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REPORT NO.
TOR-1001(2525-17)-1

(U) Briefing– Navigation Satellite Study

24 AUGUST 1966

Prepared by J. B. WOODFORD and H. NAKAMURA
System Planning Division

Prepared for COMMANDER SPACE SYSTEMS DIVISION
AIR FORCE SYSTEMS COMMAND
LOS ANGELES AIR FORCE STATION
Los Angeles, California

EL SEGUNDO TECHNICAL OPERATIONS • AEROSPACE CORPORATION
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(U) BRIEFING - NAVIGATION SATELLITE STUDY

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El Segundo Technical Operations
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declassified after 12 years.

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BRIEFING - NAVIGATION SATELLITE STUDY

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[redacted]

FOREWORD

For the past two years, the Aerospace Corporation has worked with the Air Force Space Systems Division in studying the needs for and the feasibility and design of a new Navigational Satellite System. Recently, a briefing was prepared to present the major results and conclusions of that study; this report documents that briefing. The format adopted presents copies of the briefing charts and additional commentary on facing pages. This format was chosen in order to be of maximum usefulness as a reference to those who have heard the briefing and to allow publication of the material with minimum delay. It is intended that the study will be documented in greater detail in a forthcoming report.

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CONTENTS

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NAVIGATION SATELLITE

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The objectives of the in-house study are summarized on this chart.

OBJECTIVE

- EXPLORE THE FUTURE APPLICATION OF SATELLITES TO TACTICAL NAVIGATION AND OTHER MILITARY OPERATIONS REQUIRING NAVIGATION
  - OPERATIONAL SITUATIONS
  - SYSTEM DESIGNS
  - TECHNICAL PROGRAM

The scope of the study is summarized on this chart. The uses considered were those relating to military operations. Primary emphasis was given to tactical military operations because of the present national interest in extending this country's military capability in limited war environments. The high speed maneuvering aircraft received special attention because of its importance in tactical operations and the high performance desired in its navigation subsystem. In meeting the needs of the tactical aircraft, it will be shown that the needs of many additional operations are also fulfilled at little or no penalty to the resulting satellite system.

SCOPE

- ALL MILITARY OPERATIONS REQUIRING POSITION FIXING ARE POTENTIAL USERS OF THE NAVIGATION SATELLITE SYSTEM
- THE PRIMARY SYSTEM OBJECTIVE IS TO SATISFY THE NEEDS OF TACTICAL OPERATIONS
- THE MOST CRITICAL TACTICAL USER IS THE HIGH SPEED MANEUVERING AIRCRAFT DELIVERING CONVENTIONAL WEAPONS AND STORES
- THE CURRENT STUDY IS DIRECTED ESPECIALLY TO THE TACTICAL AIRCRAFT NEEDS, BUT OTHER USER NEEDS ARE ALSO CONSIDERED

Upon the SSD/Aerospace identification of navigation as a potential mission which can be performed attractively from space, a one-year low level study was conducted. The results of the study warranted a more formal and intensive study which began in June 1965. While the study was in progress, AFSC requested inputs to a general survey of potential users of satellites in tactical war and, in particular, the use of navigation satellites. These data were supplied by SST and were incorporated into a Research and Technology Division, System Engineering Group (SEG) report delivered to AFSC. In this report, additional study of navigation satellites was recommended.

STUDY CHRONOLOGY

1 JUNE 64	— SSD/AEROSPACE IDENTIFICATION OF POTENTIAL NEED FOR A NEW NAVIGATION SATELLITE
1 JUNE 65	— STUDY INITIATED SST/AEROSPACE
12 NOVEMBER 65	— AFSC REQUESTED VIEWS ON USE OF NAVIGATION SATELLITE IN TACTICAL WARFARE
13 DECEMBER 65	— VIEWS ON USE OF NAVIGATION SATELLITE SYSTEMS SUBMITTED TO SEG, WPAFB, AS AN INPUT TO REVIEW OF TACTICAL NAVIGATION/DELIVERY SYSTEMS DEVELOPMENT
21 JANUARY 66	— SEG REPORT DELIVERED TO AFSC ● NAVIGATION SATELLITE STUDY RECOMMENDED
1 JULY 66	— IN-HOUSE STUDY COMPLETED

TECHNICAL DISCUSSION

The remainder of this briefing will describe potential users of a new navigation satellite system and what has been learned of the operational situation in which it would be used. A desirable set of attributes of a navigation satellite will be developed and will be compared with existing navigational aids. Inasmuch as this comparison will indicate a number of desirable attributes which are not possessed by current navigational aids, an initial survey of satellite navigational concepts that can meet the desired aims will be reviewed and a system design will be formulated. In the technical summary, the program needed to further define and begin implementation of such a satellite navigation system will be described.

CONTENTS

Before proceeding with an investigation of the potential needs for a new navigation satellite, a few terms as they are used herein will be defined. Navigation will be used synonymously with position and/or velocity measurement rather than in the more classic sense of steering to reach a desired destination. Absolute accuracy and relative accuracy will be used extensively in the investigation of potential users of a navigation satellite system. The distinction between absolute and relative accuracy is important because the systems considered will be generally capable of significantly higher relative accuracies than absolute accuracies.

DEFINITIONS

- NAVIGATION - STRICTLY, THE DETERMINATION OF PRESENT POSITION AND COURSE TO REACH DESIRED DESTINATION
  - BY EXTENSION, AS IN NAVIGATION SATELLITE, TO DETERMINE POSITION (AND/OR VELOCITY) WHETHER OR NOT THIS INFORMATION IS USED IN SETTING A COURSE
- ABSOLUTE ACCURACY - ACCURACY OF A FIX RELATIVE TO EARTH COORDINATES (LATITUDE, LONGITUDE)
- RELATIVE ACCURACY - ACCURACY OF TWO FIXES RELATIVE TO EACH OTHER — GENERALLY MUCH BETTER THAN ABSOLUTE ACCURACY IF FIXES ARE NOT GREATLY SEPARATED IN TIME AND DISTANCE

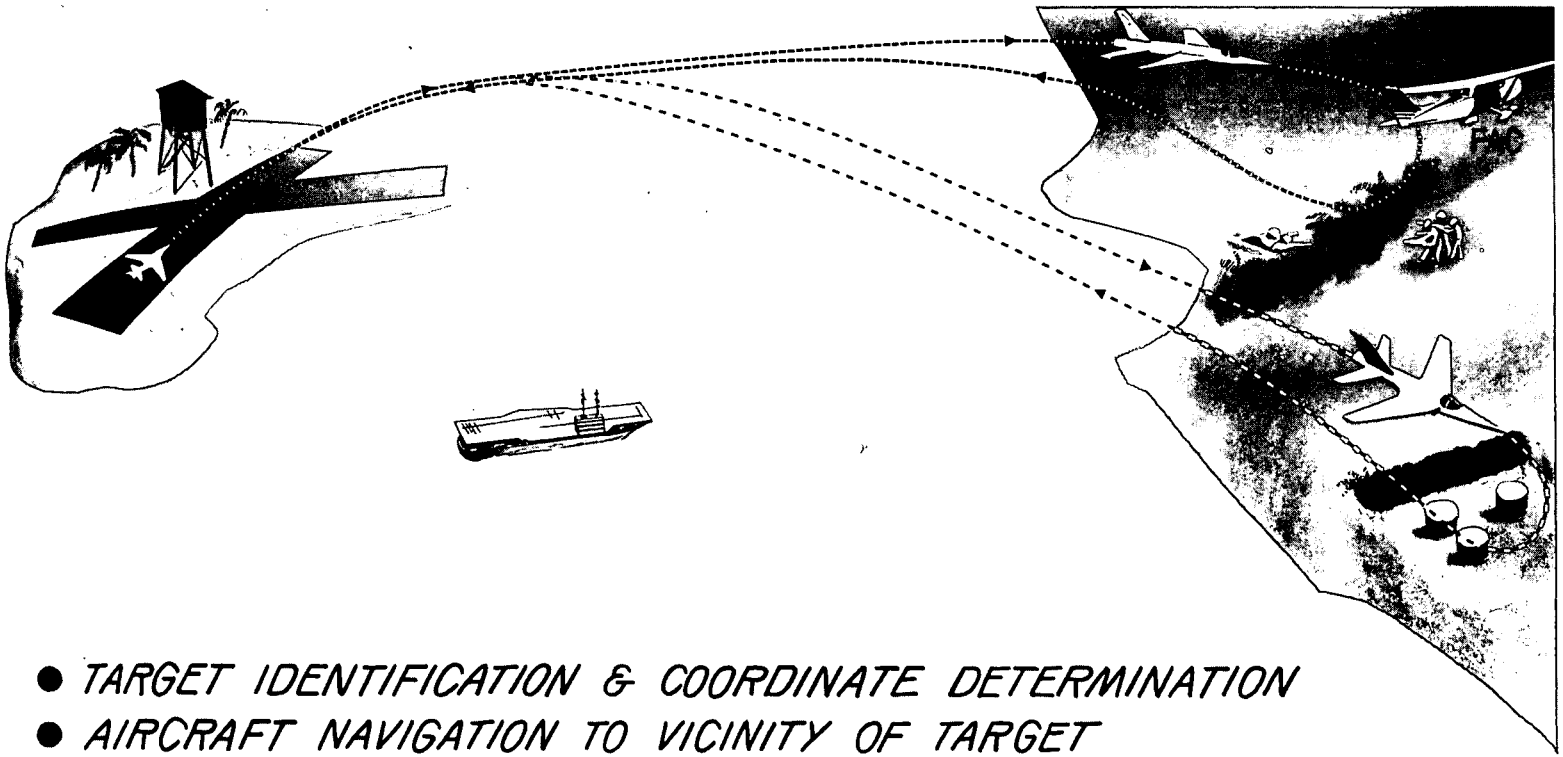
[redacted]

The following section will describe the phases of a tactical air strike and typical parameters for a navigation system designed to support each phase. A tactical air strike is selected as the main example for a variety of reasons. First, it is an operation that is clearly of great significance in a tactical operation. Second, the various phases of the operation illustrate a wide variety of operational phases quite similar to other situations. Third, some of the needs of high speed aircraft are more severe than those of other users, especially in accuracy and allowable user velocity. A navigation system suitable for use by high speed maneuvering aircraft will also serve a wide variety of other users.

POTENTIAL USERS AND OPERATIONAL SITUATIONS

The phases of a tactical air strike are summarized on this chart. The next few charts will examine each of these phases in order to develop the navigation performance which is either required for the operation or will lead to an improved capability not now possible.

TACTICAL AIR STRIKE



- TARGET IDENTIFICATION & COORDINATE DETERMINATION
- AIRCRAFT NAVIGATION TO VICINITY OF TARGET
- TARGET ACQUISITION BY AIRCRAFT
- DETERMINATION OF BOMB RELEASE POINT
- AIRCRAFT NAVIGATION BACK TO BASE
- DAMAGE ASSESSMENT

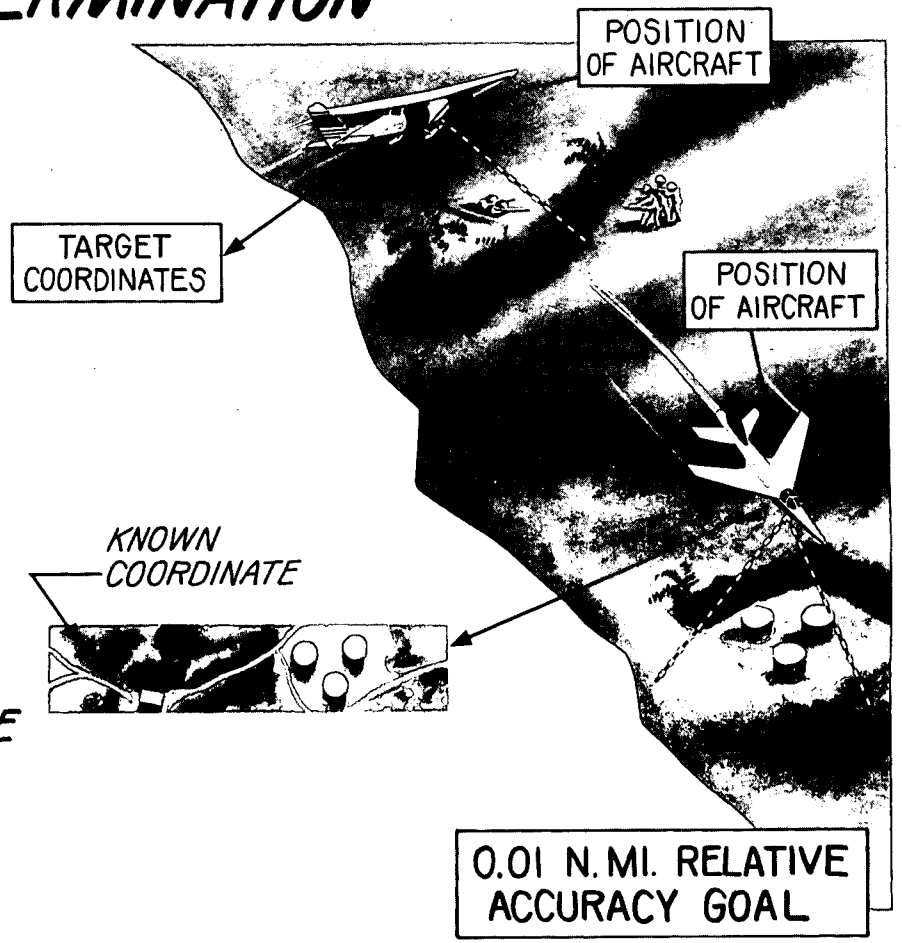
This chart summarizes the process of obtaining coordinates of a desired target. A fluid field situation being observed by a forward air controller and photographic reconnaissance of fixed targets are illustrated. In each case, the position of the aircraft is an important input in the process that terminates with the establishment of target coordinates.

TARGET IDENTIFICATION & COORDINATE DETERMINATION

- RECCE PHOTOGRAPHS OR VISUAL SIGHTING OF TARGET
- DETERMINE LOCATION OF TARGET RELATIVE TO OBSERVER
- DETERMINE LOCATION OF OBSERVER IN COORDINATE GRID OF THEATER

↓

- TARGET COORDINATES



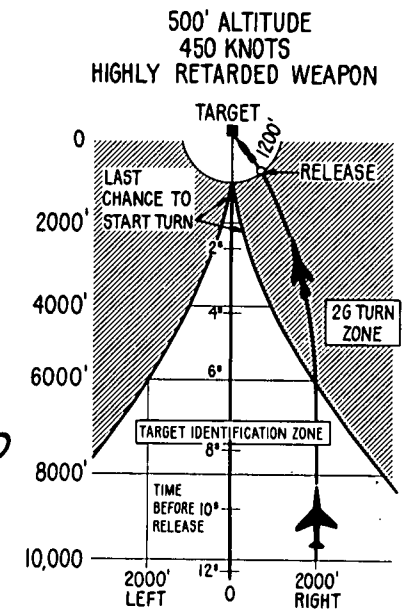
The accompanying chart summarizes the desired accuracy of a navigation system designed to guide a bomber from its base to the vicinity of the target and to allow sufficiently precise navigation of the aircraft so that acquisition of the target can be accomplished by conventional optical or radar methods. It is clear that lower accuracies compromise mission success. The graph illustrates the situation of an approaching aircraft which, for the parameters given, must acquire the target before passing the 2-G turn limit lines. In the case illustrated for a 6000 ft acquisition range, 2000 ft is the allowed maximum error which reflects a 0.1 n mi, 1-σ accuracy. If the error is larger, the aircraft will be unable to reach the proper bomb release point and, of necessity, must either seek an alternate target or make another pass over the target. Furthermore, a more accurate acquisition may allow a better CEP owing to lack of maximum acquisition conditions such as rate of turn and pilot stress. Poor accuracy at acquisition will sometimes result in the acquisition of an incorrect target with the consequence of dropping bombs on the wrong target. Furthermore, lack of sufficient position-fixing accuracy decreases survivability because repeated passes are required or because the aircraft may fly closer than planned to gun or missile emplacements.

VISUAL BOMBING

- NAVIGATION TO TARGET AND TARGET ACQUISITION

  1.0 NMI ACCURACY - EARLY PHASE
  0.1 NMI ACCURACY - AT ACQUISITION
  CONTINUOUS FIXES

- LOWER ACCURACY REDUCES MISSION SUCCESS PROBABILITY
  - REPEATED PASSES RESULT FROM OFFSET ERROR GREATER THAN 1/3 N MI
  - INCREASED CEP RESULTS FROM LATE ACQUISITION
  - INCORRECT ACQUISITION - WRONG TARGET BOMBED
  - DECREASED SURVIVABILITY



The accompanying chart illustrates a situation wherein visual or radar siting of a target is not possible. The accuracies indicated allow effective bombing without reference to visual devices. It should be pointed out that the 0.01 n mi accuracy must be relative to the grid in which the target was located but need not be of that accuracy relative to conventional global coordinates. The first item in the chart, navigation to the aiming point, refers to the navigation of the aircraft from its base to the vicinity of the target and is primarily required to aid the aircraft in avoiding hazardous areas.

BLIND BOMBING

- NAVIGATION TO AIMING POINT (0.1 N MI)
- COMPUTATION OF BOMB RELEASE POINT (ALTITUDE AND VELOCITY REQUIRED)
- NAVIGATION TO BOMB RELEASE POINT (0.01 N MI) IN SAME COORDINATE SYSTEM AS USED TO LOCATE TARGET
- GOALS
  - 0.01 N MI POSITION FIXING ACCURACY
  - 1-5 FPS VELOCITY ACCURACY
  - CONTINUOUS MEASUREMENTS

The two remaining phases of the tactical air strike mission are indicated on this chart together with the accuracies desired of a supporting navigation system. Accuracy of 1 n mi for navigation to the base should suffice, but higher accuracy gives additional mission flexibility and can allow much simpler landing aids, primarily due to a reduction in the required acquisition range. Damage assessment is normally conducted to determine mission success. The desired accuracies for this phase are quite similar to those for the original target acquisition during the bombing run.

At this point, it can be seen that a number of phases of a tactical air strike can benefit from navigational position fixing. Accuracies of 0.01 n mi relative and 0.1 n mi absolute with continuously available fixes will serve all phases of the mission.

AIRCRAFT NAVIGATION BACK TO BASE

- 1 NMI ABSOLUTE ACCURACY
- HIGHER ACCURACY ALLOWS RELAXING WEATHER CONSTRAINTS
- HIGHER ACCURACY REDUCES REQUIREMENTS ON LANDING AIDS

DAMAGE ASSESSMENT

- RE-ACQUISITION OF TARGET TO DETERMINE DAMAGE - 0.1 NMI DESIRED

[redacted]

The examination of potential users for a new navigational satellite system has, to this point, been concentrated on tactical air strikes. There are, however, many other tactical operations requiring navigation information. Operations having needs compatible with those of the air strike are summarized on this chart. The first item, short range missile launch from aircraft, is an extension of the previous tactical air strike that would allow the aircraft to avoid the enemy target vicinity. A short range air-launched missile would be launched from an appropriate point at which the navigation satellite would give position and velocity information to the missile guidance system. From this point, the short range missile could be inertially guided, command guided from the aircraft, or, eventually, could receive guidance or position fixing information directly from the navigation satellite. Missile terminal guidance may become of increasing interest as the desire to obtain very small CEPs grows in importance. The accuracy stated would allow many targets to be attacked with ballistic missiles with high-explosive warheads. Other operations that would benefit from a navigation satellite system are included in this chart and are self-explanatory.

OTHER USERS OF SYSTEM SATISFYING TACTICAL BOMBING GOALS

OPERATION	ACCURACY / FIX FREQUENCY
• AIRCRAFT SHORT-RANGE MISSILE LAUNCH	0.01 N MI RELATIVE / CONTINUOUS +2 FPS VELOCITY
• MISSILE TERMINAL GUIDANCE	0.01 N MI RELATIVE / CONTINUOUS +0.2 FPS VELOCITY
• AIR DELIVERY OF STORES	0.01 N MI RELATIVE / CONTINUOUS
• AIR TRAFFIC CONTROL	1 N MI ABSOLUTE / INTERMITTENT
• RESCUE	0.1 TO 1. N MI RELATIVE / INTERMITTENT
• POSITIONING GUNS, RADARS, ETC.	
— ON LAND	0.01 N MI RELATIVE / INTERMITTENT
— ON SEA	0.01 N MI RELATIVE / CONTINUOUS
• AIRCRAFT MAPPING	0.1 N MI ABSOLUTE / CONTINUOUS
• SHIP MISSILE LAUNCH	0.1 N MI ABSOLUTE / INTERMITTENT
• SATELLITE TRACKING	0.1 N MI ABSOLUTE / CONTINUOUS

The users identified in the preceding charts have a variety of needs for a navigation system. This and the following charts list the most stringent parameters associated with these needs in an effort to develop a system performance which is compatible with the needs of all the previously identified users.

DESIRED ACCURACY

- A VARIETY OF USERS HAVE POTENTIAL NEEDS FOR A NAVIGATION SYSTEM PROVIDING POSITION FIXES WITH
  - 0.1 NMI ABSOLUTE ACCURACY
  - 0.01 NMI RELATIVE ACCURACY
- SOME USERS HAVE POTENTIAL NEEDS FOR VELOCITY MEASUREMENTS TO 0.2 F.P.S. ACCURACY

In addition to accuracy, the utility of a navigation system is dependent on other attributes; some are summarized on the accompanying chart. It is desired to have the capability of position fixing in a region without previously having had access to the region to set up ground stations. Global coverage is the most desirable although not necessarily the most cost-effective way of ensuring this capability. Fixes need to be continuously available to meet the needs of high speed aircraft and missile applications. As in any military system, an appropriately low vulnerability is essential. However, for navigation satellite systems, it is not considered practical to provide absolute invulnerability in a total nuclear environment. It is desired that the user remain passive; i. e., no electromagnetic signals are radiated which could be used by the enemy for direction finding and consequent location of the user. As in any system, minimum cost is desired. Furthermore, it is desirable that a new navigation system be responsive to the needs of a wide variety of users, as an aid in justifying the system cost.

OTHER DESIRED CHARACTERISTICS

- COVERAGE
  - NOT DEPENDENT ON ACCESS TO THEATER FOR SET UP OF SYSTEM
  - GLOBAL DESIRED
- AVAILABILITY OF FIXES
  - CONTINUOUS
- VULNERABILITY
  - EQUIPMENT LOCATED WHERE PROTECTION AVAILABLE-PREFERABLE OUTSIDE THEATER
  - MINIMUM JAMMING SUSCEPTIBILITY
- PASSIVE USER
  - DESIRED
- COST
  - MINIMUM DESIRED
  - CHARGEABLE TO A VARIETY OF USERS

This section of the briefing will examine the properties of existing navigation aids to determine how well their capabilities and performance meet the criteria established in the preceding section. Considered here will be Loran C and D, Omega, and Transit. These systems are intended to fulfill the needs of some of the users identified earlier. Inertial navigation systems and combined Doppler or Stellar inertial systems are not treated here because they have an error growth with time (on the order of a few nautical miles per hour for a pure inertial system) that preclude most of the high precision applications under consideration. On the other hand, inertial systems provide attitude information not provided by other position fixing systems. In fact, many users will have need for both an inertial system and an independent position fixing system. Also not considered are many short range navigation systems, such as Tacan.

The systems which are considered, in addition, have a number of variants which share their principal characteristics.

REVIEW OF NAVIGATION AIDS

Loran C, Loran D, and Omega are described briefly on this chart. These three systems are two-dimension hyperbolic systems (i. e., a position fix is determined by the intersection of two hyperbolic lines of constant range difference to pairs of ground stations). They do not yield altitude, nor do they require a knowledge of altitude to determine position.

Loran C is a regional system of moderate accuracy. Loran D is a higher accuracy, shorter range system which is presently in system test. Both of these systems operate at a relatively low frequency which was necessary in order to obtain their coverage. They require three or more sizeable ground stations located within the region of coverage.

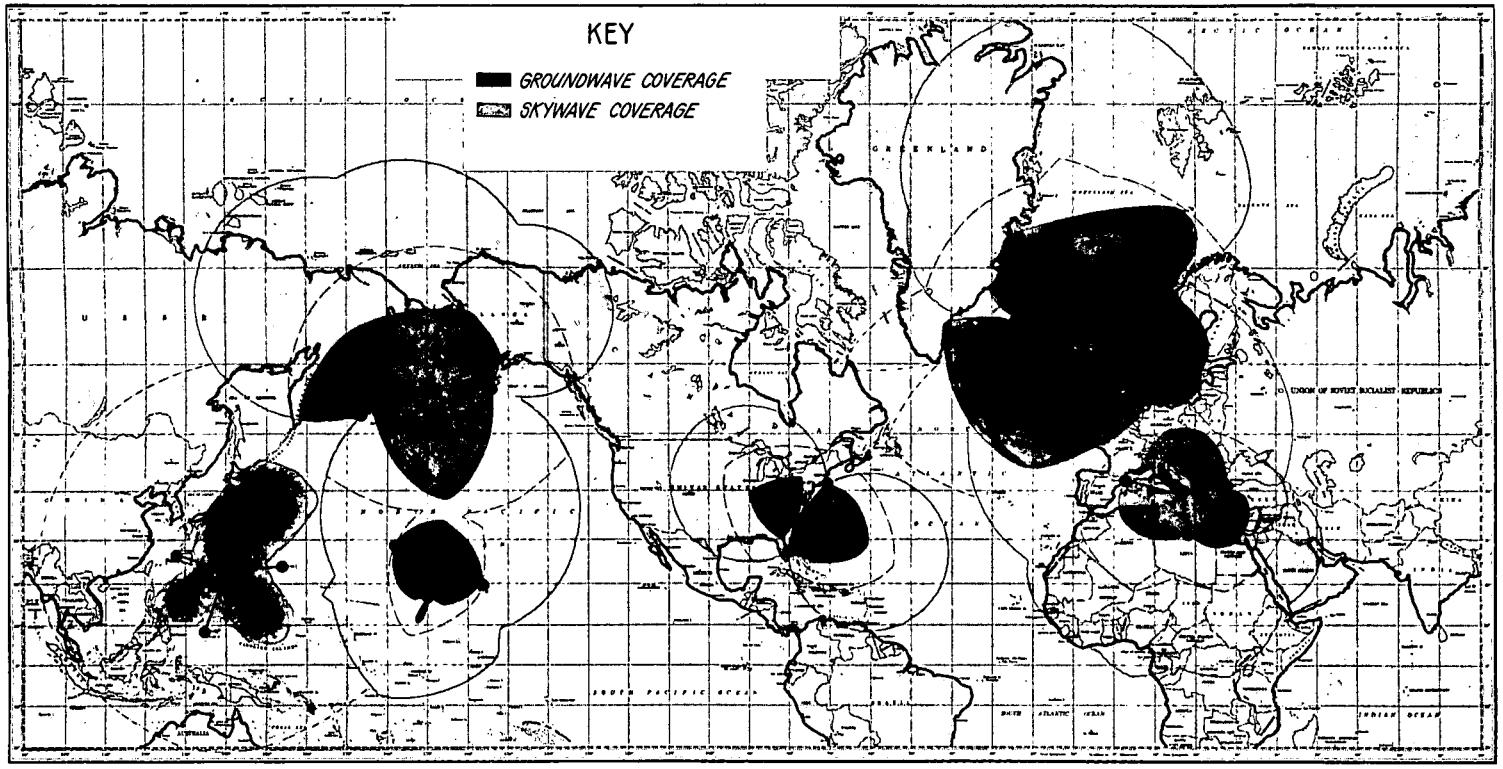
Omega is a very low frequency system of moderate accuracy. When the planned eight ground stations are in operation, the coverage will be global. The stations are large and complex but can be located outside of limited war theaters.

REPRESENTATIVE GROUND BASED NAVIGATION AIDS

SYSTEM	FREQUENCY	GROUND STATION POWER/ANTENNA	COVERAGE	ACCURACY
LORAN C	90-110 KHz	250 KW PEAK 625 FT HIGH ANTENNA	1500 N.MI. OVER WATER AT NIGHT 800-1000 N.MI. OVER WATER-DAY ~800 N.MI. BASELINE	0.5-1.0 N.MI.
LORAN D	90-110 KHz	3 KW PEAK 300 FT HIGH ANTENNA	300-500 N.MI. ~125 N.MI. BASELINE	0.1 N.MI. ABSOLUTE AT 250 N.MI. 0.01 N.MI. RELATIVE AT 250 N.MI.
OMEGA	10-14 KHz	10 KW AV COMPLEX ANTENNA	GLOBAL WITH 8 STATIONS	0.5 N.MI.-DAY 1 N.MI.-NIGHT 2 N.MI.-DAY/NIGHT PATH

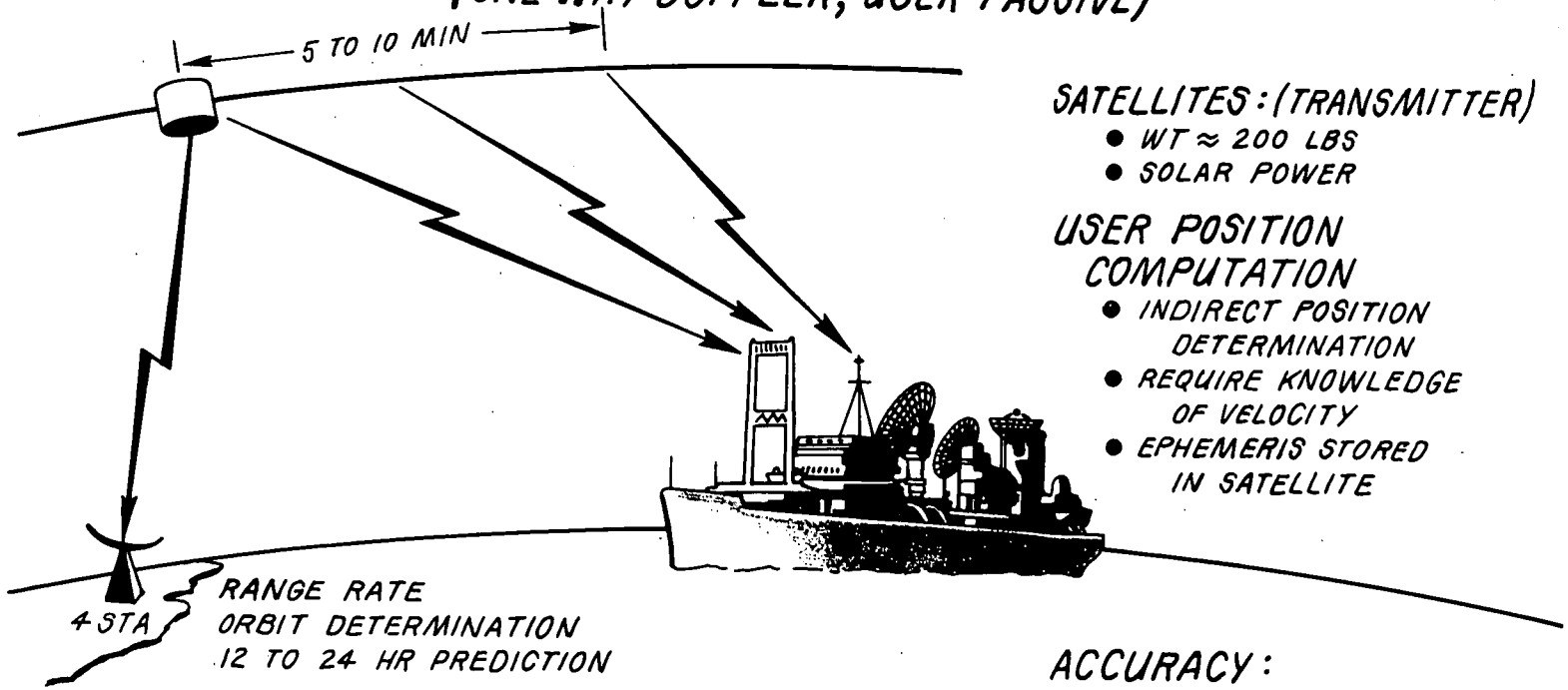
Although Omega, when fully implemented, will be a global system, the Loran systems are quite local unless a large number of stations are provided. This map shows the coverage provided by the Loran C system as it existed a year ago. Since that time, coverage has been provided in Vietnam. It is clear that many more stations would be required for truly global coverage, and that no station locations under control of this country could provide deep coverage of China or the USSR.

COVERAGE AREAS LORAN-C SYSTEM



A satellite navigation system commonly called Transit is presently operational; its management is assigned to the Navy. Transit is a sequential system wherein readings are taken on one satellite over a period of time with the satellite moving in its orbit. It is a range rate system and the user is passive. High accuracy can be obtained by fixed users, but no way is known of obtaining better than 0.25 n mi accuracy in even moderate speed aircraft. With four satellites, a fix can be obtained every 100 min.

TRANSIT SYSTEM
(ONE WAY DOPPLER, USER PASSIVE)



SATELLITES: (TRANSMITTER)
- WT ≈ 200 LBS
- SOLAR POWER

USER POSITION COMPUTATION
- INDIRECT POSITION DETERMINATION
- REQUIRE KNOWLEDGE OF VELOCITY
- EPHEMERIS STORED IN SATELLITE

ACCURACY:
- ONE PASS
  100 METERS (ABS)
  50 METERS (REL)
- SEVERAL PASSES
  5 METERS (ABS)

- ALTITUDE 600 N. MI.
- 4 SATELLITES 4 POLAR ORBITS
- FIX EVERY 100 MINUTES
- NOT SUITABLE FOR HIGH SPEED VEHICLES

The performance of existing navigation systems is summarized on this chart. Loran D will meet the identified tactical needs for accuracy, but it has limited range and vulnerable ground stations. Omega is global but does not have the desired accuracy.

The existing satellite navigation system meets the accuracy needs of fixed or slowly moving users, but requires an elaborate computer aboard the user and cannot provide continuous fixes. It cannot meet the needs of aircraft because of the lack of continuous fixes. In addition, the velocity of any aircraft introduces sizeable errors which become intolerable for hypersonic aircraft.

SUMMARY OF REVIEW

- LORAN D MEETS .01 N.MI. (R) TACTICAL NEED
  - REQUIRES 300 FT ANTENNA IN COMBAT AREA
  - REQUIRES TIME FOR SET UP
  - 300-500 N.MI. RANGE
  - TWO COMPONENT POSITION FIX
- OMEGA MEETS GLOBAL 1 TO 2 N.MI. (A)
  - TWO COMPONENT POSITION FIX
- EXISTING SATELLITES MEETS NON OR SLOW MOVING PRECISION USER NEED
  - SEQUENTIAL MEASUREMENTS
  - 5 TO 10 MINUTES FOR A FIX

Limitations of the existing navigation systems to the tactical high-speed aircraft and to other users are summarized on this chart. It is concluded that existing navigational systems do not meet the needs identified for tactical operations. Therefore, it is appropriate to consider the performance that can be achieved by a new navigation satellite designed to accommodate the needs peculiar to high-speed users and, to the extent possible, the needs of the other users identified previously.

[redacted]

LIMITATIONS OF EXISTING NAVIGATION SYSTEMS

- TACTICAL HIGH SPEED AIRCRAFT
  - ALTITUDE NOT PROVIDED BY ANY NAVIGATION SYSTEM
  - TRANSIT NOT SUFFICIENTLY ACCURATE FOR HIGH SPEED USER
  - GROUND SYSTEMS REQUIRE SET-UP TIME AND ARE VULNERABLE TO ATTACK
  - LIMITED RANGE MAY HAMPER OPERATIONS IN SOME THEATERS
  - LAND-SEA INTERFACE PROBLEMS

- LOW SPEED OR FIXED USERS
  - TRANSIT REQUIRES ELABORATE EQUIPMENT
  - TRANSIT NOT A COMMON SYSTEM WITH HIGH SPEED AIRCRAFT
  - GROUND SYSTEMS HAVE SET-UP AND VULNERABILITY PROBLEMS
  - NO SYSTEM COMPATIBLE WITH VERY SMALL USER

[redacted]

[redacted]

A variety of satellite navigation systems can be identified. It is the purpose of this section to determine which of these systems can meet the performance objectives stated previously.

INITIAL SYSTEM CONSIDERATIONS

Before considering the design of a new navigation satellite, it might be well to review changes in the technology which have occurred during the last few years that may allow the development of a navigation satellite system not previously considered feasible. The most specific change in satellite technology is the increase of mean time before failure (MTBF); MTBFs on the order of 3 to 5 yr now can be considered feasible. The introduction of integrated circuits permits high speed, general purpose digital computers to be available in shoe box size. Thus, a variety of users of a navigation system can perform the computations required to obtain position. All of the hardware required for synchronous communication satellites has been developed and tested including spin stabilization subsystems, despun antennas, and power output tubes. This hardware can be directly applied to navigation satellites. Cesium clock oscillators are now catalog items and are available for ground installation; these clocks have accuracies that at one time would have been considered unattainable. They are potentially available for use in space although the required packaging and testing have not been performed.

PRESENT TECHNOLOGY – A BASE FOR A NEW NAVIGATION SATELLITE

- MTBF IMPROVEMENTS OF COMPLEX ELECTRONIC EQUIPMENT ALLOW 3-5 YEARS SATELLITE LIFE
- DIGITAL COMPUTERS AVAILABLE WITH HIGH CAPACITY AND SMALL SIZES
- COMMUNICATION SATELLITE HARDWARE IS AVAILABLE
- CESIUM CLOCKS (OSCILLATORS) ARE DEVELOPED
  - ACCURACY OF 3 PARTS IN 10^{13}
  - AVAILABLE FOR GROUND INSTALLATION
  - POTENTIALLY AVAILABLE FOR AIRCRAFT AND SPACE

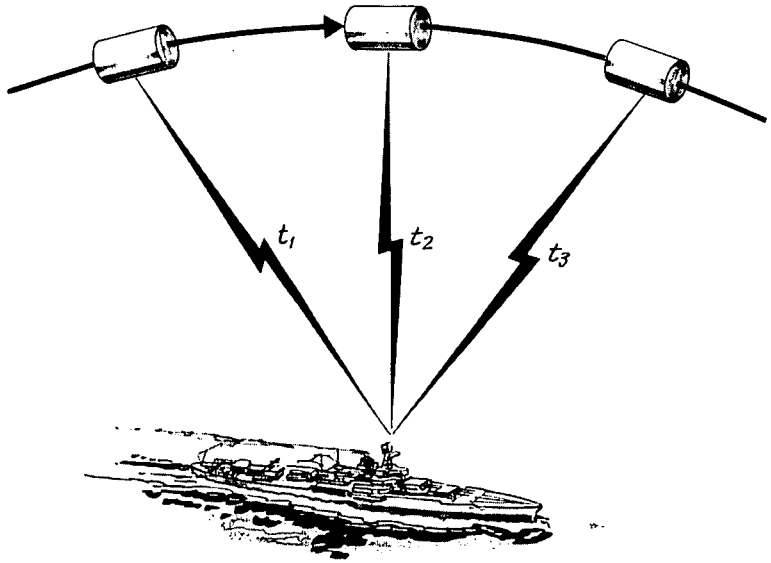
Based on the conclusions drawn from the user needs investigation, the objectives shown in this chart were developed to serve as a model for a navigation satellite system study. Global coverage is desired to accommodate a new tactical theater without delay. Regional coverage can serve as an economical substitute for global coverage if reasonable certainty exists that new theaters will develop only in a limited area. Growth from regional to global is then desirable. The users and their needs for accuracy are as developed earlier. The user equipment ground rule was taken as approximately that of a presently programmed system, Loran C, and represents a desired upper limit. In addition, a manpack set, not necessarily providing a display of the position to the user, is desirable for such purposes as target spotting. Continuous fixes are required to navigate high speed users. The passive user objective is required if radio silence is to be maintained by a user. As with all military systems, an appropriate countermeasure invulnerability is needed.

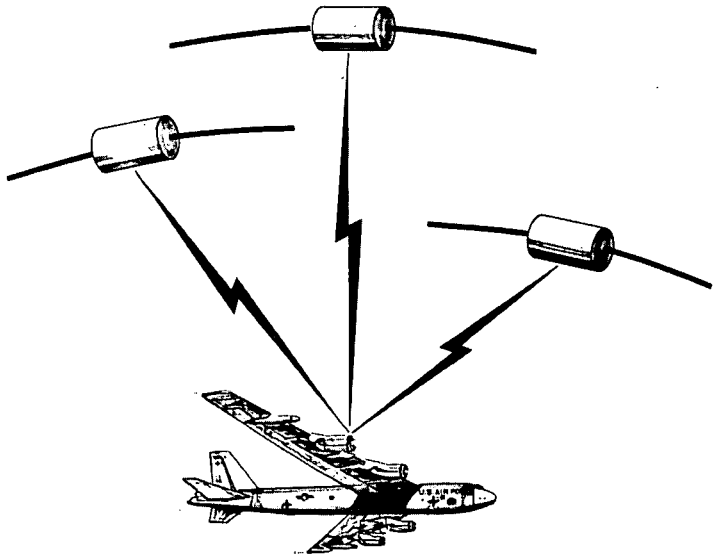
NEW NAVIGATION SATELLITE-SYSTEM OBJECTIVE

- COVERAGE
  - REGIONAL WITH GLOBAL OPTION
- USERS
  - HIGH SPEED AIRCRAFT
  - AIRCRAFT SUPPORT OPERATIONS
  - OTHER USERS, LARGE AND SMALL
  - GROWTH TO MISSILE LAUNCH AND TERMINAL GUIDANCE
- FUNCTIONS AND ACCURACY
  - POSITION
    - 0.1 NM ABSOLUTE
    - 0.01 NM RELATIVE
  - VELOCITY
    - GROWTH - 0.2 FPS
- USER EQUIPMENT
  - LESS THAN 100 LBS, LESS THAN $100,000
  - OPTION FOR MAN PACK DESIRED
- OTHER ATTRIBUTES
  - CONTINUOUS FIXES
  - PASSIVE USER AS AN OPTION
  - COUNTERMEASURE INVULNERABILITY

This chart addresses the choice between a sequential and simultaneous measurement system. A sequential system takes measurements during the passage of a satellite through the field of view. It requires the satellite to be at a relatively low altitude but minimizes the number of satellites required. Simultaneous systems make measurements from several satellites at the same time and, consequently, more satellites are required. The simultaneous method is the only one available for high speed users who require continuous measurements. In view of study objectives, it is the method selected.

SEQUENTIAL VS SIMULTANEOUS





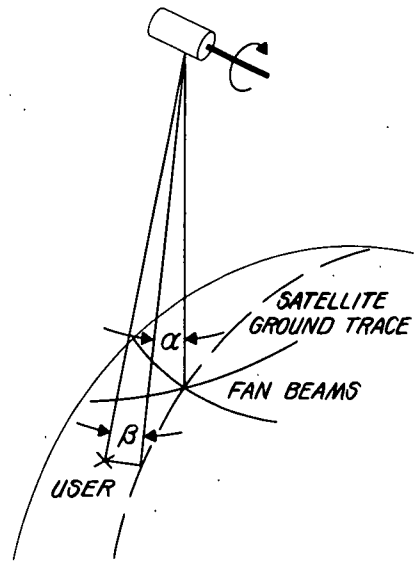
- 5 TO 10 MINUTES FOR FIX
- LIMITED TO LOW SPEED USERS
- LOW ALTITUDE SATELLITES

- INSTANTANEOUS FIX
- COMPATIBLE WITH NEAR CONTINUOUS NAVIGATION OBJECTIVES
- SYNCHRONOUS ALTITUDE

Four types of simultaneous measurements can be made. An angle measuring system is attractive because it requires but a single satellite. Unfortunately, no known angle measuring technique will yield the accuracy set as the objective of this study. Range rate methods require moderate altitude satellites and cannot be used by high speed aircraft since the velocity of the aircraft must be accurately known in order to correctly determine range rate. Thus, only the range or the range difference methods are applicable to this study.

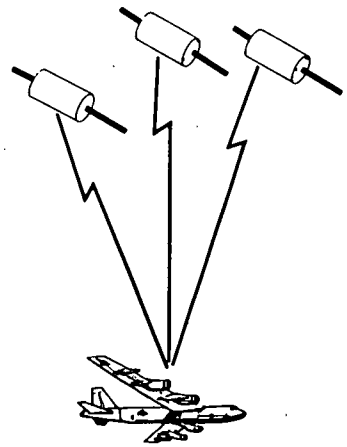
SIMULTANEOUS MEASUREMENT TECHNIQUE

ANGLES



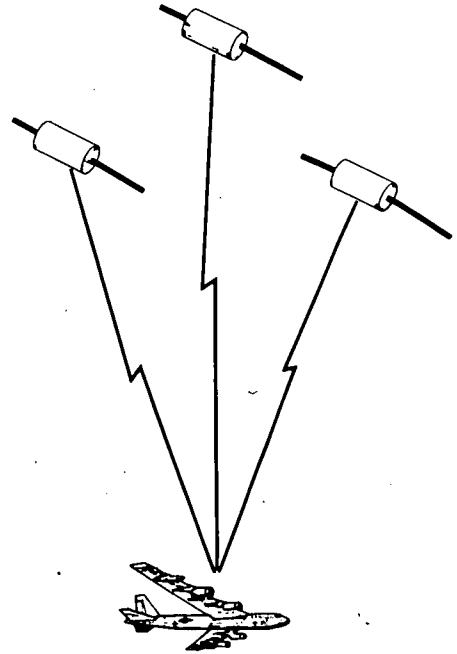
- SINGLE LARGE SATELLITE
- LOW ACCURACY

RANGE RATE
(ONE WAY DOPPLER)



- MULTIPLE MODERATE ALTITUDE SATELLITES
- INDIRECT DETERMINATION OF POSITION
- POSITION ACCURACY DEPENDENT ON ACCURACY OF USER VELOCITY

RANGE/RANGE DIFFERENCE



- MULTIPLE SATELLITES
- DIRECT DETERMINATION OF POSITION

This chart establishes synchronous altitude as the appropriate altitude for a navigation satellite. The most compelling reason for choosing a synchronous orbit is that a synchronous system allows regional coverage at minimum cost while allowing gradual extension of coverage to a global system as additional satellites are launched.

ORBIT SELECTION
(RANGE/RANGE DIFFERENCE SYSTEM)

FACTORS:

- COVERAGE - FAVORS SYNCHRONOUS
- EASE OF TRACKING (AND PREDICTING) - MAY FAVOR SYNCHRONOUS
- LINK POWER LOSS - FAVORS LOW ALTITUDE, TENDS TO BE INVARIANT AT MEDIUM/SYNCHRONOUS ALTITUDE
- ABILITY TO FIELD PART OF GLOBAL SYSTEM - FAVORS SYNCHRONOUS
- ERROR GEOMETRY - FAVORS NON-EQUATORIAL

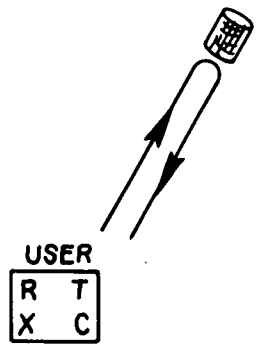
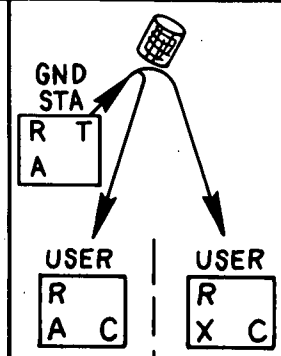
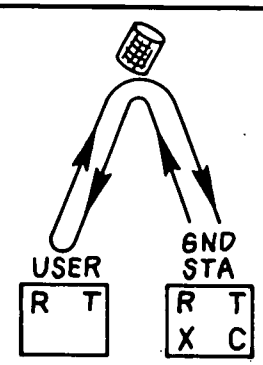
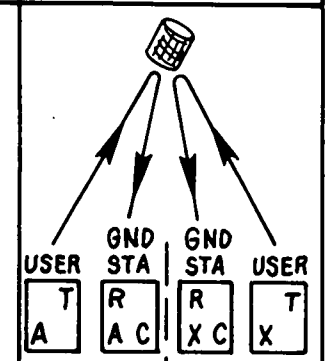
RESULTS OF ANALYSIS:

- LOW ALTITUDES RULED OUT FOR CONTINUOUS COVERAGE
- MEDIUM ALTITUDES POSSIBLE
- SYNCHRONOUS ALTITUDES APPEAR BEST
  - FIXED ANTENNAS FOR TRACKING STATIONS
  - NO HAND OFF AND REACQUISITION
  - PARTIAL GLOBAL COVERAGE POSSIBLE WITH LIMITED SYSTEM OR DURING SYSTEM ACQUISITION
  - SIMPLIFIED BOOKKEEPING BY USERS

[redacted]

It is concluded that the only way of meeting the stated objectives of the navigation satellite is with a simultaneous range or range difference system, preferably at synchronous orbit. This chart indicates at least 12 varieties of such systems; these methods are categorized by the location of the computation equipment and, hence, the location at which position fixes are supplied. The methods are further defined by whether the ranging is done by two-way (i. e., sending a signal out and then back and measuring the time of transit) or only one-way transmission. The necessary types of equipment are indicated by the letters within the user and ground station boxes. In the lower portion of the chart, the applicability of the method to range or range difference is indicated. In each case one less measurement and, consequently, one less satellite is required if an altimeter is used to measure the altitude of the user or if the altitude can be inferred by other means. The situations not requiring an altimeter will develop altitude information directly. It is shown at the bottom of the chart whether the user is active or passive. The systems on the extreme right and left are ruled out because the ranging operation is initiated by the user. The implication of this is that the number of users must be severely limited to avoid overloading the system. The two methods near the center of the chart remain under the control of the central station; hence, any number of users can be effectively controlled. The two-way mode with ground station computations is preferable for a user who is limited in the amount of equipment he can carry. The one-way mode with a crystal clock and with computations performed by the user requires no equipment beyond the present state of the art and is suitable for a more sophisticated user. A system with an atomic clock at the user is advantageous inasmuch as it requires fewer satellites, but it will not be practical until an atomic clock can be developed and flight tested for the user's environment. It is concluded that it is desirable in a new navigation satellite system to have the options of performing the two modes near the center of the chart - the two-way mode and initially the user with the crystal clock who must rely on range differences - with growth to the user with an atomic (cesium) clock.

RANGE AND RANGE DIFFERENCE SYSTEMS

LOCATION OF COMPUTATION	COMPUTATION PERFORMED BY USER		COMPUTATION PERFORMED BY GROUND STATION	
NAVIGATION RADIO LINK	2 WAY	1 WAY	2 WAY	1 WAY
USER EQUIPMENT R = RECEIVER T = TRANSMITTER X = CRYSTAL CLOCK A = ATOMIC CLOCK C = COMPUTER				
APPLICABLE MEASUREMENTS 2 SATS pph 3 SATS ppp 3 SATS ΔpΔph 4 SATS ΔpΔpΔp	✓ (ALTIMETER) ✓	✓(ALTIMETER) ✓ ✓(ALTIMETER) ✓	✓ (ALTIMETER) ✓	✓ (ALTIMETER) ✓ ✓(ALTIMETER) ✓
	USER ACTIVE	USER PASSIVE	USER ACTIVE	USER ACTIVE

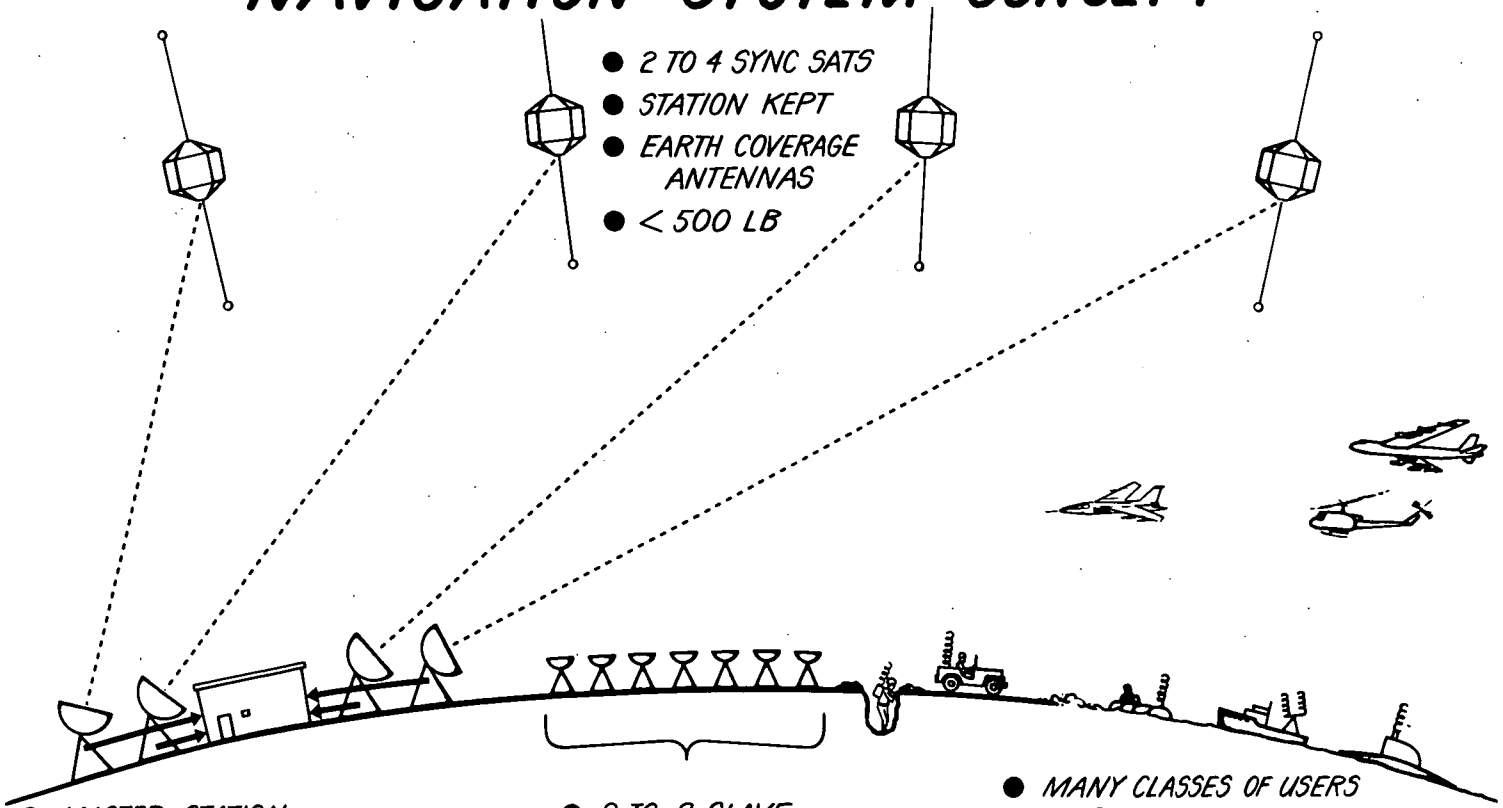
[redacted]

It has been determined by the rationale just presented that the system objectives developed earlier can be best met by a synchronous orbit satellite navigation system employing simultaneous range or range-difference measurements and two user modes - one-way passive for the sophisticated user, two-way active for the user who is severely weight and power limited. A more detailed study of the design of such a system will now be presented.

SYSTEM DESIGN

A general conceptual drawing of the navigation satellite system is shown on this chart. The master station contains a computer and a number of modest tracking antennas. The master station computes positions for the users who do not carry their own computers and tracks and determines the position of the satellites. The slave stations participate in the tracking to allow the satellite positions to be determined by real-time trilateration. The chart indicates the wide variety of users who could utilize this system.

NAVIGATION SYSTEM CONCEPT



- MASTER STATION
- 2-4 ANTENNAS
- 1 COMPUTER
- KNOWN LOCATION
- OUTSIDE COMBAT THEATER

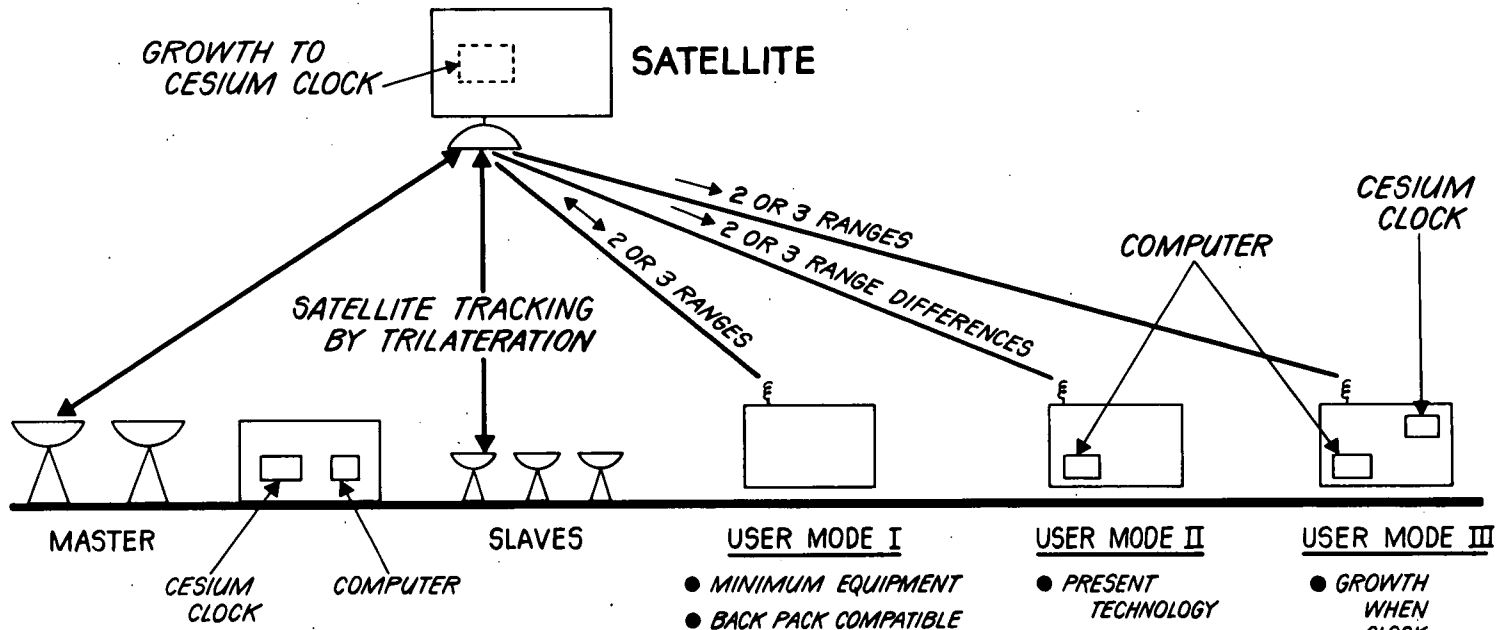
- 2 TO 8 SLAVE STATIONS
- KNOWN LOCATION
- EXTRA STATIONS FOR RELIABILITY
- OUTSIDE COMBAT THEATER

- MANY CLASSES OF USERS
  - PASSIVE USER
  - MINIMUM COST ACTIVE USER
  - HIGH SPEED USER
- ACCURACY UP TO: 0.1 NM ABS 0.01 NM REL

[redacted]

Three user modes are identified and some of their salient features are indicated on this chart. A cesium clock (atomic clock) in the satellite will allow the navigation system to survive for a number of days following destruction of the ground station. Such an option will allow limited survivability of the system after the start of an all-out war.

SUMMARY OF USER MODES



USER MODE I

- MINIMUM EQUIPMENT
- BACK PACK COMPATIBLE
- UP-LINK INCREASES VULNERABILITY
- ACTIVE-NO RADIO SILENCE
- CENTRAL COMPUTATION
- INTERMITTENT FIXES
- LIMITED NUMBER OF SIMULTANEOUS USERS

USER MODE II

- PRESENT TECHNOLOGY

USER MODE III

- GROWTH WHEN CLOCK AVAILABLE

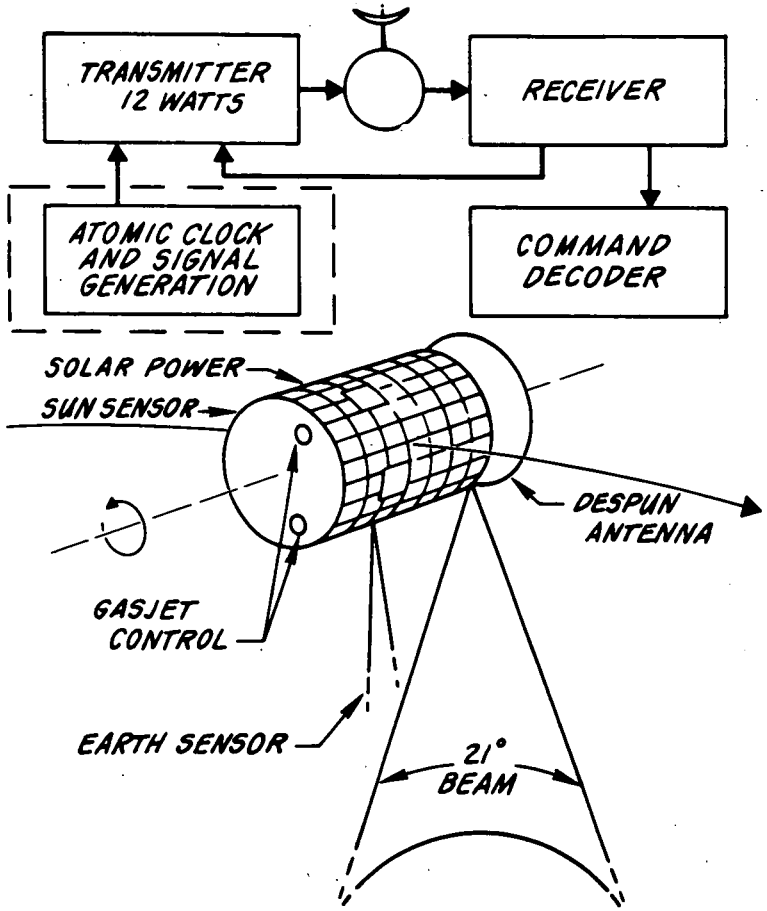
- PASSIVE
- USER COMPUTATION
- CONTINUOUS FIXES
- UNLIMITED NUMBER OF USERS

[redacted]

A possible configuration of the satellite is shown on this chart. Weights are given for the system both with and without the cesium clock. The cesium clock is contained in the communication items of the weight breakdown. In addition to the weight of the clock, many other subsystems have increased weight. With the exception of the atomic clock, which is a growth item, the vehicle is conventional and within the state of the art, relying heavily on the technology utilized in communication satellites.

SPACECRAFT SIZE AND WEIGHT

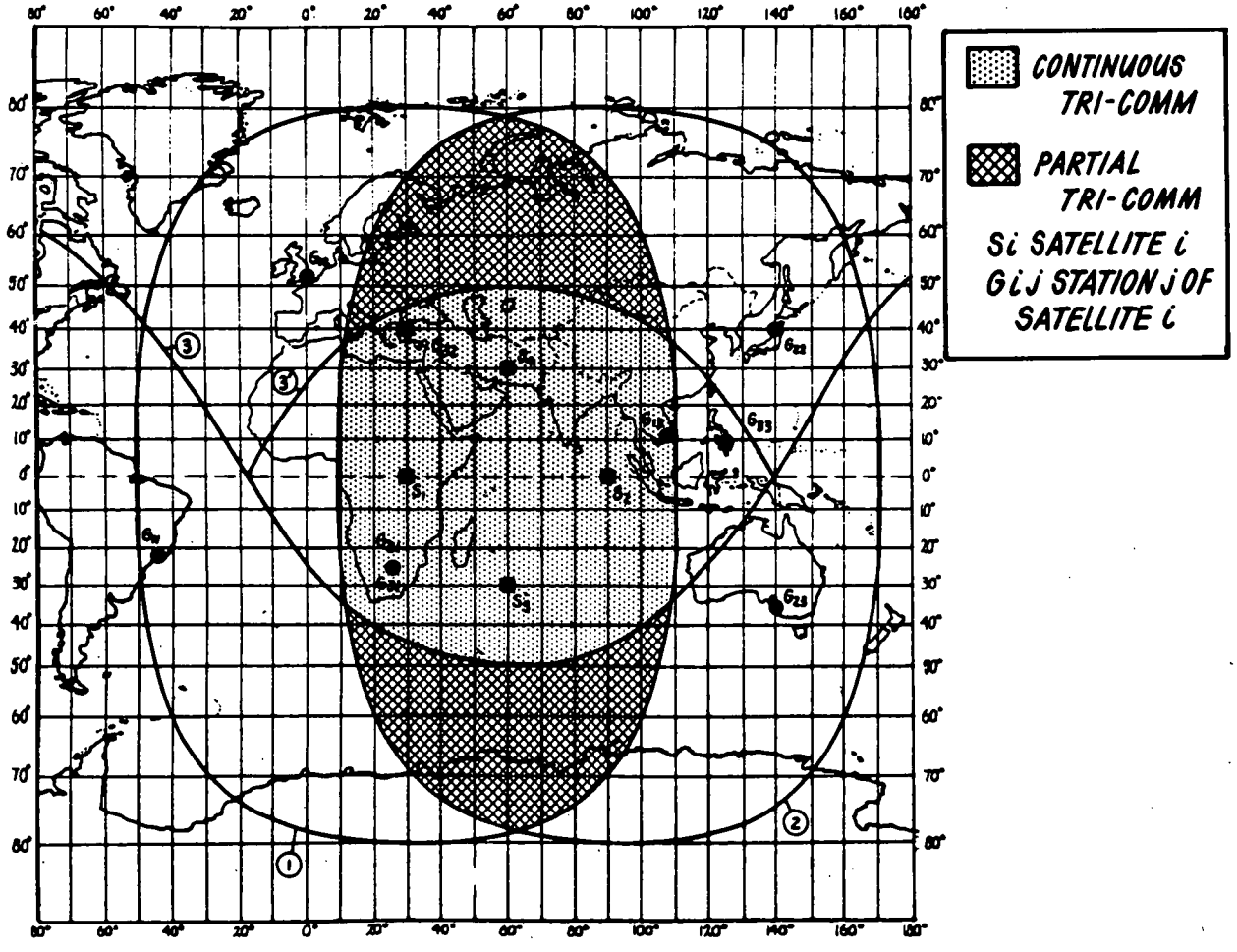
SIMPLE BLOCK DIAGRAM



	NO CLOCK	CLOCK
DIMENSIONS:		
DIAMETER	57.0 IN	(57.0 IN)
LENGTH	45 IN	(69 IN)
POWER:	95 WATTS	(145)
WEIGHT BREAKDOWN		
COMMUNICATION	63	(109)
ATTITUDE CONTROL	11	(11)
OTHER CONTROLS	11	(11)
POWER SUPPLY	85	(130)
PROPULSION	25	(35)
STRUCTURE	33	(52)
CONTINGENCY	25	(39)
WEIGHT ON ORBIT	253 LBS	(387 LBS)

A possible satellite system geometry and its coverage are indicated on the accompanying chart. Satellites are shown at longitudes of 90°E and 30°E and another is shown in a figure 8 (nonequatorial) orbit around 60°E. The dotted area receives continuous coverage from three satellites and allows good navigation performance in the case illustrated for Vietnam, India, most of central Asia, and most of Africa. In addition, the cross-hatched portion receives partial coverage from three satellites and continuous coverage from two satellites. Two satellites properly phased in the figure 8 orbit would improve coverage appreciably.

TWO & THREE SATELLITE SYSTEM GEOMETRY & COVERAGE



Other studies of coverage from various satellite geometries have established that 2 to 4 satellites will provide coverage for one region while 10 to 18 satellites would be required for continuous global coverage. In addition, schemes are available for coverage of the globe with the exception of the polar region at a saving of several satellites over the all-global system or systems in which all satellites are launched due east from ETR which results in a performance improvement for the boosters. The optimum coverage and consequently the precise number of satellites required cannot be determined until specific operational requirements are established.

COVERAGE SUMMARY AND OPTIONS

- 2-4 SATELLITES PROVIDE COVERAGE FOR ONE OR MORE LOCAL BATTLEFIELD AREA
- 10-18 SATELLITES IN SEVERAL ORBIT INCLINATIONS PROVIDE CONTINUOUS GLOBAL COVERAGE
- THERE EXIST OPTIONAL DEPLOYMENT SCHEMES
  - FOR SEMIGLOBAL COVERAGE
  - ALL SATELLITES AT ONE INCLINATION

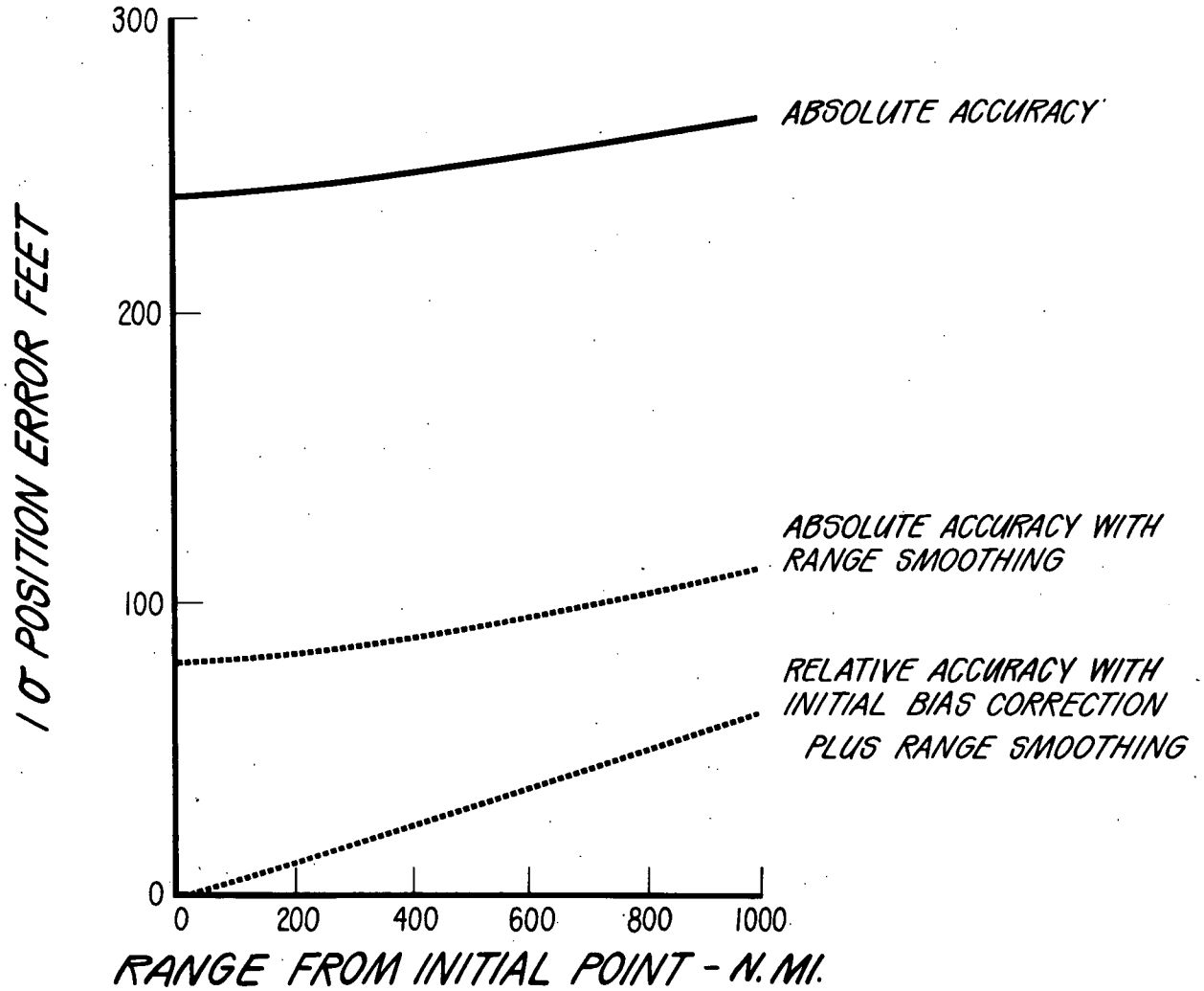
[redacted]

A variety of error analyses have been performed on the navigation system outlined in the preceding charts. In general, it has been found possible to obtain the desired accuracies over the entire region of coverage in a continuous fashion. This has generally required an extra satellite (i. e., four rather than three) for regional coverage in order to prevent decreased accuracy at specific earth locations or at specific times of day. Typical accuracies are given in this chart for several situations. In each case, a starting point of a typical mission was assumed and a departure from this position of up to 1000 n mi was allowed. The absolute accuracy (the accuracy with respect to earth coordinates) easily meets the 0.10 n mi (~600 ft) objective. Moderate range smoothing will appreciably improve this performance for users who can tolerate the resulting delay. Furthermore, the relative accuracy objectives - namely, 0.01 n mi (~60 ft) - can be met if the initial bias errors can be corrected (e. g., an aircraft setting the known location of the end of the runway into the system at take-off) or ignored (e. g., a bomber attacking a target located by a forward air controller).

[redacted]

[redacted]

NAVIGATION ACCURACY



Preliminary estimates of weight, volume, and cost of the user equipment for the three identified modes of operation are given in this chart. The figures are based upon current state of the art for all except the atomic clock which has yet to be developed for nonfixed operation. It is expected that the volume and weight of all these equipments could be substantially reduced by employing the presently emerging technology of micro-miniaturization.

USER EQUIPMENT

	VOLUME CU FT	WEIGHT LBS	POWER WATTS	COST 1000 $
MODE I				
ACTIVE USER TWO-WAY RANGE MODE				
RECEIVER, PROCESSOR, TRANSMITTER	1.2	55	110	16
MODE II				
PASSIVE USER RANGE DIFFERENCE MODE				
RECEIVER, CRYSTAL CLOCK, DISPLAY	1.1	54	79	19
COMPUTER, IF DEDICATED	0.3	30	75	20
TOTAL	1.4	84	154	39
MODE III				
PASSIVE USER RANGE MODE				
RECEIVER, ATOMIC CLOCK, DISPLAY	1.5	80	108	33
COMPUTER, IF DEDICATED	0.3	30	75	20
TOTAL	1.8	110	183	53

A first order estimate of the cost of deploying a satellite system for five years is given on this chart. Costs are given for a regional system covering an area similar to that shown on page 67 and for the additional satellites and ground stations required to convert the regional system into one providing global coverage. Operation and maintenance of the ground stations as well as the costs of user equipment are not included. Although the cost is appreciable, it is apparent that the cost of this system is not prohibitive. It is concluded that it is desirable that the needs of as many users as possible be satisfied by the system.

SYSTEM COST ESTIMATE
EXCLUSIVE OF USER EQUIPMENT
MILLIONS OF DOLLARS

	REGIONAL SYSTEM	ADDITIONAL FOR GROWTH TO GLOBAL SYSTEM
• R AND D	25	—
• SATELLITES FOR 3 YEARS CAPABILITY (4 SATS)	8	(10 SATS) 20
• LAUNCH COSTS	12	30
• GROUND STATIONS	4	11
TOTAL	49	61
• REPLENISHMENT FOR 2 ADDITIONAL YEARS	15	50
GRAND TOTAL	64	111

The system which has just been described possesses a number of attractive features in comparison with existing or programmed navigation aid systems. These are summarized on the accompanying chart. An additional feature not listed is the all-weather availability of this system.

The fundamental advantage of this system over ground-based systems is the inherent result of using high-altitude satellites - namely, wide coverage without prohibitive cost and freedom to choose a high operating (radio) frequency to meet accuracy requirements without penalizing coverage. The wide coverage permits additional flexibility in the location of the necessary ground facilities.

This satellite system, as compared with Transit, has the advantage of serving aircraft with high accuracy, resulting from the use of simultaneous range/range difference rather than sequential range-rate measurements.

OPERATIONAL ADVANTAGES OF A NEW NAVIGATION SATELLITE SYSTEM

- ACCOMMODATE HIGH SPEED AIRCRAFT WITH HIGH ACCURACY
  - 0.1 N MI ABSOLUTE, 0.01 N MI RELATIVE
- GLOBAL COVERAGE
  - NO SETUP TIME IN NEW THEATRE
  - COMMON GRID FOR ALL USERS
- GROUND EQUIPMENT FLEXIBILITY
  - UTILIZE AREAS OF LOW RISK OF ATTACK
  - REDUNDANT FACILITIES FEASIBLE
- SYSTEM CONCEPT PERMITS GROWTH
  - GUIDANCE FOR MISSILE LAUNCH
  - MISSILE TERMINAL GUIDANCE

TECHNICAL SUMMARY

It is concluded that a navigation satellite system meeting the previously stated objectives and capable of serving through multiple modes of operation the tactical users previously identified, is feasible with present technology. The development of cesium clocks suitable for operation in satellites and/or users has value for a growth system. It is appropriate at this time to consider system definition studies and an experimental demonstration of the concepts.

SUMMARY

- A SYNCHRONOUS NAVIGATION SATELLITE SYSTEM IS FEASIBLE
  - 0.1 N.MI. ABSOLUTE ACCURACY
  - ~0.01 N.MI. RELATIVE ACCURACY
- AN IMMEDIATE CAPABILITY CAN BE ACHIEVED WITH A NON-CLOCK SYSTEM
- SATELLITE AND/OR USER CESIUM CLOCK DEVELOPMENT HAS PAYOFF FOR GROWTH SYSTEM
- SYSTEM DEFINITION STUDIES AND EXPERIMENTAL DEMONSTRATIONS ARE NOW APPROPRIATE

There is an immediate need for the contractor studies to further optimize the system and complete configuration and error analyses. Concurrent with these studies, an Advanced Development Plan (ADP) can be formulated. If approved, the ADP would begin with contract definition and proceed to deploy an experimental system which could demonstrate accuracies and simulate the operational utilization of such a system. In addition, the ADP would investigate synchronous tracking and prediction and multipath restrictions. The satellite system configured in the preceding section used continuous trilateration to determine the satellite positions. If a means could be developed to predict with sufficient accuracy satellite position for a few hours to a few days in advance, a significant simplification in user and ground equipments could be realized. Multipath has been observed to be a serious problem in aircraft-to-satellite communications. It is believed that the signals employed in navigation can be made resistant to this effect, but appropriate measurements and demonstrations will be required. Concurrent technology studies would have impact on growth versions of the system.

STUDIES AND DEVELOPMENT PROGRAM

- CONTRACTOR STUDIES
  - ORBIT OPTIMIZATION - COVERAGE AND SYSTEM ERRORS
  - GROUND, SATELLITE, AND USER EQUIPMENT OPTIMIZATION
  - DEFINITION OF EXPERIMENTAL OBJECTIVES
- ADP FORMULATION
- CONTRACT DEFINITION
- DEVELOPMENT PROGRAM
  - ACCURACY DEMONSTRATION
  - AIRCRAFT MULTIPATH RESTRICTIONS
  - SYNCHRONOUS TRACKING AND PREDICTION
  - OPERATIONAL SIMULATION
- CONCURRENT TECHNOLOGY STUDIES
  - INPUT TO GROWTH VERSIONS OF SYSTEM

Some especially appropriate technology studies are indicated on this chart. The first two developments concerning cesium clocks have been previously identified. A steerable aircraft antenna and suitable operating procedures would enable the navigation satellite system to survive appreciable local jamming attempts. The helicopter presents a special environment problem because of weight limitations, vibration, and the possibility of helicopter modulation of signals. Before measurements of multipath and synchronous tracking and prediction capabilities are made in the ADP, measurements could be made using existing satellites, especially some of the synchronous or near synchronous communication satellites.

TECHNOLOGY STUDIES AND DEMONSTRATIONS

- SPACE QUALIFIED CESIUM CLOCK
- AIRCRAFT QUALIFIED CESIUM CLOCK
- STEERABLE AIRCRAFT ANTENNA
- HELICOPTER ENVIRONMENT STUDY
- PRE ADP MEASUREMENTS OF MULTIPATH AND SYNCHRONOUS TRACKING AND PREDICTION

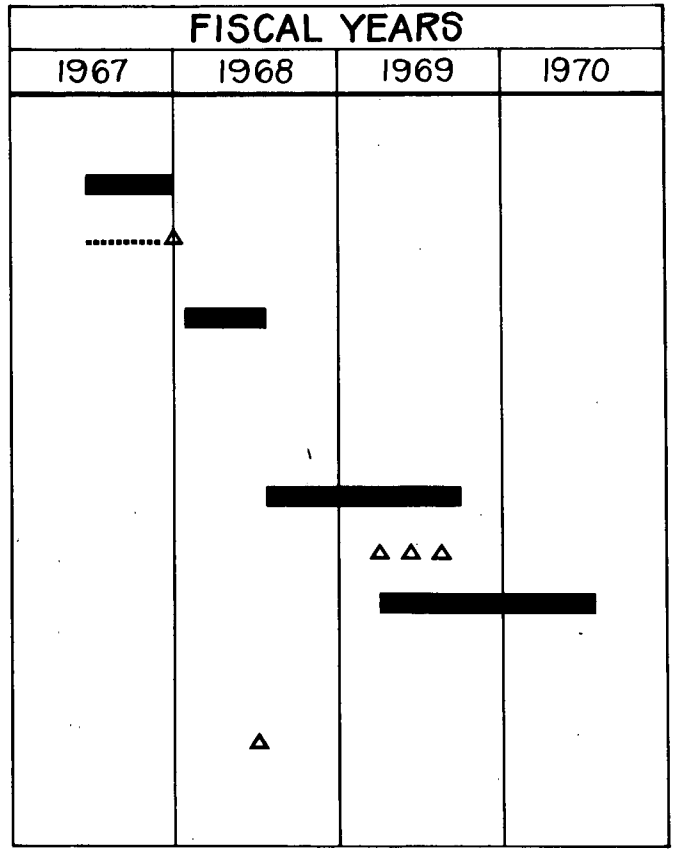
The succeeding charts will summarize the program implications of the course of action outlined.

NAVIGATION SATELLITE PROGRAM

A schedule of the various activities is given on this chart. The mid-FY 68 operational decision is based upon the knowledge gained from the first year of contractor studies. At this point, a more rapid development of an operational system could be substituted for the development program given. If, on the other hand, the decision to proceed as rapidly as possible were made in mid-FY 67, approximately one year could be saved.

SCHEDULE

- STUDIES AND CONCEPT FORMULATION
  - CONTRACTOR STUDY
  - ADP FORMULATION
- CONTRACT DEFINITION
- DEVELOPMENT PROGRAM
  - PROCUREMENT OF FLIGHT TEST EQUIPMENT
  - LAUNCHES
  - MEASUREMENTS AND DATA REDUCTION
- EARLIEST DECISION ON QUASI-OPERATIONAL SYSTEM



An estimate of the funding required for the program given in the preceding schedule is shown on this chart. Funding for the various technology studies identified as desirable inputs to the growth systems has not been included. In addition, it is assumed that launch and launch integration will be provided through the Space Experiment Support Program (SESP).

FUNDING ESTIMATE (MILLIONS)

	FISCAL YEARS				
	1967	1968	1969	1970	TOTAL
CONTRACTOR STUDIES	0.7				0.7
CONTRACT DEFINITION STUDIES		1.0			1.0
DEVELOPMENT PROGRAM (ASSUMING SESP LAUNCHES)		5.0	10.0	5.0	20
TOTAL	0.7	6.0	10.0	5.0	21.7

A breakdown of the development program item from the preceding chart is given here.

DEVELOPMENT PROGRAM
MILLIONS OF DOLLARS

	FISCAL YEAR 1968	1969	1970	TOTAL
SYSTEMS ENGINEERING				
SYSTEM INTEGRATION	.4	.4	.2	1.0
COMPUTER PROGRAMMING	.4	.4	.2	1.0
SUPPORT TO EXPERIMENTAL OPERATIONS		.7	1.3	2.0
DATA REDUCTION OF SYSTEM ANALYSIS		.5	1.0	1.5
EQUIPMENT DEVELOPMENT AND FABRICATION				
SPACECRAFT	2.0	3.8	.7	6.5
GROUND STATIONS	.7	1.9	.4	3.0
USER EQUIPMENT	1.0	2.0	1.0	4.0
AGE AND TEST SUPPORT	.5	.3	.2	1.0
TOTAL	5.0	10.0	5.0	20.0

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