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GLOBAL POSITIONING SYSTEM (GPS) FINAL REPORT

PART I
VOLUME A
Introduction and Summary

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Contract F04701-73-C-0296 [redacted]

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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
Los Angeles, California 90009

(See 1473)

TRW SYSTEMS GROUP

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

CONTROL DATA

[redacted]

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SAMSO TR 74-183

WDL Technical Report 5291
28 February 1974

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

FOREWORD

This is Part I, Volume A, 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.

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PHILCO
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Western Development Laboratories Division

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SECTION 1

INTRODUCTION

This volume is an executive overview of the scope and results of the Global Positioning System (GPS) Definition Study, prime contract F04701-73-C-0296, conducted by the Western Development Laboratories Division of the Philco-Ford Corporation. Major subcontract efforts were provided by TRW Systems Group and Control Data Corporation.

As the introductory document for the results of the GPS Definition Study, this volume summarizes, in Section 2, the significant features of the Definition Study. Section 3 identifies the study scope, structure, and study products. Section 4 summarizes the major study milestones chronologically, and identifies significant GPS conceptual changes which occurred during the conduct of the study.

Section 5 describes the general features of the Phase I GPS and identifies the Definition Study interfaces with other GPS segments. Orbital configurations, test areas, and interfaces with the Navigation Technology Segment (NTS-II) are identified. Section 6 provides an overview of the Control Segment to include requirements, segment elements, functional allocations, configuration, and performance characteristics.

Section 7 provides an overview of the User Segment to include systems engineering and design efforts, characterization of user receiver types, systems effectiveness, and test planning. Section 8 summarizes the GPS Phase I planning activity. Section 9 is a dictionary of trade studies and analyses conducted during the GPS Definition Study. Abstracts are provided for the scope and results of system-level, Control Segment and, User Segment studies that are supplied as part of this final report.

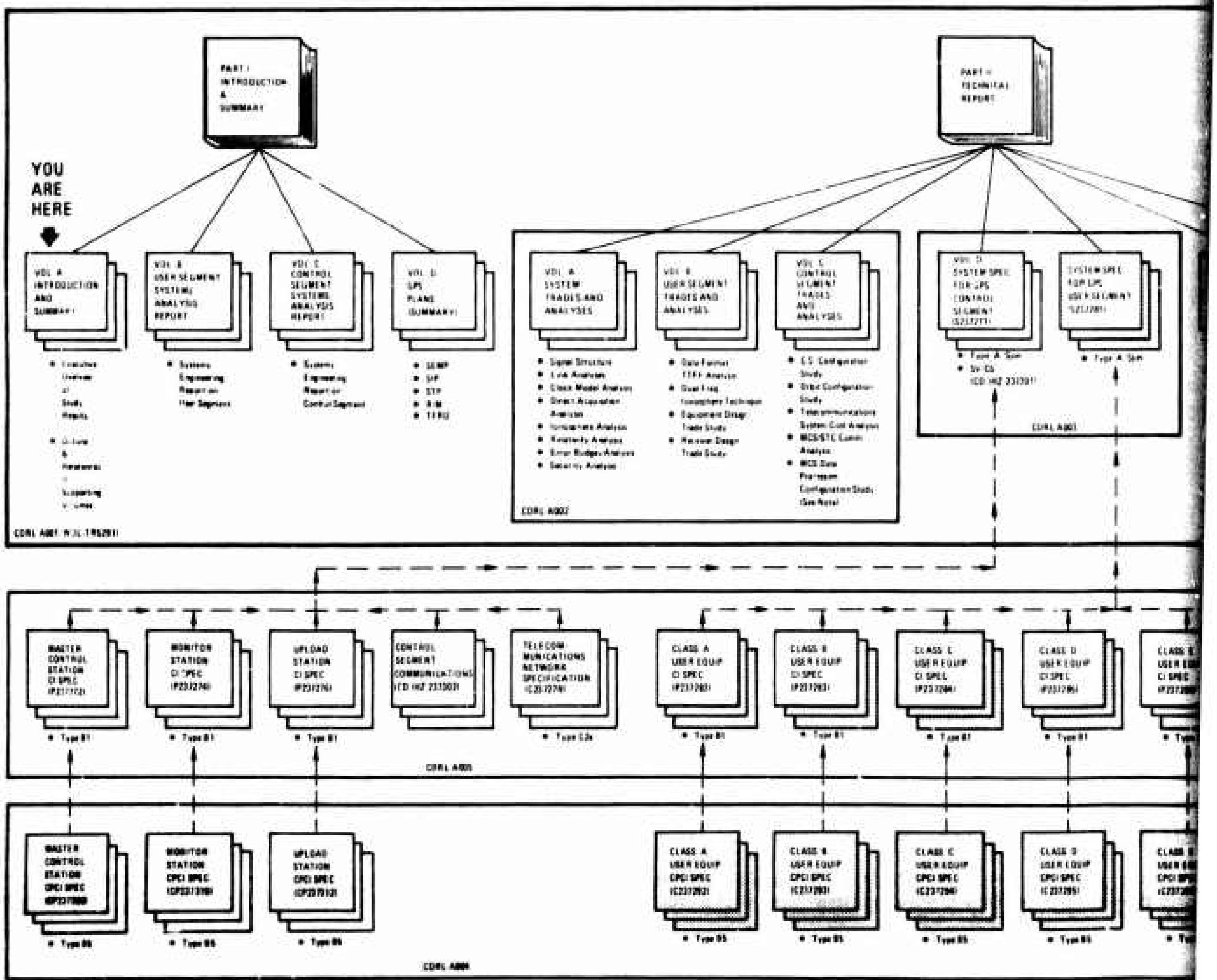
Figure 1-1 illustrates the overall structure of the GPS Definition Study Final Report and provides a means of conveniently referencing the several volumes and specifications included in this submittal. The portion of the final report submitted herewith can be conveniently grouped as follows:

a. Parts I and II of CDRL A001 (identified by WDL-TR5291) (includes A002, A003, A008, A00C)

b. CI/CPCI specification for the Phase I Control Segment (A005 and A004, respectively). These specifications can be identified by their specification number as shown in Figure 1-1 and, when grouped under the Type A Control Segment Specification (CDRL A003, Vol. D. Part II), comprise a complete System Segment Specification Tree for the Phase I GPS Control Segment

The User Segment System Specification (A003) and the supporting A005/A004 (CI/CPCI specifications, were provided to the JPO on January 30, 1974, and are denoted by the shaded portions of Figure 1-1. CDRL A006, Reliability and Maintainability Analysis for the User Segment, WDL-TR5293, was also submitted January 30, 1974.

Part III of the GPS Definition Study, CDRL A001, will be the Philco-Ford/TRW firm proposal for the Phase I GPS Control and User Segments and will be submitted on June 17, 1974. The structure and content of Part III is tentative pending final proposal instructions from the Joint Program Office (JPO).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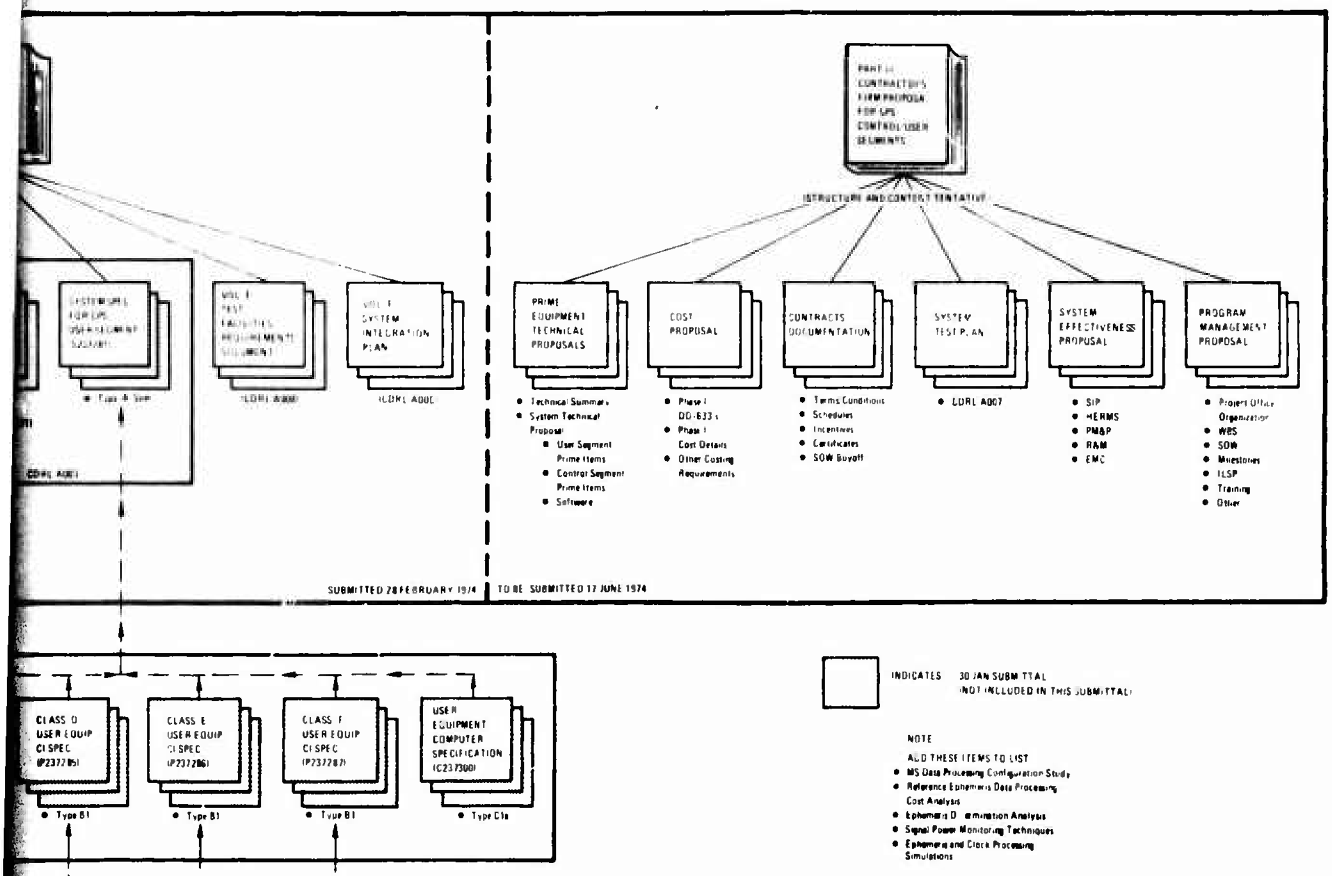

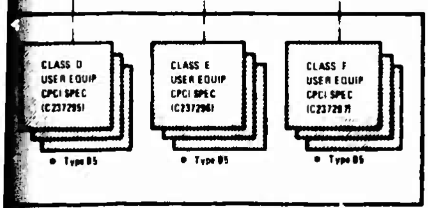

Figure 1-1 Structure of Global Positioning System Definition Study Final Report

SECTION 2

SIGNIFICANCE OF THE GPS DEFINITION STUDY

The significance of the GPS Definition Study and its results are more fully realized when one considers several facts surrounding the timing and coordination of the study efforts. First, through the formation of the Joint Program Office (JPO), the study has incorporated at a working level both the requirements and resources of the joint services in a manner that has allowed each major user to incorporate his specific performance and test requirements into the on-going study efforts. Furthermore, through the efforts of the JPO, the Definition Contractor has been able to incorporate existing technical and physical resources that reside in the Government community in a conscious effort to minimize system cost. This facet has been notably evident in the Control Segment studies as described in Part II, Volume C, of this final report.

Secondly, the study follows and incorporates the results of a significant amount of recent industry experience in the key area of user equipment design, development, and preliminary testing, ie, receiver design studies, signal structure studies, and user equipment test and evaluation (INI, INHI, Holloman Tests), an asset not available during prior GPS studies such as the "Phase Zero, DNSS" studies.

Lastly, the study incorporates carefully selected program evaluation criteria and goals such as life-cycle costing (LCC) and Design-to-Cost which serve to identify and minimize system acquisition cost, cost of ownership, and development risk while concurrently maximizing system performance and growth capabilities through legacy in engineering and design efforts.

SECTION 3

STUDY SCOPE, STRUCTURE, AND PRODUCTS

The overall scope of the GPS Definition Study was to provide an integrated approach to the definition of the Control and User Segments for Phase I of the Global Positioning System. Specifically, it was to perform systems engineering and design analyses that defined and specified the Control and User Segments' equipment items and related software; defined all objectives for the testing, test support, and test planning associated with the design and development of segment hardware/software, the verification of segment performance, and the conduct of total integrated system testing during Phase I; and provided the program planning, scheduling, and life-cycle-cost information necessary for the acquisition of the Phase I Control and User Segments. The environment defined by the study effort, in conjunction with that provided by the GPS Space System Segment, would permit highly accurate three-dimensional position, velocity, and time measurements to be demonstrated during Phase I of the GPS. The GPS Definition Study Work Breakdown Structure (WBS), illustrated in Figure 3-1, was used to achieve these study goals.

The WBS is task oriented. Tasks 1 and 2 encompassed the Control Segment efforts, with Task 1 also providing the overall systems engineering for the study. Task 3 was a major subcontract to TRW Systems Group that provided all aspects of the User Segment study efforts, while Task 4, led by Philco-Ford, encompassed the development of planning information for both the Control and User Segments. Interfaces with other GPS segments, notably the Space Segment, were coordinated with the JPO through Task 1.

The orginal GPS Definition Study contract contained a Task 5, Experimental Applications, which was to investigate the feasibility of the GPS (then DNSDP) to provide a surveillance (ATC) and/or communications function in addition to the basic navigation capabilities. This task was dropped from the study efforts based on contract redirection November 15, 1973.

Control Data Corporation was given a subcontract to provide computer systems and telecommunication interface analyses as part of Task 1. The services of Dr. Aldo daRosa, Stanford University, also were secured on a consulting basis to aid in the evaluation of ionospheric correction techniques.

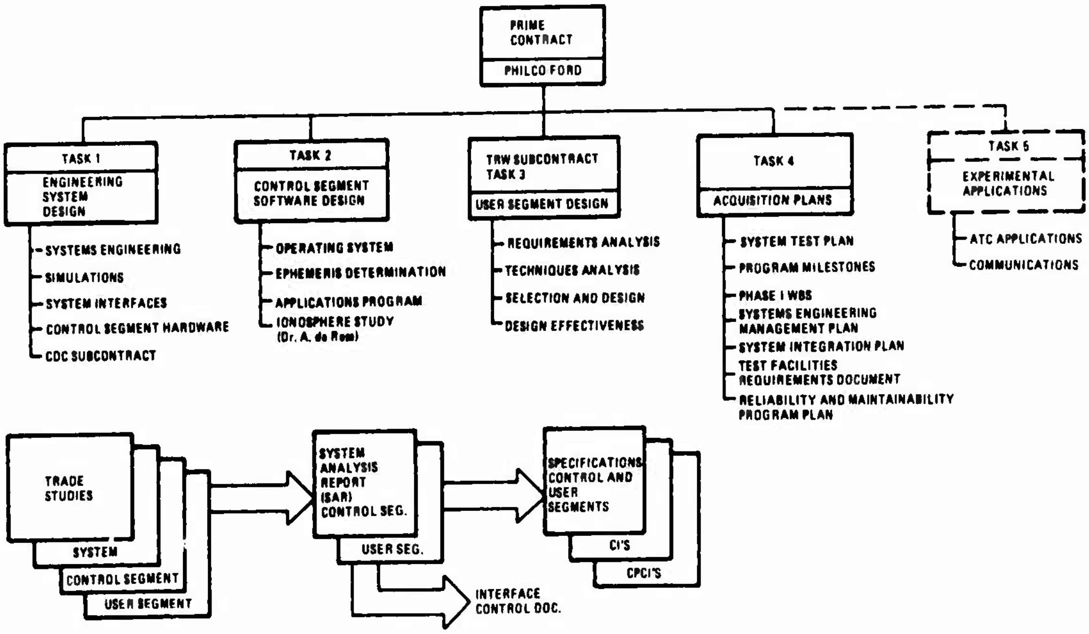

Figure 3-1 GPS Definition Study Work Breakdown Structure (WBS)

SECTION 4

STUDY FLOW AND GPS CONCEPT EVOLUTION

This section, utilizing the WBS illustrated in Figure 3-1, traces the basic flow of GPS Definition Study efforts from the onset of the contract, June 28, 1973, to the production of this portion of the final report. Included in this chronological flow, shown in Figure 4-1, are major milestones of study progress together with JPO technical direction that factored into the evolution of the current GPS concept. The following sections describe basic study inputs, milestones, concepts, major presentations, and technical direction.

4.1 CONTRACT AWARD (June 28, 1973)

As described in the GPS (then DNSDP) RFP Statement-of-Work, the original GPS concept consisted of a near-synchronous, (inverted) "rotating Y" constellation of four satellites. All analyses, trade studies, and Control and User Segment concepts were developed to support this system concept. Its basic features were a repeater or transponding satellite for the navigation signal, CONUS coverage, and monitor stations located at Vandenburg Air Force Base (VAFB), Andrews Air Force Base, and Laredo Air Force Base, Texas. The ephemeris determination process relied on pseudorange and two-way range observations derived from a combination of C and L-band links. Both L-band and UHF navigation functions were to be provided together with a feasibility study of providing an air traffic control (ATC) surveillance function plus two-way narrowband data communication (Task 5 in WBS). The results of these initial analyses were documented in detail in the Third R&D Status Report, October 9, 1973. A preliminary System Test Plan was also submitted to the Joint Program Office (JPO) during this period.

4.2 CONTRACT REDIRECTION (October 1973)

During October and November, 1973 the basic GPS concept underwent a major conceptual change. The Joint Program Office directed Philco-Ford to define the Control and User Segments for a medium altitude (12 hour) GPS orbital configuration (Alternate B). Major

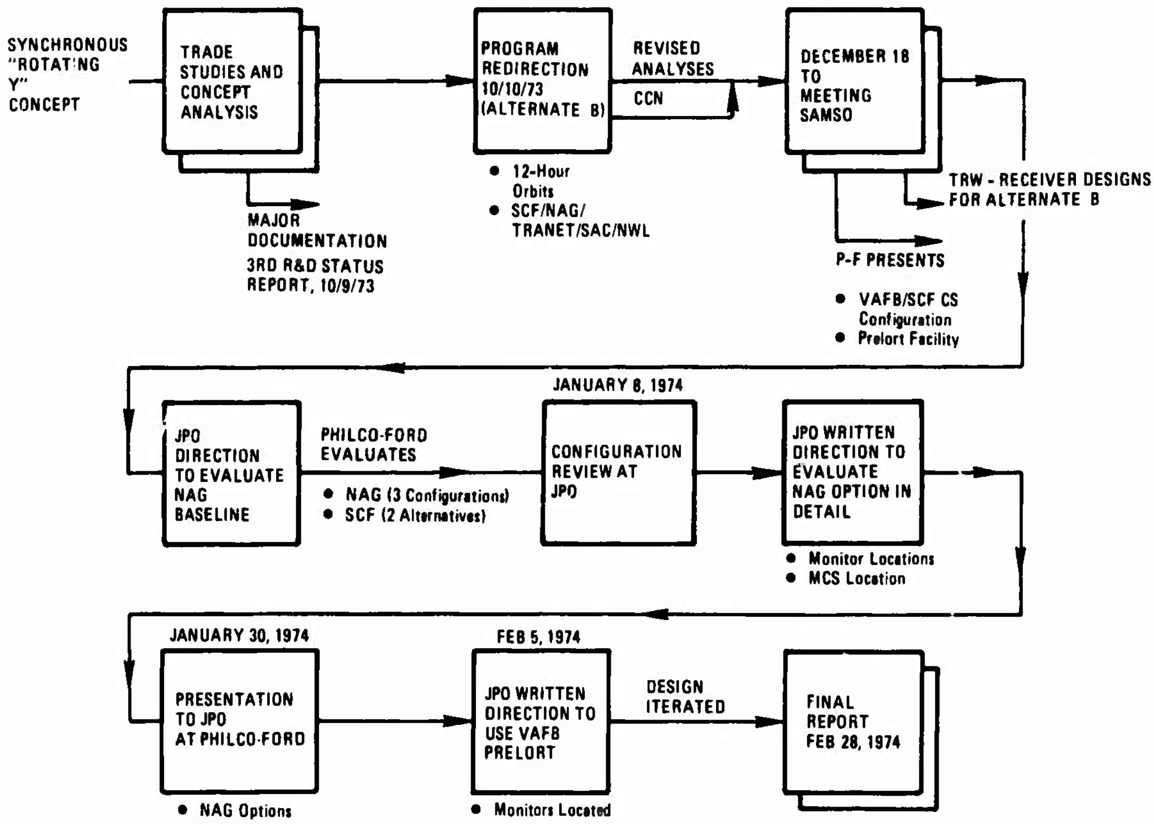

Figure 4-1 Study Flow and Evolution of Current GPS Concept

revisions of the Control Segment operational timelines were necessary to support both the basic orbital configuration and the necessity to upload a space-borne navigation subsystem. The User Segment design efforts were affected primarily in the software areas.

Direction was also provided to evaluate the applicability of various JPO resources in configuring the Control Segment. These resources included the Strategic Air Command, Naval Astronautics Group, Air Force Satellite Control Facility, and the Naval Weapons Laboratory. The System Test Plan was to be revised to include Phase I tests to be conducted by both the Army and Navy.

4.3 GPS SIGNAL STRUCTURE SELECTION

Concurrent with the redirection to a medium altitude GPS concept, the Joint Program Office announced their decision on the selection of the GPS navigation signal structure. The signal structure selected was similar to that technique studied by Philco-Ford on the Signal Definition Study contract in 1972.

4.4 TECHNICAL DIRECTION MEETING (December 18, 1973)

The December 18th TD meeting at SAMSO provided a comprehensive review of the Alternate B GPS concept. User equipment class configurations, designs and performance were identified together with life-cycle-cost considerations. The Control Segment configuration recommended at this point utilized VAFB as the Master Control Station site together with selected elements of the Satellite Control Facility.

4.5 NAVAL ASTRONAUTICS GROUP (NAG) BASELINE (January 8, 1974)

During late December and early January 1974 the JPO provided direction to evaluate the NAG Facilities at Point Mugu, California for the Control Segment baseline. The Satellite Control Facility was to be used as an alternate to this baseline. From this direction, Philco-Ford prepared five Control Segment configurations, three based on the NAG facilities, and two based on SCF utilization. These alternatives were presented in detail to the JPO on January 8, 1974. As a result of this meeting, the JPO directed Philco-Ford to evaluate several variations of the NAG configuration. These NAG configurations were presented to the JPO at Philco-Ford on January 30, 1974.

4.6 VAFB/PRELORT BASELINE (February 5, 1974)

Following the January 30 review at Philco-Ford, the JPO provided direction to relocate the GPS Control Segment Master Control Station at Vandenberg Air Force Base. Specific locations for Monitor Stations were also provided.

4.7 SUMMARY

This final report contains a complete System Analysis Report (SAR), Segment, and CI/CPCI specification for the final JPO VAFB Control Segment configuration. Specific details of this baseline are contained in Part I, Volume C of this final report.

SECTION 5

GPS SYSTEM DESCRIPTION

The Global Positioning System (GPS) is a space-based radio navigation system which will provide suitably equipped GPS users with the capability to precisely determine three-dimensional position, velocity, and time information within designated test areas. Refer to Figure 5-1. To provide this navigation service, the GPS assembles and coordinates the operation of four system segments:

a. Space Segment
b. User Segment
c. Control Segment
d. Navigation Technology Segment.

The Space Segment is composed of the space vehicle (also denoted Navigation Development Satellite (NDS)). The User Segment is composed of several navigation equipment groups, each (typically) containing an antenna, processor, control and display unit, power supply, interface units, and auxiliary sensors. The Control Segment is composed of a Master Control Station (MCS), several Monitor Stations (MSs), and an Upload Station (US) interconnected by a telecommunication network and supported by the USAF Satellite Control Facility (SCF) and the Naval Weapons Laboratory in Dahlgren, Virginia, which serves as a remote computational facility (RCF).

The Navigation Technology Segment is composed of the Navigation Technology Satellite (NTS-II), the Naval Research Laboratory (NRL) Telemetry, Tracking, and Command (TT&C) subsystem, and a Pseudo-Random Noise (PRN) Navigation Assembly.

The GPS is to be implemented in three phases. During Phase I, the basic mission will be to confirm the basic GPS concept, demonstrate the capabilities of the GPS design within designated test areas, and provide in-depth information on system cost and military value

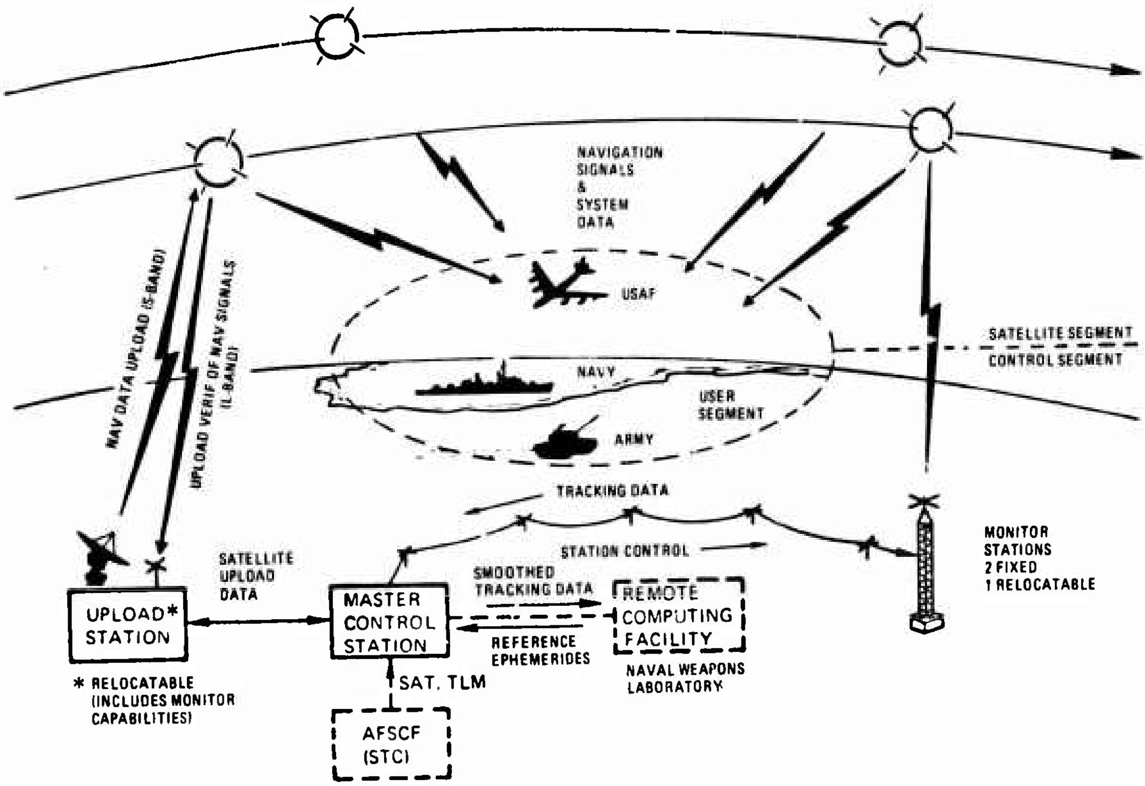

Figure 5-1 GPS Concept - Phase I

of such a system. Briefly, the Phase II objectives will be to expand the Phase I capabilities to that of a limited operational capability, namely, providing worldwide, two-dimensional navigation capability for suitably equipped users. Phase III will provide the growth to a global, three-dimensional capability for an expanded group of users.

The GPS Definition Study was primarily concerned with the definition of the Control and User Segment for Phase I. However, the study results include evaluations of the Phase II and III requirements, thus ensuring maximum legacy and growth of the Phase I segment designs. Additionally, the interfaces to other GPS segments (space, SCF, etc.) were carefully evaluated and integrated into the Control and User Segment designs so as to maximize overall GPS system operability and performance.

5.1 PHASE I SPACE SEGMENT CONFIGURATION

As described in the GPS System Specification, SS-GPS-101A, Section 3.7.1.1.7, the four space vehicles comprising the Phase I Space Segment would have nominally circular 12 hour orbits and be placed in two or three orbit planes separated by 120 degrees and inclined at 63 degrees. White Sands Missile Range (WSMR) in New Mexico would constitute the primary test area for Phase I.

As part of the System Engineering efforts in the Definition Study, Philco-Ford evaluated several orbital configurations for the Phase I tests[(1)]. The objective was to select a Phase I orbital configuration such that system performance[(2)] was optimized over WSMR. This optimization included maximizing test time[(3)], while at the same time minimizing the effects of Geometric Dilution of Precision (GDOP) over the test period. Over 100 different orbital configurations were analyzed on the computer prior to final selection.

The orbital elements and performance characteristics of the selected Phase I orbits are delineated in Table 5-1. The polar projection in Figure 5-2 identifies satellites 1, 2, and 4 as the USAF Navigation Development Satellites (NDS) while the "trailing" vehicle (satellite 3) is the Navigation Technology Satellite (NTS-II). Satellites 1 and 2 are in one plane, phased by 40 degrees, while satellites 3 and 4 in the second plane are phased by 60 degrees.

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(1) Refer to Part II, Volume C of this final report for details of this study.
(2) ie, user navigation precision.
(3) Mutual visibility of all four satellites.

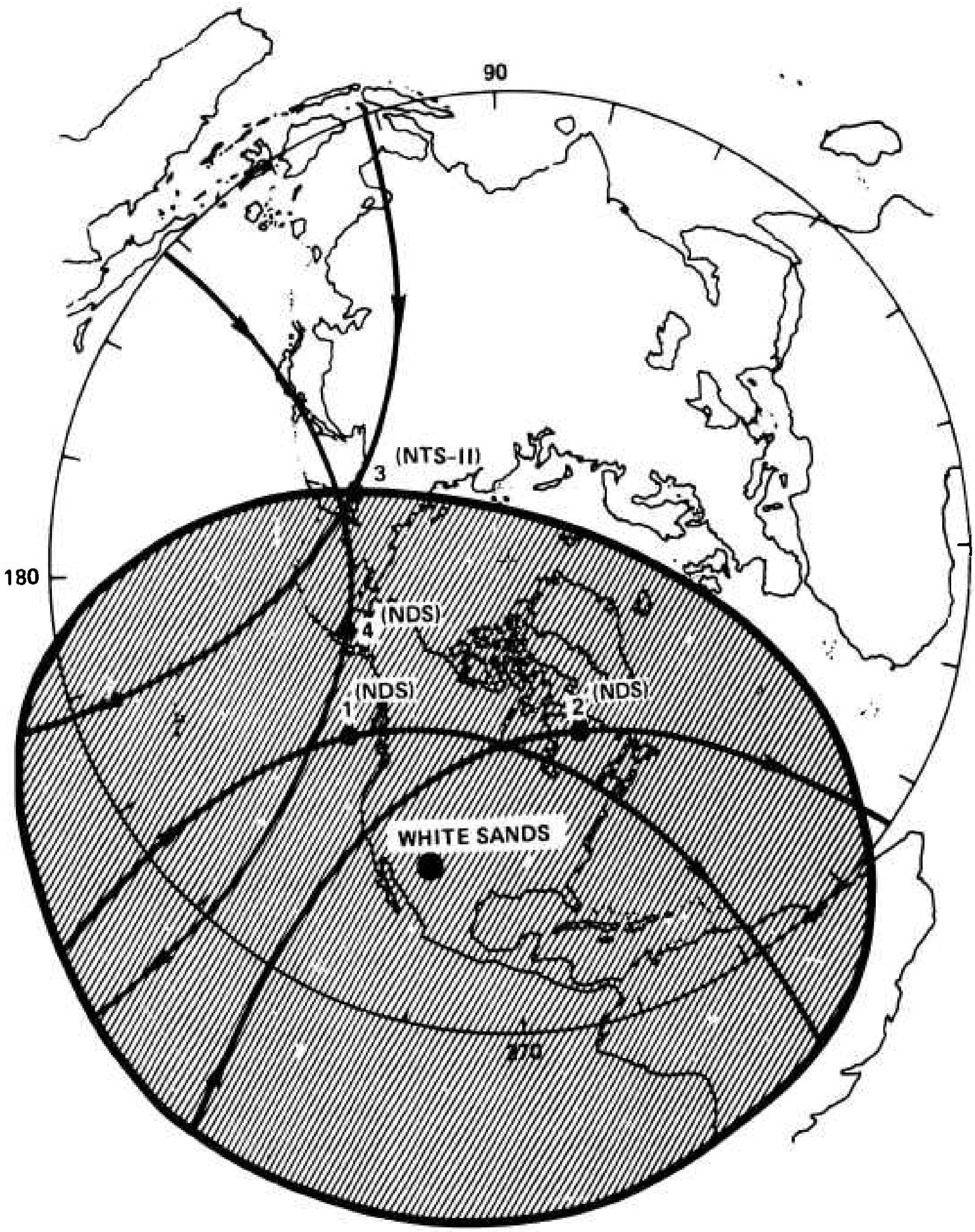

Figure 5-2 NDS/NTS-II Coverage and Ground Tracks

The operational time lines for Control Segment tracking and uploading functions[4] are based on the orbital characteristics of this Phase I Space Segment Configuration. Figure 5-3 illustrates the visibility of the Phase I Space Segment at selected monitor and navigational data upload sites.

TABLE 5-1

GPS PHASE I - BASELINE ORBITAL CONFIGURATION

Satellite Number	Arg. of Perigee (deg)	Eccentric Anomaly (deg)	Eccentricity	Inclination (deg)	Longitude of Ascending Node (deg)	Semi-Major Axis (nmi)
1	0	191	0	63	120	14341.5
2	0	231	0	63	120	14341.5
3[1]	0	214	0	63	0	14341.5
4	0	274	0	63	0	14341.5

Orbit Period (Sidereal hours)	11 hr, 57 minutes, 58 seconds
Test Time Over WSMR	145 minutes
View Time (above 5° elevation at WSMR)	145 minutes
Average GDOP During Test Time[2]	4.16
Minimum GDOP During Test	3.8
Tolerances	
Eccentric Anomally	±6°
Inclination	±2°
Ascending Node	±2°
Semimajor Axis	±0.1 nmi
Station-Keeping Requirement	~1 ft/s/yr
All Elevation Angles Above 15 degrees	75 minutes

(1) "Trailing" NTS-II Satellite
(2) GDOP as defined in Section 6.2 of GPS System Specification, SS-GPS-101A

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(4) Discussed in the Control Segment Systems Analysis Report, Part I, Volume C.

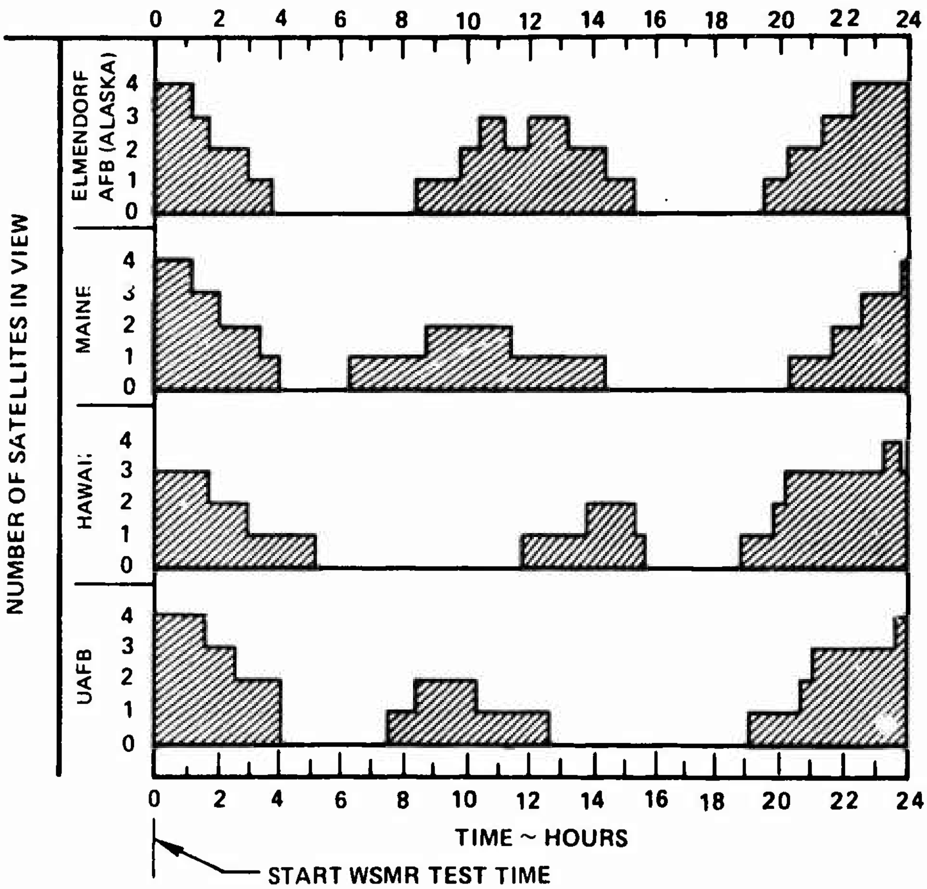

Figure 5-3 GPS Phase I Space Segment Visibility at Control Segment Elements

5.2 SPACE SEGMENT INTERFACES

The function of the NDS and NTS-II vehicles in the GPS Phase I Space Segment will be to receive S-band (SGLS) signals transmitted from the Upload Station (US) in the Control Segment(1), process these signals to extract the navigation data(2), and format and modulate the data on an internally-generated wideband PRN range code onto two L-band carriers(3). The User Segment receives these ranging codes and together with the navigation data can proceed to determine position, velocity, and time. The Control Segment, on the other hand, uses the L-band signals to verify proper uploading of the navigation data and to track the spacecraft to determine ephemerides.

The S-band uplink interface to the GPS Space Segment and the L-band Navigation and tracking downlinks just described were evaluated and documented as part of the GPS Definition Study to maximize intersegment compatibility, overall system flexibility, and performance. These interfaces are documented as Interface Control Documents (ICD) and submitted in Part II, Volume D of this final report.

The next major sections describe the Control and User Segments' requirements, functional allocations, configuration, and performance as determined during the course of the Definition Study.

(1) AFSCF Remote Tracking Stations in a backup mode.
(2) Ephemerides, satellite clock correction factors, etc.
(3) Nominally 1575 MHz (L_1) and 1250 MHz (L_2).

SECTION 6

CONTROL SEGMENT DESCRIPTION

THE GPS Control Segment (CS) consists of four elements:

- A Master Control Station (MCS)
- Three Monitor Stations (MS)
- An Upload Station (US)
- Telecommunications Network (Linking the above stations)

The prime role of the CS is to maintain the quality[(1)] of the navigation data base stored in the navigation subsystem of each GPS space vehicle. In support of this role, the CS must:

- Track the GPS space vehicles by receiving navigation signals from each vehicle (via widely separated Monitor Stations)

- Process the tracking data at the MCS into a data base update for each vehicle

- Periodically transmit the update to each vehicle via the Upland Station and verify proper receipt of the update by the vehicles.

The Control Segment does not incorporate facilities for receiving space vehicle "house-keeping" telemetry nor for generating reference ephemerides for the space vehicles (used in creating the data base update). These services are provided, respectively, by the Air Force Satellite Control Facility and a remote computing facility at the Naval Weapons Laboratory, Dahlgren, Virginia. The Control Segment configuration described in this final report is shown in Figure 6-1.

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(1) Refer to Part I, Volume C, for a detailed discussion of navigation signal quality and user equivalent range error (UERE). The system parameters contributing to this error budget are summarized in Part II, Volume C, of this final report.

In addition to its operational role, the CS must contribute to the validation of the GPS concept by providing the means for validating CS hardware/software designs and for defining CS costs at both the equipment and operational levels.

6.1 CONTROL SEGMENT FUNCTIONAL REQUIREMENTS AND ALLOCATIONS

Updating of the space vehicle navigation subsystem with navigation parameters having the required accuracy will be accomplished by the CS through its performance of the functions shown in Table 6-1. Performance of these functions is implemented within the CS to the extent required to support GPS Phase I objectives and in a manner which maximizes Control Segment legacy and has growth capability to accommodate the Phase II and III GPS requirements and objectives shown in Table 6-2.

A top-level functional flow block diagram (FFBB) of both the Control Segment operations and the Control Segment Acquisition and Activation Phase activities is illustrated in Figure 6-2. Figures 6-3 through 6-7 are first-level functional flow block diagrams for each of the mission-related top-level Control Segment functions. A detailed description of these functions is provided in both the Control Segment Systems Analysis Report, Part I, Volume C and the Control Segment System Specification, Part II, Volume D.

The allocation of these functions to the Control Segment elements is shown in Table 6-3.

A brief description of the Control Segment elements is presented in the following sections.

6.2 MASTER CONTROL STATION

The Control Segment Master Control Station (MCS) for the Phase I Global Positioning System will be located at Vandenberg Air Force Base, California within the existing building 22104. This building was formerly the Prelort Building for the Vandenberg Tracking Station of the Satellite Control Facility (SCF) System. Figure 6-8 illustrates the location of the site in relation to the surrounding area. Figure 6-9 is an aerial photograph of the Prelort facility which will house the MCS Phase I equipment.

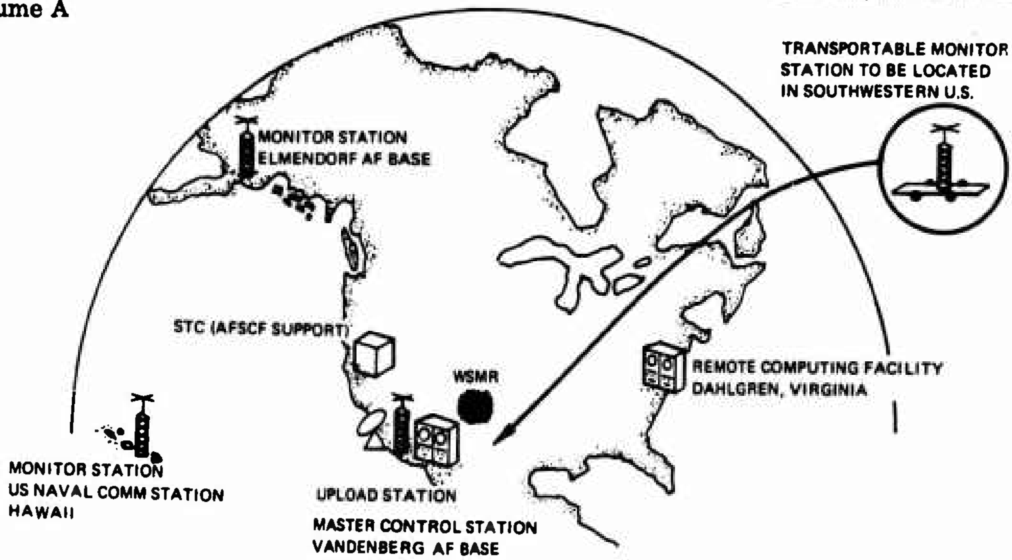

Figure 6-1 GPS Phase I Control Segment Configuration

TABLE 6-1

CONTROL SEGMENT FUNCTIONAL REQUIREMENTS

1. Control Segment Operations Control
   - Segment Initialization and Recovery
   - System Scheduling
   - Communications Function
   - Display and Control Function
   - Status Monitoring Function
2. Navigation Data Collection
   - System Calibration Data
   - Space Vehicle Tracking Data
   - System Time Standard
   - Space Vehicle Health and Status Data
   - Space Vehicle Access Key
3. Navigation Data Processing
   - Tracking Data Preprocessing
   - Reference Ephemeris Generation
   - SV Ephemeris Prediction
   - SV Clock Prediction
   - Almanac Data Generation
   - Upload Message Generation
4. Space Vehicle Navigation Subsystem Control
   - Navigation Upload Control
   - Upload Message Validation
   - Upload Message Transmission
   - Upload Verification and Retry
5. System Test/Calibration/Maintenance
   - Control Segment Calibration
   - Ionospheric Data Collection
   - Navigation Performance Evaluation
   - Space Vehicle Signal Quality Monitoring
   - Support Software Development
   - Segment Readiness Testing
   - Segment Evaluation Testing
   - Logistics Support

TABLE 6-2

CONTROL SEGMENT OPERATIONAL GROWTH REQUIREMENTS

Subject/Phase	Phase I	Phase II	Phase III
Test Area	White Sands Missile Range	A - CONUS (4 satellites) B - WORLD (2 satellites)	WORLD (4 satellites)
Backup Equipment	To be determined	As needed (Av = 0.7)	100% (Av = 0.99)
Upload	100 kbits/satellite PRIOR TO TEST PERIOD	100 kbits/satellite A - Prior to Test Period B - Once/Day	100 kbits/satellite Once/Day
Upload Time 1/2/3/4 satellites	20/30/40/50 minutes	Same as Phase I	Same as Phase I
MCS/Upload Station Comm Line	1 Hour/Day	2 Hour/Day	5 Hour/Day
Monitor Data - Quantity Data Forwarded	800 kbits/Day/Stn Once/Hour	1.6 Mbits/Day/Stn Once/Hour	5 Mbits/Day/Stn Once/Hour
MCS/NWL Comm Lines	4 Hours every 5 days 1.2 kb/s Thruput Rate (No MCS Data Compression)	9 hours every 5 days 1.2 kb/s	24 hours every 5 days 1.2 kb/s

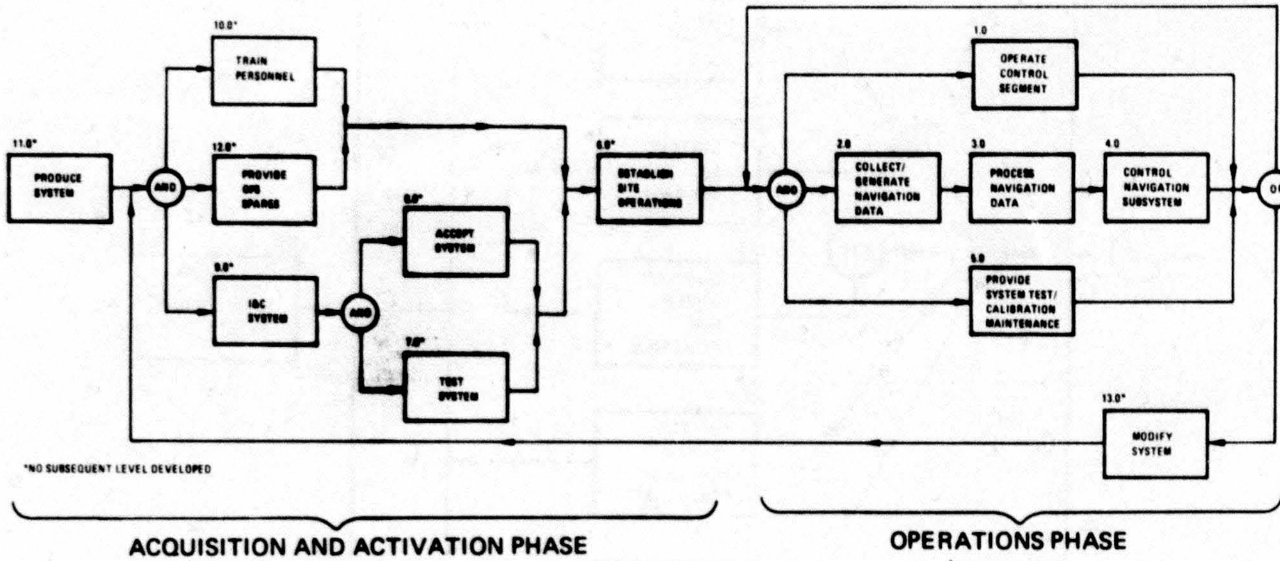

Figure 6-2 Control Segment Top Level Functional Flow Block Diagram

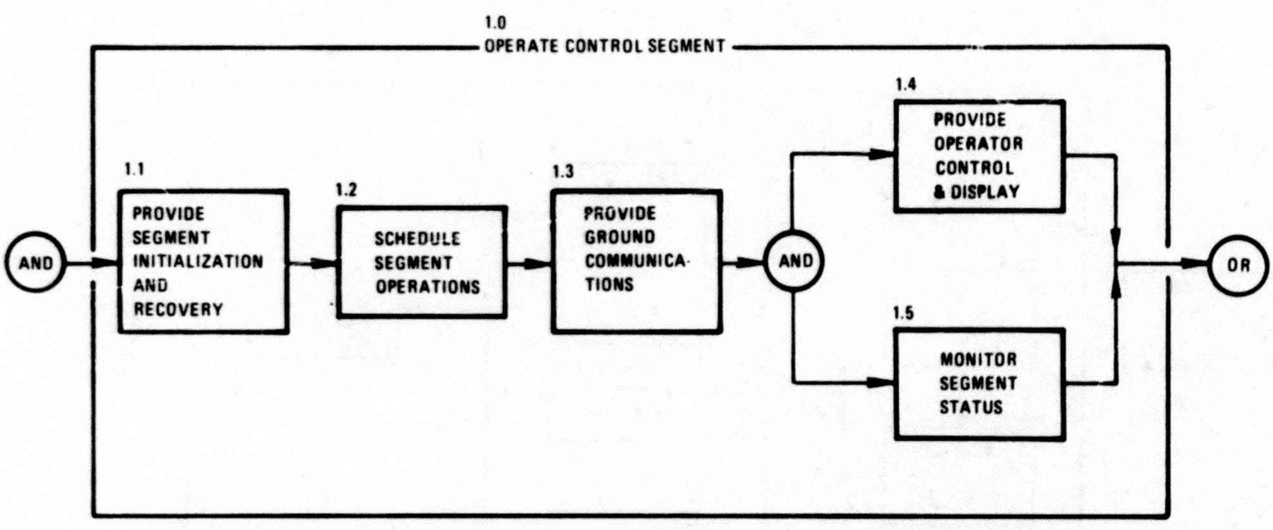

Figure 6-3 Control Segment Operations Control - First Level

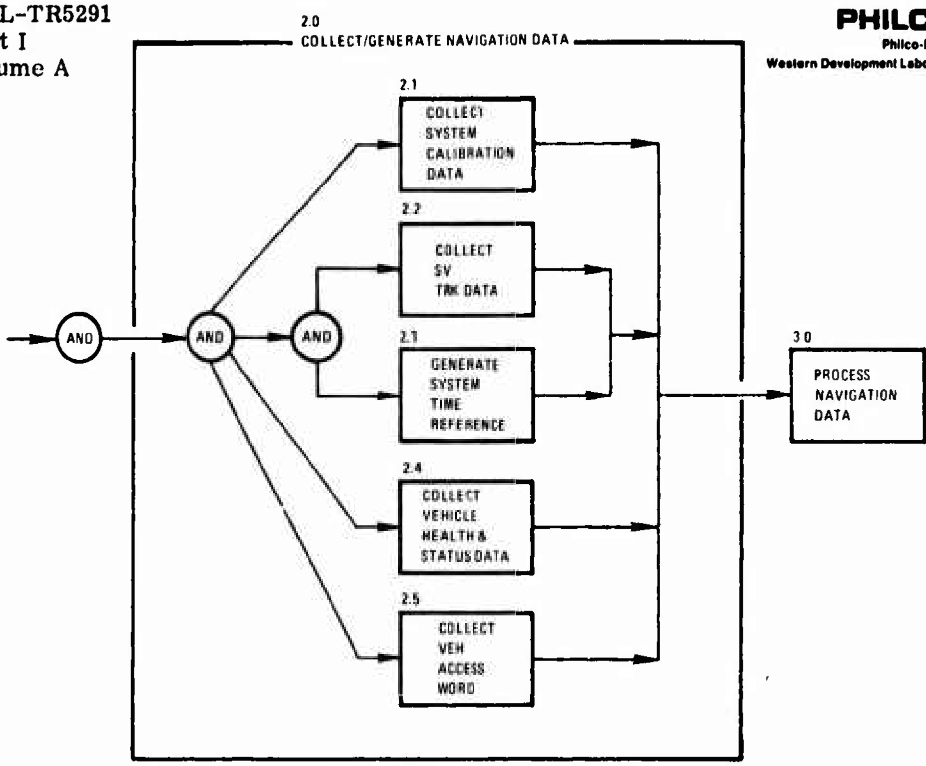

Figure 6-4 Collect/Generate Navigation Data - First Level Functional Flow Diagram

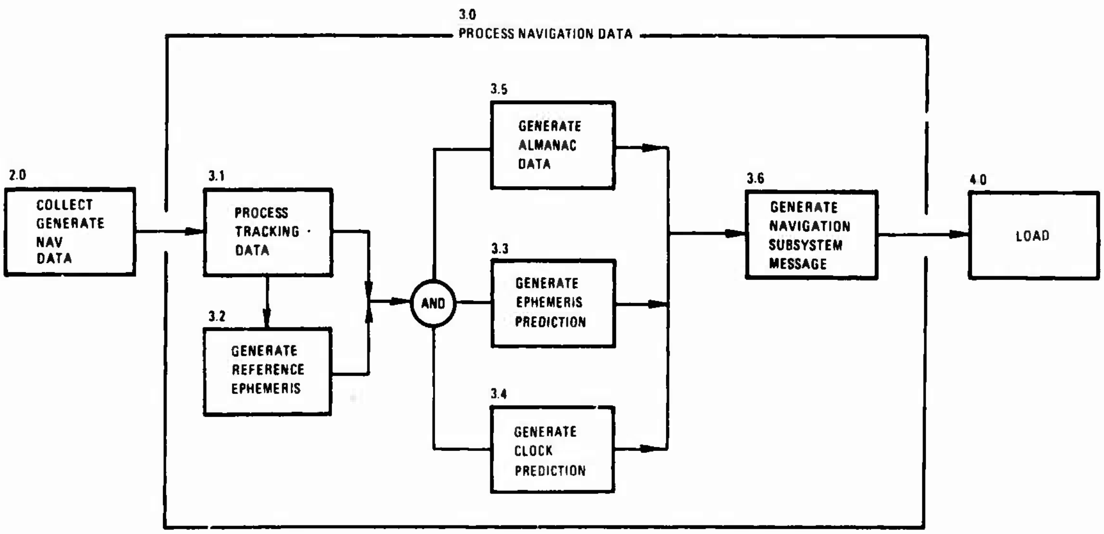

Figure 6-5 Process Navigation Data - First Level Functional Flow Diagram

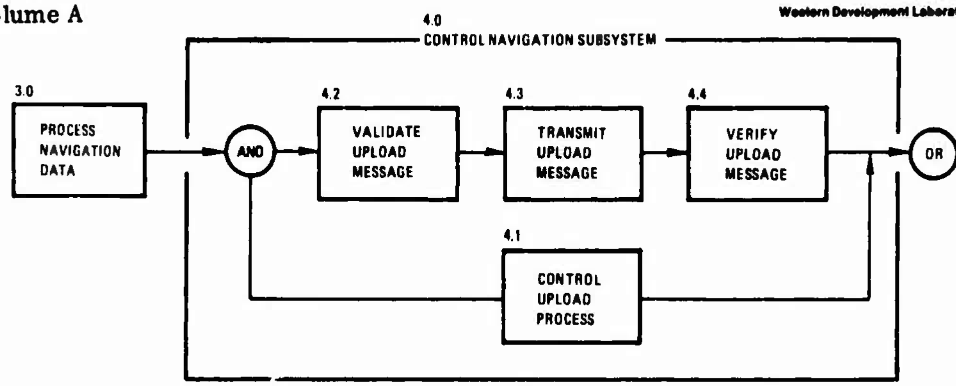

Figure 6-6 Load Navigation Payload - First Level Functional Flow Diagram

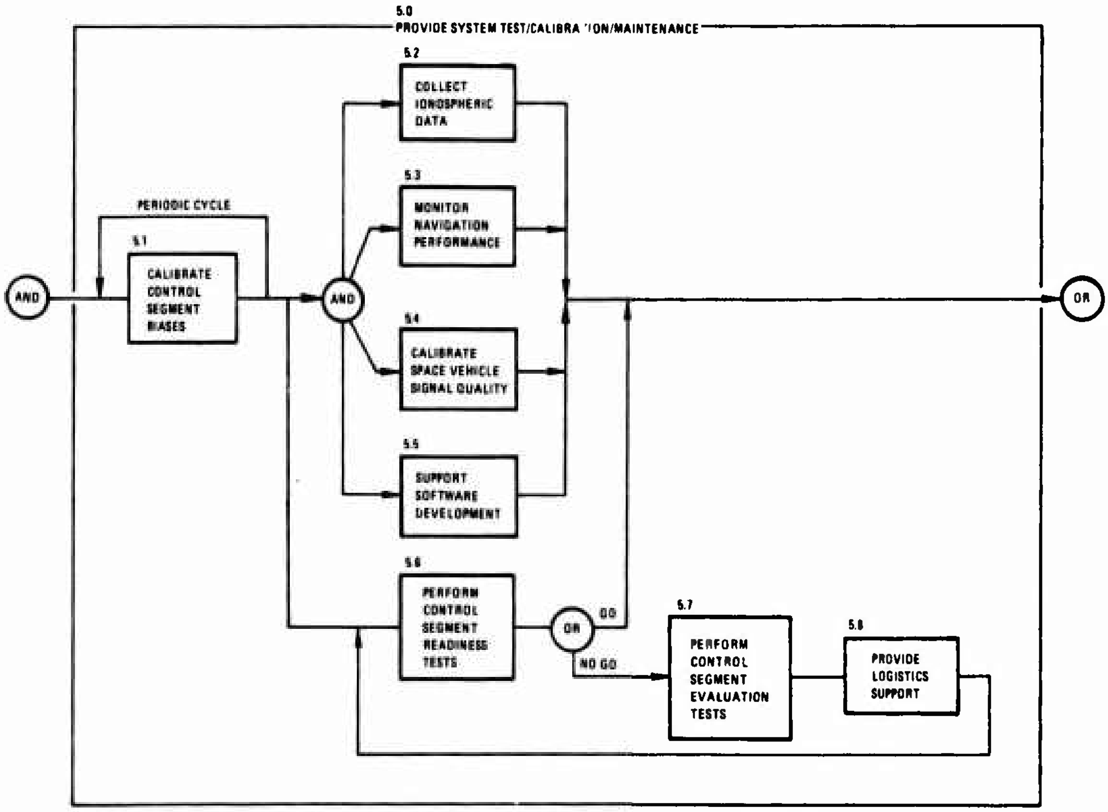

Figure 6-7 Control Segment Provide System Test/Calibration/ Maintenance - First Level Functional Flow Diagram

TABLE 6-3

ALLOCATION OF FUNCTIONAL AND INTERFACE REQUIREMENTS TO CONTROL SEGMENT

Functional Requirement \ Control Segment Element	Master Control Station	Monitor Station	Upload Station	Telecommunications Element
Navigation Data Processing	X			
Control Segment Operation Control	X			
System Time Standard	X			
L-Band Tracking/Data Collection		X	X	
Meteorological Monitor		X	X	
Navigation Data Upload			X	
Land-Line Communications				X
Interface Requirement				
CS/Space Vehicle		X	X	
CS/AFSCF	X			X
CS/Remote Computing Facility	X			X

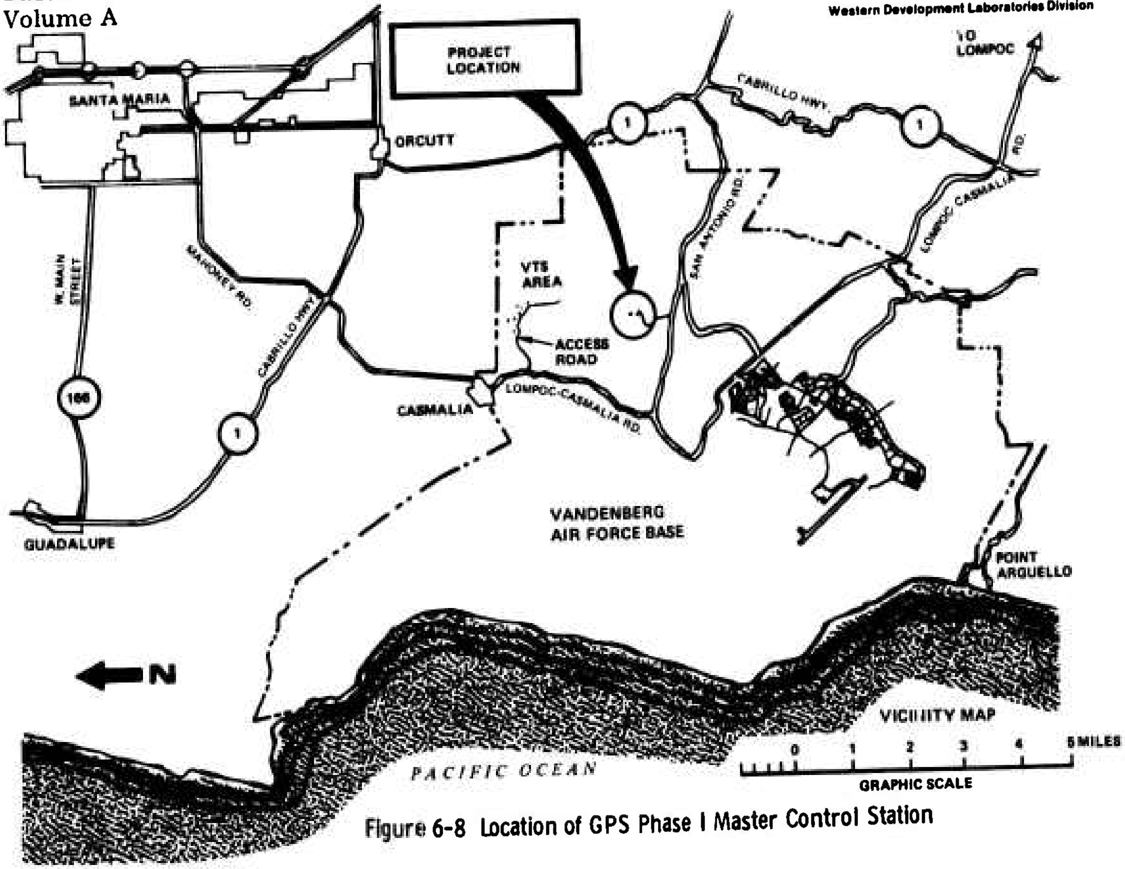

Figure 6-8 Location of GPS Phase I Master Control Station


Figure 6-9 Aerial View of Prelort Facility - MCS Phase I

The Master Control Station will contain computational equipment suitable to run algorithms to process tracking data received from Monitor Stations from these algorithms and stored calibration correction factors, the Master Control Station will generate upload messages for maintaining the satellite navigation data base. The system will be sized for an initial support of four closely spaced satellites in Phase I, but expandable to support twelve closely spaced satellites in Phase II. Phase III will require a redundant system to ensure the necessary reliability. CS Operations control will be maintained by providing an interactive display of status, performance, and scheduling for control by several operators.

A fully redundant atomic timing standard will be provided at the MCS to generate the system time base against which all other clocks (satellite, monitors, and upload station) will be compared and calibrated. Refer to Figure 6-10.

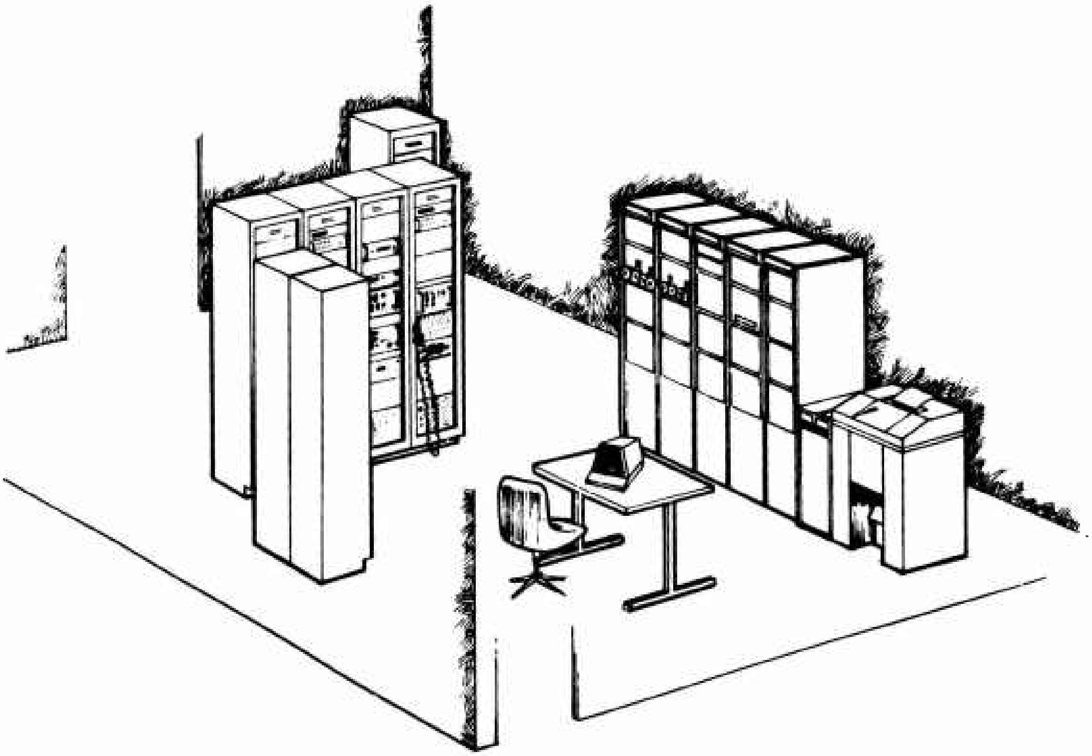

Figure 6-10 Artist's Concept of Master Control Station Equipment Configuration

Land-line communications will be provided in combinations of automatic dial-up and dedicated lines to meet cost and reliability requirements of each GPS phase. The MCS will monitor lines for bit errors, perform retransmission when errors occur, and replace noisy and faulty lines by a dial-up backup or replacement. Messages will be generated, stored, recalled, and transmitted as necessary.

6.3 MONITOR STATIONS

The function of the Monitor Stations (MS) is to receive the L_1 and L_2 navigation signals from the GPS satellites, track, and process these signals to extract pseudo-range and pseudo-range-rate data to be sent via land-line communication links to the MCS at VAFB, California. Periodically, meteorlogical data will be sampled and forwarded to the MCS to aid in the preprocessing of the raw tracking data to correct for atmospheric effects. Sequencing between satellites, links, and functions will be accomplished on a prescheduled basis established by the MCS.

The Monitor Stations are unmanned, self-testing, and autonomous in operation. Provision is made to provide human operator control/override for maintenance, initial start-up, and remote alarm situations if a self-test fails.

Physically, an MS consists of two standard 19 inch panel equipment racks as shown in Figure 6-11 plus one conical receiving L-band antenna/preamplifier package and a meteorological monitoring package. To the greatest extent possible, the Monitor Station will incorporate elements of the user equipment receiver subsystems.

The three Monitor stations will be located at the following sites:

a. U.S. Army Fort Richardson, Alaska[1]
b. U.S. Naval Communications Group, Wahiawa, Hawaii
c. Relocatable to a suitable geographic location and facility

The Monitor Stations' equipment will be integrated into the existing equipment areas[2] at the sites, and all support services, including electric power, water, sanitary, and fire protection, will be provided by the present facilities.

1. Facilities allocated to Elemendorf, AFB
2. A fourth Monitor Station capability is integrated into the Upload Station collocated with the MCS at VAFB

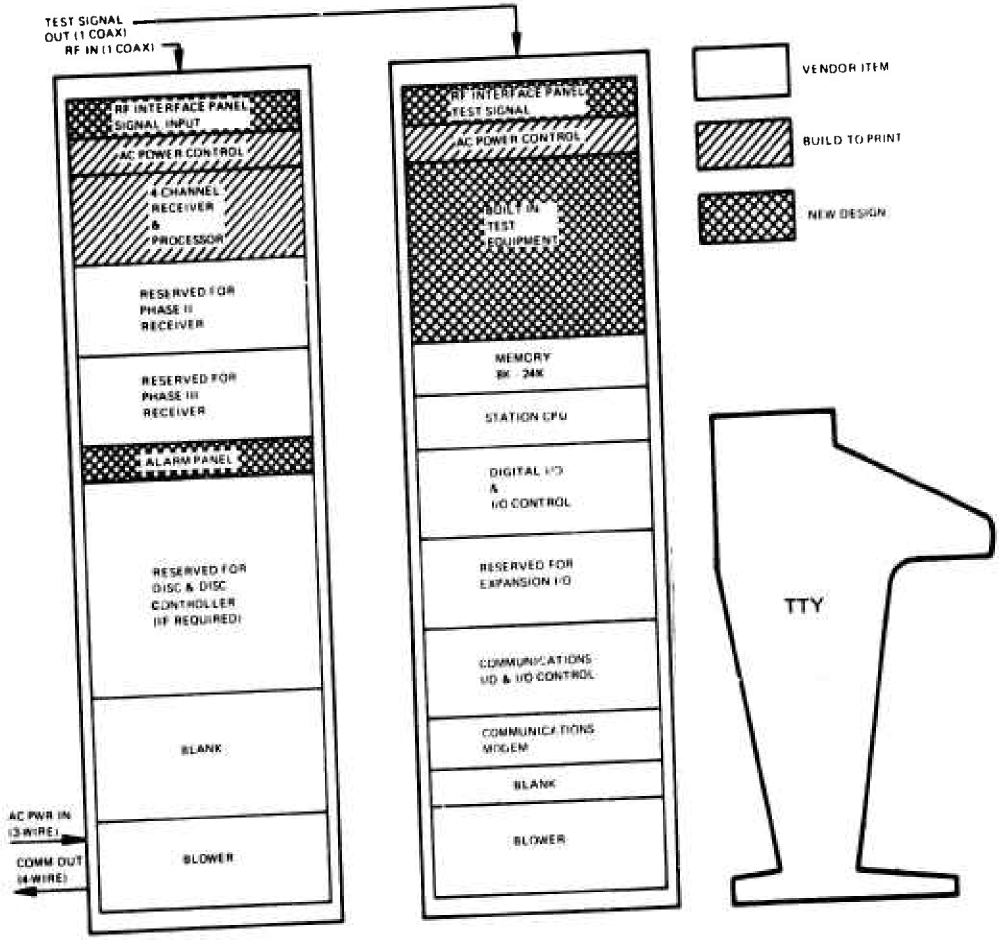

Figure 6-11 Monitor Station Configuration

The facilities assigned for installation of the Monitor Station at Fort Richardson will be shared with the U.S. Air Force 1931st Communications Group associated equipment items. The Monitor Station to be located in Hawaii will be in facilities assigned to the Naval Astronautics Group (NAG) Detachment Charlie. Both the Fort Richardson and Hawaii Monitor stations will be located within military secured areas in which access can be controlled to any degree desired. Additional details of these facilities and the Monitor Station interfaces therein can be found in Part I, Volume C.

6.4 UPLOAD STATION

The GPS Upload Station (US) will be collocated with the Master Control Station at Vandenberg Air Force Base, California. The US comprises the most diversified group of equipment of any of the Control Segment elements. To support its satellite upload function, it incorporates communications equipment linking it to the MCS, data processing equipment for upload message formatting and antenna pointing, a 1 kW S-band transmitter, and a nominal 15 ft diameter parabolic (directional) antenna. (See Figure 6-12.) To verify that the satellite uploading has been satisfactorily accomplished, the US includes L-band receiving equipment, duplicating that used at a Monitor Station, to receive an "upload accept/reject" signal from the satellite(s).

When the receiving equipment is not being used for upload verification, it serves to implement a fourth MS. In addition, the US collects meteorological data and measures satellite signal strength. A dedicated land line with a backup dial-up system will be provided for communication with the MCS.

6.5 CONTROL SEGMENT INTER-SEGMENT INTERFACE REQUIREMENTS

To fully implement the functions and facilities described in the preceeding sections, the CS must establish a number of external interfaces, ie, with the GPS space vehicles[(1)], with the Remote Computing Facility[(2)] at the Naval Weapons Laboratory at Dahlgren, Virginia and with the AFSCF[(3)]. These interfaces are allocated as shown in Table 6-4.

6.5.1 Space Segment Interfaces

6.5.1.1 S-Band Uplink to GPS Space Vehicles (US/SVS). This uplink is used principally to refresh the vehicles navigation data bases by periodically transmitting navigation payload updating messages to the vehicle. The link may also be used for limited, clear (not encrypted) commanding of navigation payload functions and for transmitting processing functions to the payload. The principal characteristics of this uplink interface are:

---

(1) See Interface Control Drawing No. Hz-237301, Part II, Volume D.
(2) See Interface Control Drawing No. Hz-237302, CDRL A005
(3) Denotes probability of uploading a frame of data incorrectly, including verification via L-band downlink.

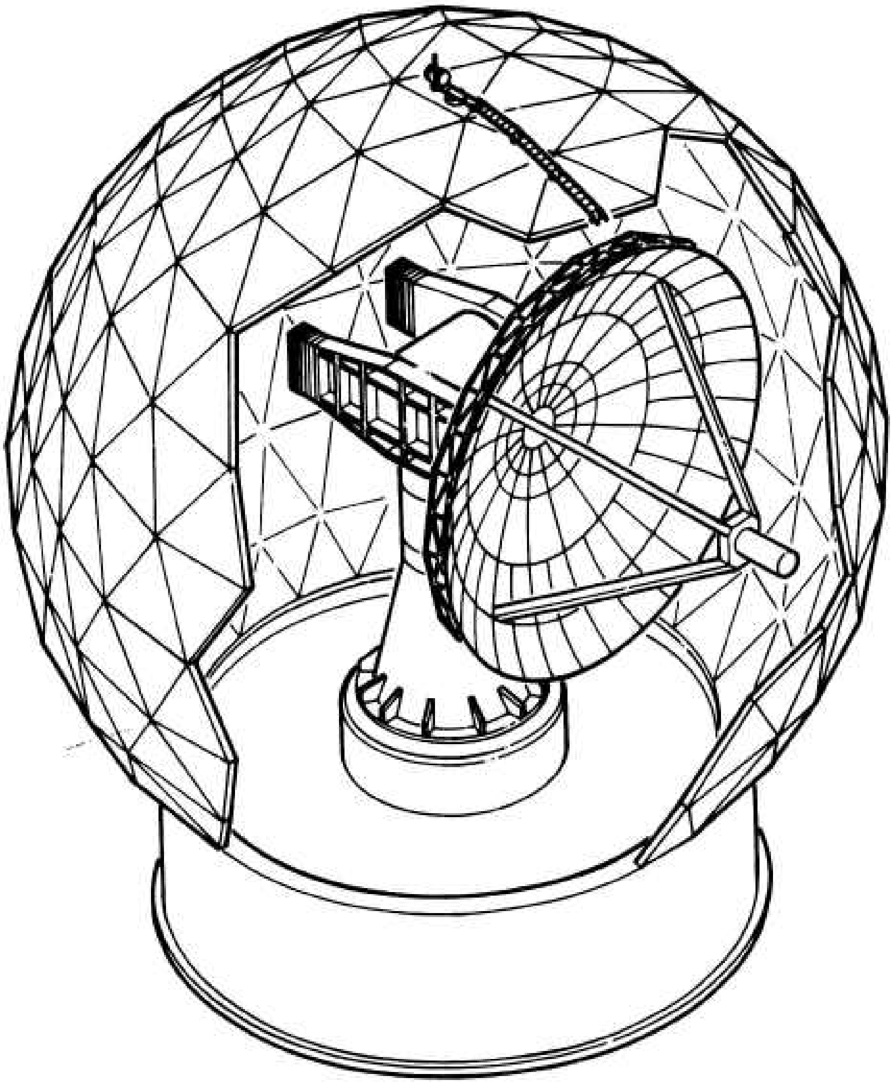

Figure 6-12 Artist's Concept of Upload Station

• Carrier frequency	One (as specified) of the 20 SGLS Channels, 1.75 GHz to 1.85 GHz
• Modulation	FSK, SGLS-compatible (1, 0, S)
• Command/data rate	1000 b/s
• Bit error rate (BER)	less than 10^{-5}
• Undetected frame error rate(3)	less than 10^{-15}

TABLE 6-4

ALLOCATION OF CONTROL SEGMENT INTERFACE REQUIREMENTS

Interface Requirement	Control Segment Element			
	Master Control Station	Monitor Stations	Upload Station	Telecommunications Element
Uplink to space vehicle			X	
Downlink from space vehicle		X	X	
CS/AFSCF Interface	X			X
CS/RCF Interface	X			X

6.5.1.2 L-Band Verification Downlink (SVS/MS). This downlink from the GPS space vehicles to the Monitor Stations and the monitor equipment in the Upload Station serves to convey upload verification data and tracking data to the Control Segment. The characteristics of this interface are described in detail in ICD Hz-237301.

6.5.2 Terrestrial Interfaces

6.5.2.1 Control Segment/Remote Computing Facility (RCF) Interface. The CS provides the RCF with "raw" tracking data nominally on a weekly basis, gathered from the Monitor Stations and smoothed by the Master Control Station. The RCF then computes reference GPS ephemerides and system calibration parameters and returns this data to the CS to serve as the basis for its near realtime orbit determination and prediction processing at the MCS. This interface will be implemented via the CS telecommunication network using a manual dial-up link (MDL) over a voice-grade, two-wire circuit.

(3) Denotes probability of uploading a frame of data incorrectly, including verification via L-band downlink.

6.5.2.2 Control Segment/AFSCF Interface. The AFSCF supports the space vehicle upload function of the CS by providing "keys" which are forwarded to the Upload Station to allow it to access the otherwise "secure" (ie, closed) space vehicle. The AFSCF and CS also exchange system/space vehicle control/coordination data; for example, the CS provides the AFSCF with upload messages in the event the AFSCF is to serve as a backup for the GPS Upload Station. This interface will also be implemented with a manual dial-up link.

SECTION 7

USER SEGMENT SUMMARY

A wide variety of tradeoffs and analyses have been conducted to define the User Segment of the GPS. Many of the tradeoffs are summarized in Section 9 of this volume and detailed in Part II, Volume B. The tradeoffs and analyses ranged in scope from GPS system definition to detailed User Segment design, system effectiveness, system test planning, and overall Phase I program planning. A brief summary of each of these activities follows.

7.1 USER SEGMENT DEFINITION

The User Segment systems engineering effort associated with the GPS Definition Study was principally concerned with the satellite to user rf signal structure and system error allocation. Throughout the project duration a wide variety of signal structures was examined and tradeoffs made with respect to each other to determine the optimum in terms of User Segment cost and system performance. These tradeoffs were made in conjunction with the JPO, and the final configuration is presented in the GPS System Specification (SS-GPS-101A), dated 29 January 1974.

System performance could be enhanced by modifying the data rates from those currently planned. This minor change is discussed in detail in Part II, Volume B. Content of the data message from the satellite to the user has also been examined, particularly with respect to satellite ephemeris prediction by the user, and ionopsheric corrections. Error analyses have been performed utilizing various ephemeris representation techniques. Details of this tradeoff are also contained in Part II, Volume B.

System performance, as influenced by both the signal structure and alternate receiver configurations, has been carefully examined. Accuracy, jamming immunity, and time to first fix are all important performance parameters affected by the signal structure and receiver implementation. In Part I, Volume B, a summary of these effects is presented. Greater detail is presented in Part II, Volume B. Part I, Volume B also summarizes the sequence of operations that occur in the user equipment from the time of system turn-on to obtaining the first navigation fix.

7.2 USER SEGMENT DESIGN AND FUNCTIONAL ALLOCATIONS

The detailed requirements for the GPS presented by the JPO have been utilized as the basis for the User Segment design. This design activity has encompassed all aspects from detailed analysis to preparing specifications. For the operational GPS, six classes of users have been considered. To meet the class requisites, three types of receivers [1] have been identified, namely:

a. Continuous tracking, L_1/L_2, C/P
b. Sequential tracking, L_1/L_2, C/P
c. Sequential tracking, L_1, C

The sequential tracking, L_1, C receiver is the least expensive of these identified herein.

The receivers have been defined from both electrical and mechanical aspects. Details are provided in Part I, Volume B. Modules within the receiver were defined based on functional as well as reliability and maintainability aspects. Tradeoffs of alternate receiver implementations are given in Part II, Volume B.

The functional areas comprising the User Segment consists of the following:

a. Navigation set
b. Auxiliary sensor systems (as required by specific users)
c. Software

[1] The above have been verbally identified by the JPO as sets X, Y and Z respectively.

Users are divided into classes as shown in Table 7-1 together with candidate missions, vehicles, and guiding specifications for each class. The User Segment is configured as shown in Figure 7-1. The individual components illustrated in Figure 7-1 are designed to accomplish the following functions:

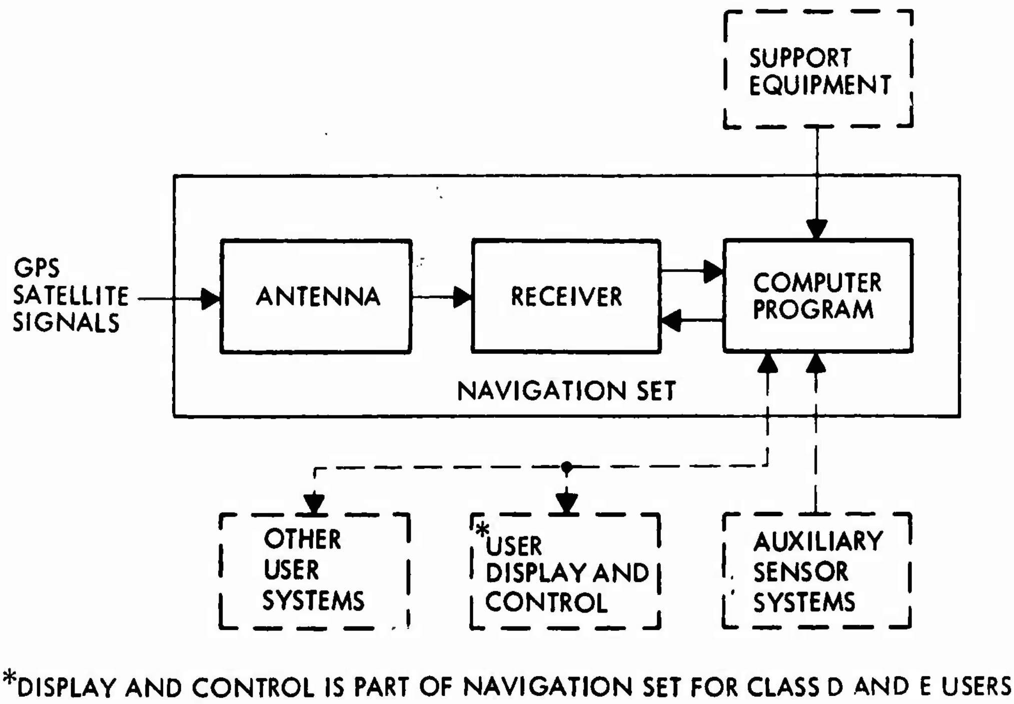

Figure 7-1 User Segment System Block Diagram

a. Navigation Set. The navigation set provides the basic satellite navigation capability. It is functionally subdivided into antenna, receiver, and computer.

b. Receiver. The receiver provides signal translation, signal recognition, signal tracking, signal acquisition, data detection, and pseudorange and pseudorange-rate measurement.

c. Computer. The computer provides computational and storage capabilities to enable operation of the computer program.

TABLE 7-1

USER EQUIPMENT CLASSES MISSIONS AND GUIDING SPECIFICATIONS

Class					
A	B	C	D	E	F
High accuracy Medium dynamics of user High immunity to electromagnetic jamming	High accuracy High dynamics of user Medium immunity to electromagnetic jamming	* Medium dynamics of user Immunity to unintentional EMI	High accuracy Low dynamics High immunity to jamming	High accuracy Low dynamics High immunity to jamming Low weight Low power	Medium accuracy Low dynamics Medium immunity to jamming
Missions					
<u>Air Force</u> Strategic B-52, F-111 Photo reconnaissance SR-71	<u>Army</u> Helicopter <u>USMC</u> Close air support helicopter <u>Navy</u> Close support and attack aircraft <u>Air Force</u> Interdiction F-4, F-105 Close air support A-7	<u>Army</u> Mission support <u>Navy</u> Mission support surface vessels ASWA/C <u>Air Force</u> Airlift C-130, C-5, C-141, C-135 Search and Rescue HH-53 Mission support C-131, C-141, T-29, T-39	<u>Army</u> Wheeled and tracked land vehicles <u>Navy</u> Mine warfare	<u>Army</u> Man backpack <u>USMC</u> Man backpack	<u>Navy</u> Submarine
Guiding Specification					
MIL-E-5400 Class 2	MIL-E-5400 Class 2	MIL-E-5400 Class 1	TBD	TBD	MIL-E-16400 Class 2

*<u>Accuracy</u>

(1) High, 50 ft
(2) Acceptable accuracy as determined by cost tradeoff Medium, 50-500 ft

d. Antenna. The antenna provides reception of radio frequency signals from the GPS satellites. The antenna includes the rf preamplifier (as required) and the cable to the receiver.

e. Computer Program. The computer program is capable of selecting appropriate satellites for viewing, pre-positioning the receiver to measure the pseudorange and pseudorange rate for the satellites, and using these measurements to determine the position and velocity of the user.

f. Auxiliary Sensor Systems[1]. The User Equipment provides for accepting inputs from other sensors for enhancement of prime navigation capability and/or when graceful degradation of system operation is required.

Antennas, control and display, interface units, computers, auxiliary sensors, and instrumentation items were examined in detail. Several of these have not been specifically selected; yet, because they are ultimately related to the ongoing test planning activity, these items are discussed in Part I, Volume B. The computers and antennas require special mention, however.

A computer specification has been prepared based upon detailed analysis of the user software. For Phase I, it is currently envisioned that only one type of user computer will be purchased and that computer will satisfy the requirements of all user classes. The actual memory size of the computer can vary from class to class but the basic computer is the same since the User Segment software does not place a severe burden on computational rate. Much of the software is common to all classes of users and thus, once developed, may be used for many applications.

The computer specification has been reviewed by the JPO and distributed to 26 computer manufacturers. Responses are expected by 6 March. Subsequent to an evaluation of these responses, an RFP will be issued and the user computer selected.

With regard to the antenna, preliminary specifications have been defined and a variety of antenna types considered. Because of the wide range of user applications and the limited

[1] Classes A and B only

space available on any user for the antenna, each specific application must be examined to ensure that desired performance will be obtained. More discussion of the antennas and their associated characteristics is contained in Part I, Volume B.

7.3 USER SEGMENT SYSTEM EFFECTIVENESS

The subjects of reliability, maintainability, life cycle costing, hardening, and EMC are included under the topic of system effectiveness. Each of these subjects has received considerable consideration during the course of the Definition Study.

A reliability and maintainability assessment of the user receiver has been performed and documented as Part I, Volume B of this final report.[1] This report defines R&M models and evaluates the models. In addition, an ORLA was performed, as well as a failure modes and effects analysis (FMEA).

A variety of items were considered under the topic of life cycle costing. For this analysis, a modified version of the JPO life cycle costing model was utilized. The modifications were in the form of extensions to the program to provide additional capability such as an option to evaluate the "discard at failure" concept. Alternate receiver configurations, in terms of number of modules and types of modules, were evaluated using different types of parts (military standard or high reliability). The analysis showed the desirability of using "hi-rel" parts and also indicated the practicality of the "discard at failure" concept. These results, considered to be preliminary in nature, will be continually upgraded as detailed design progresses.

Hardening of the user equipment was examined with respect to the B1 avionics hardening specification. The study results indicate that an inexpensive program could be undertaken to provide a level of hardening that would be satisfactory for many applications but would not necessarily meet the B1 standards. A more expensive program would be required to meet the B1 standards which might be applied to only those users who require it.

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[1] Also see WDL-TR5293, "User Segment Reliability and Maintainability Allocations, Assessments, and Analysis Report", dated 30 January 1974 (CDRL A006)

Sources of electromagnetic interference have been identified and several specific situations examined. The results indicate that for the application studied, radar altimeters, no special problem exists. However, it is also observed that each application of GPS must be examined to ensure that sufficient isolation exists between the GPS receiver and the electromagnetic interference source.

7.4 SYSTEM TEST ACTIVITIES

Phase I test planning started at contract initiation and remains an ongoing activity. A preliminary system test plan was submitted and reviewed by SAMSO. The current activity is closely coordinated with the JPO through the biweekly test plan meetings. This test planning activity is critical in that many of the decisions and analysis required in the User Segment design (for Phase I) are highly dependent on the test activities.

Facility requirements have been identified for Phase I and are detailed in Part II, Volume E, of the final report. Levels of testing, objectives, etc, have also been identified. Details on these and the test planning approach are presented in Part I, Volume B.

7.5 PHASE I PROGRAM PLANNING

Phase I program planning, similar to the test planning, has been a continuing activity since program inception. Deliverables such as a preliminary work breakdown structure, schedules, the System Integration Plan, and Phase I cost have been submitted. Because of the changing nature of the program, these documents are now obsolete. Based upon new information, provided by the JPO, the Phase I program plans are being updated. Final plans will be submitted as a portion of Part III of the final report (contractor's firm proposal) in June, 1974.

SECTION 8

SUMMARY OF GPS PLANS

The plans and management approach summarized in Part I, Volume D, of this report establish an integrated project approach to achieving the objectives established for GPS, while at the same time providing for orderly transitions from phase to phase with legacy of hardware/software maximized to the greatest extent possible within the minimum cost objective for Phase I. The overall management, engineering, and testing approach is oriented to ensuring overall GPS system functional integrity with the committment to achieving stated system performance requirements.

The integrated project approach is characterized by:

a. A system engineering discipline responsible for integrating all program requirements and achieving cost-effective design/development approaches to meeting stated requirements.

b. A management discipline responsible for effective use of resources with program cost control and minimum equipment costs as primary objectives.

c. A testing discipline responsible for assuring that all program decision elements are sufficiently demonstrated and documented.

d. A working interface between the JPO and Philco-Ford/TRW that provides the JPO with not only the elements of Government control required, but also the program visibility required to establish and maintain an effective working relationship.

This approach, which is documented in the various management plans, is neither unique nor unusual, but represents what is required for the overall program to function in an orderly and cost-effective manner.

SECTION 9

RESULTS OF SYSTEM AND SEGMENT TRADE STUDIES AND ANALYSES

This section summarizes the scope and results of system and segment-level trade studies and analyses conducted during the GPS Definition Study. These trade studies and analyses can be found in Volume A (System), Volume B (User Segment), and Volume C (Control Segment) of Part II of this final report.

9.1 SYSTEM TRADE AND ANALYSES (Reference Part II, Volume A)

Several trade studies and analyses conducted during the GPS Definition Study were categorized as "System" trades in that their scope encompassed more than one segment of the GPS System.

9.1.1 Signal Structure Analysis

9.1.1.1 Scope. This analysis is concerned with the performance of a C/A signal utilizing a class of codes different from those considered by Philco-Ford during the Signal Definition Study. Emphasis is placed on the prediction of acquisition time and multiple access performance. Data detection performance and performance of both the P and C/A signals in a jamming environment are analysized.

9.1.1.2 Results. A CW C/A-Signal design based on a 1023 bit length Gold Code was selected for GPS. It is shown that the code can be acquired in 50 seconds (90% probability) with a C/N_o of 32.0 dB-Hz using a receiver with two acquisition circuits operating in parallel. Time-to-first-fix is also calculated for both 4-channel and sequential receivers and shown to be within the mission requirements for specific user classes.

9.1.2 Link Analyses

9.1.2.1 Scope. This trade study provides a reference link budget for the L_1 and L_2 navigation signals. The S-band TT&C link is also analyzed.

9.1.2.2 Results. The required minimum received signal power at a 0 dB gain circular polarized user or Monitor Station receiver antenna is -163.1 dBW for the L_1-C/A link, -164.8 dBW for the L_1-P link, and -166.3 dBW for the L_2-P link. The average expected signal levels are at least 3 dB higher than these minimum values.

9.1.3 Clock Model Analysis

9.1.3.1 Scope. Successful operation of the GPS depends upon the ability of the user to accurately estimate the relative phase and frequency of the satellite clock(s). This estimate is performed by the user computing the clock phase/frequency from an algorithm using parameters derived by the Control Segment and transmitted to the user as part of the navigation message. This analysis describes and recommends the clock correction algorithm for GPS. The effects of the satellite environment and physically changing (by ground command) the clock frequency are discussed. Some results of laboratory measurements of two rubidium standards are presented. The sensitivity of the prediction algorithm to the update interval is also discussed.

9.1.3.2 Results. The recommended prediction algorithm is of the form:

$$T_c = TB + TF \cdot t$$

where T_c is the satellite clock phase correction measured in units of time, and TB and TF are parameters derived by the Control Segment and transmitted to the user. Methods for computation of these parameters are described. A prediction timing error of 81.6 ns rms, 10^5 seconds after last calibration is calculated for a system using a typical rubidium standard and a cesium super tube (HP option 004) as a reference. Precise modeling of the clock environment in space does not appear worth while. A more fruitful approach would appear to be that of maintaining as constant an environment as possible. Adjusting the clock frequency by ground command is not recommended because of the length of time (days) required to recomputed the prediction algorithm parameters to the accuracy required.

9.1.4 Direct Acquisition Analysis

9.1.4.1 Scope. This analysis deals with the user who has a stable clock which is synchronized to the satellite clock in a benign environment, after which the user turns off his equipment (to conserve power) except for the clock. At a later time he turns on his equipment in a hostile (jamming) environment and directly reacquires the P-signal.

9.1.4.2 Results. Direct acquisition of the P-signal without the aid of the C/A-signal is possible. Reasonable reacquisition times (less than 300 seconds) are attainable provided the user has an accurate knowledge of the phase and frequency of his clock relative to the satellite clock, and a good estimate of the satellite-to-user-range and range-rate. To do this, it is necessary for the user to synchronize his clock to GPS at some time prior to operational use. A 3-hour interval appears to be a maximum for the time between synchronization and P-signal reacquisition.

9.1.5 Ionospheric Analysis

9.1.5.1 Scope. Techniques possibly applicable to the GPS for correcting the ionospheric group delay error of L-band signals are analyzed. Two basic techniques are discussed at length: (a) prediction, based upon a time/space mathematical model, updated periodically with data gathered by GPS monitor stations, (b) direct measurement, using two L-band carrier frequencies. Also included are (a) an error analysis of the two-frequency technique, (b) final results of analysis of PN pulse distortion produced by the ionosphere, (c) derivation of the optimum division of rf power between L_1 and L_2 signals.

9.1.5.2 Results. The analysis concludes that:

a. The two-frequency technique is mandatory for highest-precision users.

b. Use of two frequencies will meet GPS high-precision requirements.

c. A sufficiently accurate prediction model has not yet been developed, even for limited geographical coverage. Experimental evaluation of prediction models of varying complexity is recommended as a Phase I activity.

d. Pulse distortion is negligible for navigation purposes.

e. The optimum L_1 power level is about 1.9 dB above the L_2 power level, at the receiver.

9.1.6 Relativity Analysis

9.1.6.1 Scope. Several possible special and general-relativity effects in the GPS are analyzed. Special emphasis is given to the apparent difference in running rates of clocks in 12 hour orbit satellites and clocks at various ground stations around the earth's surface. The effects of solar and lunar relativity perturbations are analyzed.

9.1.6.2 Results. It was concluded from the analysis that:

a. The only significant relativity effect in the GPS is the apparent difference in clock rates, and this effect is rather small.

b. Nonrelativistic doppler shift and satellite equations of motion are appropriate.

c. A clock in 12 hour orbit appears to run about 450 parts in 10^{12} faster than a clock at earth's surface. This rate difference is not quite constant, but varies about ± 18 parts in 10^{12}, due to solar effects.

d. The lunar perturbation is negligible, as are planetary effects.

e. The relativity clock shift is accurately predictable once GPS satellite orbits have been computed.

f. The relativity clock shift may be directly included as a part of the overall satellite clock offset, rate, and phase prediction model.

9.1.7 Error Budget and Analysis

9.1.7.1 Scope. This study determines the overall User Equivalent Range Error (UERE) for the complete GPS system. An error budget is produced which identifies the contributions by the Control Segment (via the ephemeris and clock informations transmitted to the user), ionospheric, troposphere, multipath, user receiver noise and quantization effects, and the satellite clock. The one sigma ranging error is calculated for two frequency correction P-signal receivers and fixed ionospheric correction C-signal receivers.

9.1.7.2 Results. The following table shows the UERE associated with the users absolute position when measurement is made two-hours after satellite clock update. Also shown are relative position UEREs for two identical simultaneous users.

Type Receiver	Absolute Position		Relative Position	
	UERE (ft)	Dominant Error Sources	UERE (ft)	Dominant Error Sources
P-signal - 2 Frequency	14	Satellite Clock and Ephemeris	4	Multipath Receiver Noise
P-signal - Fixed Ionosphere Correction	33	Ionosphere	3.5	Multipath, Receiver Noise
C-signal - Fixed Ionosphere Correction	39	Ionosphere	30	Multipath

The accuracy of the ephemeris data is sensitive to Monitor Station location errors. As this spherical uncertainty is reduced from the assumed 10 feet, the ephemeris contribution to UERE will asymptotically approach 5 feet.

9.1.8 Security Analysis

9.1.8.1 Scope. This analysis discusses techniques of achieving the ultimate security goals of the GPS which are to provide a navigation capability to the user in the presence of jamming and spoofing, and to discourage use of the high accuracy P-signal by an unauthorized user.

9.1.8.2 Results. The technique which meets these goals is to use encryption of the P-signal since this prevents unauthorized users both from receiving and using the signal himself, and from transmitting a replica of the signal in order to jam or spoof authorized users. It has been decided to limit the security objectives for Phase I to demonstrating the feasibility of transmitting and receiving a crypto-keyed P-signal.

9.2 USER SEGMENT TRADE STUDIES AND ANALYSES (Reference Part II, Volume B)

Part II, Volume B of the Final Report contains the analyses and results of the User Segment trade studies. These studies are assembled into four main groups, as follows:

a. Data message design
b. Ionospheric correction techniques
c. Equipment group design
d. Receiver design

9.2.1 Data Message Design

The data message design trade study takes into account the selection of the data rates for both the C and P data messages, the methods of transmitting the accurate ephemeris data, and the reference data, which contain the less accurate orbital elements, the C-to-P hand-over words, the frame sync patterns, including the errors allowed the receiver's recognizer circuit, the parity schemes, and the overall relationship between the C and P data messages.

9.2.2 User Ionospheric Correction Techniques

The studies of the ionospheric correction techniques are, in this trade study, limited to their impact on the user equipment. Specifically, the two-frequency technique is analyzed and compared with the methods which use single frequency measurements with a correction algorithm. The coefficients of this algorithm may be generated by the user himself, or by the Control Segment, in which case they are transmitted to all users over the L-band data link.

9.2.3 Equipment Group Design

Equipment group trade studies address the selection of the kind of GPS receiver, and the addition of inertial sensors to the group. The receivers can be either continuous or sequential trackers, operating on either the C-signal alone or on both the C and P signals, and may have a second frequency capability for ionospheric corrections. These trade studies make use of navigation accuracy analyses using computer simulations.

9.2.4 Receiver Design

The receiver trade studies discuss the functional requirements which resulted from the Definition Study. These requirements for design include overall system requirements, cost goals, built-in test equipment requirements, and packaging and manufacturing considerations.

9.3 CONTROL SEGMENT TRADE STUDIES AND ANALYSES (Reference Part II, Volume C)

Part II, Volume C contains those trade studies and analyses that had a major influence on the selection of the Control Segment configuration and the development of the segment specifications.

9.3.1 Control Segment Configuration Study

9.3.1.1 Scope. The purpose of this trade study was to determine the optimum Phase I Control Segment configuration for the GPS. The Control Segment comprises the satellite tracking, communication, system calibration, ephemeris determination, navigation data processing, CS control and monitoring, data upload, and status monitoring functions. The study considers the impact of Phase II and III requirements upon the alternative configurations. The evaluation criteria are: Phase I, II, and III recurring and nonrecurring costs, legacy, system accuracy, functional time-line conflicts, vulnerability, implementation schedule, and cost risks and potential utilization conflicts for shared equipment. Existing facilities considered for use by GPS were: SCF, NAG, SAC and NWL.

It has been assumed that the reference ephemeris would be generated weekly at the NWL facility in Dahlgren, Virginia. Upload and verification techniques were also evaluated.

9.3.1.2 Results. The study concluded that the baseline system described in detail in the System Analysis Report, Part I, Volume C, was optimum from the standpoint of Phase I cost. Although not included in the baseline, the use of the S-band downlink for upload verification provides better security and minimizes the SCF support requirements. The use of SCF facilities minimizes the Phase I implementation costs; however, this approach has higher total costs through Phase III than a dedicated equipment approach implemented after Phase I.

9.3.2 Orbit Configuration Study

9.3.2.1 Scope. The objective of this trade study was to determine the optimum orbit for each of the GPS phases. Factors considered during Phase I are GDOP and time-in-view at White Sands Missile Range (WSMR), satellite elevation angle, station-keeping requirements, and upload time provided. Factors considered during Phase IIA are GDOP and continuous time in view of four satellites at WSMR. Phase IIB considered the requirement to provide two satellites coverage worldwide. Phase III requires four useable satellites on a global basis. Over 100 possible orbit configurations were computer analyzed.

9.3.2.2 Results. The optimum Phase I orbit configuration was the SIGMA configuration. The Phase IIA choice was a subset of the optimum Phase III orbit configuration, the OMEGA-2A configuration. The Phase IIB choice was a subset of the 3 x 9 GAMMA configuration, studied earlier: the 3 x 3 subset designated GAMMA-2B. The Phase III selection was the 3 x 8 configuration, IMEGA.

9.3.3 Telecommunications System Cost Analysis

9.3.3.1 Scope. The annual costs of various telecommunications facilities are examined in this study. The analysis was directed toward potential Master Control Station and Monitor Station sites. Included in the analysis are costs for dedicated lines, dial-up lines, WATS lines, and shared NAG lines. The analysis is composed of two areas. The first area compares the various telecommunication links with respect to the different potential line types. Within this area, the shared NAG lines approach is examined in further detail. The second area examines the dial-up annual costs as a function of several store-and-forward intervals of time.

9.3.3.2 Results. The recurring telecommunications costs of the systems are dependent upon the frequency with which the Monitor Station (MS) data is forwarded to the MCS. If it is forwarded once per hour (baseline approach), dial-up line costs are only slightly less costly than dedicated lines. There is little advantage to data compression at the MS during Phase I. Telecommunication costs during Phase III can be relatively high. Data compression at the site is the most effective technique for reducing these costs, and is particularly effective if coupled with a reduction in the frequency of data forwarded to the MCS.

9.3.4 Master Control Station/Satellite Test Center Communications Analysis

9.3.4.1 Scope. The trade study evaluates four alternative methods of communications between the Master Control Station and the Satellite Test Center. No attempt is made by this report to recommend any individual option, but rather to discuss each alternative with emphasis on the following points: (a) communication line security (b) bird-buffer security, (c) personnel requirements, (d) STC space, (e) new equipment required, (f) existing equipment, (g) software, (h) cost.

9.3.4.2 Results. The use of a dedicated bird buffer (BB) at the STC to handle all GPS coordination is the least expensive, but creates serious scheduling and reliability problems. Adding communications switching equipment that allows the MCS to be connected to any BB relieves this problem, but may present a security problem. The installation of a new dedicated tape transport and miniprocessor is the highest cost approach, but presents the least risk.

9.3.5 MCS Data Processing Configuration Study

9.3.5.1 Scope. This trade addresses the general computer configuration to be employed at the MCS for Phase I of GPS. Specifically, the issue being considered is whether it uses a single integrated processor or separate processors for on-line control functions and navigation support functions.

9.3.5.2 Results. Addition of a realtime processor to the MCS to handle communications and status monitoring functions improves overall MCS availability by about 0.05%. Availability for communications and status monitoring support is improved by about 0.1%. However, the increase in hardware cost and software cost outweighs this small increase in availability. Even without the realtime processor, MCS availability is expected to far exceed Phase I goals. The recommended configuration for Phase I uses a single processor for all MCS functions.

9.3.6 Monitor Station Data Processing Configuration Study

9.3.6.1 Scope. This trade study addresses the general processor configuration for GPS Monitor Stations (MS). Specifically, it considers whether and how to employ the user equipment processor in the MS configuration.

9.3.6.2 Results. Sharing the user equipment processor for MS functions and user equipment functions involves relatively high cost, high risk, and low legacy. Using a separate processor, eliminates the high risk factor, and increases legacy. However, it also increases cost. Removing the user equipment processor provides relatively low costs, lower risk, and higher legacy.

The recommended configuration employs a Monitor Station processor, selected to be functionally/electrically compatible with the user processor, but also to satisfy MS requirements. This processor is compatible with the user equipment receiver. The processor is removed from the user equipment group, and the required subset of its functions implemented on the monitor processor.

9.3.7 Reference Ephemeris Data Processing Cost Analysis

9.3.7.1 Scope. This report analyzes the cost impact of reference ephemeris generation, particularly the cost and flexibility differences between sizing the MCS processor to generate the reference ephemerides and sizing the MCS processor to utilize an outside service (such as NWL) for the reference ephemeris production.

9.3.7.2 Results. The conclusions reached in this analysis show that the lease/buy decision is quite sensitive to the safety margins applied to Phase I instruction requirements. If the assumed margin of 75% were reduced to 0%, the conclusion could be reversed. The results are also sensitive to the time required to run the program. More refined estimates shall be generated before committments are made.

9.3.8 Ephemeris Determination Analysis

9.3.8.1 Scope. The ephemeris and clock model determination software is required to translate pseudoranging data into estimates of satellite position and clock state in such a manner that system design goals related to ephemeris and clock contributions to user geoposition accuracy can be met. Considerations, related to legacy, cost, technical risk, and the utilization of Government resources are also of prime importance. The basic concepts considered applicable in being able to meet those design goals were:

a. Simultaneous multisatellite processing concept and
b. A distributed processing concept.

In addition, several different methods of implementation of those concepts were considered, related to the applicability of existing software, filter techniques, and data management.

9.3.8.2 Results. Through simulations and other related analysis, it has been shown that the distributed processing concept produces user navigation accuracies that are competitive with those of the simultaneous multisatellite processing concept, yet, have unique computational advantages, particularly, on the GPS problem. In addition, lower implementation costs with a minimum of technical risks are achieved. Recursive processing methods were chosen on the basis of their increased flexibility in being able to incorporate clock state noise.

9.3.9 Ephemeris and Clock Processing Simulations

9.3.9.1 Scope. The simulations discussed in this report were conducted to determine the ephemeris contribution to the User Equivalent Range Error (UERE) and to ascertain its sensitivity to various parameters which could affect the system accuracy. The baseline system configuration was employed and orbit and Control Segment uncertainties assumed. The ephemeris representation technique was also analyzed to determine the optimum approach in terms of user processing complexity, message length, accuracy, and fit interval.

9.3.9.2 Results. A distributed processing concept utilizing range data from a station whose clock is designated as "master", and range-difference data from all other stations to determine satellite ephemerides and satellite clock-state parameters has been extensively simulated using the TRACE 66 program. Where the designated station is the more northerly of the several tracking stations considered (ie, Alaska), the contribution of ephemeris and clock-state determination errors to UERE is 9 feet, two hours after update. The largest single contributor to this error is the introduction of station location errors of 10 feet in each coordinate, and these errors are expected to be reduced significantly as the system matures into later phases. While TRACE-66 does not have the capability to simulate the second step in the baseline distributed processing concept, the interrelationships of all ground clocks with satellite clocks will give a derived accuracy no worse, and may be significantly better than the results reported here.

Moving the location of the fourth MS from northeastern USA to Guam did not reduce UERE over WSMR, although global performance remote from CONUS was improved, as expected. Eliminating the fourth MS altogether increased the UERE at WSMR to 11.1 feet. By designating VAFB as the ranging station with "master" clock status (in a software sense), the UERE contribution due to ephemeris and clock-state determination, at WSMR two hours after update, was predictably reduced to less than five feet, although global performance was degraded somewhat by poorer distribution of the ranging data processed.

9.3.10 Signal Power Monitoring Techniques

9.3.10.1 Scope. The report describes the use of star flux and a man-made test signal, both having known intensity, for determination of received power.

9.3.10.2 Results. Receiver output powers or the AGC voltages developed by receiving the signal of unknown power are compared to the corresponding parameter signal, and the power level of the unknown can then be determined. The report emphasizes that the actual satellite power can merely be inferred from a measurement of received power at the ground station because of unpredictable variable uncertainties in the power measurement.

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