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The NAVSTAR Global Positioning System (GPS) is an all-weather, space-based navigation system under development by the Department of Defense (DoD) to satisfy the requirement for the military forces to accurately determine their position, velocity, and time in a common reference system, anywhere on or near the Earth on a continuous basis. The Air Force Systems Command's Space Division acts as the executive agent for the DoD in managing the GPS program. The joint program office, which is located at Space Division headquarters in Los Angeles, has representatives from the Army, Navy, Marine Corps, Defense Mapping Agency, Department of Transportation, NATO, and Australia. The system is being developed in three phases: Phase I, concept validation; Phase II, full-scale engineering and development; and Phase III, production. Currently, the GPS program is in the full-scale engineering and development phase. During this phase a constellation of five to six satellites is being maintained to support testing so that the operational effectiveness of the GPS concept for both military and civilian users will be verified. The buildup of the operational constellation will

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Navstar Global Positioning System Overview

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ABSTRACT

The Navstar Global Positioning System (GPS) is an all-weather, space-based navigation system under development by the Department of Defense (DoD) to satisfy the requirement for the military forces to accurately determine their position, velocity, and time in a common reference system, anywhere on or near the Earth on a continuous basis. The Air Force Systems Command's Space Division acts as the executive agent for the DoD in managing the GPS program. The joint program office, which is located at Space Division headquarters in Los Angeles, has representatives from the Army, Navy, Marine Corps, Defense Mapping Agency, Department of Transportation, NATO, and Australia. The system is being developed in three phases: Phase I, concept validation; Phase II, full-scale engineering and development; and Phase III, production. Currently, the GPS program is in the full-scale engineering and development phase. During this phase, a constellation of five to six satellites is being maintained to support testing so that the operational effectiveness of the GPS concept for both military and civilian users will be verified. The buildup of the operational constellation will begin in late 1986 and will take approximately two years to complete. Eventhough the system is not fully operational, several potential civilian applications exist.

INTRODUCTION

The Navstar Global Positioning System (GPS) is a space-based, radio positioning, navigation, and time-transfer system that will become fully operational in the late 1980s. GPS has the potential for providing highly accurate three-dimensional position and velocity information along with Coordinated Universal Time (UTC) to an unlimited number of suitably equipped users under all weather conditions, continuously, anywhere on or near the surface of the Earth.

GPS is being developed by the U.S. Government and is in the full-scale engineering development phase. The system is managed by the U.S. Air Force Space Division as a joint program involving all the services, plus the Defense Mapping Agency, the Department of Transportation, NATO, and Australia. In this phase of the program the production baseline for the operational satellite will be established, the operational control segment will be completed, and the final determination on the configuration of user equipment to accommodate all classes of system users will be accomplished.

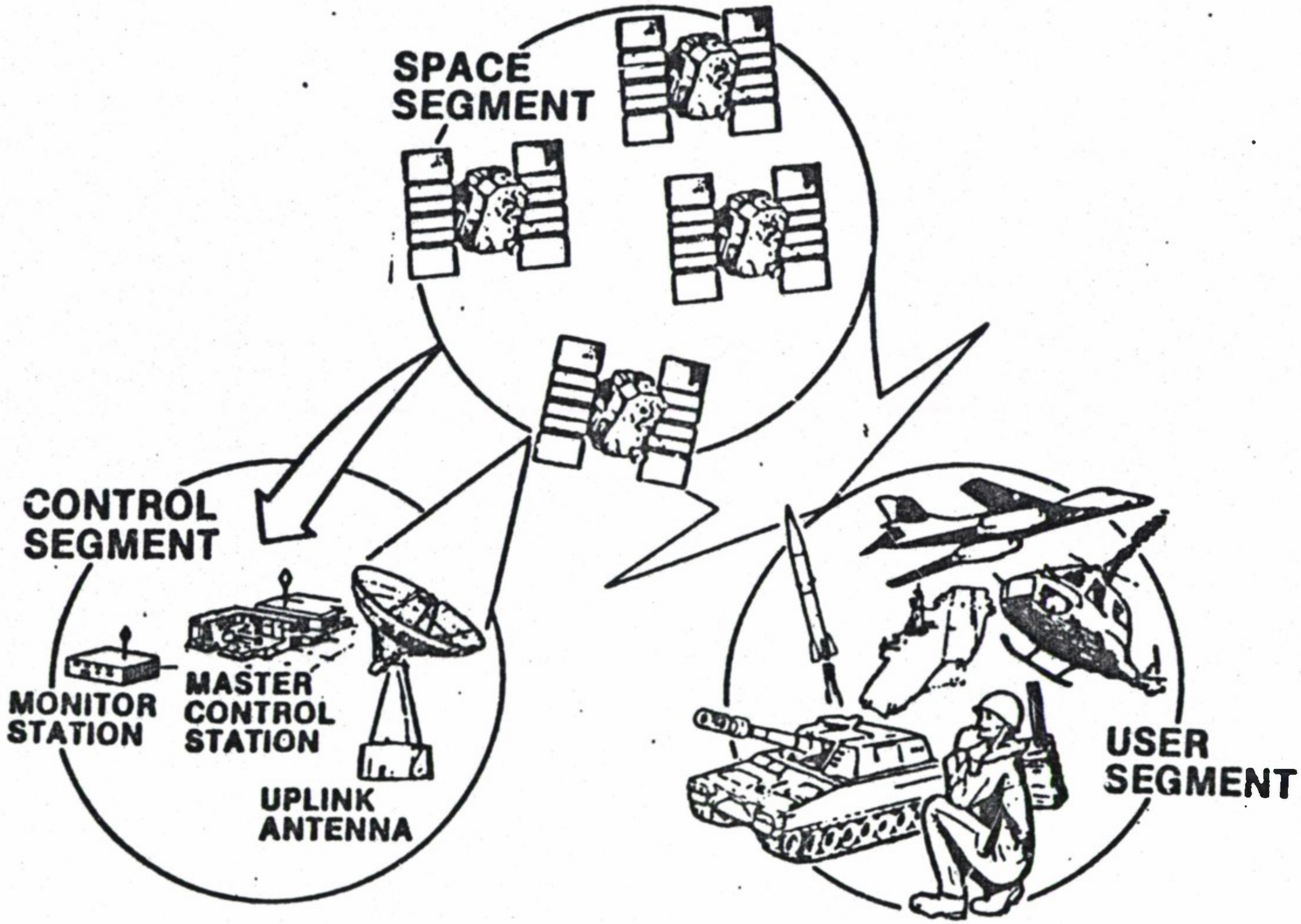
SYSTEM DESCRIPTION

The Navstar GPS navigation and time-transfer system operates on two L-band frequencies, L_1 (1575.4 MHz) and L_2 (1227.6 MHz). The system consists of three major segments: a space segment, satellites that transmit radio signals; a control segment, ground-based equipment to monitor the satellites and update their signals; and a user segment, equipment which passively receives and converts satellite signals into positioning and navigation information (see Fig. 1

When fully operational at the end of 1988, the space segment will contain 18 satellites in six orbital planes, each having three

21?

Figure 1. **GPS SYSTEM OPERATION**



≈ 26 787,6 km?

satellites. The satellites will operate in circular 20,200-kilometer orbits at an inclination of 55 degrees with 12-hour periods. Precise spacing of the satellites in orbit will be arranged such that a minimum of four satellites will be in view to a user at any time on a worldwide basis. Each satellite will transmit an L_1 and an L_2 signal. Superimposed on these signals will be navigation and system data, including a predicted satellite ephemeris, atmospheric propagation correction data, satellite clock error information, and satellite health data.

The control segment includes a master control station (MCS) and a number of monitor stations and ground antennas located throughout the world. It consists of equipment and facilities required for satellite monitoring, telemetry, tracking, commanding, and control, uploading, and navigation message generation. The monitor stations passively track the satellites, accumulate ranging data from their signals, and relay them to the MCS where they are processed to determine satellite position and signal data accuracy. The MCS updates the navigation message of each satellite and relays this information to the ground antennas which transmit it to the satellites. The ground antennas are also used for transmitting and receiving satellite control information.

The user segment includes low, medium, and high dynamic receivers designed to different requirements of various users. The user equipment is designed to receive and process signals from four orbiting satellites either simultaneously or sequentially. The processor in the receiver then converts these signals to three-dimensional navigation information in World Geodetic System coordinates. Positioning data are presented on a display unit in any other coordinate system desired by the user. In addition precise time information is available for use in the host vehicle.

SYSTEM CAPABILITIES

GPS is being developed to provide multiple users with accurate continuous, worldwide, all-weather, common-grid, three-dimensional positioning and navigation information. Because of the unique capabilites of the system, it is reversing the trend of proliferation of radio navigation systems within the U.S. Department of Defense. Table 1 compares the nominal GPS user set performance characteristics with other operational navigation systems.

To obtain a navigation solution of position and time (4 unknowns), four satellites must be selected. The GPS user measures pseudo-range and pseudo-range rate by synchronizing and tracking the navigation signal from each of the four selected satellites. Pseudo-range is the true distance between the satellite and the user plus an offset due to the user's clock bias. Pseudo-range rate is the true slant range rate plus an offset due to the frequency of the user's clock. By decoding the ephemeris data and system timing information on each satellite's signal, the user's receiver/processor can convert the pseudo range and pseudo-range rate to user three-dimensional position and velocity. Four measurements are necessary to solve for the three unknown components of position (or velocity) and the unknown user time bias (or frequency).

The navigation accuracy that can be achieved by any user depends primarily on the variability of the errors in making pseudo-range measurements and the instantaneous geometry of the satellites as seen from the user's location on Earth (Payne, 1982). Additional information on the navigation solution and navigation technique is given in Reference 3 (Milliken and Zoller, 1980).

Table 1. **NAVIGATION SYSTEM COMPARISON**

System	Position Accuracy (m)	Velocity Accuracy (m/sec)	Range of Operation	Comments
GPS	15 (SEP) 3-D	0.1 (RMS per axis)	Worldwide	Operational worldwide with 24-hour all-weather coverage.
Loran-C (Note 1)	180 (CEP)	No velocity data	U.S. Coast, Continental U.S., Selected Overseas areas	Operational with localized coverage. Limited by skywave interference.
Omega (Note 1)	2,200 (CEP)	No velocity data	Near global (90% coverage)	Currently operational with localized coverage. System is subject to multi-path errors.
Std INS (Note 2)	1,500 max after 1st hour (CEP)	0.8 after 2 hr (RMS per axis)	Worldwide	Operational worldwide with 24-hour all-weather coverage. Degraded performance in polar areas.
TACAN (Note 1)	400 (CEP)	No velocity data	Line of sight (present air routes)	Position accuracy is degraded mainly because of azimuth uncertainty which is typically on the order of ±1.0 degree.
Transit (Note 3)	200 (CEP)	No velocity data	Worldwide	The interval between position fixes is about 90 minutes. For use in slow moving vehicles

NOTES:
1. Federal Radio Navigation Plan, July 1980
2. ENAC-77-IV, Characteristic for a Moderate Accuracy Inertial Navigation System, August 1979
3. Journal of the Institute of Navigation, Volume 27, No. 2, Summer 1979

GPS NAVSTAR

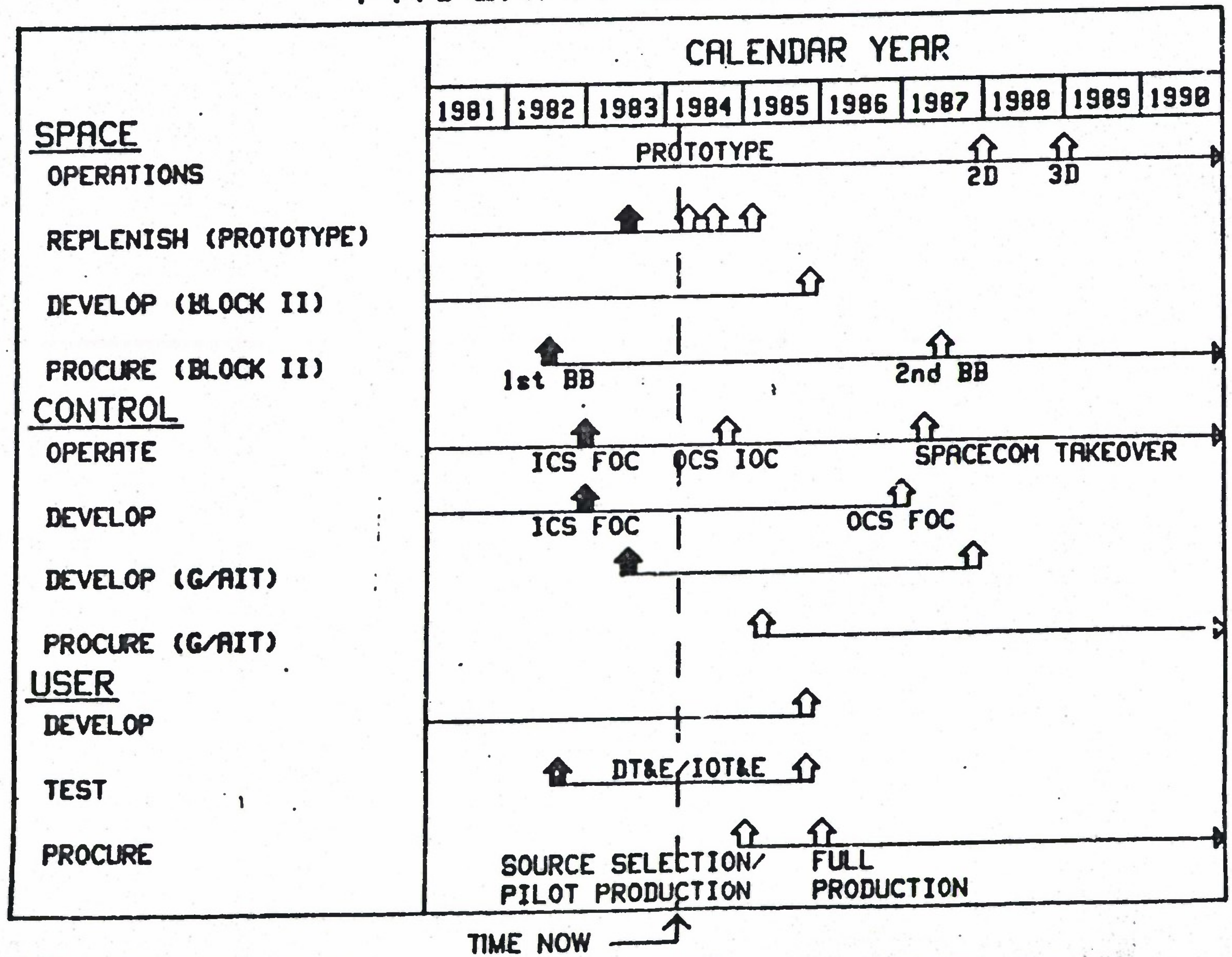
SYSTEM STATUS

In December 1973 the Defense Systems Acquisition Review Council (DSARC) authorized a step-wize, design-to-cost development and test program which would lead, in successive phases, to an operational GPS. The system concept resulted from the integration of the best features of previous navigation satellite concepts being pursued independently by the U.S. Navy and the U.S. Air Force.

The Navstar program is being developed in three phases: Phase I, concept validation; Phase II, full-scale engineering and development; and Phase III, production. The details of the schedule are shown in Figure 2. During Phase I prototype satellites were developed, a control segment was established, and advanced engineering models of user equipment were tested. Currently, the program is in Phase II. The main tasks of this phase include developing the prototype operational satellite, the operational control system, the prototype user equipment, and the completion of the developmental test and evaluation/initial operational test and evaluation (DT&E/IOT&E).

The current GPS constellation consists of a limited number of developmental satellites configured in two planes inclined at 63 degrees with respect to the equator. There are four good satellites (Navstars 3,4,6,8) plus one satellite (Navstar 1) which is generally not being used for navigation because it is operating with a quartz crystal clock. The current constellation is shown in Figure 3. The next satellite (Navstar 9) is scheduled to be launched in April 1984. The plan is to maintain a minimum constellation of five satellites for the completion of the test and evaluation period for the system. It is currently projected that the last two Block I test satellites will be launched in mid-1984 and late-1984 or in 1985 to maintain the test

Figure 2. PROGRAM SCHEDULE



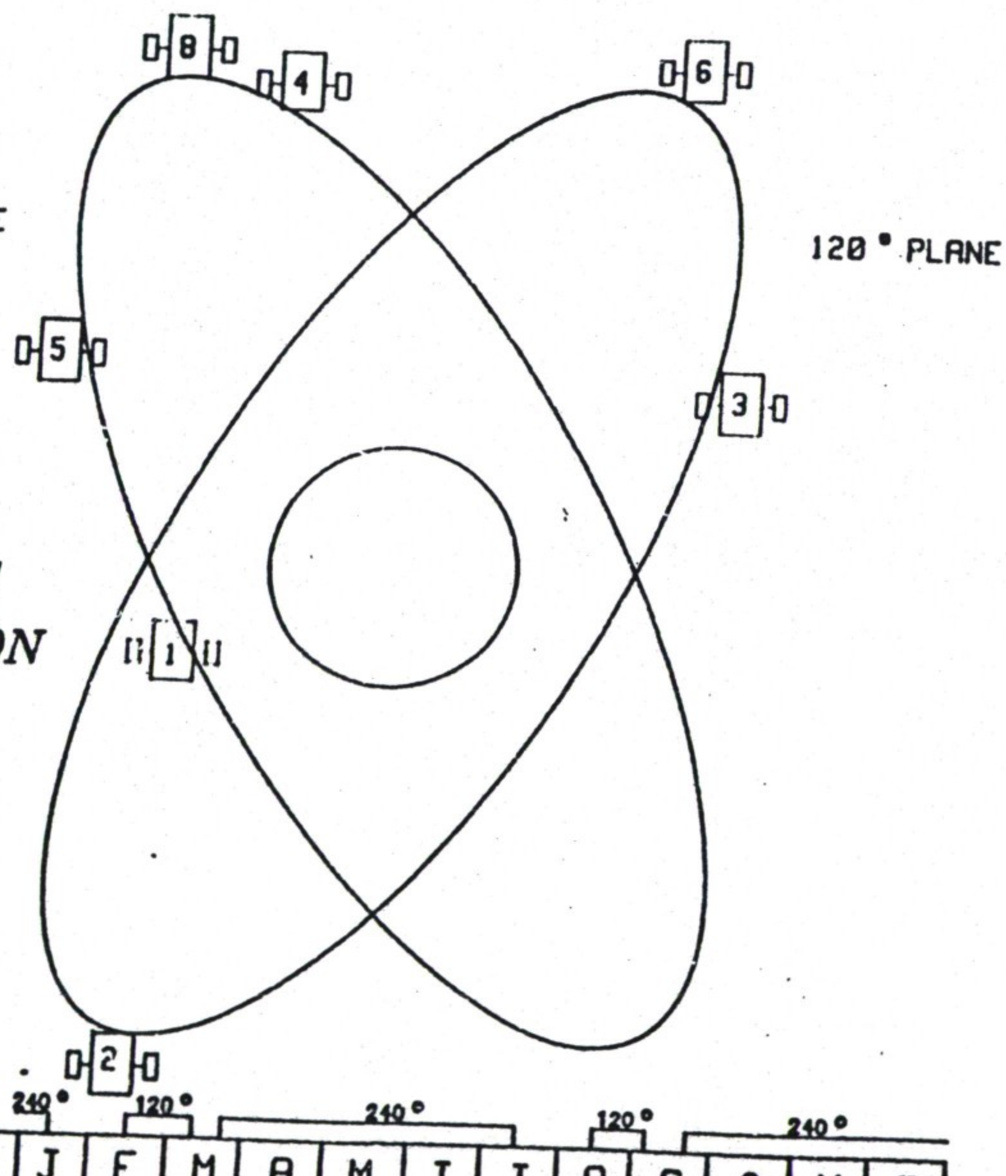


Figure 3.

NAVSTAR GPS CONSTELLATION

configuration.

The operational constellation is a 6-plane, uniform 18-satellite configuration plus three active spares. The spares are necessary to guarantee very high system availability for the 18-satellite constellation. Figure 4 illustrates the operational constellation. The planes of the constellation are 60 degrees apart in longitude with each plane containing three satellites separated by 120 degrees. The phasing from plane to plane is 40 degrees so that a satellite in one plane has a satellite 40 degrees ahead (north) of it in the adjacent plane to the east. According to the current plan, the Block II (operational) satellites will be launched at a rate of eight or nine per year beginning in October 1986. Two-dimensional coverage should be available by the latter part of 1987 and three-dimensional coverage, barring failures, should be available by the end of 1988.

The Phase I control segment consisted of a master control station and antenna located at Vandenberg AFB, CA, and monitor stations located at Vandenberg AFB, Alaska, Guam, and Hawaii. The initial control system which will fill the control segment gap between Phase I and the final operational control system became fully operational in January 1983.

The final operational control system (OCS) will consist of a master control station, three ground antennas, and five monitor stations. The master control station will be located at the Consolidated Space Operations Center (CSOC), Colorado Springs, CO. One ground antenna and monitor station will be located at Kwajalein, Diego Garcia, and Ascension. Two additional monitor stations will be located at the CSOC and in Hawaii. The initial operational capability for the OCS is scheduled for October 1984. Details of the operational control system are shown in Figure 5.

Figure 4. The Navstar Operational Constellation

18 SATELLITES PLUS 3 ACTIVE SPARES

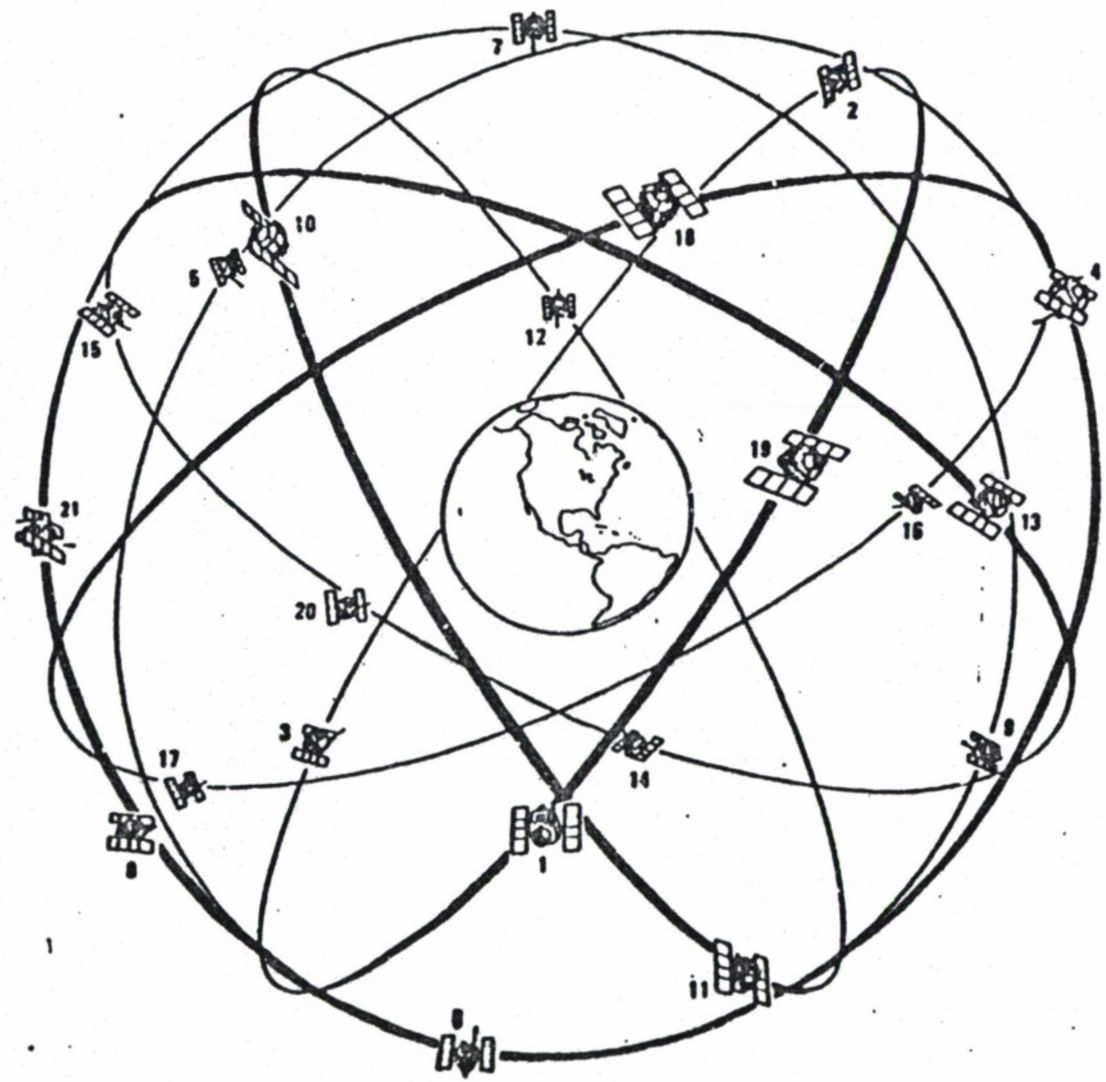
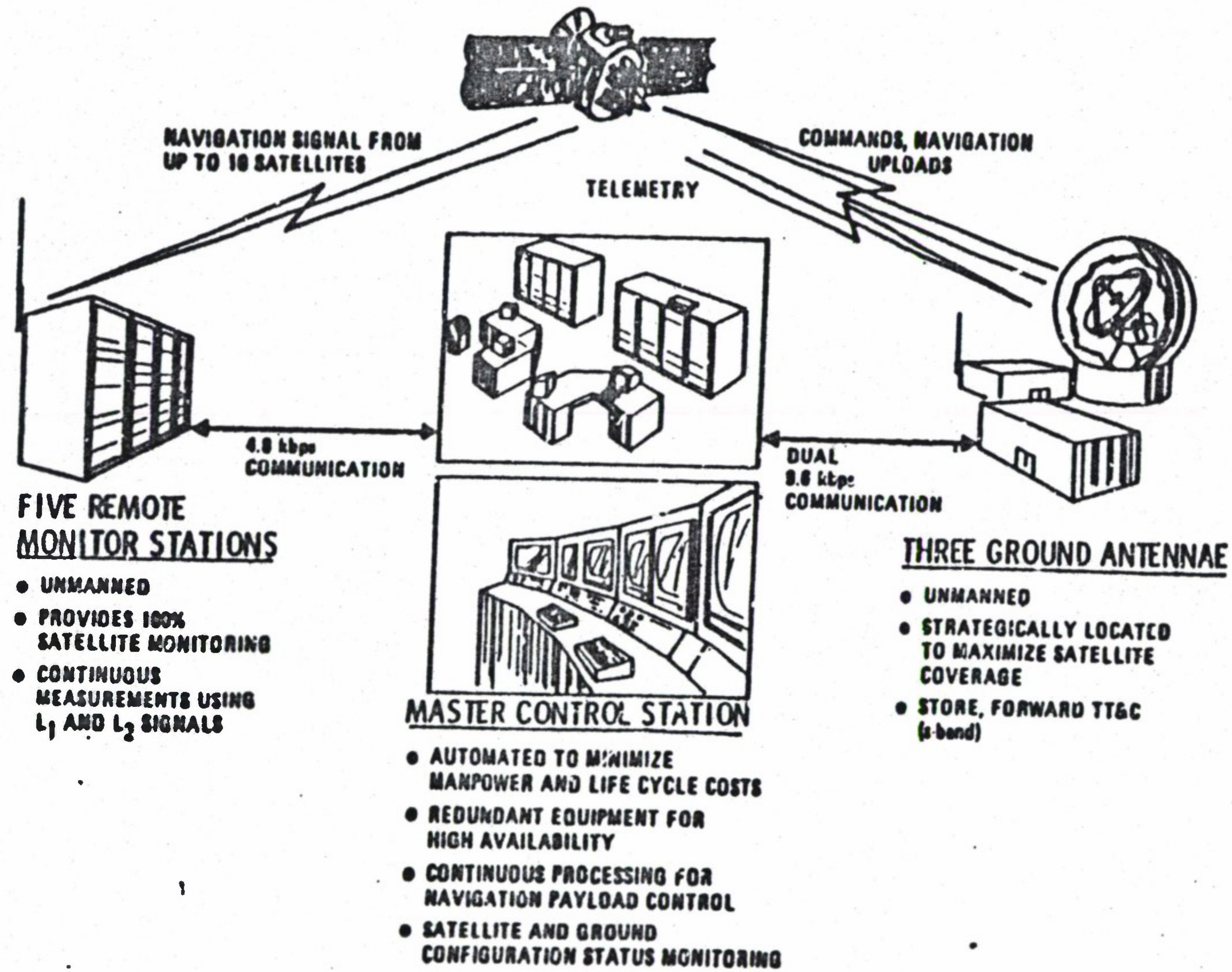


Figure 5. GPS Operational Control System



In Phase I engineering development models of user equipment sets were built and tested. The overall test objectives were to validate the GPS concept, to identify preferred set requirements, to define and bound system costs, and to demonstrate GPS military and commercial value.

Currently, two U.S. contractors are developing a family of user equipment sets for demonstration and testing in the current phase of the GPS program. In order to enhance reliability and maintainability objectives of the user equipment, three main design features have been emphasized: the development and procurement of a small number of user equipment classes, the commonality/interchangeability of units across user classes, and the utilization of a higher order language. These design features prevent the proliferation of a large number of peculiar user sets, afford the advantage of large-lot buys and common spares, and permit more efficient programming and reprogramming of requirement changes. The primary objective is to design and build a family of GPS user sets at a minimum life cycle cost consistent with performance and functional capabilities. Testing continues on the host vehicles to collect data to support the source selection decision in January 1985 for the Phase III user equipment production contract. Since 1977 more than 800 test missions have been accomplished. In virtually all of these tests the Navstar GPS has exceeded specifications.

SYSTEM MANAGEMENT

The policies for use and operation of all radio navigation systems controlled by the U.S. Department of Defense (DoD) are reflected in the Federal Navigation Plan. The plan is a joint annual publication by the Departments of Defense and Transportation.

The operational satellites will provide two unique and distinct navigation services, the Precise Positioning Service (PPS) and the Standard Positioning Service (SPS). The PPS will be available to military users and access will be controlled by the use of cryptographic devices. The PPS is the service of highest accuracy which provides a positioning accuracy of 15 meters SEP, a velocity accuracy of 0.1 meter/sec (1 sigma), and a timing accuracy of better than 35 nanosec (1 sigma). The SPS will be made available to the worldwide community of civil users and access will be controlled by a user charge device. Current policy (U.S.DoD, 1983) sets the accuracy of SPS at 100 meters with a 95% level of confidence.

The United States Congress has directed that civil and other government users will pay a fee for use of both the SPS and the PPS. These charges are currently stated at an annual fee of $3700 per user set for the PPS and $370 per user set for the SPS. Recent resolutions submitted to Congress in the wake of the Korean Airline disaster show that there is an effort to make the GPS SPS available to civil users and to remove GPS user charges. However, it would be premature to discount user charges before a congressional decison is made.

The DoD policy is for Navstar GPS to become the primary DoD radionavigation system. As GPS becomes operational, DoD will terminate operations with other radionavigation systems. Table 2 gives the planned dates for starting the phase outs of systems and the dates when the phase outs will be complete.

Table 2. DOD Plans for Existing Navigation Systems

SYSTEM	PHASE-OUT STARTS	PHASE-OUT COMPLETE
TRANSIT	1987	1992
LORAN	1987	1993
VOR/DME/VORTAC	1987	1997
TACAN	1988	1997*
OMEGA	1987	1992*

*Possible limited Navy use beyond these dates

APPLICATIONS

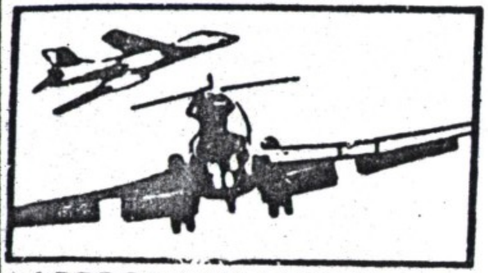
Eventhough Navstar GPS is not fully operational, several potential civilian applications exist. GPS will provide a broad spectrum of civilian users with an accurate position, velocity, and time determination capability at a reasonable cost. Ultimately, it will replace many existing navigation systems.

Many potential applications are shown in Figure 6. Civilian users of airborne, land-based, and maritime vehicles will benefit from GPS for optimal course navigation, which will in turn reduce fuel costs and transportation time. Search-and-rescue techniques can be enhanced because of the precision position identification capability of GPS. The mineral exploration and geophysical survey communities will be able to accurately locate potential petroleum bearing areas, ore bodies, and active fault belts in a shorter period of time. Other GPS applications to Mapping, Charting, and Geodesy have been given elsewhere (Senus and Hill, 1981). The GPS common grid feature will enhance many land-vehicle operations. Airborne collision avoidance systems and maritime hazard systems are also potential uses of the system. GPS time transfer applications include scientific, intra-system synchronization and inter-system synchronization uses (Van Dierendonck and Melton, 1983).

In addition to the potential applications given above, GPS has demonstrated performance in space applications and baseline determinations. Continuous 10 to 15-meter positioning in space without the use of ground tracking systems has been demonstrated on Landsat-4 using a GPS receiver (Birmingham et al., 1983). Relative positions have been demonstrated to be accurate to within several centimeters over baselines varying from hundreds of meters to tens of kilometers (Counselman et al., 1982). The potential applications for GPS are

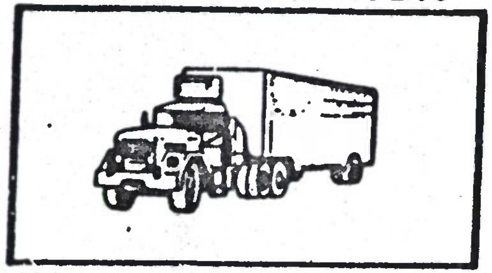
Figure 6. **CIVIL APPLICATIONS**

AIRBORNE



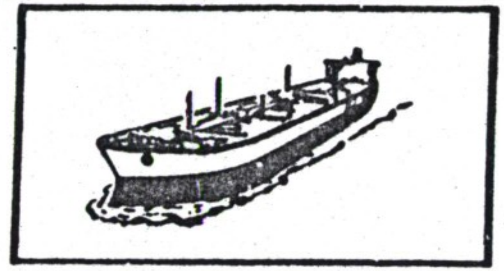
- APPROACH/LANDING
- OCEANIC ENROUTE
- DOMESTIC ENROUTE
- TERMINAL
- REMOTE AREAS
- HELICOPTER OPERATIONS

LAND NAVIGATION



- VEHICLE MONITORING
- SCHEDULE IMPROVEMENT
- MINIMAL ROUTING
- LAW ENFORCEMENT

MARITIME NAVIGATION

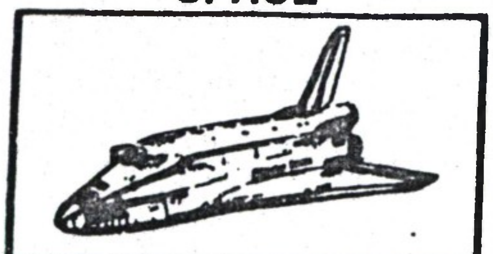


- OCEANIC
- COASTAL
- HARBOR/APPROACH
- INLAND WATERWAYS

STATIC POSITIONING/TIMING

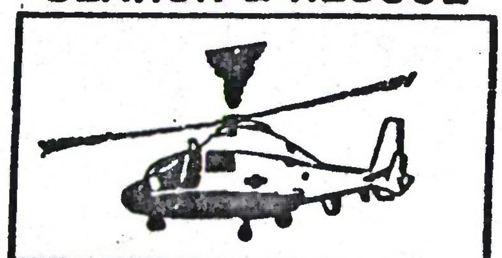
OFFSHORE RESOURCE EXPLORATION
HYDROGRAPHIC SURVEYING
AIDS-TO-NAVIGATION
TIME TRANSFER
GEOPHYSICAL SURVEYING

SPACE



- LAUNCH
- IN FLIGHT/ORBIT
- REENTRY/LANDING

SEARCH & RESCUE



- POSITION REPORTING & MONITORING
- RENDEZVOUS
- REPEATABILITY OF POSITION
- COORDINATED SEARCH
- COLLISION AVOIDANCE

boundless.

CONCLUSIONS

The Navstar GPS is evolving into a highly accurate, worldwide, all-weather navigation/positioning system applicable to the needs of both the military and civilian communities. Since 1977 extensive testing has taken place which verified the established accuracy goals and the system operation under various mission-oriented conditions. There are numerous applications for which GPS can be exploited. Even though the system is not fully operational, it is being used by diverse civilian groups such as NASA for orbit determination onboard Landsat-4 and oil companies for geodetic positioning. As the system gains acceptance by the civilian community, more sophisticated uses for the system will be established.

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