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PRELIMINARY STUDY OF NAVSTAR/GPS FOR GENERAL AVIATION

Final Report

Prepared for

National Aeronautics and Space Administration
Langley Research Center
Hampton, Virginia

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Final Report

PRELIMINARY STUDY OF NAVSTAR/GPS FOR GENERAL AVIATION

Prepared under Contract NAS1-14302

by

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Prepared for

National Aeronautics and Space Administration
Langley Research Center
Hampton, Virginia

November 1976

ACKNOWLEDGEMENT

This report was prepared by the Research Triangle Institute, Research Triangle Park, North Carolina, under Contract NAS1-14302. The work has been administered by the Navigation and Guidance Research Branch of the Flight Instrumentation Division, Langley Research Center, National Aeronautics and Space Administration. Mr. H. J. E. Reid, Jr. served as Technical Representative.

Program studies began on 22 February 1976 and were completed on 22 July 1976. Mr. R. D. Alberts served as Project Leader and was assisted by Mr. W. H. Ruedger and Ms. J. Sharpe.

ABSTRACT

This report describes the activities conducted as a planning effort to focus attention on the applicability of the Global Positioning System (GPS) for general aviation. The study has addressed the description of GPS, its impact on economic and functional aspects of general aviation avionics, as well as a declaration of potential extensions of the basic concept. The report concludes with detailed recommendations for future NASA effort(s) which will propitiously present GPS capability to the general aviation community.

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CHAPTER 1

INTRODUCTION

The NAVSTAR Global Positioning System (GPS) is a worlwide satellite-based navigation system being developed under USAF's Space and Missile Systems Organization. It is the expectation of the Department of Defense that the expensive and somewhat duplicative facilities contained in such position-determining systems as VOR, Loran, Omega, TACAN, and radar altimeters will be replaced by GPS giving a system that is jam-resistant, global, requires no foreign bases, is identical for all users, and is evolutionarily implementable.

Previous satellite system experiences, system simulations, and receiver designs have increased the confidence in this system concept to the point where, coupled with the extreme advantages offered by the system, it has caused an acceleration in the planning and programming operational implementation from 1975 to 1981. This speed-up is a direct result of the need to update the fleet of 10,000 aircraft in the near future and the hope that this can be done on time with NAVSTAR (GPS) instead of retrofitting with improved Loran C/D receivers that may in the near future become obsolete.

The GPS system will provide a world-wide capability for highly accurate continuous position, velocity, and time measurement using satellites emitting jam-resistant pseudo-random noise signals. The system enables a user to passively and securely measure position (x, y, z) and velocity to accuracies in the order of 8-10 meters and 3 cm/sec, respectively. This accuracy is achieved by measuring range and range-rate to each of four satellites selected from a rotating global net of 24. The technique employs a spread spectrum signal and range is measured by comparing the time of arrival of pseudo-random code words with respect to an on-board coder running at the same speed. A precision clock reference is utilized to achieve the required accuracy.

This report presents the results of a planning activity to determine the potential role of GPS in future general aviation operations. It is hoped that this document will form a kind of handbook for those not familiar with GPS and thus not aware of the total role possible in general avionics nor of full GPS potential for increased scope, capability, performance, etc. over and above that available from conventional avionics (and at potentially reduced cost).

Section two of this report presents a description of the GPS system and consists of an overview of the system concept, a discussion of the program and tentative schedule, a detailed discussion of GPS receiver characteristics, and a user oriented discussion of receiver operation. Sections three and four indicate the impact of GPS on economic considerations and avionic suite configuration, respectively, while section five presents representative extensions of the GPS concept. Section six presents recommended activities felt to be required in order that NASA assist in providing GPS to the general aviation community. A detailed discussion of the GPS signal format and cost learning curve considerations are included as appendixes.

It should be remarked that much of the information contained herein was obtained from various contractor reports and presentations and was not necessarily originated by the authors. As such, the timeliness of system parameters, performance measures, etc. represents best estimates as of publication, and not necessarily current values. Section six contains the only recommendations generated by RTI as a result of this study. Other (apparent) recommendations were contained in the contractor documentation from which this report was assembled.

CHAPTER 2

GPS SYSTEM DESCRIPTION

This section describes the overall GPS concept in order to serve as a cornerstone for subsequent discussions. Included are; 1) an overview of the system concept including some remarks regarding the projected capability of the Spartan receiver, as well as error and power budget allocations; 2) a brief discussion of the DOD implementation plan including calendar schedules for major milestones; 3) a detailed discussion of the user equipment; and 4) a discussion of system utilization.

2.1 Overview

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

GPS is comprised of three major subsystems. These are the space segment, the ground segment, and the user segment. The space segment consists of a network of 24 satellites which provide a user with signals from which position and velocity are derived. The ground segment monitors satellite position and uploads this information to the satellite for referral to the user. The user segment then calculates position with respect to the satellite constellation, and knowing satellite position, refers this to an earth centered or appropriate local co-ordinate system. The overall GPS concept is shown in Figure 2-1.

2.1.1 GPS system concept.-The GPS concept is basically that of multi-lateration. Knowledge of range between a receiver and a satellite locates the receiver on the surface of a sphere such that utilization of three independent satellites locates the receiver at the intersection of

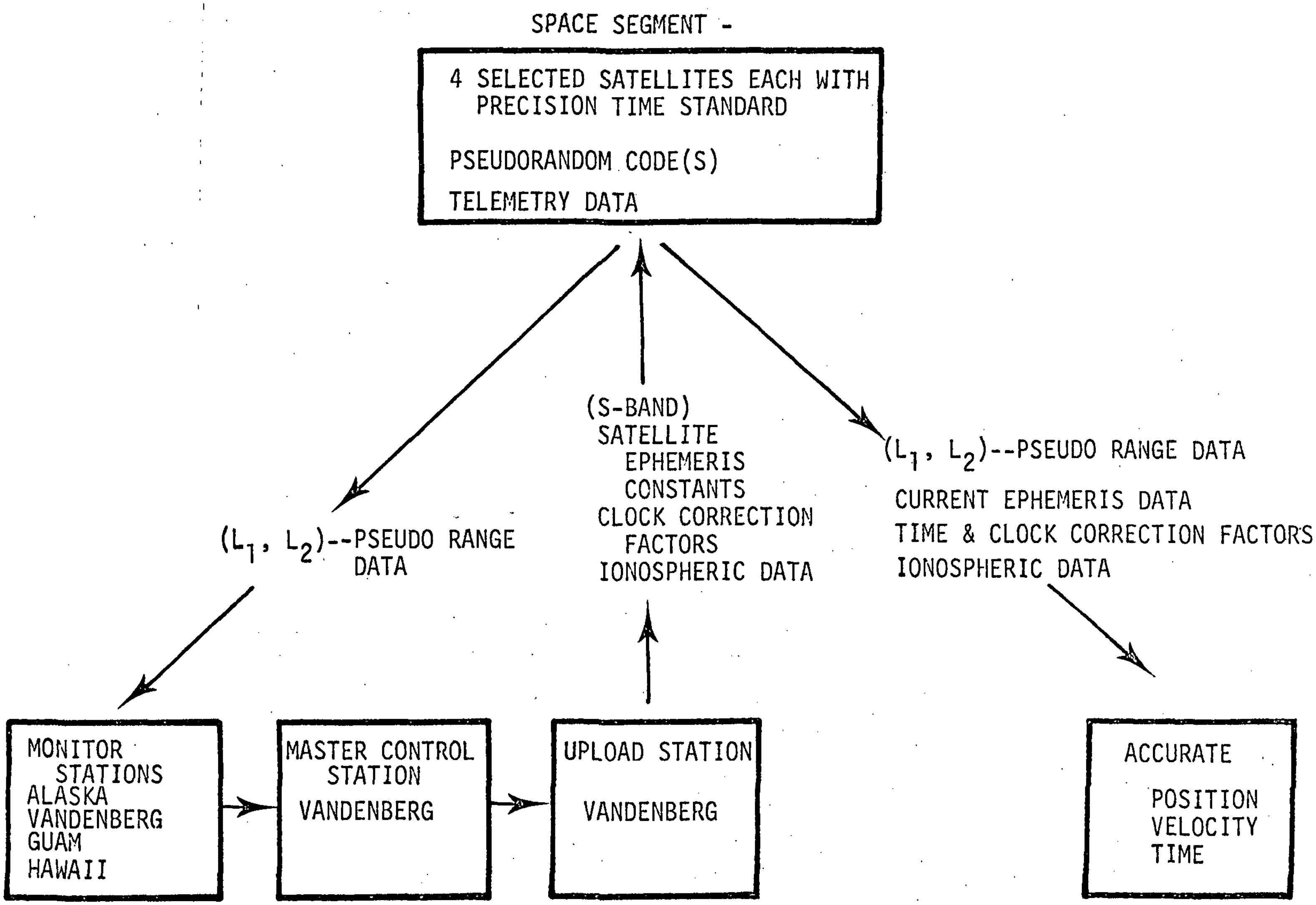

Figure 2-1. Overall GPS System Concept

the three associated spheres, given a precise time reference. The GPS concept provides for their highly accurate time reference except at the user receiver. The receiver clock is assumed to have an error and a fourth satellite is tracked in order to estimate this error.

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

$$(X_{USER} - X_{SAT''i''})^2 + (Y_{USER} - Y_{SAT''i''})^2 + (Z_{USER} - Z_{SAT''i''})^2 = (R_i - \Delta R)^2, \ i = 1, 4$$

where

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

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

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

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

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

Each satellite transmits two L-band carrier signals which are biphase modulated with a composite pseudo-random noise code. For the primary carrier (~1575 MHz), the code contains a "clear" signal for code acquisition (and for lower precision navigation), a "protected" signal for precision navigation and anti-jam capability, as well as telemetry data which includes synchronization, clock data, handover data (to acquire the "protected" code having first acquired the "clear" code), and ephemeris data. The secondary carrier (~1230 MHz) is modulated in a similar manner with the exception that the "clear" code is omitted. Transmittal of the two carriers provides for compensation of propagation delays experienced in the ionosphere.

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

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

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

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

2.1.5 Functional description.—According to presently available documentation, the precise receiver design varies with manufacturer. RTI has reviewed the Philco Ford, the General Dynamics (from the preliminary definition phase studies), the Magnavox Spartan, the Rockwell Spartan, the Collins, and the Texas Instruments receiver designs (refs. 1 through 7). All designs reviewed share some commonality. Each possesses a PN code generator which creates the replica code. This code is bit-synchronized with the incoming code and removed (usually) at the first IF. The final IF is detected synchronously (a Costas loop) for range and range-rate measurement. Telemetry data is demodulated conventionally for input to the navigation algorithm. The algorithms are processed digitally; usually with a microprocessor (in the Spartan set, an INTEL 8080). User outputs are generally available either in earth centered co-ordinates or in a local co-ordinate system which can be corrected for altitude.

The Spartan receiver has the following salient features which distinguish it from the higher performance types (ref. 3):

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

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

3. Accuracy in the range of 30-100 meters. Table 2-1 indicates a proposed error budget.

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

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

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

It should be noted that the above performance is in sharp contrast to that achievable with the high performance, 4-channel continuous

Table 2-1. GPS Error Budget (ref. 4)

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

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

receiver. For this receiver, updates are at the rate of ten per second, time-to-first-fix is on the order of seconds, and accuracy is on the order of a few meters. Also, with ground augmentation, potential accuracy is even further improved.

2.1.6 RF link (power) loss budget.— The required signal levels at the user equipment as specified in the Rockwell System Specification (ref. 8) are shown in Table 2-2.

Table 2-2. Required User Equipment Received Signal Levels

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

An RF link calculation has been extracted from the General Dynamics Contract Definition Study (ref. 2) and is included as Table 2-3. A user elevation angle of 5° is also shown and is taken as representative of worst case.

Table 2-3. RF Link Calculation of User Received Power

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

2.2 GPS Program (ref. 9)

The GPS program plan is shown in Figure 2-2. The Phase I approved program will deploy six satellites. This will give four hours of three-dimensional testing in the test areas each day. Phase II will deploy a minimum of nine satellites. This will yield periodic, precise three dimensional capability and continuous global two dimensional capability beginning in 1981. The operational system of 24 satellites would be available in 1984.

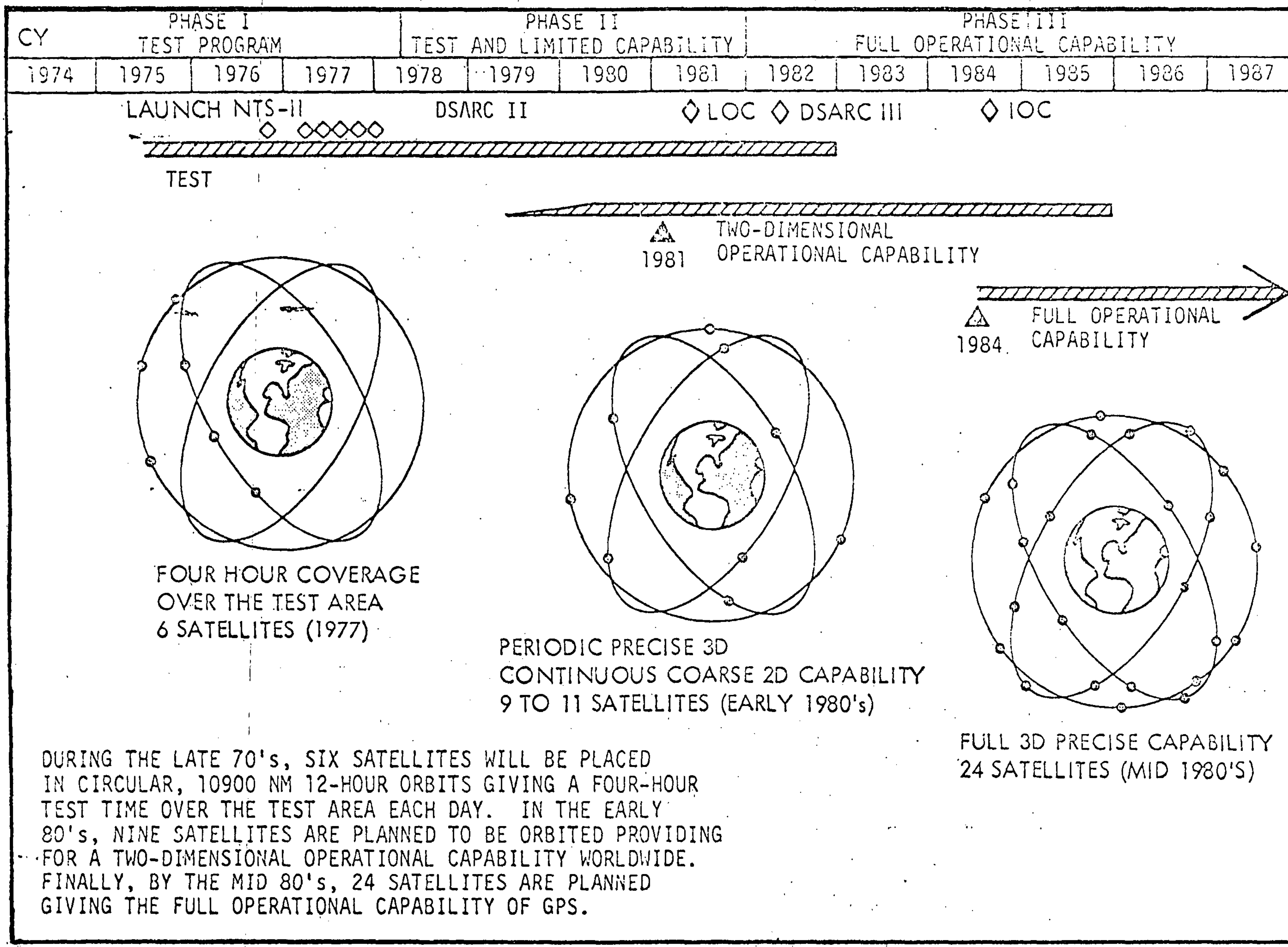

Figure 2-2. GPS Schedule (ref. 6)

The approved Phase I program will validate the basic GPS concept and measure its performance; validate the design in terms of its operational suitability and make whatever adjustments necessary to meet DOD-required operational goals; determine system cost-both acquisition and life cycle; and carry out demonstrations of military utility.

Five of the six Phase I satellites will be GPS prototypes. The other, a technology satellite developed by the Navy, will transmit GPS signals and will space-qualify a cesium clock for possible use in the operational system. It will be launched late in 1976 and will be followed by the five prototype satellites in 1977.

Phase II is the system validation phase. The military low-cost receiver will be in production and available for global limited operational capability in 1981. The more sophisticated equipments will be at pre-production status. Initial operational tests will be carried out with those user models. Additional, production-Block 1, satellites will increase the number in orbit from 6 to 9-11. Periodic three dimensional testing will occur for about 18 months. At that time the limited operational capability would be implemented by respacing the satellites.

A decision will be made at DSARC (Defense System Acquisition Review Council) III on whether to move ahead with full production of the system, achieving initial operational capability in 1984. All user equipments would be in production at this point, and operational test and evaluation would be completed.

2.3 Detailed Receiver Description

This section describes in greater detail the GPS user equipment. Included are sections describing the comparative characteristics of the Spartan receivers of the three main contractors, and a brief discussion of the signal processing proposed for the Texas Instruments receiver. The information presented has been obtained from contractor reports and briefings and as such may appear to conflict in some instances due to intervening changes, etc. For this reason, the material contained herein should be interpreted as a guide to the GPS receiver concept as opposed to a design handbook.

A detailed discussion of the GPS signal structure has been included as appendix A.

2.3.1 Comparative receiver approaches-These data on Z-prime (Spartan) receiver characteristics and approaches were extracted from the Technology Transfer Briefing presented by Maj. R. L. Bush on 14 April 1976 (ref. 10). Originally included in the list of candidates but omitted from this discussion were Draper Laboratories. This is the result of the fact(s) that the characteristics were identical to the target and that the approach employed sophisticated digital signal processing techniques thus introducing implicitly unknown cost aspects.

The baseline characteristics of the Z-prime or Spartan set are as shown in Table 2-4. These characteristics evidence a relaxation of the GPS receiver design parameters to specifically address the non-military user with an accompanying significant reduction in cost. Both the Magnavox and Texas Instruments designs reflect the general architectural theme of military versions while the Rockwell design adopts radically new parameters such as carrier frequency and signal structure with a reported substantial cost reduction.

The Magnavox approach incorporates general receiver simplification while the Texas Instruments approach leans heavily on the flexibility inherent in their modular packaging concept and is in fact a backoff from their manpack receiver design. The design philosophy for the Magnavox and Rockwell Z-prime receivers has been extracted from their Spartan Design Study Reports and are included in the following paragraphs. The Texas Instruments receiver philosophy is omitted as it is a straightforward relaxation of manpack constraints. This receiver is documented later with flow diagrams of the total receiver as well as discussion of the code and carrier tracking loops. The latter information was obtained during the April 30 briefing at LRC (ref. 7).

TABLE 2-4. CHARACTERISTICS OF Ƶ - PRIME SET CANDIDATES (REF. 10)

	TARGET	MAGNAVOX	TEXAS INSTRUMENTS	ROCKWELL INTERNATIONAL
TYPE OF NAVIGATOR	COMPLETE SELF-CONTAINED AUTOMATIC	COMPLETE SELF-CONTAINED CONTINUOUS W/MAN UNIT	COMPLETE SELF-CONTAINED CONTINUOUS W/MAN UNIT	COMPLETE SELF CONTAINED CONTINUOUS
OUTPUT	LATITUDE LONGITUDE BEARING & RANGE	LATITUDE LONGITUDE BEARING & RANGE OTHER?	LATITUDE LONGITUDE ALTITUDE BEARING & RANGE TO WAYPOINT	LATITUDE LONGITUDE BEARING & RANGE TO WAYPOINT
RECEIVER	SINGLE CHANNEL (CA) SINGLE FREQUENCY (L_1)	SINGLE CHANNEL (CA) SINGLE FREQUENCY (L_1)	SINGLE CHANNEL (CA) SINGLE FREQUENCY (L_1)	SINGLE CHANNEL (NEW SIGNAL) SINGLE FREQUENCY (UHF)
ACCURACY	150m	30-100m	200m	860m
ENVIRONMENT	NO ADDED AJ LOW DYNAMICS	NO ADDED AJ LOW DYNAMICS	NO ADDED AJ LOW DYNAMICS	NO ADDED AJ LOW DYNAMICS

TABLE 2-4. CHARACTERISTICS OF Ƶ - PRIME SET CANDIDATES (CONT'D)

	TARGET	MAGNAVOX	TEXAS INSTRUMENTS	ROCKWELL INTERNATIONAL
APPLICATION	CLASS C MIL ALL CIVIL	CLASS C MIL CIVIL (C/G AV & MARINE)	CLASS C MIL CIVIL (SEISMIC & TIMING)	NO MIL CIVIL (GEN AV & BOAT)
PHYSICAL PARAMETERS	TACAN SWAPOUT	16 Kgs 5000 HR MTBF	TACAN SWAPOUT	1/2 ATR SHORT 4.5 Kgs 95 HR MTBF
COMM SALE PRICE (MIL PRICE = 2/3)	$5000 AT 1000th UNIT	$5000	$5000	$1655 ($7680 FOR Ƶ')
SPECIFICATIONS	COMMERCIAL	COMMERCIAL	MIL-STD	COMMERCIAL
REQUIRED PRODUCTION	5,650	86,000	HIGH	15,000

Magnavox Summary (pages 16 thru 21 were extracted from the Magnavox Spartan Design Study Report, ref. 3).

General. This document provides an overview of the Spartan set development activities at the Magnavox Company. Potentially, this set may account for a large market-share of the entire GPS user equipment spectrum, and cost reduction being the major forcing function, influences all other parameters that affect the definition of this set. To ensure the development of a viable set that is truly responsive to user requirements a detailed market survey was undertaken. The ensuing user requirements were then combined with the GPS system constraints, in order to arrive at performance specifications for the Spartan set.

Spartan User Requirements. A summary of marine user requirements is given in Table 2-5 for the time periods of 1975 through 1985 and beyond. Accuracy required by these users varies from below 200 m to the 1- to 3-km range. The great majority of these users, and this must be emphasized, require accuracies of 1/2 km or better. Size, weight, and power are not very critical, but require minor constraints. Time-to-first-fix ranges from 0 to 2 min, to beyond 10 min, with the majority of users requiring a capability of 5 to 10 min. Cost limitations cover a wide spectrum, but can be contained for the most part in the range of $1500 to $5000. Airborne users on the other hand, are driven mainly by the desire to equal or better the cost/performance characteristics of VOR navigation.

Market Survey. A Spartan set in the $5000 price range would be directly applicable to the following customer community:

U. S. Navy....................700
U. S. Air Force..............500
U. S. Coast Guard............100
U. S. Army.................2,000
Merchant ships.............7,000
Fishing boats..............6,000
Trawlers..................10,000+
Commercial aviation.......10,000+
General aviation..........50,000+

Table 2-5. User Requirements (ref. 3)

note- numbers in ( ) correspond to entries in table below for the appropriate column.	Accuracy (95% of Time)				Size/Weight/ Power		Time-to-First-Fix		Data Output Desired		Cost Limitation (Total acquisition cost not including installation)	
	(1) 0 — 0.1 mi (2) 0.1 — 0.25 mi (3) 0.25 — 0.5 mi (4) 0.5 — 1.0 mi (5) 1.0 — 2.0 mi				(1) Very small required (2) Some constraints (3) Not critical		(1) 0 — 2 min (2) 0 — 10 min (3) Over 10 minimum acceptable		(1) Lat/long (2) Range/bearing to set waypoints — both rumb line and great circle (3) Range/bearing to moving rendez-vous vehicle (4) Time enroute (5) Speed and heading		(1) $0 — $200 (2) $200 — $1500 (3) $1500 — $5000 (4) $5,000 — $20,000 (5) $ over $20,000	
	coastal-confluence		high seas		all waters		all waters		all waters		all waters	
Type of Marine User	1975 to 1985	Post 1985	1975 to 1985	Post 1985	1975 to 1985	Post 1985	1975 to 1985	Post 1985	1975 to 1985	Post 1985	1975 to 1985	Post 1985
Military/high performance	1	1	3	2	2	2	1	1	1,2,3,4	1,2,3,4	5	5
Military/other	3	2	5	4	3	2	3	2	1,2,3,4	1,2,3,4	4	5
Merchant ship/large	2	1	5	4	3	3	3	3	1,2	1,2	5	4
Merchant ship/small	2	1	5	4	3	2	3	3	1,2	1,2	4	4
Fishing ship/large	2	2	2	2	2	2	3	2	1,2	1,2	4	4
Fishing ship/small	2	2	2	2	1	1	2	2	1	1	3	3
Scientific/seismic	1	1	1	1	3	2	3	3	1,2,5	1,2,5	5	5
Recreational/other	4	3	5	4	1	1	2	2	1	1	2	3

This represents only the United States market. Worldwide applications of the Spartan set could result in several multiples of the above figures.

GPS Waveform Modification. This section proposes seven changes to the planned GPS signal structure, which could potentially enhance a minimum cost Spartan set development. It must be noted that none of these modifications are absolutely required in order to develop a low-cost navigator, but that cost reductions in the range of 8 to 15 percent could be realized. The proposed changes are as follows:

a. Increase transmitted power: Simplifications and shortcuts are possible only if there is adequate signal margin. The most direct method of increasing signal margin is to transmit more power.

b. Place Spartan signal on lower frequency: Signal margin will be improved 2.1 dB, by placing the Spartan modulation on the L_2 frequency, rather than on the L_1 frequency as now planned.

c. Lower the second frequency: By dropping L_2 from its planned value to about 966 MHz, another 2.1 dB of signal margin will be obtained, and dual-channel refraction correction performance will be improved.

d. Introduce a pilot carrier: Time multiplex data modulation with a carrier to simplify the phase-tracking circuitry and to improve signal-tracking threshold performance by 3 dB.

e. Extend the Spartan PN-code length: Extend the Spartan PN-code length to 20 msec in order to simplify bit synchronization, reduce receiver processing bandwidth requirements, improve processing gain, and enable fewer codes to be used.

f. Reduce the number of PN-codes: Preferably have all satellites transmit the same Spartan PN-code, or at least all eight satellites in each orbit transmit the same code. This will permit simplifications in the coder design, reduce logic to handle code-switching, and eliminate the need for a stored ephemeris ALERT program for code-starts.

g. Provide a doppler acquisition aid: On a time multiplexed basis, cause the Spartan PN-code to be turned-off for 10 to 20 sec every 4 to 8 min on every satellite. The resultant narrowband signal would permit accurate Doppler frequency acquisition, prior to PN-code acquisition, thus, reducing accuracy requirements on the reference oscillator and improving performance of the signal detect function.

The Spartan Set. The Spartan receiver study has attempted to identify those concepts, which would lead to a minimum cost GPS navigator. This paragraph describes the concepts relating to the receiver, interface logic, and the process controller portions of the system for the present waveform. In creating a low-cost navigator, three factors are of great benefit:

a. No intentional jamming is assumed, although man-machine noises, e.g., radar signals, are considered.

b. All vehicles will experience only low-dynamics, e.g., 0.5g accelerations, or else reacquisition after high-dynamics is allowed.

c. The navigational pace is more leisurely so that a time-to-first-fix of 10 to 20 min, and fix-update intervals of 10 to 30 sec are acceptable.

The major decision was whether to employ a computer in the design. It takes very little time to realize, that at least a modest computer capability is required, in order to handle the tasks of satellite selection, initial acquisition, sequential tracking, data validation, and error correction, etc. Furthermore, the task of implementing other than computerized fix solution is staggering, not to mention the logistical problem of supplying fresh charts, graphs, and tables to the thousands of users. Therefore, the Spartan navigator must employ a digital computer for control and for automatic calculation, and display of latitude and longitude position.

With this fundamental decision made, it was then necessary to choose implementation techniques which would minimize recurring cost of production. These concepts are summarized as follows:

a. Employ a true microcomputer (CPU on a single-chip) as the system computer, and take the associated computing time penalty. The Intel 8080 has been chosen for the baseline design.

b. Operate only on the C/A-signal at the L_1 frequency.

c. Employ a dual-conversion receiver rather than a triple-conversion design.

d. Minimize high-frequency gain to that necessary to establish the system noise figure.

e. Avoid complex frequency synthesis techniques; especially those requiring frequency mixing.

f. Combine the signal and the PN-tracking channels, and employ simple Tau Dither techniques to seek the correlation peak at the expense of decreased signal margin.

g. Limit the carrier-tracking techniques only to a Costas phase tracking-loop without a backup afc loop.

h. Simplify the incremental phase modulator at the expense of range measurement resolution.

i. Minimize the use of high-speed logic which tends to increase power dissipation.

j. Employ a low final IF frequency to permit use of standard analog and integrated circuits for implementing phase comparators, phase shifters, etc.

k. Avoid the use of crystal vco's or high-speed digital phase shifters for carrier-tracking if possible.

Performance. The Spartan set is intended for use in nonhostile environments and on platforms with very-low dynamics. It will be built to commercial specifications, although intended for government and military applications, e.g., air and sea transports, tankers, etc. As such, there is a different emphasis in design of a Spartan set, as compared with all other GPS user equipments. These differences are made clear by the following summary of Spartan characteristics:

a. Spartan operates on a single GPS frequency.

b. Spartan employs only the C/A signal.

c. Accuracy is in the range of 30 to 100 m.

d. Intentional jamming is not assumed.

e. Time-to-first-fix is not a critical parameter, and will range from 5 to 10 min.

f. Time between each position fix output is only moderately critical, and is baselined between 10 to 30 sec.

g. Operational simplicity, reliability, and low-cost are mandatory.

h. A Spartan set could provide accuracies down to the 10-m range if successive measurements were taken at a fixed-location over the course of several hours.

Rockwell Summary (pages 21 thru 23 were extracted from the Spartan Design Study Report, ref. 5).

Present Receiver. Early in the study, it was concluded that a receiver/processor compatible with the existing C/A signal could not be built for under $2000. Assumed production levels and Spartan type design simplifications reduced the cost of the present receiver only by 50 percent to approximately $7,680. Its cost is driven by the accuracy criterion and the amount of computation necessary to establish the optimum spacecraft group that produces the minimum geometric dilution of precision (GDOP). The noted accuracy criterion results in a high bit-rate, continuous wave, code division multiple access system requiring carrier tracking loops (Doppler corrections), code tracking loops, multiple-matched filters using the processor to reduce cost, and the noted GDOP support.

Cost Reduction Studies Summary. In attempting to reduce costs, it became obvious that the reduced accuracy requirement (~2 km) could be supported by new signaling approaches which did not encompass the expensive techniques utilized in the present receiver design. Consequently, the study emphasis was placed on the time-of-arrival (TOA) waveform; carrier frequency; multiple access techniques; processor; processor/receiver interfacing; algorithms; and the means for correction of TOA and spacecraft location information. Conclusions reached through these tradeoffs and analyses resulted in a system concept which exceeds the accuracy/cost requirements and which may be extended to provide several classes of equipment which can satisfy a range of user demands. The concept diagram of the selected approach is portrayed in Figure 2-3. Overall receiver/processor specifications are provided in Table 2-6.

System Operation

Waveform. The selected approach employs time division multiple

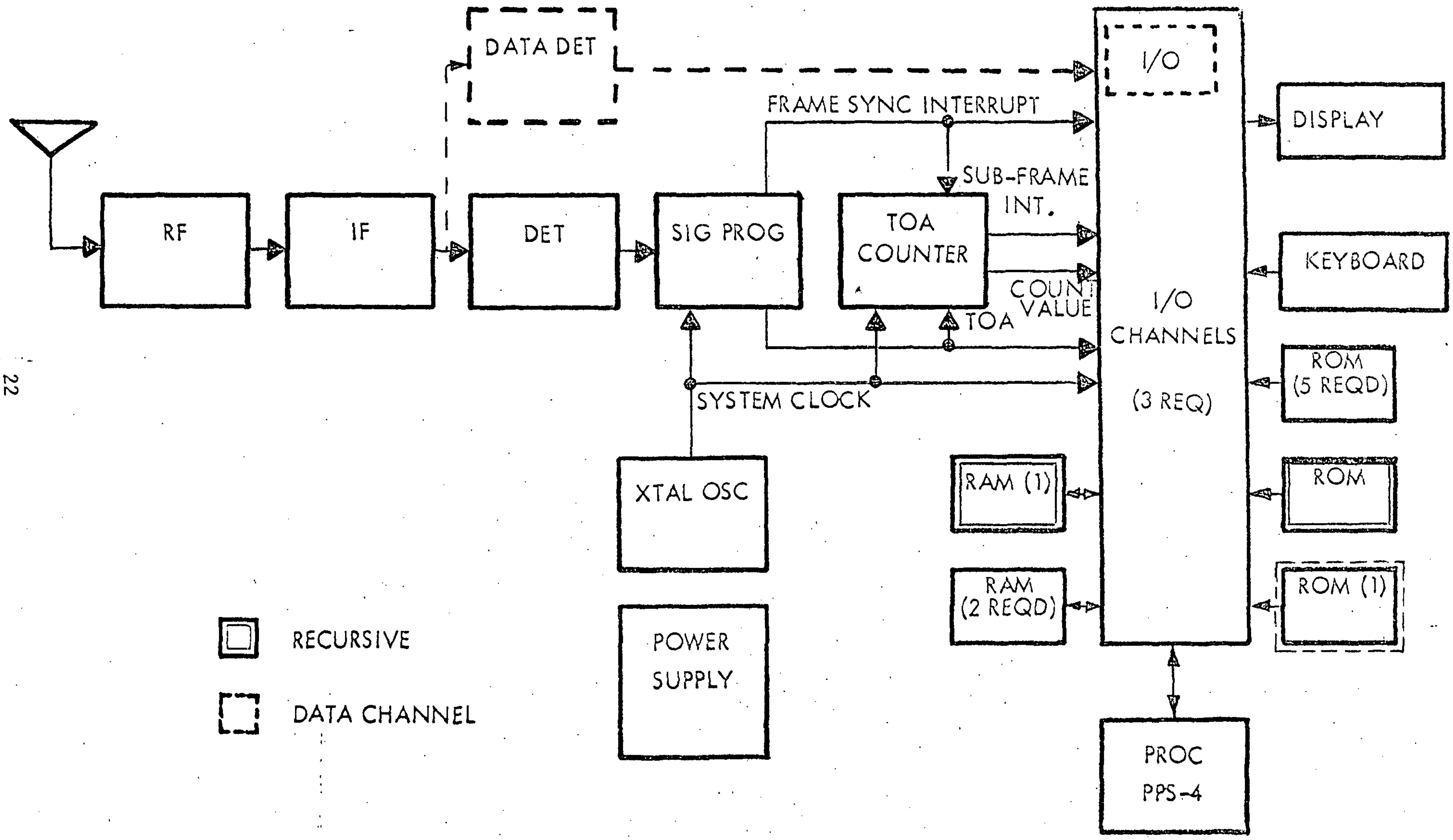

Figure 2-3. Spartan Receiver/Processor Block Diagram (ref. 5)

Table 2-6. Receiver/Processor Characteristics (ref. 5)

Characteristic	Value
Frequency:	UHF
Modulation:	Burst-FM (TDM-FSK)
System accuracy:	850 m, Class A; 1400 m, Class B
Bandwidth:	200 KHz
Processor:	Rockwell PPS-4
Navigation:	Single Point Fix or Recursion
Update:	Almanac or Data Channel
Time-to-first fix:	13 Seconds
Update rate:	3 Seconds
Size:	
Private aviation	20 cm wide by 10 cm high by 30 cm deep
Commercial aviation	1/2 ATR Short
Marine	25 cm wide by 15 cm high by 20 cm deep
Power:	12 or 24 volts dc @ 20 watts
Weight:	4.5 kg
Cost:	$1465 (Class B) or $1655 (Class A)
Reliability (MTBF):	1100 hours (Class B) 95 hours (Class A)
Development risk:	None. All parts (Spacecraft and receiver/processor) presently available

access (TDMA) to reduce the receiver costs. A frame of 1 second duration has been divided into 25 TOA time slots of 40 ms each, to provide unique addresses for all 24 constellation spacecraft plus one sync slot. The frames are transmitted 119 times and become silent for 1 frame time to designate start of a 2 min master frame. The master frame is used for spacecraft position/time data correlation, and the frame TOA transmissions are used for range difference computation. Each frame is initiated with a sync signal transmission by all spacecraft, simultaneously. Waveforms are shown in Figure 2-4.

Time Measurement. The first frame sync signal, received at the receiver processor, resets the timing circuits to begin countdown of the local clock oscillator. The received TOA signal shifts the count value into the processor each time a TOA is received. The processor then tags the spacecraft identification to the shifted value and stores the data and identification.

Position Calculation. When the TOA signal for each selected spacecraft has been received (four selected out of six or more, at any reading), the processor begins computation of the position, using pre-stored information and the time difference measurements. The pre-stored data consists of spacecraft Kepplerian constants, user's location, system time and satellite identification and optimum spacecraft group. Computation is effected by solving four equations in four unknowns, using Newton's iteration to establish most likely position. The computation is made in earth centered inertial (ECI) longitude coordinates. The computation is completed in 13 seconds as 13 iterations of 1 second each are performed. When recursive navigation is used, subsequent measurements require only 3 iterations, maximum, or 3 seconds per update.

2.3.2 Signal processor (TI receiver, ref. 7).-Both the Magnavox and Rockwell approaches to a low cost receiver incorporate deviations from the basic military version of the GPS receiver. Since the TI receiver retains the basic original GPS concept, it was selected to demonstrate the signal processing approach. Figure 2-5 shows a block diagram of the overall TI receiver including the code and carrier track loops.

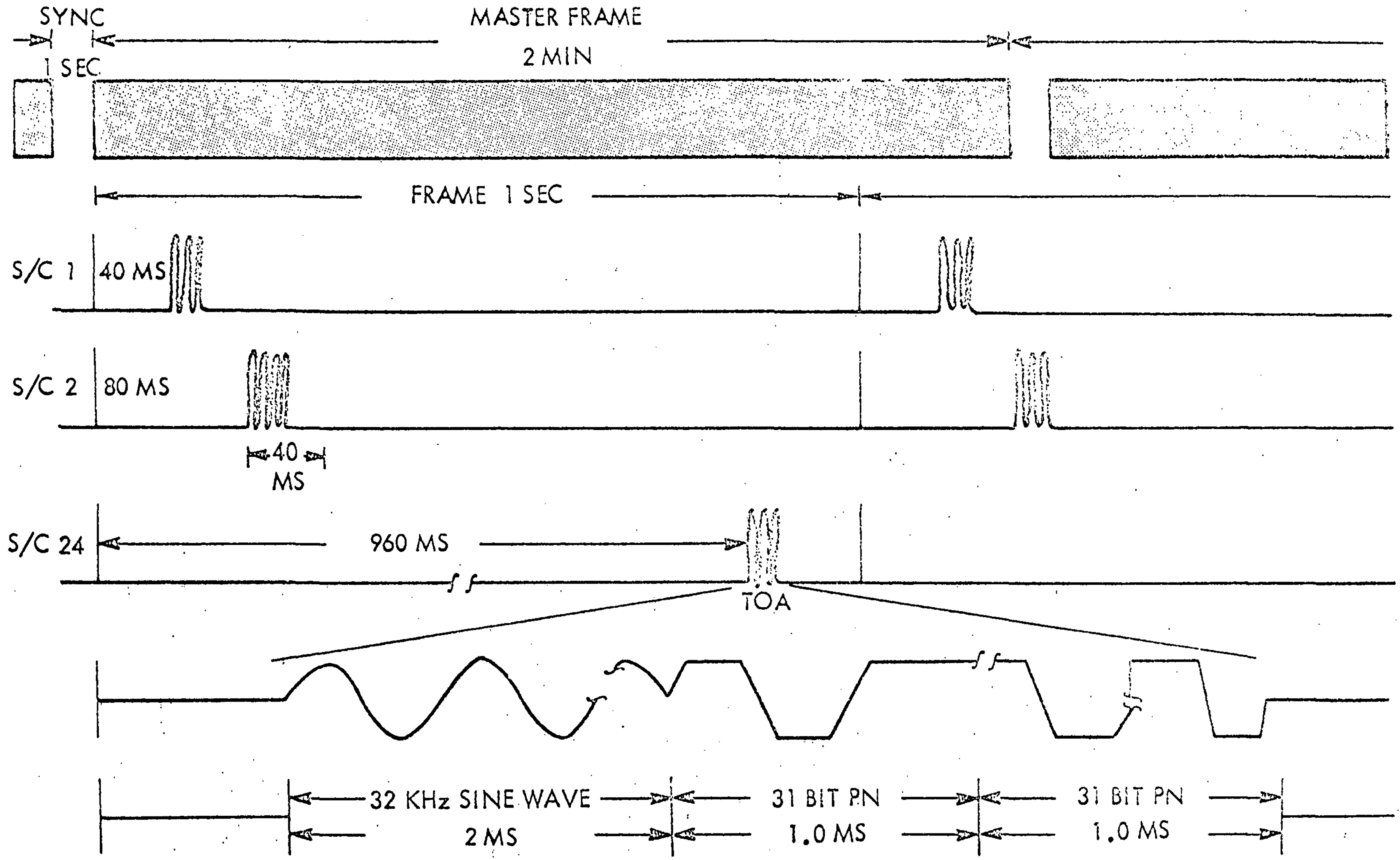

Figure 2-4. Spartan Waveforms (ref. 5)

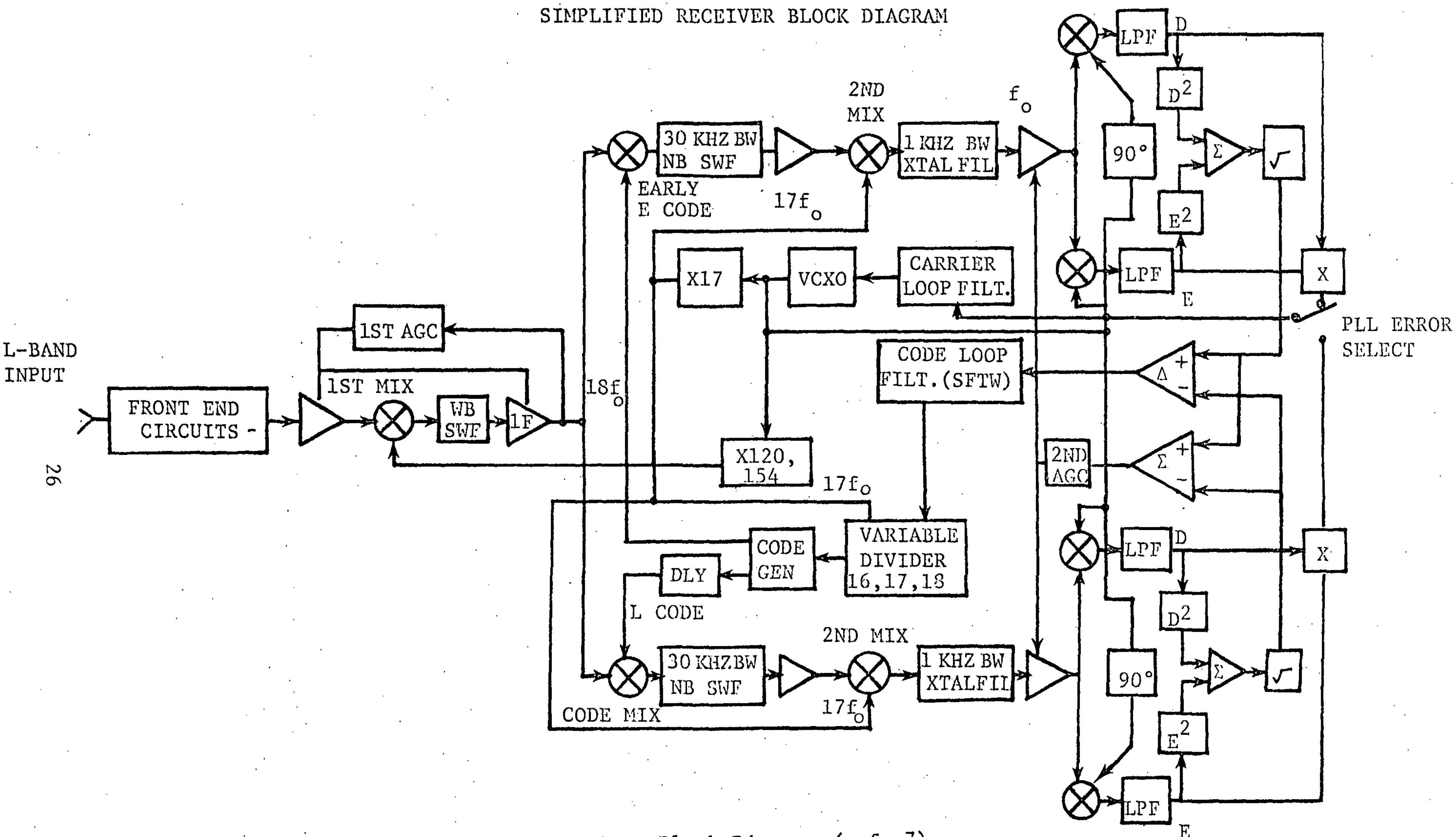

Figure 2-5. Texas Instruments Receiver Block Diagram (ref. 7)

In the code track loop a replica code is phase synchronized with the output of the first IF and the signal code removed at the code mixer. The carrier is then phase tracked for ranging data while the 50 bps data stream is demodulated and delivered to the computer for input to the navigation algorithms.

Table 2-7 describes the basic operation of the receiver in the acquisition mode. To clarify the first step in Table 2-7 with respect to the acquisition process discussed above, the 250 Hz bandwidth low-pass filter is equivalent to a 500 Hz carrier bandwidth due to foldover at the output of the synchronous detector.

Table 2-7. Basic Operation of Receiver in Acquisition Mode (ref. 7)

1.	Local oscillator preposition to place center frequency within 250 Hz low-pass filter bandwidth (software).
2.	Noncoherent code acquisition.
3.	Frequency-lock loop carrier acquisition (hardware).
4.	Costas phase-lock loop tracking (hardware).
5.	Software-controlled bit synchronization.
6.	Software-controlled data ambiguity resolution.

The noncoherent code acquisition can be best described by referring to Figure 2-6. The code loop filter consists of an analog-to-digital converter in conjunction with the software contained in the receiver control processor. After the local oscillator has been correctly prepositioned, according to step 1 of Table 2-7, the code generator is cycled through either 2,046 half-chip steps in the case of the normal mode to acquire the C/A code, or the requisite number of half-chip P code steps to acquire the P code in the direct mode. The advance or retard of the code generator output is achieved by speeding up or slowing down the code clock. The variable divider has an input of 17 f_0 from the carrier loop. During noncoherent acquisition, the VCXO signal is held at a fixed frequency determined by the range-rate sent to the receiver by the Inertial System. The code clock is speeded up by dividing by 16

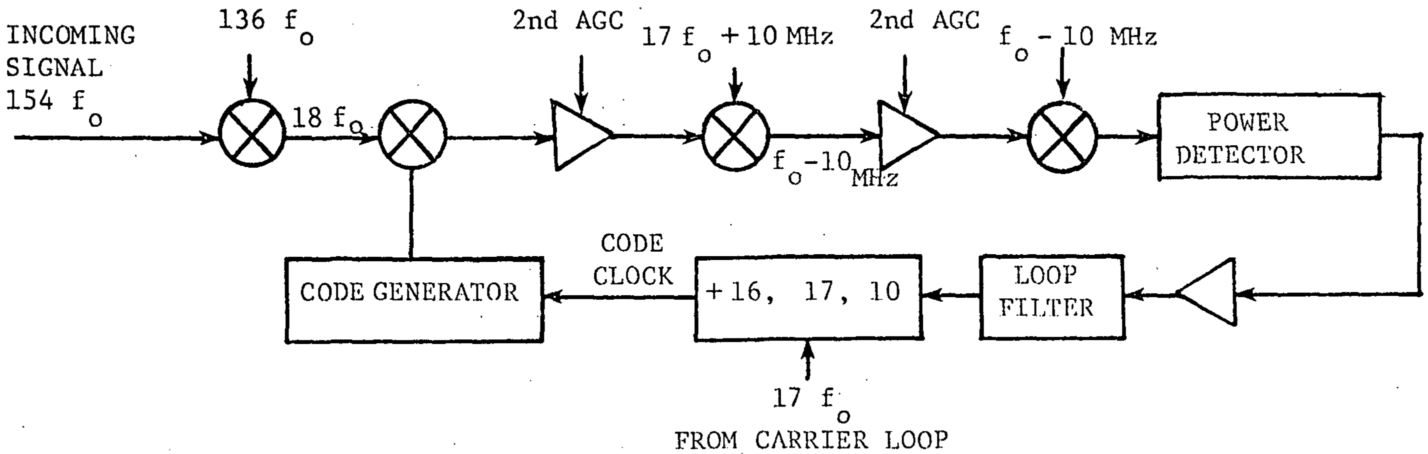

Figure 2-6. Code Loop (ref. 7)

or slowed down by dividing by 18, thus advancing or retarding the code phase with respect to that of the incoming signal. Once the signal has been acquired, the replica code is alternated four times about the expected value of the correlation peak of the signal. The receiver control processor then commands the phase of the code generator to the proper position.

Frequency-lock carrier acquisition then occurs. Figure 2-7 shows the carrier loop in simplified form. This figure best illustrates the coherent nature of the receiver showing the coherent injection of all local oscillators. The totally coherent receiver has a decided advantage over a noncoherent or mixed system in that in the noncoherent receiver the first, and more importantly, the second, IF frequency bandwidth must be sufficiently wide to pass the full Doppler, creating a dynamic range requirement considerably greater than that with the coherent receiver. For the noncoherent receiver, this dynamic range manifests itself in terms of greater dc power required to operate the second IF frequency components. For the noncoherent receiver, the final tracking system must track the full Doppler frequency, requiring a much greater tuning range.

2.4 Receiver Operations

It is appropriate to consider the potential utilization of a GPS receiver in an airborne environment. In order to represent those steps included in such utilization, the following discussion has been included from the Philco-Ford Preliminary Design Study (ref. 1). While not perhaps precisely applicable to other equipments, it does represent thinking which includes both the sophisticated four-channel receiver and the sequential low-cost receiver. The discussion is therefore considered very pertinent to this study.

2.4.1 General.-There are certain basic operational steps which will be common to all user equipment groups. They are, in sequential order:

a) Power on and warm-up
b) Input of approximate user position and velocity, and of time
c) Constellation selection
d) Search and acquisition of L_1 signal

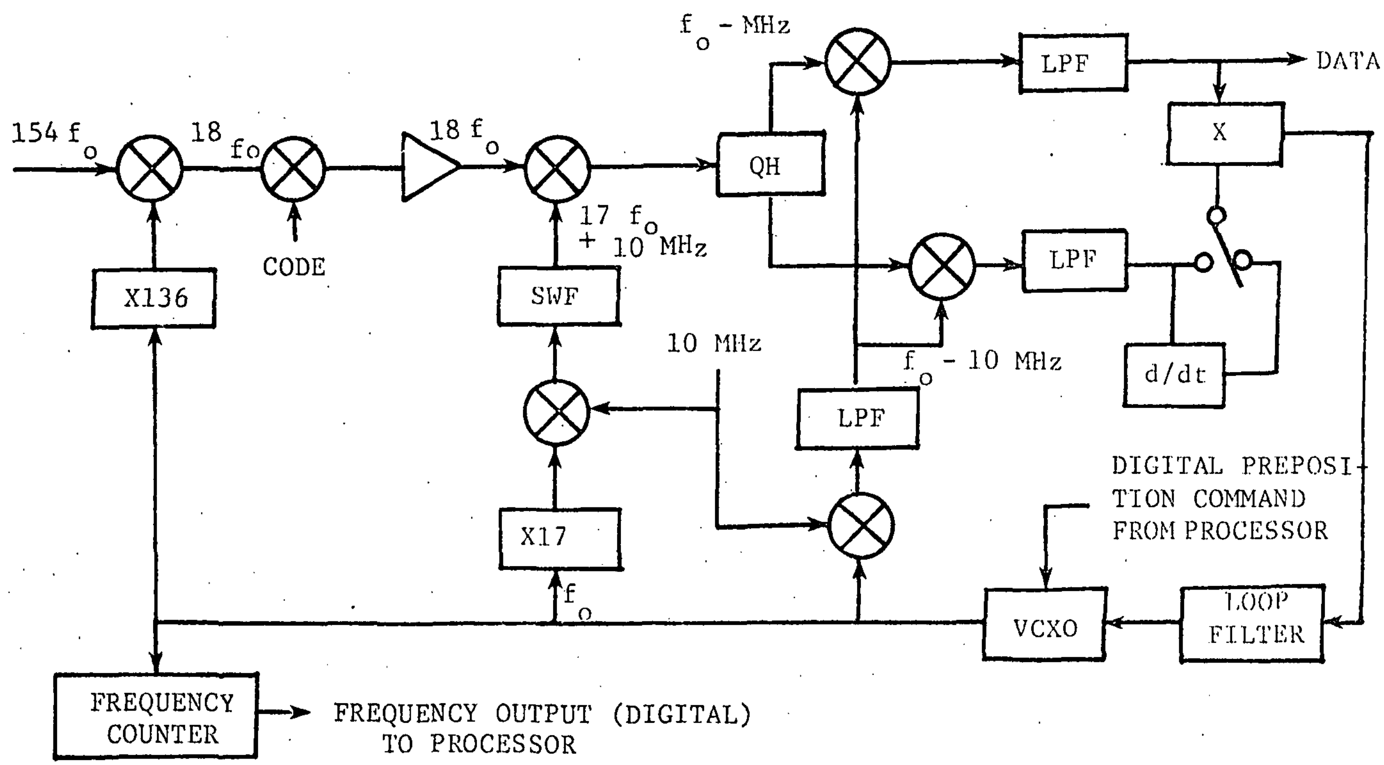

Figure 2-7 Carrier Loop (ref. 7)

e) Collection of current data

f) Pseudorange and pseudorange rate measurement of L_1

g) First navigation fix

h) Pseudorange measurement on L_2 (L_1/L_2 receivers only)

i) Continuing accurate navigation fixes

j) Data update

k) Constellation revision

It is expected that most users will perform these operations automatically, without the need for operator actions. This will allow the operator to concern himself only with the form of the navigation display, and not with the mechanism for obtaining the fixes themselves. With some users, the initial input of user's position and velocity must be manually effected, too. There is also the potential for designing extremely simple user equipment in which more of these steps would be operator effected, but such devices have not been intensively examined yet.

In the following, the operational steps are discussed in greater detail, first for the X receiver. The operational steps for the other receivers are then described, particularly where they differ from X-type steps.

2.4.2 X-receiver operations.-This user class employs a 4-channel, continuous tracking, C/P, L_1/L_2 receiver and includes inertial sensors in its equipment group.

From the time of power-on, all steps are carried out automatically under computer control. The initial input (to the computer) of the user's approximate position and velocity, is provided from the inertial or other auxiliary navigation sensors. Similarly, other, non-GPS, clocks provide the time data.

The user's position and velocity, and the time information, are needed for constellation selection. This is a process of determining which four satellites, of all those active in the GPS, should be used for navigation. In addition to this information, the constellation selection process also needs to know the approximate positions and velocities of the satellites, and those are found from the orbital elements of all satellites stored by each user in his nonvolatile memory.

The criteria for constellation selection will most probably vary from user to user. The minimum allowable elevation angle is one of the criterion; a ship user will probably want to minimize horizontal GDOP, whereas an airborne user may wish to minimize the 3-dimensional SEP * GDOP. For all cases, the constellation selection will be performed in a software subroutine. The output will be the identification of the selected satellites (which includes the feedback tap arrangements for their C-codes), and the estimates of second mixer injection frequencies needed to ensure that the received L_1 signal frequencies lie within the acquisition passband. These are related to the estimates of the Doppler shifts.

This ensures that the subsequent search for the signal need be in phase only, and not also in frequency. With high performance users, it is possible that the user-induced Doppler shift will change so much during the search process that the initial frequency estimates will not remain valid. For this reason, the user velocity has to be frequently sent to the computer during the search, and the computations for second mixer injection frequencies repeated.

Each of the L_1 receiver channels will be allocated to one of the selected satellites, and each will independently go through the following steps:

a) Set the feedback taps on its replica C-code generator.

b) Preposition its VCO (i.e., preposition its second mixer injection frequency).

c) Search in phase by stepping the C-code clock pulses the equivalent of half a chip every τ msec, where τ is about 10 msec, and will be a preset value.

d) When the lock detectors show that the L_1-C signal has been acquired, first the carrier tracking loop, and then the code loop will be

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* spherical error probable

enabled, so that the signal will be automatically tracked in both phase and frequency. The VCO prepositioning estimates are no longer needed at this point.

e) The data bit synchronizer will be enabled, and matched filter data detection can begin. There will be a real time search for the frame sync pattern, followed by acquisition and storage of the navigation message.

f) Following the navigation message is the handover word. This informs the receiver/computer exactly when to replace the replica C-code with the replica P-code at the code demodulator.

g) The channel is now properly tracking the L_1-P signal from its assigned satellite. It will make regularly scheduled measurements of pseudorange and pseudorange rate and send them to the computer (which may, however, not make use of them yet).

When all four channels have accomplished the above steps, the computer will start to make navigation fixes. The first fix will not be the most accurate one, since L_1/L_2 comparisons are yet to be made, and the navigation filter needs time before it can obtain very accurate estimates of the system biases.

Once the L_1-P signals from all four satellites are being tracked, the computer will establish a routine in which every 10 sec nominally, the receiver is reconfigured for the L_2-P signals. This changeover has been examined and it has been found that a new frequency/phase search will not be necessary, and that the tracking loops will quickly overcome the switching transient. The pseudorange at L_2 can then be measured and sent to the computer. In the computer, these measurements are processed, and a very accurate ionospheric correction factor is found, which is then applied to all subsequent L_1-P pseudorange measurements. The correction factor is, generally, updated every 10 sec.

The computer also keeps watch on the data messages. When it is seen that a new message is being transmitted (this happens every hour), the routine configuration to L_2 will be inhibited, so that the entire new message (which is carried on L_1), can be uninterruptedly acquired.

The computer also keeps watch on the values of the constellation selection parameters (elevation angle, GDOP, etc.). Based on this, it will, when necessary, command a channel to cease tracking its satellite and instead search for and acquire a replacement satellite. This process does, of course, cause some degradation in the navigation output accuracy (which is then based on measurements to only three satellites). The time for constellation revision (TCR) is not so excessive that the degradation becomes significant.

Finally, the computer is also keeping watch on the tracking loop lock status flags. Should a channel lose lock, it will, under computer control, first try to reacquire the signal by means of a small phase/frequency search in the P-domain. Should this not be successful within a specific time, then the computer will command a reacquisition using the C-signal.

As may be seen from the above, all the receiver/computer operations are automatic. The operator is needed only for control of the display unit, so that he may select the form of presentation of the navigation data, without concern of how they are generated.

2.4.3 Z-receiver operations..-This user group consists of a GPS receiver only, without auxiliary navigation sensors. Further the receiver is a low cost, 2 channel* sequential tracker, using the L_1-C signal only.

The search and acquisition of the L_1-C signals is performed automatically, and similarly to that described in the previous section. The difference is that one of the two receiver channels (Channel A), is timeshared among the four satellites but performs this search in an uninterrupted manner. As each signal is acquired, in Channel A, then Channel B is prepositioned to it, and this channel then sequentially tracks the signal. Channel A then starts searching for the next signal. When all four signals have been found by A, and hence are being sequentially tracked by B, then A is used for data collection. It is prepositioned to each signal by B, and then tracks it, continuously, until it has acquired all the navigation data. While this is going on, Channel B is sequentially tracking all four signals, and making the pseudorange and pseudorange rate measurements.

*This point has been observed to differ with alternate designs.

CHAPTER 3

GPS ECONOMICS

This section discusses economic considerations associated with GPS for the general aviation community. Included are estimated costs for candidate avionics suites for small aircraft together with cost savings potential through GPS replacement of conventional navigation functions. Also included are comments relating to the ultimate cost of a general aviation GPS capability. Included in the latter category is an address to the alternative of GPS acquisition as a spin-off from military development as opposed to direct development for general and/or commercial aviation.

3.1 Cost of Conventional Avionics Suite

In order to place the GPS concept before the general aviation user, it is appropriate to relate it to presently available navigation equipments. This relationship, in order to be meaningful, should include performance, cost and capability. This section presents representative cost information regarding currently available avionics complements. This information was extracted from the 1976 Edition of Flying—Annual and Buyers Guide (ref. 11).

The baseline aircraft considered for the general aviation community was the Cessna 172. Also considered as a bound on the top-of-the-line was the Cessna 404. The Cessna 172 was assigned an avionics complement which would produce cross-country IFR capability. This defined a modest avionics suite which included: dual navcomm, ADF, transponder, glide slope, marker beacon, and occasionally a DME. Also included in the cost estimate were a digital encoder for the altimeter and an audio panel. A minimum IFR system targeted to cost $5,000 was also defined and essentially deleted the occasional DME, the glide slope, and the ADF. A well equipped system targeted to cost $15,000 and presupposed for the Cessna 404 was defined and consisted of the basic cross-country system plus full DME, HSI, and RNAV. An attempt was made to indicate the cost of systems available and to place proper relation on cost of equipment as a function of suite capability. For the basic cross-country system, NARCO was selected as a median system with the Collins Micro-line above it and King below. The transition to the minimum system was accompanied with the substitution of Genave for King. For the well equipped system the Collins Micro-line represented the median system, the NARCO the lower cost system, and the high cost system represented by more expensive Collins equipment. The comparative system cost is shown in Table 3-5 below and breakdowns by equipment are shown for each of the three performance categories in Tables 3-2 through 3-4. In the latter three tables the more expensive Collins equipment was also shown to indicate the total range of price available to the general aviation user independently of suite capability.

Table 3-5 below presents information extracted from Table 4-1 and serves to indicate representative cost of a GPS receiver implemented system. It will be demonstrated in Section 4.1 that the GPS implementation produces additional capability, performance, and potentially reduced cost.

Table 3-5. Comparative Conventional and GPS Costs

	Conventional	GPS
Low Cost Suite	5,280 (NARCO)	GPS + 3,435
Cross-Country IFR	7,975 (NARCO)	GPS + 3,435
Well Equipped	15,875 (MICRO LINE)	GPS + 6,120

(Cost information obtained from ref. 11.)

Table 3-1. Summary Avionics Costs

System	High	Medium-High	Medium-Low	Low
Minimum (5K target)	---	Microline $7,000	NARCO $5,280	GENAVE $3,950
Basic (Cross-country IFR)	---	Microline $9,260 + $2,730(DME)	NARCO $7,975 + $2,730(DME)	KING $7,315 + $1,995(DME)
Well Equipped (15K target)	Collins $45,235	Microline $15,875	NARCO $14,420	---

(Cost information obtained from ref. 11.)

CESSNA 172 CANDIDATE AVIONICS SUITE(S)

Table 3-2. Minimum System - $5,000 (Minimum IFR)

EQUIPMENT	COLLINS (TSO'D) $	COLLINS L. COST ALT. $	NARCO $	GENAVE $
COMM 1	3480 (20A)	1280 (VHF 251)	960 (COM 11A)	1400 (ALPHA/500)
NAV 1	5510 (VIR 30)	1295 (VIR 351)	1020 (NAV 11)	
COMM 2	3480 (20A)	1280 (VHF 251)	960 (COM 10A)	800 (ALPHA/200)
NAV 2	5510 (VIR 30)	1295 (VIR 351)	550 (NAV 10)	
DIG. ENCODER (ALT)	2000 (BENDIX)	695 (NARCO AR 500)	695 (AR 500)	695 (NARCO AR 500)
TRANSPONDER	2230 (TDR 90)	670 (TDR 950)	595 (AT 50A)	595 (BETA/5000)
GLIDE SLOPE	(IN VIR 30)	--	--	--
MARKER BEACON	(IN AMR 350)	(IN AMR 350)	275 (MBT-R-LL)	160 (DELTA/303)
AUDIO PANEL	505 (AMR 350)	505 (AMR 350)	225 (CP 125)	300 (TAV/200)
TOTAL	$22,715	$7,020	$5,280	$3,950

(Cost information obtained from ref. 11.)

CESSNA 172 CANDIDATE AVIONICS SUITE(S)

Table 3-3. Recommended (LRC) Cross-Country (Basic IFR)

EQUIPMENT	COLLINS (TSO'D) $	COLLINS (L. COST ALT.) $	NARCO $	KING $
COMM 1	3480 (20A)	1280 (VHF 251)	960 (COM 11A)	
NAV1	5510 (VIR 30)	1295 (VIR 351)	1175 (NAV 12)	3300 (KX 175B)
COMM 2	3480 (20A)	1280 (VHF 251)	960 (COM 11A)	
NAV 2	5510 (VIR 30)	1295 (VIR 351)	1020 (NAV 11)	
ADF	4704 (DF 206)	1520 (ADF 650)	1495 (ADF 140)	1450 (KR 85)
DIG. ENCODER (ALT)	2000 (BENDIX)	695 (NARCO AR 500)	695 (AR 500)	695 (NARCO AR 500)
TRANSPONDER	2230 (TDR 90)	670 (TDR 950)	595 (AT 50A)	650 (KT 76)
GLIDE SLOPE	(IN VIR 30)	720 (GLS 350)	575 (UGR-3)	695 (KN 73)
MARKER BEACON	(IN AMR 350)	(IN AMR 350)	275 (MBT-R-LL)	215 (KR 21)
DME	(6655)(DME 40)	(2730)(NARCO DME 190)	(2730) (DME 190)	(1995)(KN 61)
AUDIO PANEL	505 (AMR 350)	505 (AMR 500)	225 (CP 125)	310 (KA 37)
TOTAL	$27,419*	$9,260*	$7,975*	$7,315*

*Does not include DME

(Cost information obtained from ref. 11.)

CESSNA 172 CANDIDATE AVIONICS SUITE(S)

Table 3-4. Well Equipped System - $15,000 (Adv'd IFR/RNAV Non Tso'd)

EQUIPMENT	COLLINS (TSO'D) $	COLLINS (L. COST ALT.) $	NARCO $
COMM 1	3480 (20A)	1280 (VHF 251)	1050 (COM 11B)
NAV 1	5510 (VIR 30)	1295 (VIR 351)	825 (NAV 14)
COMM 2	3480 (20A)	1280 (VHF 251)	1050 (COM 11B)
NAV 2	5510 (VIR 30)	1295 (VIR 351)	1020 (NAV 11)
ADF	4704 (DF 206)	1520 (ADF 650)	1495 (ADF 140)
DIG. ENCODER (ALT)	2000 (BENDIX)	695 (NARCO AR 500)	695 (AR 500)
TRANSPONDER	2230 (TDR 90)	670 (TDR 950)	595 (AT 50A)
GLIDE SLOPE	(IN VIR 30)	720 (GLS 350)	575 (UGR-3)
MARKER BEACON	(IN AMR 350)	(IN AMR 350)	275 (MBT-R-LL)
DME	6655 (DME 40)	2730 (DME 190)	2730 (DME 190)
HSI	3188 (331A-36)	1690 (DGO 9A)	1690 (DGO 9A)
RNAV	7973 (ANS 31)	2195 (RNAV H51)	2195 (RNAV H51)
AUDIO PANEL	505 (AMR 350)	505 (AMR 500)	225 (CP 125)
TOTAL	$45,235	$15,875	$14,420

(Cost information obtained from ref. 11.)

3.2 Cost of GPS for General Aviation

During this study, attention was directed to the cost impact of presenting GPS capability before the general aviation user. It was quickly ascertained that at this point the only realistic cost which can be addressed is cost-of-acquisition as opposed to life cycle costs. This is due to the uncertainties related to the actual performance, system architecture, and predicted production involved in total non-military application of GPS. Even in dealing with cost-of-acquisition uncertainties arise as to what real costs exhibit themselves to be when installation is considered. In the face of this uncertainty, it is nonetheless useful to state some representative cost figures and to consider some of the mechanisms which may affect them.

3.2.1 Estimated receiver cost.—The military low-cost receiver is currently predicted to have an approximate off-the-shelf cost of about $15K (ref. 10). This does not include installation and check-out. With technology developments and in-production (commercial volume) quantities, (i.e., on the order of 10,000 units or more) it is anticipated that this can be reduced to something on the order of $5K. This is the Z-prime or Spartan set and is predicated on using a single channel (C/A)-single frequency (L_1) and results in an accuracy penalty. The set is predicted to provide maximum errors on the order of a few hundred meters. Verbal communications with several contractors project the ultimate Spartan receiver to attain price levels on the order of $1500-$2000. (The Rockwell version introduces a totally new receiver concept and is also said to be able to attain a purchase price of about $1500.)

3.2.2 Independent General Aviation Development. —At this point it is interesting to perhaps consider an extension of the (Rockwell) redesign approach which would include an entire satellite navigation system instead of just the user equipment. Since general aviation is usually interested in navigation over the continental United States and adjacent waters and since a navigation signal structure not predicated on a requirement to operate in a hostile electromagnetic environment, it is possible that a navigation system which addresses the civil community might be simplistic enough to substantially reduce the individual user equipment cost. This consideration takes the form of a recommendation for further study in section 6.0 of this report.

3.2.3 Learning Curve Considerations. — Projected costs for GPS user equipment are usually associated with some "learning curve" slope. This curve essentially relates the direct-labor hours required to perform a task to the number of times the task has been performed. It is appropriate then to briefly comment on the sensitivity of the cost of "n^{th}" item and average cost of "n" items with respect to learning curve slope. Under certain conditions cost can be seen to change by perhaps a factor of two with small change in learning curve slope. This is of course a function of total items produced as well as the value of slope itself. Appendix B provides a quantitative description of learning curve considerations.

CHAPTER 4

GPS SYSTEM IMPACT

This section describes the impact that the GPS concept may have on the general aviation user. A selection of candidate avionics suites are presented along with cost information. Those functions which can be achieved with a GPS receiver are identified and costs grouped to indicate the potential savings available. It is of interest to note the increased capability available to the lower-cost conventional avionic complement with the incorporation of GPS at no additional cost. Also included in this section is a preliminary comparison of conventional performance with projected GPS performance.

4.1 Avionics Complement That GPS Can Replace

As a baseline for examining possible GPS impact on avionics requirements, it is assumed that GPS will replace existing en route and area navigation capabilities. It is further assumed that a single GPS receiver will replace redundant conventional systems in that both continuous and sequential receivers can be allowed to gracefully degrade for a large set of malfunctions. The precise impact of this latter assumption needs be examined in further detail and well could be the theme of a future effort. No assumption regarding replacement of ground system equipment is included so as to address the general aviation community without being contingent on the evolution of the commercial fleet(s).

The equipments for a GPS equipped aircraft are shown in Table 4-1 for the three categories of avionics suites described in section 3.1. Cost incremental savings shown below are also applicable to that section. Note the increased capability available to the low cost system(s) with the implementation of GPS (indicated below with an "*").

Table 4-1. Comparison of Conventional and GPS Avionics Suites

	Low Cost (NARCO)		Cross-Country (NARCO)		Well Equipped (Microline)	
Function	Conventional	GPS Impl.	Conv.	GPS Impl.	Conv.	GPS Impl.
COMM 1	960	960	960	960	1280	1280
NAV 1	1020	GPS	1175	GPS	1295	GPS
COMM 2	960	960	960	960	1280	1280
NAV 2	550	GPS	1020	GPS	1295	GPS
ADF	None	GPS*	1495	GPS	1520	GPS
Encoder	695	695	695	695	695	695
Transponder	595	595	595	595	670	670
Glide Slope Beacon	None	GPS*	575	GPS	720	GPS
Marker	275	GPS	275	GPS	(In Audio Panel)	GPS
DME	None	GPS*	(Occasional)	GPS*	2730	GPS
HSI	None	None	None	None	1690	1690
RNAV	None	GPS*	None	GPS*	2195	GPS
Audio Panel	225	225	225	225	505	505
Nominal Cost (Table 3-1)	$5,280	GPS Rcvr +$3,435	$7,975	GPS Rcvr +$3,435	$15,875	GPS Rcvr +$6,120

(Cost information obtained from ref. 11.)

4.2 Conventional System Accuracy vs GPS

Table 4-2 shows representative accuracies for conventional radio aids to navigation and direction-finding. Notice that among these, the more logical to potentially be replaced by adoption of GPS are ADF, VOR, and DME. Taking an optimistic view of conventional system performance and comparing GPS only to the conventional system instrument error (i.e., assuming that site errors can be compensated for over the long term), it becomes obvious that conventional systems can be assumed to have an error in bearing measurement of 1-2 degrees (approximately 3% of range). Figure 4-1 shows this error versus range for conventional systems, an equivalent error associated with inertial systems, and projected errors for GPS systems.

Notice that for en route navigation (i.e., range greater than about 20 km) that the Spartan receiver provides accuracy on the order of or surpassing conventional systems. Notice further that GPS Phase I and Spartan projected accuracies surpass that estimated for an inertial system and approach that required for area navigation. Also note that with ground augmentation (i.e., a surface located satellite transceiver) several significant error sources such as ionospheric delay and GDOP are reduced and thus afford substantial potential for an increase in achievable accuracy. The region shown in Figure 4-1 for accuracy with ground augmentation is based on a conservative 2:1 improvement (reasonable to achieve based on GDOP alone) and an ambitious 10:1 improvement (probably an upper limit based on maximum improvement for all possible error sources as well as multiple ground transceivers) over the DOD target of 9 meters. If in fact achievable, these accuracies are in the range of that required for precision approach and landing. The impact of the above statements is to demonstrate the potential increase in general scope of avionics functions which might be provided by GPS.

The GPS error has GDOP incorporated where the conventional systems do not and the figure is thus pessimistic with respect to GPS performance. The major portion of the data shown in the figure was extracted directly from the Rockwell briefing.

The implicit indication in Figure 4-1 that conventional systems are not continually or globablly operable is fallacious. It should however be obvious that conventional systems are ground station dependent, thus limited in achievable accuracy and geographical coverage by station location.

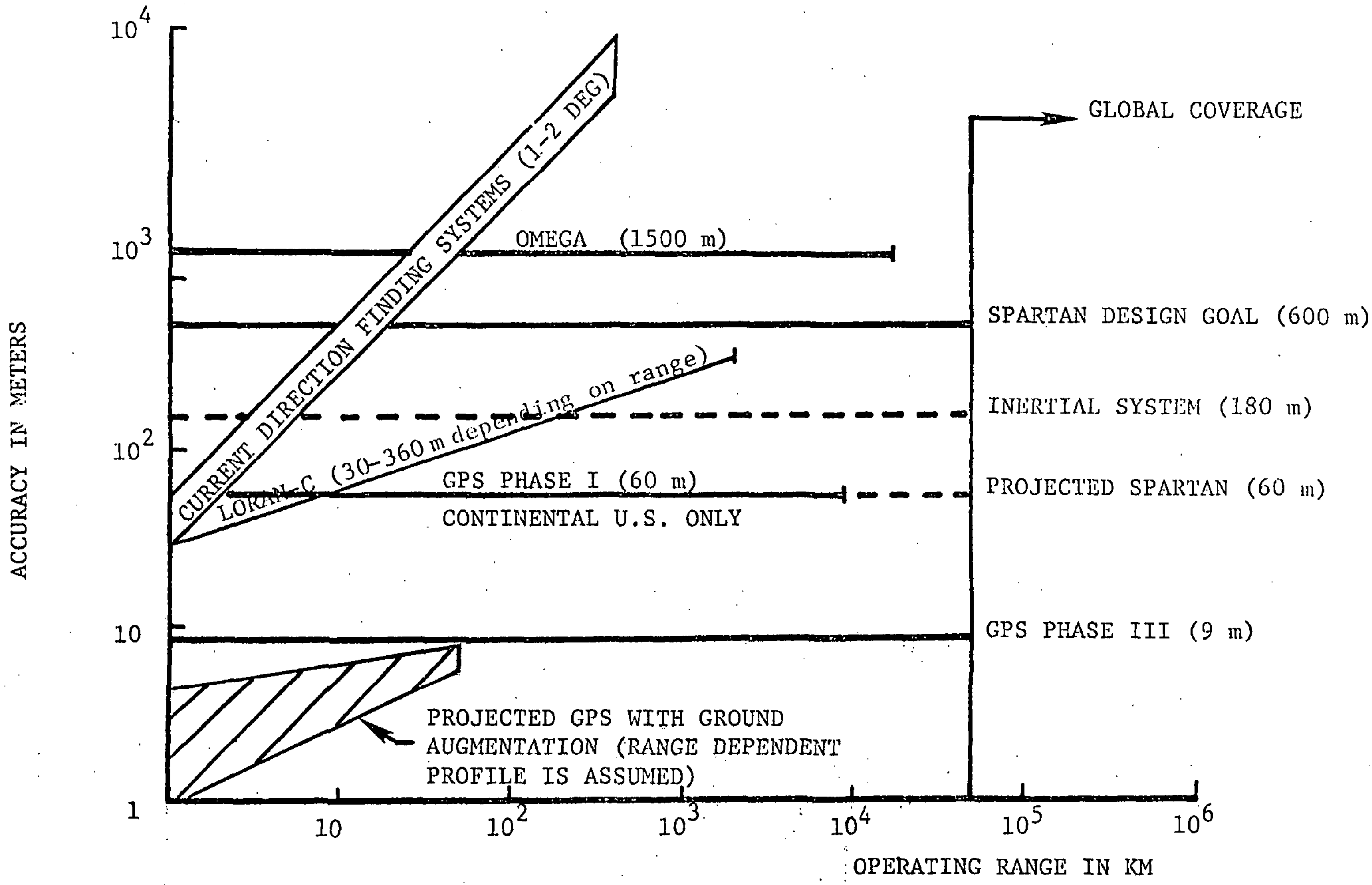


Figure 4-1. Comparison of Conventional System Accuracy with GPS (refs. 6 & 12)

Table 4-2. Range and Accuracy (ref. 12)

System	Range, Km	Error±degrees or±feet			
		Propagation	Site[a]	Instrument	Accepted System
Direction finding:					
Ground Based VHF/UHF	370[b]	Negligible	1°	1°	2°
Airborne MF	370	Up to 25°	5°	2°	Variable
Low-Frequency Range	370	Up to 25°	1°	2°	Variable
75-MHz marker	-	Negligible	None	90 m	90 m
VOR	370[b]	Negligible	3°	1°	3.5°
Doppler VOR	370[b]	Negligible	0.5°	1°	1.5°
Decca	370	Up to 3 Km	None	6 m	15 m to 3 Km[d]
Radar:					
Ground	370[b]	Negligible	None	1°/300 m	300 m
Secondary radar	370[b]	Negligible	None	3°/600 m	600 m
DME	370[b]	Negligible	None	60 m or 2%[e]	900 m
Tacan:					
Range	370[b]	Negligible	None	60 to 600 m	600 m
Bearing	370[b]	Negligible	2°	0.5°	2°
Loran-A	1,110	30 m	None	450 m	450 m
Loran-C	2,220	150 m	None	30 m	30 m to 360 m[d]
Omega	14,800	1,500 m	None	150 m	1,500 m

[a] Typical.

[b] Line of sight.

[c] Typical value. Depends on sensitivity adjustment.

[d] Depending on range.

[e] Depending on price.

[f] With correction for predictable variations. Otherwise up to 10 times this value.

CHAPTER 5

GPS POTENTIAL

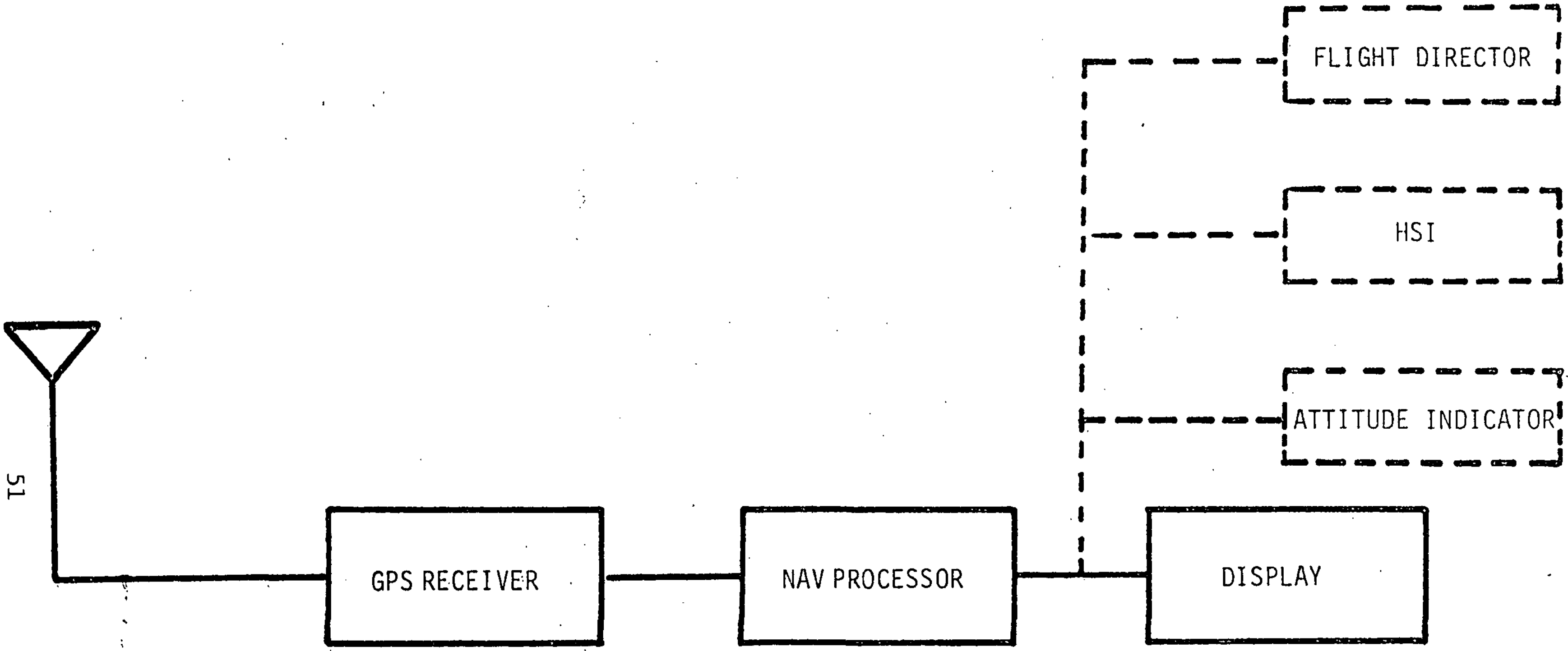
This section outlines some of the areas considered for GPS application in commercial and/or general aviation. Candidate areas include general purpose navigation, area navigation, landing, position reporting, and collision avoidance.

Figure 5-1 shows the concept of a general purpose navigator employing a GPS receiver. The system without the indicated options would require no receiver modifications while the options would introduce the requirement for interface and some additional software. The advantages of such a system would include worldwide operation and no requirement for the ground segment of conventional navigation systems. The basic navigator can be further extended to provide such features as "dynamic" airways allocation thus overcoming congestion which can arise with the present fixed route structure during heavy traffic periods or in adverse weather. Another possible extension would be the capability for overwater air traffic control to compensate for the loss in effectiveness due to the lack of ground positioning.

The GPS receiver/navigator can provide the present position solutions for use with appropriate displays, etc. to provide area navigation and (with additional software) landing functions. This capability is further enhanced if terminal areas are augmented with a surface located satellite transceiver.

A position reporting system is implementable by allowing a modified DABS to report three dimensional position instead of reporting altitude only and relying on ground tracking systems to provide x-y position data. This would relieve DABS of its precision tracking responsibility.

Several approaches are available for utilizing GPS in a collision-avoidance function. One such approach would be to assign each aircraft a time slot in a Time Division Multiple Access bus. Each aircraft would then insert his position and velocity in his time slot and monitor the bus for other aircraft in the immediate area. Another concept would make use of the accurate time reference achievable with GPS. Since all users can time synchronize within a few nanoseconds, each user could transmit a signal at a preselected epoch and monitor the transmission of other users to determine range and bearing (or some appropriate collision avoidance parameter).



DISPLAYED PARAMETERS
- PRESENT POSITION
- ALTITUDE
- VELOCITY
- COURSE TO STEER
- DISTANCE TO GO
- TIME

OPTIONS
- HSI
  - TRACK ANGLE ERROR
  - COMMAND COURSE
- ATTITUDE INDICATOR
  - PITCH AND ROLL STEERING
- FLIGHT DIRECTOR
  - CROSS TRACK DISTANCE
  - TRACK ANGLE ERROR
  - ALTITUDE ERROR

REQUIRED ADDITIONS TO BASIC GPS RECEIVER
- FOR SYSTEM WITH NO OPTIONS - NONE
- FOR SYSTEM WITH OPTIONS - INTERFACE CONVERTERS
  ADDITIONAL SOFTWARE

Figure 5-1. General Purpose Navigation (ref. 7)

CHAPTER 6

SUMMARY AND RECOMMENDATIONS

The Global Positioning System now under development by the Department of Defense shows conceptual promise of providing a sophisticated navigation capability to the general aviation community. The projected cost and capability of GPS for general aviation has been observed (in a very preliminary sense) to compare favorably with conventional avionic complements. The potential existing for the use of GPS in a terminal area and during landing with ground augmentation as well as innovative utilization of the GPS on-board computer indicates GPS may substantially increase capability beyond that currently provided by conventional systems both in precision and in functional scope.

As a primary study function, recommendations were formulated suggesting areas of future NASA GPS activities. These are included in the following paragraphs:

1. It is recommended that NASA-Langley procure a full up GPS, high dynamic user set of equipment to install in a Terminally Configured Vehicle (TCV) aircraft, or other dedicated smaller aircraft in order to test and evaluate all aspects of system performance as soon as the first six satellites appear in November 1977.

2. Procure and install transceivers at Wallops Island, Virginia and operate them in conjunction with the airborne GPS equipment in order to conduct landing experiments and make comparisons to Instrument Landing System (ILS) and Microwave Landing System (MLS) system performance.

3. It is recommended that an effort be undertaken as soon as possible to conceive and analyze a Continental Positioning System (CPS) for general aviation and compare it to GPS as far as costs, user costs, availability during emergency, etc. are concerned. The thought has occurred that the Air Force predecessor to GPS known as 621B consisted in part of a continental ground station and a geo-synchronous set of four satellites. It was further capable of accuracies similar to those claimed for GPS. A preliminary, cursory cost-performance analysis might show that a different

signal structure and frequency selection for a continental-limited positioning system could have dramatic effect on the costs to be incurred in equipping a 200,000 number user fleet of general aviation aircraft. A savings of only $1,000 per vehicle would probably pay for the whole system. Since the Air Force is global, and GA is almost all continent plus a thousand miles or so offshore, their requirements are quite different. GA can use the Air Force system, but it might well justify its own, particularly on a cost basis.

4. It is recommended that NASA establish a high level liaison with the DOD office of GPS to be sure all of NASA's requirements are represented in various sytem versions; and, in addition, NASA should collocate a significant engineer at the SAMSO project office in order to be intimately aware of all system details and changes on a current basis. These items appear to be essential if NASA intends to continue to participate in GPS and make major investments and conduct significant activities related to equipment development and standardization for the General Aviation Fleet.

5. The Air Force presentation at NASA Headquarters in April 1976 announced that they could not justify the development of a low cost GPS receiver suitable for transport or lower performance vehicles. Their population of these applications is less than 500 and does not justify the expense. However, NASA with a market of several hundred thousand potential users could very well justify a significant expenditure in this field. A well thought-out program could probably meet a receiver cost goal of $1,000-$2,000 for a single channel (Z set) suitable to replace VOR, DME, ADF, and perhaps, with aiding, ILS and MLS for GA. The potential savings in ground equipment and calibration alone achieved by using GPS is certainly beyond the development costs associated with receiver developments and are worth analyzing in detail in order to justify these development programs.

6. The space shuttle experiments requiring navigation for launch, orbit, de-orbit, approach and landing would require the full GPS and probably not a simplified continental system as proposed for GA. This application appears valid and further justifies the procurement of a

high dynamics user set. A separate planning activity task appears desirable to plan this mission oriented set of experiments in enough detail to cost and defend. Another related activity involves the use of GPS from the "back-side" as a navigation tool for Space-Tug flying out to geo-synchronous orbits to fix or replenish other satellites. This use still seems several years removed.

7. In order to achieve the cost reductions inherent in the learning curve of GPS receiver production, it appears essential that a modular approach be chosen that will allow the maximum commonality of modules between all of the users from Forest Rangers to Astronauts. For example, RF units, or clocks or decoders or microprocessors could be common to all applications and thereby less expensive. Special units could then be used as add-ons to customize designs, and make special utilizations possible. Also, modules could be examined for susceptibility to Built-in-Test self-contained on each module. At the present level of complexity of the Texas Instruments modules ($700 each) this idea might be better than equipment level BIT or Avionics System BIT. A study of this subject area is recommended.

8. Either GPS or CPS gives a vehicle a constantly updated description of its position state vector. This is certainly of use; but maximum utilization of the information would come from being able to transfer this information to other systems, vehicles and control agencies. For example, if two vehicles know where each other are very exactly, collision avoidance becomes a derived rather than a dedicated function and accomplish-able at very little expense. Furthermore, it becomes suitable for demonstration. Air Traffic Control would certainly benefit from data linked position reports, and at the forecasted accuracies of GPS, the need for and attendant expense of the ground radars now used is not as obviously necessary. Present programs of the DOD such as JTID's (Joint Tactical Information Distribution System) should be examined in detail as to suitability for this service. The completion of this development could be the starting point of a suitable but simplified version for GA. Such a planning activity is recommended.

APPENDICES

APPENDIX A

GPS SIGNAL STRUCTURE

The following discussion describes the GPS received signal structure. The mathematical description below was communicated to RTI personnel during the Texas Instruments briefing held at LRC on April 30, 1976. The detailed information regarding code generation was obtained as a rewrite of a portion of the Rockwell Space Vehicle/User Segment interface documentation (ref. 13).

A.1 L_1 Navigation Signal

The primary navigation signal at the L_1 frequency consists of the composite P and C/A signals in phase quadrature. These signals also carry digital navigation data required by the user. The P signal is a continuous-carrier biphase modulated by a 10.23 Mbps PRN ranging code. Each spacecraft radiates on the same frequency, but is uniquely designated by code-division-multiplexing techniques. System data is transmitted by Modulo-2 addition of a 50 bps digital stream with the ranging code prior to carrier modulation. As mentioned above, the C/A signal consists of a PRN/BPSK carrier with a chipping rate of 1023 Kbps. The navigation data is Modulo-2 added with the ranging code and is identical to that carried on the P signal.

A.2 L_2 Navigation Signal

The secondary navigation signal generation, modulation, and data of the L_2 navigation signal are identical to that of the L_1 P and C/A signals. Upon command either the P or C/A signal are transmitted, but not both.

A.3 Navigation Signal Structure

The P signal, P(t), is a continuous sinusoidal carrier, biphase modulated according to the Modulo-2 sum of a PN code, XP(t), and a synchronous data bit stream D(t). Figure A-1 depicts a block diagram of the combined P and C/A signal generation scheme.

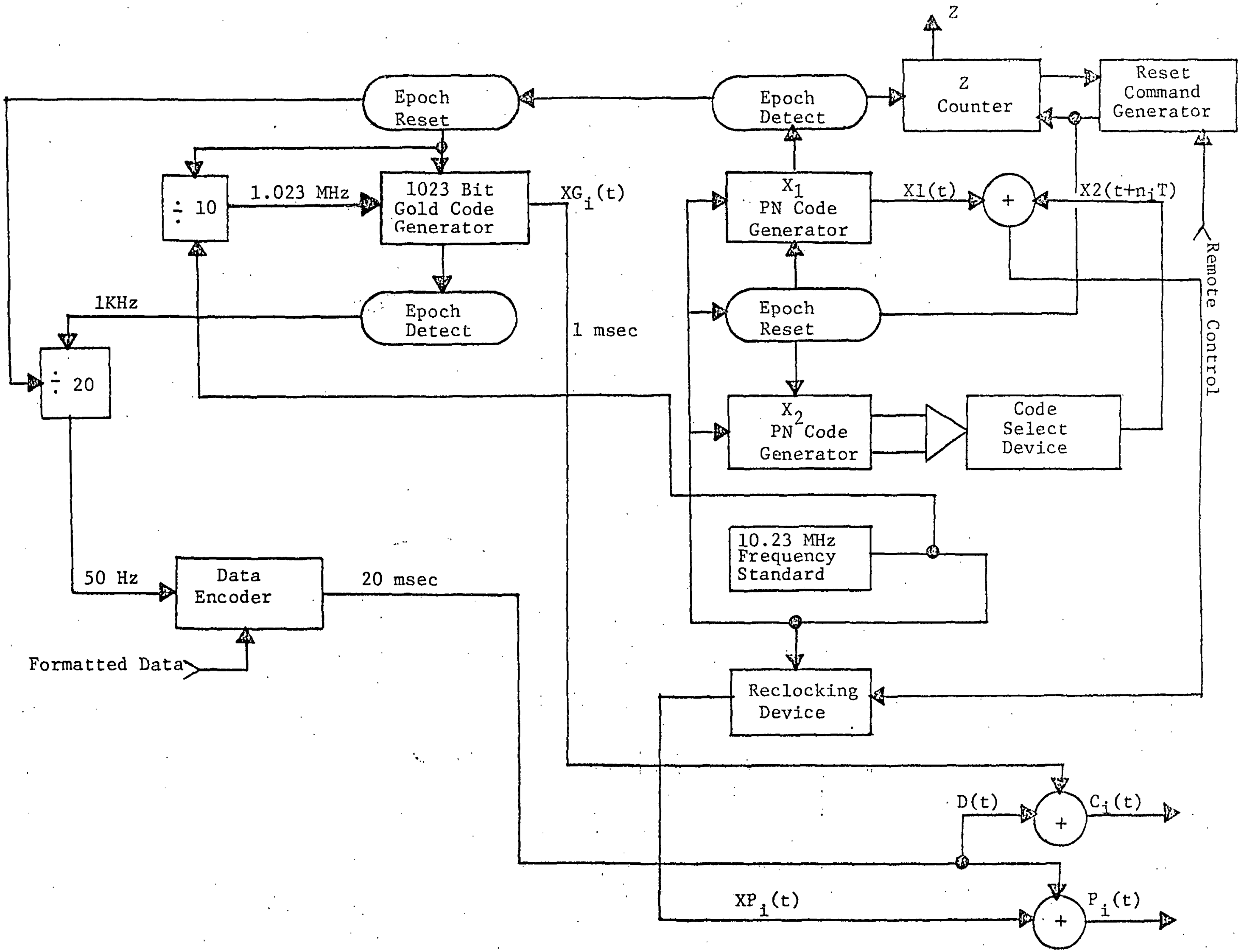


Figure A-1. Simplified Block Diagram of Combined P and C/A Signal Generator

Thus, the user equipment received signal may be written as

$$V(t)_{\substack{\text{received}\\ \text{on } L_1}} = A_1 \sin \{2\pi f_1 \left[1 + \frac{v}{c}\right] t + \pi \left[P(t) \oplus D(t)\right] + \phi_1\}$$

$$+ B_1 \cos \{2\pi f_1 \left[1 + \frac{v}{c}\right] t + \pi \left[C/A(t) \oplus D(t)\right] + \phi_1\}$$

and

$$V(t)_{\substack{\text{received}\\ \text{on } L_2}} = A_2 \sin \{2\pi f_2 \left[1 + \frac{v}{c}\right] t + \pi \left[P(t) \oplus D(t)\right] + \phi_2\}$$

$$\oplus B_2 \cos \{2\pi f_2 \left[1 + \frac{v}{c}\right] t + \pi \left[C/A(t) \oplus D(t)\right] + \phi_2\}$$

where, $V = \sqrt{A_i^2 + B_i^2}$, $i = 1, 2$, is the received carrier amplitude,

f_1 & f_2 are the transmitted carrier frequencies,

$\frac{v}{c}$ is the doppler shift,

$P(t)$ & $C/A(t)$ are appropriate PRN codes,

$D(t)$ is the data bit stream,

ϕ_1 & ϕ_2 are the telemetry link phase shifts,

and $\oplus$ denotes "exclusive or".

The protected code P(t) is generated by the Modulo-2 sum of 2-24 bit linear feedback shift registers clocked at $10.23(1 + \frac{v}{c})$ MHz generating a sequence $2^{48}-1$ bits long. (This is in apparent mild conflict with the information contained in the Rockwell Specification wherein the code is generated by the Modulo-2 sum of pairs of twelve bit registers as discussed in section A.4.)

The clear code C/A(t) is generated by the Modulo-2 sum of 2-10 bit linear feedback shift registers clocked at 1,023$(1 + \frac{v}{c})$ MHz generating a sequence $2^{10}-1$ bits long.

The chipping rate of XP(t) is 10.23 Mbps. $XP_i(t)$ is generated by the Modulo-2 sum of two PN codes, X1(t), and $X2(t + n_i T)$, where T equals the period of one P-code chip or $(1.023 \times 10^7)^{-1}$ sec. The same basic XP(t) code generator is used with each assigned one of the 32 possible XP(t) unique code phases for the SV's. Five additional code phases are reserved for other transmitters.

A.4 P-Code Generation (ref. 13)

The P channel has a chip rate of 10.23 Mbps. The P digital stream is the Modulo-2 sum of the data bit stream clocked at 50 bps, and two extended patterns clocked at 10.23 MHz (X1 and X2). X1 itself is generated by the Modulo-2 sum of the output of two 12-stage registers (X1A and X1B) short cycled to 4092 and 4093 chips respectively. When the X1A short cycles are counted to 3750, both the X1A and X2A are reset and the X1 epoch is generated. The X1 epoch occurs each 1.5 seconds, after 15,345,000 chips of the X1 pattern. The polynomials for X1A and X1B as referenced to the shift register input are:

$$\text{X1A:} \quad 1 + X^6 + X^8 + X^{11} + X^{12}$$

$$\text{X1B:} \quad 1 + X^1 + X^2 + X^5 + X^8 + X^9 + X^{10} + X^{11} + X^{12}$$

A sample of the relationship between shift register taps and the exponents of the corresponding polynomial referenced to the shift register input are shown in Figures A-2, A-3, A-4, and A-5.

Following the X1 epoch the first twelve chips of X1A contained in stages 1 through 12 (left to right) are 000100100100. The last three chips 001 of the 4095 sequence corresponding to this polynomial are omitted in shortening the sequence. The first twelve chips of X1B contained in stages 1 through 12 (left to right) are 001010101010. The last two chips of the 4095 sequence corresponding to this polynomial, 01, are omitted in shortening the sequence.

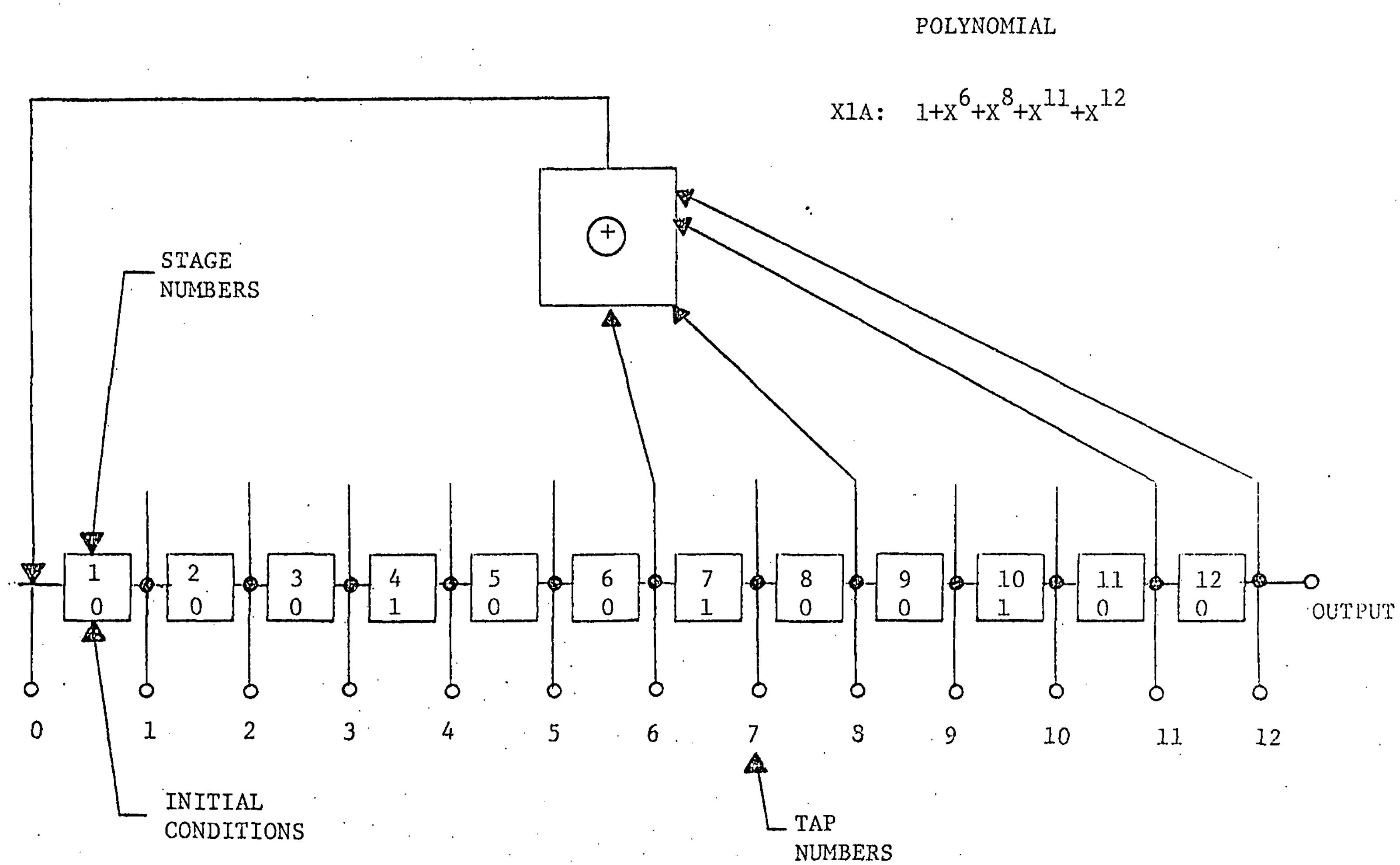


Figure A-2. X1A Shift Register Generator Configuration

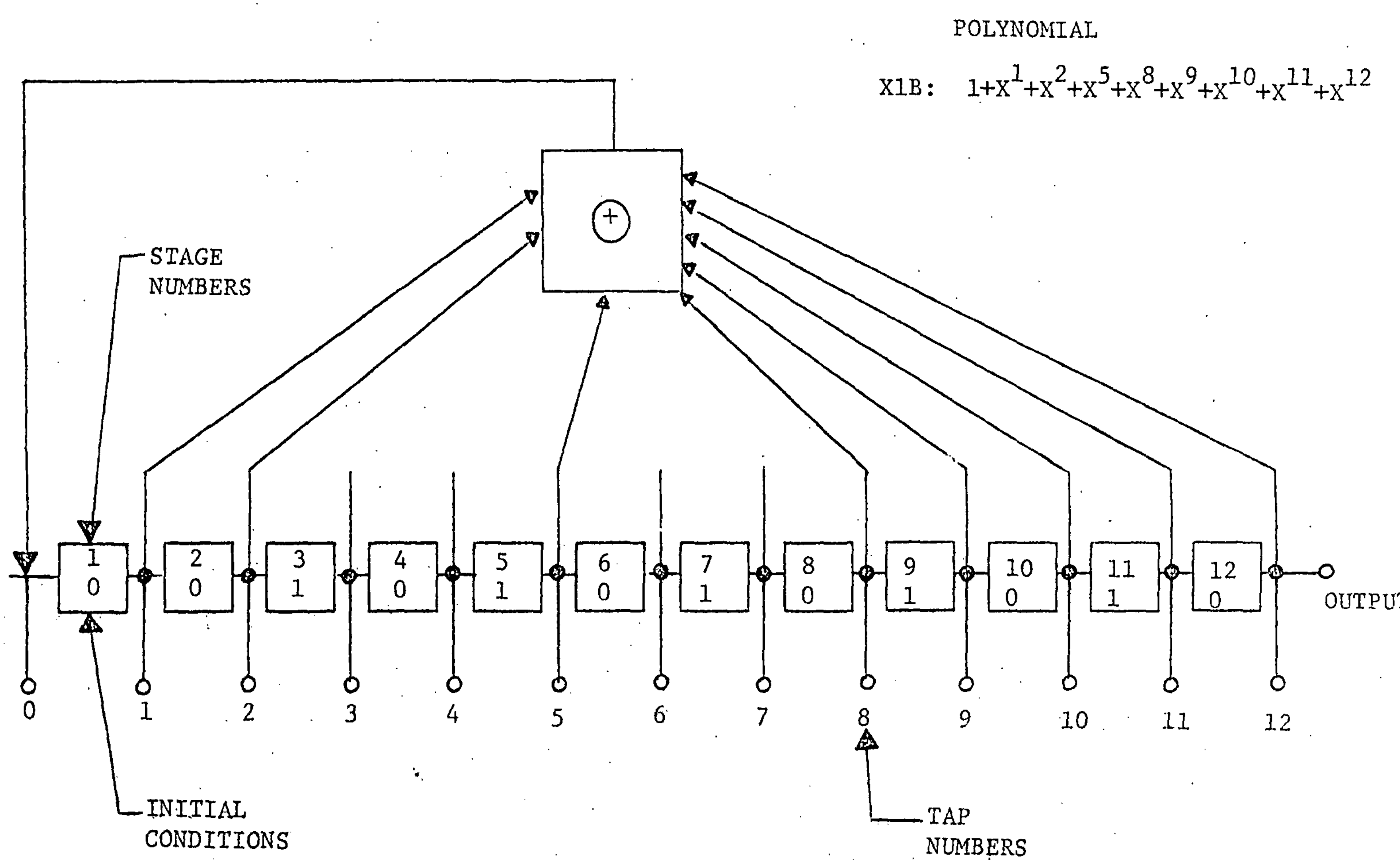


Figure A-3. X1B Shift Register Generator Configuration

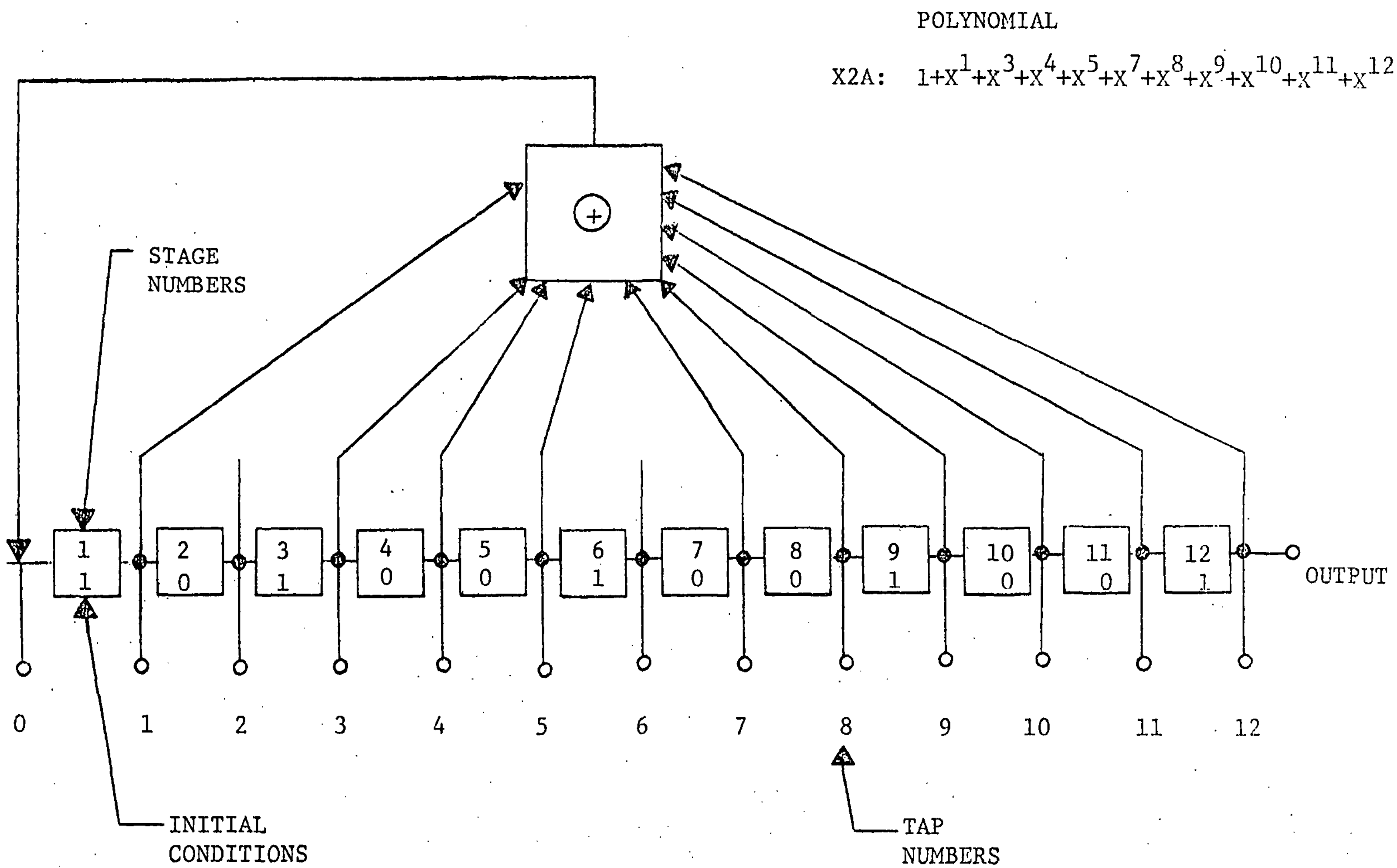


Figure A-4. X2A Shift Register Generator Configuration

POLYNOMIAL

X2B: $1+X^2+X^3+X^4+X^8+X^9+X^{12}$

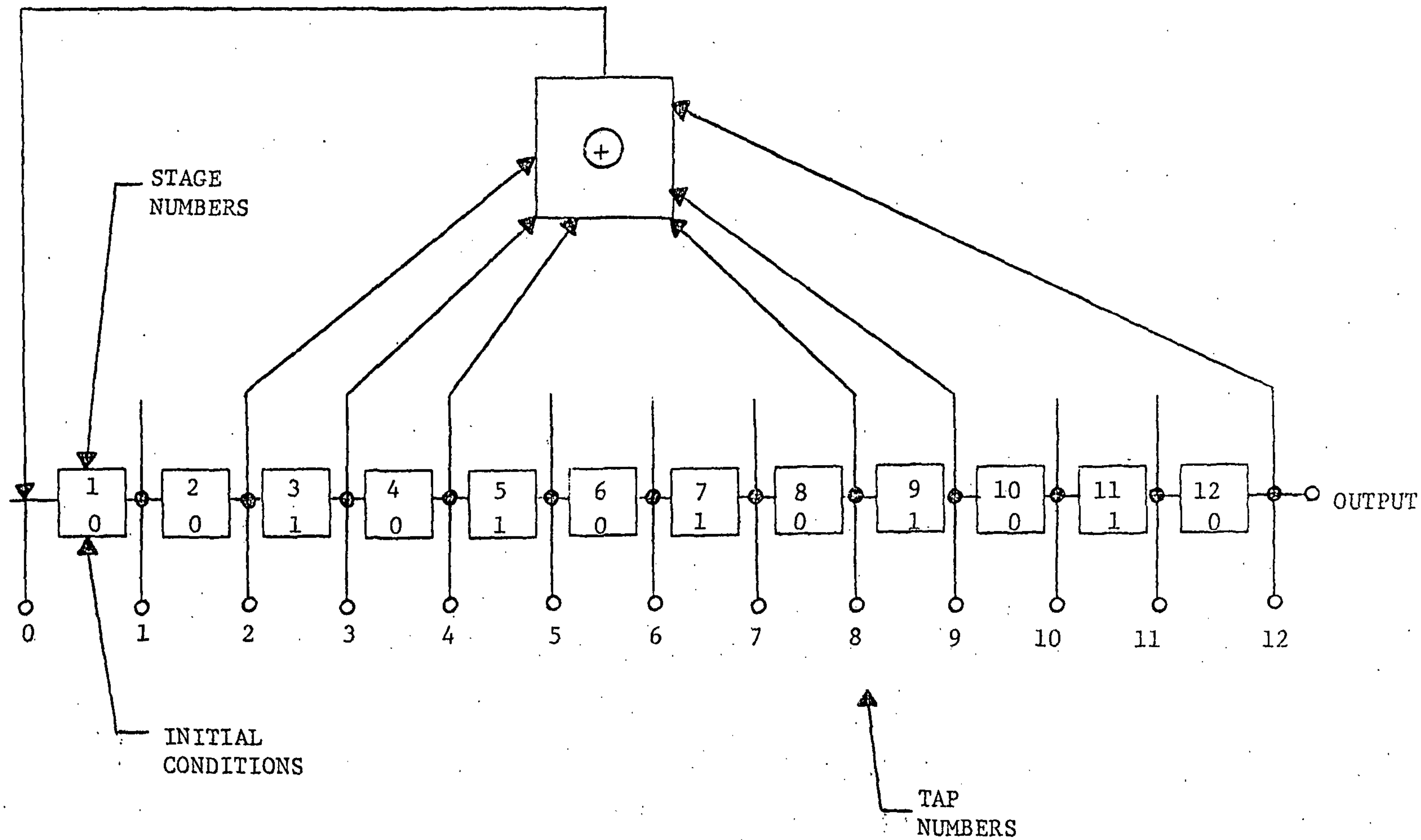


Figure A-5. X2B Shift Register Generator Configuration

At the occurence of each epoch, X1A and X1B each begin at the first chip of their respective sequences. Shortly before X1A completes the 3750th (last) cycle of each 1.5 second epoch interval, X1B completes its 3749th cycle. Thereupon, X1B is stopped, at the final chip of their respective sequences.

X2 is similarly generated by the Modulo-2 sum of the output of two 12-stage registers (X2A and X2B) short-cycled to 4092 chips and 4093 chips respectively. The polynomials for X2A and X2B as referenced to the shift register input are:

$$\text{X2A:}\quad 1 + X^1 + X^3 + X^4 + X^5 + X^7 + X^8 + X^9 + X^{10} + X^{11} + X^{12}$$

$$\text{X2B:}\quad 1 + X^2 + X^3 + X^4 + X^8 + X^9 + X^{12}$$

The first twelve chips of X2A in stages 1 through 12 (left to right) are 101001001001. The last three chips, 100, of the 4095 sequence corresponding to this polynomial, are omitted in shortening the sequence. The first twelve chips of X2B in stages 1 through 12 (left to right) are 001010101010. The last two chips of the 4095 sequence, 01, are omitted in shortening the sequence. At the beginning of each 1-week interval, all four 12-stage coders begin their sequences together. Thereafter, each time that X2A is in its 3750th cycle, when X2B completes its 3749th cycle, X2B is stopped until X2A completes its 3750th cycle. Then both X2A and X2B remain in their final state for 37 more of the 10.23 MHz pulses, and then both begin at the first chip of their respective sequences. The period of X2 is accordingly 15,345,037 chips. During the last cycle of X1A of a one-week interval, each of X1B, X2A and X2B are halted upon reaching the last chip of their respective sequences until X1A completes its cycle and all four registers begin their sequences together. The X2 sequence is delayed by a selected integer number of chips, i, ranging from 1 to 32 and then is added Modulo-2 to the X1 sequence to produce $XP_i(t)$. The spacecraft P-code mechanization is shown in Figure A-6. Signal component timing is shown in Figure A-7.

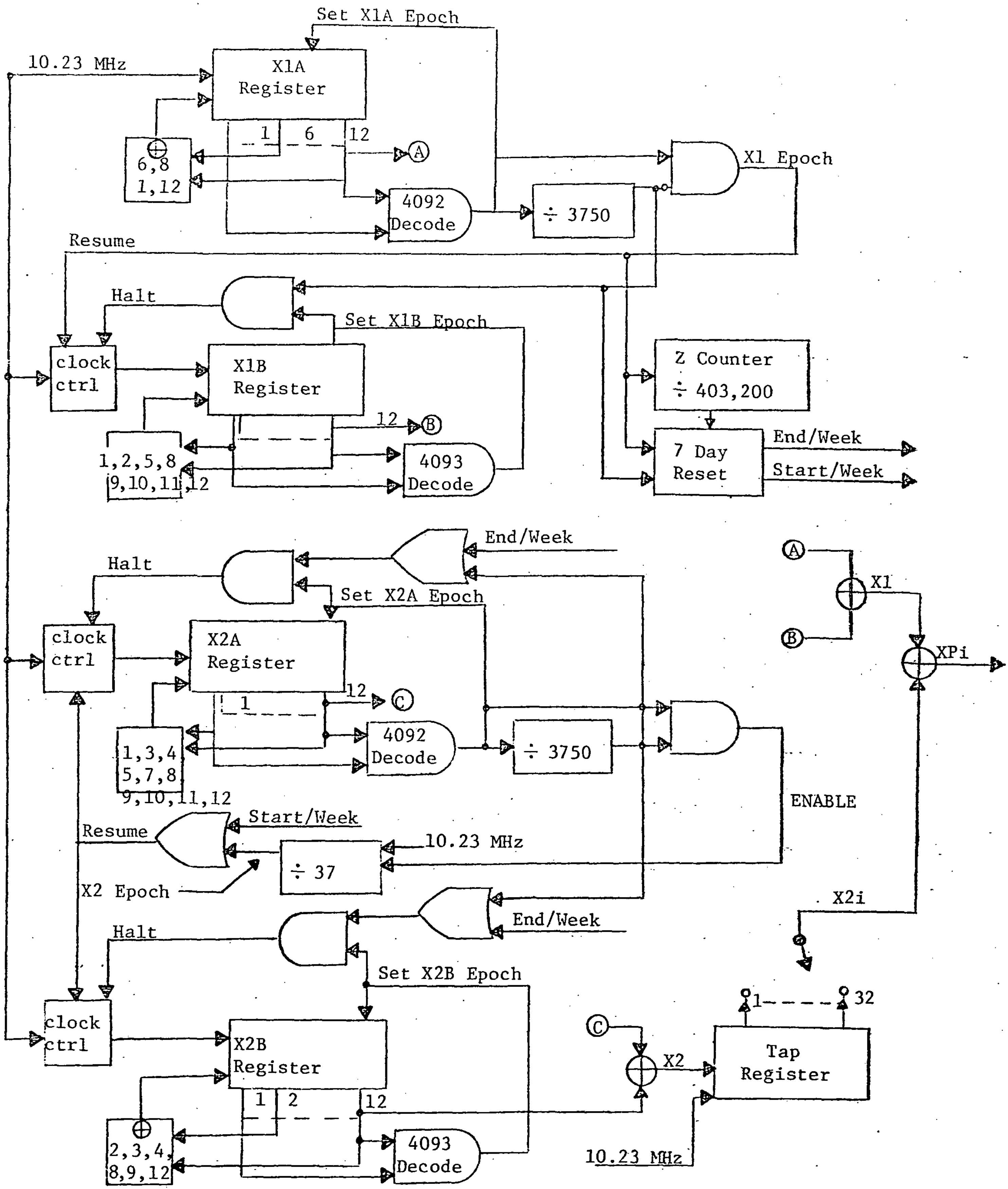


Figure A-6. P Code Generation

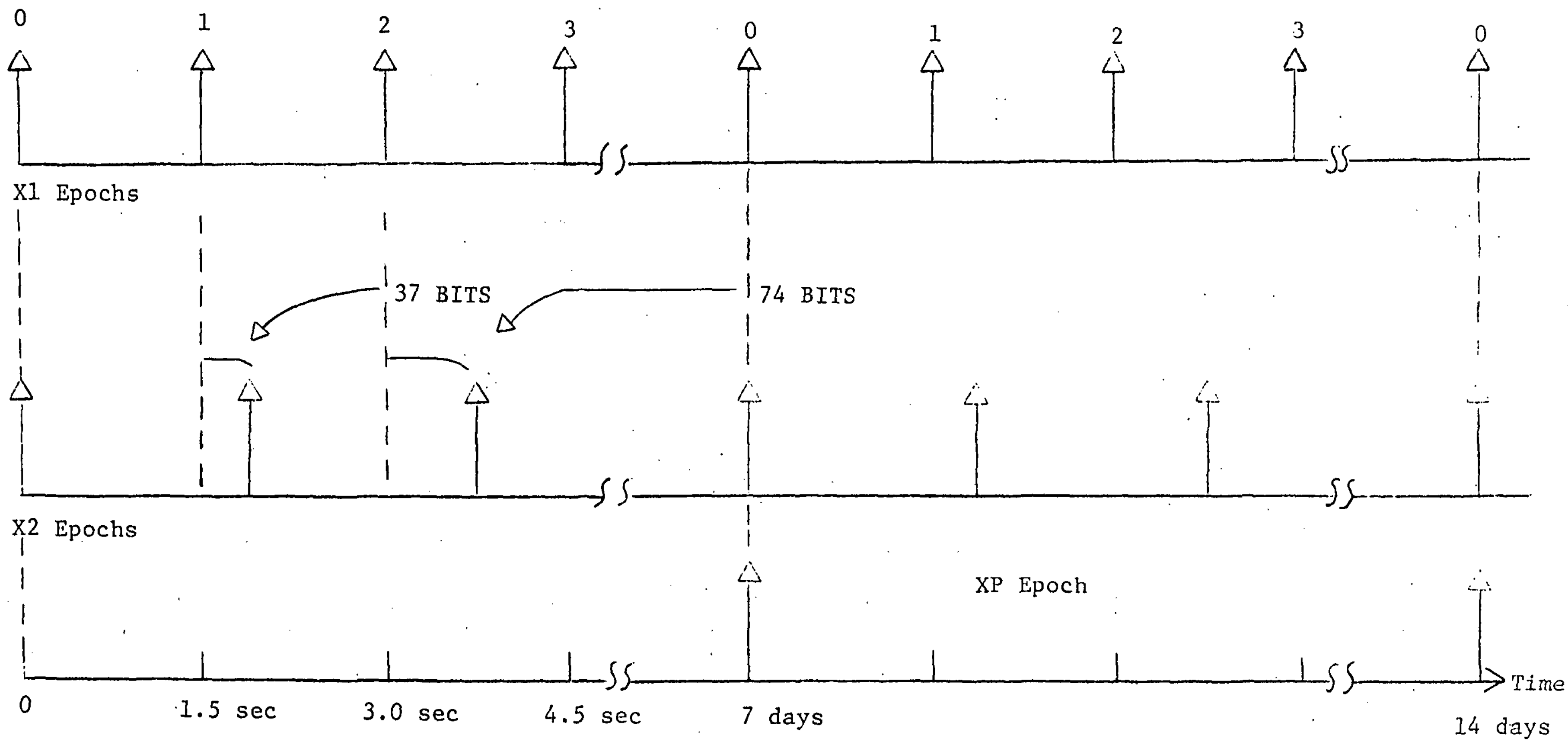


Figure A-7. P Signal Component Timing

2.5 C/A Code Generation (ref. 13)

The C/A channel has a chip rate of 1.023 Mbps. The C/A digital stream is the Modulo-2 sum of (1) the data bit stream of 50 bps (D), and (2) a 1023 bit linear pattern of 1.023 Mbps ($XG_i(t)$). Epochs of the G code and the transitions of D are aligned with the X1 epochs of the P code. The code is itself the Modulo-2 sum of two 1023 linear patterns G1 and $G2_i$ generated by 10 stage shift registers having the following polynomials as referenced to the shift register input (See Figures A-8 and A-9:

$$G1 = X^{10} + X^3 + 1$$

$$G2 = X^{10} + X^9 + X^8 + X^6 + X^3 + X^2 + X^1$$

$G2_i$ phases are chosen by the phase selector which is the Modulo-2 sum of the contents of a pair of stages. The C/A code mechanization is shown in Figure A-10. C/A signal timing is shown in Figure A-11.

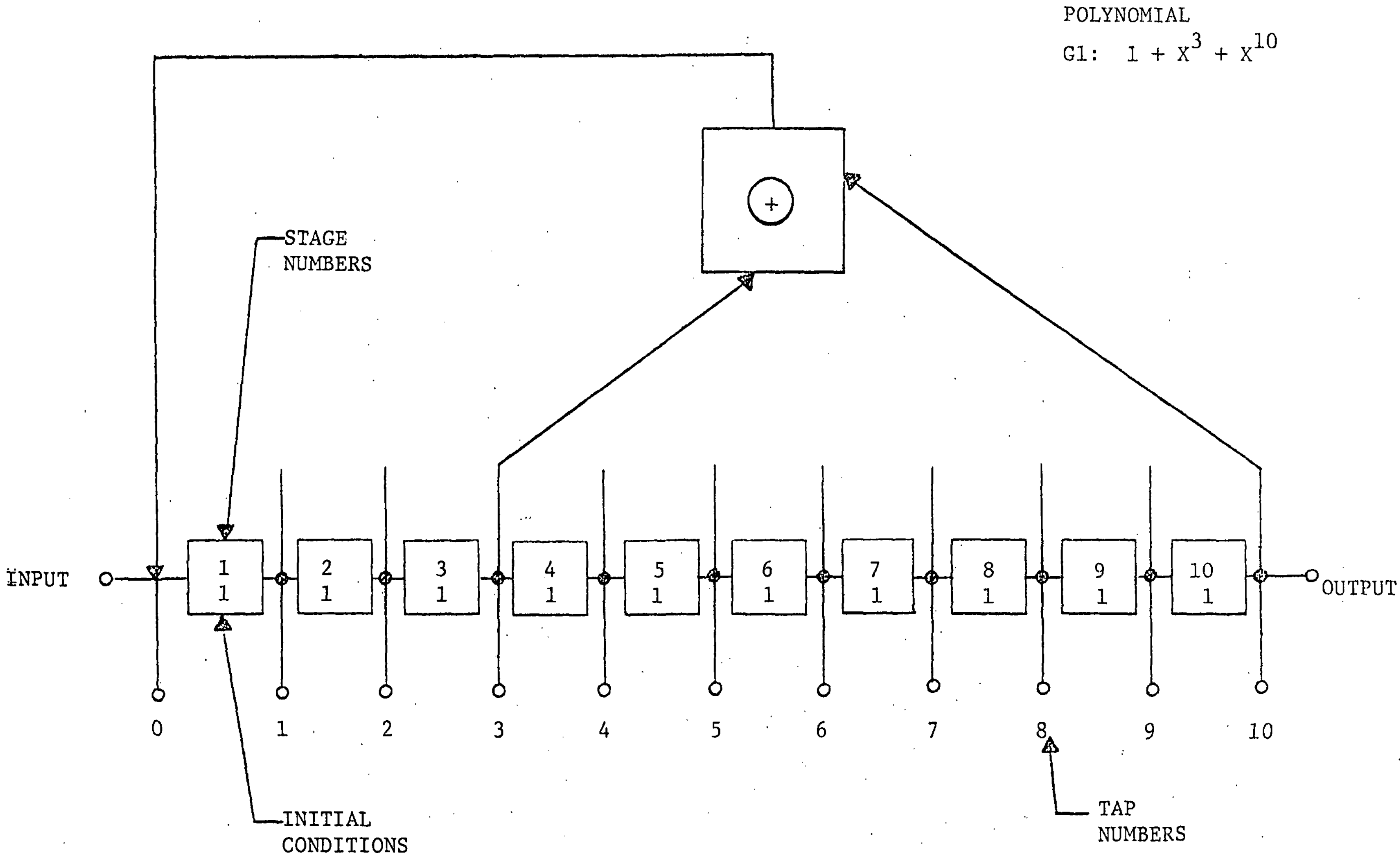


Figure A-8. G1 Shift Register Generator Configuration

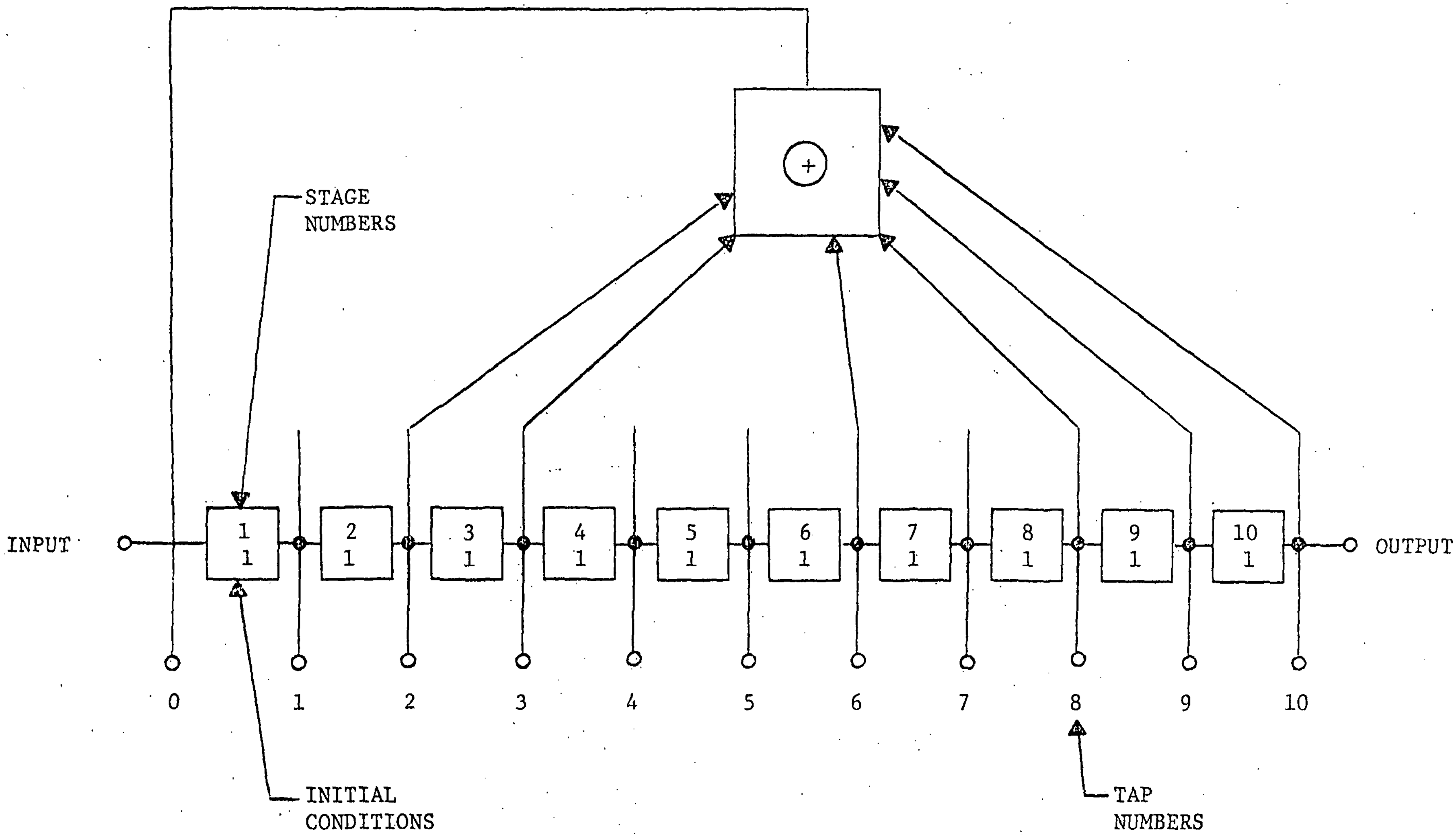


Figure A-9. G2 Shift Register Configuration

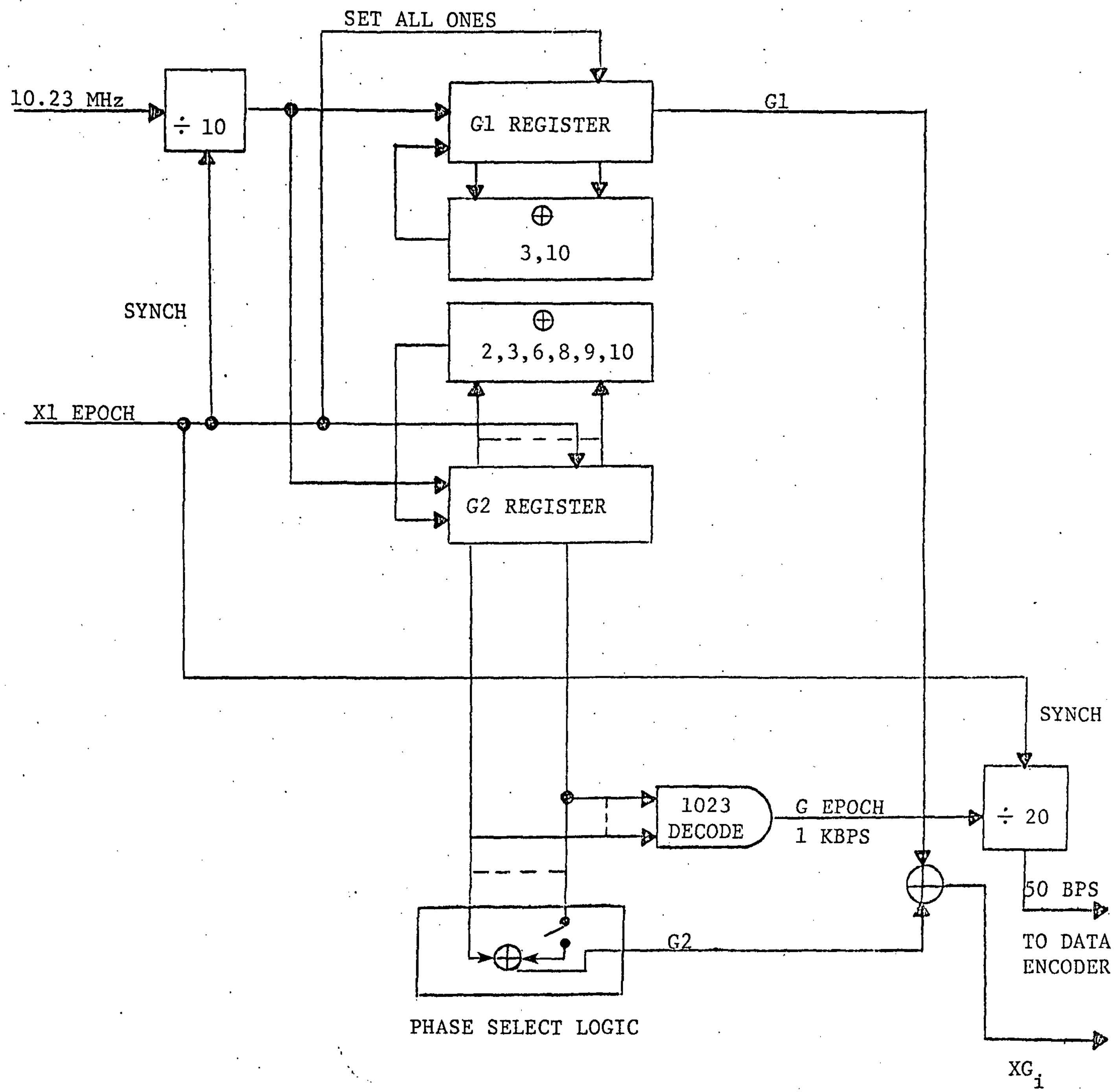


Figure A-10. C/A Code Generation

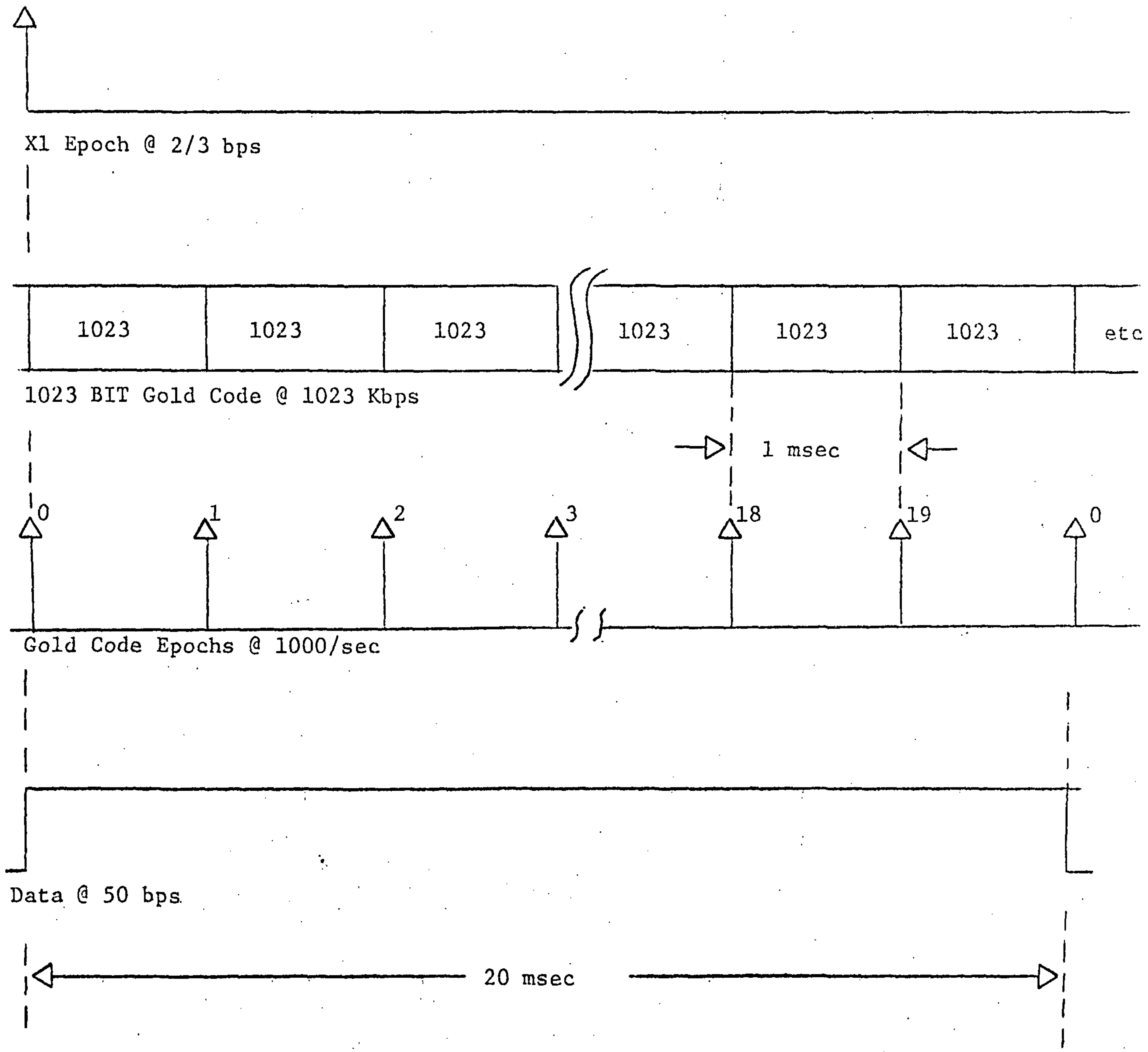


Figure A-11. C/A Signal and Data Component Timing

APPENDIX B

LEARNING CURVE CONSIDERATIONS

It has been well known among planning personnel and managers of product development that a requirement for anticipating effective and competitive price structure is the acquisition of a dominant market position. This allows taking advantage of the so-called "learning curve" which predicts relative price advantage as the production volume increases. In its most common form the learning curve relates the direct-labor hours required to perform a task to the number of times the task has been performed. For a wide variety of activities this relation has been found to be of such a form that the time (i.e., relative cost) decreases by a constant percentage whenever the number of trials is doubled. The cost of the j^{th} item can be expressed (relative to cost of the first item) as:

$$C_j = P^{\log_2 j}$$

where P is a parameter related to the slope of the curve, P taking on values between 0 and 1. P = 1 implies no learning in that the cost of any item is always equal to the cost of the first item. As P varies downward from 1, more and more learning is experienced and the per unit cost decreases more rapidly with the number of units.

It is an obvious extension to consider the average cost (again relative to the first unit cost) of a production of N units. This is given as

$$\bar{C}_N = \frac{1}{N} \sum_{j=1}^{N} P^{\log_2 j}$$

Both C_N, the cost of the N^{th} unit, and $\bar{C}_N$, the average cost over N units are shown in Table B-1 for various values of N. It should be remarked that the summation in $\bar{C}$ was calculated using a trapezoidal approximation of C_N vs N and is thus not accurate for small valves of N. The expected approximation error is on the order of 10% of the calculated value.

Table B-1. Cost Learning Curve Values

	P = 0.9		P = 0.85		P = 0.8	
N	C_N	$\bar{C}_N$	C_N	$\bar{C}_N$	C_N	$\bar{C}_N$
1	1	1	1	1	1	1
10	0.70	0.85	0.58	0.79	0.48	0.74
10^2	0.50	0.62	0.34	0.49	0.23	0.39
10^3	0.35	0.44	0.20	0.29	0.11	0.19
10^4	0.25	0.31	0.12	0.17	0.05	0.09
10^5	0.17	0.22	0.07	0.09	0.02	0.04
10^6	0.12	0.15	0.04	0.05	0.01	0.02

C_N = per unit cost of N^{th} item relative to cost of first item ($= p^{\log_2 N}$)

$\bar{C}_N$ = average cost of N items relative to cost of first items ($= \frac{1}{N}\sum_{j=1}^{N} p^{\log_2 j}$)

P = learning curve factor

Note: Calculation of $\bar{C}_N$ used trapezoidal approximation of C_N vs N & is not accurate for small N ($\varepsilon \approx 10\%$).

It then is possible to examine the sensitivity of various learning curve slopes on the projected cost of acquisition of a GPS receiver.

It can be observed that a change in slope from 0.85 to 0.8 can reduce the cost of the 10,000th unit from twelve percent of first unit cost to five percent of first unit cost. Further, the same change in slope can reduce the average cost of 10,000 units from seventeen percent of first unit cost to nine percent of first cost. The sensitivity to learning curve slope appears even more significant as the total number of production units is increased. For example, if the number of units is increased to 100,000, the average cost for a 0.85 slope can drop from twelve percent to seven percent of first unit cost, while for a 0.8 slope the average cost can drop from five percent to two percent of first unit cost. Knowledge of the appropriate learning curve slope is therefore critical in accurate cost forecasting.

While not considered as a part of this study, it should be remarked that various slopes are appropriate to various equipments dependent on redundancy, modularity, architecture, etc. In order to project cost-of-acquisition of a GPS receiver, it will be necessary to specify these criteria.

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