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DEFINITION STUDY OF LAND/SEA CIVIL USER NAVIGATIONAL LOCATION MONITORING SYSTEM FOR NAVSTAR GPS

USER REQUIREMENTS AND SYSTEMS CONCEPTS

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16. Abstract

The objective of this definition study is to develop concepts, and analyze technical/cost tradeoffs, leading to the design of a low-cost GPS civil-user mobile terminal whose purchase cost is substantially an order of magnitude less than estimates for the military counterpart. A further objective is to define ground station requirements for position monitoring of civil users requiring this capability and the civil user navigation and location-monitoring requirements. It is the latter subject that is addressed in this report, namely: 1) to review existing survey literature to ascertain the potential users of a low-cost NAVSTAR receiver and to estimate their number, function, and accuracy requirements, and 2) to define system concepts for low cost user equipments for in-situ navigation and the retransmission of low data rate positioning data via a geostationary satellite to a central computing facility.

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1.0 INTRODUCTION

The NAVSTAR GPS provides the civil community with a revolutionary position location capability and with a number of highly desirable system attributes which may be exploited for operations on both a national and global basis. GPS provides worldwide navigation coverage, all-weather operations, continuous availability, and an unsaturable number of users with operation in an absolute common grid reference. To exploit this potential, the designer's challenge is to provide the user community the level of system capability that it requires at the lowest cost. The civil applications of GPS can only be viable if user equipment costs are carefully and critically minimized.

An objective of this definition study is to develop concepts, and analyze technical/cost tradeoffs, leading to the design of a low-cost GPS civil-user mobile terminal whose purchase cost is substantially an order of magnitude less than estimates for the military counterpart. A further objective is to define ground station requirements for position monitoring of civil users requiring this capability and the civil user navigation and location-monitoring requirements. It is the latter subject that is addressed in this report.

In the Comptroller General's Report to the Congress of the United States* it was stated that current navigation plans call for the continued development, modernization, or expansion of seven systems which it is believed could be replaced in whole or in part by the military's NAVSTAR Global Positioning System (GPS). Regarding coverage and accuracy the report further states:

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* "Navigation Planning - Need for a New Direction," by the Comptroller General, A Report to the Congress of the United States, LCD-77-109, March 21, 1978.

"The NAVSTAR System could be made to provide global, two-dimensional coverage by 1981. Initial accuracies (which depend in part on the satellite population) will be on the order of 300 feet. When the full population of 24 satellites becomes operational in late 1985, military users and others employing receivers using all of the satellites' signals can expect accuracies on the order of 30 feet. Civil and military users employing the lower cost receivers, which use only the non-deniable signal component, can expect accuracies beginning at about 900 feet and improving to 300 feet by 1985. . . . .

The key to civil acceptance of the NAVSTAR/GPS is an assurance of signal availability and system accuracy and the development of low cost civilian versions of the GPS receiver. The early development of low-cost NAVSTAR receivers will allow the curtailment of planned expenditures for the modification and improvement of existing navigation systems. Industry's acceptance of a development plan for low cost NAVSTAR receivers is dependent on the potential marketplace for the system. The purpose of this report is twofold, namely: 1) to review existing survey literature to ascertain the potential users of a low-cost NAVSTAR receiver and to estimate their number, function, and accuracy requirements, and 2) to define system concepts for low cost user equipments for in-situ navigation and the retransmission of low data rate positioning data via a geostationary satellite to a central computing facility.

User categories investigated herein have been limited generically to those operating on land and at sea. Airborne users have been excluded intentionally.

2.0 DESIGN CONCEPTS

The investigation of a Land/Sea user-receiver terminal for the NAVSTAR/GPS has considered two fundamentally different approaches to providing a position location system in the hands of the civil user community. One concept is in essence a low-cost civilian version of the GPS military Z-Set, currently being developed for the U.S. Air Force (SAMSO), while the other is an evolutionary, redesigned, low-cost version of the Z-Set that utilizes navigation-aiding by signals from a geo-stationary reference satellite (REFSAT), a concept developed by the NASA/Goddard Space Flight Center. In the following sections both concepts will be described on a functional level.

2.1 THE NAVSTAR/GPS USER Z-SET

The NAVSTAR/GPS military-user community is divided categorically into six classes dependent on the following user requirements: accuracy, dynamics, and anti-jam characteristics. The classes of military user equipments are designated A through F, and M, and are presented in Table 2.1.

TABLE 2.1 CLASSES OF GPS MILITARY USER EQUIPMETS

CLASS	PREDOMINANT CHARACTERISTICS	TYPICAL PLATFORM VEHICLE
A	High Accuracy/High Antijam	B-1
B	High Accuracy/High Dynamics	F-4
C	Low Cost	C-130 Aircraft
D	Low Dynamics	Ships
E	Small	Manpack
F	Fast Fix	Submarine
M	Expendable	Missile

Due to the high costs involved in undertaking development of all the aforementioned classes of military user equipment separately, the NAVSTAR/GPS Phase I development program is comprised of four types of sets (referred to as X, Y, Z and Manpack) to emulate the basic levels of receiver sophistication required. The relationship between the Phase I development sets and the GPS user class emulated is presented in Table 2.2.

TABLE 2.2 RELATIONSHIP BETWEEN NAVSTAR/GPS PHASE I MILITARY SETS AND USER CLASS

SET	USER CLASS EMULATED
X	A, B, F
Y	D
Z	C
MANPACK	E

In the following section a brief description is presented of each of the development GPS user equipments.

2.1.1 X-SET

The military user equipment X-Set simultaneously receives L_1/L_2 signals as shown in Figure 2.1. The X-Set receiver functions are managed by a digital process controller which controls receiver operating modes and performs various signal processing functions. Each of the four carrier channels contains pseudonoise (PN) sequence generators, associated circuits for generating the signal replicas, and correlators for recovering the desired sig al. The code channel is used to measure the pseudorange from the PN sequences generated in the receiver, whereas four dedicated carrier channels are employed to

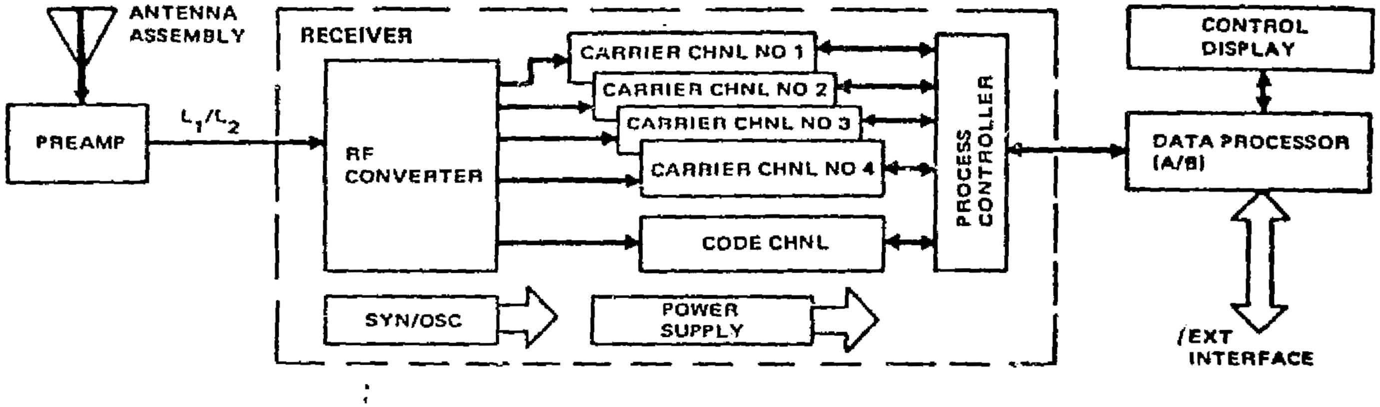

FIGURE 2.1 USER X-SET FUNCTIONAL BLOCK DIAGRAM

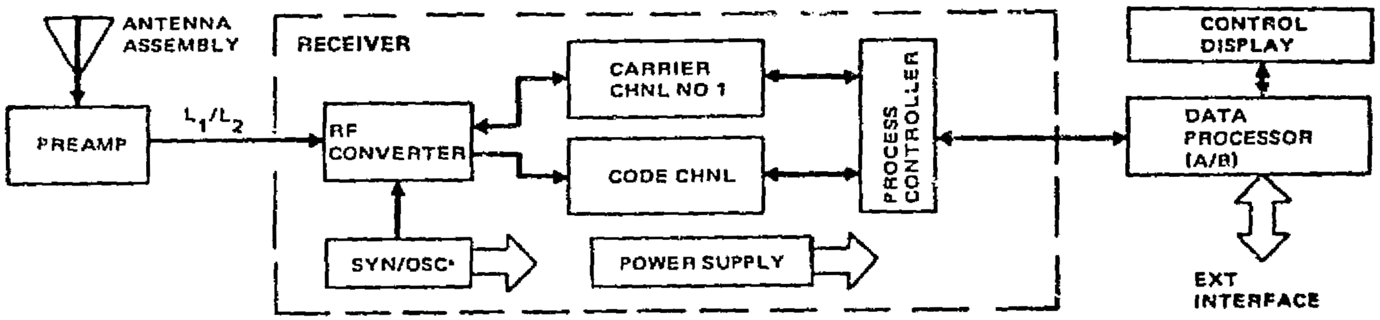

FIGURE 2.2 USER Y-SET FUNCTIONAL BLOCK DIAGRAM

track continuously four individual satellites, only one dedicated code channel is time-shared with each carrier channel. The X-Set simultaneously measures pseudorange and pseudo-delta range from each of the four satellites. The X-Set data processor uses the measurements and data to determine three-dimensional position and velocity and estimate user clock corrections. Using the L_1/L_2 dual-frequency capability, a real-time ionospheric correction measurement is derived to give the X-Set improved navigational accuracy.

2.1.2 Y-SET

Functional and physically, a set Y is similar to set X (see Figure 2.2) however, instead of providing a carrier channel for each of four signals, one carrier channel is used sequentially to receive the L_1/L_2 navigation signals between each of the four required satellites. Because of these functional reductions, the Y-Set inherently contains fewer hardware components. The basic reductions are in the carrier channel where only one carrier channel is used.

The greatest differential between the Y-Set and the X-Set may be in terms of unaided navigation performance. Both sets have nearly identical specifications when operating with an inertial guidance system. However, test results are expected to show considerable differences under unaided dynamic environments.

2.1.3 Z-SET

The Z-Set shown in Figure 2.3 is unique from X and Y in many ways; Z tracks the C/A code and L_1 signal only and is a sequential receiver. By now it should be apparent that in the Z-Set low cost is achieved by compromising performance. The very high precision available

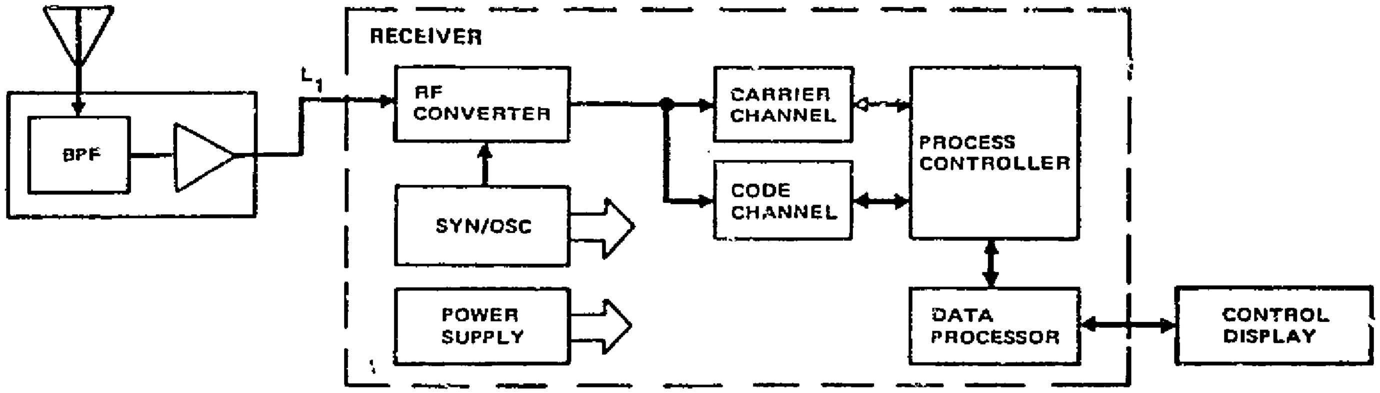

FIGURE 2.3 USER Z-SET FUNCTIONAL BLOCK DIAGRAM

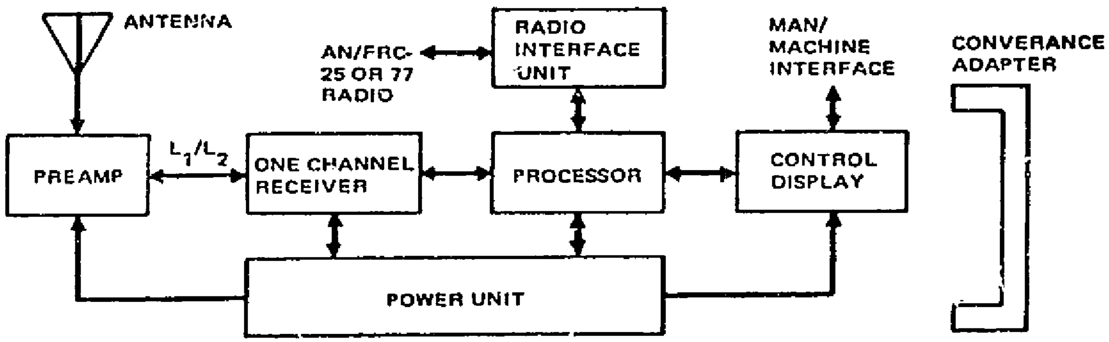

FIGURE 2.4 MANPACK FUNCTIONAL BLOCK DIAGRAM

in the X and Y sets from the P code, and the direct L_1/L_2 ionospheric correction, are missing in the Z-Set to save recurring hardware cost.

Most other performance is like that for the Y-Set except for parameters dependent upon use of the P code, or direct L_1/L_2 ionospheric correction. The Z-Set must meet the applicable MIL-Specs for both airborne and shipboard installation. For shipboard usage, the set is protectively enclosed in a heavy steel casing.

2.1.4 MANPACK SET

A block diagram of the Manpack set is shown in Figure 2.4. The Manpack set is similar to the Y-Set, but differs in the following manner: 1) it contains an integrated processor which has dual functions of receiver control processing and navigation processing; 2) it is implemented with more extensive Hybrid/LSI elements; and 3) the design provides for extremely low-power consumption within a densely packaged form factor. The Manpack provides both P-signal and C/A-signal capability combined with L_1/L_2 dual frequency for precise navigation accuracy.

2.1.5 SUMMARY OF PRESENT USER SETS

Present capability of the X, Y, Z, and Manpack sets currently being developed, and their performance capability, are summarized in Table 2.3.

2.1.6 DETAILS OF THE MILITARY USER Z-SET

The major components of the military Z-Set are presented functionally in Figure 2.5. The Z-Set is segmented into the antenna subsystem, preamplifier subsystem, receiver/processor subsystem, and control/display subsystem. Each of these major elements are described herein.

TABLE 2.3 CAPABILITIES OF CURRENT NAVSTAR/GPS MILITARY USER SETS

	CONFIGURATION			
	X	Y	Z	MANPACK
Simultaneous Satellites Tracked	4	1	1	2
Signal				
o Acquisition	C/A	C/A	C/A	C/A
o Navigation	P or C/A	P or C/A	C/A	P or C/A
Antenna	Dual	Single	Single	Single
Ionospheric Correction Interface	2-Frequency	2-Frequency	Modeling	2-Frequency
o IMU	Yes	Yes	No	No
o Baro Altitude	Yes	Yes	No	No
o External Clock	Yes	Yes	No	Yes
Size	0.12 m^3	0.10 m^3	0.03 m^3	0.018 m^3
Weight	62 kg	60 kg	17 kg	11 kg
Power	515 Watts	460 Watts	151 Watts	35 Watts
MTBF	500 Hours	500 Hours	500 Hours	500 Hours
Time to First Fix TTF (Seconds)				
o Normal (C/A)	80	200	225	110
o Direct (P) (Internal)	100	250	--	225
J/S Margin				
o Carrier Track (P)	50	50	30	50
o Code Track (P)	45	45	30	45
o Data Recovery (C/A)	43	43	30	43
Pseudo-Range Accuracy 1σ (Meters)	1.5	1.5	15	1.5
Delta-Range Accuracy 1σ (Meters)	0.012	0.012	0.012	0.012
Reacquisition Time (Seconds)	10	10	10	10

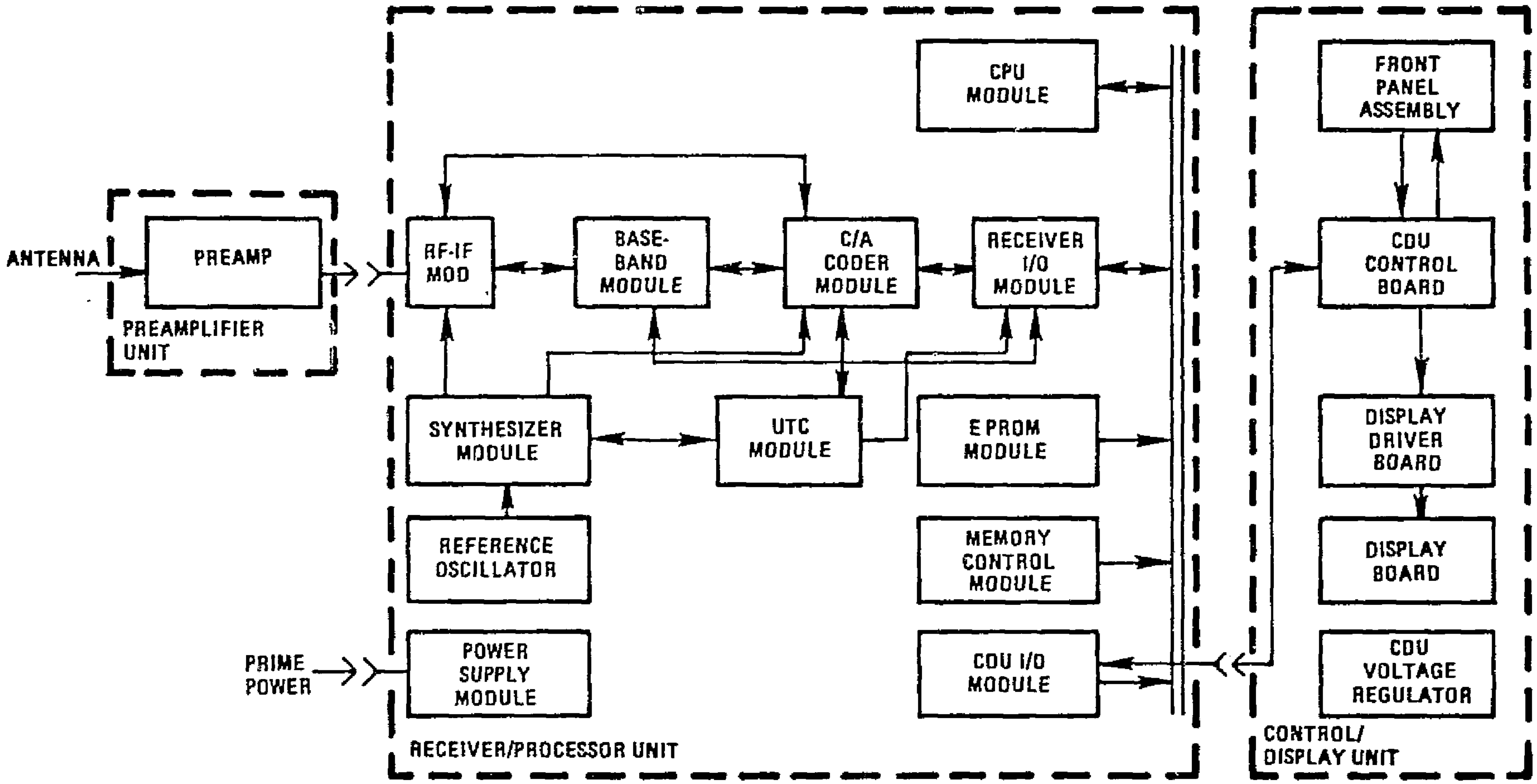

FIGURE 2.5 Z-SET MAJOR COMPONENTS FUNCTIONAL BLOCK DIAGRAM

2.1.6.1 Antenna Subsystem

The antenna subsystem is intended to be mounted on the exterior of the user vehicle at a location with maximum unobstructed view of the sky. Characteristics of the Z-set antenna are presented in Table 2.4.

2.1.6.2 Preamplifier Subsystem

The preamplifier is designed to have sufficient gain to establish the receiver noise figure and to include sufficient filtering prior to preamplification to select the GPS L_1 signal and reject out-of-band interference. Nominal preamplifier performance characteristics are presented in Table 2.5.

2.1.6.3 Receiver/Processor Subsystem

The receiver, as shown in Figure 2.5 is capable of accepting the L_1 GPS RF output from the preamplifier. The major operating modes consist of search and track. Prior to and during the search mode, aiding information such as user position, dynamics, and time are entered into the processor via the control/display unit or other receiver/processor interfaces. The processed information supplied to the receiver from the processor is used to search sequentially for four satellite signals. During the track mode the receiver has the capability to sequentially track any 4 of 37 NAVSTAR GPS signals for a C/A signal at the L_1 frequency. Aiding information received from the data processor during the track mode is utilized to optimize receiver performance. During track, the receiver demodulates navigation data and performs error detection, as well as making pseudorange and delta-range measurements. The data derived during the track mode is supplied to the processor for subsequent calculation of user position, velocity, and system time.

TABLE 2.4 NAVSTAR/GPS Z-SET ANTENNA CHARACTERISTICS

Description	Characteristics
Frequency	1575.42 MHz ±10 MHz
Gain*	> 0 dBic 10-90° elevation
Azimuth 0-360°	>-1.0 dBic (average) 5°-10° elevation
Characteristic impedance	50 ohms nominal
VSWR	1.5:1 max
50 ohms nominal (incl isol + cable to preamp)	
Polarization	RHCP
Axial ratio**	< 3 dB at 90° < 5 dB at 45° <16 dB at 5°
Back lobe (free space)	<-15 dBic
Group delay variation	2 ns peak, 5 -90° elevation
Temperature	-40 to +85°C
Physical characteristics:	
Weight Height	< 1.0 kg 10.5 cm above mounting plane
Diameter:	
at base at radome	25.4 cm 12.7 cm
Connector	Type N female (or TNC)

*Including axial ratio losses.
**On a 7 feet x 12 feet ground plane.

TABLE 2.5 NAVSTAR/GPS Z-SET PREAMPLIFIER PERFORMANCE

Description		Characteristics
Number of antenna signal inputs		1
Number of RF signal outputs		1
Nominal input/output center frequency:		
L_1		1575.42 MHz
L_1 bandwidth selectivity before preamp:		
Before amplifier	Total	
$BW_{3\ dB}$	$BW_{3\ dB}$	26 ±8 MHz; 24 ±8 MHz
$BW_{60\ dB}$	$BW_{70\ dB}$	<250 MHz; <150 MHz
Nominal input/output impedances		50 ohms
Maximum input/output VSWR (L_1 ±8 MHz)		1.5:1
Maximum noise figure reference preamplifier input		5.0 dB
Input signal levels:		
Maximum		-150 dBw
Minimum		-163 dBw
Dynamic range (signal plus jammer)		-163/-125 dBw
J/S		25 dB at -150 dBw
Burnout protection		0 dBm minimum
Gain at L_1		30-39 dB
Phase linearity (±2.0 MHz)		±5 deg
Group delay variation (over ±2.0 MHz range)		10 ns
Input power (dc supplied via output conn.)		0.5 watt
Temperature (operating)		-40 to +55°C
Weight		2.27 kg
Volume		1830 cm^3

2.1.6.4 Control/Display Subsystem

The control/display (CD) subsystem (Figure 2.6) provides the means by which Z-Set operation is maintained. The operator is provided with manual controls and visual readouts to enable entry and readout of the functions and parameters necessary to perform the following:

1) control the operation of the GPS user equipment

2) readout the host-vehicle three-dimensional position, ground speed, ground track and time

3) perform waypoint navigation.

2.2 THE REFSAT CONCEPT

A functional description of the REFSAT concept is presented in Figure 2.7. The REFSAT approach narrowband FSK data signals transmitted from a geostationary satellite. An L-Band downlink is transmitted at the lower edge of the GPS L_1 carrier (1575.42 MHz) and is passed through a common front-end into dual IF amplifiers. The REFSAT concept, developed by Sennott, Choudhury and Taylor,* is in contrast with the signal processing functions performed by the conventional NAVSTAR/GPS user terminal as shown in Figure 2.8. The authors have summarized (Table 2.6) the various operations performed for position fixing on a GPS signal.

2.2.1 REFSAT DOWNLINK SIGNAL FORMAT

The REFSAT downlink signal is an FSK data stream (Figure 2.9) consisting of a series of frames divided into 4 sub-frames of 128 bits each, and comprised of the following:

o Synchronization and Framing	24 bits
o Satellite position referenced to REFSAT system frame epoch	72 bits (24 bits each x,y,z)
o Doppler Gradient	24 bits
o Code Select	8 bits

* J. W. Sennott, A. K. Choudhury & R. E. Taylor, "The REFSAT Approach to Low-Cost GPS Terminals," NASA Goddard Space Flight Center, TM#79655, April 1979.

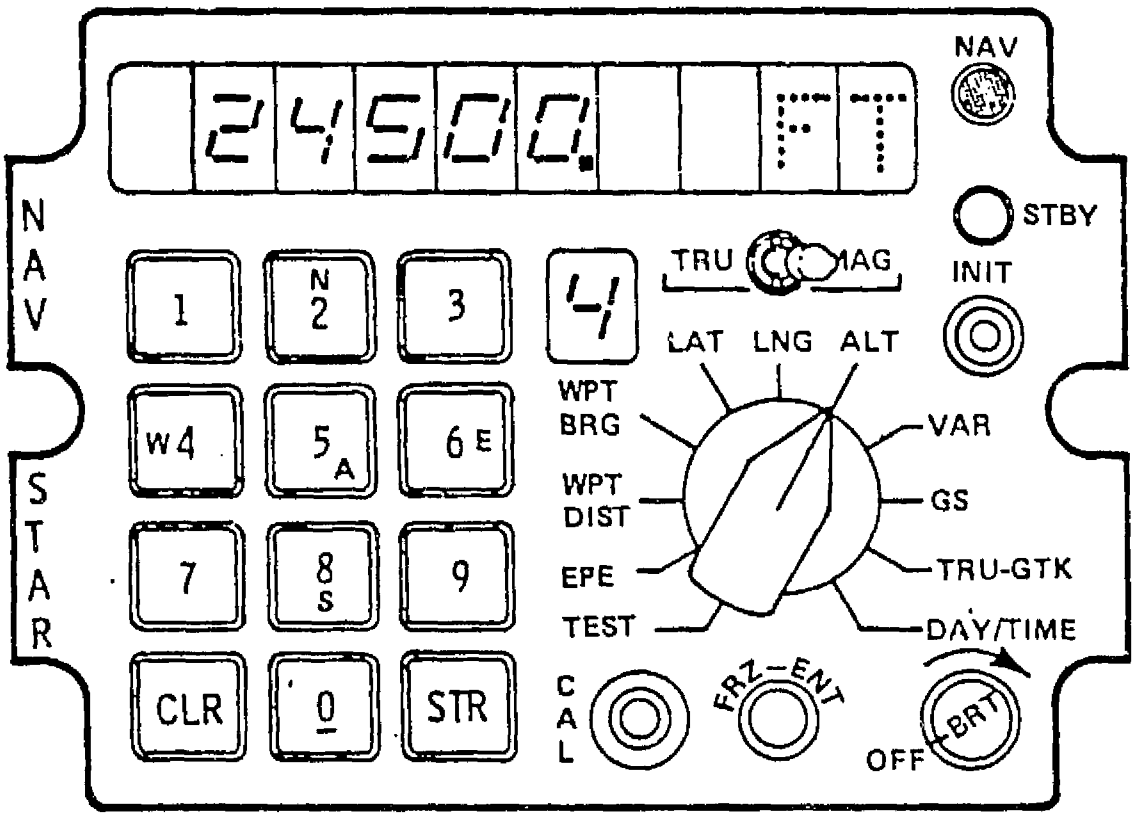

FIGURE 2.6 Z-SET CONTROL/DISPLAY UNIT

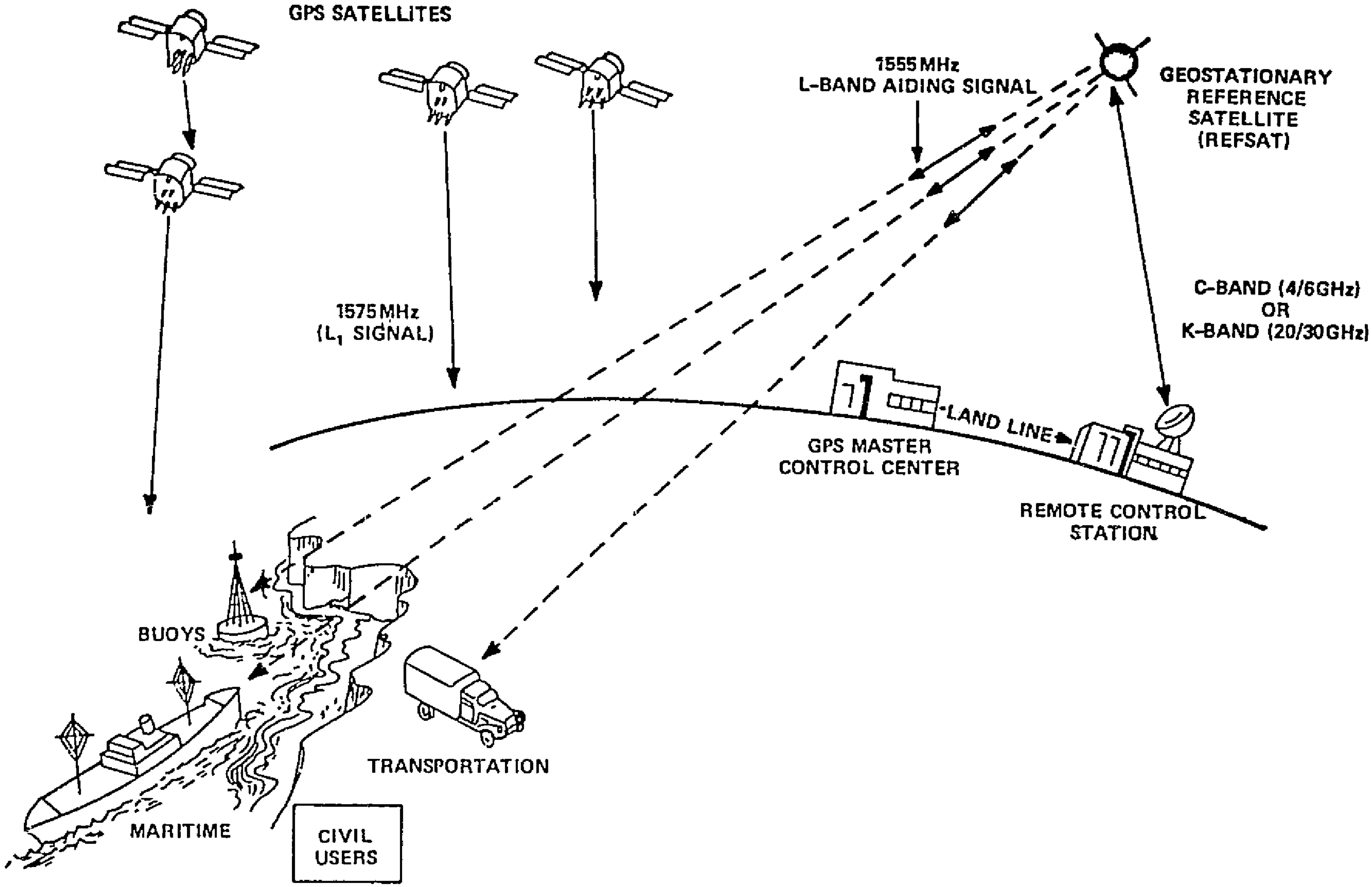

FIGURE 2.7 NAVSTAR GPS CONCEPT USING GEOSTATIONARY REFSAT

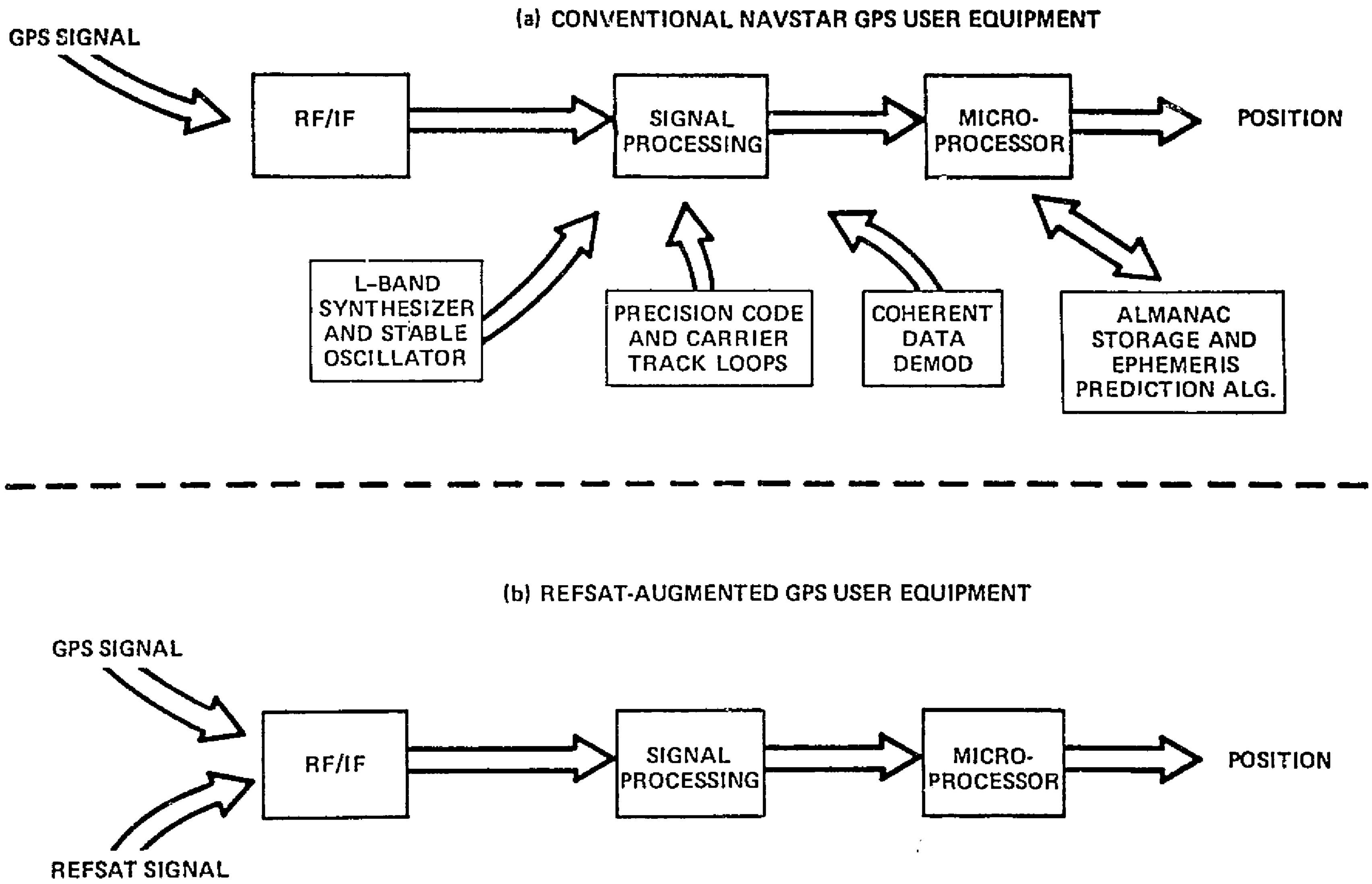

FIGURE 2.8 REFSAT VS. CONVENTIONAL RECEIVER

TABLE 2.6 GPS RECEIVER FUNCTIONS COMPARISON

		Conventional GPS Terminal		
Major Function	**Sub-Function**	**Hardware**	**Software**	**REFSAT Simplification**
Signal Acquisition	1. Initial Satellite Selection		GPS Almanac Compute satellites in view	Eliminate this software/ storage function
	2. Doppler Acquisition	1 part 10^7 synthesizer (in oven)	Compute range rate for selected satellites	VCXO to 1 part in 10^5
	3. Delay Acquisition	PSK spread spectrum programable synthesizer (in phase & quadrature)	Filter error signals Advance/retard commands	Reduce code generator precision
Signal Tracking	4. Fine Delay Track	Delay-lock loop	Filter error signals Advance/retard commands	No punctual code, employ interpolation
	5. Fine Doppler Acquisition	AFC loop	Filter error signals VCXO freq. step commands	Not essential for all users
	6. Carrier Phase Track	Costas loop	Filter error signals VCXO phase step commands	Eliminate entirely
Position Fixing	7. Telemetry Acquisition	PSK demodulate using above phase reference		Simple non-coherent FSK
	8. Ephemeris Update		Real-time predictor	Eliminate entirely
	9. Position Computation		Pseudo range to lat.-long. conversion	

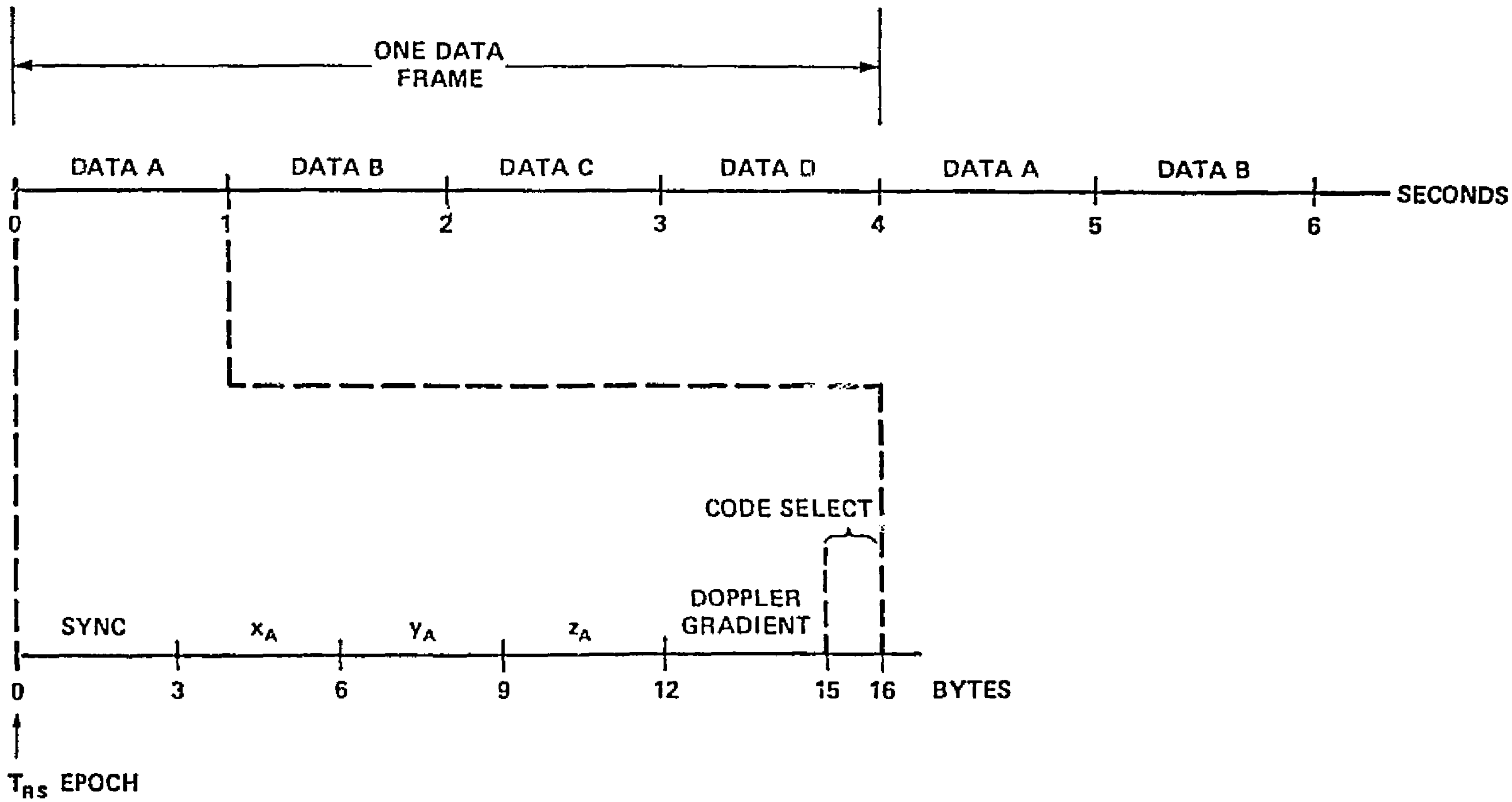

FIGURE 2.9 REFSAT DATA FORMAT

The REFSAT user terminal first acquires the noncoherent FSK data stream from which satellite selection is derived and completes the signal acquisition process with a C/A code scan identical to that for the conventional terminal.

The GPS-REFSAT terminal, unlike the conventional equivalent, accomplishes the signal tracking function through application of a code-delay interpolation process, in which code step pairs separated by one chip are employed. This procedure simplifies the code generators and tracking filters, and eliminates the need for a Costas carrier tracking loop.

The GPS REFSAT terminal provides (via the FSK data link) updated GPS satellite coordinates every 4 seconds, thus eliminating most of the storage and computation associated with the hourly updating of GPS satellite ephemerides required for the conventional terminals. A simplified functional description of the REFSAT User Terminal is presented in Figure 2.10.

2.2.2 REFSAT CARRIER MODULATION

In addition to receiving the NAVSTAR/GPS L_1 signal, the REFSAT concept involves reception of a second, geostationary, reference satellite (REFSAT) signal to provide acquisition- and navigation-aiding digital data from a remote control ground station by means of a radio link. To relay the digital data, the baseline REFSAT signal design is frequency-shift-keying (FSK) modulated by a subcarrier which is phase modulated onto a prime carrier. The two subcarrier frequencies considered are 9 kHz and 17 kHz, the data rate being 128 bps. This means that the effective deviation ratio is 62.5. The optimum bandwidth for limiter-

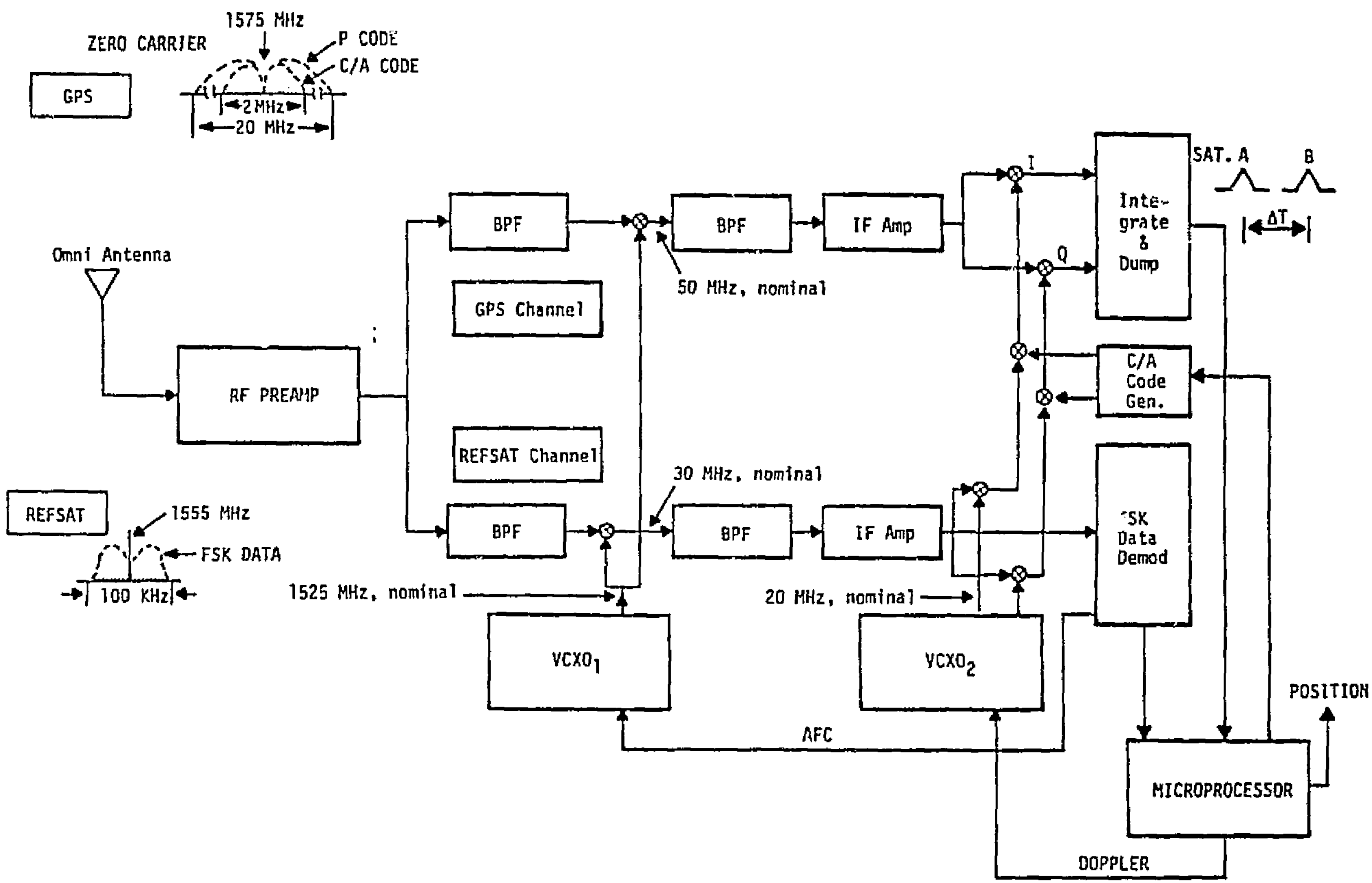

FIGURE 2.10 REFSAT USER TERMINAL BLOCK DIAGRAM

discriminator demodulation is therefore 8 kHz. Since this is a digital signal format, there are no discriminator thresholding problems normally associated with an FM system.

Frequency offsets up to 800 Hz should present no substantial degradation. If the baseline BPF/Envelope Detector/Largest or Detector is used, then frequency offsets are very degrading to the system. Unfortunately the optimum FSK devision ratio (0.7 for NRZ) cannot be used due to practical limitations in frequency stability. It would therefore seem wise to use a limiter-discriminator detector with a wide frequency tolerance. The coherent integration of the optimum detector is again a factor when frequency tolerance is critical. The limiter-discriminator performance is based on postdetection integration and thus has a higher tolerance for frequency offsets.

The REFSAT signal channel has an available power signal-to-noise ratio (SNR) of

$$SNR_{REFSAT} = 40.6 + [-154-(-160)] -10 \log 8000 = 7.6 \text{ dB}.$$

Table 2.7 shows the SNR needed for various bit error rates. It is seen that the SNR_{REFSAT} is more than adequate.

TABLE 2.7

PROBABILITY OF ERROR FOR NRZ AND MANCHESTER PSK

IF BT	DEV. RATIO	ED/NO (DB)	IF CNR (DB)	NRZ P(E)	MANCHSTR P(E)
80.00	90.00	20.03	1.00	2.88E¯4	2.76E¯4
		20.53	1.50	8.16E¯5	9.08E¯5
		21.03	2.00	1.76E¯5	1.81E¯5
		21.53	2.50	2.73E¯6	2.97E¯6
		22.03	3.00	2.95E¯7	3.34E¯7
		22.53	3.50	2.31E¯8	2.42E¯8
		23.03	4.00	9.08E¯10	1.03E¯9
		23.53	4.50	1.76E¯11	2.43E¯11
		24.03	5.00	1.39E¯13	2.97E¯13
		24.53	5.50	8.96E¯16	1.52E¯15
		25.03	6.00	1.39E¯19	3.34E¯19

3.0 USER REQUIREMENTS

Operational requirements for land/sea users of the NAVSTAR/GPS are wide and varied depending on their function. In this section a survey of expected user requirements is presented, with estimates of user population and demand.

3.1 MARINE NAVIGATION REQUIREMENTS

Virtually all of the world's ocean-going ships (over 1000 tons), most ships operating in coastal waters (100 to 1,000 tons) and some fishing boats and larger pleasure boats (under 100 tons) use navigational systems. Probably 90% of all ships and boats do not carry navigational aids (other than a compass) because they are close to shore, in coastal areas, or in inland lakes and rivers; however, as the number of craft increases the need for a primary navigation system is increased. Furthermore, as the user's cost for such systems is reduced the potential application to small craft increases.

The purpose of a navigation system is to provide to the mariner a means by which position information is provided for safe navigation under all conditions of cloud cover, sea state, and visibility. Moreover, traffic separation schemes would be enhanced and the number of collisions reduced if an accurate navigation system were available to all marine craft. In the following sections various aspects of marine user operational requirements will be presented.

3.1.1 MARINE USER CHARACTERISTICS

In general, civil marine users can be categorized into merchant vessels, fishing vessels, survey and scientific vessels and other specialized ships, and pleasure craft. As will be seen, the latter category comprises by far the majority of civil marine craft. There is one more category of vessel which deserves special note, namely the unattended buoy. Theatered or drifting, this type of craft is enjoying increased usage in both high seas and estuarian waterways.

The merchant ships include passenger liners, dry cargo ships, and towboats with their barges. Vessels of this type usually operate from port-to-port in transporting their cargo (passenger and/or goods), and the desire of these shipowners for a highly accurate navigation system is based more on economic considerations than any other.

Vessels engaged in oil and mineral exploration, oceanographic and hydrographic research, dredging, and other functions are classified as survey and scientific ships. Navigational accuracy requirements for this category of shipping is based on their particular mission. For example, oil exploration requires a higher degree of position fixing than cable laying. On the other hand, a high degree of accuracy is required if the cable laying ship is on a mission of repairing a trans-oceanic cable. In general, survey and scientific vessels traverse all areas from inland waterways to the high seas.

There are many types of fishing vessles some of which operate in relatively protected waters and others which operate on the high seas. Most fishing operations are performed in relatively shallow water and usually relatively close to land. In general the operational navigation requirements for commerical fishing operations are influenced primarily by the confines and shipping patterns of the coastal and confluence zone.

The preponderance of pleasure craft, at this time, rely on visual and audible navigation aids. More often than not, highly accurate navigation equipment is not installed in pleasure craft because of the high cost of such systems to the owner.

The final class of marine user can be referred to as unmanned vessels, and comprises primarily oceanographic and hydrometeorological buoys. The buoys are equipped with a variety of sensors which measure such parameters as sea and air temperature, wind velocity and direction, salinity, etc., and are of two types - drifting and moored. Accuracy requirements for these unmanned platforms are determined by the type of experiments being performed.

3.1.2 MARINE USER POPULATION

There is a great disparity between reference sources with regard to the number and classification of seacraft. In the OMB report to the Congress over 7 million seacraft were estimated to operate in the United States. The distribution of these ships is shown in Table 3.1.

TABLE 3.1 OMB ESTIMATE OF SHIP POPULATION*

CATEGORY	UNITED STATES	OTHER NATIONS	TOTAL
U.S. Naval Ships	800	10,900	11,700
Civilian Ships & Boats			
over 1,000 tons	900	21,500	22,400
100 to 1,000 tons	3,200	35,600	38,800
under 100 tons	7,400,000	2,700,000	10,100,000
TOTAL Shipping	7,404,900	2,768,000	10,176,900

On the other hand the Department of Transportation National Plan for Navigation has a somewhat different distribution of U.S.

* Op.Cit.

shipping. The marine user population according to this report is different as well. A summary of the DOT population estimates is shown in Table 3.2.

TABLE 3.2 DOT ESTIMATES OF U.S. SEA VESSELS

CATEGORY	POPULATION	REMARKS
<u>Over 100 tons</u>		
Merchant	38,000	11,000 at sea
Fishing	9,000	14,000 in 1980
<u>Over 5 tons</u>		
Merchant	26,000	
Oil Exploration	2,000	
Tow Boats	6,000	
Charter Boats	3,800	Recreation
Fishing	21,000	
Pleasure Craft	10,000,000	
TOTAL	10,105,800	

Still another survey of user requirements and population prepared for the Office of Telecommunications Policy* offers a slightly different categorization and user population estimate. The distribution of user class in the survey was based primarily on user navigational accuracy requirements and operating range. A summary of their findings are presented in Table 3.3.

TABLE 3.3 OTP ESTIMATE OF USER POPULATION

ACCURACY	USER POPULATION
1000 to 3000 meters	<20,000
100 to 1000 meters	<33,400
10 to 100 meters	<10,000
1 to 10 meters	<11,400
Less than 1 meter	<100
TOTAL	Approximately 75,000

* "Radio Navigation Study," Volume 1, prepared by Computer Sciences Corporation for the Office of Telecommunications Policy, February 1975.

3.1.3 THE MARINE ENVIRONMENT

According to the National Research Council,* and others, the maritime environment can be divided into three categories, namely: high seas, coastal and confluence regions, and harbor and harbor-entrance zones.

Generally, high seas refers to those waters in which no land mass is visible, nor is there any other form of visual navigation aids (buoys, etc.). Navigation through these waters in general is based on sextant, compass, and radio navigation.

Traffic patterns in the coastal and confluence zone (CCZ) can be either point-to-point (e.g., domestic or foreign trade), directed (hydrographic research, fishing, etc.), or recreational. The CCZ is bounded geographically from the harbor entrance point to 50 nautical miles offshore or to the extremes of the continental shelf, whichever is greater. The zone is characterized by the convergence of oceanic traffic patterns as vessels near their destination. The accuracy requirements in the CCZ are governed by both natural hazards and the increase in traffic density.

Coastwise traffic lands, fairways, and precautionary areas at harbor entrances have been established within the CCZ to lessen the risk of collision. Within these areas there is a need for greater accuracy, as indicated by the lane widths described in Table 3.4.

On the inland side of the CCZ boundary we have the Harbor and Harbor Entrance (HHE) area and other inland waterways. It is in these areas that the greatest precision in navigation is required to avoid

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* "Practical Applications of Space Systems, Marine and Marine Uses," prepared for the Space Applications Board, Assembly of Engineering, National Research Council (1975).

TABLE 3.4 PRECAUTIONARY AREAS OF THE COASTAL AND CONFLUENCE ZONES

AREA	LAND WIDTH	SEPARATION	REMARKS
Coastwise Lanes	Two 1 NM	lanes are 2 NM apart	One way lanes
Harbor Approach	Two 1 NM lanes out to 7 NM from harbor entrance	Buffer Zone	One way lanes
	Two 5 NM lanes from 7 NM to 50 NM	Buffer Zone	One way lanes
Fairways	One 2 NM lane	Each vessel expected to stay in its own 1 NM half-fairway	Two way lanes

both collision and grounding. These areas are characterized by shallow water, narrow channels, pier areas, and a variety of other obstacles and the vessels are confined to a limited amount of water area for maneuvering. Navigation errors in these areas have a far greater potential for disaster than in the CCZ or high sea areas.

The principle constituents of the HHE include coastal harbors, bays, sounds, estuaries, and rivers which have ports for ocean vessels. On the other hand, inland waterways are classified as all those navigable waterways in the U.S. which are not included in the HHE. Two major examples are the Mississippi River and the Intercoastal Waterway.

3.1.4 MARINE NAVIGATION SYSTEM REQUIREMENTS

There are three key factors which govern the applicability of navigation systems to the marine environment, namely coverage, availability, and accuracy. Each of these factors are governed by the class of vessel and the environment in which it is operating. The National Plan for Navigation prepared for the Department of Transportation* has established goals for marine navigation systems requirements. Those requirements are presented in Table 3.5 categorized by the operating environment of vessel traffic.

In the OTP report on radio navigation the marine navigation requirements are categorized according to the class and function of vessel. A summary of those requirements is presented in Table 3.6.

Gilbert,** in a paper prepared for the Advisory Group for Aerospace Research and Development sets forth a list of marine population and radionavigation requirements (Table 3.7) and/or accuracy and coverage which presents the requirements by user class and includes

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* "Department of Transportation National Plan for Navigation," November 1977, Report No. DOT-TST-78-4.

** Gilbert, Glen A., et.al., "Civil Applications of NAVSTAR GPS," prepared for Advisory Group for Aerospace Research and Development (AGARD) North Atlantic Treaty Organization, August 1978, Confidential Preprint.

TABLE 3.5 DOT MARINE NAVIGATION GOALS

MARINE ENVIRONMENT	COVERAGE	AVAILABILITY	ACCURACY
High Seas	Worldwide Primarily Northern Pacific & Northern Atlantic	o 100 percent desired o 2 hour intervals will suffice	o 4 NM until year 2000 o 2 NM after that time o 2 NM desired
Coastal and Confluence Zones	Continental U.S. Southern and Southeastern Alaska Great Lakes	99.7 percent minimum	0.25 NM
Harbor and Harbor Entrance Areas and other Inland Waterways		99.7 percent minimum	Small vessels: 100-200 ft Major ships: 50 feet Congested waterways: 10 ft

TABLE 3.6 MARINE NAVIGATION REQUIREMENTS BY SHIP CLASS

CLASS/FUNCTION	OPERATING RANGE	ACCURACY (METERS)	UPDATE INTERVAL	WEIGHT (KG)	COMMUNICATION	SPEED (Km/Hr)	USER'S POPULATION	REMARKS
SAR, Ships	Coastal + High Seas 1000-10,000 Km	1000-3000	Continous	<1000	Not Required	10-100	<100	Speed includes Helicopter
SAR, People	Coastal + High Seas 1000-10,000 Km	1000-3000	Continuous	<1000	Not Required	10-100	<10,000	Speed Includes Helicopter
Ship Navigation, Transit	High Seas 1000-10,000 Km	1000-3000	≤3 hours	<1000	Not Required	0-50	<10,000	
Bathythermograph & Meteorological	High Seas 1000-10,000 Km	100-1000	≤3 hours	<1000	Not Required	0-50	<100	
International Treaty Observance	High Seas 1000-10,000 Km	100-1000	≤60 min.	<100	Not Required	0-50	<1000	Near Appropriate Boundaries
Ship Navigation, Transit	Coastal 100-1000 Km	100-1000	≤60 min.	<1000	Not Required	0-50	<10,000	
Ship Navigation, Track Following	High Seas 1000-10,000 Km	100-1000	≤60 min.	<1000	Not Required	0-50	<1000	New Requirement
Hydrographic Charting	High Seas 1000-10,000 Km	100-1000	Continuous	<1000	Not Required	0-10	<100	
Law Enforcement	Coastal + High Seas 100-1000 Km	100-1000	<5 sec.	<10	Not Required	0-50	<1000	Primarily Coast Guard
Fisheries Research	Coastal + High Seas 100-1000 Km	100-1000	<5 sec.	<10	Not Required	0-10	<100	
Midwater Trawling	Coastal + High Seas 100-1000 Km	100-1000	<5 sec.	<10	Not Required	0-10	<10,000	

TABLE 3.6 MARINE NAVIGATION REQUIREMENTS BY SHIP CLASS (Cont.)

CLASS/FUNCTION	OPERATING RANGE	ACCURACY (METERS)	UPDATE INTERVAL	WEIGHT (KG)	COMMUNICATION	SPEED (Km/Hr)	USER'S POPULATION	REMARKS
Ship Navigation	Fairways 10-100 Km	100-1000	≤5 sec.	<100	Not Required	0-50	<10,000	Particularly Gulf of Mexico
Bottom Trawling	Coastal 10-100 Km	10-100	Continuous	<10	Not Required	0-10	<10,000	Relative with Respect to Trawling Experience & OGS
Geomagnetic Survey	High Seas 100-1000 Km	100-1000	<5 sec.	<10	Not Required	0-10	<100	Primarily NOS
Lobster Pot Reporting	Coastal 10-100 Km	1-10	<5 sec.	<10	Not Required	0-10	<1000	Primarily East Coast
Buoy Placement (Army Eng.)	Coastal 10-100 Km	1-10	<5 sec.	<1000	Not Required	0-10	<100	
Buoy Placement (C.G.)	Coastal 10-100 Km	1-10	<5 sec.	<1000	Not Required	0-10	<100	
Collision Avoidance, VTS Coastal Radar	Estuary/Bays/Channels 10-100 Km	1-10	Continuous	<1000	Not Required	0-10	<10,000	Where Installed
Seismograph Survey	Coastal 10-100 Km	1-10	Continuous	<1000	Not Required	0-10	<100	Oil Field Development
Buoy Placement	Fairways, Channels 10-100 Km	1-10	<5 sec.	<1000	Not Required	0-50	<100	
Channel Dredging, Sweeping	Channels 10-100 Km	1.0	Continuous	<1000	Not Required	0-10	<100	

TABLE 3.7

MARINE NAVIGATION ACCURACY REQUIREMENTS
AND USER POPULATION DISTRIBUTION

USER	POPULATION		AREA/ACCURACY REQUIREMENT		
	Documented U.S. over 5 G.T.	World over 100 G.T.	High Seas	CCZ	HEZ
Merchant		34,347			
tanks tank barge	2,590	5,869	4NM	.25NM	
cargo cargo barge	17,956	27,708	4NM	.25NM	
lighter	33				
Passenger	6,805	770		.25NM	
Special Purpose		3,980			
Cable	10				
Dredging	494				6 ft
Oil Exploration	2,315		50 ft		
Ferry	267				
Fire Boats	39				
Ice Breaker	2				
pile driving	82				
pilot boat	104				
police boat	47				
patrol boat	53				
water boat	10				
whaler	2				
welding	12				
wrecking	22				
Tow boats	6,309			.25 NM	
Other		3,980			
hydrographic			.1NM	8M-5M	
minerology			10 ft		
meteorology			1-3NM		
bathymetry			3NM		
special/scientific			0-0.1NM	0-0.1NM	
Miscellaneous	1,297				
Pleasure	1,400,000 est		0.5-1NM	0-0.1	
Yachting	37,924		0.5-1NM	0-0.1	
Fishing	21,583	11,949			
research				.5NM	
COD	2				
Oystering	830				for safe nav
pots, netters			.025NM	100 ft	for safe nav
party boats					.025NM
bottom travel				.025NM	
purse seine				0.2NM	
drift gillnet				0.5NM	
trolling	4,200			0.5NM	
shrimping			0.5NM	0.5NM	
midwater trawl			0.5NM	0.5NM	
scalloper					
clammers					

accuracy requirements versus area of operation for total world population for vessels over 100 gross tons and U.S. vessels over 5 gross tons.

3.2 LAND PLATFORM NAVIGATION REQUIREMENTS

In the Department of Transportation's National Plan for navigation land user characteristics are based on two generic system concepts, namely: surveillance and location identification. Unlike their marine counterparts, landbased users are more concerned with mobilization, and coordination of service vehicles rather than the enroute navigation and collision avoidance. In general, the characteristics of these systems are such that the following operational functions are required:

1) An emergency alarm function operated on an as-needed basis

2) Accurate user vehicle location information

3) A communications link.

Surveillance and location systems such as the NAVSTAR/GPS can increase operating efficiency of a variety of services. For example, in urban areas public safety vehicles would enjoy a faster response time and public transportation vehicle schedules could be recorded more accurately. In remote areas accurate position determination would lead to improved coordination in search and rescue operations, and law enforcement activities.

3.2.1 CHARACTERISTICS OF THE LAND USER

In surveillance systems position data is required for the use of supervisory and dispatch personnel as an aid to keeping track of the location and flow of a variety of vehicles.

Typical of surveillance systems is the Automatic Vehicle Monitoring (AVM) system. Both the Law Enforcement Assistance Administration (LEAA) and the DOT's Urban and Mass Transit Agency (UMTA) have been instrumental in developing this concept. To date a variety of location aids have been experimented with, including LORAN-C, electronic signposts, OMEGA, etc. The NAVSTAR/GPS user receiver for Land/Sea users has all the attributes to make it an integral part of any vehicle surveillance system. The land users have been categorized in the DOT report according to the following:

a. Vehicles operating in urban areas whose maximum linear dimension is 10 to 35 miles.

b. Users operating between urban centers over an area of up to 500 miles.

c. Interstate buses, trucks, trains, etc. who operate over linear distances from 600 to 3000 miles.

The location identification function of a position determination system is somewhat different than the surveillance function, although the same equipment would most likely be used. Location identification is required to position an object on a known grid. For example, the delivery of goods and services to a rural dwelling or the pinpointing of objects or incidents along highways by public safety and highway maintenance operations require such position information. Air surveys of geological faults, search and rescue operations, etc. usually require a followup by land operations and as such accurate location identification is required.

3.2.2 LAND USER POPULATION

The number of potential land users of a GPS position location system is in the millions. There is always great difficulty in estimating the exact size of the type of user population because they are dispersed by both class and geography. One estimate* for U.S. civil land use of location identification systems is presented in Table 3.8.

* Gilbert, et.al., op.cit.

TABLE 3.8

ESTIMATE POTENTIAL U.S. CIVIL LAND USE OF LOCATION IDENTIFICATION SYSTEMS

police vehicles	170,000
fire vehicles	200,000
emergency medical vehicles	28,000
urban transit vehicles	50,000
interstate buses	20,000
intercity trucks	1,000,000
delivery vehicles	1,200,000
utility company vehicles	100,000
taxis	50,000
census inventory	50,000
land transportation statistics and inventory	10,000
geological survey and exploration	2,000
Total estimated market size	2,880,000

3.2.3 ACCURACY AND COVERAGE REQUIREMENTS

Unlike marine operations position determination of land users is a relatively new area; because of this, and the wide variety of users and functions, firm requirements for navigational accuracies and coverage have not appeared, save in a few instances. Contained herein is a summary of land based user requirements based upon a survey published literature.

In the DOT National Plan for Navigation the user categories are divided into three groups: urban, statewide, and transcontinental, as shown in Table 3.9.

At this time, the number of land users is still quite small; however, that number is expected to increase in forthcoming years, especially with the potential of a relatively low cost navigation receiver. As can be seen from the preceding analysis, reliable population figures and accuracy requirements are virtually non-existent.

3.2.4 LAND USER COST BOUNDS

A cost model was developed* to determine the basic bounds of a cargo security system, based on unit life, maintenance, support equipment, etc. A summary of that cost analysis for a $1000/year/vehicle system is presented in Figure 3.1.

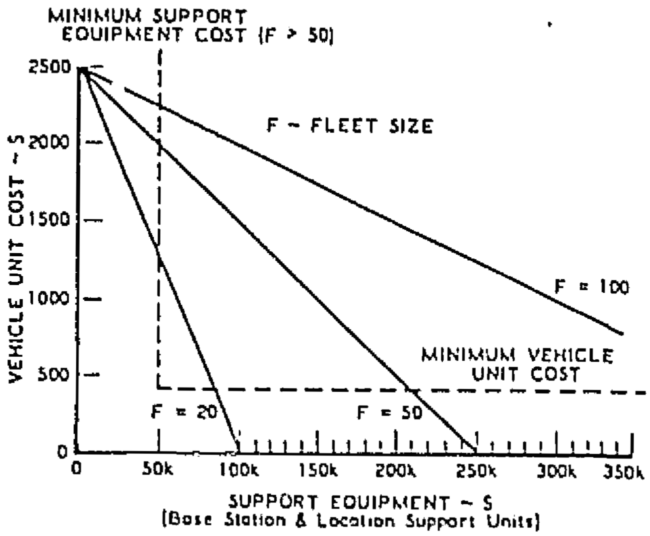

FIGURE 3.1 SYSTEM COST LIMITS

The author assumed a minimum cost of $400 per vehicle unit irrespective of the technique, sensor interfaces, and installation. For a 50 vehicle fleet he estimates that the per vehicle cost for the location and identification system would be on the order of $600/year.

Gilbert, et.al.,* on the other hand, have stated that the market for land use of the GPS system is relatively sensitive to cost and estimated that the receiver and data recorder for the position location user equipment should cost less than $1500.

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* Wilson, G.D., "A Cargo Security System," loc.cit.

** loc.cit.

TABLE 3.9 DOT CATEGORIZATION OF LAND USER REQUIREMENTS

USER CATEGORY	ACCURACY REQUIREMENT	UPDATE INTERVAL (SEC)
URBAN		
Police Car	50 feet	30 to 60
Taxi Cab	500 feet	30 to 60
STATEWIDE		
Most Applications	200 to 1000 feet	30 to 60
Highway Maintenance	50 feet	30 to 60
TRANSCONTINENTAL	1/4 to 1 mile	30 to 60

In an evaluation of a cargo security system,* G. D. Wilson has indicated that the response time of police cruisers cannot be significantly increased when a truck's location accuracy is less than 500 feet. He concludes that a minimum accuracy of 600 feet at a 95% confidence level is adequate, but that an accuracy of 300 feet is desirable.

In discussions with Mr. Donald T. Carson of the U.S. Marshal's Service several years ago it was indicated that the agencies providing personal security for high ranking U.S. Government officials while traveling in automobiles desired to know the location of such VIP vehicles to within two city blocks.

The Radio Navigation Study** prepared for the Office of Telecommunications Policy has a somewhat different estimate of the accuracy requirements for civil land users, as shown in Table 3.10.

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* "Cargo Security System," Geoffrey D. Wilson, presented at the 1975 Carnahan Conference on Crime Countermeasures, Report No. 75CH0958-9 AES, May 7-9, 1975.

** Ibid.

TABLE 3.10 CIVIL USER ACCURACY REQUIREMENTS*

CLASS/FUNCTION	OPERATING RANGE	ACCURACY (METERS)	UPDATE INTERVAL	WEIGHT (KG)	COMMUNICATION	SPEED (Km/Hr)	USER'S POPULATION	REMARKS
Police Cruisers (Urban)	10-100 Km	500	30 sec.	<10	Required	10-100	<10,000	50-100 Vehicles in Each Area
Emergency Vehicles (Urban)	10-100 Km	500	30 sec.	<10	Required	10-100	<10,000	10-20 Vehicles in Each Area
Public Trans., Utility Veh., Commercial Veh., (Urban)	10-100 Km	±500	30 sec.	<10	Required	10-100	<10,000	1000 Vehicles Reporting
Long Distance, Highway Patrol, Railroads + Trucks	100-1000 Km	1000-3000	1 min.	<10	Required	10-100	<10,000	100-1000 Vehicles Reporting in Update Interval

* Reference Source: "Radio Navigation Study," prepared for the Office of Telecommunications Policy, Final Report, February 1975.

3.3 SUMMARY

The purpose of this section is to survey user requirements for a NAVSTAR/GPS land/sea position determination system. Although the accuracy requirements, number of users and reporting interval presented vary according to source, two factors clearly emerge, namely:

1. The number of civil land/sea users number at least in the tens of thousands, perhaps even hundreds of thousands.

2. For more than 90% of the users in the categories surveyed, horizontal accuracy requirements less than 100 meters was not required.

Of the two generic categories (i.e., land/sea) surveyed, it is the maritime community that has a greater grasp on its position location accuracy requirements. Marine users alone constitute a large portion of the civil user community. If one merely projects a forecast for land users, however, it is not difficult to arrive at a user community of 100,000 if it is assumed that there are one thousand vehicles per urban area and at least one hundred major urban areas.

To summarize, estimates of the civil user (non-avionic) population have been made along with potential accuracy requirements for application to navigation and position identification. These estimates are presented in Appendix I for civil navigation and position identification respectively.

4.0 CIVILIAN REFSAT-SET ACQUISITION AND TRACKING

In the following sections, the acquisition and tracking requirements for the civilian REFSAT-SET will be discussed. Then three REFSAT-SET design approaches will be described. The first is a baseline design suggested by NASA/Goddard which involves frequency tracking in the REFSAT channel. The second is a design which modifies the baseline to incorporate more stable local oscillators, thus minimizing the need for frequency tracking. Finally, the third design is a further modification of the baseline design to incorporate sequential detection.

4.1 ACQUISITION REQUIREMENTS

The first requirement of the REFSAT receiver will be to demodulate the REFSAT digital data. This was discussed in Section 2. Having determined which GPS satellite codes to use, the local pseudonoise (PN) code generator will select the proper C/A code.

In the REFSAT-SET, the GPS L_1-signal Doppler offset (± 2 kHz for CONUS) is frequency-scanned in 200-Hz increments and C/A-code phase in sub-microsecond steps. When code correlation occurs, a "hit" is declared.

Starting at the "all ones" state, and offset in frequency by the maximum expected frequency difference, the correlation process will be initiated. If "no hit" is registered then the next frequency cell will be searched by sending a new frequency number to the VXCO which controls the final frequency seen by the correlator.

If after all the frequency cells have been searched, a no hit is declared, then the code clock will be advanced by a fraction of a chip. The frequency is offset to the maximum once more and the whole process repeats.

When a correlation hit is encountered the frequency and code epoch are noted and stored in the associated microprocessor memory. The next satellite's code is loaded into the local PN generator, and the acquisition process described above repeats.

Finally the fourth satellite is acquired; the system then enters the tracking mode.

4.2 TRACKING-MODE REQUIREMENTS

Since continuous tracking of the GPS codes, for example with a delay lock loop, is not envisioned at this time, both frequency and code tracking is essentially identical to that for acquisition.

The acquisition procedure, however, will be modified for the tracking mode by making use of the frequency and code epoch numbers stored earlier for each visible satellite. Since the Doppler-frequency difference for each satellite is known via the REFSAT data channel, this information could be used to advance or retard the frequency tracking VCXO. Also the code epoch will allow a much shorter code phase uncertainty.

Since the reacquisition is on the order of milliseconds, the tracking procedure is to reacquire sequentially each satellite. After the fourth reacquisition, the terminal's geographical position is calculated using range-difference measurements. The position is sent to the display and the whole tracking sequence is repeated.

If at any time tracking fails, then the code and frequency offsets will be opened up further and reacquisition will be repeated. After a certain period of time, initial acquisition is repeated.

4.3 THE REFSAT-SET BASELINE DESIGN

The baseline REFSAT receiver is shown in Figures 4.1, 4.2 and 4.3. The first local oscillator introduces a frequency offset of ± 15 kHz

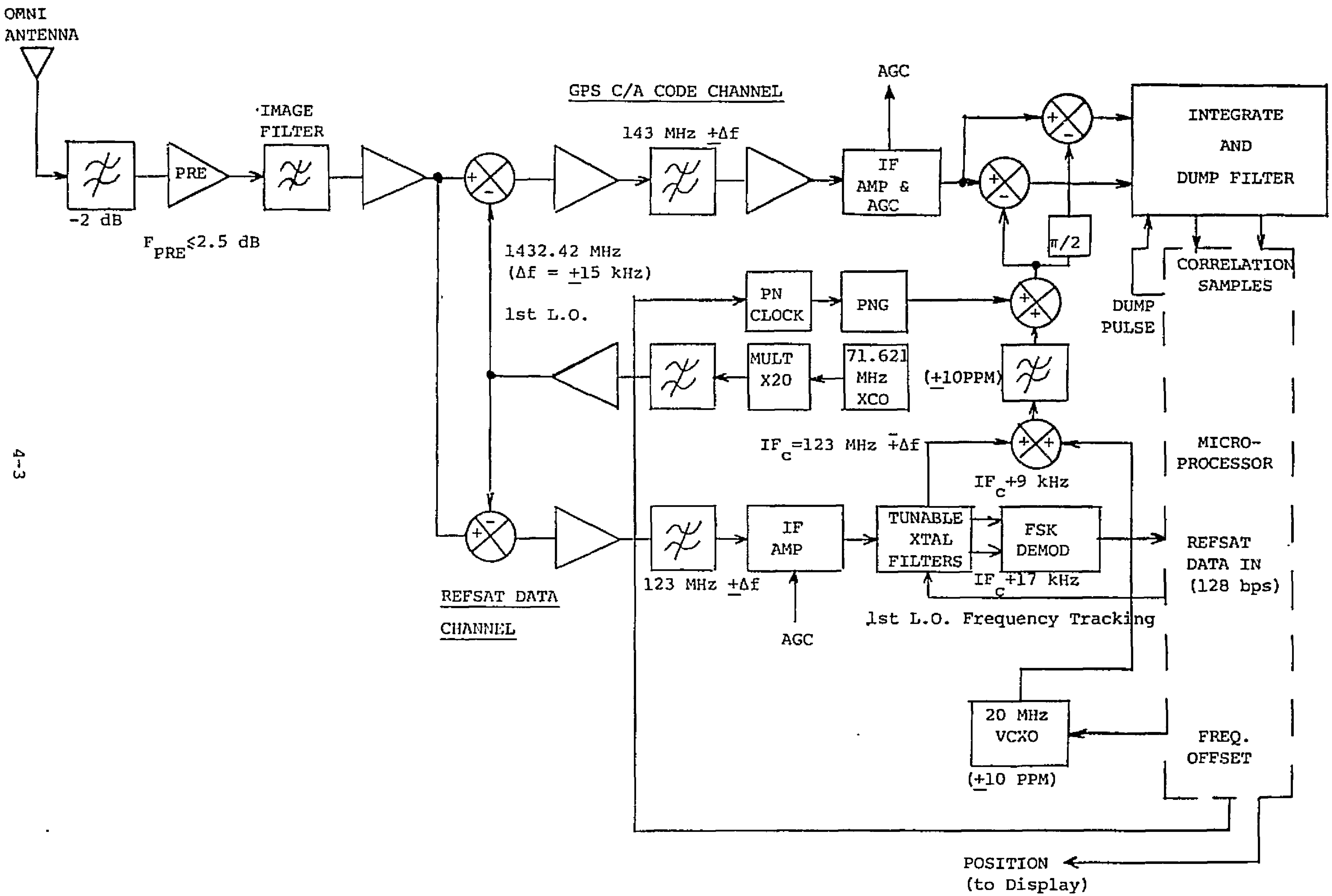

FIGURE 4.1 REFSAT MOBILE TERMINAL (RMT) RECEIVER

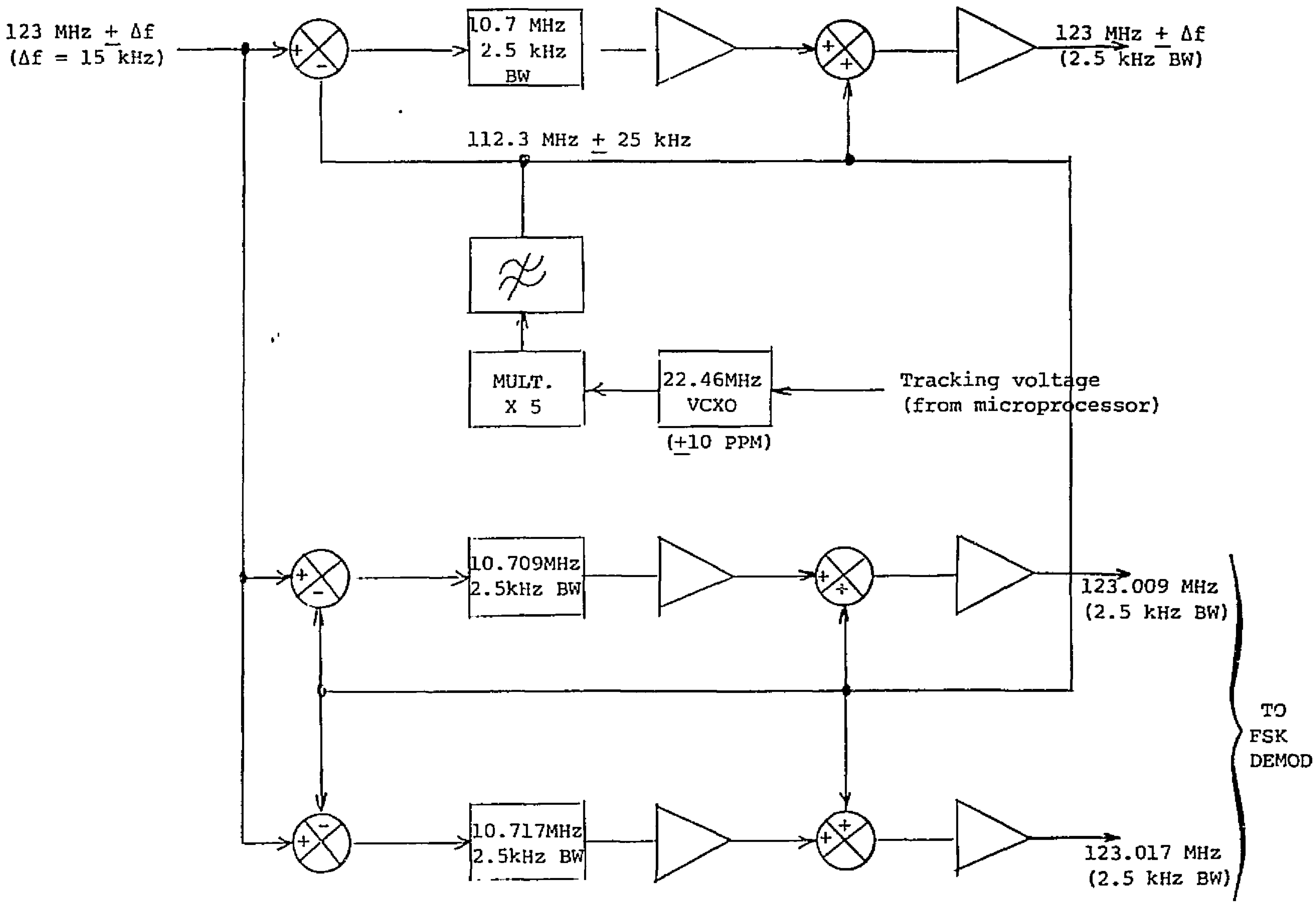

FIGURE 4.2 TUNABLE CRYSTAL FILTERS

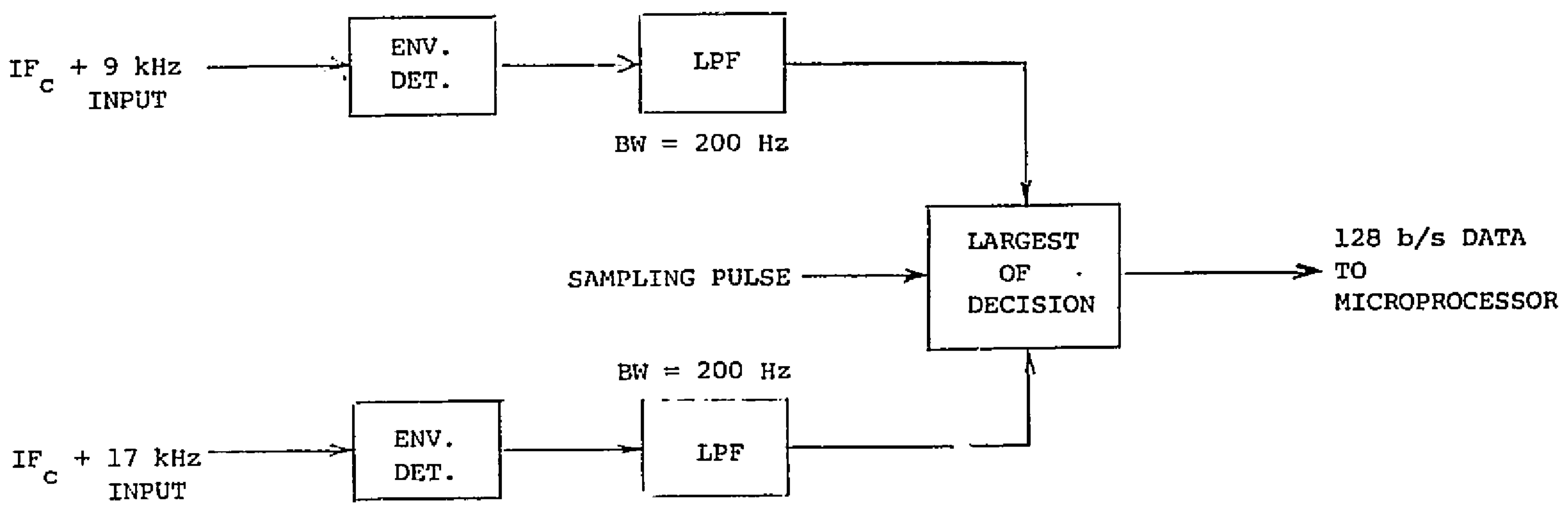

FIGURE 4.3 FSK DATA DEMODULATOR

due to the low (1 part 10^{-5}) frequency stability of the front-end local oscillator. This design employs a phase-lock loop which tracks the residual carrier thus providing frequency correction for any offset which may be present.

This correction is applied to the REFSAT channel, so that the data demodulator has no local oscillator frequency offset to deal with, and applied also to the GPS channel for correction of frequency offset.

The design uses a VXCO as the tracking oscillator along with two mixers, buffers, and a crystal bandpass filter. Cost for this part of the receiver, in small quantities, is about $400, the bulk of which is due to the VXCO (about $300).

Recalling that the purpose of the circuit in Figure 4.2 is to compensate for the relatively unstable, but low-cost first local oscillator, it may be that the added complexity of the tracking circuit, together with its acquisition and tracking requirements will offset benefits for a less-costly first local oscillator. This leads to the second design.

4.4 REFSAT-SET FIXED INTERVAL DESIGN

The second receiver design option is shown in Figures 4.4 and 4.5. Figure 4.4 incorporates a more stable and expensive first local oscillator thus eliminating the tracking circuit discussed in relation to the Baseline design. The oscillator considered is a temperature compensated crystal oscillator with a stability of 3×10^{-8}, and an aging rate of 3×10^{-9}/day. The turn-on power drawn by the oscillator is 7 watts and the run power is 4 watts at 25°C. Since prime power is not expected to be a problem, the use of the oven oscillator not only buys more stability, but also accommodates wide temperature variations if encountered.

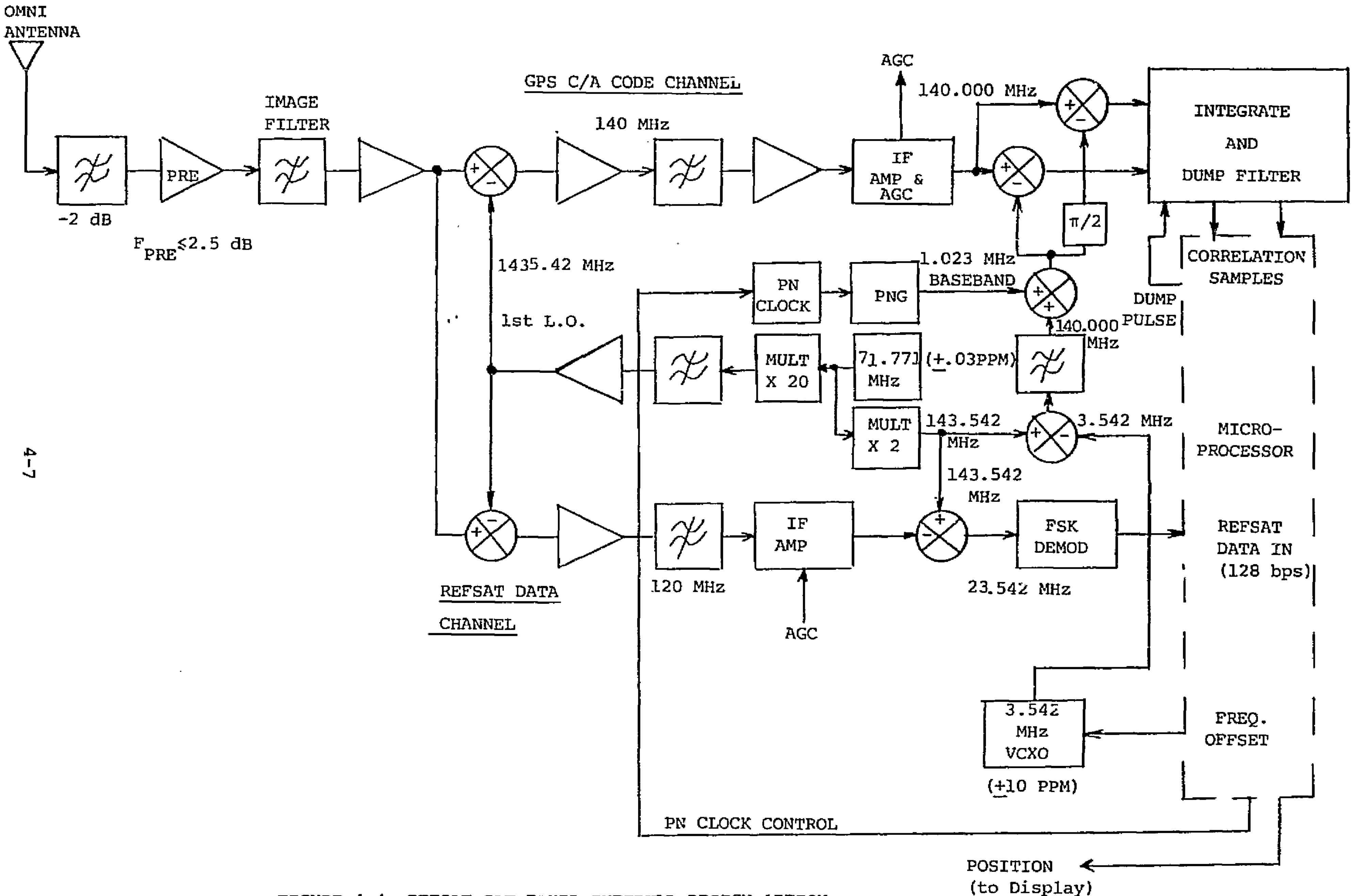

FIGURE 4.4 REFSAT-SAT FIXED-INTERVAL DESIGN OPTION

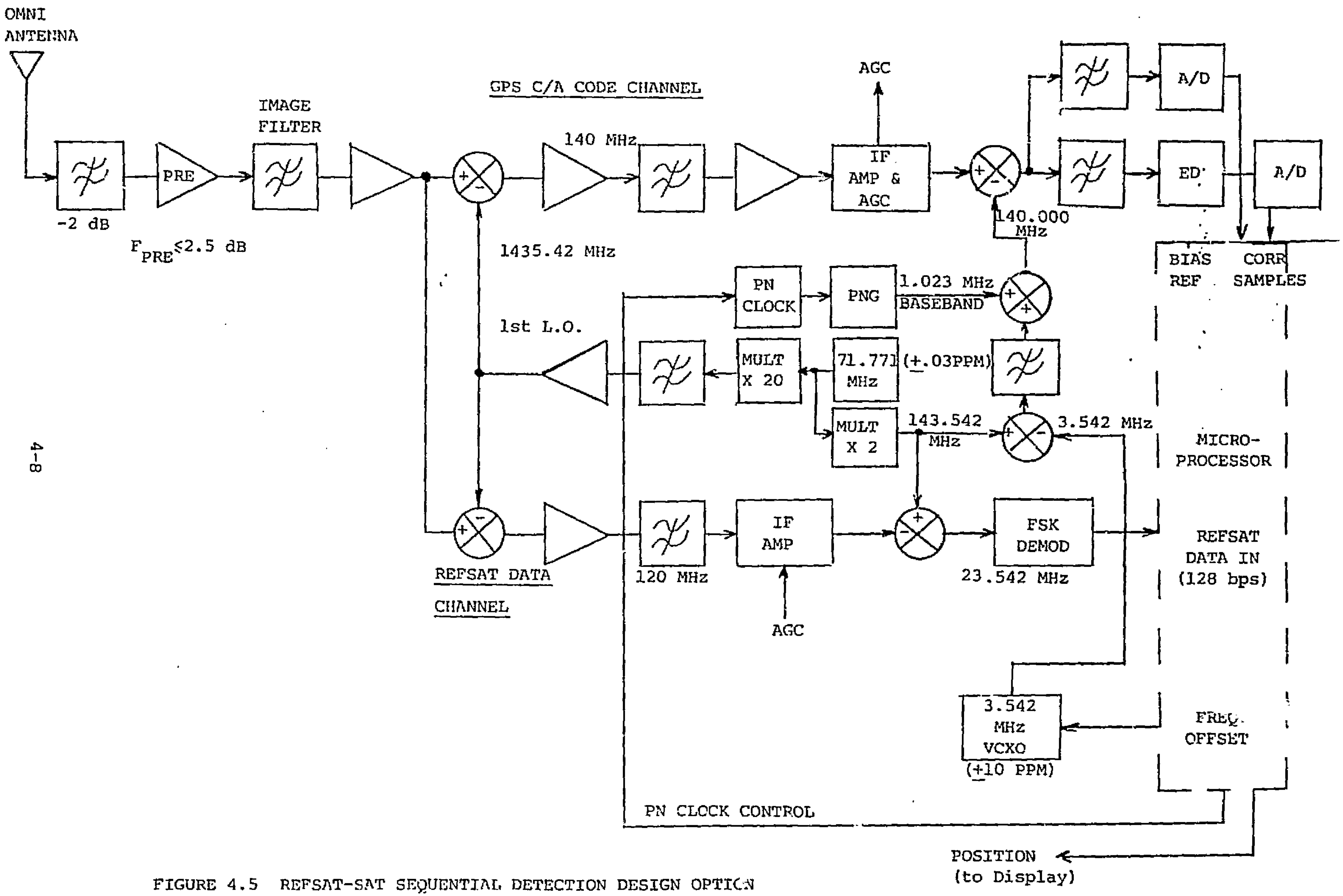

FIGURE 4.5 REFSAT-SAT SEQUENTIAL DETECTION DESIGN OPTION

Production (>10,000 units) costs as quoted by Vectron Laboratories is on the order of $125.

It should be noted that the aging rate is such that about 3 months would have to pass before the local oscillator offset was 10% of the maximum doppler uncertainty. Also the frequency search associated with the code acquisition and tracking compensates for aging in that channel. The REFSAT channel can tolerate frequency offsets of 1600 Hz or more without any degradation, hence retuning after a year or more is all that would be required. More tolerance can be designed into the data channel if needed.

When the receiver is turned off no aging occurs so the retuning interval would really be after a year of usage.

Figure 4.5 is essentially the same as Figure 4.4 except that a simplification is allowed by replacing the integrate and dump quadrature code correlators by a bandpass two pole filter in tandem with an envelop detector. The price paid is about 1 dB in SNR as will be seen later in the analysis of the performance of this detector.

These two detectors use a fixed interval correlation, that is, every code and frequency cell search takes the same time as dictated by the probability of detection and the probability of false alarm desired.

4.5 SEQUENTIAL DETECTOR DESIGN

Figures 4.4 and 4.5 also serve this design because the detection process change is only in the microprocessor algorithms employed. More will be said about this in the following section.

4.6 ACQUISITION PERFORMANCE ANALYSIS

Table 4.1 lists the parameters of interest in the analysis of the acquisition detector's performance.

TABLE 4.1

REFSAT/GPS PARAMETERS

1. GPS/L1 (C/A) Frequency (MHz)	1575.42
2. REFSAT Frequency (MHz)	1555.42
3. Received Power (GPS/L1) (dBw)	-151(max.),-160(min.)
4. Received Power (REFSAT) (dBw)	-154
5. Preamp Noise Figure (dB)	2.5
6. Received Sky Temperature (°K)	100
7. Receiver Prefilter Loss (dB)	2
8. GPS Doppler Offset (Hz)	4000 (max.)
9. GPS C/A Code Length (chips)	1023
10. GPS C/A Code Rate (MHz)	1.023
11. Receiver Antenna Gain (dBi)	0 (nominal)
12. Probability of Detection	90%
13. Probability of False Alarm	10^{-4}

The first item to be calculated is the equivalent receiver noise figure, F_R, referred to the antenna.

$$F_R = 1 + \frac{T_R}{T_0} \tag{4.1}$$

$$T_R = T_{SKY} + (L-1)\, T_{PHY} + L\, T_{PRE}, \tag{4.2}$$

where T_R is the receiver noise temperature, L is the prefilter loss (1.585), T_{PHY} is the physical temperature of the prefilter, and T_{PRE} is the preamplifier noise temperature. Since $T_{PRE} = (F-1)\, T_0$, where $T_0 = 290$ and F = 1.778, then

$$\begin{aligned} T_R &= 100 + (1.585-1)\, 290 + 1.585\, (1.778-1)\, 290 \\ &= 627.33°K. \end{aligned} \tag{4.3}$$

$$F_R = 5 \text{ dB} \tag{4.4}$$

Using either T_R or F_R the noise density becomes

$$N_0 = KT_R = -200.6 \text{ dBw/Hz} \tag{4.5}$$

The worst case signal-to-noise density is therefore

$$S/N_0 = -160 - (-200.6) = 40.6 \text{ dB-Hz}. \tag{4.6}$$

There are three more degradation factors to be taken into account. The first is correlation loss. Since the correlation timing (PN epoch) will not in general be perfect, the loss due to code offset is given by

$$L_c = 10 \log [(1-|\Delta|/T_{CHIP})^2]. \tag{4.7}$$

For example for a $\Delta = 1/2$ chip the loss is 6 dB; for $\Delta = 1/4$ chip the loss is 2.5 dB.

The next loss term is that due to frequency offset Δf (see Appendix 1 for derivation of the loss term). The result is

$$L_F = 10 \log Sa^2(\pi \Delta f T_c), \tag{4.8}$$

where $Sa(x) \triangleq (\sin x)/x$ and T_c is the coherent integration time of the integrate and dump (I&D) predetection filters.

The final loss term is an implementation loss to reflect the use of physical components to perform theoretical functions. This will be taken to be $L_I = 1$ dB.

4.6.1 FIXED INTERVAL DETECTION

Consider fixed sample interval detection, that is, integration up to T_0 seconds, checking the threshold condition, declaring a hit if exceeded, and declaring a no hit if not. For a probability of detection (P_d) of 90% and a probability of false alarm (P_f) of 10^{-4}, standard radar detection theory indicates a need of 11.7 dB. Since the SNR out of an I&D is $2E_c/N_0$, the available SNR is

$$SNR_{AVAIL} = 2ST_c/N_0 \tag{4.9}$$

$$= 3 + 40.6 + 10 \log T_c - 10 \log L_c L_F L_I. \tag{4.10}$$

Assuming 1/2 chip incremental searches, 200 Hz frequency search increments, and T_c = 1 code length, then

$$SNR_{AVAIL} = 3 + 40.6 - 30 - 6 - 0.58 - 1 = 6.02 \text{ dB}. \tag{4.11}$$

It is evident that the P_d and P_f cannot be met. If 1/4 chip increments are used then 3.5 dB can be gained, but this is still not enough. The frequency loss is already small so nothing can be gained there. It appears that T_c = 2 code lengths is necessary. Reworking and assuming 1/4 chip increments gives

$$SNR_{AVAIL} = 3 + 40.6 - 27 - 2.5 - 2.4 - 1 = 10.7 \text{ dB}. \tag{4.12}$$

Note that the doppler loss went up from 0.58 dB to 2.4 dB. Any further offset in frequency would be devastating. It is also clear that 1/4 chip increments buys much in the way of decreased loss and is therefore a good tradeoff.

4.6.1.1 Multiple Hit Detection

Equation (4.12) shows that about 1 dB more is needed to achieve the performance required. If, however, detection is declared only after four consecutive hits then a P_{d1} = 98% and $P_{f1} = 10^{-1}$ will give the same overall performance with only a 10% rise in search time, i.e.,

$$T_s' = T_s + T_s P_{f1} + T_s P_{f1}^{\,2} + T_s P_{f1}^{\,2} \tag{4.13}$$

$$P_d = P_{d1}^4 \tag{4.14}$$

$$P_f = P_{f1}^4 \tag{4.15}$$

For the P_{d1} and P_{f1} the SNR required is only 9.2 dB. Therefore per (4.12) the requirements can be met with 1.5 dB margin even in the worst case. Readjusting parameters to meet the specifications (worst case) gives T_c = 1 code length (see (4.11) with adjustment for 1/4 chip increments).

The time to acquire a single GPS satellite signal is then

$$T_{ACQ} = (1+P_{f1})(\ell_{CL}\ell_C\ell_F\ell_{CI}T_c)$$

$$= 1.1\left[(1)(1023)\left(\frac{4000}{200}\right)(4)\left(\frac{1023}{1.023\text{x}10^6}\right)\right] = 88 \text{ seconds}, \quad (4.16)$$

where ℓ_{CL} = number of code lengths integrated, ℓ_c = code length, ℓ_F = number of frequency cells searched, ℓ_{CI} = number of chip increments, T_c = coherent integration time.

It must be remembered that this is the worst case maximum time to acquire. Since four satellites will be acquired the likelihood of worst case and maximum time is small. The average time would be closer to the real case, thus

$$\overline{T}_{ACQ} = 44 \text{ seconds}. \quad (4.17)$$

After frequency and code have been acquired a code reacquisition time on the order of milliseconds will be realized.

4.6.2 SEQUENTIAL DETECTOR

The main problem associated with predetection integration as indicated in Section 4.6.1 is that the more integration that is done to build up the SNR for detection, the narrower the equivalent bandwidth. A narrow bandwidth poses a problem when frequency offset is present, that is, for more integration, there is more offset loss.

Postdetection accumulation of samples, however, avoids this problem. Appendix 3 gives a derivation of sequential detection performance which is a postdetection technique. In general it is faster than fixed sample size detection and is about as easy to implement.

Sequential detection is optimized when the processing computes likelihood ratio values exactly. However, practical considerations often suggest the convenience of a simplified implementation, still retaining the sequential testing concept.

A simplified block diagram of a noncoherent sequential detection circuit is shown in Figure 4.6 which utilizes a bandpass filter followed by an envelope detector. Analytically, this configuration is further complicated by the memory in the bandpass filter, but remains a straightforward simulation. The analysis in Appendix 4 is based upon an I&D bandpass filter design and so, by definition, eliminates the memory problem.

The sequential detection process tests each search position until the integrated voltage falls below the dismissal threshold. As shown in Figure 4.6, a bias term is subtracted from the integrated voltage; hence, there are two parameter adjustments available to optimize performance with a non-ideal sequential detection test. Synchronization is declared if dismissal does not occur within the allotted truncation interval of the test; otherwise the search clock is moved to test the next search position. Thus, the search rate is determined by the average time to dismiss an incorrect search position. The width of the bandpass filter determines the frequency tolerance.

In Figure 4.7, the performance of the I&D version of the sequential detector is given. This is the result of the analysis of

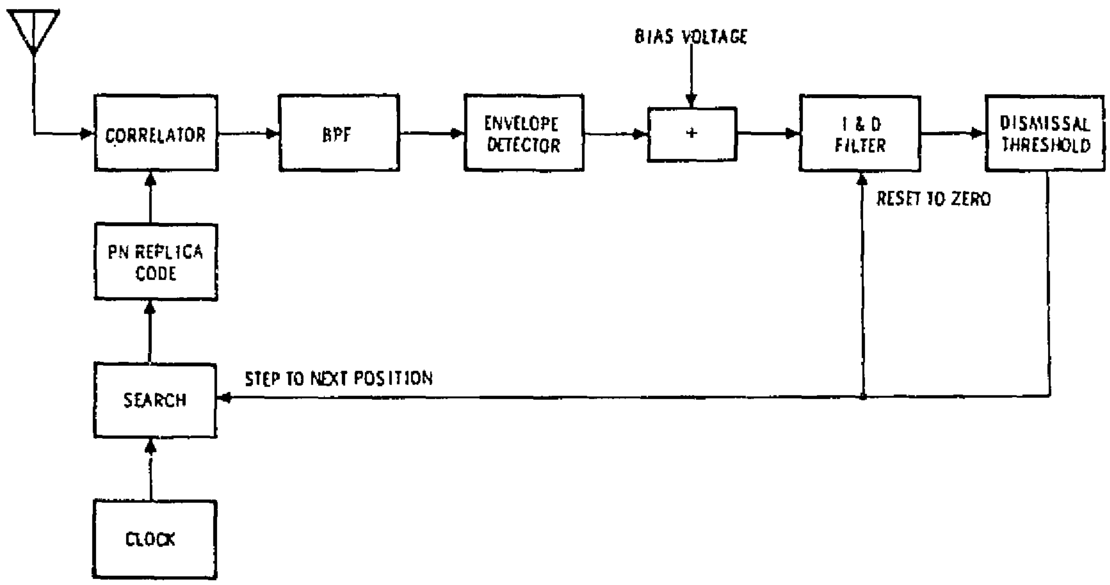

FIGURE 4.6 SEQUENTIAL DETECTOR CIRCUIT

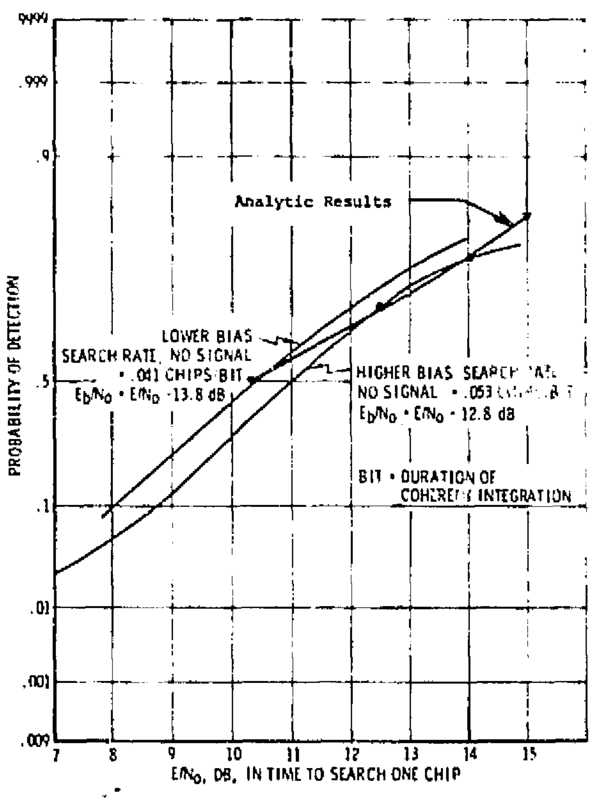

FIGURE 4.7 SYNCHRONIZATION PERFORMANCE

Appendix 4. The result agrees within tenths of dB's with simulations performed by Magnavox Research Laboratories under the direction of Dr. Charles Cahn. The simulation in Figure 4.7 assumes an I&D BP filter.

Figure 4.8 shows the performance when a two-pole BP filter is used in place of the I&D filters. The loss in performance is 1 dB. However, the gain in implementation is as shown in Figure 4.5, that is, no timing is required in the predetection process and only 1/2 the number of components are needed.

Using the two-pole filter the energy to noise ratio in the time to search one chip is

$$\frac{E}{N_0} = \frac{ST_{search}}{N_0} = 13 \text{ dB}. \tag{4.18}$$

Since

$$\frac{S}{N_0} = 40.6 - 1 = 39.6 \text{ dB}, \tag{4.19}$$

the average search rate is

$$R_S = 457 \text{ chips/second}. \tag{4.20}$$

Per Figure 4.8, a frequency offset up to three times the search rate is allowable without significant performance degradation. This means that a frequency offset of up to 1400 Hz can be tolerated. Note the vast increase in this tolerance when postdetection methods are employed. Let the frequency cells be 1 kHz wide in order to accommodate any additional offsets. The time to acquire is then

$$\overline{T}_{ACQ} = \left(\frac{1023}{457}\right)\left(\frac{4000}{1000}\right) = 9 \text{ seconds}. \tag{4.21}$$

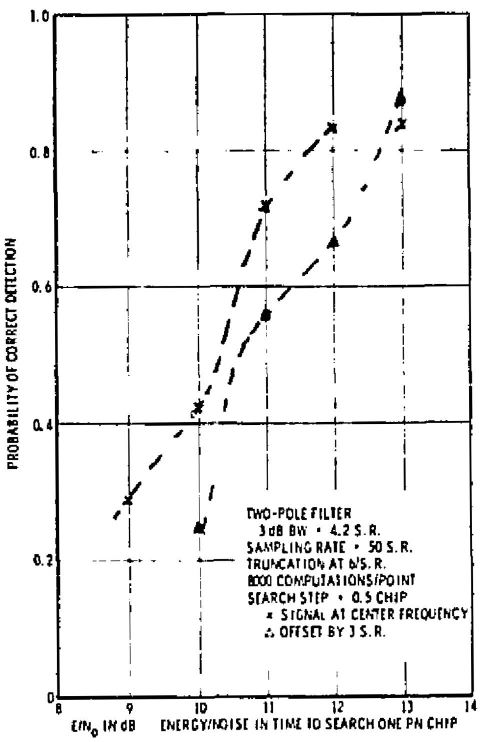

FIGURE 4.8 SEARCH PERFORMANCE WITH TWO-POLE FILTER

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OF POOR QUALITY

5.0 SYSTEM CONSIDERATIONS

Under the REFSAT concept GPS navigation data is broadcast to the users on a regular basis; the user vehicles can, depending on the type of service being performed, report their position back to a central location for distribution. The notion of using a geostationary satellite for vehicle position reporting has wide and varied application throughout the civilian community. In view of the user population (>100,000), however, there are several system aspects which must be evaluated, namely: the accessing technique, access control philosophy, and the impact on the design of user equipment.

5.1 MULTIPLE ACCESS OPTIONS

Considered herein is a comparison of three multiple access techniques which have application to the REFSAT position reporting function. The intent here is not to select a multiple access approach but rather to evaluate on a qualitative basis the virtues of each.

5.1.1 FREQUENCY DIVISION MULTIPLE ACCESS (FDMA)

In FDMA, the available repeater bandwidth is divided into a number of non-overlapping frequency bands which constitute the access channels. In the demand access control technique any user wanting to communicate is assigned a communication or working channel by the access control procedure. The channel assignment does not affect a wideband hard-limiting repeater. The number of channels, their bandwidth, and their spacing within the available repeater bandwidth are assigned on the basis of the immediate needs of the communication network. The constraints on the assignment of channels and the type of signals they can carry are discussed in the following sections.

When several signals are simultaneously present at the repeater input, they interact causing a number of disturbances to the smooth translation through the repeater. The major source of these disturbances is the nonlinear characteristic of the repeater. This nonlinearity is responsible for the intermodulation distortion, weak signal suppression, and, in part, for intelligible crosstalk.

Although linear repeaters may be used to reduce or eliminate these losses, they have an extremely poor efficiency from a power transfer viewpoint. For this application, therefore, we will assume a limiting repeater in both directions.

Intermodulation noise may be in the band of a desired signal, or it may be out-of-band noise. In once case it contributes additive disturbance and in both cases it reduces the power available to the desired signals at the repeater output.

A survey of the literature shows that with a large number of uniformly spaced channels (>8) that the center channels will have a carrier-to-intermodulation noise (C/IM) of about 9 dB (assuming equal amplitude signals). There are two techniques most often used to reduce this loss, namely: backing off the output power by several dB (with a corresponding reduction in power efficiency) or non-uniform channel spacing (at the expense of increased transponder bandwidth requirements).

When two or more independent signals pass through a saturated repeater the power ratio of any two components at the output will generally differ from the power ratio of the same two components at the input with the stronger signal enhanced at the expense of the weaker. Worst case suppression in a hard-limiting repeater results when the inputs are two constant-envelope signals with one greater than the other by at least a factor of four (6 dB). Then on a relative basis output power of the smaller signal will be about 6 dB below the input power. If the larger of the two signals is a Gaussian signal, then the small signal is reduced by about 1 dB. A large number of constant-envelope signals of nearly equal power at the repeater input behave like the Gaussian signal case, so that any one constant-envelope signal among them would be suppressed about 1 or 2 dB.

If a system is designed so that suppression of 1 or 2 dB and intermodulation noise for a small signal is acceptable, then a hard-limiting repeater can be used with a mix of input signals, however, with a mix of signals the output power ratios between the signals will vary as users enter and leave the network. By designing for worst case (i.e., all channels busy) satisfactory performance is assured with appropriate AGC.

In computing the required system bandwidth, frequency guard bands must be provided. The orthogonality of the signals in FDMA is obtained by complete separation of the signals in the frequency domain.

The total available bandwidth W_A is divided into N equal user channels, each separated by an amount, δ (the guard band) and the available signal bandwidth per channel is $(W_A/N)-\delta$ Hz. If the separation between channels is such that crosstalk can be considered negligible, then the performance of this system will be equivalent to that of an ideal orthogonal system.

5.1.2 TIME DIVISION MULTIPLE ACCESS (TDMA)

In the TDMA concept user transmission do not overlap in time. Each channel is assigned exclusive use of the repeater during specified time slots, and the signals pass through the repeater with virtually no interaction. An access channel in TDMA designates a particular time slot within the "TDMA frame" which is composed of the number of time slots equivalent to the number of required channels. The "frame repetition rate" of the system will normally be adequate to provide the real time transfer of the information.

A TDMA system must be synchronized so that a user can demultiplex the signal received from the satellite. The most attractive approach is to have a signal emitted by the satellite designated as a time reference, or satellite clock. If the transmitting users advance their transmission frame an amount equivalent to the transit time to the satellite, then their transmission will be time correlated to the satellite clock. Since all the users are synchronized to the satellite clock they can properly demultiplex the signals.

TDMA practically eliminates the need for uplink power coordination because the transmissions do not pass through the repeater simultaneously. Only in the unlikely event that time side-lobes in the pulse modulation of a strong transmitter might interfere with a weak adjacent channel is there need for power control. The satellite repeater bandwidth must be broad enough relative to the signal bandwidth to provide memoryless operation so that the effects of bandwidth limiting does not cause the signals to overlap time slots. The users can transmit message information in any manner they desire, provided only that the waveforms are compatible with the repeater and do not overlap their assigned time slots.

An access channel normally consists of a sequence of equally spaced time slots of the same length. The time axis is divided into frames of length T_F and the i-th access channel consists of the i-th time slot in each time frame. Adjacent time slots are separated by a guard time, Δ, so that each time slot duration is equal to $(T_F/N)-\Delta$.

5.1.3 CODE DIVISION MULTIPLE ACCESS (CDMA)

In Code Division Multiple Access (CDMA), each user signal occupies the full bandwidth of the transponder. Each of the signals are deliberately modulated by a digital code at a rate comparable to approximately 1/2 transponder bandwidth. Codes used in this application exhibit high autocorrelation and low cross correlation properties, such as maximal length sequences. The distinction between the various user signals is in the orthogonality between code sequences.

If the power of any of the signals is small compared to the sum of the input signal powers, suppression loss due to limiting in the satellite transponder will only amount to about 1 dB since the sum of the other spread spectrum signals at the input will approx[illegible] Gaussian noise.

Since the transmitted user signals will most likely be out of code phase synchronization and off in carrier frequency due to oscillator and timing errors, the receiver must go through an acquisition mode, that is a search over the range of frequency and code phase uncertainties.

Passage of many signals through a limiter creates intermodulation products, however, the processing gain minimizes these effects by making the interfering signals appear as equivalent Gaussian noise sources.

5.1.4 SUMMARY

A summary of the aforementioned multiple access techniques including characteristics, advantages and disadvantages is presented in Table 5.1.

5.2 ACCESS CONTROL TECHNIQUES

Since a potentially large number (>100,000) of users are to be accommodated by a single node (the REFSAT), the problem of multiple access and the control of that access must be solved; therefore, the subject of this section is a comparison of candidate access control techniques.

Three basic access control techniques: full time access, demand access, and random access, with procedural variations, are considered herein; they may be implemented by more than one type of multiple access technique (i.e., TDMA, FDMA, CDMA or combinations thereof).

5.2.1 CHARACTERISTICS OF ACCESS CONTROL

Full time access control is the technique where a unique frequency (FDMA), time (TDMA) slot, or code (CDMA) is assigned to each subscriber on a permanent basis (as long as the user platform is active). Full time access will result in a very inefficient use of the system capacity (based on a projected low per user communication traffic rate).

Demand access is a control technique where each user acquires access to the satellite through a limited number of channels by requesting access and being assigned a channel. After a user has completed its communication it relinquishes access to the satellite. The channel assignment by the Control Station may be either a frequency channel (FDMA), time slot (TDMA), or a code sequence (CDMA).

TABLE 5.1 SUMMARY OF MULTIPLE ACCESS TECHNIQUES

TYPE	CHARACTERISTICS	ADVANTAGES	DISADVANTAGES
FDMA	o Repeater bandwidth divided into non-overlapping frequency bands o Any modulation technique can be used although FM or PM preferred	o No network timing required o Repeater loading determined with simple procedures o Channel assignment simplifies user equipment	o Intermodulation products may reduce system performance o Power coordination required to maintain efficiency repeater usage
TDMA	o User signals received at repeater sequentially o Angle modulation o Common network time reference	o Minimized mutual interference o Insensitive to uplink user power disparities o Maximized data rate for given satellite output power	o Network time distribution a critical factor
CDMA	o Simultaneous multiple access over same channel o Pseudorandom sequence code generation on carrier	o Users share common frequency o A large number of unique user codes can be generated with minimum complexity o No network timing required o Processing gain to offset interference	o Wide bandwidth occupancy per user o Synchronization requires search in time and frequency o Repeater loading must be monitored

Random access refers to those techniques where each of the users may transmit at any time on a channel with no time or frequency coordination with any of the other users. Mutual interference will result because of the simultaneous use of the same channel by more than one user. In random access techniques the mutual interference may be reduced to a low enough level to permit satisfactory communication link quality. This can be done by reducing the number of users per channel thereby reducing the number of interference events (narrowband random access) or by spectrum spreading by using pseudonoise modulation to limit the interference to an acceptable level (wideband random access).

5.2.2 PERFORMANCE OF ACCESS CONTROL TECHNIQUES

The access control techniques must be evaluated by comparing the degree of complexity and a number of performance parameters, including: total access time, probability of blocking or interference, number of supervisory channels required, and system timing requirements.

The total service time T_T is composed of the access time, T_a, and delay time, T_d, and the service time, T_s. The access time, T_a, is the total time elapsed from the moment a user desires to transmit a message up to the point at which a channel has been assigned by the Control Station. The value of T_a will depend on the access control technique. The delay time, T_d, will be dependent upon the type of system (lost call or queue). In a lost call system, the delay time is dependent on the probability of lost call and the times to replace the call. While in a first come-first served queue system, the delay time is dependent on the queue length. The service time, T_s, is that period over which the channel is occupied.

5.2.2.1 Polling Access Control

The polling sequence may consist of a variable length polling frame comprised of a number of time slots equal to the number of users actively using the REFSAT system. In each time slot, the Control Station transmits a message consisting of an address and either 1) an interrogation for channel access or 2) a directed request for the user to transmit via a specific channel assignment (for example, a user operations center requesting information from a user in the field). The interrogated user who wants a channel will respond with an access request message assumed here to consist of frame sync, address, message type and user I.D.

In this access control technique, the access time is a function of the polling delay, the time occupied in the access request procedures and the transmission of a channel assignment. The average $\overline{T}_a$ will be

$$\overline{T}_a = \frac{N}{2} T_I$$

where

N is the number of active users

T_I is the interrogation time per user.

5.2.2.2 Orderwire Random Access Control

Since access to the orderwire is random, blocking could occur. The probability of no blocking is the probability that not more than one access request is transmitted during the time duration of an access request message. Blockage occurs when the orderwire channel is occupied by more than one user at a time in which case the call is lost and must be placed again. Since the access request message arrivals follow a Poisson distribution, the probability of blockage for the time of one access request message is

$$P_b = 1 - \sum_{k=0}^{1} P_t(K)$$

where

P_b is the probability of blockage

$$P_t(k) = e^{-\lambda\tau} \frac{(\lambda\tau)^k}{k!}$$

λ is the average message arrival rate, and

τ is the message length.

This results in

$$P_b = 1 - e^{-\lambda\tau}(1 + \lambda\tau).$$

5.2.2.3 Random Access Control

The random access technique is a lost call system in the sense that there is no queue formed and as such delay time is not a parameter; therefore, the characteristic sought is the probability of finding an unused channel. In essence, there is no control of channel usage in random access. The assurance of gaining access is by virtue of providing a sufficient number of channels to reduce the blocking probability per channel.

By making the valid assumption of Poisson arrival statistics and exponential service times, the Erlang Loss Formula can be used to determine the probability of finding all channels busy, P_L, where

$$P_L = P(C) = \frac{\frac{\rho^C}{C!}}{\sum_{k=0}^{C} \frac{\rho^k}{k!}}$$

where

ρ is the utilization factor in Erlangs or the total offered load

C is the number of servers or channels.

Then the probability of finding at least one channel open on the first try is $1-P_L$ and at least one channel open in k tries is $(1-P_L^k)$.

It should be noted that there will be a significant increase in the number of required channels when any form of access control is removed and access is strictly random, i.e., where any user desiring access merely starts his message transmission on a channel of his choice with no direction or knowledge of channel occupancy.

5.3 REFSAT LINK ANALYSIS

The current REFSAT concept includes a two-way data transmission link between user platform and a central ground station via the REFSAT. Present plans indicate a preference for FSK carrier modulation and a data rate of 128 b/s. To ascertain the impact of these communications requirements on both the user and the REFSAT a computation of the link performance has been prepared.

The purpose of the forward link (i.e., REFSAT to user platform) is to make available to the user community pertinent information regarding the GPS satellite constellation and satellite navigation data. The forward link analysis of Table 5.2 indicates that to support a data rate of 128 b/s over an FSK link with a receiver time-bandwidth, BT, product of 80 the required REFSAT EIRP is approximately 34 dBW (minimum).

The user report link is designed to allow a user platform to report its position back to a central location for distribution to the various operations centers of the user community. As seen in Table 5.3 the required user EIRP for transmitting at 128 b/s is, on a parametric basis, 7.3 + G/T_s dBW. Based on the assumptions of Table 5.3 this corresponds to a maximum user EIRP of 16.8 dBW, which is on the order of 50W and consistent with output powers of standard police car radios.

TABLE 5.2

FORWARD LINK ANALYSIS

PARAMETER	VALUE
Spacecraft EIRP (dBW)	EIRP
Pointing Loss (dB)	1.0
Space Loss (dB)	187.8
Boltzmann's Const. $\frac{dBW}{K\text{-}Hz}$	-228.6
User G/T_s (dB/K)	G/T_s
User $\frac{P_r}{KT_s}$ (dB-Hz)	EIRP + $\frac{G}{T_s}$ + 39.8
Margin (dB)	3.0
Data Rate (dB)	21.1
Required $(E_b/N_0)^*$ (dB)	22.0
Required EIRP (dBW)	6.3 - G/T_s
<u>Assumptions</u>	
Preamp Noise Figure, dB	2.5
Preselector Noise Figure, dB	2.0
Effective Receiver Temp (K)	524.9
Sky Temp (K)	100
System Temp, T_s (K)	624.9
User Antenna Gain (dBi)	0
G/T_s (dB/K)	27.96
Minimum REFSAT EIRP (dBW)	34.26

* See Table 2.7.

TABLE 5.3

USER REPORT LINK ANALYSIS

PARAMETER	VALUE
User EIRP (dBW)	EIRP
Path Loss (dB)	187.8
Spacecraft $\frac{G}{T_s}$ (dB-K)	G/T_s
Boltzmann's Const. $\left(\frac{dBW}{K\text{-}Hz}\right)$	-228.6
Pointing Loss (dB)	1
Transponder Loss (dB)	1
$\frac{P}{kT_s}$ (dB-Hz)	EIRP + $\frac{G}{T_s}$ + 38.8
Data Rate (dB)	21.1
Margin (dB)	3.0
Required $\frac{E_b}{N_0}$ (dB)	22.0
Required EIRP (dBW)	7.3 - G/T_s
<u>Estimated EIRP* (dBW)</u>	
$BW_3 = 11°$	12.5
$BW_3 = 18°$	16.8

* If it is assumed that the earth temperature is 290° and the effective receiver temperature is 438° (4 dB N.F.) then the system temperature is 728° (28.62 dB).

The gain for the 11° and 18° beamwidth antennas are 23.4 dBi (55%) and 19.1 dBi (55%) respectively with corresponding G/T_s of -5.2 dB/K and -9.5 dB/K.

6.0 CONCLUSIONS AND RECOMMENDATIONS

The REFSAT concept as envisioned by NASA/GSFC appears to be a viable one. With regard to the user equipment there is good reason to believe that a significant cost savings and receiver simplification would be achieved if a more stable (on the order of 3×10^{-9}) reference oscillator were used and the tunable crystal filters were eliminated. Implementation of the recommended changes would reduce the number of discrete components and in all likelihood eliminate one printed circuit board from the user terminal.

Magnavox is of the opinion that a considerable amount of detailed analysis is required for the determination of the most cost-effective multiple accessing approach. Although GSFC prefers a TDMA concept there is accompanying disadvantage of providing network time distribution. The criticality of a time reference can be minimized if the access control is based on a polled concept or a random orderwire concept. We have not selected a multiple access approach herein but rather evaluated on a qualitative basis the merits of each. There is a great need however to investigate the multiple accessing and access control requirements in great detail.

It has become apparent during the performance of this study that the major cost drivers for the user terminal are the RF components, the oscillator, and frequency synthesizer and that the cost impact of digital hardware (i.e., special purpose logic, microcomputer, and C/A coder), if one projects over the next ten years, is relatively small.

APPENDIX 1

SUMMARY OF CIVIL LAND/SEA USER POPULATION AND ACCURACY REQUIREMENTS

TABLE A GPS CIVIL APPLICATIONS NAVIGATION REQUIREMENTS (NON-AVIATION)

MARITIME NAVIGATION USER	TYPE	LOCATION AREA	HORIZONTAL ACCURACY (METERS)	UPDATE INTERVAL	EST.# OF TERMINALS	ACCEPTABLE COST	EST. PROBABILITY OF USE	REFERENCE SOURCE
I. U.S.C.G. VESSELS A. LAW ENFORCEMENT	ALL TYPES	CCZ (200 NM), HIGH SEAS 100-1000 KM	100-1000	<5 SEC.	<1000	<$10K	0.8	REF. (1) PP. 2-8
B. SAR, PEOPLE	ALL TYPES	CCZ (200 NM), HIGH SEAS 1000-10,000 KM	1000-3000	CONTINUOUS	<10,000	<$10K	0.8	REF. (1) PP. 2-8
II. U.S. MERCHANT FLEET (U.S. OWNED, U.S. & FOREIGN REGISTRY)	>5000 DWT	WORLDWIDE	500 (CCZ,HHE), 7000 (HIGH SEAS)	1 MIN.	2000	<$10K	0.5	REF. (6) PP. B-47 REF. (3) PP. 21
III. U.S. TOWING VESSELS & BARGES	>100 HP (TOWING) >1000 DWT (BARGES)	CCZ WORLDWIDE	500 (CCZ,HHE), 7000 (HIGH SEAS)	1 MIN.	<5000 (TOWING) <30,000 (BARGES)	<$10K	0.1	REF. (3) PP. 24-31 REF. (6) PP. B-47
IV. U.S. PASSENGER SHIPS	>5 GT	CCZ WORLDWIDE	500 (CCZ,HHE), 7000 (HIGH SEAS)	1 MIN.	<7000	<$50K	0.5	REF. (6) PP. B-47
V. U.S. RECREATIONAL BOATS	≤65 FT. LENGTH	CCZ,HHE, WORLDWIDE	200 (CCZ,HHE), 2000 (HIGH SEAS)	1 MIN.	<9 MILLION	<$2K	0.01	REF. (6) PP. B-47 REF. (3) PP. 37-40
VI. U.S. DOMESTIC FISHING VESSELS	>5 GT	CCZ,HHE, WORLDWIDE	500 (CCZ,HHE), 1000 (HIGH SEAS)	1 MIN.	<20,000	<$2K	0.02	REF. (3) PP. 32-36 REF. (6) PP. B-47

LEGEND:

- CCZ COASTAL AND CONFLUENCE ZONE
- HHE - HARBOR & HARBOR ENTRANCE AREA
- DWT - DEADWEIGHT TONNAGE (LONG-TON CARGO WEIGHT)
- HP - HORSEPOWER
- GT - GROSS TONS (1GT = 100 FT.^{3})

TABLE B GPS CIVIL APPLICATIONS LOCATION REQUIREMENTS

USER	TYPE	LOCATION AREA	HORIZONTAL ACCURACY (METERS)	UPDATE INTERVAL	EST.# OF TERMINALS	ACCEPTABLE COST	EST. PROBABILITY OF USE	REFERENCE SOURCE
I. MARITIME A. U.S. DOMESTIC FISHING VESSELS	ALL TYPES	CCZ,HHE, WORLDWIDE	200-1000	12 HRS.	100,000	<$2K	0.05	REF.(3)PP.36 REF.(6)PP.B-47
	<5 GT	CCZ,HHE WORLDWIDE	200-1000	12 HRS.	<20,000	<$5K	0.1	
B. FOREIGN FISHING VESSELS	>26 FT.	CCZ + 100 MI.	2000-5000	12 HRS.	1000	<$5K	0.5	REF.(9)
C. OIL TANKERS (FOREIGN REGISTRY)	≥10,000 DWT	CCZ	2000-5000	15 MINS.	3700	<$5K	0.7	REF.(8)PP.6-7
D. U.S. TOWING VESSELS & BARGES: 1. TOWING 2. BARGES	>100 HP >1000 DWT	CCZ,HHE, WORLDWIDE	1000-7000	15 MINS.	<5000 <30,000	<$2K	0.2	REF.(3)PP.24-31 REF.(6)PP.B-47
E. GENERAL CARGO		CCZ,HHE, WORLDWIDE	1000-7000	15 MINS.	<8300	<$5K	0.2	
II. U.S. COMMERCIAL LAND SHIPPING								
A. TRUCKS	REGULAR	U.S.	2000-10,000	4 HRS.	1000	<$2K	0.05	REF.(1)PP.2-10 REF.(2)PP.A-44 REF.(4)PP.A5-99 TO 101
	SPECIAL SHIPMENT		2000	30 MINS.	300			
B. R.R. FREIGHT CARS	SENSATIVE CARGO	U.S. COVERAGE TO CENTRAL POINT AT EACH RAILROAD	1000	15 MINS.	1000	<$2K	0.1	

TABLE B (Cont.) GPS CIVIL APPLICATIONS LOCATION REQUIREMENTS

USER	TYPE	LOCATION AREA	HORIZONTAL ACCURACY (METERS)	UPDATE INTERVAL	EST. # OF TERMINALS	ACCEPTABLE COST	EST. PROBABILITY OF USE	REFERENCE SOURCE
III. METEOROLOGY & OCEANOGRAPHY								
A. BUOYS	OCEAN DATA	WORLD OCEANS	200-1000	30 MINS.	1000	<$5K	1.0	REF. (4) PP. A5-92 A5-93
	METEOR DATA		10,000					
B. BALLOONS	METEOROLOGICAL	WORLDWIDE	1000-2000 (H) ±100 (V)	15 MINS.	1000	<$2K	0.7	
	RADIO SONDE	U.S.	1 M/SEC.	5 SECS.	73,000	<$0.1K	0.5	REF. (10) PP. B-18,19
C. OTHER DATA COLLECTION PLATFORMS	ENVIRONMENTAL, WILDLIFE, ETC.	U.S. NORTH AMERICA	1000-2000	12 HRS.	>1000	<$2K	0.7	REF. (4)
IV. LAND-BASED VEHICLES								
A. URBAN: 1. POLICE CRUISER	AUTO	100-400	15-500	30 SECS.	2000	<$2K	0.2	
2. EMERGENCY VEHICLES	MOBILE	100-400	150-500	30 SECS.	<10,000	<$2K	0.3	REF. (1) PP. 2-10, REF. (2) PP. A-44, REF. (10) PP. 31-37
3. PUBLIC TRANSPORTATION	AUTO	100-400	150-500	30 SECS.	<3000	<$2K	0.1	
4. UTILITY VEHICLES	AUTO	100-400	150-500	1 MIN.	<3000	<$2K	0.1	
5. PARK POLICE	AUTO	100-400	50-500	1 MIN.	<2000	<$2	0.2	

TABLE B (Cont.) GPS CIVIL APPLICATIONS LOCATION REQUIREMENTS

USER	TYPE	LOCATION AREA	HORIZONTAL ACCURACY (METERS)	UPDATE INTERVAL	EST. # OF TERMINALS	ACCEPTABLE COST	EST. PROBABILITY OF USE	REFERENCE SOURCE
IV. LAND-BASED VEHICLES (Cont)								
B. FEDERAL LAW ENFORCEMENT:								
1. DRUG ENFORCEMENT ADMIN.								
2. IMMIGRATION NATURALIZATION SERVICE								
3. CUSTOMS								
C. OTHER: 1. FORESTRY SERVICE	MANPACK AUTO	1000-10,000	150-300	1 MIN.	700	<$5K	0.7	REF. (2) PP.A-44
2. STATE POLICE PATROL	AUTO	1000-10,000	1000-3000	1 MIN.	<10,000	<$10K	0.3	REF. (1) PP.2-10, REF. (2) PP.A-44, REF. (10), PP.31-37
3. RENTAL CARS								
V. GEOLOGY (EXTRACTABLE INDUSTRIES)	EXPLORATORY SEARCH PARTIES	GLOBAL	30, 10 (1980's)	1 HR.	<500	<$5K	0.3	REF. (11), PP.16
VI. GEODESY (*)	FIXED IN REMOTE LAND AREAS	GLOBAL	0.02-0.10 (3 DIMENSIONS)	12 HRS.	<100	(**)	0.5	REF. (11), REF. (12), PP.13-14

* TO MEASURE RELATIVE MOTION OF TECTONIC PLATES WITH VELOCITIES ON THE ORDER OF 1-10 CM PER YEAR.
** NOT KNOWN. SUBJECT TO REQUIREMENTS OF GEODETIC COMMUNITY.

TABLE B (Cont.) GPS CIVIL APPLICATIONS LOCATION REQUIREMENTS

USER	TYPE	LOCATION AREA	HORIZONTAL ACCURACY (METERS)	UPDATE INTERVAL	EST.# OF TERMINALS	ACCEPTABLE COST	EST. PROBABILITY OF USE	REFERENCE SOURCE
VII. COMMERCIAL TRUCKING	LOCAL	URBAN	200	1/HR. to 1/DAY	<100,000	<$1000/YR	0.8	REF. (14)
	INTERSTATE	CONTINENTAL U.S.	1500 MAX.	1/HR.	<200,000	<$1000/YR	0.8	REF. (1) VOL.1&2

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APPENDIX 2

FREQUENCY OFFSET LOSS

APPENDIX 2

FREQUENCY OFFSET LOSS

The in-phase sample out of the predetection I&D filter for a sinusoidal signal input with frequency offset ω_d, perfect PN correlation and amplitude A is

$$M_{ci} = A \int_0^T \cos\ (\omega_d t-\psi)dt = A\ \left.\frac{\sin\ (\omega_d t-\psi)}{\omega_d}\right|_0^T$$

$$= A \left[\frac{\sin\ (\omega_d T-\psi)\ +\ \sin\ \psi}{\omega_d}\right]$$

$$= A \left[\frac{2}{\omega_d} \sin\ (\omega_d T/2)\ \cos\ (\ \frac{1}{2}\ (\omega_d T-2\psi))\right]. \tag{1}$$

The square is

$$M_{ci}^{\ 2} = A^2 T^2 Sa^2 (\omega_d T/2)\ \cos^2 (\ \frac{\omega_d T}{2} \cdot \psi). \tag{2}$$

The quadrature phase is

$$M_{si} = A \int_0^T \sin\ (\omega_d t-\psi)dt = A\ \left.\frac{\cos (\omega_d t-\ )}{\omega_d}\right|_T^0$$

$$= \frac{A}{\omega_d} \left[\cos\ \psi\ -\ \cos\ (\omega_d T-\psi)\right] = \frac{-A^2}{\omega_d} \sin\ (\omega_d T/2)\ \sin\ \left(\frac{-\omega_d T}{2} + \psi\right). \tag{3}$$

Its square is

$$M_{si}^{\ 2} = A^2 T^2 Sa^2 (\omega_d T/2)\ \sin^2 \left(\frac{\omega_d T}{2} - \psi\right). \tag{4}$$

The sum of the squares gives the envelope squared and is given by

$$M_{si}^{\ 2} + M_{ci}^{\ 2} = [AT\ Sa (\omega_d T/2)]^2. \tag{5}$$

The decision variable is seen to be degraded by

$$L_F = Sa^2(\pi \Delta f T), \tag{6}$$

where $\Delta f = \omega_d/2\pi$ was defined.

APPENDIX 3

COHERENT SEQUENTIAL DETECTION

APPENDIX 3

COHERENT SEQUENTIAL DETECTION

The fastest theoretical detection scheme is that employing a sequential detector. One form is shown in Figure 1 for a coherent sequential detector. The detection parameter Z_s is given by

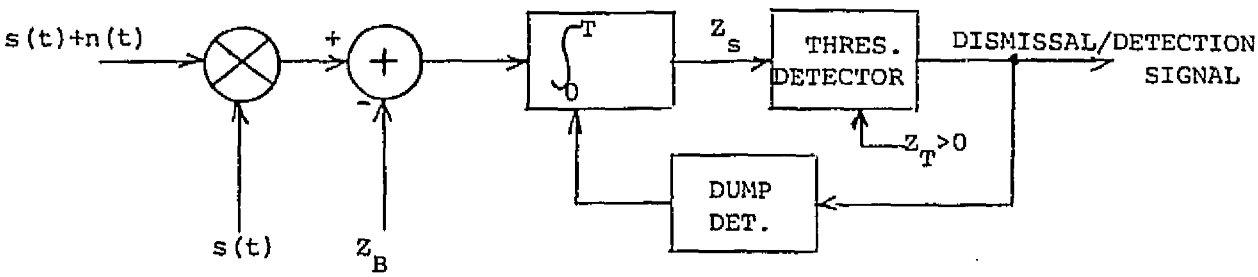


FIGURE 1 A COHERENT SEQUENTIAL DETECTOR

$$Z_s = \int_0^T s^2(t)dt + \int_0^T s(t)n(t)dt - Z_B T, \qquad (1)$$

where Z_B is a bias. In Figure 1, Z_T (assumed positive) is the dismissal threshold. If this dismissal time, T_0, is reached without dismissal then detection is declared. Intuitively, a sequential detector is faster than a fixed interval detector because most of the search time is devoted to the no signal case, and fixed interval detectors treat the noise and the signal-plus-noise case the same. A sequential detector, however, dismisses the noise only case faster than the signal present case. An example is shown in Figure 2.

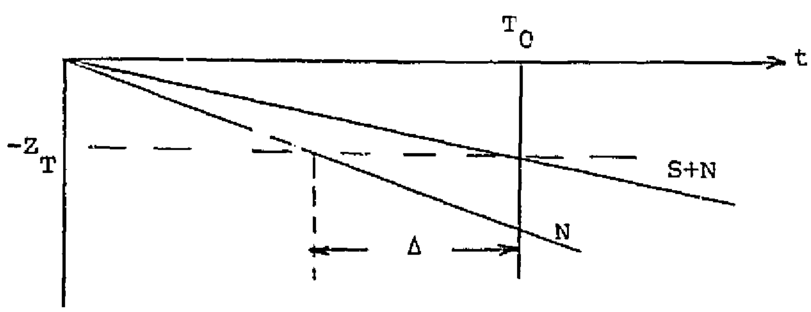


FIGURE 2 SEQUENTIAL DETECTOR TYPICAL DETECTION CURVES

A fixed interval detector takes T_0 for S+N and N trajectories. A sequential detector takes T_0 for S+N and $T_0 - \Delta$ for N hence the search speedup by the factor Δ.

With only noise present we have

$$Z_n = \int_0^T s(t)n(t)dt - Z_B T. \tag{2}$$

The probability of a dismissal is given by

$$P_{DIS} = P\{Z \leq - Z_T | T < T_0\}, \tag{3}$$

where T_0 is the prestated maximum dismissal time and Z_T is the threshold. Note that if Z_T is negative the definition of dismissal changes in (3). The average, $\bar{T}$, of the time T determines the average search time and will be smaller than T_0. At very low signal-to-noise ratios (SNR), however $T \to T_0$ and therefore $\bar{T} \to T_0$. As the SNR increases $\bar{T} \to 0$ and the speed up factor is asymptotically very great.

The above intuition and/or logic can be proven analytically.

$$P(T) \triangleq \text{probability of a dismissal at time } T$$

$$\doteq P\{Z_n \leq - Z_T\}. \tag{4}$$

The approximation is very close since the signal present case is a very small percentage of the overall search time. Again the PN search case is an example. Equality will therefore be used in (4) in the following analysis.

$$P(T) = P\left\{\int_0^T s(t)n(t)dt \leq TZ_B - Z_T\right\}. \tag{5}$$

Assume s(t) has power P, and that n(t) is stationary White Gaussian noise with zero mean and variance σ_n^2, then

$$P(T) = \int_{-\infty}^{TZ_B - Z_T} \frac{e^{-\sigma^2/2\sigma_n^2}}{\sqrt{2}\ \sigma_n^2}\, d\alpha = 1-Q[(TZ_B-Z_T)/\sigma_n]$$

$$= 0.5 + 0.5 \text{ erf } [(TZ_B-Z_T)/\sqrt{2}\ \sigma_n], \tag{6}$$

where

$$\text{erf}(x) \triangleq \frac{2}{\sqrt{\pi}} \int_x^{\infty} e^{-\alpha^2} d\alpha. \tag{7}$$

Now

$$\sigma_n^{\ 2} = \int_0^T \int_0^T \overline{s(\alpha)n(\alpha)s(\beta)n(\beta)}\, d\alpha d\beta$$

$$= \frac{N_0}{2} \int_0^T s^2(\alpha)dt = PN_0T/2 \tag{8}$$

where $N_0/2$ is the power spectral density of the noise and

$$\frac{1}{T} \int_0^T s^2(t)dt = P, \tag{9}$$

was used.

$$P(T) = 0.5\left[1+\text{erf}[(TZ_B-Z_T)/\sqrt{N_0PT}]\right]$$

$$= 0.5\left[1+\text{erf}[(TZ_B{}'-Z_T{}')/\sqrt{PT}]\right]:\ Z' \triangleq Z/\sqrt{N_0} \tag{10}$$

To determine $Z_B{}'$ and $Z_T{}'$ and T_0 we go to the probability of detection (P_d) and the probability of false alarm (P_f).

$$P_f = 1-P(T_0) = 0.5\left[1-\text{erf}[(T_0Z_B{}'-Z_T{}')/\sqrt{PT_0}]\right]. \tag{11}$$

$$P_d = P\{Z_s > -Z_T\} = 0.5\left[1-\text{erf}[(T_0Z_B{}'-Z_T{}'-P'T_0)/\sqrt{PT_0}]\right], \tag{12}$$

where $P' \triangleq P/\sqrt{N_0}$.

For a given P/N_0, P_d, and P_f the parameters T_0 and $Z_T{}'$ may be determined.

Let

$$P_d = 0.5\left(1-\text{erf}(K_{PD})\right), \quad P_f = 0.5\left(1-\text{erf}(K_{PF})\right) \tag{13}$$

From (12) and (13)

$$\text{erf}[(T_0 Z_B'-Z_T'-P'T_0)/\sqrt{PT_0}] = \text{erf}(K_{PD}) \tag{14}$$

This implies that

$$(T_0 Z_B'-Z_T'-P'T_0)/\sqrt{PT_0} = K_{PD} \tag{15}$$

$$Z_T' = T_0(Z_E'-P')-\sqrt{PT_0}\,K_{PD} \tag{16}$$

From (11) and (13)

$$(T_0 Z_B'-Z_T')/\sqrt{PT_0} = K_{PF} \tag{17}$$

Using (17) we obtain

$$Z_T' = T_0 Z_B'-K_{PF}\sqrt{PT_0} \tag{18}$$

Equating (16) and (18) gives

$$T_0 = (K_{PF}-K_{PD})^2/(P/N_0) \tag{19}$$

Using (18), equation (10) becomes

$$P(T) = 0.5\left[1+\text{erf}[\left((T-T_0)Z_B'+K_{PF}\sqrt{PT_0}\right)/\sqrt{PT}]\right] \;:\; T<T_0 \tag{20}$$

As an example, for $P_d = 0.5$, $K_{PD} = 0$; for $P_f = 10^{-4}$, $K_{PF} = 2.63$. For $P/N_0 = 1$ this would give

$$P(T) = 0.5\left[1+\text{erf}[\left((T-6.92)Z_B'+6.92\right)/\sqrt{T}]\right]. \;:\; T<6.92 \tag{21}$$

Now to maximize $P(T)$ for small T, to give minimum $\overline{T}$, (fastest search process), it would seem that Z_B' as small as possible should be the choice,* but $Z_T'>0$ was tacitly assumed. If $Z_T'<0$ then the dismissal probability, P_d, and P_f would become complements i.e., 1-P due to the definition of detection, dismissal, etc. Therefore from (18) and (19)

$$Z_B > P/[1-(K_{PD}/K_{PF})] \tag{22}$$

is required (equation (16) and (19) give the same result).

---

*This is opposite to intuition as applied to Figure 1 and comes about from the definition (18) of Z_T' in terms of Z_B'.

Therefore theoretically

$$Z_B = P/[1-(K_{PD}/K_{PF})] \tag{23}$$

is the optimum value. In practice a slightly larger value would be used. We now have using (23) as a design value,

$$P(T) = 0.5[1+\mathrm{erf}(K_{PF}\sqrt{T/T_0})]. \tag{24}$$

Thus an optimum sequential detector would be adaptive, responding to signal strength per (23). It would also decrease the dismissal time T_0 per (19) and give an average search time of

$$\overline{T} = \int_0^{T_0} \alpha \; dP(\alpha) = \int_0^{T_0} \alpha \left(\frac{dP(\alpha)}{d\alpha}\right) d\alpha. \tag{25}$$

The fact that Z_B is a function of only P is puzzling until one realizes that Z_B acts like negative signal, i.e., when signal is present

$$Z_S = (P-Z_B)T + \int_0^T s(t)n(t)dt. \tag{26}$$

Finally Z_T is given by

$$Z_T = \sqrt{N_0}\; [(K_{PF}-K_{PD})^2(Z_B/P)-K_{PF}(K_{PF}-K_{PD})] \tag{27}$$

for design purposes.

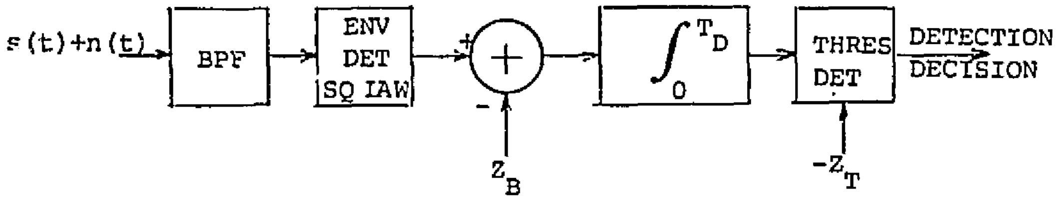
APPENDIX 4

NONCOHERENT SEQUENTIAL DETECTION

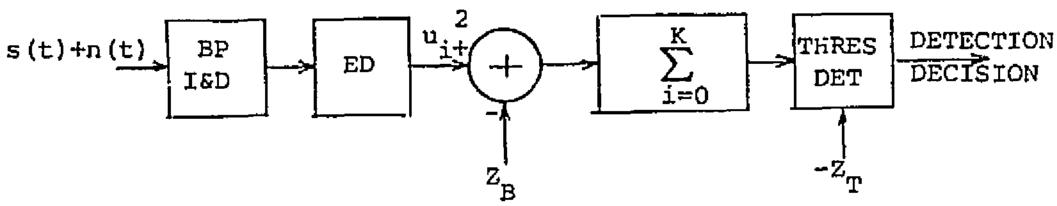
APPENDIX 4

NONCOHERENT SEQUENTIAL DETECTION

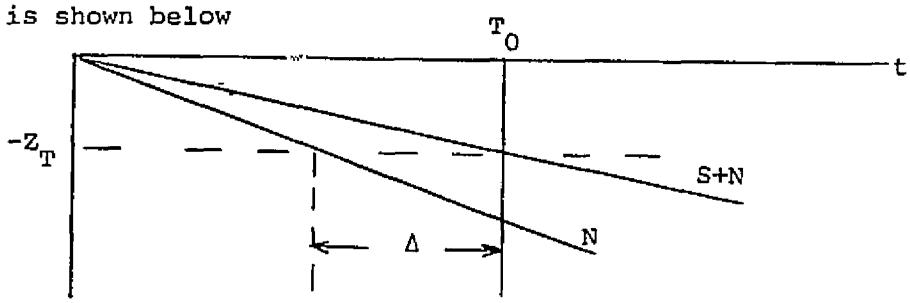
The fastest theoretical detection scheme is sequential detectors. A noncoherent approximation to the theoretical is shown below



$Z_B > 0$ is the bias, $Z_T > 0$ is the dismissal threshold, and T_D is the dismissal time. If the BPF is an I&D, and the post-detection integrator an accumulator, then one has



Intuitively, a sequential detector is faster than a fixed interval detector because most of the search time is devoted to the no signal case, thus fixed intervals treat noise and signal + noise the same. A sequential detector dismisses noise present and searches faster. An example is shown below



A fixed interval detector takes T_0 for S+N and N trajectories. A sequential detector takes T_0 for S+N and $T_0-\Delta$ for N hence if K_s positions must be searched the fixed interval detector takes (assuming signal at the last cell) T_F seconds to find the signal cell, that is,

$$T_F = K_s T_0, \tag{1}$$

C-2

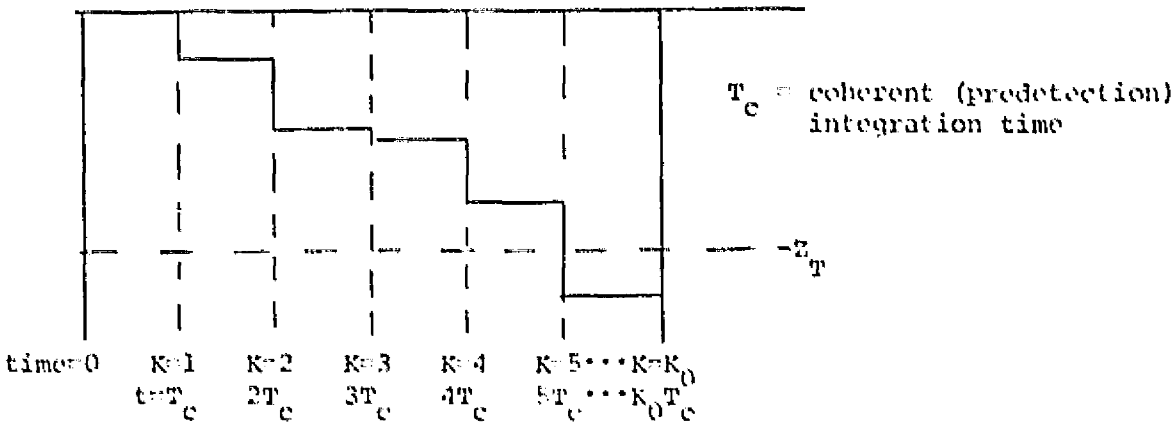
whereas a sequential detector takes

$$T_{SD} = K_s(T_0 - \overline{\Delta}) \tag{2}$$

for a savings of $K_s\overline{\Delta}$. For large SNR the savings is very large; for small SNR it is not, but if K_s is large the savings is still significant in an absolute sense.

Per reference [1] the decision variable is

$$u(K) = \sum_{i=1}^{K} u_i^2 \; : \; K = \text{number of coherent integrations} \tag{3}$$



$$P(K) = P\left\{\sum_{i=1}^{K} u_i^2 - KZ_B \le -Z_T\right\} \tag{4}$$

where $Z_T > 0$ is assumed and Z_B is the bias of the sequential detector. Normalizing by σ_b^2 (the noise power in each sample u_i) gives

$$Z_B' \triangleq Z_B/\sigma_b^2 \; , \; Z_T' \triangleq Z_T/\sigma_b^2 \tag{5}$$

$$P(K) = 1 - P\left\{\sum_{i=1}^{K} u_i^2 > KZ_B - Z_T\right\}$$

$$= 1 - P_{fa}$$

$$= 1 - \frac{1}{2}\,\mathrm{erfc}\left[\frac{(KZ_B' - Z_T' - 1)\sqrt{K}}{\sqrt{2\left(\frac{4}{\pi} - 1\right)}}\right] \tag{6}$$

This is an approximation good [2] within 0.3 dB for $K \geq 8$. The probability of detection is given by Blake [2]

$$P_d = \frac{1}{2}\,\mathrm{erfc}\left[\frac{(K_0 Z_B' - Z_T' - b)\sqrt{K_0}}{\sqrt{2\left[4\,\frac{(1+SNR)}{\pi} - b^2\right]}}\right], \tag{7}$$

$$\text{where } b \triangleq e^{-SNR/2}\left[(1+SNR)\,I_0\left(\frac{SNR}{2}\right) + SNR\; I_1\left(\frac{SNR}{2}\right)\right], \tag{8}$$

and SNR = signal-to-noise ratio per coherent integration.

For an I&D BPF, SNR = $2E_c/N_0$: E_c = energy per coherent integration = $2PT_c/N_0$: T_c = coherent integration time interval. K_0 = dismissal parameter, i.e., $K_0 T_c$ = dismissal time.

Let $2P_d = 1-\mathrm{erf}(K_{PD})$, $2P_{fa} = 1-\mathrm{erf}(K_{PF})$

$$\frac{(K_0 Z_B' - Z_T' - b)\sqrt{K_0}}{\sqrt{2\left[\frac{4}{\pi}\,(1+SNR) - b^2\right]}} = K_{PD}. \tag{9}$$

$$\frac{(K_0 Z_B' - Z_T' - 1)\sqrt{K_0}}{\sqrt{2\left[\frac{4}{\pi} - 1\right]}} = K_{PF}. \tag{10}$$

$$\text{Let } A_s = \sqrt{2\left[\frac{4}{\pi}\,(1+SNR) - b^2\right]}. \tag{11}$$

$$A_0 = A_s \; : \; SNR = 0. \tag{12}$$

Therefore

$$K_0 = (A_0 K_{PF} - A_s K_{PD})^2/(b-1)^2. \tag{13}$$

Note that K_0 is very sensitive to b! Using (10) gives

$$Z_T' = K_0 Z_B' - 1 - \frac{A_0 K_{PF}}{\sqrt{K_0}}, \tag{14}$$

and (6) becomes

$$P(K) = 0.5\left[1+\operatorname{erf}\left[\left[(K-K_0)Z_B'+\frac{A_0K_{PF}}{\sqrt{K_0}}\right]\frac{\sqrt{K}}{A_0}\right]\right] \tag{15}$$

Note that as in the coherent case Z_B' is bounded below by the fact that $Z_T > 0$ is required. This gives

$$Z_B' > \left(1+\frac{A_0K_{PF}}{\sqrt{K_0}}\right)\Big/K_0. \tag{16}$$

Using the equality gives

$$P(K) = 0.5\left[1+\operatorname{erf}\left[\left[\frac{K}{K_0}\left(1+\frac{A_0K_{PF}}{\sqrt{K_0}}\right)-1\right]\frac{\sqrt{K}}{A_0}\right]\right] \tag{17}$$

Note that Z_B' is now a function strictly of SNR in comparison to the coherent case where it was only a function of signal power. The dismissal time $T_0 = K_0T_c$ is still a function of SNR.

A program was written to compute (17). The result is shown in Figure 1 along with simulation results [3]. The E/N_0 in the figure is given by

$$E/N_0 = 2\overline{K}\ E_c/N_0, \tag{18}$$

where E_c is the energy per coherent integration and

$$\overline{K} = \sum_{K=1}^{K_0-1} K[P(K)-P(K-1)] \tag{19}$$

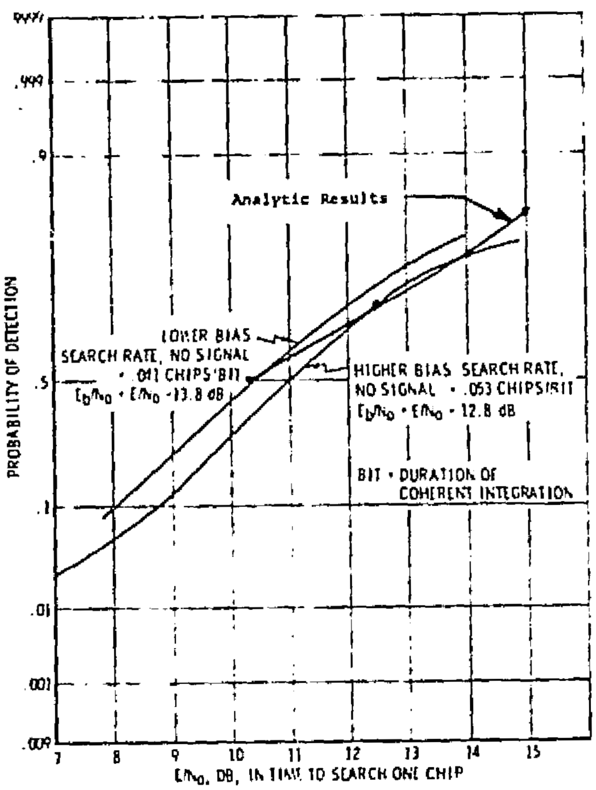


FIGURE 1   SYNCHRONIZATION PERFORMANCE

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