CR 86165

December, 1968
Final Report

# Navigation|Traffic Control Satellite Mission Study

Contract No. NAS 12-596

## Volume IV
## Critical Technology, Growth and Economic Summaries

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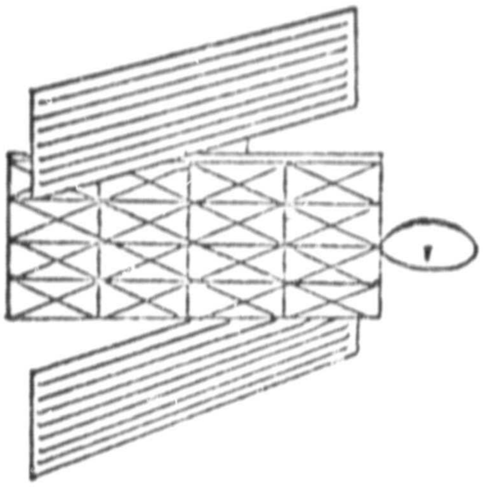

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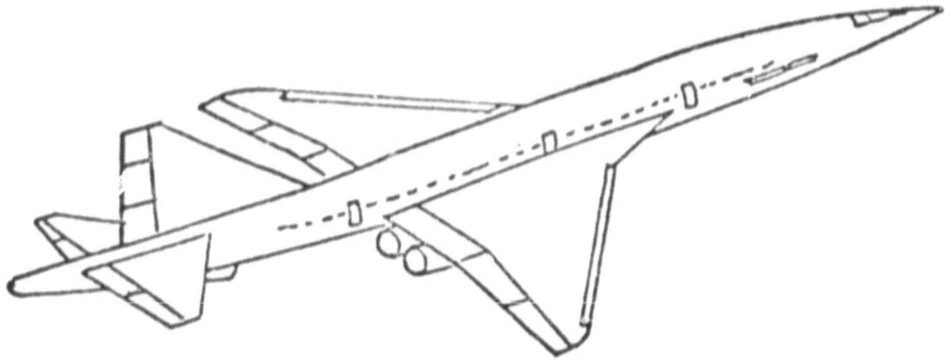

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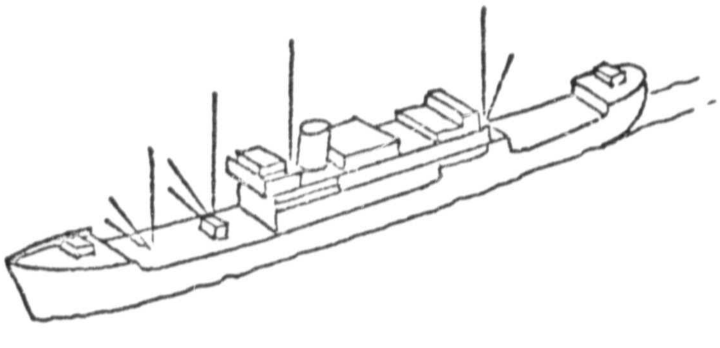

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## PREFACE

The objective of this study is to identify the technological and economic factors involved in the implementation of a navigation/traffic control satellite system that would provide for efficient and safe operation of aircraft and ships over ocean areas by 1975.

### Organization of Final Report

The final report of the Navigation/Traffic Control Satellite Mission Study prepared by RCA is comprised of four volumes.

Volume I is a summary of the study and presents in concise form the objectives and results of the overall effort.

Volume II describes the candidate navigation/traffic control satellite systems which were investigated and compared, and documents the performance and cost analyses which were conducted in order to select a preferred system concept.

Volume III presents the mechanization of the preferred system after detailed trade-off analyses of various alternatives for the major elements and subsystems. Preliminary designs of the user equipments, spacecraft, and ground stations are described. The results of a performance analysis of the selected system, and cost estimates of an operational system configuration are tabulated.

Volume IV describes (1) the critical technology areas requiring further development, (2) a recommended experimental spacecraft and program for demonstrating the feasibility of the system concept in an operational environment, (3) the economic factors for developing and implementing the system for the North Atlantic and Globally, (4) the expanded coverage and growth capabilities of the system, and (5) the additional applications for which the system can be used.

### Contributors to the Study

This report represents a concerted effort by RCA personnel from (1) the Systems Engineering, Evaluation and Research (SEER) group, who led the technical effort and performed the overall system's analyses; (2) the Astro-Electronics Division (AED), who analyzed and designed the spacecraft and (3) the Aerospace Systems Division (ASD), who analyzed and designed the user equipments.

The principal RCA participants in this study were Michael W. Mitchell, Program Manager and Technical Director; Harry Rose and Leroy Tangradi, RF Design and Communications; Brian Stockwell, Space System Design and Integration; Carl Heldwein and Gerald Zerfas, User Equipments; William Lindorfer, Spacecraft Systems; Sajjad Durrani, Phased Arrays; Frank Taylor, Space Communications; Alfred Smith, Signal Processing; Morris Levinson, Error Analysis; and Jerome Barnla and Jack Breckman, Consultants.

Grateful acknowledgement is made for the suggestions and critiques of Mr. Ernest Steele, NASA-ERC Technical Monitor, and Mr. Eugene Ehrlich of NASA, Headquarters.

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## Section 1

# CRITICAL TECHNOLOGY DEFICIENCIES AND PROJECTED ADVANCEMENTS

### 1.1 INTRODUCTION

All of the techniques, equipments and operational procedures recommended in this report for the implementation of a Nav/TC satellite system to serve the North Atlantic by 1975 require technologies which are current state of the art. In many instances similar equipments, such as receivers, transmitters, precision oscillators, IF circuitry, phase detectors, computers, etc., are already in existence as available commercial products or developed items for one of the U.S. government agencies. However, these equipments have not been optimized for navigation satellite systems and have often not been demonstrated in space. Additional developments are required to indicate the full potential of the recommended system to meet the cost-effectiveness goals indicated at the beginning of this study.

In addition, some of the subsystems are in a very early state of development, and it seems reasonable to assume that substantial gains (possibly even significant breakthroughs) can be realized during the next two or three years if development programs are initiated soon. The spacecraft steerable phased array antenna for relaying voice communications is a case in point. An engineering model at 1.8 GHz currently under development by NASA-Goddard for data relay functions is an indication of the advanced status of present day technology for spacecraft phased array antennas. However, several companies including RCA are at the point of evolving improvements in solid-state electronics which will reduce the size, weight and power requirements of electronically steerable antennas within the next few years. These should be investigated at L-band frequencies in conjunction with the development of phased arrays for spacecraft applications.

In the following sections, technology deficiencies and projected advancements are discussed for each of the major terminals identified with the Nav/TC satellite system, the user equipments, the spacecraft and the ground stations.

## 1.2 USER EQUIPMENTS

Present trends in the development of solid-state, L-band power transistors and L-band, low-noise, solid-state amplifiers indicate that adequate components and parts will be available soon for the construction of low-weight, low-cost, L-band receivers and transmitters applicable to aviation and marine user requirements.

The required frequency standard for the passive airborne navigation user equipment was previously expected to be a critical item requiring an advancement in the state of the art. Recent advancements have been made in this area and this item is no longer considered to be critical.

A crystal frequency standard has been demonstrated by Frequency Electronics, Inc. Their Model FE-10A-MOD-L unit is claimed to have a long term frequency stability of 2 parts in $10^{11}$ per 24 hours which is equivalent to less than 600 feet range error at the end of an 8-hour flight. This range error is compatible with a one nautical mile navigation accuracy.

Hewlett Packard also advertises an oven controlled crystal oscillator with stabilities of 5 in $10^{11}$ per 24 hour period with a current price of $3000.

The required frequency standard for the marine user remains a problem, however, due to the duration of a ship's voyage. A 10-day or 240-hour voyage would require a frequency standard whose absolute accuracy is on the order of one part in $10^{12}$ to maintain a 1-nmi accuracy. This presently requires the use of a high accuracy atomic standard.

To provide one nautical mile accuracy for smaller vessels where equipment costs are extremely important, further developments should be sponsored with the objective of reducing the cost and complexity of atomic frequency standards. An alternative technique would be to incorporate "active" navigation equipment for the marine user, and have him update his clock once per day or as often as his navigation precision requirements dictated. In this way, a crystal clock would be sufficient.

In any event, since the cost of a precision clock is directly chargeable to the user interested in passive navigation, and this may constitute the most costly item in his overall navigation package, the need exists for developing an inexpensive precision crystal clock. A suggested achievable price for a simplified model, in production quantities of 1000 or more, is $1000.

The aviation user L-band antenna development is not considered to be difficult, although particular attention must be paid to multipath rejection. The problem does not appear to be reflection from ocean surfaces since the antenna (3-dB gain) size is small (8 - 10 inch diameter) compared to the fuselage diameter of most aircraft, and in an upward-looking configuration the aircraft body provides excellent shielding from RF energy reflected from below. However, the aircraft fuselage appendages and vertical stabilizers in the tail section are potential sources of multipath. Thus, each aircraft presents a unique problem in the design of the antenna. Experiments need to be conducted with several of the most likely aircraft configurations before a particular antenna design can be selected.

## 1.3 SPACECRAFT SUBSYSTEMS

During the mission study, several spacecraft configurations were developed and analyzed with the view of determining how well they met the various functional requirements of the Nav/TC system. One particularly interesting configuration, depicted in Figure 1-1, specified two 330-pound spacecraft. It provided for passive and active navigation, traffic surveillance, and data relay links. It did not include any voice channels, and thus was short of the overall capabilities desired for an operational Nav/TC system

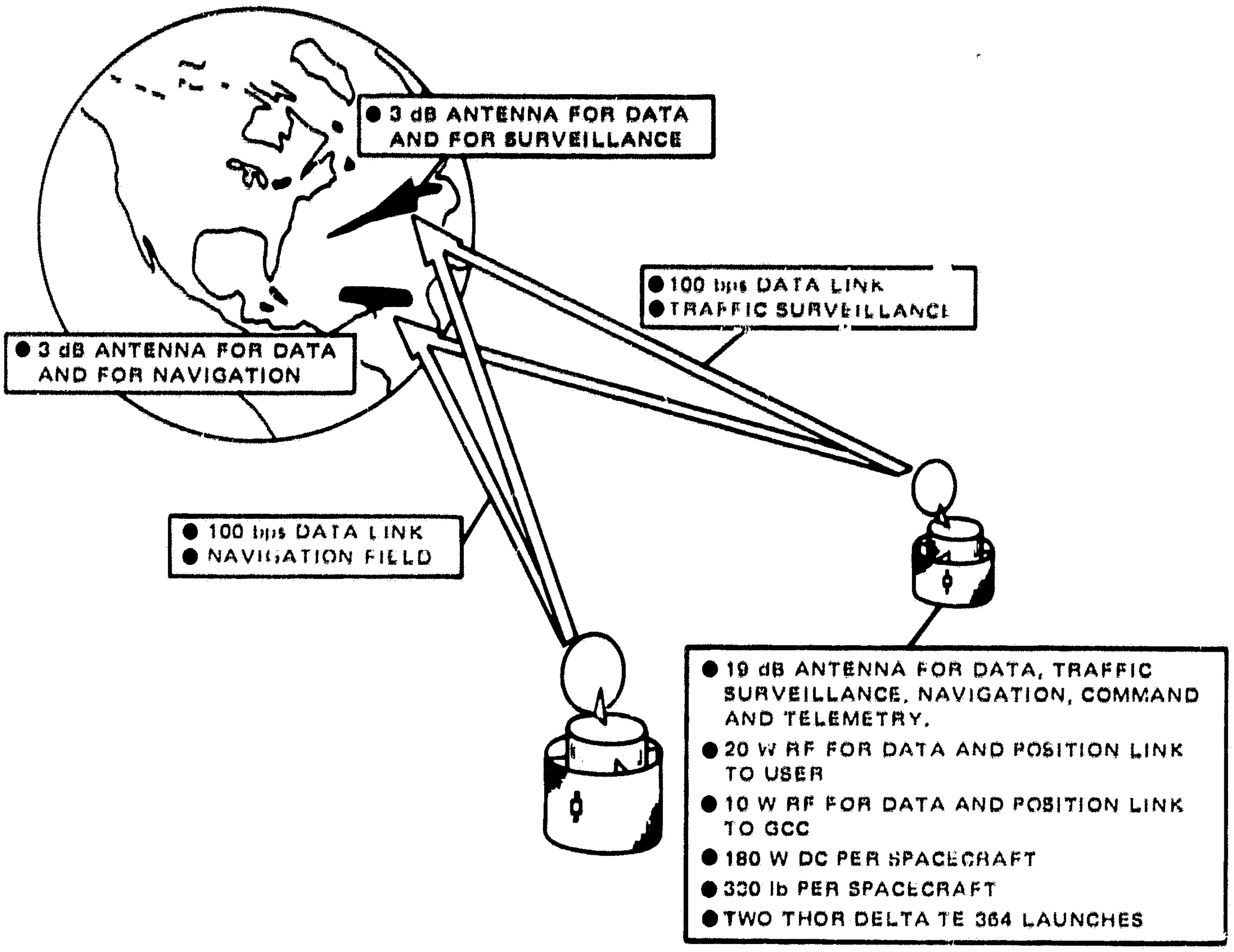

Figure 1-1. L-band Data/L-band Position Location

as set down by the initial guidelines of the study. It is mentioned here because this spacecraft and all its subsystems can be designed and constructed now without requiring any new R&D effort. It represents an excellent vehicle for fully demonstrating the functions and problems of an operational position location-data relay system for transoceanic service.

The addition of voice communications led to the recommended L-band configuration shown in Figure 1-2. The spacecraft weight increased to 760 pounds to accommodate, primarily, the increased effective radiated power (ERP) of the voice links. The

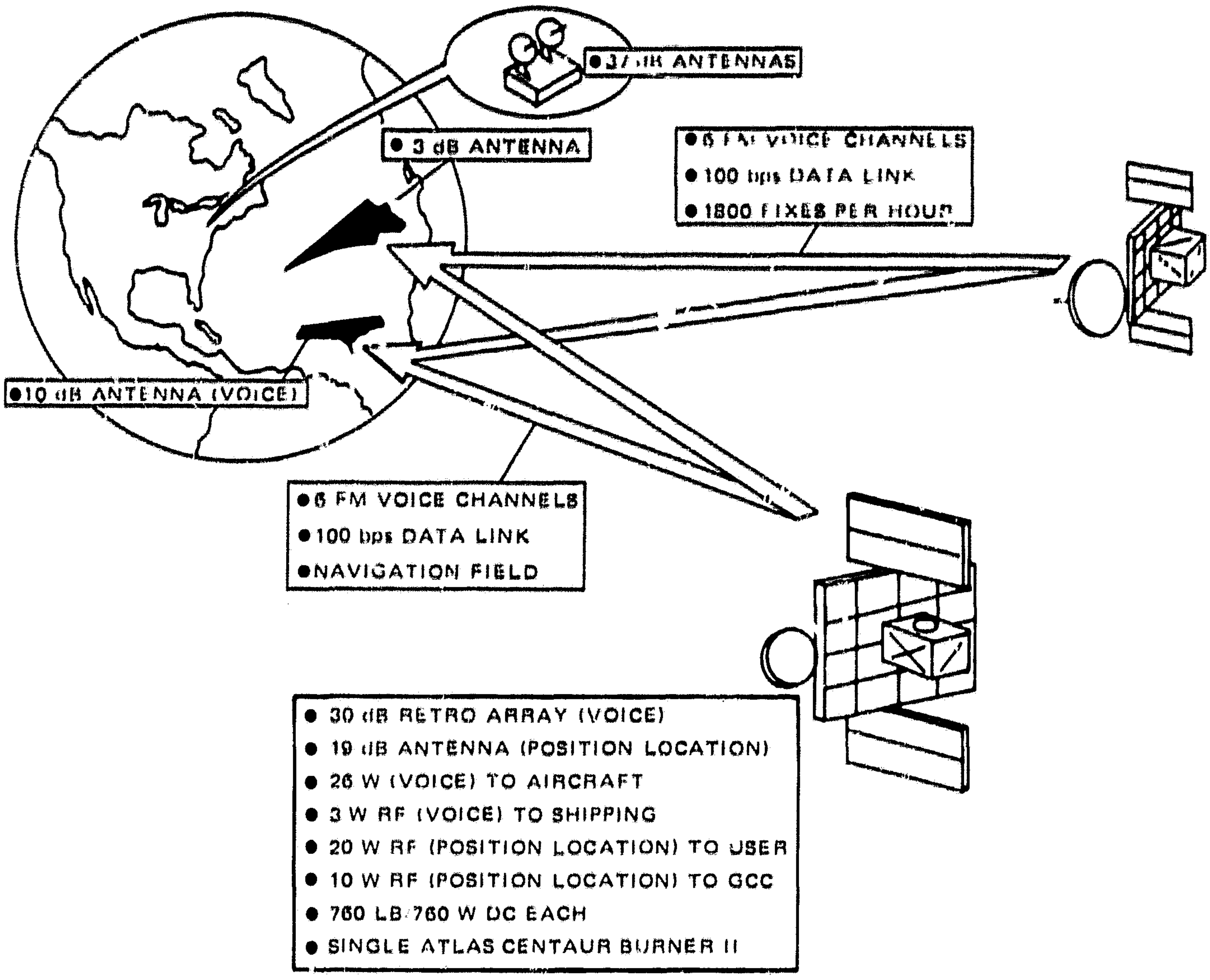

Figure 1-2. Operational System

message here is very evident. It points out that improvements in the voice equipment design can result in large payoffs in terms of reduced weight and costs. Additional analysis of the spacecraft L-band retrodirective phased array leading to the development of an experimental model and flight testing is recommended.

Suggested tasks for additional study and development are described below:

Expanded Link Analysis - Perform L-band, 2-way link budgets based on aircraft with hemispherical beam antennas in which satellite antenna beam coverage extends from sector (North Atlantic for example) to worldwide (approximately earth hemisphere) areas. Assume state-of-the-art transmitter power and noise figures for the aircraft equipment, including appropriate margins and degradation factors. Define the spacecraft equipment performance in terms of ERP and receiver sensitivity G/T (ratio of antenna gain to system noise temperature).

Operational Procedures - Perform tradeoff studies of different methods of providing acquisition and handover of voice links; that is, pointing the satellite antenna receive and transmit beams at appropriate aircraft. Include provisions for multiple antenna beams and/or simultaneous channels up to 10 per satellite.

Array Type Selection - Perform tradeoff studies of the advantages and disadvantages of different kinds of phased arrays, and select a preferred technique for North Atlantic service with growth capabilities in area coverage and additional channels.

Multipath Analysis - Analyze depth of fading, fading rate, coherence bandwidth, spacial effects, and methods of combating multipath (signal design, antenna polarization, etc.) and constraints on aircraft antenna.

Specifications - Prepare block diagrams of all major components and specify performance in terms of ERP, G/T, number of beams, weight, prime power and size.

Breadboard Development - Build an engineering breadboard of a segment of the array (or all of it) based on preceding criteria to demonstrate performance in terms of ERP, G/T, number of beams, radiation patterns, acquisition, modulation tests, weight, power and size. This segment can be based on several existing R&D programs, numbered among which is an RCA program which resulted in:

(1) A lightweight antenna element of optimum gain and weight, with the appropriate beamwidth which presently operates over the 1750 - 2300 MHz band. This unit would be scaled to the appropriate frequencies.

(2) A lumped element, 3-stage microcircuit transistor amplifier capable of providing one watt at 20% efficiency. This unit has been tested at 1800 MHz.

(3) Various microcircuit up-converters, mixers, preamplifiers, and filters which provide the needed performance but at a slightly different frequency. These can be readily scaled.

These components form the basis of a phased array communication system that can be readily constructed and tested (with a minimum of engineering design) to prove the feasibility of the L-band phased array system and at a minimum cost.

This approach is discussed further in Section 2 in conjunction with a recommended experimental spacecraft design.

## 1.4 GROUND STATIONS

There are no critical technology deficiencies in any of the proposed equipments for the ground stations and no problems are anticipated in the implementation of the various systems and subsystems which are required to directly support the Nav/TC system.

There are, however, many areas of the ground complex which need additional in-depth studies in order to fully appreciate the potential capabilities and problems of an operational Nav/TC satellite system. Four of the more apparent subjects which need further clarification are discussed in the following paragraphs.

Data Processing and Display - The large amounts of data generated by a traffic surveillance system needs to be digested and displayed if it is to be effective. However, depicting the flight paths of 200 aviation users simultaneously may be more than a traffic controller bargained for. A study is required to analyze various techniques for data analysis and display which will provide traffic controllers with all the essential information they need, without overtaxing them with superfluous facts.

Operations During Emergencies - The recommended Nav/TC system provides traffic surveillance, passive navigation, and voice communication capabilities. For emergency or search and rescue operations, it is obvious that the basic system provides the necessary ingredients. However, more study is required to configure an optimum system which will provide all of these services simultaneously without penalizing the system with excessive or inefficient RF channel capacity. In addition, an emergency mode of operation which is automatically instituted without interruption of the basic Nav/TC operation needs investigation.

Airport or Marine Terminal Station Interfaces with Nav/TC Satellite System - Equipment and operational requirements for hand-over of a user from the Nav/TC satellite system to an air terminal system needs to be explored in greater depth. The assumption that a terminal station can receive position data and time of arrival information via a simple communication link from the satellite GCC is valid. However, it misses the potential improvement that is possible by the existence of the satellite system. A study is required to investigate concepts for improving terminal navigation systems via Nav/TC satellites and configure an operational plan for hand-over from transoceanic passage to the terminal system.

First-Order Doppler Elimination for Air Traffic Surveillance Functions - The relative motion between aircraft and satellites results in a doppler shift from nominal frequency at the receivers of either of these terminals. In an air traffic control situation, the user is continuously "locked-on" to the satellite signal so that the doppler offset presents no problem to him. However, the control center must interrogate a field of users and receive each of their transponded signals at a time interval of 2 seconds or less.

Because of the narrow receiver bandwidths required to maintain signal-to-noise integrity, search time could be quite excessive.

One method to eliminate this doppler offset at the control center is for the user to retransmit the compliment of the frequency offset of his received signal; e.g., if the user receives the satellite signal with a +4.2 kHz offset, he transmits his carrier at a -4.2 kHz offset. The net result is zero offset at the control center.

A study is recommended to determine the methods that can be used to eliminate or nearly eliminate this frequency offset. Tradeoff analyses of the complexity and cost of implementing this method in lieu of a priori knowledge of each user's velocity in a traffic network should be part of this investigation.

## Section 2

## EXPERIMENTAL PROGRAM REQUIREMENTS

### 2.1 EXPERIMENTAL SPACECRAFT

It has been previously stated that no proof of feasibility appears to be required for any aspect of the recommended Nav/TC satellite system since no breakthroughs in technology are required to design and construct an operational system. However, any system responsible for the safety and economic operation of commercial traffic, particularly where human lives are at stake, needs to be demonstrated in a realistic environment on a 24-hour per day basis before it can be deemed ready for operational status. There are many aspects of the operational Nav/TC system shown in Figure 1-2 which have not been demonstrated in a space environment. The retrodirective phased array is a case in point. Consequently, an experimental spacecraft with all the features of an operational system but having less than full capacity is described in this section. It would allow a lower cost "buy-in" than the full system, but would demonstrate all of the features of the full system thus allowing the potential users of the system to gain experience and confidence.

Figure 2-1 shows the overall experimental system that resulted from the analysis, Figure 2-2 shows the details of the spacecraft, and Table 2-1 the comparative cost analysis for the full and reduced systems. These relative cost estimates have been based upon the manufacture of just two flight vehicles in each case to avoid the distorting assumption of an on-going "experiment."

The experimental spacecraft represents a limited version of the operational vehicle; in particular, the phased array gain has been reduced 3 dB to make the experimental array one half the size of the operational versions. This reduction has been appropriately compensated by an increase in voice channel RF power, so that the user package is identical to that for the full system — no gain enhancement is required.

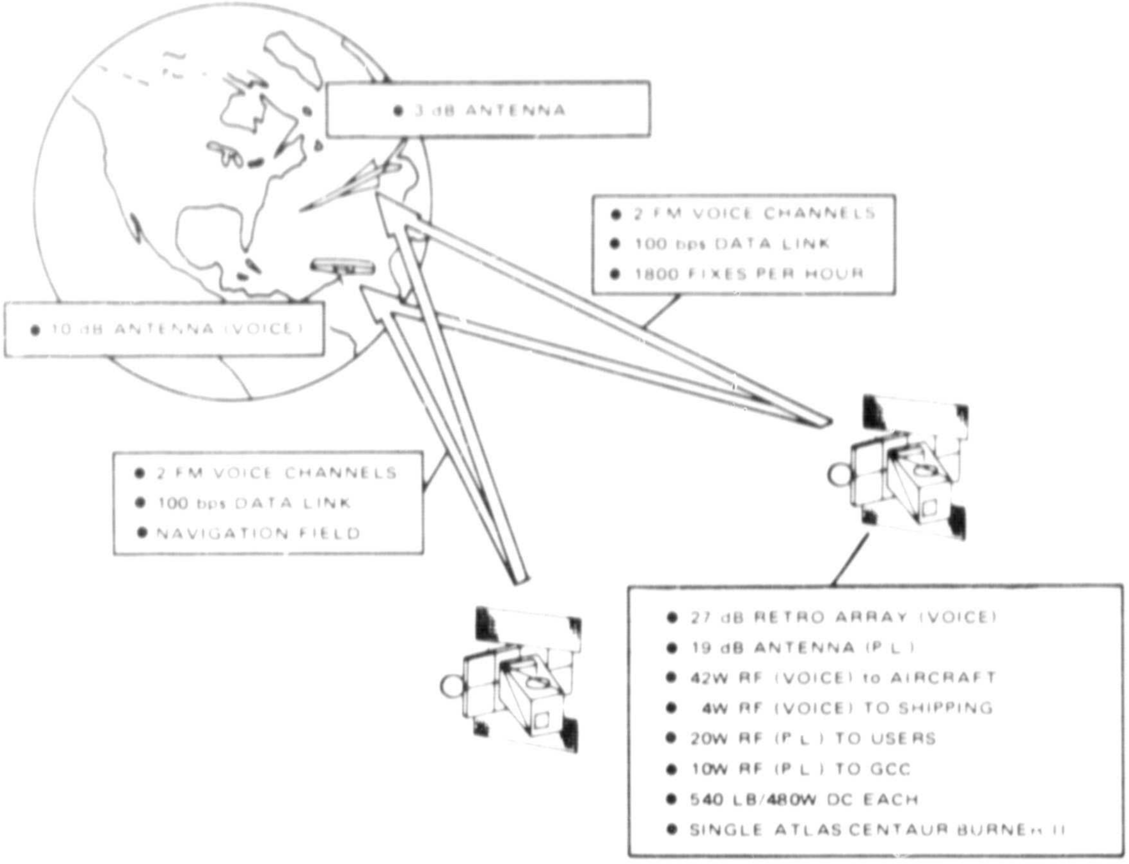

Figure 2-1. Experimental System Capability

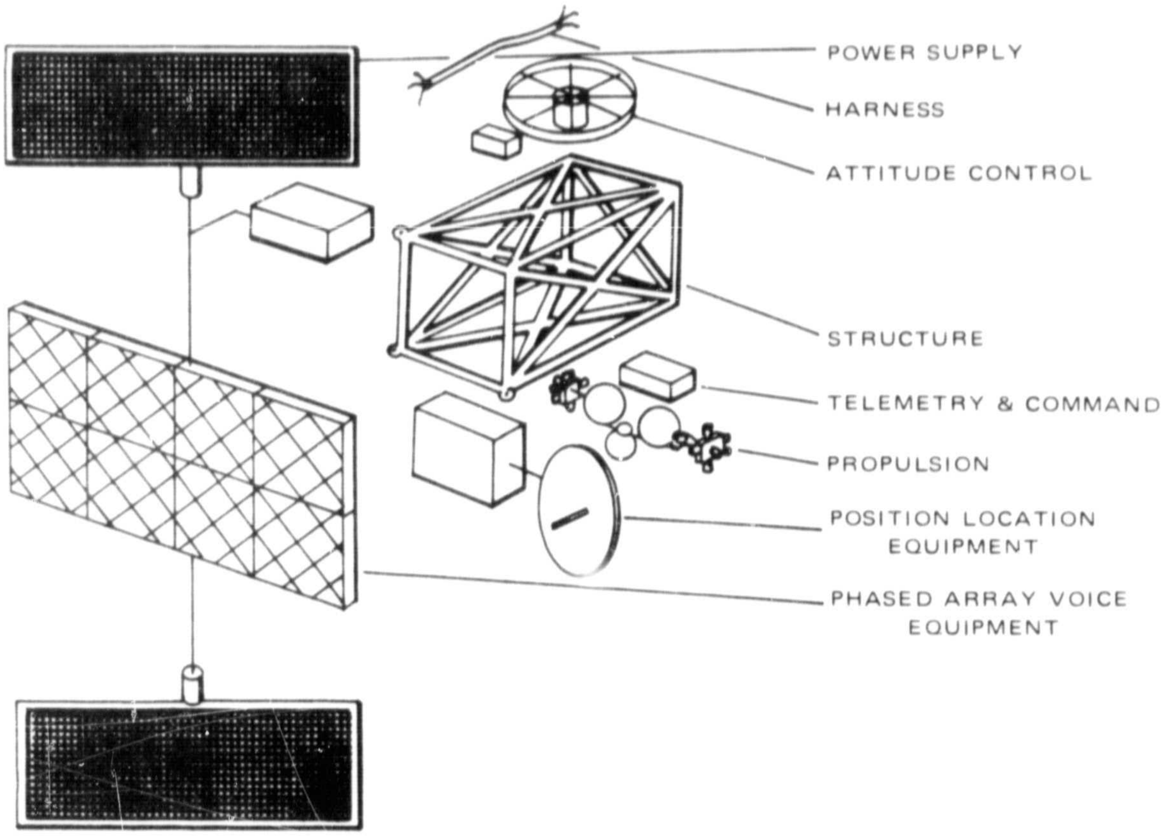

Figure 2-2. Experimental Spacecraft

TABLE 2-1. SYSTEM COSTS (dollars in thousands)

| | Experimental System | | Operational System | |
|---|---|---|---|---|
| | Development | Per Copy | Development | Per Copy |
| Navigation/Traffic Control/Data Link | 250 | 220 | 250 | 220 |
| Voice Communications | 2500 | 440 | 2500 | 880 |
| Telemetry and Command | 250 | 100 | 250 | 100 |
| Power Supply | 750 | 1000 | 1250 | 1600 |
| Attitude Control | 750 | 250 | 750 | 250 |
| Secondary Propulsion | 500 | 240 | 500 | 240 |
| Structure and Integration | 550 | 400 | 750 | 550 |
| Testing | 750 | 300 | 1250 | 500 |
| Contingency | 1575 | 740 | 1875 | 1085 |
| | $7875 | $3690 | $9375 | $5425 |
| Total Cost for R&D, One Prototype Two Flight Models | 18,945 | | 25,650 | |
| Booster Cost | 13,100 | | 13,100 | |
| Total Installation Cost | $32,000 | | $39,000 | |

One of the major causes of the relatively high cost of the experimental system is the need for the Atlas-Centaur booster. At 540 pounds, the experimental spacecraft is an awkward weight in terms of available NASA boosters (Titan IIIB and Atlas-Agena are both USAF vehicles) and consequently the Atlas-Centaur was selected to be used to launch both spacecraft simultaneously. This is an expensive booster that would in this case be under-utilized.

If a single experimental spacecraft is employed, allowing voice experiments and line of position determination, matters improve somewhat since most of the battery capability can be deleted and a considerably lighter vehicle results. (This deletion is reasonable now, since a single spacecraft experiment is truly just that, and eclipse operation is not warranted.) Figure 2-3 shows a simple sketch of this test configuration.

Table 2-2 presents in detail the weight breakdown for the experimental spacecraft, both with and without full battery capability. Deletion of most of the batteries causes the vehicle weight to go down to 408 pounds, and it becomes possible to effect deployment of the reduced spacecraft using the Atlas SLV3A-Burner II kick stage combination, at about \$5M compared with \$13M for the Atlas-Centaur. Of course, two such launches would yield a complete system at less cost than a single Centaur launch, but the lack of eclipse capability would become a serious drawback in this more complete representation.

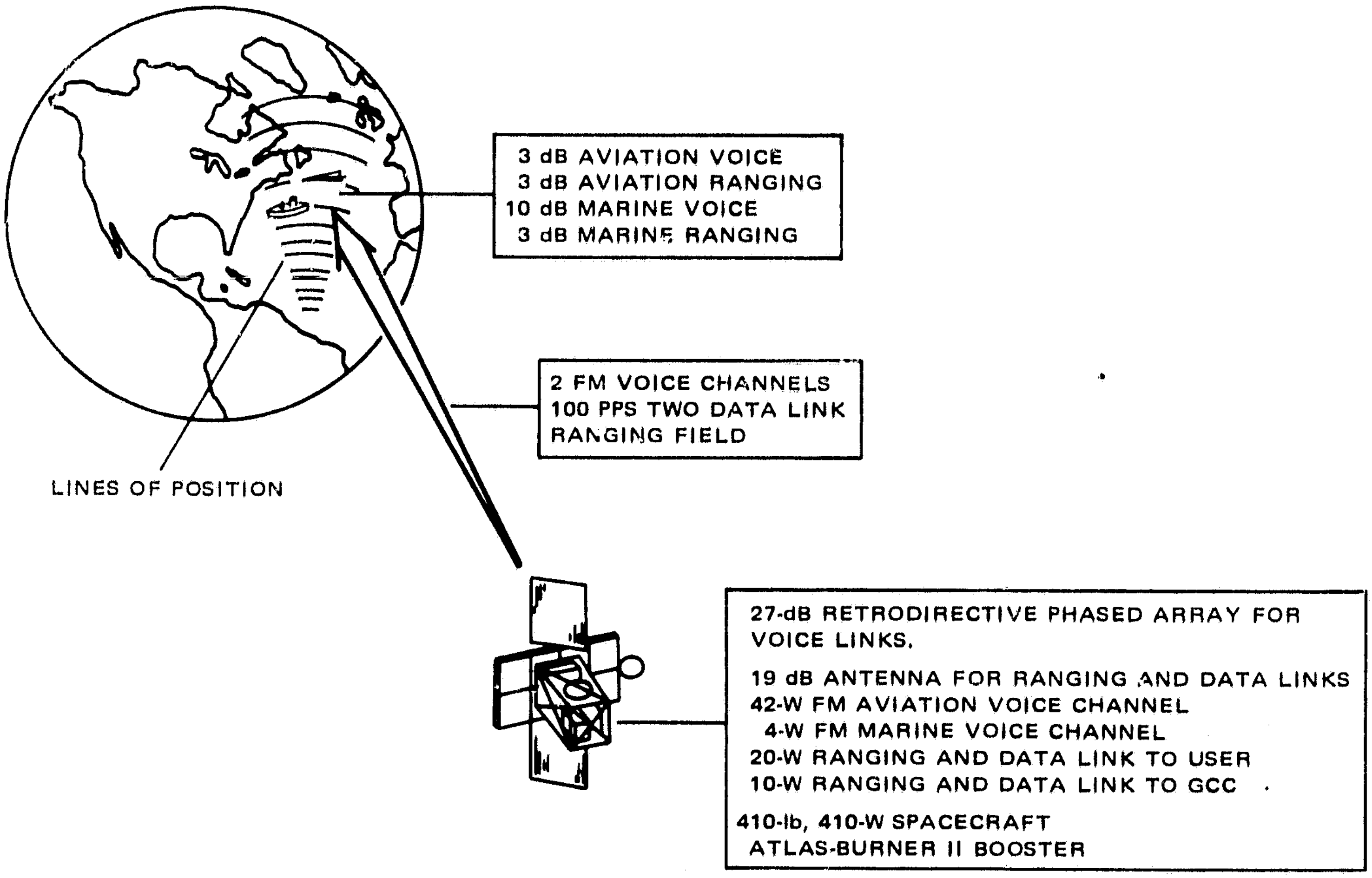

Figure 2-3. Single Spacecraft Experiment

## TABLE 2-2. EXPERIMENTAL SPACECRAFT - WEIGHT BREAKDOWN

| Subsystem | Weight (lb) | Power (w) |
|---|---|---|
| Navigation antenna | 3.0 | - |
| Forward link nav. transponder | 8.0 | 10.0 |
| Forward link power amplifier (TWTA) | 10.0 | 66.0 |
| Backward link navig. transp. | 8.0 | 10.0 |
| Backward link power amplifier (TWTA) | 10.0 | 33.0 |
| Antenna diplexer | 5.0 | - |
| | 44.0 | 119.0 |
| Array antenna elements (8) | 32.0 | - |
| Receivers (8) | 1.6 | 2.5 |
| Transmitters (20% efficiency) | 1.6 | 230.0 |
| Signal processors (16) | 1.6 | 4.0 |
| Summing and Distribution Equipment | 10.0 | - |
| | 46.8 | 236.5 |
| Command receiver (2) | 2.5 | 1.0 |
| Command decoder (2) | 10.0 | 2.0 |
| Telemetry assembly unit | 8.0 | 6.0 |
| Telemetry transmitter (2) | 1.5 | 5.0 |
| Diplexer | 1.0 | - |
| Antenna | 2.3 | - |
| | 25.3 | 14.0 |
| Momentum Wheel | 20.0 | - |
| Wheel drive | 15.0 | 5.0 |
| Roll/pitch sensors (2 and 2) | 4.0 | 1.0 |
| Pitch control electronics | 8.0 | 4.0 |
| Nutation damper | 4.0 | - |
| Solar array drives (2) | 20.0 | 10.0 |
| Solar sensors (2) | 2.0 | - |
| | 73.0 | 20.0 |
| Propellant tanks (2) with bladders | 8.0 | - |
| Thrust chamber assemblies (12) | 11.0 | - |
| Pressurant system | 4.0 | - |
| Support structure | 10.0 | - |
| Miscellaneous | 6.0 | - |
| Hydrazine | 28.0 | - |
| | 67.0 | - |
| Solar array (44 lb)* → | 52.0 | - |
| Power reg. and charge control (14 lb, 7w) → | 16.0 | 8.0 |
| Batteries (14 lb, 8w) → | 135.0 | 78.0 |
| (72 lb, 15w) → | 203.0 | 86.0 |
| Cable Harness | 15.0 | - |
| Structure | 65.0 | - |
| | 80.0 | - |
| TOTAL VEHICLE (408 lb, 405w) → | 539 | 476 |

*The effect of battery deletion (leaving essential eclipse services only) is shown in parentheses.

The SLV3A-Burner II vehicle is current and is capable of placing 970 pounds at stationary altitude, so that the net stationary payload is about 460 pounds. The shroud diameter goes up to 77 inches (internal) via use of the Convair OV1 fairing, and would necessitate additional folding of the phased array antenna. This would not be a problem.

The utility of a single spacecraft experiment should not be underestimated. The cost of this would be about $22M, calculated on a comparable basis with the $32M and $39M costs quoted previously, which is a significant reduction. Yet this experiment would demonstrate multiple channel L-band voice (to operational standard receivers), would provide a two-way data link to the user field, and would allow a realistic demonstration of ranging measurements for both the active and passive mode of navigation. Also, the accuracy of the system can be determined since all the significant elements contributing to system errors are present in a single ranging measurement. The primary limitation is that a single range measurement plus altitude data will provide only one line of position, (LOP), a circle. A position fix can be made if supplementary information is available for estimating the user's location on the LOP. For an experimental setup the user test locations would be surveyed in advance or one or more independent means would be available to locate user positions. There would be no obstacle to fully evaluating the performance of the ranging technique employed by the system.

## 2.2 TEST PROGRAM PLANS

An experimental program in three phases is recommended, including laboratory tests, field tests with land based and marine vehicles and flight tests for evaluation of the most sensitive user. Each of these phases would prove most effective if chronologically completed in the order indicated above. A brief description of the goals of this program are discussed below:

Laboratory Experiments - This series of experiments should investigate the pertinent characteristics of all the navigation equipment used in vehicle and airborne experiments. Initially laboratory generated stimuli should be used, then signals from the satellite should be used. In general terms, the items which should be investigated in the laboratory experiments include:

- Receiver characteristics such as noise figures, frequency tracking characteristics, and acquisition times.
- Transmitter characteristics (bandwidth limitations, phase stability of modulating tones, etc.)
- Phase stability and accuracy of tone processing circuits.
- Multipath signal effects on tone phase stability and receiver phase lock-loop performance.
- Tone reference stabilities.
- Optimum modulation parameters considering satellite bandwidth limitations, effects of multipath, and simultaneous voice transmissions.
- Effects of antenna parameters on phase measurements of received satellite signals.
- Propagation stability of tone phase for both passive and active modes.

Some of the specific questions which can be answered by a properly designed series of laboratory experiments are as follows:

- What are the optimum indices in a non-multipath environment?
- What are the effects of an interfering non-coherent [illegible], source such as the man-made radio noise to be found in an industrial area?
- How stable is tone phase and what are the bandpass characteristics of the satellite for both limiting and non-limiting input signal conditions?
- What are the effects of varying the carrier frequency within the satellite passband?
- What is the functional relationship between phase accuracy and stability versus tone modulation index, signal levels at the satellite and at the user receiver, signal position within the satellite passband and combined navigation/voice transmissions?
- What are the effects of receiver sensitivity?

- How well can the equipment perform doppler tracking?
- How long does it require to acquire a signal?
- What are the effects of multipath on the susceptibility of the phase lock loop to unlocking?
- How long and to what accuracy can one tone generator (the user's) independently stay in phase with a second tone (the ground station)?
- What are the relative drift rates under quiescent conditions and what are the drift rates under vibration conditions as would be encountered in a marine or airborne vehicle?
- What are the effects of time of day and weather conditions upon phase accuracy and stability?

In addition to finding answers to the above questions, the specific equipment to be employed in the land vehicle and airborne experiments should be exercised and their characteristics determined for reference and comparison.

Ground Vehicle Experiments - For these experiments, the user equipment should be mounted in a mobile van. One purpose of these experiments is to demonstrate the primary modes of satellite navigation while the user is stationary and on the ground at known locations. A second purpose is to obtain experimental data on new equipments such as user antennas. These tests should be conducted at many locations where an accurate bench-mark location can be obtained. By careful selection of locations on constant latitude and constant longitude lines the effects of GDOP and of elevation angles of the satellites (that is, the refractive effect of the ionosphere and troposphere) can be investigated.

In addition, the noise, multipath and other natural effects which were simulated in the laboratory series of experiments can now be verified. The full range of navigation and communication modes should be exercised. Experiments should include both active and passive modes and the circular and hyperbolic techniques. It should be noted that it is possible to achieve substantial changes in latitude and longitude within the Continental

U.S. (CONUS). However, certain effects such as the low elevation angle effects (strong refractive effects) can only be achieved near the boundaries of the satellite coverage region such as at about 75° ground arc from the sub-satellite point. Such conditions, near the edge of satellite coverage, can easily be achieved if surveyed positions on the North American Continent are considered (especially Alaska) and if the land vehicle experiments are not limited to CONUS. Wherever possible, the results of the land vehicle experiments should be compared to the laboratory experiments in order to determine if any unpredicted differences occur which will necessitate additional analysis and/or experiments. In addition, the boundaries of useful navigation should be determined whether these limits arise from geometric or propagation causes.

Airborne Experiments - This series of experiments would complete the evaluation of the satellite navigation communication techniques. These experiments should be conducted over the same region as the land based experiments, in order to duplicate the results. Experiments should also be conducted with the user over the ocean. Aircraft results can be compared to "surveyed" results in two ways. First, when an aircraft is on a runway it is in a surveyed position. Second, by means of a time clock plus an optical and/or photographic technique, the position of an aircraft can be recorded with respect to some surveyed point which is visible from the aircraft.

Employing these methods, all of the land based experiments can be repeated to assure that the same results obtain. In addition, the survey can be extended to ocean areas. In addition to the survey, accuracy tests experiments should be performed at many different altitudes. Low altitudes and low satellite elevation angles are of interest over all terrains and sea states since multipath effects are expected to be maximum in these circumstances. The airborne experiments should establish the performance boundaries just as the land based experiments were utilized to establish performance boundaries. Final verification of equipment performance, particularly the user antenna, should be conducted during the flight test experiments.

## 2.3 TEST PROGRAM SCHEDULE

A tentative schedule for conducting the test program is shown in Figure 2-4. The major tasks include:

1. Development and simultation of an analytical model considering propagation, geometry, and other error sources from which capabilities and limitation predictions of performance can be made.

2. Development of a data reduction plan to reduce and compare the analytically predicted and actual performance data taken with experimental hardware.

3. Laboratory development and testing of experimental hardware for the user and ground stations.

4. Development and execution of a test plan for evaluating the system concept in the laboratory, ground tests across the continental U.S., and a flight test over land and water to establish the capabilities and limitations of an operational system.

5. Evaluate and summarize the results of the recommended program in terms of the mechanization for an operational system considering fully the economic impact on, and the performance provided to the variety of users expected.

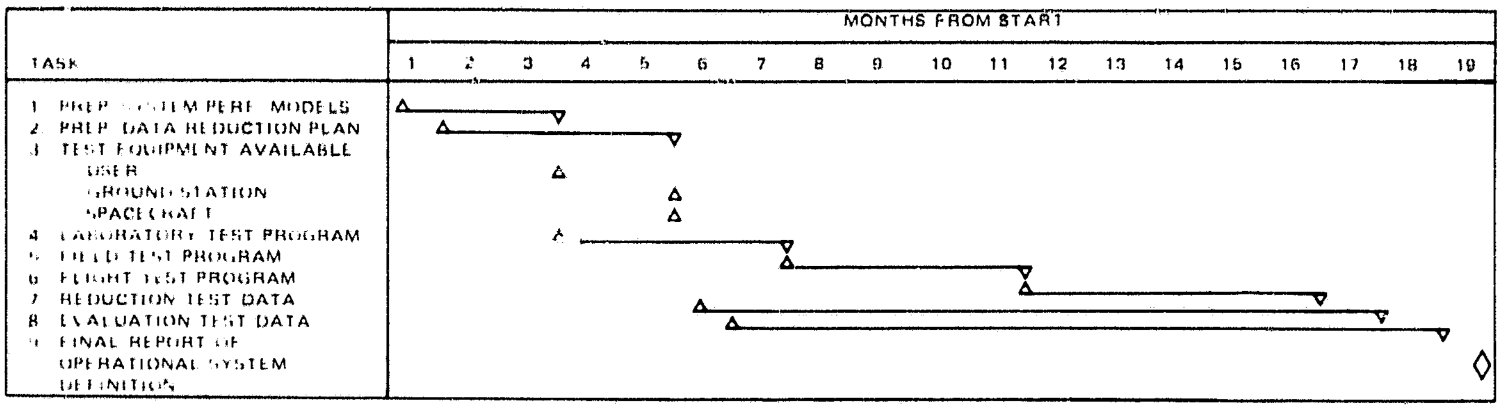

Figure 2-4. Experimental Program Schedule

An 18-month program is visualized assuming equipment will be available as each new phase is initiated. This will also allow operations to be demonstrated under most of the foreseeable environmental circumstances.

# Section 3

# ECONOMIC ANALYSIS SUMMARY

## 3.1 INTRODUCTION

In the course of developing a preferred system configuration during the Phase II effort of this study, three interesting alternatives evolved which were analyzed, compared and evaluated.

1. The first was a two-satellite L-band ranging system which included position location functions (both passive and active) and narrow-bandwidth data links. It was called the "Nav/TC/Data" System, and was included in this study because it provided a means of departure from other less promising navigation satellite techniques.

2. The second alternative had the same Nav/TC/Data equipments as No. 1, but included four VHF aviation and four VHF maritime voice channels (divided between the two spacecraft). It was called the "Nav/TC/Data/VHF Voice" system. It was subsequently rejected as having limited growth potential for the post-1975 era, although it appears to be of interest for the 1971-1972 to 1975 era if the aviation industry implements a VHF COMSAT System and develops VHF voice user equipment. This system is included in the cost comparisons herein, but is not recommended for development for use beyond 1975.

3. The third alternative, and the one recommended for development, has the same L-band Nav/TC/Data equipment as No. 1, but includes six L-band aviation and six L-band maritime voice channels (divided between two spacecraft). It is identified as the "Nav/TC/Data/UHF Voice" system. This is the recommended operational system discussed in Volume I of this report.

The cost analysis summarized herein compares all of these systems and is based on estimates which were presented in Sections 4 and 5 of Volume III.

## 3.2 SPACE SEGMENT COSTS

The most advanced of these alternatives, in terms of both capacity and technology requirements (which remain modest nonetheless) is the Navigation/Traffic Control/UHF

Voice Channel system. This was estimated to require about \$9.4M in development funding, or \$14.8M if the prototype is included in development, and about \$5.4M for each subsequent flight spacecraft. Corresponding numbers for the VHF system are \$12.3M for development (including prototype) and \$4.5M for each copy respectively, while for the Navigation/Traffic Control only system they reduce to \$5.7M and \$2.0M. In the same descending order of complexity and capability, the costs of installation of the space systems required for operation are seen to be \$38.8M, \$34.3M and \$17.3M — in each case including the development and prorotype costs, the cost of the operational spacecraft, and the cost of the first launch(es).

Now the reliability discussions of Section 4 and 5 in Volume III can be interpreted to lead to rather conservative estimates for system life, each of the three major blocks of the VHF spacecraft having an estimated MTTF of about 35,000 hours. The three blocks mentioned are the voice subsystem (three out of four channels), position location subsystem, and the spacecraft bus. Strictly, the corresponding block failure rates have to be taken in combination, and also cognizance has to be taken of the simultaneous need for two working spacecraft. These factors applied together would lead to very low values of total system MTTF, but the result would be distinctly unrealistic in view of the manifold possibilities for graceful failure, and of the reliability gains that could be expected during system design and development.

At this stage in the system design it is probably fairer to base overall system life predictions upon results obtained from real spacecraft rather than upon parts counts prior to detailed design. On this basis it appears reasonable to revert to the estimate presented in Section 2.4.4.2, where the system MTTF (for the Navigation/Traffic Control only system) was set at 4.6 years. The corresponding lifetime for a system with voice capability added is about 3 years — and at this level of examination VHF cannot be easily separated from UHF, although the latter should be more reliable by virtue of the inherent redundancy of the phased array system. The reduced reliability caused by the introduction of (VHF) voice capability allows for only three channels out of four to be working, but in any case the estimate can only be approximate prior to exact definition of the shape of the wear-out curve.

With these assumptions the initial production of four flight articles will nominally support operation for 9 years in the case of the Navigation/Traffic Control only system, and for 6 years when Voice is added. It is now possible to derive per annum costs for the space segments of the total system, assuming development write-off over these periods and allowing for the necessary replacement launches. This reduces to an annual cost of $3.2M for the Navigation/Traffic Control only system, and of $9.4M and $10.5M for those systems with voice capability added. The latter figure is for the UHF voice system, and provides 50% more capacity than the VHF system at relatively little additional cost (12%).

It appears from this admittedly simplified analysis that:

(1) The Navigation/Traffic Control only function can be had at relatively low cost. In the post 1975 period, some 200,000 crossings of the North Atlantic region can be expected each year, so that the per flight cost of the service (for the space segment costs only) amounts to $16.

(2) Given the addition of voice capability to the basic service, the UHF system is the most cost effective and can offer voice communications at an additional cost of about $36/flight. This cost is for a service of six aviation channels, and is slightly pessimistic in that six maritime channels are here assumed to be carried "free." These latter of course make much less demand upon the system, and pro-rating on a basis of RF power, the aviation cost reduces to but $33/flight. It should be remembered here that this cost provides a peak hour service of at least three one-minute conversations per flight, given traffic densities on the high side of current estimates. Also, the estimated annual cost per voice channel of $1.2M provides a measure of cost effectiveness.

(3) The per flight cost of the VHF voice system, above the basic Navigation/Traffic Control function and deducting for Maritime channels as in (2), amounts to $28/flight at 200,000 crossings per year. The channel capacity would however be inadequate at that traffic rate, and a truer number might be 50% higher in terms of peak hour flights adequately served. The annual cost per voice channel of $1.4M in this case actually reflects some reduction in effectiveness compared to the UHF (L-band) voice system in (2) above.

## 3.3 GROUND SEGMENT COSTS

The estimated costs for the ground portion of the Navigation/Traffic Control system were presented in Section 6.6 of Volume III. It was shown there that the following costs could be anticipated for a North Atlantic system:

Master Control Station - one required at $1000K
two suggested at $2000K

Calibration Station - three required at $90K

One of the Calibration Stations could in fact be combined with Master Control in order to effect some small economy, but this will not be taken into account here. The ground segment cost, for equipment only, but excluding display, thus amounts to $2090K.

It is necessary to make allowances for building and land costs. These were estimated at around $1.9 million, thus increasing the base cost to $4.0M. As a matter of interest and as an example the costs for the Rosman N. C. STADAN facility are:

| | |
|---|---|
| Site development | $ 160,000 |
| Facility construction | 1,250,000 |
| Instrumentation | 2,005,000 |
| Design Services | 85,000 |

Thus in that instance the equipment costs represented somewhat less than 60% of the total cost. This proportion is fairly typical of that sort of facility (Johannesburg, Woomera, Far East Station) and has been applied in the present instance.

The question of running or operating costs is a further complication. Maintenance can be covered by setting aside 10% of the initial cost per year, leading to an annual maintenance cost of $0.4M, but staffing expenses are more open to question. All the facilities will be on 24-hour operation, and making elementary assumptions about the necessary manpower it is easy to come up with an annual outlay in salaries of ≈$1.0M.

The total ground segment cost (including initial outlay written off over 10 years) thus amounts to $1.8M/year, or $9/flight in a 200,000 flight year — for the position location function only. This estimate is consistent with STADAN station costs.

The addition of voice capability to the system necessitates both an increase in the ground equipment and an increase in staff. Noting the number of channels involved (8 at VHF or 12 at UHF) the number of personnel required could as much as double.

In addition, further transmitter-receiver assemblies are required at each terminal at an extra cost of perhaps $30K per channel, or say $480K to $720K depending upon which option is exercised. In sum, the voice requirements can be expected to add between $0.9M and $1.2M to the annual costs allowing for acquisition, maintenance and staffing, and to increase the per flight ground levy to $14 at VHF and to $15 at UHF. These are of course very approximate figures but sufficient for present purposes.

## 3.4 USER EQUIPMENT COSTS

These have been detailed elsewhere for both the Navigation/Traffic Control and Voice functions, and are considered to be a user charge and thus only of indirect interest in the present context. They are summarized in Section 3.3 of Volume III.

## 3.5 TOTAL SYSTEM COST

The space and ground segment costs derived in the preceding paragraphs are shown in Table 3-1. The essential alternative appears to lie between System 1 (providing Navigation/Traffic Control only) at an initial cost for operation of $21M, and System 3 (providing in addition 12 UHF Voice channels) at an initial cost for operation of $43M. The respective annual costs as tabled amount to $5.0M/year and $13.5M/year, these latter sums including write-off of the initial capital outlay as well as system operation and replenishment.

## 3.6 COSTS OF R&D OF DEFICIENT TECHNOLOGY

A summary of the costs of an experimental program for demonstrating system performance appears in Table 2-1 of this volume.

There are no specific technology deficiencies in terms of critical items which require special R&D efforts. Thus, the test program mentioned above represents the principal developmental effort prior to the design and construction of an operational system.

## TABLE 3-1. TOTAL SYSTEM COSTS

| | System 1 Nav/TC/Data | System 2 Nav/TC/Data/VHF Voice | System 3 Nav/TC/Data/UHF Voice |
|---|---|---|---|
| Spacecraft development including prototype | $ 5.7M | $12.3M | $14.8M |
| Cost of flight spacecraft, each | $ 2.0M | $ 4.5M | $ 5.4M |
| Total cost of four vehicle program | $13.7M | $30.2M | $36.5M |
| Total booster cost | $15.2M | $26.2M | $26.2M |
| Total cost of space segment | $28.9M | $56.4M | $62.7M |
| Nominal system life | 9 years | 6 years | 6 years |
| Prorated cost of space segment | $ 3.2M/yr | $ 9.4M/yr | $10.5M/yr |
| Cost of ground segment | $ 4.0M | $ 4.5M | $ 4.7M |
| Cost of ground segment prorated over 10 years | $ 0.4M/yr | $ 0.5M/yr | $ 0.5M/yr |
| Maintenance | $ 0.4M/yr | $ 0.5M/yr | $ 0.5M/yr |
| Staffing | $ 1.0M/yr | $ 1.7M/yr | $ 2.0M/yr |
| Total annual cost of ground segment | $ 1.8M/yr | $ 2.7M/yr | $ 3.0M/yr |
| Total annual space/ground system cost | $ 5.0M/yr | $12.1M/yr | $13.5M/yr |
| Cost per flight at 200,000 flights per year* | $25/flight | $61/flight | $68/flight |
| Approximate cost per flight discounting maritime services | $25/flight | $56/flight | $64/flight |

*System II cannot support this load and the real per flight costs would be considerably higher in terms of flights usefully served.

## 3.7 SCHEDULE FOR IMPLEMENTATION OF RECOMMENDED NAV/TC SYSTEM

An estimated schedule for the design and construction of the operational version spacecraft (System III in Table 3-1) is shown in Figure 3-1. Since the spacecraft is the pacing item in the development of the overall Nav/TC system, the schedule for implementation of the user and ground equipments can easily fit within the 30 month period (shown in Figure 3-1) between program initiation and completion of the first two flight vehicles.

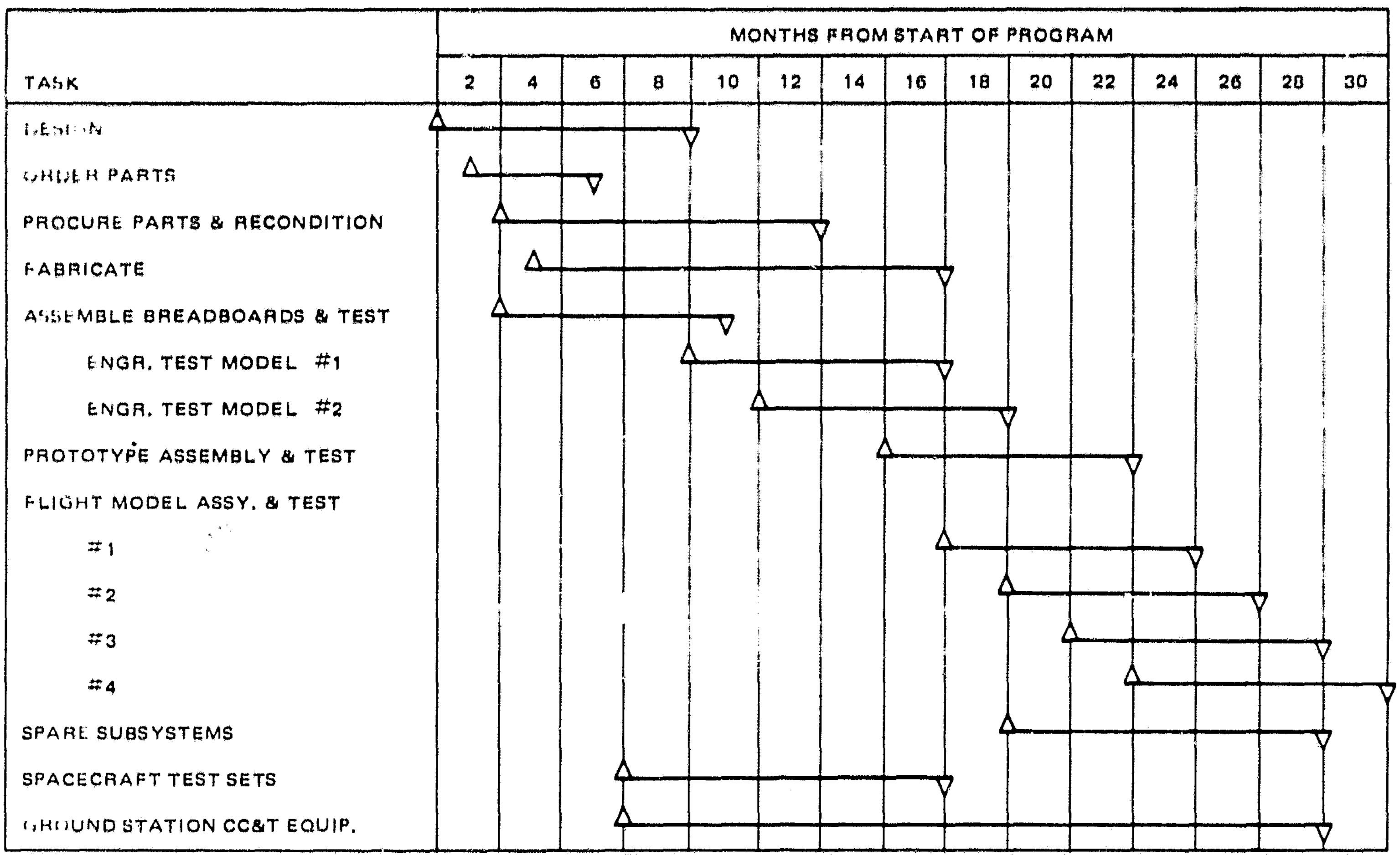

Figure 3-1. Schedule for Operational Spacecraft Implementation

The experimental program for verification of the performance of a phased array, discussed in Section 2 of this volume, will obviously have to precede the construction of the operational spacecraft. This experimental activity may not be unique to this program, and as a matter of interest a 9-month contract was recently let to industry (Airborne Instrument Laboratories) to allow fabrication of an experimental S-band, two-channel array (albeit of limited gain). This array is destined for use in a Data Relay Satellite (DRSS).

Depending somewhat upon the technology status following current investigations, a further 18-month period might reasonably be allowed for phased array development and experimentation, leading to a program duration of between 4 and 4-1/2 years to first operational system launch. Meeting an implementation date of 1975 appears entirely feasible.

# Section 4

# EXPANSION TO GLOBAL SERVICE

## 4.1 SYNCHRONOUS EQUATORIAL SATELLITE SYSTEM

An attractive feature of two-satellite ranging systems is that expanded coverage around the earth can be accomplished with the addition of only four synchronous equatorial satellites to the two for the North Atlantic region. In actuality, the North Atlantic spacecraft are in a position to serve the South Atlantic area without the introduction of any modifications other than increased traffic handling capacity. The resulting six satellite system for global service can provide the following coverage:

(a) Voice and Data Communications: From 70° North to 70° South latitude globally.

(b) Position Location Services:

- Global coverage between 20° to 70° North and 20° to 70° South latitude at full precision.
- Equatorial ring between 10° to 20° North and 10° to 20° South latitudes at reduced precision (approximately 1/2 of nominal).
- Equatorial ring between 10° North and 10° South latitude, precise longitude determinations can be made, but latitude estimates are degraded.

The total ground station requirements are three ground control stations (GCC) and six trilateration stations (TS) for tracking the satellites. Reasonable locations from the viewpoint of mutual satellite visibility and convenience are shown in Table 4-1.

Estimated cost of the space segment and ground stations based on implementation only, assuming development costs were amortized with the original North Atlantic system, are shown in Table 4-2.

TABLE 4-1. GROUND STATION LOCATIONS FOR GLOBAL SYSTEM

| Ground Control Stations | Location |
|---|---|
| #1 | Puerto Rico |
| #2 | Kwajalein |
| #3 | Madagascar |
| **Trilateration Stations** | |
| #1 | Buenos Aires, Argentina |
| #2 | Maine, USA |
| #3 | Japan |
| #4 | Perth, Australia |
| #5 | Honolulu |
| #6 | Madagascar |

TABLE 4-2. GLOBAL SYSTEM COSTS

| | Cost per Unit | No. Required | Total |
|---|---|---|---|
| Spacecraft | $ 5.5M | 6 | $33M |
| Boosters (2 S/C per launch) | 13.0M | 3 | 39M |
| Ground Control Stations | 2.0M | 3 | 6M |
| Trilateration Stations | 0.1M | 6 | 1M |
| Ground Bldgs. and Facilities | 1.0M | 3 | 3M |
| | | TOTAL | $82M |

User equipments need not be altered for the North Atlantic user since no change in channel frequencies are required. The global user, however, requires additional channel capability in both receiving and transmitting equipment to utilize the services from each of the six satellites.

## 4.2 SYNCHRONIZATION OF NAVIGATION SIGNALS

A user traversing from one region to another will be utilizing a different pair of satellites for the position location functions, and needs to know the phase relationship of the navigation signals if there is to be uninterrupted service during "handover." An attractive method of eliminating this problem is to have all the satellites in synchronism so that at any instant of time, the tone signals emanating from the satellites are in phase.

This necessitates a master control station which maintains the system clock. Since only three control stations are involved in the global system, the two "slave" stations can communicate with the master station through a satellite relay. Figure 4-1 illustrates this arrangement. Station A (the master station) energizes satellites A1 and A2. Station C can observe satellite A-2 and monitor its signal. Knowing the precise range from Satellite A2 to Station C, Station C is now in a position to adjust its phase shifters so that the signal transmitted to its satellites, C1 and C2, are in phase. Station B can observe satellite A1's signal and make the necessary adjustments to assure its satellites B1 and B2 are in phase. Figure 4-2 shows a block diagram of the synchronization process at each of the ground stations.

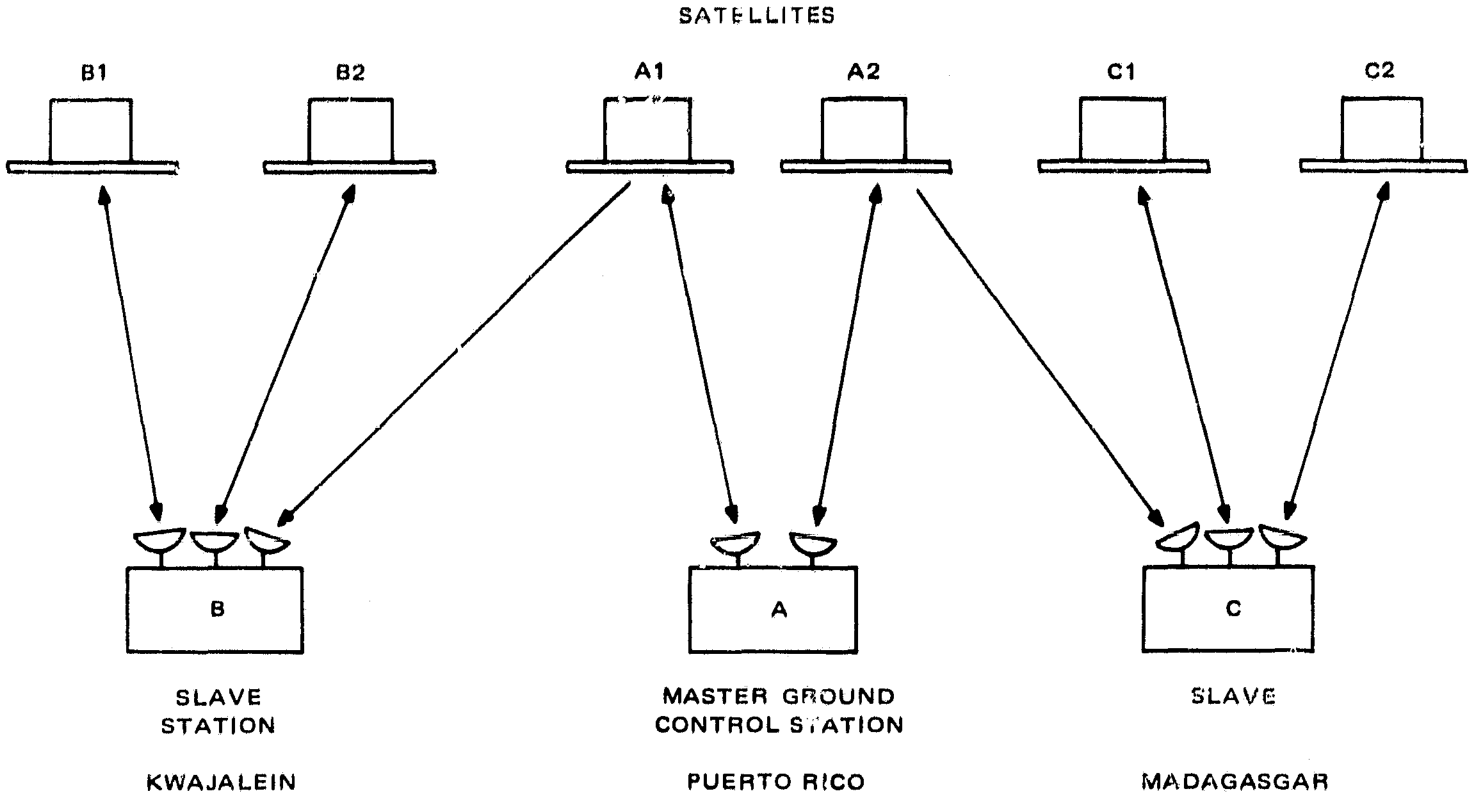

Figure 4-1. Global System Synchronization Links

## 4.3 FULL EARTH COVERAGE INCLUDING POLES

A full global coverage system was configured in an earlier report by RCA* in which satellites were placed in three orthogonal synchronous orbits, one equatorial and two polar, with six satellites in each orbit (five satellites in each orbit provided full coverage

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*Final Report "Phase Difference Navigation Satellite Study" Dated December 1967.

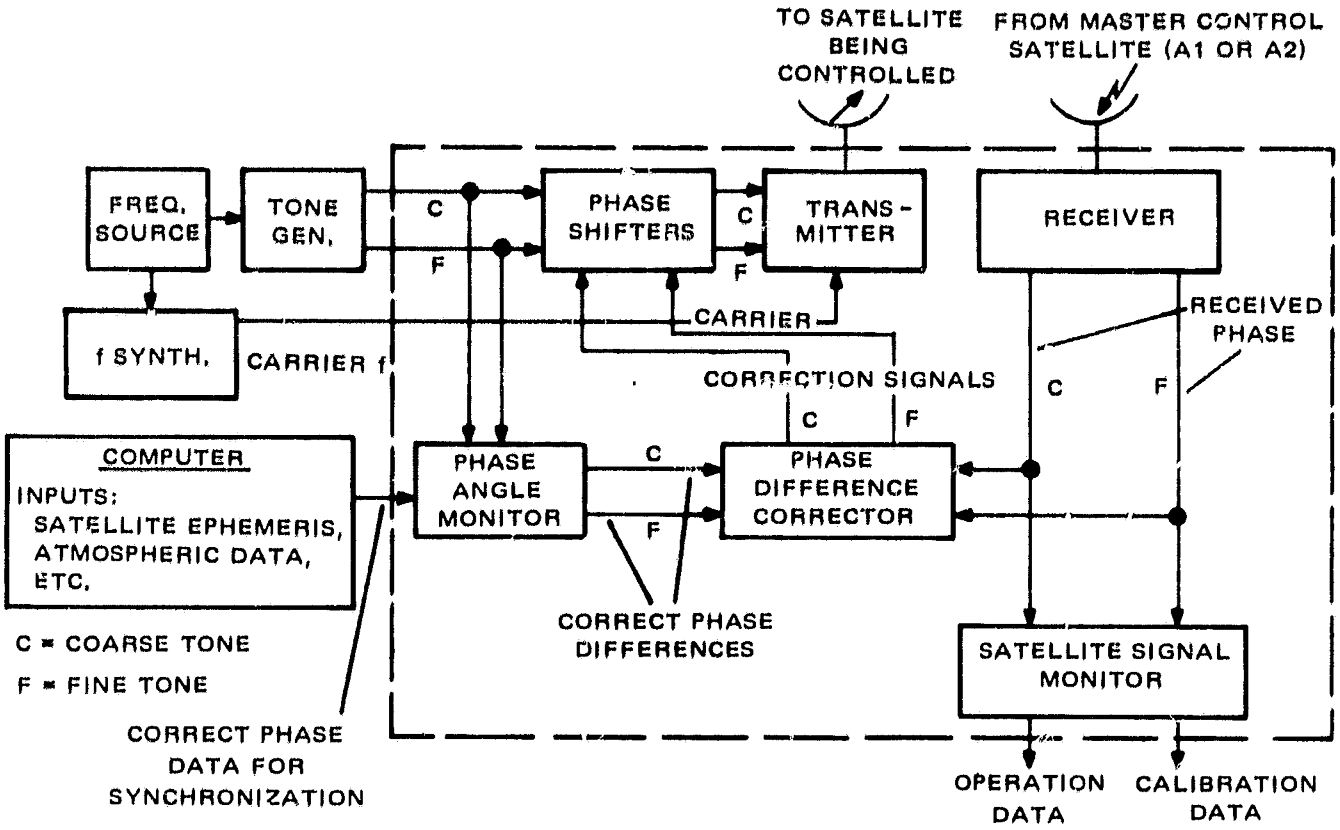


Figure 4-2. Simplified Block Diagram of Synchronization of Satellite Signals

also). This arrangement allowed for range-range navigation and provided means for determining altitude as well (three satellites in view of a user are required for a altitude measurement). An interesting feature of this configuration was that it allowed range-difference navigation (hyperbolic lines of position) to be performed also since three satellites were in view of any user on any part of the globe. It was the only global arrangement for hyperbolic navigation which had modest GDOP penalties (less than three). Thus, it provided a precision navigation system for the passive user without requiring a synchronized clock to be part of the user's equipment. The signal design (CW tone modulated on an L-band carrier) is entirely compatible for hyperbolic as well as circular navigation techniques. Details of this system can be obtained from the referenced report.

Section 5

# GROWTH POTENTIAL AND ADDITIONAL APPLICATIONS

## 5.1 GROWTH FEATURES

The Nav/TC system configured for this study has the evolutionary capacity to provide growth in terms of additional users, increased coverage and additional services.

(1) Increased traffic capacity can be achieved through the addition of Nav/TC channels, or increasing system transmitter power and reducing the time interval for a position fix. Additional voice channels would require a spacecraft with larger power generating capacity.

(2) Expanded coverage globally with the exception of the Poles and a narrow strip around the equator can be accomplished with the addition of four synchronous equatorial satellites to the two for North Atlantic service. This is discussed in Section 4 of this volume.

(3) Search and rescue operations can be served simply by tieing in SAR agencies to the traffic control communications system. An analysis of this service was beyond the scope of this effort, but is recommended for future study.

(4) Oceanographic surveys require navigation precisions on the order of 0.1 nmi or better. The addition of higher tones to the Nav/TC navigation signals can provide higher precision. The principal limitation to accuracy is the error caused by ionospheric refraction, and satellite position uncertainties. Both of these errors are substantially reduced for relative position fixes within a thousand miles or less.

(5) Collision avoidance is made possible through frequent user fixes by the Ground Control Center (GCC). A traffic control center can analyze flight patterns to determine whether a collision potential exists, and can make appropriate advisories to the users in danger. In addition the existence of a common RF grid over the Atlantic provides an opportunity for users to transmit their positions to other users in their vicinity, thus offering a Proximity Warning Indication (PWI) system.

Time did not permit a thorough evaluation of the potential of the Nav/TC satellite system to provide collision avoidance capabilities. However, in the next section, a technique is described which provides the user means to monitor his local air space and to detect potential collision situations in sufficient time for making corrective maneuvers. An on-board device is described which utilizes the satellite navigation signals for determining the location and velocity of other users in the vicinity.

## 5.2 ANTI COLLISION SYSTEM

### 5.2.1 INTRODUCTION

The general term "Anti-Collision System" (ACS) applies to three types of safety systems, namely:

Proximity Warning Indicator (PWI)
Air Traffic Control (ATC)
Collision Avoidance System (CAS)

A brief description of these systems is followed by the discussion of a method which enables these functions to be obtained with the help of airborne modules, assuming that a satellite-aided navigation system exists.

PWI systems are purely passive. They use visual beacons (or other devices; e.g., IR aids) to warn other pilots of the presence of a PWI-equipped vehicle; however, the vehicle itself cannot detect the presence of other aircraft.

ATC systems are generally confined to the immediate vicinity of the ground terminal, although the coverage could be enhanced by the use of satellites. The current ATC systems use ground-based radar to detect aircraft. The operation is helped if the aircraft carries a transponder to amplify the signal and transmit altitude information and identification data; a voice link is also commonly provided. An ATC system provides collision avoidance in the region of coverage by allowing the ground-based controller to observe and identify all aircraft in this region, evaluate the threat of collision, and issue instructions for appropriate maneuvers. The Nav/TC system configured during this study specially provides this type of operation for the North Atlantic or globally by making it possible for an Air Traffic Control Center to maintain nearly continuous position data on all aircraft within the region of interest, independent of cockpit derived position fixes. However, the ground controller is liable to make errors (due to human factors) and suffers from poor resolution, limited coverage, and possible saturation (due to excessive number of aircraft). Some of the drawbacks can be reduced through automation, but improvement of resolution cannot be expected without modifying the basic approach to implementation.

CAS systems have been under intensive study during the past ten years, but no satisfactory solution has been found. It is virtually impossible to obtain protection from non-cooperating aircraft, because then the vehicle to be protected must carry a very elaborate radar; such an airborne radar system has been shown to be unfeasible because of large power requirements and inadequate warning time.

Several concepts have been proposed for CAS for cooperative aircraft. The Air Transport Association (ATA) is actively sponsoring the study and tests of the so called "Time-Frequency" (TF) System. This system requires each cooperating aircraft to carry a transponder and a highly stable clock, for a total estimated cost of $30 to $50 thousand per plane. (The system also needs a network of ground stations containing atomic time standards for purposes of calibration and synchronization.) Each transponder radiates at a precise frequency and time; it also receives the radiated signals of all neighboring aircraft and determines their range (bv time delay), range rate (by Doppler shift) and altitude (by digital message). Flight tests for the system are scheduled for the Spring of 1969.

The TF system has the advantages of being able to handle a large number of aircraft without saturation, and the capability of performing auxiliary functions similar to Distance Measuring Equipment, ATC Transponder, obstruction marker, and Search and Rescue beacon. However, the over-riding drawbacks are the high cost of airborne equipment (due to the need of a precision clock) and the cost of an extensive time-synchronized ground network.

### 5.2.2 EXTENSION OF SATELLITE-AIDED NAVIGATION SYSTEM TO OFFER PWI AND CAS FUNCTIONS

The use of satellite-relayed signals to allow an aircraft user to obtain an accurate position fix has been the basic subject of discussion in this report. It will be assumed that a navigation system exists; i.e., the ground control station transmits signals to satellites which relay them to the field of users. The operation may be "passive" — in which case the users determine their positions by noting the incoming signal phase angles — or "active", if the users are provided with transponders which repeat the phase information back to ground. (The latter mode allows inclusion of the Air-Traffic Control function.)

A user equipped for satellite-aided navigation (passive or active) can easily acquire the PWI function by adding a special receiver-transmitter module in the aircraft. The basic concept is illustrated in Figure 5-1. The user demodulates the incoming satellite signal to extract the phase information, and broadcasts it — along with altitude data — by suitably modulating a carrier. (The choice of modulation is an important consideration and is discussed later.) The PWI signals from all neighboring aircraft are monitored by any plane equipped with a collision avoidance module, as described later, and are used by the latter to determine a possible threat.

The PWI function is relatively straight-forward, since it only comprises a demodulation and re-modulation operation on the received navigation signals. It is estimated that the receiver-transmitter module would cost between $500 and $1000. However, a PWI-carrying vehicle only warns other aircraft of its presence without protecting itself from others.

A Collision Avoidance System can be set up by requiring that all aircraft carry PWI and the larger planes (e.g. commercial airliners) carry compatible collision avoidance modules (CAM's). The success of a CAM depends on its ability to separate the numerous PWI signals being received at the same frequency. (Note that the frequency must be the same to conserve spectrum and to allow low-noise narrow band reception without

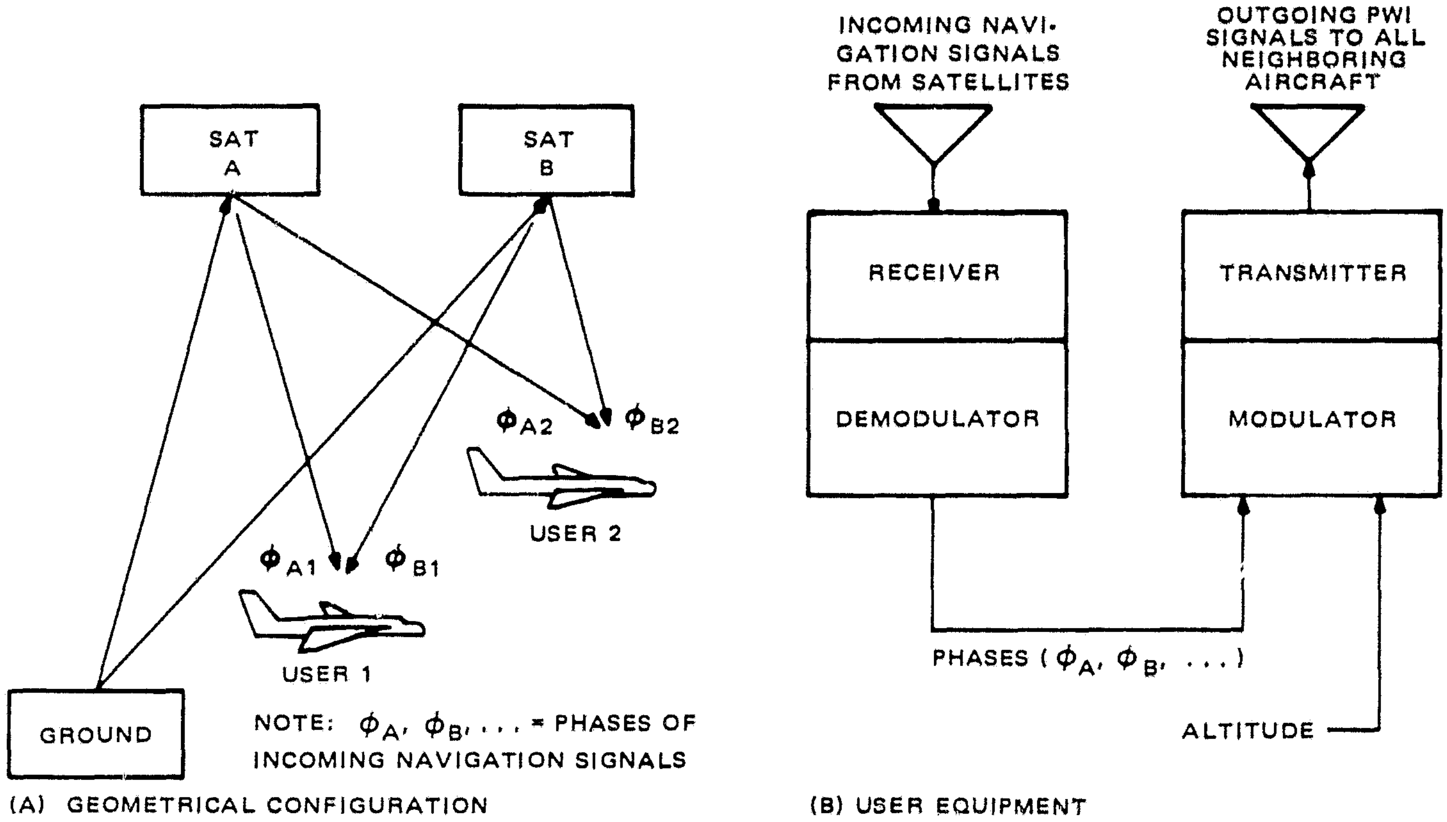


Figure 5-1. Addition of the PWI Function to a Navigation System

the need of frequency search over a wide-band.) The problem of identifying and separating the individual PWI signals is similar to the multiple access problem and requires detailed signal design study, as pointed out earlier.

### 5.2.3 SIGNAL DESIGN

One possible signal design for the PWI and CAS functions is described next. It is a binary FSK pulsed carrier system, requiring no time synchronization among the various users or between the user and the observer. The information to be transmitted (i.e., phases of the navigation signals detected by the user, his address and his altitude) is converted into a binary coded sequence at each user and is transmitted as a sequence of carrier frequency pulses at frequency P (binary "1") or Q (binary "0"). The pulse duration is taken as 1 $\mu$s, with a pulse repetition rate of 1000 pps. It is assumed that the message consists of a 70-bit word and is transmitted continuously; thus, e.g., in the simplest case when the user is stationary, the same message is broadcast over and over again. The detailed structure of the 70-bit message is such as to allow identification of the start of the message, in spite of the absence of a common time reference between user and observer, as discussed later.

Figure 5-2 shows three users, A, B and C transmitting arbitrary messages, starting at arbitrary times. Pulses emitted by different users are very unlikely to be superimposed so long as the numbers of users is much less than the ratio of pulse repetition period to pulse duration (i.e.) 1 ms/1 $\mu$s, or 1000). This holds so long as each transmitter has good short time stability for the period of signal processing. Note that time synchronization with the satellite or other user aircraft is not required; the only requirement is that the sequence of pulses maintain its periodicity and relative position with respect to other pulse-sequences during the time of signal processing.

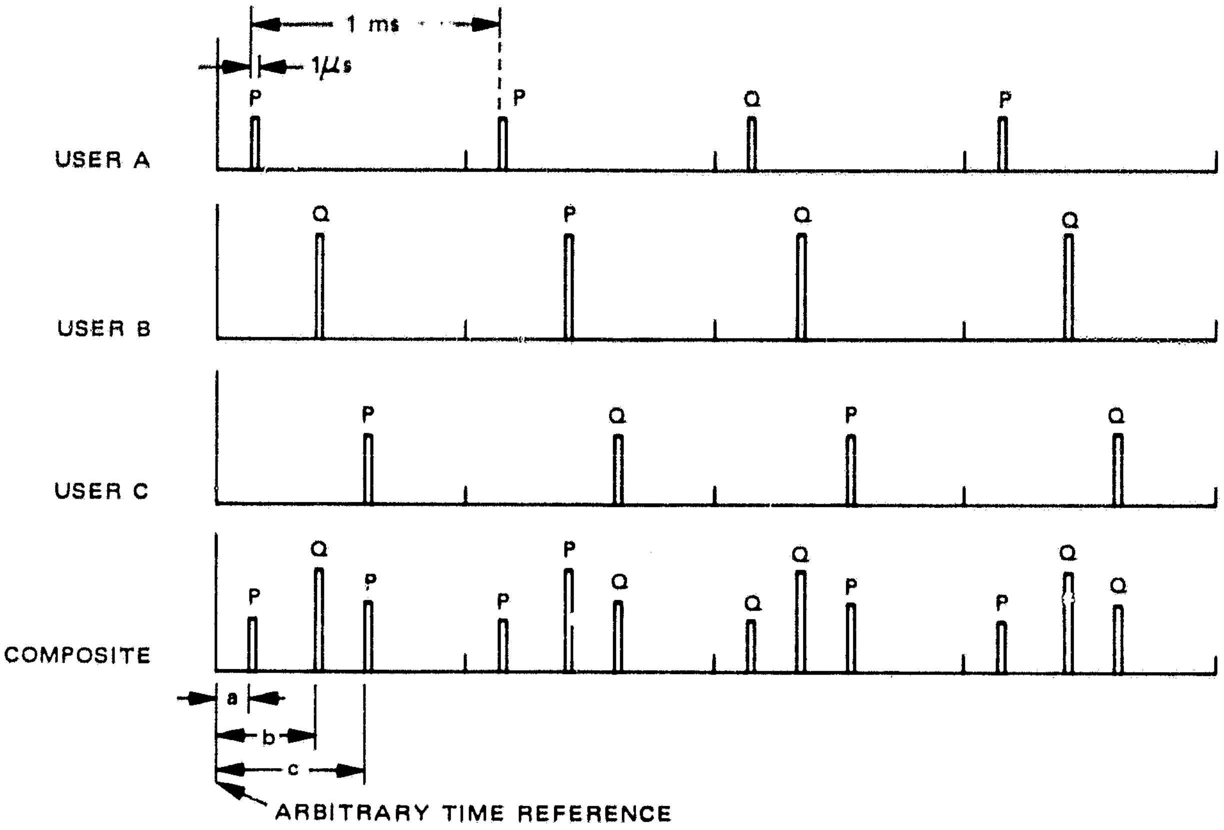


Figure 5-2. PWI Signals Using Binary FSK Pulsed Carriers

The pulse sequences transmitted by users A, B and C arrive at the Collision Avoidance Module (CAM) as a composite sequence which also shown in Figure 5-2. The CAM faces the task of resolving the composite into its three components, i.e. "acquiring" the users A, B and C separately. Basically this is done by exploiting the facts that (1) each user signal consists of a series of periodic pulses, and (2) the times of pulse arrival (a, b, c) are distinct. The periodicity allows the enhancement of signal by circulating it through a 1 ms delay line; in the ideal case, when successive pulses from any user arrive exactly 1 ms apart, this results in the addition of a number of pulses from that user. The distinction in times of arrival allows the signals to be separated.

In practice, the successive pulses may not arrive exactly 1 ms apart. For example, the time "a" depends on the distance of user A from the observer, and also on the propagation parameters; while the distance may remain constant during the period of observation, the propagation parameters may change, thus changing the time of arrival. Oscillator instability may cause another variation from pulse to pulse. It is therefore necessary to conduct a search in time (over a pulse-interval of 1 ms) in order to determine the apparent time of arrival of each user signal and then to track the signal in the presence of these variations.

The search is conducted, as shown in Figure 5-3, by setting up a "file" of 1000 time bins, each 1 microsecond long, and examining each bin for the presence or absence of a pulse. (Note that the occurrence of a carrier - at both frequencies P and Q - indicates the presence of a pulse. Hence the carrier frequency must be ignored, i.e. the outputs of P and Q filters must be combined, before conducting the time-of-arrival search.) For the composite signal of Figure 5-2 incident on the search file of Figure 5-3, the bins corresponding to times a, b, c will show significant voltages as an indication of the presence of pulses at these times, while other bins will either have low voltages, or no voltages at all (in the ideal case), as indicated in Figure 5-3.

After the time-of-arrival has been isolated and identified, it is possible to lock on it with a narrow time-gate so that any future variations are automatically tracked.

### 5.2.4 ACQUISITION

The acquisition of various user signals is followed by demodulation and detection to recover the original messages. This is shown in Figure 5-4 for one user. The P and

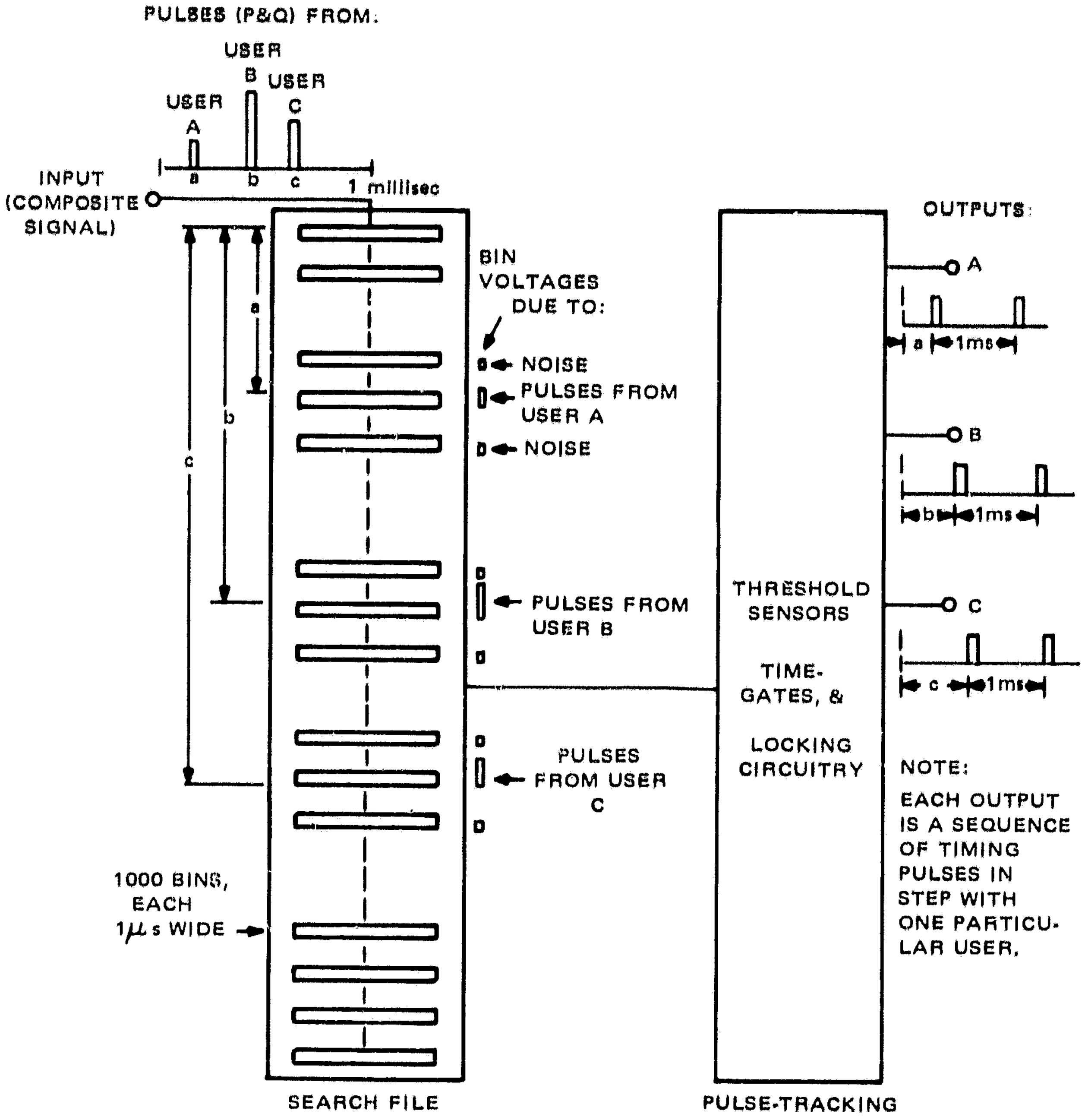
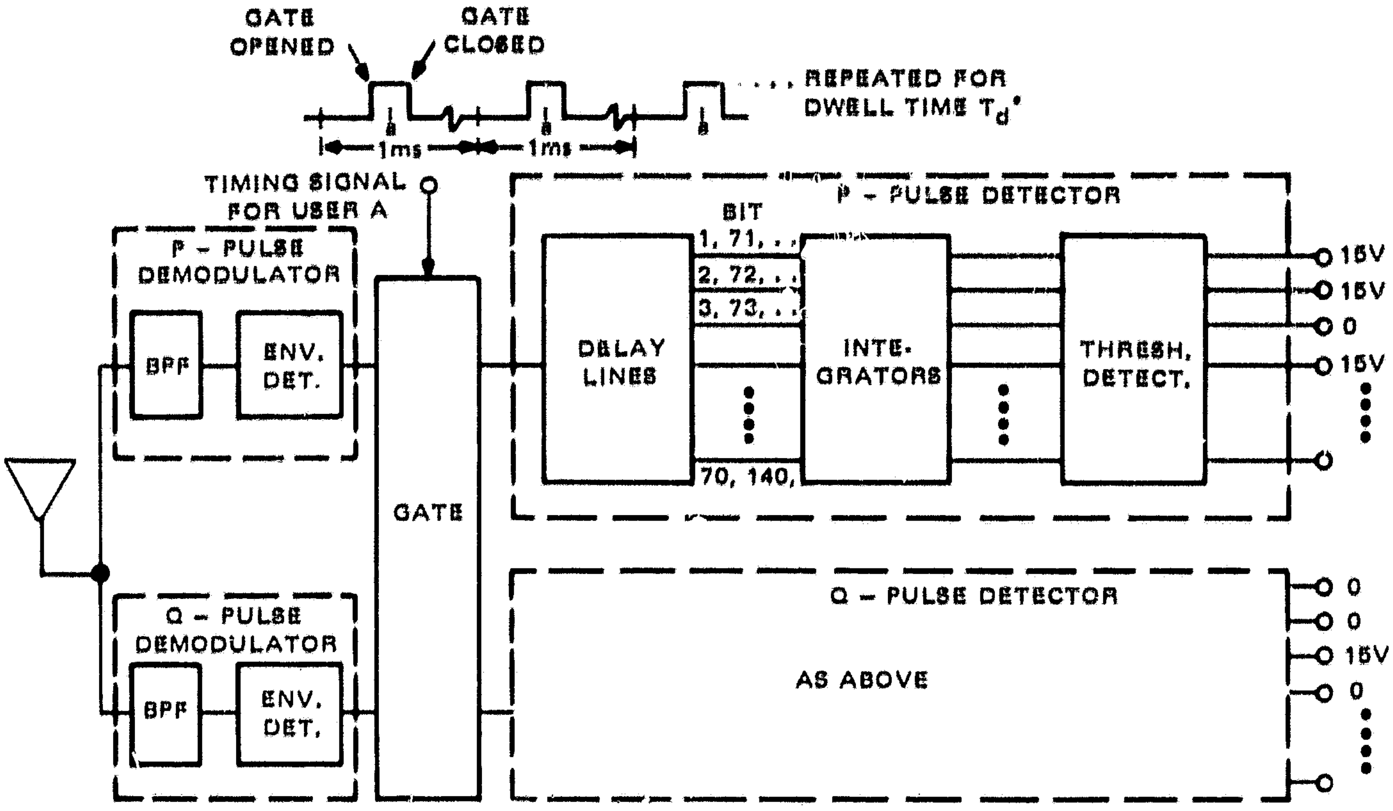


Figure 5-3. User Pulse Acquisition and Tracking

Q pulses are envelope detected and applied to a bank of 70 integrators with successive time delays of 1 ms, the process being continued for a dwell period of $T_d$ second. For illustration, assume $T_d = 1.05$ sec. so that the bank of integrators contains 15 complete cycles of the 70 bit word. (Recall that each bit is represented by a P or Q pulse in a 1 ms interval). Since the integrator output for a single pulse is V if the pulse is present, and 0 if it is absent, the total output for 15 pulses is either 15 V or 0. (The presence of noise — or the choice of $T_d$ different from an integral multiple of word duration — results in deviation of the voltage from these values.) The threshold detector



*$T_d$: 1.05 SEC; THIS PASSES 15 FULL CYCLES OF THE 70 BIT WORD (EACH BIT BEING A 1 $\mu$s PULSE OF CARRIER FREQUENCY P OR Q, WITH BIT PERIOD OF 1-ms)

Figure 5-4. Pulse Demodulation and Detection for User A

determines the presence or absence of a pulse on the basis of integrator output, and results in the message sequence 1101 . . . for user A, as shown in the figure.

It will be recalled that a user is assumed to continuously transmit the message, and there is no time synchronization between user and observer. Hence, the demodulated sequence will, in general, be a cyclic repetition of the original message with an indeterminate time-shift. The start of the message can be identified only by (1) assigning it a distinctive format (e.g. a single 0 followed by seven ones) and (2) making sure that no other part of the message (i.e. the address or data) takes on this format. The second requirement can be met by setting aside certain locations in the bit-stream for exclusive occupation by zeros. Details of the structure are omitted.

### 5.2.5 CONCEPT SUMMARY

The principle of operation of the Collision Avoidance Module is summarized in the block diagram of Figure 5-5, which uses the blocks developed in Figures 5-3 and 5-4 and

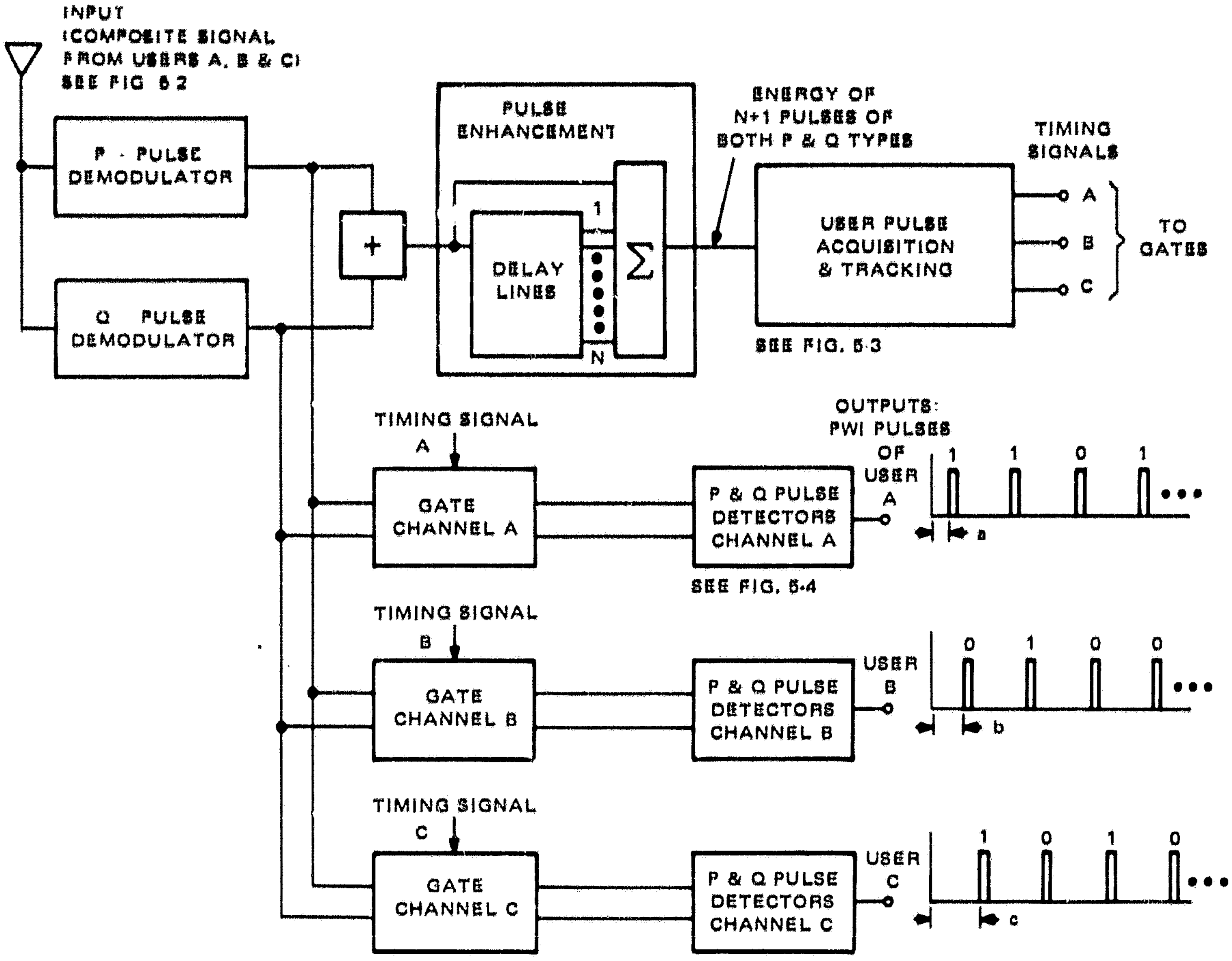


Figure 5-5. The Collision Avoidance Module-Pulse Acquisition and Detection

conforms to the preceding discussion. The outputs of various channels in Figure 5-5 correspond to the PWI signals received from different users and must be decoded to obtain the individual address, altitude and phase information. Figure 5-6 shows how the resulting information is used, along with the observer's altitude and phase information, to select the users lying within certain altitude limits (say ±1000 feet relative to the observer) and compute their relative positions for display. Additional computations (e.g. range, range-rate, time to close, and distance at closest approach) can also be performed from the available data and recorded as shown. A more sophisticated

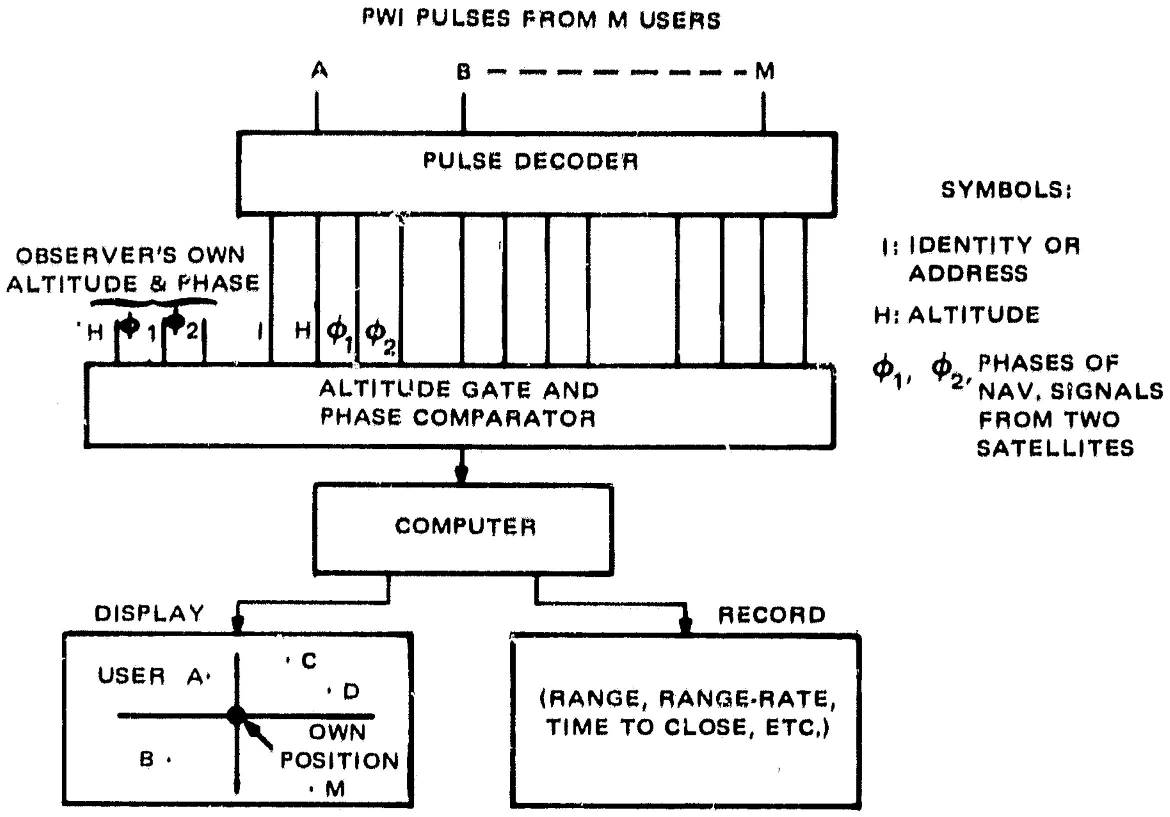


Figure 5-6. The Collision Avoidance Module-Data Processing and Display

system may use these results to automatically determine the collision threat and prescribe (or execute) corrective action.

In summary, the preceding discussion has outlined a method of incorporating proximity warning indication and collision avoidance systems when the basic satellite-aided navigation system is available. The basic concept is quite simple, but further study of modulation and signal processing techniques is needed for detailed evaluation. Other points needing further investigation are the size and cost of equipment, in particular the collision avoidance module. However, the foregoing description is sufficient to demonstrate the feasibility of the proposed concept and justifies the start of additional studies.