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SHUTTLE GLOBAL POSITIONING (GPS) SYSTEM DESIGN STUDY

FINAL REPORT

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Prepared for

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ACRONYMS

ADL	Advanced Development Laboratory, Rockwell
AGC	Automatic Gain Control
AJ	Antijam
BER	Bit Error Rate
BITE	Built-In Test Equipment
C&W	Caution & Warning
C&T	Communications & Tracking
ECLSS	Environmental Control and Life Support System
EIRP	Effective Isotropic Radiated Power
EMC	Electromagnetic Compatibility
ESTL	Electronics System Test Laboratory, JSC
FCC	Flight Control System
FSL	Flight System Laboratory, Rockwell
GDOP	Geometric Dilution of Precision
GN&C	Guidance, Navigation & Control
GPC	General-Purpose Computer
GPS	Global Positioning System
GSE	Ground Support Equipment
HPA	High-Power Amplifier
ICD	Interface Control Document
ID	Identification Number
IMU	Inertial Measurement Unit
JPO	Joint Program Office
LRU	Line Replaceable Unit
MCC	Mission Control Center
MCDU	Malfunction CRT Display Unit
MMU	Mass Memory Unit
MTU	Master Timing Unit
QAVT	Qualification Acceptance Vibration Test
SAIL	Systems Avionics Integration Laboratory, JSC
SRU	Shop Replaceable Unit
STS	Space Transportion System
SV	Space Vehicle
TPS	Thermal Protection System
TTFF	Time to First Fix
VSWR	Voltage Standing Wave Ratio

1.0 INTRODUCTION

This report documents the investigations made by Axiomatix of certain aspects and problems of the Shuttle/GPS navigation system. Much of Axiomatix's involvement in the Shuttle/GPS project during the last year was in support of the Shuttle/GPS panel meetings. Only part of Axiomatix's contributions to these meetings is suitable for formal documentation, as presented in this report.

One of the major tasks Axiomatix was responsible for during this phase of the contractual effort was development of a Shuttle/GPS test philosophy and test plan outline. This was accomplished and is documented in Section 2.0. The other major task was preparation of an Interface Control Document (ICD) between NASA and the GPS Joint Program Office (JPO). This ICD is to define those interfaces between the GPS and the Shuttle which are unique to the Shuttle. A first draft of this ICD is given in Section 6.0.

Development of a phase slope specification for the Shuttle GPS antenna, as presented in Section 4.0, is the result of a meeting with the Rockwell Autonetics System Engineering Office for the MMBRS program. They had found that phase modulation caused by vehicle maneuvers and antenna phase shift could potentially degrade system performance if not accounted for. The specification developed by Axiomatix, while not an antenna design driver, will ensure that such a problem does not occur with the Shuttle/GPS system.

An investigation of Shuttle/GPS jamming vulnerability, as documented in Section 5.0, was motivated by a question of the possible effectiveness of providing increased jamming protection in the GPS Receiver/Processor Assembly (R/PA). Our analysis demonstrates that it would not be effective, within the constraints of the present program, to provide for additional protection.

Finally, an expression for the GPS signal-to-noise density ratio, C/N_0, which accounts for the effect of the Shuttle Thermal Protection System (TSP) tiles is developed in Section 3.0.

2.0 SHUTTLE GPS TEST PHILOSOPHY

2.1 Introduction

The Global Positioning System (GPS) is a worldwide navigational system which provides the user with position and velocity data referenced to a Cartesian earth-centered, earth-fixed coordinate system. The GPS user equipment permits on-board, real-time computation of the user vehicle state vector with position estimated to within 30 ft, velocity to within 0.2 ft/s and time to within a fraction of a microsecond.

The user pseudorange and range rate are determined by measuring the navigation signal transmit time between a number of GPS satellites with precisely known ephemerides and the user and scaling the transmit times by the speed of light. The term pseudorange is used to denote that, since the user clock is not directly synchronized with the satellite clocks, the initial range measurements will be in error by the amount of user clock offset. Therefore, the user must acquire at least four satellites to determine the pseudorange of each satellite to obtain a user clock correction and thus calculate the user's true position coordinates.

When fully operational by 1986, the GPS will consist of a total of 24 active NAVSTAR satellites in three orbit planes of eight satellites, each offset from one another by 120° in longitude. Each satellite will transmit its precise ephemeris, clock correction data and an "almanac" of orbital parameters and clock correction estimates for all other system satellites. Each day, the ground control center will uplink ephemeris correction and other data to all satellites for subsequent user use, thus ensuring continued system accuracy.

While there will be many GPS users, this report discusses only the Space Transportation System (STS) or Space Shuttle. The purpose of this report is to outline an STS/GPS test philosophy and test plan for NASA. To be discussed is the overall test philosophy starting with the STS/GPS equipment components known as line replaceable units (LRU's), progressing through system integration, and finally ending with the orbital flight tests. The test plan will expand upon the test philosophy and outline the required tests for each phase. The main objective of the test philosophy and test plan is to ensure that the Shuttle GPS equipment is being properly tested, tested early enough in the program to discover and resolve potentially costly downstream problems and, at the same time, minimize the testing costs.

Before developing the overall test philosophy, a brief description of the STS/GPS equipment components or LRU's would be appropriate. Figure 1 shows the overall STS/GPS integrated baseline system block diagram consisting of three segments: the space segment, the orbiter system segment and the ground system segment. This report will concentrate on the Orbiter system segment and the LRU's composing the GPS set shown in Figure 1.

Figure 2 shows the baseline Orbiter system block diagram consisting of two separate channels which are switched to select four GPS satellites with a favorable geometry or minimum geometric dilution of precision (GDOP). The individual LRU's are listed as follows:

- Antenna assembly
- Receiver preamplifier assembly } Incorporation into one
- RF power dividers } LRU being considered
- Receiver/processor assembly (R/PA)

2.2 Test Philosophy

As previously stated, the test philosophy objective is to ensure that the STS/GPS navigation system is properly tested in an expeditious and cost-effective manner with a minimum of duplication. The testing will verify the system in a logical sequence and minimize overall costs by uncovering problems as early as possible in the program.

In the past, some very complicated engineering systems have been designed and manufactured with a minimum amount of attention directed towards compatible interfaces, subsystem testing, and assuring that subassemblies meet the required specifications. The philosophy in these instances has been to use system integration to discover problems. Of course, the users of this type of philosophy usually feel that anything more than minimal testing at the lower levels is a waste of time and money. At the same time, they feel very optimistic that the system will function properly once fully integrated.

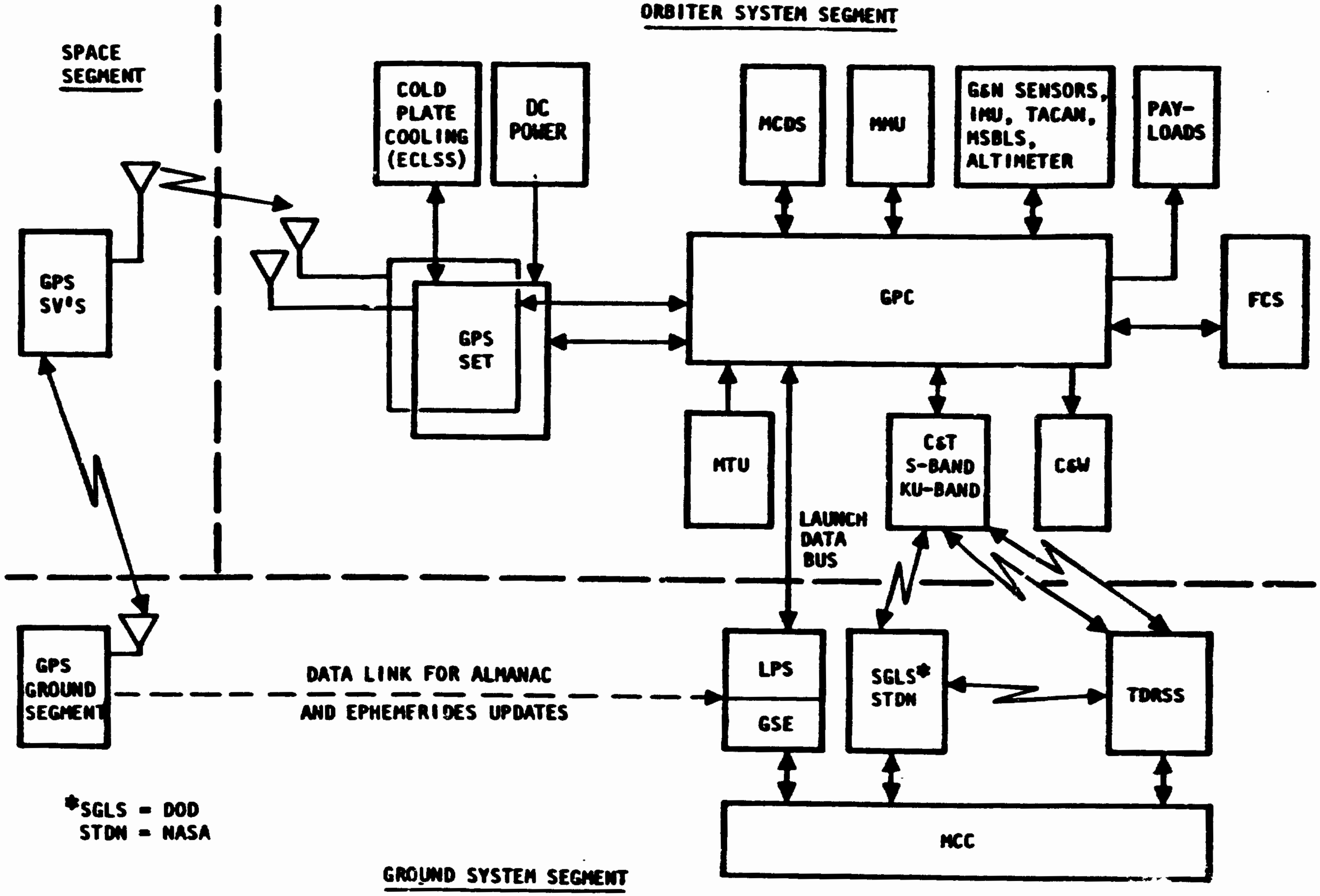


Figure 1. Integrated Baseline System Block Diagram

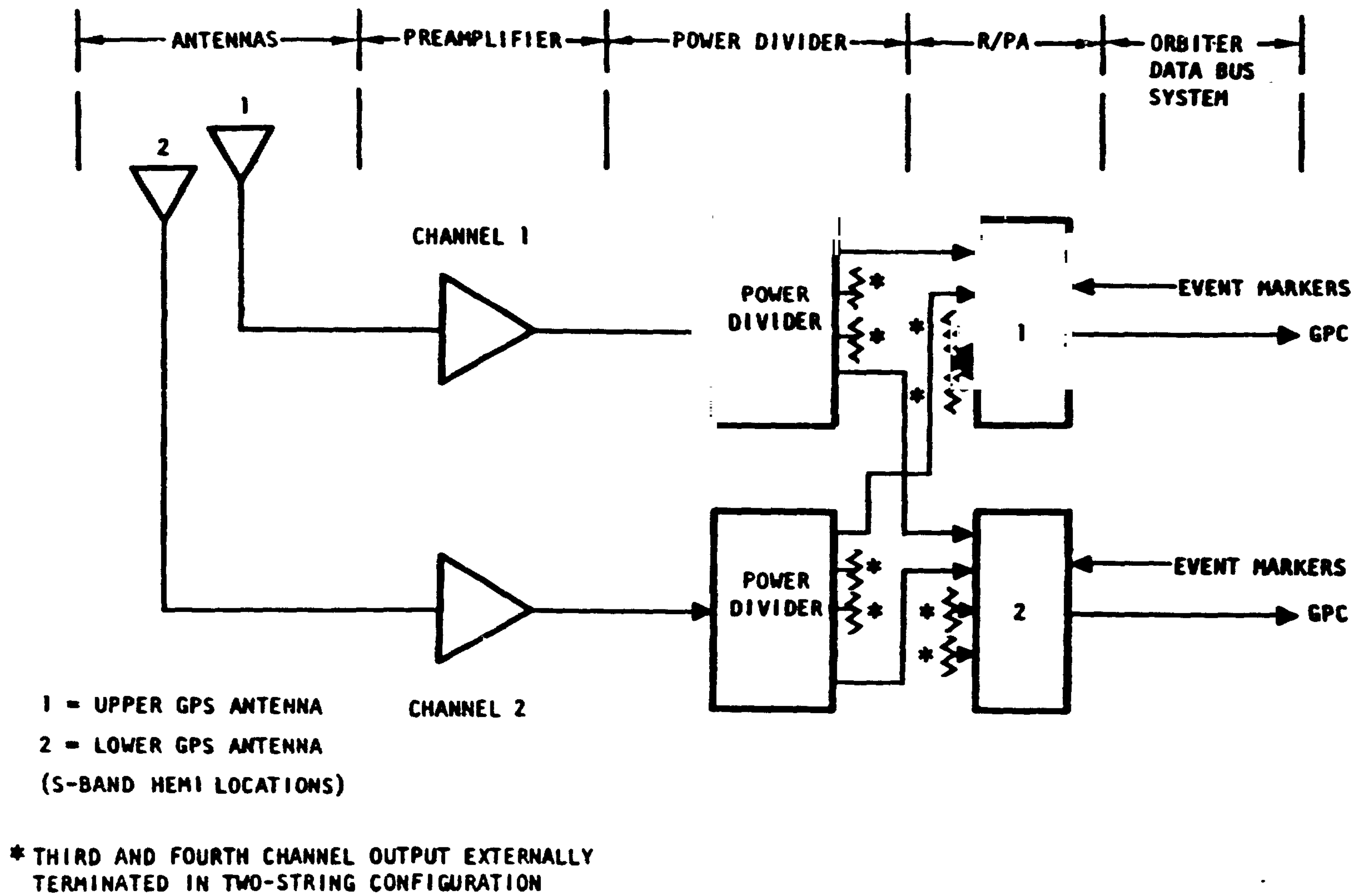


Figure 2. Base, ˈcer System Block Diagram

Unfortunately, when major problems are discovered at the system level, recuperation is extremely expensive and time-consuming. For example, in especially large programs, by the time the prototype or qualification LRU's are integrated into a system, there exists a large group of support personnel such as design engineers, systems engineers, test and documentation personnel, not to mention the purchasing of flight components and the early phases of flight unit manufacturing. Suppose that, upon integration, a major design problem develops. At this point in the life of the program it is too late to temporarily reassign some or all of the support personnel, so they must be sustained in order to be available for future use. The program now goes into the "panic" mode, which usually involves severe schedule disruptions, a penalty cancellation for some previously purchased components, purchasing new components on a premium and priority basis, overtime for some personnel, and paying other personnel who are no longer productive because they must wait for the problem to be solved. If the problems are severe enough, other systems or programs may also be impacted, causing even further delays.

Another situation will occur where the LRU's are rigorously tested individually, but the systems integration tests are either superficial or do not occur until after the flight units are being manufactured. Should the integrated LRU tests be superficial, a major problem is likely to occur during orbital flight tests. Should the integrated LRU tests be accomplished after flight units are being manufactured, the same "panic" mode consequences as previously described will occur.

The net result of the previous scenarios will be large cost overruns and long schedule delays. The purpose of the test philosophy to be developed in this report is to minimize the effects of the "panic" mode by successfully detecting and resolving problems at an early stage of the program.

One straightforward method would be to test all the assemblies, subassemblies and LRU's as early in the project as possible. This would allow the program to retain its flexibility in solving design problems without adversely affecting the overall schedule.

Even though detailed LRU testing minimizes system problems, assuming that the LRU's meet their respective specifications does not guarantee that the system will function when integrated, especially since the various LRU's are manufactured by different subcontractors. Therefore, the integrated system testing, like the LRU testing, must be accomplished early enough in the program and with adequate detail to uncover problems. Again, as with the LRU tests, the program has retained its flexibility to respond to unforeseen situations.

Because the Shuttle is such a complicated and large program, it is vulnerable to disruptions caused by significant problems detected at the LRU or systems level. With proper planning, however, potential problems can be anticipated. Figure 3 shows a typical STS/GPS design, development and testing sequence which embodies the elements of the early test philosophy. By using this sequence and the general philosophy already discussed, a comprehensive test philosophy and test plan may now be developed.

Figure 4 outlines the test sequence and test location required to verify the individual LRU performances, substantiate the interfaces and, finally, confirm the end-to-end performance. The logical LRU's to use in this test sequence would be the prototypes and qualification units as outlined in Figure 3. In the following section, each step indicated in Figure 4 will be discussed along with the rationale for recommending that particular test location.

2.3 LRU Test Philosophy

2.3.1 Tests Required

All SRU's (which are the modular components within the LRU's) and LRU's must be adequately tested by the subcontractor to ensure that the equipment delivered to the contractor meets specification. This includes all acceptance and qualification tests which requires the subcontractor to produce the required test plans and procedures and to possess the proper test equipment. Therefore, a substantial amount of baseline LRU performance data will be generated by the subcontractor.

2.3.2 Test Location

The desired test location would be the LRU subcontractors; however, there may be situations that require the use of outside testing laboratories.

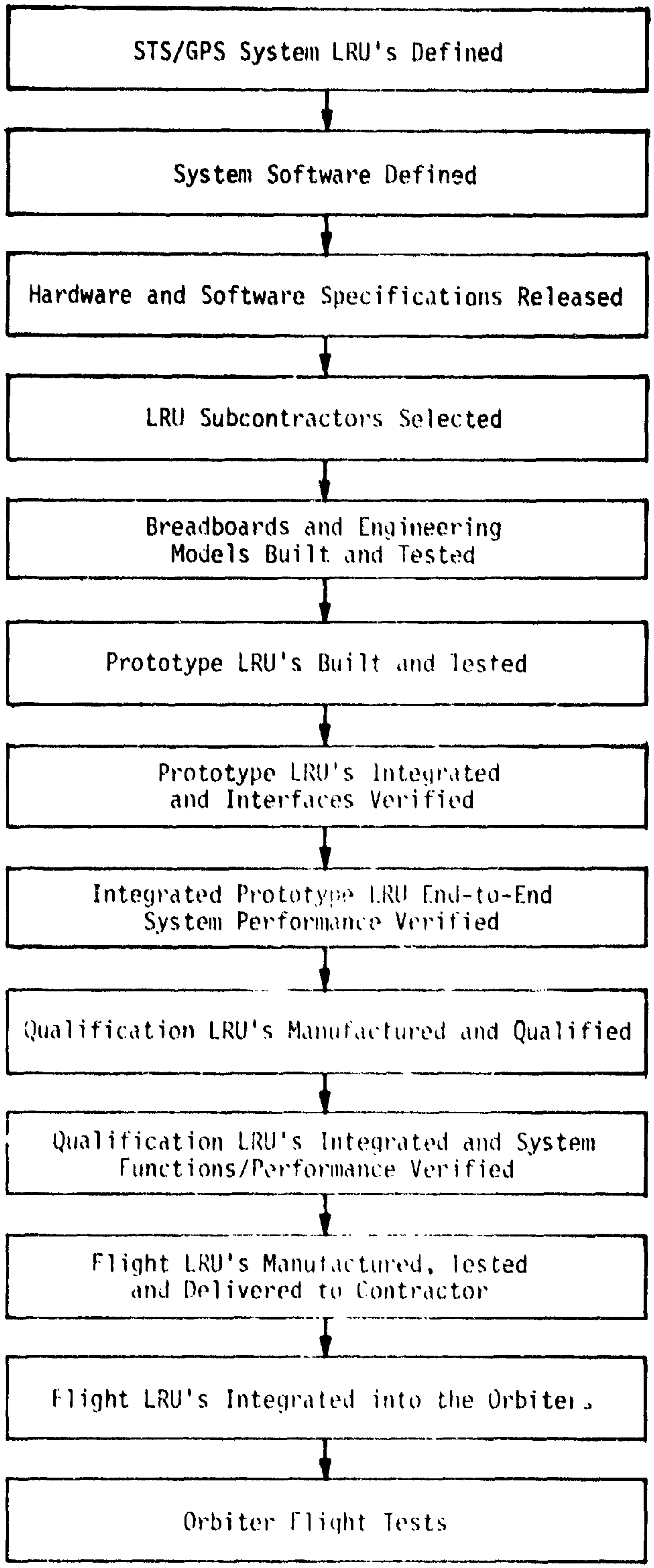


Figure 3. Typical STS/GPS Design, Development and Testing Sequence

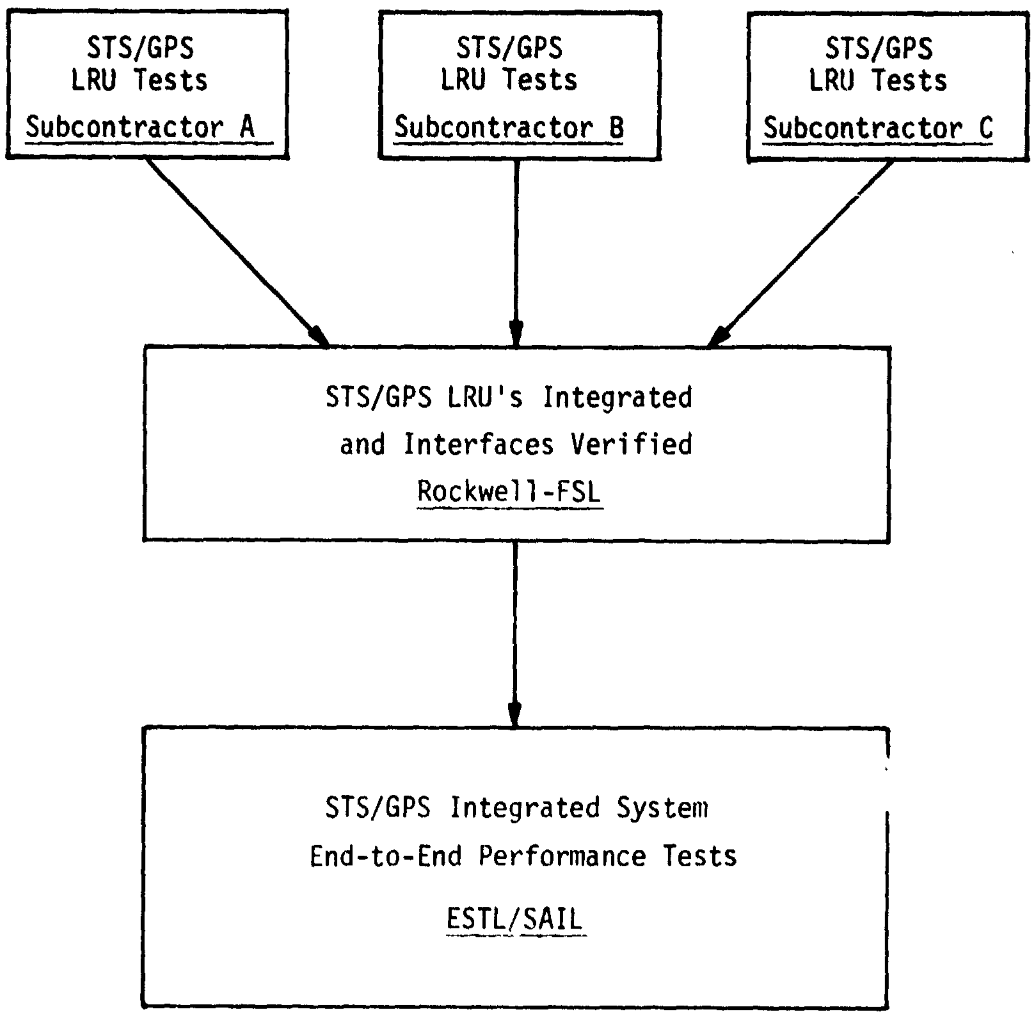


Figure 4. STS/GPS Test Sequence

2.3.3 Rationale

The contractor must be assured that the equipment delivered by the subcontractor meets all aspects of the LRU specification. To minimize the cost impact of design or manufacturing problems, any potential problems must be detected at the earliest possible time. Another advantage of detailed SRU and LRU testing is that, by having baseline LRU data traceability, troubleshooting is simplified in the event of future system performance problems.

2.4 Interface Test Philosophy

2.4.1 Tests Required

The individual LRU's must be integrated and all interfaces verified for compatibility.

2.4.2 Test Location

The Flight System Laboratory (FSL), Rockwell, Downey. FSL was previously known as the Advanced Development Laboratory (ADL).

2.4.3 Rationale

One central group within the contractor's organization must be responsible for verifying all interfaces. If more than one group is responsible, it is possible for incompatible interfaces to exist and not be discovered until late in the test program, which obviously causes very expensive delays. This will be the first time that the STS/GPS LRU's from the various LRU subcontractors will be integrated as a system and, thus, represents the beginning step of system performance verification.

2.5 Integrated System Test Philosophy

2.5.1 Tests Required

The integrated STS/GPS user equipment may be characterized as demodulating an RF signal, processing the resultant digital signal and, finally, interfacing with one of the Orbiter's general-purpose computers (GPC). It is possible and extremely practical to divide the integrated system end-to-end performance tests into two sections: RF link verification and computer software verification. The RF link tests would verify the GPS-to-Orbiter RF link up to and including the demodulated data at the R/PA LRU. The software verification test would start with the demodulated RF data at the R/PA LRU and continue to the GPC. As stated, there are some very practical and cost-effective reasons to divide the integrated system test into two sections; these reasons will be developed shortly.

2.5.2 Test Location

The RF link tests will be held at the Electronics System Test Laboratory (ESTL), NASA-JSC; software tests will be conducted at the Systems Avionics Integration Laboratory (SAIL), NASA-JSC.

2.5.3 Rationale

It is possible for the Shuttle contractor to verify the end-to-end integrated system performance; however, this may result in some undesired future consequences. Since the Shuttle is a very long program, its mission life will surely outlast the subcontractor's involvement in the program and may even outlast the contractor's involvement (except for some sustaining effort).

As typically happens when a contractor or subcontractor is no longer heavily involved in a program, the associated test equipment is modified for other uses and key personnel reassigned. The net result is that when in-flight anomalies occur, resolution may be very time consuming and expensive since the support test equipment may no longer exist or the appropriate personnel no longer be available.

Since the Shuttle and GPS are multidecade programs and since anomalies will occur during orbital missions, it is desirable that the RF link and software simulation test equipment and the test personnel be within the organization using the Shuttle. Because the user organization is NASA, JSC is the logical choice to conduct the integrated system tests.

RF link tests are required to uncover any system performance problems because, historically, some LRU's have met their individual specifications but have experienced some system problems at integration. It is imperative that these tests be performed prior to Orbiter integration of flight equipment since RF link problems occurring after Orbiter integration are very expensive. A practical method of verifying the RF link performance is to simulate a flight mission with simulated GPS satellites, space-loss simulators and other test equipment.

Since the STS/GPS system is computer-controlled, the system software must be validated. As with RF link performance problems, any software anomalies discovered later in the project usually result in extra costs and delays. One method to verify the software would be to provide an RF stimulus to the R/PA and monitor the system performance.

The integrated system tests are divided between the ESTL and the SAIL because each laboratory has unique capabilities and expertise which complement the other, and these laboratories are able to conduct the required system tests with minimum cost impact. The ESTL has the capability of verifying the RF link and the SAIL has the capability of verifying systems which interface with the GPC.

2.6 Orbital Flight Tests

The orbital flight tests should serve simply as the final system performance verification. If the proper test planning has been executed through early detailed LRU and system integration tests as previously described in this report, only minimal problems will occur during this last test phase. The net result of following the aforementioned test sequence is an STS/GPS system that has been tested in an expeditious and cost-effective manner with a minimum of duplication.

2.7 Test Philosophy Conclusions

Each LRU must be qualified through very detailed testing by each LRU subcontractor, thus providing baseline performance data and ensuring that the LRU specifications are met. Early problem detection is critical to a successful program, especially when attempting to minimize costs; so, after the LRU's are tested, they must be integrated and the interfaces verified. The contractor is the logical choice for the task since one group and only one group must be held responsible for detecting incompatible interfaces.

The integrated LRU's must also be tested end-to-end to confirm the system performance. The test facilities at NASA-JSC are the logical choice due to their specialized test equipment and because these facilities will be used to support all Orbiter missions. The contractor's test facilities may be modified for other uses at some future time and would be unable to support the Shuttle program should problems arise.

Both test laboratories at NASA-JSC, ESTL and SAIL have unique capabilities which complement each other. By exploiting the strengths of both laboratories, NASA will be able to assure a minimum of system problems and thus avoid costly overruns and delays.

2.8 Specific STS/GPS Tests

In the previous section, the STS/GPS test philosophy was developed. In this section, the STS/GPS test plan will be discussed; this will include the LRU tests, the interface tests, the RF link tests and overall integrated systems tests. With the STS/GPS system being a very long-range program, the tests covered in this section will be only those tests up to and including the integrated system tests at NASA-JSC. As the program is further defined, a more detailed test plan may be developed covering those phases that follow the NASA-JSC testing.

2.8.1 LRU Tests

The LRU testing phase starts with the engineering model, continues with the prototypes and culminates with the qualification unit, which is tested to demonstrate that the LRU design meets the overall performance objectives. The subsequent flight units are subjected to an acceptance test which is similar to but not as rigorous as the qualification test. The purpose of the acceptance test is to demonstrate that the flight units have been properly manufactured.

This section will concentrate primarily on discussing the qualification tests since they represent the most comprehensive of the LRU tests. All other LRU testing, whether for prototypes or flight units, are essentially selected segments of the qualification test procedures with less severe test conditions.

A typical LRU qualification test sequence is listed as follows:

- Acceptance test (reference) or full functional
- Electrical power test
- EMC
- Cabin atmosphere
- Post-cabin atmosphere limited functional test
- Thermal cycle
- Post-thermal cycle limited functional test

- Qualification and flight vibration
- Post-vibration limited function test
- Acceleration
- Post-acceleration limited functional test
- Thermal vacuum
- Post-thermal vacuum limited functional test
- Life test
- Post-life test limited functional test
- Shock
- Full functional test
- Leakage test.

Table 1 more fully explains the nature of the tests listed in the above LRU qualification test sequence. Each LRU, of course, will have certain specific parameters that must be verified during acceptance and qualification testing. The remainder of this section lists some typical parameters that should be verified.

2.8.2 Antenna Assembly LRU

Typical antenna parameters to be verified are listed as follows:

- Interfaces
- Frequency range/bandwidth
- Gain
- VSWR
- Radiation pattern
- Polarization
- Axial ratio.

2.8.3 Receiver Preamplifier Assembly LRU

Typical receiver preamplifier parameters to be verified are listed as follows:

- Electrical power characteristics
- Warm-up time
- Interfaces
- Input/output impedances

Table 1. LRU Qualification Test Purposes

1. Acceptance Test (Reference) or Full Functional: Provides baseline comparative data.
2. Electrical Power Test: Selected functional tests are performed to assure that the LRU meets all performance requirements, including power consumption under high and low primary input power conditions.
3. EMC: This test determines the electromagnetic compatibility of the LRU.
4. Cabin Atmosphere: The LRU is exposed to salt fog and subsequently exposed to humidity and thermally cycled while selected functional tests are performed.
5. Limited Functional Test: This test verifies the post-cabin atmosphere LRU performance.
6. Thermal Cycle Test: The LRU is cycled limit-to-limit 10 times and selected functional tests are conducted at high and low temperature extremes to verify acceptable performance.
7. Limited Functional Test: This test verifies the post-thermal cycle LRU performance.
8. Vibration: The LRU is subjected to two different vibration tests in each of three orthogonal axes--qualification acceptance vibration test (QAVT) and flight vibration test. Selected functional tests are performed during both vibration tests.
9. Limited Functional Test: This test verifies post-vibration LRU performance.

Table 1. LRU Qualification Test Purposes (Contd)

10.	Acceleration. The LRU is subjected to acceleration in each of three orthgonal axes.
11.	Limited Functional Test: This test verifies post-acceleration LRU performance.
12.	Thermal Vacuum Test: Selected functional tests are conducted to assure that the LRU meets all performance requirements in a low-pressure, constant-temperature environment.
13.	Limited Functional Test: This test verifies post-thermal vacuum LRU performance.
14.	Life Test: The LRU is subjected to a given number of on/off cycles.
15.	Limited Functional Test: This test verifies the post-life test LRU performance.
16.	Shock Test: With the unit off, the LRU is shock-tested in each of three orthogonal axes (both directions).
17.	Full Functional Test: By comparing this test with the first functional test results, any performance degradation is detected.
18.	Leakage Test: Since some LRU's are pressurized internally, the leak rate must be verified.

- Input/output protection
- VSWR
- RF output power
- Frequencies
- Bandwidth
- Gain
- Gain stability
- Gain ripple
- Dynamic range
- Noise figure
- Interference rejection.

2.8.4 RF Power Dividers LRU

Typical RF power dividers parameters to be verified are listed as follows:

- Interfaces
- VSWR
- Port-to-port isolation
- Amplitude imbalance
- Input/output impedances
- Insertion loss
- Frequency range
- Phase imbalance

2.8.5 Receiver/Processor Assembly (R/PA) LRU

Typical R/PA parameters to be verified are listed as follows:

- Interfaces
- Warm-up time
- VSWR
- Input frequencies
- Doppler shift & rate
- Antenna selection
- Acquisition time
- Tracking threshold
- Oscillator stability
- Interference rejection
- AGC
- BER
- BITE
- Electrical power characteristics
- Input/output protection
- Input/output impedance
- Noise figure
- Frequency response
- Acquisition (P & C/A codes)
- Satellite selection
- In-lock tracking
- Tracking phase error
- Received signal transients
- Data demodulation
- Navigation data generation
- Pseudorange accuracy
- Delta pseudorange accuracy
- Data accuracy versus constant g load.

2.9 Interface Tests

In this phase, the individual LRU's are integrated and all interfaces verified for compatibility. These tests would be performed at FSL, Rockwell, Downey, and typical tests would include the following:

- GPC/R/PA data transmission checks
  --GPC error testing
  --R/PA error testing
  --Data bus noise testing
- Power and transient susceptibility
- System initialization tests
- BITE tests
- Data format checkout
  --All avionics interfaces
- Limited R/PA functional tests
  --Commands
  --Moding, etc.
- Limited RF receiver functions
  --RF input hardwired to preamplifier
  --Manual antenna management
- Limited navigation processor functions
  --Simple trajectory program input
  --Minimum Orbiter dynamics or taped trajectory segments.

2.10 Integrated Systems Test

In this phase, both the RF link performance and the system software are verified. Because the ESTL and the SAIL have unique and complementary functions, it is practical and cost-effective to separate the integrated system tests into the RF link performance which will be verified by the ESTL and the system software performance which will be verified by the SAIL.

The ESTL or RF link performance tests would include the following tests as a function of P_{REC}/N_0, doppler shift, C/A and P codes:

- Threshold carrier-to-noise ratio
- BER
- False lock susceptiblity
- Receiver modes
- RF acquisition, including acquisition threshold, acquisition time, and acquisition probability
- Output signal-to-noise ratio
- Percent data loss
- Tracking capability
- Pseudorange and range rate accuracy
- Time to first fix (TTFF), determined from past test analysis of data

The SAIL or software performance tests would include the following tests:

- Satellite selection
- Redundancy management
- Crew override capability
- Memory loads and dumps
- Time synchronization
- Accuracy prediction
- Navigation accuracy (C/A and P codes)
- Denial of accuracy
- Antenna management
- Ground control
- System BITE and self-test
- Displays
- GPC state aiding
- GPS/GPC state vector handoff
- Time to first fix (TTFF) (C/A and P codes)

As previously stated, the purpose of the integrated system test is to verify the end-to-end GPS/STS equipment performance and, for cost and practical reasons, these test should be divided into the RF link tests performed by the ESTL and the software verification performed by the SAIL. The problem is that the ESTL does not possess a GPC in order to perform real-time navigation solutions and the SAIL does not possess the proper RF source to simulate the RF link. One solution would be to conduct joint ESTL/SAIL tests. Unfortunately, the coordination and scheduling required to make such joint tests would be extremely difficult, if not impossible, because each laboratory is heavily committed to other Shuttle programs already scheduled for test. This dilemma is easily resolved if NASA purchases the properly designed GPS satellite simulator.

Figure 5 outlines the basic GPS simulator block diagram, and Table 2 discusses the minimum simulator requirements. The ESTL can perform many if not all of the RF tests by accumulating R/PA data in real time, but analyzing the data in nonreal time. With the proper R/PA output data storage, the ESTL does not require a GPC. Also, nondynamic signal simulation is accomplished by manually variable RF power outputs, doppler shifts and space losses.

Even though the ESTL is verifying the RF link performance in great detail, the SAIL still needs an RF source to stimulate the R/PA. It may be argued that the SAIL could conduct tests by injecting digital data into the R/PA processor but, in Axiomatix's opinion, this is not a satisfactory test method. TTFF and navigation accuracy measurements

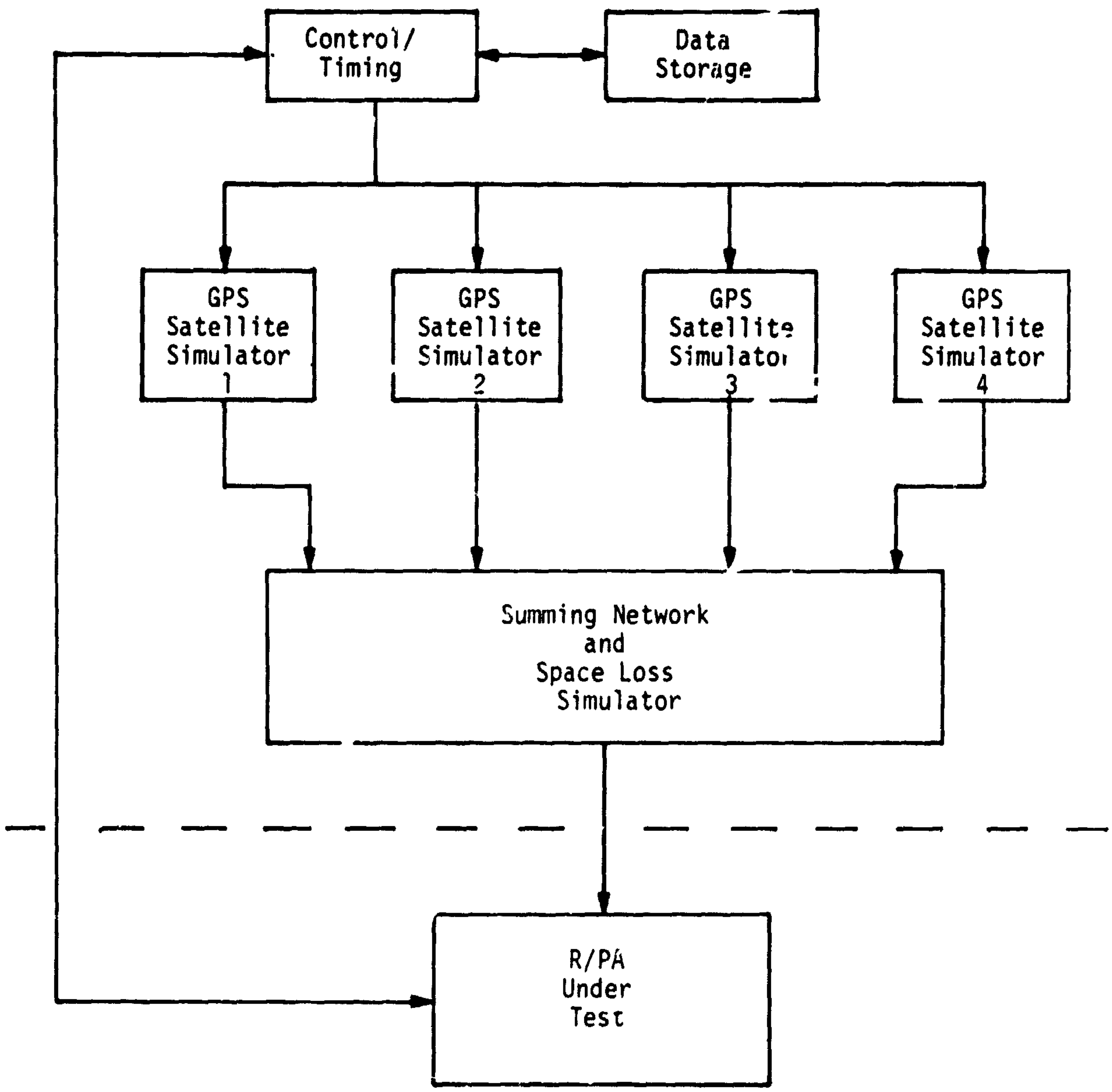


Figure 5. GPS Simulator Block Diagram

Table 2. GPS Simulator Requirements (Minimum)

- Simulation of four satellites simultaneously
- Storing or recording of R/PA output data in real time
- Manually variable signal parameters for all four satellites
- Signal Parameters:
  - L_1,L_2 carriers
  - L_1,L_2 differential propagation delay
  - C/A, P codes including all 37 satellite identification numbers (ID's)
  - Vari ble doppler shifts
  - Variable space-loss simulator
  - Navigation message
- User dynamics may want to be simulated.

should be conducted with an RF stimulus because not doing so leaves the R/PA vulnerable to hidden problems which will surface in the future. Also, in order to perform the TTFF and navigation accuracy measurements, the simulator must simulate a minimum of four GPS satellites simultaneously.

Since the SAIL requires an RF source, it may be further argued that the SAIL should conduct all the RF tests. As previously stated in this report, the ESTL possesses test equipment, expertise and the personnel to conduct the RF tests in a more cost-effective manner than the SAIL, and NASA should exploit the strengths of both laboratories.

2.11 Conclusions

The basic philosophy developed in this report was to test the LRU's, the integrated GPS/STS equipment interfaces and the integrated system end-to-end performance as soon as possible in the program schedule. Early problem detection is critical for a project to avoid schedule delays and minimize costs. Obviously, system problems discovered late in a program's life have very

It is recommended that the detailed LRU tests be conducted by the respective LRU subcontractors. The integrated GPS/STS equipment interfaces should be verified by one (and only one) group, and the Shuttle contractor is the logical choice. The integrated system end-to-end performance should be performed by the ultimate Shuttle user, NASA, because the Shuttle is a multidecade program and NASA needs the capability to resolve in-flight anomalies. It is further recommended that the NASA-JSC tests be separated into the RF link tests conducted by the ESTL and the software verification conducted by the SAIL.

3.0 EFFECT OF TPS TILE ON SNR OF THE SHUTTLE/GPS SYSTEM

3.1 Introduction

It is recognized that a lossy TPS tile which is inserted on top of a flush-mounted GPS antenna will both attenuate the signal power and increase the system noise temperature. Since the tile surface temperature can be quite high (on the order of 2000°F), it is important to have an exact expression for evaluating the resulting signal-to-noise ratio that is available at the GPS receiver input. The following paragraphs develop the expression for signal power-to-noise density ratio for the physical model which is shown in Figure 6. Furthermore, it is proved, as one would suspect, that this S/N_0 is independent of the point in the circuit that it is referenced to. Finally, a short discussion is given which establishes that the background, or sky noise, or, equivalently, antenna noise temperature, is independent of the antenna polarization.

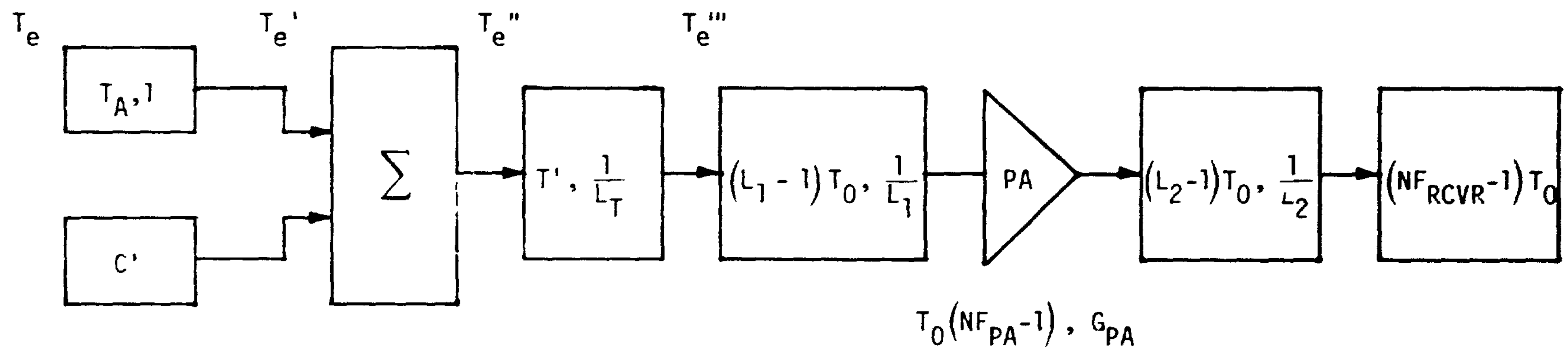
3.2 Discussion of Signal-To-Noise Ratio (SNR)

A generalized mathematical model of the system is shown in Figure 7. This model consists of serial elements, each having an effective temperature and an effective gain. The first element is the sky noise observed by the antenna field of view. The temperature of this element is T_A, or what is often referred to as the antenna temperature. This element has unity gain, which is not to be confused with antenna gain. The next element is the tile loss element, which has an effective temperature given by

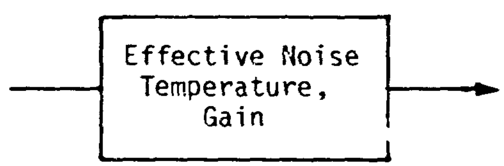
$$T_{TILE}' = T_{TILE}(NF_{TILE} - 1) = T_{TILE}(L_{TILE} - 1) \qquad (1)$$

where T_{TILE} is the physical temperature of tile (°K) and L_{TILE} is the tile RF loss ($L_{TILE} > 1$). The effective gain of the tile is the inverse of the loss, or $G_{TILE} = 1/L_{TILE}$.

Note that, if the tile were a conventional earth-based radome, then $T_{TILE} \doteq 290°K$; however, for the post-blackout use, $T_{TILE} > 290°K$. The next serial element is the RF circuit loss between the antenna and the preamplifier. This is followed by the preamplifier, the RF circuit loss between the preamplifier and the receiver and, finally, the receiver element. The noise temperature referenced to the input of the first



C' = antenna output signal power
with no tile attenuation



NOTE: All losses are numerically ≥ 1

Figure 7. Mathematical Model of Receiving Circuit

serial element, that is, at the outside of the tile, is given by

$$T_e = T_A + T_T(L_T - 1) + \frac{T_0(L_1 - 1)}{1/L_T} + \frac{T_0(NF_{PA} - 1)}{1/L_T \; 1/L_1}$$

$$+ \frac{T_0(L_2 - 1)}{1/L_T \; 1/L_1 \; G_{PA}} + \frac{T_0(NF_{RCVR} - 1)}{1/L_T \; 1/L_1 \; 1/L_2 \; G_{PA}} \quad (2)$$

The noise temperature at the output of the first series element T_e' is altered by the gain of the first element, which is unity. Thus, $T_e' = T_e$. Furthermore, the signal power at the output of the first element is C' (Watts). The noise temperature at the output of the second element, i.e., at the input to the RF circuit, is simply T_e' times the gain of the second element, or

$$T_e'' = T_e' \frac{1}{L_T} = T_e \frac{1}{L_T} \; . \quad (3)$$

Likewise, the signal power at the output of the second element is

$$C'' = C' \frac{1}{L_T} \quad (4)$$

so that the signal-to-noise density ratio at this point is given by

$$\frac{S}{N_0} = \frac{C''}{kT_e''} = \frac{C' \frac{1}{L_T}}{kT_e \frac{1}{L_T}} = \frac{C'}{kT_e} \quad (5)$$

This is seen to be the same S/N_0 as at the input to the second element. It can be shown in a similar manner that the signal-to-noise density ratio is the same for any point in the serial circuit as long as noise temperature and signal power are both correctly referenced to this same point. Thus, the signal-to-noise density ratio can be written as

$$\frac{S}{N_0} = C'\left\{k\left[T_A + T_T(L_T - 1) + T_0(L_1 - 1)L_T + T_0(NF_{PA} - 1)L_T\, L_1 + \frac{T_0(L_2 - 1)L_T L_1}{G_{PA}} + \frac{T_0(NF_{RCVR} - 1)L_T L_1 L_2}{G_{PA}}\right]\right\}^{-1}$$

where C' is the signal power that would appear at the antenna output terminals without the tile in front of the antenna.

3.3 Discussion of Sky Noise Versus Antenna Polarization

There sometimes exists some confusion over the concept of an effective sky temperature which is primarily due to the distribution of energy. There are three vibrational modes for the radiating molecules: one for each of the three vibrational orthogonal axis, each of which has an RMS thermal energy level of 1/2 kT, for a total energy of 3/2 kT. The fact that a microwave receiver detects linear polarization implies that only one third of the total energy (1/2 kT) is measured. However, by definition, the effective sky temperature is still T since it is related by Boltzmann's constant and therefore, when considering the input noise contribution, the sky temperature is not altered by polarization orientation considerations.

Equivalently, since linear polarization can be decomposed into equal left-hand and right-hand circular polarization (LHCP and RHCP) components, the vibrational modes can also be treated as sources of circular polarization. A circularly polarized receiver will receive either the LHCP or RHCP components from both of the two linear orthogonal polarizations, for a total received energy of 1/2 kT, so that again the sky temperature is independent of the type of polarization.

4.0 SHUTTLE GPS ANTENNA PHASE SLOPE SPECIFICATION

As the Shuttle maneuvers, i.e., pitches or rolls, the line-of-sight (LOS) signal path between the Orbiter and the GPS satellite is viewed via a different Shuttle/GPS antenna aspect angle. In general, the phase shift which an RF carrier experiences when "passing through" or being received by an antenna varies as a function of the antenna aspect angle. Thus, Shuttle maneuvers introduce a carrier phase modulation on the GPS signal. It is necessary that the GPS receiver suffer minimal degradation as a result of this phase modulation. One approach to guaranteeing minimal degradation is to control the phase slope of the Shuttle GPS antenna. A typical antenna phase slope characteristic is depicted in Figure 8. The analyses which follow establish the requirement that the maximum phase slope of the Shuttle GPS antenna be no greater than 20° electrical per mechanical degree. Discussion with the Rockwell Shuttle antenna engineers indicates that this constraint is not a design driver and should easily be met.

4.1 Calculation of Tracking Error Variances

Since the total loop phase error will be small if the operating correctly, a linearized model of the phased-lock loop has been used. The closed-loop transfer function, when optimally tracking a frequency offset Ω_0 and ignoring the initial random phase, is derived in [4] and is given by

$$H(s) = \frac{1 + 1.5/W_L\ s}{1 + 1.5/W_L\ s + 9/8W_L^2\ s^2} \tag{6}$$

where W_L is the double-sided loop bandwidth in Hz.

Since the expected value of the tracking error will be zero in a properly designed loop, the tracking error is found in a mean-squared sense, or

$$\sigma_d^2 \triangleq \frac{1}{2i} \int_{-i\infty}^{i\infty} |1 - H(s)|^2\ |\tilde{d}(s)|^2\ ds \tag{7}$$

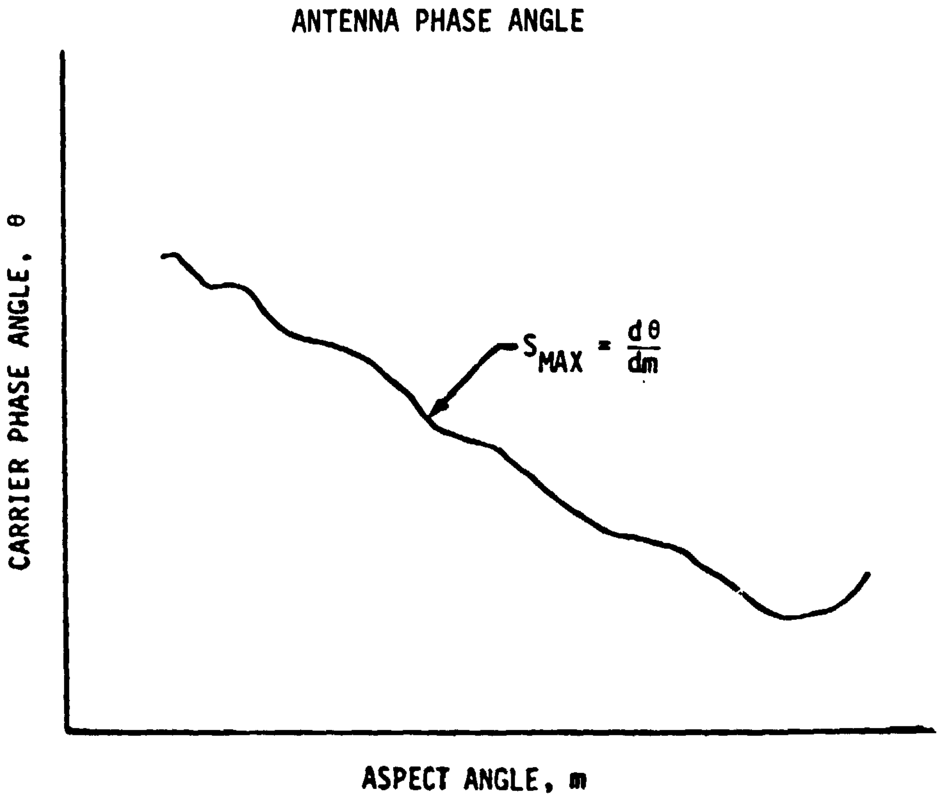


Figure 8. Illustration of Typical Antenna Phase Slope

where d(s) is the Laplace transform of d(t) and d(t) is the phase modulation due to doppler = $\Omega_0 t$. Insertion of the loop transfer function defined in (6) yields a mean-squared tracking error dependent on frequency offset and loop bandwidth, or

$$\sigma_d^2 = 0.42\, \Omega_0^2 / W_L^3 \tag{8}$$

For a desired tracking error less than 2° or an error variance less than 4° and a two-sided loop bandwidth of 40 Hz, the acceptable frequency offset Ω_0 is bounded by ±778.98°/s.

4.2 Calculation of Tolerable Antenna Phase Slope

By definition, the frequency offset is the rate of change of the phase θ(t) with respect to time, or

$$\Omega_0 = \frac{d\theta(t)}{dt} . \tag{9}$$

The maneuvering rate of the Orbiter is a function of its roll rate r(t) and pitch rate p(t) and is given by

$$\frac{dm}{dt} = \text{maneuver rate} = \sqrt{\left(\frac{dr(t)}{dt}\right)^2 + \left(\frac{dp(t)}{dt}\right)^2} \tag{10}$$

Therefore, dθ/dm, the phase rate of change due to pitch and roll maneuvers, is equal to

$$\frac{d\theta}{dm} = \frac{d\theta}{dt}\frac{dt}{dm} \tag{11}$$

Maximum roll and pitch rates in the Orbiter are 30°/s and 10°/s, respectively. The worst case regarding additional phase modulation due to maneuvers is the barbecue mode, which is essentially free-fall conditions, at the maximum roll and pitch rates. The scenario yields a worst-case value of Ω_0 = ±778.98°/s and a corresponding GPS antenna phase slope of ±24.63°/°.

4.3 Calculation of Tolerable Slope from Loop Steady-State Error

Another approach to calculating the maximum allowable antenna phase slope is to calculate the GPS receiver steady-state carrier tracking loop error that results from the Shuttle maneuvers. We begin by assuming a perfect integrator second-order loop with a one-sided loop noise bandwidth of $B_L \leq 10$ Hz (worst case) and $\delta = 0.707$. We will allow the loop error to be $\phi_{ALLOWABLE} \leq 4°$. Once again, the maximum Shuttle maneuver rate is given by

$$\frac{dm}{dt} = \sqrt{(\text{ROLL RATE})^2 + (\text{PITCH RATE})^2} = 32°/s$$

and the maximum Shuttle maneuver acceleration is given by

$$\frac{d^2m}{dt^2} = \sqrt{(\text{ROLL ACCELERATION})^2 + (\text{PITCH ACCELERATION})^2}$$

$$= 63°/s^2$$

The antenna phase slope is defined as

$$S_{MAX} = \frac{d\theta}{dm} = \frac{d\theta}{dt}\left(\frac{dm}{dt}\right)^{-1} = \frac{d^2\theta}{dt^2}\left(\frac{d^2m}{dt^2}\right)^{-1}$$

The steady-state error for the second-order loop is given by

$$\phi_{ss} = \frac{\dot{\omega}}{\omega_n^{\,2}} = 0.28\,\frac{\ddot{\theta}}{B_L^{\,2}}$$

and the maximum phase slope is given by

$$S = \frac{\phi_{ss}\,B_L^{\,2}}{0.28\,\ddot{m}}$$

or $S_{MAX} \leq 23°/°$ for the assumptions given.

4.4 Conclusions

Both transient and steady-state analyses indicate a maximum allowable antenna phase slope of 23°. A specification of $S_{MAX} \leq 20°$ is recommended. This should be readily achievable from the Shuttle GPS antenna design being contemplated.

5.0 SHUTTLE GPS JAMMING IMMUNITY

The question has been asked: "Should the inherent jam protection of the Shuttle GPS receiver be enhanced with additional anti-jam signal processing techniques?"

The analysis that follows concludes that such an undertaking would not produce effective results.

The antijam protection afforded by the properties of the P-code spread spectrum modulation is given by

$$AJ = 10 \log R_{P\ CODE} - 10 \log BW_{PROCESS} - 10 \log S/N_{MIN} \qquad (12)$$

where R_{PCODE} is the P code chipping rate (10 Mchips/s), $BW_{PROCESS}$ is the bandwidth of the receiver process to be jammed (assume code loop jamming with BW = 1 Hz), and S/N_{MIN} is the minimum required signal-to-noise ratio (in $BW_{PROCESS}$) for receiver functioning (assume 20 dB). Based on (12) and the assumed parameter values, the ideal or theoretical AJ margin is found to be 50 dB.

The jammer has a great advantage of range. This advantage is given by

$$\text{RANGE ADVANTAGE} = 20 \log \frac{R_{SAT}}{R_{JAMMER}} \qquad (13)$$

where R_{SAT} is the line-of-sight range from the NAVSTAR satellite to the Shuttle (nominally, 10,000 miles) and R_{JAMMER} is the line-of-sight range from the jammer to the Shuttle (assume 200 miles). Thus, the jammer range advantage is approximately 34 dB. The required jammer power or EIRP to jam the Shuttle GPS is thus given by

$$\begin{aligned} \text{JAMMER EIRP} &= \text{SAT EIRP} + \text{AJ} - \text{RANGE ADVANTAGE} \qquad (14) \\ &= 24\ \text{dBW} + 50\ \text{dB} - 34\ \text{dB} \\ &= 40\ \text{dBW (nominal)} \end{aligned}$$

If we assume a jammer antenna of "nominally" three ft in diameter (21 dB gain) and a commercially available off-the-shelf HPA of 1 kW, we see that the nominal jammer EIRP of 50 dBW is approximately 10 dB greater than that required to jam the Shuttle GPS receiver. Furthermore, military HPA's of much greater power capability are available. Thus, it can be concluded that, if the jammer "sees" the Shuttle GPS omniantenna, he can "easily" jam the GPS signal. This would seem to preclude the use of a GPS antenna that simultaneously views the earth and the NAVSTAR. From Figure 9, it can be seen that an antenna in the upper-middle TACAN slot would be vulnerable to jamming since, when the Orbiter is in "level" flight at approximately a 200-mile altitude, this antenna will view the earth. Furthermore, if the Orbiter deviates more that approximately 20° from level flight, the upper GPS antenna will also view the earth.

Two possible approaches to providing increased AJ protection to the Shuttle GPS receiver are loop rate aiding from the GPS and an electronic phased array, null-steering antenna. Figure 10 shows a block diagram of a code loop rate-aiding scheme that would allow the GPS R/PA to continue code tracking and pseudorange measurements in a jamming environment. Preliminary analysis indicates that an improvement in AJ performance on the order of 10 dB can be obtained by this technique. In light of the preceding discussion on jammer EIRP, it would seem that this approach is not to be recommended for this particular Shuttle/jammer scenario.

An electronic phased array, null-steering antenna, of which a generic block diagram is shown in Figure 11 can provide additional jamming protection. Open literature indicates that at least 30 dB of additional AJ may be obtained by this technique. However, this technology requires very expensive and lengthy development efforts.* Also, such an antenna would require substantially more Orbiter "real estate" than is currently available.* Thus, null-steering, phased-array antennas do not appear to be a viable alternative.

The conclusion is reached that, for this phase of the Shuttle GPS development program, no additional techniques should be explored for enhanced AJ capability.

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*Based on Collins GDM program experience.

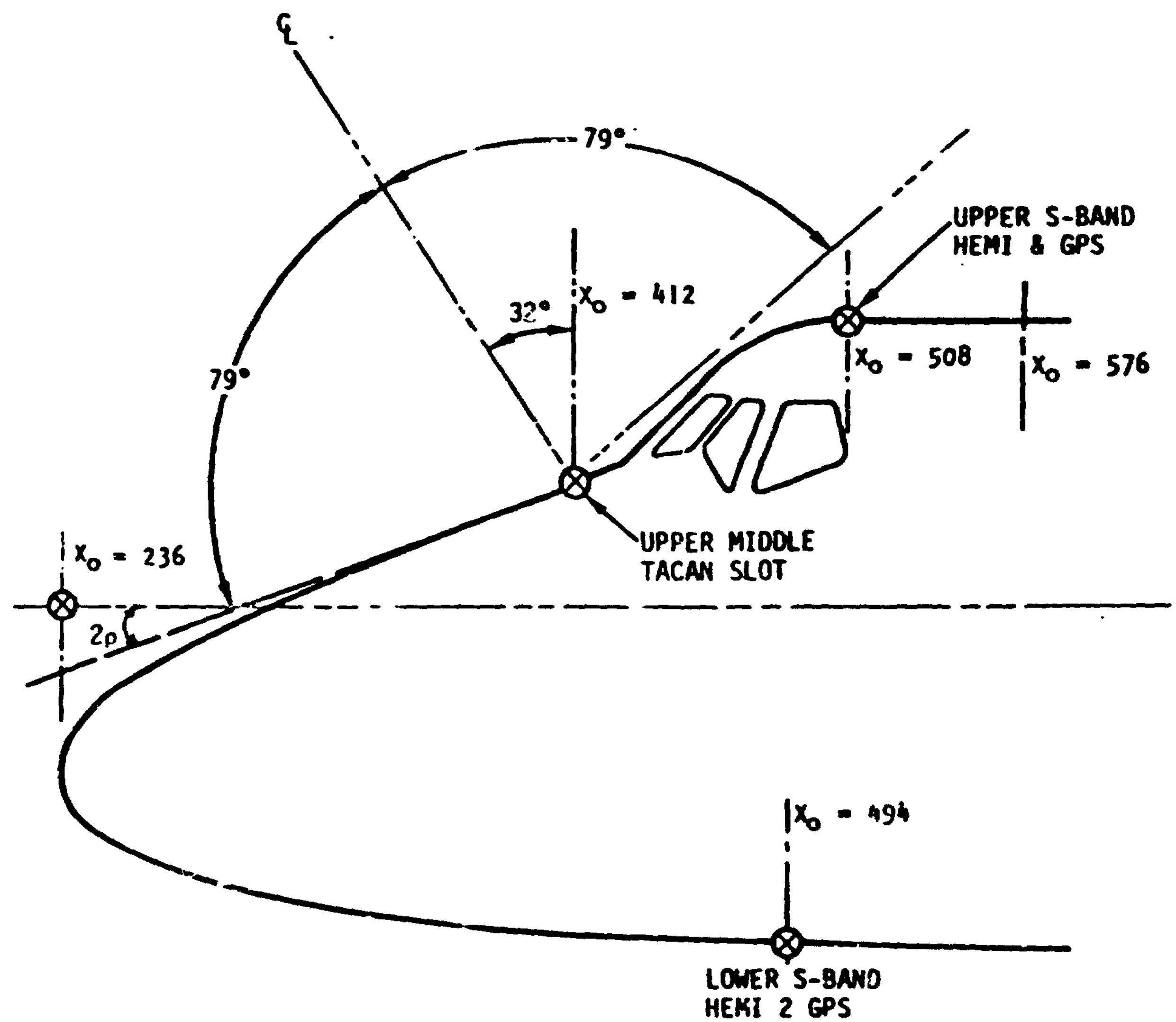

Figure 9. Visibility of GPS Antenna Locations

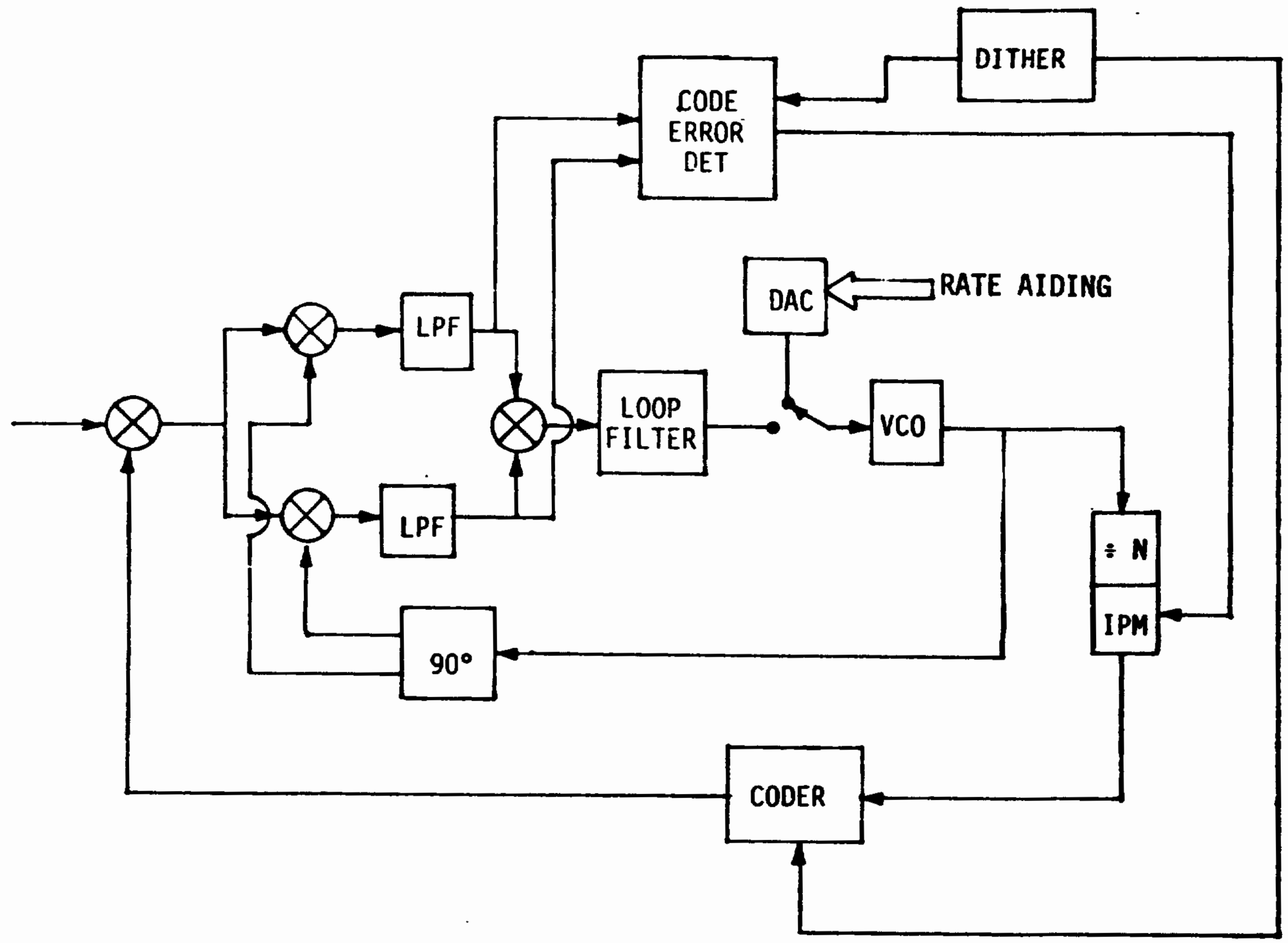

Figure 10. Closed-Loop Code Tracking with Rate Aiding

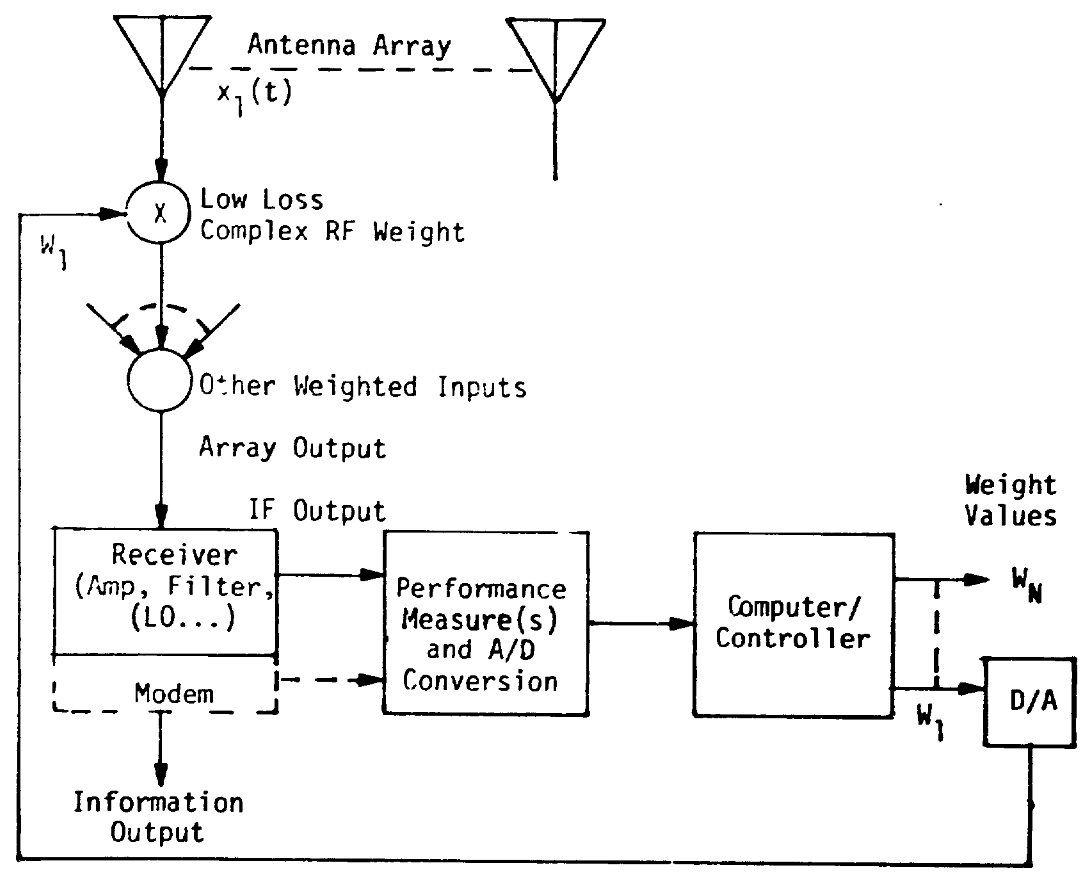

Figure 11. Generic Phased-Array Null-Steering Adaptive Array Circuit

6.0 SHUTTLE GPS/AFJPO ICD

As explained in a previous report [5], because of the criticality of the Shuttle navigation function and because GPS navigation entails elements external to the Space Shuttle Transportation System (STS), it is necessary to establish an Interface Control Document (ICD) between the GPS system and the Shuttle. Examples of the external elements include the NDS and ONS Space Vehicle Navigation Subsystems and the PRN Navigation Assembly signal characteristics.

Such an ICD has been established for the conventional user system segment, which does not include the Space Shuttle or any other space-borne users of GPS. This ICD, MH08-00002-400, Space Vehicle Navigation Subsystems and NTS PRN Navigation Assembly/User System Segment and Monitor Station, is a valid starting point for the GPS/Shuttle ICD. It alone, however, is not sufficient to guarantee the successful utilization of GPS by the Shuttle. An example of one shortcoming is that this ICD specifies the GPS signal power level at the earth's suface but not at the orbital altitudes at which the Shuttle operates. The current ICD for earth-bound users reflects the fact that the GPS satellite antenna patterns are shaped to provide a maximum power density approximately uniformly over the earth's surface, with rapid fall-off beyond the edge of the earth. The Shuttle/GPS ICD must specify the equivalent "pointing loss" for several Shuttle orbital altitudes or must specify the Effective Isotropic Radiated Power (EIRP) versus angle of the satellite/earth centerline.

A first draft of a candidate ICD follows in Appendix A.

REFERENCES

1. Rosen, E., and Van Leeuwen, A., "STS/GPS Navigation System Design Data Base," Space Systems Group, Rockwell International, Downey, California, SD 78-SH-0042B, August 1979.

2. Rosen, E., and Van Leeuwen, A., "STS/GPS Navigation System Design Definition Document, "Space Systems Group, Rockwell International, Downey, California, SD-78-SH-0042, October 1979.

3. Van Leeuwen, A., Rosen, E., and Carrier, L. M., "The Global Positioning System and its Application in Spacecraft Navigation," Space Systems Group, Rockwell International, Downey, California, STS 79-0024, March 1979.

4. Lindsey, W. C., Synchronization Systems in Communication and Control, Chapter 4, Prentice-Hall, Inc., 1972.

5. Nilsen, P. W., "Shuttle Global Positioning System (GPS) Design Study," NASA Contract No. NAS 9-15387C, Axiomatix Final Report No. R7901-4, January 20, 1979.

APPENDIX A

INTERFACE CONTROL DOCUMENT

SPACE VEHICLE NAVIGATION SUBSYSTEM

AND

PRN NAVIGATION ASSEMBLY/SPACE SHUTTLE RECEIVER-PROCESSOR SYSTEM

PRELIMINARY DRAFT

June 22, 1979

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1. SCOPE

1.1 Scope. This Interface Control Document (ICD) establishes the design and control of the NAVSTAR Global Positioning System (GPS), Space Vehicles' Navigation subsystem, and PRN Navigation Assembly interfaces with the Space Shuttle Orbiter (SSO) GPS Receiver/Navigation Processor System. The intent of this ICD is to ensure operational compatibility of the interfacing segments by documenting those interfaces required to achieve the Space Shuttle Mission Navigation objectives.

1.2 Key Dates. The following dates reflect the major milestones for which the system achieves operational capability:

Item	Date
NAVSTAR Launches	TBS
Initial Operational Capability (IOC)	TBS
Full Operational Capability (FOC)	TBS

1.3 ICD Approval and Changes. Interface responsibilities are defined in terms of Johnson Space Center (JSC) and NAVSTAR GPS Joint Program Office (GPS/JPO-SAMSO/YE) responsibilities. The portion of the interface identified as the SSO is the responsibility of JSC. The portion identified as the NAVSTAR GPS Space Segment and Ground Control Segement is the responsibility of the GPS JPO. Design requirements and parameters in this ICD are subject to the bilateral control of JSC and GPS JPO.

2. APPLICABLE DOCUMENTS

2.1 Government Documents. The following documents of the issue specified contribute to the definition of the NDS Space Vehicle (SV) NAV Subsystem and NTS PRN Navigation Assembly/SSO GPS Receiver/Processor interface and form a part of this ICD to the extent specified herein.

SPECIFICATIONS

Federal

None

Military

None

Other Government Activity

SS-GPS-101B 15 Apr 1974	System Specification for the NAVSTAR Global Positioning System, Phase I; including Appendix I, Appendix II, SCN I, SCN II
SS-SVS-101A 20 June 1974	System Segment Specification for the Space Vehicle System Segment of the NAVSTAR Global Positioning System, Phase I
SS-US-101B 30 September 1974	System Segment Specification for the User System Segment for the NAVSTAR Global Positioning System, Phase I
SS-CS-101B 30 September 1974	System Segment Specification for the Control System Segment of the NAVSTAR Global Positioning System, Phase I

2.2 Non-Governement Documents. The following documents of the issue specified contribute to the definition of the NDS Space Vehicle NAV Subsystem and NTS PRN Navigation Assembly/SSO GPS Receiver/Processor interface and form a part of this ICD to the extent specified herein.

SPECIFICATIONS

None

OTHER PUBLICATIONS

(TBS)

3. REQUIREMENTS

3.1 Interface Definition. The NDS Navigation Subsystem and the PRN Navigation Assembly shall be compatible with the SSO GPS Receiver/Processor.

The Navigation Subsystem consists of the PRN Signal Assembly, the Frequency Standard Assembly and the Antenna Assembly. A functional flow diagram of the GPS system and its interfaces is shown in Figure 1.

3.1.1 Navigation Subsystem. The space vehicle navigation system shall provide continuous earth coverage for a navigational signal comprised of both a clear/acquisition (C/A) signal and a precision (P) signal on one L-Band carrier and a precision (P) signal or a (C/A) signal on a second L-Band carrier. The navigation signal shall be composed of pseudo-random noise (PRN) ranging code signals. Superimposed data shall provide satellite system time for acquisition aiding, the space vehicle ephemerides and clock correction. The navigation signals shall be available to the SSO GPS Receiver/Processor (see paragraph 3.3.2.7).

3.1.2 RF Characteristics PRN phase modulated signals shall be generated and radiated in two bands, L_1 and L_2. The L_1 carrier component shall be bi-phase shift key (BPSK) modulated by separate PRN codes which contain the required navigation information. One carrier component shall be a precision (P) navigation signal, and the other shall be a clear acquisition (C/A) signal. The P and C/A carrier components shall be in phase quadrature and their relative RF power levels shall depend upon which of the two operating modes is utilized. The L_2 carrier signal shall be bi-phase modulated by the same P or C/A signals used to modulate L_1, selectable by ground command. The L_1 and L_2 carriers and all modulation rates shall be derived from a common frequency source. (For operating modes, see 3.3.2.1.3).

3.1.3 Baseband Characteristics. Characteristics of the baseband P and C/A codes shall be as follows with the frequency and time tolerances being controlled by the SV frequency standard (see Paragraph 3.3.2.9).

	P	C/A
Chipping Rate (Mbps)	10.23	1.023
Code Repetition Period	7 days	1 millisecond
Data rate (bits/sec)	50	50
Frame length (bits)	1500	Same

a. PRN P Code. The PRN P code shall be a ranging code, $XP_i(t)$, of 7 days in length at a chipping rate of 10.23 Mbps. The code generation technique shall have the capability of generating a set of 37 sequences of 7 days length. Each of the sequences shall be mutually exclusive. The space vehicle code generators shall be capable of generating a set of 32 sequences of 7 days length which shall be selectable prior to launch. The remaining 5 sequences shall be reserved for other transmitters. The 7 day sequence shall be the modulo-2 sum of two subsequences called X_1 and X_2. The X_1 sequence shall be 15,345,000 chips (1.5 seconds) long. The X_2 sequence shall be 15,345,037 chips long. The phases of the 37 codes are defined in Table I.

b. PRN C/A Code. The PRN C/A code shall be a Gold code, $XG_i(t)$ of 1 millisecond in length, at a chipping rate of 1023 Kbps. The epochs of the Gold code shall be synchronized with the X_1 epoch of the P code. The P and C/A code selections are shown in Table I.

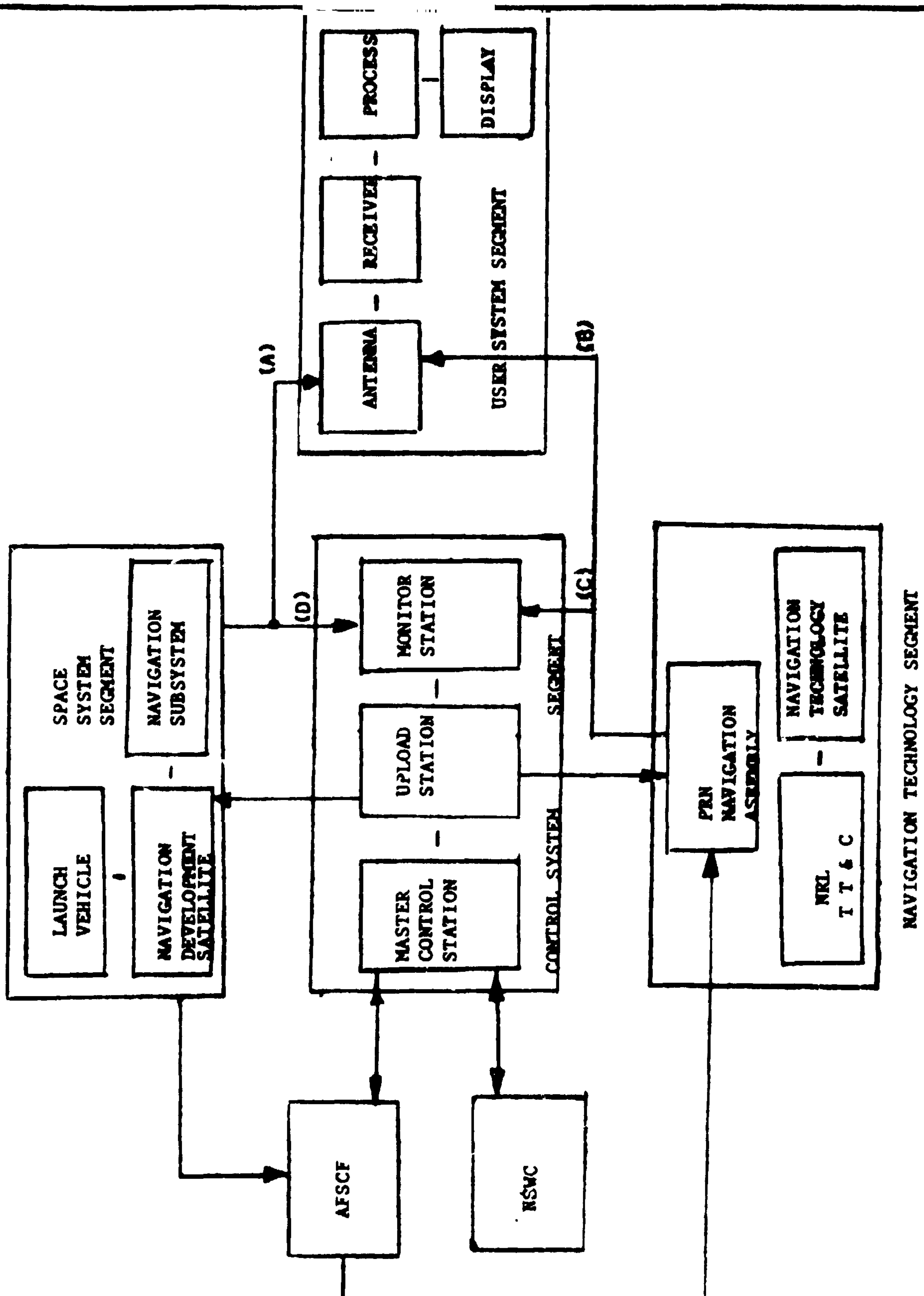

Figure 1. Functional Flow Diagram

INTERFACE CONTROL DOCUMENT

THIS DOCUMENT SPECIFIES TECHNICAL REQUIREMENTS AND NOTHING HEREIN CONTAINED SHALL BE DEEMED TO ALTER THE TERMS OF ANY CONTRACT OR PURCHASE ORDER BETWEEN ALL PARTIES AFFECTED

SIZE	CODE IDENT NO.	DRAWING NO.
A	03953	

SCALE	REV	SHEET 9

Table 1. Code Phase Selection

GPS PRN Signal No.	Manuf. Part No.	Useage	Code Phase Selection		Code Delay Chips		First 10 Chips Octal	First 12 Chips Octal
			C/A ($G2_i$)	P ($X2_i$)	C/A	P	C/A	P
1	Engr. Model	Telecom Sim.	2 ● 6	1	5	1	1440	4444
1	1261708G9	FSV-7	2 ● 6	1	5	1	1440	4444
2	1261708G1	NTS-2	3 ● 7	2	6	2	1620	4000
3	1261708G2	QTV	4 ● 8	3	7	3	1710	4222
3	1261708G10	FSV-8	4 ● 8	3	7	3	1710	4222
4	1261708G3	FSV-1	5 ● 9	4	8	4	1744	4333
5	1261708G4	FSV-2	1 ● 9	5	17	5	1133	[illegible]
6	1261708G5	FSV-3	2 ● 10	6	18	6	1455	4355
7	1261708G6	FSV-4	1 ● 8	7	139	7	1131	4344
8	1261708G7	FSV-5	2 ● 9	8	140	8	1454	4340
9	1261708G8	FSV-6 (QTV Refurb)	3 ● 10	9	141	9	1626	4342
10			2 ● 3	10	251	10	1504	4343
11			3 ● 4	11	252	11	1642	
12			5 ● 6	12	254	12	1750	
13			6 ● 7	13	255	13	1764	
14			7 ● 8	[illegible]	256	14	1772	
15			8 ● 9	15	257	15	1775	
16			9 ● 10	16	258	16	1776	
17			1 ● 4	17	469	17	1156	
18			2 ● 5	18	470	18	1467	
19			3 ● 6	19	471	19	1633	
20			4 ● 7	20	472	20	1715	
21			5 ● 8	21	473	21	1746	
22			6 ● 9	22	474	22	1763	
23			1 ● 3	23	509	23	106[illegible]	
24			4 ● 6	24	512	24	1706	
25			5 ● 7	25	513	25	1743	
26			6 ● 8	26	514	26	1761	
27			7 ● 9	27	515	27	1770	
28			8 ● 10	28	516	28	1774	
29			1 ● 6	29	859	[illegible]	1127	
30			2 ● 7	30	860	30	1453	
31			3 ● 8	31	861	31	1625	
32			4 ● 9	32	862	32	1712	
33	GDE-1	Grnd Transmtr #1	5 ● 10	33	863	33	1745	
*34	GDE-2	Grnd Transmtr #2	4 ● 10	34	950	34	1713	
35	GDE-3	Grnd Transmtr #3	1 ● 7	35	947	35	1134	
36	GDE-4	Grnd Transmtr #4	2 ● 8	36	948	36	1456	
*37	GDE-5	Grnd Transmtr #5	4 ● 10	37	950	37	1713	4343

Note: In the octal notation for the first 10 chips of the C/A code as shown in this column, the first digit (1) represents a "1" for the first chip and the last three digits are the conventional octal representation of the remaining 9 chips. (For example, the first 10 chips of the C/A code for PRN Signal Assembly No. 1 are: 1100100000)

Legend: ● is an "exclusive or"

*Recognize C/A codes 34 and 37 are common

c. Downlink System Data. The transmitted system data D(t) shall, as a minimum, carry space vehicle ephemerides, system time, space vehicle clock behavior data, system status messages, and C/A to P signal handover information. The data stream D(t) shall be common to both the P and C/A signals on both L_1 and L_2. The data frame format and content shall conform to the requirements established by paragraph 3.3.2.10.

3.1.4 GPS Time. GPS time shall be maintained by the Control Segment. The space vehicles' clocks shall be set and their time shall also be maintained by the Control Segment via primary upload of the Navigation Processor. This space vehicle time shall be within 2^{-10} seconds (approximately 1 ms) of GPS time. Corrections to maintain this time should occur no more frequently than once per year, but could occur weekly if the frequency accuracy specified in Paragraph 3.3.2.9 cannot be maintained.

GPS time spans one week (604, 800 seconds). At the end of each week it resets to zero. This weekly epoch occurs (approximately) at midnight Saturday night-Sunday morning, where midnight is defined as 0000 hours on the Universal Coordinated Time (UTC) scale, which is referenced to the Greenwich Meridian. Over the years GPS time may differ from UTC (modulo one week) by a few seconds. This is because GPS time shall be a continuous time, while UTC is corrected with leap seconds once a year (0000 hours, New Years Day) as required to keep it in step with the sun. GPS time shall be known, however, to within 100 microseconds of UTC. The difference shall be maintained and published by the Control Segment.

3.2 Interface Identification.

3.2.1 Space Vehicle NAV Subsystem and NTS PRN Navigation Assembly/SSO GPS Receiver/Processor. The SSO GPS Receiver/Processor shall utilize the navigation signals (L_1 and L_2) specified in paragraph 3.3.2.1 of this ICD for the purpose of determining position, velocity, and system time. This interface is noted as (A) and (B) on Figure 1.

3.3 Criteria.

3.3.1 Interface Criteria. The NDS Navigation Subsystem and the NTS PRN Navigation Assembly shall be compatible with the SSO GPS Receiver/Processor. The Navigation Subsystem consists of the PRN Signal Assembly, the Frequency Standard Assembly, and Antenna Assembly.

3.3.2 Interface Functions. An antenna diplexer unit in the SV NAV subsystem shall accept two separate phase-modulated carrier signals (L_1 and L_2), provide spectrum filtering to minimize out-of-band emissions, and combine these signals into a common port for simultaneous transmission to the antenna. The SV antenna radiates the signals which are received by the SSO GPS Receiver/Processor.

3.3.2.1 Radio Frequency Characteristics. The RF navigation signals radiated by the SV shall be provided by a PRN Assembly on the NAV subsystem aboard each of the SV's. The NAV subsystem shall provide the user with PRN RF signals in the L_1 and L_2 frequency bands.

3.3.2.1.1 RF Signal Structure. The PRN signal shall have modulated data consisting of information that includes handover data, space vehicle ephemerides, clock correction, and processor data upload verification. The two types of signals provided shall be as follows:

a. A clear/acquisition (C/A) signal provided on L_1. On L_2 band, the C/A signal may be substituted for the P signal, by ground command.

b. Precision (P) signal for properly equipped users provided on both L_1 and L_2 bands.

3.3.2.1.2 Navigation Data Update. SV navigation data required by the SSO GPS Receiver/Processor shall be updated by the MCS through the ULS in a SGLS-compatible mode. These data shall be stored in the NAV memory/processor module. Storage capacity shall be provided in each memory/processor module. These data shall be transmitted to the SSO GPS Receiver/Processor via the P and C/A signals at a data rate of 50 bps.

3.3.2.1.3 Operating Modes. The NAV subsystem shall be capable of operating in the nine modes shown in Table II. The modes are differentiated by the specific combinations of P and C/A signals on L_1 and L_2. Normal mode for the P and C/A signals on L_1 is -163 dBw and -160 dBw, respectively. Normal mode for P and C/A on L_2 is -166 dBw. High power mode is -158 dBw (C/A). Standby means that no RF carrier is transmitted. Modes 7 and 8 are for ground checkout. (See 3.3.2.7.1 for details on the SSO GPS Receiver/Processor signal levels.)

Table II. Operating Modes

Mode	L_1 Link		L_2 Link	
	P	C/A	P	C/A
1	Normal	Normal	Normal	Note 4
2	Normal	Normal	Note 4	Normal
3	Normal	High	Normal	Note 4
4	Normal	High	Note 4	Normal
5	Normal	Normal	Note 3	Note 3
6	Normal	High	Note 3	Note 3
7	Note 3	Note 3	Normal	Note 4
8	Note 3	Note 3	Note 4	Normal
Standby	Note 3	Note 3	Note 3	Note 3

Notes:
1. High power will be on the NDS space vehicle only.
2. Mode control shall be effected through the TT&C system.
3. No RF carrier is transmitted.
4. Modulation not present.

3.3.2.1.3.1 NTS-II Operating Modes. NTS-II shall not be capable of transmitting in modes 3, 4 and 6.

3.3.2.1.4 Frequency Plan. The carrier frequencies for the L_1 and L_2 signals shall be coherently derived from the (nominal) 10.23 MHz oscillator frequency. To compensate for general relativistic effects, the actual SV frequency standard frequency is 10.23 MHz offset by -4.45×10^{-10} $\Delta f/f$ or a Δf of -4.55×10^{-3} Hz. This is equal to 10.22999999545 MHz. The nominal carrier frequencies are:

L_1 = 1575.42 MHz
L_2 = 1227.6 MHz

The definition of in-band channel allocation for both the L_1 and L_2 carriers shall be $\pm$10.23 MHz about center frequency for both P and C/A signals.

3.3.2.1.5 Out-of-band Emissions. The sideband RF power outside of the in-band channel allocation shall result in a field strength at the user such that the flux densities for the L_1 and L_2 P signals shall not exceed the values shown in Figures 2 and 3, respectively.

3.3.2.1.6 Signal Coherence. All transmitted signals shall be coherently derived from the same on-board frequency standard and all digital signals shall be clocked in coincidence with the PRN transitions for the P-signal and occur at the P-signal transition speed. The effective phase difference between the P and C/A signals on L_1 shall be less than 5 nanoseconds (one sigma) during all operations.

3.3.2.2 Code Waveform Characteristics.

3.3.2.2.1 Pulse-to-Pulse Jitter. Pulse-to-pulse jitter is defined as the variation in the transition time of the leading edge of any code chip. The pulse-to-pulse jitter value shall be consistent with the correlation loss specified in paragraph 3.3.2.7.3d.

3.3.2.2.2 Incidental AM. Incidental AM on the P and C/A signals shall be less than 1 db.

3.3.2.2.3 Delete (N/A)

3.3.2.2.4 Carrier Phase Noise. The phase noise spectral density of the unmodulated carrier shall be such that a phase locked loop of 10 Hz one-sided noise bandwidth shall be able to track the carrier to an accuracy of 0.1 radians RMS. The typical transmitted carrier phase noise spectral density versus frequency is given in Figure 4.

3.3.2.3 Spurious Transmissions. In-band spurious transmissions shall not be greater than -40 db referred to the unmodulated carrier level.

3.3.2.4 Equipment Group Delay Variation. Equipment group delay variation is defined as the uncertainty in group delay as observed at the L-band radiated output with respect to the frequency standard output. The effective group delay uncertainty of either L_1 or L_2 shall be less than 1.5 nanoseconds (one sigma).

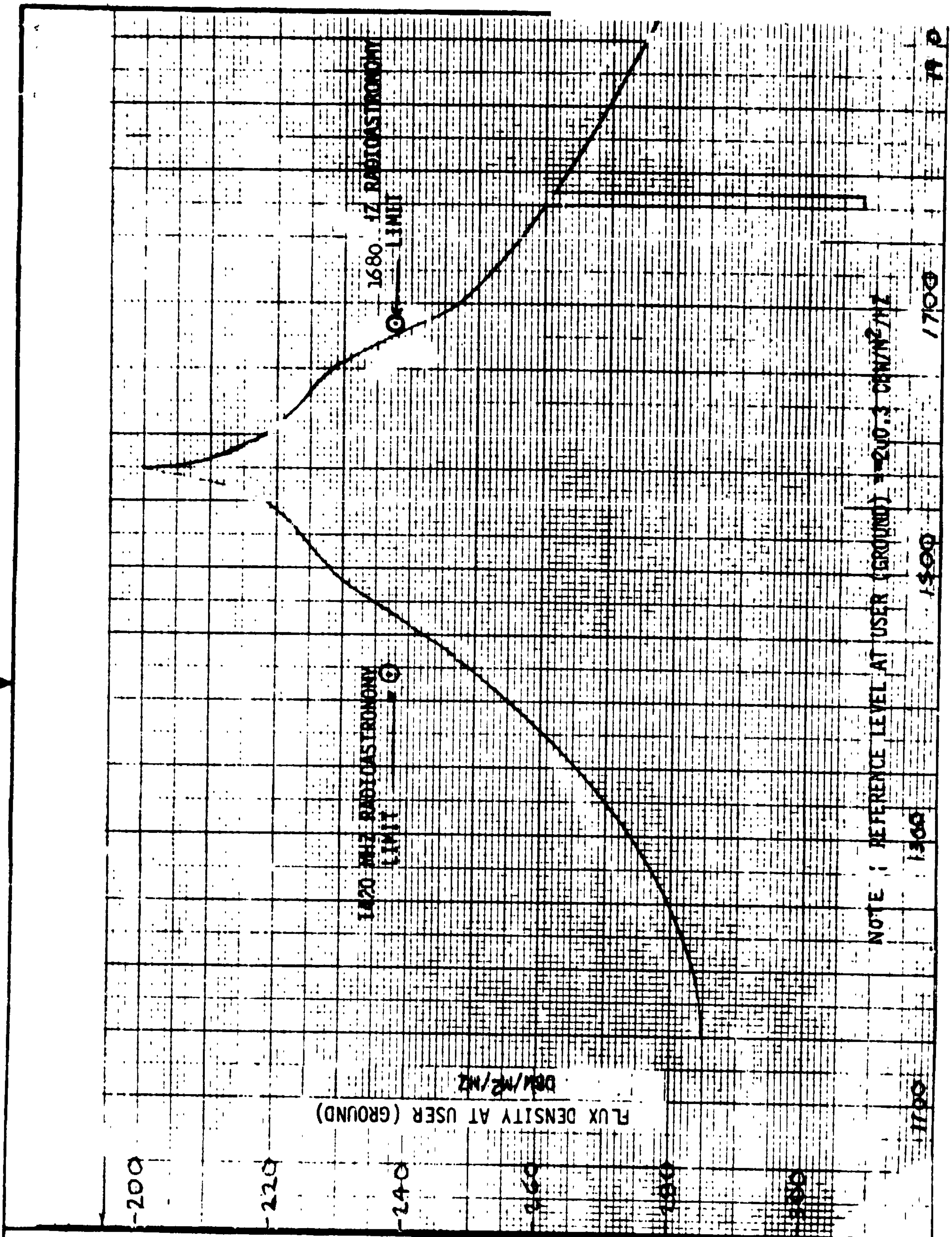

Figure 2. L_1 P Signal - Flux Density at Ground vs Frequency

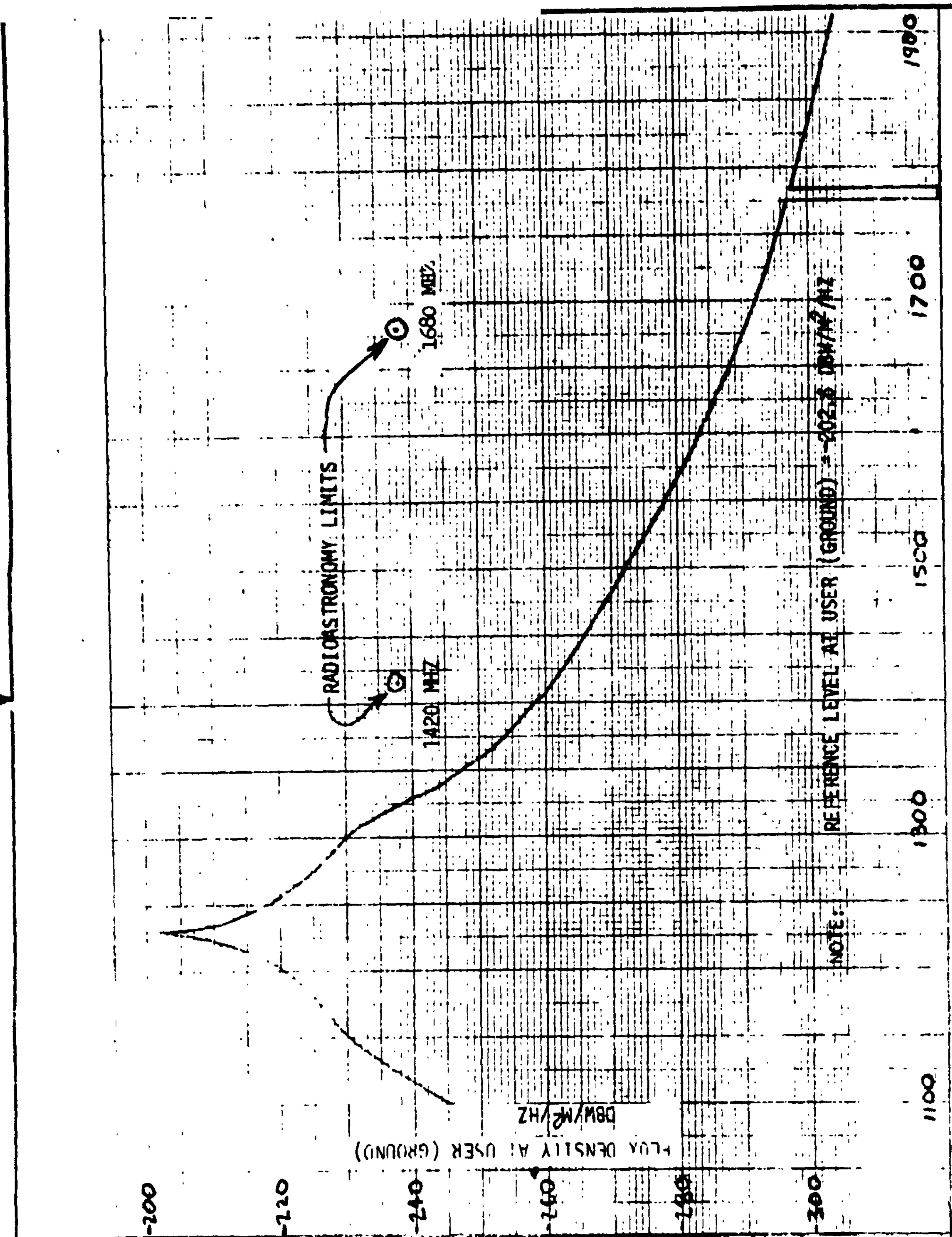

Figure 3. L_2-P Signal - Flux Density at Ground vs Frequency

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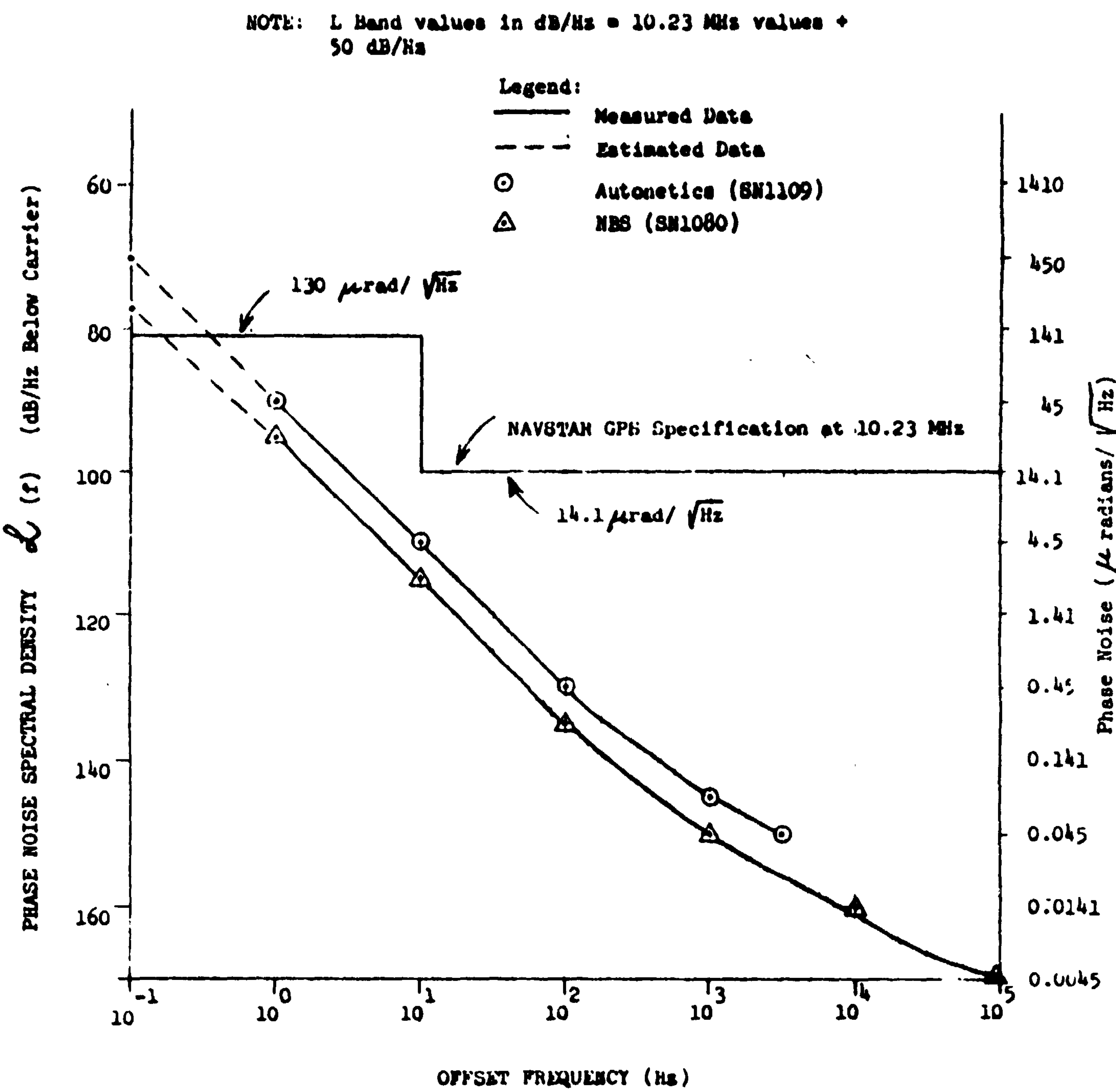

Figure 4. Typical Transmitted Carrier Phase Noise Spectral Density vs. Offset Frequency at 10.23 MHz

3.3.2.4.1 $(L_1-L_2)P$ Differential Group Delay. The differential group delay between the radiated L_1 and L_2 P signals shall be specified as consisting of random plus bias components. The mean differential delay shall be defined as the bias offset in the $(L_1-L_2)P$ differential delay. For a given Navigation Subsystem redundancy configuration, the mean delay shall not exceed 15.0 nsec. The random variations about the mean shall not exceed 1.5 nsec (one-sigma).

3.3.2.5 Timing Accuracy. The codes will always be maintained by the Control Segment within 976 microseconds of system time for each SV. In addition, the effective time difference between space vehicle time and system time shall be maintained within 10 microseconds. Space vehicle time is defined as the mathematical combination of PRN code phase and the time asynchronization terms in the space vehicle almanac (Ref. para. 3.2.2.10.5.3).

3.3.2.6 GPS Satellite Antenna Polarization. The transmitted GPS signals will be right-hand circularly polarized. The maximum ellipticity for the L1 and L2 signals for the range of angles ϕ, as defined by Figure 5, shall be as given in Figure 6.

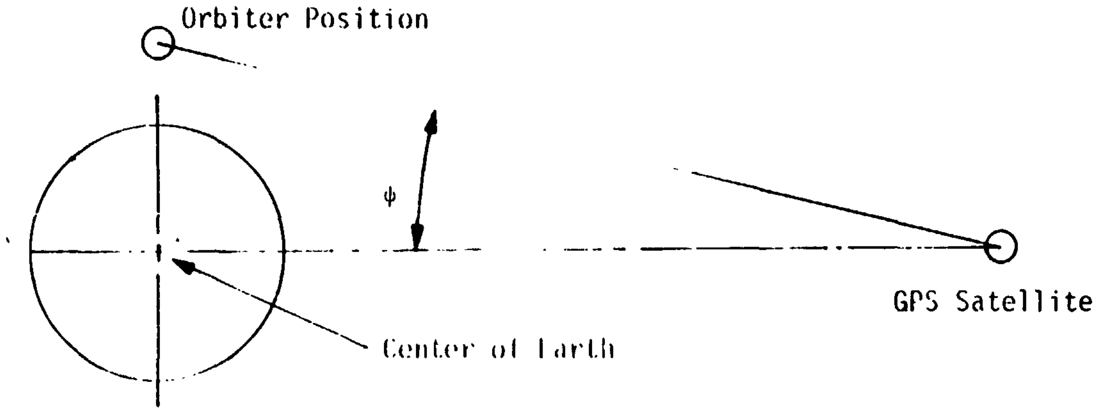

Figure 5. Definition of Angle ϕ For Specification of GPS Signal Ellipticity

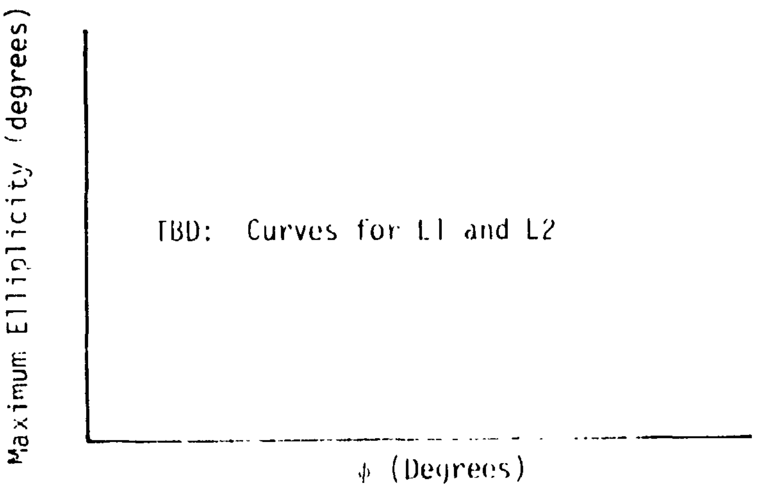

Figure 6. GPS Signal Maximum Ellipticity

3.3.2.7 GPS Signal Levels at the Space Shuttle

3.3.2.7.1 Minimum Incident RF Flux Density

3.3.2.7.1.1 On-Orbit Minimum Incident RF Flux Density

When the Space Shuttle Orbiter is in orbit, as represented by the sample orbits listed in Table III, the incident RF flux density at the Orbiter shall not be less than the values given in Table IV. These values shall be valid for conditions when the angle between the line of sight (LOS) path between the Orbiter and the GPS satellites and the path tangent to the earth's surface from the Orbiter is TBD degrees or more, as shown in Figure 7.

Table III. Sample Orbiter Orbits for Specification of Minimum Flux Density

Orbit Type	Perigee	Apogee	Inclination
TBD	TBD	TBD	TBD

Table IV. Minimum GPS Incident RF Signal Flux Density at Orbiter

	Minimum Flux Density at Orbiter (dBw/M^2)			
Orbit	L1-P	L1-C/A	L2-P	L2-CA
TBD	TBD	TBD	TBD	TBD

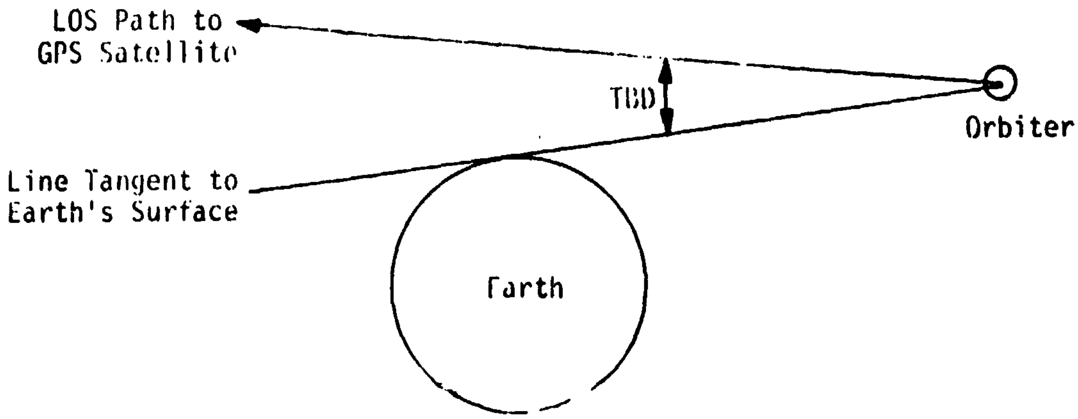

Figure 7. Geometry for Specifying Minimum GPS RF Flux Density at Orbiter in Orbit

3.3.2.7.1.2 In-Atmosphere Minimum Incident RF Flux Density

When the Space Shuttle is located in altitude (relative to sea level) between 0 feet and TBD feet, the minimum incident RF flux density at the Shuttle shall be as given in Figure 8. The LOS elevation angle is defined as the angle between the local horizontal and the LOS path from the Shuttle to the GPS satellite.

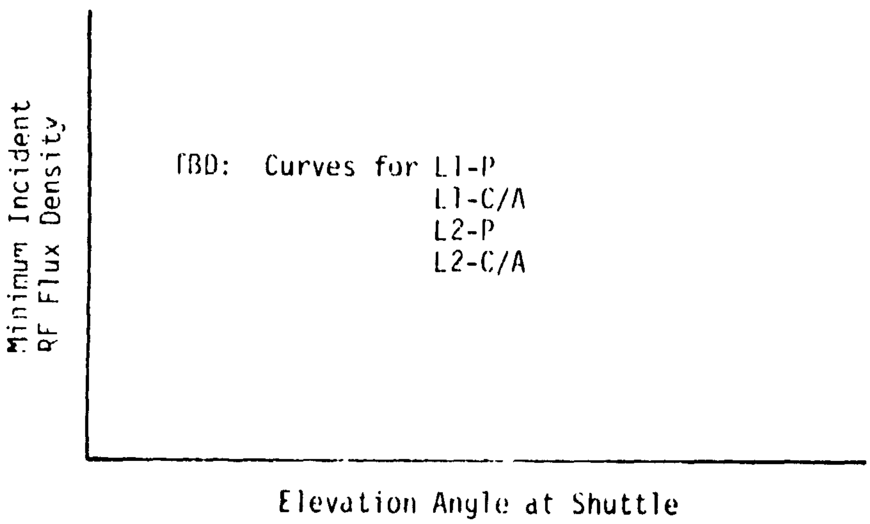

Figure 8. Minimum Incident Flux Density at Shuttle Located in the Atmosphere

3.3.2.7.2 Pointing Loss Slope

It is recognized that there may be Shuttle missions outside the envelope described by Table III. For these cases, the minimum incident flux density is given by the pointing loss slope shown in Figure 9. The angle θ is defined in Figure 10.

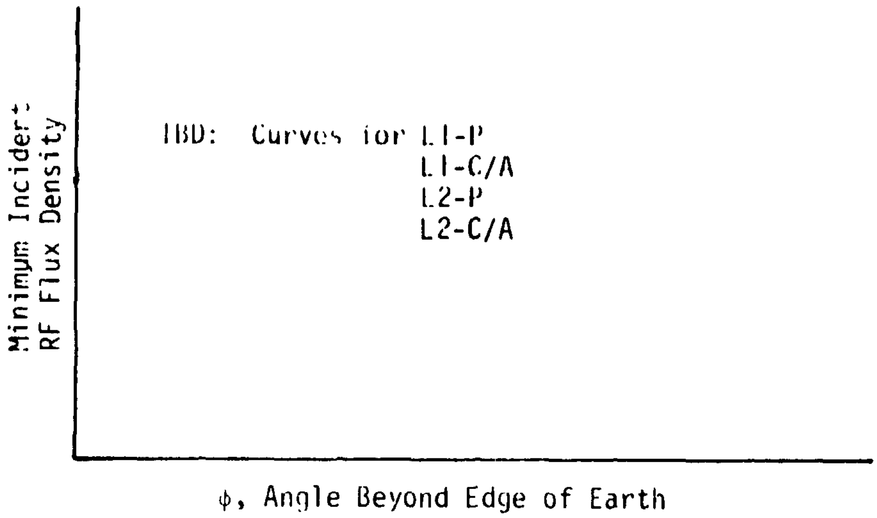

Figure 9. Pointing Loss Slope for GPS Minimum Incident RF Signal Flux Density

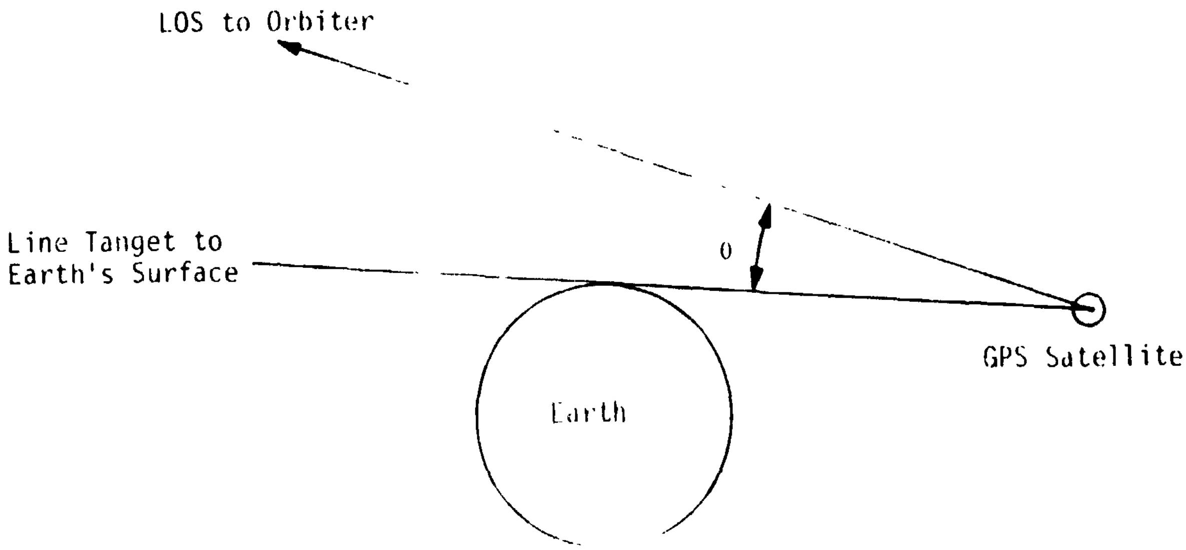

Figure 10. Definition of Angle for Pointing Loss Slope

3.3.2.7.3 L_1 Navigation Signal. The primary navigation signal at the L_1 frequency shall consist of the complete P and C/A signals in phase quadrature. These signals shall also carry digital navigation data required by the user.

a. The P-signal shall be a continuous-carrier biphase modulated by a 10.23 Mbps PRN ranging code. Each SV shall radiate on the same frequency, but be differentiated by code-division-multiplexing techniques. System data shall be transmitted by Modulo-2 addition of a 50 bps digital stream with the ranging code prior to carrier modulation.

b. The C/A signal shall consist of a PRN/BPSK carrier with a chipping rate of 1023 kbps. Navigation data shall be Modulo-2 added with the ranging code and shall be identical to that carried on the P-signal.

c. P and C/A signals shall be transmitted on the same L_1 carrier in phase quadrature ± 100 mr (peak); the relations between composite signal phase and code states are shown in Table V. Crosstalk between the P and C/A signals shall be less than -20 dB. The total AM modulation on the total composite carrier observed only in the middle 50 nanosecond portion of each chip shall be less than 1 dB. The nominal rise/fall time of the RF modulated waveform shall contribute to the correlation loss specified in paragraph 3.3.2.7.3d.

d. Correlation loss is defined as the difference between the radiated SV power in a 20.46 MHz bandwidth and the signal power recovered in an ideal 20.46 MHz bandwidth correlation receiver. The correlation loss apportionment is as follows:

1.	SV modulation imperfections	0.6 dB
2.	Ideal UE receiver waveform distortion (due to 20.46 MHz filter)	0.4 dB

Table V. Composite L_1 Transmitted
Signal Phase and Code State Relationships for Normal Mode

Composite L_1 Signal Phase	Code State	
	P	C/A
0°	0	0
-70.5°	1	0
+109.5°	0	1
180°	1	1
Note: Positive angles lead, negative angles lag.		

3.3.2.7.4 <u>L_2 Navigation Signal</u>. The secondary navigation signal generation, modulation, and data of the L_2 navigation signal shall be identical to that of the L_1 P and C/A signals. Upon command either the P or C/A signal shall be transmitted, but not both.

3.3.2.8 <u>Navigation Signal Structure</u>. The P signal, P(t), shall be 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). Fig. 11 depicts a simplified block diagram of the combined P and C/A signal generation scheme. The chipping rate of XP(t) shall be 10.23 Mbps. $XP_i(t)$ shall be generated by the Modulo-2 sum of two PN codes, X1(t), and $X2(t+n_iT)$, where T equals the period of one P-code chip or $(1.023 \times 10^7)^{-1}$ sec. The same basic $\overline{XP}(t)$ code generator shall be used with each assigned one of the 32 possible XP(t) unique code phases for the SV's. Five additional code phases will be reserved for other transmitters. (see Table I).

3.3.2.8.1 <u>P-Code Generation</u>. The P channel shall have 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:

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

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

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 12, 13, 14, and 15.

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.

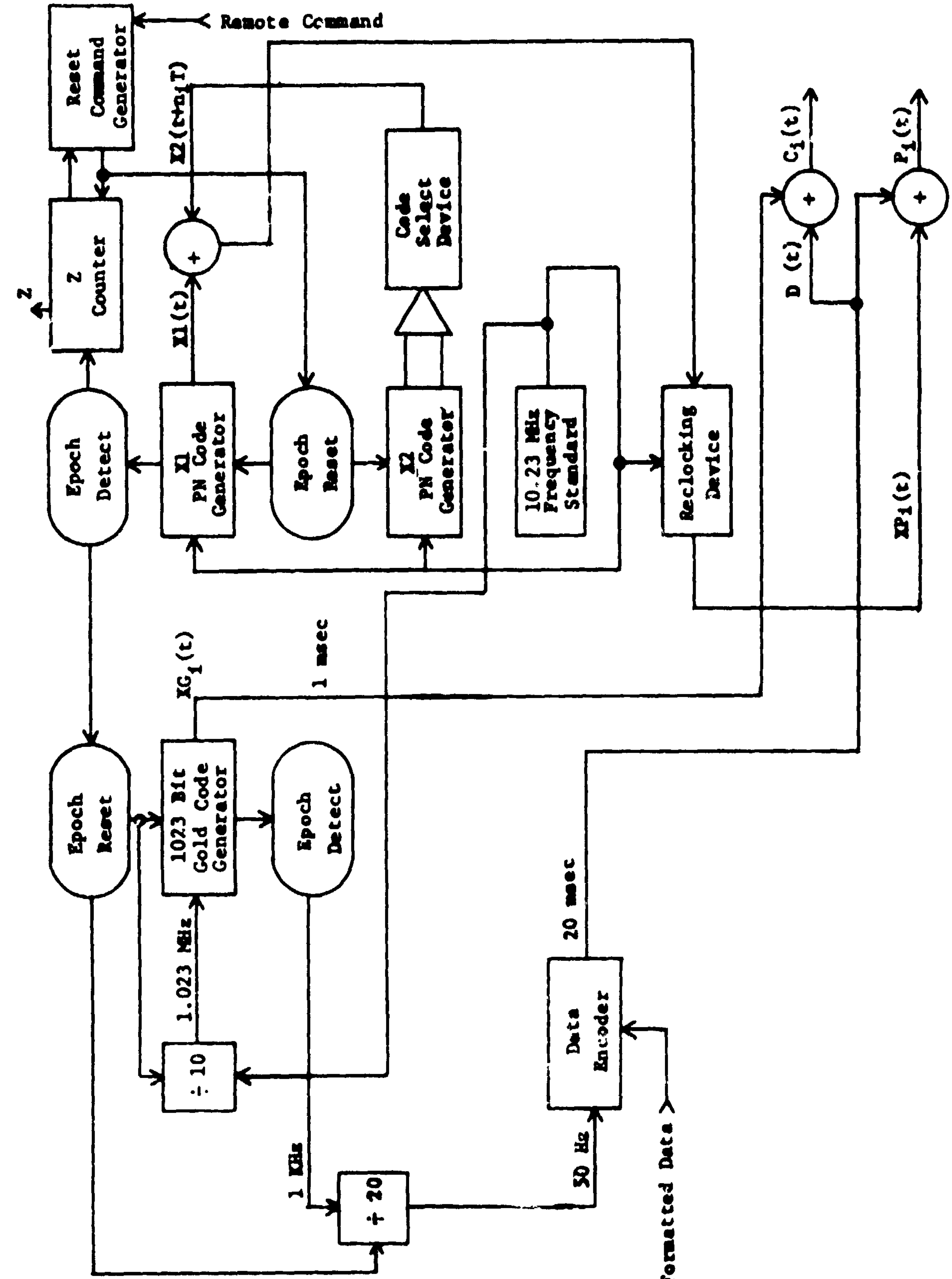

Figure 11

Simplified Block Diagram of Combined P and C/A Signal Generator

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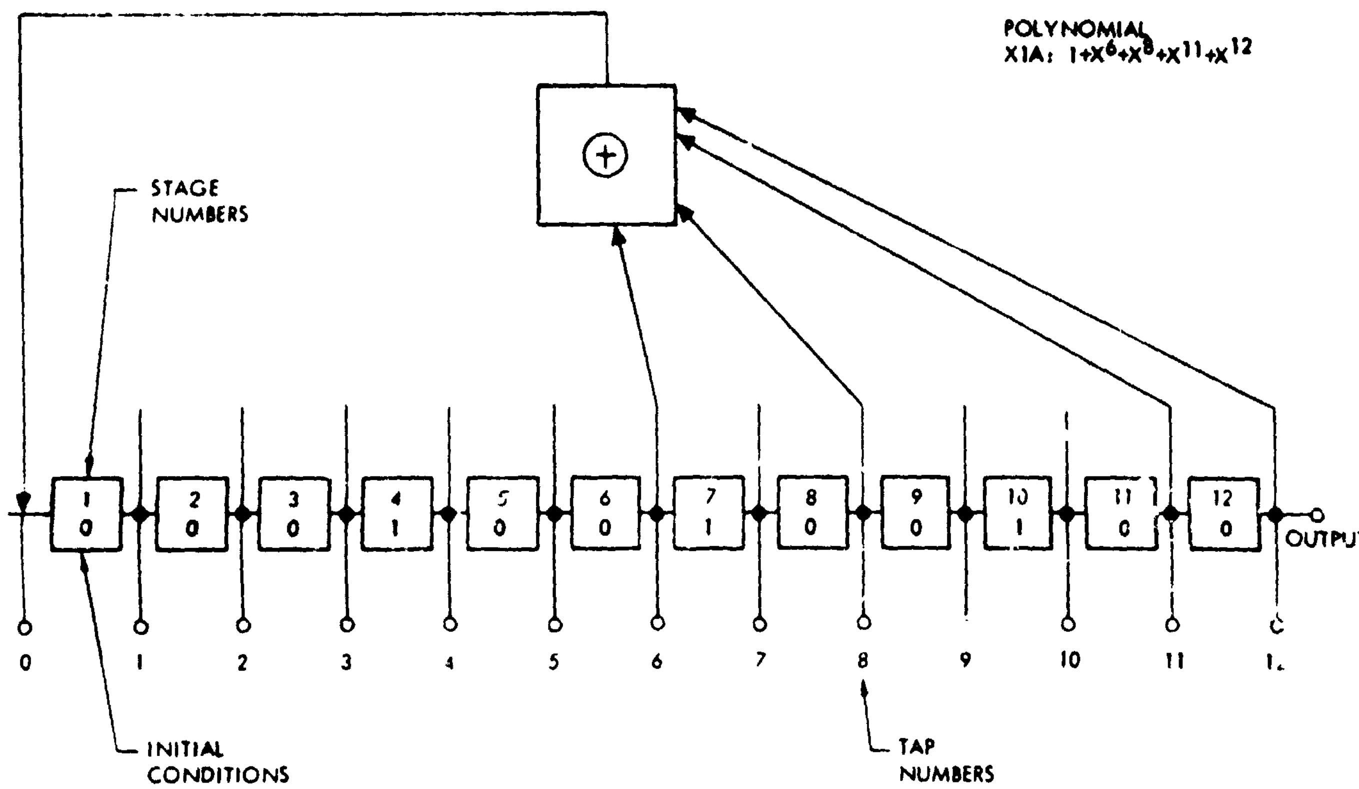

Figure 12. X 1A Shift Register Generator Configuration

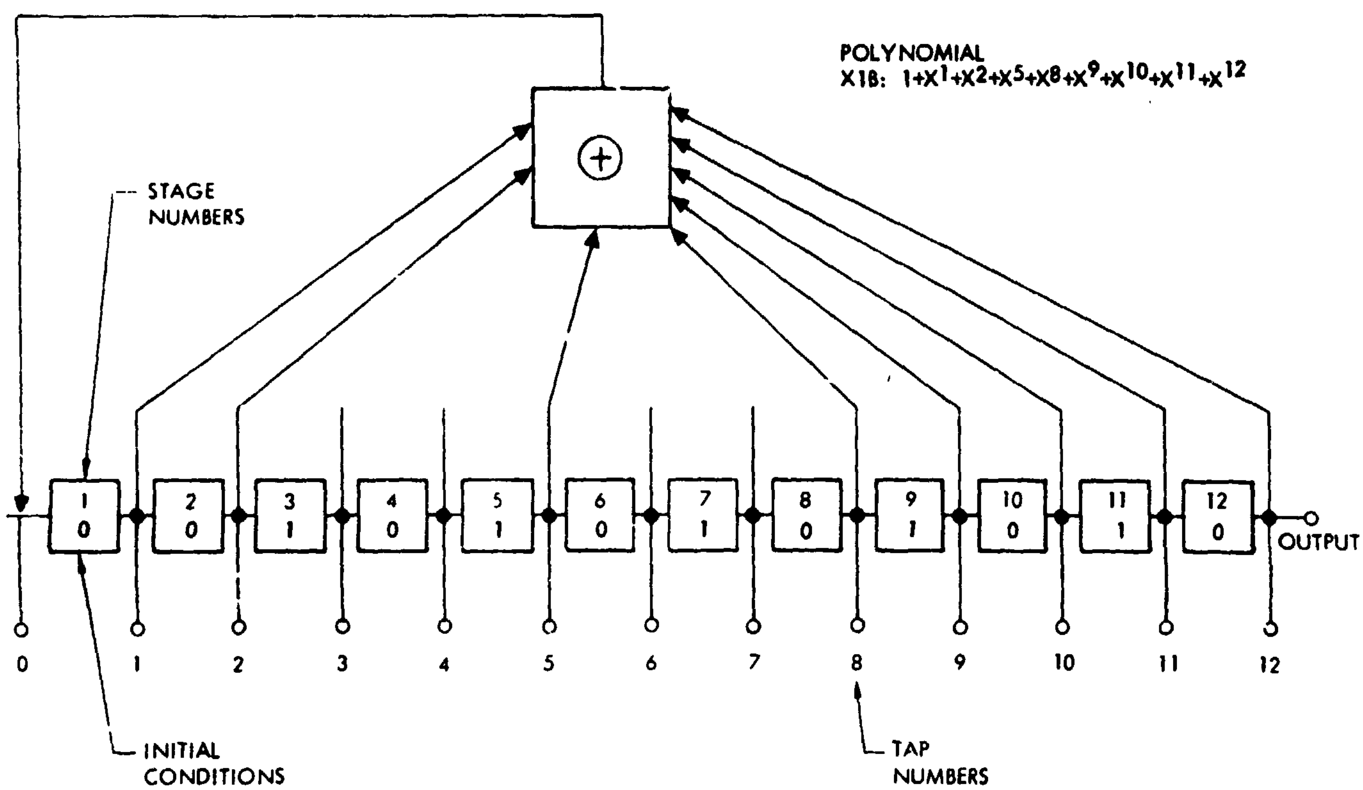

Figure 13. X 1B Shift Register Generator Configuration

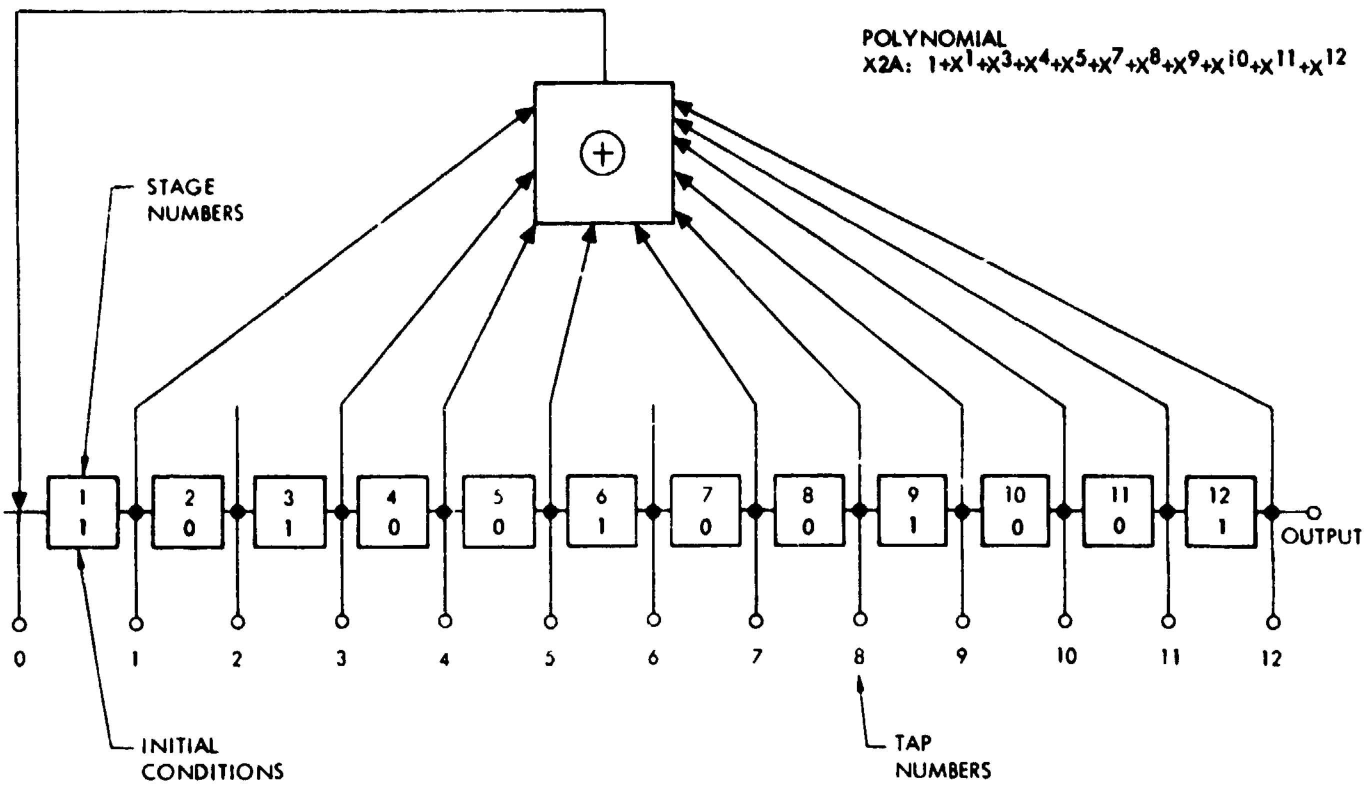

Figure 14. X 2A Shift Register Generator Configuration

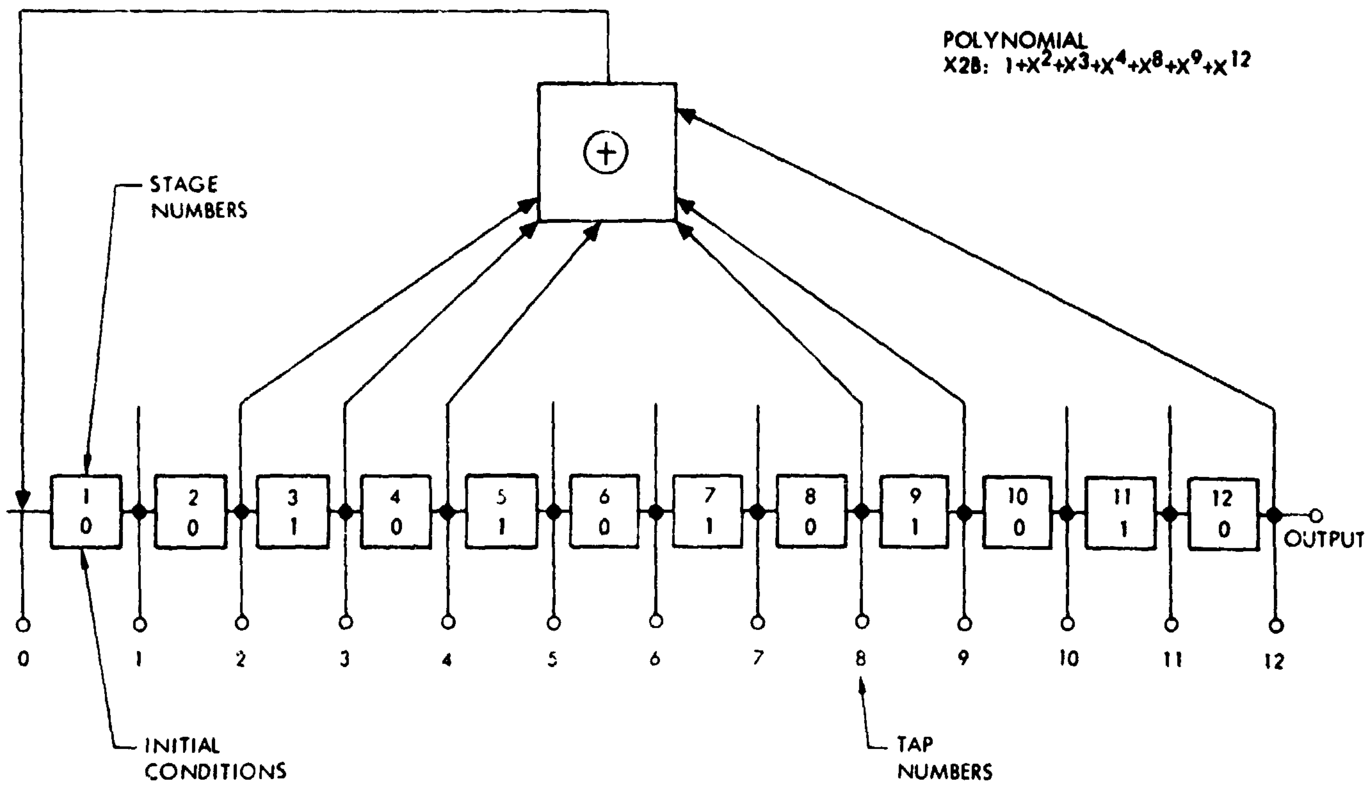

Figure 15. X 2B Shift Register Generator Configuration

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 its cycle, until X1A completes its cycle, whereupon both begin a new epoch at the first 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:

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

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

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 16. (The End-of-week signal occurs 400 usec before the Start-of-week signal.) Signal component timing is shown in Figure 17. The P-code reset timing and the final code vector states are shown in Tables VI and VII, respectively.

3.3.2.8.1.1 Z Count. The Z-count is defined as the 19 bit binary number that is equal to the number of X1 epochs that have occurred since the end of the previous week. The range of the Z-count is from 0 to 403,199. The epoch that is coincident with the start of the present week is defined as the zero state of the Z-counter. The relation between actual Z-count and the Z-count message in the HOW is shown in Figure 18.

3.3.2.8.2 C/A Code Generation. 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 C/A 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 bit 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 19 and 20):

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

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

$G2_i$ phases are chosen by the phase selector which is the Modulo-2 sum of the contents of a pair of stages. The code phases and first ten chips of the C/A code are shown in Table I. The C/A code mechanization is shown in Figure 21. C/A signal timing is shown in Figure 22.

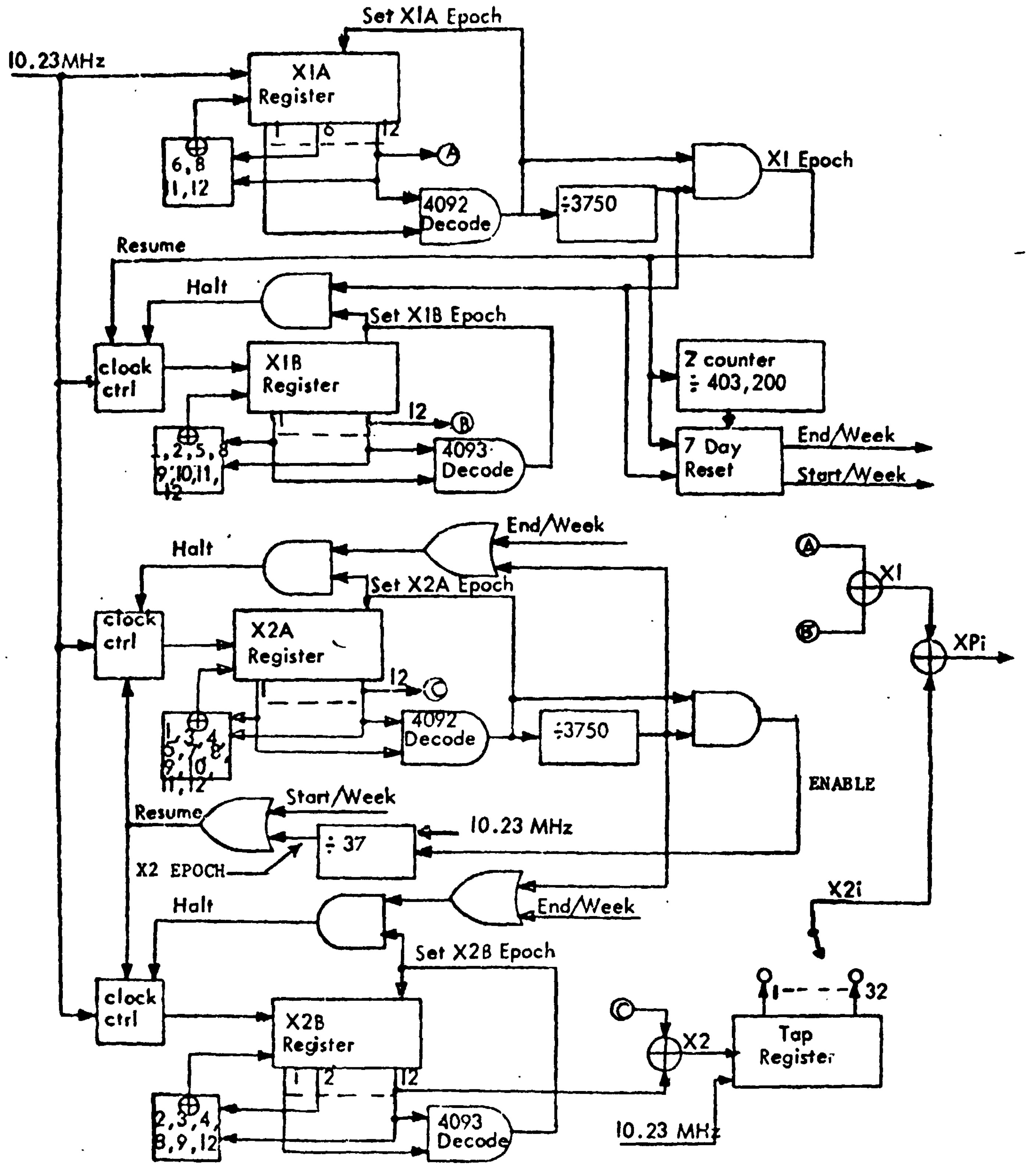

Figure 16. P Code Generation

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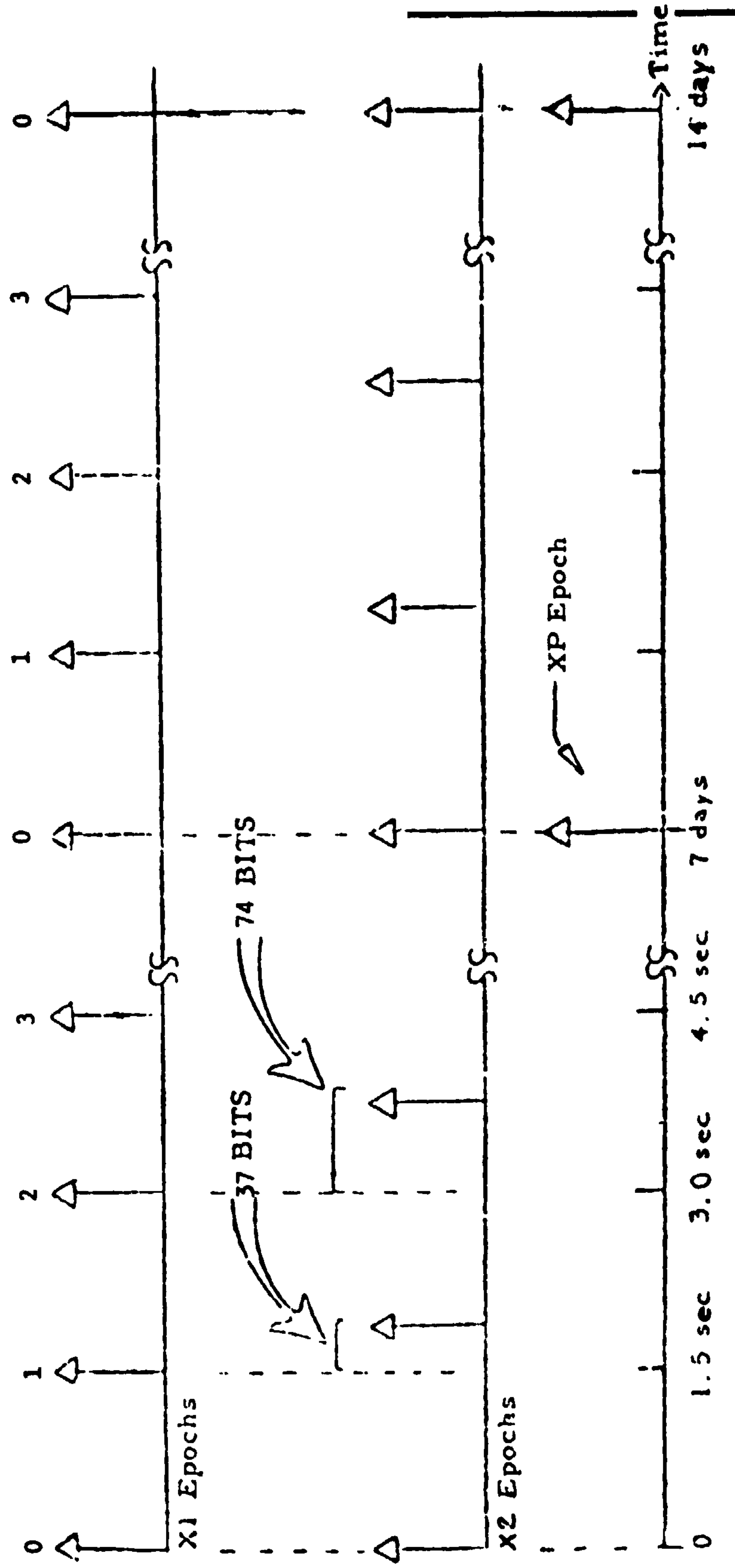

Figure I7. P Signal Component Timing

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Table VI. P-Code Reset Timing
(Last 400 μsec of 7 Day Period)

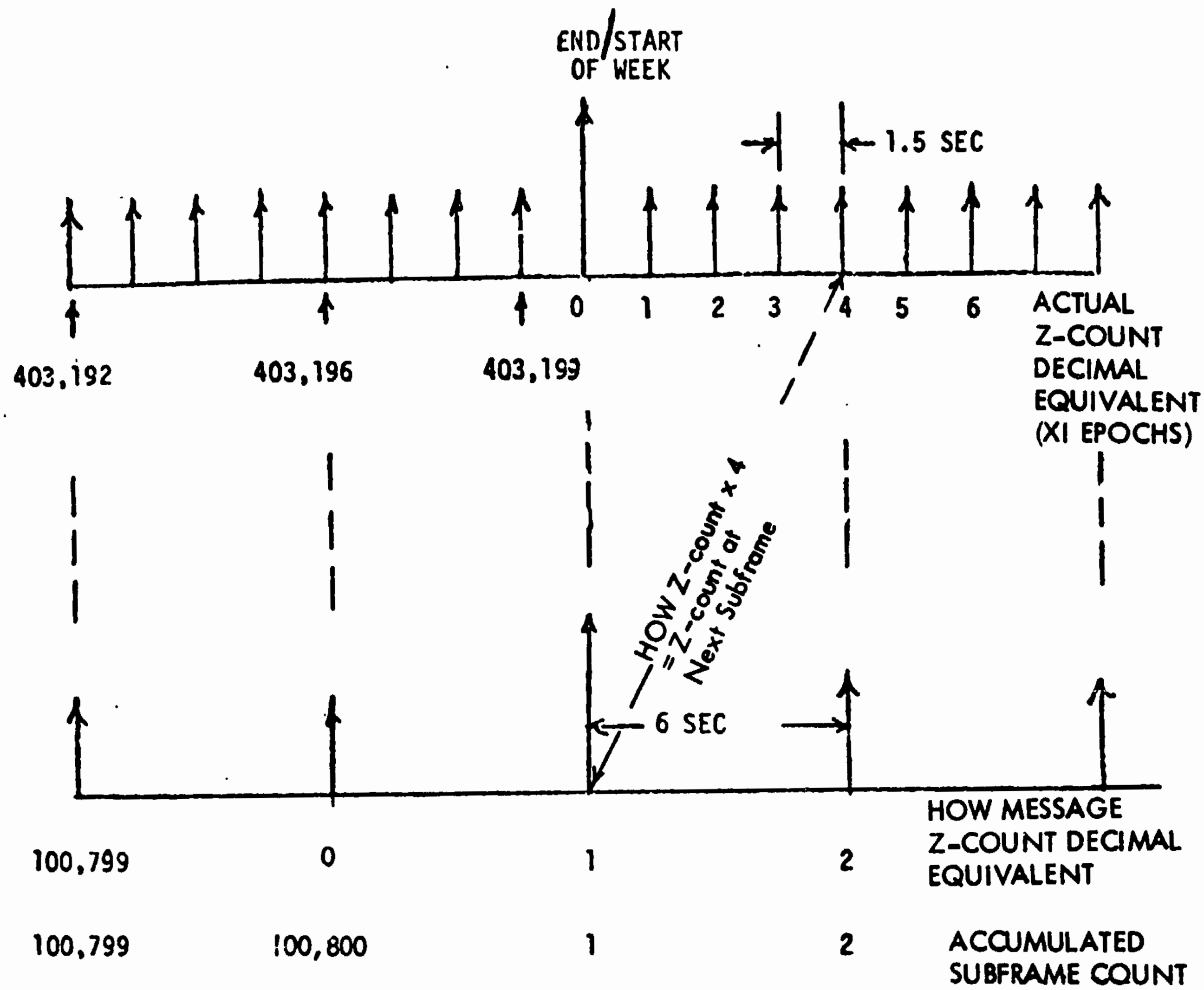
Register And Count			
X1A	X1B	X2A	X2B
1	345	1070	967
.	.	.	.
.	.	.	.
.	.	.	.
3023	3367	4092	3989
.	.	.	.
.	.	.	.
.	.	.	.
3127	3471	4092	4093
.	.	.	.
.	.	.	.
.	.	.	.
3749	4093	4092	4093
.	.	.	.
.	.	.	.
.	.	.	.
4092*	4093	4092	4093

*Last Chip of week

Table VII. Final Code Vector States

	X1A	X1B	X2A	X2B
Chip No. Vector State	4091 100010010010	4092 100101010101	4091 111001001001	4092 000101010101
Chip No. Vector State	4092 000100100100	4093 001010101010	4092 110010010010	4093 001010101010
Vector State for 1st Chip following Epoch	001001001000	010101010100	100100100101	010101010100

Note: First Chip in each sequence is output bit whose leading edge occurs simultaneously with the epoch.



NOTES:

1. HOW Z-count = 17 most significant bits of 19 bit actual Z-count at the start of next subframe. To convert from HOW Z-count to actual Z-count at the start of next subframe, multiply by four.

2. First subframe starts synchronously with End/Start of week epoch.

Figure 18. Time Line Relationship Between Actual Z-Count and HOW Message Z-Count

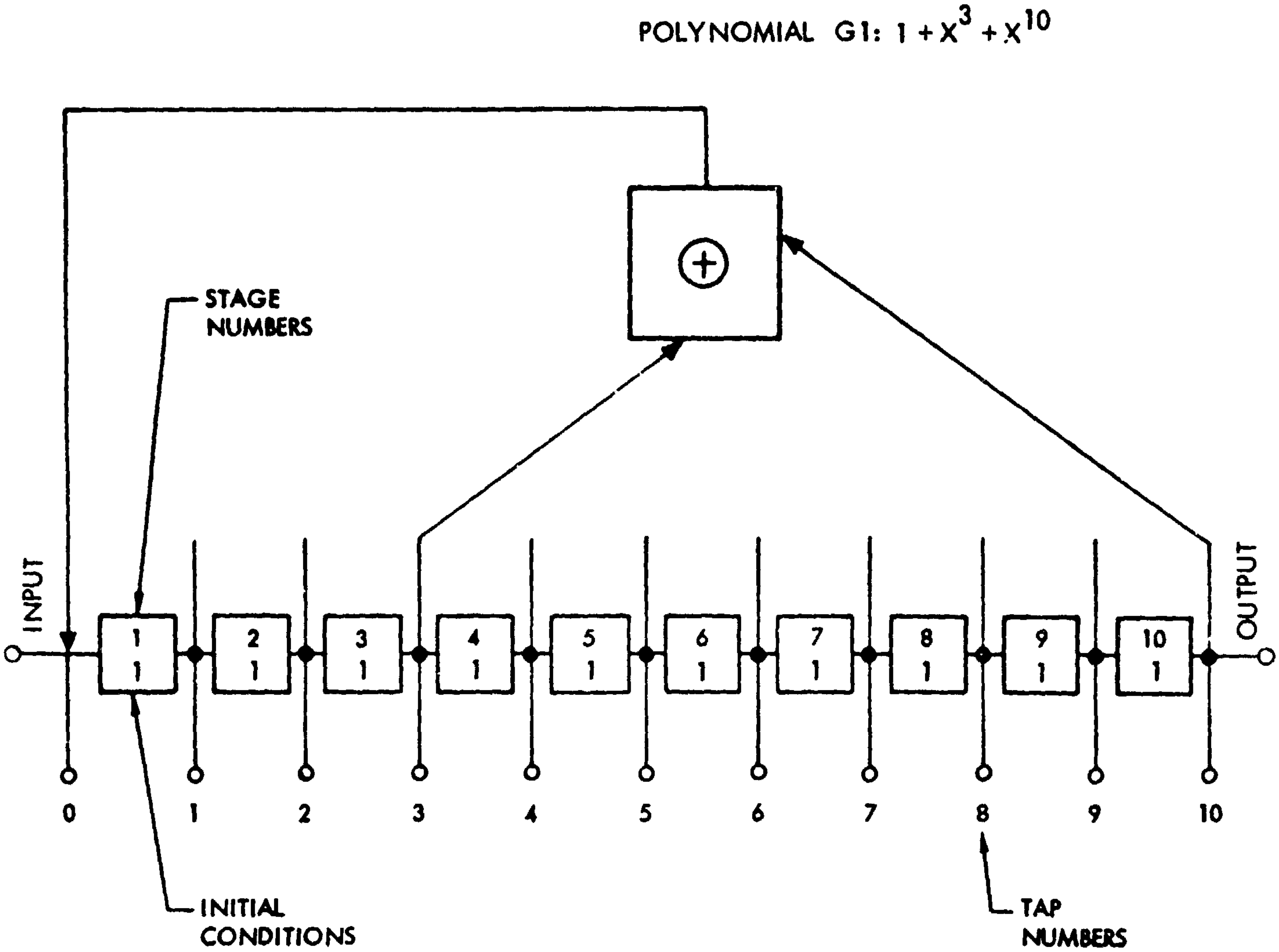


Figure 19. G1 Shift Register Generator Configuration

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

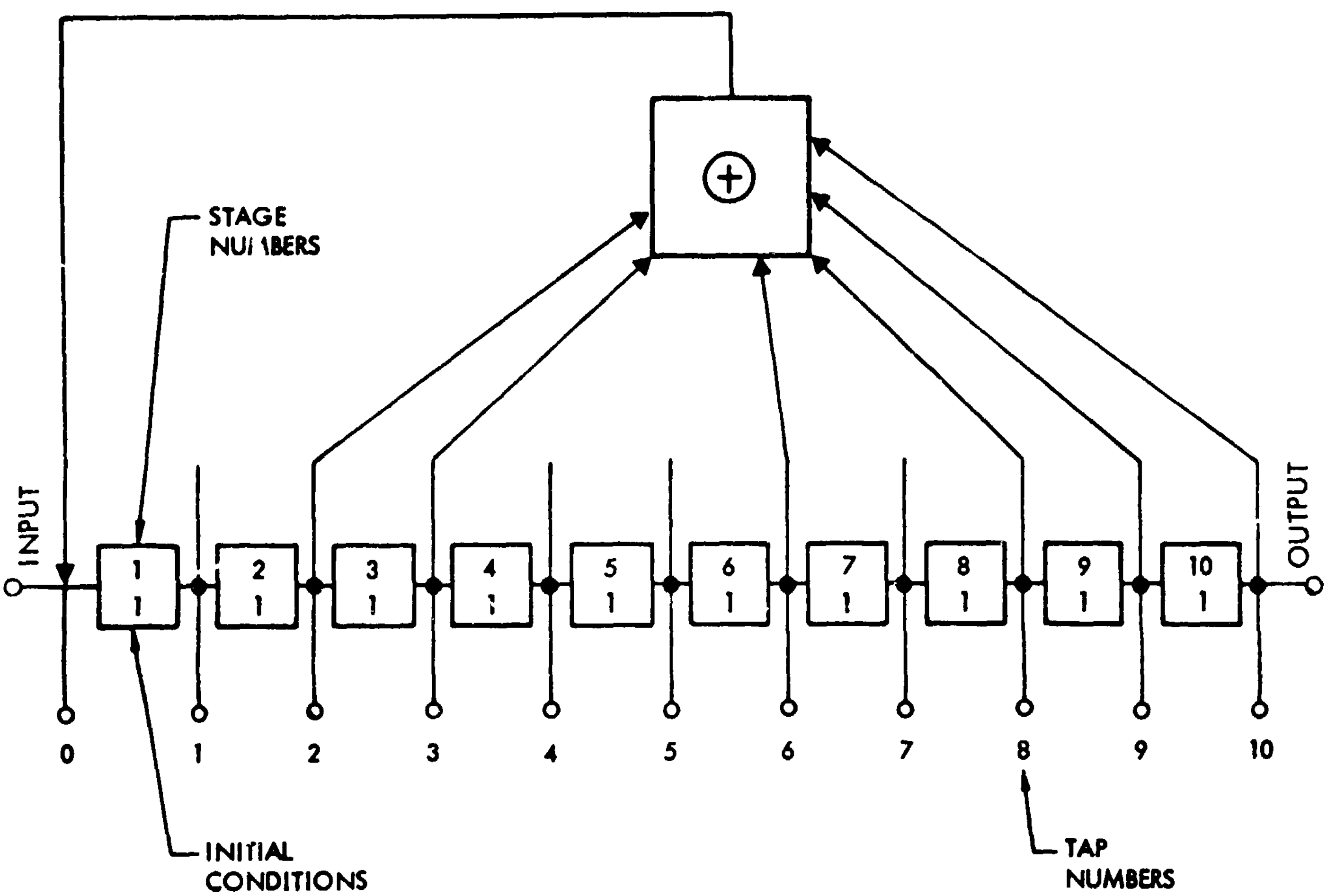


Figure 20. G2 Shift Register Configuration

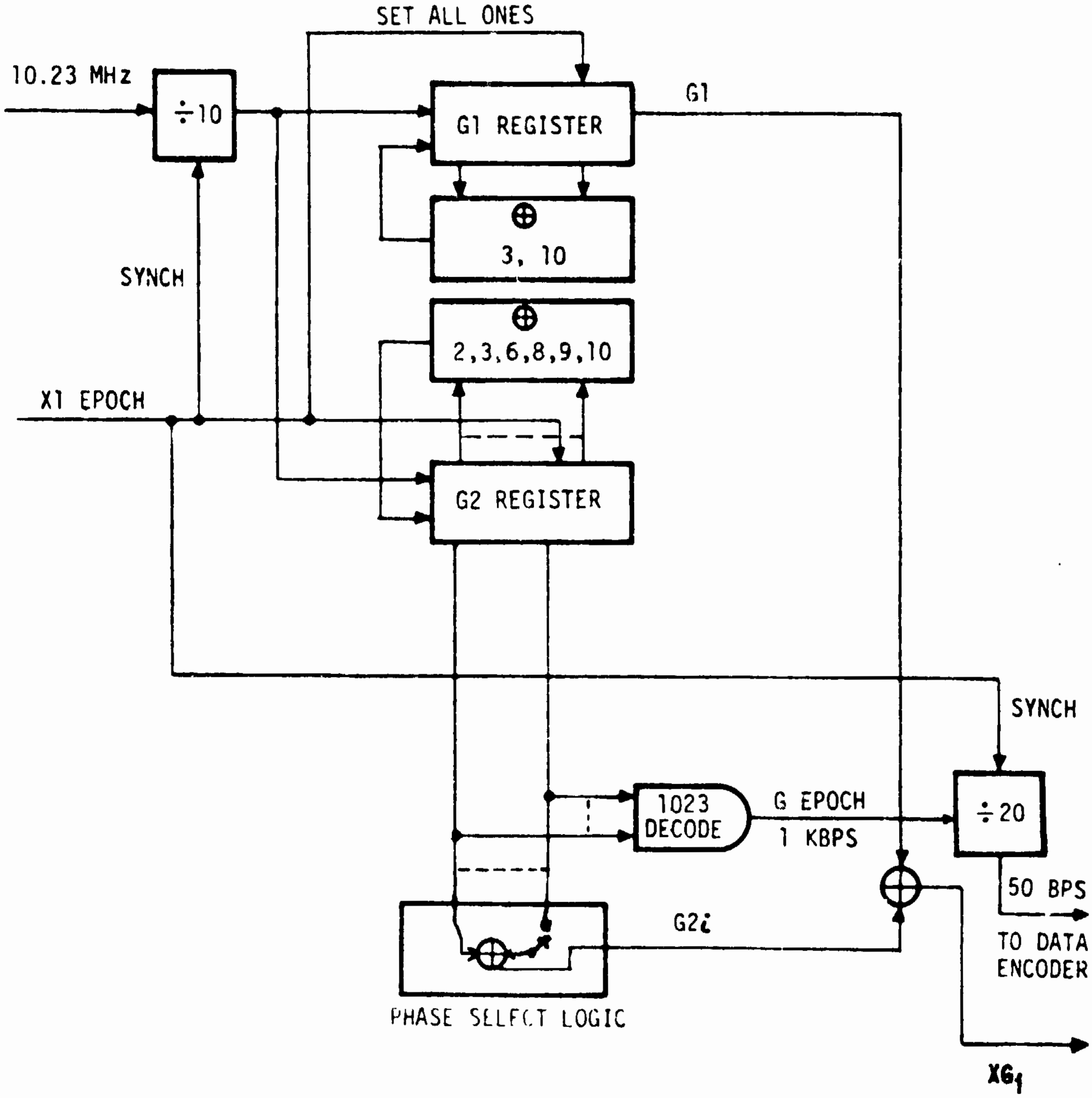


Figure 21. C/A Code Generation

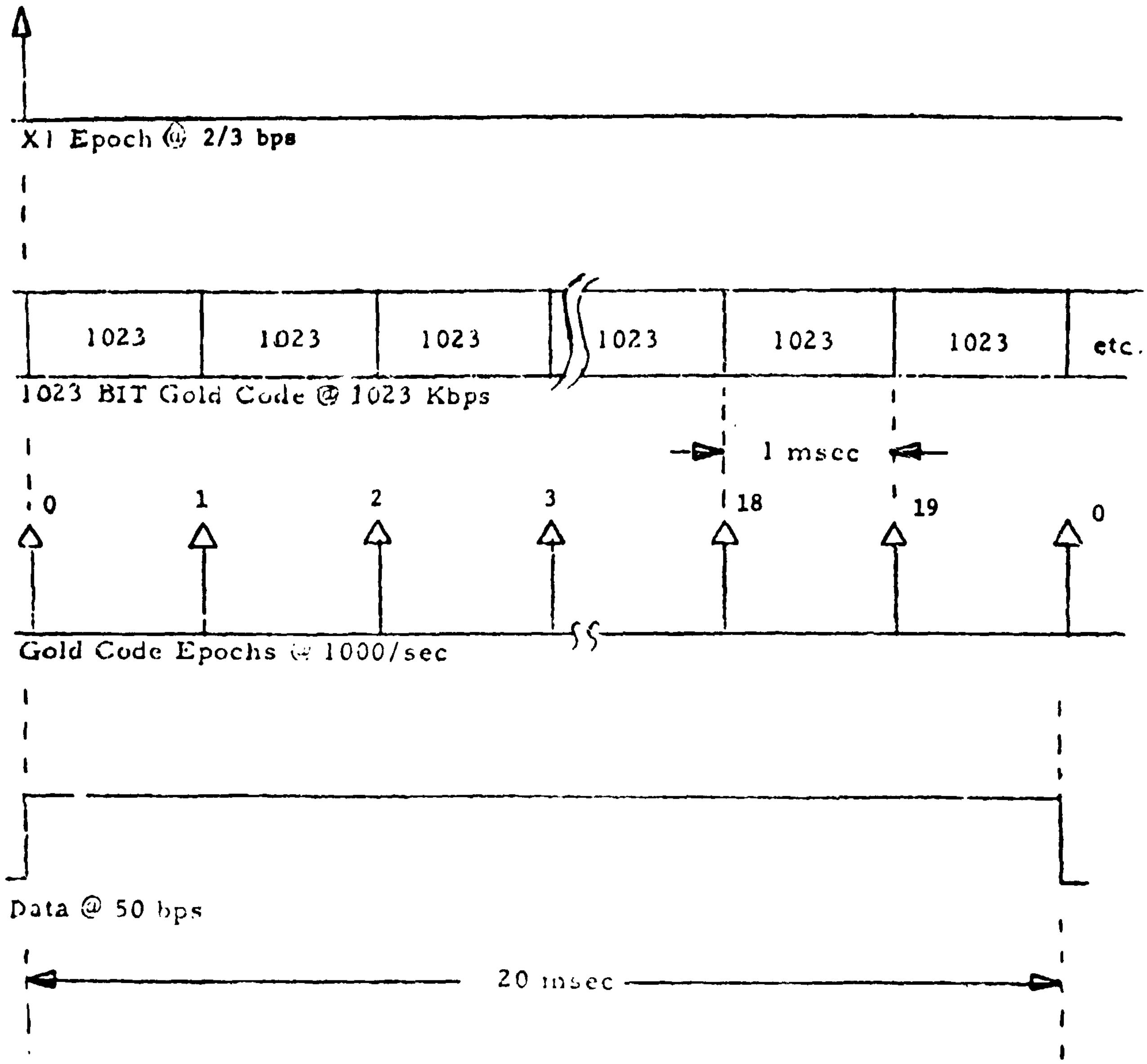


Figure 22. C/A Signal and Data Component Timing

3.3.2.9 Frequency Standard. A highly accurate frequency standard shall be provided as part of the NAV subsystem as a common source for coherently deriving carrier RF signals and for clocking of the PRN generators. The frequency shall be adjustable via the TT&C in steps no smaller than 4×10^{-12} $\Delta f/f$ over a range of $\pm 2 \times 10^{-9}$ $\Delta f/f$ around nominal. The nominal output frequency shall be 10.23 MHz. (See paragraph 3.3.2.9.2 for exact frequency).

3.3.2.9.1 Frequency Standard Drift. Linear frequency drift shall not exceed 1×10^{-12} per day after 24 hours of continuous operation.

3.3.2.9.2 Frequency Accuracy. The exact output frequency of the frequency standard adjusted for relativistic effects shall be 10.22999999545 MHz plus or minus 3.725 parts in 10^9 as maintained by the Control Segment through the AFSCF.

3.3.2.10 Signal Data. The signal data shall allow the user to navigate successfully with the GPS. As a minimum, the signal data shall carry space vehicle ephemerides, system time, space vehicle clock behavior data, transmitter status information, and C/A to P signal handover information. The data stream, D(t), shall be common to both the P and C/A signal on both L_1 and L_2.

3.3.2.10.1 Data Rate and Format. The data shall be non-return to zero, at 50 bps. The data format is as shown in Figure 23. The complete data message shall be called a frame. The frame shall have a length of 1500 bits. Each frame shall be made up of five subframes, each subframe being 300 bits long. Each subframe shall consist of 10 words, each 30 bits long; MSB of all words transmitted first.

3.3.2.10.2 Data Frame Contents. Each data frame shall contain telemetry words (TLM), handover words (HOW), both generated by the SV and data blocks generated by the CS. There shall be no more than 8 data blocks. The data blocks are distributed within the subframes as specified in paragraph 3.3.2.10.5. The contents of the TLM and HOW words and the data blocks are discussed in the following subparagraphs. Two options may exist regarding parity, i.e. Option (1) the SV generates (calculates) parity for the TLM/HOW words only and the CS generates parity for the data words, and Option (2) the SV generates all parity.

Each subframe shall contain a TLM word and a HOW word and shall start with the TLM/HOW pair. The TLM word shall be transmitted first, immediately followed by the HOW. The latter is followed by the data blocks (See Figure 23). Thus, a TLM/HOW pair shall occur every six seconds in the data frame.

3.3.2.10.3 Telemetry Word (TLM). Each TLM word is 30 bits long, occurs every six seconds in the data frame and is the first word in each subframe. The format is as shown in Figure 24. Bit 1 is transmitted first. Each TLM word shall begin with a preamble followed by the TLM message and 6 parity bits. Notification of a roll momentum dump shall be provided by a roll momentum dump flag in the HOW, a five bit function code and eight bits of the truncated Z-count contained in the Z-count buffer of the SV processor at the initialization of the roll momentum dump. (See Figure 25). These eight bits are obtained as follows: Of the 19 bits Z-count, the three most significant bits are truncated and the eight least significant bits are truncated. The remaining eight bits are placed into bit positions 15 through 22 of the TLM word (See Figure 25). Of any number of roll momentum dumps, the last one will be recorded. After a momentum dump has taken place, the truncated Z-count for the momentum dump is over-written when any other telemetry request has been processed. The contents of the TLM message are shown in Table VIII.

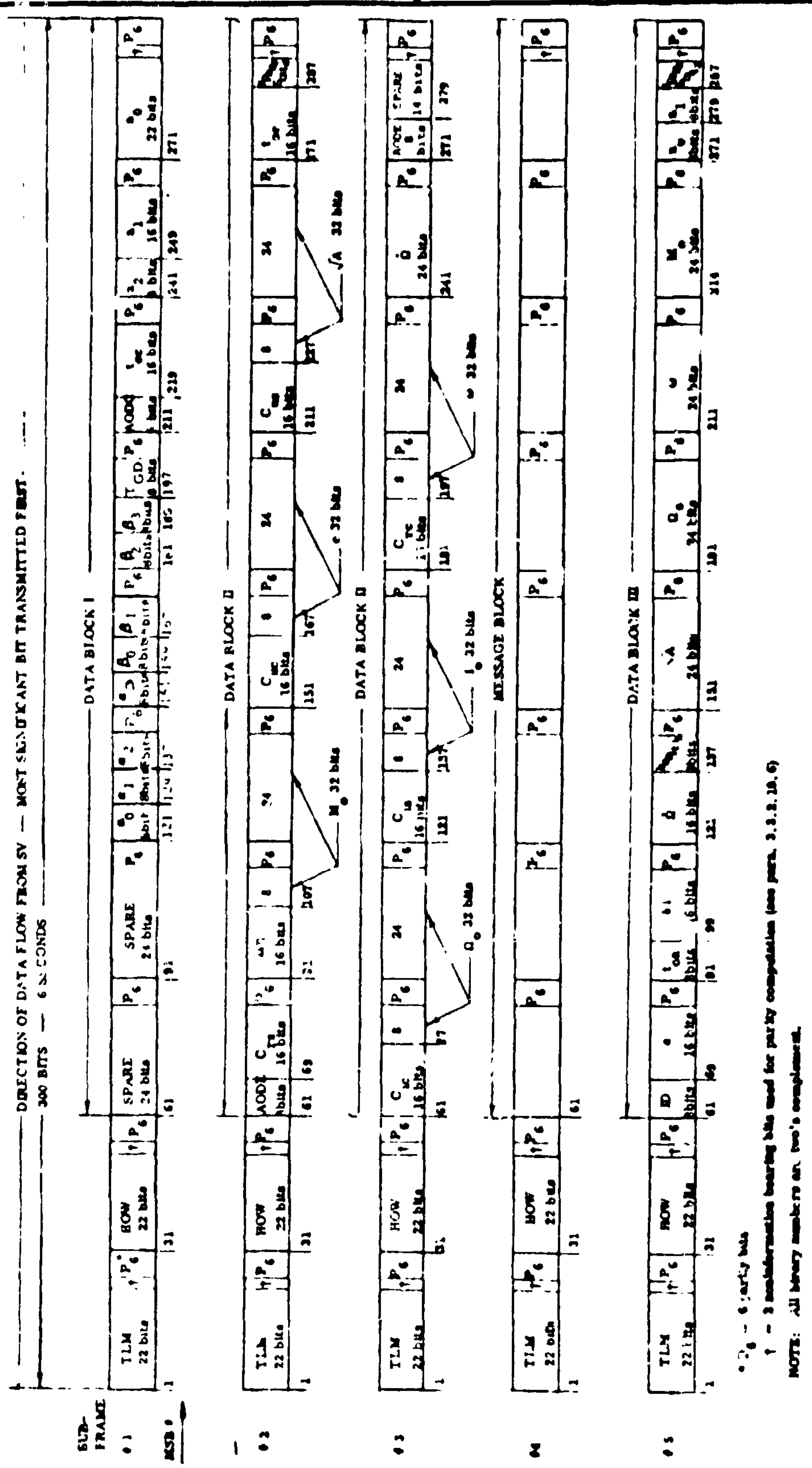


FIGURE 23. SIGNAL DATA FRAME CONTENT

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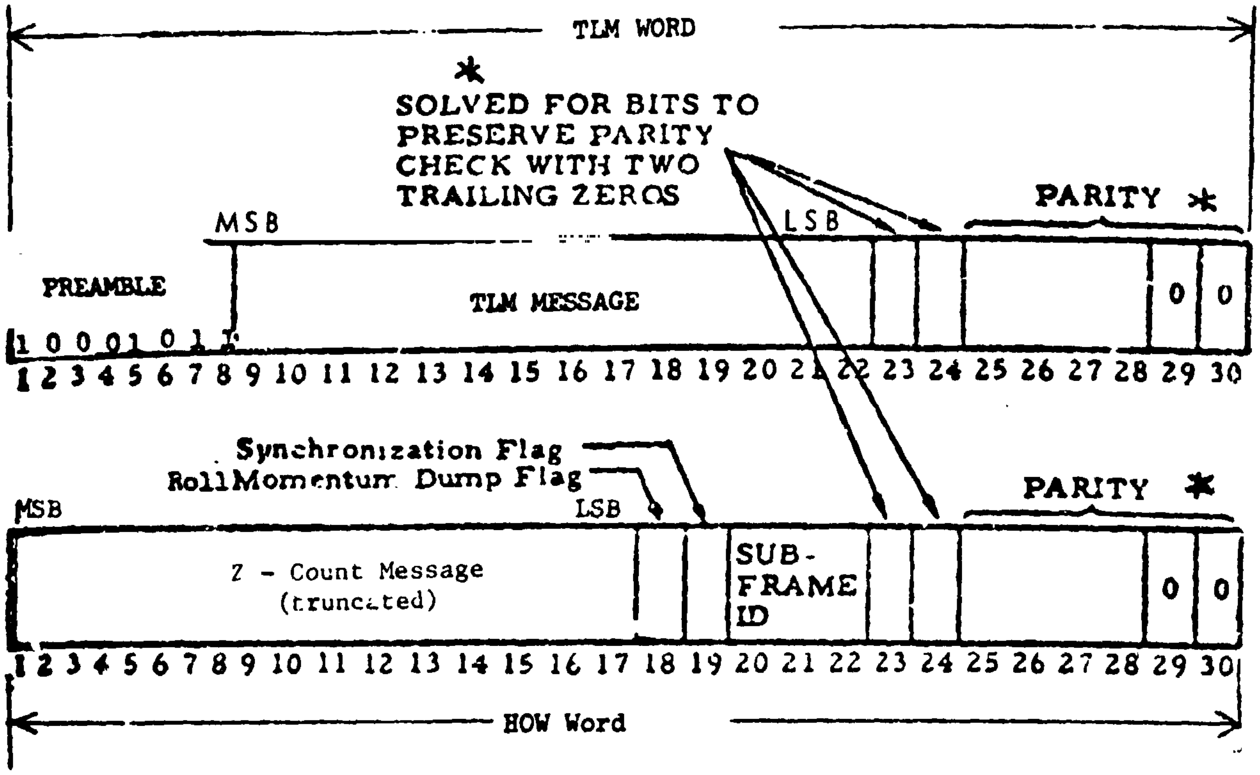

* As shown when TLM/HOW Parity Encoding only is selected. (Option 1) When Parity Encoding for all data is selected, bits 23 a d 24 contain non-information bearing data, and bits 29 and 30 contain 0 or 1, as required. (Option 2)

Figure 24. TLM/HOW Message Format

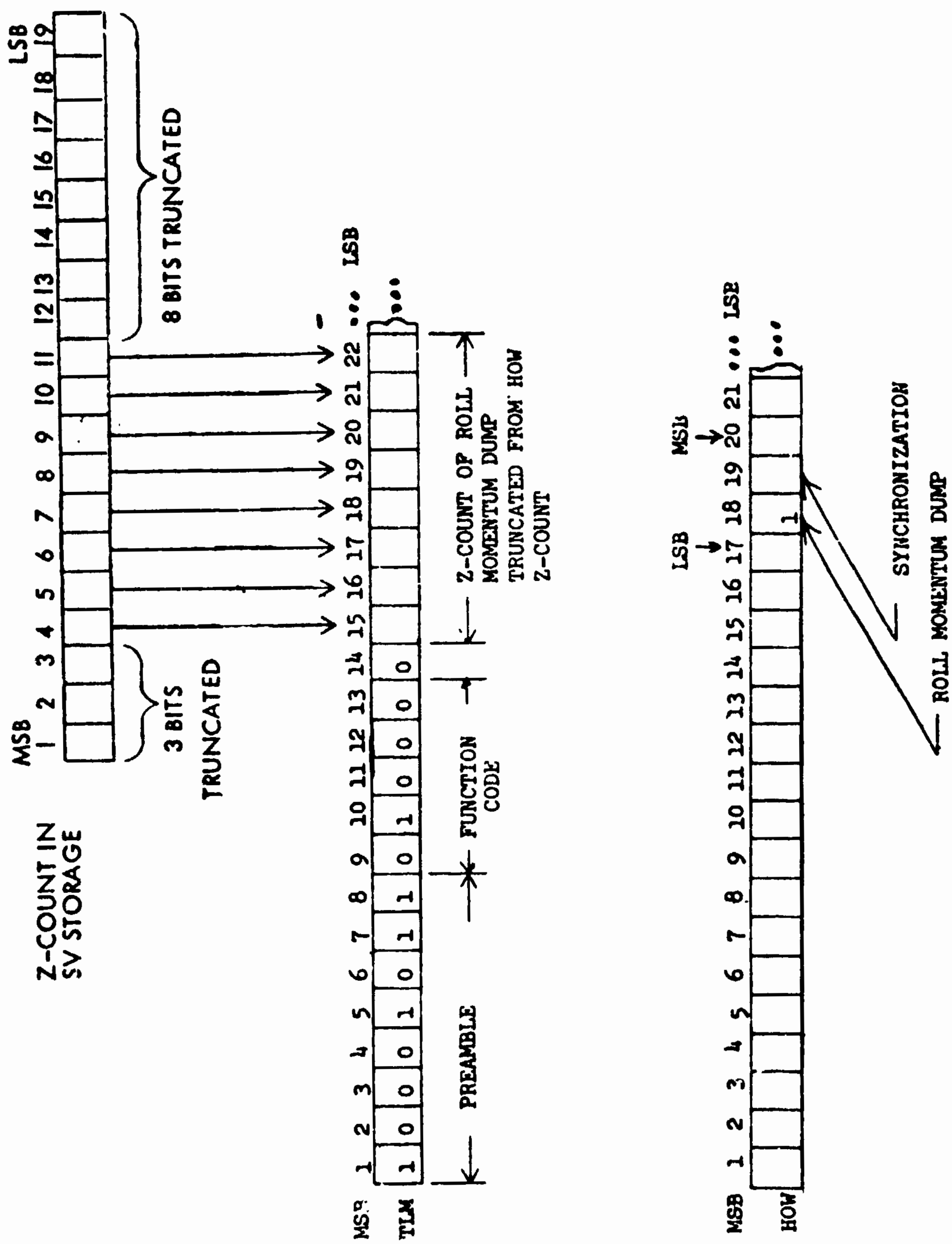

Figure 25. Roll Momentum Dump as Shown in TLM and HOW Words

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Table VIII. TLM Message Contents

	State	Function Code Bits 1 to 5	Magnitude Bits 6 to 14	Remarks
PRIMARY UPLOAD STATUS	Indeterminate/EOM	00000	000000000	End of message block received.
	Indeterminate Timeout While S-bits Are Not Being Transmitted	00000	111111111	This message will be present upon the occurance of a primary or alternate upload timeout. Occurs only after an upload data block.
	Indeterminate Timeout While S-bits Are Being Transmitted	00000 or 00000 or 00001	111111111 or 111100100 or 111100100	One of these messages will be present upon the occurance of a primary or alternate upload timeout. Occurs only after an upload data block.
	Symbol Error	11000	0000 0 (1 0 S D/A)	The illegal pattern is transmitted in the rightmost 4 bits of the magnitude.***
	S in Word	11001	Word count where** S occurred; right adjusted	S occurred illegally in bit position 2 through 17.
	Word Parity Error	11010	Word count of** parity error; right adjusted	Bad parity in indicated word. Word count applies only to upload data block.
	Word Count Error	11011	Illegal word** count, right adjusted	First S occurred in bit position 1 but the resultant word count was in disagreement with word count header. Pertains to upload data blocks only.
	Checksum Error	11100	000000000	Imprc er checksum. Block unidentified. Applies to upload data blocks only.
	Attempt to Write in Protected Area	11110	000 (data block number)	This is the only error message containing the block number.
	Address Reject	11101	00000 (pointer)	Pointer +1 points to currently effective address. Pointer is an integer from 0 to 15 inclusive.
	Address Accept	00010	000000000	Address block is considered to be block zero.
	Block Accept	00010	000 (block number)	Block accept with no errors.
DIAGNOSTIC	Diagnostic Test Passed	10000	111110010	Test Result is Go*
	Diagnostic Test Not Passed	10000	111110100	Test Result is No-Go*
	Attempt to Test Protected Page	10000	111111000	*
	RAM Dump	10000	0 (8 RAM bits)	Messages occur sequentially until requested memory dump has been completed.
OTHER	Bootstrap Routine Has Executed	00000	000000000	Initializes to same code as Indeterminate/EOM; message stands until overwritten by any other message.
	Roll Momentum Dump Has Occurred	01000	0 (Z-Count, truncated)	Most recent roll momentum dump time is recorded, with 3 MSB and 8 LSB truncated.

Status Message Priority
- 1st: New block accept
- 2nd: Untransmitted previous block accept
- 3rd: First error in block
- 4th: Roll Momentum Dump

Notes
1. Primary upload status error message listed in the table, if received, indicates that error types listed earlier in the table did not occur.
2. An alternate upload by the AFSCF or any other AFSCF command will result in a Primary Upload status error indicated. Usually this error indication will be for a word parity error but other error indications, i.e., symbol error parity error, S in word, Word Count Error and Checksum Error are possible.
3. Shutdown of the SV command receiver will probably result in a symbol error indication or possibly an S in word indication.

*Function code and magnitude appear as shown for one subframe and are then superseded by function code and magnitude that were previously present.
**Word count in magnitude field is actual word count minus 1 (one).
***A one (1) is set for each of the 4 symbol components that is present. If all 4 bits are 0 they will be reported as all 1's via NAV Data TLM.

3.3.2.10.4 Handover Word (HOW). The HOW shall be 30 bits long and shall be the second word in each subframe immediately following the TLM word. A HOW occurs every six seconds in the data frame. The format and content of the HOW shall be as shown in Figure 24. The MSB is transmitted first. The HOW begins with the upper-most significant 17 bits of the Z-count. These 17 bits correspond to the Z-count at the X1 epoch which occurs at the start (leading edge) of the next following subframe. Bit 18 is reserved for the roll momentum dump flag and bit 19 for a synchronization flag. The roll momentum dump flag (a "1" in bit 18) indicates that a roll momentum dump has occurred since the last upload. This flag is reset at a new End-of-Message transmission at the conclusion of the next upload. When bit 19 is "0", the SV is in synchronization. Synchronization is defined as the condition in which the leading edge of the TLM word is coincident with the X1 epoch. If bit 19 is a "1", this condition does not exist, i.e., the SV is not in synchronization and further data may be erroneous. Bits 20 through 22 contain the Subframe Identification. These three bits show which subframe it is within the frame (See Table IX).

Table IX. Subframe Identification

Bit →	20	21	22	Subframe
	0	0	1	1
	0	1	0	2
	0	1	1	3
	1	0	0	4
	1	0	1	5

3.3.2.10.5 Data Block Contents. The contents of the data blocks are described in the following subparagraphs.

3.3.2.10.5.1 Data Block I. The content of Data Block I shall be the SV clock correction parameters. These parameters shall be the three polynomial coefficients, a_0, a_1 and a_2, the L_1-L_2 correction term for the L_1 only User, T_{GD}, the eight ionospheric correction parameters α_n and β_n; n = 0, 1, 2 & 3; a reference GPS time since weekly epoch, t_{oc}, and the age of data (clock), AODC. The GPS weekly epoch shall occur at midnight Saturday night - Sunday morning (see paragraph 3.1.4).

The polynomial shall describe the SV PRN code phase offset referenced to the phase center of the antennae, Δt_{SV} with respect to GPS system time, t, at the time of data transmission. These coefficients describe the offset for the interval of time (one hour as a minimum) in which the parameters are transmitted. The polynomial shall also describe the offset for an additional one-half hour (i.e., one-half hour subsequent to the beginning of transmission of the next set of coefficients) to allow the user time to receive the message for the new interval of time (one hour as a minimum).

The age of data word (AODC) shall provide the user with a confidence level in the SV clock correction. AODC represents the time difference (age) between the Data Block I reference time (t_{oc}) and the time of the last measurement update (t_L) used to estimate the correction parameters. That is,

$$AODC = t_{oc} - t_L$$

AODC shall indicate the GPS time of week at which the correction parameters were estimated, to provide the User with a confidence level in the SV clock correction.

3.3.2.10.5.1.1 SSO GPS Receiver/Processor Algorithm for SV clock correction. The SSO GPS Receiver/Processor shall correct the time received from the SV with the equation (in seconds)

$$t = t_{SV} - \Delta t_{SV} \quad (1)$$

where

$$\Delta t_{SV} = a_0 + a_1 (t - t_{oc}) + a_2 (t - t_{oc})^2 \quad (2)$$

Here

t ~ GPS time (seconds)

t_{SV} ~ SV PRN code phase time at message transmission time (seconds)

t_{oc} ~ Data Block I reference time (seconds)

a_0, a_1, a_2 ~ Data Block I parameters

Note that equations 1 and 2 as written are coupled. While the coefficients a_0, a_1 and a_2 are generated by using GPS time as indicated in equation 2, sensitivity of t_{SV} to t is negligible. This negligible sensitivity will allow the SSO GPS Receiver/Processor to approximate t by t_{SV} in equation (2). Since GPS time spans only one week, the value of t must account for beginning or end of week crossovers. That is, if the quantity $t-t_{oc}$ is greater than 302400, subtract 604800 from t. If the quantity $t-t_{oc}$ is less than -302400, add 604800 to t.

The parameters a_0, a_1 and a_2 shall include all general relativistic effects of the SV clock. The relativistic effects shall be included in the coefficients by the MCS as follows:

$$\bar{a} = \bar{a}_m + \bar{a}_r$$

where

$\bar{a}$ ~ the vector of clock coefficients in Data Block I

$\bar{a}_m$ ~ a vector of clock coefficients generated by using the clock model, excluding relativistic effects

$\bar{a}_r$ ~ a vector of coefficients due to relativity, generated as follows:

$$a_{0r} = -4.443 \times 10^{-10} \frac{\text{sec}}{\sqrt{\text{meter}}} e \sqrt{A} \sin E (t_{oc})$$

$$a_{1r} = -4.443 \times 10^{-10} \frac{\text{sec}}{\sqrt{\text{meter}}} e \sqrt{A}\, n \cos E (t_{oc})/[1-e \cos E (t_{oc})]$$

$$a_{2r} = 2.2215 \times 10^{-10} \frac{\text{sec}}{\sqrt{\text{meter}}} e \sqrt{A}\, n^2 \sin E (t_{oc})/[1-e \cos E (t_{oc})]^2$$

The orbit parameters used here are described in discussions for Data Block II (paragraph 3.3.2.10.5.2).

These coefficients are sufficiently accurate to the extent that the approximations given below are valid:

$$\sin n\,(t-t_{oc}) \approx n\,(t-t_{oc})$$

and

$$\cos n\,(t-t_{oc}) \approx 1 - \frac{n^2}{2}\,(t-t_{oc})^2$$

For e = .02, and $t-t_{oc}$ < 45 min. these approximations provide errors less than .5 nanosecond. After 45 minutes these errors of approximation degrade as:

$t-t_{oc}$	error
1 hr	1 ns
2 hr	8 ns
3 hr	26 ns
4 hr	60 ns

This form of correction for relativity does not provide a graceful degradation to the clock correction. The user may achieve more graceful degradation if he subtracts the vector $\bar{a}_r$ from the coefficients received in Data Block I and corrects time with both the resulting polynomial and with the offset due to relativity given by,

$$\Delta t_r = \left(-4.443 \times 10^{-10}\ \frac{\text{sec}}{\sqrt{\text{meter}}}\right) e\,\sqrt{A}\,\sin E\,(t)$$

thus,

$$\Delta t_{SV} = (a_0 - a_{0r}) + (a_1 - a_{1r})\,(t-t_{oc}) + (a_2 - a_{2r})\,(t-t_{oc})^2 + \Delta t_r$$

3.3.2.10.5.1.2 Data Block I Format. Data Block I shall occupy the third through tenth 30 bit words (including parity) of the first subframe (see Figure 23). The third and fourth 30 bit words of the first subframe (see Figure 23) are spares. The spare words shall contain a simple bit pattern in the information bearing bits (i.e., bits 1-24) and parity in the remaining 6 bits.

The number of bits, the scale factor of the least significant bit (LSB), which shall be the last bit received, the range and the units of the parameters shall be as specified in Table X.

3.3.2.10.5.2 Data Block II. The content of Data Block II shall be the ephemeris representation parameters. These parameters shall be an extension to Keplerian Orbital Parameters describing the orbit during the interval of time (nominally one hour) for which the parameters shall be transmitted. They shall also describe the orbit for an additional one-half hour to allow the user time to receive the message for the new interval of time (one hour). The definitions of the parameters are given in Table XI.

The age of data word (AODE) shall provide the user with a confidence level in the emphemeris representation parameters. AODE represents the time difference (age) between the Data Block II reference time (t_{oe}) and the time of the last measurement update (t_L) used to estimate the representation parameters. That is,

Table X. Data Block I Parameters

Parameter	No. of Bits	Scale Factor (LSB)	Range	Units
Spare	24	-	-	-
Spare	24	-	-	-
α_0	8	2^{-31}	$\pm 2^{-24}$	seconds
α_1	8	2^{-31}	$\pm 2^{-24}$	seconds
α_2	8	2^{-29}	$\pm 2^{-22}$	seconds
α_3	8	2^{-28}	$\pm 2^{-21}$	seconds
β_0	8	2^{8}	$\pm 2^{15}$	seconds
β_1	8	2^{9}	$\pm 2^{16}$	seconds
β_2	8	2^{10}	$\pm 2^{17}$	seconds
β_3	8	2^{12}	$\pm 2^{19}$	seconds
T_{GD}	8	$2^{-31} \simeq 4.66 \times 10^{-10}$	$\pm 2^{-24} \simeq \pm 5.96 \times 10^{-8}$	seconds
AODC	8	$2^{11} = 2048$	$2^{19} = 524288$	seconds
t_{oc}	16	$2^{4} = 16$	604,784	seconds
a_2	8	$2^{-55} \simeq 2.78 \times 10^{-17}$	$\pm 2^{-48} \simeq \pm 3.553 \times 10^{-15}$	sec/sec^2
a_1	16	$2^{-43} \simeq 1.14 \times 10^{-13}$	$\pm 2^{-28} \simeq \pm 3.725 \times 10^{-9}$	sec/sec
a_0	22	$2^{-31} \simeq 4.656 \times 10^{-10}$	$\pm 2^{-10} \simeq \pm 9.766 \times 10^{-4}$	seconds

(±) indicates that sign bit shall occupy the most significant bit (MSB)

NOTE: All binary numbers will be two's complement.

Table XI. Elements of Coordinate Systems

$\mu = 3.986008 \times 10^{14} \frac{\text{meters}^3}{\text{sec}^2}$	WGS 72 VALUE OF THE EARTH'S UNIVERSAL GRAVATIONAL PARAMETER
$\dot{\Omega}_e = 7.292115147 \times 10^{-5} \frac{\text{rad}}{\text{sec}}$	WGS 72 VALUE OF THE EARTH'S ROTATION RATE
$A = (\sqrt{A})^2$	SEMI-MAJOR AXIS
$n_o = \sqrt{\frac{\mu}{A^3}}$	COMPUTED MEAN MOTION
$t_k = t - t_{oe}$*	TIME FROM EPOCH
$n = n_o + \Delta n$	CORRECTED MEAN MOTION
$M_k = M_o + nt_k$	MEAN ANOMALY
$M_k = E_k - e \sin E_k$	KEPLER's EQUATION FOR ECCENTRIC ANOMALY
$\cos v_k = (\cos E_k - e) / (1 - e \cos E_k)$ $\sin v_k = \sqrt{1 - e^2} \sin E_k / (1 - e \cos E_k)$	TRUE ANOMALY
$\phi_k = v_k + \omega$	ARGUMENT OF LATITUDE
$\delta u_k = C_{us} \sin 2\phi_k + C_{uc} \cos 2\phi_k$	Argument of Latitude Correction — SECOND HARMONIC PERTURBATIONS
$\delta r_k = C_{rc} \cos 2\phi_k + C_{rs} \sin 2\phi_k$	Radius Correction — SECOND HARMONIC PERTURBATIONS
$\delta_{ik} = C_{ic} \cos 2\phi_k + C_{is} \sin 2\phi_k$	Correction to Inclination — SECOND HARMONIC PERTURBATIONS
$u_k = \phi_k + \delta u_k$	CORRECTED ARGUMENT OF LATITUDE
$r_k = A(1 - e \cos E_k) + \delta r_k$	CORRECTED RADIUS
$i_k = i_o + \delta_{ik}$	CORRECTED INCLINATION
$x'_k = r_k \cos u_k$ $y'_k = r_k \sin u_k$	POSITIONS IN ORBITAL PLANE
$\Omega_k = \Omega_o + (\dot{\Omega} - \dot{\Omega}_e) t_k - \dot{\Omega}_e t_{oe}$	CORRECTED LONGITUDE OF ASCENDING NODE
$x_k = x'_k \cos\Omega_k - y'_k \cos i_k \sin\Omega_k$ $y_k = x'_k \sin\Omega_k + y'_k \cos i_k \cos\Omega_k$ $z_k = y'_k \sin i_k$	EARTH FIXED COORDINATES

*t is GPS system time at time of transmission, i.e., GPS time corrected for transit time (range/speed of light). Furthermore, t_k shall be the actual total time difference between the time t and the epoch time t_{oe}, and must account for beginning or end of week crossovers. That is, if t_k is greater than 302400, subtract 604800 from t_k. If t_k is less than -302400, add 604800 to t_k.

3.3.2.10.5.2.1 SSO GPS Receiver/Processor Algorithm for SV Ephemeris Determination. The SSO GPS Receiver/Processor shall compute the earth fixed coordinates of position of the SV's antenna phase center with a variation of the equations shown in Table XI. Data Block II parameters are Keplerian in appearance. The value of these parameters, however, are obtained via a least squares curve fit of the predicted SV antenna phase center ephermeris (time-position quadruples; t, x, y, z).

The figure of merit used to measure the quality of the above referenced curve fit is User Equivalent Range Error (UERE). UERE is the projection of the curve fit error onto the User range. The curve fit procedure used provides UERE to the predicted SV ephemeris of less than .01 meter, one sigma. Truncation of Data Block II parameters increases the one sigma error to .1 meter. UERE increases when Data Block II parameters are used beyond their period of applicability. The degradation is as follows: Data Block II information is changed nominally each hour. Define Block II - ONE to be the information in Data Block II during the first hour in which the SV is tracked. Similarly define Block II - TWO to be the second hours information. Now define t_2 to be that time when the SV stops transmitting Block II - ONE and starts transmitting Block II - TWO. During the time t_2 to t_2 + 1/2 hour, use of Block II - ONE causes no degradation due to a time overlap enforced in the curve fit process. At the time t_2 + 1 hour, Block II - ONE will provide UERE of about 1 meter, one sigma, and at t_2 + 2 hours, Block II - ONE will provide UERE of about 10 meters, one sigma.

The sensitivity of SV's antennae phase center position to small perturbations in most Data Block II parameters is extreme. The sensitivity of position to the parameters $\sqrt{A}$, C_{rc} and C_{rs} is about 1 meter/meter. The sensitivity of position to the angular parameters is on the order of 10^8 meters/semi-circle, and to the angular rate parameters is on the order of 10^{12} meters/semi-circle/second. Because of this extreme sensitivity to angular perturbations, the value of π used in the curve fit is given here. π is a mathematical constant, the ratio of a circle's circumference to its diameter. Here π is taken as

$$\pi = 3.1415926535898$$

The equation given in Table XII provide SV's antennae phase center position in earth-centered earth-fixed Cartesian coordinates. This system is characterized as follows:

x - is in the true equatorial plane in the direction of the Greenwich meridian.

z - is along the true earth spin axis, positive in the northern hemisphere.

y - completes the right hand system, y = (z) x (x)

3.3.2.10.5.2.2 Data Block II Format. Data Block II shall occupy the third through tenth 30 bit words (including parity) of the second and third subframes (see Figure 23). Values for Data Block Block II parameters are given in Table XIII. The AODE word is provided in both subframes for linkage between the two subframes. Whenever the AODE received in the third subframe is different from that received in the second subframe, the difference indicates that new data is being transmitted, and the collection process must be extended until the received AODE words agree. The Control Segment shall insure that any change in the Data Block II data will be accomplished with a simultaneous change in both AODE words.

3.3.2.10.5.3 Data Block III. The content of Data Block III shall consist of Almanac Data for 25 SVs. When required, the almanac message for dummy SVs shall be transmitted to maintain 25 pages within the almanac table. The dummy SVs shall be designated as the 0^{th} SV. Identification will be via the SV-ID parameter (i.e., bits 61 through 66 in the third word of the fifth subframe shall contain zeros). The almanac message for the dummy SVs shall

Table XII. Data Block II Definitions

M_o	MEAN ANOMALY AT REFERENCE TIME
Δn	MEAN MOTION DIFFERENCE FROM COMPUTED VALUE
e	ECCENTRICITY
$\sqrt{A}$	SQUARE ROOT OF THE SEMI-MAJOR AXIS
Ω_o	RIGHT ASCENSION AT REFERENCE TIME
i_o	INCLINATION ANGLE AT REFERENCE TIME
ω	ARGUMENT OF PERIGEE
$\dot{\Omega}$	RATE OF RIGHT ASCENSION
C_{uc}	AMPLITUDE OF THE COSINE HARMONIC CORRECTION TERM TO THE ARGUMENT OF LATITUDE
C_{us}	AMPLITUDE OF THE SINE HARMONIC CORRECTION TERM TO THE ARGUMENT OF LATITUDE
C_{rc}	AMPLITUDE OF THE COSINE HARMONIC CORRECTION TERM TO THE ORBIT RADIUS
C_{rs}	AMPLITUDE OF THE SINE HARMONIC CORRECTION TERM TO THE ORBIT RADIUS
C_{ic}	AMPLITUDE OF THE COSINE HARMONIC CORRECTION TERM TO THE ANGLE OF INCLINATION
C_{is}	AMPLITUDE OF THE SINE HARMONIC CORRECTION TERM TO THE ANGLE OF INCLINATION
t_{oe}	REFERENCE TIME EPHEMERIS
AODE	AGE OF DATA (EPHEMERIS)

Table XIII. Data Block II Parameters

Parameter	No. of Bits	Scale Factor (LSB)	Range *	Units
AODE	8	2^{11}	524,268	seconds
C_{rs}	16	2^{-5}	±1024	meters
Δn	16	2^{-43}	±4E-9	semi circles/sec
M_o	32	2^{-31}	±1	semi circles
C_{uc}	16	2^{-29}	±6E-5	radians
e	32	2^{-33}	.5	dimensionless
C_{us}	16	2^{-29}	±6E-5	radians
$\sqrt{A}$	32	2^{-19}	8192	$meters^{\frac{1}{2}}$
t_{oe}	16	2^{4}	604,784	seconds
Spare	6	-	-	-
C_{ic}	16	2^{-29}	±6E-5	radians
Ω_o	32	2^{-31}	±1.	semi circles
C_{is}	16	2^{-29}	±6E-5	radians
i_o	32	2^{-31}	±1.	semi circles
C_{rc}	16	2^{-5}	±1024	meters
ω	32	2^{-31}	±1	semi circles
$\dot{\Omega}$	24	2^{-43}	±9.5E-7	semi circles/sec
AODE	8	2^{11}	524,288	seconds
Spare	14	---	---	---

* (±) indicates that the sign bit shall occupy the most significant bit (MSB).

NOTE: (a) All binary numbers will be two's complement.
(b) Table XI has been deleted. Information has been incorporated in Figure 23.

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contain a simple bit pattern. For 12 or fewer SVs, almanacs may be repeated within the table. The almanac shall be transmitted on a rotating page basis. The Control Segment shall schedule almanac transmission on a per vehicle basis in such a manner as to allow for recovery of the Almanac table.

3.3.2.10.5.3.1 <u>Almanac</u>. The Almanac shall be a subset of the Data Block I and II parameters with reduced precision plus SV health and identification. The User algorithm is essentially the same as the User algorithm used for computing the precise ephemeris from Data Block II parameters (see Table XII). The Almanac content for one SV is given in Table XIV. All parameters appearing in the equations not included in the content of the Almanac are assumed zero. A close inspection of Table XIV will reveal that the parameter δ_i is transmitted, as opposed to the indication in Table XII that the value is computed. In this respect the application of Table XII equations differ between the almanac and the ephemeris.

The user is cautioned that the sensitivity to small perturbations in the parameters is even greater for the almanac than for the ephemeris, with the sensitivity of the angular rate terms on the order of 10^{14} meters/semi-circle/second.

Over the time span of applicability it is expected that the Almanac will provide UERE of less than 2500 meters, one sigma. An indication of the degradation of the UERE provided by a given Almanac as a function of time past the initial transmission is as specified below:

Time	UERE estimated by analysis (meters)
1 day	1000
1 week	2500
2 weeks	5000
3 weeks	10000
4 weeks	15000
5 weeks	2000

The time past initial transmission (AODA) may be computed as

$$AODA = t_k + 302,400$$

where the computation of t_k is described in paragraph 3.3.2.10.5.3.2.

3.3.2.10.5.3.2 <u>Almanac Reference Time</u>. The almanac reference time, t_{oa}, is the multiple of 2^{12} seconds truncated from 3.5 days after the time that [illegible] is applicable almanac begins transmission. The almanac shall be renewed each 6 days [illegible]imum. Therefore, the almanac reference time is not ambiguous. GPS time t shall [illegible] differ from t_{oa} by more than 3.5 days. The time from epoch t_k (see Table XI) shall be [illegible] described in Table XI except that t_{oe} shall be replaced with t_{oa}. However, if the U[illegible]shes to extend the use time of the alamanc beyond the time span that it is being tr[illegible], he must account for crossovers into time spans where these computations of [illegible] valid.

This may be accomplished by computing t_k at the GPS time t_c that the [illegible]manac was collected, and storing it as t_{kc}. That is,

$$t_{kc} = t_c - t_{oa}$$

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A	03953	

SCALE	REV	SHEET 50 OF

Table XIV. Data Block II Content

Parameter	No. of Bits	Scale Factor (LSB)	Range *	Units
ID	8	1	255	discretes
e	16	2^{-21}	2^{-5}	dimensionless
t_{oa}	8	2^{12}	602,112	seconds
δ_i	16	2^{-19}	$\pm 2^{-4}$	semi circles
SV Health	8	1	255	discretes
$\dot{\Omega}$	16	2^{-38}	$\pm 2^{-23}$	semi circles/sec
$\sqrt{A}$	24	2^{-11}	2^{13}	meters$^{1/2}$
Ω_0	24	2^{-23}	± 1	semi circles
ω	24	2^{-23}	± 1	semi circles
M_0	24	2^{-23}	± 1	semi circles
a_0	8	2^{-17}	$\pm 2^{-10}$	sec
a_1	8	2^{-35}	$\pm 2^{-28}$	sec/sec
SPARE	6	--	--	--

* (±) indicates that the sign bit shall occupy the most significant bit (MSB).

i_0 = .333333333 semi-circles

NOTE: All binary numbers will be two's complement.

corrected for end of week crossover. The time of year t_{cy} corresponding to t_c should also be computed and stored as

$$t_{cy} = (D_{tu} - 1) \times 86400 + t_c \bmod 86400$$

where D_{tc} is the day of year at the Greenwich Meridan at time t_c. If the GPS time of its use is t_u, the time of year t_{uy} corresponding to t_u is then

$$t_{uy} = (D_{tu} - 1) \times 86400 + t_u \bmod 86400$$

where D_{tu} is the day of year at the Greenwich Meridian at time t_u, corrected for crossovers into new years since the time of collection (i.e., add 365 or 366 for each crossover). The time from epoch t_k at that time is simply

$$t_k = t_{uy} - t_{cy} + t_{kc}$$

which is valid even during the time span during which the almanac is being transmitted. For almanacs that are not collected, but are furnished from an external source, it suffices to define the time of collection t_c as the recording time and the day of year D_{tc} as the recording day of year. This time and day of year will accompany the almanac and will always be within 3.5 days of the reference time t_{oa}.

3.3.2.10.5.3.3 Aging Parameters. The clock aging parameters shall consist of a first-order polynomial which, when used to adjust SV time shall provide time to within 10 microseconds of GPS time. The polynomial shall be described by an 8-bit constant term a_0 and an 8-bit first-order term, a_1. The clock correction to the SV PRN phase time t_{SV} shall be applied as follows:

$$t = t_{SV} - \Delta t_{SV}$$

where

t ∿ GPS time (seconds)

t_{SV} ∿ SV PRN code phase time at transmission (seconds)

and

$$\Delta t_{SV} = a_0 + a_1 t_k$$

where the computation of t_k is described in paragraph 3.3.2.10.5.3.2.

Over the span of applicability it is expected that the clock aging parameters will provide UERE of less than 2000 meters, one sigma. In fact, the UERE is due to the truncation of a_0 and a_1, and may be computed for all times as

$$\text{UERE} = \frac{c}{\sqrt{3}} \sqrt{2^{-34} + 2^{-70} t_k^2} \text{ meters}$$

one sigma, where c is the speed of light (see Paragraph 3.3.2.10.5.5) and the computation of t_k is described in paragraph 3.3.2.10.5.3.2.

3.3.2.10.5.3.4 SV Health and Status. The satellite HEALTH word occupies bits 137 through 144 of the fifth subframe. The three most significant bits (i.e., bits 137, 138 and 139) indicate health of the navigation data. The remaining five bits indicate health of the signal components. The format of the satellite HEALTH word follows:

BITS

137	138	139	
0	0	0	→ ALL DATA OK
0	0	1	→ PARITY FAILURE ~ some or all parity bad
0	1	0	→ TLM/HOW FORMAT PROBLEM ~ any departure from standard format (e.g., preamble misplaced and/or incorrect, etc.) except for incorrect Z-count as reported in HOW
0	1	1	→ Z-COUNT IN HOW BAD ~ any problem with Z-count value not reflecting actual code phase
1	0	0	→ DATA BLOCK I AND/OR II ~ one or more elements in Data Block I and/or II are bad
1	0	1	→ DATA BLOCK III ~ one or more elements in Data Block III are bad
1	1	0	→ ALL UPLOADED DATA BAD ~ one or more elements of Data Block I and/or II and III are bad
1	1	1	→ ALL DATA BAD ~ TLM and/or HOW and one or more elements in Data Blocks I and/or II and III are bad

BITS

140	141	142	143	144	
0	0	0	0	0	→ ALL SIGNALS OK
0	0	0	0	1	→ ALL SIGNALS WEAK (i.e., 3 to 6 dB below specified power level due to reduced power output, excess phase noise, SV attitude, etc.)
0	0	0	1	0	→ ALL SIGNALS DEAD
0	0	0	1	1	→ ALL SIGNALS HAVE NO DATA MODULATION
0	0	1	0	0	→ L_1 P SIGNAL WEAK
0	0	1	0	1	→ L_1 P SIGNAL DEAD
0	0	1	1	0	→ L_1 P SIGNAL HAS NO DATA MODULATION
0	0	1	1	1	→ L_2 P SIGNAL WEAK

BITS

140	141	142	143	144	
0	1	0	0	0	→ L_2 P SIGNAL DEAD
0	1	0	0	1	→ L_2 P SIGNAL HAS NO DATA MODULATION
0	1	0	1	0	→ L_1 C SIGNAL WEAK
0	1	0	1	1	→ L_1 C SIGNAL DEAD
0	1	1	0	0	→ L_1 C SIGNAL HAS NO DATA MODULATION
0	1	1	0	1	→ L_2 C SIGNAL WEAK
0	1	1	1	0	→ L_2 C SIGNAL DEAD
0	1	1	1	1	→ L_2 C SIGNAL HAS NO DATA MODULATION
1	0	0	0	0	→ P SIGNAL WEAK
1	0	0	0	1	→ P SIGNAL DEAD
1	0	0	1	0	→ P SIGNAL HAS NO DATA MODULATION
1	0	0	1	1	→ C SIGNAL WEAK
1	0	1	0	0	→ C SIGNAL DEAD
1	0	1	0	1	→ C SIGNAL HAS NO DATA MODULATION
1	0	1	1	0	→ L_1 SIGNAL WEAK
1	0	1	1	1	→ L_1 SIGNAL DEAD
1	1	0	0	0	→ L_1 SIGNAL HAS NO DATA MODULATION
1	1	0	0	1	→ L_2 SIGNAL WEAK
1	1	0	1	0	→ L_2 SIGNAL DEAD
1	1	0	1	1	→ L_2 SIGNAL HAS NO DATA MODULATION
1	1	1	0	0	→ SV IS TEMPORARILY OUT ∿ do not use this SV during current pass
1	1	1	0	1	→ SV WILL BE TEMPORARILY OUT ∿ do not use this SV during period for which almanac is valid
1	1	1	1	0	→ SPARE
1	1	1	1	1	→ SPARE

3.3.2.10.5.3.5 SV Identification. The satellite ID word occupies bits 61 through 68 of the fifth subframe. The two most significant bits (i.e., bits 61 and 62) designate the ICD revision and/or addendum to which the navigation data structure for that SV complies. When bits 61 and 62 are zero this condition shall indicate the current Navigation Data structure as of Sept. 19, 1975. The addendum will delineate modification in the standard navigation data format due to planned and/or unplanned orbit anomalies (e.g., highly eccentric orbits, excessive inclination angle, high altitude orbit, etc.). The remaining six bits given the numerical designation of that SV. The satellites are numbered 1 to 63. The 0^{th} SV is designated as a dummy SV. The number of dummy SV's in the almanac message is arbitrary to maintain 25 pages within the almanac table.

3.3.2.10.5.3.6 Data Block III Format. Data Block III shall occupy the third through tenth word (including parity) of the fifth subframe (see Figure 23). The number of bits, the scale factor of the least significant bit (LSB), which shall be the last bit received, the Range and the units of the parameters shall be as specified in Table XIV.

3.3.2.10.5.4 Message Block. The Message Block shall occupy the third through tenth 30-bit word (including parity) of the fourth subframe (see Figure 23). The Message Block provides space for the transmission of 23 8-bit ANSCII characters (reference: ANSCII x3.4-1968). The remaining 8 bits shall be non-information bearing. The ANSCII characters shall be limited to the following set:

ANSCII

Alphanumeric Character	Character	Code (Octal)
A - Z	A - Z	101 - 132
0 - 9	0 - 9	060 - 071
+	+	053
-	-	055
. (Decimal Point)	.	056
' (Minute mark)	'	047
° (Degree sign)	°	045
/	/	057
Blank	Space	040
:	:	072
" (Second mark)	"	042

NOTES: 1. Only ANSCII characters A-Z, 0-9 and the Space will be used in subframe 4 during Phase I.

2. ANSCII characteris will be transmitted with odd parity.

3.3.2.10.5.5 Speed of Light. The speed of light used by the Control Segment for generating the Data Blocks described in the above paragraphs is:

$$c = 2.99792458 \times 10^8 \text{ meters per second}$$

which is the official WGS-72 speed of light. The SSO GPS Receiver/Processor shall use the same value for the speed of light in its computations.

3.3.2.10.6 The Data Frame Parity. The data signal shall contain parity coding according to the following conventions.

3.3.2.10.6.1 Parity Option 1. This parity option shall link 30 bit words within and across subframes of 10 words. The SV shall compute parity only for the TLM and HOW, the first two words of the 10-word subframe, using the (32, 26) Hamming code described in Table XV. The satellite parity computation shall compute zeros for the last two bits, D_{29} and D_{30}, of both the TLM and HOW. D_1, $D_2 \ldots D_{30}$ shall be the data transmitted from the satellite. The parity of the NAV data words numbered 3 through 10 shall be computed by the Control Segment in accordance with the (32, 26) Hamming code described in Tables XVI and XVII. Table XVI shall be used for words 3 through 9 and Table XV shall be used for word 10. By using Table XVII for the computation of parity, the uploaded NAV data shall have zeros for D_{29} and D_{30} in the tenth (last) word in every subframe. For the Control Segment computation of parity for word 3, zeros shall always be used for D_{29}^* and D_{30}^*, the last two bits of the HOW (the previous word).

3.3.2.10.6.2 Parity Option 2. This parity option shall be characterized by having the satellite compute all parity. This option shall not apply to NDS-1 through NDS-6 and NTS-2. The future use of this option during Phase I will in no way require a change to the SSO GPS Receiver/Processor parity computation. However, the use of this option shall not require that the last two bits of the HOW, TLM and the 10th words of the subframe contain zeros.

3.3.2.10.6.3 SSO GPS Receiver/Processor Parity Algorithm. As far as the SSO GPS Receiver/Processor is concerned, several options are available for performing data decoding and error detection. Figure 26 presents an example flow chart which defines one way of recovering data (d_n) and checking parity. The parity bit D_{30}^* is used for recovering raw data. The parity bits D_{29}^* and D_{30}^* along with the recovered raw data (d_n) are Modulo-2 added in accordance with the equations appearing in Table XVI for $D_{25} \ldots D_{40}$ which provide computed parity to compare with transmitted parity $D_{25} \ldots D_{30}$. Regardless of the parity encoding scheme used for satellite transmission during Phase I, the SSO GPS Receiver/Processor parity algorithm shall be transparent (no change required) to the encoding scheme.

Table XV. Option I Satellite Parity Encoding Equations for TLM and HOW

$D_1 = d_1$

$D_2 = d_2$

$D_3 = d_3$

$\vdots \qquad \vdots$

$D_{21} = d_{21}$

$D_{22} = d_{22}$

$D_{23} = D_{29}^{*} \oplus d_1 \oplus d_7 \oplus d_8 \oplus d_{11} \oplus d_{13} \oplus d_{14} \oplus d_{16} \oplus d_{17} \oplus d_{18} \oplus d_{19} \oplus d_{21}$

$D_{24} = d_1 \oplus d_3 \oplus d_5 \oplus d_6 \oplus d_7 \oplus d_9 \oplus d_{10} \oplus d_{14} \oplus d_{15} \oplus d_{16} \oplus d_{17} \oplus d_{18} \oplus d_{21} \oplus d_{22}$

$D_{25} = D_{30}^{*} \oplus d_2 \oplus d_3 \oplus d_5 \oplus d_6 \oplus d_7 \oplus d_8 \oplus d_{10} \oplus d_{12} \oplus d_{16} \oplus d_{19} \oplus d_{20} \oplus d_{21}$

$D_{26} = d_1 \oplus d_2 \oplus d_4 \oplus d_5 \oplus d_9 \oplus d_{10} \oplus d_{11} \oplus d_{12} \oplus d_{13} \oplus d_{16} \oplus d_{17} \oplus d_{19} \oplus d_{22}$

$D_{27} = D_{29}^{*} \oplus d_1 \oplus d_3 \oplus d_4 \oplus d_5 \oplus d_7 \oplus d_8 \oplus d_{12} \oplus d_{13} \oplus d_{14} \oplus d_{15} \oplus d_{16} \oplus d_{19} \oplus d_{20} \oplus d_{22}$

$D_{28} = D_{29}^{*} \oplus d_1 \oplus d_2 \oplus d_4 \oplus d_5 \oplus d_6 \oplus d_7 \oplus d_9 \oplus d_{11} \oplus d_{15} \oplus d_{18} \oplus d_{19} \oplus d_{20}$

$D_{29} = 0$

$D_{30} = 0$

Where

$d_1, d_2, \ldots, d_{22}$ are the raw data bits

$D_{23}, \ldots D_{30}$ are the parity bits

The symbol (*) is used to identify the last 2 bits of the previous transmitted word.

$D_1, D_2, D_3 \ldots D_{28}, D_{29}, D_{30}$ are the bits transmitted by the satellite

$\oplus$ is the "modulo-2" or "exclusive-or" operation.

Table XVI. Option I Control Segment Parity Encoding Equations for Words 3 through 9

$$D_1 = d_1 \oplus D_{30}^*$$

$$D_2 = d_2 \oplus D_{30}^*$$

$$D_3 = d_3 \oplus D_{30}^*$$

$$\vdots \qquad \vdots$$

$$D_{24} = d_{24} \oplus D_{30}^*$$

$$D_{25} = D_{29}^* \oplus d_1 \oplus d_2 \oplus d_3 \oplus d_5 \oplus d_6 \oplus d_{10} \oplus d_{11} \oplus d_{12} \oplus d_{13} \oplus d_{14} \oplus d_{17} \oplus d_{18} \oplus d_{20} \oplus d_{23}$$

$$D_{26} = D_{30}^* \oplus d_2 \oplus d_3 \oplus d_4 \oplus d_6 \oplus d_7 \oplus d_{11} \oplus d_{12} \oplus d_{13} \oplus d_{14} \oplus d_{15} \oplus d_{18} \oplus d_{19} \oplus d_{21} \oplus d_{24}$$

$$D_{27} = D_{29}^* \oplus d_1 \oplus d_3 \oplus d_4 \oplus d_5 \oplus d_7 \oplus d_8 \oplus d_{12} \oplus d_{13} \oplus d_{14} \oplus d_{15} \oplus d_{16} \oplus d_{19} \oplus d_{20} \oplus d_{22}$$

$$D_{28} = D_{30}^* \oplus d_2 \oplus d_4 \oplus d_5 \oplus d_6 \oplus d_8 \oplus d_9 \oplus d_{13} \oplus d_{14} \oplus d_{15} \oplus d_{16} \oplus d_{17} \oplus d_{20} \oplus d_{21} \oplus d_{23}$$

$$D_{29} = D_{30}^* \oplus d_1 \oplus d_3 \oplus d_5 \oplus d_6 \oplus d_7 \oplus d_9 \oplus d_{10} \oplus d_{14} \oplus d_{15} \oplus d_{16} \oplus d_{17} \oplus d_{18} \oplus d_{21} \oplus d_{22} \oplus d_{24}$$

$$D_{30} = D_{29}^* \oplus d_3 \oplus d_5 \oplus d_6 \oplus d_8 \oplus d_9 \oplus d_{10} \oplus d_{11} \oplus d_{13} \oplus d_{15} \oplus d_{19} \oplus d_{22} \oplus d_{23} \oplus d_{24}$$

where

$d_1, d_2 \ldots\ldots d_{22}$ are the raw data bits

$D_{25}, \ldots\ldots, D_{30}$ are the parity bits and equations

The symbol (*) is used to identify the last 2 bits of the previous transmitted word.

$D_1, D_2, D_3 \ldots D_{29}, D_{30}$ are the bits uploaded by the control segment, and are subsequently transmitted by the satellite in that same form.

$\oplus$ is the "modulo-2" or "exclusive-or" operation.

Table XVII. Option I Control Segment Parity Encoding Equations for Word 10

$$D_1 = d_1 \oplus D_{30}^*$$

$$D_2 = d_2 \oplus D_{30}^*$$

$$\vdots \qquad \vdots$$

$$D_{22} = d_{22} \oplus D_{30}^*$$

$$D_{23} = D_{29}^* \oplus d_1 \oplus d_7 \oplus d_8 \oplus d_{11} \oplus d_{13} \oplus d_{14} \oplus d_{16} \oplus d_{17} \oplus d_{18} \oplus d_{19} \oplus d_{21}$$

$$D_{24} = d_1 \oplus d_3 \oplus d_5 \oplus d_6 \oplus d_7 \oplus d_9 \oplus d_{10} \oplus d_{14} \oplus d_{15} \oplus d_{16} \oplus d_{17} \oplus d_{18} \oplus d_{21} \oplus d_{22}$$

$$D_{25} = D_{30}^* \oplus d_2 \oplus d_3 \oplus d_5 \oplus d_6 \oplus d_7 \oplus d_8 \oplus d_{10} \oplus d_{12} \oplus d_{16} \oplus d_{19} \oplus d_{20} \oplus d_{21}$$

$$D_{26} = d_1 \oplus d_2 \oplus d_4 \oplus d_5 \oplus d_9 \oplus d_{10} \oplus d_{11} \oplus d_{12} \oplus d_{13} \oplus d_{16} \oplus d_{17} \oplus d_{19} \oplus d_{22}$$

$$D_{27} = D_{29}^* \oplus d_1 \oplus d_3 \oplus d_4 \oplus d_5 \oplus d_7 \oplus d_8 \oplus d_{12} \oplus d_{13} \oplus d_{14} \oplus d_{15} \oplus d_{16} \oplus d_{19} \oplus d_{20} \oplus d_{22}$$

$$D_{28} = D_{29}^* \oplus d_1 \oplus d_2 \oplus d_4 \oplus d_5 \oplus d_6 \oplus d_7 \oplus d_9 \oplus d_{11} \oplus d_{15} \oplus d_{18} \oplus d_{19} \oplus d_{20}$$

$$D_{29} = 0$$

$$D_{30} = 0$$

where

$d_1, d_2, \ldots\ldots, d_{22}$ are the raw data bits

$D_{23}, \ldots\ldots, D_{30}$ are the parity bits

The symbol (*) is used to identify the last 2 bits of the previous transmitted word.

$D_1, D_2, D_3, \ldots\ldots, D_{28}, D_{29}, D_{30}$ are the bits uploaded by the control segment, and are subsequently transmitted by the satellite in that same form.

$\oplus$ is the "modulo-2" or "exclusive-or" operation.

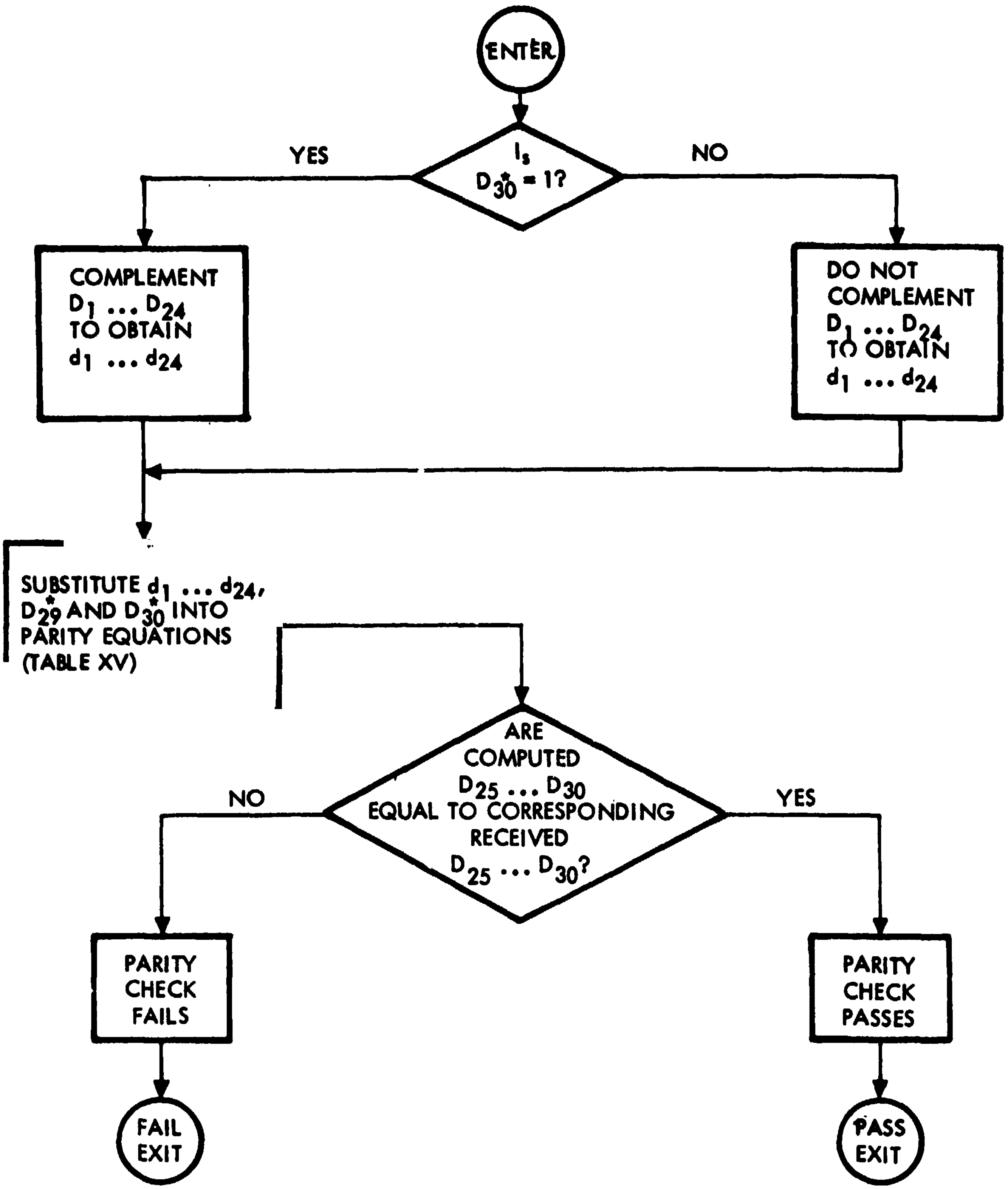

Figure 26. Example Flow Chart for User Implementation of Parity Algorithm

3.4 GPS GROUND TRANSMITTERS

It is recognized that it may be desirable to establish ground stations whose function is to radiate a GPS navigation signal of the same format as that described within the ICD. Since the Space Shuttle is a unique GPS user in terms of visibility to potential ground transmitters, it is necessary to control and regulate these transmitters according to the paragraphs below.

3.4.1 Power Level. The maximum EIRP of any GPS ground transmitter shall be as follows:

L1P	TBD
L1C/A	TBD
L2P	TBD
L2C/A	TBD.

3.4.2 PRN Code Phase. The phase of the C/A and P codes used for ground transmitters shall be as defined in Table I of this ICD. The TBD code phases shall be reserved for use in Shuttle ground transmitters.

3.4.3 Data Rate and Format. The data format for the ground transmitter data which is modulated on the navigation signal is TBD.

3.4.4 Data Frame Contents. TBD.

3.4.5 Telemetry Word. TBD.

3.4.6 Handover Word. TBD.

3.4.7 Data Block Contents. TBD.

3.5 GPS NAVSTAR CONSTELLATION DEFINITION

The GPS satellite (NAVSTAR) constellation shall consist of a minimum of 24 active operating satellites placed in 12-hour circular orbits in three orbital planes of TBD inclination. The eight satelites in each plane shall be evenly spaced. The GPS operational constellation, nominal parameters, are summarized in Table XVIII.

3.6 SPACE SEGMENT PERFORMANCE

Each ONS of the SS shall meet the requirements of Table XIX for 24 hours after an update by the CS. Each clock and navigation subsystem shall be stable, modelable and predictable to the values shown. ONS perturbation effects including solar pressure, outgassing and attitude control activity shall be modelable and predictable such that the values shown in Table XIX are achieved.

Table XVIII. GPS Operational Constellation, Nominal Parameters

Period	11:57:59.200002		
Eccentricity	0.02 (max)		
Inclination	55 degree (a)		
Argument of Perigee	0o		
Orbital Plane	A	B	C
Right Ascension of Ascending Node (b), degrees	240	120	0
Longitude of Ascending Node, degrees	0	15	-15
	45	60	30
	90	105	75
	135	150	120
	180	195	165
	225	240	210
	270	285	255
	315	330	300

(a) Inclination for NDS satellites is 63 degrees

(b) Referenced to Astronomical Coordinates of 1950.0 as of 21 March 1977, 0 hours, 0 minutes GMT and regressing at -0.04945 degree/day

Table XIX. GPS System Error Budget

ERROR SOURCES	ERROR SOURCE (a) RESPONSIBILITY, METER SS	CS	US	SYSTEM BUDGET, METER
CLOCK & NAVIGATION SUBSYSTEM STABILITY	2.7(b)	2.7(b)	---	2.7
PREDICTABILITY OF SV PERTURBATIONS	1.0(b)	1.0(b)	---	1.0
OTHER	0.5(b)	0.5(b)	---	0.5
EPHEMERIS AND CLOCK PREDICTION	---	2.5	---	2.5
OTHER	---	0.5	---	0.5
IONOSPHERIC DELAY COMPENSATION	---	---	2.3(c)	2.3
TROPOSPHERIC DELAY COMPENSATION	---	---	2.0(c)	2.0
RECEIVER NOISE AND RESOLUTION	---	---	1.5(c)	1.5
MULTIPATH	---	---	1.2(c)	1.2
OTHER	---	---	0.5(c)	0.5
1σ SYSTEM UERE				5.3

(a) NDS error budget is specified in SS-GPS-101A.

(b) Requirements that shall be joint responsibility between SS and CS.

(c) The US shall meet these requirements to the extent specified in SS-US-200.