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NAVIGATION/TRAFFIC CONTROL SATELLITE MISSION STUDY

VOLUME I
SUMMARY

J.H. CRAIGIE, ET AL.

JUNE 1969

Electronics Research Center
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Prepared under Contract No. NAS 12-595 by

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ABSTRACT

This report describes an analysis which has been performed for the NASA Electronics Research Center relating the operational requirements of the projected civil aviation and marine traffic in the North Atlantic Ocean Area in the post-1975 era to the projected communications, position determination, and satellite technology. The result is a synthesis of a system composed of satellites, ground stations, and hardware in various user craft which provides transoceanic traffic control as well as a wide variety of operational support services for aviation and marine craft.

This Navigation/Traffic Control Satellite System employs a number of multipurpose satellites that provide passive navigation capabilities to any and all users; voice and data communications to aviation and marine subscribers; automatic data reporting for air traffic control surveillance; and a growth capability to collision avoidance and stationkeeping. The high performance attainable with the recommended all L-band system will provide operational flexibility and growth potential. There are no real "deficiencies in technology" as was considered likely at the outset of this study. The status of L-band technology today is such that the design, development, and demonstration program can be initiated immediately. The Design and Development/Preoperational Program recommended for the development and demonstration of the basic satellite configuration and ground stations, is estimated to cost $67 Million.

Volume II of this report, System Analyses, includes the requirements, communications, position determination, and satellite subsystem analyses. Volume III describes the operational system, the Design and Development/Preoperational System, the programs required to bring them into being, and a wide number of applications to which this system can be applied.

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1. INTRODUCTION AND APPROACH TO THE PROBLEM

1.1 STUDY OBJECTIVES, APPROACH, AND SCOPE

1.1.1 Background and Objectives

It is apparent that as the world population and the mobility of this population increases, the requirements on navigation and communication systems for air and sea craft likewise increase. Safety, economy, and convenience are all served by better navigation and communication capabilities. It became evident several years ago that space technology had matured to the point where the performance, reliability, and cost of communications and navigation satellite techniques make worthwhile the serious consideration and quantitative investigation of such systems. Accordingly, NASA's stated objective of this study has been "to identify the technological and related economic factors involved in implementation of a Navigation/Traffic Control Satellite System that would provide for more efficient operation of aircraft and ships over ocean areas by 1975." (Ref. 1)

1.1.2 Approach to the Problem

The Navigation/Traffic Control Satellite (NTCS) Mission Study has been more comprehensive than a simple feasibility study as the basic feasibility of the system was established several years ago. The requirements analyses and examination of alternate approaches comprised a significant portion of the study effort. On the other hand, it has been less detailed with regard to the ultimate selected design than a typical preliminary design study. The various steps taken in the mission study include:

1) The definition of the NTCS System, emphasizing air traffic control and operational support in the North Atlantic, with consideration of the North Atlantic maritime service and growth to worldwide operation.

2) Examination and development of system requirements, including both desired general characteristics and specific quantitative operational requirements for the North Atlantic Ocean Area.

3) Selection of the best satellite-based position determination technique. Candidates included passive and active user ranging, spinning fan-beam, and several interferometer techniques.

4) Analysis of the communications problem, including communications technology forecasts, studies of propagation characteristics, modulation techniques, and power budget analyses and the conceptual design of the communication subsystem.

5) Performance of a preliminary conceptual design of the NTCS System, concentrating on major items such as large aircraft user hardware, air traffic control data link, and satellite design.

6) Recommending an appropriate NTCS development program, and developing the associated design and development/preoperational program, and operational program plans and costs.

1.2 SYSTEM CONCEPT

The Navigation/Traffic Control Satellite System concept has been an outgrowth of the Ad Hoc Joint Navigation Satellite Committee (Reference 2) and the continuing National Aeronautics and Space Administration program, both at the Office of Space Science and Applications, and at the Electronics Research Center.

1.2.1 Basic Elements of the System

In addition to people, procedures, and the natural environment of the earth itself, there are three basic elements of the Navigation/Traffic Control Satellite System which need to be considered in its conceptual design. The first element is made up of the satellites themselves, which provide basic navigation data and high quality, highly reliable communications relay services. The second basic element of the system — called user equipment or user hardware, is made up of the electronics equipment used by the various system customers. It consists of antennas, receivers, data processors, displays, and the like. The third major element of the system is made up of the various ground stations which provide satellite system support such as satellite tracking and stationkeeping, and user mission support such as air traffic control, meteorological advisory services, and relay of company communications.

1.2.2 Functions

The Navigation/Traffic Control Satellite System must be configured such that the following functional services can be provided:

- Communications
- Surveillance
- Navigation
- Collision avoidance.

The communications, surveillance, and navigation functions make up the basic elements of a number of missions, such as air traffic control, search and rescue operations, and assistance to the recovery of manned and unmanned spacecraft. Other missions, such as scientific or commercial exploration, usually involve two or more of these functions. In the air traffic control mission, which is the one considered in greatest detail in the study, the relative emphasis and importance of all four basic functions will vary between the North Atlantic case and the Continental United States case. For this reason, although the study emphasis was on the North Atlantic, we considered it important in the early conceptual phase to examine potential roles, and the potential capability of this system, and to configure the system such that it is capable of growth.

1.2.3 Users

NASA has, from the outset, intended that the operational system be available and economically beneficial to a broad spectrum of users including:

- Large aircraft
- Large ships
- General aviation
- Small marine craft
- Specialized users such as scientific projects or expeditions.

The reason that the Navigation/Traffic Control Satellite System must cater to a broad spectrum of users is one of economics. The system will be more viable and of greater economic benefit if it can be applied to a wide variety of uses by many different subscribers.

1.2.4 Coverage

The Ad Hoc Joint Navigation Satellite Committee recognized that an immediate need exists for an improved air traffic control system over the North Atlantic Ocean. For this reason the North Atlantic Ocean Area has received primary emphasis in the study; but, recognizing the obvious benefits of a worldwide system of this type, NASA incorporated into the study requirements the ability of the system to function on a worldwide basis and called for an examination of the impact on the system design of the expansion to worldwide coverage.

2. NORTH ATLANTIC OCEAN AREA REQUIREMENTS

Analyses were performed which developed North Atlantic communications and air traffic control surveillance requirements. The analyses which developed these requirements are described briefly in the following paragraphs and are discussed in detail in Volume II. The recommended air traffic control surveillance capability for a 60-mile lateral separation in 1975 is:

- Accuracy: 1 nmi (1σ) position uncertainty
- Fix Rate: Subsonic - 1 fix per 80 to 100 sec
Supersonic - 1 fix per 20 to 24 sec
Total: 10,000 to 12,000 fixes/hr
- Provides: Multiple observations of off-course aircraft prior to airspace violation

A significant portion of the Navigation/Traffic Control Satellite Mission Study was spent in examining the major elements of requirements for reliable, full-time air/ground communications in transoceanic flight. A communications load analysis was performed which examined the nature and scope of aircraft and marine communications anticipated in the North Atlantic region in 1975 in order to determine the number of communications channels required for a Navigation/Traffic Control Satellite System. Typical aviation and marine messages were constructed and a queuing analysis was performed in order to estimate communications channel requirements for the NTC Satellites. The recommended North Atlantic communications capability is:

- Aircraft: 11 voice channels (peak load)
1 emergency voice channel
3 data channels (1200 bit/sec)
- Marine: 2 data channels (1200 bit/sec)
1 emergency data channel (1200 bit/sec)
Off-peak use of aircraft voice channel
- Search and Rescue:
  - Operations: Pre-empt 1 or 2 aircraft voice channels
  - Training: Off-peak use of aircraft voice channels
- Total: 12 voice channels
6 data channels (1200 bit/sec)

2.1 AIR TRAFFIC CONTROL AND OPERATIONAL SUPPORT

The majority of aircraft that fly the North Atlantic connect the eastern seaboard of the United States with European capitols such as London and Paris; although there are a number of flights across the so-called Polar routes, e.g., from Los Angeles to Scandinavia. The latter traffic, although it imposes a communications and navigation requirement on the Navigation/Traffic Control Satellite System, does not impact the major problem – which is air traffic control of a rapidly increasing number of aircraft flying the principal path between New York/ Washington, and London/Paris. Also, in this principal path area there is very little crossing traffic, such as would be produced by a flight from Iceland to Ascension Island. Furthermore, when the traffic is heavy going eastbound, it is light going westbound, and vice versa. The foregoing set of traffic flow characteristics results in a pattern for air traffic in the North Atlantic Ocean Area, which is fairly typical of major over-ocean air routes. Clearly, all aircraft would like to fly the optimum path between their point of departure and destination. The attempt to minimize the cost and time penalties of nonoptimum routing provides ample motivation for reduction of separation standards. A surveillance system was synthesized which supports substantially reduced separation distances.

Clearly, in order to quantify the system requirements associated with control of air traffic, the air traffic itself must be quantified. An examination of a number of forecasts (References 1-7) indicated that the maximum volume of traffic in the North Atlantic corridor in 1975 at any given time will probably be approximately 170 subsonic and 20 supersonic aircraft.

In Volume II lateral separation standards, aircraft population, position determination accuracy, position determination frequency, the magnitude of aircraft heading reference errors, pilot reaction time, and aircraft turning performance are considered; certain quantitative relationships between those parameters are developed, and the air traffic control surveillance capability listed on Page 5 resulted. It is the objective of the NTCS System to prevent air space violations by taking note of an impending violation at the air traffic control center far enough in advance to allow the air traffic controller to warn the pilot in time to prevent him from flying into an adjacent lane of traffic. This model assumed reliable communications and both the willingness and the ability of the aircraft to respond to the warning and/or the corrective heading instructions of the air traffic controller.

2.2 MARINE NAVIGATION AND CONTROL

Ships traditionally navigation international waters at will, guided somewhat by "rules of the road" as agreed to by international convention. In the past the need for precision and frequency of navigational information has depended primarily upon the proximity to harbors, waterways or obstructions, except for special missions such as search and rescue. This operational freedom has resulted in a steadily increasing collision rate, and tonnage losses rose by 150 percent in 1966 (Reference 8). Larger ships experience about 100 potential collisions a year and there were 2320 actual collisions between 1960 and 1966 (Reference 9). The evolving need is for both a reduction in hazard and also an increased ability to define and follow optimum courses. The advent of the fast automated ship and the potential for general employment of the surface effect ships which can cruise as fast as 80 knots create a new class of requirements for safe, expeditious operation (Reference 10). There is an implied need for control of traffic in certain areas that might be implemented in a manner similar to air traffic control for providing safe, expeditious transit along desired routes. This implies the definition of assigned channels or lanes and the provision of a capability for either self-determination or central control of safe separation intervals. Although quantitative marine navigation and surveillance capacity capabilities for the NTCS are hypothesized in Volume II, a strong case for these postulated requirements cannot be made at this time. The scope of this study did not allow the quantitative investigation and analysis that would be required to make such a case. Accordingly, the NTCS System requirements reflect only a limited surveillance capability, which is reflected as part of the communications load.

2.3 RECOMMENDED NTCS SEARCH AND RESCUE CAPABILITY

It is recommended that one or two aircraft voice channels be allocated on a pre-empting basis to search and rescue operations. A full-time emergency voice channel is available for aircraft at all times and a full-time emergency data channel is available to marine craft at all times. Thus, at the outset of an emergency, the alarm can be triggered on an immediate basis. The air traffic control agency can immediately be notified and also immediately assign empty channels or vacate and reassign channels for the search and rescue operation. It is estimated that channels in use could be completely vacated within several minutes, a great deal faster than a large search and rescue operation can be put into operation to the degree that would require full-time use of these channels. With regard to position determination, Reference 2, indicates that the search and rescue requirements for absolute accuracies are similar to those required for air traffic control, e.g., 1 nmi, but the relative accuracy requirements are more stringent, e.g., 1000 feet.

3. OPERATIONAL NAVIGATION/TRAFFIC CONTROL SATELLITE SYSTEM

3.1 GENERAL

The Navigation/Traffic Control Satellite Mission Study included the examination of a number of position determination techniques and communication subsystem approaches, both voice and data; and the selection of the most promising overall system design approach. This section describes that selected approach. The worldwide NTCS System is comprised of a number of multipurpose, communication-plus-navigation satellite in synchronous equatorial, and in synchronous inclined elliptical orbits, providing near worldwide coverage, but clearly favoring the Northern Hemisphere. Communications include both voice and data transmissions between aviation and marine craft and approrpiate ground stations. The position determination subsystem is a satellite-based hyperbolic navigation concept developed by TRW for NASA (Ref. 11). An alternate technique possible with this system is for a user to calibrate his own (relatively inaccurate) crystal oscillator, using four one-way range measurements. He then has sufficient data to solve for his position, altitude, and accurate time. Similarly, the user who want to measure velocity and rate of climb measures either the range rate difference from the Doppler of each of these signals or the four inaccurate range rates.

In the ultimate configuration, near worldwide coverage is obtained. As an example, an aircraft in most of the North Atlantic, the Continental United States, or Europe, would be able to see four synchronous equatorial, and, at least, one synchronous inclined satellite. This constellation would provide him with a fix with one sigma position determination uncertainties of approximately 70 to 200 feet, including geocentric altitude, and a communications capability of seventeen voice and nine 1200 bit/sec data channels. With very minor modifications to the user hardware, the system could also provide the user with 0.2 to 0.4 ft/sec velocity and rate of climb accuracy. If the inclined satellite is lost, all six elements of position and velocity are still available, but for aircraft in the northern latitudes, the altitude and rate of climb information suffers significantly increased geometric dilution of precision (GDOP) and is of little value.

Assuming aircraft altitude is known to several hundred feet, very good latitude and longitude information is still obtainable. Finally, if only two synchronous equatorial satellites are available, excellent latitude and longitude information is still available, but the accuracy is time-dependent. The user's clock will have been calibrated prior to takeoff, but cannot continually be calibrated in flight as in the case when three or more satellites are visible. Similar considerations hold for aircraft in other areas of the world.

Clearly, with respect to position determination capability as well as communications capacity, the Navigation/Traffic Control Satellite System provides an operational capability of unprecedented quality, operational redundancy, and—in the event of satellite failures—a partial operational capability.

The recommended program which will bring the NTCS system into operation is described in Section 4.2 The program phases are defined as follows:

- PHASE I: Design and Development (D and D)/Preoperational Program. This phase consists of the design, development, and demonstration of the basic satellite configuration, user hardware, and ground stations.
- PHASE II: North Atlantic Operation. This phase will consist of the qualification of the final satellite configuration, stationing of three synchronous equatorial satellites, and establishment of ground stations.
- PHASE III: Extension to World-Wide Operation. This phase will consist of the stationing of seven additional satellites and the establishment of additional ground stations.

3.2 SATELLITE CONFIGURATION

The NTC Satellite will exist in three similar configurations with a high degree of commonality between configurations. In fact, the basic structure and dimensions (except for solar array) will be identical. The program and satellite nomenclature, and satellite payload and design data are shown in Figure 1. Configuration A will be the Phase I, D and D/Preoperational spacecraft. It will weigh approximately 720 pounds and will have as its payload one voice, one data, and one ranging channel.

CONFIGURATION DATA
(DIFFERENCES BETWEEN THE THREE CONFIGURATIONS)

	A	B	C
PAYLOAD	1 VOICE 1 DATA 1 RANGING	1 VOICE 1 DATA 1 RANGING	4 VOICE 2 DATA 1 RANGING
DESIGN LIFE	3 YEARS [1]	7 YEARS [1]	7 YEARS
MTTF	45 - 60 MO [2]	45 - 60 MO [2]	45 - 60 MO [2]
DC POWER REQUIREMENTS	445	450	760
WEIGHT (DRY)	650 [2]	660 [2]	950 [2]
ATTITUDE CONTROL REACTION WHEELS	PITCH	ROLL, YAW	PITCH
PRODUCTION COST	$7.9M [3,4]	$7.0M [3,4]	$7.5M [3,4]
LAUNCH VEHICLE	THOR/DELTA (WITH 9 CASTOR II'S)		TITAN IIIB/ AGENA

(1)PRESENT CONFIGURATION A/B DESIGN LIFE OF 3 YEARS WOULD BE INCREASED TO 5 TO 7 YEARS IN PRELIMINARY DESIGN.

(2)WEIGHT WOULD BE INCREASED IN ORDER TO INCREASE MTTF FROM 45 TO APPROXIMATELY 60 MONTHS IN PRELIMINARY DESIGN.

(3)REFLECTS INCREASE IN MTTF FROM 45 TO 60 MONTHS.

(4)BASED 2,4, AND 15 ARTICLES, RESPECTIVELY.

FLIGHT PROGRAM PHASES

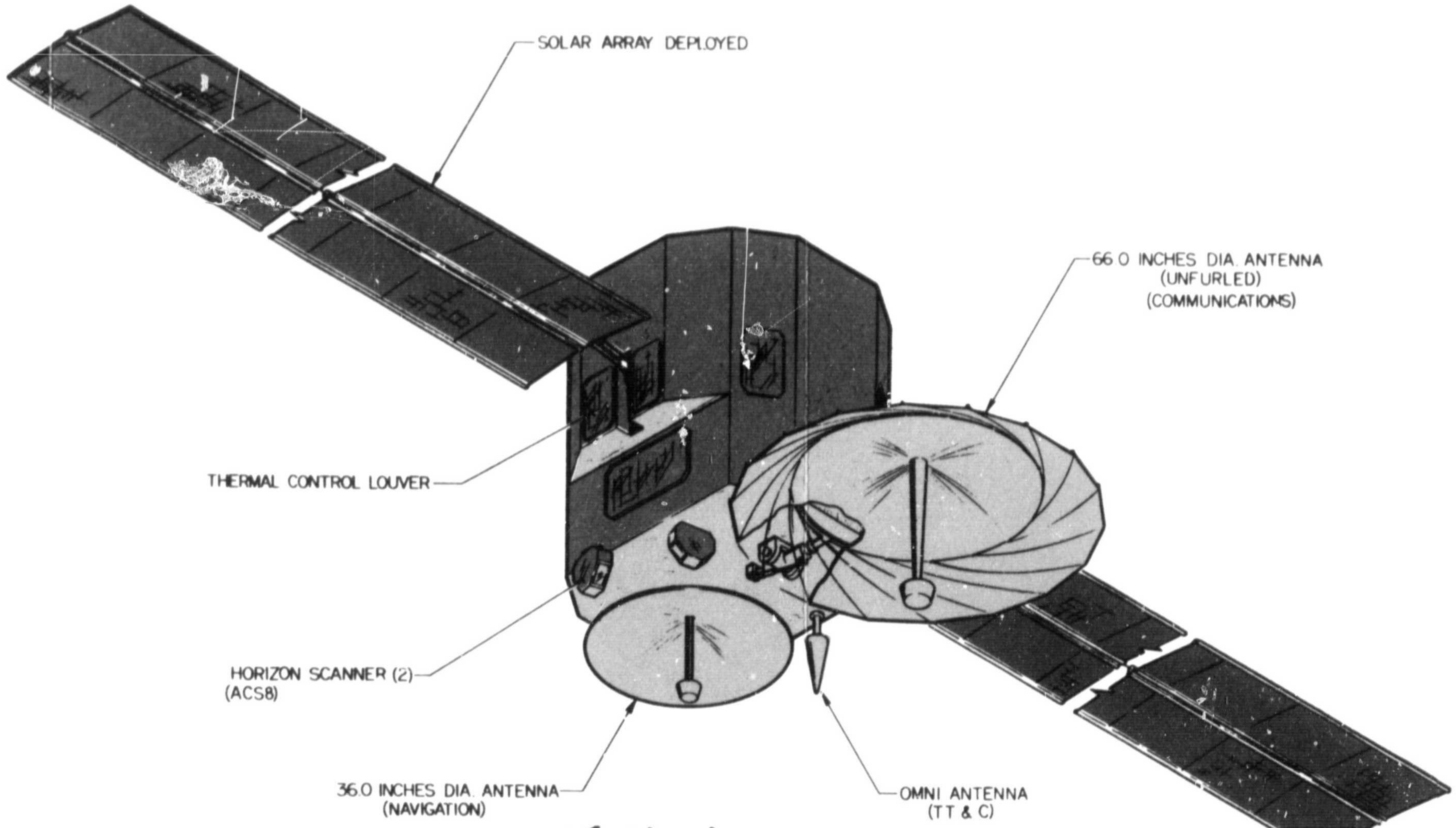
I	D AND D/PREOPERATIONAL PROGRAM (1972 - 1973)
II	NORTH ATLANTIC OPERATION (1974 - 1979)
III	EXTENSION TO WORLDWIDE COVERAGE(1976 - 1979)

CONFIGU
CONFIGU
CONFIGU

Foldout #1

NOMENCLATURE

CONFIGURATION A	DEVELOPMENT AND PREOPERATIONAL	THE GEOSTATIONARY NTC SATELLITE WHICH WILL BE USED TO DEMONSTRATE THE POSITION DETERMINATION AND COMMUNICATIONS CAPABILITY OF THE SYSTEM AND TO DEVELOP AN OPERATIONAL CAPABILITY.
CONFIGURATION B	OPERATIONAL	INCLINED ORBIT CONFIGURATION, PROVIDING NEAR - POLAR COMMUNICATIONS AND IMPROVED POSITION DETERMINATION CAPABILITY (E.G., EXCELLENT ALTITUDE, EQUATORIAL NAVIGATION).
CONFIGURATION C	OPERATIONAL	THE "STANDARD" GEOSTATIONARY NTC SATELLITE CONFIGURATION.



Foldout # 2

SPACECRAFT DATA
(SAME FOR ALL THREE CONFIGURATIONS)

DIMENSIONS

DIAMETER: 60" (DYNAMIC ENVELOPE)
HEIGHT: 57" (LESS ANTENNAS)

STABILIZATION

THREE - AXIS STABILIZED TO 00.5 DEG
TWO - AXIS IR EARTH SENSORS
MOMENTUM WHEEL
ATTITUDE/VERNIER VELOCITY (COLD GAS)
GYRO REFERENCE DURING POWERED FLIGHT

PROPULSION

N_2O_4/MMH (I_{SP} = 300 SEC)

100 lbf THRUST (I = 380,000 LB - SEC)

THERMAL CONTROL

PASSIVE, E.G., COATINGS, INSULATION
ACTIVE, E.G., HEATERS , LOUVERS

ELECTRIC POWER

SUN - ORIENTED SOLAR ARRAY
3 NICKEL - CADMIUM 20 AMP - HR BATTERIES

TELEMETRY, TRACKING, AND COMMAND

S - BAND, OMNIDIRECTIONAL (2 CONICAL ANTENNAS)

COMMUNICATIONS ANTENNA (L - BAND)

NET GAIN (BORESIGHT) -26 DB
BEAMWIDTH (3 DB) - 8 DEG

NAVIGATION ANTENNA (L- BAND)

NET GAIN (BORESIGHT) - 20.5 DB
BEAMWIDTH (3 DB) - 14.5 DEG

Figure 1. Navigation/Traffic Control Satellite

Foldout #3

Configuration B will be an operational version of Configuration A and will be employed in synchronous inclined elliptical orbits. It will weigh approximately 730 pounds and will differ from Configuration A only in the yaw control design. Configuration C (Figure 2) will be the standard operational spacecraft and will be employed in synchronous equatorial orbits. It will weigh approximately 950 pounds and will provide four voice, two data, and one ranging channels. It will be similar to Configuration A, but will have greater communications capacity and therefore requires more power, thermal control, and propellant.

The NTC Satellite will be a three-axis stabilized spacecraft with an earth-oriented antenna and sun-oriented solar panels. Earth and sun sensors are employed for attitude sensing. Nitrogen gas jets provide the control capability. The structure will be partially cylindrical and partially rectangular, and will entail honeycomb mounting platforms for the various spacecraft components. Thermal control will consist of both active and passive techniques, e.g., heaters, insulation, louvers, and surface coatings. Propulsion during injection will consist of approximately a 100-pound thrust liquid engine using MMH and N_2O_4, which will yield an I_{sp} of 300 seconds. A gyro reference package is used during acquisition of earth/sun references and injection only. Pitch and roll control torque is provided by gimballing the engine during this phase. Configurations A and C will use a pitch momentum wheel for yaw control, and Configuration B will use a yaw sun sensor and a yaw reaction wheel. All spacecraft will employ a high-gain antenna for voice and data communications and an earth coverage antenna for position determination.

The communications antenna is 5.5' in diameter when fully deployed. This antenna is stowed upright and articulated 90° in the operational mode. The center portion of the antenna (4' diameter) is a solid light-weight aluminum honeycomb material; the unfurlable outer antenna section is composed of aluminum wrap-around ribs and Mylar covering. A strap is used to hold the ribs secure during launch and is released by pyrotechnic strap cutters at deployment. The earth coverage antenna (used for position determination) is 3' in diameter and is constructed of aluminum honeycomb.

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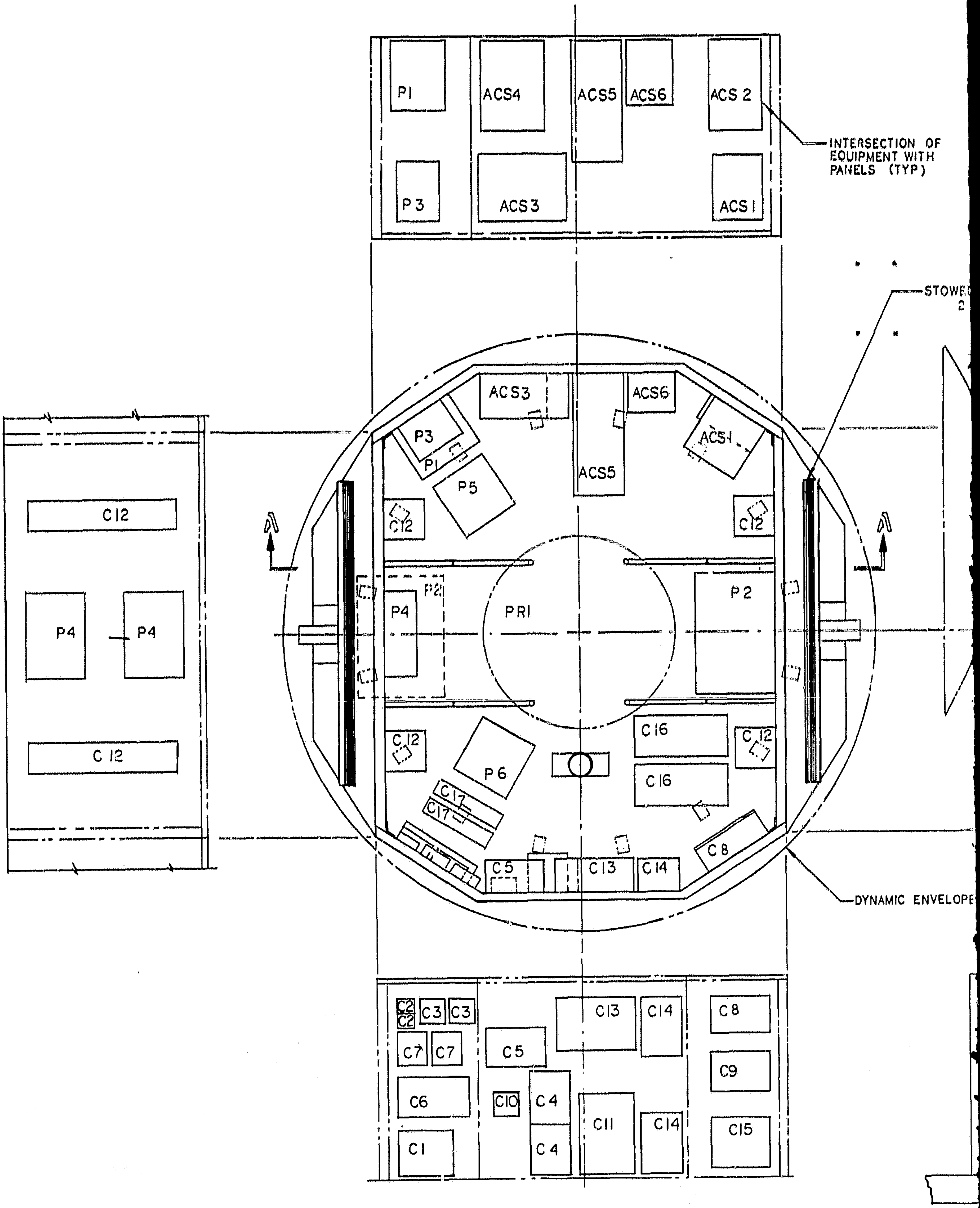
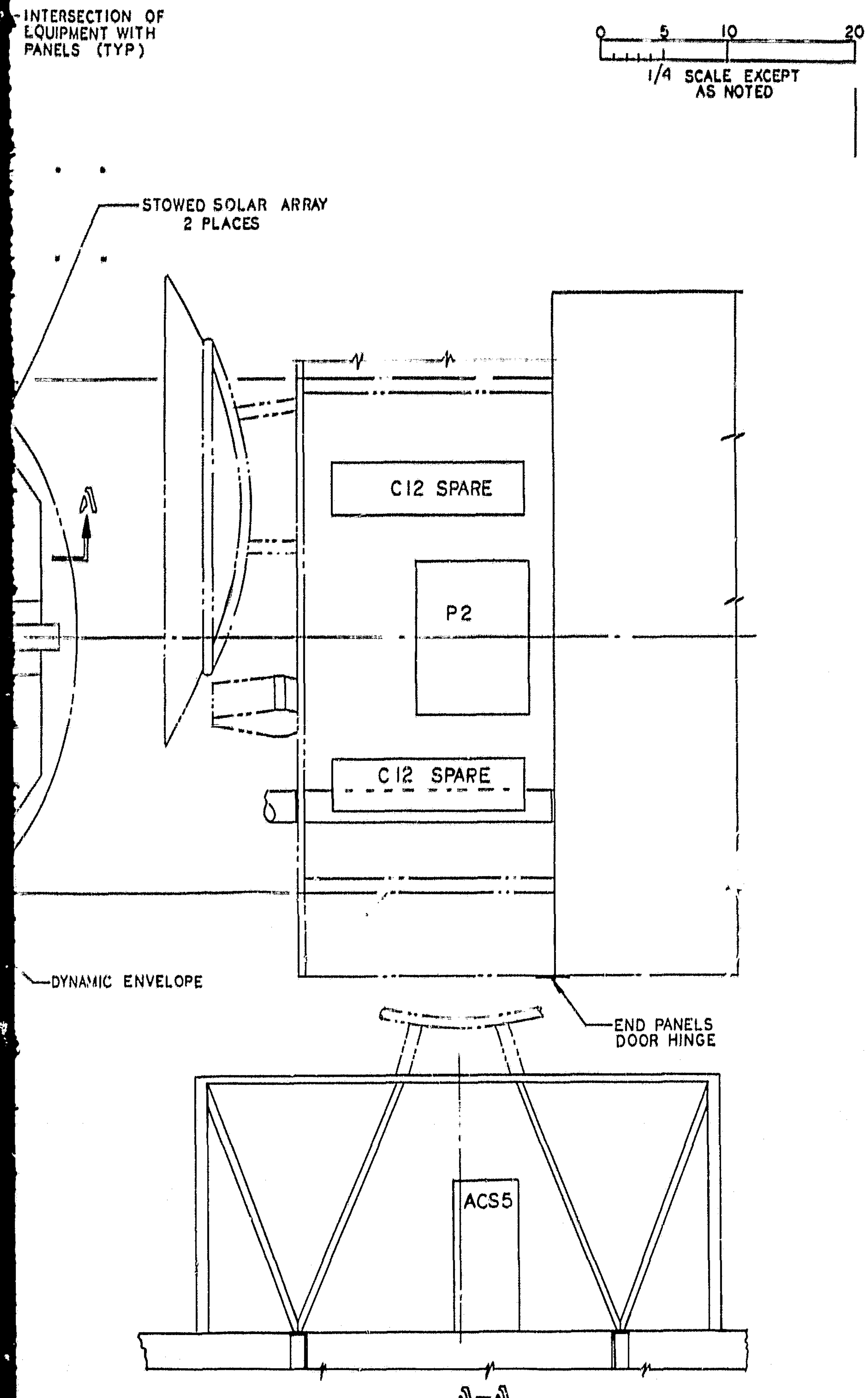
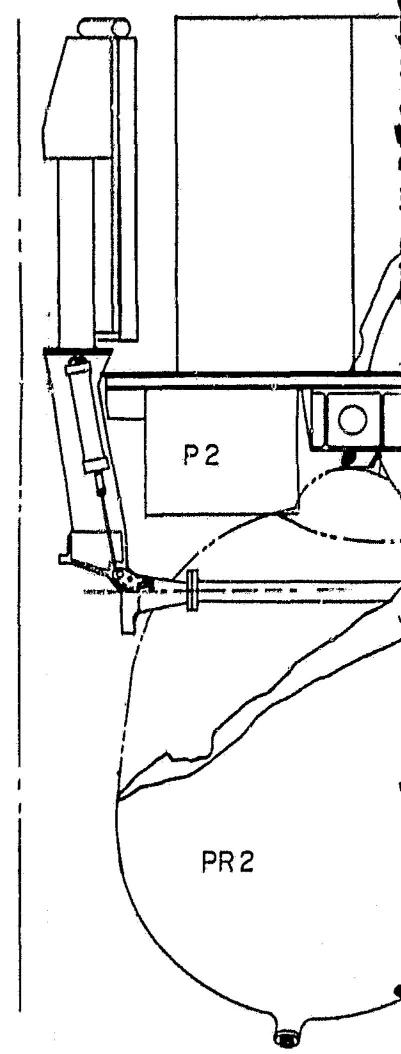


Foldout # 1

Na	
E	
Code	Equipm
C1	Diplexer (S-band)
C2	Hybrid
C3	Command receive
C4	Command decode
C5	Telemetry transmi
C6	Telemetry encode
C7	Receiver selection
C8	L-band diplexer
C9	Frequency multip
C10	Isolator
C11	Transmitter
C12	TWT and power s
C13	Receiver
C14	Solid state power
C15	Frequency synthe
C16	Reference oscillat
P1	Power control uni
P2	Battery





Foldout #2

Navigation/Traffic Control Satellite Equipment Identification Code			
de	Equipment	Code	Equipment
	Diplexer (S-band)	P3	Central dc/dc converter
	Hybrid	P4	Shunt Assembly
	Command receiver	P5	Electrical integration unit
	Command decoder	P6	Telemetry integration module
	Telemetry transmitter		
3	Telemetry encoder	ACS1	Gyro reference assembly
7	Receiver selection	ACS2	Sensor electronics
3	L-band diplexer	ACS3	Control electronics
0	Frequency multiplexer (L-band)	ACS4	Actuation electronics
10	Isolator	ACS5	Reaction wheel
11	Transmitter	ACS6	Reaction wheel electronics
12	TWT and power supply	ACS7	Sun sensor assembly
13	Receiver	ACS8	Horizon sensor assembly
14	Solid state power amplifier	ACS9	Solar array drive
15	Frequency synthesizer		
16	Reference oscillator	PR1	Pressurance (N) tank
		PR2	Oxidizer (N_2O_4)
1	Power control unit	PR3	Fuel (MM_H)
2	Battery	PR4	Engine assembly

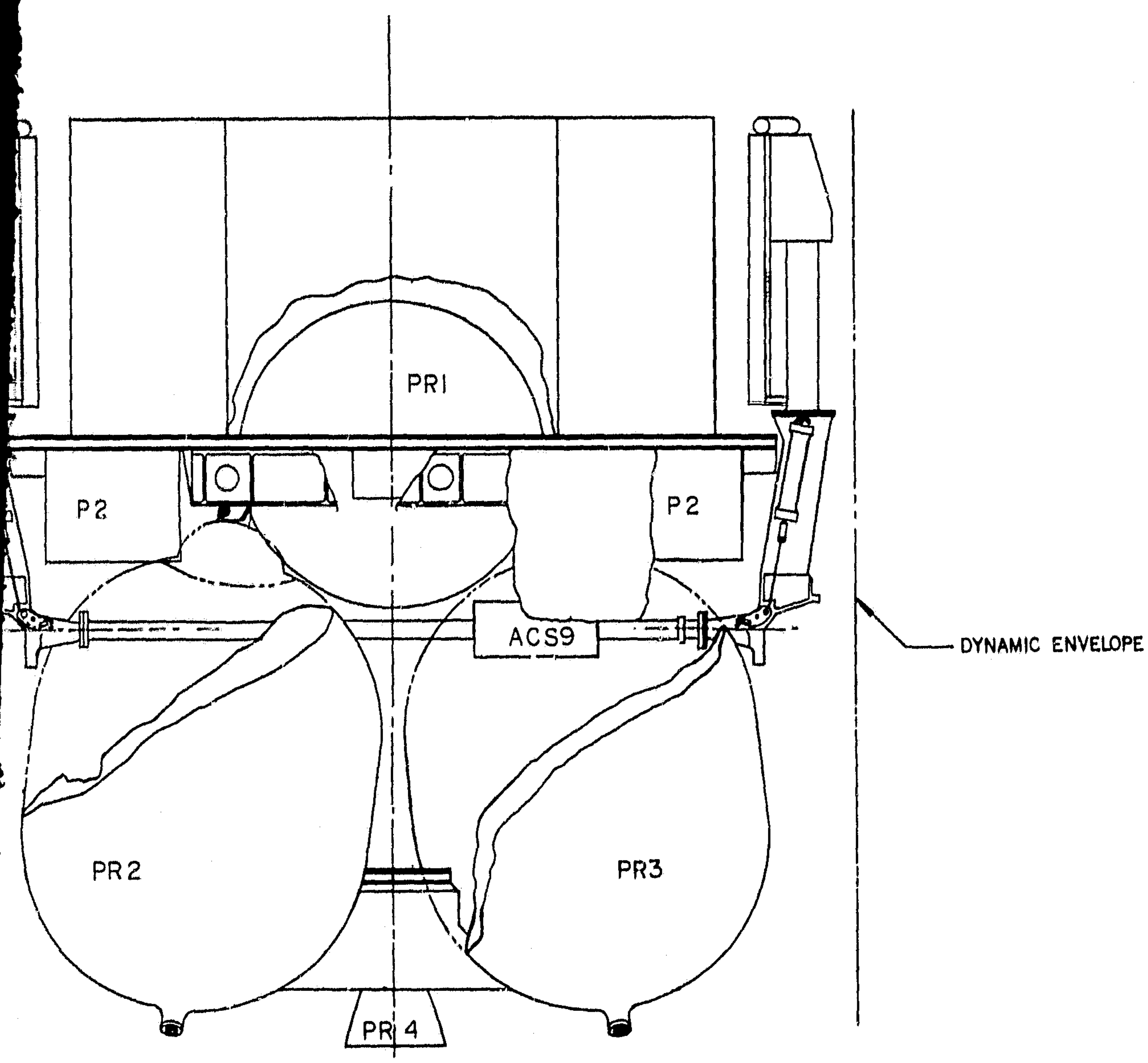


Figure 2. Inboard Profile NTC Satellite (Configuration C)

Foldout #3

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The power subsystem is comprised of an accordion foldout solar array and rechargeable 20 ampere-hour nickel cadmium batteries. The accordion foldout arrays utilize a 0.008" thick silicon cells protected by bonded cover glass mounted to a Kapton substrate. A total of 48 panels (17 by 30 inches each) can provide approximately 1400 w of power at begining of life. A single central deployable boom supports each array from a tubular cross piece at the end of the boom.

3.3 USER HARDWARE

The user hardware analysis described in this report places very heavy emphasis on commercial aviation users. From a position determination viewpoint, a range of users was examined in Reference 11. From a communications standpoint, the user hardware for voice and data communications is much the same for all classes of users except for antenna design, input/output, and display hardware. While those factors—especially the antenna gain for marine users—deserve further attention during the preliminary design phase, they are not considered to be pacing items in terms of program feasibility, or testing requirements. The resulting commercial carrier avionics package is an integrated satellite communications/navigation system that provides capabilities for communicating voice and data message, as well as supplying aircraft position information in digital form to the ground terminal. The recommendation is made that the user hardware for the D and D/Preoperational phase be prototype and/or development flight versions of the operational user hardware, rather than special engineering test equipment.

The user system, shown in block diagram form in Figure 3, consists of three main subsystems:

- The Transmitter/Receiver Unit
- The Digital Unit
- The NAVSTAR Unit.

Additional peripheral equipment consists of display and control units.

The transmitter/receiver unit transmits and receives to and from the satellite system via a radio frequency link operating in the L-band

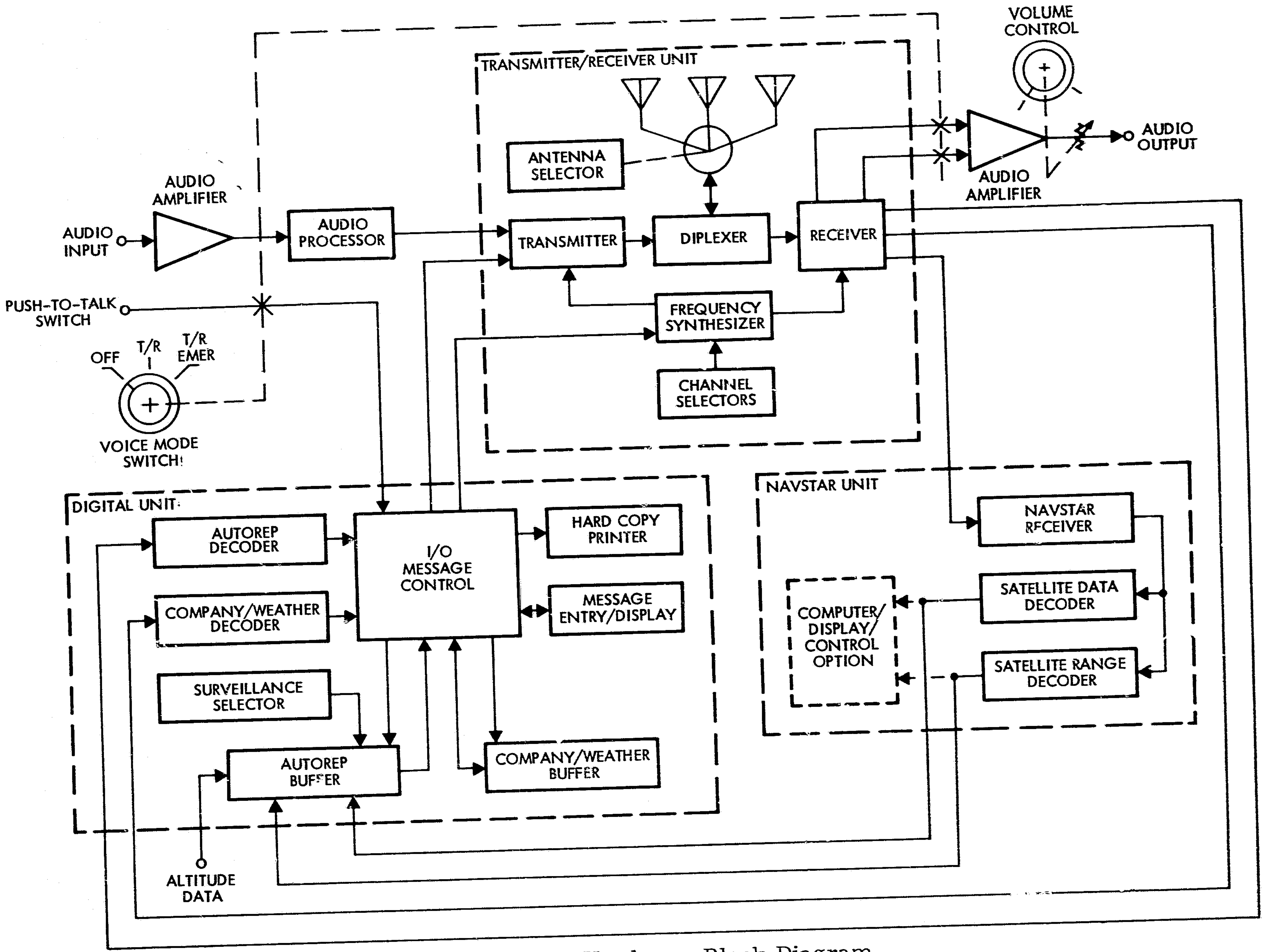


Figure 3. User Hardware Block Diagram

spectrum. Modulation and detection of the voice and data communication are provided in this unit along with a translated down (i. e., from L-band) RF signal that is supplied to the NAVSTAR processor.

The digital unit arranges, stores, and releases, in the form of data, both processed NAVSTAR information and weather/company printed messages. The latest NAVSTAR position determination information is continually updated and stored in this digital unit, and this raw data is then communicated automatically to the ground terminal via the satellite on command from the ground station. The weather/company are printed messages that are communicated also via the satellite to and from the ground terminal. Weahter/company messages from the aircraft are first stored in this digital unit and then released on command from the ground as a time interleaved data signal with the Autorep message.

The NAVSTAR unit receives the RF signal from the transmitter/receiver unit, amplifies and detects the NAVSTAR signal, then demodulates the information received from a group of satellites. This digital signal identifies each satellite and gives the time of day and range information. This processed information is relayed to the digital unit for retransmission to the ground terminal.

Elements of the position determination user hardware when it is used as a navigation system are an antenna and receiver/processor (which decodes the data and forms a digital number from the range measurement). Most users will have a digital computer for their data processing; however, the computations required can be simplified for the lowest cost and lowest performance users (Ref. 11) to obviate the need for an electronic computer, allowing hand calculator operation.

Three typical user antenna configurations are shown in Figure 4. Other configurations are possible and can be expected to find practical application. These antennas have been tested at TRW on a scale model F-100. While the F-100 model is not considered representative of aircraft which will use the Navigation/Traffic Control System, the tests indicated generally satisfactory antenna performance. In particular, the tail area resulted in poor gain because of the location of the antennas on the centerline of the fuselage. It is felt that better gain characteristics should achieve more optimum mounting.

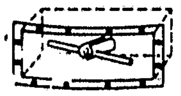
Type	Radiation Pattern	Gain	Axial Ratio (db)	Mounting	Dimension
Curved Dipole Turnstile 	Hemispherical	-3 to 4 db Over 160° Cone	<5	Low Profile	Hemispherical 2-1/2 in. Height 3 in. Rad
Conical-Log Spiral 	Hemispherical	-3 to 5 db Over 160° Cone	<5	Medium Profile	Cone Shape 7-in. Height
Slot Dipoles (Three Required) 	Hemispherical	0 to 6db Over 160° Cone	<5	Flush	7 x 2.5 x 1.9 in.

Figure 4. Antenna Configurations for NAVSTAR Users

The recommended antenna for large aircraft is the slot dipole. Flush mounting and additional signal margin is achieved. This is done at the expense of switching between three antennas, but this switching is not considered to be a particularly costly or complex operation. For navigation only, either the curved dipole turnstile (2-1/2'' profile) or the conical log spiral (7'' profile) would find general use, as no switching would be required.

3.4 GROUND STATIONS

The Design and Development/Preoperational phase of the NTCS Program will involve the setting up of remote tracking stations at – for example – Shannon and Gander, and a temporary Master Control Center at the Federal Aviation Agency's National Aviation Facilities Experimental Center (NAFEC), as well as obtaining operational support at NASA's Rosman and Goddard facilities. For the North Atlantic Ocean Area Operational phase, a remote tracking station at Ascension Island could be added to the Shannon and Gander net, and a permanent master control center is set up at J.F. Kennedy Airport in New York. (All of these locations are intended simply as examples.) For world wide coverage, two additional master control stations and three additional remote tracking stations will be required.

User mission support, as typified by the combined air traffic control/ weather/company operational support functions performed at a station such as the Gander, Newfoundland, Oceanic Control Center, include:

- Surveillance of aircraft position

- Computation and data processing of present and future projected positions of controlled aircraft as well as uncontrolled aircraft in the area of which the Center has knowledge and the associated conflict searches, i.e., the determination of potential airspace violations, and/or mid-air collisions, and the determination of appropriate corrected actions.

- The transmission and receipt of voice and data communications to include normal air route traffic control information such as requests for clearance changes, new clearances, traffic advisories, and acknowledgements; weather advisories, both air-to-ground, and ground-to-air; company communications; and messages of an emergency nature.

- Weather observation and forecasting services typical of those aeronautical and maritime meteorological services provided today, augmented to include items such as high altitude radiation warnings for supersonic transports.

Standard orbit determination techniques are employed by the NTCS system. The measurement technique is multilateration. The basic tracking information consists of range, range rate, and satellite identification with the range rate data being of marginal benefit. The data are also used to provide real-time system status checks. Telemetry data are derived on board the satellite as a result of monitoring certain spacecraft functions and are transmitted on command.

When the NTCS satellites are launched, normal range facilities with the unified S-band system and STADAN net are utilized for ascent trajectory monitoring and positioning in the desired orbit. After final positioning, the dedicated ground system will accept the NTCS satellites for operation and maintenance.

3.5. COMMUNICATIONS AND POSITION DETERMINATION COVERAGE

3.5.1 Atlantic Ocean Regional Coverage (Figure 5a)

The coverage provided by two synchronous equatorial satellites stationed at 15°W and 56°W longitude during the Phase I D and D/ Preoperational program is shown in Figure 5. Note that the entire East

Coast of the U.S., and Western Europe as well, receive communications and position coverage. Thus a large amount of testing can be land-based or performed immediately off-shore.

The coverage provided by the third (35°W) satellite is clearly redundant. This satellite provides the additional ranging information which provides very accurate and essentially non-time-detendent latitude/longitude for all but the polar and equatorial regions.

3.5.2 Synchronous, Elliptical, Inclined Satellite Coverage (Figure 5b)

Synchronous equatorial orbits have several limitations. They cannot be used to derive altitude information in the mid-latitudes; they cannot provide accurate North-South position data in the equatorial regions; and they cannot provide communication and navigational coverage in the polar regions. All of these features, plus considerably improved X-Y position determination accuracy and system redundancy in case of satellite outage, can be obtained by supplementing the equatorial orbit satellites with synchronous satellites in highly inclined orbits.

The inclined synchronous orbit selected has a pear-shaped ground track over the North and South Atlantic with apogee occurring at the apex of the pear, at 52.5°N latitude and 35°W longitude, just halfway across the Atlantic from Nova Scotia to London. The orbit is elliptic with 0.35 eccentricity and 52.5 inclination. In its 24-hour period, a satellite in such an orbit will spend 12 hours in the top region of the pear, with its subsatellite point remaining throughout this time above 28°N latitude. The position determination accuracy considerations are discussed in Section 4, Vol. III. The communications coverage provided by the high gain communications antenna at four points in time are shown in Fibure 5b.

3.5.3 Global Coverage (Figures 5c and 5d)

Position determination coverage obtained with the nine synchronous equatorial satellites is indicated in Figure 5c. It should be noted that excellent longitude information, but very poor latitude information, is available near the equator without the inclined satellites. Their inclusion provides excellent 3-dimensional position determination in all areas of full coverage. Section 4 of Volume II contains a detailed discussion of the coverage available for various operational configurations.

The communications coverage obtainable with the ultimate worldwide system (Constellation No. 8) is shown in Figure 5d. For convenience of notation, the synchronous equatorial satellites to the West of the Greenwich meridian are given even numbers and to the East are given odd numbers. The inclined pair covering the Atlantic are numbered 10 and 11, whereas the inclined pair covering the Far East are numbered 12 and 13. Inspection of the figure shows that the circular 8-degree beam described in Paragraph 2.2.5.1 will give excellent Northern Hemisphere coverage throughout the world. It is not clear, however, that full Northern Hemispherical coverage would make sense for a program sponsored and funded by the United States. Indian Ocean maritime route coverage would clearly be of greater economic benefit to the Western World than USSR/China coverage. Accordingly, coverage indicated by the curves labeled Alt. 3, Alt. 5, Alt. 7 are obtained simply by moving the centerline or aim point of the communications antenna on the No. 3, No. 5, and No. 7 satellites to approximately 2 degrees South, straight down, and approximately 2 degrees North of the subsatellite point, respectively.

The curves labeled 10a, and 11a, show the communications coverage provided by satellites 10 and 11 at the 6- and 18-hour points, whereas the curves 10b and 11b show the coverage 6 hours later. As pointed out in Volume II, Paragraph 4.8.3, the coverage provided by the inclined satellite at apogee is excellent, but for the system as presently configured, the satellite does not provide this coverage for as long as is really desirable. Therefore, the preliminary design phase could well see the inclined satellite inclination and/or eccentricity increasing. Note it is also conceivable that the need for this satellite coverage from both a communications and position determination standpoint might not warrant its development and implementation.) Satellites 12 and 13 are shown only at the zero and 12-hour points on the orbit to simplify the chart. The Southern Hemisphere coverage provided by these satellites is only incidental. When the synchronous inclined satellites are near perigee, their coverage area is quite small and they are moving fairly rapidly at this point, the necessary consequence of any eccentric inclined orbit.

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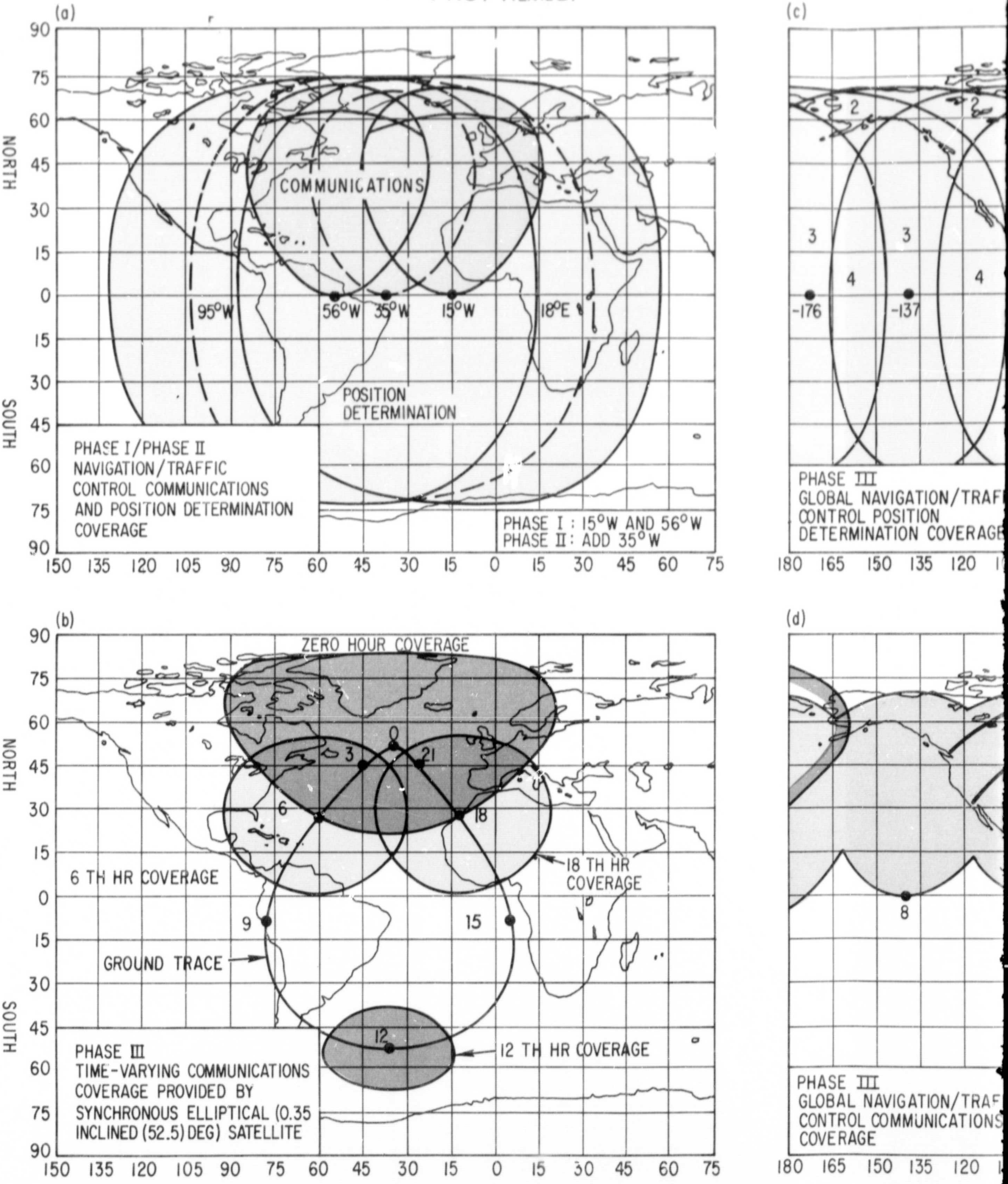

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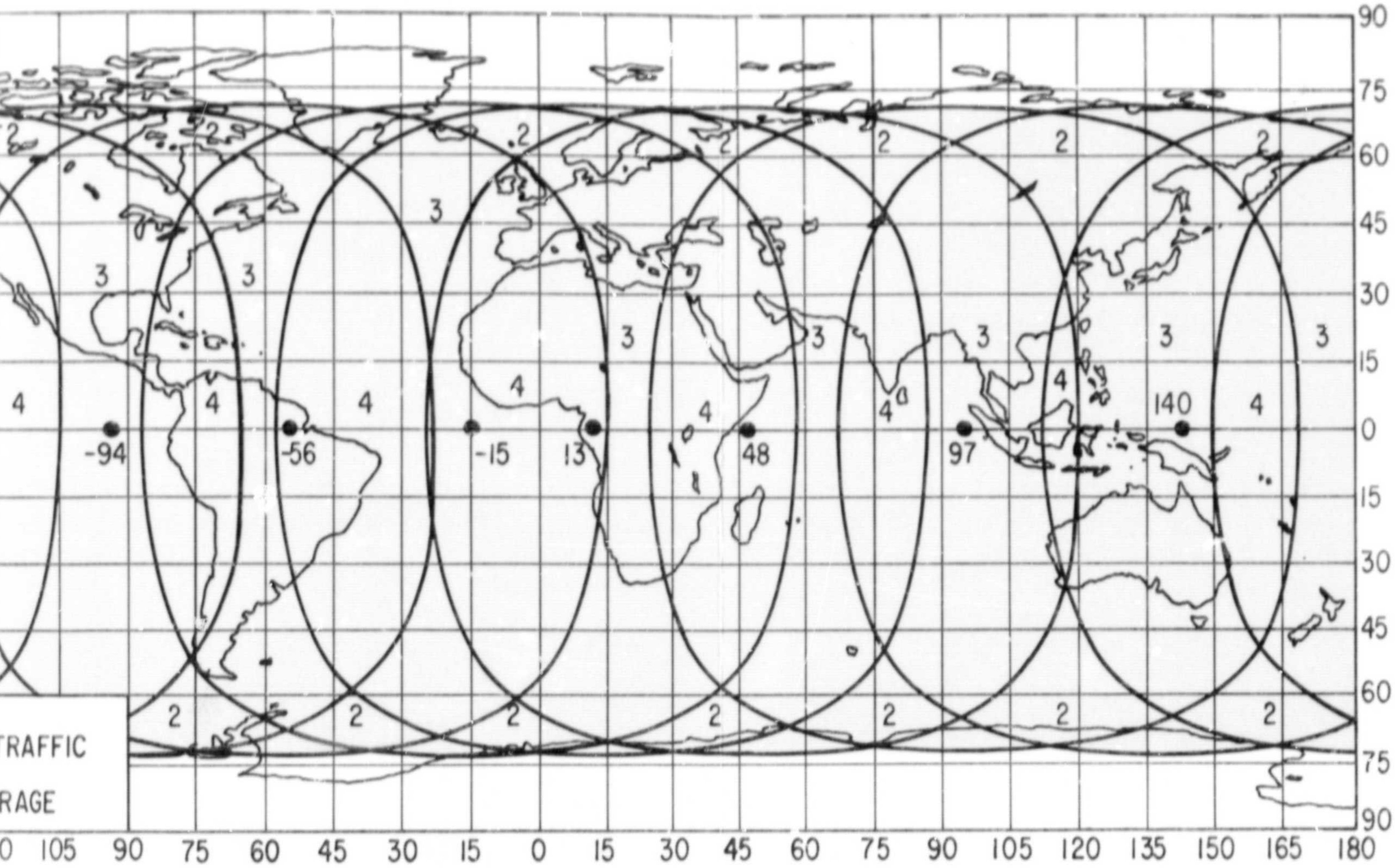
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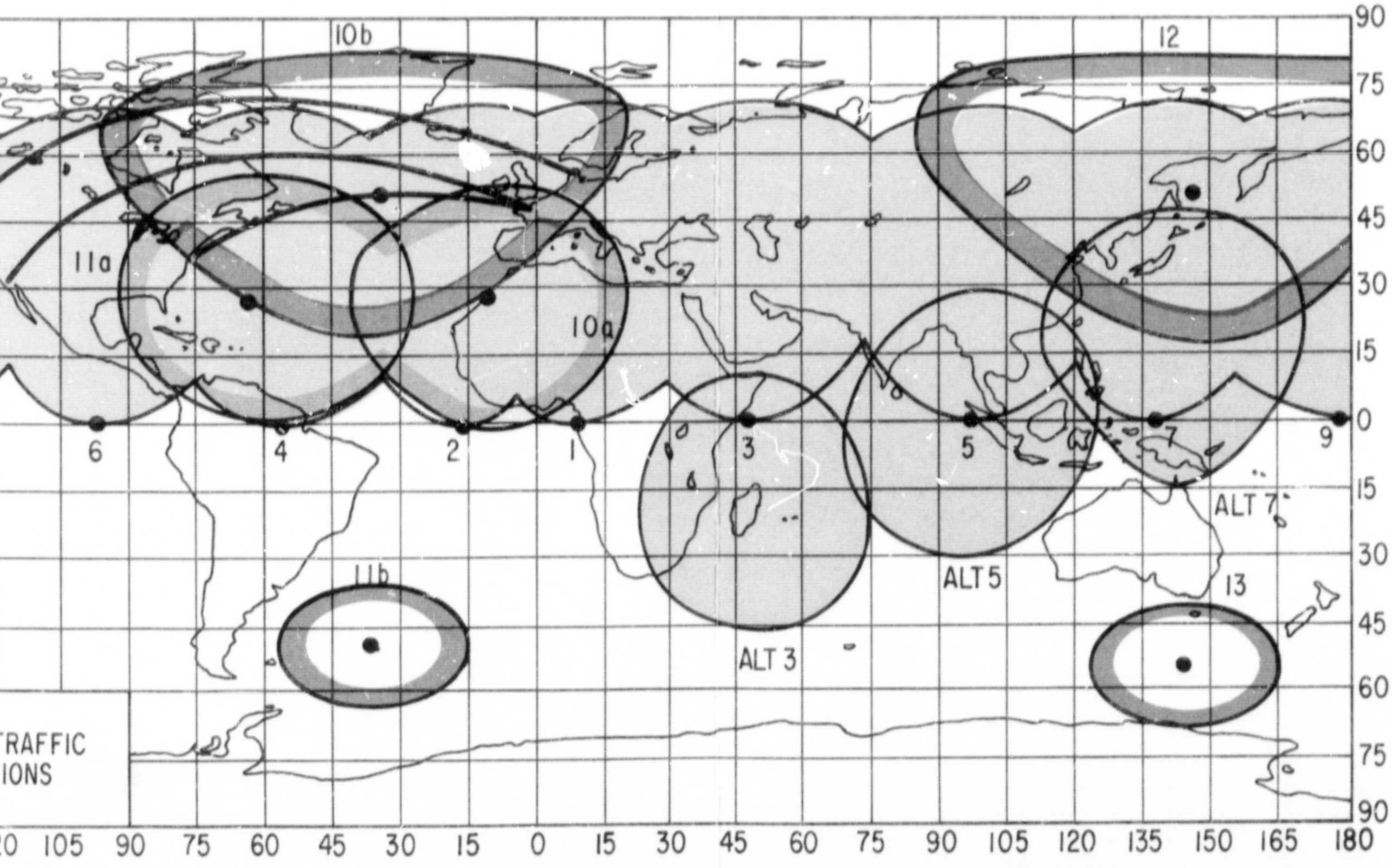
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4. PROGRAM PLAN AND COSTS

4.1 INTRODUCTION

This section will present recommendations for a design, development and demonstration program which would bring about the operational Navigation/Traffic Control Satellite System capability described in this study, and will include the estimated expenditures required. As in the remainder of the study, emphasis is placed on commercial jet aircraft as the primary users of this system, and detailed user hardware costing was limited to this class of users.

This section will outline briefly the recommended program; describe the methodology of costing; present cost estimates for the major design, development, and demonstration program; and will discuss briefly some recommended NTCS-related systems and technology efforts.

It should be pointed out that there are no real "deficiencies in technology" as was considered likely at the outset of the study. The status of technology today is such that the design, development and demonstration program could be initiated immediately.

4.2 THE NAVIGATION/TRAFFIC CONTROL SATELLITE SYSTEM PROGRAM

The various program phases defined in Paragraph 1.3 are described below and the major milestones are shown in Figure 6.

4.2.1 Phase I: Design and Development/Preoperational Program

Phase I consists of the design, development, and demonstration of the basic satellite configuration, the ground control stations, and aircraft user equipment. Major Phase I accomplishments will include the launching of two satellites in July and September of 1972, setting up a temporary Master Control Center at the Federal Aviation Agency's National Aviation Facilities Experimental Center (NAFEC), and two Remote Tracking Stations at Shannon and Gander; development of six sets of user hardware; and the flight test program itself, beginning with the launching of the first satellite, and running for fifteen months to September 1973.

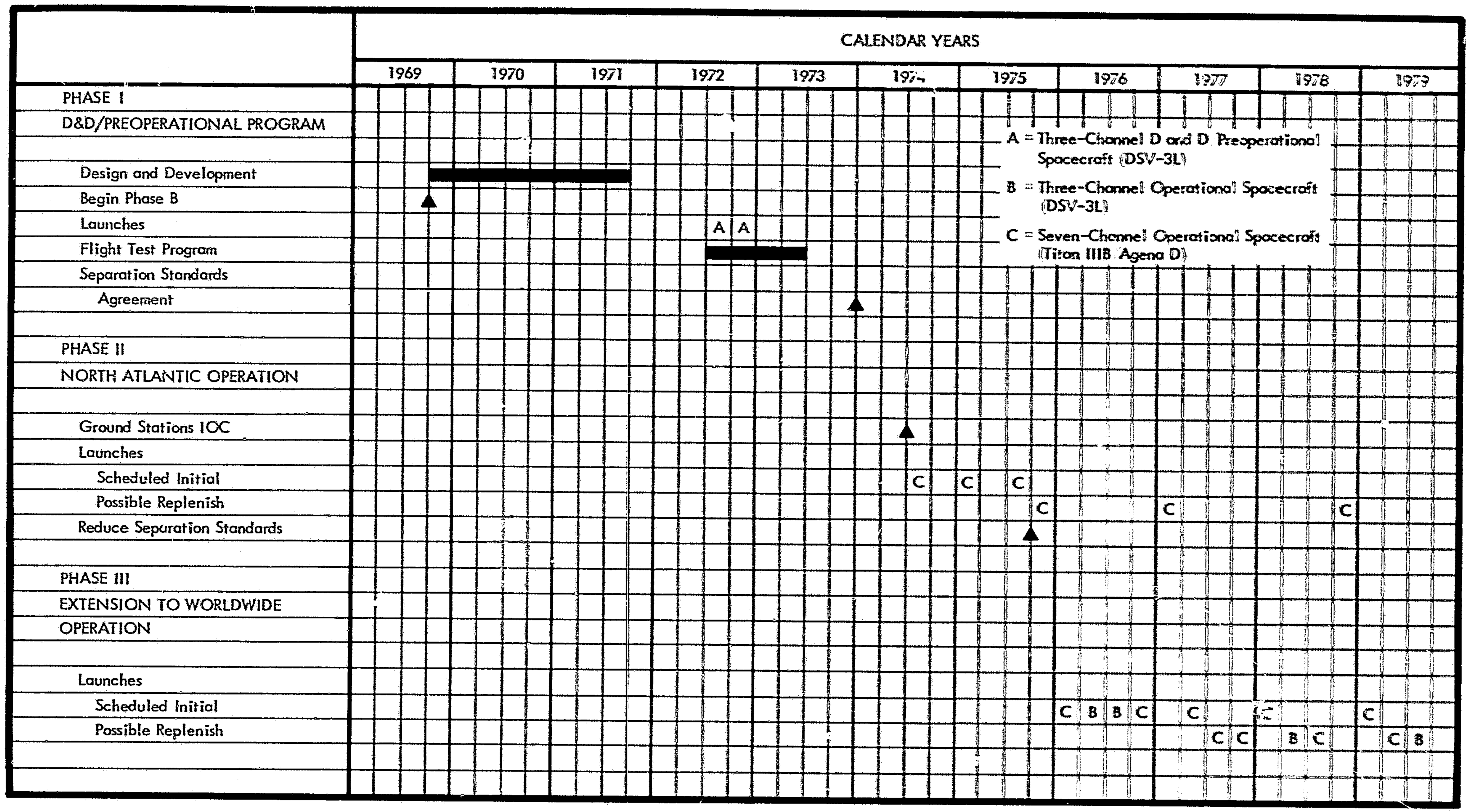

Figure 6. NTCS Program Milestones

4.2.2 Phase II: North Atlantic Operation

Major accomplishments in Phase II will include development of the final satellite configuration, stationing of three synchronous equatorial satellites, establishing a dedicated Master Control Station at J. F. Kennedy Airport, and adding an additional Remote Tracking Station on Ascension Island.

4.2.3 Phase III: Extension to Worldwide Operation

Phase III involves the stationing of seven additional satellites, and the establishment of two additional dedicated master control stations and three remote tracking stations. It should be noted that this is a 10-satellite constellation as opposed to a possible ultimate 13-satellite constellation (see Section 4, Volume II) which provides further coverage of possible utility subsequent to 1980.

4.2.4 Phase Zero: Subsystem Test and Related Systems and Technology Programs

As indicated earlier, the status of satellite and avionics technology is such that no basic research or exploratory development is required in order to advance the state of the art in some area critical to Navigation Traffic Control Satellite development. However, there are a number of related systems and technology areas in which funded efforts would enhance the overall NTCS Program. They include:

- SATELLITE

  L-band phased array antenna

  L-band transmitter

  Long life, high I_{sp} stationkeeping

  Solar array/primary power design

- USER

  Aircraft antenna design, installation and test

  Voice processing studies and test

  Communications hardware development and test

- SYSTEM STUDIES

  Continental U.S. air traffic control

  Search and rescue

  ATC interface

  Data handling

  Position determination/communications subsystem aircraft integration

  Marine applications

  Collision avoidance.

These programs represent efforts that can usefully precede the NTCS preliminary design if that phase is delayed. For example, improvement in high-power, solid-state L-band transmitters for satellites would yield improved NTCS performance which would be commensurate with the cost of the program, but this performance improvement is not vital to the program. The continental U.S., ATC interface, and data handling studies, if not performed separately, would eventually be incorporated into a full-scale NTCS design and development program. Finally, TRW has been funded under separate contract (see References 12 and 13) to delineate and study detailed test programs for the navigation portion of the system. These studies are described grossly and test objectives and costs are called out in Section 5.4 of Volume III.

4.3 PROGRAM COSTS

4.3.1 Methodology

The basic parametric data used in developing the Navigation/Traffic Control Satellite System cost models were taken from the TRW Systems data bank and are based on TRW and other contractor experience on related satellite, ground station, and airborne hardware programs. Responsible study engineers selected subsystem equipment based on technical objectives and NTCS program requirements. The estimates contained in these cost models are expressed in 1969 dollars and have been burdened through G and A, but do not include contractor fee.

Since the Navigation/Traffic Control Satellite Mission Study has been basically a feasibility study, the cost figures herein represent that level of detail and accuracy. The effort represented herein is consistent with the design effort itself. It is felt that the preliminary design phase, which would optimize the system, would be the major source of costing changes as opposed to uncertainties in the costing of the existing design which are considered to be in the neighborhood of 20 percent.

Development effort was assumed to include breadboard and test, engineering model fabrication and test, and qualification model fabrication and test; cost estimates were included to cover this effort.

The Navigation/Traffic Control Satellite configuration which is described herein is not an optimized design. In particular, with the weight margins presently available, the satellite MTTF can and should be increased to something like 50 to 75 months. Study cost and time limitations prevented such an optimization. Since the design described herein has a 45-month MTTF, it requires a high replenishment rate. Clearly, the preliminary design phase would include such a design refinement, with a corresponding reliability increase. This reliability tradeoff is discussed in Appendix D, Volume II. The satellite costs and the launch replenishment rate chosen and costed are a reasonable approximation of what the final optimized satellite design would require, i.e., the cost estimates already include approximately a $1.25 M cost increase per satellite to achieve a 60-month MTTF, the projected replenishment rate.

The booster costs for the DSV-3L-TE-364 and the Titan IIIB/ Agena D boosters were provided by NASA Headquarters. These figures represent the launch vehicle hardware costs and also the cost of launch and range support.

The user hardware costs for the communications and surveillance functions for commercial air carriers are projected to be on the order of $75 K. Assumptions used for the user equipment costing effort are described in Section 5, Volume II.

4.3.2 Cost Estimates

Table 1 presents preliminary cost estimates for the various elements of the Navigation/Traffic Control Satellite System. A more detailed cost breakdown can be found in Volume II of this report.

	PHASE I D&D/Preoperational		PHASE II North Atlantic		PHASE III Worldwide
	Development	Implemertation	Development	Implementation	Implementation
Satellite Program	$38, 000	$15, 300	$14, 350	$ 56, 350	$107, 650
	55, 800		70, 700		107, 650
Launch Vehicles		9, 600		62, 200	110, 600
Ground Stations	1, 640			10, 450	23, 730
NTCS Program Costs	67, 040		143, 350		241, 980
User Equipment	15, 100	1, 200			
	16, 300				
TOTAL	83, 340		143, 350		241, 980

Table 1. Navigation/Traffic Control Satellite Program Cost Estimate

5. SPECIAL PURPOSE AND APPLICATIONS

In addition to the aviation, marine, and rescue operations previously discussed, there are a number of special purpose missions and applications which were considered during the study. They are discussed in greater detail in Volume III.

5.1 COLLISION AVOIDANCE

TRW has considered several techniques for using such satellite systems to provide the CAS function, including:

- Cooperative systems based on the use of a single satellite dedicated for CAS
- Cooperative systems based on the use of a constellation of satellites capable of providing multiple functions including CAS

Since broad-area coverage can be provided easily by a system of NTC Satellites, the design of a system for collision avoidance based on the use of satellite-transmitted signals appears very attractive. Since the number of dedicated satellites required is small, the space segment cost of the CAS is minimized, and the per user cost becomes very low.

5.2 FISHING AND OCEANOGRAPHIC VESSELS

Potential ways in which fishing or oceanographic vessels might utilize the Navigation/Traffic Control Satellite System include:

- General navigation
- General communications
- Future fisheries forecasting systems — communications and position determination
- Coordination of fishing effort — communications and position determination
- Trawl Fishing — relative navigation
- Regulation of fishing boundaries — surveillance
- Fixed-point oceanographic data acquisition

- Drogue or free-drift buoys—position determination and communications

- Offshore oil and dredging—navigation

- Underwater storage point—position determination

5.3 SOLAR FLARE SENSING AND WARNING

The effects of solar flare eruptions on manned aerospace vehicles, such as very high altitude aircraft and orbital vehicles, fall in two general categories: (1) radiation damage to materials both biological and inert and (2) perturbations of the near earth space environment, including radio blackout from changes in the upper atmosphere. Particularly, with the advent of high altitude commercial airline operations, the public will demand that potential hazards to SST passengers from solar radiations be virtually nonexistent. A desirable alternative or addition to the ESSA solar flare warning system might be to incorporate a solar flare monitoring subsystem in the Navigation/Traffic Control Satellite. The warning data could then be transmitted directly to the aircraft communication network for immediate dissemination. The flare monitoring subsystem on the satellite would necessarily require a data processing unit which would be able to discriminate between the characteristics of a potentially dangerous flare and a harmless one. With present knowledge of the characteristics of solar flares, perhaps the most that could be achieved is an indication from the sensor subsystem that a flare has occurred, with some indication of its magnitude. Th , would warn pilots and airline officials that a significant flare has occurred, and that there is a potential danger. The very important advantage of incorporating the flare sensors in the NTC Satellite is that the warning would be immediate and direct to the aircraft, avoiding the warning delays involved with the communication networks and agency coordination.

5.4 SPACE NAVIGATION

It is possible to extend the use of the Navigation/Traffic Control Satellite System to space missions, both earth-orbital and lunar; such utilization of NTC Satellites would provide manned spacecraft with a simple yet precise onboard navigation system superior to an optical system and independent of an earth-based tracking and computing system*. A synchronous satellite navigation system, in fact, can achieve some significant advantages over the ground-based navigation (i.e., tracking) system for manned spacecraft because of the more extensive geometry provided by the 22,000 mile orbital radius of the satellites. Put very simply, any system which can provide accurate ranging to a spacecraft from a widestance geometry while requiring small, light onboard components will be a very attractive solution to the onboard space navigation problem.

*The satellites themselves must, of course, be supported by such a system for ephemeric determination but it is much simpler than, say, the Manned Space Flight Network (MSFN) now used for Apollo tracking.

6. MAJOR CONCLUSIONS

6.1 POSITION DETERMINATION

The recommended passive ranging technique for basic position determination provides high accuracy, full-time availability, and non-saturability for navigation; and — when measurements are relayed to a traffic control center via full-time satellite communications systems — provides an excellent surveillance tool. Active ranging is also a very attractive position determination technique. In fact, if one looks no further than North Atlantic air traffic control in 1975, it is on a par with passive ranging. However, due to the saturability of active ranging systems, its attractiveness in supporting a broad customer base and its growth potential for the air traffic control mission are limited. Angle measurement position determination techniques such as active and passive interferometers, spinning interferometers, or spinning fan beams are not attractive in this application and do not merit further consideration. The high frequencies required (C-band or higher) in turn require high aircraft antenna gain or high satellite power in order to obtain adequate accuracies. The development programs would involve considerable risk and would yield a system which is simply noncompetitive with ranging techniques. Finally, when a requirement for reliable communication and position determination is considered, the desirability of dividing the communications load among several satellites eliminates the one desirable feature of angle measurement devices, i.e., that a position fix can be obtained using a single satellite. The need for near 100 percent availability of the satellite system would simply preclude the use of a single satellite.

6.2 CARRIER FREQUENCY

The Navigation/Traffic Control Satellite System should be an all L-band system. VHF is currently a prime contender for satcom to low performance terminals such as aircraft, but is subject to major limitations of spectrum, and will probably eventually become obsolete for this service. Furthermore, VHF satcom antennas require switching between two modes and are significantly heavier than the L-band antennas. At L-band, switching is also required, but the space loss is not high enough to require the high-gain highly directive user antennas required for C-band. Thus small, light, simple user antennas are adequate. The spectrum is available and excellent position determination accuracies can be achieved.

6.3 SYSTEM DESIGN

The Navigation/Traffic Control Satellite System should employ a number of multipurpose satellites that will provide passive navigation capabilities to any and all users; voice and data communications to aviation and marine subscribers; automatic data reporting for air traffic control surveillance; and a growth capability to collision avoidance and stationkeeping. The high performance attainable with the recommended all L-band system will provide operational flexibility and growth potential.

6.4 TECHNOLOGY

There are no real "deficiencies in technology" as was considered likely at the outset of this study. The status of L-band technology today is such that the design, development, and demonstration program can be initiated immediately.

6.5 PROGRAM PLAN AND COSTS

A three-phase Navigation/Traffic Control Satellite System program should be initiated as soon as possible. Phase I, consisting of the design and development of satellites and ground stations, and demonstration of the Navigation/Traffic Control Satellite System capability and performance, is estimated to cost $67 Million. Phase II, the initial operational phase, would provide essentially full operational service in the North Atlantic from the third quarter of CY 1975 through CY 1979 and would cost approximately $143 Million. Phase III, Expansion to Worldwide Coverage, would provide expanding operation to a ten-satellite system during the four years beginning January 1976, and would cost about $243 Million. The user hardware costs for the communications and surveillance functions for commercial air carriers in Phases II and III are projected to be $77K and $68K per aircraft, respectively.

7. RECOMMENDATIONS

Specific immediate recommendations resulting from this study are:

- Initiate a Continental U.S. Air Traffic Control Study to determine the proper role of the NTCS and the resulting impact on NTCS design.
- Concentrate the Navigation/Traffic Control Satellite System effort. Focus it towards the development of an all L-band passive ranging and communications system. Since the final acceptance of the system is dependent on user experience, a preoperational satellite system development should be initiated as soon as practical.

8. REFERENCES

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12. "Test Plan for NAVSTAR Navigation System: Volume I, Test Plan Description," TRW Report No. 08710-6023-R0-00, Contract NAS 12-539, November 1968.

13. "Applications Technology Satellite-F L-band Air Traffic Control Communications-Navigation Experiment," TRW Report No. 08710-6015-R000, Contract NAS 12-539, June 1968.

9. NEW TECHNOLOGY

Four items which were conceived or developed as part of the TRW Navigation/Traffic Control Satellite Mission Study and are considered candidate New Technology items are as follows:

- The Passive Polar or "Big Omni" navigation satellite technique, described briefly in Paragraph 5.1.2.5, Volume II, and in detail in Reference , was conceived during the TRW preproposal phase for this study, but was incorporated into the contract when the proposal became a deliverable item.

- Autorep, the automatic transmission of aircraft position or data from which position can be determined, was first conceived during TRW's "Study of a Navigation and Traffic Control Technique Employing Satellites," under Contract NAS 12-539. The technique was substantially refined during this study and is described in Paragraph 4.6.3 of Volume II.

- An Optimal Interleaving Technique for increasing the capacity of active ranging schemes was conceived during the study and is referenced in Paragraph 5.1.2.2, Volume II. Since active ranging techniques were not employed in the NTCS System this technique was not further developed or discussed in the report.

- During the course of the Mission Study TRW conceived an approach for temporary storage and emergency transmission of aircraft status and/or maintenance information. This concept, described briefly in Paragraph 6.1, Volume III, involves sensing of aircraft subsystem data, and the storage of this information in either analog or digital format. This concept would be intended for use, i.e., transmission, only when an aircraft is in an emergency condition or if it appeared that such a condition was imminent.

No judgment is made or intended herein as to the patentability of the above items. They are reported because they were innovations developed under contract to NASA and, to the best knowledge of the innovators, represented original thinking.