NAVSTAR:

GLOBAL POSITIONING SYSTEM AN EVOLUTIONARY RESEARCH AND DEVELOPMENT PROGRAM

By: Col. B. W. Parkinson
U.S. Air Force
Space and Missile Systems Organization

ABSTRACT

The Global Positioning System has recently been renamed the NAVSTAR Global Positioning System. It was known as System 621B or Defense Navigation Satellite System, and within the Navy it was known as TIMATION. NAVSTAR represents a combination of the concepts that were known as TIMATION and those knonw as System 621B into a Joint Program. This combination was directed by Secretary Clements on 17 April 1973. A DSARC review was held on the 13th of December and a final decision was made to approve this program on the 22nd of December by Secretary Clements. NAVSTAR is a multiservice program (See Figure 1) with the Joint Program Office at SAMSO which is proceeding into its Phase I Concept Validation Program. I would like to describe the system and the Concept Validation Program with you at this time.

The current status of satellite navigation systems within DOD is described in Figure 2. The existing operational system is called TRANSIT. For a host of reasons, it does not satisfy a broad base of users (See Figure 3). Particularly, anyone with dynamics in their positioning or navigation problem. Therefore, we are motivated to move ahead to a Global Positioning System that potentially can eventually replace TRANSIT and serve a host of other users as well (See Figures 4 and 5). The initial operational capability would be achieved in about 1984. The Phase I Program incorporates the efforts of the Naval Research Laboratory, with their Navigation Technology Satellites (NTS), NTS-1 and NTS-2. The Joint Program Office will develop prototype Navigation Development Satellites (NDS) that will be described later. The basic system capability is three dimensions of position, three dimensions of velocity and very precise system time.

I'd like to now discuss that systems concept which consists of a Space Segment, a ground based Control Segment, and the User Segment (See Figure 6). The operational system would

GPS ORGANIZATION

JOINT PROGRAM MANAGER	COL B. W. PARKINSON
DEPUTY PROGRAM MANAGERS	
AIR FORCE	LTC S. W. GILBERT
AFLC	MAJ R. O. BYRNE
ARMY	LTC P. WEBER
DEFENSE MAPPING AGENCY	MR P. E. FREY
MARINE CORPS	LTC J. BARRY
NAVY	CDR W. G. RUSTON

FOR ADDITIONAL COPIES OF THIS DOCUMENT OR ADDITIONAL INFORMATION CONTACT GPS PROGRAM CONTROL (SAMSO/YEC).

SAMSO/YEC
P O BOX 92960
WORLDWAY POSTAL CENTER
LOS ANGELES CA 90009

AUTOVON 833-2737

TELEPHONE 643-2737
(AREA CODE 213)

FIG 1

DOD NAVIGATION SATELLITE SYSTEMS

OPERATIONAL GPS OBJECTIVES

- PRECISE GLOBAL NAVIGATION CAPABILITY
  - 3 DIMENSIONAL LOCATION
  - 3 DIMENSIONAL VELOCITY
  - TIME

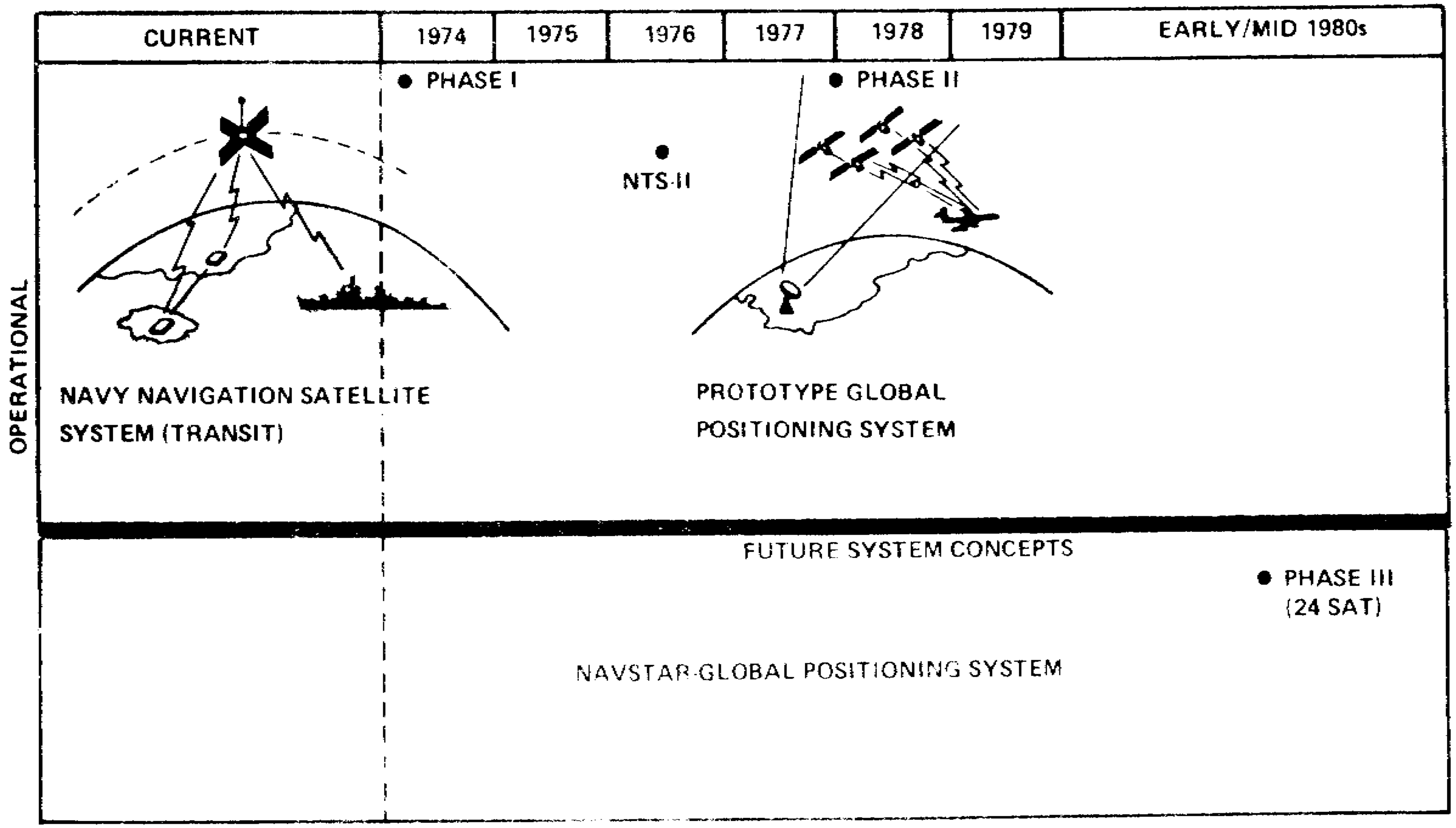


FIG 2

THE NEED FOR A UNIVERSAL NAVIGATION SYSTEM

- UNIVERSAL PERFORMANCE

  INCREASE EFFECTIVENESS & CAPABILITY

- LOWER COST

  REDUCE PROLIFERATION OF POS/NAV SYSTEM[S]

FIG 3

AIRCRAFT NAVIGATION AVIONICS

AIRCRAFT TYPE	NAVIGATION				
	TCN	LRN	ILS	DF	VOR
AIE	X		X	X	X
A7A/D		X	X	X	
B52	X	X	X	X	X
C5	X	X	X	X	X
C7A	X		X	X	X
C119	X	X	X	X	X
C123	X	X	X	X	X
C124	X	X	X	X	X
C130	X	X	X	X	X
KC135	X	X	X	X	X
C141	X	X	X	X	X
F4C/E	X			X	
F4D/RF4C	X	X		X	
F102	X		X	X	X
F104	X		X		X
F105		FEW	X	X	X
F106A/B	X		X	X	
F111				X	
OV10A				X	
NO. DIFF. TYPES	(9)	(10)	(23)	(21)	(8)

FIG 4

NAVIGATION AVIONICS COSTS

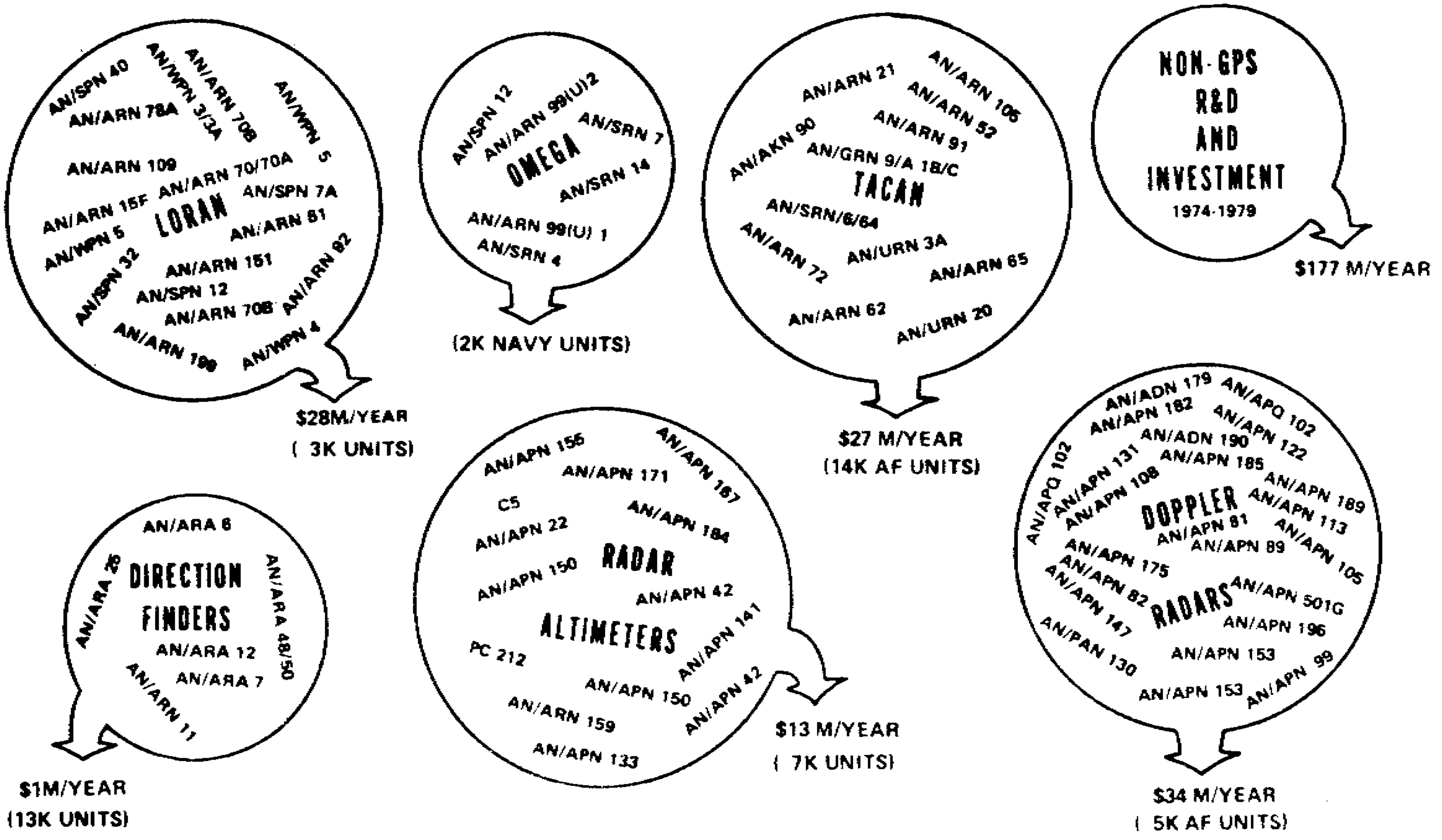


FIG 5

GPS CONCEPT

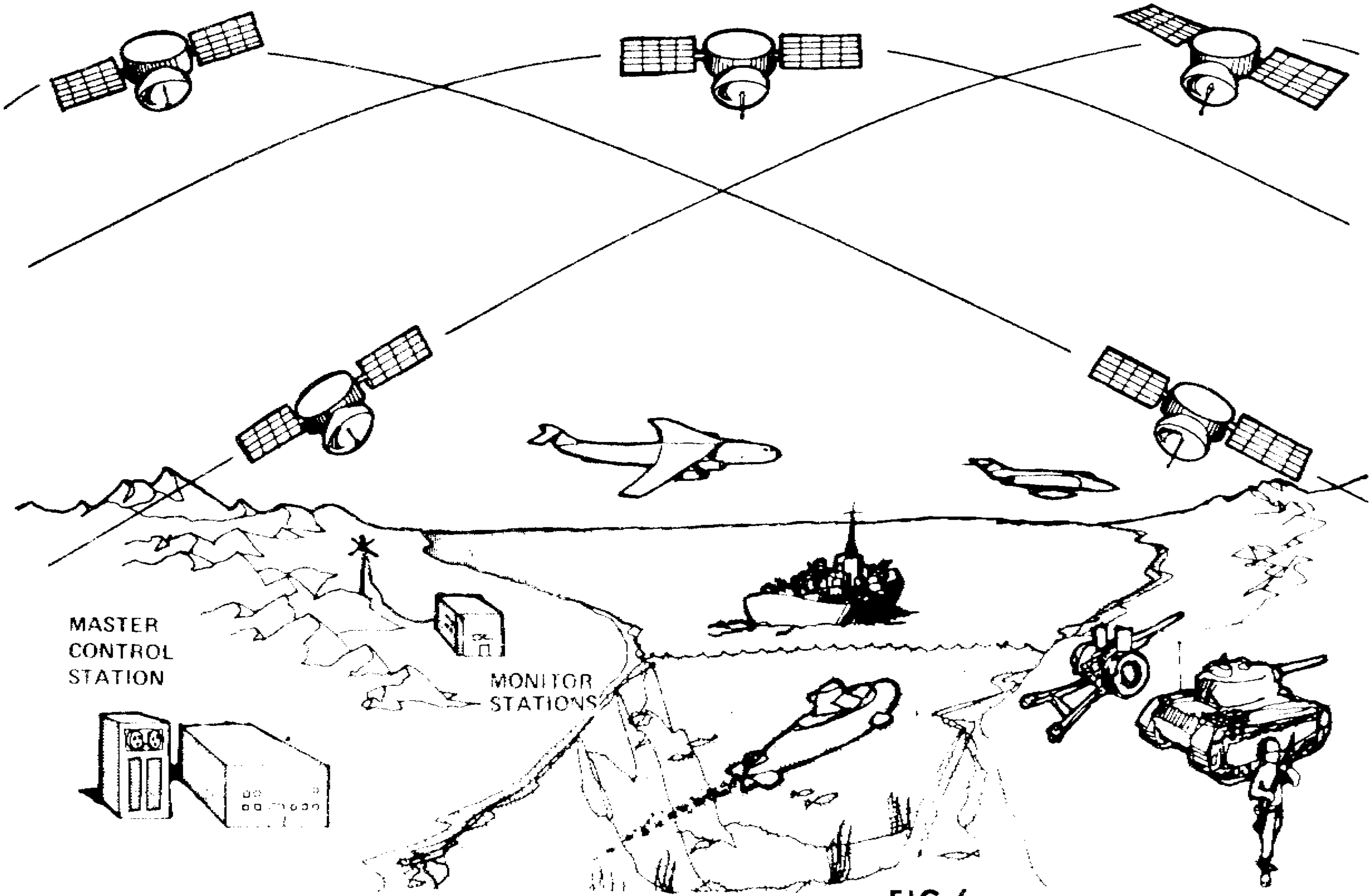


FIG 6

deploy three planes of satellites in circular, 10,000 nautical mile orbits with an inclination of 63^{o}. Each plane would contain eight satellites. This deployment insures that at least six satellites are continuously in view from any point on the earth. The Master Control Station would be located in the United States with four monitor stations located on United States territory. The user equipment classes would satisfy a host of DOD users and will also be offered to the civilian community. We expect the spacecraft weight to be 800 pounds, with 300 watts end-of-life power. It would employ a dual-frequency pseudo-random noise navigation signal. For general use, only the primary NAV signal at 1600 MHz would be used. The basic tracking technique for the Control Segment is one-way tracking. A unique feature of the system is that the satellite employs an atomic spaceborne clock. We are projecting an operational clock of about 10^{-13} seconds per second drift rate. This is the state-of-the-art for cesium clocks as exemplified by the Hewlett-Packard Laboratory standards.

The basic system technique is described in Figure 7. The Control Segment tracks the satellites and predicts their future position as well as the future behavior of these clocks. It periodically uploads that information into the satellite's memory. The satellites continuously transmit their signal which is a spread-spectrum L-Band signal with a 10 MHz chipping rate and a 20 MHz bandwidth. If a user has a clock which is synchronized to these satellite clocks, he can measure the time difference between transmission and reception. This is then multiplied by the speed of light to find the range. Thus, contact with three of these satellites would determine three spheres and his location would be at the intersection of those three speres. Unfortunately, the assumption of the user's synchronized clock would be very expensive. To satisfy that problem, he listens to a fourth satellite, thereby giving him four pieces of information from which he derives three coordinates of position and one coordinate of time. This really represents synchronizing his very crude, by flight qualified atomic standards, crystal-based clock. So the basic technique of listening to four satellites to derive the user's coordinates is more economically attractive.

The orbital configuration for the operational system is depicted in greater detail in Figure 8. There will be three orbital planes, each inclined approximately 63^{o} to

System Technique

PSEUDO-RANGING TO FOUR SATELLITES

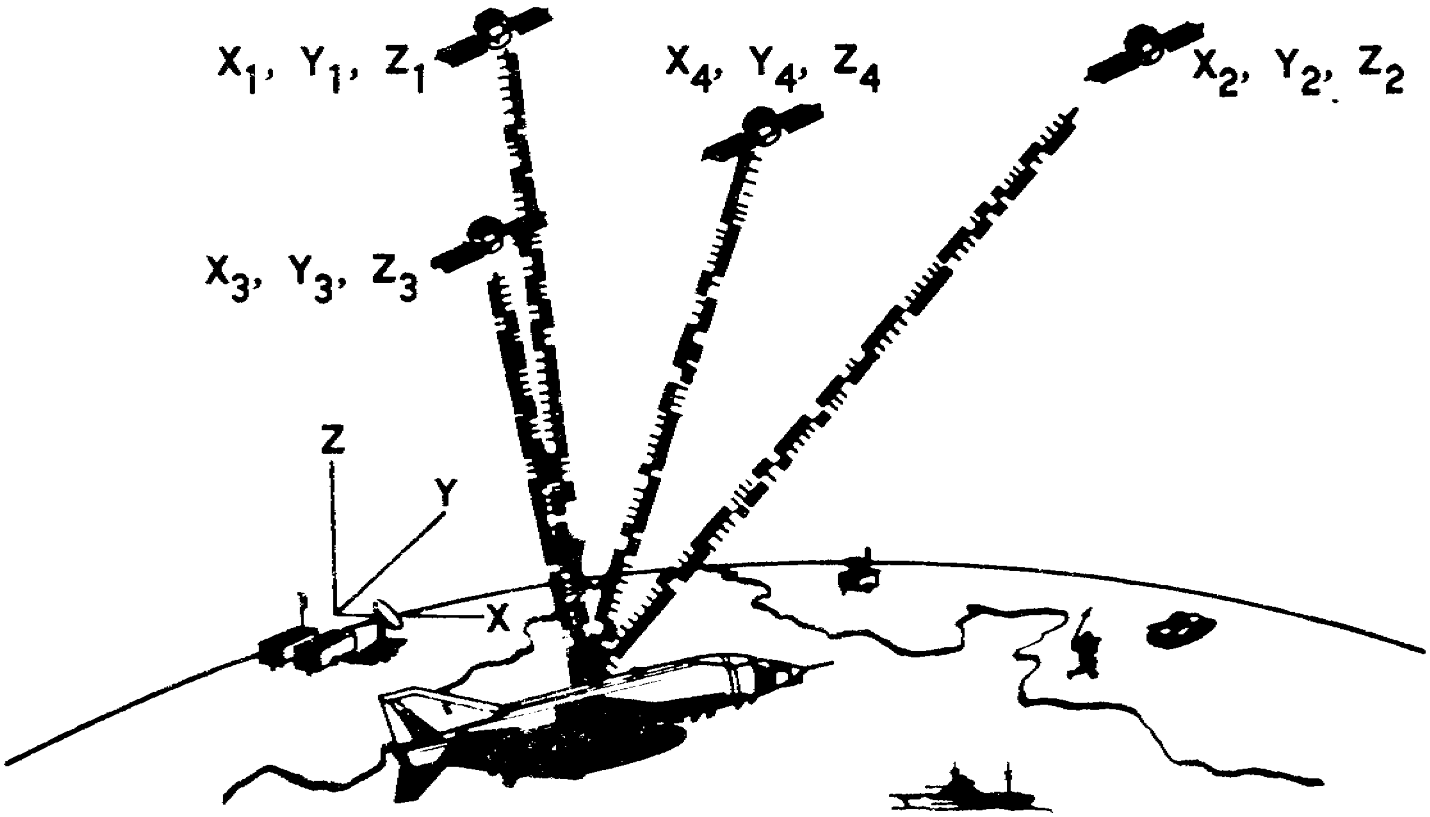
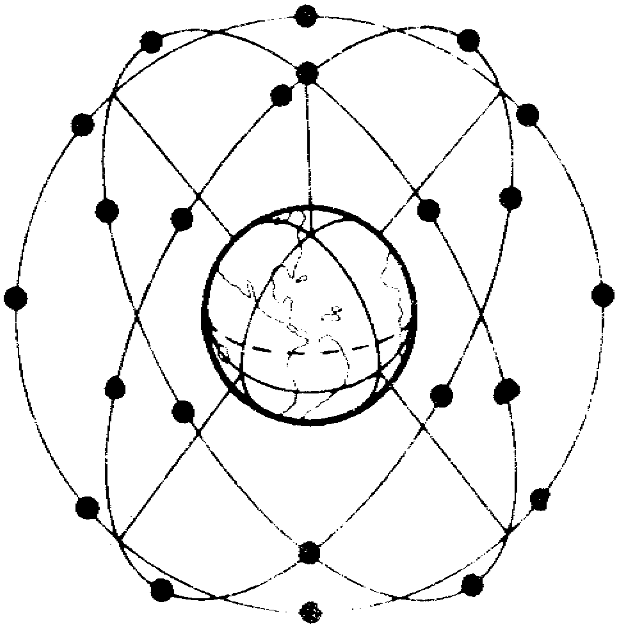


FIG 7

ORBITAL CONFIGURATION



SPACECRAFT CONFIGURATION

PHASE 1	OPERATIONAL
6 SATS	24 SATS
800 LBS	900 LBS
400 WATTS	450 WATTS
NAV SIGNALS	
$-1200\ MH_Z$	SAME
$-1600\ MH_Z$	SAME
ONE WAY TRACKING	SAME
10^{-12} CLOCK STABILITY	10^{-13} CLOCK STABILITY

FIG 8

the equator. The 24 satellites will have an orbital period of 12 hours. This will give a minimum of six satellites in view continuously at all global locations and on the average there will be 8 or 9 satellites in view. Approximate upper bounds on the satellite weight and power as well as other spacecraft parameters are listed on the right.

The baseline global positioning system will rely on Master Stations in the United States only (See Figure 9, 10 and 11). The Master Station and computing facilities will be located at one of several alternative locations, each of which already has a computing facility or a spacecraft control and telemetry system. During the first phase of development, overseas Monitor Stations would be used to help develop the worldwide ionospheric model.

We don't require the accurate clocks in any of these applications. It's cheaper for everyone to simply listen to four satellites. In fact, the user who knows his altitude can get by with just listening to three satellites, and again, he doesn't have to have an accurate clock. Even a user with a cesium clock would get out of synchronization by the end of a week. That is, the navigation function would be somewhat impaired, if the requirement was for 100 foot accuracy. If that's not a problem, he can get by with a three-channel receiver, for example, and at a potential cost saving. On the other hand, it may be to your advantage to listen to all four satellites and synchronize your cesium clock to a world-wide standard.

The six user classes that we project in the operational system are portrayed in Figure 12. These are the major classes with the cost of user equipment for unit buys in thousands of dollars. Class A is for the dynamic user in a potentially high jamming environment that demands the ultimate in precision. The two parellel definition efforts that we undertook have estimated the costs to be between $28,000 and $29,500. Class B is for the high dynamic user. Class C is an interesting class. Here we're addressing low acquisition cost with Low Life Cycle cost as well. The range we now project for a complete piece of Class C user equipment is $15,000 to $16,000. Class D is for surface vehicles.

Class E is a man-pack which also has applications for

CONTROL SYSTEM SEGMENT EQUIPMENT

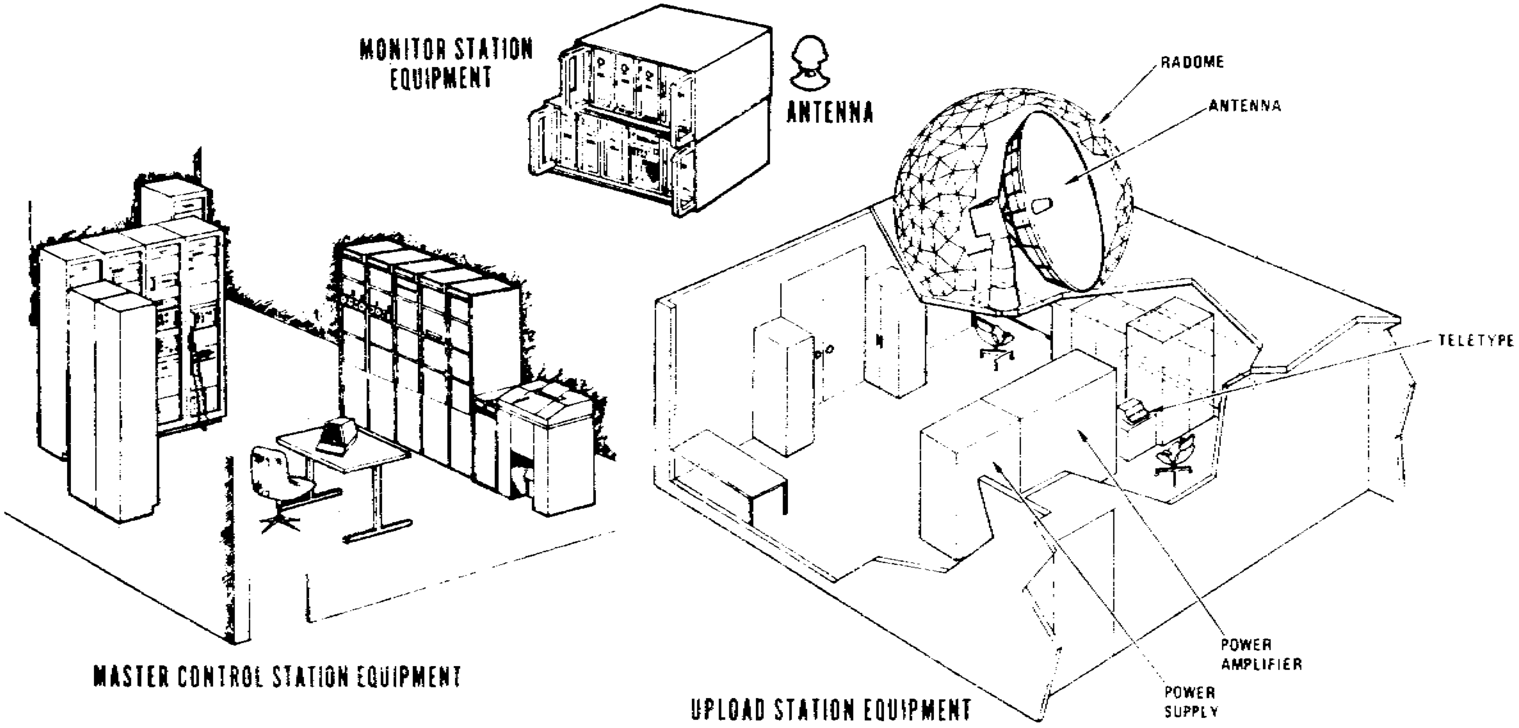


FIG 9

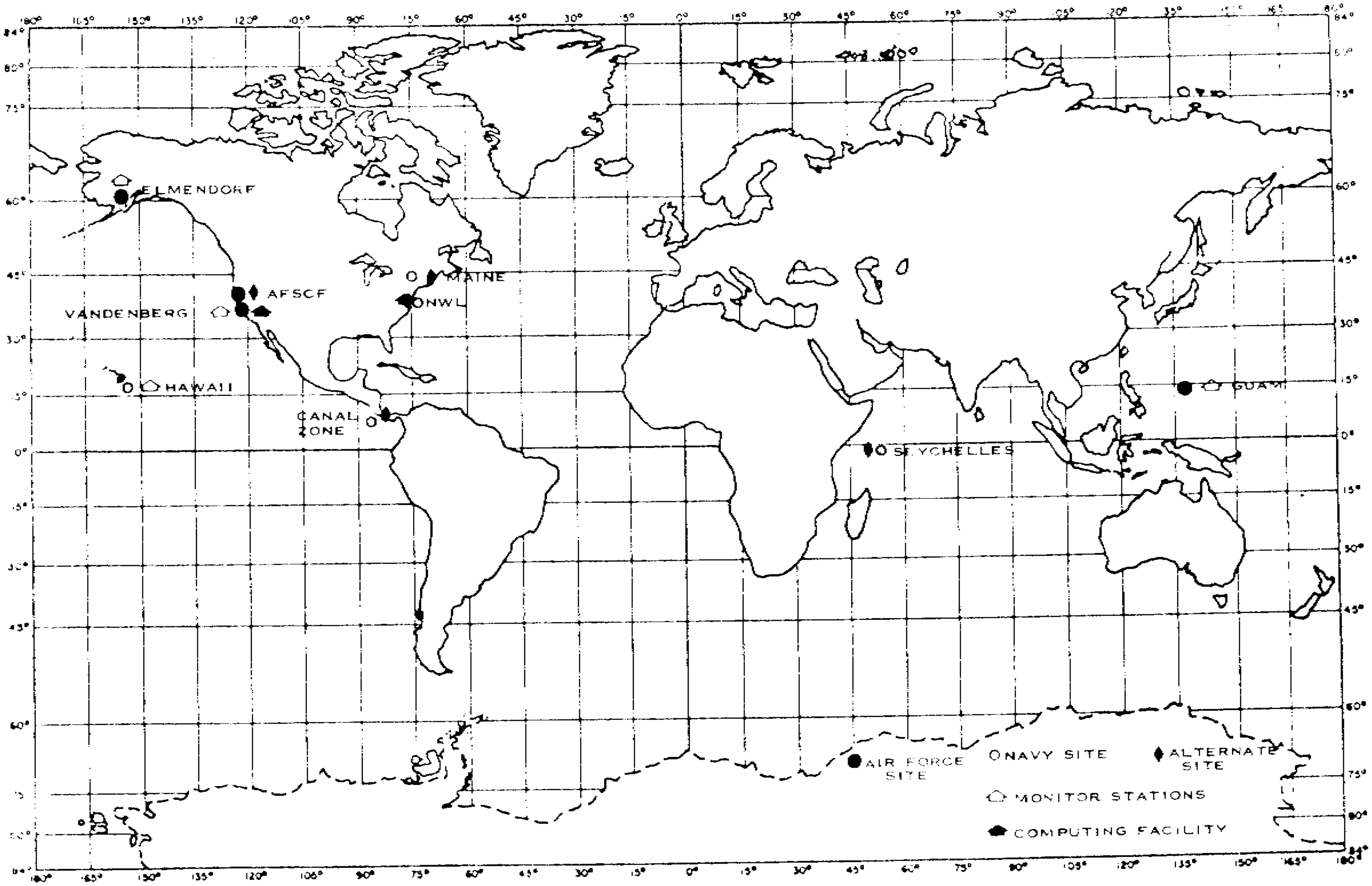

ELMENDORF
MAINE
AFSCF
NWL
VANDENBERG
HAWAII
CANAL ZONE
SEYCHELLES
GUAM
AIR FORCE SITE
O NAVY SITE
♦ ALTERNATE SITE
MONITOR STATIONS
COMPUTING FACILITY

FIG 10

BASELINE USER EQUIPMENT

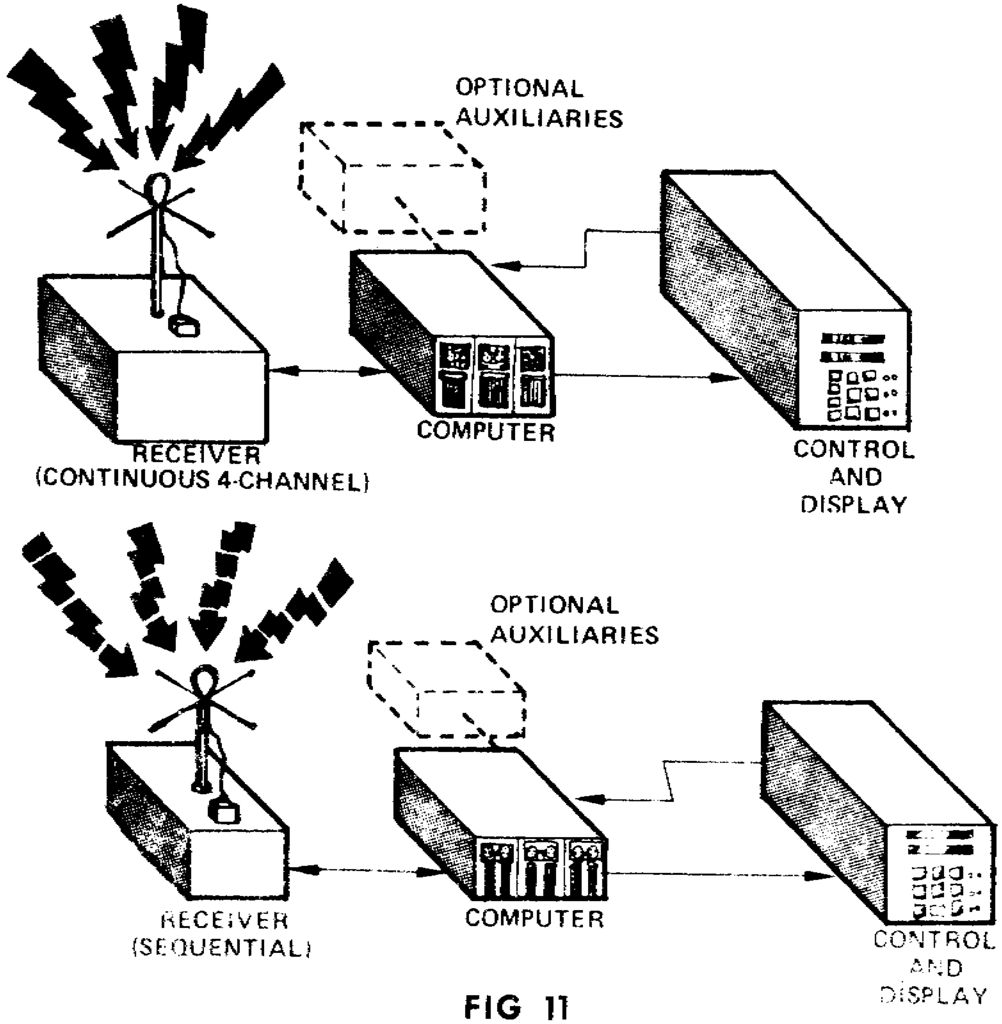


FIG 11

GPS User Classes

1000 UNIT BUY DOLLARS IN $1,000

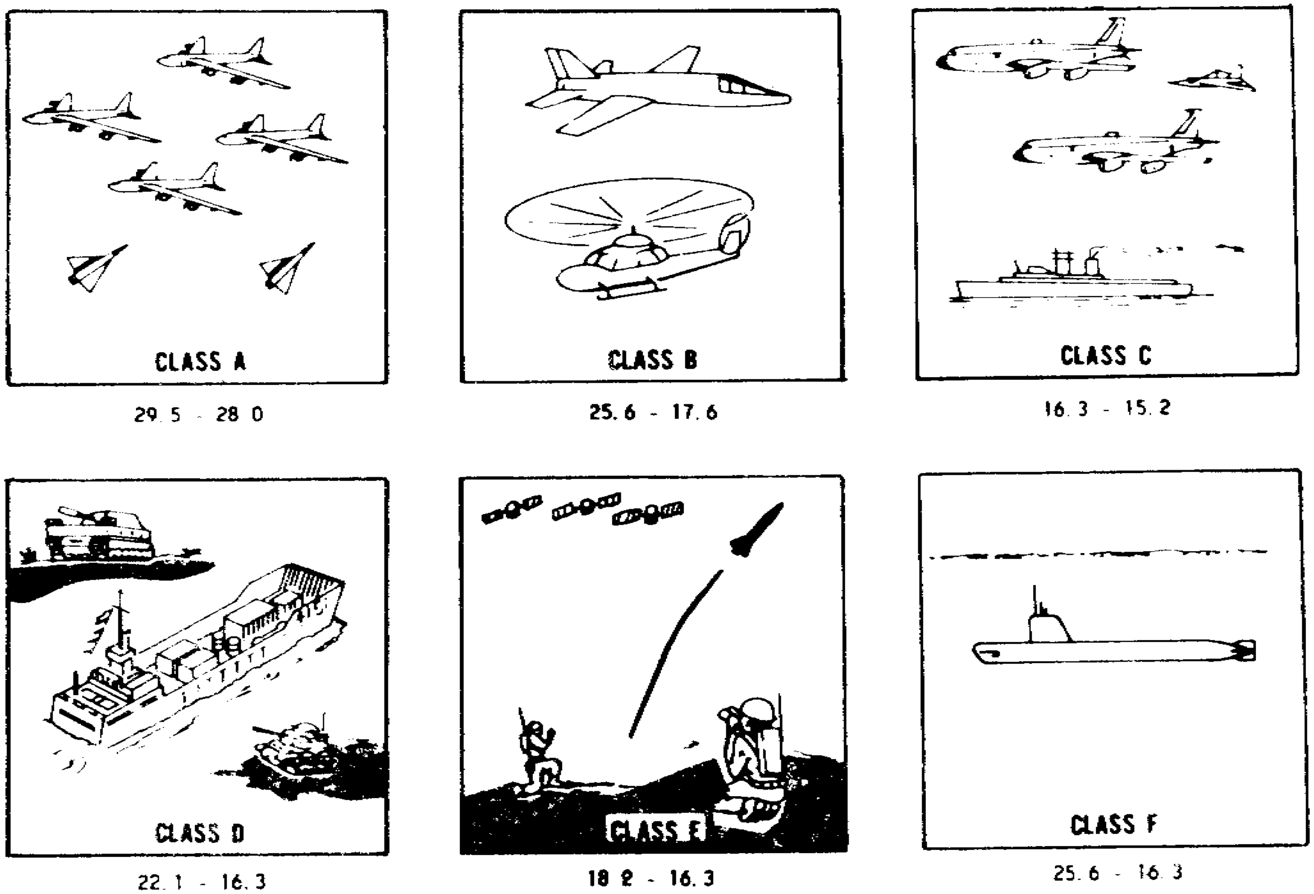


FIG 12

self-navigation of satellites. It also has application to the midcourse guidance of missiles because it is small, light weight and rugged. Class F is for submarines. Further consolidation efforts seem possible with savings to DOD by reducing logistic requirements.

In Figure 13 is shown the expected system accuracy for the mature operational system. Fifty percent of the time in the horizontal plane it is 16 feet; and in the vertical plane it is 20 feet. These figures are the result of extensive simulations by The Aerospace Corporation in Los Angeles, The Analytical Sciences Corporation in Massachusetts as well as the Naval Weapons Laboratory, who have performed analysis of the TRANSIT program. In fact, we intend to use the Naval Weapons Laboratory orbit determination in our ephemeris determination.

This is an unclassified system except for two aspects. The measured performance capability of the full-up system would be Confidential. The quantitative evaluation of survivability/vulnerability will be Secret. The projections I'm showing you are not classified. We have done our best to make this system as unclassified as we can. It makes it a lot easier to develop the system. As soon as the first person gets a piece of user equipment, the capability of the system would be pretty obvious. We didn't see much point in needlessly over classifying it.

The characteristics of the system I've described are very interesting, (See Figure 14) giving accurate three-dimensional position as well as velocity. The velocity is considerably better than a foot a second. These accuracies are available as a world-wide common grid. As a result of having the pseudo-random noise transmission, the system has the ability to be made secure and have a good anti-jam capability. It is passive with a continuous readout system available instantaneously to every user. It is unsaturable and therefore can service any number of users.

We are also addressing life cycle cost very early in the development. We have had a Deputy Program Manager for Logistics since the beginning of this program, and our efforts in that direction I think are significant.

The applications are very wide ranging from precision weapons delivery through search and rescue, (See Figure 15).

EXPECTED GLOBAL POSITIONING SYSTEM ACCURACY

	HORIZONTAL	VERTICAL
50% OF TIME	5m	7m
90% OF TIME	8m	10m

FIG 13

UNIVERSAL POSITIONING SYSTEM CHARACTERISTICS

- ACCURATE 3 DIMENSIONAL POSITION & VELOCITY
- WORLD WIDE COMMON GRID
- SECURE/AJ CAPABILITY
- PASSIVE & ALL WEATHER OPERATION
- REAL-TIME CONTINUOUS
- UNSATURABLE
- LOW LIFE CYCLE COST
  - SYSTEM
  - USER

FIG 14

GLOBAL POSITIONING SYSTEM
APPLICATIONS

MISSIONS	SPECIAL USES
● LAND ● TROOP MOVEMENT ● CONVOY ● ARMOR ● MOBILE ARTILLERY ● GEODESY	● ARTILLERY SURVEY ● FIRE SUPPORT ● TROOPS IN CONTACT ● CLANDESTINE FORCES
● SEA ● PATROL ● PASSIVE RENDEZVOUS ● TASK FORCE OPERATIONS ● HARBOR CONTROL	● SSBN ● ASW ● SAR ● PILOTAGE ● BUOY/SHOAL/REEF LOCATIONS ● BEACH HEAD
● AIR ● CLOSE AIR SUPPORT ● FERRYING ● TACTICAL DEPLOYMENT ● REFUELING ● RECONNAISSANCE ● APPROACH/LANDING	● BLIND/VISUAL AIDED BOMBING ● MISSILE INITIALIZATION/INERTIAL UPDATE ● MIDCOURSE GUIDANCE ● CARP/HARP ● RPV/RCV ● BARE BASE
● SPACE ● SATELLITE EPHEMERIS ● SPACE VEHICLE POSITION	● SPACE TRANSPORTATION SYSTEM ● SATELLITE TRACKING
● SPECIAL OPERATIONS ● INTELLIGENCE ● RANGE INSTRUMENTATION	● PASSIVE ELINT ● PHOTO RECCE/MAPPING ● TARGETING ● SENSOR IMPLACEMENT ● COR/WEAPON SYSTEM TEST SCORING

FIG 15

We recently briefed the Commandant of the Coast Guard and some of his staff, and they suggested some additional applications that we had not previsouly considered. In the area of pilotage they were very interested in the man-pack. They suggested that the harbor pilot arrive onboard ship with a man-pack which gives him both position and velocity.

He can take it to the bridge and simply read out the coordinates of the ship as it is coming into the harbor and thereby be able to navigate in fog or darkness without any difficulty. There is an application in Anti-Submarine Warfare (ASW) in which the Navy is very interested.

Now, I want to briefly describe the results of the Holloman Test program (See Figure 16). Holloman tests were conceived as a simulation of the satellite system. Four L-Band pseudo-random noise spread-spectrum transmitters were placed on the desert floor. The mobile calibration station was also placed there which has the same function as a tracking station, but it was only tracking the clock in this case, because of course, the transmitters weren't moving. We placed two competing types of receivers in a C-135 and overflew this complex. We recorded their inputs and then compared that with the location of the airplane as determined by the White Sands Missile Range Tracking complex.

The comparisons that you see in Figure 17 are comparisons between NAVSTAR-indicated aircraft location and the location as assessed by the White Sands Missile Range Tracking complex. The test simulates satellite-type geometry from about 40 to 120 seconds on the graph. I have three axis of data, up, north and east. Again, it is a 3-D system - zero to fifty feet.

To show that these weren't simply pathological results, here is the cumulative distribution as a percent of time. Errors were measured through this area navigation test for each of the competing receivers (See Figure 18). Ninety percent of the time, the Magnavox receiver on all three axis was within about 15 feet and 90 percent of the time the Hazeltine receiver was within about 22 feet. This is a summary of the test results which demonstrated performance of both continuous and sequential receivers. I didn't show you the velocity comparison, but it demonstrated accuracies which were better than a foot per second. We also ran a

USER EQUIPMENT DEFINITION AND EXPERIMENTS PROGRAM

HOLLOMAN AFB - WHITE SANDS MISSILE RANGE

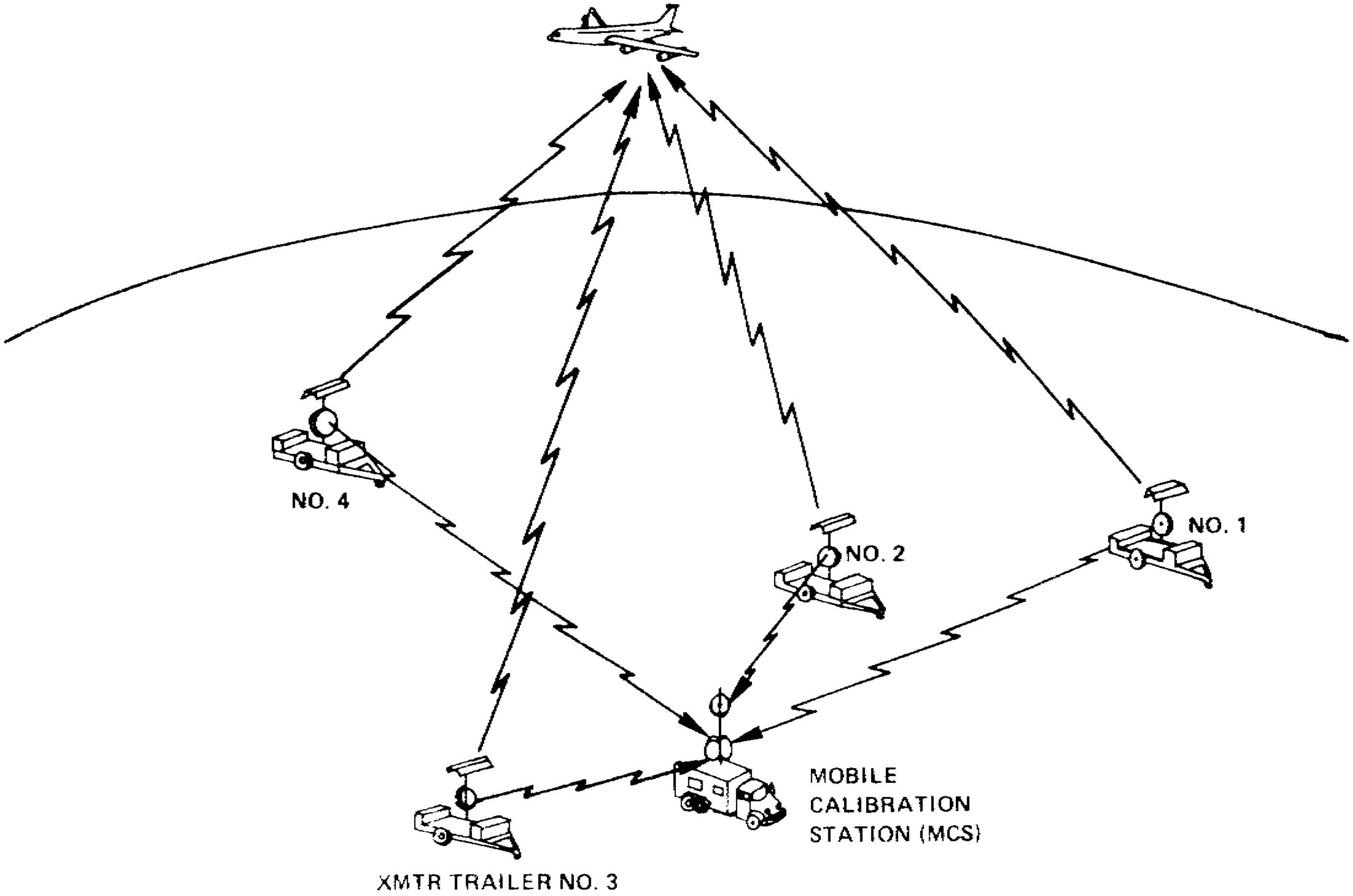


FIG 16

HAFB FLIGHT TEST
POSITION RESULTS AREA NAV

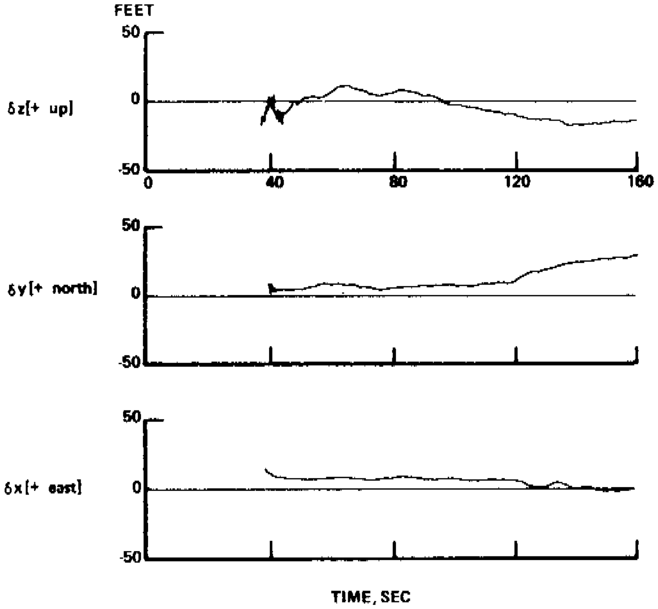


FIG 17

CUMULATIVE DISTRIBUTION OF POSITION ERRORS
(AREA NAV TEST)

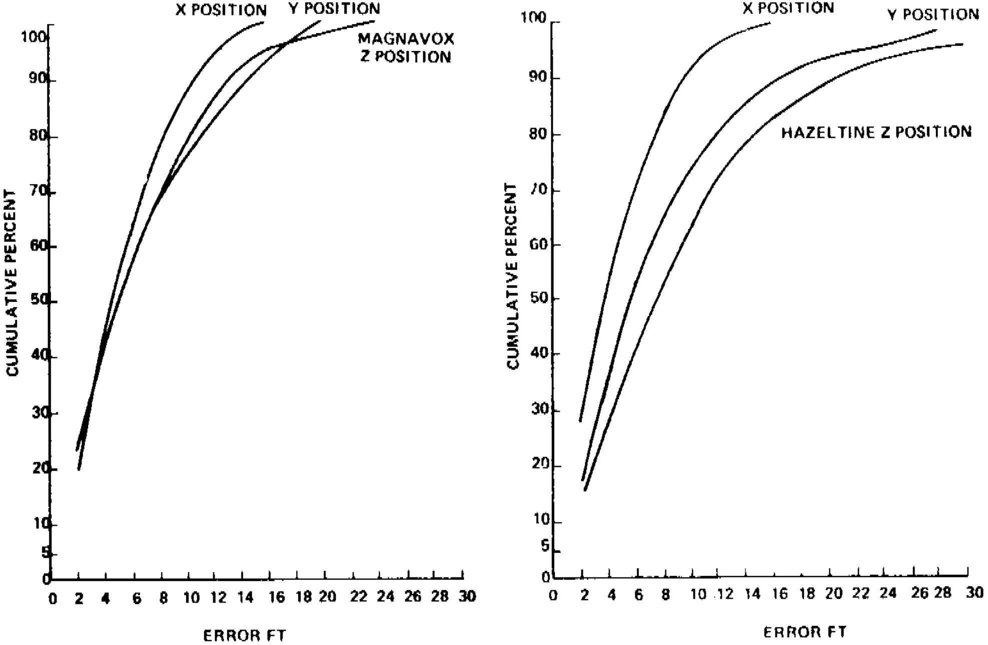


FIG 18

second series of tests which were called our ILS tests. In this test we were flying approaches to the runway as shown in Figure 19.

For this ILS purpose, our position accuracy is better than 5 feet (See Figure 20). One of the more important results here is engineering feedback to the next generation of receiver design.

The major test results are summarized in Figure 21. The Holloman Tests verified the system error budget through actual flight tests. Both continuous and sequential receivers were demonstrated. The continuous receiver simultaneously receives the navigation signals from four satellites; the sequential receiver listens to the satellites one at a time. Accuracies better than 15 feet in position and 1 FT/SEC in velocity were achieved. The most significant result is that data is already available to feed into user equipment design improvements.

The first phase of this program to arrive at a Global Positioning System is a Concept Validation Phase (See Figure 22). Its objectives are four-fold: to be certain that the basic concept is sound; to make such adjustments in that concept as necessary to get to the best design; to pin down the system cost, both for the user considering life cycle cost, and the cost of overhead; and, to demonstrate the military value in selected operations demonstrations.

The method of achieving these objectives will also evolve into the operational system (See Figure 23). This will be done using prototype operational satellites deployed in operational orbits with five satellites developed by the Global Positioning System Program Office. For the sixth satellite, we're relying on the Naval Research Laboratory to put up a follow-on experimental satellite (NTS-2) which would also have our signal structure on board. By time-phasing these six satellites to arrive over the test area, we get up to three hours of good geometry. This permits very good development tests for the receivers we will be developing. The Master Control Station will be a prototype of the Operational Master Station. The Monitor Stations, which are really no more than a piece of user equipment, would be prototypes of the operational system as well. We have a program for developing user equipment for all the user classes shown. It's an orderly phased approach that

ILS APPROACH TESTS

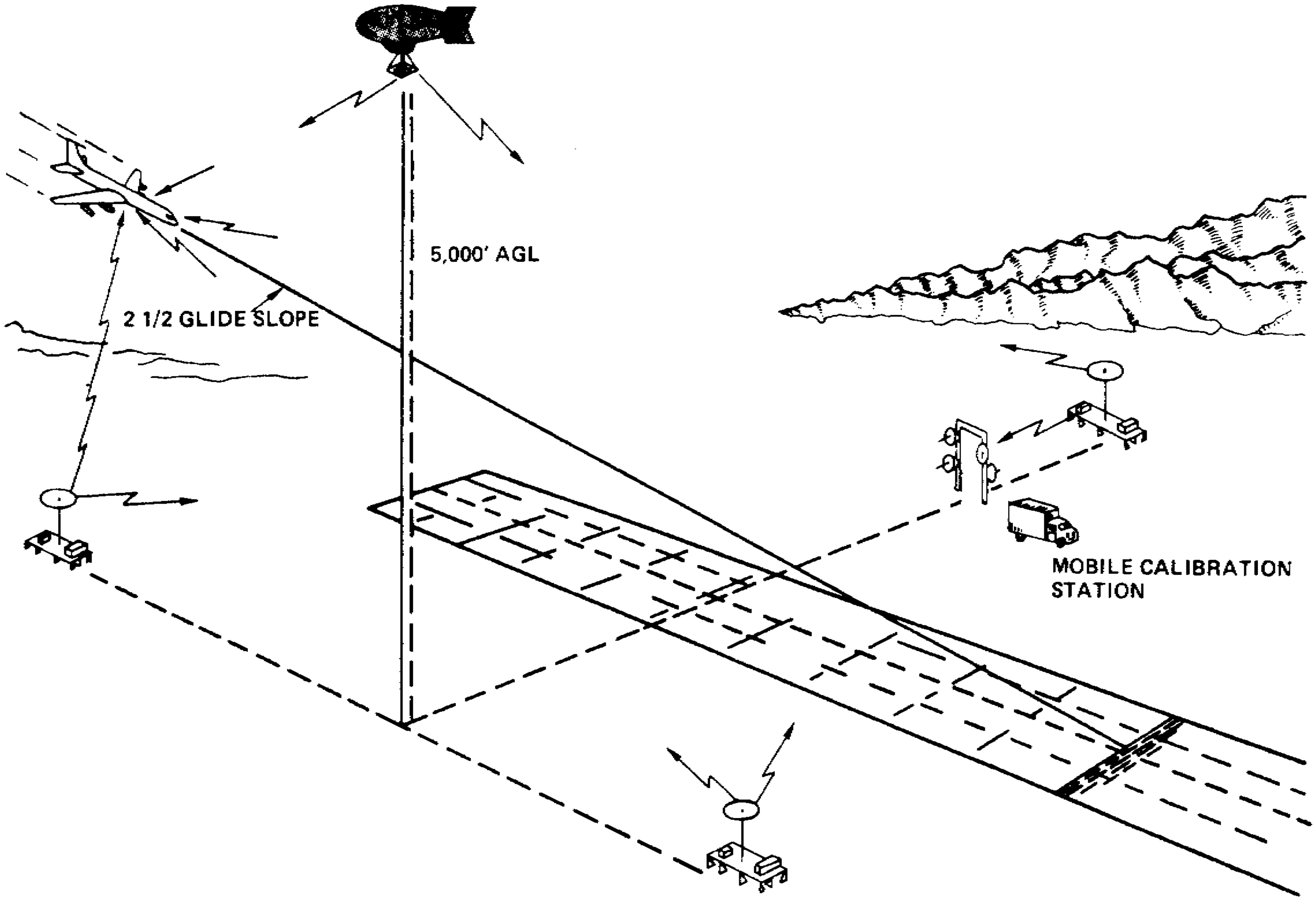


FIG 19

HAFB FLIGHT TESTS TYPICAL ILS RESULTS

11 STATE FILTER SOLUTION WITH INITIALIZATION

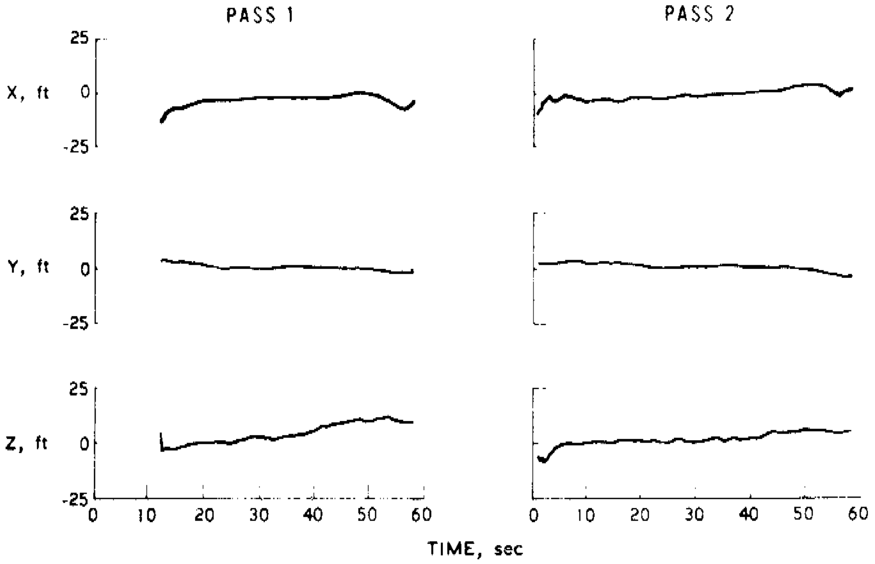


FIG 20

TEST RESULTS

HOLLOMAN NAVSAT SIMULATION/INI

- DEMONSTRATED PERFORMANCE OF BOTH CONTINUOUS & SEQUENTIAL RECEIVERS
- CONTINUOUS RECEIVER ACCURACIES
    - AREA NAV – POSITION: LESS THAN 15 FEET
      – VELOCITY: LESS THAN 1 FOOT/SECOND
    - ILS – POSITION: LESS THAN 5 FEET
- ENGINEERING FEEDBACK TO THE DESIGN

FIG 21

GPS VALIDATION PROGRAM OBJECTIVE

PROVIDE INFORMATION TO MAKE THE NEXT DECISION

- VALIDATE THE GPS CONCEPT
- VALIDATE THE PREFERRED DESIGN
- DEFINE SYSTEM COSTS
- DEMONSTRATE MILITARY VALUE

FIG 22

GPS-PHASE 1

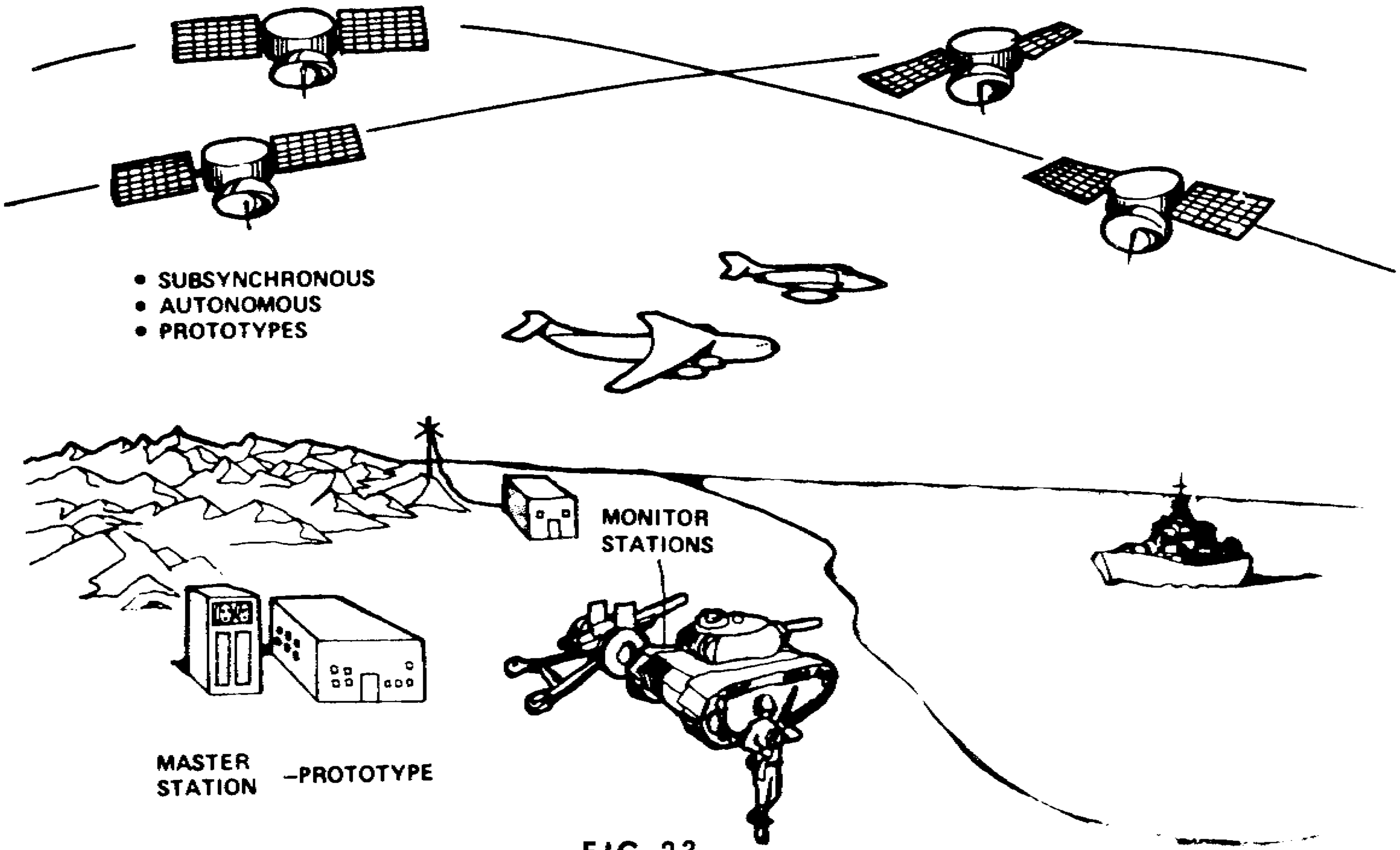


FIG 23

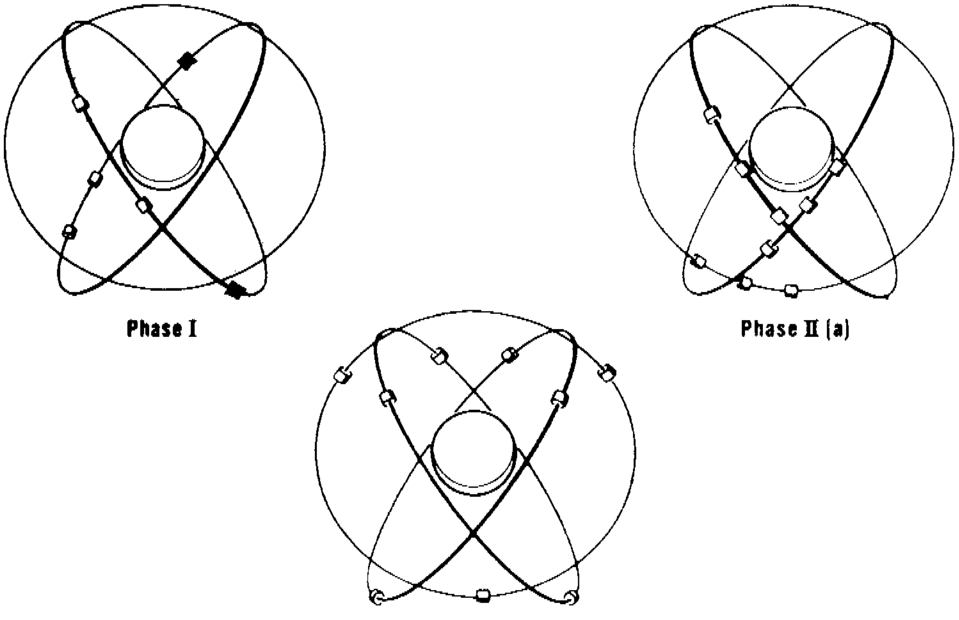
first goes through advanced development models and then proceeds into engineering development.

The orbital configuration by phases evolves into our total capability as shown in Figure 24. Phase I has the five satellites that I've just described, with a sixth one from the Naval Research Laboratory. Phase II, which would begin with a DSARC II decision, augments these satellites out to three satellites in each of three rings. Fully operational spacing time phases arrival over the test area, and gives us a full operational test for about eighteen months. At the end of that period, which would be about 1981, we reposition these satellites, spacing them uniformly in their orbits giving us a world-wide, continuous, limited operational capability. That means that there is a line of position available for anyone at all times instantaneously. As a matter of fact, eighty percent of the time, the user who knows his altitude can get a complete fix. This is a very significant capability, and I think makes a real step forward in terms of the program legacy.

In Figure 25 is shown the program schedule by calendar year. The first evolutionary step was approved with DSARC I in December. It is a Concept Validation Phase, with the user equipment split into two broad categories: the low-cost user (which is designated as Class C) and the more sophisticated classes. In Phase I the low-cost receiver will progress into a prototyping status. The sophisticated user will be lagging slightly, still being in the development status during Phase I. In 1978 we complete development test and evaluation. The satellites to support it are the six that I've just described. The Ground Control Segment moves forward as a prototype. Our system capability, initially, would be ground testing using a simulated satellite complex we developed at Holloman Air Force Base and then proceeding on with periodic 3-D capability as the four satellites arrive over our test area.

Phase II is the system validation phase. The low-cost equipment will be in production so it is available for the world-wide limited operational capability in 1981. The more sophisticated classes would be brought forward to the prototype status, i.e., just before production; they could be called preproduction models. IOT&E, initial operational tests, will be carried out using those user models. Six additional satellites will give us nine and allow for spares. These would actually be production, Block-1 satellites.

Orbital Configurations by Phase



Phase I

Phase II (a)

Phase II (b)

FIG 24

GPS PROGRAM SCHEDULE

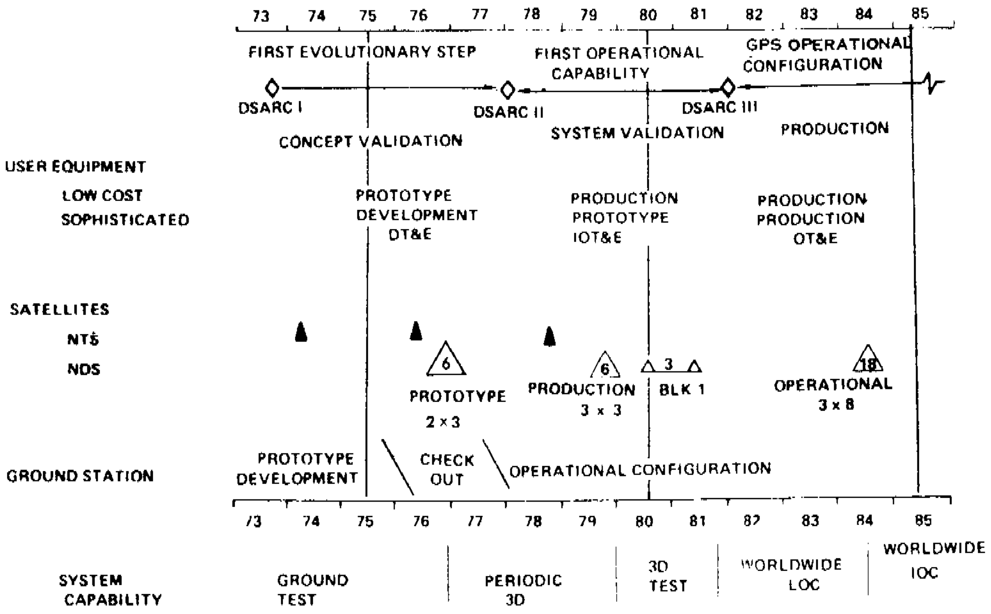


FIG 25

Three-dimensional testing would occur for about eighteen months, then the limited operational capability would be implemented by respacing the satellites using the onboard propellant capability.

A favorable decision at DSARC III would move ahead with full production of the system, achieving initial operational capability in 1984. All user equipments would be in production at this point, and we would complete our operational test and evaluation.

In Figure 26 is shown some of the future test work that will be ongoing during Phase I. The demonstration of performance, through the demonstration of selected operational missions, Naval surface vessels are certainly included. All along the Air Force has had user command participation. I've asked my Navy Deputy to insure that we also get Navy user command participation in the design and overseeing the results of these initial tests, because we feel it is quite important.

There's an application for replacing range instrumentation and the accuracies available are equivalent to roughly the kinds of accuracies expected from very sophisticated ranges. Furthermore, you're not pinned down to a single geographic area. You could achieve these accuracies anywhere. Then you have two options, you could either telemeter back that position or your could record it on tape for later recovery via some other technique. That application is clear. It would be premature to do it during Phase I.

SPECIAL FEATURES
DT&E AND LIMITED IOT&E
PHASE I

- EARLY DEMONSTRATION OF PERFORMANCE
- DEMONSTRATION OF OPERATIONAL MISSIONS
    - COORDINATE BOMBING
    - APPROACH LANDING NAVIGATION
    - AERIAL REFUELING
    - ARMY LAND OPERATIONS
    - NAVAL SURFACE VESSELS
    - SPECIAL TECHNIQUES ANTIJAM AND VULNERABILITY
- USER COMMAND PARTICIPATION

FIG 26

QUESTION AND ANSWER PERIOD

MR. FISCHER:

On the slide showing the landing test results, I noticed it mentioned an 11 state filter. I wonder if there's a simple description what those 11 state are? I was assuming 9 states for vehicle motion and two for clocks, is that anywhere near correct?

COL. PARKINSON:

No. I think it's 6 states for vehicle motion and something like 5 states for clock or perhaps 4 states for clock because you see, you have to also model all the individual clocks in this case. I'm not certain what all the states were anymore, but the important thing is he had to not only model the position of the receiver itself, he also had to model the error that was being generated from our transmitters because they were not all locked in. They were running open loop. So he had to accept that as part of the model.

DR. COHEN:

This is a very bold and exciting project and one which will get a lot of use, but you should be made aware that the radio astronomers will receive it as a mixed blessing. There will be doubt with 1,200 and 1,400 megahertz radiation which will fall on them continuously and maybe forever.

1,200 megahertz is in the red shifted hydrogen band from external galaxies which receive some use and will receive even more. It's not a radio astronomy protected band, but it is one which will be very useful in scientific research and one which clearly will become unusable, at least within some number of your megahertz. I don't know what the effects of band widths of your transmissions would be.

COL. PARKINSON:

At that frequency, 20 megahertz. But you have to recognize that the signal itself is below the noise floor in an omni antenna.

I'm not certain that it's quite the problem here.

DR. COHEN:

Well, I don't know. I think you said 400 watts.

COL. PARKINSON:

That's 400 watts DC power, but the actual power that's being radiated could be as much as 100 watts.

DR. COHEN:

Haven't there been some experiments with some other satellites in the 1,600 megahertz region and rather far away from your nominal band that found that the interference is very, very strong and wiped out radio astronomy measurements? The point is that radio astronomers detect and work with signals which are very much below the noise floor by a factor of 1,000 or 10,000.

COL. PARKINSON:

Well, I certainly register your comment. Assuming that you have a degree of directivity in those antennas, I personally don't think that the spread spectrum signal can be a lot of trouble.

DR. COHEN:

In these same experiments that I described it was found that when they were within three degrees of pointing at a satellite, they were wiped out entirely. For some extremely sensitive measurements they were wiped out whenever the satellite was above the horizon.

After 1984 your system will have from 6 to 9 satellites in view at all times from every point on the earth. I think that that will reaffirm that systems are getting more sensitive all the time. My guess is that there will be some bands which will become closed, in a sense, to very sensitive radio astronomy use.

I'd be delighted, sir, to send you a report that the National Radio Astronomy Observatory has just written on this particular interference problem.

DR. ALLEY:

If you assume a reasonable circularity of orbit, that you might hope to achieve, there will be a modulation with a 12-hour period having an amplitude of 12 nanoseconds in the ability to transfer time due to the potential effect of general relativity.

COL. PARKINSON:

Well, of course that's a highly predictable thing. Therefore, it doesn't show up in an error budget since we would be calibrating it out. The effect is on the order of 2, 200 nanoseconds times the eccentricity of the orbit and it is a sizeable effect and one that we have to correct our clocks for.

We'll correct our clocks in such a way that the user is insensitive to that effect and doesn't even know it's there. The very fast moving user still has to worry about his own relativistic problem.

MR. KEATING:

You mentioned minimization of the proliferation of global navigation systems. How does your system relate to other systems which are global such as OMEGA, and perhaps loran, which may possibly some day become global? Are you in completion with them?

COL. PARKINSON:

Yes, I guess my feeling right now is that the competition is not one that I'm involved in. I'm offering up and building a system, and then the user community will have some choices to make.

If I could hold down the cost of user equipment, provide a highly accurate worldwide grid which is reliable and always available, then the user community will have a choice to make. And I think that's the best way to look at the problem, rather than looking at it as though I'm trying to turn off all the loran transmitters in the world—because I'm not.