configuration. On the other hand, a third user, located similarly to the second but to the east instead, sees

```
HDOP = 16.449
VDOP = 15.903
PDOP = 22.879
TDOP = 16.555
GDOP = 28.240,
```

values which are considerably greater than either the baseline
or the four-beacon configuration.

The explanation for this phenomenon has already been given in
Figure B-4. Indeed, if one rotates the vertical at the third user's
position through an angle of 45.29 degrees in a westerly direction,
then, with respect to this new "vertical," satellite #1 and the
pseudolite appear at an elevation of 44.71 degrees; satellites
#3 and #4, at 48.48 degrees. As Figure B-4 demonstrates, four beacons
at such similar elevations inevitably produce the poor performance
observed by the third user.

B.1.3 Discussion

The preceding sections have attempted to present a quantitative
method whereby the accuracy of the GPS multilateration system can
be assessed and to apply this technique to the case of pseudolite-
augmentation. The results obtained, although not demonstrating the
sort of striking performance improvement one would hope for, never-
theless indicate the feasibility of using pseudolites to improve
navigation accuracy in the near-terminal area.

It is clear, however, that the analyses presented are, to a
certain extent, oversimplified and, hence, incomplete. Indeed,
attention is restricted to the isolated problem of static position
estimation in the context of an idealized satellite/pseudolite
geometry. Although the results thereby obtained are claimed to be
pertinent to the stated goal of assessing the performance gain to
be achieved with pseudolite augmentation, nevertheless it is realized
that considerable analysis remains to be done to provide a definitive

evaluation. The discussion which follows attempts to identify problem areas which have not been addressed.

It is noted in the analysis section that the companion problems of static position estimation and static velocity estimation are, to a great extent, separable. In the interests of simplicity, therefore, it is logical to examine only the more fundamental of the two, namely the former, to gauge the performance of the satellite/ pseudolite configurations considered. However, the more comprehensive problem of real-time trajectory estimation, which effectively subsumes the two static estimation problems, demands that position and velocity be treated jointly and not separately. Indeed, the techniques commonly employed to solve the dynamic estimation problem require the development of a user dynamical model by means of which the motion of the user may be predicted reasonably accurately from one measurement, or observation, instant to the next. For example, with the notation of Section B-1.1, one might employ the simple model

$$X(t_k) = X(t_{k-1}) + (t_k - t_{k-1})\, \dot{X}(t_{k-1})$$

$$+ \frac{1}{2}(t_k - t_{k-1})^2\, \ddot{X}(t_{k-1})$$

$$\dot{X}(t_k) = \dot{X}(t_{k-1}) + (t_k - t_{k-1})\, \ddot{X}(t_{k-1})$$

$$\ddot{X}(t_k) = \ddot{X}(t_{k-1})\ ,$$

to predict user motion, where t_{k-1} and t_k denote two successive time instants at which observations of user position (including clock bias) and velocity (including clock drift) are obtained. The object, then, is to use the observations together with the model to derive position, velocity, and acceleration estimates.

Now examination of the first of the model relations above (or simple intuition) suggests that the accuracy with which a dynamic position estimate can be made depends both on the accuracy

of the corresponding static position estimate and on that of the static velocity estimate. Stated another way, improving the accuracy of both of the static estimates should lead to a double improvement in the accuracy of the dynamic position estimate, an effect which is obviously not incorporated in Figures B-7 through B-14. It follows, therefore, that Section B-1.2 cannot represent a complete assessment of pseudolite-augmented GPS and underestimates, for the most part, the performance of this concept.

A suggested study to remedy this deficiency would involve an application of, say, Kalman filtering methodology to the problem posed above. Thus, for example, one could examine the position errors associated with aircraft flight through a terminal area traffic pattern to touchdown, particular attention being paid to the rate at which navigation updates are obtained, the effect of aircraft maneuvers on accuracy, and the impact of any time delays in pseudolite acquisition.

A second area in which implications of potential significance have been made concerns various satellite-related factors: their orbital motion and their random errors. Thus, the entire question of orbital kinematics is circumvented by postulating the satellite configuration of Figure B-2, which is effectively specified by a single parameter. Moreover, the ranging errors of all satellites are assumed to possess identical satistical properties, irrespective of satellite/user geometry.

Although it is doubtful that realistic modelling of satellite motion and/or ranging accuracy would lead to a significant change in the results presented, nevertheless an accurate appraisal of performance requires that these factors be accounted for. Thus, for example, it would be desirable to identify for the complete GPS satellite constellation the sort of satellite geometries available to a user and the extent to which they resemble or differ from the simple geometry of Figure B-2. (More generally, the problem of picking an optimal satellite cluster for navigation should be considered.)

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The question of satellite accuracy has a number of facets. With respect to the simple analysis of Section B-1.1, one might improve realism by simply including in the standard deviation of a satellite's ranging error a factor to account for satellite/user orientation and the degree to which a signal propagation path connecting them must pass through the earth's atmosphere. Furthermore, one could improve the overall analysis by a more careful consideration of the effect of errors in the data transmitted from satellite to user; namely, satellite ephemeris and clock bias. Note that these errors are essentially ignored in the earlier analysis by treating them as "equivalent ranging errors."

As in the case of satellites, the performance of pseudolites has likewise been treated somewhat lightly. Of particular interest in this case is the question of how a pseudolite clock is obtained and, then, of how accurate the clock is. Thus, one could imagine equipping the pseudolite with its own GPS receiver, through which it obtains clock information directly from satellites. An alternative solution might be to slave the pseudolite to the GPS master clock (ground-based) through a calibrated and carefully controlled land-line. Although the former procedure may not provide the accuracy of the latter, nevertheless, it has the advantage of representing a purely passive addition to the overall system.

ATTACHMENT A TO APPENDIX B

MULTILATERATION ALGORITHM

The purpose of this appendix is to outline an algorithm for solving equations (B-11) and (B-12), thereby obtaining the initial estimates $\hat{x}_0$, $\hat{y}_0$, $\hat{z}_0$, $\hat{\delta}_0$, $\hat{\dot{x}}_0$, $\hat{\dot{y}}_0$, $\hat{\dot{z}}_0$, and $\hat{\dot{\delta}}_0$. The algorithm focuses first on the range equations (B-11) to obtain the first four of these estimates; it uses these results, then, in the range rate equations (B-12) to calculate the final four estimates. It is assumed throughout that N beacons are employed, where N is no less than four.

The range equations are first written in the compact form

$$(X - X_i)^T (X - X_i) = (d_i{}^{\circ} - \delta)^2 , \quad i = 1, \ldots, N, \quad \text{(B/A-1)}$$

where

$$X = \begin{bmatrix} x \\ y \\ z \end{bmatrix} , \qquad X_i = \begin{bmatrix} x_i \\ y_i \\ z_i \end{bmatrix} , \qquad \text{(B/A-2)*}$$

and the noise term δ_i has been declared negligibly small. Subtracting the (i + 1)st from the ith of these equations gives, for $i = 1, \ldots, N - 1$,

$$(X_{i+1} - X_i)^T X - (d^{\circ}_{i+1} - d_i{}^{\circ}) \delta$$

$$- \frac{1}{2}(r^2_{i+1} - d^{\circ 2}_{i+1} - r^2_i + d^{\circ 2}_i) = 0 , \qquad \text{(B/A-3)}$$

where $r^2_i \triangleq X_i{}^T X_i$. Expressed in matrix form, the equations (B/A-3) appear as

$$AX - \delta B - C = 0 \qquad \text{(B/A-4)}$$

where A is an (N - 1) x 3 matrix,

---

*In contrast to Section B-1.2, the column vector X now does not contain δ as a fourth element.

$$A = \begin{bmatrix} (X_2 - X_1)^T \\ \vdots \\ (X_N - X_{N-1})^T \end{bmatrix}, \tag{B/A-5}$$

and B and C are $(N - 1)$ - column vectors,

$$B = \begin{bmatrix} d_2{}^\circ - d_1{}^\circ \\ \vdots \\ d_N{}^\circ - d_{N-1}^\circ \end{bmatrix} \tag{B/A-6}$$

$$C = \frac{1}{2}\begin{bmatrix} r_2{}^2 - d_2^{\circ 2} - r_1{}^2 + d_1^{\circ 2} \\ \vdots \\ r_N{}^2 - d_N^{\circ 2} - r_{N-1}^2 + d_{N-1}^{\circ 2} \end{bmatrix}. \tag{B/A-7}$$

Now for any arbitrary but fixed δ, the value of X which renders the left-hand side of (B/A-4) the smallest, i.e., which minimizes the length of this vector, is given by

$$X(\delta) = (A^T A)^{-1} A^T C + \delta (A^T A)^{-1} A^T B \triangleq X(0) + \delta H . \tag{B/A-8}$$

Note that, when N = 4, A is a square matrix and this formula reduces to the familiar form

$$X(\delta) = A^{-1} C + A^{-1} B . \tag{B/A-9}$$

It is seen, therefore, that the more complicated expression (B/A-8) extends the solution (B/A-9) to the case in which more than four beacons are used.

The expression (B/A-8) is next substituted into the original equation (B/A-1) for i = N, giving

$$(X(\delta) - X_N)^T (X(\delta) - X_N) = (X(0) - X_N - H)^T (X(0) - X_N - H)$$

$$= (d_N{}^\circ - \delta)^2 . \qquad \text{(B/A-10)}$$

Expanding terms and rearranging give the quadratic equation

$$[1 - H^T H]\delta^2 - 2[d_N{}^\circ - H^T(X(0) - X_N)]\delta$$

$$\text{(B/A-11)}$$

$$+ [d_N^{\circ 2} - (X(0) - X_N)^T (X(0) - X_N)] = 0 ,$$

the two solutions to which are denoted δ_1 and δ_2. In turn, corresponding to these solutions are the respective solutions for position, $X(\delta_1)$ and $X(\delta_2)$, found from (B/A-8).

The two solutions $(X(\delta_1), \delta_1)$ and $(X(\delta_2), \delta_2)$ are next tested for credibility; employing subsidiary information, the user is assumed capable of rejecting properly one of the solutions as being unrealistic. The remaining solution is then taken to define the initial estimates $\hat{x}_0$, $\hat{y}_0$, $\hat{z}_0$, and $\hat{\delta}_0$.

Experience has indicated that the proper solution to use in the case of satellite beacons alone is obvious: it is the one corresponding to the smaller of δ_1 and δ_2. The addition of pseudolites, however, invalidates this simple criterion; indeed, the proximity of pseudolites to the user can lead to positions $X(\delta_1)$ and $X(\delta_2)$ which are reasonably near one another. Indicated, therefore, **is the need for** more care in choosing δ_1 or δ_2 as the proper clock bias term.

Attention is next shifted to the range-rate equation (B-12) into which has been substituted the position estimate just obtained. Inspection of the resulting equation indicates that it can be written in the compact form

$$Q_i \dot{X} + \dot{\delta} = \dot{d}_i{}^\circ + Q_i \dot{X}_i , \quad i = 1, \dots, N, \qquad \text{(B/A-12)}$$

where $\dot{X}$ and $\dot{X}_i$ denote the time-derivatives of the vectors (B/A-2) and

Q_i denotes the ith row of the direction-cosine matrix defined in (B-34). Writing these N equations in matrix form gives

$$Q\dot{X} + \dot{\delta}J - \dot{D}^\circ - V = 0 \;,$$

(B/A-13)

where J and $\dot{D}^\circ$ are the N-column vectors defined in (B-23) and (B-20), respectively, and V is the N-column vector

$$V = \begin{bmatrix} Q_1\dot{X}_1 \\ \cdot \\ \cdot \\ \cdot \\ Q_N\dot{X}_N \end{bmatrix}$$

(B/A-14)

The values of $\dot{X}$ and $\dot{\delta}$ which minimize the left-hand side of (B/A-13) are given by

$$\begin{bmatrix} \dot{X} \\ \dot{\delta} \end{bmatrix} = (\Phi^T\Phi)^{-1} \, \Phi^T(\dot{D}^\circ + V)$$

(B/A-15)

where Φ is defined in (B-14). Note that, analogous to (B/A-8), this formula simplifies to

$$\begin{bmatrix} \dot{X} \\ \dot{\delta} \end{bmatrix} = \Phi^{-1}(\dot{D}^\circ + V)$$

(B/A-16)

when N = 4. The values defined by (B/A-15) are taken, of course, to be the initial estimates $\hat{\dot{x}}_0$, $\hat{\dot{y}}_0$, $\hat{\dot{z}}_0$, $\hat{\dot{\delta}}_0$.

ATTACHMENT B TO APPENDIX B

COMPUTER ROUTINES TO EVALUATE MULTILATERATION ACCURACY

This appendix contains listings of the computer routines used to obtain the numerical results presented in Section B-1.2. The routine SDOP is the master routine; a second slave routine, SINV, is used to compute a matrix inverse. These subroutines should be self-explanatory.

```fortran
              SUBROUTINE SDOP(NS, NP, XB, YB, ZB, K, XU, YU, ZU,
                             HDOP, VDOP, PDOP, TDOP, GDOP, IND)
        1
C
C*****   PURPOSE:  COMPUTE DILUTION OF PRECISION MEASURES
C*****            FOR SATELLITE/PSEUDOLITE MULTILATERATION SYSTEM.
C*****   INPUT:   NS=NUMBER OF SATELLITES;
C*****            NP=NUMBER OF PSEUDOLITES;
C*****            (XB(I),YB(I),ZB(I),I=1,NS)=SATELLITE POSITIONS;
C*****            (XB(I)YB(I),ZB(I),I=NS+1,NS+NP)=PSEUDOLITE POSITIONS;
C*****            K=PSEUDOLITE ACCURACY FACTOR;
C*****            (XU,YU,ZU)=USER POSITION.
C*****   OUTPUT: HDOP=HORIZONTAL DILUTION OF PRECISION;
                 VDOP=VERTICAL DILUTION OF PRECISION;
C*****            PDOP=POSITION DILUTION OF PRECISION;
C*****            TDOP=TIME DILUTION OF PRECISION;
C*****            GDOP=GEOMETRIC DILUTION OF PRECISION;
C*****            IND=VALIDITY INDICATOR (IND. NE. Ø FOR GOOD SOLUTION).
C*****   RESTRICTIONS:  NS+NP<=1Ø; IF NP>Ø, THEN K>Ø.
C
         REAL K
         DIMENSION XB(1Ø),YB(1Ø),ZB(1Ø)
         DIMENSION SI(1Ø),C(1Ø,4),PI(4,4),P(4,4)
C
C****    COMPUTE NUMBER OF BEACONS
C
         N=NS+NP
C
C****    SET UP RANGE-ERROR COVARIANCE MATRIX
C
         DO 21Ø I=1,N
         SI(I)=1.
         IF(I. GT. NS) SI(I)=1. /K/K
21Ø      CONTINUE
C
C****    SET UP DIRECTION-COSINE MATRIX
C
         DO 22Ø I=1,N
         DX=XU-XB(I)
         DY=YU-YB(I)
         DZ=ZU-ZB(I)
         DR=SQRT(DX*DX+DY*DY+DZ*DZ)
         C(I,1)=DX/DR
         C(I,2)=DY/DR
         C(I,3)=DZ/DR
         C(I,4)=1.
22Ø      CONTINUE
C
C****    COMPUTE INVERSE OF
C****             POSITION-ESTIMATE-ERROR COVARIANCE MATRIX
C
```

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```
          DO 240 I=1,4
          DO 240 J=1,I
          DPI=0
          DO 230 L=1,N
          DPI=DPI+C(L,I)*SI(L)*C(L,J)
230       CONTINUE
          PI(I,J)=DPI
          PI(J,I)=DPI
240       CONTINUE
C
C****     INVERT INVERSE OF
C****               POSITION-ESTIMATE-ERROR COVARIANCE MATRIX
C
          CALL SINV(4,PI,4,P,4,1,IND)
C
C****     COMPUTE DOP MEASURES
C
          HDOP=SQRT(P(1,1)+P(2,2))
          VDOP=SQRT(P(3,3))
          PDOP=SQRT(P(1,1)+P(2,2)+P(3,3))
          TDOP=SQRT(P(4,4))
          GDOP=SQRT(P(1,1)+P(2,2)+P(3,3)+P(4,4))
          RETURN
          END
```

```
             SUBROUTINE SINV(M, A, NA, B, NB, NIT, IND)
C
C*****    PURPOSE:   COMPUTE INVERSE OF POSITIVE-DEFINITE MATRIX.
C*****    INPUT:     ((A(I,J),J=1,M),I=1,M)=GIVEN MATRIX;
C*****               NA=STORAGE DIMENSION ALLOCATED TO A;
C*****               NB=STORAGE DIMENSION ALLOCATED TO B;
C*****               NIT=NUMBER OF NEWTON-RAPHSON ITERATIONS DESIRED.
C*****    OUTPUT:    ((B(I,J),J=1,M),I=1,M)=INVERSE MATRIX;
C*****               IND=EXISTENCE INDICATOR (IND. NE. Ø IF
C*****                       GIVEN MATRIX POSITIVE-DEFINITE).
C*****    RESTRICTIONS:  2<=M<=MINØ(4,NA,NB).
C*****    SUBROUTINES REQUIRED:  MINØ,SQRT
C*****    METHOD:   SQUARE-ROOT TECHNIQUE FOLLOWED BY NEWTON-
C*****              RAPHSON ITERATION.
C
         DIMENSION A(NA,NA),B(NB,NB)
         DIMENSION S(4,4),D(4,4)
         IND=Ø
         IF(M. LT. 2. OR. M. GT. MINØ(4,NA,NB)) RETURN
C
C***     SQUARE-ROOT TECHNIQUE
C
         IF(A(1,1). LE. Ø ) RETURN
         S(1,1)=SQRT(A(1,1))
         DO 11Ø J=2,M
         S(1,J)=A(1,J)/S(1,1)
11Ø      CONTINUE
         IF(M. EQ. 2) GOTO 15Ø
         DO 14Ø I=2,M-1
         T=Ø.
         DO 12Ø L=1,I-1
         T=T+S(L,I)*S(L,I)
12Ø      CONTINUE
         IF(A(I,I).LE.T) RETURN
         S(I,I)=SQRT(A(I,I)-T)
         DO 14Ø J=I+1,M
         T=Ø
         DO 13Ø L=1, I-1
         T=T+S(L,I)*S(L,J)
13Ø      CONTINUE
         S(I,J)=(A(I,J)-T)/S(I,I)
14Ø      CONTINUE
15Ø      CONTINUE
         T=Ø
         DO 17Ø L=1,M-1
         T=T+S(L,M)*S(L,M)
17Ø      CONTINUE
         IF(A(M.M).LE.T) RETURN
         S(M,M)=SQRT(A(M,M)-T)
         DO 22Ø J=1,M-1
         D(J,J)=1./S(J,J)
         DO 22Ø I=J+1,M
         T=Ø.
```

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```
          DO 210 L=J, I-1
          T=T+S(L,I)*D(L,J)
210       CONTINUE
          D(I,J)=-T/S(I,I)
220       CONTINUE
          D(M,M)=1./S(M,M)
          DO 320 I=1,M
          DO 320 J=1,I
          T=0
          DO 310 L=1,J
          T=T+D(L,I)*D(L,J)
310       CONTINUE
          B(I,J)=T

          B(J,I)=T
320       CONTINUE
          IND=1
C
C***      NEWTON-RAPHSON ITERATION
C
          IF(NIT.LE.0) RETURN
          DO 470 N=1,NIT
          DO 420 I=1,M
          DO 420 J=1,M
          T=0.
          DO 410  L=1,M
          T=T+A(I,L)*B(L,J)
410       CONTINUE
          IF(J.EQ.I) T=1.+T
          S(I,J)=T
420       CONTINUE
          D(1,1)=B(1,1)
          DO 440 I=2,M
          DO 430 J=1, I-1
          D(I,J)=B(I,J)
          D(J,I)=B(J,I)
430       CONTINUE
          D(I,I)=B(I,I)
440       CONTINUE
          DO 460 I=1,M
          DO 460 J=1,I
          T=0.
          DO 450 L=1,M
          T=T+D(I,L)*S(L,J)
450       CONTINUE
          B(I,J)=B(I,J)+T
          B(J,I)=B(I,J)
460       CONTINUE
470       CONTINUE
          RETURN
          END
```

APPENDIX C - RNAV SYSTEM SURVEY

C.1 GPS SYSTEM DESCRIPTION*

The Global Positioning System (GPS) is a sophisticated satellite navigation system which will potentially provide a highly diverse (in terms of requirements) worldwide user community with precision position and velocity estimates. Predictions of achievable accuracy are such that the potential exists for GPS obviating at least some of the current, more conventional, navigation systems. GPS schedule calls for a developmental system by 1977, limited capability by 1980, and a fully operational system by 1984. A major thrust of the GPS program is to reach an expanding user community through the development of low-cost systems. It is toward that end that this description is addressed.

GPS is comprised of three major subsystems. These are the space segment, the ground segment, and the user segment. The space segment consists of a network of 24 satellites which provide the user with signals from which position and velocity are derived. The ground segment monitors satellite position and upload this information to the satellite for referral to the user. The user segment than calculates position with respect to the satellite constellation, and knowing satellite position, refers this to an earth centered or appropriate local coordinate system. The overall GPS concept is shown in Figure C-1.

GPS system concept - The GPS concept is basically that of multilateration. Knowledge of range between a receiver and a satellite locates that receiver on the surface of a sphere such that utilization of three independent satellites locates the receiver at the intersection of the three associated spheres, given a precise time reference. The GPS concept provides for their highly accurate time reference except at the user receiver. The receiver clock is assumed to have an error and a fourth satellite is tracked in order to estimate this error.

---

* This discussion was extracted from the previous RTI study final report [C-1] and is included for completeness.

SPACE SEGMENT -

```
┌─────────────────────────────────┐
│ 4 SELECTED SATELLITES EACH WITH  │
│    PRECISION TIME STANDARD       │
│                                  │
│ PSEUDORANDOM CODE(S)             │
│                                  │
│ TELEMETRY DATA                   │
└─────────────────────────────────┘
```

(S-BAND)
SATELLITE
EPHEMERIS
CONSTANTS
CLOCK CORRECTION
FACTORS
IONOSPHERIC DATA

(L_1, L_2)--PSEUDO RANGE DATA

CURRENT EPHEMERIS DATA
TIME & CLOCK CORRECTION FACTORS
IONOSPHERIC DATA

(L_1, L_2)--PSEUDO RANGE
DATA

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```
┌──────────────┐   ┌──────────────┐   ┌──────────────┐        ┌──────────────┐
│ MONITOR      │   │MASTER CONTROL│   │UPLOAD STATION│        │  ACCURATE    │
│   STATIONS   │──▶│   STATION    │──▶│              │        │              │
│ ALASKA       │   │              │   │  VANDENBERG  │        │  POSITION    │
│ VANDENBERG   │   │  VANDENBERG  │   │              │        │  VELOCITY    │
│ GUAM         │   │              │   │              │        │  TIME        │
│ HAWAII       │   │              │   │              │        │              │
└──────────────┘   └──────────────┘   └──────────────┘        └──────────────┘
```

Figure C-1. Overall GPS System Concept [C-1]

Three dimensional position and time are obtained by solving the set of simultaneous equations:

$$(X_{USER} - X_{SATi})^2 + (Y_{USER} - Y_{SATi})^2 + (Z_{USER} - Z_{SATi})^2 =$$

$$(Ri - \Delta R)^2, \; i = 1,4$$

where

X, Y, Z are user and satellite position co-ordinates,

R_i is the (measured) range to the i^{th} satellite,

and

ΔR is the error in measured range due to user clock error.

Each satellite is equipped with its own atomic time standard as is each ground station. A master clock is located in the master control station and all clocks are referenced to it. Each satellite is advised of its current bias with respect to the master clock and this information provided (via telemetry data) to each user receiver. The user then knows precisely the time a transmission left the satellite and knows within his own clock error (which he can determine) the time he received the signal and can thus determine range-to-satellite accurately.

The Space Segment - The space segment consists of a constellation of satellites orbiting in three distinct planes, each separated by 60 degrees of longitude. A total constellation contains 24 satellites (i.e., 8 satellites per plane). The satellite orbits are circular at 20,000 km giving a 12 hour period with an inclination of approximately 63°. This ensures that at least 6 satellites (with elevation in excess of 5°) are in view from any point on the earth.

Each satellite transmits two L-band carrier signals which are bi-phase modulated with a composite pseudo-random noise code. For the primary carrier (1575 MHz), the code contains a "clear" signal for code acquisition

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(and for lower precision navigation), a "protected" signal for precision navigation and anti-jam capability, as well as telemetry data which includes synchronization, clock data, handover data (to acquire the "protected" code having first acquired the "clear" code), and ephemeris data. The secondary carrier (1230 MHz) is modulated in a similar manner with the exception that the "clear" code is omitted. Transmittal of the two carriers provides for compensation of propagation delays experienced in the ionosphere.

The "clear" code is generated at a 1.023 MHz chipping rate and has a code length of 1 ms. The "protected" code is generated at a 10.23 MHz chipping rate and has a code length of 265 days, truncated to seven days. Both "clear" and "protected" code sequences are spacecraft unique. The telemetry data occurs at a 50-bit-per-second rate. For clarity and conciseness, more detailed code parameters are omitted here but are included in the detailed signal structure description contained in Appendix A of [C-1].

The Ground Segment - The ground segment tracks the satellite constellation and provides each satellite with daily updates correcting its ephemeris coordinates and its clock bias factors. The ground segment is conveniently subdivided into three functional elements; the monitor station's function is to receive the two L-band carrier signals and to process them to extract pseudorange and pseudorange-rate data to be forwarded to the master control station for correction of atmospheric effects. The monitor station contains a precision atomic time reference used in obtaining ranging data, data clocking, and time-of-day. The master control station then processes the tracking data received from the monitor stations to generate the update messages. The fully redundant atomic time reference maintained at the master control station generates the system time base against which all other clocks (satellite, monitor stations, and upload station) are compared and calibrated. The master control station performs orbit determination from monitor station inputs, generates ephemeris data (normally nine orbital parameters), and formats this with clock data for upload to the spacecraft. The upload station transfers the navigation data to the satellite via an S-band link. In addition it verifies that the data has indeed been correctly loaded.

The User Segment - The user community is categorically divided by DOD into six classes dependent on user requirements. The requirements which determine each class are accuracy, user dynamics, and immunity to electromagnetic warfare. Three levels of receiver sophistication have been designated to satisfy the user requirements. The "X" receiver addresses the user with high to medium performance requirements with regard to all three of the above. The "X" receiver is "continuous" in the sense that four satellites are tracked simultaneously to provide a full navigation solution at each receiver iteration (approximately 10 solutions per second). For the user with low dynamics, system complexity (and cost) is reduced by adopting a "sequentially" tracking ("Y") receiver which commutates through the ensemble of four satellites required for a solution and produces an output at the completion of the cycle (approximately 2 solutions per second). If a reduction in achievable accuracy is allowed, the receiver can be designed to operate only on the "clear" code resulting in a much simpler version. This is the so-called "Z" or low-cost GPS receiver and is the probable candidate for general aviation interest.

As mentioned previously, the GPS receiver tracks pseudorange and pseudorange-rate from four satellites in order to solve for three coordinates of position and velocity and the user clock bias. Computing the user clock error at each navigation solution obviates the requirement of an accurate clock at the receiver while still maintaining overall precision. This has the further advantage that effectively the user is provided with a precision time standard.

Functional description - According to presently available documentation, the precise receiver design varies with manufacturer. RTI has reviewed the Philco Ford, the General Dynamics (from the preliminary definition phase studies), the Magnavox Spartan, the Rockwell Spartan, the Collins, and the Texas Instruments receiver designs (Reference C-2 through C-8). All designs reviewed share some commonality. Each possesses a PN code generator which creates the replica code. This code is bit-synchronized with the incoming code and removed (usually) at the first IF. The final IF is detected synchronously (a Costas loop) for range and range-rate measurement. Telemetry data is demodulated conventionally for input to the navigation algorithm. The algorithms are processed digitally, usually with a

microprocessor. User outputs are generally available either in earth centered coordinates or in a local coordinate system which can be corrected for altitude.

The Spartan receiver has the following salient features which distinguish it from the higher performance types (Reference C-4):

1. It operates on a single GPS frequency. Operation on a single frequency results in a reduced capability to compensate for ionospheric delay. In lieu of a second frequency, the delay calculation is based on use of an ionosphere model.

2. It currently employs only the "clear" signal. Utilization of the "clear" code reduces the code chip rate by a factor of ten which (reportedly) reduces achievable accuracy.

3. The accuracy is in the range of 30-100 meters. Table C-1 indicates a proposed error budget.

4. Time-to-first-fix is not a critical parameter and may be on the order of minutes. Time-to-first-fix requires reception of one full telemetry frame from each of 4 satellites sequentially. Each frame is approximately 30 seconds long; thus, a lower bound on time-to-first-fix is approximately two minutes.

5. Time between fix is only moderately critical and is baselined between 10 and 30 seconds. Once the receiver has gotten a first-fix and is in track, it is estimated to take 3-6 seconds per satellite to complete the necessary processing. Sequencing through four satellites can then be expected to take 12-24 seconds to output one navigation solution.

In the event the navigation solution algorithm is updated each time a satellite is sequenced, this time is reduced to be on the order of 3-6 seconds.

It should be noted that the above performance is in sharp contrast to that achievable with the high performance, 4-channel continuous receiver. For this receiver updates are at the rate of ten per second, time-to-first-fix is on the order of tens of seconds, and accuracy is on the order of

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Table C-1. GPS Error Budget [C-5]

Source	Clear Code Only	Single Protected Code	Two Protected Code
ephemeris	1.5	1.5	1.5
satellite clock and electronics	1.0	1.0	1.0
troposphere (model)	1.5	1.5	1.5
ionosphere (model)	15.0	5.0	zero
receiver noise	3.0	1.5	2.5
multipath	1.25	1.25	2.0
Total (meter-RMS)	15.5	6.0	4.0
	(Z Rcvr)		(X Rcvr)

(Assuming a geometric-dilution-of-precision of 1.5 to 3, the 15.5 meter RMS for clear only code translates to approximately 35 meters while the 4.0 meter RMS for the two protected codes translates to approximately 9 meters.)

seconds, and accuracy is on the order of a few meters. Also, with ground agumentation, potential accuracy is even further improved.

RF Link (Power) Loss Budget - The required signal levels at the user equipment as specified in the Rockwell System Specification [C-9] are shown in Table C-2.

An RF link calculation has been extracted from the General Dynamics Contract Definition Study [C-3] and is included in Table C-3. A user elevation angle of 5° is also shown and is taken as representative of worst case.

Table C-2. Required User Equipment Received Signal Levels [C-9]

	FREQUENCY	
	L_1	L_2
C/A Signal (dBw)	-163	N/A
P-Signal (dBw)	-163	-166

Table C-3. RF Link Calculation of User Received Power [C-3]

	ZENITH			USER ELEVATION ANGLE=5°		
	L_1		L_2	L_1		L_2
	C/A	P	P	C/A	P	P
Satellite Transmitter Power (dBw)	14.25	11.25	6.35	14.25	11.25	6.40
RF Losses (dB)	1.0	1.0	1.0	1.0	1.0	1.0
Antenna Polarization Loss (dB)	0.25	0.25	0.25	0.25	0.25	0.25
Antenna Gain (dB)	15	15	15	12	12	12
Satellite EIRP (dBw)	28	25	20.1	25	22	17.15
Path Loss (dB)	182.5	182.5	180.6	184.2	184.2	182.3
Atmospheric Absorption (dB)	-	-	-	0.85	0.85	0.85
Total Power at User Antenna (dBw)	-154.5	-157.5	-160.5	-160	-163	-166

C.2 621B SYSTEM DESCRIPTION

621B is a military predecessor to the NAVSTAR/GPS system very similar
in concept. The essential difference is in the satellite constellation
where three arrays of four satellites each were stationed in geosynchronous
orbits. One of each of the four had zero inclination and appeared
stationary to the user while the other three were at progressively
increasing inclination resulting in the effect of a rotating "Y" with
respect to the user. As in GPS pseudo-random ranging was also part of the
system concept.

This discussion differs from the others in this appendix in that due
to the combination of pertinent documents being Limited Distribution and of
the relative age of the program resulted in relevant literature being
difficult to procure. The specific receiver discussed here does, however,
shed light on the system concept. The discussion is reproduced in near
entirety for completeness.

Defense Navigation Satellite System (DNSS)/621B Receiver Description [C-10]

A pictorial representation of the DNSS is shown in Figure C-2 and a
composite block diagram for the receiver is shown in Figure C-3. The
incoming PN spread-spectrum NAVSAT signal is a biphase PSK signal clocked
at a 10 MHz rate, resulting in an overall bandwidth of 20 MHz as measured
across the first nulls of a $(\sin x/x)^2$ power spectrum. The incoming
signal is at a carrier frequency of 1575 MHz and is amplified by a low
noise (approximately 5 db noise figure) transistorized preamplifier. The
amplified signal is then down-converted to an IF frequency of 75 MHz using
low-side injection. The nominal input signal level is at -123 dbm,
exclusive of any potential jamming signal effects.

DNSS

SATELLITE SIGNALS
PSEUDO NOISE CODE
ACQUISITION CODE
CLEAR CODE
DATA

MASTER STATION
COMMAND
CONTROL
TRACKING

REMOTE
TRACKING
STATIONS
(2 OR 3)

Figure C-2. DNSS [C-2]

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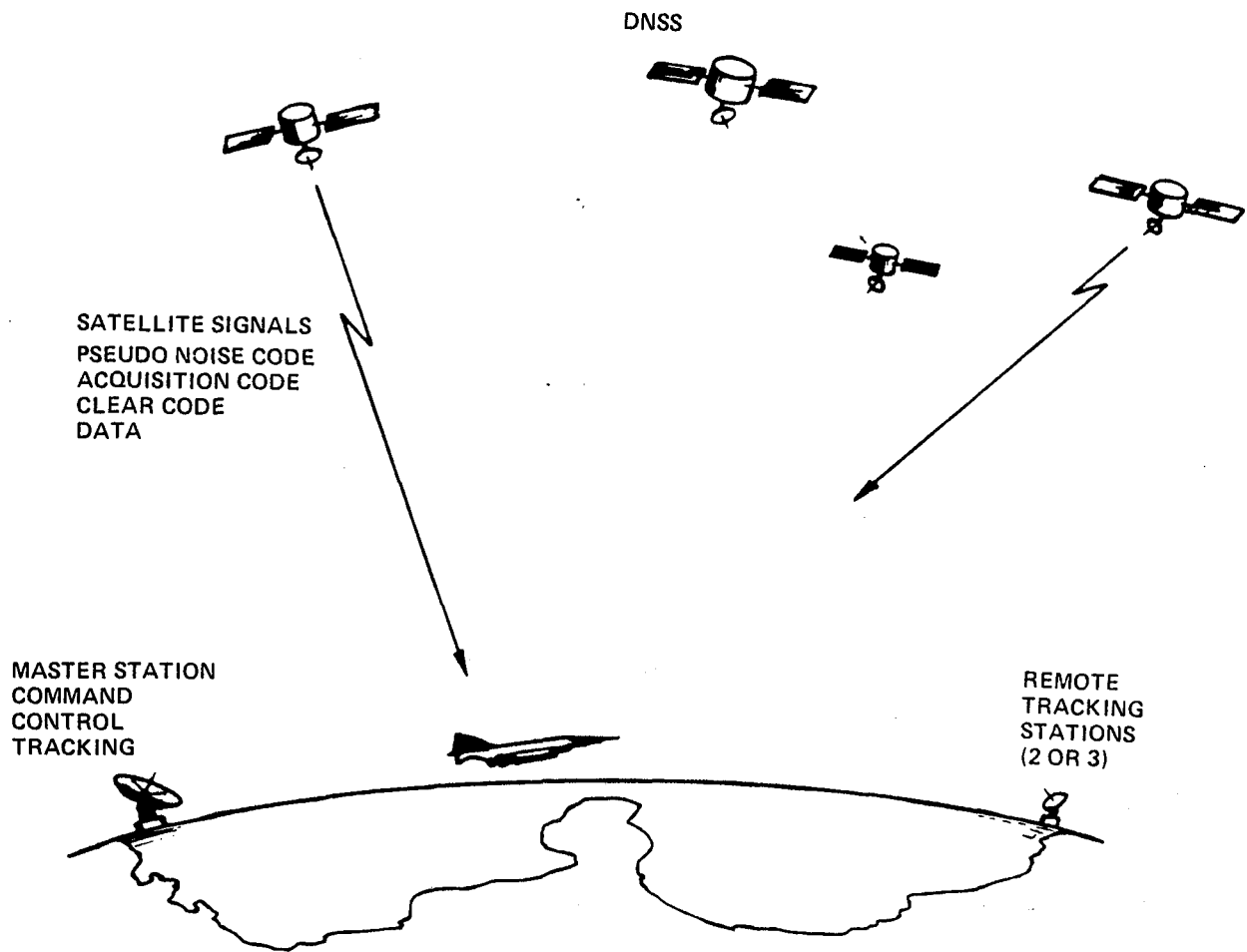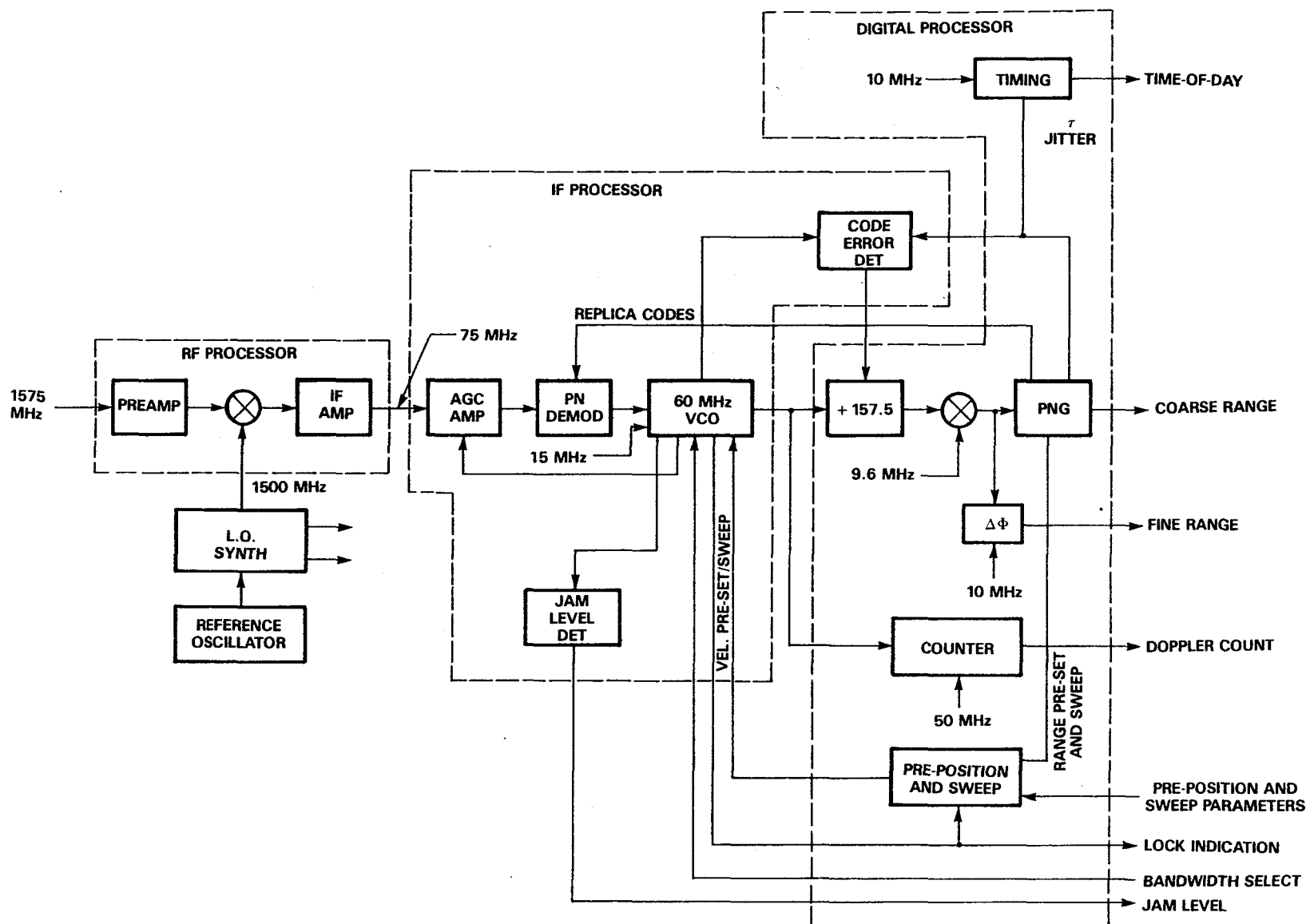
Figure C-3. Composite Block Diagram, Time-Shared DNSS/621B Receiver [C-2]

The 75 MHz IF signal is amplified by an AGC amplifier and applied to a PN demodulator, which functions as a PN signal correlator so as to derive antimultipath and antijam protection. The AGC amplifier nominally operates at full gain (30 db) until PN signal correlation is realized, at which time a coherent AGC voltage is developed by the subsequent VCO loop so as to maintain a relatively constant output signal level from the AGC amplifier and into the PN demodulator.

The PN demodulator is fed with a replica PN code consistent with the particular satellite whose navigational signal is to be processed. When time synchronization is realized, the output of the PN demodulator is a CW sinusoid. A 60 MHz VCO is phase locked to the output of the PN demodulator and performs a number of functions as delineated below.

a. The VCO output is fed to a cycle counter so as to derive a measure of the carrier doppler and, therefore, the satellite range-rate. Prior to the actual counting process, the VCO signal is multiplied in frequency by a factor of 256 so as to provide an ultimate resolution of about 0.08 mm per count.

b. The VCO signal is divided down in frequency by the ratio of the carried frequency to code-lock frequency or, in this case, by 157.5. A reference frequency signal is then added to the output of the divider to form a nominal 10 MHz clock signal for driving the local PN code generator (labeled as PNG). It should be noted that that technique automatically scales the carrier doppler to the required code-doppler factor, eliminating code dynamics considerations.

c. A coherent AGC signal is developed for control of the AGC amplifier.

d. A jam-level detector signal is developed to provide an indication as to the relative input jamming signal levels.

e. A code tracking error signal is developed to perform fine phasing of the local PN code generator.

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Since the PN code generator is clocked at 10 MHz, each clock interval (or chip) is equivalent to about 30 m in range. A coarse range measurement to 30 m is accomplished by essentially sampling the state of the PN code generator. A fine range measurement with a resolution of about 10 cm is accomplished by a vernier measurement technique whereby one-chip interval (about 30 m) is subdivided into 256 increments.

Precision phase control and tracking of the PN code signal is accomplished by means of a time-shared delay lock loop. Thus, in the PN demodulator, a slight code "dither" modulation is applied which manifests itself as a low-modulation index amplitude modulation on the VCO output. This AM signal is coherently detected and compared to the locally generated dither reference signal to form a bipolar tracking error signal. This error signal is used to change the division ratio of the divide by 157.5 divider so as to provide code phase incrementing in 16 cm steps.

The functioning of the NAVSAT receiver requires a phase locked VCO condition and a time synchronized PN demodulator. When considering a high doppler environment, this factor entails a frequency search to realize carrier VCO phase locking and a time search to realize PN code synchronization. A computer aided pre-position and sweep circuit is incorporated to:

a. Select the PN code generator logic corresponding to the satellite whose range/range-rate measurement is to be performed.
b. Preset the PN code generator to the expected time position.
c. Preset the VCO to the expected frequency corresponding to the expected velocity/doppler.

The receiver then performs a sweep in frequency and time to achieve signal acquisition, which is culminated in VCO carrier tracking and code tracking. The carrier VCO loop contains three selectable loop bandwidths, namely, 20 Hz, 100 Hz, and 1000 Hz, with the lowest value providing maximum antijam protection; whereas, the largest bandwidth provides the maximum signal search rates during acquisition modes. In a similar manner, the code loop has controllable loop bandwidths to enable a trade-off between signal acquisition/tracking times versus range readout accuracy.

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RF Processor/L.O. Synthesizer

A functional block diagram of the RF processor/L.O. synthesizer is shown in Figure C-4. The RF processor portion consists of the preselector filter, preamplifier, down conversion mixer, and IF amplifier. Two separate IF outputs are provided at a 75 MHz IF frequency, with one output part used to drive the IF-processor portion of the receiver and the second output part is provided for ultimate inclusion of a short code matched filter for initial acquisition purposes.

The theoretical receiver sensitivity at carrier-loop threshold is shown in Table C-4 as a function of the carrier-loop bandwidth. Receiver sensitivity is defined as that input signal level above which the carrier loop remains in a tracking condition.

PN Demodulator

A functional block diagram of the PN modulator (including AGC amplifier is shown in Figure C-5 and uses two sequential balanced modulators to realize a high CW signal rejection capability (approximately 70 db). The satellite code is depicted as the "X" code; whereas, the "Z" code is a locally generated PN code used to realize improved CW rejection signal capability. When the locally generated "X" code is time synchronous with the received coded signal, ideal correlation is realized and the output of the demodulator is a sinusoid at 75 MHz (assuming no information has been superimposed on the PN code at the transmitter).

To enable subsequent fine code phasing, a portion of the incoming signal is multiplied by a "dithered" version of the satellite code, designated as $x(\tau)$ in the figure. The resultant signal is attenuated and summed with the main correlated signal. The net effect of the "dither" modulation is to add a small square-wave amplitude modulation on the composite correlated signal that is subsequently recovered and used to derive a code tracking error signal for fine code phasing control.

Carrier Loop

The essential elements of the carrier loop are depicted in Figure C-6. The loop is a superheterodyne phase locked VCO with the phase detector portion operating at 15 MHz. The overall loop bandwidth is selectable and

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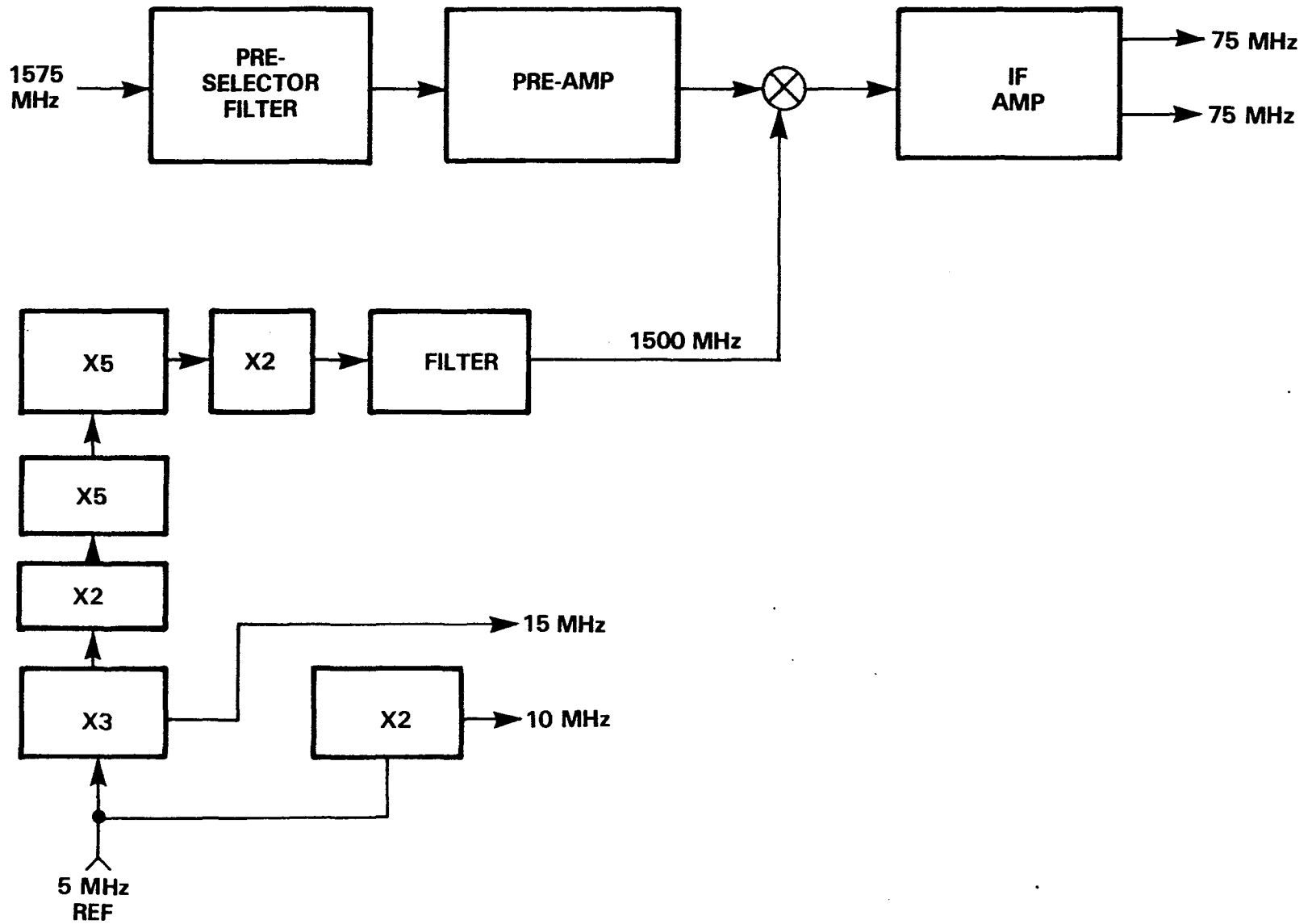
Figure C-4.   RF Processor/L.O. Synthesizer

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Table C-4. Receiver Sensitivity (Theoretical)

		20 Hz	100 Hz	1000 Hz
Loop bandwidth	db	13	20	30
Loop threshold	db	6	6	6
Threshold C/N_0	db/Hz	19	26	36
Input N_0	dbm/Hz	-174	-174	-174
Receiver noise figure	db	5.5	5.5	5.5
Receiver N_0	dbm/Hz	-168.5	-168.5	-168.5
Tracking threshold	dbm	-149.5	-142.5	-132.5
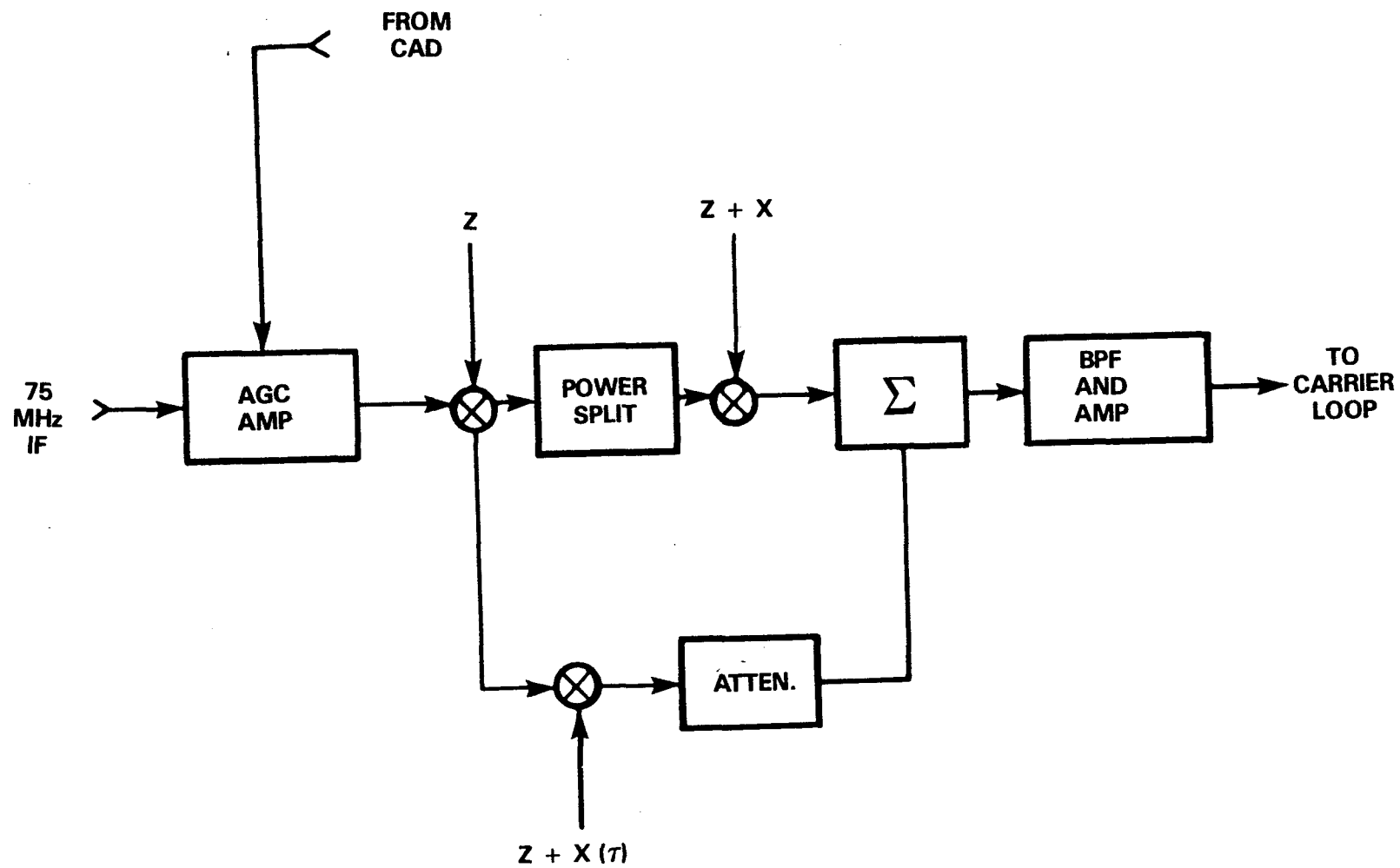
Figure C-5. Block Diagram, PN Demodulator
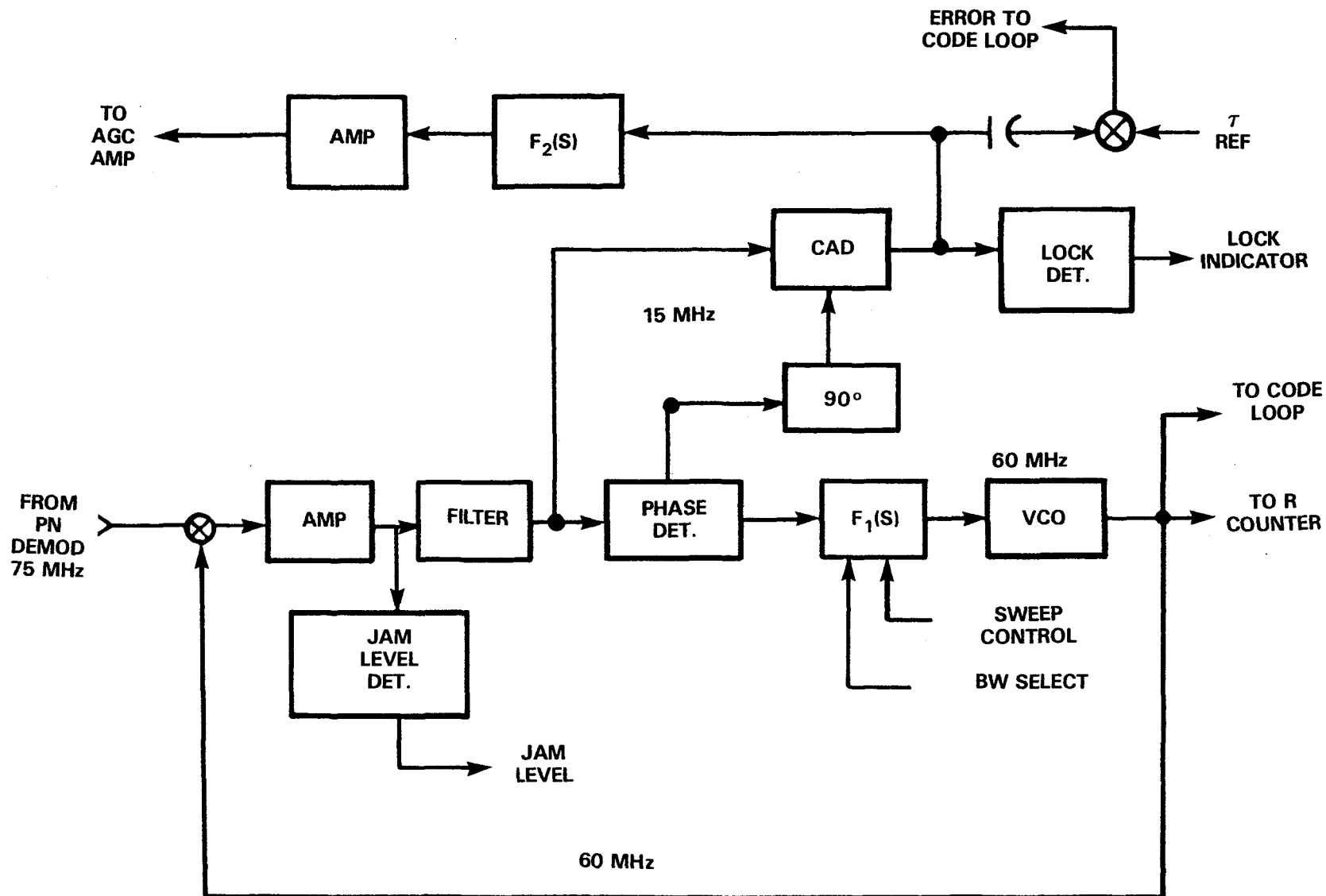
Figure C-6. Carrier Loop

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can be either 20, 100 or 1000 Hz. A sweep control capability is incorpo-
rated to aid in carrier frequency acquisition. When PN code correlation is
realized in the PN demodulator, the input to the carrier loop is a sinusoid
at 75 MHz with associated carrier doppler. The VCO output, when tracking,
is 60 MHz with accompanying carrier doppler. The carrier signal is
detected coherently by a coherent amplitude detector whose output is:

a. Used in a threshold comparison circuit to establish a carrier-lock
    indication.
b. Used to supply an AGC control voltage to the AGC amplifier.
c. Multiplied by a local "dither" reference to derive a code tracking
    error signal.

Code-Clock Derivation and Control

A 10 MHz code-clock signal is derived in the receiver by dividing the
carrier VCO frequency by the ratio of carrier to code frequencies which,
for the NAVSAT test program, is 1575/10 = 157.5. Since the carrier VCO
frequency is nominally at 60 MHz rather than at 1575 MHz, it is necessary
to insert a reference frequency to upconvert the divided signal to the
nominal 10 MHz value, as shown in Figure C-7.

In the actual implementation, the divider is implemented as a divide
by 7, followed by a divide by 45, followed by an X2 multiplier circuit.
For fine code phase control, the developed code error tracking signal is
used to change the divide ratio by $\pm$ 1 count, which is equivalent to ad-
vancing or retarding the code clock in 16 cm steps.

Prepositioning and Sweep

To enable the receiver to initially acquire a particular satellite
signal, a preposition and sweep circuit is incorporated into the receiver
design. As shown in Figure C-6, the carrier loop contains provisions for
accepting velocity (frequency) estimates from an external computer to
preposition the carrier VCO to the expected carrier frequency. A velocity

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VCO
60 MHz

$\div\ 157.5$

$+$

$+$

CODE CLOCK

$(10 - \dfrac{60}{157.5})$ MHz
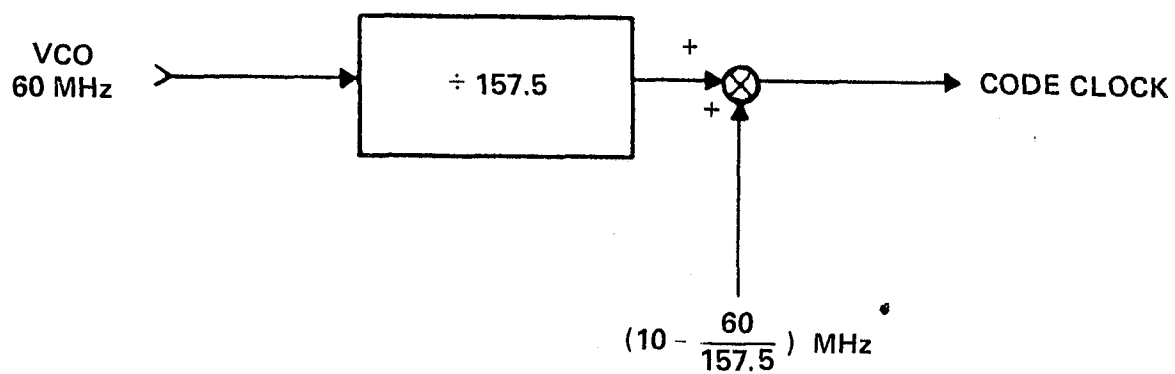
Figure C-7.   Code Clock Derivation

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sweep circuit is also incorporated to automatically search over the velocity (frequency) uncertainty range.

The code prepositioning circuit is illustrated by Figure C-8. A read only memory in the computer stores sixteen different 25-bit words corresponding to sixteen different equally spaced time loadings of the PN code generator (the satellite PN code is generated by a 25-bit shift register whose sequence length at a clock rate of 10 MHz is about 3.355 sec). One of these words is loaded into the receiver PN code generator corresponding to an expected future state of the received PN code. In addition, a timing signal is furnished to the receiver by the computer indicating the time at which the PN generator loading is expected. At the designated time marker, the receiver initiates a PN code search in 1/2-chip increments (15 m increments).

As is noted above, the signal search generally entails both a carrier frequency search and a code phase search. The current receiver design incorporates either a fast-velocity/slow-range, or a fast-range/slow-velocity search. The fast-velocity/slow-range search pattern is depicted in Figure C-9.

The receiver is initially furnished an estimate of the unexpected carrier frequency ($\dot{\hat{R}}$) and expected code phase ($\hat{R}$). However, due to errors in these estimates, a search is required both in the frequency and range domain. For the process depicted in Figure C-9, a frequency sweep is accomplished at a fixed code phase position. If correlation is not realized as detected by the carrier lock circuit, the receiver PN code phase is retarded by 1/2-chip (15 m) and the frequency sweep repeated. The current sweep parameters are depicted by Table C-5.

Using the fast-range/slow-velocity sweep, the entire code phase uncertainty is initially swept at a constant carrier frequency. Where correlation is not realized, a new carrier frequency estimate is selected and the range sweep repeated. Where carrier frequency errors are relatively small, then essentially only a range sweep is required as a part of the signal acquisition process.

READ ONLY
MEMORY
(COMPUTER)

25 BIT WORDS
$4 \times 16 = 64$ WORDS

LIBRARY
SELECT

PNG

OUTPUT

FEEDBACK
LOGIC

SATELLITE
CODE
SELECT

$$\triangle T = \frac{3.355}{16} = 210 \text{ MILLISECONDS (APPROXIMATELY)}$$
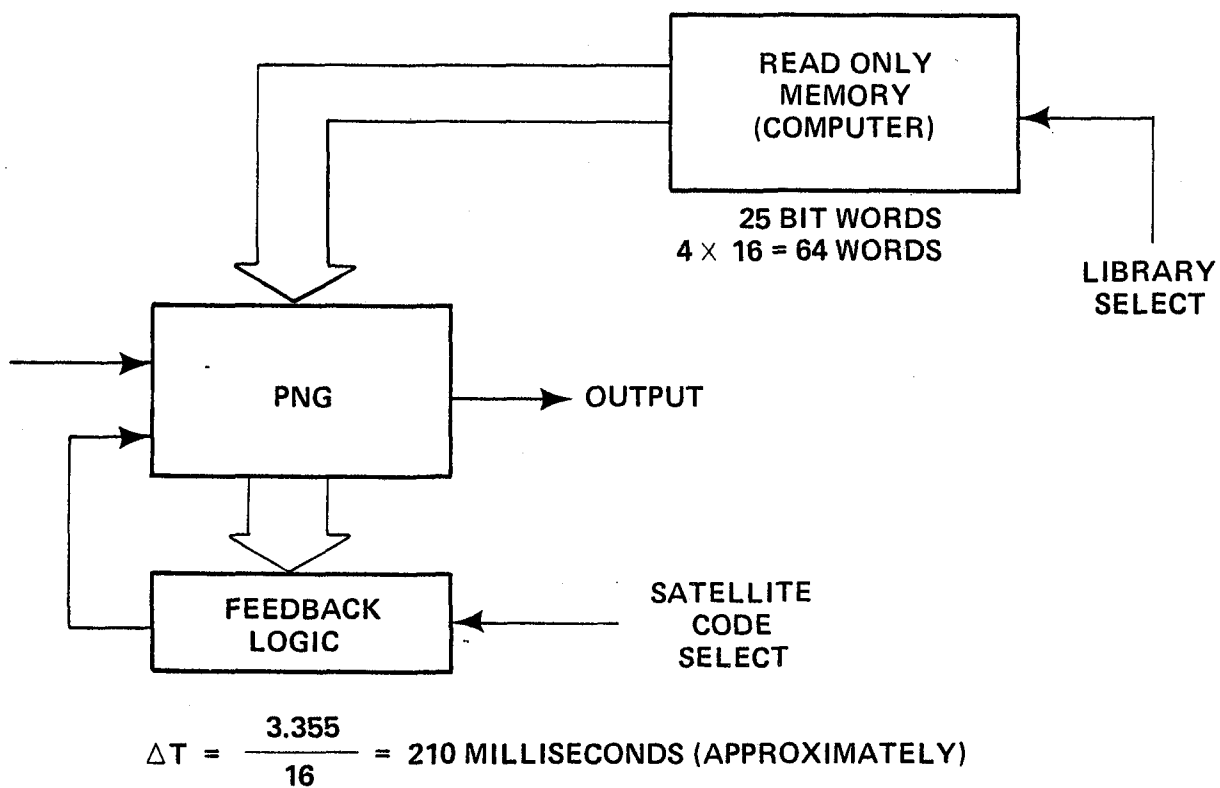
Figure C-8. Code Pre-positioning
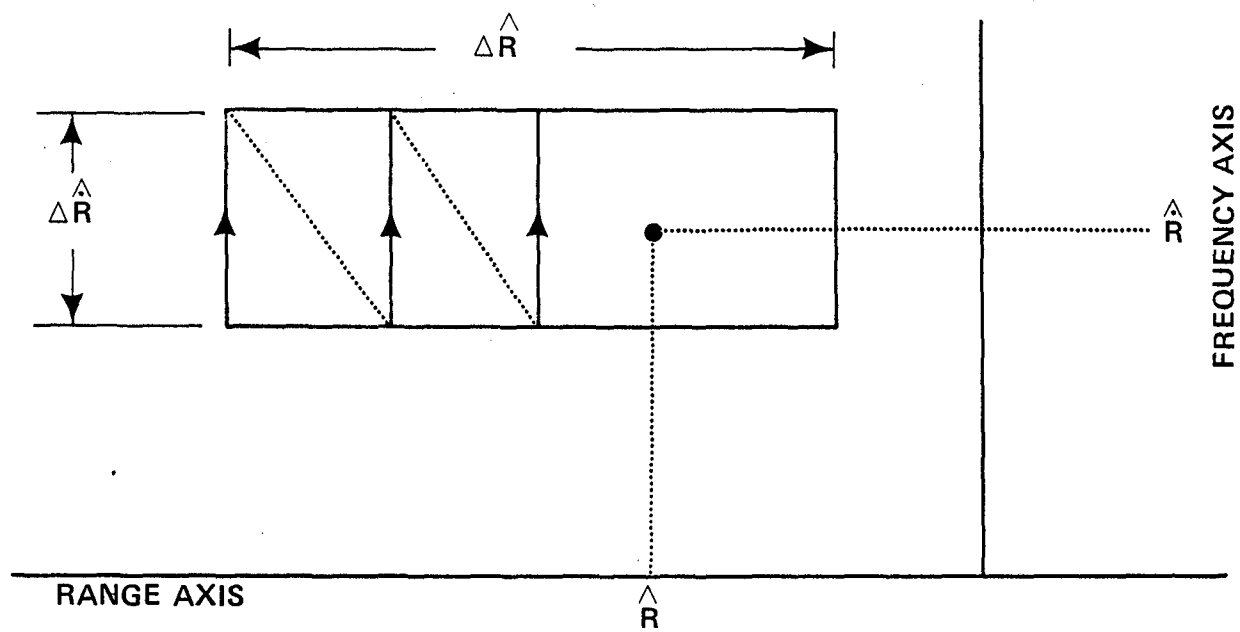
Figure C-9.   Search Process

Table C-5. Sweep Parameters

Carrier BW	Velocity Sweep Rate		Range Sweep Rate
	Hz/sec	m/sec/sec	
20 Hz	22.7	5	15 m/velocity sweep
100 Hz	727.6	148	15 m/velocity sweep
1000 Hz	46,600	9469	15 m/velocity sweep

Range and Range-Rate Measurements

Coarse pseudorange measurements are accomplished by essentially reading the state of the PN code generator at the designated time periods. Since the PN code is repetitive over an approximate 3.5 sec interval, the coarse range can be determined by essentially reading the state of a counter which is reinitialized each time the PN code reaches its epoch. The resultant coarse range-resolution capability is slightly under 30 m. To realize higher resolution range readouts to better than 0.3 m, a fine range-readout circuit is incorporated into the receiver.

Pseudorange-rate is determined by essentially counting the carrier VCO doppler cycles over a fixed-time interval.

Receiver Acquisition Considerations

Initial satellite signal acquisition will be accomplished with the aid of an acquisition code and should pose no serious problems--even during flight. Continual or dynamic acquisition will be a function of several factors, including the receiver bandwidth, the accuracy of initial position estimates, and the extent of unknown acceleration errors. Acquisition is accomplished by automatically scanning phase and frequency about a computer estimated phase and frequency to a selected satellite.

C.3 LORAN-C SYSTEM DESCRIPTION

System Concept--

LORAN-C is a hyperbolic navigation technique operating in the LF frequency range. Area coverage is supplied by a LORAN-C "chain" consisting of a master and at least two secondary stations separated by distances on the order of 900-1300 km. System operation consists essentially of a pulsed transmission from the master station followed, after a specific delay, by sequential pulsed transmissions from each secondary station. The delay periods are such that, within each service area, no two transmissions overlap and therefore arrive in the original order. The master station signal consists of a group of eight pulses spaced 1 ms apart followed by a ninth pulse 2 ms later. The secondary station transmission(s) consist of eight pulses spaced 1 ms apart only. The carrier within each pulse envelope is bi-phase modulated to identify the master station pulse group from the secondary station pulse group. Secondary station identification is achieved by order of transmission. Chain identification is obtained by transmitting successive pulse groups at different group repetition intervals.

Position fixing is achieved by determining differential distance (i.e., time-of-arrival differences) between the user and pairs of transmitters. Each difference locates the user on the locus of a hyperbola. The intersection of two such hyperbola defines a position fix.

Obviously, the system depends upon correct synchronization of the transmissions from each station. To achieve this monitor stations are incorporated which measure a fixed, known time difference from each station. When a station is not operating properly, it is notified and then a message encoded on its transmission to notify users of this condition.

LORAN-C Transmitter--

The functional requirement fulfilled by the LORAN-C ground station(s) is to transmit a carefully timed pulse such that the time difference discussed in the above paragraphs may be accurately measured. The

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transmitted pulse envelope allows the groundwave to be extracted from skywave interference by employing a controlled rise time and measuring the zero crossing between the third and fourth cycles. Figure C-10 illustrates a LORAN pulse. Maximum power is reached at the peak of the eighth cycle (@72.5 s for a positive phase coded pulse and decays experimentally in 400 s. The leading several cycles of the pulse are carefully controlled in amplitude in order to be an aid in cycle identification.

Master stations are synchronized with the U. S. Naval Observatory master clock, while the secondary stations are synchronized with the master station. All stations utilize Cesium beam clocks such that precision time is available throughout the chain.

LORAN-C Receivers--

The LORAN receiver acquires and measures the time-of-arrival of signals from a master and at least two secondary stations. The receiver may process either the groundwave signal or the skywave signal with substantially superior performance being achieved with utilization of the groundwave signal. A block diagram of receiver operation is shown in Figure C-11.

Signal acquisition is achieved by first performing a master search consisting of searching in time for a group of master signal pulse transmissions of known repetition rate with an identifiable phase coding sequence. Second, lock-on to the master signal is achieved utilizing a coherent detector. Finally, a secondary search searches and locks on to two secondary transmissions with the aid of a time base synchronized with the master signal. During the acquisition process, the receiver locks on to a particular cycle of the received signal. This is the third cycle of the groundwave signal. The LORAN pulse shape is carefully maintained such that the third cycle can be identified by the normalized slope of the pulse. Look-ahead detectors are employed to ascertain when skywave signals are being tracked.

After acquisition, the receiver tracks the signal by means of a second order phase lock loop. In order to overcome noise, minimize the effects of CW interference, and to follow aircraft maneuvers, the loops have slow response times with integration times on the order of ten seconds.

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10μSEC

CYCLE ZERO
CROSSING TO BE
IDENTIFIED AND
TRACKED
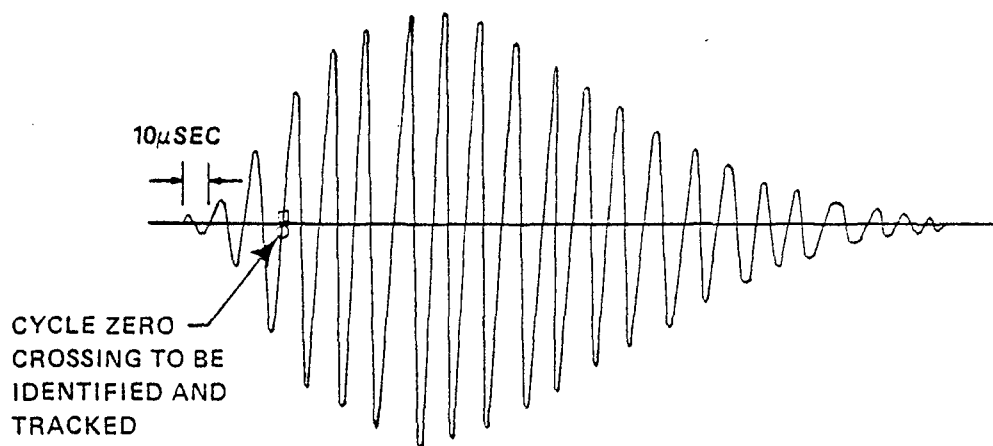
Figure C-10.   LORAN-C Transmission Pulse [C-11]

MASTER SIGNAL
TIMING

START

SIGNAL
ACQUISITION
Master Search
Secondary Search

SIGNAL
SETTLING
1. Ground Wave
2. Cycle Ident

SIGNAL
TRACKING

TIME
DIFFERENCE
COUNTER

DISPLAY

SELECT GRI
FOR TRIAD

SELECT SECONDARY
SIGNALS

SECONDARY SIGNAL
TIMING
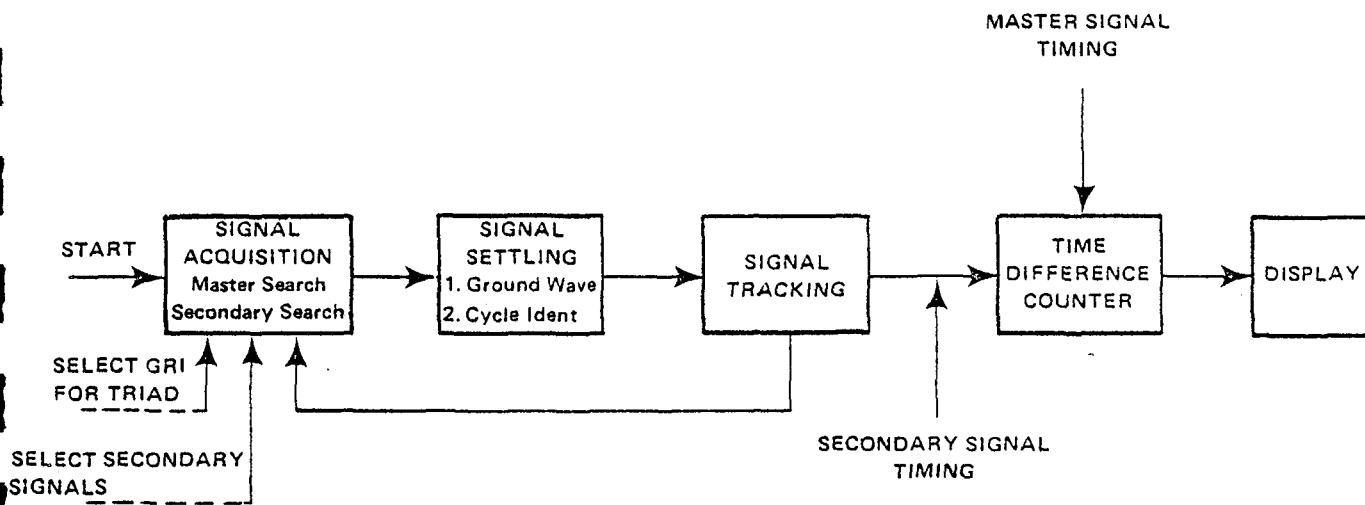
Figure C-11.   Operation of LORAN-C Receiver [C-11]

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Notwithstanding, the loop bandwidth represents a compromise between the above wide-band influence and the narrow-band requirements imposed to achieve high accuracy. As the signal is tracked, two types of time difference measurements are made. The pulse envelope provides a coarse range difference with carrier phase acting as a vernier measurement. The coarse measurement enables the receiver to determine skywave conditions and resolve lane ambiguity inherent in carrier phase measurement. The latter, in reality, provides the ultimate accuracy of the system.

One problem can arise in the dual measurement scheme. Since group envelope and phase velocities are different, there results a phase shift of the pulse envelope with respect to the 100Khz carrier. This can be compensated for if the phase is small so that lane ambiguities are not encountered and by careful calibration and monitoring of the receiver.

Performance--

LORAN performance may be categorized in three areas. These are accuracy, coverage, and availability of signal. Implicit in the latter two areas are redundancy features and system reliability.

System Accuracy--

Position inaccuracies in the LORAN-C system are dependent on:
1. geometrical configuration of the stations contributing to a fix,
2. prediction error, and
3. instrument errors in ground station and user equipments.

Geometrical Considerations--

LORAN stations may be arranged in various geometries. Due to the variable divergence of the hyperbolic lines generated by a station and the variable angle between sets of hyperbolic lines, the geometrical dependence of LORAN accuracy also becomes variable throughout a coverage area. Geometrical Dilution of Precision (GDOP) contours have been generated by the U. S. Coast Guard for both operational and planned chain configurations.

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These are then available to the user. Typical GDOP values may be categorized to lie in the range of 2-4 for usual station-user geometries. These numbers represent the ratio of achievable accuracy in navigation coordinates to accuracy in LORAN grid.

Predictive Considerations--

Computation of the LORAN time-difference grid is based on station locations and on assumptions of ground conductivity and dielectric constants. Were the computation to be based on the assumption of uniform conductivity and dielectric constant, the error experienced would be nearly 3-5 μseconds. To reduce this to about 0.5 μs, computations for each point on the grid are based on best-estimate predictions of conductivity and dielectric constants over the propagation path. The error is further reduced by comparison between predicted and measured time-difference values at locations where precise position data is available (such as the monitor stations).

The hyperbolic LORAN-C grids are highly accurate as well as extremely stable. Over continental areas where geographic positions are referred very accurately to a specific geodetic datum, the LORAN-C grid and the geodetic grid can be made to correspond within 0.06 μs by calibration instrument errors.

Instrument errors include systematic introduced by the ground station equipment, the user equipment, and errors resulting from noise contamination during reception. Instrument errors in ground station equipment result primarily from secondary station synchronization error. Modern transmitters specify 4 operating modes ranging from "optimum" (achieved 95% of the time--full power timing precision of $\pm$ 40 μs) to "standard" (achieved 99.7% of the time--half power timing precision of $\pm$ 200 μs).

Receiver error contributors include timing accuracy, phase measurement error, band limiting, and receiver resolution and are in the range of $\pm$ 25 μs to $\pm$ 50 ns for quality receivers.

One of the more predominant errors in achieving repeatable accuracies is that due to the effects of noise. Analyses [C-11] have indicated errors in the observed time differences of $\pm$ 0.05 μs for signal-to-noise ratios of 1:1 and $\pm$ 14 μs for signal-to-noise ratios of 1:3.

LORAN-C COVERAGE

LORAN coverage extends laterally out to about 1600 km from the master station for ground wave reception and about twice that for usable skywave reception. Coverage is available spatially continuously throughout the service area. Coverage extends to high altitudes although no altitude information is provided to the user.

Area coverage for long-range navigation is, of course, dependent on station location. Figure C-12 shows proposed implementation to achieve coverage for the U.S. Coastal Confluence Zone. Total CONUS coverage may be attained by addition of the five stations shown in Figure C-13. Station implementation in foreign countries could provide nearly global navigation capability. Complete global coverage would necessarily be sensitive to diplomatic constraints.

The important points regarding coverage with respect to the GA user are two: one, no z-direction information is available and, two, CONUS coverage appears to be a reasonable expansion of current implementation plans.

LORAN-C Availability of Signal

The availability of signal, or signal reliability, relates to the probability that a usable signal is available to provide the intended service at any given time. This may be viewed as two subcategories: first, the reliability of transmitter station operation, and two, the influence of propagation effects on the reception of accurate signals.

The failure of a master station eliminates coverage over those areas not provided duplicate coverage by another chain while secondary station outage results in degraded performance in that station's service area. This has prompted the U.S. Coast Guard to place increased station reliability as a major goal in their "LORAN-70's Program." One area for increased reliability is the development of a solid-state transmitter designed as multiple parallel-operation units. Unit failure thus causes partial reduction in output power and station operation continues "gracefully degraded."

The new station names represent
approximate geographic areas, not
specific locations and these areas
are subject to change.

The construction of new stations
and modification of existing stations
is subject to congressional appropri-
ation of the necessary funds.

LEGEND

EXISTING STATIONS
● NEW STATIONS
(M) MASTER STATIONS
S SECONDARY STATIONS
DS DOUBLE SECONDARY
STATIONS

Figure C-12.   Proposed LORAN-C Coverage of U.S. Coast Guard Implementation
Program [C-11]

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The new station names represent approximate geographic areas, not specific locations and these areas are subject to change.

The construction of new stations and modification of existing stations is subject to congressional appropriation of the necessary funds.

LEGEND

● U.S. COAST GUARD STATIONS (EXISTING AND PROPOSED)

⊙ ADDITIONAL STATIONS REQUIRED FOR COMPLETE COVERAGE

M MASTER STATIONS

S SECONDARY STATIONS

DS DOUBLE SECONDARY STATIONS

Figure C-13. Proposed LORAN-C System for Complete Coverage of Conterminious United States and Alaska [C-11]

Other developmental areas arrived at increasing station reliability include new timing equipment, a monitor and control group, further antenna design communications net development, and advanced power source provision. Station reliability is now forecast at 0.997 with 95% probability. Probability of failure of two or more stations is forecast to be negligible.

Noise considerations affecting the LORAN-C signal availability include atmospheric noise and precipitation noise. Atmospheric noise in the 20 Khz band at 100Khz generally consists of sharp impulses spaced by long periods of relative quiet. Censoring techniques are used to discard signals during high noise bursts effectively. Resistance to precipitation static is accomplished by use of dischargers, propitious antenna location, and effective receiver design. It is probable that noise effects do not largely influence signal availability in the coverage area.

Approximate Costs of U.S. Coast Implementation Plan [C-11]

Table C-6 below shows approximate cost per chain of LORAN-C implementation by the U.S. Coast Guard to be used primarily by marine users in the coastal/confluence areas.

Table C-6. LORAN-C Costs (CCF)

Chain	Cost (millions)
East Coast & Great Lakes	16.1
Gulf of Mexico	11.5
West Coast	18.0
Alaska	15.0
Total	60.6

In order to cover the CONUS, as would be required by aviation users, additional stations are required for coverage over the central portion of the United States. The previous discussion regarding coverage indicated that this can be achieved with the addition of five additional stations in the CONUS and one in Alaska. At an assigned construction expense of 4.5

and 6.0 million dollars respectively, the incremental cost to provide this capability is $28.5 million.

Assuming an annual station operating and maintenance cost of 150 thousand dollars (350 thousand dollars for the Alaskan stations), the total operating cost became 5.15 million dollars with 1.1 million being the incremental aviation costs. The total LORAN ground facility costs are then summarized in Table C-7 below.

Table C-7. Summary LORAN-C Costs

Total Costs including aviation	$89.1 million
Operation/Maintenance	5.15 million
Incremental Aviation Facility Costs	28.5 million
Incremental Aviation Operation/Maintenance Costs	1.1 million

C.4 OMEGA SYSTEM

System Concept

Omega is a hyperbolic, long-range, radio navigation system operating at a very low frequency (VLF) band at 10.14 Khz and employs continuous wave transmissions. Position location using Omega is based on the fact that ideally the signals from two-phase synchronized, physically separated, transmitters will have a phase relationship which is geometry dependent. In the Omega chain each station broadcasts for a finite period of time (approximately 1 second) at the same frequency as the other stations in a preassigned sequence. Conceptually, Omega determines position on a line-of-position (constant phase difference) from a single frequency at 10.2 Khz. However, this results in "laning" and introduces ambiguities at 15 km intervals. To avoid this, while a given station is transmitting at 10.2 Khz, others are transmitting at other frequencies and the beat or difference frequency between these transmissions used to resolve the lane ambiguity by effectively widening and affecting the lanes.

The Omega system concept employs accurate clock installation only at the transmitting stations. User equipment is required to identify each station broadcast and to measure the relative phases of received signals. Because station broadcasts are in a sense time-division multiplexed, station identification is accomplished easily after initial synchronization. Phase comparison is achieved by comparison with an interval reference at 10.2 Khz.

Since carrier cycles cannot be distinguished, the hyperbolic lines-of-position defined by constant phase difference are not unique. Phase space is thus divided into lanes which are a function of the transmitted frequency and of the subtended angle between the two stations. Finest lane resolution is obtained on the baseline between two receivers where a lane is one-half wavelength, or at 10 Khz approximately 15 km. This results in the fact that lane ambiguity can be easily resolved at the beginning of a flight but that techniques for in-flight resolution are required.

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Dodge [C-11] focused on two methods which have been applied to general aviation receivers. These are based on the use of multiple frequency transmissions and on employing a lane counter. Multiple sequential transmissions at 10.2, 11.33, and 13.6 Khz by each station and employing frequency differencing techniques result in triple coincidence approximately every 130 km. Recommendations have been formulated for implementing additional modulation to extend the unambiguous range to approximately 13,000 km; however, it was determined to be more advantageous to transmit additional frequencies instead.

In the second method the receiver is equipped with a lane counter which records the number of lanes traversed. When the lane count is maintained, no ambiguity exists. Problems occur, however, when cycle slippage or signal loss is encountered. While both techniques have been implemented for general aviation, the lane counter is reasonably straightforward; whereas, the multiple-frequency approach requires more signal processing.

Transmitter Signal Format

The Omega signal is designed so that the eight stations transmit a sequence of three continuous wave pulses (at 10.2, 13.6, and 11.31 khz). Each phase is about one second in duration and the total time for the commutation pattern is ten seconds (thus the Omega system position update rate is constrained to be greater than ten seconds). The specific pulse duration varies from 0.9 to 1.2 seconds interspersed with off-times of 0.2 seconds. After transmission of the first three pulses, no transmission occurs during the remaining 6.5 seconds of the commutation period. This format allows unique station identification within the signal format. Figure C-14 illustrates the Omega signal format. At any given time three stations are transmitting each at one of three different frequencies. The Omega signal format is flexible in the sense that the 6.5 second off-time remains available for user diversification. Among concepts considered for this time slot are the transmission of additional signals to: expand the unambiguous lane width, provide station identification, provide introsystem communication, etc.
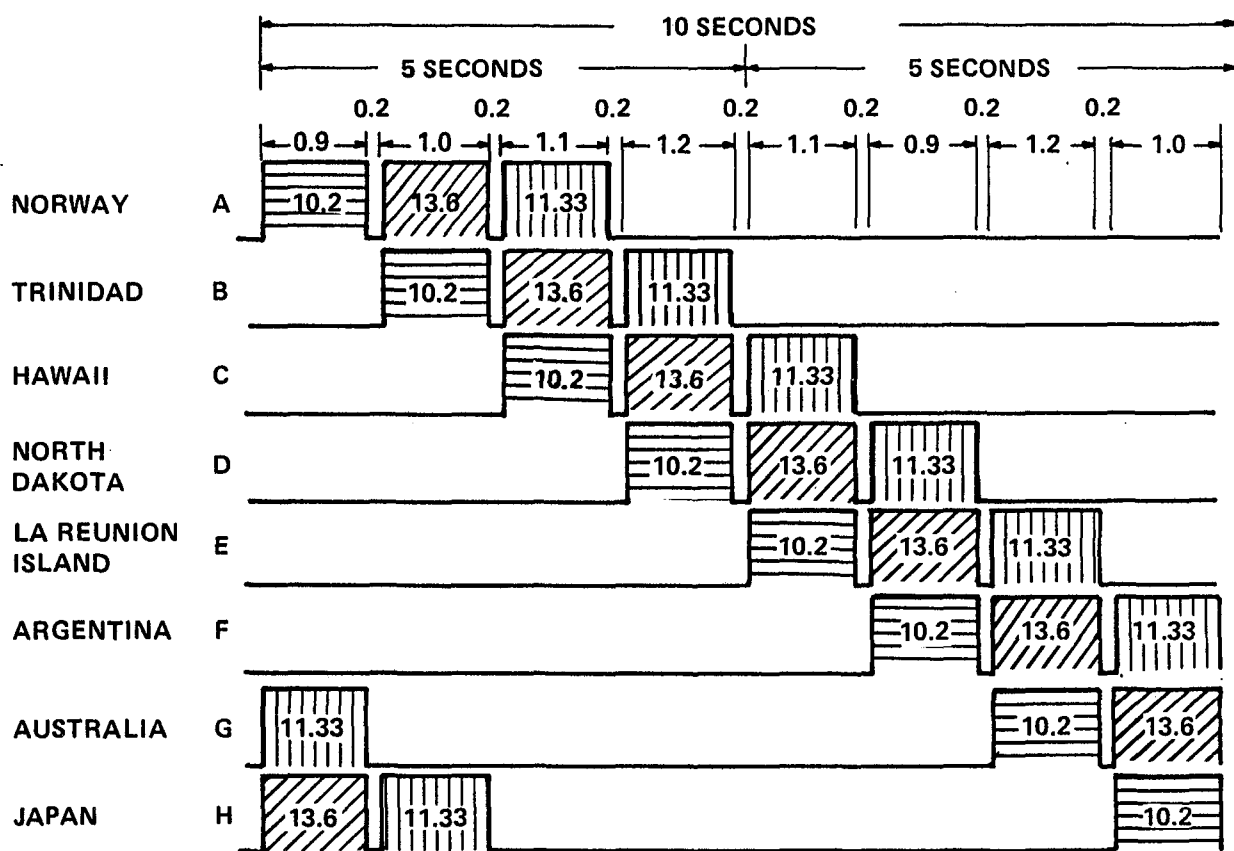
Figure C-14. Omega Navigation Signal Format [C-11]

VLF Propagation Impact

A key feature in the Omega System design is the choice of VLF as a transmitting frequency. The propagation characteristics at VLF provide global coverage with only eight transmitter sites. While the propagation characteristics at VLF are of a nature to provide global coverage, it also introduces anomalies due to the waveguide behavior of propagation between the earth's surface and the ionosphere. Problems arising include modal interference as well as diurnal variations in the propagation path due to the changing height of the ionosphere. Modal interference is a current research topic, while diurnal variations are compensated for by utilizing accurate prediction of ionospheric behavior with solar angle.

The overall accuracy of the Omega System is primarily determined by the degree to which phase changes can be predicted and accommodated. A very promising scheme to meet both objectives is the concept of differential Omega.

Differential Omega

An approach to compensating for the propagation introduced errors in Omega performance is to take advantage of the fact that the errors are locally highly spatially correlated. This allows the utilization of a ground located receiver to simultaneously measure position and compare the measurement to the known receiver position. The position in error correction factor can then be relayed to the airborne receiver and used to adjust the airborne measurement for propagation variations. The propagation variations are cancelled to the extent that they are actually spatially correlated at the fixed monitor station and the mobile reserve station. This correlation is generally high at short relative distances and degrades as the distance betwen the two increases. Typical useful range of operation from the monitor site is on the order of 85 km.

Omega Receiver

Dodge [C-11] postulates that the Omega receiver for general aviation application need be fully automatic, three frequency and digitally

implemented. The receiver would provide for:

1) synchronization with the signal format,
2) relative phase determination,
3) lane ambiguity resolution,
4) signal timing availability.

The need for the first three requirements has been aluded to previously. The fourth requirement results from the need to display position information in a form most useful to the general aviation user. It has been advocated that the display be that of distance to a way point and cross-track error (this is perhaps a more expensive but nonetheless cost/effective technique).

Omega Performance

The performance achievable with Omega is perhaps best addressed by considering differential mode operation. While this represents an increase in overall system complexity, it likely also represents an upper bound on what can be achieved to minimize propagation introduced errors. Accuracy of Omega in the differential mode is primarily dependent on:

1) user equipment accuracy and resolution,
2) the degree to which measurements at the monitor site and user equipment are correlated,
3) the geometry of the stations contributing to the position fix.

User equipment accuracy is dependent on timing accuracy, phase measurement error, band limiting effects, display resolution, etc. A typical error for standard Omega receivers is on the order of 1% of the lane-width.

A very significant error source in differential operation resides in the reduction in spatial correlation which occurs when the separation distance between the monitor site and the user equipment increases. In lieu of theoretical prediction of the magnitude of the error as a function of distance, Figure C-15 shows the results of experimental data demonstrating the separation distance dependence.

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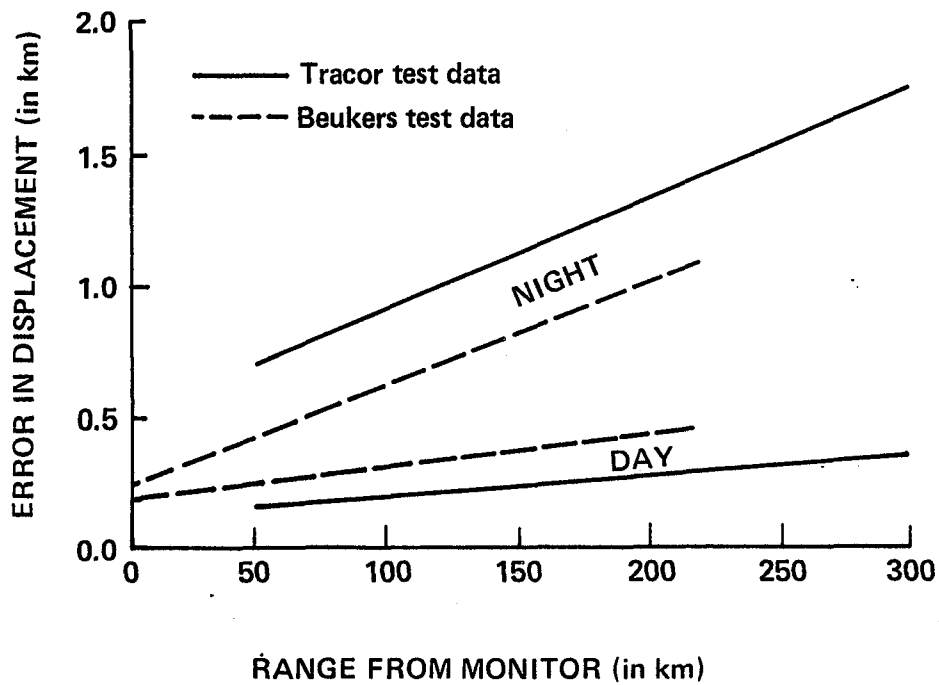
Figure C-15. Differential Omega Position Fix Accuracy [C-11]

The geometry of station configuration has less effect than for LORAN.
Omega is, like LORAN, a hyperbolic navigation system and, thus, the position
accuracy is dependent on hyperbolic divergence and crossing angle of the
lines-of-position at the fix. However, the extremely long baseline lengths
of the Omega system tend to deemphasize this effect.

APPENDIX D - EVALUATION FACILITY EXAMPLES

D.1 EVALUATION FACILITY EXAMPLES

As an input to the facility configuration, a mini-survey was undertaken of known literature regarding similar facilities. Four anticipated and/or existing facilities were identified. These are the Systems Engineering Laboratory at the IBM Electronic System Center, a proposed simulation laboratory, again by IBM for the Avionics Laboratory at Wright- Field, the Communications Systems Evaluation Laboratory (CSEL), and the Digital Avionics Integration System (DAIS) hot-bench, both at the Avionics Laboratory. These four examples are described in the following paragraphs.

SYSTEMS ENGINEERING LABORATORY [D-1]

The systems Engineering Laboratory was created to support all phases of electronic system development from concept to hardware verification. In its diverse effort, experience, and facilities, the Systems Engineering Laboratory addressed concern for the increasing capabilities in every area pertinent to avionic systems and aerospace computers. As a result, extensive simulation, research, and test laboratories support the Center's study programs.

The original function of the Systems Engineering Laboratory was to support the design, development, and use of various types of electronic systems destined for any mobile vehicle operation (aircraft, spacecraft, or submarine). The laboratory was not only responsible for the integration and operation of the various components making up the system, using either simulated or prototype hardware, but was also responsible for evaluating the performance of an operation(s) using the system in real time. To carry out these responsibilities and functions in support of the ESC's requirements and any other special programs, the Systems Engineering Laboratory was equipped with a state-of-the-art simulator and a computer complex that was staffed with qualified personnel. That organization is shown in Figure D-1. As the names imply, each group was responsible for a particular phase of the total simulation effort. However, there was considerable liaison and interaction between the groups so that an efficient and responsive team effort was available for any size program.

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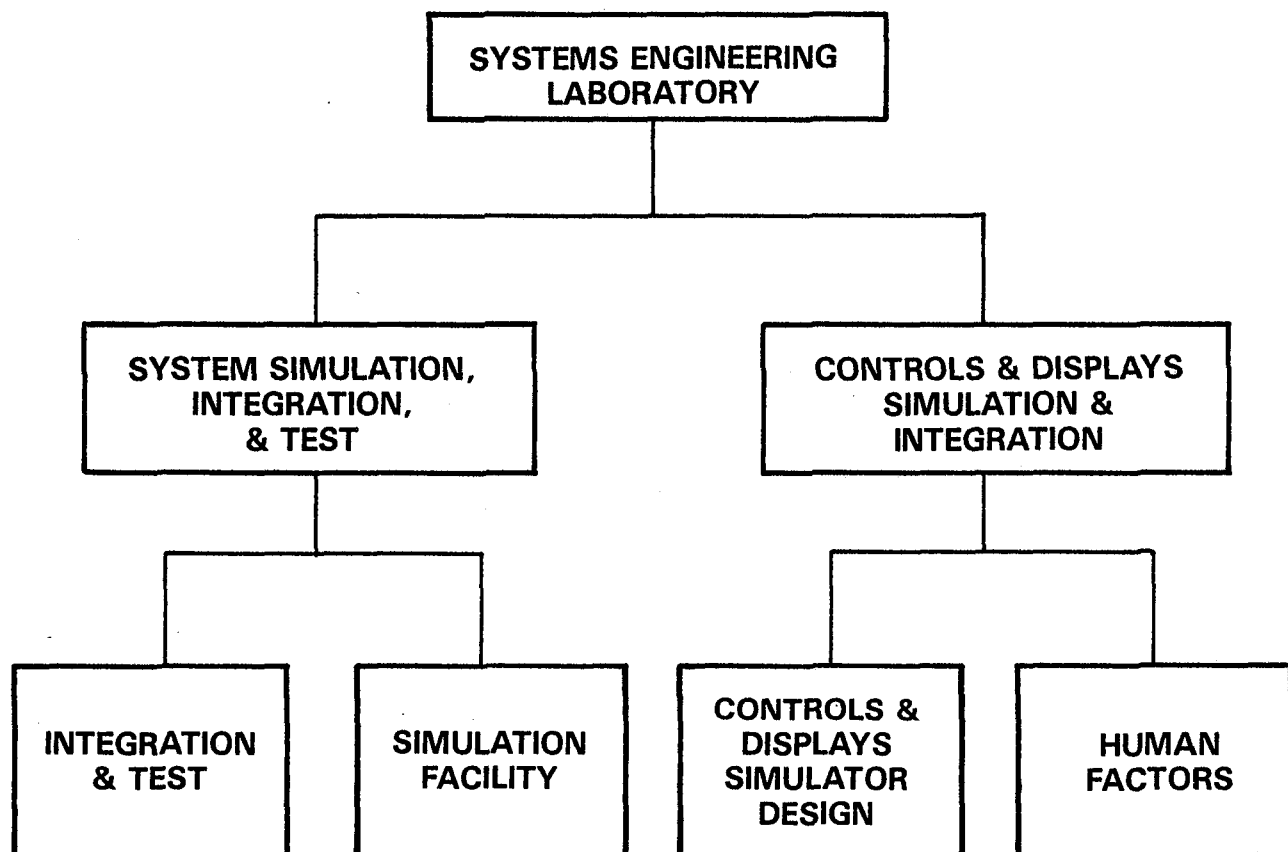
Figure D-1. Systems Engineering Laboratory Organization

The Systems Engineering Laboratory was (at time of IBM report publication) supporting the development of two avionic systems, one related to a tactical aircraft and the other to a strategic aircraft. The tactical aircraft, LTV's A-7 Corsair, was then operational and the laboratory was responsible for the prototype hardware integration and verification of the new bombing/navigation avionic system. Actual flight hardware was integrated and exercised under computer control to assure compatibility of the various system components with the actual on-board computer. As shown in Figure D-2, the various components included a head-up display subsystem, an inertial measurement unit, a Doppler radar, an attack radar, and an air data package. The laboratory computer complex had been programmed to simulate the external environment with the resulting stimuli providing appropriate signal to the various components. The response of each component to the stimuli and its subsequent interaction with the on-board computer was then evaluated. All interface hardware, including signal converters, intercomponent cabling, and control panels were exercised to assure system compatibility. System performance relative to the on-board computer programming was to be measured in terms of the system's prime function of accurate weapon delivery under tactical situations.

Due to the critical nature of the B-1A (Advanced Manned Strategic Aircraft) mission requirements, human factor studies of man/machine interfacing was an ongoing study. As a result, periodic refinement and updating of electronic sybsystem concepts and related displays were a requirement of the simulation laboratory.

A B-1A cockpit simulator was (again at report publication) in the design stage for evaluation of a full crew strategic mission.
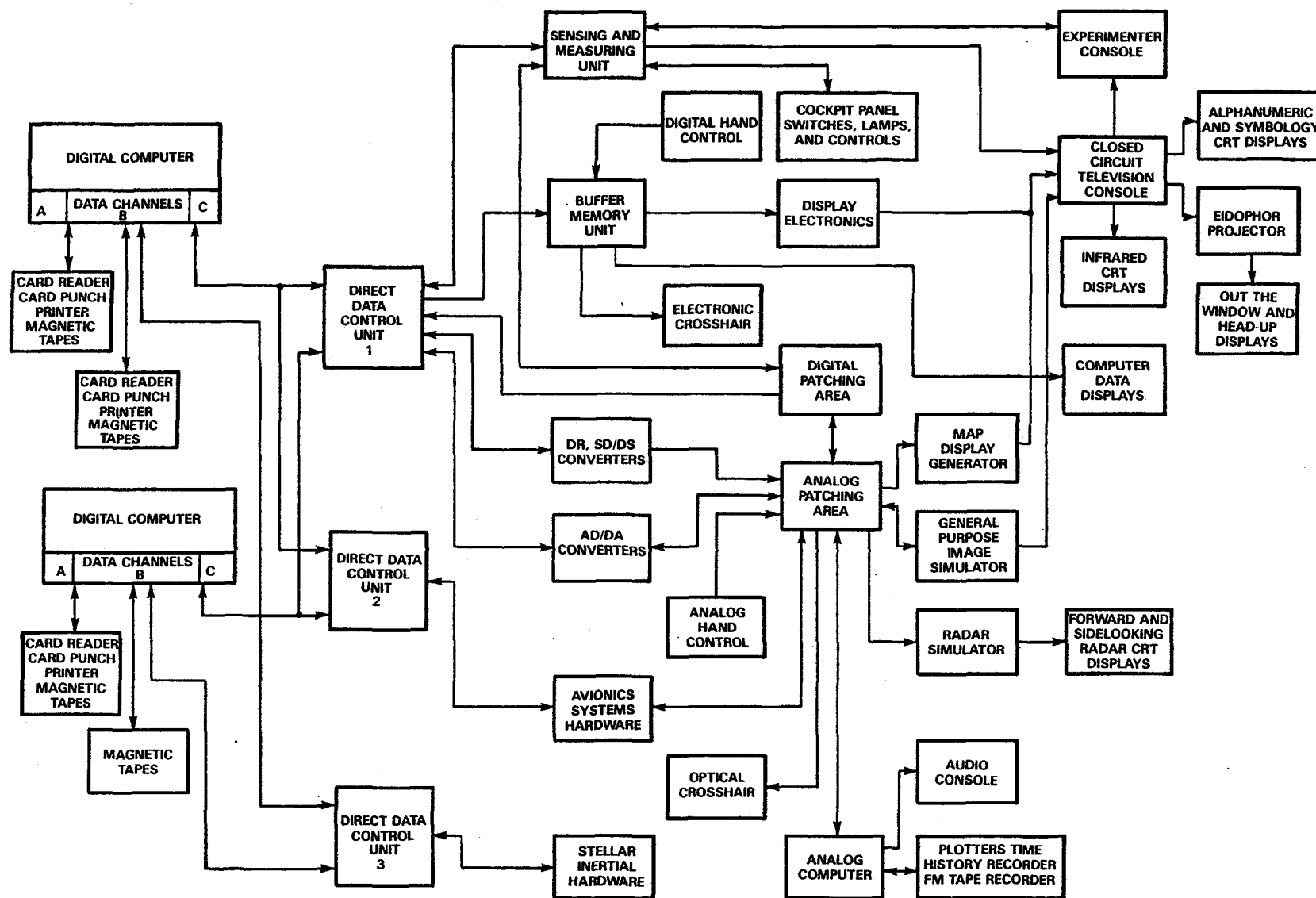
Figure D-2. Interconnection of the Simulation Facility Equipment [D-1]

The complex problem of integrating fire control, electromagnetic threat, and other aircraft threat information on the same display was also investigated. An approach to solving this problem was the use of color to increase the information handling capabilities of the display and thus allow the operator to meet and handle increasingly complex situations.

A multicolor display device was tested and evaluated. Instrumenting this state-of-the-art device into a multicolor display subsystem was to provide a vehicle for human factors evaluation. The display was to be interfaced with control panels, a digital computer, a special data display unit, and a buffer memory unit.

Human Factors personnel were to conduct dynamic interface evaluation of man/computer interaction via the color dimension within a severe air-borne threat environment. Ground mapping techniques were also to be evaluated.

A sonar simulation program was also in the design state at IBM publication time. This simulator was to be used to evaluate the potential capabilities of a new concept in sonar display generation. These displays were to be evaluated by experienced sonar operators to determine which display concept affords maximal pattern recognition qualities. These studies were also to serve as an aid in ultimate hardware design.

The laboratory described herein was to be applicable to the solution of a wide range of problems. Programs associated with military and commercial computer systems for aircraft, space vehicles, surface and subsurface craft reportedly could all be addressed. The extensive computer complex, the wide range of peripheral simulation hardware and the competent staff of professionals were believed to enhance the laboratory's position for responding expeditiously to a variety of projects such as:

- Systems simulation
- Weapon delivery techniques
- Dynamic flight simulation
- Target acquisition, ranging and tracking
- Fix-taking for navigation
- Multisensor, multidisplay studies
- Systems hardware integration
- Controls and displays investigation
- Crew procedural studies
- System performance tests
- Target detection, identification and attack
- Head-up display studies
- Systems analysis.

AFAL SIMULATION LABORATORY (STUDY) [D-2]

This study effort addressed the problem of providing a design for a comprehensive, integrated, and flexible laboratory configuration capable of supporting anticipated AFAL avionics simulation and integration requirements over the 1973 through 1980 time frame.

Primary emphasis was placed on a modular design concept for both hardware and software elements to enable flexible configuration/reconfiguration of the laboratory as required to support simulation/integration of a wide spectrum of avionics configurations and design concepts.

The basic approach included the identification, definition, and partitioning of specific capabilities relating to avionics simulation and integration tasks. The required hardware and software resources were identified and specified. A matrix analysis technique was employed to relate capabilities to required resources as shown in Table D-1. Maximum utilization was made of existing AFAL hardware and software resources.

The basic elements which provide the interface flexibility necessary to implement the modular laboratory configuration are:

1) Interface Adapter/Controller (IAC)
2) Analog Patch and Distribution System
3) Digital Patch and Distribution System

Table D-1. Laboratory Capabilities/ Resources Matrix [D-2]

Key: X Required
      C Candidate

HARDWARE RESOURCES   **SOFTWARE RESOURCES**

Column headers (Hardware Resources):
Item / User (AA, AAU, AAT)
2. GP Digital Computer & Peripherals
3. Off-Line Data Processing Systems & Peripherals
4. Interface Adapter/Controller
5. General Purpose Digital CRT Displays
6. Keyboard Typewriter Terminals
7. Signal Converter
8. Analog Computer
9. Patchable Digital Logic
10. Analog/Digital Patch & Dist. System
11. MUX Controller
12. Closed Circuit TV & Image Conditioning System
13. Landmass Simulator
14. Aural Effects Simulator
15. Avionics Hardware Support/Test Elements
16. Laboratory Interphone System
17. Special Effects Simulator
18. Image Protection/Collimation System
19. Recorders: Video, Audio, Hard Copy
20. Operator Station Controls/Displays
21. Cockpit Simulator Fixed Base
22. Cockpit Simulator Moving Base
23. Avionics Sensor Static Simulator Bench
24. Avionics System Elements
25. Avionics Hardware Support Facilities
26. Avionics Sensor Stimulators
27. Burroughs Multi-Processor & Peripherals
28. PDP 11/45 Processor & Peripherals
29. MUX Data Bus Simulator
30. Laboratory Display Systems
31. Software Evaluation Test Station-Control Computer
32. Software Evaluation Test Station-Interface Unit
33. Software Evaluation Test Station-Computer Test Set
34. Software Evaluation Test Station-Keyboard Display
35. Software Evaluation Test Station-Magnetic Tape Unit
36. PDP 11/20 & Peripherals
37. Signal Synthesizer
38. Channel Simulator
39. Unit Test Equipment

Column headers (Software Resources):
2. Modular Avionics Software
3. Operating System
4. HL Compiler
5. Assembler
6. Linkage Editor
7. Software Simulator
8. Interface Test Program
9. Program Validation/Debug Package
10. Display Support/Control Software
11. Real Time Control Programs
12. Laboratory Interface Software
13. Cockpit/Work Station Software
14. Simulator Drive Software
15. Data Acquisition, Reduction, Analysis
16. Initial Condition Software
17. Aircraft 6DOF Motion/Environmental Program
18. Error Analysis
19. Avionics Sensor Models
20. Flight Path Profile Generator
21. Hardware Stimulator Software
22. Operator/System Discrete Event Program
23. Diagnostics
24. Communications Laboratory Software
25. Information Management Laboratory Software
26. Numerical Analysis of Analog Signals

Capability (row labels):

Modular Avionics Software Studies
- Real Time Executive Program
- Weapon Delivery Software
- Navigation Software
- Display Software
- CITS Software
- Display Symbology Software
- Display/Control Interactive Support Software
- MUX Data Bus Support Software
- Sensor Stabilization Control Software

Analytical Simulation
- Avionics System Simulation
- Avionics Error Analyses
- Avionics Performance Optimization

Avionics Integration & Test
- Support Hardware Unit Testing
- Support Software Unit Testing
- Avionics Hardware Unit Testing
- Avionics Software Unit Testing
- Avionics Interface Testing
- Avionics Hardware Integration
- Avionics Software Integration
- Avionics Hardware/Software Static Integration
- Avionics Dynamic Validation Testing
- Air Vehicle Compatibility Testing

Man/Machine Interface Development & Optimization
- Target Acquisition/Identification Studies
- Target Designation/Tracking Studies
- Multi-Sensor Display Studies
- Weapon Delivery System/Display Studies
- Navigation Aids/Display Studies
- ECM Display Studies
- Image Enhancement Studies
- Multi-Function Display Studies
- Format/Symbology Studies

Display Technology/Device Studies
- New Technology Device Studies
- Multi-Function Switches/Key Studies

Basic Avionics Information Processing R & D
- MUX Data Bus Studies/Optimization
- MUX Data Bus Adapter Optimization
- Multi-Processor Configuration Studies

Communications R & D
- Channel Modeling
- Propagation Studies
- Modulation/Demodulation Studies
- Man-Made Interference Studies

Other
- Data Reduction/Analysis
- Digital Recording, Display & Analog Signals
- Analysis of Analog Signals by Digital Methods

The IAC provides the capability to interface all applicable laboratory equipment with any laboratory computer. In addition, programmable digital logic provides flexible capability to support as yet unspecified laboratory interfaces. Extra signal distribution capacity provides for cost-effective future expansion.

The recommended configuration shown in Figure D-3 enables the performance of a wide range of avionics simulation/integration tasks including: mathematical simulation; dynamic man/machine-in-the-loop simulation; avionics hardware/ software module development and integration testing; display/computer/data bus device/technology studies/evaluations; basic research in signal processing; and communications systems analysis, synthesis, and evaluation.

COMMUNICATION SYSTEM EVALUATION LABORATORY (CSEL) [D-3]

CSEL is a combined hardware/software facility designed to analyze, synthesize, and model advanced communication systems. The laboratory centers about a computer-based simulation facility, which is capable of creating a variety of hostile RF signal environments at UHF and L-, X-, and K-band. To this facility may be interfaced for testing and evaluation, either laboratory-model communication hardware, actual communication hardware, or a combination of elements of both. To aid in the construction of laboratory communications systems, CSEL provides a high-speed, programmable signal processor and a spectrum of communication equipment, including modems, terminals and antenna systems.

It is important to note that this simulation facility produces simulated signal environments in the appropriate RF band. Thus, it qualifies as a hardware simulator, control over which is exercised dynamically by a digital computer operating in real time. Initial configuring of the simulator is also performed through the digital controller by means of a series of user commands, which the system software interprets and translates into control signals to the communication hardware.

Interfacing communication terminals to the Signal and Interference Generator RF hardware then provides a realistic test bed for the terminals, in which one cannot only troubleshoot the equipment, but also test its
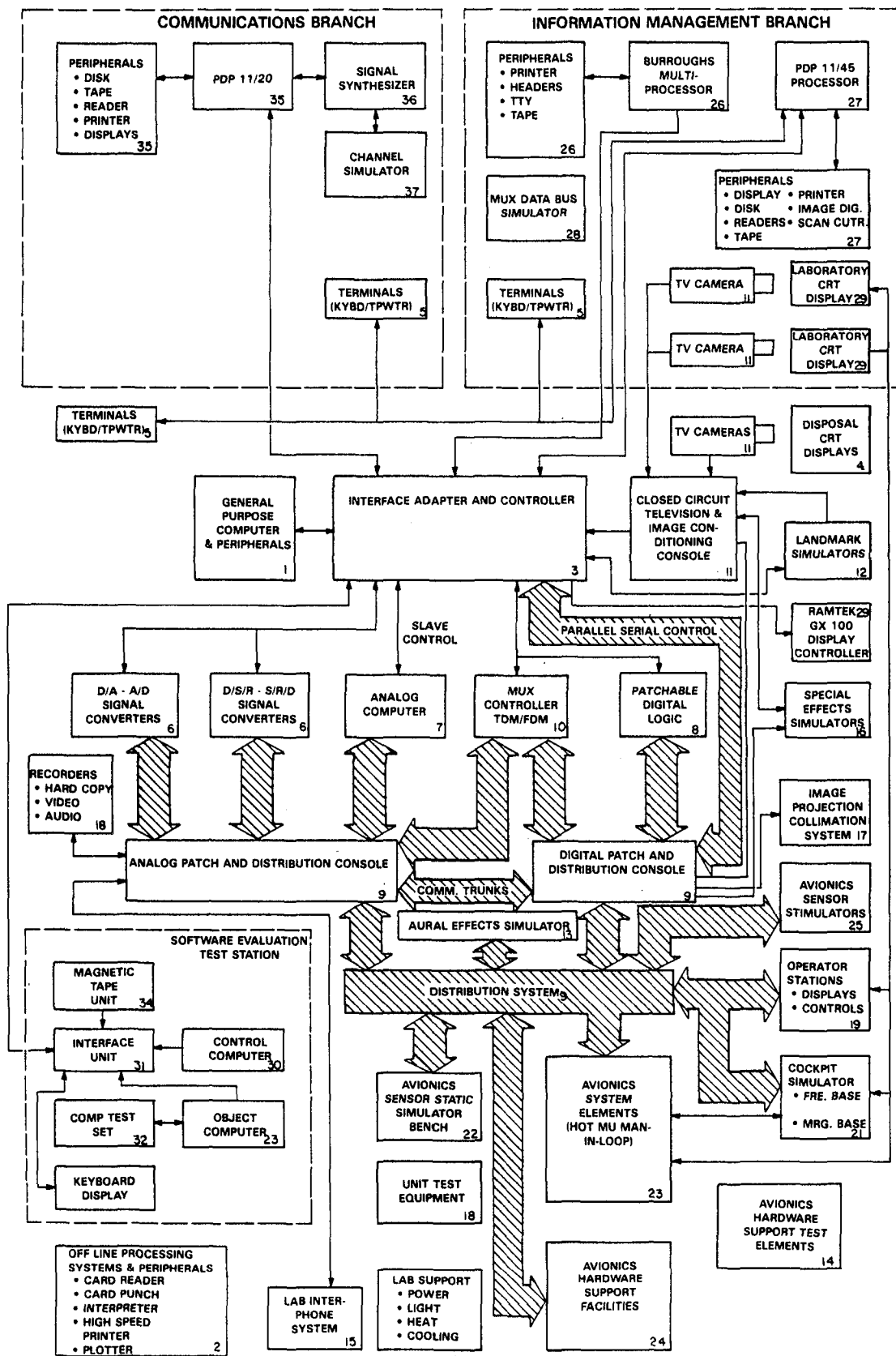
Figure D-3. Proposed AFAL Laboratory Configuration [D-2]

performance with respect to such environmental effects as jamming and fading. The user can specify these effects with relative ease and can vary them readily from one test run to the next, thereby obtaining a complete characterization of the performance capabilities of the equipment.

A typical application of CSEL is illustrated by tests performed to determine the suitability of the LES-8/9 communication satellites for use with the Airborne Command Post. In these tests, CSEL was used not only to troubleshoot K_a-band communication hardware, but also to ascertain the vulnerability of the communication system to various types of jamming.

To accomplish these goals, CSEL was equipped with appropriate K-band and UHF communication modems, terminals, and antennas. This configuration allowed use of the communication satellite in a laboratory system equipped with a qualification model of the AN/ASC K_a-band airborne communication terminal, together with antenna systems, to establish communication links with LES 8/9. This equipment, when combined with the Signal and Interference Generator, allowed the realization of actual satellite communication channels into which were introduced controlled-interference efforts in the form of jamming, fading, and doppler. To reinforce this capability, the high-speed signal processor was programmed to simulate satellite processing when LES-8/9 were unavailable to use.

Current emphasis in CSEL is shifting toward a study of the performance of communication systems linking remotely piloted vehicles with air- and ground-based command posts. To this end, the facility is being upgraded to include the elements of a video processing and display capability. Future studies envisioned for CSEL involve satellite-based navigation systems and the performance they obtain in a hostile environment.

DIGITAL AVIONIC INFORMATION SYSTEM (DAIS) TEST FACILITY [D-3]

The purpose of the DAIS project is to demonstrate a coherent solution to the problem of proliferation and nonstandardization of aircraft avionics, to develop and test in a hot-bench configuration (known as the Integrated Test Bed) the DAIS concept, and to permit the Air Force to assume the initiative in the specification of avionics configurations for future Air Force weapon systems acquisitions. The DAIS design approach

reflects a total system concept that is functionally oriented rather than hardware oriented.

The heart of the DAIS system is the redundant time division multiplex data bus shown in Figure D-4. This bus allows information from the aircraft subsystems (e.g., avionics units, stores management, power control) interfaced by remote terminals (RT) to be communicated along the bus and to a set of shared DAIS processors through Bus Control Interface Units (BCIU) in the processors. Mission software developed through simulation with the Software Design and Verification System (SDVS) in non-real-time interaction with aircraft and environmental models, can be exercised in real time in the ITB facility. For example, a pilot flying a simulated cockpit views a simulated, computer-generated scene and interacts with displays in the cockpit generated DAIS mission software. The aircraft external environment and flight dynamics are simulated by models executed by the host computer. During such a simulated flight, the mission software/processor performance is monitored by the Super Control and Display Units (SCADU), while the bus performance is monitored by the Bus Monitor Unit (BMU). The results of the real-time simulation can then be compared with those predicted by earlier non-real-time simulations. System performance is, thus, verified in the laboratory instead of in the field.
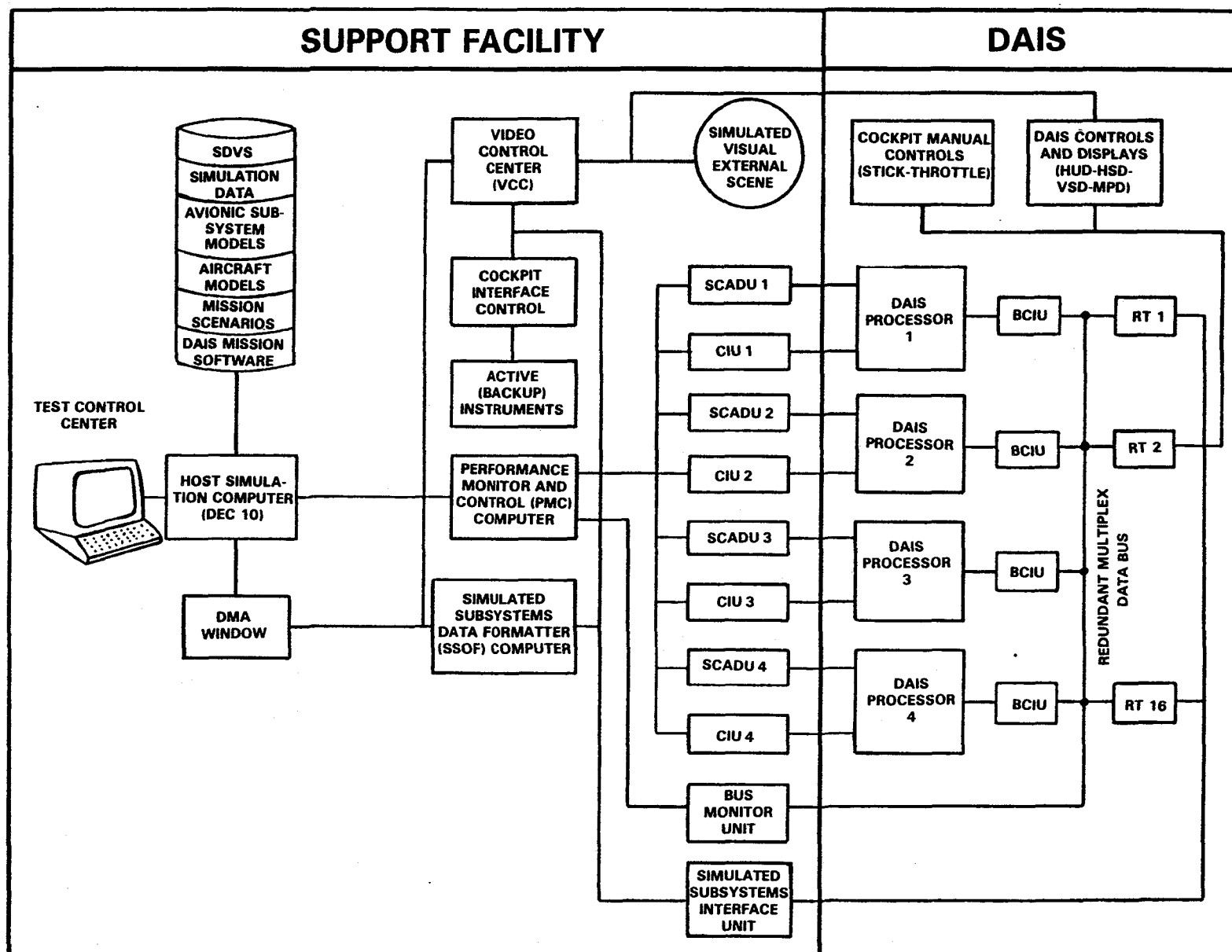
Figure D-4. Simplified Block Diagram of DAIS ITB Facility [D-3]

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