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WDL-TR5291
28 February 1974

SAMSO TR 74-183

GLOBAL POSITIONING SYSTEM (GPS) FINAL REPORT

PART I

VOLUME B
User Segment System Analysis Report

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Contract F04701-73-C-0296

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Submitted to:
DEPARTMENT OF THE AIR FORCE
HEADQUARTERS SPACE AND MISSILE SYSTEMS ORGANIZATION (AFSC)
P.O. Box 92960, Worldway Postal Center
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see 1473

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PHILCO Ford
Philco-Ford Corporation
Western Development Laboratories Division
Palo Alto, California 94303

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WDL Technical Report 5291
28 February 1974

GLOBAL POSITIONING SYSTEM (GPS)
FINAL REPORT

PART I - VOLUME B
USER SEGMENT SYSTEM ANALYSIS REPORT

Contract F04701-73-C-0296

Prepared for

DEPARTMENT OF THE AIR FORCE
HEADQUARTERS SPACE AND MISSILE SYSTEMS ORGANIZATION (AFSC)
Los Angeles, California 90009

ATTENTION: YEEU

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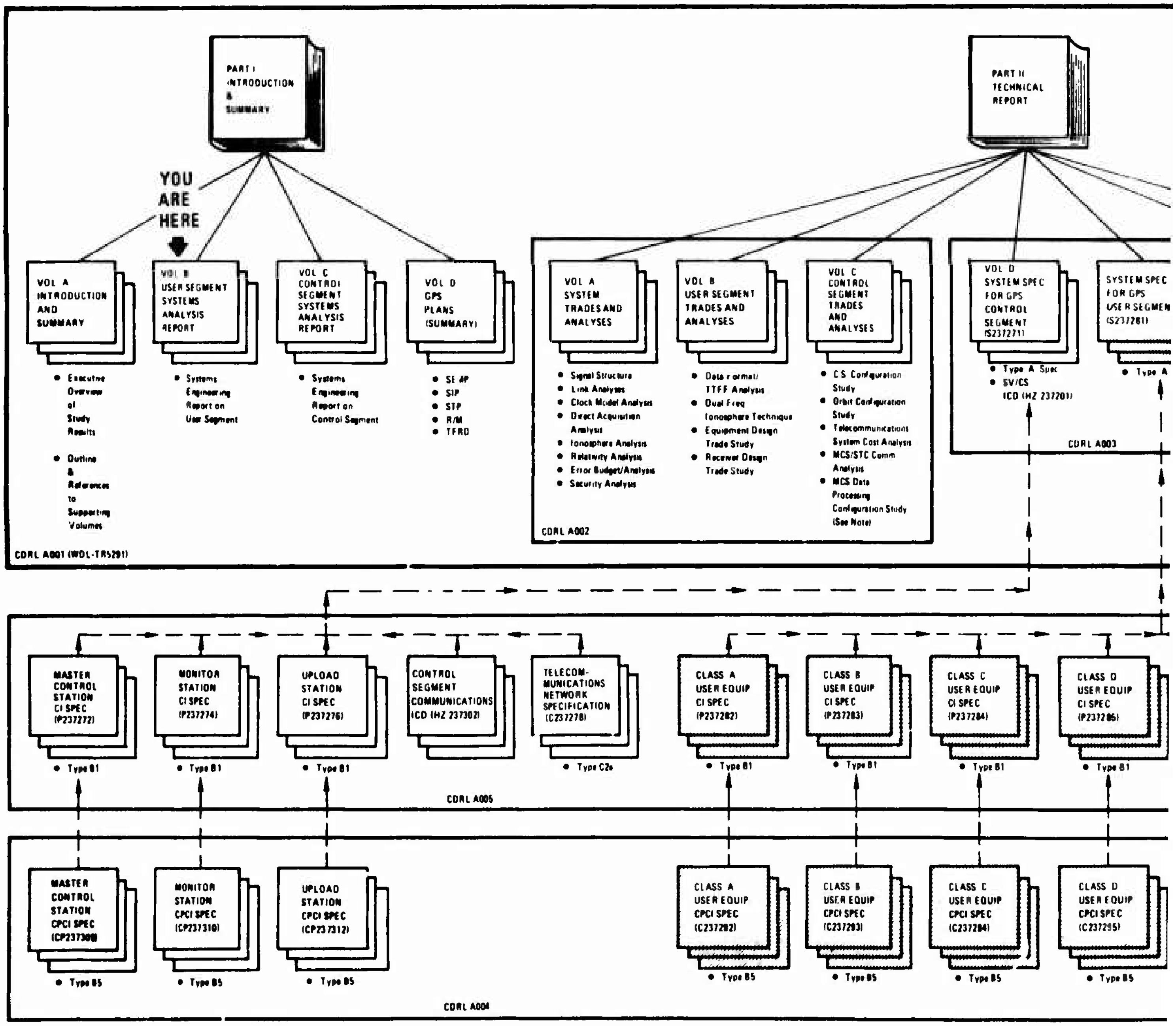
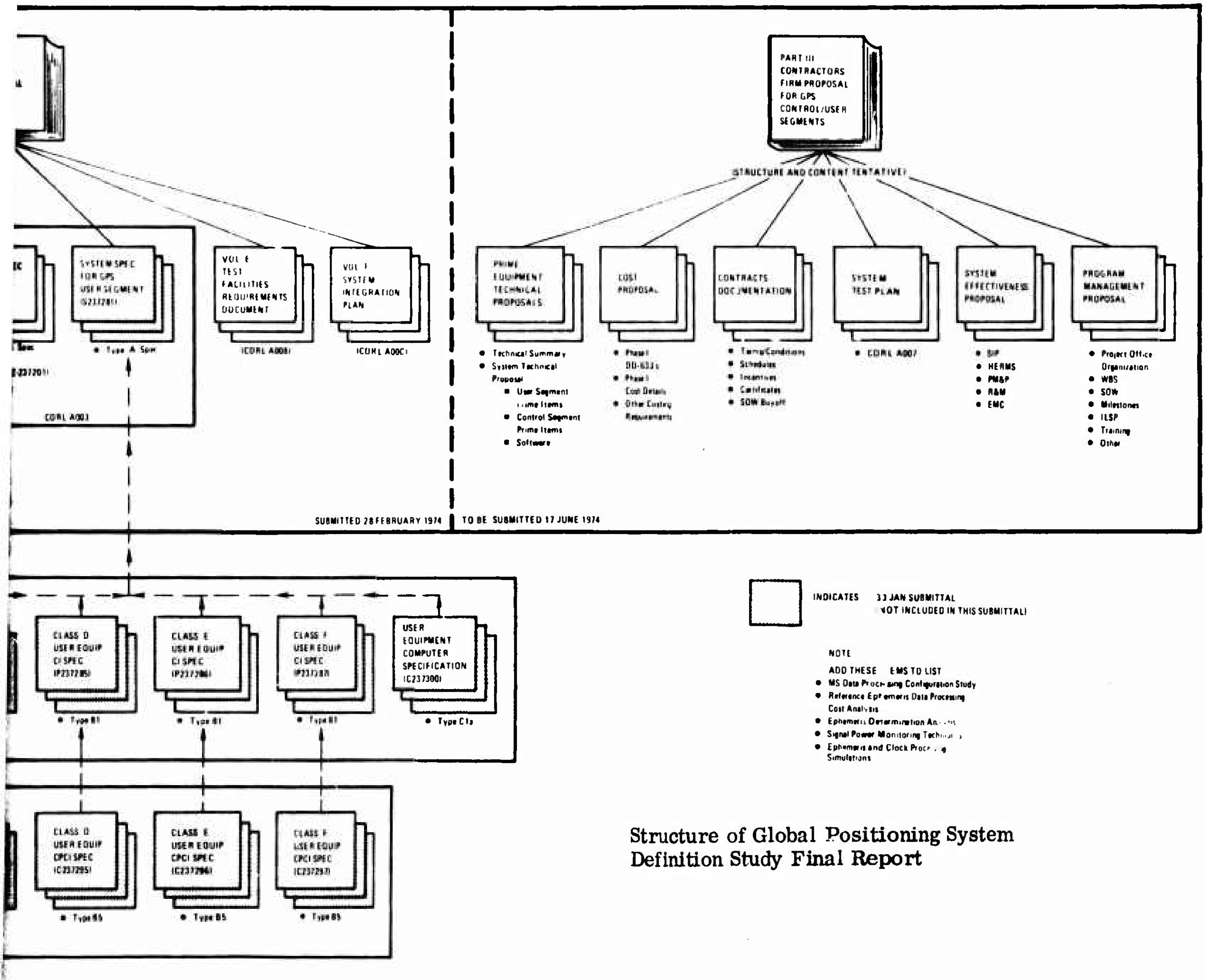
PHILCO-FORD CORPORATION
Western Development Laboratories Division
Palo Alto, California 94303

FOREWORD

This is Part I, Volume B, of the GPS Definition Study Final Report, submitted by Philco-Ford in accordance with Sequence Number A001 of Exhibit A to Contract F04701-73-C-0296. The period of performance for the report submitted herein is from 28 June 1973 to 28 February 1974. The following figure identifies the structure of the Final Report and the relationship of this volume to other volumes of this submittal.


PART I
INTRODUCTION
&
SUMMARY
YOU
ARE
HERE
VOL A
INTRODUCTION
AND
SUMMARY
• Executive Overview of Study Results
• Outline & References to Supporting Volumes
VOL B
USER SEGMENT
SYSTEMS
ANALYSIS
REPORT
• Systems Engineering Report on User Segment
VOL C
CONTROL
SEGMENT
SYSTEMS
ANALYSIS
REPORT
• Systems Engineering Report on Control Segment
VOL D
GPS
PLANS
(SUMMARY)
• SE AP
• SIP
• STP
• R/M
• TFRD
CDRL A001 (WDL-TR5291)
PART II
TECHNICAL
REPORT
VOL A
SYSTEM
TRADES AND
ANALYSES
• Signal Structure
• Link Analyses
• Clock Model Analysis
• Direct Acquisition Analysis
• Ionosphere Analysis
• Relativity Analysis
• Error Budget/Analysis
• Security Analysis
VOL B
USER SEGMENT
TRADES AND
ANALYSES
• Data Format/ TTFF Analysis
• Dual Freq Ionosphere Technique
• Equipment Design Trade Study
• Receiver Design Trade Study
VOL C
CONTROL
SEGMENT
TRADES
AND
ANALYSES
• CS Configuration Study
• Orbit Configuration Study
• Telecommunications System Cost Analysis
• MCS/STC Comm Analysis
• MCS Data Processing Configuration Study (See Note)
CDRL A002
VOL D
SYSTEM SPEC
FOR GPS
CONTROL
SEGMENT
(S237271)
• Type A Spec
• SV/CS ICD (HZ 237201)
SYSTEM SPEC
FOR GPS
USER SEGMEN
(S237281)
• Type A
CDRL A003
MASTER
CONTROL
STATION
CI SPEC
(P237272)
• Type B1
MONITOR
STATION
CI SPEC
(P237274)
• Type B1
UPLOAD
STATION
CI SPEC
(P237276)
• Type B1
CONTROL
SEGMENT
COMMUNICATIONS
ICD (HZ 237302)
TELECOM-
MUNICATIONS
NETWORK
SPECIFICATION
(C237278)
• Type C2a
CLASS A
USER EQUIP
CI SPEC
(P237282)
• Type B1
CLASS B
USER EQUIP
CI SPEC
(P237283)
• Type B1
CLASS C
USER EQUIP
CI SPEC
(P237284)
• Type B1
CLASS D
USER EQUIP
CI SPEC
(P237285)
• Type B1
CDRL A005
MASTER
CONTROL
STATION
CPCI SPEC
(CP237308)
• Type B5
MONITOR
STATION
CPCI SPEC
(CP237310)
• Type B5
UPLOAD
STATION
CPCI SPEC
(CP237312)
• Type B5
CLASS A
USER EQUIP
CPCI SPEC
(C237282)
• Type B5
CLASS B
USER EQUIP
CPCI SPEC
(C237283)
• Type B5
CLASS C
USER EQUIP
CPCI SPEC
(C237284)
• Type B5
CLASS D
USER EQUIP
CPCI SPEC
(C237295)
• Type B5
CDRL A004



NOTE

ADD THESE ITEMS TO LIST

- MS Data Processing Configuration Study
- Reference Ephemeris Data Processing Cost Analysis
- Ephemeris Determination Analysis
- Signal Power Monitoring Techniques
- Ephemeris and Clock Processing Simulations

Structure of Global Positioning System Definition Study Final Report

2

CONTENTS

CONTENTS (Continued)

FIGURES

FIGURES (Continued)

TABLES

1. INTRODUCTION

A wide variety of tradeoffs and analyses have been conducted to define the User Segment of the GPS. The purpose of this document is to provide a summary of the most important considerations that led to the User Segment design. More complete details of the major system tradeoffs and receiver design are contained in Part II, Volume B, of this document.

A User Segment Specification has been prepared along with both CI and CP Specifications for six user classes. A Computer Specification has also been prepared, and is being used as a basis for discussion with many computer vendors.

Details of the GPS Phase I are highly dependent upon the test planning activities currently underway in conjunction with the JPO. Critical technical decisions are yet to be made which depend upon the results of the test planning activities as well as a detailed analysis of the Phase I schedule. For example, the detailed design of interface units depends upon the computer selection, the test beds, and IMU selection as well as the approach (interface with an IMU directly or to an IMU processor) taken. These decisions will be partly judged by the schedule and cost risk associated with each approach.

Section 2 of this volume provides details on the system level tradeoffs and resultant user operation. Performance of the GPS receivers is also presented. Section 3 contains a summary of the elements of the User Segment with particular emphasis placed on the electrical and mechanical aspects of the receiver. Control and displays, computer, antennae, interface units, auxiliary sensors, and software are also summarized.

Reliability, maintainability, life cycle costing, equipment hardening, and EMC are discussed in Section 4. Section 5 contains a summary review of the test planning activities and approach.

2. SYSTEMS ENGINEERING

2.1 SIGNAL STRUCTURE

A considerable amount of analytic effort was expended on the GPS signal structure. This resulted in the structure described in the GPS System Specification, published by SAMSO, SS-GPS-101A, dated 29 January 1974. This signal is functionally illustrated in Figure 2-1.

All the various components of the signal, including the carriers, are coherently derived from the same oscillator, and hence their frequencies are simply related. This is shown in Table 2-1. The multipliers, m and n, which raise the frequency source to the L_1 and L_2 RF frequencies, have not yet been fixed. These multipliers should, however, be integers to minimize the user equipment cost. For example, a value of 154 for m would provide an L_1 frequency of 1.57542 GHz and 120 for n would provide an L_2 frequency of 1.2276 GHz.

The System Specification allows some freedom in selecting the difference in lengths between the two components of the P-code. In algebraic terms, if N_1 and N_2 are the lengths of the X1 and X2 components, then

$$N_1 = 15,345,000$$

and

$$N_2 = N_1 + K$$

where K is an integer between 1 and 33, inclusive.

Since N_1 and N_2 must be relatively prime for the composite code length to be equal to N_1N_2, there are, in fact, only a few allowable values for K, namely

$$K = 1, 7, 13, 17, 19, 23, 29, \text{ or } 31.$$

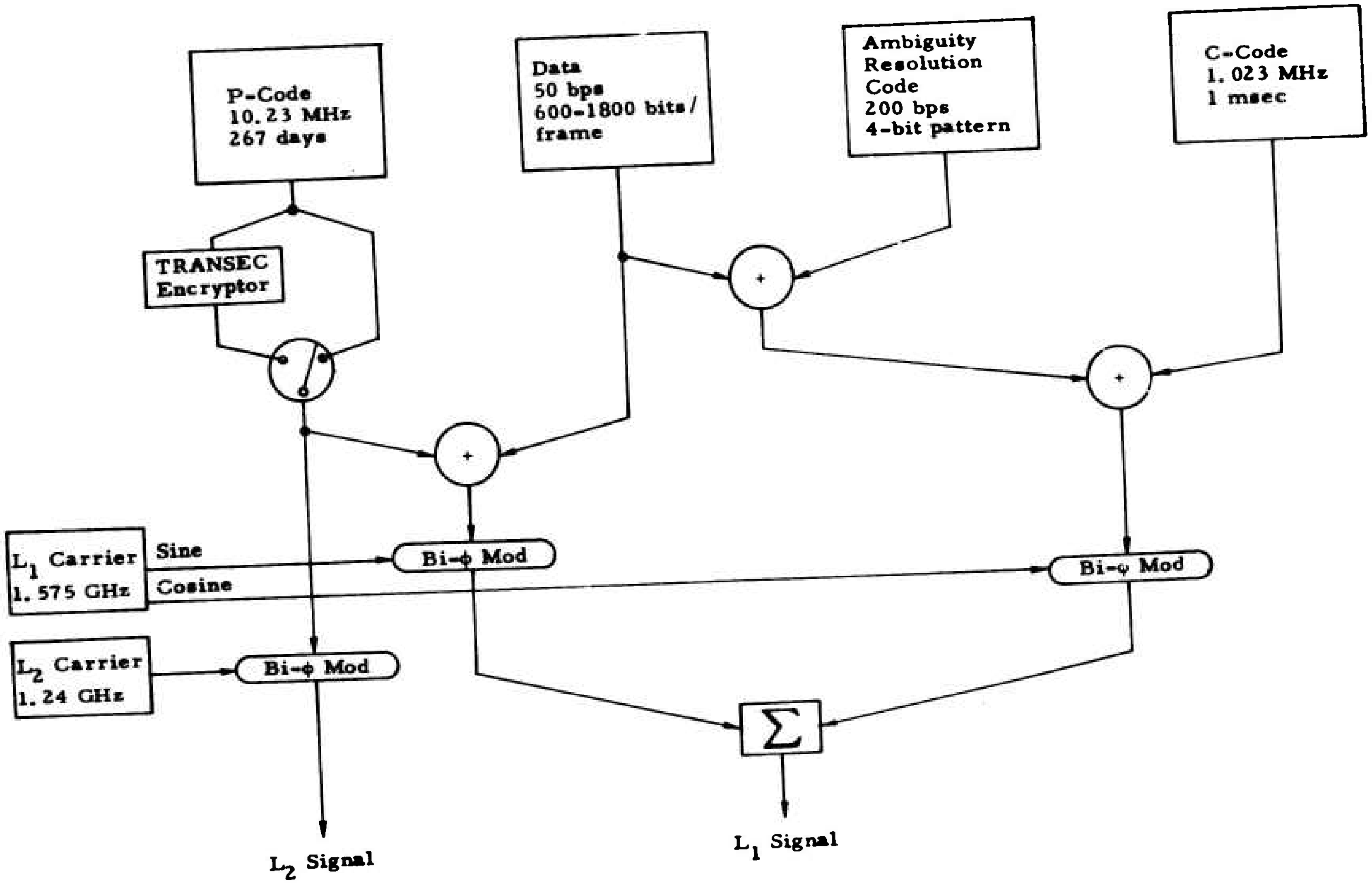


Figure 2-1. Functional Representation of GPS Signal Structure

Table 2-1. Signal Frequencies

Signal Component	Frequency Deviation	Nominal Frequency	
Frequency source	f	5.115	MHz
P-code clock	2f	10.23	MHz
C-code clock	f/5	1.023	MHz
L_1 carrier	mf*	1.57542	GHz
L_2 carrier	nf**	1.2276	GHz
C-code epoch rate	$f/(5 \times 1023) = f_c$	1	KHz
Data clock	$f_c/20$	50	Hz
Ambiguity resolution clock	$f_c/5$	200	Hz

* m equal 154.

** n equal 120.

Since the advantage of $K > 1$ is not significant, our design is presaged on the selection of $K = 1$. The code lengths and periods are then as shown in Table 2-2.

In Part II, Volume B of this report ("User Segment Trade Studies"), an important alternative to the signal structure is presented for consideration. This alternative employs different data rates for P and C, and dispenses with the ambiguity resolution code. The two rates are,

C-data fc/6 = 166.6 Hz, nominally

P-data fc/(6 x 16) = 10.4 Hz, nominally

where fc = C-code epoch rate (see Table 2-1.)

The trade study analyses also resulted in other alternatives and extensions of detail to the signal structure, which are of lesser significance. They are all described in Part II, Volume B.

2.2 RECEIVER OPERATIONS

2.2.1 General

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

a) Power on and warm-up
b) Input of approximate user position and velocity, and of time
c) Constellation selection
d) Search and acquisition of L_1 signal
e) Collection of current data
f) Pseudorange and pseudorange rate measurement of L_1
g) First navigation fix
h) Pseudorange measurement on L_2 (L_1/L_2 receivers only)
i) Continuing accurate navigation fixes
j) Data update
k) Constellation revision

Table 2-2. Code Lengths and Periods

Code	Chipping Rate	Code Length	Code Period
P-Code			
X1 component	10.23 MHz	15,345,000 chips	1.5 sec
X2 component	10.23 MHz	15,345,000 chips	~1.5 sec
Composite	10.23 MHz	~2.35 x 10^{12} chips	~266 days
C-Code	1.023 MHz	1023 chips	1 msec
Ambiguity Resolution Code	200 Hz	4 chips	20 msec

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

In the following, the operational steps are discussed in greater detail, first for User Classes A, B, and F (which all have similar sequences). The operational steps for the other classes are then described, particularly where they differ from Class A steps.

2.2.2 Classes A, B, and F Operations

These three user classes can be considered together here since they all employ a 4-channel, continuous tracking, C/P, L_1/L_2 receiver, and all include inertial sensors in their equipment groups.

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

The user's position and velocity, and the time information, are needed for constellation selection. This is a process of determining which four satellites, of all those active in the GPS, should be used for navigation. In addition to this information, the constellation selection process also needs to know the approximate positions and velocities of the satellites, and those are found from the orbital elements of all satellites stored by each user in his nonvolatile memory. The different ways of transmitting and storing these elements are comparatively discussed in the User Segment Trade Studies, Part II, Volume B.

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

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

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

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

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

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

d) When the lock detectors show that the L_1-C signal has been acquired, first the carrier tracking loop, and then the code loop will be enabled, so that the signal will be automatically tracked in both phase and frequency. The VCO prepositioning estimates are no longer needed at this point.

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

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

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

When all four channels have accomplished the above steps, the computer will start to make navigation fixes. The first fix will not be the most accurate one, since L_1/L_2 comparisons are yet to be made, and the navigation filter needs time before it can obtain very accurate estimates of the system biases. The time needed to make the first fix (time-to-first-fix, or TTFF) has been thoroughly investigated, and is discussed in Part II, Volume B. The time needed to make the first fix of ultimate accuracy is expected to be just a few seconds longer than the TTFF.

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

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

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

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

There are other operational steps, automatically effected, whose need has not yet been firmly established, and hence are considered only provisional at this stage. These include bandwidth changes in response to detected jamming levels, and changes in the start-up sequence in the presence of medium jamming (handover to P before initial navigation data collection).

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

2.2.3 Class C Operations

User Class C equipment groups consist of a GPS receiver only, without auxiliary navigation sensors. Further the receiver is a low cost, 2-channel sequential tracker, using the L_1-C signal only.

Compared with Classes A, B, and F, the Class C operator has additional tasks to perform, but these are only needed at start-up. He must input his approximate position (latitude, longitude, and altitude), the date, the approximate time, and his speed and course. He must also fly reasonably straight and level during the search and acquisition regime. In practice, this will not be a difficult constraint, since he will usually start navigating before taxiing his aircraft.

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

In all other respects, the Class C operations are like those just described for Classes A, B, and F. Channel B is dedicated totally to sequential tracking and measurement, while Channel A is used for data collection, the watch for data change, for reacquisition of temporarily lost signals, and for acquisition of new satellites at times of constellation revision.

2.2.4 Classes D and E Operations

These user classes are similar to Class C, in that they do not include auxiliary navigation sensors, and in that they use a 2-channel sequential tracking receiver. However, they differ from Class C operations in two ways.

Firstly, they operate on the L_1-P signal, so they do make use of the handover word. During the initial start-up as each L_1-C signal is found by Channel A, it stays tracking the signal (uninterruptedly), until it has acquired the navigation data and the handover word. Then it prepositions Channel B (for the P-signal), so that this channel can keep sequentially tracking. Thus, in this receiver, Channel B is (normally) used only with P-signals.

The other difference with Class C, is that the operator does not input his course and speed at start-up; nor does he have to restrict his dynamics at this time. This is because the maximum operating velocities of those users are sufficiently low that frequency prepositioning can always be made, with sufficient accuracy, by assuming that the user is stationary.

2.3 RECEIVER PERFORMANCE

The receiver performance parameters of most specific significance to systems engineering are the measurement accuracies and the jamming immunity. Both of these parameters are summarized in the following sections.

2.3.1 Measurement Accuracy

The pseudorange and pseudorange rate measurement accuracies were analyzed and reported in Reference 2-1. The results of this work are summarized in Tables 2-3 and 2-4. In Table 2-3, an entry is made for range instrumentation error. This arises from the way in which the code tracking delay lock loop is implemented. The C-code noise error is more than 10 times greater than the P-code noise error, since different bandwidths have been assumed for the two processors.

Reference 2-1. DNSDP-AG-230, "Receiver Range and Range Rate Measurement Errors", 7 January 1974

Table 2-3. Random Measurement Errors

	$(C/N_o)_e$ dBHz						
	24	26	28	30	32	34	36
C-code range measurement error (S. D., in meters)							
Noise	73.7	47.8	31.3	20.9	14.3	10.0	7.2
Quantization	.05	.05	.05	.05	.05	.05	.05
Instrumentation	.19	.19	.19	.19	.19	.19	.19
Total	73.7	47.8	31.3	20.9	14.3	10.0	7.2
P-code range measurement error (S. D., in meters)							
Noise	3.87	2.68	1.89	1.37	1.04	.79	.61
Quantization	.05	.05	.05	.05	.05	.05	.05
Instrumentation	.19	.19	.19	.19	.19	.19	.19
Total	3.87	2.68	1.90	1.38	1.07	.82	.64
Range rate measurement error (S. D., in m/sec)							
Noise	.052	.040	.030	.024	.021	.015	.012
Quantization	.001	.001	.001	.001	.001	.001	.001
Total	.052	.040	.030	.024	.021	.015	.012

Table 2-4. Bias Measurement Errors

	Range Acceleration (gs)			
	1	2	4	7
Range bias (meters)	.03	.06	.12	.20
Range rate bias (meters/sec)	.14	.29	.58	1.01

The errors in Table 2-3 are shown for various values of the carrier-to-noise density ratio of either the P- or C-signal, at the receiver input, and effective after jamming reduction by the spread spectrum code demodulation.

In addition to the random errors, there will also be bias errors if there is range acceleration, and the carrier tracking loop is of second order. These errors are shown in Table 2-4. Although the range rate errors are worst case, and assume that the acceleration is present at the beginning of the velocity counting interval, but not at the end (or vice versa), they are sufficiently large to suggest that, for many applications, the carrier tracking loop will have to be of the third order rather than the second.

2.3.2 Jamming Immunity

There are three ways in which a GPS user can achieve jamming immunity in his operations:

1) By working with the P-signal, so that the jammer power is spread over a wide spectrum in the replica code demodulator (whereas the desired signal, which is transmitted in a spread spectrum, is concentrated into nearly a line spectrum by the same demodulator).

2) By using a very narrow bandwidth carrier tracking loop after the code demodulator. Since the desired signal has been collapsed into a line spectrum, all of its energy is passed through the narrow band filters; however, the jammer signal is spread over

a wide band, and the amount of its energy which is passed through the filter, and hence interferes with proper operation, is proportional to the bandwidth.

3) By using directive receiving antennas so that the gain in the direction of the satellites is considerably greater than the gain in the direction of the jammer.

It is illustrative at this point to derive an expression for the jamming immunity in terms of the parameters which might be selected to improve it, that is, in terms of the carrier loop tracking bandwidth and the antenna directivity.

Let J = jammer power, as would be received by an isotropic antenna

S = P-signal power, as would be received by an isotropic antenna

G_j = actual antenna gain, referenced to receiver input, in the direction of the jammer

G_s = actual antenna gain, referenced to receiver input, in the direction of the satellite

N_o = receiver noise density

R_p = P-code chipping rate

B = two-sided noise bandwidth of carrier tracking loop

SNR = signal-to-noise ratio in carrier tracking loop

Then, it can be readily shown that,

$$\mathrm{SNR} = \frac{SG_s}{B(N_o + JG_j/R_p)}$$

One useful measure of jamming immunity is the maximum withstandable J/S ratio. Note that this is not the ratio of actual received powers, but the ratio of powers which would be received if an isotropic antenna were used. Another way of looking at this is to recognize that J/S is the ratio of field strengths in the user's location. The criterion for withstanding jamming is, of course, that the SNR must be above some minimum. Thus, we can derive from the previous equation,

$$(J/S)_{max} = \left[\frac{G_s}{B(SNR)_{min}} - \frac{N_o}{S}\right]\left[\frac{R_p}{G_j}\right]$$

Typical values for these terms are

$$S = -163 \text{ dBw}$$

$$N_o = -199.6 \text{ dBw/Hz}$$

$$R_p = 10.23 \text{ MHz}$$

$$SNR_{min} = 6 \text{ dB}$$

$$B < 50 \text{ Hz}$$

$$G_s > -3 \text{ dB}$$

With these fixed values, and limits on B and G_s, it can be shown that

$$(J/S)_{dB, max} \sim 64.1 + (G_s/G_j)_{dB} - 10 \log B_{hz}$$

This expression is plotted in Figure 2-2. As may be seen, a 50 dB jamming immunity is reasonably readily achievable (with a nondirective antenna, and a 20 Hz loop bandwidth). However, to achieve greater immunity than 50 dB, one must use either very narrow tracking loop bandwidths (which will have to be aided), or highly directive antennas (four of them, which will have to be pointed at the satellites), or both.

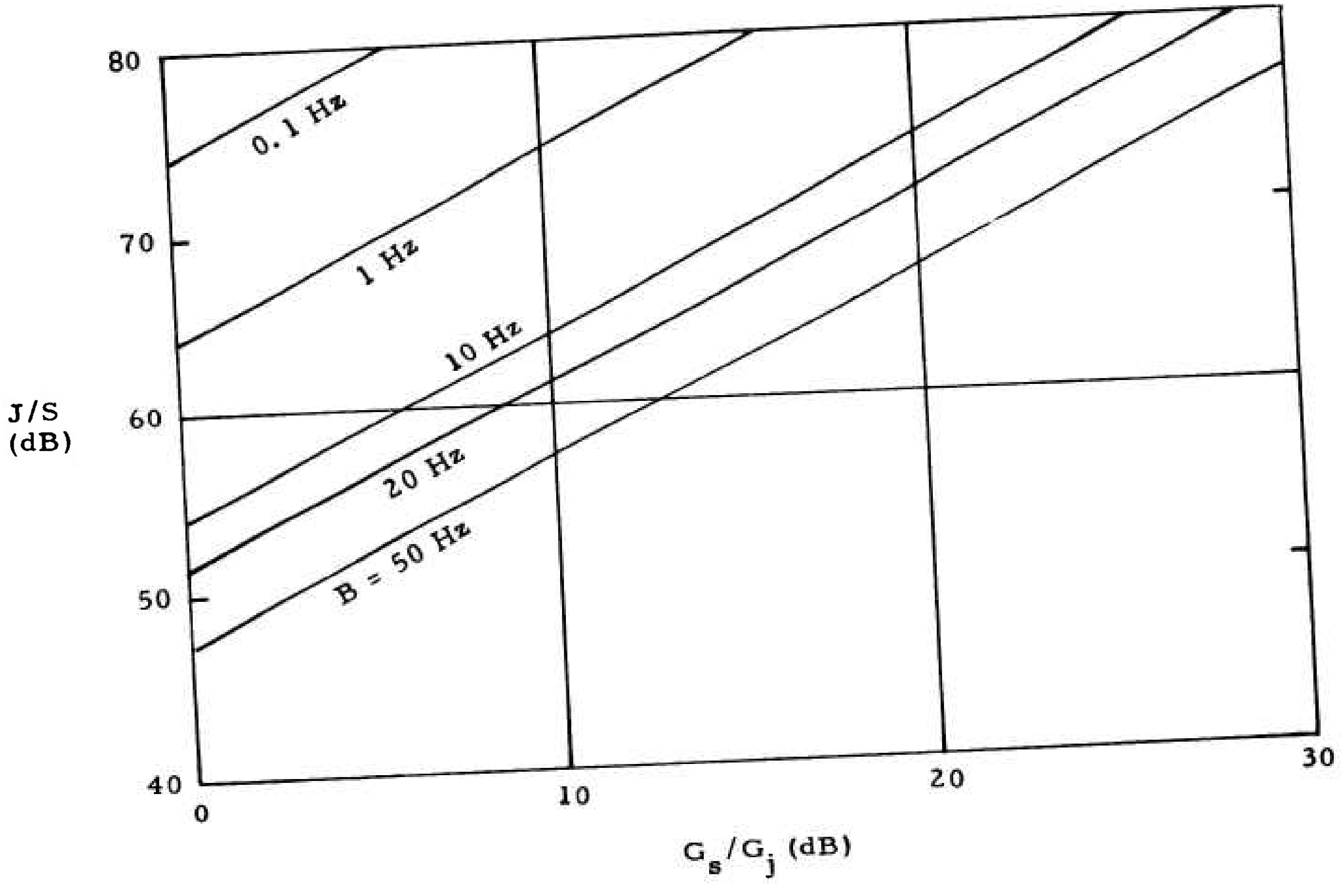


Figure 2-2. Jamming Immunity

3. USER EQUIPMENT DEFINITION

Using the six classes of users defined by the JPO, the requirements of each were examined and reduced to equipment and software requirements. This process served to demonstrate a high degree of commonality between the equipments for the different classes. This commonality can be utilized in reducing the design and test scope of the Phase I program and thereby, the risk. It also contributes to a large cross class usage of basic hardware to reduce life cycle costs.

The resulting equipment and software requirements have been examined to determine the types of design which can satisfy these requirements and which are practical at low cost. This has led to the definition of three basic receiver types and three antenna types. A single computer and control/display answer the Phase I needs. Software deltas allow for differing performance needs. Software, written in a higher order language, facilitates the progression from the Phase I computer to an operational diversity of computers.

For Phase I testing, equipment has been defined in terms of equipment groups, the heart of which will become the GPS navigation set. The equipment group contains all the facility for testing and equipment group peculiar data collection.

3.1 EQUIPMENT GROUP DESIGN

Table 3-1 summarizes the driving performance and environmental requirements for each of the six classes. Classes A and B share the desire for high accuracy under high dynamic conditions which require continuous tracking of the satellite signals. Classes C, D, and E require slightly less accuracy and operate in comparatively mild environments so the satellite signals may be sequentially sampled. Class F differs from Classes D and E by requiring a very short acquisition time so that it is desirable to simultaneously acquire the satellite signals. Thus, all classes require two basic types of receiver: a continuous tracker or a sequential tracker. Class C is

Table 3-1. Summary Differentation of GPS User Classes

		CLASS A	CLASS B	CLASS C	CLASS D	CLASS E	CLASS F
ENVIRONMENTS	DYNAMICS	4g, 2K f/s	7g, 2K f/s	2g, 800 f/s	1g, 100 f/s	1g, 100 ft/sec	1g, 75 ft/sec
	JAMMING	80 dB	50 dB	20 dB	50 dB	50 dB	50 dB
	VEHICLE	TACTICAL/ STRATEGIC	TACTICAL	TRANSPORT	GROUND VEHICLES	MAN	SUBMARINES
PERFORMANCE	POSITION ACCURACY	15M	15M	45M	60M	60M	15M
	TIME TO FIRST FIX (TTFF)	3 MIN	3 MIN	5 MIN	5 MIN	5 MIN	1 MIN

unique in not using the protected code and is therefore a special case of the sequential tracker. Thus, 3 basic receivers and associated software modules are required for Phase I.

Classes A and B are also unique in that the high performance requires the use of auxiliary sensors to provide "carry through" position and velocity inputs to the receiver during dropouts caused by maneuvers or intensive jamming. Two types of aiding sensors are candidates, an inertial measurement system and an attitude heading and reference system (AHARS) supplemented by accelerometers. The outputs of these are input to the filter (in the computer) which combines the auxiliary sensor and GPS data.

In addition to the basic GPS navigation set and auxiliary sensors, an equipment group as defined herein provides the supporting equipment and instrumentation for test and demonstration. Figure 3-1 shows the basic equipment group for Classes C, D, E, and F. Configuration change between Class C and D, E, or F is accomplished by replacing the receiver and entering the proper software. The equipment mounts in racks on a pallet or in a communications shelter. This provides for maximum flexibility in moving from vehicle to vehicle or laboratory and allows for complete verification of the equipment groups at the factory integration floor.

Figure 3-2 shows the block diagram of the equipment group for Classes A and B. Note that in providing for the interface between the aiding sensor and the GPS computer, the existing computer is retained along with its unique software and interfaces to the IMU. This allows for little or no change to that software and those interfaces and simplifies the GPS Phase I integration task. For operational systems the possibility of integrating both functions in the same computer is a system by system consideration.

Figure 3-3 shows a conceptual rack up of a Class A (or B) equipment group in a test rack for an F4C. Alternatively, it would be packaged in a pod as represented in Figure 3-4.

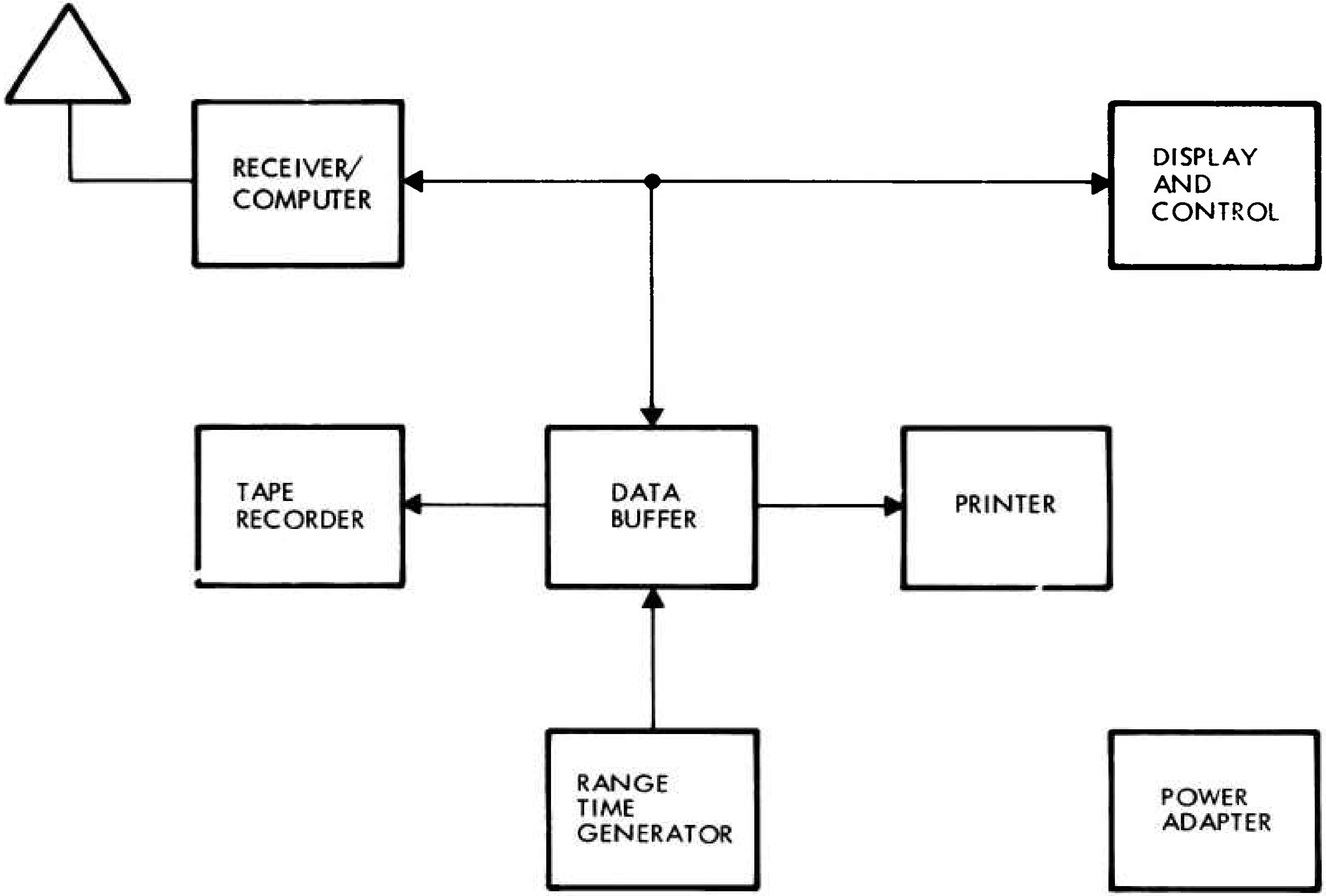


Figure 3-1. Equipment Group Block Diagram Classes C, D, E, and F

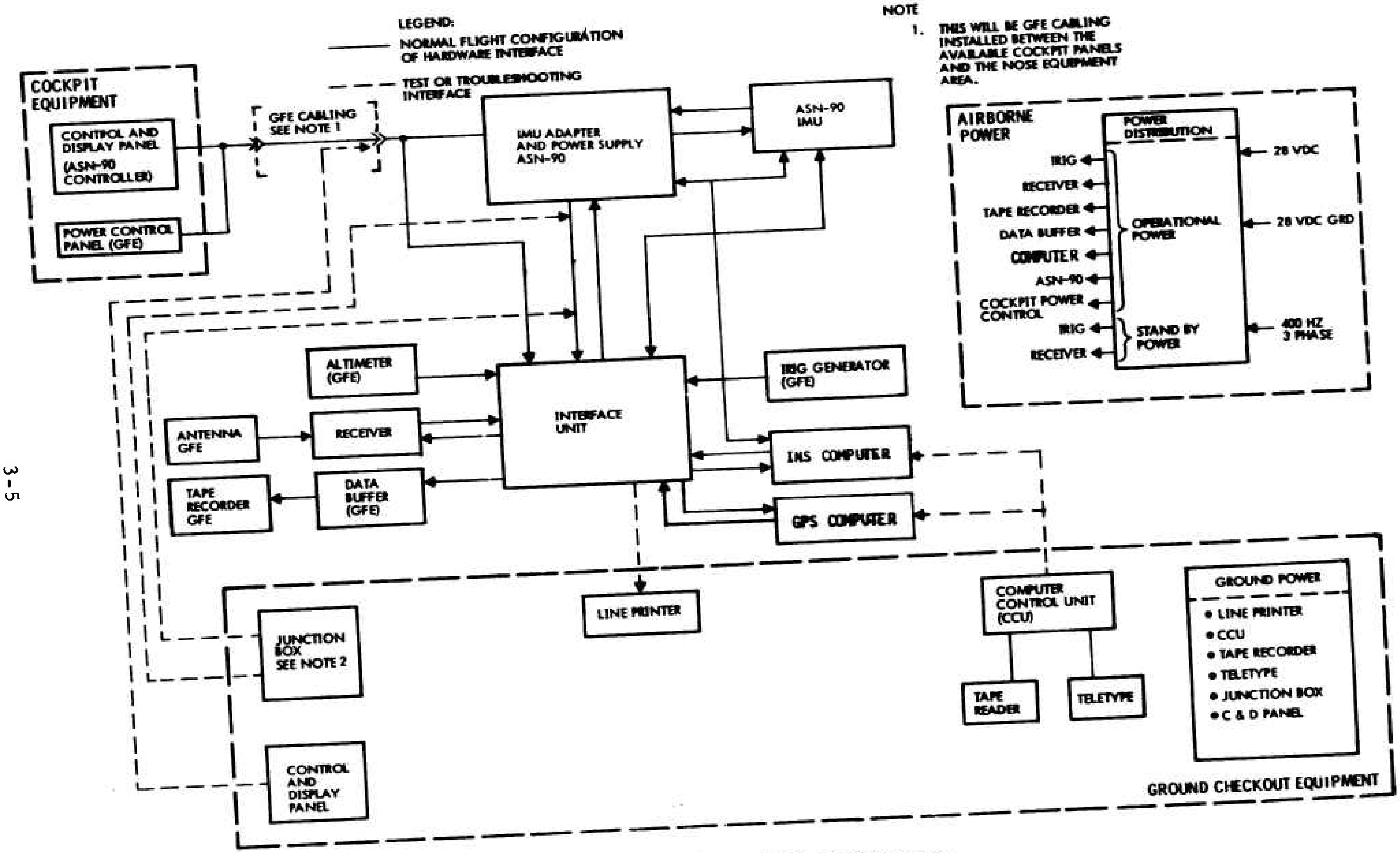
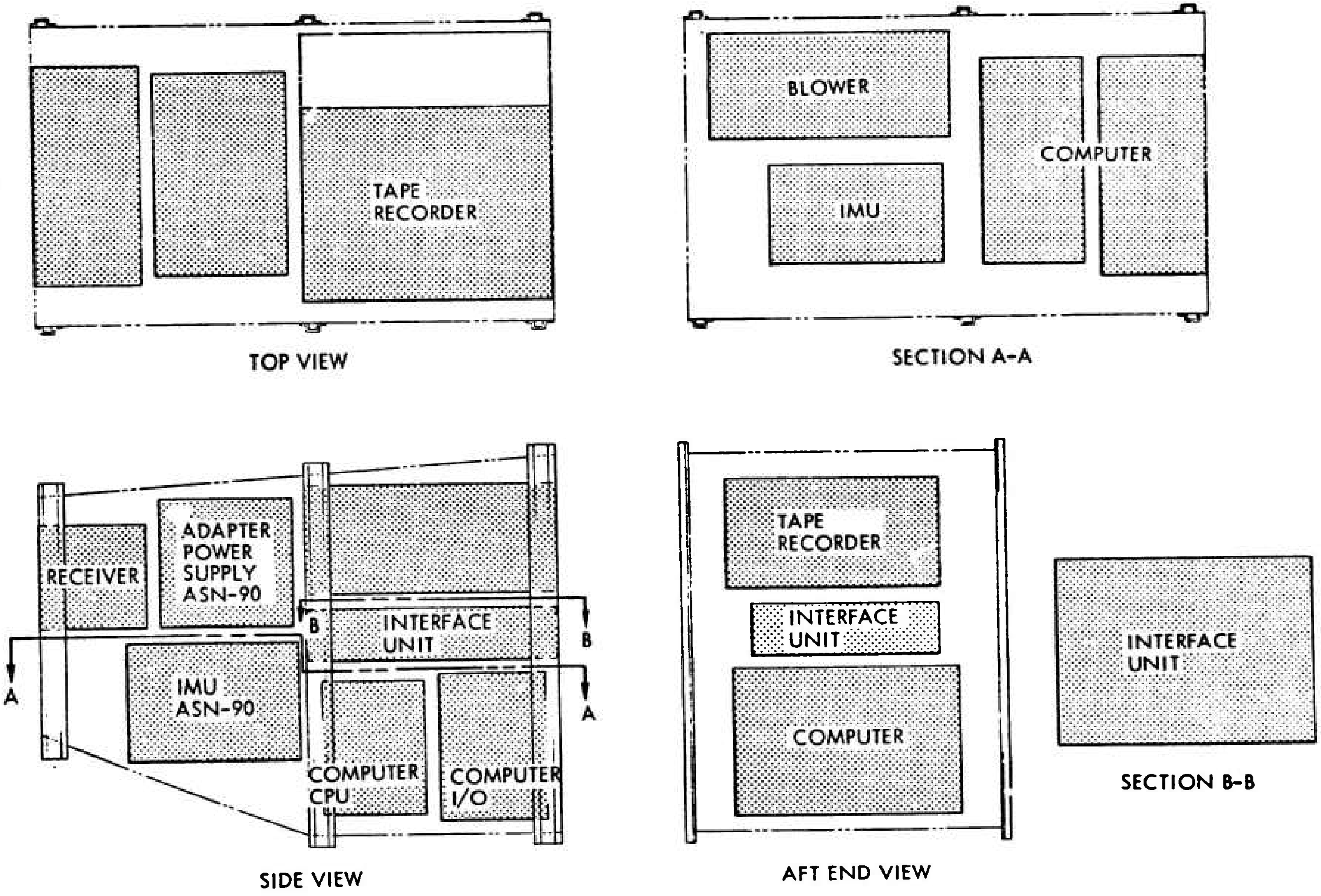


Figure 3-2. F-4 Equipment Block Diagram



TOP VIEW

SECTION A-A

SIDE VIEW

AFT END VIEW

SECTION B-B

Figure 3-3. RF-4C Forward Bay Electronic Equipment Rack

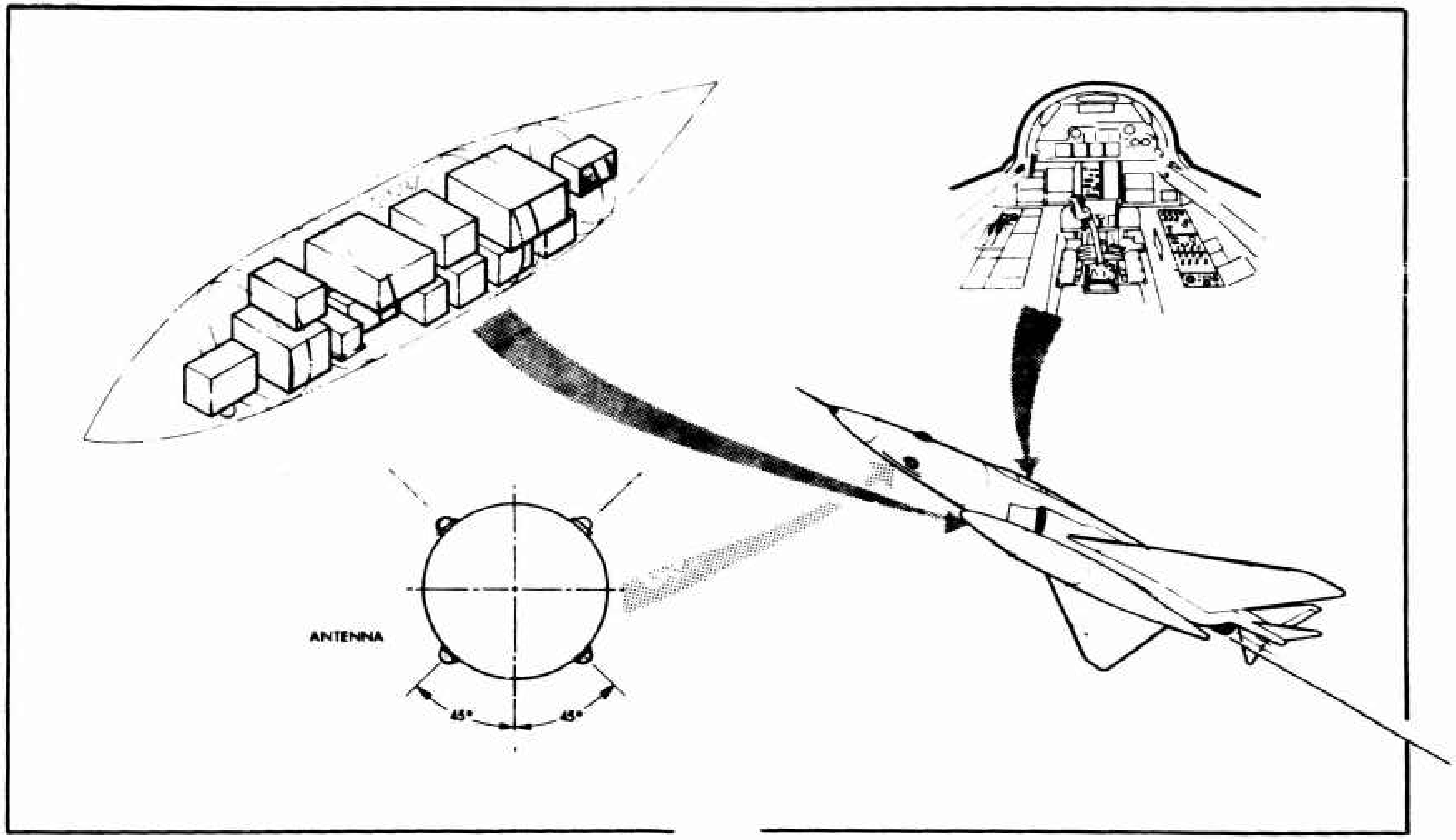


Figure 3-4. Pod Mounted GPS User Equipment Configuration

The following sections describe, in more detail, the elements that make up the equipment groups.

3.2 RECEIVER TYPES AND DESCRIPTION

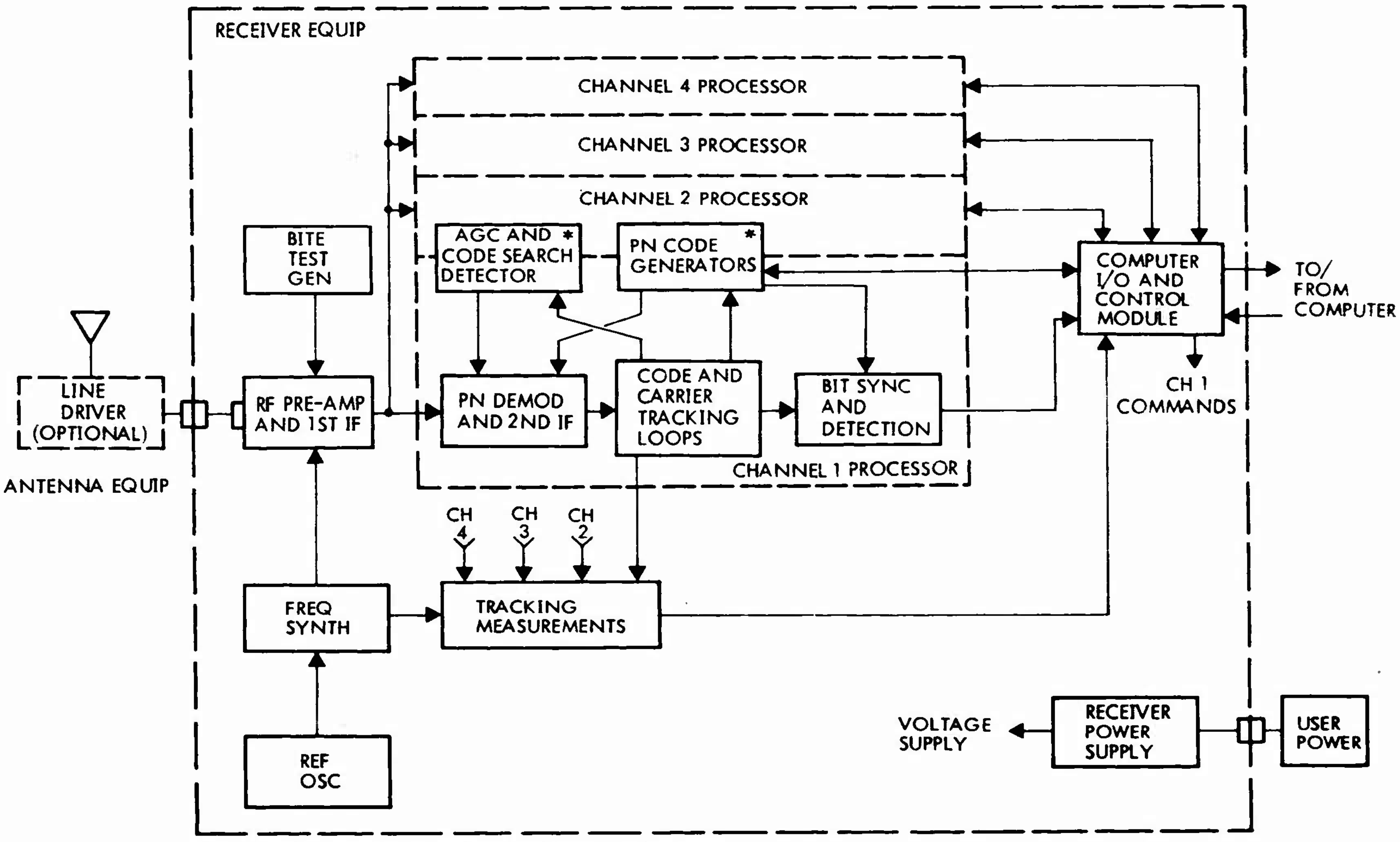
The receiver design effort supported the system definition so that items, such as signal structure definition, link budget, time to first navigation for position error allocation, could be optimized. The receiver design activity stressed feasibility of design concepts, minimization of life cycle cost and functional operation.

As indicated above, three basic receiver types (see Table 3-2) have been defined that will meet the GPS system requirements. The baseline receiver design is a continuous four channel tracking type designated as Type I (see Figure 3-5). This basic type will meet the requirements of User Classes A, B, and F. Two other types of receivers have evolved from the system definition study. The Type II receiver serves the needs of user Classes D and E. This receiver is referred to as a sequential tracking C/P receiver. The Type III receiver is a low cost model intended to serve only the needs of Class C users. It is referred to as a sequential tracking C receiver.

Table 3-2. GPS Receiver Types (Phase I)

	User Class	Frequency	
Type I	A, B, and F	L_1/L_2	Continuous P, C/A
Type II	D and E	L_1	Sequential P, C/A
Type III	C	L_1	Sequential C/A

A summary description will be given of the baseline Type I receiver followed by an explanation of the differences of the Type II and III receivers. Each receiver design has been divided into a number of basic module partitions for commonality. Care has been taken in the receiver designs such that all three receiver types make maximum use of these basic common modules. Therefore, the differences between receiver types are primarily in the number of modules required to make up the receivers and their operation.



* MODULE CONTAINS CIRCUITS FOR TWO CHANNELS

Figure 3-5. Module Block Diagram

For a more detailed description of the GPS receivers and analysis, see Part II, Volume B of the Final Report. The baseline receiver is a four channel, dual frequency Operation L Band type. It incorporates digital processing under computer control and employs phase coherent code and carrier tracking to obtain pseudorange and range rate tracking making continuous measurements on four GPS satellites.

The design is based on TRW experience gained with the receivers designed and operated at Holloman AFB on the Integrated Navsat Inertial System (INI) and the Integrated Navsat Hybrid Inertial System (INHI). The receivers used in these programs have proven very reliable and many of the techniques and circuits developed for these receivers can be incorporated directly into the GPS receivers.

The GPS receivers have been partitioned into modular blocks (see Figure 3-5) and each module utilizes built-in test (BIT) to facilitate automatic fault location and to minimize maintenance time. Definition of the modules was based upon functional allocations and life cycle cost analysis (see Section 4).

3.2.1 Module Definition

The circuitry for the receiver is built on plug-in modules. Faults in the receiver will be detected, and isolated in the failed module using BIT. The modules can then be quickly removed and replaced.

The baseline receiver has been partitioned into functional circuit modules using the following criteria.

1. Maximum commonality between receiver types.
2. Related functions are grouped together.
3. The number of interface signals between modules is minimized.
4. Digital logic is built exclusively on digital modules, and analogue circuitry build on analogue modules wherever practical.

The following Table 3-3 shows the twelve basic modules that are used in all receiver.

Table 3-3. Type I Receiver Module Listing

MODULE NO.	DESCRIPTION	QUANTITY PER RECEIVER
1	RF Pre-Amp and First IF Amp	1
2	Frequency Synthesizer	1
3	Reference Oscillator	1
4	BIT Test Generator	1
5	PN Demodulator and 2nd IF	4
6	Code and Carrier Tracking Loops	4
7	AGC and Code Search Detector	2
8	Tracking Measurements	1
9	PN Code Generators	2
10	Bit Sync and Detection	4
11	Computer I/O and Receiver Control	1
12	Receiver Power Supply	1

3.2.2 Continuous Tracking Receiver Type I

Figure 3-6 is the detail block diagram of the Type I receiver. Following is a summary description of its operation.

3.2.2.1 RF Pre-AMP and First IF

The RF Pre-AMP and First IF Module receives L-band signals from either the antenna or the BIT test generator, filters out-of-band spurious radiation in the preselector bandpass filter, and then amplifies the signal in a low noise pre-amp. Overload protection is provided at the module input to protect against burnout from excess in-band RF power. A postselector bandpass filter provides image

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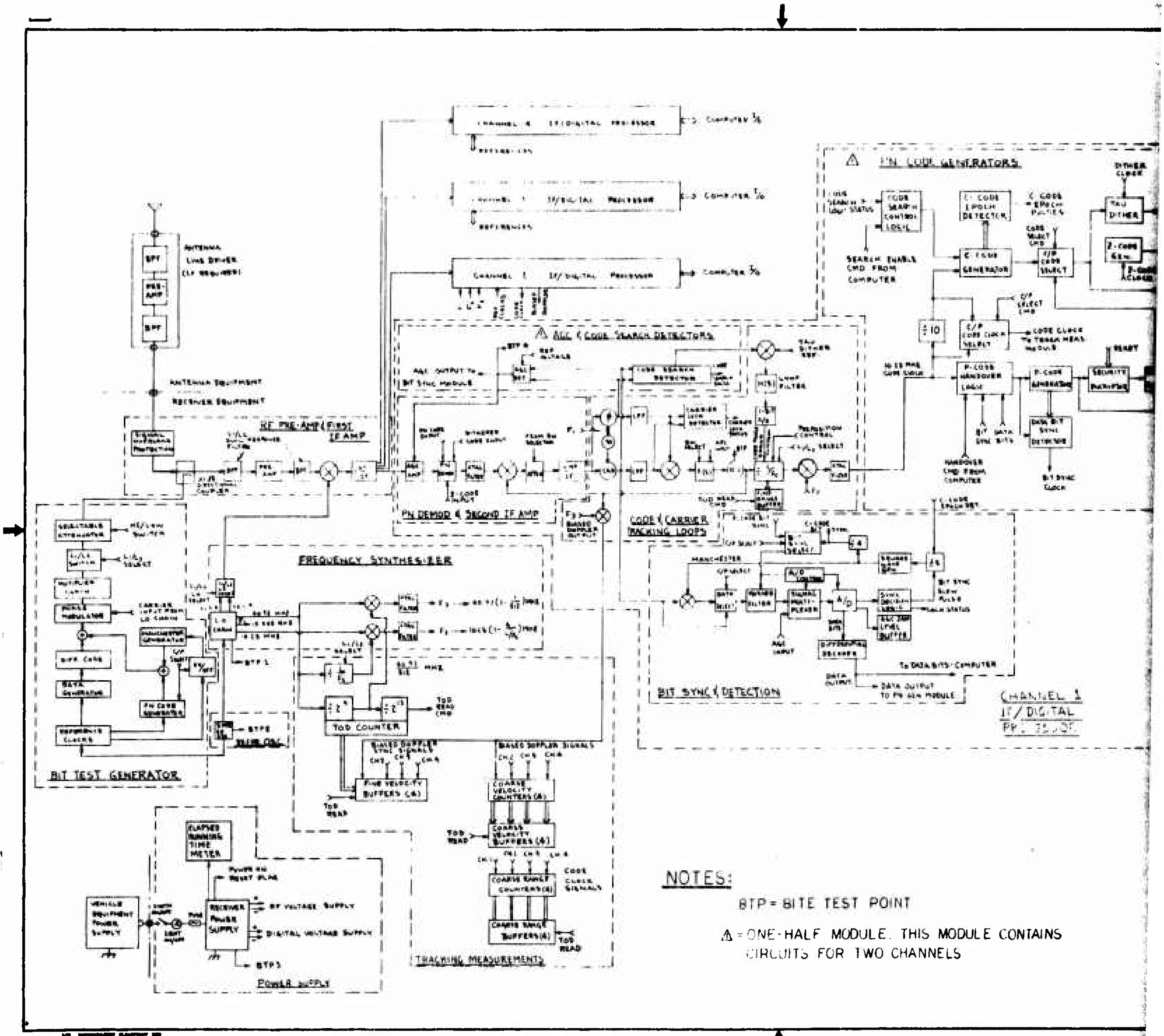


NOTES:

BTP = BITE TEST POINT

⚠ = ONE-HALF MODULE. THIS MODULE CONTAINS CIRCUITS FOR TWO CHANNELS

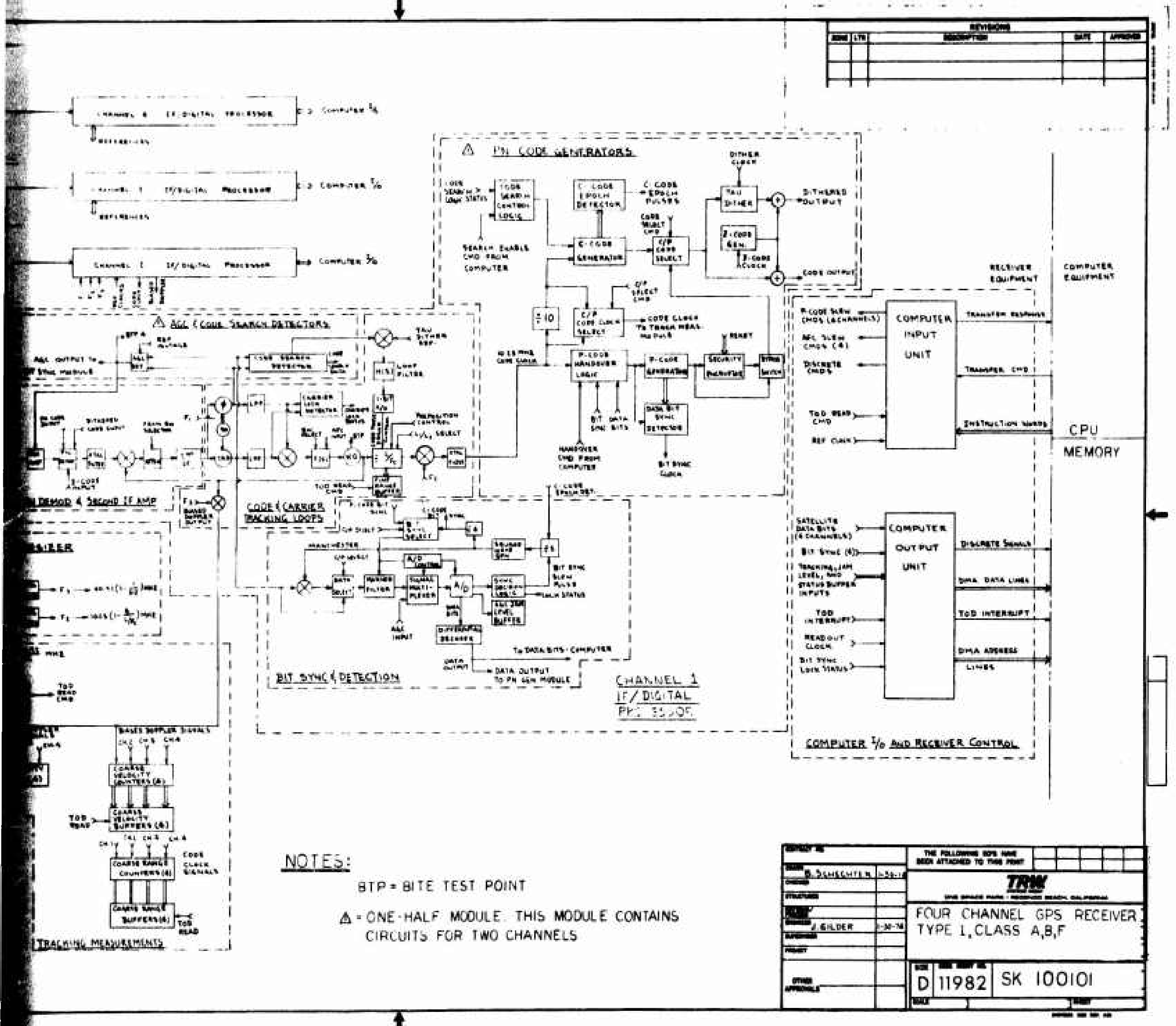

REVISIONS
CHANNEL 4 IF/DIGITAL PROCESSOR
COMPUTER I/O
REFERENCES
CHANNEL 3 IF/DIGITAL PROCESSOR
CHANNEL 2 IF/DIGITAL PROCESSOR
PN CODE GENERATORS
CODE SEARCH CONTROL LOGIC
C-CODE EPOCH DETECTOR
C-CODE EPOCH PULSES
C-CODE GENERATOR
C/P CODE SELECT
TAU DITHER
DITHER CLOCK
DITHERED OUTPUT
P-CODE GEN.
P-CODE CLOCK
CODE OUTPUT
SEARCH ENABLE CMD FROM COMPUTER
÷10
C/P CODE CLOCK SELECT
CODE CLOCK TO TRACK MEAS.
P-CODE HANDOVER LOGIC
P-CODE GENERATOR
SECURITY
RESET
BIT SYNC BITS
DATA BIT SYNC DETECTOR
BIT SYNC CLOCK
HANDOVER CMD FROM COMPUTER
AGC & CODE SEARCH DETECTORS
AGC OUTPUT
BTP
CODE SEARCH DETECTOR
TAU DITHER REF
LOOP FILTER
CARRIER LOCK DETECTOR
LPF
DEMOD & SECOND IF AMP
CODE & CARRIER TRACKING LOOPS
C-CODE EPOCH DET.
BIT SYNC SELECT
MANCHESTER
MATCHED FILTER
SIGNAL MULTIPLEXER
A/D
SYNC DECISION LOGIC
REGISTER LEVEL BUFFER
DIFFERENTIAL DECODER
AGC INPUT
BIT SYNC SLEW PULSE
LOCK STATUS
TO DATA BITS COMPUTER
DATA OUTPUT
DATA OUTPUT TO PN GEN MODULE
BIT SYNC & DETECTION
CHANNEL 1 IF/DIGITAL PROCESSOR
SYNTHESIZER
TOD READ CMD
BASES DOPPLER SIGNALS
CH 1 CH 2 CH 3 CH 4
COARSE VELOCITY COUNTERS (4)
COARSE VELOCITY BUFFERS (4)
TOD READ
COARSE RANGE COUNTERS (4)
CODE CLOCK SIGNALS
COARSE RANGE BUFFERS (4)
TRACKING MEASUREMENTS
RECEIVER EQUIPMENT
COMPUTER EQUIPMENT
P-CODE SLEW CMDS (4 CHANNELS)
AFC SLEW CMDS (4)
DISCRETE CMDS
TOD READ CMD
REF CLOCK
COMPUTER INPUT UNIT
TRANSFER RESPONSE
TRANSFER CMD
INSTRUCTION WORDS
CPU
MEMORY
SATELLITE DATA BITS (4 CHANNELS)
BIT SYNC (4)
TRACKING, JAM LEVEL, AND STATUS BUFFER INPUTS
TOD INTERRUPT
READOUT CLOCK
BIT SYNC LOCK STATUS
COMPUTER OUTPUT UNIT
DISCRETE SIGNALS
DMA DATA LINES
TOD INTERRUPT
DMA ADDRESS LINES
COMPUTER I/O AND RECEIVER CONTROL
NOTES:
BTP = BITE TEST POINT
△ = ONE-HALF MODULE. THIS MODULE CONTAINS CIRCUITS FOR TWO CHANNELS
THE FOLLOWING SCFS HAVE BEEN ATTACHED TO THIS PRINT
B. SCHECHTER
J. GILDER
OTHER APPROVALS
TRW
ONE SPACE PARK • REDONDO BEACH, CALIFORNIA
FOUR CHANNEL GPS RECEIVER
TYPE 1, CLASS A,B,F
D
11982
SK 100101

Figure 3-6

rejection. Local oscillator (LO) frequencies are injected into a mixer to produce a first intermediate frequency (IF) of 55 MHz. The IF is amplified in the first IF amplifier, and the signal is distributed to the four PN Demod and 2nd IF modules.

The design of the RF Pre-Amp module provides for receiving either the L_1 or L_2 carrier. This is accomplished by designing the pre-and post-selector bandpass filters as dual response filters having 30 MHz passbands about the L_1 and L_2 center frequencies. The pre-amp is a wide band device employing low noise figure transistors which passes both L_1 and L_2 signals. The desired carrier is translated to 55 MHz, while the undesired carrier is rejected by the bandpass characteristics of the first IF amplifier.

3.2.2.2 Reference Oscillator

The reference oscillator is a crystal oscillator whose frequency is 5.115 MHz. This oscillator provides the timing reference for all locally generated signals in the receiver, and is the source of a time-of-day interrupt which is used to synchronize computer operations with the receiver. The 5.115 MHz frequency drives the frequency synthesizer, which produces and distributes all the locally generated reference signals.

3.2.2.3 Frequency Synthesizer

The frequency synthesizer module accepts a precision 5.115 MHz reference frequency from the Reference Oscillator and generates a number of local signals used for rf reference frequencies and for digital timing. A local oscillator multiplier chain generates frequencies at 10.23 MHz, 15.345 MHz, 40.92 MHz, and the first IF injection frequency (referred to as L_1. L.O. or L_2L.O.). The 40.92 MHz clock is sent to the Tracking Measurements module, which produces divided down versions of the clock. These signals are then mixed as shown to produce reference frequencies at 10.23 $(1-\frac{L}{F_C})$MHz, and 40.92 $(1-\frac{L}{F_C})$MHz. Here F_C is the 10.23 MHz code clock frequency, and L is the L_1 or L_2 carrier frequency.

3.2.2.4 BIT Test Generator

The BIT Test Generator Module is used to produce a test signal at L-band which is coupled into the receiver in the RF Pre-Amp Module with a 30 dB directional coupler. The test signal is used to evaluate the receiver under computer control thus locating failures to the module level for quick repair of the receiver by module replacement. Maximum use of computer algorithms, rather than elaborate test hardware, is used to reliably detect and isolate faults.

The test signal is a replica of a typical satellite signal, generated from reference frequencies produced by the frequency synthesizer. Test generators produce PN codes, the manchester code, and a pseudorandom data word which is phase modulated on a test carrier which is multiplied up to L-band. A selectable attenuator provides for strong signal and threshold level checkout of the receiver.

3.2.2.5 PN Demodulator and Second IF

The PN Demod and Second IF module, accepts the amplified first IF signal, adjusts the receiver gain with the AGC amplifier, demodulates the selected PN code, and mixes the demodulator output with the VCO frequency to produce the second IF frequency. The second IF signal, which is at 15.345 MHz, is amplified by the second IF amplifier, and sent to the Code and Carrier Tracking Loops module.

The AGC amplifier is controlled by a control voltage received from its AGC detector. The AGC output then goes to a PN demodulator which utilizes a locally generated code to reconstruct the carrier of a desired satellite and generates a code tracking error signal. The PN demodulator employs sequential balanced mixers and a locally generated coincidence code to provide 70 dB suppression to a CW jammer. The demodulator output is applied to a 20 KHz crystal bandpass filter which suppresses jammer and thermal noise power by 27 dB. The filter carrier is applied to the second mixer and multiplied against the 40.92 MHz VCO output signal from the carrier tracking loop. The mixer output is a signal at 15.345 MHz which, when the carrier loop is locked, is phase coherent with the 15.345 MHz reference produced by the local frequency generator. The mixer output is amplified by the second IF amplifier, and sent to the carrier tracking loop.

3.2.2.6 Code and Carrier Tracking Loops Module

The code and carrier tracking loops module, contains the circuitry to phase lock a Voltage Controlled Oscillator (VCO) to the incoming signal obtained from the second IF amplifier, and to generate a code clock whose phase is adjusted such that a reference PN code generator is kept running in phase with the received PN code modulation.

The tracking loop is a Costas type, since the carrier is fully suppressed by the biphase modulation. A 15.345 MHz reference frequency is used to detect the in-phase (I) and quadrature (Q) components of the receiver carrier. Low pass filters follow the multipliers to establish the optimum noise bandwidth for tracking. The filter also accepts an AFC control signal which prepositions the VCO and assures rapid carrier acquisition. The loop filter output drives the VCO, whose output is used to close the tracking loop at the second mixer, and to provide a doppler signal to the Tracking Measurement Module.

An indication of carrier lock is obtained by passing the I- and Q-signals through square law detectors, and subtracting the Q from the I component. This signal is filtered and compared against a reference voltage to obtain lock status.

3.2.2.7 AGC and Code Search Detectors Module

This module contains two AGC detector circuits and two code search detector circuits.

The AGC detector serves to maintain a constant noise power at its input when signal is not present, and to maintain a constant signal to noise power when the signal is present.

The Code Search detector is a noncoherent envelope detector followed by a threshold comparison device. The AGC circuit is designed to keep the noise power constant, even in the presence of jamming, so that the false alarm probability of the detector output is correct. When signal is present, the output of the detector is greater than the threshold level established for detection. The detector then produces an in-lock indication, which stops the code search and enables the tau dither code tracking loop.

The AGC detector is a noncoherent detector which accepts I- and Q-input signals from the carrier tracking loop. The signals are passed through predetection low pass filters to establish the desired noise bandwidth, and then square law detected. The I and Q components are summed and post detection low pass filtered to generate a noncoherent AGC error signal. This signal is added to a reference voltage and amplified to obtain the AGC control voltage.

The noncoherent code search detector functions in a similar manner to the AGC detector. The differences are that a narrower predetection filter bandwidth is used, and the signal out of the post detection low pass filter is compared against a pre-established reference voltage. This reference is set up so that when the reference code is not correlated with the received code, the signal into the voltage comparitor (which is proportional to noise power) is less than the reference voltage, and the code lock indicator is out-of-lock. When the received and reference codes are correlated, the signal into the voltage comparitor (which is now proportional to signal plus noise power) is greater than the reference voltage, and the code lock indicator is in-lock.

The lock detector is used to determine the status of the code search during initial acquisition of a new satellite. The selection of bandwidths and threshold reference voltage determine the false alarm and missed detection probabilities which affect the code acquisition time.

3.2.2.8 Tracking Measurement Module

The Tracking Measurements Module, obtains measurements of course velocity, fine velocity, and course range. It also generates two reference clocks for use by the Frequency Synthesizer module, and a receiver time-of-day (TOD) pulse which serves as a read command, and as an interrupt to the computer.

Velocity measurements are obtained by mixing the VCO signal from each carrier tracking loop with the locally generated F_3 reference signal. (This is done in the code and carrier tracking loop modules). The output of the mixing process is a signal whose frequency is the sum of a bias frequency, $\frac{40.92}{512}$ MHz, and the difference between the local oscillator 15.345 MHz and the received carrier frequency down-converted to 15.345 MHz. This difference frequency contains the doppler shift frequency, and is called biased doppler.

Course velocity is measured by clocking a counter with the biased doppler signal, and reading the state of the counter at each TOD read command (each 0.102-second intervals). Fine velocity is measured by reading from the time of day (TOD) counter the time between the read command the end of the current cycle of biased doppler. Since the TOD counter is clocked at 40.92 MHz, the fine velocity count has a resolution of about 25 nanoseconds.

Course range measurements are made by counting cycles of each code clock in a binary counter called the Course Range counter. Whenever the TOD read command occurs, the counter contents are parallel shifted into the course range buffer for readout to the computer. Since the code clocks are slaved to the received code clock from each satellite, the counter contents represents a measure of range. The quantization level of the count is one code chip, which represents about 100 feet for the P-Code, and 1,000 feet for the C-Code.

3.2.2.9 PN Code Generators Module

The PN Code Generators module, accepts a 10.23 MHz code clock from the code and Carrier Tracking Loops module, generates the replica C or P code, and produces a PN Code output and a dithered PN code output which is used to demodulate the PN code from the received satellite signal.

The module provides code search control logic for initial acquisition of the C code, and provides a C-code epoch detector which provides C-code epoch pulses to the Bit Sync and Detection Module. P-code handover logic is used to decommutate P-code handover information obtained from the C channel data, and start the P-code PN generators running in synchronism with the received P-code. A data bit sync detector observes P-code generator epochs to derive bit sync for extracting P-channel data.

The module provides an interface for a security encryption device which is supplied by the government. A bypass switch is included to permit use of the receiver in either a secured or unsecured mode.

3.2.2.10 Bit Synchronization and Detection Module

The Bit Sync and Detection Module detects data bits in the received signal, obtains a bit sync pulse, decodes the differentially encoded data, and provides data bits and bit sync to the PN Code Generator module and the computer I/O and Receiver Control module.

The data signal is obtained from the coherent amplitude detector output of the Costas tracking loop (I-signal). A locally generated replica of the Manchester code square wave is multipled with the received data signal to remove the Manchester code. The Manchester decoding is bypassed using the data select switch if data is extracted from the P-code.

Bit synchronization is obtained as follows. When data is extracted from the P-code, bit sync occurs in coincidence with a particular state of the P-code generator. Thus, a bit sync detector circuit detects the receiver's P-code generator state which coincides with bit sync, and generates a bit sync pulse.

When data is extracted from the C-code, bit sync occurs in coincidence with one of the C-code PN generator epochs. However, there are twenty epochs for every bit sync occurrence, and four epochs for every Manchester code transition. An epoch detector generates pulses coincident with the receiver C-code generator epochs. These pulses are divided by five, and the resultant pulses drive a local Manchester code generator. The Manchester pulses are further divided by four to obtain replica bit sync pulses. The bit sync decision logic slows the divide by five counter until the digitized magnitude of the matched filter output is maximized. The sync decision logic then declares an in-lock condition, and bit sync is automatically obtained by dividing down the C-code epoch pulses.

3.2.2.11 Computer I/O and Control Module

The Computer Input-Output (I/O) and Control Module provide the necessary logic and control circuitry to transfer control information from the computer to the receivers, and to transfer satellite data, tracking measurements, and receiver status from the receiver to the computer. In addition, a single interrupt (the time-of-day pulse) is sent to the receiver reference clocks.

The module also contains circuitry necessary to configure the receiver according to the configuration commanded by the computer, and to execute carrier and code pre-positioning.

3.2.2.12 Receiver Power Supply Module

The Receiver Power Supply Module accepts primary power from the user vehicle supply bus, and converts the input power to dc voltages adequate for operation of the analogue and digital circuitry. The module includes a primary power on-off switch, fuse, on-off light, and elapsed running time meter. The power supply itself will provide AC to DC conversion from aircraft 400 Hz power, and provide adequate filtering and voltage regulation for proper operation of the receiver. A power-on reset flag (POR) is set each time power comes on. The flag is turned off by the computer, indicating recognition of a POR condition in the receiver. This is important, since a power glitch in the receiver will introduce timing glitches in the reference clocks which run off the reference oscillator. When a POR occurs, the receiver will remain configured in the state it was in prior to power interruption. It will be up to the computer to decide if the receiver should change its configuration in response to a power glitch.

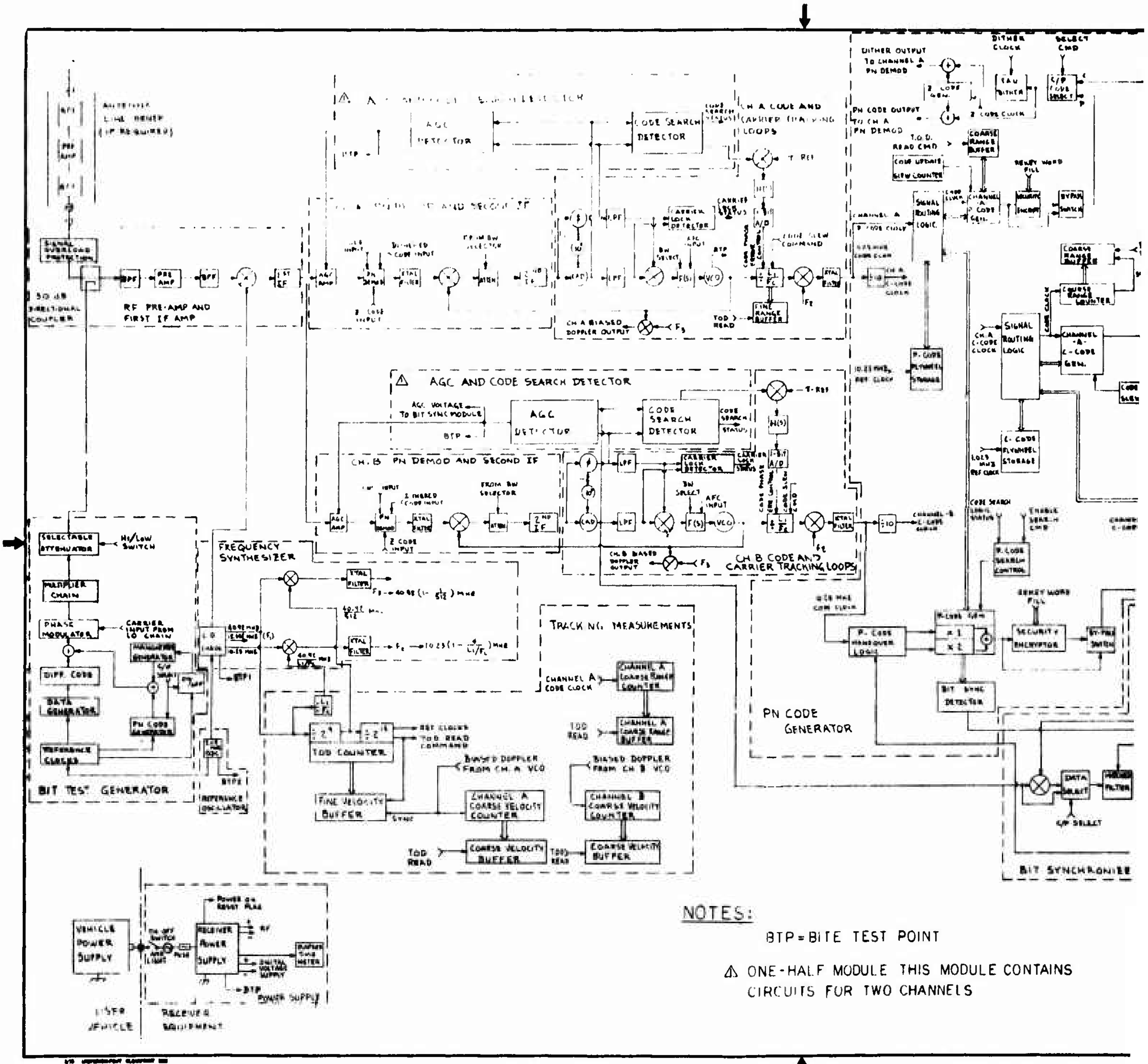
A built-in test point (BTP) will provide voltage sensing to insure that the power supply is providing voltages in the allowable voltage range.

In the continuous receiver described in this baseline, two separate plug-ins constitute the power supply module.

3.2.3 Sequential Tracking Receivers (Types II and III)

This section discusses details of sequential tracking receivers. There are two types of sequential trackers of interest. A Type II receiver tracks four satellites sequentially in either the C-channel or the P-channel. The block diagram for this type of receiver is shown in Figure 3-7. It uses many of the same modules as the Type I receiver (continuous tracker). The PN code generator module and the Computer I/O and Control Module are somewhat different. The Frequency Synthesizer Module does not require L_2 carrier capability and the Tracking Measurement Modules need counters for only one satellite, not four. The PN generator module must provide flywheel storage for the state of the PN codes of those satellites not being tracked, but which are in the user's constellation. Since the user may navigate in either C or P, flywheel storage is provided for both C and P Code PN generators.

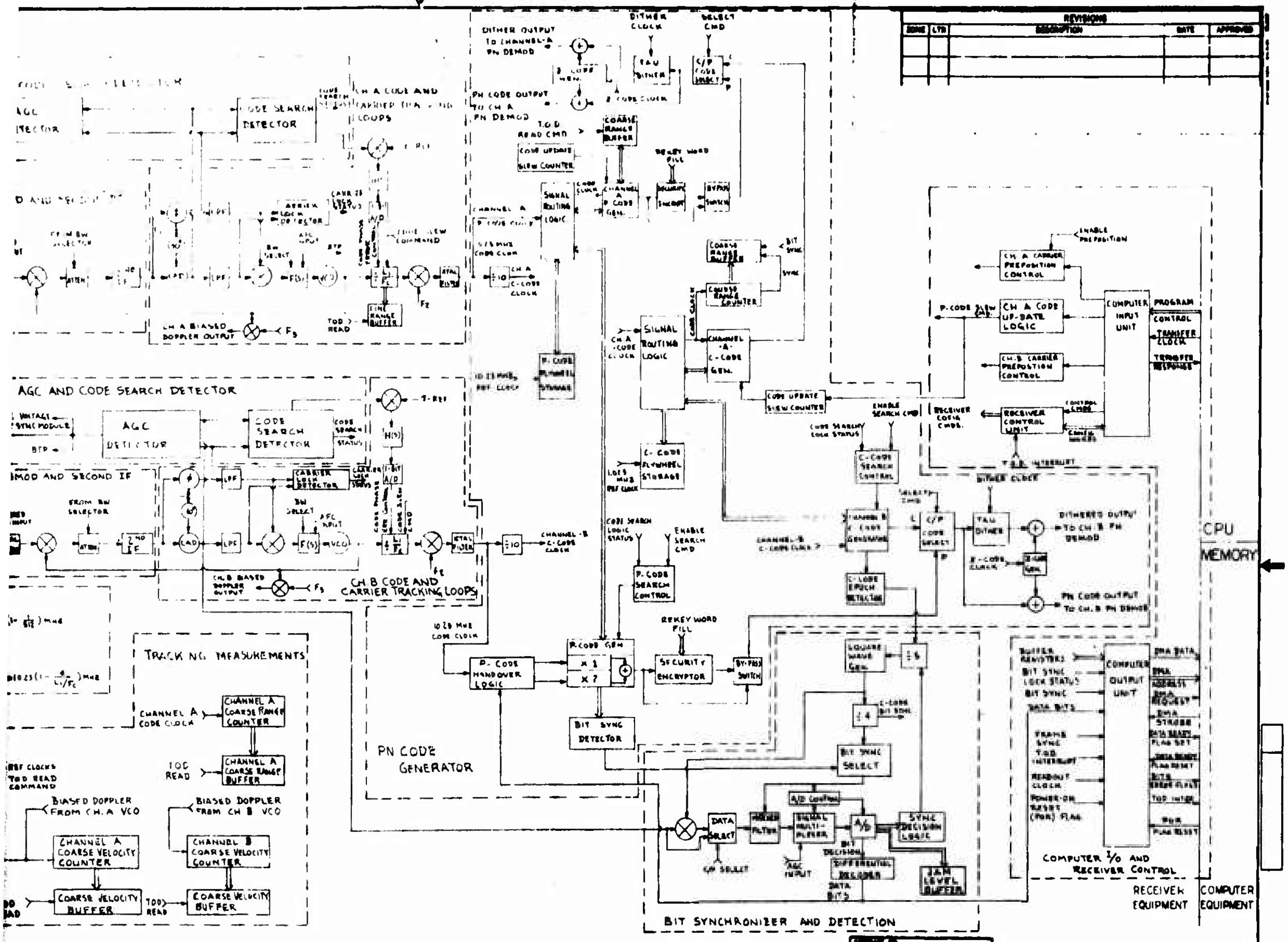
The Sequential receiver contains two processing channels. Channel A is used for obtaining tracking measurements from each of the satellites whose code and carrier states have been acquired, and are therefore in the constellation of sequentially tracked satellites. Channel B is used to acquire new satellites for constellation revision, and for receiving satellite data from any satellite in view without interfering with the sequential tracking of the navigation constellation.



NOTES:

BTP = BITE TEST POINT

⚠ ONE-HALF MODULE THIS MODULE CONTAINS CIRCUITS FOR TWO CHANNELS



NOTES:

BTP = BITE TEST POINT

⚠ ONE-HALF MODULE THIS MODULE CONTAINS CIRCUITS FOR TWO CHANNELS

DRAWN	B SCHECHTER	2-5-74
ENGINEER	J. GILDER	2-5-74

TRW
ONE SPACE PARK • REDONDO BEACH, CALIFORNIA

SEQUENTIAL GPS RECEIVER
TYPE II CLASSES D,E

SIZE	CODE IDENT NO.	
D	11982	SK-100002

Figure 3-7

2

The computer I/O and Control Modules must accommodate those features of the Sequential receiver which are unique from the continuous tracking receiver. Its design is therefore somewhat different, but its principles of operations are the same.

The Type III receiver is a sequential tracker which tracks only C-channel signals. Its construction and operation are the same as the Type II receivers, but all P-code hardware functions are removed. This receiver is the lowest cost receiver.

3.2.4 Mechanical Design

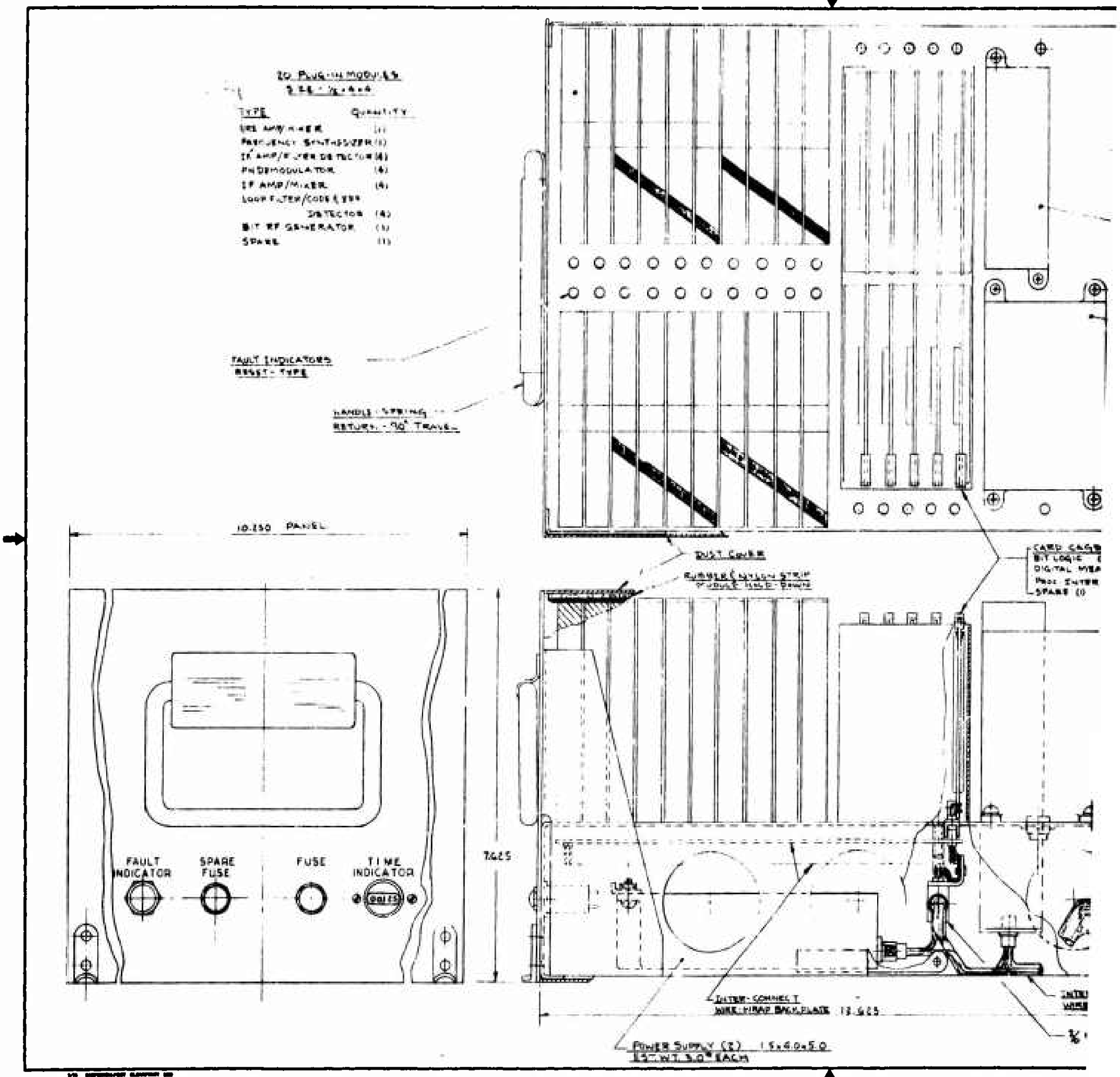
The packaging of the GPS receiver for airborne applications was based upon modular construction in a Short Air Transportable Racking (ATR) case per MIL-E-5400 Class 2 and provides for low-cost economic production.

The basic Type I design is in accordance with the requirements of MIL-C-172 for an MS-91403 case. As depicted in Figure 3-8, the unit configuration is basically a short ATR, having the parameters of 10.125 wide x 7.62 high x 12.56 long.

The construction of the receiver consists primarily of a .05" aluminum chassis fabricated in a manner to achieve minimum weight without sacrificing structural strength. A .06" panel is attached as shown to form the front face. Gussets attached to the chassis and front panel further strengthen the unit.

The rear mounting interface utilizes DPA rack and panel connectors that accommodates power, signal, and RF-connections. Connector alignment is achieved by the rear guide pin receptacles that interface with the aircraft mounting guide pins. The guide pins in conjunction with the hold-down hooks attached to the front panel serve as structural support for the receiver.

The receiver is designed to contain up to 20 plug-in modules of similar external configuration, for RF/IF processing functions and up to 10 PC cards for digital functions that are contained in a card cage. Interconnections between modules have been reduced as much as possible by sharing related functions in a common module. It is significant to note


20 PLUG-IN MODULES
SIZE ½ x 4 x 4
TYPE QUANTITY
VHF AMP/MIXER (1)
FREQUENCY SYNTHESIZER (1)
IF AMP/FILTER DETECTOR (4)
PN DEMODULATOR (4)
IF AMP/MIXER (4)
LOOP FILTER/CODE & BPR DETECTOR (4)
BIT RF GENERATOR (1)
SPARE (1)
FAULT INDICATORS
RESET-TYPE
HANDLE-SPRING RETURN-90° TRAVEL
10.250 PANEL
DUST COVER
RUBBER & NYLON STRIP
MODULE HOLD-DOWN
CARD CAGE
BIT LOGIC
DIGITAL MEA
PROC INTER
SPARE (1)
FAULT INDICATOR
SPARE FUSE
FUSE
TIME INDICATOR
7.625
INTER-CONNECT
WIRE-WRAP BACKPLATE 13.625
POWER SUPPLY (2) 1.5x4.0x5.0
EST. WT. 3.0# EACH
⅜

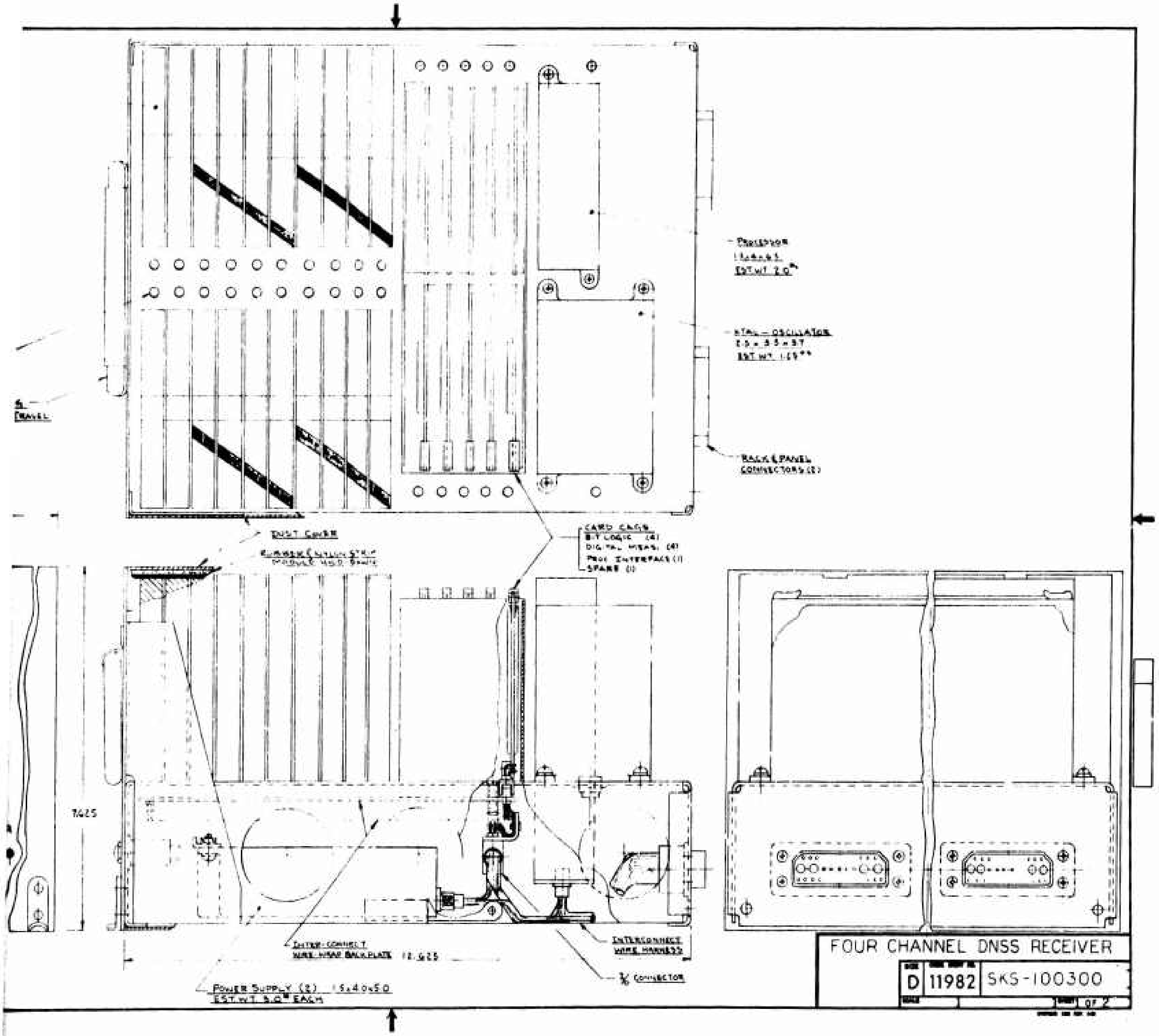

PROCESSOR
11x4x4.5
EST WT 2.0#
XTAL - OSCILLATOR
2.5 x 3.5 x 3.7
EST WT 1.5#
BACK & PANEL
CONNECTORS (2)
DUST COVER
RUBBER & NYLON STRIP
MODULE HOLD DOWN
CARD CAGE
BIT LOGIC (4)
DIGITAL MEAS. (4)
PROC INTERFACE (1)
SPARE (1)
7.625
INTER-CONNECT
WIRE WRAP BACKPLATE
12.625
INTERCONNECT
WIRE HARNESS
¼ CONNECTOR
POWER SUPPLY (2) 1.5x4.0x5.0
EST WT 3.0# EACH
FOUR CHANNEL DNSS RECEIVER
D
11982
SKS-100300
OF 2

Figure 3-8

that the 20 modules and 10 PC cards also represent growth possibilities since higher densitv of packaging is anticipated.

The XTAL oscillator and power supplies are also plug-in modules. All interconnect wiring and coax-connectors are located and accessible from the bottom of the chassis.

To provide accessibility to the module back plate interconnect, the power supply modules may be removed via a disconnect plug, or pivoted outward to provide testing without the utilization of an adapter plug and harness.

To provide BIT capability, fault indicators are included adjacent to each module that isolates the fault to an SRU.

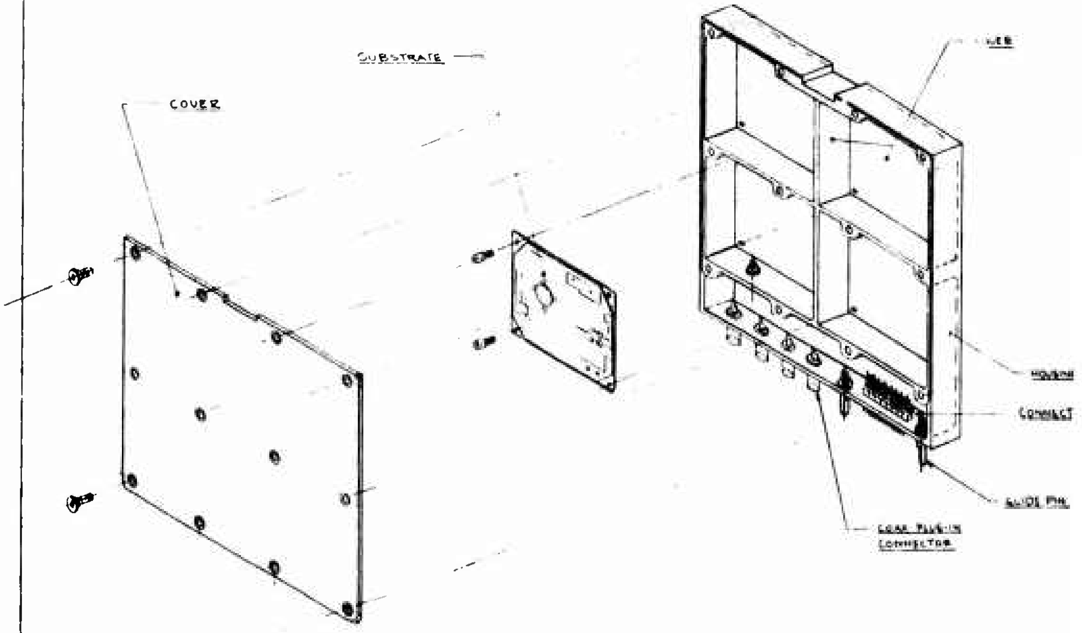
The front panel contains the following items:

a) Handle
b) Hold-down hooks
c) Fuses and holders (2)
d) Elapsed time indicators
e) Fault indicators (latch-type) isolation to LRU

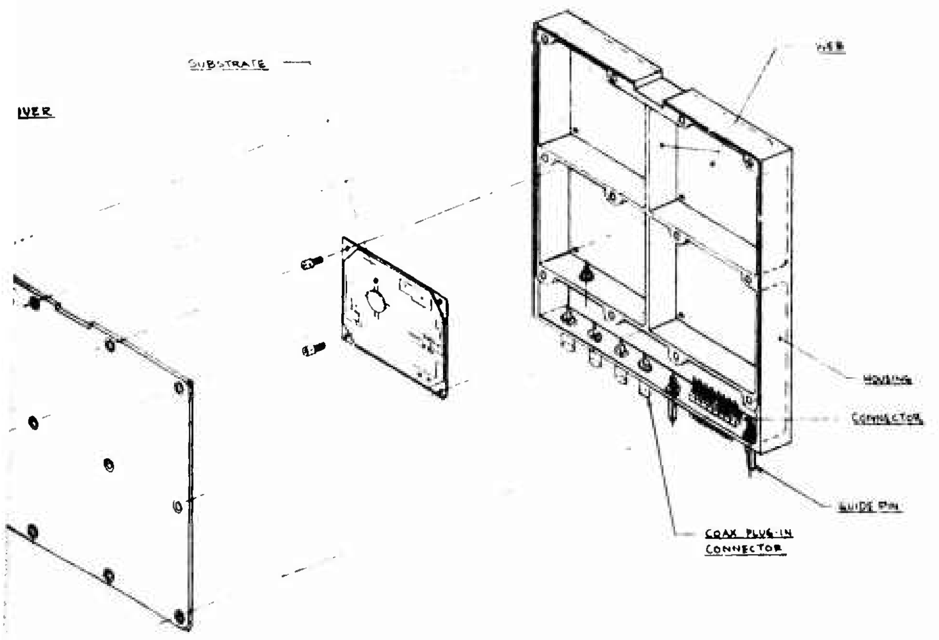
Currently the concept is based around a common modular diecast housing having partitions separating the module into one or four compartments. RF input/output connections are accomplished via coax connectors of the plug-in type on the base of each module. Signals that do not require shielding, such as power, controls, and low data rate pulses, will use normal open wire connections. See Figures 3-9 and 3-10.

Two open connector concepts are shown: 1) Individual insulated contacts inserted into a defined hole pattern integral with the module, and 2) conventional connector separately mounted in the module. Guide pins are used as polarization pins to preclude any mismatch of modules.

Several concepts have been reviewed for the interconnecting of the modules and the input/output rack and panel interface connector. It is significant to note that a high degree of maintainability efficiency has been designed into the unit since all modules, back plate interconnect



TYPICAL 4-SUBSTRATE MODULE PACKAGE



TYPICAL 4-SUBSTRATE MODULE PACKAGE

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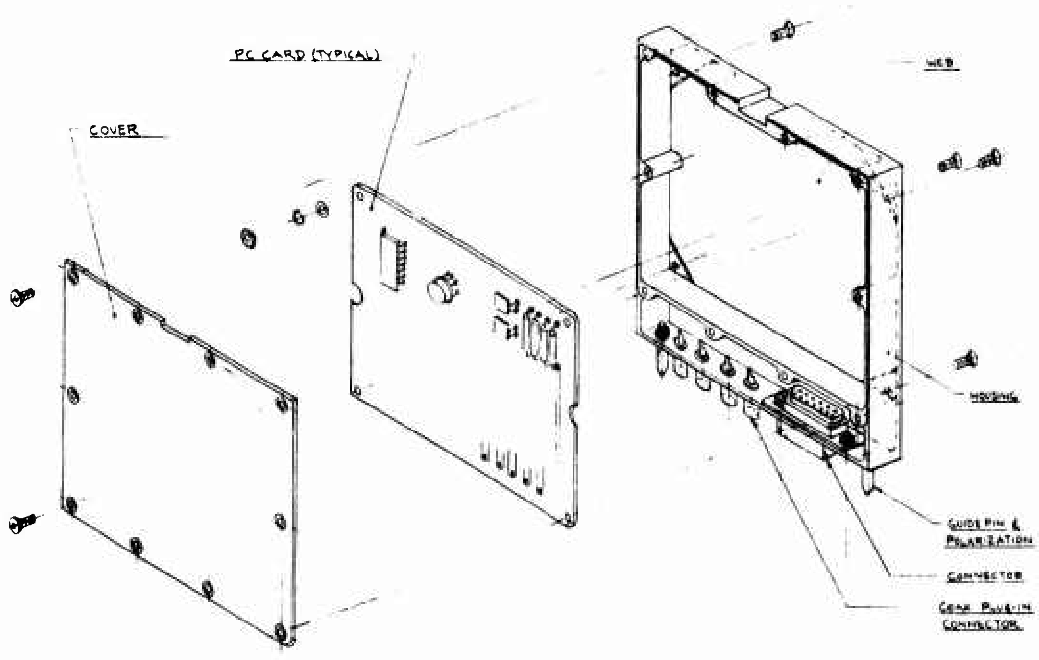
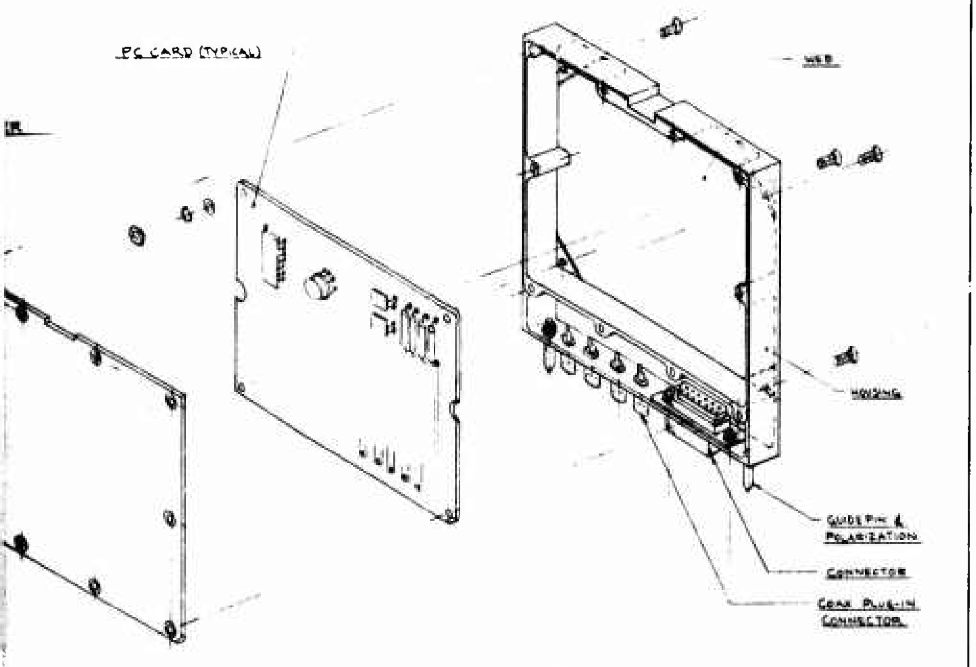
3 of 5

Figure 3-9



TYPICAL PC CARD MODULE



TYPICAL PC CARD MODULE

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4 of 5

Figure 3-10

2

plate, and wiring interconnect harness can be considered as independent assemblies and comply with the plug-in concept.

Interconnect options are:

1) Wire-wrap using automatic assembly
2) Mother-board (multilayered)
3) Flat-cable
4) Hardwire (solder or crimped)
5) Combination

Wire-wrap was selected as the baseline wiring method. The advantages of wire-wrap are that it provides a programmable automatic production type of technique with economic advantages, design flexibility, and ease of repairability.

Cover

The dust cover is fabricated from .04" aluminum having cutouts in the back face for the rack and panel connectors and guide pins. The top and bottom surfaces contain a series of 1/8" diameter punched holes for the free convection of the internal heat to the outer ambient. Two 1/2" wide strips of rubber (closed cell) and nylon of suitable thickness are bonded to the upper surface of the cover. These strips coincide with the grooves on the top surfaces of the modules to physically contain the modules, and to assure electrical continuity to their mating connectors on the back plate under the environmental physical requirements. Quick release captive fasteners contain the cover to the chassis.

Physical Characteristics

Size	10.125" x 7.625"H x 12.563"L
Volume	1000 cubic inches/0.0168 M^3
Weight	28.5 lbs (estimated) 13.0 Kg
Dissipation	60 watts (maximum)

Thermal Considerations

Power dissipation in the receiver is less than 60 watts.

An array of 1/8" diameter holes in the top and bottom surfaces of the dust cover allows cooling air to flow through the electronics. Cooling air entering the bottom of the receiver washes the external surfaces of all the modules and exits at the top. All modules are enclosed and, therefore, are not subjected to contamination.

Critical devices are mounted on conductive surfaces that contribute to maintaining the devices well within their operational rating.

The watts/square inch density relative to the 540 sq in exterior surface area is approximately 0.11 w/sq in. This heat dissipation is considered well within the art of natural cooling, convection, and radiation. External cooling other than natural convection and radiation is, therefore, not considered. Temperature rise in the air stream is anticipated not to exceed 20°C.

EMI Consideration

A high degree of RF isolation is provided by the inherent design of the modules. The module containers are pratitioned to minimize local RF effects. To prevent radiated noise from entering or leaving the enclosure, the modules are RF sealed. Filters are provided on input/output power and signal lines to reduce the effects of conducted interference.

Maintainability

To achieve the maintainability goals, the plug-in modular concept is maximized throughout the design. Virtually all circuitry is packaged on printed circuit cards and contained on plug-in type modules. The dust cover utilizes quick-turn fasteners for easy removal and access to the modules. Fault indicators are provided to quickly assess and isolate to an SRU. Card extractors are provided to facilitate removal of PC cards. Guide pins and polarization is provided to preclude mismatch of modules. Modules are provided with a diagonal white strip that runs in a progressively diagonal fashion to facilitate quick visual location of each module.

The modules plug into a connector backplate that is mounted onto the chassis. This connector plate is prewired and can be defined as a plug-in, since by simply removing the I/O connectors via jack-screws and the coax's connectors will enable quick replacement.

The XTAL oscillator is also modularized and plugs into its receptacles. Quick-turn fasteners are provided on these modules to maintain physical environmental integrity.

The power supplies are contained beneath the connector backplate and accessible from below. These units are contained by two quick-turn release fasteners that interface with a structural support bracket that also provides good heat-sinking to the chassis. The opposite end of the power supply is contained on a cradle that is integral with the chassis, but has the capability of enabling the power supply to pivot outward and provides complete accessibility to the connector backplate and the coax connectors thereon. Removal of the mounting screws that maintain the power supply to the cradle and disconnecting the plug-in hardness connector via jack screws contained on the connector, enables the removal of each power supply.

The interconnect wiring harness has been designed to provide easy replaceability, and simply requires removal of the fasteners that contain the connectors to the chassis.

The 5.115 MHz crystal oscillator, located at the rear section of the chassis, contains high quality components in a ruggedized construction design that is vibration compensated to assure high reliability and optimum performance.

Mechanical Design Considerations for Sequential Receivers

The basic design is similar to that of the four channel GPS receiver and was specifically designed for maximizing the plug-in modules utilized in the aforementioned unit.

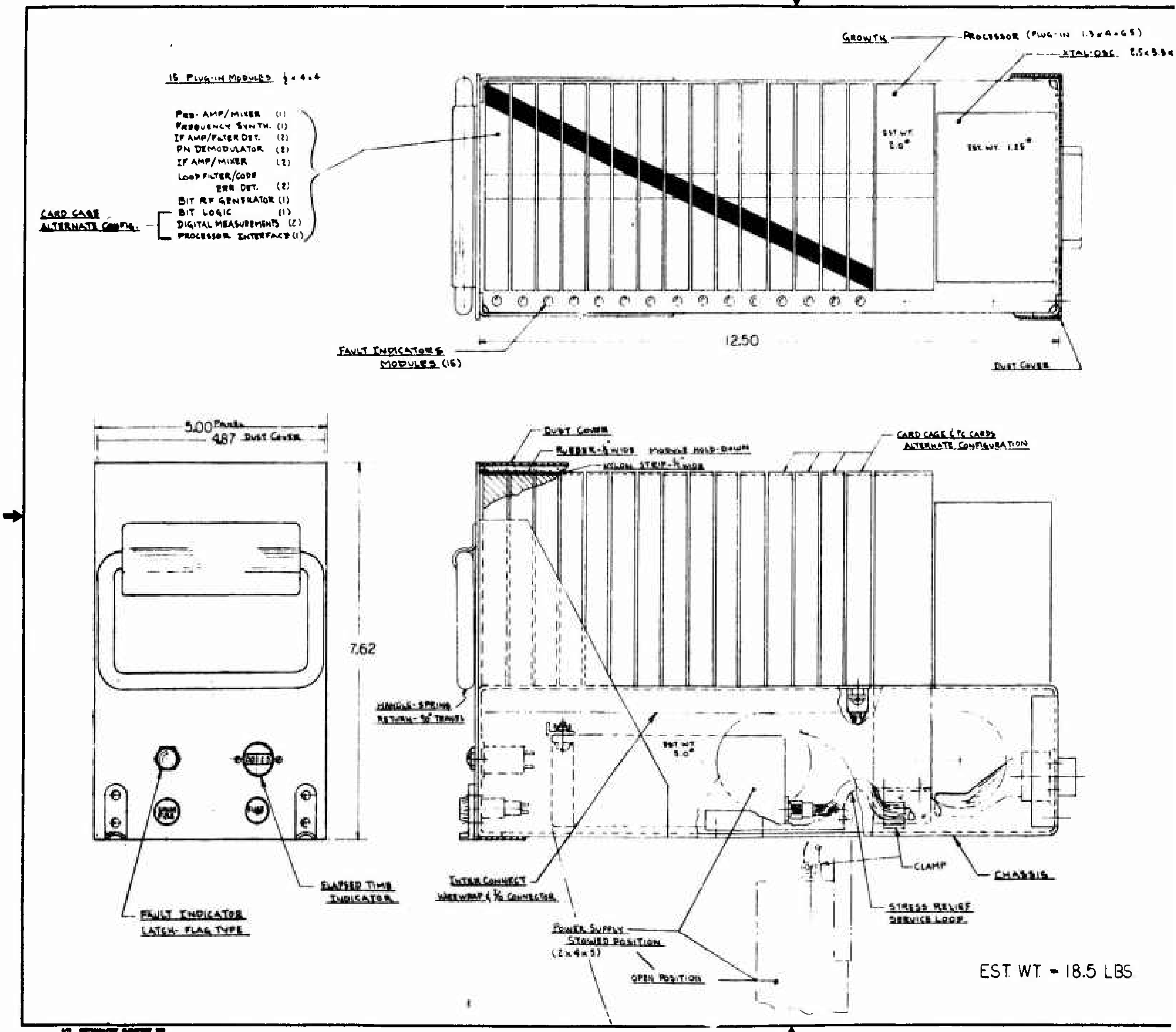
The basic design is also in accordance with the requirements of MIL-C-172 for a MS-91403 case. The unit configuration is shown in Figure 3-11, and configures the envelope of a 1.2 short ATR, having the physical parameters of 4.875 wide x 7.624 high x 12.562 long.

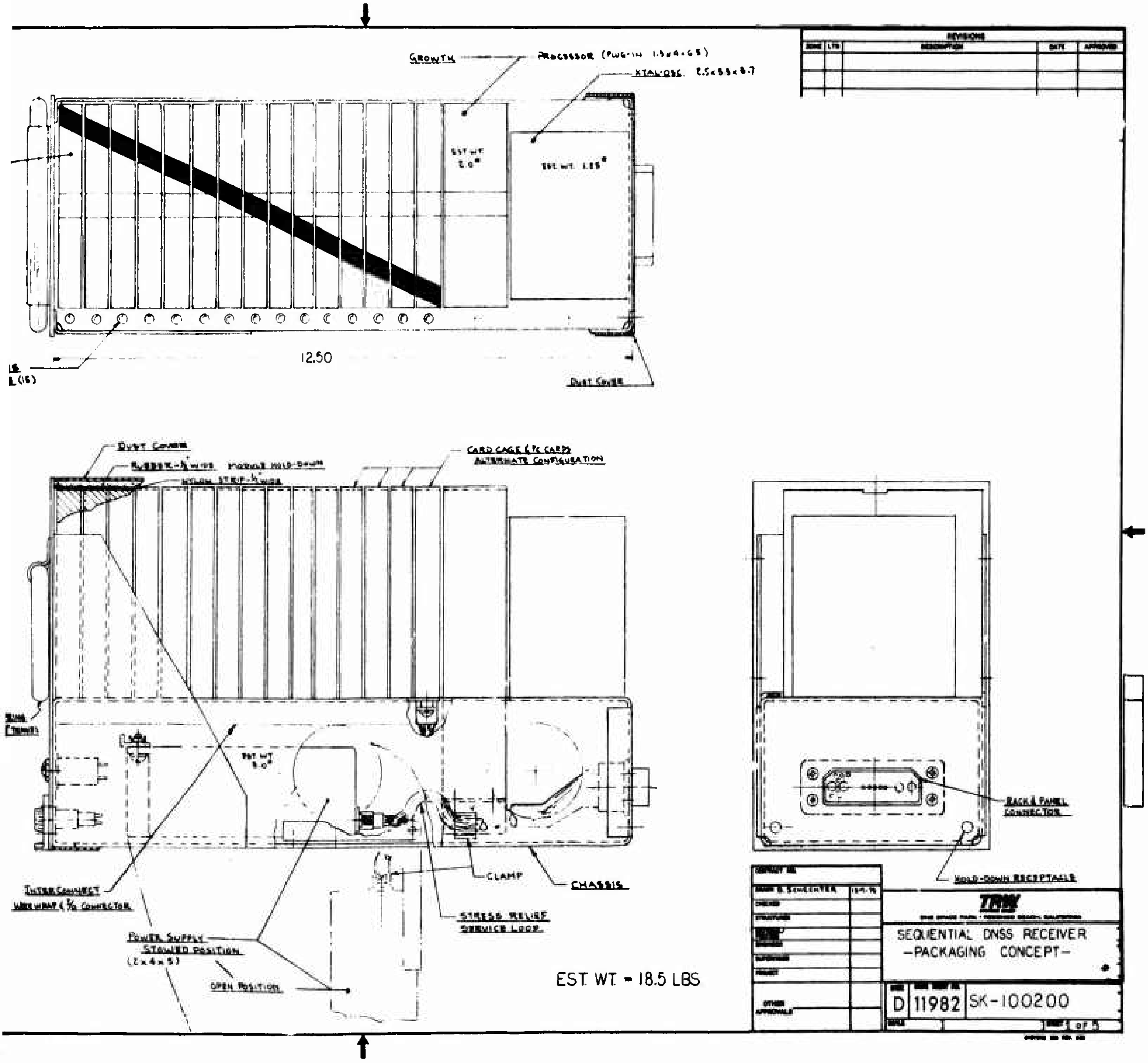
3.3 COMPUTERS

The computer for an operational navigation set performs the functions listed in Table 3-4. In addition, for the test phase, it will log data to printers and recorders to assist in inflight test monitoring and postflight data reduction. The sum of these functions do not require any unusual speed, memory size, or special requirements on the computer. Further, although the operand size reaches 29 bits, it is still possible to use a 16 bit word length computer because the number of words in excess of 16 is relatively small. The use of 16 rather than 32 bits size will significantly reduce computer hardware costs.

Table 3-4. Computer Functions

Initialization
Executive
Acquisition
Data assembly
Measurement processing
Satellite selection
Orbit propagation
Pseudorange geometry
Filter
Navigation computation
User input/output
Navigation set input/output
Auxiliary sensor processing
Self-test


15 PLUG-IN MODULES ½ × 4 × 4
PRE-AMP/MIXER (1)
FREQUENCY SYNTH. (1)
IF AMP/FILTER DET. (2)
PN DEMODULATOR (2)
IF AMP/MIXER (2)
LOOP FILTER/CODE ERR DET. (2)
BIT RF GENERATOR (1)
BIT LOGIC (1)
DIGITAL MEASUREMENTS (2)
PROCESSOR INTERFACE (1)
CARD CAGE ALTERNATE CONFIG.
GROWTH
PROCESSOR (PLUG-IN 1.3 × 4 × 6.5)
XTAL-OSC. 2.5×3.3×
EST WT 2.0#
EST WT 1.25#
FAULT INDICATORS MODULES (15)
12.50
DUST COVER
5.00 PANEL
4.87 DUST COVER
7.62
FAULT INDICATOR LATCH-FLAG TYPE
ELAPSED TIME INDICATOR
DUST COVER
RUBBER-⅛ WIDE MODULE HOLD-DOWN
NYLON STRIP-⅛ WIDE
CARD CAGE & PC CARDS ALTERNATE CONFIGURATION
HANDLE-SPRING RETURN-90° TRAVEL
EST WT 5.0#
INTERCONNECT WIREWRAP & ½ CONNECTOR
POWER SUPPLY STOWED POSITION (2×4×5)
OPEN POSITION
CLAMP
CHASSIS
STRESS RELIEF SERVICE LOOP
EST WT - 18.5 LBS



GROWTH
PROCESSOR (PLUG-IN 1.5×4×6.5)
XTAL OSC. 2.5×3.5×8.7
EST WT 2.0#
EST WT 1.25#
12.50
DUST COVER
L(15)
DUST COVER
RUBBER-¼ WIDE MODULE HOLD-DOWN
NYLON STRIP-¼ WIDE
CARD CAGE & PC CARDS
ALTERNATE CONFIGURATION
EST WT 5.0#
INTERCONNECT
WIREWRAP & P/C CONNECTOR
POWER SUPPLY
STOWED POSITION
(2×4×5)
OPEN POSITION
CLAMP
CHASSIS
STRESS RELIEF
SERVICE LOOP
EST. WT. = 18.5 LBS
RACK & PANEL
CONNECTOR
HOLD-DOWN RECEPTACLE
REVISIONS
ZONE
LTR
DESCRIPTION
DATE
APPROVED
CONTRACT NO.
B. SCHECHTER
CHECKED
STRUCTURES
OTHER APPROVALS
TRW
SEQUENTIAL DNSS RECEIVER
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SK-100200
OF 5

Figure 3-11

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Since the computer is not a technological issue, the use of off-the-shelf units is desirable. In Phases II and III, it can be expected that newer computers and perhaps a variety of computers will assume the tests performed by the Phase I computer. This raises the question of effects on GPS of a changing receiver/computer interface. A standard avionics interface such as envisioned by the DAIS program would satisfy the differences in hardware, and, to a smaller extent, the software differences. Elimination of the majority of software differences is accomplished by use of a higher order language such as Fortran.

Examination of the requirements for the user classes reveals that the same basic functions are required for most classes. The variation is more one of degree than function. This leads to the conclusion that a single type of computer can be used across all classes for Phase I. In later phases, optimization of the computer to specific applications (such as the manpack) can take place.

A type Cla specification for the user segment computer has been prepared. The reader is referred to the Philco Ford/TRW Specification Numbered C237300, dated 30 January 1974, entitled "Prime Item Product Function Specification for User Segment Computer Global Positioning System (GPS)".

3.4 CONTROL AND DISPLAY

The operational user will be interested in the display of the following classes of parameters:

a) Position

b) Navigation

c) Time

d) Data being entered

e) GPS/equipment status

The readout expression of these parameters will vary with the user mission and, in some cases, his mode of operation, i. e., position stated in terms of latitude and longitude, distance and heading to waypoint, local grid coordinates, etc. Units and resolution may vary. Methods of presentation will vary. Operationally, when integrated with existing avionics, it will be desirable to use existing displays.

Table 3-5 shows user inputs by classes. Again the facility for entry of these data may already exist onboard a particular user. For cases where a dedicated unit for control and display is required, a panel, such as Figure 3-12 depicts, provides the facilities needed.

For Phase I, the control and display functions can be adequately provided by use of existing units supplemented by GPS peculiar add-ons. Figure 3-13 depicts a Class A display and control implementation. The left panel is a TALONS display and control which is typical of the type which can be used. The right hand panel contains those GPS peculiar controls and indicators which are not accommodated by the existing design. This panel displays the GPS/inertial combined position or the GPS derived position by operator selection. Inertial derived position is available separately via the INS control and display panel. All three values are available for recording for postflight analysis.

Specific details and definition of the control and display units will be presented when the test vehicles, equipment groups, etc., are assimilated with the ongoing test planning activity.

3. 5 ANTENNAE

3. 5. 1 Discussion

Antennae for various users were defined subsequent to preparing preliminary specification of the antenna characteristics. The preliminary specifications, Table 3-6, were based upon system considerations such as link budgets, satellite power, etc. A brief explanation of the specified parameters is presented below.

Table 3-5. User Inputs

	CLASSES A AND B	CLASS C	CLASSES D AND E	CLASS F
COURSE	AUTO	✓	NR	NR
SPEED	AUTO	✓	NR	NR
LAT-LON	✓	✓	✓	✓
SYSTEM TIME	✓	✓	✓	✓
WAY POINT DESIGNATION	TBD	✓	TBD	TBD
DESIRED COURSE	TBD	TBD	TBD	TBD
OPERATING MODE	✓	✓	✓	✓
DISPLAY MODE	✓	✓	✓	✓

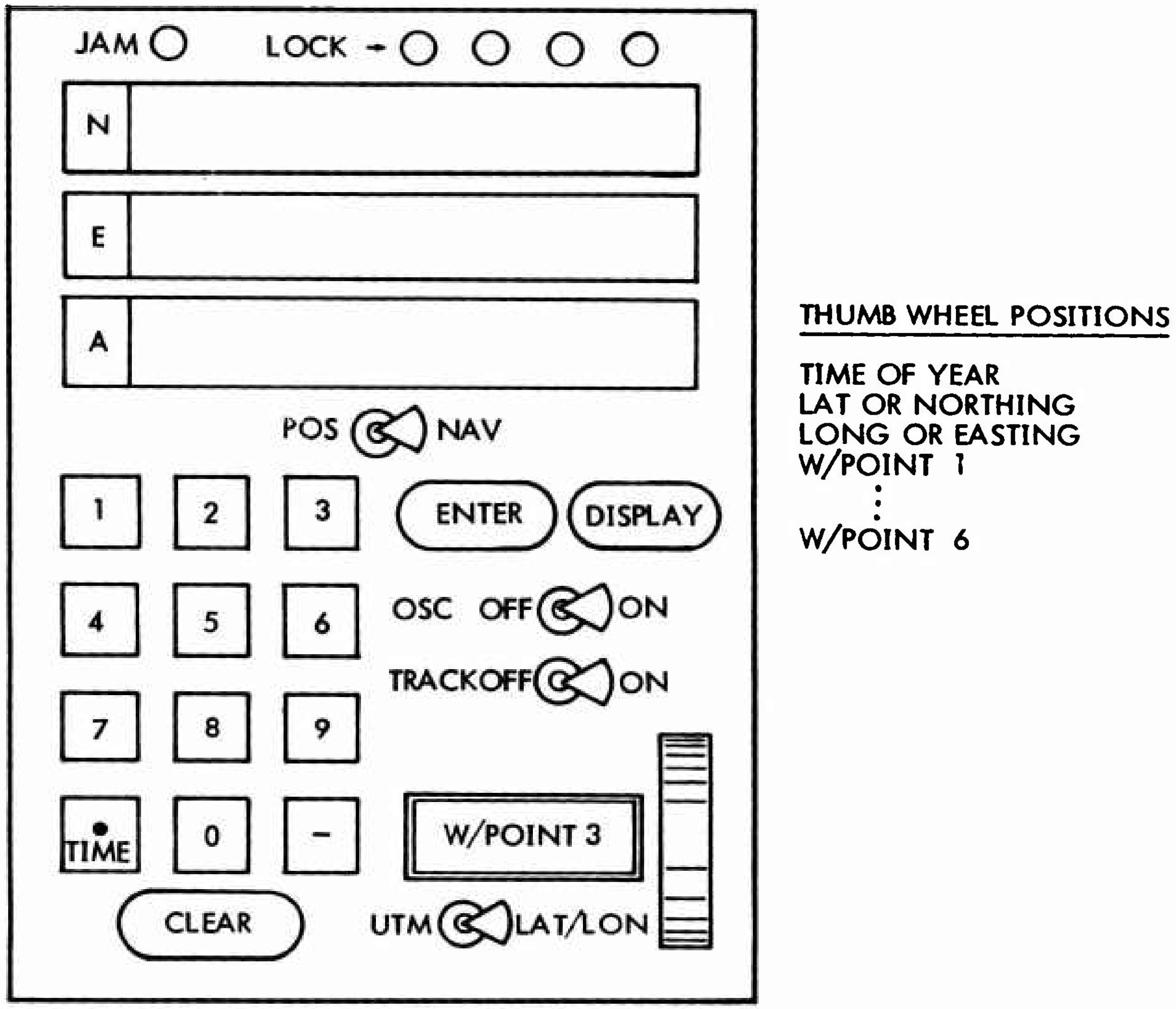


Figure 3-12. Aircraft Pos-Nav Console

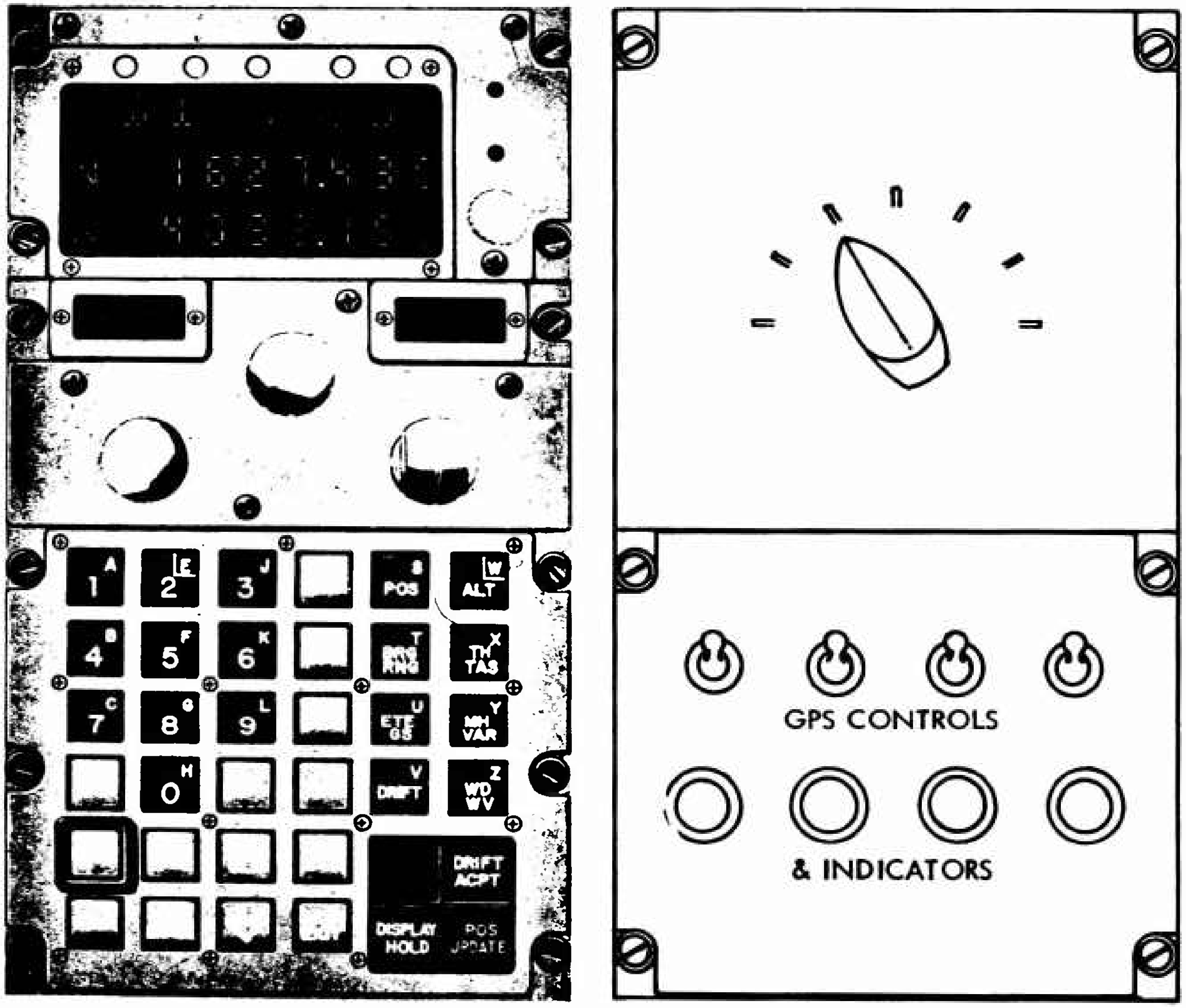


Figure 3-13. Conceptual Phase I Control and Displays

Table 3-6. Electrical Performance Specification for GPS Antenna

Performance	The antenna or antenna array is used to receive radio frequency signals from satellites.
Functional Characteristics	
Frequency Bands	The antenna shall operate in the frequency bands of 1.23 to 1.25 GHz and 1.565 to 1.585 GHz.
Polarization	The antenna shall be right-hand circularly polarized (RHCP). The definition of "right-hand circular" is in accordance with the IEEE Standards on Radio and Wave Propagation.
Passband VSWR	The input impedance of the antenna shall present a voltage standing wave ratio (VSWR) of 1.3 or 1 or less when referenced to 50 ohm resistive over the specified frequency band.
Gain and Radiation Patterns	In response to RHCP, the antenna shall provide a quasi-omnidirectional pattern in the upper hemisphere. The antenna shall have a minimum gain of -1.0 dBi toward the zenith. The antenna gain shall exceed -2 dBi over 95 percent of the 160-degree radiation cone centered at the zenith. The gain shall exceed -4 dBi over 90 percent of the angular region between 160-degrees and the horizon.
Axial Ratio	The maximum axial ratio shall be 5 dB over 90 percent of the 160-degree radiation cone centered at the zenith.
Radome	The presence of radome (if necessary) should not degrade the above stated requirements.

Gain and Radiation Pattern

The upper hemispherical pattern requirement represents optimum coverage for the user antenna since it will enable the user to receive signals from the greatest number of satellites. The additional satellites visible by the user (beyond the minimum of three or four) will improve the system accuracy if properly selected.

A cone of 160° coverage is considered the primary viewing direction because of the larger errors at lower elevation angles. In addition, it was felt that the user antenna should have a minimum backlobe so that very little of the noisy earth environment (including multipath) will be illuminated when the antenna is operating in its normal position pointing skyward.

Polarization

Circular polarization is selected because it possesses desirable characteristics for rejecting multipath signals and provides the best overall system performance in areas of atmospheric and rainfall effects. Multipath rejection is accomplished when reflection from ground or water reverses the sense of circular polarization. The reflected waves with their reversed polarization sense are then partially rejected by the circularly polarized user antenna.

VSWR

The antenna bandwidth is usually defined as the frequency band for a given VSWR which is the ratio of the antenna impedance to the transmission line impedance. The antenna impedance, which is frequency-dependent, depends on many factors, such as geometry and proximity to surrounding objects. The specified antenna impedance for a navigation satellite user antenna is established for a VSWR of less than 1. 3:1.

Axial Ratio

The axial ratio of an antenna radiation pattern is an indication of the antenna's circular quality and should be maintained at a small value. As the axial ratio becomes lower, smaller polarization losses result. For example, based on a 2-dB axial ratio for the satellite antenna and a

5-dB axial ratio user antenna, the polarization loss will be between 0.1 to 0.68 dB. The range of losses will depend on the orientation of the two major axes of the satellite transmit antenna and the user receiver antenna. When the two axes coincide, the polarization loss is at a minimum; when the major axes are orthogonal to each other, a maximum polarization loss occurs.

3.5.2 Antenna Types

For supersonic aircraft, it is mandatory that the antenna does not introduce appreciable drag. It is also desired that no elaborate structural modifications be required. For this application, and possibly for subsonic A/C as well, a flush mounted crossed slot antenna has been proposed. The cross slots meet the requirements of Table 3-6. Gains at the horizon are approximately -2 dB with respect to circular isotropic. A sketch of a crossed slot antenna is shown in Figure 3-14.

For other users not requiring flush mounting, a conical log spiral is the recommended configuration. The spiral exceeds the specified requirements and effectively achieves 0 dBi over the entire upper hemisphere with respect to circular polarization. Also the axial ratio is generally less than 4 dB over the hemisphere.

The antenna performance of a conical log-spiral antenna can be properly specified in terms of the following five parameters:

1) Included cone angle, $2\theta_o$
2) Armwidth angle, δ
3) Spiral rate, α
4) Base diameter, D
5) Apex diameter, d

A conical log-spiral antenna with these parameters is shown in Figure 3-15.

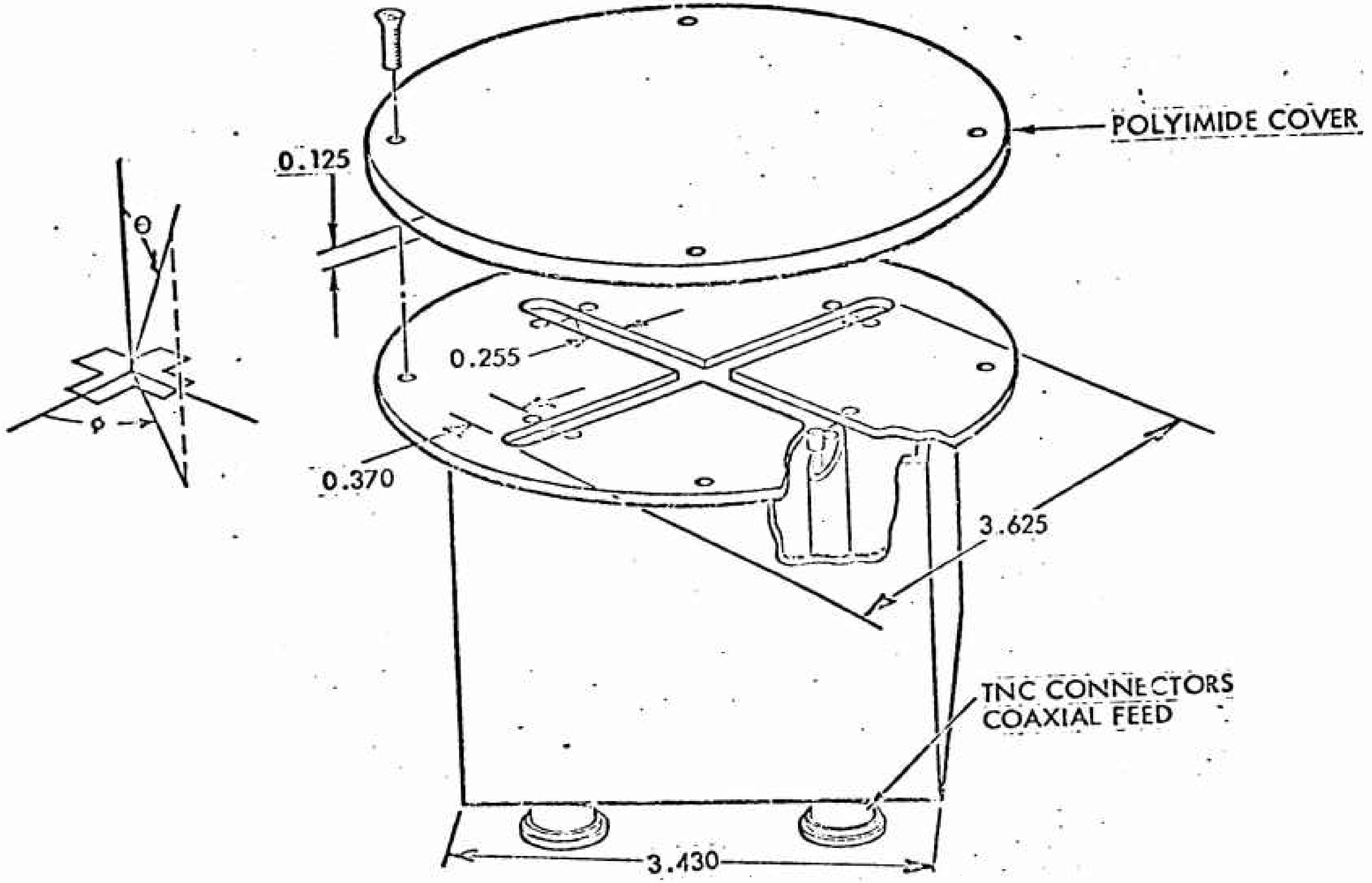
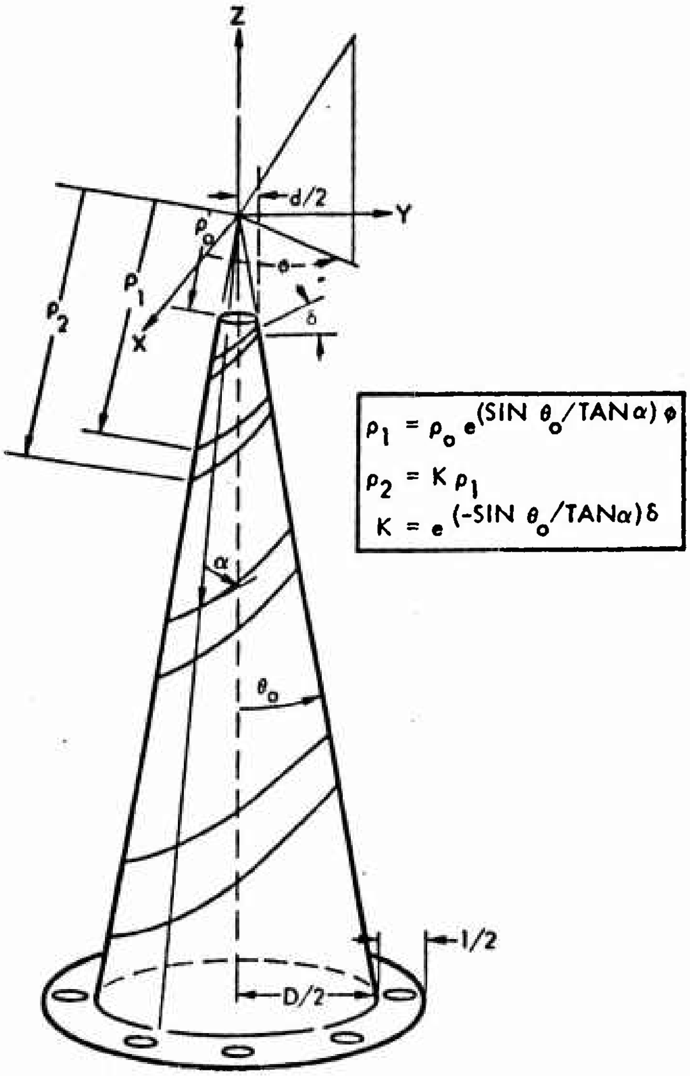


Figure 3-14. Cross-Slot Cavity Backed Antenna



$$\rho_1 = \rho_o e^{(\mathrm{SIN}\ \theta_o/\mathrm{TAN}\alpha)\phi}$$

$$\rho_2 = K\rho_1$$

$$K = e^{(-\mathrm{SIN}\ \theta_o/\mathrm{TAN}\alpha)\delta}$$

Figure 3-15. Conical Log-Spiral Antenna

The apex diameter d, and the base diameter, D, are selected for the highest and lowest frequency of operation.

3.6 AUXILIARY SENSORS

Auxiliary sensors provide two significant user benefits:

1) Continuous tracking of vehicle dynamics
2) Continuous navigation during satellite signal losses.

Considering number two first, this capability could be used by any class as a backup, degraded, or in the submarine case, the prime mode of navigation. The constitution and degree of integration of the GPS receiver and other sensors is determined by the mission objectives of the user.

For vehicles having high dynamics and require high accuracy, it is desirable to supplement the GPS receiver so that rapid reacquisition of the satellite signal will result in the event the signal was lost due to the dynamics or masking of the antenna by the vehicle. By including an auxiliary measurement of attitude and attitude changes on the aircraft, the computer estimates of range and range rate to the satellites can remain within the tracking limits for a significant period, this affording the rapid reacquisition.

The prime candidate as an auxiliary sensor is the inertial navigation system, many of which are currently in use in high performance aircraft. They provide continuous incremental measurements which are then combined with GPS receiver measurements in a recursive filter to provide the navigation solution. If the GPS signal is lost due to antenna occulting or jamming, the filter continues to solve for position and velocity, even if all satellites are lost. When the satellite signal is again available, the onboard maintenance of position and velocity allows quick signal reacquisition. Conversely, when satellite signals are available, the GPS measurements, being of higher precision, drive the total navigation solution to minimum error states. Table 3-7 shows some of the inertial sets recently tested or employed in Air Force/Navy aircraft. Selection among these is narrowed by the criteria of Table 3-8. Recommendations as to which should be used for Phase I will be made subsequent to more detailed analysis of the testing required, test vehicles, and cost (risk) of system integration.

Other sensors, such as altimeters, air data systems, attitude and heading reference systems, accelerometers, etc., can also be utilized as aiding devices. As in the case of the IMU, recommendations on the use and selection of these sensors will be made as the test planning process continues.

Table 3-7. Inertial Navigators

Designation	Manufacturer	Accuracy	Cost	Size	Wt	Pwr	Used On
ASN-48 /ASN-46 Computer	Litton LN-12	2.5 → 5 n.mi./hr	280	2.16	86		F4
ASN-56 /ASN-46 Computer	Litton LN-12	2.5 → 5 n.mi./hr	75	2.85	121		RF4C(327)
ASN-57/58	Singer	3.n.mi./hr			45	N	Navy
ASN-63 /ASN-46 Computer	Litton LN-12		70	2.27	96		F4
ASN-82		3.3 n.mi./hr		0.35	20		
ASN-84	Singer GPK-20	1 n.mi./hr	160K	2	85		P3C
ASN-86	Litton LN-15	0.5 → 0.7 n.mi./hr		1.94	84		OV-10
ASN-90	Singer	.01°/hr	72K		65		A7(348)
ASN-100	Singer	3 n.mi./hr	165K		105		F105
ASN-109	Litton LN-30	1 → 2 n.mi./hr		0.3	16		F15
Carousel IV	Delco	1.0 n.mi./hr		1.28	63		747
Carousel V	Delco	1.0 n.mi./hr		1.28	63		C5

Table 3-7. Inertial Navigators (Continued)

Designation	Manufacturer	Accuracy	Cost	Size	Wt	Pwr	Used On
GEANS (ASN-101 ?)	**Honeywell**	**0.05 n.mi./hr 90% inst CEP**		**2.5**	**140**		**KC135**
LTN-51	**Litton**		**107**				**707**
LTN-58	**Litton**						**DC-10**
CAINS	**Litton**						**F-14**
N-16H	**Autonetics**						**F-111 E**
MICRON	**Autonetics**	**1 n.mi./hr**		**0.6**	**3**		
FLIP	**Northrop**	**1 n.mi./hr**		**1.28**	**63**		**C5A**
KT-70	**Singer**	**2 n.mi./hr**			**20**		**L-1011**

Table 3-8. INS Selection Criteria

1) Available in inventory (or current production)
2) Previous application to high performance A/C
3) Accuracy
4) Digital computer with proven platform management software
5) Good reliability/maintenance available
6) Reasonable size, weight, and power

3.7 INTERFACE HARDWARE

The interface hardware provides the special interfaces required for Phase I test flexibility without institutionalizing it as a part of the prime equipment design. Its functions are:

1) Multiplexing into the computer inputs from the receiver, controls, auxiliary sensors.
2) Demultiplexing computer outputs to the receiver, display, auxiliary sensors, instrumentation, and external systems.
3) Providing operator control to equipment group operation (i. e., power switching, etc.)
4) Power conversion/isolation.
5) Signal conversion facilities as required for interface compatibility.

It is represented in Figure 3-16 by the I/O block and the power supplies/inverter block. It will be composed of a combination of off-the-shelf adapters and, where necessary, special logic and control circuits. Due to the use of a single computer for Phase I across all classes and the degree of standardization of other elements of the receiver groups, the interface hardware also varies little from equipment group to equipment group.

Figure 3-17 shows one method of providing an interface between an inertial system and GPS. This example uses the ASN-90/91 INS and the ROLM 1602 computer. The actual implementation will be dependent on the INS and GPS computer selected. For this example, most of the interface is accomplished by standard hardware cards, only the time of day clock being special. Only minor software changes in the ASN-91 would be required.

3.8 SOFTWARE

The computer program requirements for the various user classes were developed. Figure 3-18 depicts the program functions of the Class

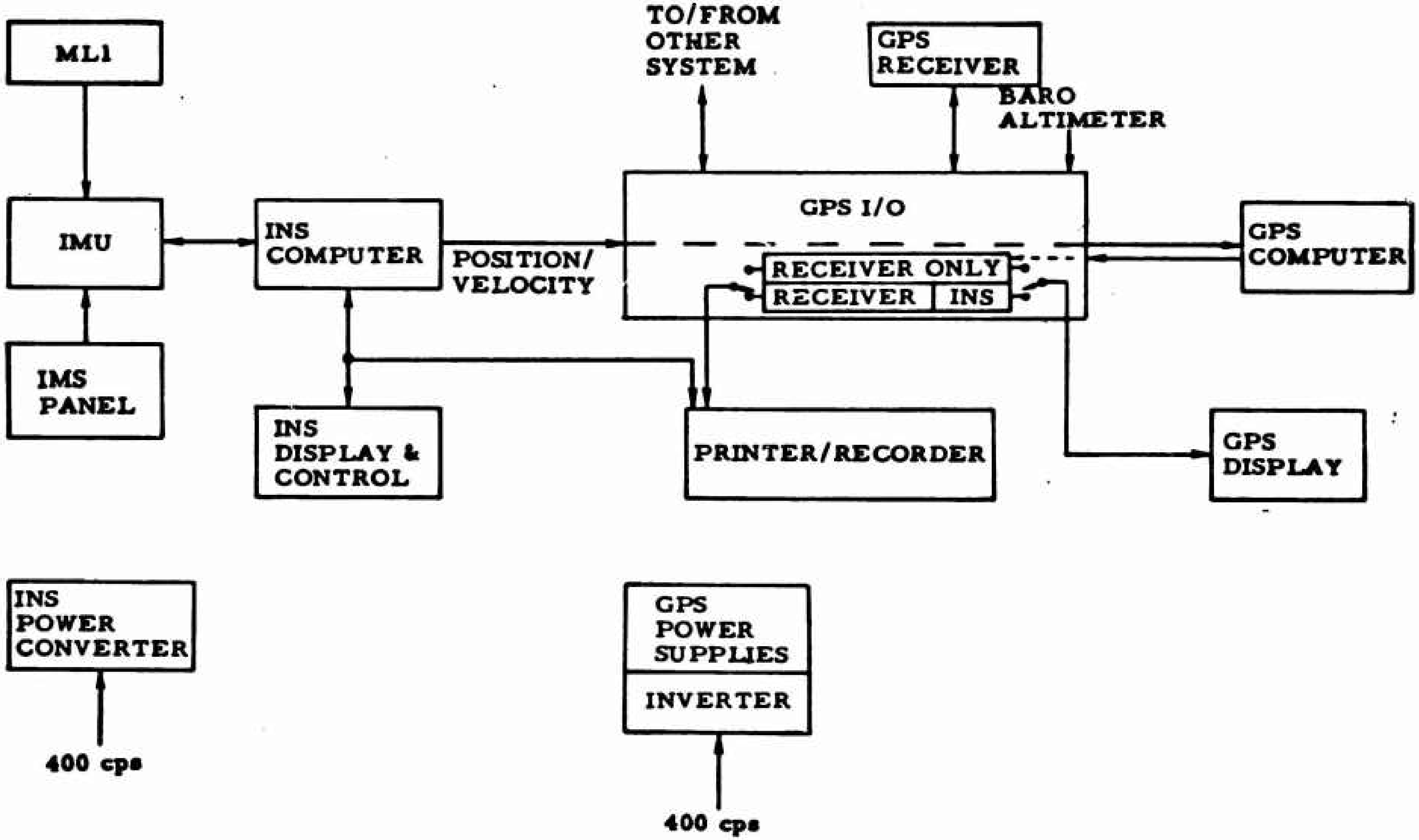


Figure 3-16. GPS Phase I Integrated System

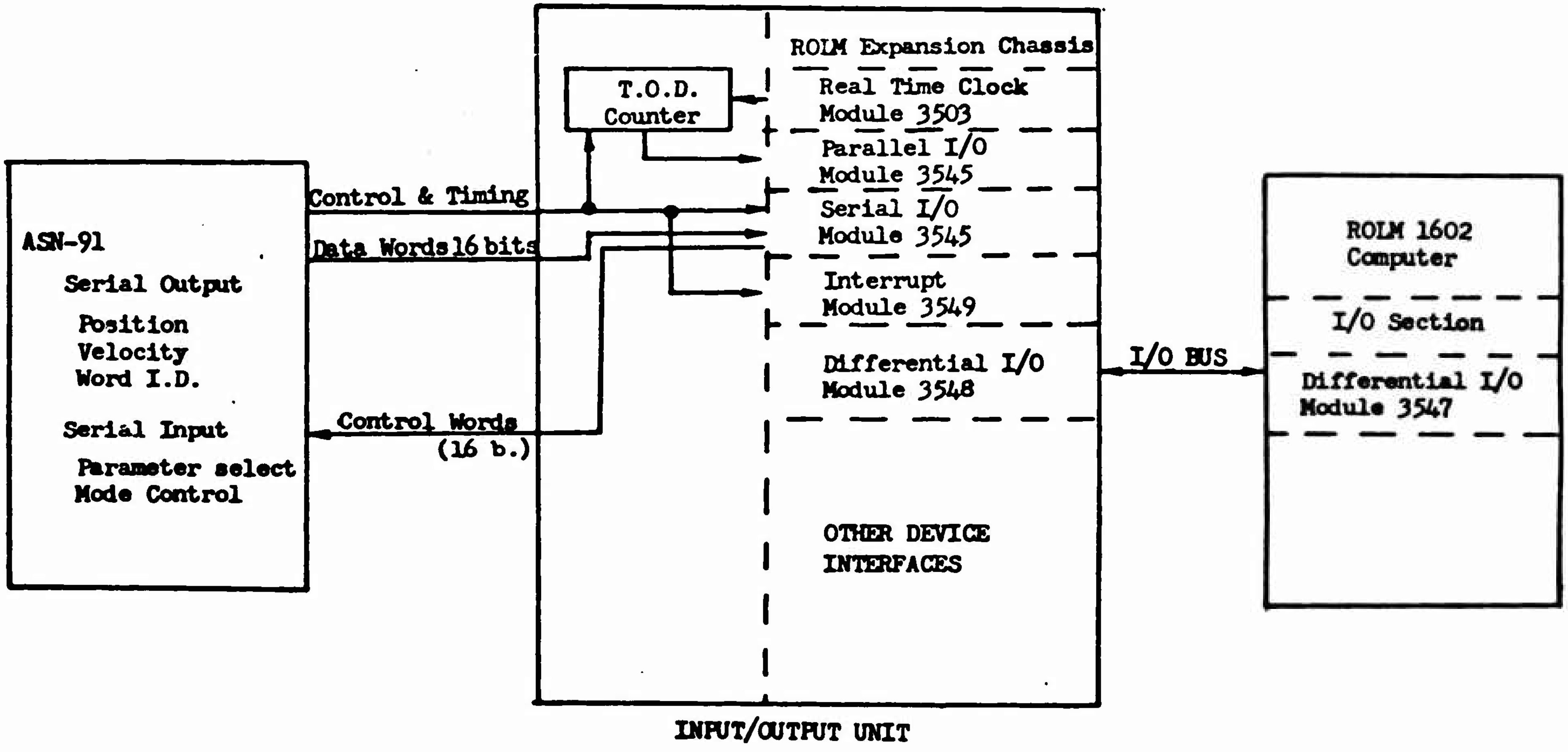


Figure 3-17. ASN-91/ROLM 1602 Interface Block Diagram

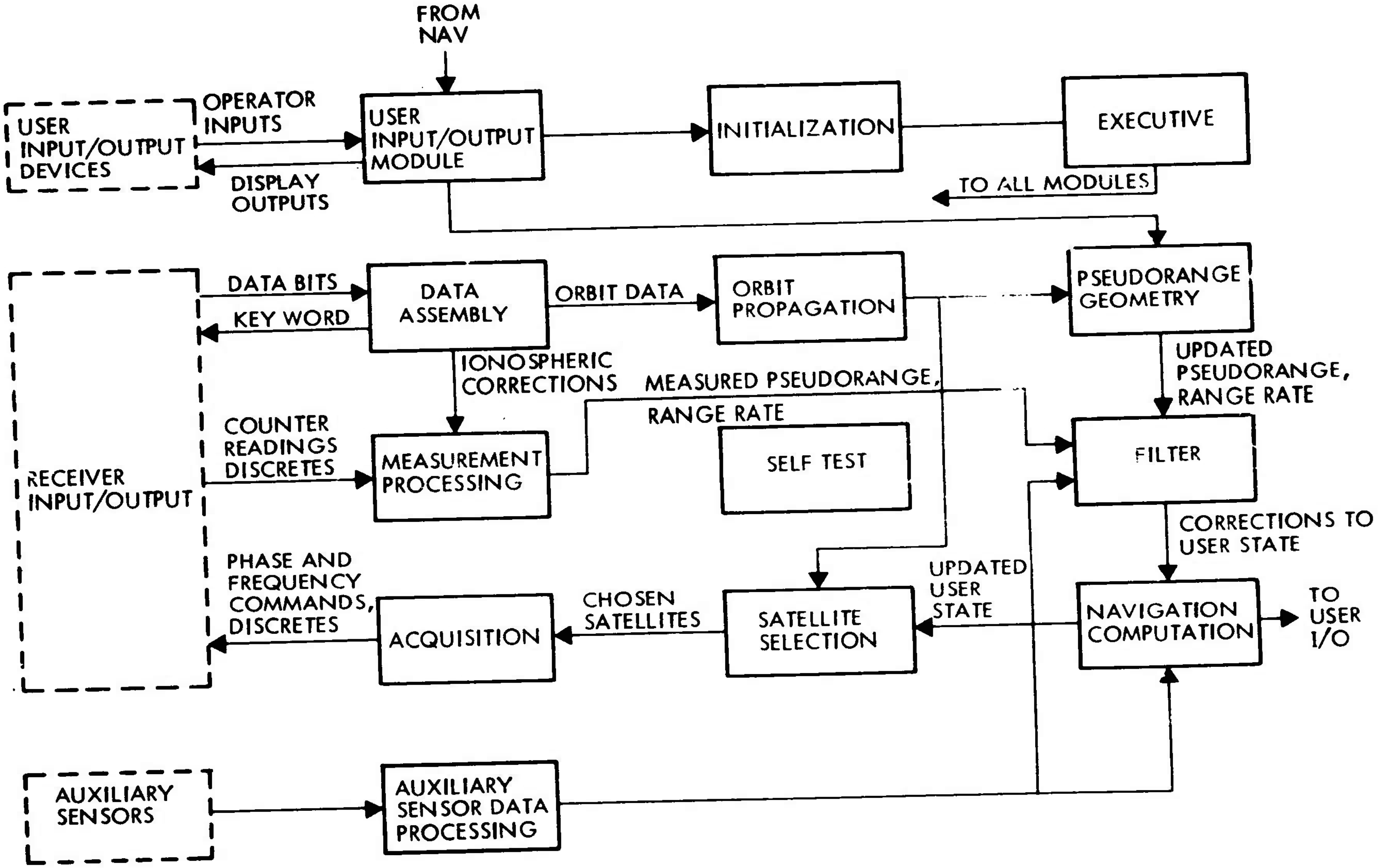


Figure 3-18. Class A User Navigation Program Functional Block Diagram

A user software and Figure 3-19 depicts the Class C user software. Again, the requirements between classes are largely of degree with some functions (such as auxiliary sensor data processing) deleted for the simpler user. The program has been organized using a synchronous executive so that processing proceeds in a predetermined order and rate. Table 3-9 shows the approximate interaction rates required for the various functions. The "as-required" functions are those primarily used during acquisition, hand-over or self-test.

Table 3-10 shows the estimated memory usage for the low cost user (Class C). These estimates were derived by comparison for similar functions from the INI/INHI programs; for dissimilar functions (acquisition, data assembly, satellite selection, and orbit propagation), specific methods of implementation were identified and estimated. The resulting program utilizes only 20-40 percent of the duty cycle of candidate avionics computers, depending on the features and speed of a particular machine. For the class A and B users, the addition of the axuiliary sensor data and a recursive filter result in an increase in memory storage of about 4k-16 bit words. The impact on duty cycle is small since a total filter solution is performed at a low rate.

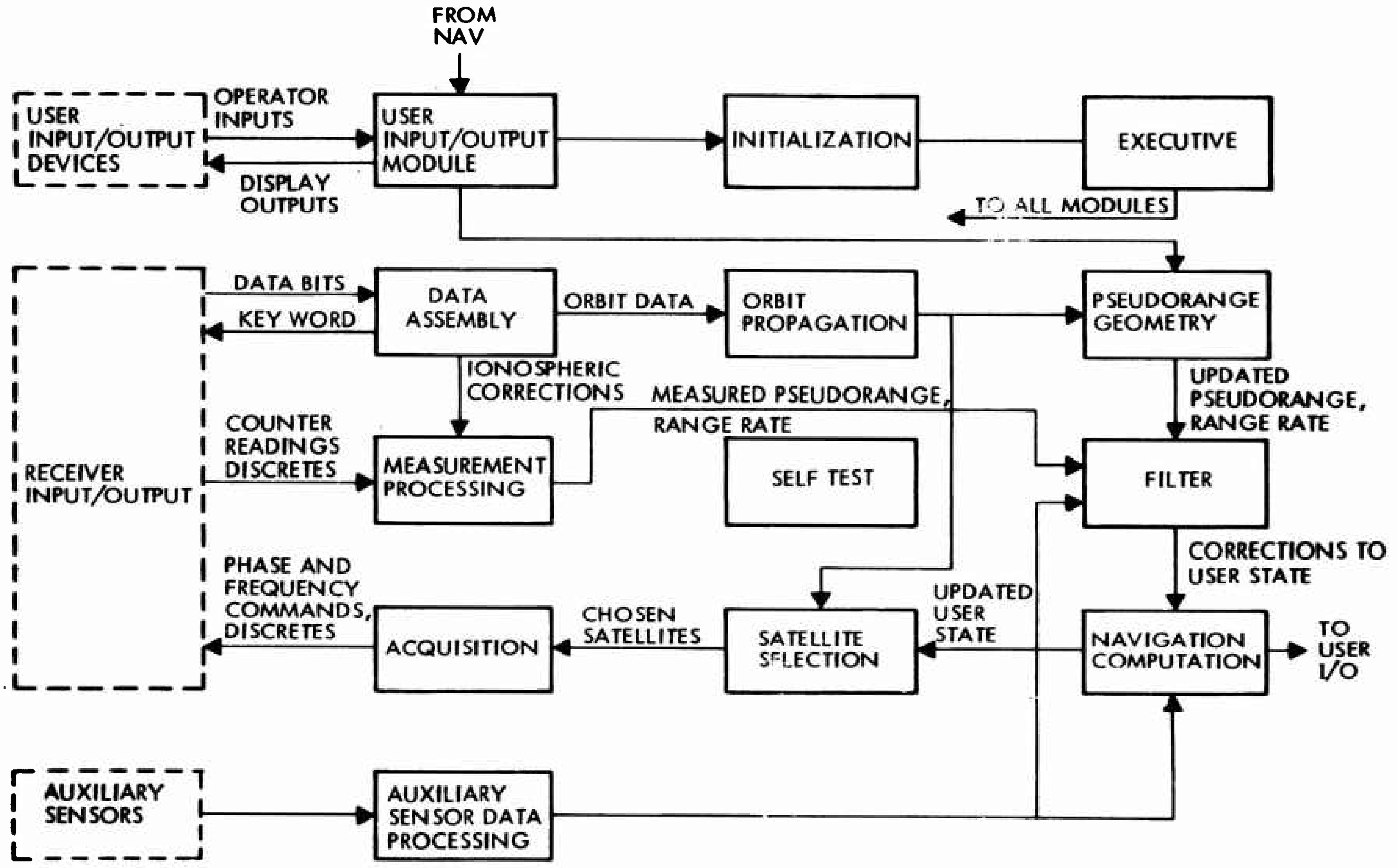


Figure 3-19. Class C User Navigation Program Functional Block Diagram

Table 3-9. Computational Rates

Function	Computational Rate
Initialization	As required
Executive	8/sec
Acquisition	As required
Data assembly	60 min
Measurement processing	8/sec
Satellite selection	As required
Orbit propagation	8/sec
Pseudorange geometry	8/sec
Filter (segment)	8/sec
Navigation computation	8/sec
User input/output	8/sec
Navigation set input/output	8/sec
Auxiliary sensor data processing	8/sec
Self-test	As required

Table 3-10. Low Cost User Software Requirements

Function	16 Bit Instructions	16 Bit Data	32 Bit Data
Initialization	100	50	50
Executive	400	200	--
Acquisition	350	200	50
Data Assembly	250	900	--
Measurement Processing	200	75	30
Orbit Propagation	200	200	50
Satellite Selection	550	450	--
Pseudorange Geometry	200	--	50
Filter	300	--	100
Navigation	250	--	100
Display	900	200	250
Subroutines	400	--	200
	4100	2075	880
			x2
Total	7935 16 Bit Words		1760

4. SYSTEM EFFECTIVENESS

Major items considered under the "system effectiveness" title are reliability and maintainability, life cycle costing, user equipment hardening, and EMI. Each of these is considered in turn.

4.1 RELIABILITY AND MAINTAINABILITY

A reliability and maintainability analysis was conducted for the GPS receiver and documented in Reference 4.1. In addition to a failure modes and effects analysis (FMEA), this document contains proposed built-in test concepts, maintenance philosophies, reliability and maintainability models and associated calculations, and an Optimum Repair Level Analysis (ORLA).

The analysis, based upon an early receiver configuration (1 December 1973), is being updated as additional detail on the receiver design is obtained. The baseline receiver was comprised of eleven types of modules so defined to provide commonality between the various types of receivers. Each module was defined in detail so that a piece parts costing and reliability analysis could be conducted. Parts failure rates (both military and high reliability) were appropriately modified by K factors for an airborne application. Utilizing military standard parts, the sequential receiver MTBF was calculated to be 1170 hrs, whereas the high reliability parts provided a receiver with 6400 hrs.

The ORLA analysis considered a "module discard at failure" concept and a "depot repair" concept. Intermediate level repair was not considered after initial analysis indicated that this was not the optimum method of support. Again, receivers were considered using both military and high reliability parts. In the former case, three modules were candidates employing the high reliability parts. Since the analyses were

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Reference 4.1. WDL-TR-5293, "User Segment Reliability and Maintainability Allocations, Assessments, and Analysis Report", dated 30 January 1974 preliminary, no firm recommendation was made on the two options. However, a maintenance concept for each alternative was established. These concepts are summarized in Tables 4-1 and 4-2.

4.2 LIFE CYCLE COST ANALYSIS

Subsequent to the Reliability and Maintainability Assessment Report analyses described in Section 4.1, additional analysis was performed utilizing the SAMSO Life Cycle Cost Model. The latter analysis utilized the current receiver design as well as modified module configurations that resulted from the earlier R&M work. Full details of the life cycle cost analysis are contained in Reference 4.2.

Based upon the still preliminary nature of the cost and MTBF numbers as well as some limitations in the life cycle cost model, the following conclusions were reached:

1) Base repair for the receiver is not cost effective.

2) Utilization of high reliability parts in the receivers is cost effective.

3) Module discard, rather than repair, appears cost effective.

A summary of the LCC analysis test cases is presented in Table 4-3. Full details of the assumptions are contained in Reference 4.2. Because of the commonality of modules between the sequential and continuous tracking receivers, the inputs to the computer program are in terms of the sequential receiver modules. The continuous tracking receivers are fully considered in the analysis, and are composed of the required number of common modules.

4.3 HARDENING

A brief study was conducted to define the nuclear environment for hardening effects of the GPS user equipment, indicate the probable effects

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Reference 4.2. DNSDP-DEW-274, "TRW Life Cycle Cost Analysis as of January 1974", dated 13 February 1974

Table 4-1. Maintenance Concept Summary (Depot Repair)

Receiver Maintenance Concept

- Three levels of maintenance:

  Organizational

  Intermediate

  Depot

Organizational Maintenance

- Pre-mission, post-mission, and in-mission end-to-end status testing of the equipment will use BIT equipment.
- No servicing will be required.
- Corrective maintenance will consist of fault isolation to a line replaceable unit (LRU) using BIT, removal and replacement of an LRU and verification of fault correction using BIT.

Intermediate Maintenance

- Intermediate maintenance will be performed either on the vehicle or in the base shop.
- Fault isolation to a shop replaceable unit (SRU) will use BIT.
- Repair will be by replacement of the SRUs.
- Verification of the corrective action will use BIT.
- SRUs will be returned to the depot for repair.

Depot Maintenance

- Depot maintenance will include overhaul, repair, and refurbishment of LRUs and SRUs.
- Performance of Time Compliance Technical Orders.
- Performance of Analytical Condition Inspections.

Table 4-2. Maintenance Concept Summary (Module Discard at Failure)

Receiver Maintenance Concept

- Two levels of maintenance:

  Organizational

  Intermediate

Organizational Maintenance

- Pre-mission, post-mission, and in-mission end-to-end status testing of the equipment will use BIT equipment.
- No servicing will be required.
- Corrective maintenance will consist of fault isolation to a line replaceable unit (LRU) using BIT, removal and replacement of an LRU and verification of fault correction using BIT.

Intermediate Maintenance

- Intermediate maintenance will be performed either on the vehicle or in the base shop.
- Fault isolation to a shop replaceable unit (SRU) will use BIT.
- Repair will be by replacement of the SRUs.
- Verification of the corrective action will use BIT.
- SRUs will be discard-at-failure items.

Table 4-3. Matrix of Test Cases and Results of LCC Calculations

Sequential Receiver Design Configurations						Results of LCC Calculations ($ Millions)			
Config. No.	No. of Receiver Modules	Type of Parts	Test Points ?	Receiver Cost	Receiver MTBF	Run No.	Maint. Concept	Total LSC	Total LCC
①	16 Modules	Hi-Rel	Test Points Included In Design	$ 7861	3867 Hrs	5	Base/Depot Repair RTS = .5	437.92	1363.50
						6	Base/Depot Repair RTS = .9	427.77	1353.34
						4	Depot Only Repair NRTS = 1.0	324.25	1249.83
②	16 Modules	Hi-Rel	No Test Points Discard Option	$ 7115	4297 Hrs	10	Optimum Discard with Depot Only Repair	292.40	1193.13
						Discard Option	Discard Option Savings	31.85	56.64
							% Reduction	9.8%	4.5%
③	16 Modules	MIL-STD	Test Points Included In Design	$ 6774	683 Hrs	1	Base/Depot Repair RTS = .5	600.98	1491.92
						2	Base/Depot Repair RTS = .9	571.35	1462.29
						3	Depot Only Repair NRTS = 1.0	508.15	1399.10
④	16 Modules	MIL-STD	No Test Points Discard Option	$ 6163	758 Hrs	9	Optimum Discard with Depot Repair Only	417.95	1289.39
						Discard Option	Discard Option Savings	90.20	109.71
							% Reduction	17.8%	7.8%
⑤	8 Modules	MIL-STD	Test Points Included In Design	$ 6132	683 Hrs	13	Base/Depot Repair RTS = .5	747.59	1619.79
						14	Base/Depot Repair RTS = .9	716.52	1588.72
						15	Depot Only Repair NRTS = 1.0	656.55	1528.75

of the nuclear environment on the systems and circuits, and to provide general guidelines to minimize the deleterious effects. Details of that study are contained in Reference 4.3.

The environment chosen is the Air Force Specification for the B-1 bomber.

The nuclear radiation and EMP effects include:

Gain degradation
Logic circuit scrambling
Spurious signals
Semiconductor and metalization burnout

Hardening against these effects may be accomplished by using one or more of the following methods:

Surge arrestors
Circumvention
Hardened registers
Photocurrent compensation
Shielding
Piece part selection and derating

It is envisioned that the user equipment might be hardened to two levels. Level I hardening would incorporate hardening measures which could be included in the design with small incremental cost increases. The equipment produced under the Level I criteria would be suitable for many applications, but probably would not survive the criteria listed for the B-1. Level II hardening would include the additional, relatively expensive, measures necessary to allow the equipment to survive the environments.

Reference 4.3. DNSDP-OEA-071, "DNSDP Nuclear Hardening", dated 5 September 1973

The development of a hardened equipment design depends upon the recognition of radiation sensitivities, the assessment of their effects on system operation, and the application of design techniques to limit undesirable responses to the radiation environment. The circuit functions of primary concern are those involving semiconductor devices.

For Phase I planning purposes, no major hardening activity is envisioned. Rather, hardening experts will be utilized as part of the hardware design review process to ensure that designs are not employed that mitigate against eventual hardening. This approach, not only provides the JPO with a minimum cost Phase I Program, but also allows for the eventual hardening of the equipment in a cost effective manner.

4.4 ELECTROMAGNETIC INTERFERENCE (EMI)

The GPS receivers will be subjected to a wide range of electromagnetic environments which could degrade performance. These environments may be the result of unintentional interference or intention such as enemy jamming.

The GPS system utilizes wideband pseudorandom-noise (PRN) modulation techniques to provide significant protection against interference and jamming. While the receiver RF and IF processors track and reconstruct the received spectrum signal, the energy contained within undesired narrowband signals is dispersed over a wide bandwidth where it is rejected by the narrowband IF following the PRN demodulator. Theoretically, up to 70 dB of suppression to CW jamming signals can be realized by this technique. The narrowband IF also affords considerable rejection to wideband pulse or swept CW signals which are typical of the more common L-band interferers encountered by the GPS receiver.

Reference 4.4 contains the results of an EMC survey and analysis for the GPS receivers. Table 4-4, extracted from that reference, summarizes the L-band transmitter interference to the GPS receivers.

Reference 4.4. DNSDP-GEC-108, "EMC Survey", dated 27 September 1973

Table 4-4. Summary of L-Band Transmitter Interference to GPS Receivers

Military System Transmitters	Frequency Band (MHz)	Comments
TACAN/DME ATC radar beacon	960-1215 1030-1090	Low probability sources of interference to co-sited GPS due to sideband splatter. May be troublesome in shipboard environment.
L-band search and air-route surveillance radar	1215-1400	Severe source of interference due to high power broadband pulse spectra.
Mobile communications	1427-1535	Potential interference sources due to proximity of GPS receiver band. May also be responsible for intermodulation, cross-modulation and other nonlinear effects.
Aeronautical radionavigation	1540-1660	Particular sources of interference to airborne GPS receivers are co-sited radar altimeters and collision avoidance systems. Transmitter spectral sideband energy is again responsible.
Meteorological aids	1670-1700	No problems envisioned.
Fixed and mobile communications	1710-1850	Same as above for mobile communications.

Radar systems comprise the primary potential interference sources to receivers operating in the L-band frequency range. Of particular concern are airborne radar altimeters in the 1600 MHz to 1660 MHz region. Other potential interferers include high-power ground-based and shipboard long-range radars. In some instances, co-sited UHF communications transmitters may provide in-band signals via the mechanisms of cross-modulation, intermodulation, and other nonlinear effects. These will be most evident in shipboard installations where the hull, superstructure, and other topside devices contain numerous nonlinear junctions.

Two situations, involving the GPS receiver and the AN/APN-133 radar altimeter were examined as typical interference situations. The first was an APN-133 equipped aircraft overflying a surface based GPS receiver. This analysis indicated that interference only occurred if the AC altitude was less than 250 meters above the GPS user. Since 250 meters are less than the normal overflight altitude, and moreover, at that altitude, the overflight time is insignificant, the AN-133 would not be a source of interference under normal circumstances.

The second case considered was the potential interference of GPS equipped aircraft that was also equipped with an AN/APN-133 radar altimeter.

For the case considered, no interference problem existed because of the large (110 dB) path loss between the two antennae.

The above example points out the analysis that will be required for each type installation of the GPS receivers. Whether on aircraft, shipboard, or other vehicle, an analysis of the effect of nearby transmitters, structures, etc., will be required to ensure nondegraded operation of the GPS system.

5. SYSTEM TEST PLANNING

The system test planning process for the GPS user equipment, as outlined in Figure 5-1, has been accomplished to the depth necessary to define:

a) Overall test program scope in the GPS System Test Plan, WDL-TR-5299.

b) Test equipment and facility requirements in a series of Test Facility Requirements Documents, WDL-TR-5419 A-O.

c) Test concepts that establish levels of testing for each GPS user equipment group.

5.1 GPS SYSTEM TEST PLAN

A preliminary System Test Plan was submitted to the JPO in accordance with CDRL A00D in September 1973. This plan is currently under revision for submittal in June 1974.

The test planning process is an iterative one, in which the testing baseline is preliminarily established, and then refined as program requirements become more firmly established, testing philosophy is adopted, and test resources are identified. Recent initiation of bi-weekly test planning meetings with JPO test personnel has resulted in significant insight into Army and Navy test philosophy and requirements, and an overall improvement in our knowledge of test vehicle, equipment, and facility availability. This new information will be translated into updated GPS User Equipment Test Plans for the final submittal of the System Test Plan in June 1974.

The general scope of the GPS user equipment Phase I testing is depicted in Figure 5-2, which defines the relationship of the initial test and evaluation of the Engineering Development Models to the Low Cost Prototype and the Class A-F Development Models. Further definition of these tests in terms of test objectives, specific assignment of user equipment groups to test vehicles, and test schedules will be presented in the final System Test Plan.

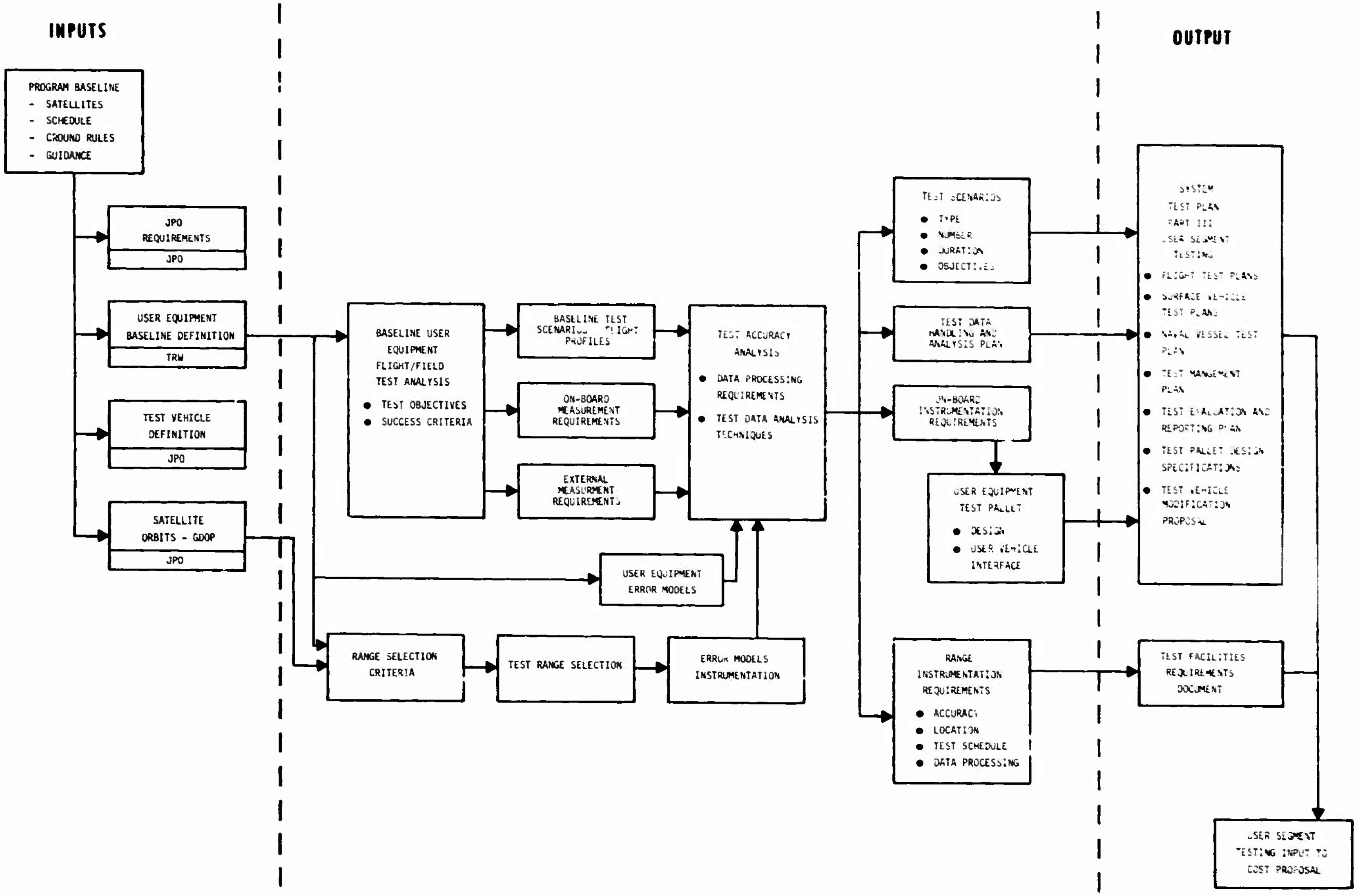

Figure 5-1. GPS User Equipment Phase I Test Planning Process

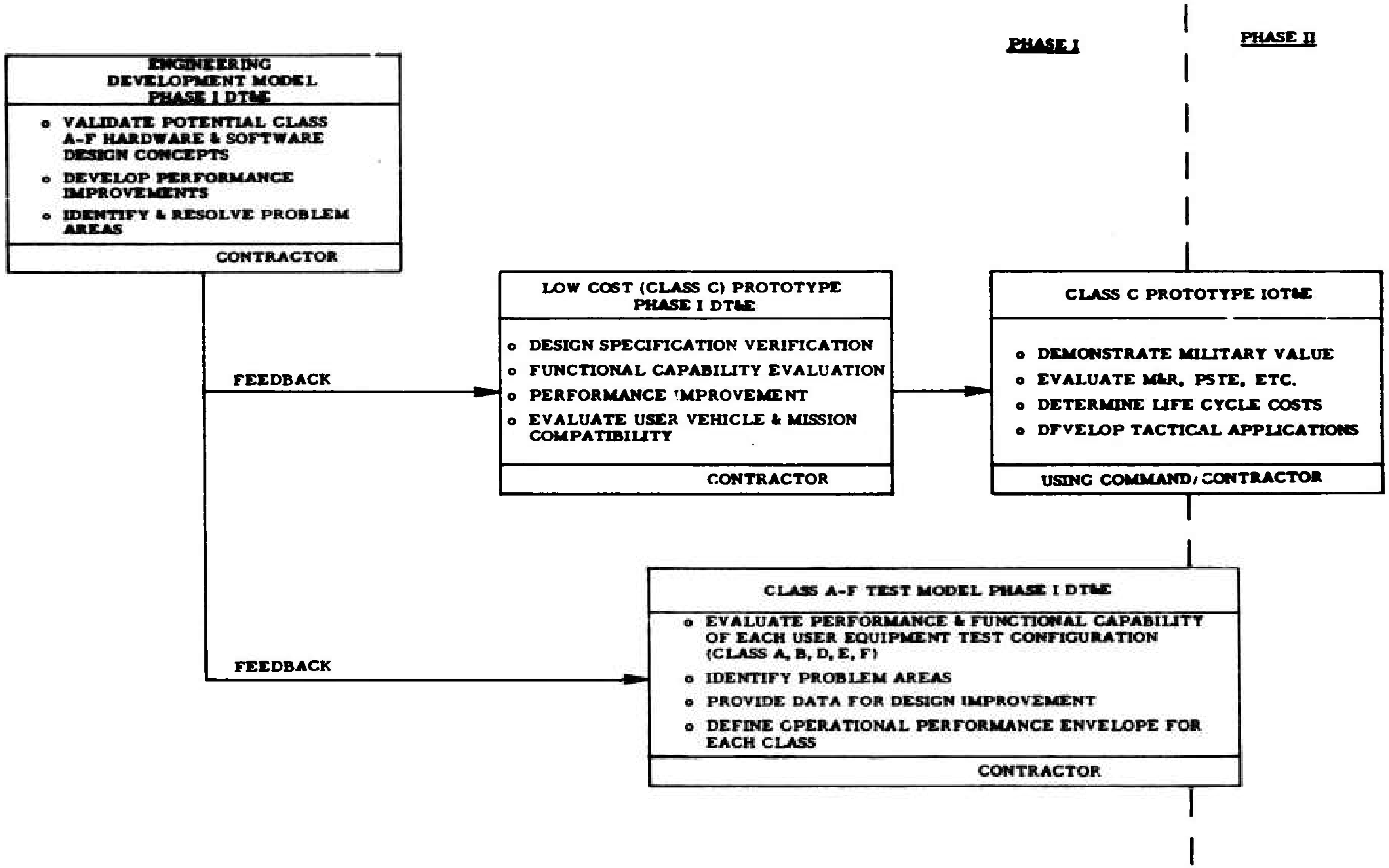

Figure 5-2. Phase I Test Program Scope

5.2 TEST FACILITIES REQUIREMENTS DOCUMENT

The test requirements analysis accomplished as an integral part of the test planning process has resulted in the identification of test equipment and facilities needed for successful completion of the GPS test program. The Government owned test facilities and equipment required have been identified in fifteen separate Test Facility Requirements Documents (TFRDs). The preliminary TFRDs are contained in Part II, Volume E of this report.

The requirements have been derived from the test objectives defined in the GPS System Test Plan for test and evaluation of:

a) Generalized Development Models (DT&E)

b) Low Cost (Class C) Prototypes (DT&E, IOT&E)

c) Classes A-F Development Models (DT&E)

Required test facilities include test ranges capable of precision metric tracking of aircraft, aircraft support facilities, surface vehicle proving grounds, ocean range areas for sea trails, dockside support facilities, supersonic wind tunnel, and jamming simulation facility.

Required vehicles to be used as user equipment test beds include cargo aircraft, high performance bomber, fighter and attack aircraft, helicopter, transportable communication shelters, surface ships, and submarine.

Specific requirements for each of these facilities and vehicles are defined in the following TFRDs:

TFRD No. 1 - Flight Test Range - White Sands Missile Range
TFRD No. 2 - Test Support Facility - Holloman Air Force Base
TFRD No. 3 - Inverted Range Ground Transmitters
TFRD No. 4 - Aircraft Test Bed C-130E
TFRD No. 5 - Aircraft Test Bed C-141
TFRD No. 6 - Aircraft Test Bed RF-4C
TFRD No. 7 - Aircraft Test Bed A-7

TFRD No. 8 - Helicopter Test Bed H-1

TFRD No. 9 - Communications Shelter Test Bed

TFRD No. 10 - Surface Vehicle Test Range - WSMR

TFRD No. 11 - Surface Ship Test Bed

TFRD No. 12 - Submarine Test Bed

TFRD No. 13 - Ocean Range and Dockside Support Facilities - PMR

TFRD No. 14 - Jamming Simulator Facility - Ft. Huachuca

TFRD No. 15 - Supersonic Wind Tunnel

5.3 LEVELS OF TESTING

Levels of testing to be accomplished during the GPS User Equipment Phase I Test Program have been preliminarily outlined so that equipment group test configurations can be defined, and onboard instrumentation, test software, and range instrumentation can be sized and cost estimates generated. In Phase I, three categories of user equipment will be tested:

1) Generalized Development Models
2) Low Cost Prototypes (Class C)
3) Classes A-F Development Models

To accomplish GPS user equipment development objectives, a minimum of 29 receivers will be needed. These will be utilized in 23 test equipment group units configured for specific test beds, as shown in Table 5-1, Receiver/Equipment Group Requirements Matrix. Several equipment group types will probably be required by the combination of receiver types, ancillary equipment, test instrumentation, and test vehicle space availability.

5.3.1 Generalized Development Model

Two Generalized Development Model brassboard units will be fabricated and used for laboratory and field testing that will validate design concepts and identify problem areas (see Figure 5-3). Test results should strongly influence Low Cost (Class C) Prototype design as well as Classes A-F test model design. Principal test objectives are related to each of the two test units in Table 5-2. As with INHI, internal (onboard) test

Table 5-1. Receiver/Equipment Group Requirements Matrix

					Receiver Type			
		Equip Groups			1	2	3	4
User Class	Test Bed	Type		Brassboard	Cont $L_1 L_2$ P&C	Seq. $L_1 L_2$ P&C	Seq. L_1 P&C	Seq. L_1 C
A-F General Dev. Models	TRW Lab	I	1	1				
	C-130 & Surf. Veh.		1	1				
Low Cost C Prototypes	TRW Lab	II	1					1
	C-141 DT&E		1					1
	H-1 DT&E		1					1
	Comm. Shltr DT&E		1					1
	Surf. Ship DT&E		1					1
	Landing Cr. DT&E		1					1
	USAF IOT&E	IIa	2					2
	USA IOT&E		2					2
	USN IOT&E		3					3
	USMC IOT&E		3					3
A Dev. Model	RF-4C DT&E	III	1		1	1		
B Dev. Model	A-7 DT&E	IV	1		1	1		
D Dev. Model	USA Comm. Shltr. DT&E	V	1			1 →		
E Dev. Model	Manpack DT&E	VI	1			1 →		
F Dev. Model	USN Ship DT&E	VII	1		1			
Spares	In-Plant				1	1		2
	Totals		23	2	4	5	0	18

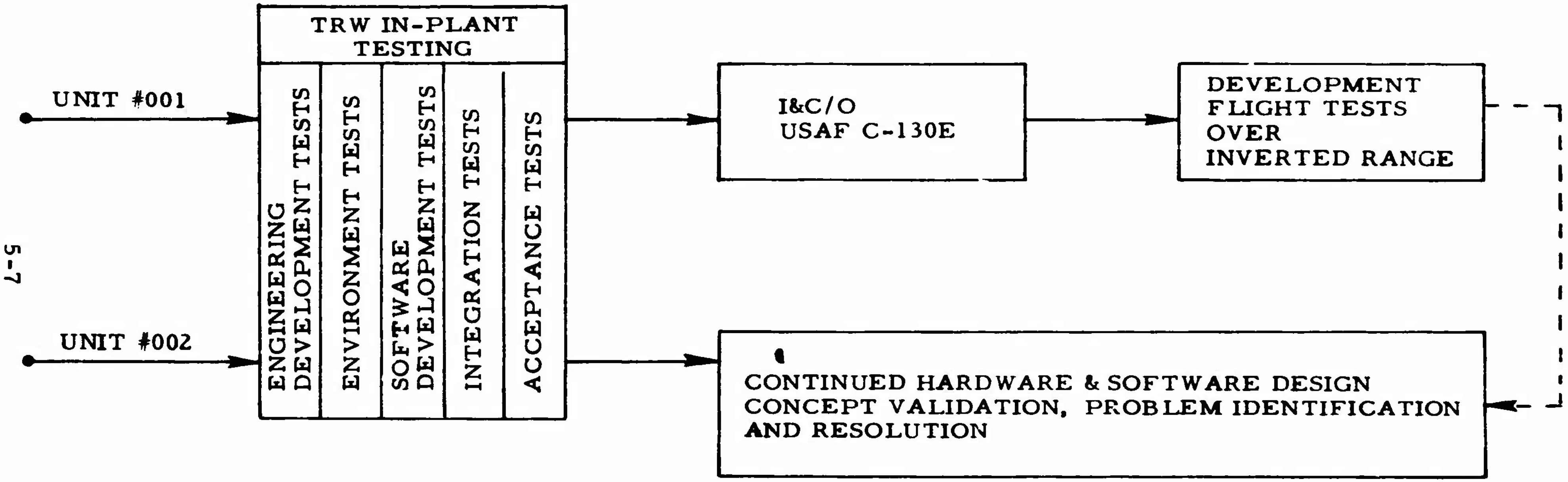

Figure 5-3. Generalized Development Model Phase I Test Program Flow

Table 5-2. Test Objective Matrix Engineering Development Model Test Equipment Units 001 and 002

Test Objective	TRW Lab	Inverted Range Flight Test
1. Evaluate concepts for acquisition/reacquisition	001 002	001
2. Determine position and velocity accuracy	001 002	001
3. Determine receiver sensitivity and identify problems associated with:		
- Input signal (range)	002	
- Jamming spoofing	002	
- Satellite geometry	001	001
User dynamics	001	001
4. Evaluate L_1, L_2 ionsophere propagation	002	
5. Determine filter characteristics	002	
6. Evaluate performance with auxiliary sensors	002	001
7. Evaluate performance monitoring (fault detection) concepts	002	

data will be recorded on magnetic tape. Test data required in near real time for inflight analysis and test control will be available to the test operator from C/D displays and an onboard printer. The external (metric tracking and meteorological) data to be obtained from WSMR is identified in the TFRD and, in more detail later, in the PRD, Program Requirements Document.

5.3.2 Low Cost (Class C) Prototype

The 18 Class C Prototype receivers (including spares) will be required in Phase and will be utilized in 16 equipment groups as shown in the Phase I Test Program Flow (Figure 5-4). Six of the units will be used for contractor DT&E testing, ten units allocated to the IOT&E test vehicles, and two spares. Principal test objectives are related to each of the test units as shown in Table 5-3. User equipment test units fabricated for contractor testing (DT&E) will incorporate test data measurement, recording, and display capability for inflight quick-look analysis by the test operators, as well as sufficient internal data to be combined with external (range) data in the more detailed post-test accuracy analysis.

IOT&E data requirements will be less stringent, with more emphasis on R&M, PSTE, and operational mission demonstration data. The equipment groups allocated to IOT&E will, therefore, require less instrumentation than that required during DT&E for problem identification and performance evaluation. The deletion of the magnetic tape recorder and associated interface hardware and software for IOT&E would result in a significant cost saving.

External data requirements and test facility requirements are identified in TFRDs for each of the test areas used during DT&E and IOT&E testing.

5.3.3 Classes A-F Development Models

A minimum of nine Classes A-F Development Model receivers will be required for Phase I development testing in five equipment groups. All Classes A-F Development Model Phase I DT&E will be conducted by the contractor (TRW) with participation by the appropriate JPO test support agencies and user groups.

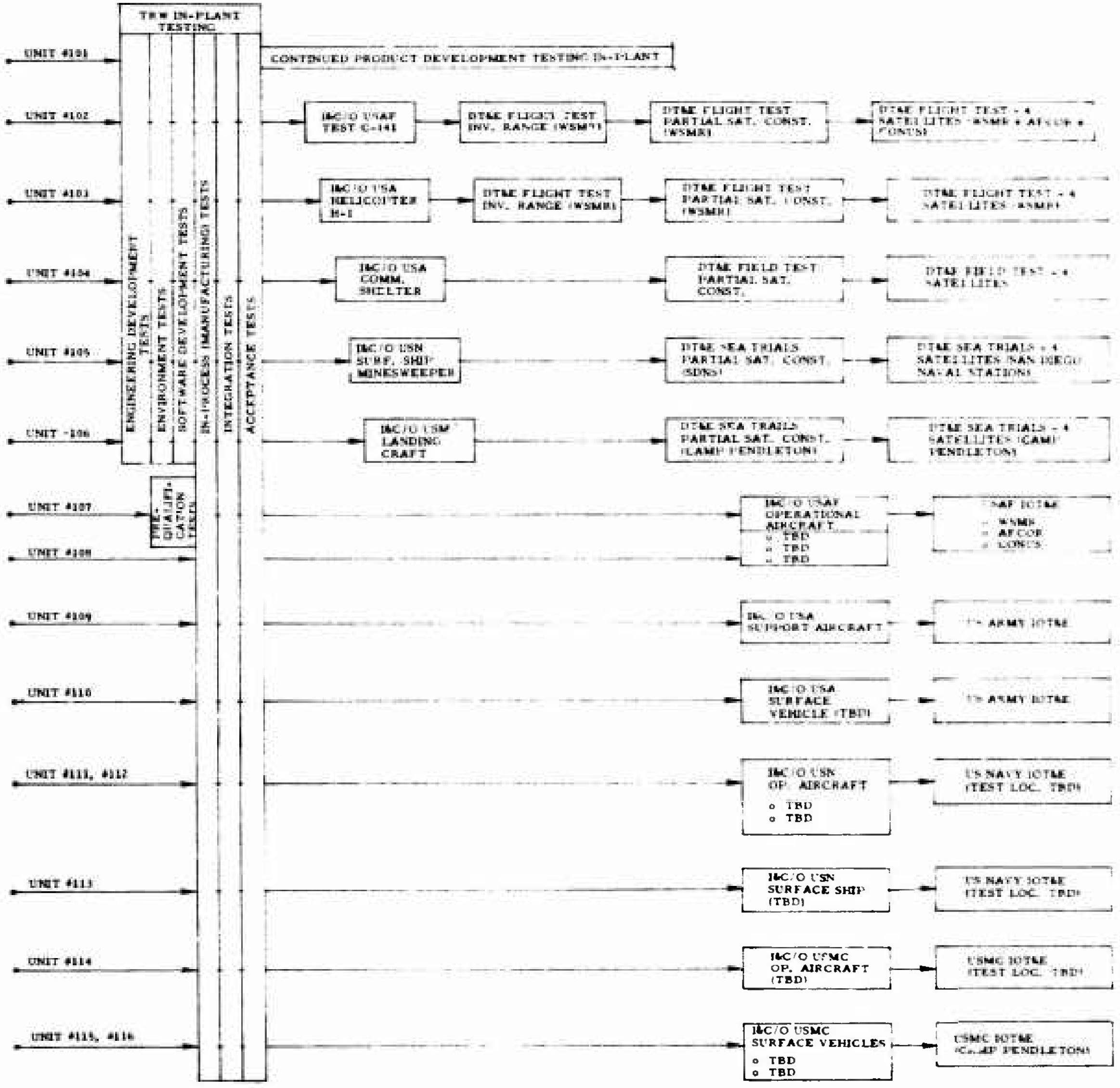

Figure 5-4. Class C Low Cost Prototype Phase I Test Program Flow

Table 5-3. Test Objective, Low Cost (Class C) Prototype Test Equipment Units 101-116

Test Objective	Lab	In-plant	CT&E Field Testing				IOT&E
			I & C/O	Inv. Range	Flight Test	Field Test	
1. Determine position and velocity accuracy (relative)	101			102 103	102 103	104, 105 106	107- 116
2. Determine position and velocity accuracy (absolute)					102 103		
3. Determine acquisition time	101			102 103	102 103	104, 105 106	107- 116
4. Evaluate measurement loss (dropouts)	101			102 103	102 103	104, 105 106	
5. Determine reacquisition time	101			102 103	102 103	104, 105 106	107- 116
6. Evaluate satellite constellation revision capability				103		104, 105 106	
7. Evaluate receiver sensitivity to:							
- Input signal (range)	101						
- Jamming, spoofing	101					104	
- User environment (foliage, multipath, EMI, temperature, vibration, etc.)	101	101			102, 103	104, 105 106	107- 116
- User dynamics	101				102, 103	104, 105 106	107- 116
8. Determine U. E. maintainability (MTTR)		101	All		102, 103	104, 105 106	107- 116
9. Determine U. E. reliability (MTBF)		101			102, 103	104, 105 106	107- 116
10. Determine availability and life cycle costs	Analysis						
11. Evaluate nuclear survivability							
12. Evaluate integrability with existing nav aids							
13. Demonstrate extended periods of continuous use							107- 116
14. Demonstrate common coordinate reference capability							107- 116
15. Demonstrate military value including:							
- Refueling rendezvous							107
- Search and rescue							107
- Airlift and enroute navigation							108
- Photomapping and phototargeting							109
- ASW task group rendezvous							111-113
- Landing craft assult							115, 116
- Mine laying operation							113
- Infantry unit maneuvering							110

The Class A Development Model will alternately use Type 1 and Type 2 receivers in a test equipment group installed on a USAF RC-4c (refer to Figure 5-5).

The Class B Development Model will alternately use Type 1 and Type 2 receivers in a test equipment group installed on a USAF A-7 aircraft.

The Class D Development Model will utilize a Type 2 receiver in a test equipment group installed in a US Army standard communications shelter. Upon completion of prescribed tests, the receiver will be converted to Type 3 and the tests repeated.

The Class E Development Model will similarly utilize a Type 2 receiver for manpack tests, then repeat with the receiver converted to Type 3.

The Class F Development Model will utilize a Type 1 receiver in a test equipment group configured for USN ship/submarine testing.

Principal test objectives are related to each of the test units as shown in Table 5-4. Each of the test equipment groups will include instrumentation appropriate to the type of receiver and the extent of testing required to verify performance of the user equipment class. External data requirements and test facility requirements are identified in TFRDs for each of the test areas used during Phase I DT&E.

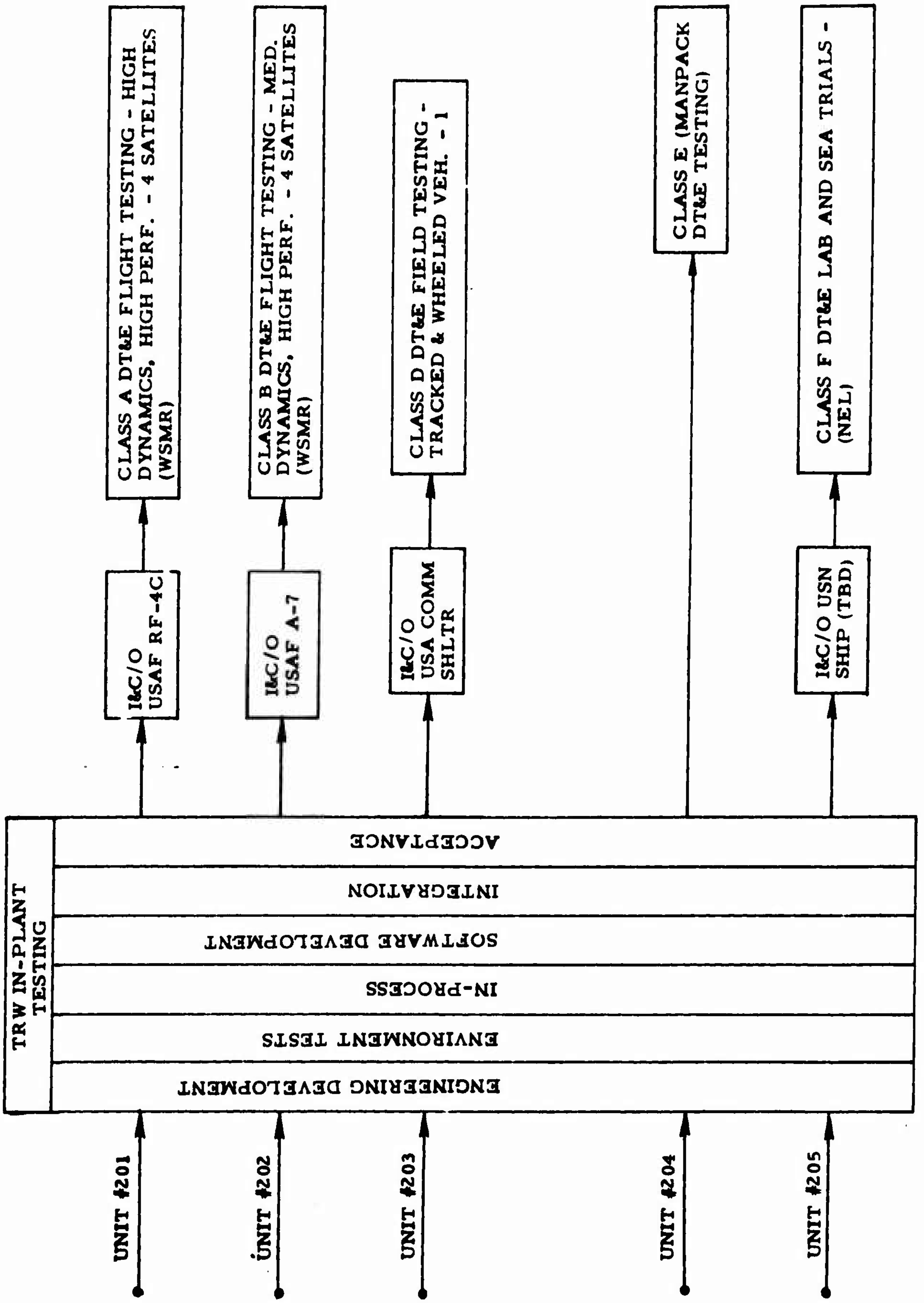

Figure 5-5. Class A-F Development Model Phase I Test Program Flow

Table 5-4. Test Objective Matrix, Classes A-F Test Model Test Equipment Units 201-205

Test Objective	Lab	In-plant	CT&E Field Testing		
			I & C/O	Flight Test	Field Test
1. Determine position and velocity accuracy (relative)	201, 202 203, 205			202, 203 204	202 205
2. Determine position and velocity accuracy (absolute)	201			203 204	202 205
3. Determine acquisition time	201				
4. Evaluate measurement loss (dropouts)	201			203 204	202 205
5. Determine reacquisition time	201			203 204	202 205
6. Evaluate satellite constellation revision capability	201			203 204	202 205
7. Evaluate receiver sensitivity to:					
- Input signal (range)	201			203, 204	202, 205
- Jamming, spoofing	201				
- User environment		All	All	203, 204	202, 205
- User dynamics	All	All		203, 204	
8. Evaluate L_1, L_2 ionosphere propagation	201			203 204	
9. Evaluate filter characteristics	201			203 204	202 205
10. Evaluate receiver performance with auxiliary sensors	201	203 204		203 204	
11. Evaluate performance monitoring (fault detection) capability	201	All	All	202, 203 204	202 205
12. Evaluate common coordinate reference capability				203 204	202 205
13. Evaluate nuclear survivability					
14. Evaluate security/deniability	201, 202				
15. Determine military value of each user equipment class configuration					
- Coordinate bombing				204	
- Aircraft landing aid				204	
- Phototargeting				203	
- US Army and USMC backpack tactical utilization (TBD)					202
- US Army and USMC surface vehicle tactical utilization (TBD)					202
- US Navy surface ship tactical utilization (TBD)					205
- US Navy submarine tactical utilization (TBD)					205
16. Obtain date for preliminary estimates of:					
- Maintainability (MTTR)		All			
- Reliability (MTBF)		All		203	202
- Availability		All		204	205
- Life cycle cost		All			

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13. ABSTRACT

Results of signal structure, receiver operations and performance studies are presented along with general definition of equipment group designs and descriptions including discussions of system effectiveness and test planning issues using satellites.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
- Satellite Radio Navigation						
- L Band						
- Pseudo Ranging						
- Pseudo Random Noise (PRN) Code						
- Modulation, Bi Phase Shift Key (PSK)						
* User Equipment performance						
* Life-cycle-cost						
* Test planning						