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CONCEPT FOR A SATELLITE-BASED ADVANCED AIR TRAFFIC MANAGEMENT SYSTEM

Volume II. System Functional Description and System Specification

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16. Abstract

This volume provides a functional description and specification for the Satellite-Based Advanced Air Traffic Management System. The system description is presented in terms of the surveillance, navigation, and communications functions along with the additional supportive sub-functions needed to implement the basic functions. The volume includes a description of the basic system and backup philosophy, the system architecture and information flow between the elements required to achieve a cohesive system organization, and the satellite constellation and tracking subsystem. A preliminary system specification in the format of MIL-STD-490A is also presented.

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GLOSSARY

AATMS	Advanced Air Traffic Management System
ACC	Airport Control Center
ADF	Automatic Direction Finder
ADIZ	Air Defense Identification Zone
AGL	Above Ground Level
AMF	Analog Matched Filter
AOPA	Aircraft Owners and Pilots Association
ARINC	Aeronautical Radio, Inc.
ARTCC	Air Route Traffic Control Center
ARTS	Automated Radar Terminal System
ATC	Air Traffic Control
ATCAC	Air Traffic Control Advisory Committee
ATCRBS	Air Traffic Control Radar Beacon System
ATCS	Air Traffic Control System
ATM	Air Traffic Management
CA	California
CARD	Civil Aviation Research and Development
CAS	Collision Avoidance System
CCC	Continental Control Center
CNI	Communication Navigation Identification
CNMAC	Critical Near Midair Collisions
COMM	Communications
CONUS	Continental United States
CP	Central Processor
CST	Central Standard Time
CW	Continuous Wave

GLOSSARY (continued)

DABS	Discrete Address Beacon System
DOD	Department of Defense
DOT	Department of Transportation
DME	Distance Measuring Equipment
DNSDP	Defense Navigation Satellite Development Program
DNSS	Defense Navigation Satellite System
ERP	Effective Radiated Power
ESRO	European Satellite Reserach Organization
EST	Eastern Standard Time
ETA	Estimated Time of Arrival
FAA	Federal Aviation Administration
F&E	Facilities and Equipment
FL	Florida
FM	Frequency Modulation
FSS	Flight Service Station
GA	General Aviation
GAATMS	Ground-Based Advanced Air Traffic Management System
GDOP	Geometric Dilution of Precision
GFE	Government Furnished Equipment
IAC	Instantaneous Airborne Count
ICAO	International Civil Aviation Organization
ID	Identification
IFR	Instrument Flight Rules
ILS	Instrument Landing System
IMC	Instrument Meteorological Conditions

GLOSSARY (continued)

I/O	Input/Output
IOP	Input Output Processor
IPC	Intermittent Positive Control
IPS	Instructions Per Second
IR	Infrared
JFK	Kennedy International Airport
LA	Los Angeles
LAT	Latitude
LAX	Los Angeles International Airport
LORAN	Long Range Navigation
LOS	Line-of-sight
LRR	Long Range Radar
MIPS	Million Instructions Per Second
MLS	Microwave Landing System
MODEM	Modulator-Demodulator
MSL	Mean Sea Level
MTBF	Mean Time Between Failures
NAFEC	National Aviation Facilities Experimental Center
NAD	North American Datum
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NAV	Navigation
NDB	Non-Directional Radio Beacon
NEF	Noise Exposure Factor
NFCC	National Flow Control Center

GLOSSARY (continued)

NMAC	Near Midair Collisions
NOTAM	Notice to Airmen
NOZ	Normal Operating Zone
NWS	National Weather Service
O&M	Operations and Maintenance
PCA	Positively Controlled Airspace
PIREPS	Pilot Reports
PN	Pseudo-Noise
PPM	Pulse Position Modulation
PWI	Pilot Warning Indicator
RAM	Random Access Memory
RCAG	Remote Control Air-to-Ground Facility (Present System)
RCAGT	Remote Communication Air-Ground Terminal
RCC	Regional Control Center
R&D	Research and Development
RDT&E	Research, Development, Test, and Evaluation
RF	Radio Frequency
RNAV	Area Navigation
ROM	Read-Only Memory
SAATMS	Satellite-Based Advanced Air Traffic Management System
SAMUS	State Space Analysis of Multisensor System
SID	Standard Instrument Departure
S/N	Signal-to-Noise
SNC	Surveillance, Navigation, Communication
STAR	Standard Arrival Routes
STC	Satellite Tracking Center
STOL	Short Takeoff and Landing

GLOSSARY (continued)

TACAN	Tactical Air Navigation
T&E	Test and Evaluation
TCA	Terminal Controlled Airspace
TOA	Time of Arrival
TRACAB	Terminal Radar Approach/Tower Cab
TRACON	Terminal Radar Approach Control
TRSA	Terminal Radar Service Areas
TRW	Thompson Ramo Wooldridge
TSC	Transportation Systems Center
TX	Texas
VFR	Visual Flight Rules
VHF	Very High Frequency
VMC	Visual Meteorological Conditions
VOR	Very High Frequency Omni-Directional Range
VORTAC	Very High Frequency Omni-Range TACAN
VVOR	Virtual VOR
2D	Two Dimensional
3D	Three Dimensional
4D	Four Dimensional

1. INTRODUCTION

The Satellite-Based Advanced Air Traffic Management System (SAATMS) study was initiated as a result of the concern stated in the Civil Aviation Research and Development (CARD) Policy Study Report and voiced by the Department of Transportation Air Traffic Control Advisory Committee (ATCAC) regarding the limitations of the present traffic control system servicing the demand projected for the 1990 time frame. Specifically, three problem areas were identified which urgently require solution if aviation growth is to be accommodated. These areas were as follows:

(1) The shortage of terminal capacity

(2) The need for new means of assuring separation

(3) The limited capacity and increasing costs of Air Traffic Control (ATC)

In an effort to alleviate these problems, the Department of Transportation has initiated a number of programs. One of these programs was directed toward a long-term system termed the SAATMS. The initial definition of the SAATMS was started in 1971 and resulted in what was then termed the Fourth Generation Air Traffic Control System.

Autonetics participated in a three-phase study of the Fourth Generation Air Traffic Control System during 1971 and 1972 (Ref. 1). These three phases were directed toward the definition of the best conceivable air traffic control system. The design concepts were to be unconstrained by present or planned changes to the present system. The objectives of the study were to formulate an advanced traffic management system capable of meeting the forecast demands at significantly lower costs and greater safety than predicted for the present system.

During Phase I, the goals of the Air Traffic Control (ATC) system were examined and operational analyses were conducted to establish the demand distributions for the 1975 through 1990 period. The distributions were used to establish capacity and top level functional requirements. With the functional requirements as a guide, a large number of candidate systems was defined. These concepts were evaluated, compared, and refined. Through an iterative process, many concepts were discarded or combined; and two concepts were eventually chosen for further analysis.

During Phase II, the functional requirements analysis was extended. The two selected concepts were defined in more detail in conjunction with several potential operational concepts. Performance measurements were identified and each concept was evaluated in terms of these measures and the total system cost. The concepts were also compared with a Ground-Based Advanced Air Traffic Management System (GAATMS).

The Phase III effort concentrated on defining a hybrid system utilizing the best features of the two Phase II concepts. The hybrid system was evaluated and compared to the Phase II systems and GAATMS and, on the basis of reduced cost and improved services, selected as the recommended fourth generation approach. Operational phase-in criteria for the hybrid system were identified and a plan was developed for transitioning from the present system and GAATMS to the Fourth Generation Air Traffic Control System. An investigation of the advanced technology expected to be available for use in the fourth generation system was also completed.

The present SAATMS study is based on the previously defined hybrid system approach and is directed toward a delineation of a SAATMS as evolved from the hybrid system. This SAATMS is distinct from an alternate system, the ground-based concept, which is based on the upgrading of the present and planned systems. In this context, the SAATMS concept is a revolutionary design as opposed to the evolutionary GAATMS concept. This is not to imply that an orderly transition into the SAATMS design is any more costly or involved than transition into the GAATMS, but only that several different and more efficient technologies have been incorporated into the SAATMS design.

The objectives of this study are to fully define and definitize a design concept capable of safe and economic management of a national air traffic management system during the period from 1995 and beyond. More specifically, the study is directed toward showing the feasibility of the SAATMS to meet its capacity goal in a safe, economical, and viable manner within the constraints of the technology foreseeable within its developmental time frame.

1.1 SAATMS Concept Definition

In October of 1972, a concept definition study for SAATMS was initiated. The objectives of this study were as follows:

(1) To complete the definition of the SAATMS concept formulated under the previous study (Ref. 1).

(2) To evaluate the recommended system concept in terms of system and subsystem performance, cost, and system and subsystem sensitivities.

(3) To describe the SAATMS concept with a systems specification, a transition plan, and an RDT&E plan.

This study was one of several performed by an industry team under the direction of the Transportation System Center (TSC) to define the SAATMS. Included, among others, were studies to develop the following:

(1) System requirements for the SAATMS, Autonetics
(2) Application of automation to the SAATMS, TRW
(3) Requirements for centralized strategic control, The Boeing Company

In addition, the Mitre Corporation was tasked with defining a ground-based concept as a candidate GAATMS. Although schedule constraints did not permit incorporation of the results of these studies into the SAATMS definition, a close interface was established and preliminary data were interchanged.

In accordance with the objectives of this study, the Autonetics effort was organized into three major areas. The first dealt with defining and refining the details of the SAATMS concept formalized in the previous study. This area was further subdivided into two parts: the functional definition and the operational definition.

The functional definition dealt with mechanization and configuration of the system. The initial part of the study established feasibility of a satellite system, with particular emphasis placed upon the aircraft-to-satellite link and the satellite constellation effects. Specifically, the effects of multiple access noise, aircraft antenna patterns, aircraft maneuvers, and low power users were investigated. Additionally, the interaction of the satellite constellation design with these effects and the resultant subsystem accuracy was determined. The last half of the study dealt with the detailed mechanization of the various functions, services, and the overall architecture of the system. In these tasks, emphasis was placed upon integration of system functions and user avionics, both to minimize avionics costs and to reduce government operations and maintenance expenditures. The functional definition not only included the airborne surveillance and navigation functions but additionally developed mechanizations for landing aids and airport surveillance and navigation techniques. The functional mechanization was performed for the gate-to-gate operation of the system.

The operational definition expanded the previously defined operational concept and developed the detailed services and their implementation. Included here were the definition of the user classes, their restrictions, requirements and services, the overall management concept, the airspace structure and its interaction with the system mechanization and configuration, and a detailed description of the tasks required from both the pilot and the ground to effect each of the system services for various users in different airspaces.

The second major area was concerned with evaluating the system and subsystem performance of the recommended version of the SAATMS. A detailed error analysis of the surveillance and nagivation subsystems and their performance as well as an evaluation of the overall system performance were included. While the subsystem performance was concerned with functional accuracies, the system level evaluations dealt with capacity, delay, and safety measures. Additionally, the sensitivity of both the system and subsystem measures to changes in requirements and demand was determined. Besides these quantitative evaluations, a set of qualitative evaluations was performed. These qualitative evaluations included measures such as vulnerability to intentional interference, growth capability, ease of transition, and technical risk. Finally a set of cost data was prepared. The cost categories included research and development, facilities and engineering, and operations and maintenance.

The third area of the study was concerned with the generation of data describing the recommended SAATMS configuration, i.e., a systems specification, a transition plan, and an RDT&E plan. The system specification stated the operational and performance requirements for the system, allocated the requirements to functional areas, and defined the interfaces among these functional areas. In general, the specification format is in accordance with MIL-STD-490. The transition plan described the method of changing from the in-being air traffic control system to the SAATMS. Included were descriptions of the operational and functional transition requirements and time phasing, the increased user benefits and costs, and the method of parallel operation during the transition period. The RDT&E plan described the efforts necessary to accomplish the SAATMS development testing and implementation. Items specific to the SAATMS concept were identified, as were items generic to any satellite system.

1.2 SAATMS Requirements - Quality Service at Nominal Cost

The ultimate worth of any air traffic management system is its acceptance by the users. This acceptance is based primarily on the quality of the services provided and the costs of achieving these services. Thus, the aim of the SAATMS is to provide, for as long a time as feasible, quality service at nominal user and government costs. Many factors enter into determining the quality of the AATMS services. These include the following:

(1) Capacity - The maximum number of aircraft departures, flights, and landings per unit time which can be accommodated with a minimum amount of delay.

(2) Safety - The overall capability of the system to maintain or improve upon the present accident rates regardless of demand or mode of system operation.

(3) Ease of Implementation - The difficulty of the operational transition from the in-being system.

(4) Service Capability - The ability of the system to provide the projected air traffic control services to users on a timely, economic, and safe basis, regardless of demand or mode of system operation.

(5) Environmental Impacts - The ability to support future needs with minimum undesirable effects on the environment, specifically noise, and undesirable sites for ground support equipment.

(6) Adaptability - The ability to tolerate various classes of aircraft and airborne equipment off nominal modes of operation due to such causes as hardware malfunctions, adverse weather conditions, and changes in traffic demands.

(7) Cost - The expenditures, both initial and operational, required by the users and the federal and state governments to achieve a common specified level of safety, capacity, and reliability.

(8) Technological Risk - The degree of resource commitment required to achieve assurance that an adequate system can be provided.

Accordingly, the design requirements developed by TSC for the SAATMS have been organized along these lines.

1.2.1 Capacity

The SAATMS shall have the capacity to service the demand levels postulated for the post 1995 time frame assuming a fully working system and visual meteorological conditions. The demand to be serviced as a function of varied meteorological conditions is given in Table 1.2-1.

Table 1.2-1. Demand as a Function of Meteorological Conditions

Meteorological Condition	Demand (%)		
	Aircarriers	General Aviation	Military
VMC	100	100	100
Category I	100	90	100
Category II	100	20	100
Category IIIA	90	10	90

The allowable delays at any airport under the conditions in Table 1.2-1 shall be limited to those arising from multiple scheduled departures and arrivals, wind variations, and capacity limitations. The departure and arrival delays during an average busy hour shall be 6 min or less for 50 percent of the operations, 15 min or less for 90 percent of the operations, 30 min or less for 99.9 percent of the operations.

The quantitative measures of capacity and delay are defined below:

(1) Bulk Capacity - Number of operations per unit time in a saturated situation for a specified safety level and arrival/departure ratio.

(2) Instantaneous Capacity - Number of operations per unit time for a specified safety level and arrival/departure ratio with a specified arrival and departure delay distribution.

(3) Departures/Hour - Number of aircraft departures per unit time for a given airport configuration.

(4) Arrivals/Hour - Number of aircraft arrivals per unit time for a given airport configuration.

(5) Operations/Hour - Total number of aircraft operations (arrivals, departures, missed approaches) per unit time.

(6) Capacity Efficiency - Ratio of the peak number of actual operations per delay factor to the number of operations with no delay factor for a specified safety level and arrival/departure ratio.

(7) Average Delay - The average delay incurred from all operations conducted per unit time.

1.2.2 Safety

The SAATMS shall provide a level of safety equal to that provided by today's system (1972) for the demand levels postulated for the post 1995 time frame.

The quantitative measures of safety are defined below:

(1) Missed Approaches/Hour - The number of actual approaches rejected just prior to commitment, per unit time.

(2) Collision Frequency - The number of collisions which occur per unit time.

(3) False Alarm Rates - Number of erroneous safe volume intrusions per unit time.

(4) Conflicts/Year - The number of vehicle safe volume intrusion incidents per unit time.

Because of the difficulty in establishing an absolute number associated with the safety level of today's ATC system, the evaluation of the AATMS is performed relative to the current ATC system. This method of relative evaluation tends to relieve the problem of empirical validation of models used for analysis and design but still permits quantitative comparisons.

1.2.3 Transition

The SAATMS shall evolve in an orderly fashion from the elements of the system planned to be in place in 1982. Transitioning from the 1982 in-being ATC system to the 1995 SAATMS represents a major changeover in both government-supplied system equipment and user avionics equipment. However, the transition will be accomplished with no disruption of service and minimum imposition on the users. Users will not be required to equip aircraft with duplicate sets of equipment to perform identical functions in different geographic areas. Users will be allowed to retain in-being avionics for a reasonable lifetime period before SAATMS avionics are required. This period will vary from 7 to 10 years. No requirement has been placed on the in-being ATC system subsystems to be compatible with the SAATMS integrated waveform equipment.

1.2 4 Service

The SAATMS shall have the capability of providing acceptable levels of service to the various users and user types projected for the post 1995 time frame. The services to be provided include the following:

(1) Airport/Airspace Use Planning - This is the strategic or long-range control service concerned with the establishment and modification of plans for airspace and airport use. It is related to both safety and efficiency and involves an agreement between the user and the control authority. It includes such things as

(a) The flight planning process

(b) Flow control, both national and local

(c) Conflict prevention by planning

(d) Development of an airspace structure

The outputs to the user are flight plans, flow plans, advisories, and the definition of airspace boundaries.

(2) Flight Plan Conformance - This is the strategic or long-range service that promotes implementation of the plans developed above and includes

(a) Monitoring for conflicts within the plan

(b) Resolution of those conflicts

(c) Monitoring to determine deviations from plan

(d) Corrections back to the plan or modifications to the plan (terminal area only)

The outputs to the user are corrections to keep him on flight plan and changes to flight plan.

(3) Separation Assurance - This is a short-term service related to safety. It consists of both short-term conflict prevention (tactical conflict detection and resolution) and tactical collision prevention. Short-term conflict prevention includes

(a) Monitoring for predicted violations of airspace volume reserved about an aircraft

(b) Resolution of predicted violations

Tactical collision prevention includes

(a) Monitoring for actual violation of reserved airspace volume

(b) Resolution of actual violations

In either case, the output to the user is instructions to resolve the conflict. The resolution instructions do not represent a flight plan change but may result in a flight plan change after resolution has been effected.

(4) Spacing Control - This is a short-term service related to efficiency and includes

  (a) Runway Configuration Scheduling - Allocation of slots for takeoff and landing.

  (b) Sequencing - Ordering of aircraft enroute as well as into the takeoff and landing slots provided by scheduling.

  (c) Spacing - Adjustment of inter-aircraft spacing to promote efficiency.

(5) Airborne, Landing, and Ground Navigation - This is the service that provides position location capability.

(6) Flight Advisory Services - This is the service that provides information to the pilot during all flight phases except preflight planning. It provides weather and traffic information and includes the present Automatic Terminal Information Service.

(7) Information Services - This service is similar to the preceding one except that the information is provided during the preflight planning phase. It provides information about weather, traffic, facilities, routes, obstructions, regulations, and procedures.

(8) Record Services - This service provides the required "permanent records" of operations and events.

(9) Ancillary Services - This service provides the special services listed in the present controllers manuals and includes

  (a) Weather observation

  (b) Military flight handling

  (c) Transborder flight handling

  (d) Search and rescue coordination

(10) Emergency Services - These are services provided in response to air failures. The services are provided in the event of either:

  (a) Controllable Emergencies - Those during which the aircraft can respond to control instructions or can carry out established procedures applicable to the emergency situation.

(b) Uncontrollable Emergencies - Those during which neither control instructions nor established procedures can be implemented.

1.2.5 Environment

The SAATMS shall be designed such that the Noise Exposure Factor (NEF) shall have a value less than 30 at any point outside the airport boundary. Facilities and equipment shall be planned and installed so that minimum adverse impact on the environment will occur.

1.2.6 Security

The SAATMS shall be designed against both intentional (jamming) and unintentional man-made interference. The system shall be sufficiently decentralized such that disasters (floods, hurricanes, earthquakes) will not compromise the failure mode capabilities of the system.

1.2.7 Compatibility

The SAATMS shall be designed to interface with all elements of the airport system. It shall also be capable of interfacing with and supporting U.S. military air defense, training, and logistics operations without compromising system service. The system shall also be capable of interfacing with foreign ATC systems without compromising system service.

1.2.8 Reliability

Under normal operation, the system shall have fail-operational capability. The system shall have fail-safe capability after having failed operationally and fail-soft capability after having failed safely.

(1) Fail-Operation - A mode of operation under contingency or failure conditions that permits system operation at full capacity and specified safety.

(2) Fail-Safe - A mode of operation under contingency or failure conditions that, although compromising other nominal system attributes (e.g., capacity), retains the same level of safety required for normal modes of operation.

(3) Fail-Soft - A mode of operation under contingency or failure conditions that retains the same level of safety required for normal modes of operation for some specified period of time.

1.3 The 1995 Airfleet - 362,000 Aircraft

The operational environment defined for the SAATMS Concept Definition Study was developed by TSC from current demand data and projections of future air traffic conditions. The uncertainty of these forecasts was compensated for by selecting a range of demand levels and growth rates. The low and nominal demand levels for the 1995 and post 1995 time period are shown in Table 1.3-1 along with the 1972 figures and 1984 FAA projections. The 1995 levels are assumed to increase to the post 1995 levels, i.e., 275,000 to 529,500 and 362,000 to 1,034,000. The 1995 nominal level has been used as the design criterion for the SAATMS design. The growth characteristics of the SAATMS have been based upon the post 1995 high demand level.

Table 1.3-1. Airfleet Projections

Type of Aviation	1972	1984	1995		Post 1995	
			Low	Nominal	Nominal	High
Aircarriers	2,360	3,600	5,000	7,000	9,500	14,000
General Aviation	131,000	217,000	250,000	335,000	500,000	1,000,000
Military	20,000	20,000	20,000	20,000	20,000	20,000
Totals	153,360	240,600	275,000	362,000	529,500	1,034,000

As can be seen, the primary growth rate occurs with the general aviation users. The distribution of the general aviation fleet by aircraft type is shown in Table 1.3-2 for the nominal demand level. There are several significant items that occur as a result of this large number of relatively low class users.

(1) The users comprising the greatest percentage of the airfleet can least afford significant avionics expenditures to receive services from the system.

(2) To be responsive to the user needs, the system must supply services to the users in the airspace in which these users normally operate, i.e., the lower altitudes regions

(3) The regions of highest aircraft densities can be expected to be in those areas reserved for the general aviation user.

(4) To be fully accepted by the general aviation user, the SAATMS must not impede his freedom of flight.

(5) The majority of the aircraft will not be using the primary aircarrier airports and, in fact, may be using airports remote from the large metropolitan centers.

(6) The present accident rate among users of the smaller, remote airports results primarily from a lack of surveillance information. In a future system, low cost surveillance and separation must be provided.

(7) Present FAA statistics indicate that in the enroute regions, i.e., greater than 30 nmi from an airport, 80 percent of general aviation users fly at 6,000 ft or less, 64 percent fly at 4,000 ft or less, and 22 percent fly at 2,000 ft or less. Thus, in a future ATM system, surveillance, communications, and navigation services must be provided essentially down-to-the-ground level, if the separation assurance service is to be provided for these users.

Table 1.3-2. General Aviation Fleet Distribution

Aircraft Type	Aircraft Volume
Single Engine Piston, 1 to 3 places	80,000
Single Engine Piston, 4 or more places	170,000
Multi-engine Piston, under 12,500 lb	40,000
Multi-engine Piston over 12,500 lb	10,000
Turbo Prop and Jet	35,000

1.4 SAATMS - An Integrated System

The SAATMS concept is for an integrated system designed to yield a comprehensive air traffic management system on a national level. As such, the system concept includes not only a group of equipments designed to implement specific functions but also defines the operational concept for moving and controlling traffic within the system. In this context, the system is integrated both functionally and operationally.

As the SAATMS operational concept becomes better defined, it becomes clear that the needs and capabilities of aircraft differ in ways that affect both the services they are capable of receiving from the system and their ability to be controlled by the system. The definition of user classes provides a basic structure in which rules and procedures for different aircraft categories can be stated. The reason for categorizing aircraft into user classes is to insure that the airspace structure and system management concept are compatible with the needs and capabilities of the aircraft using the system.

There are three basic SAATMS user classes: controlled, cooperative, and uncontrolled. These avionics classes define the minimum price of admission into controlled, cooperative, and uncontrolled airspace. Both controlled and cooperative users share mixed airspace.

Uncontrolled users have no avionics requirements and are not considered to be part of the SAATMS. They are confined to posted regions in low density areas at altitudes below 3,000 ft AGL. They may not intrude into cooperative airspace nor may they land at airports with control towers. These aircraft receive no services from the system. Since they do not carry surveillance or communications equipment, uncontrolled users cannot be permitted into cooperative or controlled airspace under any traffic density conditions.

The cooperative user requires the following avionics as a minimum price for entry into the system:

(1) Surveillance transmitter

(2) Two-way digital L-band communications

(3) Two-way L-band voice communications

(4) Navigation (Virtual VOR) display and control panel

For this price, the cooperative user receives the service of navigation assurance. In addition, the VVOR system provides him with a form of Area Navigation (RNAV). This user can also fly in controlled airspace in off peak hours with a clearance from the system.

To fly in controlled airspace the following equipment is required:

(1) Surveillance transmitter
(2) Two-way digital L-band communications
(3) Two-way L-band voice communications
(4) Satellite navigation processor
(5) Satellite navigation display
(6) All of the above must be backed up
(7) VVOR display and control panel.

For this price in avionics, the controlled user receives the same separation assurance as the cooperative user plus a sophisticated 4D RNAV capability. In addition, he receives preferred routing, priority for the airspace he is using, the right to use primary aircarrier airports at all times, and a guaranteed arrival slot at his destination airport.

The basic system functions include communications, surveillance, and navigation. These functions are used to implement the operational concept. Mechanization of the functions is predicated on the use of satellites because of the CONUS-wide coverage and multifunctional capability they afford. The universal coverage and multifunction capabilities of satellites allow the use of both a centralized control facility and integrated avionics. These result in significant cost savings both for the government and the user.

In the following sections of this volume, a detailed description of the functional aspects of the system is presented. This is followed by a description of the subsystems that comprise the system, system operation, performance evaluation, and the qualitative assessment of the system. These are contained in Volumes III, IV, and V. These volumes completely define the system in the proposed ultimate configuration.

1.5 Reference

1. C71-61/301, Fourth Generation Air Traffic Study, Volumes I through IV, June 1972, Autonetics, Anaheim, California.

2. SYSTEM FUNCTIONAL DESCRIPTION

2.1 Introduction

The Satellite-Based Advanced Air Traffic Management System (SAATMS) concept is designed to provide the basic surveillance, navigation, and communication functions required to implement an integrated air traffic control system for the Continental United States (CONUS) and the adjacent oceanic regions. The basic system design is predicated upon the use of earth orbiting satellites.

This volume of the report is structured toward providing a functional description of the system. The equipments comprising the system elements are described in Volume III, while the system operation is discussed in Volume IV. The basic description is in terms of the surveillance, navigation, and communication functions with the additional supportive subfunctions needed to implement these basic functions.

Section 2.2 includes a description of the basic system and backup philosophy. Section 2.3 describes the system architecture and the information flow between the elements required to achieve a cohesive system organization. Section 2.4 describes the satellite constellation and tracking subsystem which constitutes the heart of the SAATMS. Thus, the overall system operational inter-relationship is described in these three sections.

2.2 General System Overview

The design of a large scale system such as the SAATMS is, by all standards, complex. This section is intended to introduce the overall system architecture and the basic functions of the system. As such, it does not provide a complete definition of the entire SAATMS design but will indicate the general features of the system design.

Three separate areas of the system design will be discussed: the general system architecture, the primary functional modes of the system, and the system backup philosophy. These brief introductions will set the overall system intent. Later paragraphs will expand on these areas and provide a complete definition of the total system.

2.2.1 General System Architecture

The SAATMS design is an integrated system designed to yield a comprehensive air traffic management system on a national level. In a geographic sense, the system is highly distributed but achieves cohesiveness through the use of a constellation of satellites. These satellites provide the communication link that allows the most remotely located airport or site in the system to be fully integrated into the total system.

Through the use of satellites, the SAATMS design affords the basic communications, surveillance, and navigation functions from ground level upward over the entire CONUS region and far into the contiguous land and oceanic regions.

The surveillance function employs satellites to relay surveillance data from active users. Each aircraft active in the system transmits a surveillance pulse encoded with the user's unique identification code. The satellites that are in view of the user relay these signals to control centers where the instantaneous aircraft position and velocity can be generated for every active aircraft in the system. This technique is employed for aircraft in both enroute and terminal airspace, but the system absolute accuracy is enhanced in high density airspace through the use of calibration stations. This surveillance system allows the control centers to actively participate in the conflict resolution, airspace segregation, and control generation required to achieve comprehensive air traffic control.

The satellite system also provides one of the two basic navigation modes intrinsic in the SAATMS design concept. By transmission of navigation signals, the satellites provide basic data which allow equipped aircraft to compute their position and velocity. This navigation mode is completely independent of the surveillance system. This mode is available for aircraft in both enroute and terminal airspace and is usable from ground level upward. An alternate navigation system is also provided to aircraft through the satellite surveillance and communication features.

All the digital data and voice channels required for ground-to-air communications are provided through satellites for enroute and terminal approach airspace. This is supplemented by direct aircraft-to-ground digital data and voice channels for use at airports. All the airports, control centers, and remote sites are interconnected through the satellite system. These channels are separate from the ground-to-air channels. Either voice or digital data can be accommodated on these channels.

The satellite system provides the basic functions that allow the implementation of the air traffic management system. The actual control elements in the SAATMS design are to a large degree the computational elements which perform the automation tasks. The segmentation of these computer elements to various ground facilities will then establish the basic system architecture. In delineating the ground system elements, the basic elements and major tasks assigned to each element will be described. A later section will then consider the site processing and thereby completely define the total architecture.

There are three major ground jurisdictional units which provide the basic framework of the SAATMS design: the Continental Control Center (CCC), the Regional Control Center (RCC), and the Airport Control Center (ACC). There are numerous Airport Control Centers, two Regional Control Centers, and one Continental Control Center within the system. Figure 2.2-1 depicts the basic jurisdictional areas covered by each of these elements.

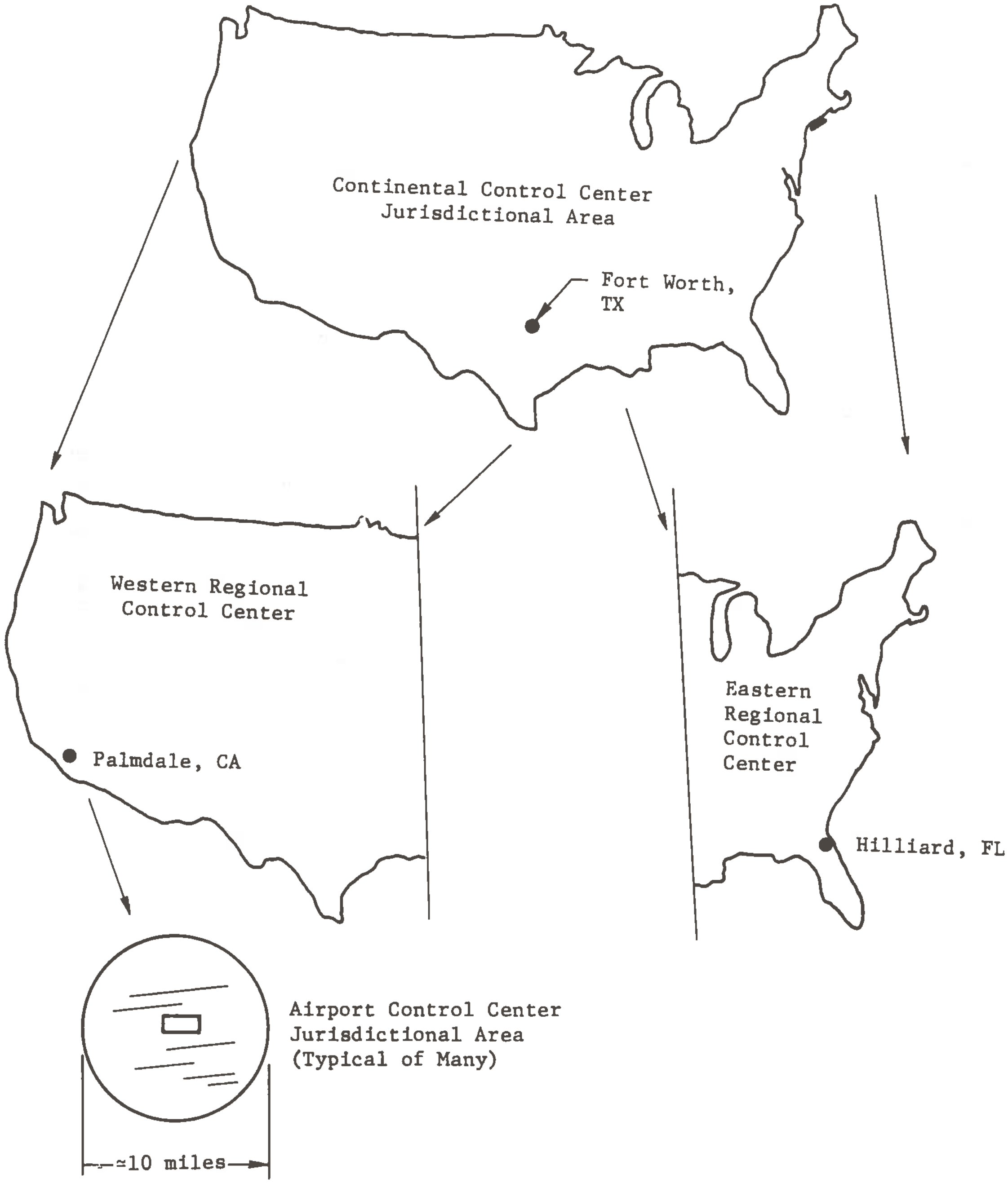


Figure 2.2-1. Basic Jurisdiction Elements

A potential location for the CCC is Fort Worth, TX. This center serves as an executive command and monitor center for the entire system during normal operation. It has the responsibility for flow control, satellite tracking, and new aircraft acquisition. In the event of a catastrophic failure of either or both RCC's or in the event of a national emergency, the CCC can assume limited control of the entire system. Conversely, the RCC's are autonomous and can provide normal services and interchange data without reliance on the CCC.

Potential locations for the RCC's are Palmdale, California, and Hilliard, Florida. These control centers serve as primary command and control elements for their assigned regions. They have primary aircraft tracking responsibility for all users within their respective regions and have control responsibility for all users in enroute, transition, and oceanic airspace but not for aircraft within ACC jurisdictional regions. All communications to and from user aircraft in the control jurisdiction are disseminated from and received at these centers during normal system operation.

Potential locations for the CCC and RCC's were chosen to provide extensive geographic distribution so that no two sites could be affected by a single natural disaster. The Florida and California sites were selected to serve one-half of CONUS plus the adjacent oceanic regions. The Texas location for the CCC was chosen because it is nearly equi-distant from the RCC's, thus enabling it to easily backup either center. The southerly latitudes were chosen to facilitate visibility of the equatorial satellites. The specific locations of Hilliard, Palmdale, and Fort Worth were chosen because the FAA currently has centers in these cities.

Airport Control Centers are located at all primary aircarrier airports and those secondary and feeder airports that have manned control towers. These centers have command and control responsibility for all aircraft within their jurisdiction. All ground surveillance and control, airport arrival control, and runway management control fall within the domain of the ACC's. Communications to all aircraft in the jurisdiction are handled through the ACC.

There are a number of automation functions that are accomplished at each of these locations. These automation levels and their assignment to proper jurisdictions are described in Section 2.2.2.

In addition to the ground facilities, the other major system element is the satellite constellation. The satellites provide for navigation signals; relay of surveillance, voice, and digital data from aircraft to the ground facilities; relay of voice and digital data from the ground facilities to aircraft; and transmittal of digital data among facilities.

There are a total of 15 satellites in the selected constellation: 6 geostationary satellites with equatorial subsatellite points and 9 incline, eccentric orbit, geosynchronous satellites whose subsatellite points share a common figure eight ground track. Figure 2.2-2 shows the subsatellite points for the selected constellation.

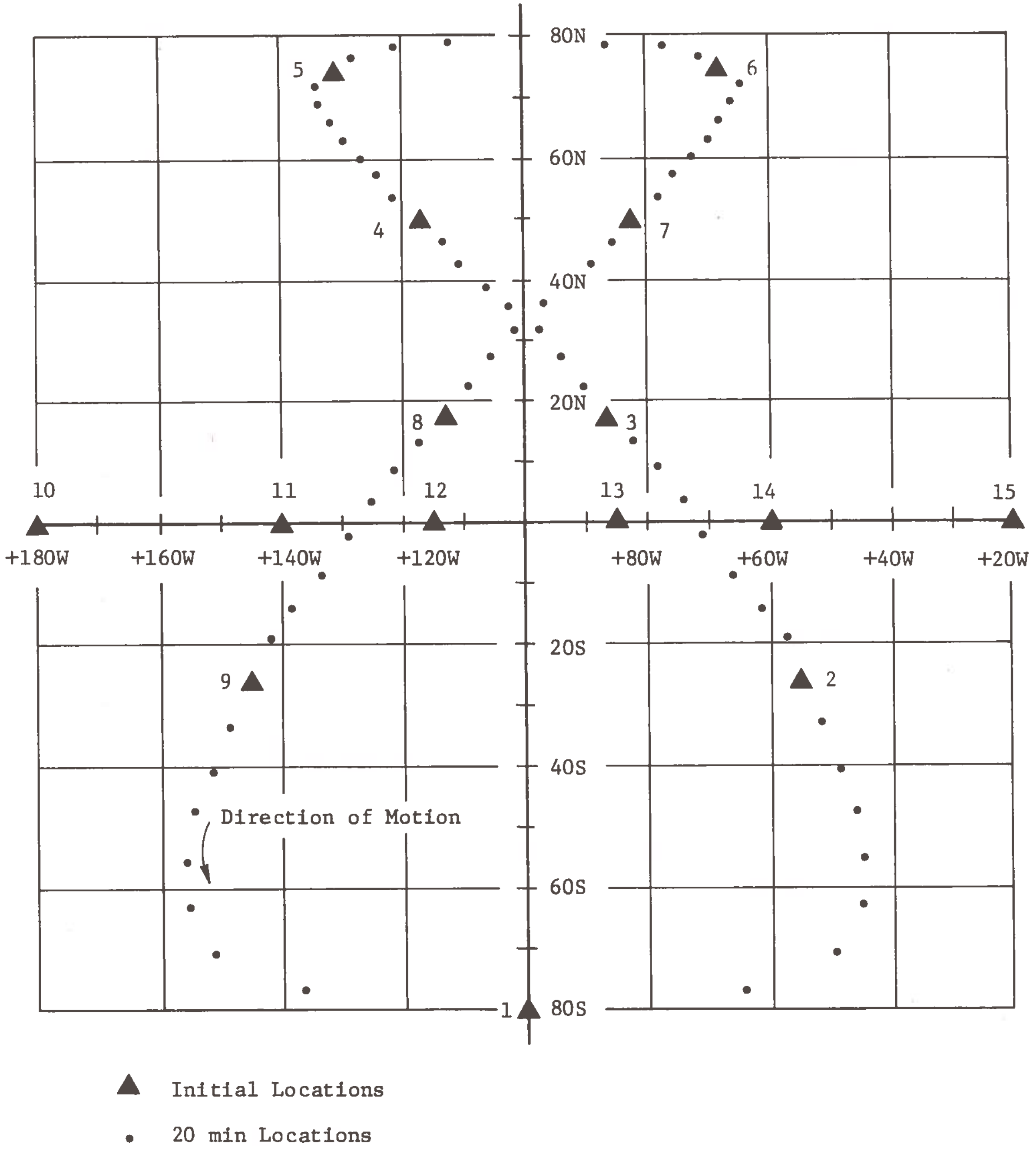


Fig. 2.2-2. Constellation Subsatellite Points

The functional elements, along with the satellite constellation, constitute the basic system architecture. Within this framework, the major functions of communications, surveillance, and navigation are mechanized and the services of separation assurance and path conformance are provided.

2.2.2 Primary Functional Modes

The functional modes of the system are surveillance, navigation, and communications. Each of the primary functional modes is described in the following paragraphs.

2.2.2.1 Airborne Surveillance Description

The basic elements involved in the surveillance function are depicted in Fig. 2.2-3. All active aircraft participating in the system periodically transmit a surveillance pulse containing the aircraft identification code. While the transmission rate is periodic, it is not synchronized among users. The surveillance pulses are received by L-band satellite receivers which convert the randomly spaced pulses to C-band and retransmit them to the earth.

The C-band satellite surveillance signals are received by antennas which track each satellite. Several downlink frequencies are used to insure that only single satellites are viewed by each antenna. The signals are decoded to identify the Time of Arrival (TOA) and the associated Identification (ID) code as received from each satellite. These data are used by the RCC's and CCC's for surveillance position computation.

Acquisition computers at the CCC and RCC scan all of the incoming TOA/ID data for purposes of identifying users entering the system. Aircraft entering the system transmit a surveillance pulse once each 2 sec. This rate is maintained until acquisition is achieved. Once the aircraft is acquired, the computer performs a position computation and assigns track responsibility to the RCC in whose jurisdiction the aircraft is located. Once an aircraft is acquired and assigned to an RCC, subsequent reception of the TOA/ID is ignored by the acquisition computer.

The tracking responsibility for an aircraft at an RCC begins when an acquisition computer assigns the responsibility or when an aircraft is handed off to the RCC by the adjacent center. This responsibility for tracking the aircraft continues (1) until the aircraft exits one RCC domain and a handoff to the other RCC is accomplished, (2) until the aircraft exits the system at an ACC or other airport, or (3) until unexpected termination of surveillance signals occurs and contingency measures are initiated.

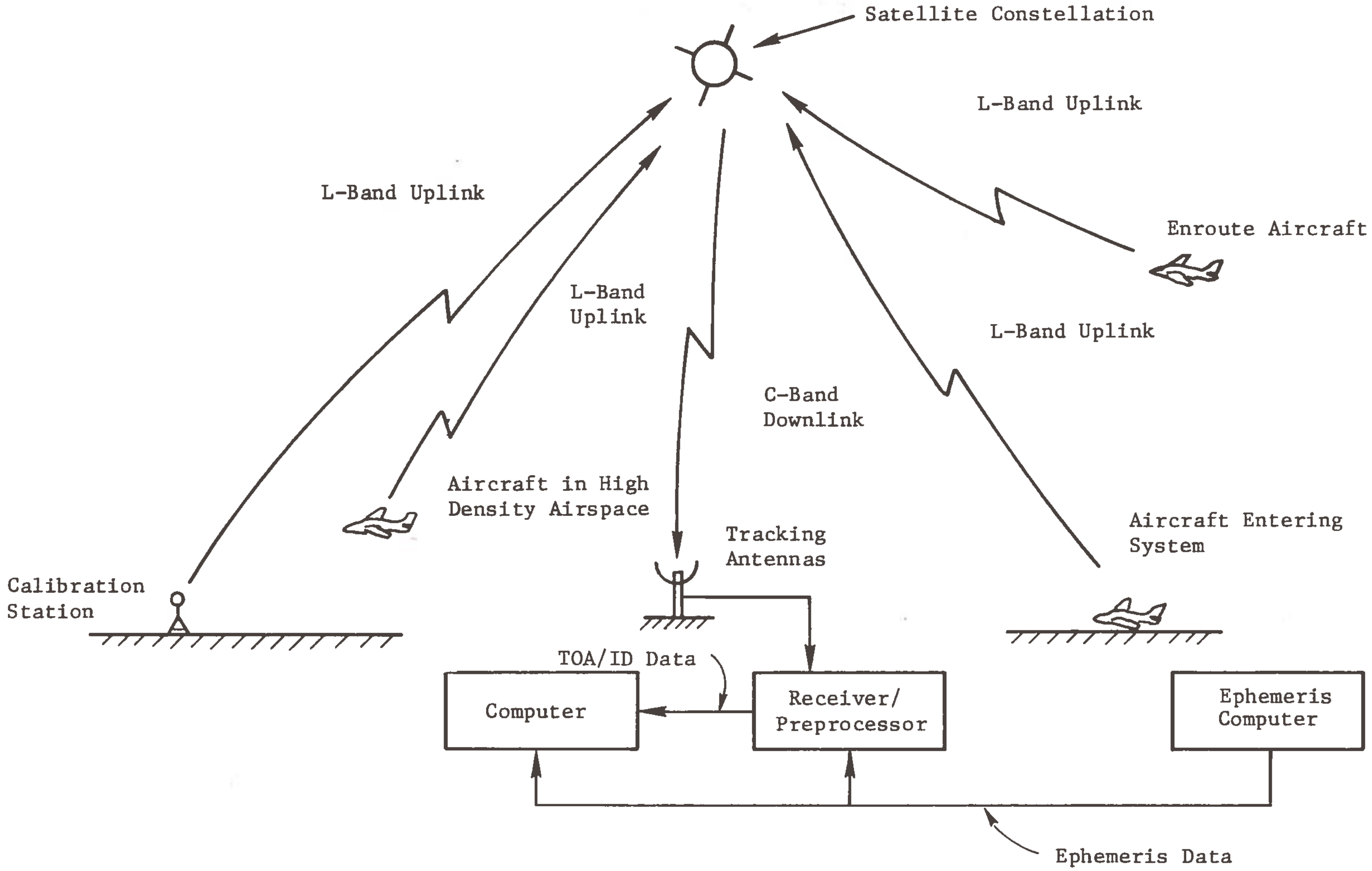


Fig. 2.2-3. Surveillance Functional Elements

During the tracking phase, surveillance pulses are transmitted once each 8 sec. The RCC can, however, command an aircraft to transmit at higher rates. Higher rates are routinely used in high density terminal areas. The RCC computes the position and velocity for each aircraft under its jurisdiction based upon the TOA's of the surveillance pulses as received from all those satellites that are visible from the aircraft.

The position algorithm employed by the acquisition computer differs from that employed by the tracking computer. The acquisition computer computes position using TOA data from four satellites using a Puri mechanization. This quickly yields a deterministic position solution from a single set of received pulses; thus, target acquisition is rapid. The tracking computer employs a suboptimal Kalman filter to estimate position and velocity of the aircraft since this yields better position accuracy than the Puri mechanization.

The Kalman filter mechanization employed in the tracking computer uses differences between the time of arrival of surveillance pulses from satellites as the basic observable for computing position and velocity. Each tracking region is segmented into subregions with a single filter being employed for all aircraft within the subregion. Within the subregion, the number of visible satellites and the order in which surveillance pulses should be received is computed based on the ephemeris data.

With the a priori knowledge of the approximate position of the aircraft and the observable TOA sequence, the Kalman filter gains can be precomputed. Each TOA difference observable is used as a scalar to update the position and velocity state vector.

This selected tracking mechanization has several advantages over alternate schemes. The computation of gains for a subregion drastically reduces the storage and speed requirements of the computers at a minor reduction in accuracy. The Kalman filter is only slightly sensitive to gain errors. The use of a scalar Kalman filter is simpler to mechanize than a vector filter since the size of the the multidimensional filter changes as the number of visible satellites changes. Additionally, the use of the Kalman filter takes maximum advantage of the available information content in the surveillance pulses consistent with noise uncertainties.

Certain position errors resulting from the physics of the multilateration scheme result in correlated errors between closely spaced aircraft. These errors include those caused by ionospheric and tropospheric delays and by satellite ephemeris errors. The total position error may be reduced by estimating these errors using a calibration station. In enroute areas where only relative position errors are important, the calibration station is not required. In high density airspace, the calibration station provides increased absolute position accuracy.

The calibration station consists of a standard surveillance transmitter fixed at a known geographic position. By computing the station position using the tracking algorithm, an estimate of the correlated error may be made. These data can then be used to correct the position of all aircraft in the region surrounding the calibration station. The absolute position error of these users will be reduced and better control can be provided.

2.2.2.2 Airborne Navigation Description

There are two primary navigation modes provided in the SAATMS design. For suitably equipped aircraft, a navigation scheme based on satellite signals is provided. This scheme is completely independent from the surveillance scheme. For aircraft which do not possess the navigation avionics, a simpler, less expensive navigation scheme is employed. This scheme is based on retransmitted surveillance data processed in a VOR format.

2.2.2.2.1 Satellite Navigation Scheme

The satellite navigation scheme is intended for military, aircarrier, and general aviation aircraft that require high accuracy navigation. The basic elements involved in the navigation function are depicted in Fig. 2.2-4.

The aircraft receives signals from the satellites. These signals include a precisely timed marker pulse plus ephemeris data. The navigation signals are transmitted by the satellites individually with each satellite transmitting every 3 sec. Spacing between satellite transmission is 0.2 sec. The aircraft does not receive a signal each 0.2 sec, however, since not all satellites are in view at any given time.

The ephemeris data transmitted by the satellite consist of the satellite position coordinates at its transmission time and its transmission time error with respect to master time. The aircraft measures the time of arrival of the pulse. Using these data plus the satellite position data allows the aircraft to estimate its position and velocity. Accurate TOA measurements can be achieved since the satellite clock bias error allows the aircraft to accurately synchronize its clock with master time.

Since the aircraft must measure the TOA of the marker pulse very accurately, a pseudo-noise (PN) coded navigation pulse is used. This also places less stringent RF link requirements on the system because of the processing gain achieved through pulse energy compression in the analog matched filter detector employed. Only a single PN code is used since the system is time ordered and the required ephemeris data are transmitted following the timing pulse.

The algorithm used to compute the aircraft position and velocity is a scalar Kalman filter mechanization. The observables are the TOA of the navigation signals. Again, as in the case of the surveillance tracking algorithm, this mechanization has advantages over alternate mechanizations. The filter gains for navigation are computed by the individual aircraft rather than for several aircraft as is the case in the surveillance tracking.

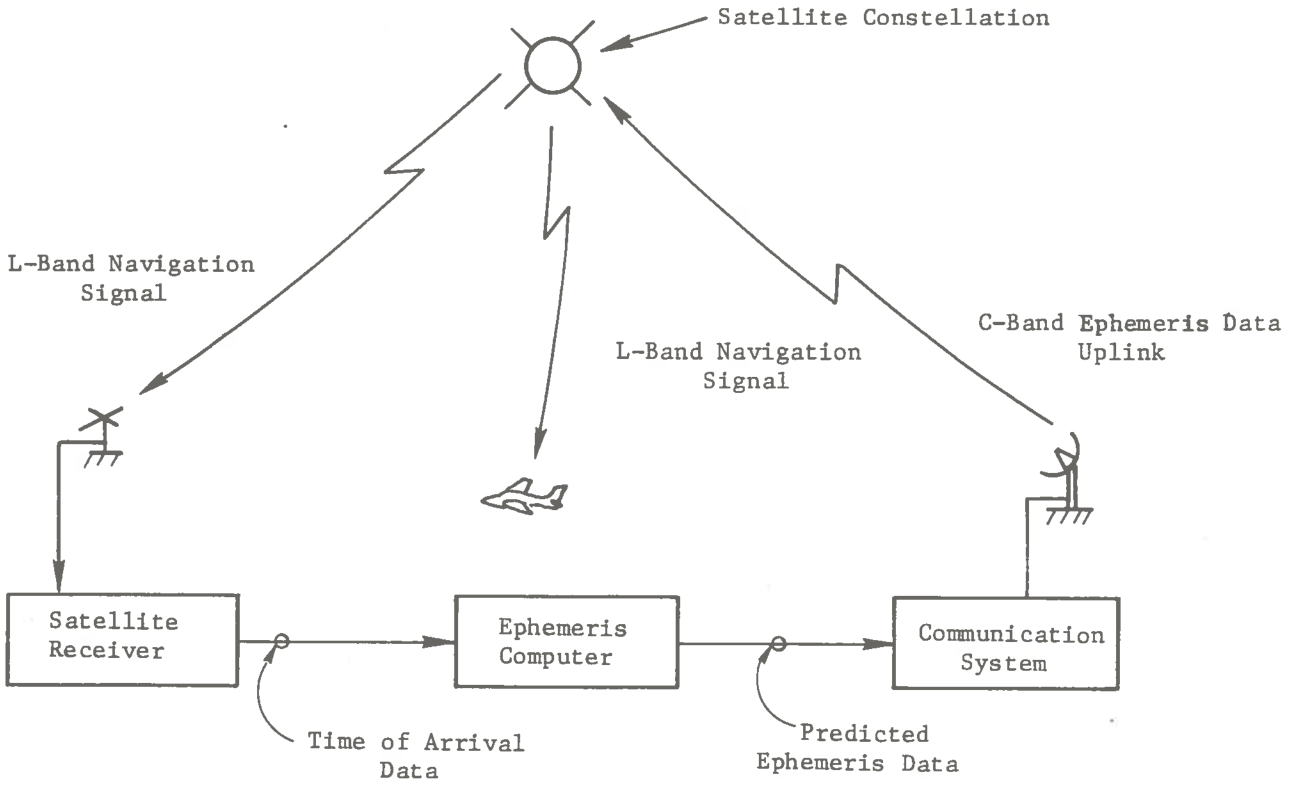


Fig. 2.2-4. Satellite Navigation Functional Elements

The same navigation pulses used by the aircraft are also used to predict the satellite ephemeris data. Satellite receivers measure the TOA of the navigation signals at known geographic locations. These data are distributed to the ephemeris computer where the predicted satellite ephemeris is computed. The ephemeris is then directed to the communication system which inserts the predicted ephemeris into the satellite for navigation purposes. These data transmissions are accomplished via the satellite communications network.

The C-band ephemeris data link and the L-band navigation signal downlink are not dedicated links. Since the navigation signals occupy approximately 5 percent of the available time, the links are shared with the ground-to-aircraft digital communications link.

2.2.2.2.2 Virtual VOR

The navigation scheme employed by the lower class user is based on ground processing of surveillance data. The technique is called virtual VOR (VVOR) due to its operational similarity to the present VOR system from a user viewpoint.

Physically, the VVOR system consists of a ground processor, the normal ground/aircraft communication links, an aircraft signal processor, and an aircraft display. Functionally, the user requests the system to provide navigation from some grid point to another fixed grid point. Based on the surveillance data for the user, the ground system processor computes the course required to place the aircraft on the selected path and the distance to the selected destination point.

The communication link is used to transmit these data to the user. The user processor decodes these signals for display to the pilot. The effective display quantities are similar to having a VOR/DME system on the aircraft, except that many more effective VOR stations are present. Essentially, then, a VOR/DME system with RNAV capability exists.

2.2.2.3 Communications Description

The communications subsystem is designed to provide the basic data interchange between all of the ground, satellite, and airborne elements in the SAATMS design. Basically, all airborne-to-satellite or ground links operate in the L-band region (approximately 1.6 GHz), while all ground-to-satellite links operate in the C-band region (approximately 5.0 GHz).

The effect of the frequency allocation employed in the SAATMS design is that users are required to carry only L-band equipment. The ground system basically employs only C-band equipment except for ACC's which communicate directly with aircraft on L-band links and the satellite tracking sites which only receive the L-band navigation signal.

Table 2.2-1 is a complete description of the communication links associated with the SAATMS design. Seven L-band and seven C-band segments are required to implement the system with a total spectrum usage of 75 MHz in L-band and 67 MHz in C-band. The communications system design includes the capacity required to communicate with all controlled airports and cooperative airports that have control tower personnel.

The surveillance communications employ an L-band uplink from aircraft to satellites and a C-band downlink from satellites to ground sites. The basic surveillance signal is a spread spectrum pulse sequence. The aircraft identification is encoded in each surveillance sequence. The surveillance signals require a 20 MHz channel to allow accurate timing of the pulse time of arrival at the ground sites.

Five overlapping channels with a 0.25 MHz center-to-center frequency spacing are used on the satellite downlink. The ground sites must measure the time of arrival of each surveillance pulse from each satellite. Separation of the same code sequence from different satellites is achieved through the space diversity of the satellite and high gain, narrow beam satellite tracking antennas. To further isolate the signals, the slight shift in center frequency between adjacent satellites is also used.

The navigation and ground-to-aircraft digital data links are time shared over both the ground-to-satellite C-band link and the satellite-to-aircraft L-band link. The basic time share mechanism is based on the satellite transmission of navigation data. Each 3 sec, a satellite will transmit navigation data for approximately 4 msec. Only one satellite transmits at a time with the time between transmission set at 0.2 sec. Thus, the total navigation transmission uses only 20 msec plus 95 msec guard time or 115 msec per sec.

During the time the satellite L-band transmitter is not used for navigation, it is transmitting ground-to-aircraft digital data over part of the channel used for the navigation pulse. Fifteen MHz of the 20 MHz spread spectrum channel are used in this way. The remaining 5 MHz of the channel is used for local ground-to-aircraft direct communications. This signal is inhibited during navigation transmission time.

Digital data on the C-band uplink are transmitted to the satellite time spaced so that they do not arrive at the satellite during navigation time. During the interspace time, the satellite ephemeris data are transmitted to the satellite for storage. These data are later retrieved for use during subsequent navigation transmission periods.

The remaining digital data and voice links are dedicated channels for use in systems intercommunications. All the ground-to-ground communications are accomplished using the geostationary satellites. This eliminates the need for tracking antennas at ACC's.

TABLE 2.2-1. SAATMS COMMUNICATIONS LINK DESCRIPTION

Function	Path	Link	Band	Bandwidth	No. of Channels	Channel Bandwidth	Type of Data	Comments
Surveillance	A-S	Uplink	L1	20 MHz	1	20 MHz	Surveillance Pulse	Independently transmitted by all aircraft
	S-G	Downlink	C1	21 MHz	5	20 MHz	Surveillance Pulses	Five overlapping channels separated by 0.25 MHz
Navigation	S-A S-G	Downlink	L2 + L3	20 MHz	1	20 MHz	Navigation Pulses (also used for tracking)	Time ordered and shared with digital data transmission to aircraft
	G-S	Uplink	C2	15 MHz	1	15 MHz	Ephemeris Insert Data	Time ordered and shared with digital data uplink to the satellite
Communication – Data and Voice	A-S	Uplink	L4	15 MHz	1	15 MHz	Digital Data	Asynchronous aircraft-to-ground data link
	S-G	Downlink	C3	15 MHz	1	15 MHz	Digital Data	
	G-S	Uplink	C2	15 MHz	3	5 MHz	Digital Data	Ground-to-aircraft data link, time ordered and shared with navigation links
	S-A	Downlink	L2	15 MHz	3	5 MHz	Digital Data	
	T-A	Local LOS	L3	5 MHz	1	5 MHz	Digital Data	
	G-S	Uplink	C4	3 MHz	600	5 kHz	Digital Data	Ground-to-ground link interconnecting RCC's and ACC's; employs four equatorial satellites with space diversity to achieve 2,400 channel capability
	T-S	Uplink	C4	3 MHz	600	5 kHz	Digital Data	
	S-G	Downlink	C5	3 MHz	600	5 kHz	Digital Data	
	S-T	Downlink	C5	3 MHz	600	5 kHz	Digital Data	
	G-S	Uplink	C6	5 MHz	150	25 kHz	Voice	Ground-to-aircraft voice link
	S-A	Downlink	L5	5 MHz	150	25 kHz	Voice	
	A-S	Uplink	L6	5 MHz	150	25 kHz	Voice	Aircraft-to-ground voice link (two channels reserved for air-to-air mode)
	S-G	Downlink	C7	5 MHz	150	25 kHz	Voice	
	T-A	Local LOS	L7	10 MHz	400	25 kHz	Voice	Local traffic voice links with ACC's
	A-T	Local LOS	L7	10 MHz	400	25 kHz	Voice	

Notes: 1. Path abbreviations: A = Aircraft, S = Satellite, G = Ground (RCC), T = Tower (ACC or Remote Site)

2. Total spectrum usage: L-Band = 75 MHz, C-Band = 67 MHz

2.2.3 System Backup Philosophy

The SAATMS design philosophy is based on the requirement that sufficient backup functions and equipments be provided to achieve fail-operational, fail-safe, and fail-soft capability for increasing degrees of equipment failures. In this context, fail-operational implies full system capacity and safety, fail-safe implies reduced system capacity at full system safety, and fail-soft implies full system safety for a specified period of time, all under various levels of system function, automation, and equipment failures.

The primary mediums employed to achieve these degrees of system reliability are redundancy of functions, equipments, and automation; geographic dispersion of system elements; and an intrinisic capability to reconfigure the system through designed adaptability. In short, the degrees of system reliability are achieved through total system design.

Due to the complexity of the SAATMS design, the backup capabilities must be discussed concurrently with the detailed system architecture. It should be noted that the backup capability exists primarily because of the data mobility that can be achieved through the satellite constellation based communications system.

2.3 System Architecture and Interconnection

The basic system architecture is established by the subsystem functions and their task specific goals.

The system architecture and interconnection are constrained by the requirement to interface the user with the system in all flight phases during both normal and backup modes of system operation. In the introduction to the system architecture, the RCC's and CCC's were viewed as single entities. In point of fact, they will be revealed as conglomerates of many individual functions. These functions are semi-autonomous of overall center operation in many cases.

In this description of the system architecture, the general system operations are described in an overall sense. The total number of sites involved and their interconnections are described first, and then the processing requirements for implementation of these sites are described. This allows a logical presentation of a comprehensive description of the integrated system.

2.3.1 Architecture Established by Functions

The system architecture is segmented into functional elements that are based on system, automation, and processing specific goals. The functional elements include satellite, surveillance, user-control, flow-control, and communication associated functions.

2.3.1.1 Simple, Versatile Satellite Communications

A primary attribute of the SAATMS design is a simple, versatile communications system that interconnects all elements of the system. The satellite based communications system was selected because it yields coverage from ground level upward over all the CONUS and the adjacent airspace regions.

The satellites act as relay stations to interconnect ground based sites and to relay communications with all users active in the system. Additionally, direct user-to-ground communications are employed at ACC's. The majority of the communication messages are digitally encoded but full voice interconnection is also provided.

The interconnection of ground sites is accomplished through the geostationary satellites which appear to be fixed in space over equatorial sites. These satellites exhibit only small temporal location changes. This allows high gain, fixed, directional antennas to communicate with the satellite's low gain, low power communication circuits.

Each of four equatorial satellites contains 600 transmit-receive channels located in the C-band region. Twenty-four hundred channels are available for ground-to-ground intercommunications when the space diversity of the satellites is employed. Since the satellites do not discriminate between channel usage, these circuits are as adaptable as the ground system will allow.

The low gain, broad coverage antennas employed on the satellites combined with high gain, directional antennas at the ground site allow full interconnection of the system. As shown in Fig. 2.3-1, all channels of all satellites are available to all sites. This allows dynamic channel assignments between the majority of the sites.

The data mobility afforded by the SSATMS ground-to-ground communications allows easy automation of the control functions because of high speed ACC/RCC communication. Further, a system backup for equipment malfunctions is easily accomplished because of the uncomplicated implementation of channel reassignment. The versatility of the system is such that there is actually no such thing as a remote site except in a purely geographical sense. The addition of new ACC's or the tie-in of existing facilities to the system can also be easily accomplished.

The individual channel bandwidths in this system are 5 kHz each, which allows the digital data to be sent at a 2.4 kb rate.

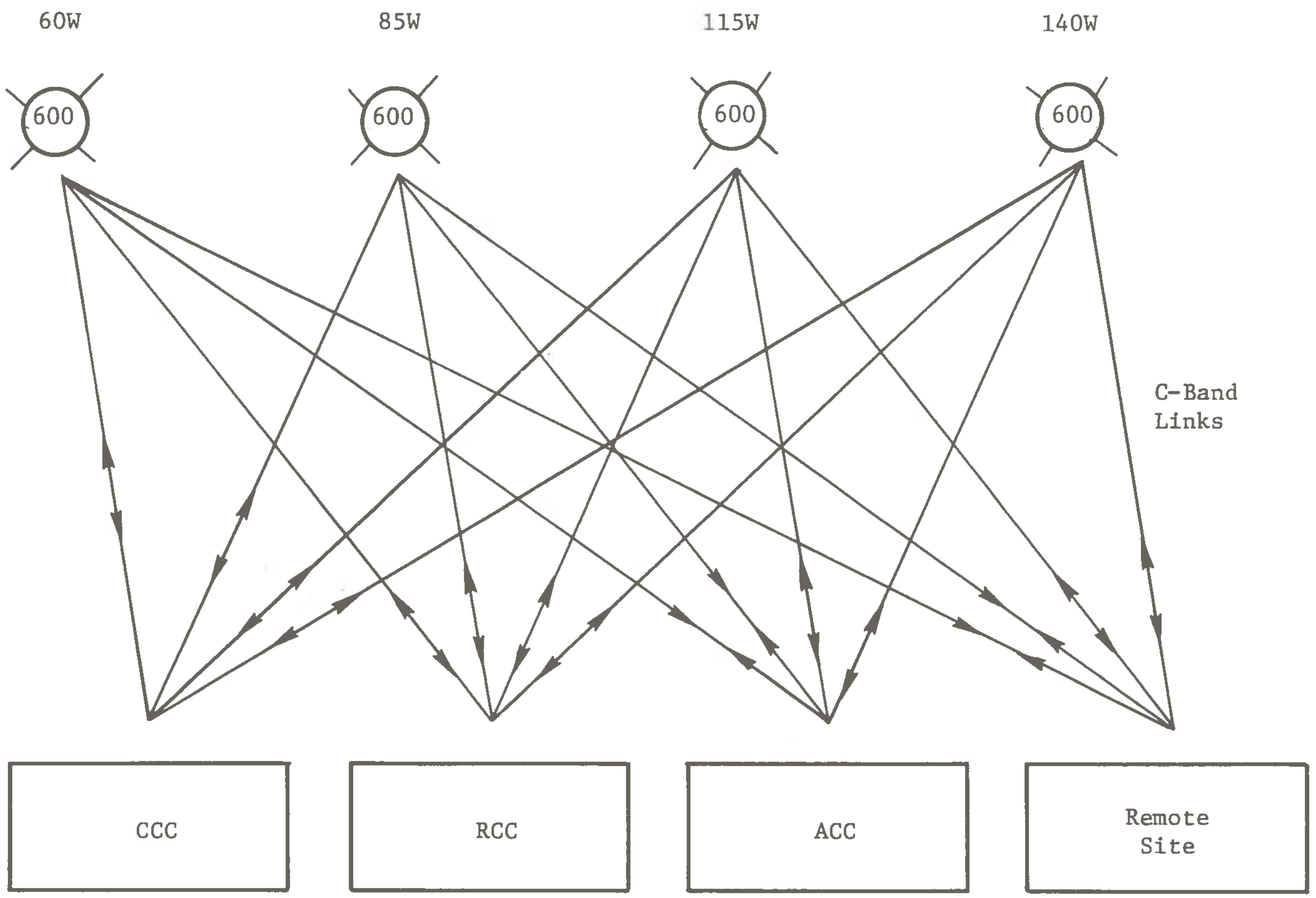


Fig. 2.3-1. Ground-to-Ground Communication Network

The user-to-ground communications are shown in Fig. 2.3-2. This system design is such that users are required to have only L-band communication equipment. This equipment will provide both voice and digital data capability.

Almost all of the intercommunication between the user and the system is relayed via the satellites to the RCC's. Terminal communications are provided between user and ACC's via direct L-band links. At airports without ACC's, the user communicates with the system via the satellites.

Backup communications to aircraft are provided by the CCC in the event of RCC failures. Direct ACC-to-user communications are also practical as a backup throughout the area adjacent to the ACC. The communication system is designed to be basically a digital system with voice backup. Thus, several levels of communication backup are contained in the basic system design.

The versatility of the system is most evident from the point of view of the user. The system does not require that multiple frequency changes be effected during the course of a typical flight. Even with a coast-to-coast flight, only three handoffs are required and at most three frequency changes, i.e., one satellite and two ground communication frequency shifts. Note that regardless of the user's location, the satellite based communication system will provide positive data exchange from the ground based system to the user.

The communications system is a straightforward design intended to provide the maximum versatility and adaptability with a minimum of extraneous elements. The system allows a cohesive, integrated air traffic control and management system to be geographically dispersed without attendant communication complexity.

2.3.1.2 Accuracy Achieved Through Satellite Tracking

The accuracy of the surveillance and navigation system is dependent on the accuracy of the satellite position locations and the timing of the system. The satellite tracking subsystem provides both the position location and timing functions for the entire system. The operation of the system requires that additional equipment sites, Satellite Tracking Centers (STC), be defined.

Figure 2.3-3 depicts the general form of the satellite tracking subsystem. The STC's are collocated facilities as shown in Table 2.3-1.

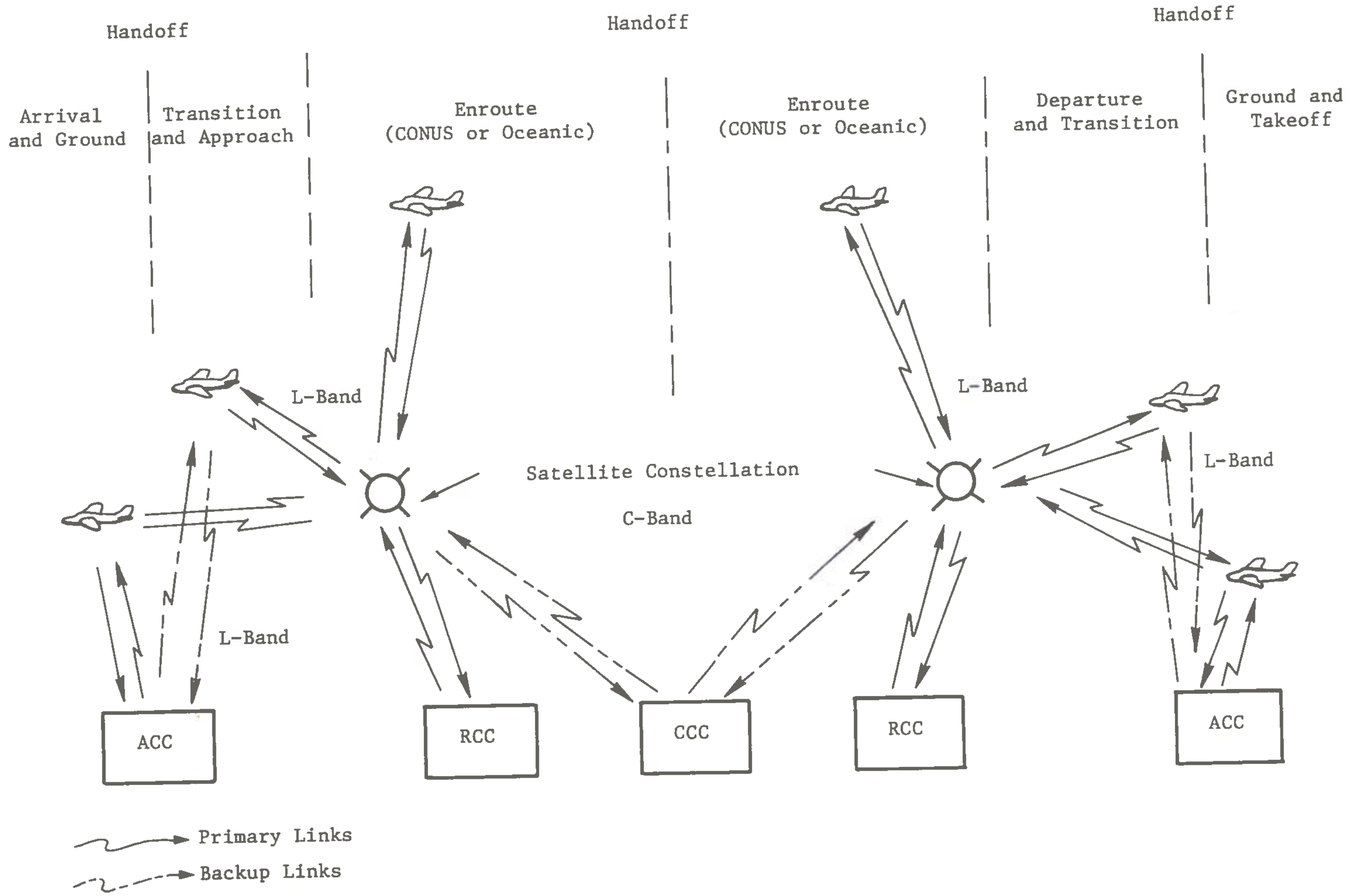


Figure 2.3-2. Voice and Digital Ground-to-User Links

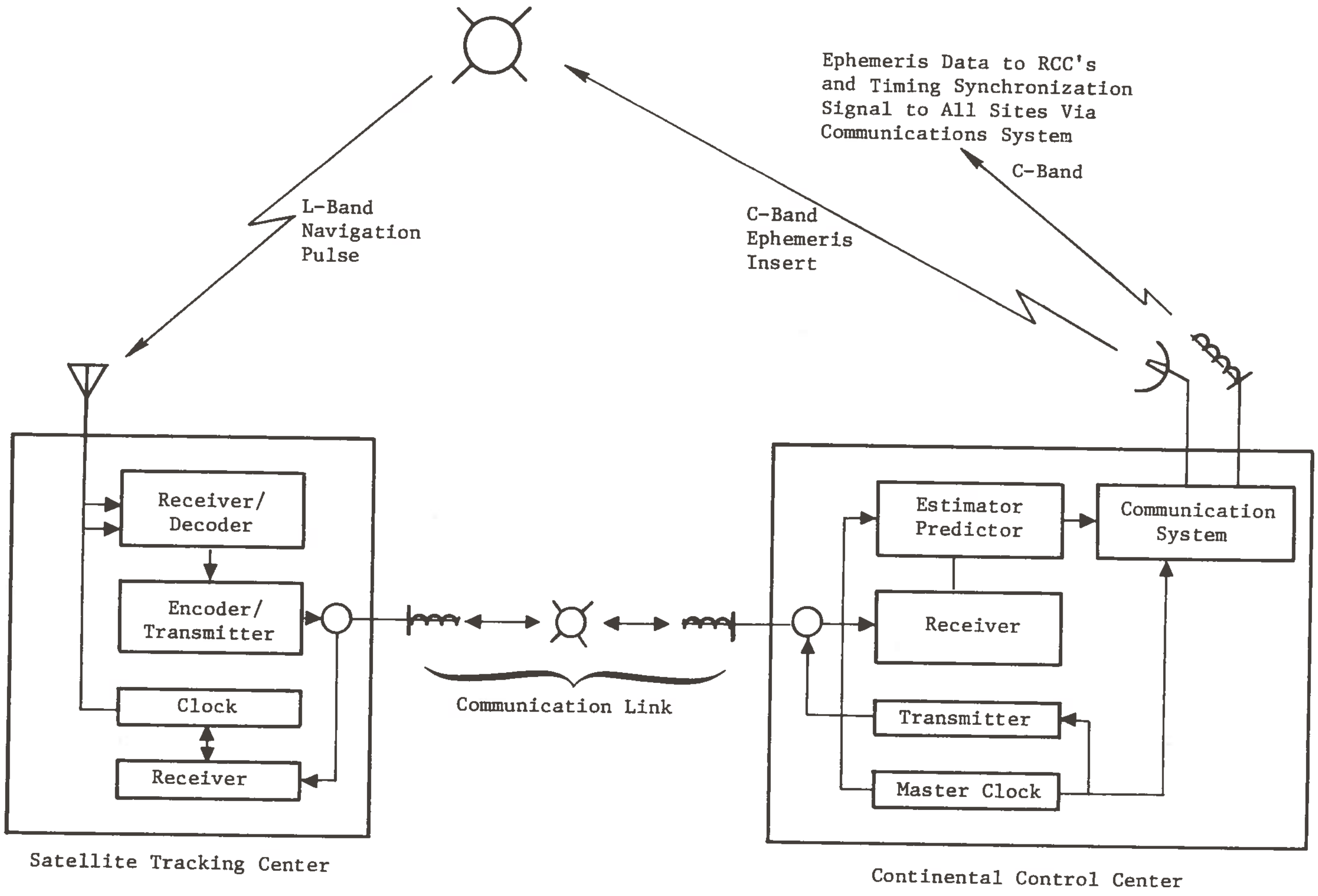


Figure 2.3-3. Satellite Tracking Subsystem

Table 2.3-1. Satellite Tracking Center Locations

STC Site	Collocated With
Fort Worth, TX	CCC
Palmdale, CA	RCC
Hilliard, FL	RCC
Seattle, WA	ACC
Albany, NY	ACC
Honolulu, HI	ACC
San Juan, PR	ACC

The selected satellite tracking method is a one-way ranging mechanization. This system uses the navigation pulses transmitted by the satellites to generate the observables. The TOA's of the navigation pulses are measured using a high precision clock as reference time. These TOA data are sent to the CCC for ephemeris computation.

The one-way ranging mechanization selected has several advantages over alternate methods. The use of the navigation pulse for the ranging pulse reduces the amount of satellite hardware. The one-way ranging technique introduces less ionospheric and tropospheric errors than does a two-way ranging scheme. The receiver decoder is a very simple device and operates directly into the normal communications system used for collocated facility to CCC communications.

The clock used to measure the TOA's is synchronized to the system master clock which is located in the CCC. The CCC clock and the RCC clocks are rubidium standard atomic clocks with the RCC clocks slaved to the CCC clock. All ACC clocks are high precision, oven controlled crystal clocks. These clocks are synchronized to the system master clock using the communications system.

The TOA data from the STC's are used by the CCC to estimate and predict the satellite ephemeris. These data are used to compute the satellite positions and to estimate each satellite's clock error. The communications system is used to insert the predicted ephemeris data into the satellite for navigation purposes and for distribution to RCC's.

The ephemeris data transmitted to the satellite are the satellite's predicted position in an earth fixed orthogonal coordinate system for a given navigation pulse transmission time. The timing error between the estimated transmission time and the time the pulse should have been transmitted is also inserted. The position data are quantized to one meter for high precision. By employing the earth fixed coordinate system for satellite ephemeris data, the user's navigation system is not required to do any coordinate transformations to use the data. The position data are predicted to the actual transmission times of the satellite to eliminate the requirement for the user's navigator to interpolate data. The transmission of the satellite's timing error with respect to master time allows the user's navigation system to synchronize its clock to master time.

The ephemeris data are transmitted to the RCC's for use in the surveillance position computation and for use in pointing the satellite tracking antennas. The predicted ephemeris are given with respect to master time.

The accuracy of the surveillance and navigation systems are directly related to the accuracy of the ephemeris prediction. The surveillance multilateration mechanization is dependent on the position accuracy of the satellite at the time it transponds the surveillance signal. Similarly, the navigation pseudo-range multilateration mechanization depends on the accuracy of the satellite's position knowledge at navigation pulse tranmission times. The proposed satellite tracking system achieves this accuracy through the estimator-predictor resident in the CCC.

2.3.1.3 Surveillance Subsystem Allows Automation

The SAATMS design allows automation of the user control function since the surveillance system provides high speed accurate range-independent and reliable user position and velocity data. Since the surveillance data are so critical to the system operation, a completely redundant user tracking mechanization is employed.

The division of the system into one CCC and two RCC's is partially based on the desire to provide completely redundant tracking. The site locations for the RCC's and CCC are based primarily on the surveillance requirement. By selecting a central location for the CCC, the site is able to view all of the satellites required for CONUS coverage but does miss some of the outer oceanic areas. This allows the CCC to track all CONUS aircraft as backup to either RCC. The RCC's are placed on the east and west coasts to expand the oceanic coverage. A southerly location is selected for the sites to provide coverage for equatorial and inclined orbit satellites with southern hemisphere subsatellite points.

Each RCC has the capability to track 20,000 instantaneous aircraft, while the CCC can track 35,000 aircraft. The capability to expand each site to handle 64,000 aircraft is implicit in the initial computer sizing. A further modification for even larger numbers of aircraft is possible.

The surveillance derived position and velocity data are extremely critical to the automation of the system. Most of the automatic and manual control commands to users are based on or derived from these data. Because of the critical nature of this system, the CCC is capable of tracking all of the CONUS aircraft to provide a 100 percent backup of the RCC's.

2.3.1.3.1 Complete Backup of Surveillance Data

The general interconnection of the surveillance system is depicted in Fig. 2.3-4. The eastern and western RCC's are responsible for tracking all aircraft within their respective regions. The CCC tracks all aircraft. The status of the aircraft and their surveillance data are determined and stored in a file. These files contain the instantaneous state of all active users in the system.

A monitor and control function is resident in the CCC. This routine notes the user status of the entire system. When an aircraft transitions from the eastern RCC to the western RCC or conversely, both the individual RCC's and the CCC are updated to reflect this event. The monitor function tests the file data to determine RCC and CCC coincidence.

In the event of an RCC failure, there are two backup modes which can be exercised. In the event of a partial or full failure of the RCC preprocessor, acquisition, or tracking routines, the CCC file can be used to update the RCC file on a continuing basis. This allows the RCC user control routines to be employed. In the event of a total failure of either or both RCC's, the CCC can provide a limited control of the entire system. In this event, some of the outer fringe oceanic traffic may be lost or exhibit lower surveillance accuracy, but all CONUS users will be maintained at the same high service level.

2.3.1.3.2 Critical Processing Task Detailed

The critical preprocessing, acquisition, and tracking mechanization is required to derive the position and velocity of each active user in the system. Figure 2.3-5 depicts the general scheme to accomplish this task. The mechanization is required to track only those aircraft that are truly in the system and to reject those that are not within the domain of the tracker and those phantom (non-present) aircraft that appear.

The surveillance pulses transmitted by the aircraft consist of a spread spectrum sequence of pulses that constitute the aircraft ID. These pulses are relayed by the satellite to the satellite tracking antennas located at the RCC's and the CCC. The pre-processors are required to measure the TOA of the first pulse and decode the associated identification sequence from the randomly arriving surveillance data.

The spread spectrum signals are compressed by analog matched filters and the arrival times are measured for each pulse arriving. These digital TOA signals are stacked while the identification sequence takes place. The ID decode matrix looks at the incoming pulse sequence and identifies viable ID signatures. These are then associated with the correct TOA associated with the first pulse. Note that those TOA measurements associated with other than first pulse are dropped from the TOA stack. The ID/TOA word stack is used as a queue during high peak activity periods to prevent data loss due to finite sorter access time.

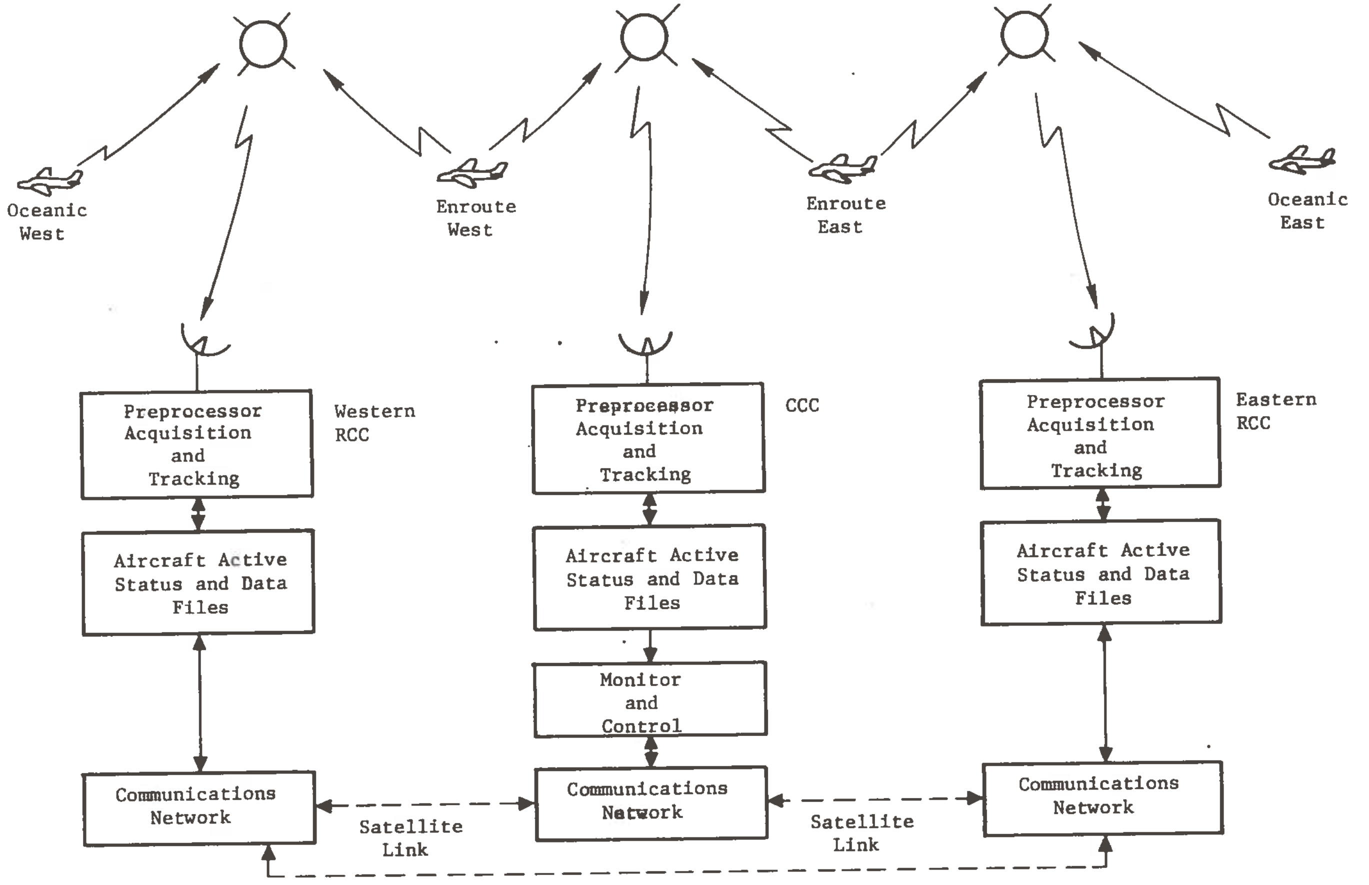


Figure 2.3-4. Surveillance Subsystem Interconnection

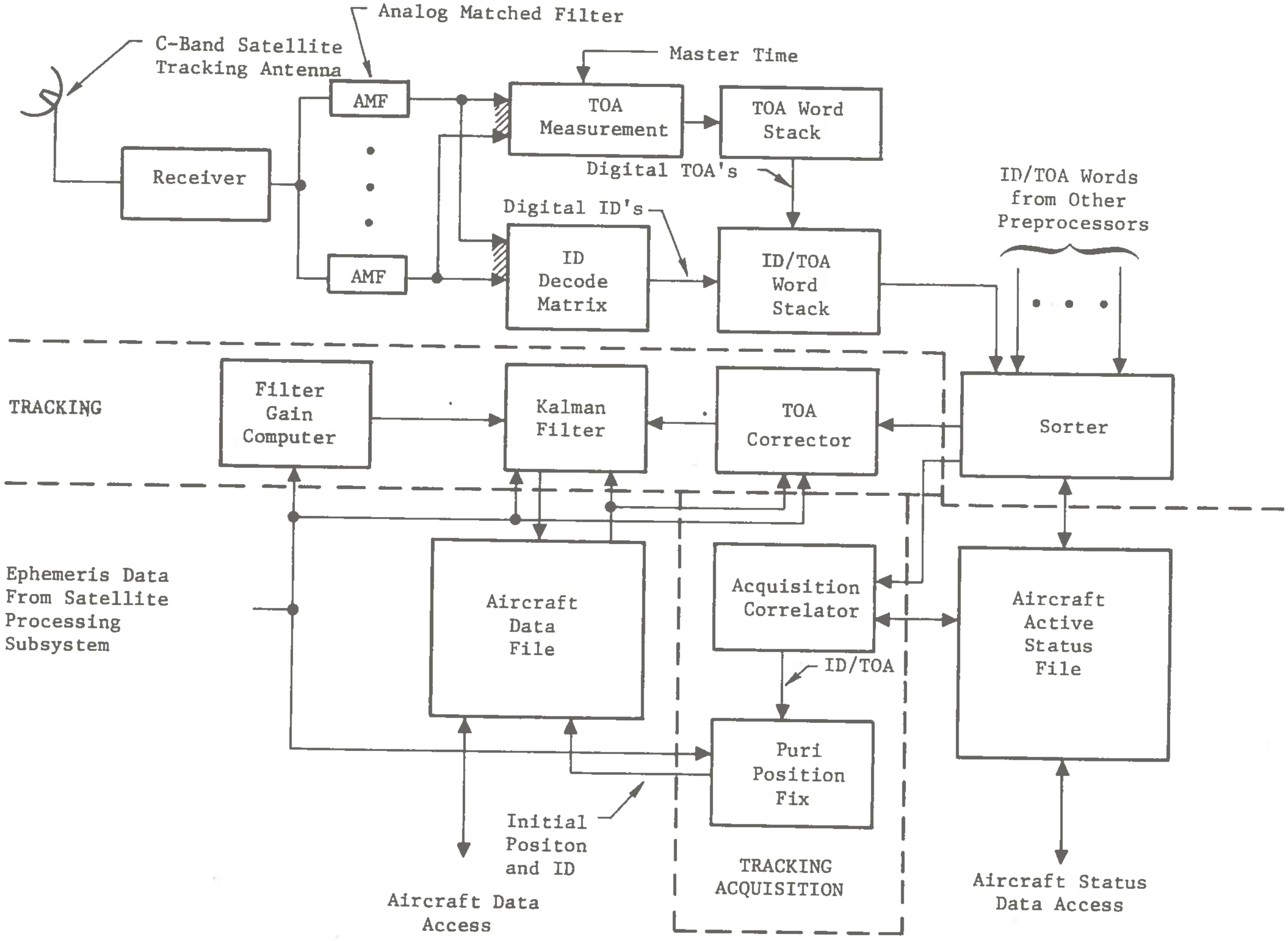


Figure 2-3-5. Surveillance Subsystem Preprocessing, Acquistion, and Tracking

The ID/TOA stack contains viable signatures as well as phantom signatures resulting from overlapping surveillance signalling. The sorter is used to segregate these data. Those data being tracked by the particular site are directed to the tracking processor. Those data being tracked by another site are eliminated. Those data remaining are directed to the tracking acquisition processor. Those data belonging to ID's which have not been assigned are also eliminated. Thus, some of the phantom signatures have been eliminated while some have been directed to the associated processors.

The initial sorting is accomplished using a two-bit (four-state), high speed access memory available through the aircraft active status file. This status file contains the ID associated track, track elsewhere, not valid, not being tracked statuses for each of the one million possible aircraft ID's.

For the not being tracked case, the ID/TOA data are directed to the track acquisition processor. Here an initial test is made to see if ID/TOA data are available from four or more satellites as would be the case for valid aircraft. The data are eliminated if this test is not passed. The test passed case results in a file being established. If the ID is not received from four or more satellites within slightly more than 2 sec (the normal acquisition mode transmission time), the data are deleted. If three successive groups of data from four or more satellites are received, an acquisition has been made and the latest set of ID/TOA data are used to compute a user position.

The position algorithm used for the initial position estimation is the Puri mechanization. This algorithm yields a position estimate which can be used to initiate the aircraft data file. The acquisition correlator also tests the position to determine if the aircraft is to be tracked elsewhere and sets either the track or track elsewhere bit in the active status file. Additionally, the status file is updated to cause a communication message to be sent to the user acknowledging his presence and requesting the normal 0.125 Hz surveillance transmission rate, rather than the 0.5 Hz acquisition rate. For aircraft being tracked, the initial position data are sent to the aircraft data file for use in the Kalman tracking filter routine.

The sorter directs ID/TOA data for tracked aircraft to the tracking processor. These data are normally received from each of the user-visible satellites once each 8 sec. Some phantom signatures and valid signatures at the acquisition rate are also received but are rejected by time window tracking. Two corrections are applied to the TOA data prior to forming differential TOA's for use in the Kalman filter. Time-of-arrival values are corrected for preprocessor delays in the antennas, receivers, and analog matched filters and for ionospheric and tropospheric delays. These deterministic errors are removed and differences between successive TOA's are formed as observables for the Kalman filter.

The Kalman filter estimates the aircraft position and velocity using TOA differences. This filter is a suboptimal, recursive version employing scalar observables. By using the observables as scalar quantities, the problem of needing to change the order of the filter with a differing number of visible satellites is eliminated. By computing the filter gains for regions of position rather than for individual aircraft, a substantial processing gain is also realized.

The filter estimates of the aircraft position and velocity are stored in the aircraft data file along with other aircraft specific quantities. The aircraft data file differs from the aircraft active status file in that only those aircraft being actively tracked have any data stored in the data file. These two files are the main memory for the entire surveillance processing subsystem since they contain the status of the entire user fleet at any instant in time.

The preprocessor, acquisition, and tracking section derives the user's position and velocity. The routines are designed to rapidly acquire new users and to reject phantom signatures with high probability.

2.3.1.3.3 Calibration Stations Improve Accuracy

The position and velocity data derived during surveillance exhibit two different classes of errors. These errors lead to a relative accuracy of surveillance and an absolute accuracy of surveillance. The use of calibration stations in high density geographic regions can improve the absolute accuracy of the system.

The most important surveillance accuracy as far as system safety is concerned is the relative uncertainty in the positions of two closely spaced users. If the absolute error of the user is unknown relative to some fixed ground point but the relative inaccuracy between aircraft is known, the safe separation of aircraft can be maintained.

The absolute accuracy of surveillance becomes important in high density airspace where control of aircraft in transition and arrival airspaces is accomplished. In these regions, the accuracy of surveillance relative to geographically defined airspace structures is required.

The error sources that lead to the absolute errors are correlated among closely spaced users. These errors include ionospheric and tropospheric errors, satellite ephemeris errors, and similar type errors. The bulk of this type of error may be removed by the use of calibration stations. Calibration stations are similar to aircraft surveillance transmitters but are located at fixed, known geographic positions.

The surveillance tracking system treats the calibration station exactly like any active user. A position computation on the calibration station is performed. This value is compared to the known position of the station and a correction is computed. This correction may then be used to correct the surveillance position of all aircraft in the neighborhood of the station. This will reduce the absolute error of these aircraft data.

The mechanism to perform this routine is implicit in the Kalman gain boundary routine. Only one calibration station is located within a Kalman gain boundary so that all those aircraft within the boundary receive the same correction.

2.3.1.4 User Control Based on Surveillance

The generation of control commands and advisories for the active user of the system is based directly on the surveillance data. This results from the basically spatial nature of any automated air traffic management system.

The surveillance data are used to form the basic conflict and control decisions. These data are available on all system users regardless of altitude or location. Hence, separation assurance or advisories can be provided to all aircraft at all times.

There are many ways to structure the control aspects of the system design. The SAATMS design concept is to provide the basic data to allow control to be implemented. The design is extremely adaptable to alternates in many of the control aspects. One of the many possible configurations is presented.

2.3.1.4.1 User Control is Predominantly Centralized

The generation of user control and advisories is predominantly centralized and resident in the CCC and RCC's. The control and advisories that are generated for aircraft within ACC jurisdictions originate at the ACC. Figure 2.3-6 depicts the general user control processing mechanization.

The majority of the control commands directed to users and the requests and acknowledgments originated by users are in the form of digitally encoded messages. Many of the ground generated commands and the responses to user generated messages are automated within the ground processing equipment. This presumes only a modest degree of automation.

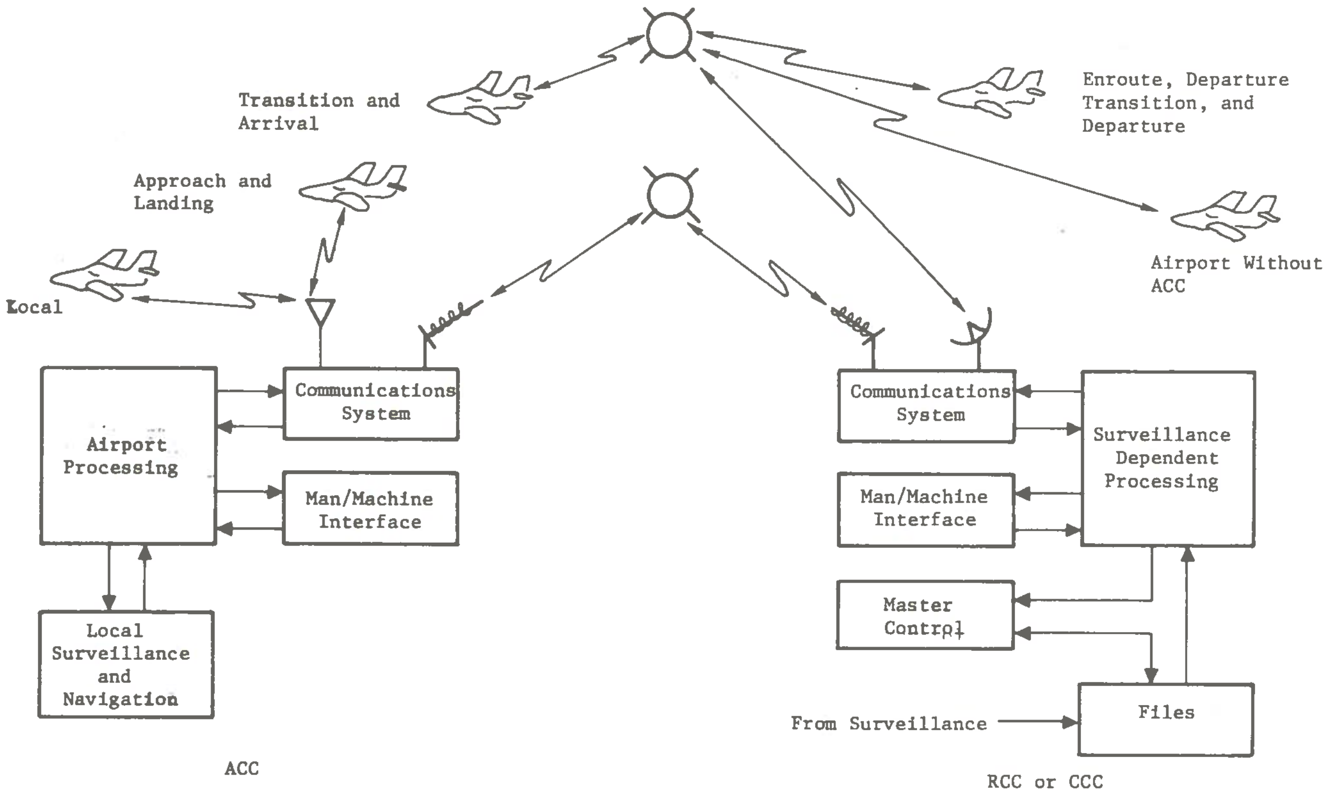


Figure 2.3-6. User Control Processing Mechanization

The man/machine interfaces indicated in Fig. 2.3-6 are for control/monitor functions. The RCC will provide these interfaces for those areas other than ACC associated functions. The ACC's will provide the interface for Transition and Arrival, Approach, Landing, and Ground Control. Note that although the Transition and Arrival processing is accomplished at the RCC, the control/monitor function can easily be made a local function due to the satellite's communication versatility.

2.3.1.4.2 Some User Controls Easily Automated

A majority of the highly repetitive user control/response sequences lend themselves to automation. Those control/response sequences that are derived from surveillance position and velocity data fall within this class. This occurs primarily because of the speed at which data are available and the accuracy of these data.

The general scheme of the position derived processing is depicted in Fig. 2.3-7. There are seven major functions that are primarily dependent on the position information in the aircraft data file and the aircraft status contained in the aircraft active status file. These major functions are done in parallel, rather than in series, to minimize system delay and to allow easy expansion to higher levels of air traffic density.

Within the major functions, parallel processing is also employed. The overall effect of this computer structure is similar to the branches of a tree. The outputs of the system are then recombined to form inputs to the communications system. This type of processing structure is required or unacceptable system delays may occur. As added benefits, both easy expansion to higher demand levels and simple equipment redundancy configurations result from this approach.

The master controller directs the dissemination of the aircraft data file to the various major functions based on the aircraft status as available from the active status file. Most of the routines are entered each time a new surveillance position is computed, but others are done with different periodicities.

The handoff/boundary control has three major functions: handoff of aircraft to the adjacent RCC, handoff of aircraft to ACC's, and selection of the proper region for application of the gains to be used for tracking. This routine has the capability to update or change the aircraft status stored in both the active status and data files.

The handoff/boundary control must contain three spatial geometries. One geometry describes the region in terms of primary responsibility, secondary responsibility (i.e., oceanic and contiguous land areas), and the buffer handoff zone. Another geometry segments the primary and secondary regions into filter boundary regions, while the third geometry is the jurisdiction of all airports in the system.

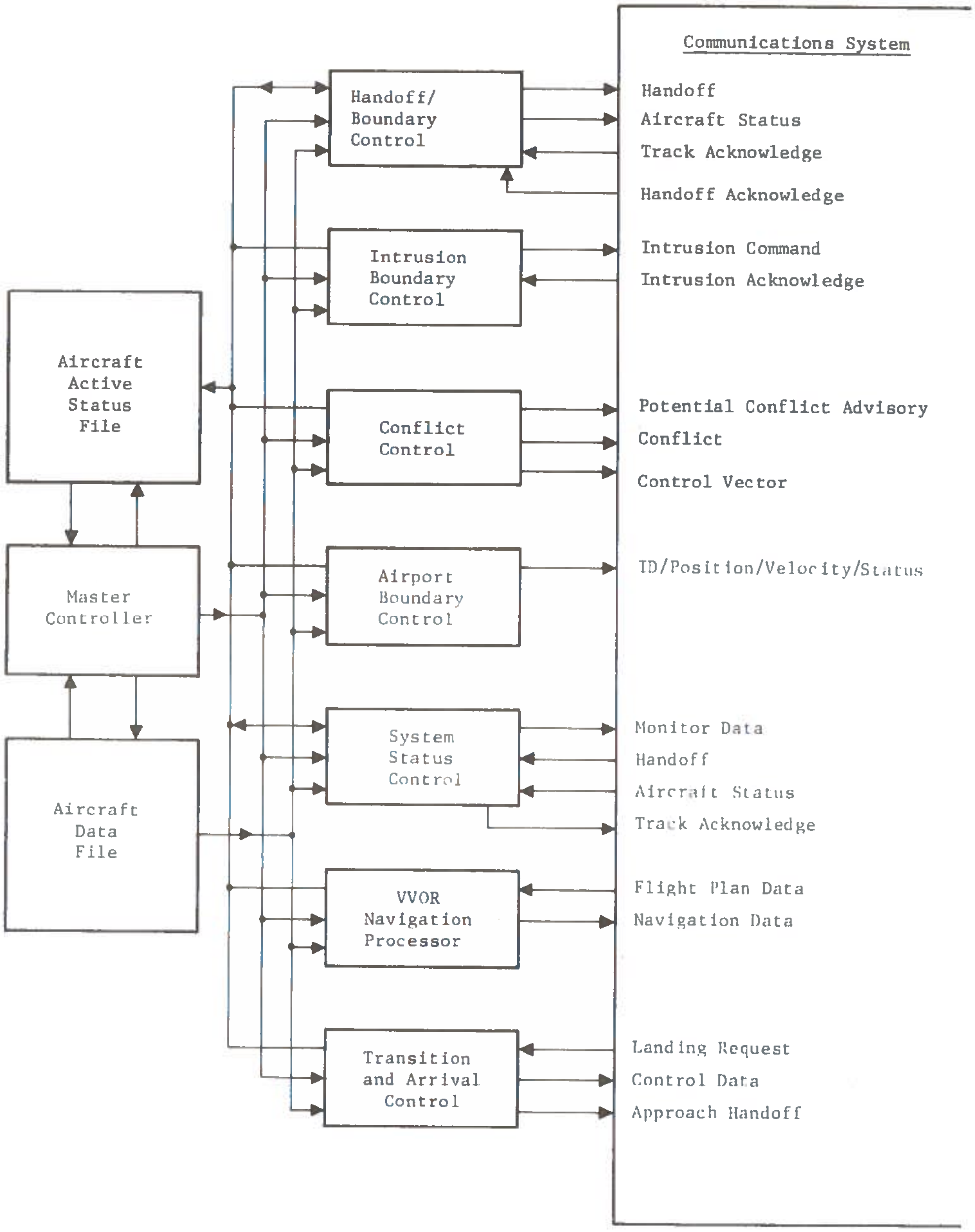


Figure 2.3-7. Position Derived Surveillance Processing

The primary and secondary responsibility areas differ in that conflict avoidance can only be assured in the primary airspace. The primary airspace is that region of CONUS composed of controlled, mixed, and cooperative airspace. Uncontrolled airspace and all airspace outside CONUS and its territorial water are secondary airspace. Traffic into and out of primary airspace will be advised of their transition. The active status file will be updated to reflect this transition so that the conflict control algorithm can determine if conflict control or advisories should be provided.

The region between the RCC jurisdictions contains a buffer zone through which both centers track the user. When an aircraft enters the buffer zone, the center tracking the aircraft communicates the contents of the active status file and the data file for that aircraft to the other RCC. Once the receiving RCC has initiated tracking, an acknowledgment of this is transmitted to the other RCC. During the boundary flight phase, both RCC's perform conflict intervention, but the primary control responsibility is vested in the originating RCC. When the aircraft exits the buffer zone, the receiving RCC will assume control. The user will be informed of the assumption of control only if he has been transitioned from one RCC to the other; otherwise, the original RCC retains control. No information to that effect will be transmitted to him. However, once an aircraft exits the RCC's control zone, the active status file and data file are cleared so that tracking is vested in the proper RCC.

The filter gain boundary regions are established to allow the correct Kalman filter gains to be selected. The aircraft data file contains the correct filter gain schedule which is changed as required based on the position of the user. When a new region is entered, the handoff/boundary controller revises the data file as appropriate. No user notification is required.

The geometry associated with the airports is required to effect handoff to the correct entity. When an aircraft enters an ACC jurisdiction, the handoff is accomplished to the ACC. If the airport does not have an ACC, separation responsibilities are assigned to the user. Acknowledgment of the handoff must be received prior to this event. Again, the files of the user are updated to reflect the user's status.

The intrusion boundary control is used to keep aircraft within allowable airspace regions. The primary goal of this routine is to protect positive controlled airspace. Cooperative aircraft are restricted from enroute airspace over 12,000 ft above MSL, from transition and arrival regions associated with primary aircarrier ACC's, and from primary aircarrier ACC jurisdictions. These zones are spatially described in the intrusion boundary control geometry.

The intrusion boundary control also protects all aircraft from entering restricted airspace. Again this implies a spatial geometry in the controller.

The intrusion boundary control issues intrusion commands to the user over the communications system. Acknowledgment of the command is required. Failure to acknowledge is flagged to a contingency controller for action due to the potential criticality of unintentional intrustion into the wrong airspace.

The major function of the conflict control is to increase system safety by maintaining safe separation between aircraft and by providing intervention commands in the event of imminent conflict. Not all aircraft are provided this function by the control. Aircraft located within airport boundaries and aircraft in transition and arrival airspace do not receive this service from this routine. Aircraft within ACC jurisdictions receive this service from the ACC. Aircraft at airports without ACC's operate on an advisory basis within the airport jurisdictional boundaries. Transition and arrival conflicts are prevented by providing intrusion boundary control and by the transition and arrival control routines.

Conflict advisories rather than conflict control are provided in certain airspace regions. This occurs since conflict intervention cannot be guaranteed. In oceanic and contiguous land regions and in uncontrolled airspace, separation assurance cannot be guaranteed due to the possibility of aircraft that are not equipped with surveillance transmitters and are therefore unknown to the system.

The conflict control routine is the same for detecting possible conflicts in either event. Potential conflict advisories are relayed to the users involved when user separation becomes smaller than a threshold value. When the separation positions and user velocities are such that a conflict will develop unless control is exercised, the system will compute control vectors to alleviate the conflict. These controls will be communicated to the users involved for immediate action.

The airport boundary control is used to provide ACC's with the system status on all active aircraft in their immediate vicinity. The ACC boundaries are not used for the geometry of this routine. Expanded boundaries are employed to allow for anticipated incoming aircraft and to allow for system monitoring and emergency operations.

The system status control function is designed to accept handoffs from the other RCC, to accept handoffs from ACC's, to remove users from the system, and to provide system status for monitor functions. The system status control interfaces with the handoff/boundary control of the other RCC.

The handoff from the ACC's to the RCC is more a monitor function than a control function because the RCC track jurisdiction includes the ACC so that the RCC can determine when the user exits the ACC boundary. Aircraft that exit the system at an ACC will inform the ACC of their intent for transmittal to the RCC. This will result in the update of the active status and data files.

The system status control will periodically test the times of the last surveillance reception for each user in the aircraft data file. If more than six successive updates have elapsed without receipt of a position update, the system status control will initiate a data test. If the last reported position were in an airport, the track file for the user will be updated to reflect the removal of that user from the system. If the aircraft is in a fringe area (oceanic or contiguous land region) or if the aircraft is not within an airport jurisdiction, the aircraft data will be flagged to a contingency center for disposition. The former case could arise because the user failed to report his intent to exit the system operating domain. The latter case always implies some level of emergency.

Aircraft that are exiting the system at the fringes of the SAATMS coverage must remove themselves from the system. Although a hard boundary on the system could be established, a slightly larger range of services can be established with a soft boundary; i.e., the users enter the system simply by activating their surveillance transmitter at the acquisition rate in the oceanic area and then flying into the system.

The VVOR navigation processor computes the navigation data for use by all aircraft requesting this service when the flight plans are filed. The flight plan data consist of the sequence of checkpoints the user specifies along his route. The flight plan data originate in the system flow associated processing. The navigation data are periodically transmitted to the user via the digital communications system link. Revisions to the flight plan must be accomplished via the flow control processing rather than directly to this routine.

The transition and arrival control routine provides the queueing, merging, spacing, and collison avoidance control in the transition and arrival airspace associated with primary aircarrier and secondary feeder airports. This airspace is protected by the intrusion boundary control and is limited to controlled aircraft. The airspace structure is contained in the spatial geometry of the control routine.

Transition and arrival airspace may differ during peak and low density demand situations but the basic structure must be pre-specified. All of the transition and arrival tubes, the merging points, and the approach tubes to the runways are specified in the geometry.

Controlled aircraft request a landing on their enroute arrival at the transition zone, specifying their final destination. Their request is acknowledged and control data are prvoided to the ACC boundary. When the aircraft enters the approach zone of the ACC, the user is handed off to the ACC for control purposes.

2.3.1.5 Flow Control on a National Level

The SAATMS flow control network is designed to provide the flow management and user planning interface on a national level for both controlled and cooperative users of the system. A basic tenet in the SAATMS design concept is required to be explained to fully appreciate the philosophy behind the flow control system.

The SAATMS design concept is that system safety is assured through surveillance accuracy and automated conflict intervention. Further, system capacity is primarily a function of the ability to handle high density traffic at airports on an instantaneous basis. Again this is achieved through surveillance and transition and arrival control. Flight plan conformance is the responsibility of the user, not the system. The intent of the flow control network is to provide the user with the information required for flight planning, the expected demand levels to be encountered, and the extent of possible delays.

The flight plan is a contract between the user and the system. The system cannot and will not penalize the user for abuses to this contract on a real time basis. After-the-fact penalties may be extracted. Flight planning is an attempt to minimize conflicts between users, but all potential conflicts are actively prevented by the conflict intervention function. Capacity is maintained by serving all arriving aircraft on a first come, first serve basis at any airport the user is authorized to use. If there are more users scheduled than can be accommodated, the system can warn the user of expected delays, but it cannot exclude or discriminate between instantaneous authorized users.

The user is provided with the maximum amount of data during the flight planning phase. A system is provided that yields the navigation data necessary for the user to make good his plan. The user is then obligated to conform to the plan and most generally will. If a deviation is required, the means to modify the flight plan are available. It is incumbent on the user either to conform to or to modify his plan. Both unscheduled conflict resolutions and missed terminal reservations may be used to penalize non-conforming users on an after-the-fact basis.

The flow control network is a strategic method of assuring safety and capacity. The conflict intervention and transition and arrival controls are tactical methods of assuring safety and capacity but the strategic planning for transition and arrival are made available for ACC usage.

The flow control network is segmented into a number of individual tasks at both the CCC and the RCC's as indicated in Fig. 2.3-8. The interconnection of the three major sites and the other remote sites is accomplished using the satellite based communications system. The remote sites include the ACC's, the National Weather Service, the administrative section of the Federal Aviation Administration, and Flight Service Stations (FSS).

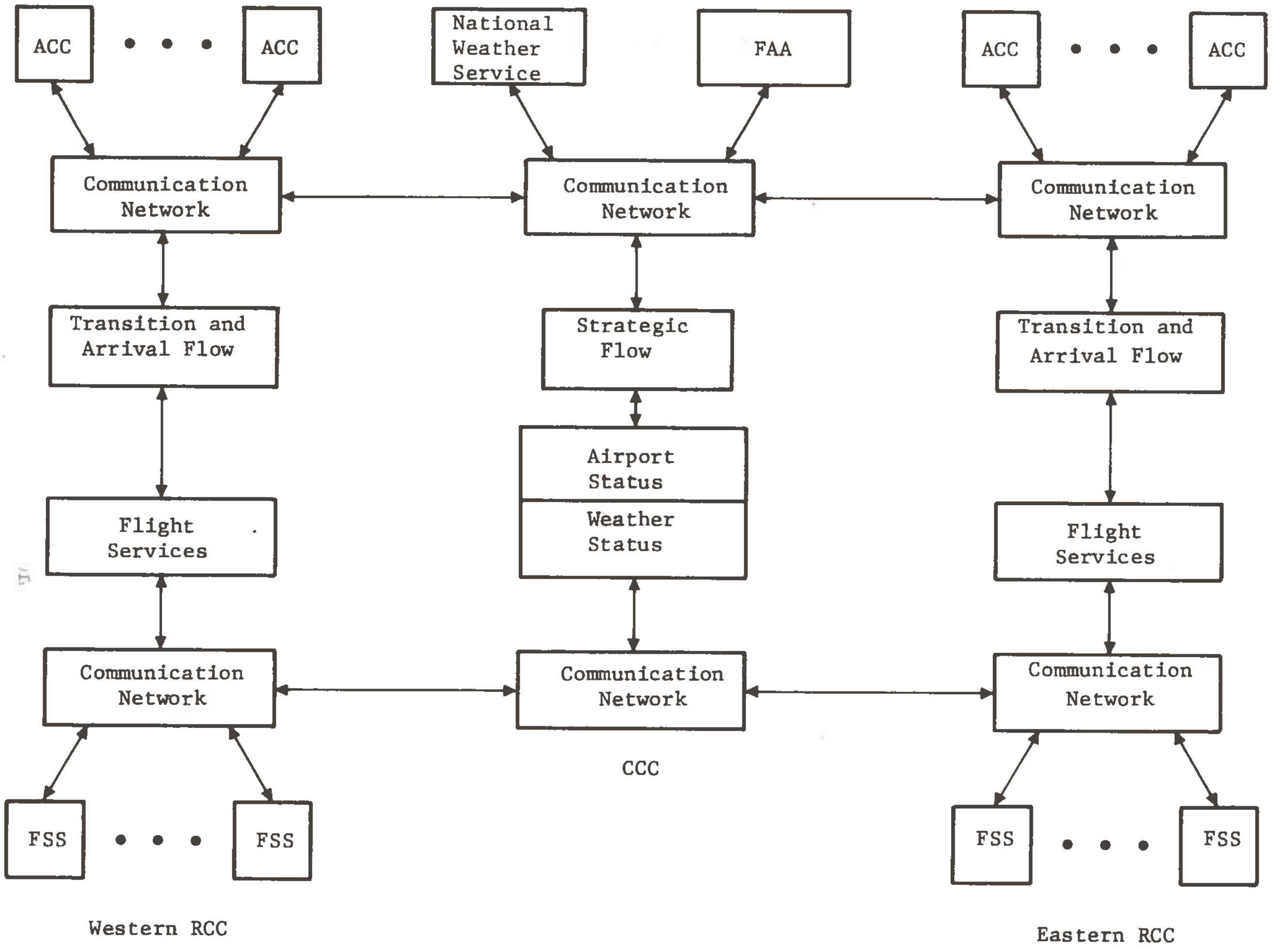


Figure 2.3-8. National Flow Control Network

The FSS's serve as the major user interface with the system for flight planning and approvals. Flight plan updates during flights are accomplished via the user-to-ground communication links at the RCC's. Weather and airport status are available at the FSS as well as the system status. Flight plans filed at the FSS are used to update the transition and arrival flow and strategic (enroute) flow plans. Conflicts in the strategic flow are resolved and the original or alternate plans are approved. The transition and arrival plans are updated and expected delays are transmitted to the user.

Flight Service Stations will include both ACC collocated facilities as well as remote sites. The remote stations will be telephone sites connected to the ACC sites via satellite links.

The weather data system will probably require a detailed restructuring to allow its operation within the automated flow control system. More sophisticated data gathering and formatting will be required. Ideally, weather data should be available to the user as either regional reports or for specific flight plan requests as well as for specific airports. These data should be available at several future forecast times.

The airport status is reported from the ACC's. All requests for departures and arrivals within the flight plan will result in the complete status of the selected airports being provided to the users. These data will include the instantaneous status of airport runways and equipments and the availability of services provided.

The flight service will provide the conflict resolution and airport demand level projection for cooperative users. The national flow provides these services for controlled users. Controlled users will receive scheduled demand and delay status rather than the simpler projected demand data based on statistical data. Those controlled and cooperative flight plans with VVOR navigation requests will result in data storage for user control during flight.

The transition and arrival flow will contain the scheduled flow of controlled users into an ACC. This routine will also predict delays due to excess demand. The transition and arrival status into all ACC's for both controlled and cooperative users will be supplied to the ACC's. In the event of unexpected situations that could lead to the inability of the ACC to provide for the scheduled demand, the ACC's will initiate notices to all affected users.

The flow control network, through the CCC and RCC, thus provides for flow control and user information on a national basis. Both controlled and cooperative users are provided with a central facility for flight planning activities.

2.3.1.6 Optional ACC Structure Envisioned

Because of the many site specific requirements intrinsic in existing airport designs, a very flexible approach to the ACC structure must be adopted. It is envisioned that there will be many optional choices involved in the equipments and automation of the ACC's. Some of the more basic, generic ACC design elements will be discussed, but specific requirements can only be nominally detailed.

A general structure of an ACC is depicted in Fig. 2.3-9. The basic elements include landing navigation and ground surveillance and navigation. As has been previously stated, the amount and types of ACC processing and the level of man/machine interface is uncertain. This will be resolved through present and future automation studies.

The landing navigation system for ACC's will be Microwave Landing Systems (MLS), Instrument Landing Systems (ILS), or some modification of these types of systems. The coverage of the landing system need not be extreme due to the accuracy of satellite based navigation and surveillance. A 6- to 10-deg azimuth beam with coverage to 10 miles is adequate for ACC purposes. A 6- and 3-deg glideslope is highly desirable for noise abatement but is not required for operational safety. Primary aircarrier airports should have the MLS system with ILS (VVOR) capability at secondary and feeder airports as a minimum. Since these systems are independent of the integrated SAATMS avionics, this will have minor system impact.

Ground surveillance methods of many types have been proposed. Methods such as multilateration, infrared systems, beacons, cables, radar, and loop detectors have been proposed. Any of these systems could be used depending on the level of cost, accuracy, and automation desired. From an accuracy and automation standpoint, the multilateration method should be implemented at primary aircarrier airports. Secondary and feeder airports will use a less expensive infrared system.

The system's communication allows for the dissemination of surveillance data to the ACC's. The amount and type of display and processing are again both flexible and optional. The integration of the ACC's into the system requires a modicum of ACC to RCC intercommunications. This may be manually or automatically accomplished at the ACC. The preferred method is obviously the automation controlled method. In any event, the level of ACC processing will allow many options in the design and operation of ACC's.

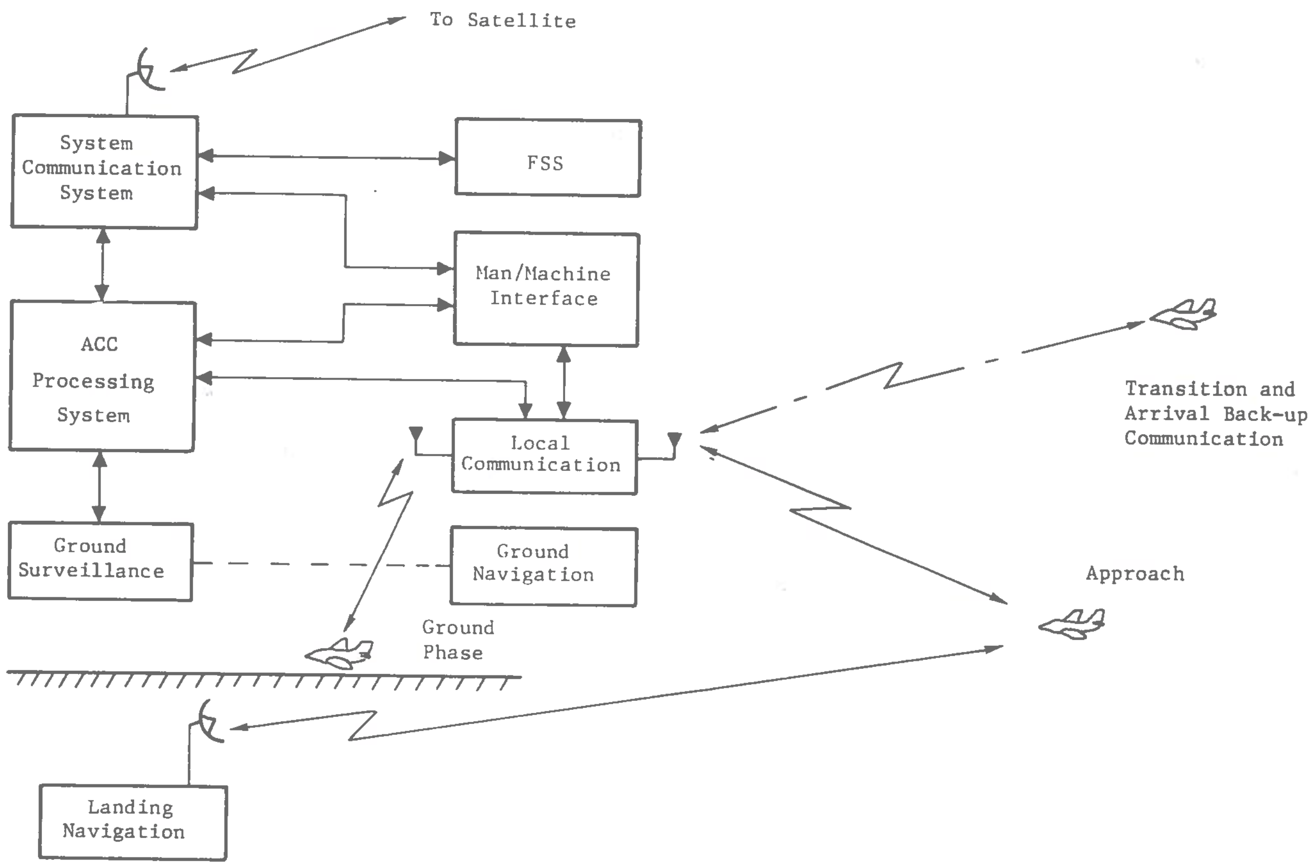


Figure 2.3-9. Generic ACC Architecture

2.3.2 Mostly Digital Communications

Most of the information flow between system elements is via digital data link. In the case of air-to-ground, ground-to-air, and air-to-air communications, a voice link is provided for two purposes, to provide a random (non-canned) message capability and to back up the digital links. The following paragraphs describe the information flow between various system elements. The description includes a listing of message types, the content of each message, and an estimate of how often each message is sent.

2.3.2.1 All Digital Ground-to-Ground Communications

The communications interconnect between ground elements is shown in Table 2.3-2. The ground-to-ground message, message content, and frequency are shown in Table 2.3-3. The message frequency is based upon an assumed peak loading for demand level II and the results of a message analysis study. The assumed peak IAC is 40,000 aircraft consisting of 15,000 controlled; 4,500 aircarriers, 2,000 military, and 8,500 GA (25 percent of the GA IAC); and 25,000 cooperative GA.

The CCC performs several basic functions:

(1) It acts as a central planning center receiving and disseminating flight plan and flow plan data to the flight service stations and RCC's.

(2) It relays weather information between the aircraft and the National Weather Service (NWS).

(3) It acts as a control and monitoring center and backs up the RCC.

In addition to backing up the RCC's, the CCC sends the master clock synchronization signal to the satellite tracking centers and RCC's and satellite ephemeris data to the RCC's. These data are all transmitted via satellite.

Table 2.3-2. Ground-to-Ground Communications Interconnect

From \ To	CCC	RCC	ACC	FSS	NWS	STC
CCC		X	X	X	X	X
RCC	X	X	X			
ACC	X	X		X		
FSS	X	X	X			
NWS	X	X				
STC	X					

Table 2.3-3. Ground-to-Ground Communications

From	To	Message	Content	Frequency	Basis
CCC	RCC	Aircraft flow schedules	Aircraft type ETA Airport ID	1/hr	Procedure
		Master clock update	Time synchronization signal		
		Satellite position	Ephemeris data	1/hr	Procedure
		Weather	Weather information	4/hr	Procedure
	ACC	Surveillance Data	Aircraft ID, position, and altitude for all aircraft within a 20 nmi radius of ACC	Every 8 sec/ aircraft	Surveillance update rate
		Handoff (prime mode)	Aircraft ID Acknowledge tracking initiated	180/hr/ACC	Peak arrivals/hr
		Handoff if no acknowledgement	Request voice contact with aircraft for purpose of handoff	0.5/day/ACC	Assumption
	FSS	Pilot briefing information	Weather Traffic at checkpoints and destination NOTAMS Projected delays	1000/hr peak	Assumes 2 controlled GA/ACC/hr (excludes 100 primary and half of secondary airports)
		Flight plan alternatives	Route Altitude ETA and EDT	1000/hr	
		Flight plan approval	Confirmed flight plan including projected weather, traffic, and delays	1000/hr	

Table 2.3-3. (continued)

From	To	Message	Content	Frequency	Basis
RCC	NWS	Pilot reports	Weather Altitude Location Source (aircraft and pilot ID)	700/hr	10 percent of air-carrier and military IAC plus 0.5 percent of controlled GA
	STC	Master clock update	Time synchronization signal		
	CCC	Traffic flow at TCA transition zone	Airport ID Number of aircraft in transition and arrival phases	1/hr	Procedure
		Flight plan revisions	Aircraft ID Course change Altitude change ETA change	375/hr	5 percent of controlled aircraft/RCC
		RCC status	Processing capacity Equipment status	1/day and when changes occur	Procedures
		Update track file due to handoff	Aircraft ID Time of handoff Receiving jurisdiction ID	35,000/hr peak	50 operations/hr/ACC (average of 700 ACC's)
	RCC	Handoff (prime mode)	Aircraft ID Aircraft active status file Aircraft data file Acknowledge tracking initiated	400/hr	1 percent of peak IAC
		Handoff if no acknowledgement	Request voice contact with aircraft for purpose of handoff	1/day	Assumption

Table 2.3-3. (continued)

From	To	Message	Content	Frequency	Basis
RCC	ACC	Surveillance data	Aircraft ID, position, and altitude for all aircraft within a 20 nmi radius of ACC	Every 8 sec/ aircraft	Surveillance update rate
		Handoff (prime mode)	Aircraft ID Acknowledge tracking initiated	180/hr/ACC	Peak arrivals/hr
		Handoff if no acknowledgement received from aircraft	Request voice contact with aircraft for purpose of handoff	0.5/day/ACC	Assumption
ACC	CCC	Airport status	Runway condition	4/day/ACC	Procedure
	RCC		Equipment status Weather		
	RCC	Active runways	Active runway numbers Runway reversals	2/day/ACC (average)	Assumption
ACC	RCC	Handoff (prime mode)	Aircraft ID	180/hr/ACC	Peak arrivals/hr
		Handoff if no acknowledgement received from aircraft	Request voice contact with aircraft for purpose of handoff	0.5/day/ACC	Assumption
	FSS	Pilot briefing	Active runway Departure routes Taxi routes Altimeter setting Wind	100/hr	Assumed average controlled plus cooperative requests at feeder airports
FSS	CCC RCC	Pilot briefing request	Information type Location	1000/hr peak	Same as CCC to FSS

Table 2.3-3. (continued)

From	To	Message	Content	Frequency	Basis
FSS	RCC	Flight plan request	Aircraft ID Pilot ID Number of passengers Route Altitude Estimated departure time ETA Fuel on board (hours, minutes, reserve) Alternate airports	1000/hr peak	
		File flight plan	Discrete	1000/hr	
	ACC	Pilot briefing request	Discrete	100/hr	
		Departure plan request	Estimated departure time Preferred route	100/hr	
		File departure plan	Discrete	100/hr	
NWS	CCC RCC	Weather data	Weather information	4/hr	Procedure
STC	CCC	L-band navigation pulse	Processed TOA data	12/hr	Procedure

The RCC communicates via satellite with the other RCC, the CCC, and the ACC's in its jurisdiction. The RCC sends flight plan revisions and traffic flow data to the CCC so that it may keep the flow plan up to date. It sends surveillance data to all ACC's in its jurisdiction. All other ground-to-ground communications are concerned with the handoff function.

The ACC sends status and runway information via satellite to the RCC and CCC. It is also connected to the collocated flight service station via land line.

The STC receives navigation pulses from the satellite. It processes these pulses and sends them via the satellite to the CCC where satellite position is calculated.

2.3.2.2 Ground-to-Air Communications

Messages sent from the ground to the aircraft are presented in Table 2.3-4. All messages can be either digital or voice except where noted. The form of the message may be different depending upon whether it is voice or digital. For example, a digital boundary intrusion command may consist of a discrete boundary intrusion light and a steering command. The voice message might be, "Turn right 10 degrees."

Ground-to-air communications from the RCC are via satellite while communications from the ACC are via a direct line-of-sight link. Weather reports from the NWS are in the form of a radio broadcast over a voice channel using the satellite link. It is assumed that the broadcast would last 5 min and be repeated every 15 min.

Frequency data for messages from the RCC are on a CONUS-wide basis. They show the peak load on the communications links for both RCC's. In the case of VVOR data, it is assumed that at demand level II, peak demand for VVOR services would be 30,000 aircraft. The data would be transmitted to each aircraft an average of once every 30 sec. The frequency data for messages from the ACC are on a per ACC basis.

2.3.2.3 Air-to-Ground Communications

The air-to-ground messages are shown in Table 2.3-5. In addition to the message content shown, all messages include aircraft ID. Communications with the RCC are via satellite, while communications with the ACC are via a local line-of-sight link. Most messages are sent via voice with a limited number of canned digital messages available.

Table 2.3-4. Ground-to-Air Communications

From	Message	Content	Frequency*	Basis
RCC	Boundary intrusion Conflict avoidance Vectors	Altitude change Turn left/turn right Velocity change	400/hr	1 percent IAC/hr
	Traffic advisories	Aircraft type Location X, Y, Z Direction of flight	2000/hr	5 times conflict rate; Includes aircraft at airports and in oceanic regions
	Flow advisories - voice only	Estimated delay Alternates available	700/hr	Assumes 1/ACC/hr average
	Clearances - digital only	Surveillance acquisition	100/sec	Sizing estimate
		Enter TCA	9000/hr	180/hr/prime ACC for half of all such ACC's
		Flight plan modification	300/hr	2 percent of peak controlled IAC
		Hold	100/hr	1 percent/prime ACC/hr
		Proceed	400/hr	1 percent of peak IAC/hr
	Surveillance derived position	Latitude Longitude Altitude	400/hr	1 percent of peak IAC/hr
	VVOR - digital only	Range to destination Bearing Course deviation	1000/sec	30,000 aircraft at 30 sec/update
	Metering and spacing	Route ID Waypoint location Time at each waypoint Course deviation Vertical steering Speed change Path stretch vector	180/hr/TCA	Peak arrivals/hr

*Total of 2 RCC's or per ACC as applicable

Table 2.3-4. (continued)

From	Message	Content	Frequency*	Basis
RCC	Handoff	Digital communication frequency change Voice communication frequency change Acquisition advisory Contact receiving jurisdiction command-voice	35,000/hr	50 operations/hr/ACC
	Surveillance rate change-Digital only	Discrete	100/sec	Sizing estimate
ACC	Clearances	Takeoff Landing Taxi	720/hr	2/operation with 360 operations/hr assumed
	Surface guidance	Course deviation - digital only	1 every 8 sec/ aircraft	Navigation update rate
		Proceed/hold	720/hr	Same as Clearances
	Taxi route assignment	Route ID	360/hr	operations/hr
	Runway assignment	Runway ID	360/hr	operations/hr
	Pilot briefing - voice only	Altimeter setting Wind	100/hr	Pilots share single message
	Conflict intervention	Turn left/turn right Hold	5/hr	1 percent of aircraft inside ACC boundary
	Traffic advisories - voice only	Aircraft type Location Direction of movement	100/hr	Pilots share single message
	Handoff (arriving aircraft)	Acquisition advisory	180/hr	

*Total of 2 RCC's or per ACC as applicable

Table 2.3-4. (continued)

From	Message	Content	Frequency*	Basis
ACC	Handoff (departing aircraft)	Digital communication frequency change Voice communication frequency change Contact receiving jurisdiction-voice only	180/hr	
	Flow advisories	Estimated delay Alternates available	10/hr	Assumption
	Waveoff	Waveoff discrete Return to field {Voice only Alternate destination	5/hr	Assumption
	Traffic pattern assignment-voice only	Clearance into pattern Follow aircraft XX Report on downwind	200/hr	Peak arrivals/hr at feeder airport operating 3 runways
	Departure route change	New departure route	1/hr	Assumption
NWS	Weather briefing - voice only	Weather report	4/hr	Procedure

*Total of 2 RCC's or per ACC as applicable

Table 2.3-5. Air-to-Ground Communications

To	Message	Content	Frequency	Basis
RCC and CCC	Flight plan modification - voice only	Route change	750/hr	5 percent of controlled aircraft
		Altitude change		
	Request clearance to enter TCA - Digital only	Discrete	9000/hr	180 arrivals/hr for 50 prime ACC's
	Request clearance to enter controlled airspace - voice only	Intent	25/hr	0.1 percent of peak cooperative IAC
	VVOR destination - digital only	Grid coordinates - latitude/longitude	50/sec	30,000 users update position every 10 min
	Navigation data	Position Altitude	4/min	
	Acknowledge	Discrete	17,500/hr	Based on handoff per hr
	Pilot weather reports - voice only	Weather Altitude Location	700/hr	Assumption
	Aircraft status	Fuel Equipment/avionics	700/hr	Assumption
	Request for advisories - voice only	Traffic Weather Delays	100/hr	Assumption
	Emergency	May Day Lost Assistance needed	20/day	Assumption

Table 2.3-5. (continued)

To	Message	Content	Frequency	Basis
ACC	Request to enter control zone - voice only	Location Altitude Request discrete	200/hr	Peak arrivals/hr at feeder airports with 3 runways
	Clearance request	Taxi Takeoff Landing	720/hr	2/operations with 360 operations/hr assumed
	Acknowledge	Discrete	400/hr	.Peak operations/hr plus other messages
	Request for advisories - voice only	Traffic Wind Altimeter setting	100/hr	Assumption
	Aircraft status	Fuel Equipment/avionics	5/hr	Assumption
	Emergency - voice only	Gear Fuel Engine Other aircraft emergency messages	1/hr	Assumption

2.3.2.4 Air-to Air-Communications Available for Pilot Confidence

SAATMS has built in a capability for transmitting aircraft-to-aircraft navigation data. These data can be used to show the pilot where other nearby aircraft are located. The data are independent of the ground system and, as such, can give the pilot a means for verifying that the ground based conflict intervention function is operating correctly.

To take advantage of this capability, the user will have to upgrade his avionics to enable him to both transmit and receive the navigation messages. In addition, he will have to add a situation display to present the navigation data. An additional capability that would also be added is collision avoidance. This involves adding a processor to determine, through the use of navigation data, if conflicts exists.

The data to be transmitted consist of the aircraft ID, latitude, longitude, altitude, speed, heading, and intent. The total message would be on the order of 100 bits. The data would be sent in digital format over a voice channel using a low power line-of-sight (non-satellite) link. Because of the cost of upgrading avionics to obtain this capability, it is assumed that only sophisticated, controlled aircraft will be so equipped.

2.4 Satellite Constellation and Tracking Subsystem

The SAATMS satellite constellation and tracking subsystem provides the structure and accuracy potential for the communications, surveillance, and navigation subsystem functions. The satellite constellation and tracking subsystem has been subjected to analysis and found to provide sufficient accuracy potential to support the SAATMS design goals. Although a complete design optimization has not been accomplished, the system design has been shown to be a viable concept.

In the following paragraphs, a detailed description of the satellite constellation design is presented. Then the tracking subsystem is described, followed by a summary of the analysis results for both areas. The detailed analysis results and the methods used to obtain these results are presented in Volume IX of this report.

The rationale for the use of satellites transcends the usual coverage and accuracy arguments. The basic reasons for the use of satellites are (1) their versatility in providing AATMS functions and (2) the low cost of the functions relative to alternate systems. Simple economics and the multifunctional potential of the satellite constellation are compelling arguments. The constellation and tracking functions, detailed herein, constitute one of many possible configurations. The intent is prime; the proposed configuration is argumentative.

2.4.1 Redundant Satellite Constellation Employed

A satellite constellation has been defined for SAATMS that insures complete CONUS coverage under extremes of operational conditions through the use of redundancy. This redundancy takes the form of providing more satellites in the constellation than would normally be required. As a result, under normal operational conditions, the system can provide extensive coverage beyond CONUS and can accommodate a fair degree of user degradation with only minor coverage effects. Further, the system has at least the anti-jam potential of the existing air traffic control system.

2.4.1.1 General Coverage Problem Elucidated

The general coverage problem results from the desire to provide navigation and surveillance capability through the satellite constellation. The accuracy potential of these functions is related to the constellation selected as well as the type of satellite employed. Either navigation or surveillance requires that a minimum of four satellites be used to achieve a three-dimensional position fix at any given time. Where fewer than four satellites are usable, no coverage is provided. If more than four satellites are visible, the potential accuracy of the system is improved.

The SAATMS design is based on the goal of providing surveillance and navigation within CONUS and the contiguous regions. Because global utilization of the system is not required, the general class of satellites considered can be restricted to geosynchronous satellites. These satellites do not exhibit large extremes in longitude motion relative to an earth fixed point and therefore can be utilized for longer periods of time than non-geosynchronous satellites.

Geosynchronous satellites are characterized by an orbit period of exactly one sidereal day. A sidereal day differs from a solar day of 24 hr by approximately 3 min 56 sec as depicted in Fig. 2.4-1. Here it should be noted that, because the earth is in orbit about the sun, the earth revolves 360 deg in the period t_1 to t_2 but that a solar day occurs in the period t_1 to t_3 when the sun has the same angle relative to an earth fixed point. Geosynchronous satellites are thus characterized by returning to the same point over the earth once each sidereal day.

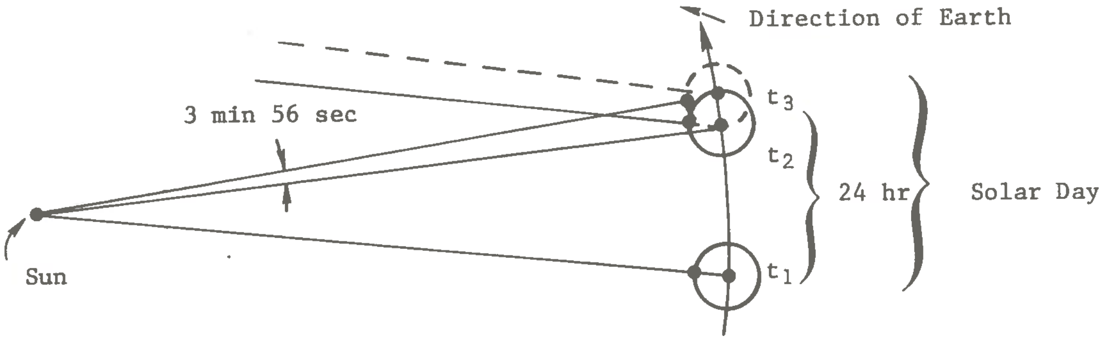


Fig. 2.4-1. Solar Day and Sidereal Day

The three parameters associated with the geosynchronous satellites that characterize their temporal behavior with respect to the earth is their orbit eccentricity, their argument of perigee, and their inclination with respect to the equator. The effect of these parameters may be seen by the trace of the subsatellite point on the earth's surface, i.e., the trace of the line between the center of the earth and the satellite where it cuts the earth's surface. Figure 2.4-2 shows the trace of the subsatellite points for three different eccentricities (e) where the perigee or time of closest approach to the earth is at some given extremum of longitude, i.e., the argument of perigee is 270 deg.

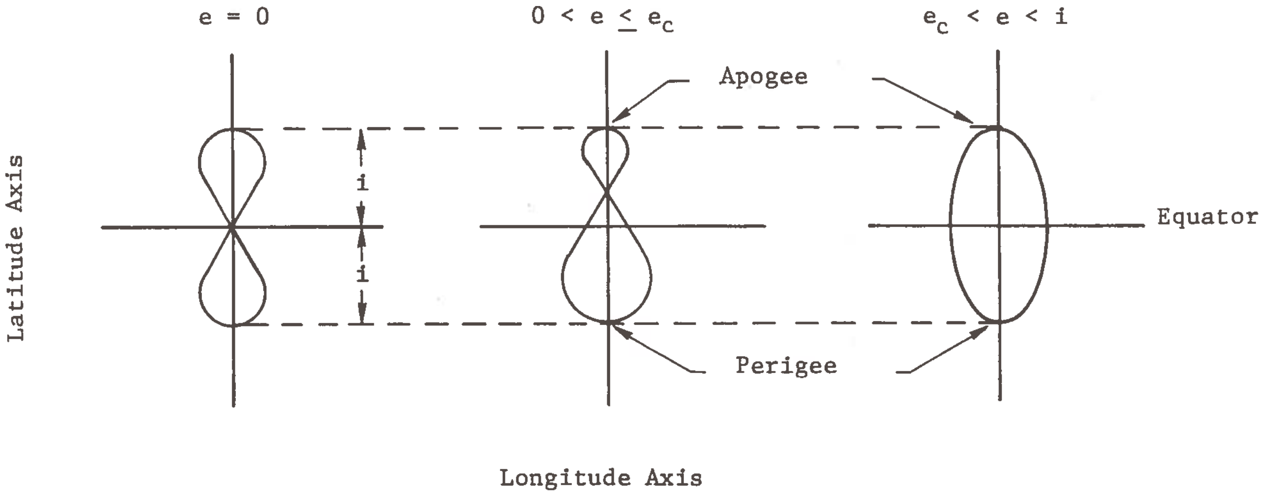


Fig. 2.4-2. Subsatellite Ground Traces

It should be apparent from the figure that the longitude excursions of these cases are limited. Further, it should be noted that for $e > 0$, the time the subsatellite points are in the northern hemisphere exceeds that in the southern hemisphere. Both of these factors tend to make the time of satellite usefulness to CONUS coverage greater than for non-geosynchronous satellites. As the inclination angle decreases toward zero, the subsatellite points become primarily equatorially directed. For $e = 0$ and $i = 0$, the motion ceases and the satellite appears to be in a fixed location relative to the earth, i.e., become geostationary.

As can be shown, the use of only equatorial geosynchronous satellites is not feasible. Although these satellites are always useful, the accuracy potential of this type of constellation is extremely poor. A combination of geosynchronous satellite types is required.

The accuracy potential of the surveillance and navigation functions of a satellite constellation is generally measured using the Geometric Dilution of Precision (GDOP) measure. The GDOP measure relates the rms uncertainty in the user's location (σ_u) to the rms uncertainty in the satellite's location (σ_s) or

$$\sigma_u = \text{GDOP} \cdot \sigma_s$$

All entities are some given, fixed location. The GDOP measure assumes that all σ_s values for all satellites are composed of uncorrelated, zero mean phenomena with equal variance in three-dimensional Euclidian space. It is further assumed that a single set of observations is used to compute the user's position.

There are several unrealistic assumptions implicit in using the GDOP criteria for computing navigation and surveillance accuracies. They do not, however, restrict its usefulness in comparing different satellite constellations or the same constellation under various conditions. The GDOP measure was used for analytic purposes in all constellation studies performed. See Ref. 1 for additional details on the GDOP measure. (The references for this volume are presented in Section 2.4.3.)

All analyses performed on satellite constellations were accomplished using digital programs to compute GDOP topographic maps. These maps exhibit temporal changes as the satellites shift location with time.

The essential coverage problem reduces to the selection of a particular satellite constellation which will provide acceptable area coverage in terms of the GDOP criteria. This implies that some criteria be established to indicate which satellites are usable at any given time.

Previous satellite constellation studies have generally relied on visibility criteria based solely on the satellite's angle above the user's horizon. While this usually bounds both the multipath and atmospheric delay phenomena, visibility is not based on angles alone unless isotropic satellite and user antenna patterns and constant satellite-to-user ranges are assumed. The visiblity properties must be based solely on the net available signal energy and the background noise energy.

The GDOP maps generated for this study include a visibility criterion based on the energy received at the satellite for a given surveillance system RF configuration. This criterion is much more restrictive than the usual angle criteria and, furthermore, penalizes high eccentricity (long range) satellite configurations. Due to the reciprocity of the RF links, a single visibility criterion is applicable to both the surveillance and navigation problems.

The GDOP measure used is based on the inclusion of all visible satellites rather than the more usual four best visible satellites. This is justified simply on the basis that all of these data are incorporated in both surveillance and navigation. For surveillance, this is a significant departure from previous practice. This results from the unique method of employing Kalman filter gain boundaries to achieve the processing simplification required to make filtering practicable.

A minor approximation to the constellation results should be noted. This approximation stems from the inclusion of all visible satellites in the GDOP results even though there is only a finite probability of viewing all these satellites in a single snapshot of the constellation. Assume for the moment that there is a 0.998 probability of viewing each of the 15 satellites in the constellation (an impossible feat but worst case). Then the probability of achieving the stated results would be

$$P_r = (0.998)^{15} \simeq 97\%$$

To be precise, the effect of the loss of each satellite and group of satellites should be computed. The GDOP map should then be reconstructed using the probability weighted averages of these cases.

Outside of the computational complexity, there are two compelling reasons not to bother with this degree of sophistication. Note that the constellation is never completely visible from any given location, thereby increasing the odds to nearer 99 percent. Further, since the surveillance and navigation mechanizations are filter routines, the effect of a single or multiple satellite loss is far greater in terms of GDOP than in terms of system accuracy. As a point of fact, the GDOP results will indicate an infinite error if fewer than four satellites are visible, while the filter would only cause a slightly increased error in the same situation if it were bounded in duration.

With these basic arguments in hand, the rationale for the constellation selection and the potential for the satellite system should be more easily understood.

2.4.1.2 Constellation Design and Performance

The satellite constellation selected for the SAATMS design consists of six geostationary and nine inclined geosynchronous satellites. Table 2.4-1 lists the parameters of the satellite orbits and Fig. 2.4-3 shows the subsatellite points for the constellation at the initial time.

There are two different types of satellites employed in this constellation. The inclined orbit satellites are designed to point their antennas at their subsatellite points. The geostationary satellites point their antennas into the northern hemisphere at the 35N longitude points on their longitudinal line. The required satellite attitude sensing system for subsatellite pointing is less complex, lighter, and less expensive than for fixed site pointing.

The preliminary analysis results of Ref. 2 establish the applicability and desirability of the north pointing geostationary satellites and indicate that substantially increased coverage and more uniform GDOP results from this technique. Since the geostationary satellites must possess three-axis attitude sensing and stabilization, they naturally lend themselves to use in the ground-to-ground communication system.

The satellite system proposed differs somewhat from the hybrid system design of Ref. 3. The SAATMS constellation satellites are all of the same basic design although they differ in the amount of communications equipment carried. The hybrid system oceanic satellites were of different design. The SAATMS concept allows the same system and user avionics to be employed for both CONUS and oceanic flight domains. This is a less expensive and less complex alternative than previously envisioned.

The performance potential of the constellation is given in terms of a GDOP map. The lines of constant GDOP are plotted as a function of latitude and longitude over the area indicated in Fig. 2.4-3. These maps were generated on the basis of the nominal parameters of Table 2.4-2.

Table 2.4-1. Geosynchronous Satellite Constellation Parameters

Satellite Number	Inclination (deg)	Eccentricity	Argument of Perigee	Time From Perigee (hr)	Longitude of Perigee
1	80	0.25	270	0	100W
2	80	0.25	270	2 1/3	100W
3	80	0.25	270	5 1/3	100W
4	80	0.25	270	8	100W
5	80	0.25	270	10 2/3	100W
6	80	0.25	270	13 1/3	100W
7	80	0.25	270	16	100W
8	80	0.25	270	18 2/3	100W
9	80	0.25	270	21 1/3	100W
10	0	0	-	-	180E
11	0	0	-	-	140W
12	0	0	-	-	115W
13	0	0	-	-	85W
14	0	0	-	-	60W
15	0	0	-	-	20W

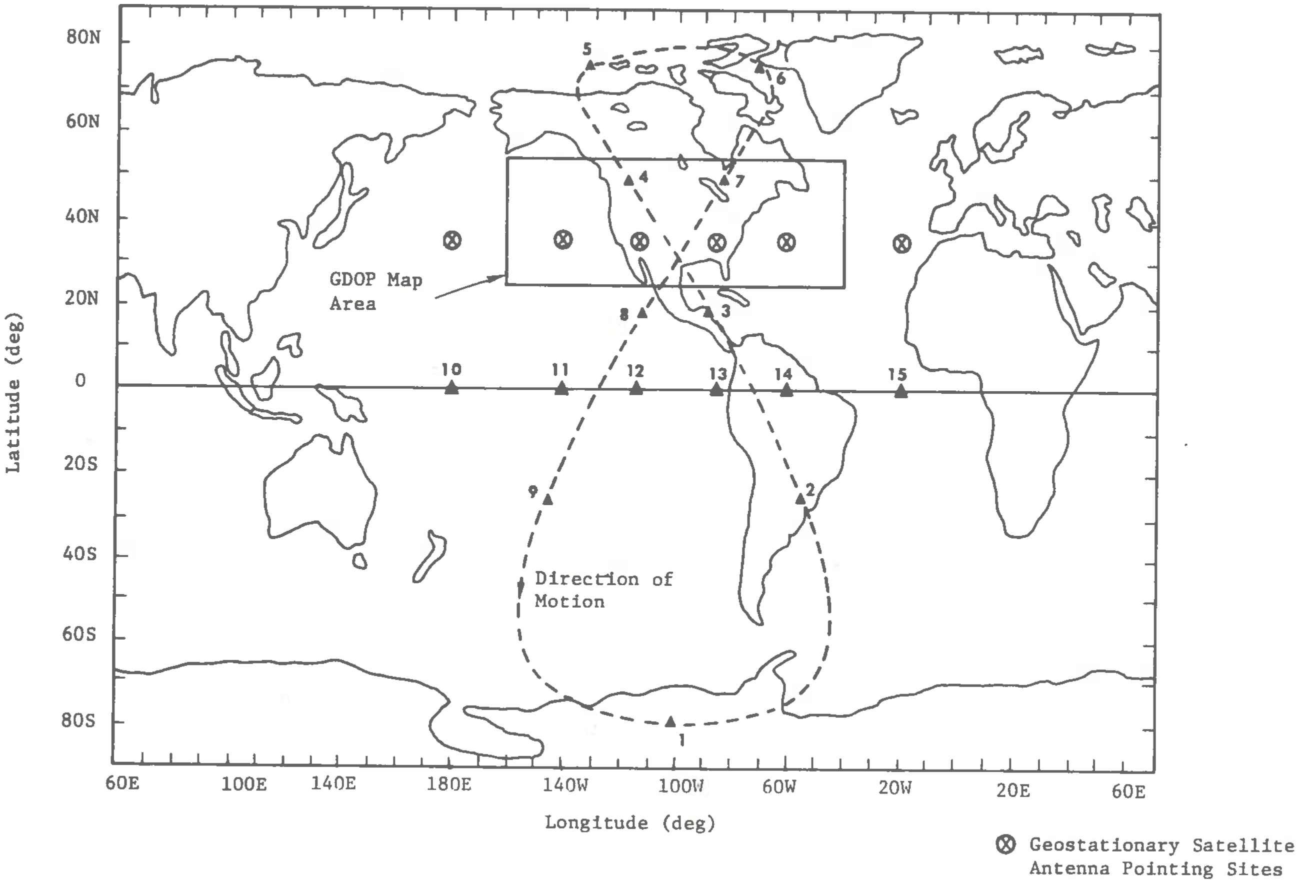


Figure 2.4-3. SAATMS Constellation Subsatellite Points

Table 2.4-2. Nominal RF Parameters

Parameter	Value
Transmitter Power	2 kw
Aircraft Antenna Beamwidth	150 deg/55% Efficiency
Satellite Antenna Beamwidth	10 deg/70% Efficiency
Single ID Code Pulsewidth	40 μsec
Frequency	1.6 GHz
Detection Loss	3.2 db
Miscellaneous Losses	2.0 db
Equivalent S/N Ratio at -178 dbj Level (per pulse)	13.3 db

There are a number of GDOP maps of interest with respect to the constellation. The nominal GDOP is a function of time due to the satellite's motion. The satellite constellation has a basic period of 160 min due to the inclined orbit satellite spacing. GDOP maps for the nominal constellation for each 20 min interval in a period are shown in Fig. 2.4-4.

Two important facts are to be noted from these maps:

(1) The GDOP is a very slowly changing spatial function over the entire CONUS region.

(2) GDOP changes very little as a function of time.

The value of GDOP varies from 3 to 5 over the entire map range for CONUS proper. The preceding factors tend to illustrate that both navigation and surveillance accuracies are only mildly influenced by geographic location or time.

The nominal GDOP maps assume that the users are in level flight. For surveillance purposes, a much more important situation occurs when the aircraft is executing a turn. In this situation, it is important to track the user when a bank angle is present. The effect of bank angles on GDOP was computed on a worst-case basis. The antenna pattern is tipped over by the amount of the bank angle and the centerline of the antenna is pointed in various azimuth relationships to the vertical. Ten-degree azimuth steps about the vertical are taken as shown in Fig. 2.4-5. GDOP is computed for each of the steps and the largest values for each sweep are used to generate the maps.

Thus, the resulting GDOP maps for the bank angle cases are worst-case results. Users on the edges of the satellite coverage clearly can always bank in some direction that will point their antennas away from the main cluster of satellites such that the GDOP will increase or go infinite. This is illustrated by Fig. 2.4-6. While CONUS located aircraft are only minimumly affected by the bank angle, aircraft in the outer oceanic region can be seriously affected.

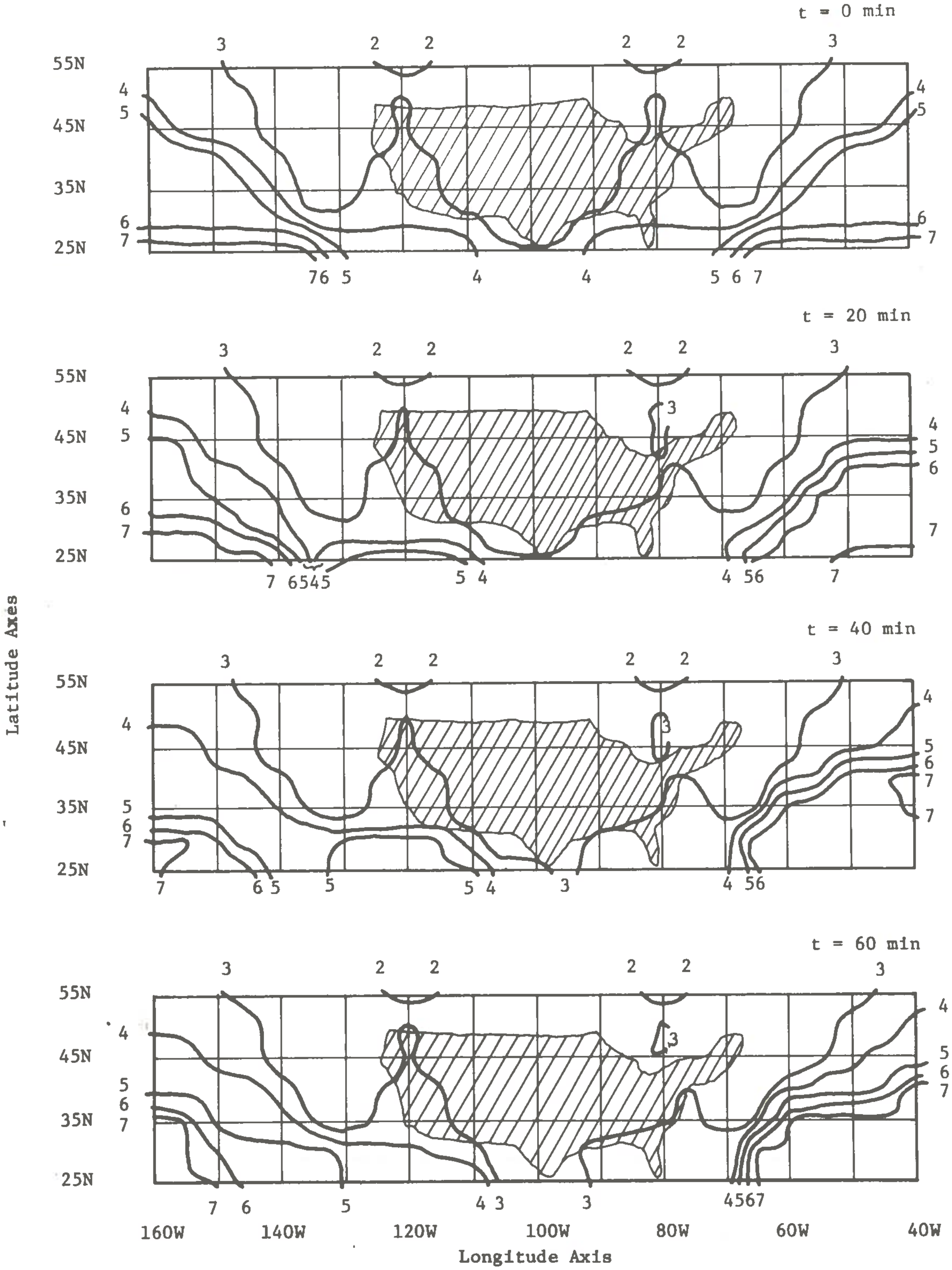


Figure 2.4-4. Nominal Conditions GDOP Results

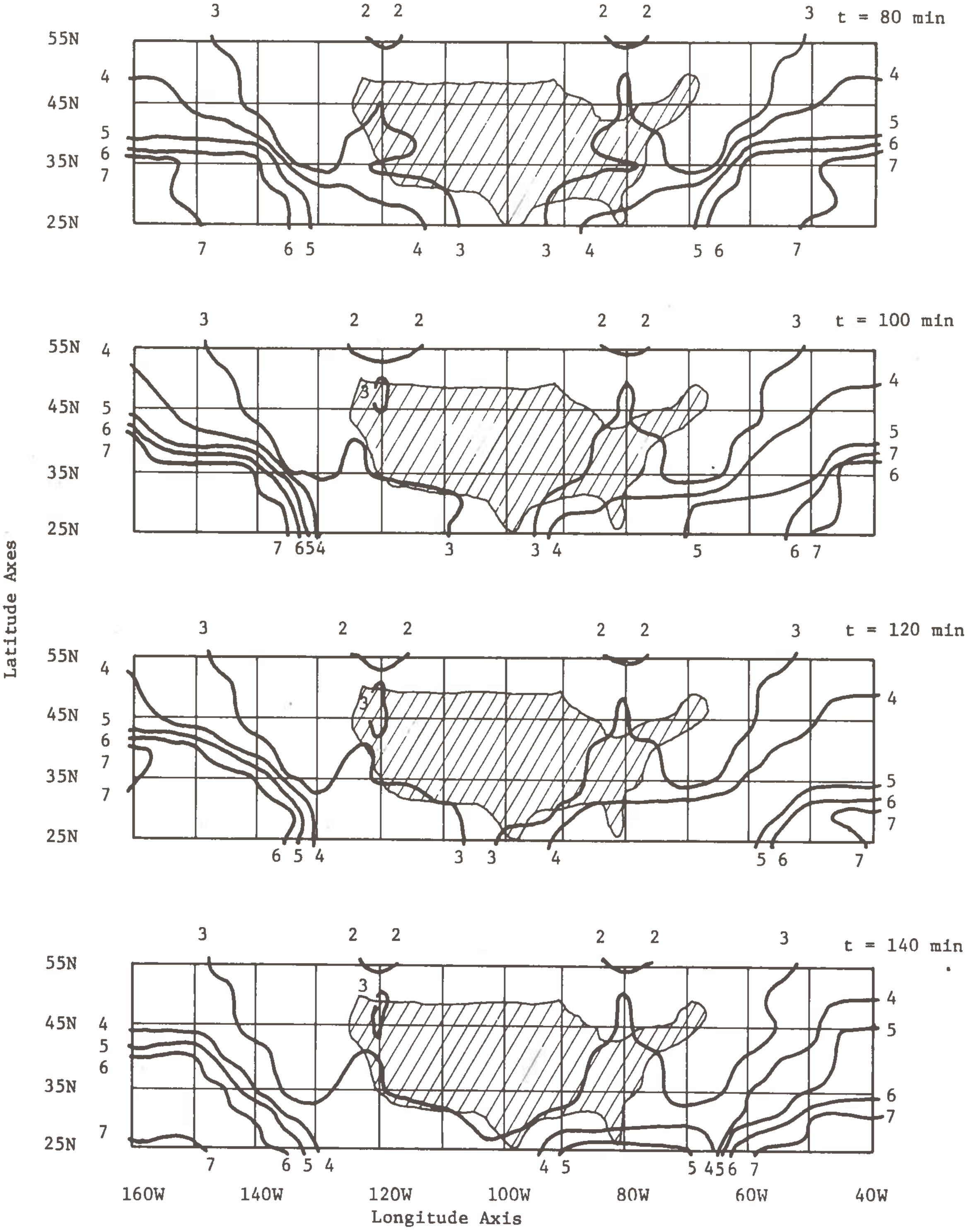


Figure 2.4-4. (Continued)

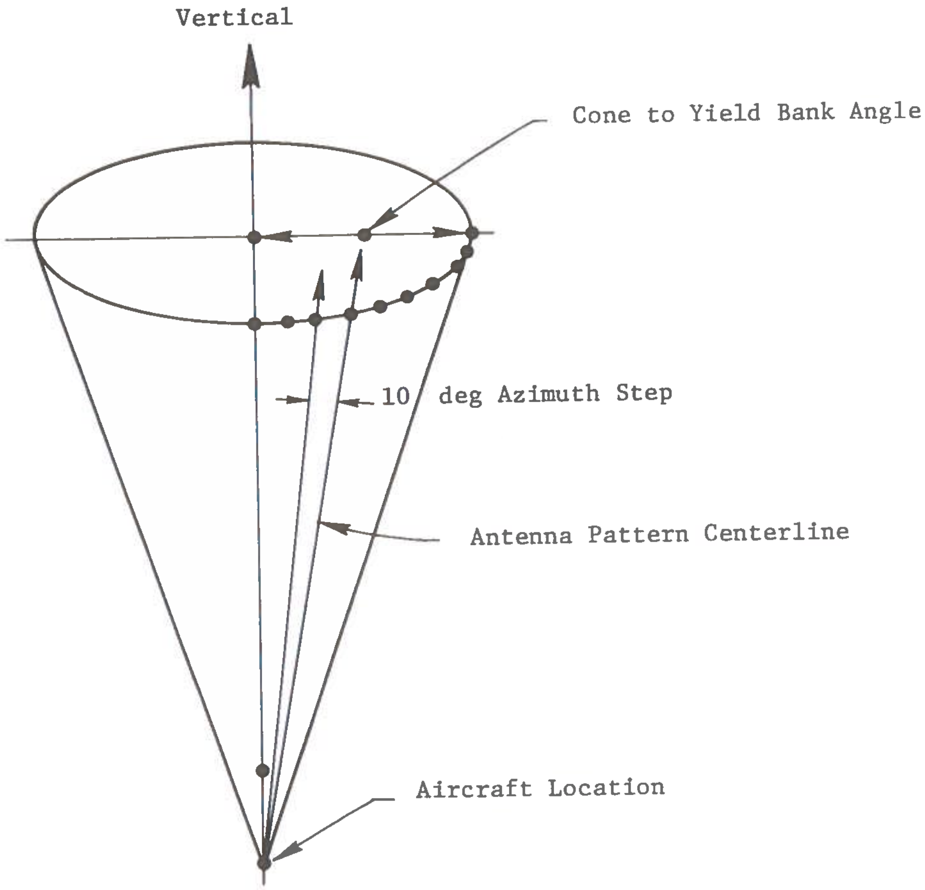


Fig. 2.4-5. Bank Angle Diagram

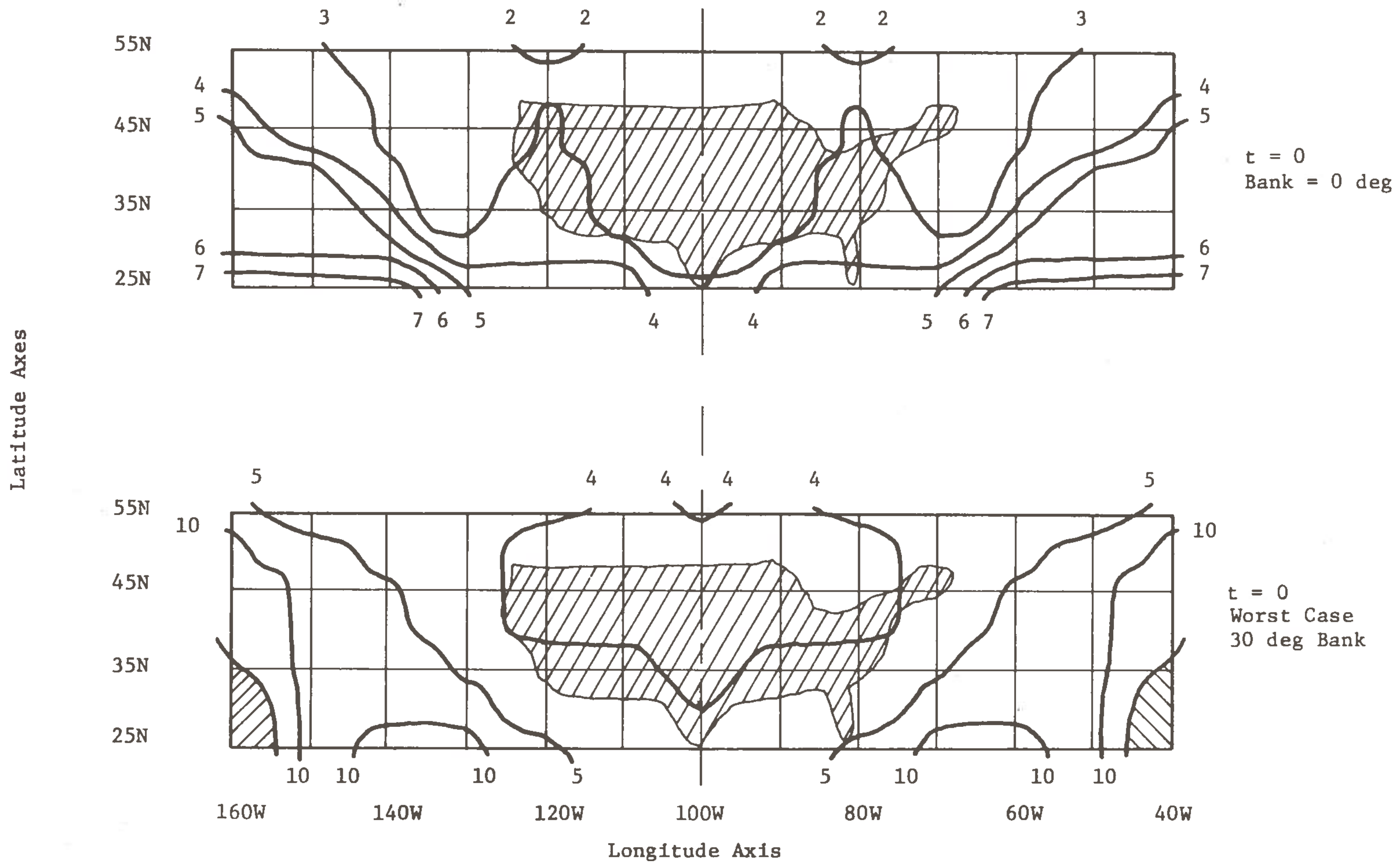


Figure 2.4-6. Effect of Bank Angle on GDOP

The situation is really not as critical for the oceanic case as might be suspected. Aircraft bank angles of 30 deg are extremes of normal maneuvers and are generally of short duration. Because of the filter mechanization, only a short-term increase in surveillance error would occur.

A more marginal situation exists with respect to the effects of received energy. Figure 2.4-7 shows the sensitivity of GDOP to 2 db changes in received energy. For a 2 db loss in energy, the value of GDOP almost doubles in certain regions. This degradation is not catastrophic and has more impact on surveillance than navigation, since alternate coding schemes can be used without introducing additional multi-access noise. As a point of fact, a user must be acquired by the surveillance system before being allowed to take off. A seriously degraded user would be unable to maintain a consistent signal track and would be denied entry. In-flight failures are rare.

The combined effect of 3 db power loss and bank angles of 10, 20, and 30 deg is shown in Fig. 2.4-8. Here progressive degradation occurs until, at a 30 deg bank, there are regions within CONUS where four satellites are not visible. This must be recognized as a transient phenomenon and not equated to system failure. The progressive degradation will only yield slightly worsened system accuracy.

The analysis results presented to this juncture are predicated on the availability of all 15 satellites. Figures 2.4-9 through 2.4-12 show the effect on GDOP for progressive non-availability of satellites due to failure or jamming. In all cases, the worst-case times were selected such that a maximum GDOP results. Note that for the case where an inclined satellite is not available, the basic period of the constellation reverts to a sidereal day rather than the usual 160 min.

In general, serious GDOP degradation does not occur for the nominal CONUS user until four critical satellites are non-available. The results, shown in Fig. 2.4-12, are strong functions of time. The GDOP values for four non-available satellites tend to change rapidly as the inclined satellite moves with respect to the earth.

The constellation does provide some level of usefulness even with four non-available satellites. CONUS accuracy can show serious degradation, but system failure does not occur. Further, for the jamming case, these results are only applicable to surveillance. There is no feasible, viable method for jamming the navigation function.

The GDOP results indicate that the constellation selected for the SAATMS design is adequate to provide the surveillance and navigation coverage. The constellation provides the basic coverage, user degradation protection, and satellite non-availability protection required of a SAATMS satellite system. This constellation is undoubtedly not the most optimum but is feasible.

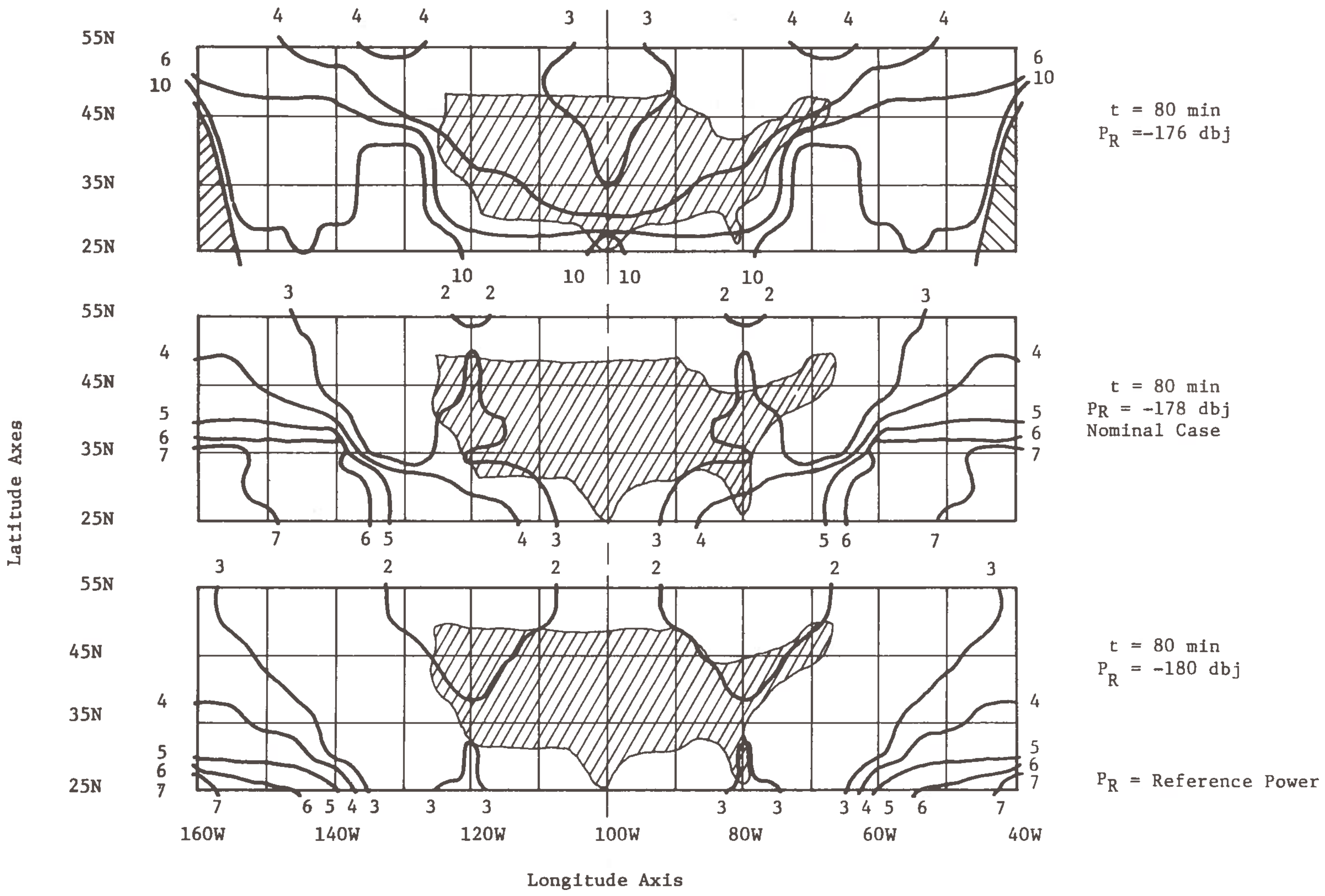
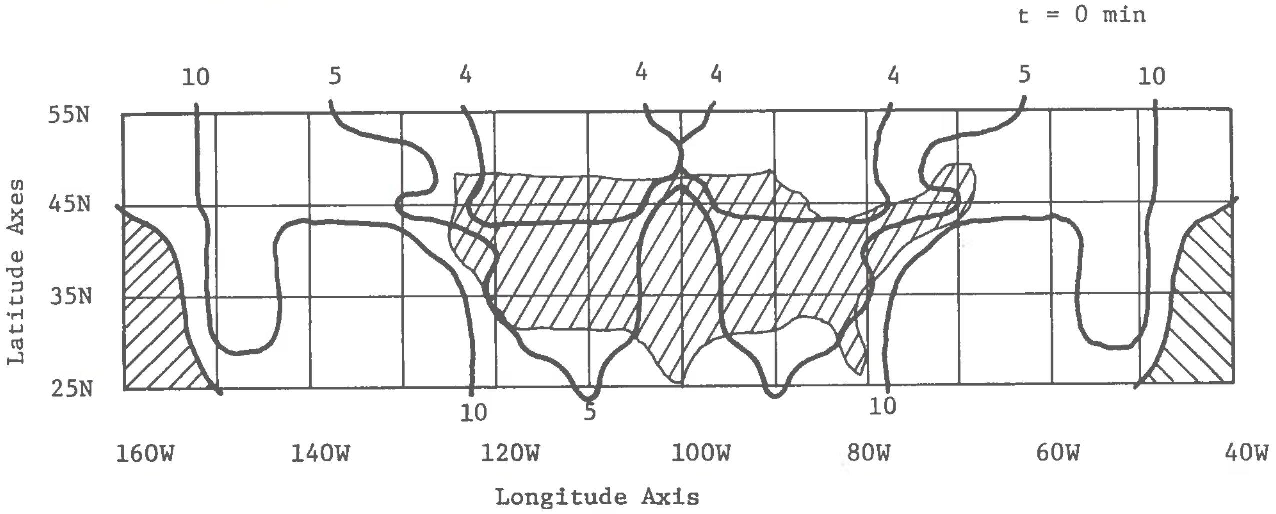


Figure 2.4-7. Reference Power Sensitivity GDOP Maps

a. Low Power User (-3 db) at 0 deg Bank



b. Low Power User (-3 db) at 10 deg Bank

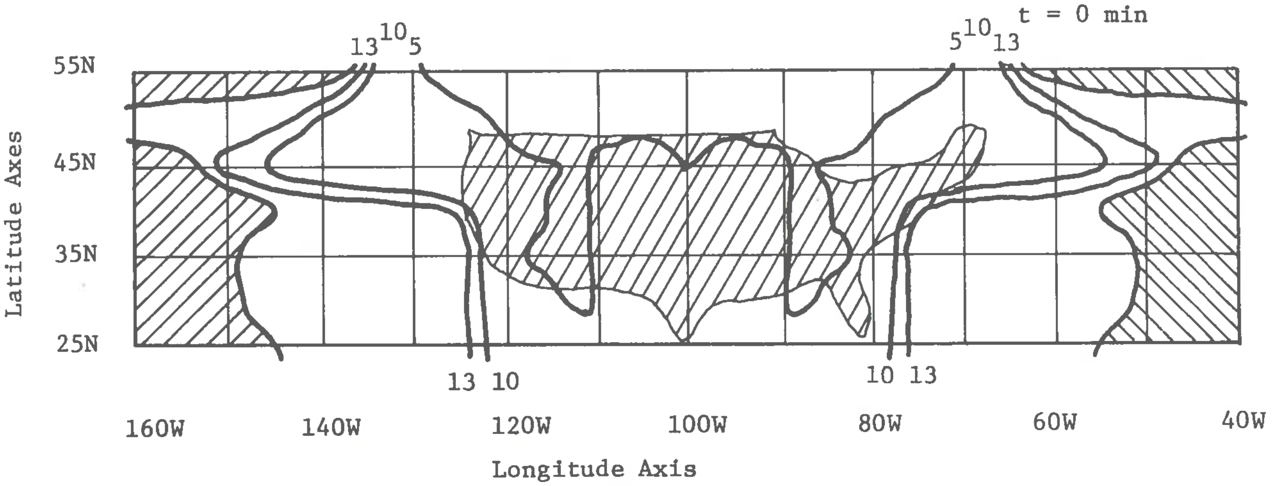
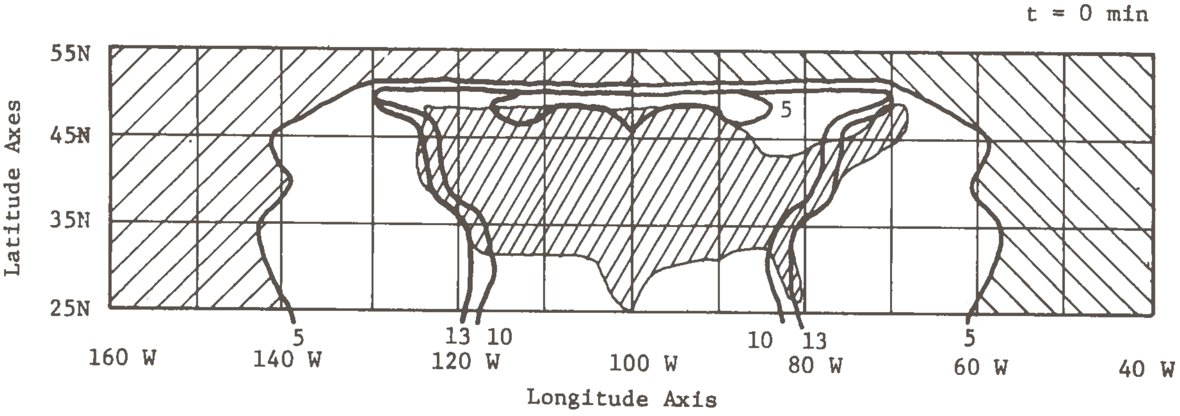


Fig. 2.4-8. Combined Low Power User at Worst-Case Bank Angle

c. Low Power User (-3 db) at 20 deg Bank



d. Low Power User (-3 db) at 30 deg Bank

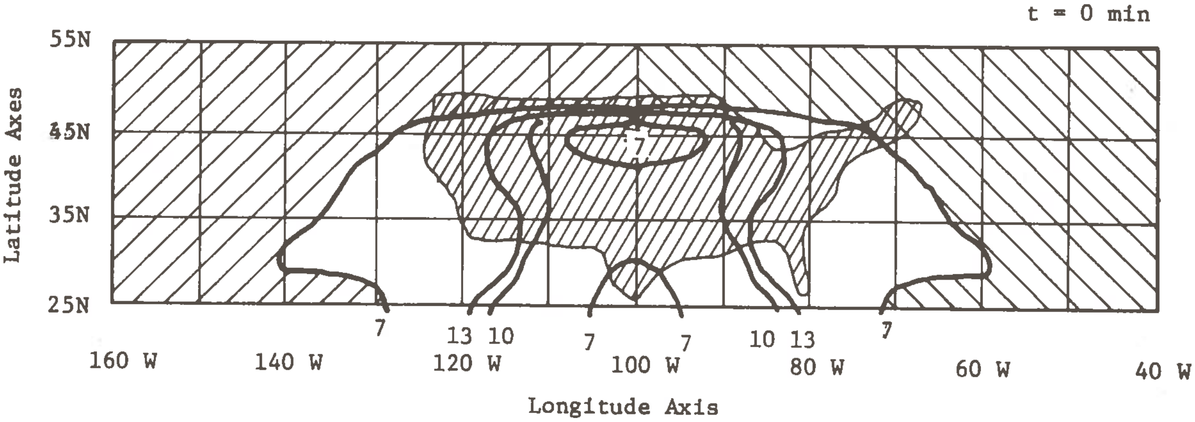
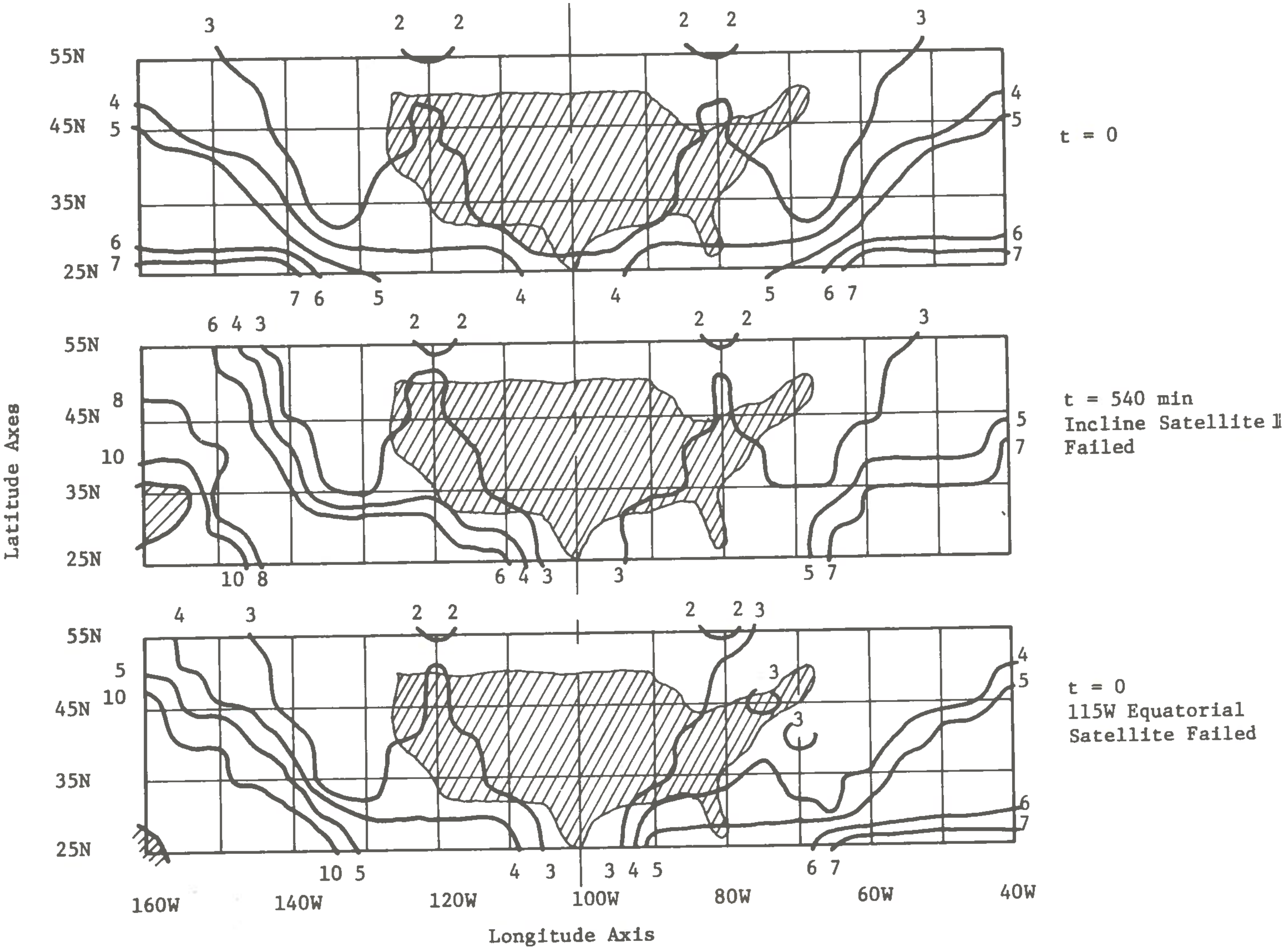


Figure 2.4-8. Combined Low Power User at Worst-Case Bank Angle (Continued)


t = 0

t = 540 min
Incline Satellite I
Failed

t = 0
115W Equatorial
Satellite Failed

Figure 2.4-9. Satellite Non-Availability Worst-Case Results, One Failed Satellite

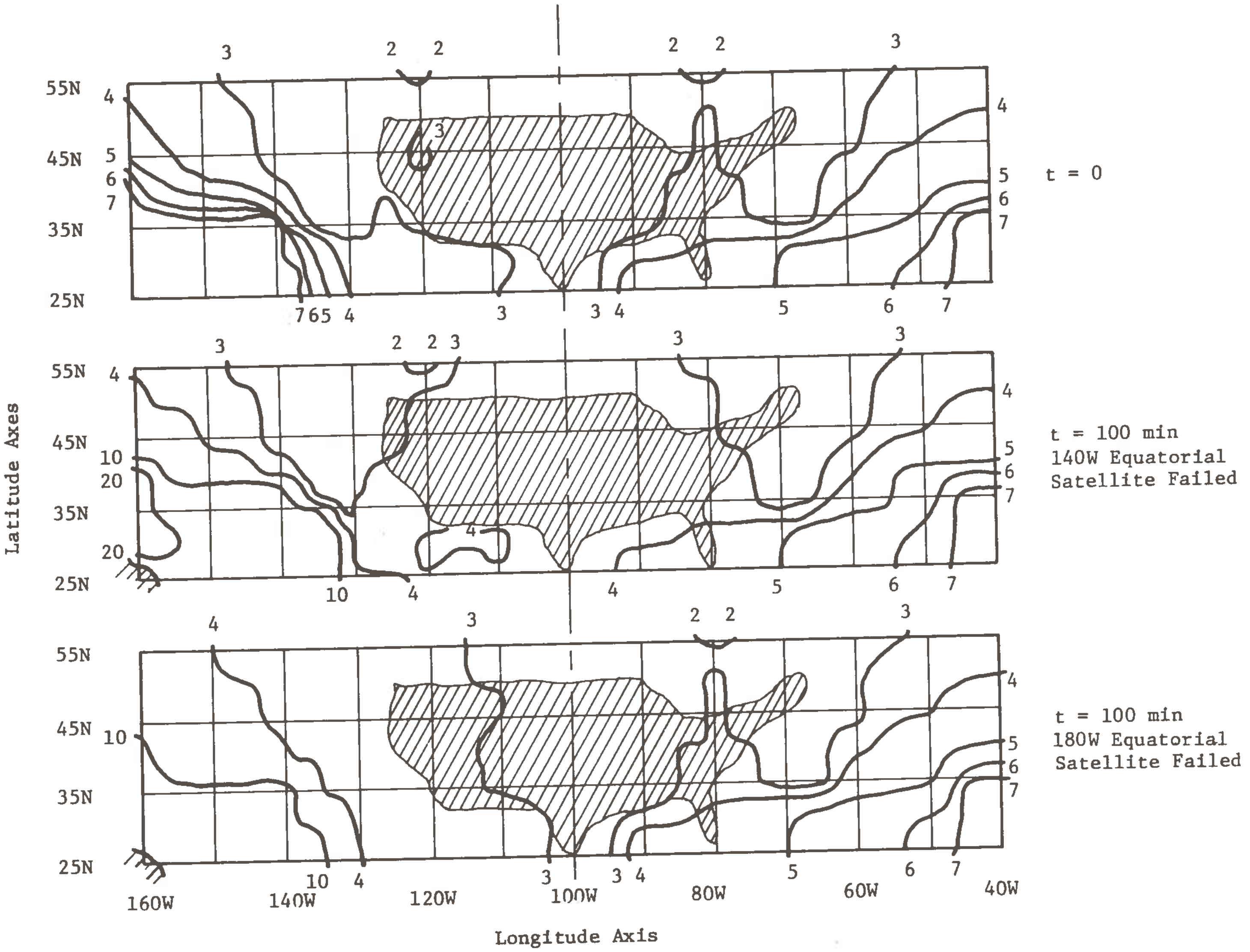
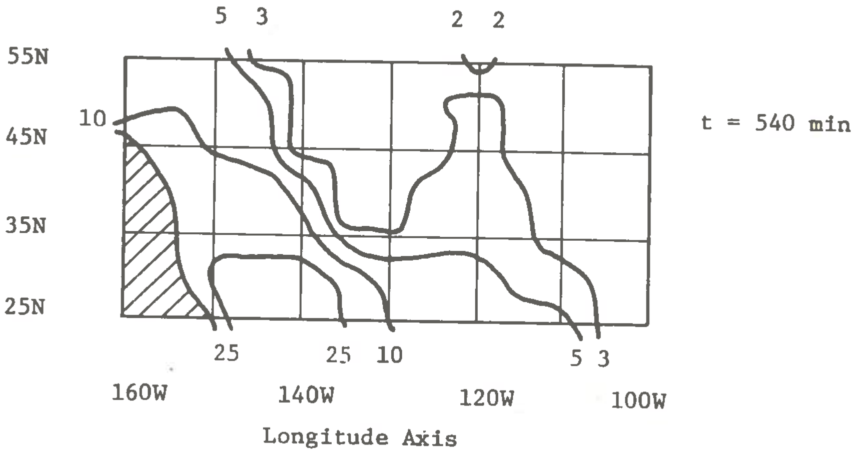


Figure 2.4-9. Satellite Non-Availability Worst-Case Results, One Failed Satellite. (Continued)

a. Constellation Minus One Equatorial, 115W and One Inclined Satellite



Latitude Axes

b. Constellation Minus One Equatorial, 140W and One Inclined Satellite

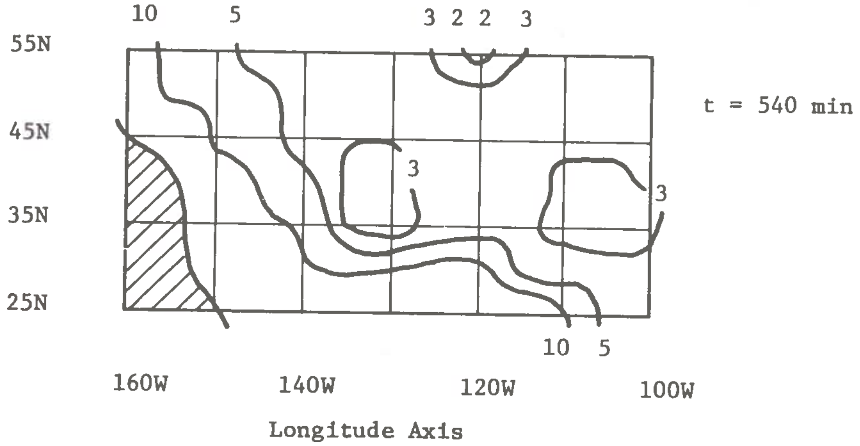
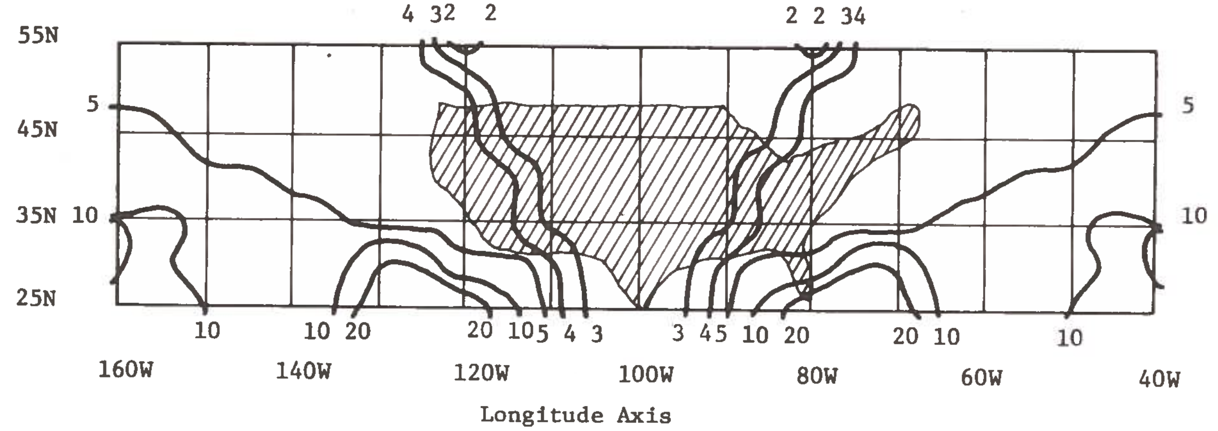


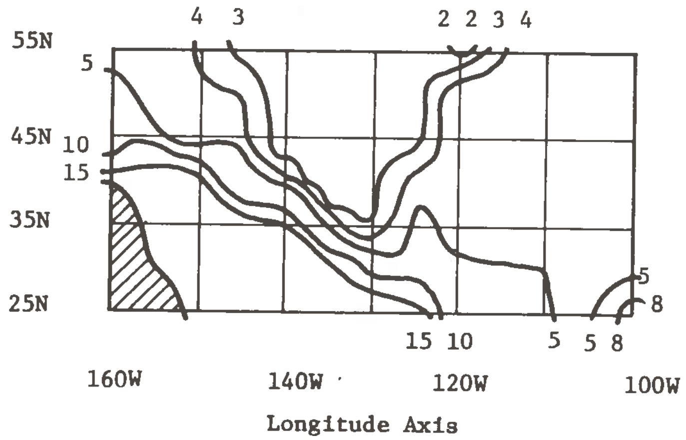
Figure 2.4-10. Satellite Non-Availability Worst-Case Results, Two Failed Satellites

c. Constellation Minus Two Equatorial Satellites, 115W and 85W



t = 80 min

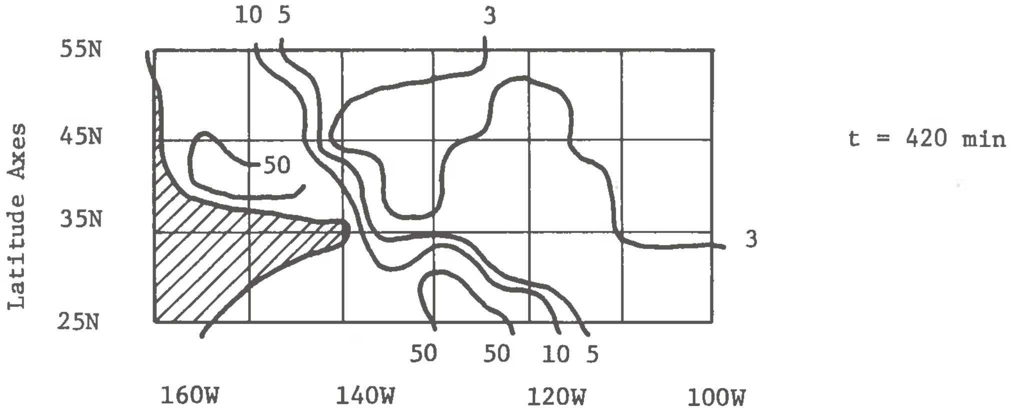
d. Constellation Minus Two Equatorial Satellites, 115W and 140W



t = 120 min

Figure 2.4-10. Satellite Non-Availability Worst-Case Results, Two Failed Satellites (Continued)

a. Constellation Minus One Equatorial, 115W, and Two Adjacent Inclined Orbit Satellites



b. Constellation Minus One Equatorial, 115W, and Two Inclined (Spaced One Apart) Satellites

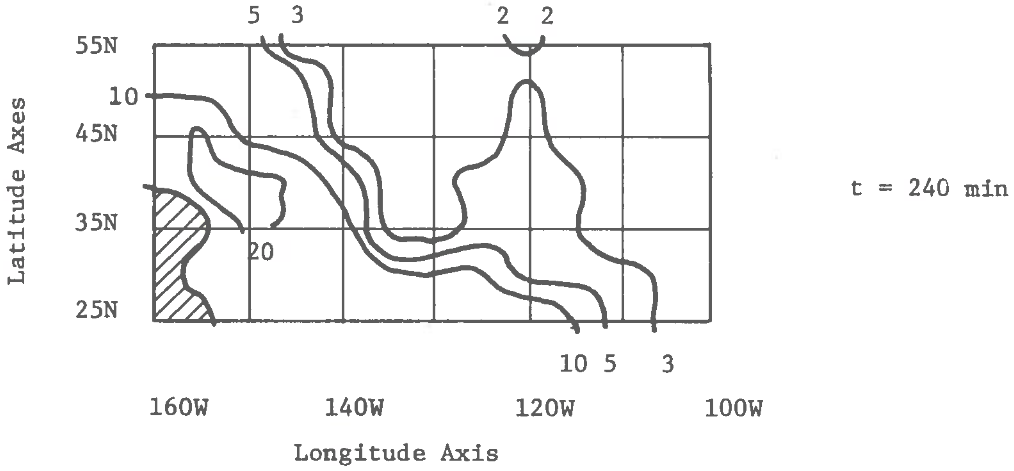
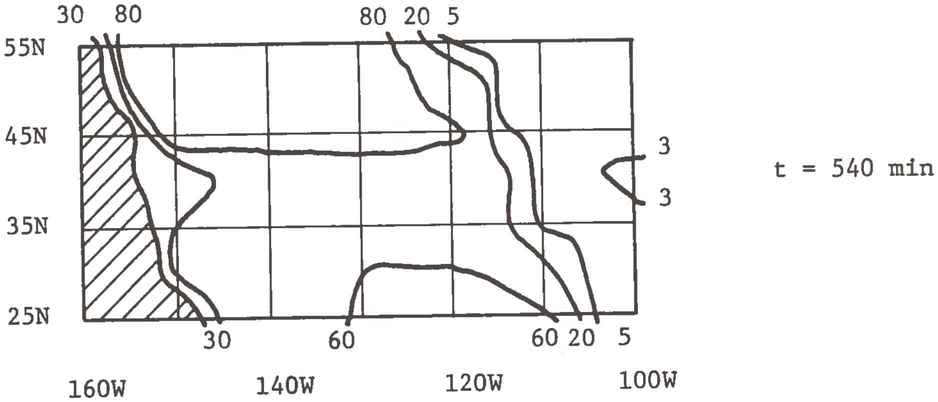


Fig. 2.4-11. Satellite Non-availability Worst-Case Results, Three Failed Satellites

a. Constellation Minus Two Equatorial, 115W and 85W, and Two Adjacent Inclined Orbit Satellites



b. Constellation Minus Two Equatorial, 115W and 85W, and Two Inclined (Spaced One Apart) Satellites

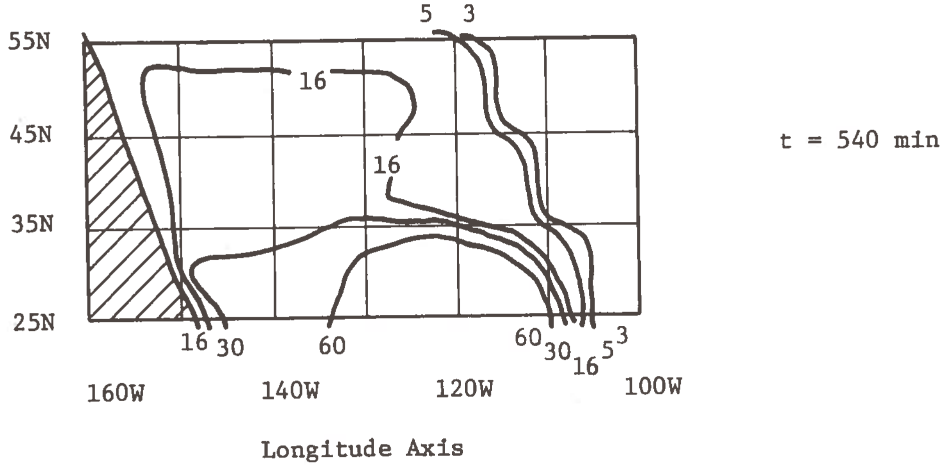


Fig. 2.4-12. Satellite Non-Availability Worst-Case Results, Four Failed Satellites

One of the more serious charges that could be leveled against the constellation design involves the long-term perturbation of the orbits. Due to the orbit parameters selected, two major orbit instabilities result. The ascension of the ascending node precesses and the perigee point has an in-plane precession rate. The former effect can be reduced by proper adjustment of the satellite radius vector. The latter effect may be eliminated by active station keeping or by a different choice of inclination. Insufficient time was available in this study to evaluate the long-term perturbation effect or to investigate alternate constellation designs. Further efforts on constellation design optimization are warranted.

2.4.2 Tracking Subsystem

The satellite tracking subsystem performs the functions of collecting and processing satellite tracking data, predicting satellite ephemerides, and transmitting the predicted ephemeris data to the satellites for use in navigation. The primary functions of this subsystem are performed by the Satellite Tracking Center (STC) and the Continental Control Center (CCC). The flow of information among these subsystem components is depicted in Fig. 2.4-13. Descriptions of all tracking functions are given in the subsequent paragraphs.

The STC receives the L-band navigation signal transmitted periodically by each satellite. The time-of-arrival (TOA) of each signal is measured using the reference time signal generated by the CCC. For a given satellite, the measured TOA's over a short interval are reduced to a single value at the midpoint of the interval by a simple preprocessing scheme. This preprocessing includes smoothing and editing functions and the determination of a figure-of-merit for each data interval. The final data value, interval midpoint time, and figure-of-merit are transmitted through a communications link to the CCC. In addition, the STC periodically decodes the navigation data (position and clock rate error) from each satellite and transmits them to the CCC for the navigation data verification function.

The proposed system configuration includes five STC's collocated at the following locations: Palmdale, CA; Fort Worth, TX; Hilliard, FL; Albany, NY; and Seattle, WA. Also, STC's are located in Puerto Rico and Hawaii to provide good tracking geometry for the outermost equatorial satellites.

The CCC is the nerve center of the tracking subsystem. The functions of the CCC include the following:

(1) Precorrecting the measurements obtained from the STC's for known errors, such as mean ionospheric and tropospheric delays and a priori satellite clock offset and rate bias errors.

(2) Updating the estimates of the orbit and the on-board clock rate errors for each satellite by processing the precorrected tracking data through a recursive maximum likelihood estimation algorithm.

(3) Predicting the ephemeris and clock errors for several hours ahead and transmitting these data periodically to the RCC's for use in the surveillance and navigation algorithms.

(4) Comparing the navigation data received from the satellites via the STC's with the original ephemeris prediction to verify proper performance of the tracking subsystem communication links.

(5) Generating the reference time signal for use throughout the SAATMS.

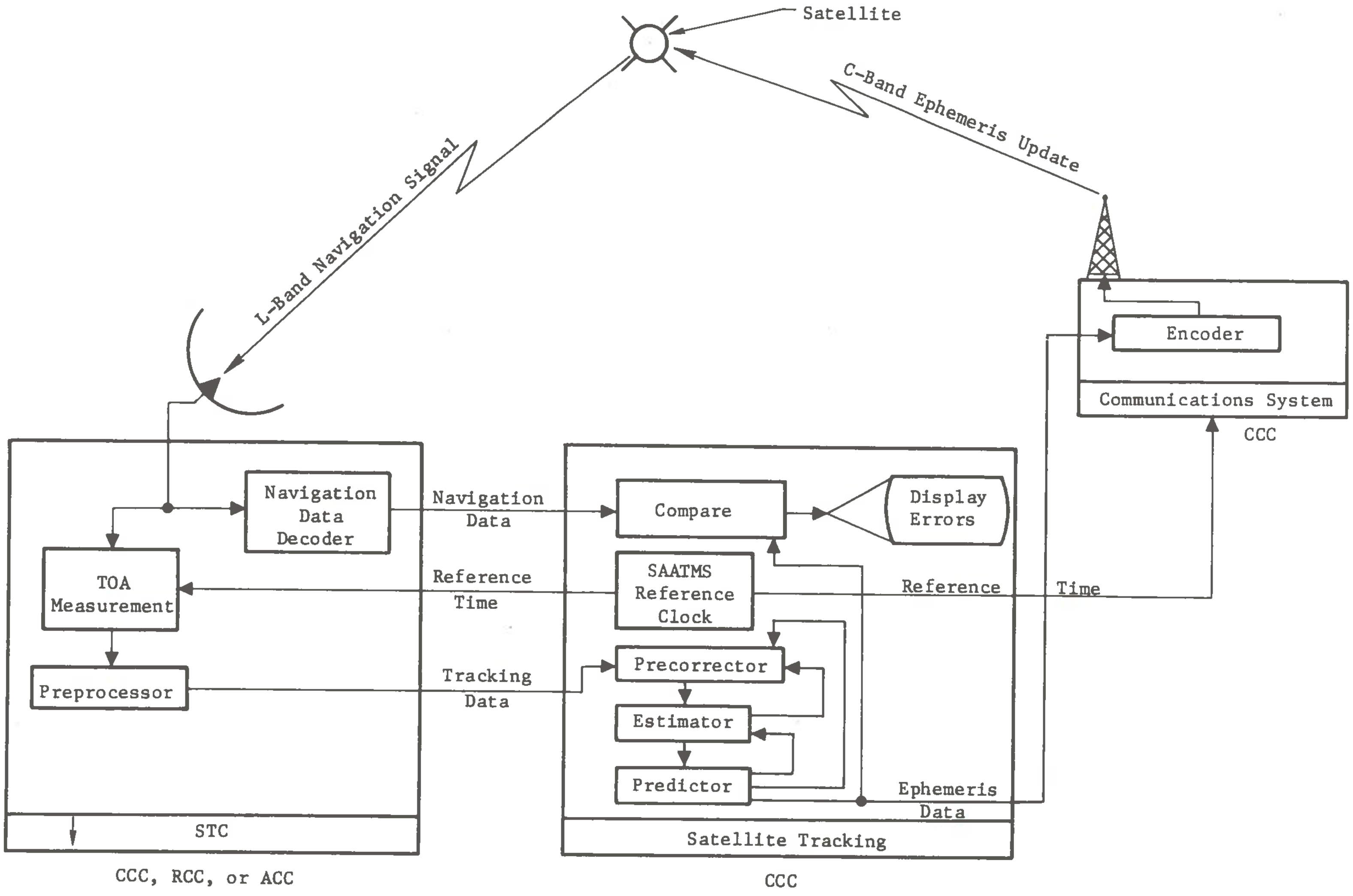


Figure 2.4-13. Tracking Subsystem Flow

2.4.2.1 Mechanization

The technical approach and equations mechanized in the tracking subsystem to perform its stated functions are described in this section.

2.4.2.1.1 TOA Measurement Preprocessor

Observations are in the form of TOA measurements of the pseudo-noise pulse transmitted by the satellite at L-band. Each satellite will transmit a pulse once every 3 sec. These observations essentially measure the distance between the tracker and the satellite, i.e., the range. The rate of one measurement per 3 sec is much higher than necessary to define the range as a function of time. Also, the real time computational requirements will limit the ephemeris estimation update rate. The measurement rate could be decreased by merely disregarding some of the data, but this would unnecessarily waste information. A better approach is to reduce a group of TOA measurements to a single improved measurement by a simple smoothing and editing (preprocessing) algorithm.

The suggested algorithm involves a least-squares curve fit to independent (non-overlapping) spans of data. For equi-spaced measurements and constant length data spans, the calculation of the coefficients of the least-squares polynomial can be mechanized as the product of an m × n matrix of constant coefficients and an n vector of observations. Here, m is the number of polynomial coefficients (three for a quadratic).

Assume a reference time of zero at the transmission of the first pulse. All subsequent measurements are in terms of elapsed time from the reference time. Then the nominal transmission time for the n^{th} pulse is $n(\Delta T)$, where ΔT is the ideally constant interval between pulses. Let T_n be the measured time-of-arrival of the n^{th} pulse at the STC. Then the k^{th} observation vector is defined as

$$\bar{Y}_k = \begin{bmatrix} T_{n_1} - n_1(\Delta T) \\ \\ T_{n_1} + 1 - (n_1 + 1)\ (\Delta T) \\ \vdots \\ \\ T_{n_2} - n_2(\Delta T) \end{bmatrix} \qquad (1)$$

where

$n_1 = (k - 1)\, n + 1$

$n_2 = kn$

The vector of polynomial coefficients is completed by

$$\overline{C}_k = [A]\ \overline{Y}_k = \begin{bmatrix} C_1 \\ C_2 \\ C_m \end{bmatrix}_k \tag{2}$$

where the constant matrix [A] is a function only of m, n, and ΔT and will not be derived here. The smoothed measurement y_k is defined as the value of the polynomial at the midpoint $n_k = 0.5\ (n_1 + n_2)$ of the data span, and the time of the smoothed value is $t_k = n_k(\Delta T)$. A simple wild point rejection scheme can be implemented prior to smoothing, based on a test and replacement operation on the first differences (and possibly second differences) of the elements of $\overline{Y}$. Also, a figure-of-merit can be defined for each smoothed value y_k by some norm of the residuals of $\overline{Y}_k$ about the smoothing polynomial.

2.4.2.1.2 Tracking Data Precorrector

It is well known that the tracking data are corrupted by random and systematic measurement errors. A priori information is available for certain of the systematic errors which enable precorrections to be made to the data before being processed by the estimator. Such precorrections enhance the estimation process in two ways:

(1) The magnitude of the difference between the predicted and observed satellite trajectory is reduced, thereby aiding convergence of the estimation process. This follows, since the higher order terms neglected in the linearized system model will in fact be smaller.

(2) The number of system states to be estimated can sometimes be reduced, thus increasing the statistical degrees of freedom of the estimation process.

In the present case, errors considered as candidates for precorrection include propagation delays of the signal during transit of the ionosphere and troposphere, initial transit time offset, and satellite oscillator bias. The precorrection model for these terms has the following form

$$y'_k = y_k - \delta\hat{y}_o - \hat{b}n_k(\Delta T) - \frac{KQ\eta}{Cf^2} - \frac{K_T}{C\sin\left(E_{ref_k}\right)} \tag{3}$$

where the prime denotes corrected value and the symbol ^ denotes an estimate. The parameters of this model are defined below:

$\hat{y}_o$ = the estimate of the reference time offset

$\hat{b}$ = the estimate of the satellite oscillator bias

K = a physical constant

η = the predicted columnar electron content

f = the signal carrier frequency

C = the speed of light

K_{T_1} = an empirical constant (typically 8.8)

E_{ref_k} = the predicted elevation angle of the signal ray path at the STC

$Q = \csc\sqrt{E^2_{ref_k} + K^2_{T_2}}$

where

K_{T_2} = an empirical constant (typically 20.3)

The estimates $\delta\hat{y}_o$ and $\hat{b}$ are obtained through a feedback loop from the estimator, which is described in the next section. Values for η are obtained from predicted ionospheric parameters. Estimates of E_{ref_k} at each observation time are computed by the predictor based on the most recent information from the estimator. This function is also discussed in subsequent paragraphs.

2.4.2.1.3 Estimator

The smoothed and precorrected observations, y'_k, are essentially range measurements which are corrupted by systematic errors (ε_k) and random errors (w_k). In equation form,

$$y'_k = \frac{1}{C} r_k + \varepsilon_k + w_k \tag{4}$$

where r_k is the distance from the STC to the satellite at time t_k. The objective of the estimation process is to obtain an optimum (minimum mean square) estimate of the position $\overline{R}(t)$ and velocity $\dot{\overline{R}}(t)$ of the satellite at the time of the most recent observation. It is convenient at this point to define a system state vector $\overline{X}(t)$ as the vector of constant and/or time varying elements which are to be estimated. A requirement for obtaining a minimum mean square estimate of $\overline{X}(t)$ is that its derivative $\dot{\overline{X}}(t)$ be a linear function of $\overline{X}(t)$. That is, the system equation must be of the form

$$\dot{\overline{X}}(t) = [F(t)]\,\overline{X}(t) + [G(t)]\,\overline{u}(t) \tag{5}$$

where

$[F(t)]$ is referred to as the system description matrix

$[G(t)]$ is the noise distribution matrix

$\overline{u}(t)$ is a vector of white noise random processes which drive the system

If $\overline{R}(t)$ and $\dot{\overline{R}}(t)$ were defined as system states, i.e.,

$$\overline{X}(t) = \begin{bmatrix} \overline{R}(t) \\ \dot{\overline{R}}(t) \\ \vdots \end{bmatrix} \tag{6}$$

the system equation would be nonlinear. (For a detailed discussion of these equations, see Volume IX.)

However, if a reference solution $\overline{R}_{ref}(t)$, $\dot{\overline{R}}_{ref}(t)$ were known such that

$$\frac{|\overline{R}(t) - \overline{R}_{ref}(t)|}{|\overline{R}_{ref}(t)|} = \frac{|\overline{\Delta R}(t)|}{|\overline{R}_{ref}(t)|} << 1 \tag{7}$$

and

$$\frac{|\dot{\overline{R}}(t) - \dot{\overline{R}}_{ref}(t)|}{|\dot{\overline{R}}_{ref}(t)|} = \frac{|\dot{\overline{\Delta R}}(t)|}{|\dot{\overline{R}}_{ref}(t)|} << 1 \tag{8}$$

And if the state vector were defined as

$$\overline{X}(t) = \begin{bmatrix} \overline{\Delta R}(t) \\ \dot{\overline{\Delta R}}(t) \\ \vdots \end{bmatrix} \tag{9}$$

Then, the linear form of the system equation would be a sufficiently accurate approximation to the actual nonlinear equation. The restriction expressed by the preceding inequalities in no way impedes the estimation process since the reference solution can be reset to the estimates of $\overline{R}(t)$ and $\dot{\overline{R}}(t)$ whenever the difference of the estimated and reference solutions exceeds a present tolerance.

It is also necessary to define a linear relationship between the observations y'_k and those system states which are observable, in this case, $\overline{\Delta R}(t_k)$ or simply $\overline{\Delta R}_k$. Equation (4) showed that y'_k is linearly related to the distance r_k. Let this distance be represented by the distance to the reference solution, r_{ref_k}, plus a term $(\Delta r)_k$ due to the difference between the reference solution and the actual position of the satellite.

$$r_k = r_{ref_k} + (\Delta r)_k \tag{10}$$

Also realize that a sufficiently accurate linear relationship exists between $(\Delta r)_k$ and the vector difference $\overline{\Delta R}_k$.

$$(\Delta r)_k \simeq [M_R]_k \, \overline{\Delta R}_k \tag{11}$$

where the row matrix $[M_R]_k$ can easily be computed from geometry, using small angle approximations where necessary. Substituting these two relations into Eq. (4) and defining a new quantity $(\Delta y)_k$, we can write

$$(\Delta y)_k \equiv y'_k - \frac{1}{C} r_{ref_k} = [M_R]_k \, \overline{\Delta R}_k + \varepsilon_k + w_k \tag{12}$$

If the systematic errors, ε_k, can be expressed as linear functions of their parameters

$$\varepsilon_k = [M_\varepsilon]_k \, \overline{X}_{\varepsilon_k} \tag{13}$$

then, the measurement matrix $[M_R]$ and state vector $\overline{X}$ can be augmented and Eq. (12) can be written as

$$(\Delta y)_k = \left[[M_R] \;\middle|\; [0] \;\middle|\; [M_\varepsilon] \right]_k \begin{bmatrix} \overline{\Delta R} \\ \dot{\overline{\Delta R}} \\ \overline{X}_\varepsilon \end{bmatrix}_k + w_k \qquad (14)$$

Or simply

$$(\Delta y)_k = [M]_k \, \overline{X}_k + w_k \qquad (15)$$

This is termed the measurement equation and relates the observable to the system states. The error parameters in $\overline{X}_\varepsilon$ include tracker site location errors, reference time offset δy_o, satellite oscillator bias b, satellite oscillator random variations, residual ionospheric and tropospheric delays, uncertainty in the speed of light, and uncertainties in the coefficients of the gravity potential function. The offset error, δy_o, enters into the observation directly, i.e., the element of [M] for that error is unity. The oscillator bias, b, introduces an observation error proportional to elapsed time t_k. (For a detailed definition of all error models, refer to Volume IX.)

Periodically, after processing a segment of tracking data, the estimates $\widehat{\delta y}_o$ and $\hat{b}$ used by the precorrector will be updated by the current values in $\overline{X}$. Simultaneously, those values in $\overline{X}$ will be reset to zero, prior to processing the next segment of data. Similarly, the position and velocity state estimates $\hat{\overline{\Delta R}}_k$ and $\hat{\dot{\overline{\Delta R}}}_k$ are periodically reset to zero and the reference solution values of $\overline{R}_{ref_k}$, $\dot{\overline{R}}_{ref_k}$, and r_{ref_k} are reset to the current estimates, e.g.,

$$\overline{R}_{ref_k} = \overline{R}_{ref_k} + \hat{\overline{\Delta R}}_k$$

However, since these states are time varying, the reference solution values must be precomputed by the predictor. This is discussed further in the following sections.

Having defined the system state equation and the measurement equation, the estimation algorithm remains to be discussed. Suboptimal classes of estimators were not considered for this problem since the computational capacity will not be a critical factor. Two types of minimum mean square estimation algorithms can be used. In the first type, all tracking data in a given segment are compiled into a large array; and a single evaluation of the weighted least-squares equation is performed, yielding position and velocity estimates at one point, say the time of the most recent observation. In the second type, the tracking data from each observation time are processed through a recursive formulation of the weighted least-squares equations, yielding position and velocity estimates at each observation time. The second type of estimation algorithm, usually referred to as Kalman filter, is preferred for the following reasons:

(1) Lighter computational load due to the smaller size of the data arrays at each processing time

(2) Availability of intermediate estimation results, which enables the experienced analyst to assess in real time the accuracy and convergence characteristics of the estimation process

(3) Ability to reset the reference solution and/or the precorrection parameter at any time

2.4.2.1.4 Predictor

The predictor receives updated current estimates of satellite position and velocity and measurement error parameters after each segment of data is processed by the estimator. The position and velocity are then extrapolated ahead in time by integrating accelerations computed from the best estimate of the gravity potential function. These extrapolated position and velocity values comprise the ephemeris data which are transmitted to the RCC for eventual use in navigation and surveillance functions.

For navigation purposes, the ephemeris data are extrapolated to the actual time of transmission of the satellite navigation signal; the error in that transmission time must also be computed. For example, to compute the navigation ephemeris data for the n^{th} pulse, the time of that pulse is first computed using the current best estimate of reference time offset and oscillator bias according to

$$t_{p_n} = n\,(1 + \hat{b})(\Delta T) + \delta y_o \qquad (16)$$

The ephemeris data are then integrated to t_{p_n} to obtain $\hat{\dot{\bar{R}}}_{p_n}$ and $\hat{\dot{\bar{R}}}_{p_n}$. The time error as follows is also noted.

$$\Delta t_{p_n} = t_{p_n} - n(\Delta T) \qquad (17)$$

Notice that this function must be performed for each of the 15 satellites and that the epochs, t_{P_n}, for each satellite will be different.

For surveillance purposes, a similar extrapolation is performed to predict the ephemeris data for each of the 15 satellites. In this case, however, the data are integrated to evenly spaced intervals of the reference time base. That is, the surveillance ephemeris data for the n^{th} time point will be integrated to

$$t_n = n(\Delta T) \tag{18}$$

Thus, two sets of ephemeris data are predicted for each satellite: a first set referenced to transmission times of the navigation signal from that satellite and a second set referenced to the CCC generated reference time base. This second set of predicted ephemeris data is denoted $\overline{R}_{ref}$ and $\dot{\overline{R}}_{ref}$ and is used to define the reference solution for the estimator. A value for r_{ref}, the distance from the STC to the reference satellite position, is computed according to

$$r_{ref} = |\overline{R}_{ref} - \overline{R}_{STC}| \tag{19}$$

where $\overline{R}_{STC}$ is the best estimate of the location of the STC. A value of r_{ref} is computed for each observation time in the next data segment and fed back to the estimator for use in forming the observation $(\Delta y)_k$. Also, the predicted elevation angle is computed for each observation time according to the equations

$$\overline{R}_T = [T]\,(\overline{R}_{ref} - \overline{R}_{STC}) \tag{20}$$

$$E_{ref} = \sin^{-1} \frac{R_{T_3}}{|\overline{R}_T|}$$

and fed back to the precorrector for use in the precorrection model. In this calculation, [T] is a 3 ×3 transformation matrix which expresses the reference position $\overline{R}_{ref}$ in a North-West-Up coordinate system located at the STC. Note that the quantities r_{ref} and E_{ref} are dependent on the location of the STC. It is therefore necessary to repeat these calculations for each STC which provides tracking data to the CCC.

Since each satellite must transmit navigation data which define its position at the transmission time, the calculation of $\hat{\overline{R}}_{p_n}$ and Δt_{p_n} must be performed at (nominal) 3 sec intervals. The surveillance data $\overline{R}_{ref}$ and $\dot{\overline{R}}_{ref}$ are also computed at 3 sec intervals. The quantities r_{ref} and E_{ref} are only required at the times of preprocessed observation, however, so they are calculated at a lower rate.

2.4.2.2 <u>Satellite Ephemeris Impacts Surveillance and Navigation Accuracies</u>

The accuracy of satellite ephemeris data is of fundamental importance since it limits the attainable system accuracy for navigation and surveillance. It is therefore necessary to define the attainable tracking subsystem accuracy in terms of predicted ephemeris errors and to assess the impact of these errors on total system accuracy. This section describes the approach used in the tracking subsystem error analysis and summarizes the results obtained. A detailed discussion of the error analysis can be found in Volume IX.

2.4.2.2.1 <u>Approach</u>

Section 2.4.2.1 contains a description of the methods used to estimate and predict the satellite ephemeris given TOA measurements from STC's. The accuracy of the estimation and prediction process is affected by errors in the measurements, errors in the gravity potential function, and other unmodeled forces acting on the satellite such as solar radiation pressure, solar and lunar gravity, atmospheric drag, etc. If a priori statistics (variances and covariances) are defined to adequately describe the distributions of the various errors, the statistics can be propagated through the estimation and prediction process. Attainable ephemeris accuracy can then be defined in terms of the resulting estimation error covariances. This approach was used to estimate the effects of measurement errors and gravity model errors. The effects due to other unmodeled forces were treated separately and are discussed in the following paragraphs.

Due to the large number of errors considered and the complex nature of the relationships between the observations, the errors, and the estimates, it is necessary, from a practical standpoint, to implement the error covariance propagation on a digital computer. An existing general purpose IBM 360 computer program for performing error analyses of large systems was available. This program, the State Space Analysis of Multisensor Systems (SAMUS), was also adaptable for use in the error analysis of the SAATMS subsystems. A detailed description of SAMUS is presented in Volume IX.

SAMUS can be executed in various modes. For the tracking subsystem analysis, a priori error statistics were used to initialize the state covariance matrix and precorrected observations were assumed to be available from several STC's. After processing the covariance matrix through the estimation equations for several segments of assumed observation data, the resulting error covariance matrix was propagated ahead in time without assuming any additional observations. This latter step simulated the error propagation by the predictor. Thus, SAMUS was utilized for analysis of both estimation and prediction errors.

2.4.2.2.2 Modeled Errors and A Priori Statistics

Based on previous experience in evaluation of tracking systems and recent articles on related studies, a list of potential errors affecting TOA measurements was compiled. From this list, those errors considered potentially significant for the present case include the following:

(1) Tracker site location errors

(2) Reference time offset

(3) Satellite oscillator bias

(4) Satellite oscillator random variations, including a random walk term and a fractional Brownian motion (flicker noise) term

(5) Residual ionospheric and tropospheric delays

(6) Speed of light uncertainty

(7) TOA measurement uncertainty (white noise)

In addition to these measurement errors, uncertainties in the first several coefficients of the earth's gravity potential function, including the central force field constant μ, are also modeled. Initially, all of the modeled errors are assumed independent, and the covariance matrix is initialized with estimates of their variances based on the nature of the error and results of other studies found in the literature. A priori values used in the analysis are tabulated in Table 2.4-3. Detailed discussions of the error models used can be found in Volume IX. The subsequent paragraphs contain a brief discussion of the sources of the data presented in Table 2.4-3.

The STC site location uncertainty value of 20 ft in each direction is a very conservative estimate of the geodetic survey error for any location in the CONUS relative to the North American Datum (NAD). This is based on a tabulation of geodetic coordinate standard errors (Ref. 4). Uncertainties for locations outside the CONUS may be slightly larger at the present time, but they are continuously being improved. Uncertainties in the local datum relative to the geoid are not considered since SAATMS is designed to service only the CONUS and surrounding region.

The error model for transmission times of satellite navigation pulses is made up of four terms. The first two terms, a bias and a drift rate, are systematic and thus can be estimated by processing sufficient data. Their a priori statistics, therefore, are not critical and will be reduced by estimation. The bias uncertainty of 10^{-6} sec is very conservative and can easily be reduced by prelaunch calibration of the satellite oscillator. The drift rate error (constant

Table 2.4-3. A Priori Error Statistics

Term	Error Source	RMS Value
1	STC Site Location (East-North-Up)	20 ft
2	Reference Time Bias	10^{-6} sec
3	Satellite Oscillator Drift Rate	$(10^{-9})t$ sec
4	Satellite Oscillator Random Walk	$(10^{-10})\sqrt{t}$ sec
5	Satellite Oscillator Flicker Noise	$(1.33 \times 10^{-12})t$ sec
6	Residual Ionospheric Delay (E(t) = Elevation Angle at Receiver at Time t)	$8.3 \csc \sqrt{E(t)^2+(18\ \mathrm{deg})^2}$ ft
7	Residual Tropospheric Delay (≈10%)	$\csc [E(t)]$ ft
8	Speed of Light	1/3 ppm
9	Gravity Coefficients μ J_2 Other Spherical Harmonic Coefficients	 2.79×10^{10} ft^3/sec^2 0.1 % 20 %
10	TOA Measurement Quantization	1 ft

frequency offset) of 10^{-9} is based on the design requirements for the satellite navigation signal generator. The remaining two terms, a random walk and flicker noise, are random errors whose future values cannot be predicted based on their present values. Of these two terms, the flicker noise, or fractional Brownian motion term is predominant in the long term. Its statistics were obtained from a study by Barnes (Ref. 5). The less critical random walk statistics were somewhat arbitrarily selected such that the resulting rms position error would not exceed 6 ft after 1 hr.

The form used for the rms residual ionospheric delay term can be found in several empirical studies, e.g., Ref. 6. The values of the two numerical constants used in the expression are typical of the values found in the various reports.

The tropospheric delay is corrected by an expression of the form

$$\Delta T = -K \csc E(t) \tag{21}$$

where K is typically 8.8. For this study, the rms correction error is assumed to be approximately 10 percent of the correction.

The speed of light uncertainty of 1/3 ppm is based on current measurement accuracy.

The uncertainty used for μ, or GM (gravitational constant time earth mass), is a fairly well accepted value associated with recent determination of gravity potential spherical harmonic coefficients, such as the DODWGS66 set. The rms value of 20 percent applied to the spherical harmonic coefficients in a rough estimate obtained by comparing several different sets of harmonic coefficients. This value is not critical since the uncertainty in μ is the major gravity model error contributor.

The value for TOA measurement quantization is an upper bound based on the radar range equation, which expresses the range uncertainty in terms of transmitter power, gains, path length, thermal noise, etc. The actual value computed was much less than 1 ft.

2.4.2.2.3 Reference Trajectory and Tracking Data

As discussed in Section 2.4.1, the satellite constellation is made up of nine satellites in inclined orbits and six in geostationary equatorial orbits. For purposes of tracking subsystem accuracy evaluation, a single satellite in the inclined orbit was selected to define the reference trajectory for the following reasons:

(1) Due to the number of satellites in inclined orbits and the path of their subsatellite points, they represent a more typical case for navigation and surveillance usage, especially in the CONUS.

(2) The inclined orbit is more susceptible to gravity field perturbations and, in this sense, is a "worst-case" compared with the equatorial orbit.

(3) The equatorial, circular orbit is a special case which represents a singular point in the general formulation of the orbit equations. The additional information to be gained does not justify reformulating the problem to handle this case.

A satellite may be tracked by one or more of the seven STC's from which the satellite is visible. This analysis assumes continuous data from Palmdale, CA, Fort Worth, TX, and Hilliard, FL, STC's as they track the selected satellite whenever it is visible. From these locations, the satellite is visible to all three STC's about 72 percent of the time and slightly longer for two of them. With these assumed tracking configurations and data sources, the state covariance matrix was propagated for a sufficient number of segments to achieve a steady state estimation error. Then, the state covariance matrix was propagated an additional 8 hr, assuming no more tracking data, to characterize the prediction effects.

2.4.2.2.4 Unmodeled Errors

The mechanization and performance evaluation of the tracking subsystem thus far discussed implies that no external forces other than the earth's gravity acts on the satellite. This section discusses the effects of other perturbative forces such as lunar and solar gravity, solar radiation pressure, and atmospheric drag. The main factors determining the relative importance of these effects for the present case are as follows:

(1) Radial distance of the orbit from the geocenter

(2) The procedure of frequent and continuous ephemeris updates

The first factor, distance from the geocenter, is sufficient to determine that atmospheric drag is negligible. According to Ref. 7, at the altitudes being considered, perturbative accelerations due to solar and lunar gravity effects are both of the order of 10^{-5} ft/sec^2, while that due to atmospheric drag is of the order of 10^{-8} ft/sec^2. For purposes of comparison, the oblateness term (first zonal harmonic) of the earth's gravity field is of the order of 10^{-5} ft/sec^2.

Solar radiation pressure effects are a function of the satellite cross-sectional area to mass ratio. Using preliminary design information and assuming worst-case reflectivity characteristics, the magnitude of the perturbative acceleration due to this effect was computed to be of the order of 10^{-7} ft/sec^2. The calculation is based on the results of a development by Koskela (Ref. 8).

For the present case then, atmospheric drag and solar radiation pressure are the least important of the perturbative effects being considered. If ephemeris predictions were required over many revolutions of the satellite, the secular effects of these perturbations would become significant. However, since predictions are only required for 8-hr periods with continuous re-initialization and estimation of the satellite ephermeris, these two terms can safely be neglected.

Solar and lunar gravity effects, however, must clearly be considered. These terms were not included in the performance evaluation, either for reference trajectory propagation or as error model terms. It is planned, however, that they will be included in the operational mechanization for reference trajectory propagation as temporal terms in the gravity potential function. Since they can be accurately defined, their omission here does not limit the accuracy of the performance evaluation results.

2.4.2.2.5 Summary of Performance Evaluation Results

As previously mentioned, the evaluation results are based on the use of three tracking sites with the inclined orbit as the reference trajectory rather than the geostationary equatorial orbit. The results obtained are felt to be representative of both types of orbit and may be an upper bound for the equatoral orbit case, since the latter is not sensitive to earth model oblateness perturbations and since only three tracking sites were assumed.

Results are expressed as estimation uncertainties (one-sigma errors) of position and inertial velocity. The uncertainties are presented in an orthogonal coordinate system, defined as follows:

Radial - Upward, along a geocentric vertical

Tangential - Tangent to the orbit, in direction of motion

Normal - Perpendicular to the orbital plane and completes the right-hand set

Results obtained by propagating the uncertainties show that initial estimates are in a transient response state. After several revolutions, the transient effects begin to diminish, but no results were propagated for a sufficiently long time to actually obtain steady-state estimates. This effect is graphically depicted in Fig. 2.4-14, which is a plot of radial position uncertainties. The maximum and minimum position uncertainties on the fourth day are listed in Table 2.4-4.

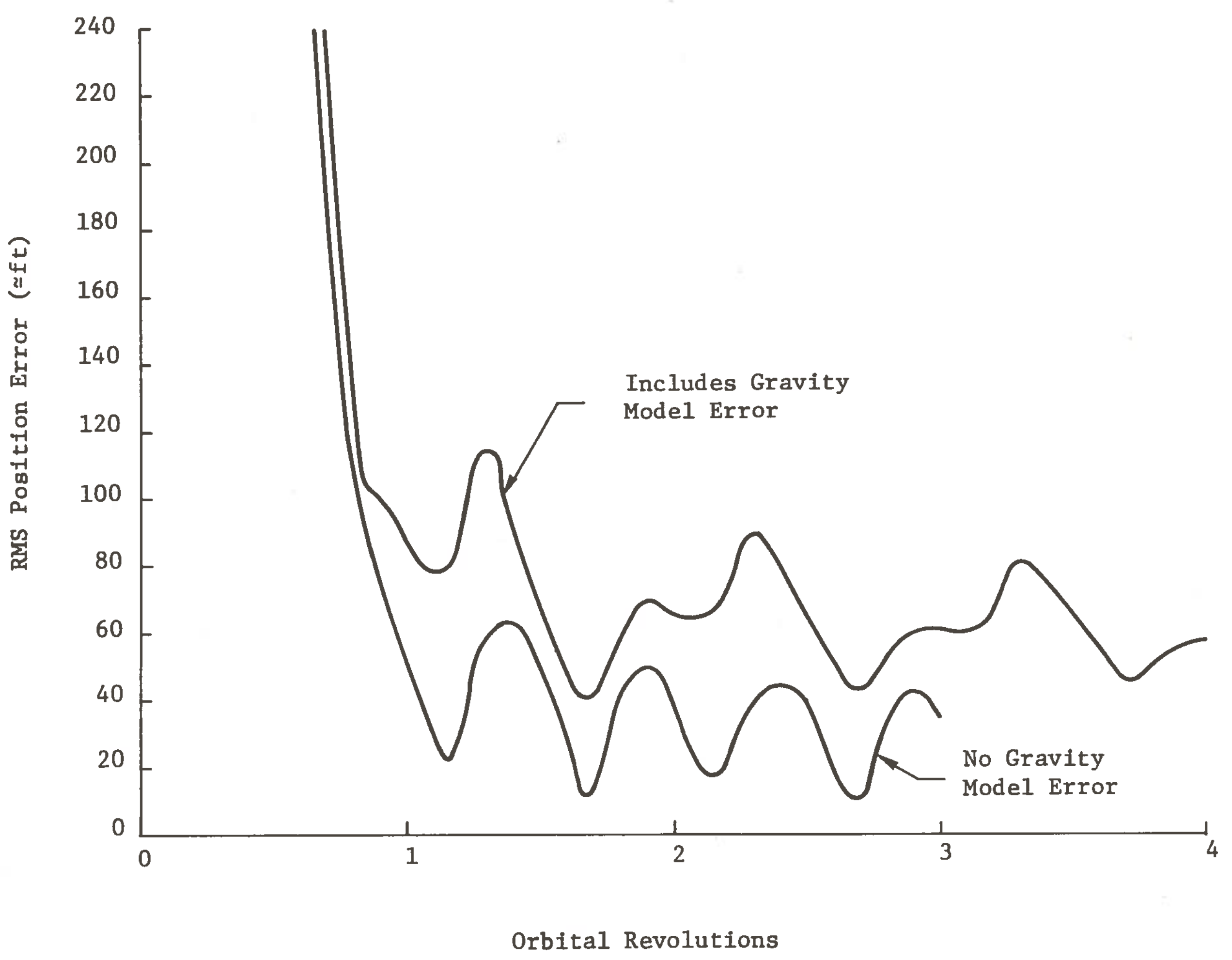


Fig. 2.4-14. Radial Position Estimation Uncertainty, Three Tracking Sites

Table 2.4-4. Maximum and Minimum Position Uncertainties

Satellite Position Uncertainties (ft)		
Coordinate	Maximum Value	Minimum Value
Radial	80	45
Tangential	260	195
Normal	170	20

It is emphasized that these results assume data from three STC's tracking the satellite for four revolutions. At this point, the magnitudes of the oscillations in the uncertainties are still decreasing somewhat from one revolution to the next. It is also clear that use of data from more than three STC's will further decrease the uncertainties. Therefore, these results are properly interpreted as conservative estimates of the attainable tracking subsystem accuracy.

When considering the effect of ephemeris errors on navigation and surveillance accuracies, the radial component of the position error is of primary importance. This is obvious from geometry, since the altitude of the satellites is several orders of magnitude greater than that of the aircraft. Based on the present results, a reasonable estimate of the ultimate steady-state radial position error is 50 to 60 ft rms for three tracking sites.

It has been determined that the principal contributor to the total ephemeris error is the uncertainty in the gravity constant μ. The results are highly sensitive to the statistics and error propagation model assumed for this term. Figure 2.4-14 shows the difference in the radial estimation uncertainty due to gravity model errors. It is obvious that if the uncertainty in μ and the other gravity coefficients can be reduced, much greater tracking accuracies can be obtained. A detailed discussion of the tracking subsystem error analysis, including presentation of results showing the effects of the various error contributions, is presented in Volume IX.

It should be noted that these results assume no significant unmodeled errors. In the presence of unmodeled errors, which is the general case, the actual estimation error uncertainties will diverge from the results presented here after a sufficiently long time interval. Several techniques, similar to that presented in Ref. 9, have been developed for preventing divergence. In the present case, small unmodeled errors do exist, including the solar radiation pressure and atmospheric drag effects previously discussed. A method such as that in Ref. 9 could be applied. However, a simple scheme could be adequate for the present case due to the continuous nature of the estimation and prediction process. After some relatively long time interval to be optimally selected (probably on the order of weeks), the estimation error covariances for position and velocity, and possibly for satellite oscillator drift rate, would be reinitialized to their a priori values. The reference trajectory would be set to the current best estimate. The new error covariances would be propagated in parallel with the old set, until the new or re-initialized estimation process approached steady state. Then the old set would be discontinued and all results would be based on the new solution. In this way, the long term effects of unmodeled error would not continue to accumulate.

2.4.3 References

1. Concept Formulation Studies of the Surveillance Aspects of the Fourth Generation Air Traffic Control System; ATC-7 Project Report; Massachusetts Institute of Technology, Lincoln Laboratory, 21 September 1971

2. C72-1206.1/201, Preliminary Technical Report, System A Concept Definitions, Advanced Air Traffic Management System (AATMS), DOT-TSC-508, December 1972

3. C71-61/301, Fourth Generation Air Traffic Study; June 1972, Autonetics, Anaheim, California

4. AFETR Geodetic Coordinates Manual, June 1968

5. "Atomic Timekeeping and the Statistics of Precision Signal Generators," James A. Barnes, IEEE Proceedings, February 1966

6. "Ionospheric Correction to Tracking Parameters," J.J. Freeman Associates, Final Report NASA Contract NAS 5-9782, November 1965

7. "Prediction of the Position and Velocity of a Satellite After Many Revolutions," C.I.T. J.P.L. TR-32-1267, Contract No. NAS 7-100, April 1970

8. "Orbital Effects of Solar Radiation Pressure on an Earth Satellite," P.E. Koskela, J. Astronautical Science, Fall 1962

9. "Decision-Directed Adaptive Recursive Estimator: Divergence Prevention," Nahi and Schaeffer, IEEE Transactions on Automatic Control, February 1972

3. SYSTEM SPECIFICATION FOR SAATMS

A preliminary system specification for the SAATMS is presented in Appendix A. The specification is based upon data presented in Section 2 of this volume and in Volumes III and IV of this report. The format used in developing the specification was modeled after MIL-STD-490A. To preserve that format and to make the specification a self-contained document within this volume, a separate numbering system was used. The specification outline is as follows:

1.0 Scope
2.0 Applicable Documents
3.0 Requirements
4.0 Quality Assurance
5.0 Preparation for Delivery
6.0 Notes
10.0 Appendix

Only sections 1.0 through 3.5 have been completed at this time.

APPENDIX SYSTEM SPECIFICATION

1.0 SCOPE

This specification establishes the system design and the system and subsystem performance requirements for the Satellite-Based Advanced Air Traffic Management System (SAATMS). The SAATMS is intended for the management of air traffic in the Continental United States of America (CONUS) and the contiguous land and oceanic regions in the period of 1995 and beyond.

2.0 APPLICABLE DOCUMENTS

The following documents of the exact issue shown form a part of this specification to the extent specified herein. In the event of conflict between the documents referenced herein and the contents of this specification, the contents of this specification shall be considered a superseding requirement.

2.1 Government Documents

Specifications: To be determined.

2.2 References

"Concept for a Satellite-Based Advanced Air Traffic Management System" Final Report, DOT-TSC-OST-73-29, prepared for Department of Transportation, Transportation Systems Center, Contract DOT-TSC-508-4, dated October 1973.

3.0 REQUIREMENTS

3.1 General Description

The SAATMS shall provide safe and economical management of air traffic in the Continental United States (CONUS) and adjacent oceanic regions. The system shall be capable of meeting the air traffic control demands forecast for the period 1995 and beyond. The system shall provide to the user the services required for safe and efficient operation during each phase of flight.

The system shall be based on the definition of operational requirements, system performance requirements, system implementation requirements, and subsystem performance requirements. The basic system shall be a satellite based system rather than a ground based system. The system shall be highly automated and shall require a minimum of operating personnel for manual control during normal operations.

The system operational requirements include flight services, user classes, airspace structure, and management concepts. The flight services define the services to be provided the user by the system. The user classes define the interfaces available between the system and user as a function of aircraft performance, pilot proficiency, and aircraft avionics. The airspace structure defines where and how aircraft may fly within the system. The management concept defines how the system is managed to optimize traffic flow and safety.

The system performance requirements include system safety and capacity. Capacity requirements include both system demand levels and system delays.

The system implementation requirements shall specify the number and type of ground facilities associated with the system, the satellite constellation requirements, and the user equipment requirements.

The system shall be based on the definition of three types of aircraft operations, i.e., controlled, cooperative, and uncontrolled. Of these only the first two shall be active participants in the system and shall be provided services. The third category of operational aircraft shall be restricted to certain uncontrolled airspace. Controlled aircraft shall be required to file a flight plan with the system, to operate in accordance with the assigned route, and to carry certain avionics equipment. The cooperative aircraft shall not be required to file a flight plan nor operate in accordance with an assigned route, but shall be required to carry certain minimum avionics equipment.

The system shall employ a constellation of satellites which shall provide coverage of CONUS and contiguous regions. Coverage shall be defined such that it allows specific performance of surveillance, navigation, and communications subsystem performance. Ground facilities to interface with the satellite constellation shall be provided.

The ground facilities shall provide for interface with the satellite constellation, for satellite tracking and control, for surveillance and navigation computations, for user and ground facility intercommunications, for air traffic command and control, and for implementation of the system management concept. Three major jurisdictional elements shall be defined: Continental Control Center (CCC), Regional Control Center (RCC), and Airport Control Center (ACC).

There shall be one CCC located centrally within CONUS. This center shall serve as the executive command and monitor center for the entire system during normal system operation. In the event of a catastrophic failure of either or both RCC's, or in the event of a national emergency, the CCC shall assume limited control of the entire system.

There shall be two RCC's; one located on the eastern edge and one located on the western edge of CONUS. The RCC's shall serve as primary command and control elements for their assigned regions. The RCC's shall have primary aircraft tracking responsibility for all active users within their regions. The RCC's shall have primary control responsibility for all aircraft within their respective regions except for those aircraft within ACC jurisdictions. All communications to and from users within the RCC's control jurisdiction shall be disseminated from and received at these centers during normal system operation. The RCC's shall be autonomous and shall provide normal services and intercommunicate data with users without reliance on the CCC.

The ACC jurisdiction shall be a region of approximately 5 mi radius about the runways of primary aircarrier airports and those secondary and feeder airports having manned control towers. There will be 600 to 800 ACC's with the exact number fluctuating diurnally with control tower manning levels. The ACC's have primary command and control responsibility for all aircraft within their jurisdiction. All ground surveillance and control and runway management control shall be within the domain of ACC's. Communications to all aircraft in the ACC jurisdiction shall be handled through the ACC.

The subsystems associated with the system shall include surveillance, navigation, communication, and satellite tracking. All of these subsystems shall be implemented through the satellite constellation in conjunction with ground facilities and user equipment as applicable.

The surveillance subsystem shall maintain an active file on the status, position, and velocity of each active user in the system. Each RCC shall contain provisions to serve approximately 60 percent of the peak Instantaneous Airborne Count (IAC). The CCC shall contain provisions to serve 100 percent of the peak IAC.

Two independent methods shall be used to provide navigation data to users for flight conformance implementation. One navigation method shall be provided via the satellite constellation and shall be independent of the surveillance subsystem. The other method shall consist of ground facility computation of navigation quantities for transmission to users over the communications subsystem. The ground computations shall be based on data provided by the surveillance subsystem.

The communications subsystem shall provide for the interconnection of all ground based facilities and for the interconnection of users and ground based facilities. The primary communications interconnection links shall be digital links. Secondary voice links shall be provided for user to ground facility intercommunications.

The satellite tracking subsystem shall provide for the positional prediction of all satellites in the constellation. This subsystem shall support surveillance, navigation, and communication subsystem functional and performance requirements.

3.2 Operational Requirements

3.2.1 Introduction

The operational requirements shall define the flight services, user classes, airspace structure, and management concepts. These requirements shall constitute the operational architecture for the system.

3.2.2 Flight Services

3.2.2.1 Flow Planning

The system shall assist the user in selecting the optimal routes from an economical and weather point of view. This shall include providing weather, traffic, and flight advisory data for use in preparing flight plans. Facilities shall be provided for submitting, revising, and approving flight plans. Provisions for disseminating approved flight plans to cognizant facilities shall be included. Methods for users to modify their flight plans in flight shall be included.

3.2.2.2 Separation Assurance and Advisories

The system shall provide a method for controlling each active user in controlled and cooperative airspace in a manner such that conflicts with other users are prevented. The system shall provide advisories to controlled and cooperative users in uncontrolled and oceanic airspace of potential conflicts with other controlled and cooperative aircraft. The system shall provide traffic advisories to users within airport jurisdictions that do not contain ACC's.

3.2.2.3 Boundary Control and Advisories

The system shall set the boundaries for various airspace regions, including buffer zones. It shall control or advise users as required to maintain the airspace integrity. Cooperative users shall be controlled to prevent their intruding into controlled airspace. Controlled users shall be advised of their transition into cooperative, uncontrolled, or oceanic airspace. Cooperative users shall be advised of their transition into uncontrolled or oceanic airspace. Controlled and cooperative users shall be controlled to prevent their intrusion into restricted airspace. All users shall be advised of their transition from one jurisdiction to another jurisdiction, i.e., RCC to RCC, ACC to RCC, RCC to ACC, or RCC to airport jurisdiction without an ACC.

3.2.2.4 Flight Plan Conformance

The system shall provide navigation data to users to allow flight plan conformance to be achieved. Flight plan conformance shall be the user's responsibility.

3.2.2.5 Navigation

The system shall provide navigation services for several flight phases. Satellite navigation and/or surveillance derived navigation shall be provided to all active users. The system shall provide approach and landing navigation at all primary aircarrier ACC's for use under Instrument Meteorological Conditions (IMC). The system shall provide navigation control in IMC at primary aircarrier ACC's on runways, taxiways, and ramps.

3.2.2.6 Flight Advisory Services

The system shall provide weather and traffic information and other supplementary data to users on a request basis.

3.2.2.7 Emergency Services

The system shall perform the necessary monitor functions to detect system or user contingency conditions. The system shall inform all affected users of emergency conditions and shall assist users as required. The system shall initiate and coordinate search and rescue operations.

3.2.2.8 Weather Services

The system shall collect and collate weather data at frequent intervals. These data shall be disseminated for the purposes of flight planning and for flight advisories.

3.2.2.9 Statistical Service

The system shall collect, store, and analyze data pertaining to system operation. These data shall be used to evaluate system performance, plan for system growth, and aid in flight planning.

3.2.2.10 Arrival Transition and Approach Control

The system shall provide for control of aircraft in the arrival transition and approach zone associated with primary aircarrier ACC's and some secondary and feeder ACC's. The control shall be in the form of metering, spacing, sequencing, and merging control to optimize airport capacity.

3.2.3 User Classes

3.2.3.1 Aircraft Performance Classes

Aircraft performance classes shall be divided into three categories. An individual aircraft may be in one or more category depending on the aircraft characteristics during flight phase.

3.2.3.1.1 Class 1 - Class 1 aircraft shall have a cruise altitude of between 3,000 and 12,000 feet, a cruise speed between 90 and 200 knots, a landing speed of less than 100 knots, and a gross weight of less than 12,500 pounds.

3.2.3.1.2 Class 2 - Class 2 aircraft shall have a cruise altitude between 10,000 and 29,000 feet, a cruise speed between 200 and 400 knots, a landing speed between 100 and 120 knots, and a gross weight between 13,000 and 100,000 pounds.

3.2.3.1.3 Class 3 - Class 3 aircraft shall have a cruise altitude of 30,000 feet and up, a cruise speed of 0.7 Mach and up, a landing speed of 120 knots and greater, and a gross weight between 20,000 and 700,000 plus pounds.

3.2.3.2 Pilot Proficiency

Pilot proficiency shall be categorized into four levels.

3.2.3.2.1 Level 1 - Level 1 is the highest level of pilot proficiency. This level shall consist of pilots capable of flying in controlled airspace and landing in Instrument Meteorological Conditions (IMC) (including use of the Microwave Landing System).

3.2.3.2.2 Level 2 - Level 2 category shall include pilots having the capability of the first level, except that they are training for IMC landings.

3.2.3.2.3 Level 3 - Level 3 shall be similar to Level 2, except that the pilots shall have no instrument landing capability and shall not be students acquiring such a capability.

3.2.3.2.4 Level 4 - Level 4 shall consist of all pilots capable of flying in cooperative airspace only.

3.2.3.3 Avionics Capability

3.2.3.3.1 Controlled Users - In order to fly in controlled airspace, users shall be required to carry the following avionics equipment: (1) surveillance transmitter, (2) two-way digital L-band communication, (3) two-way L-band voice communications, (4) satellite navigation processor, (5) satellite navigation display, (6) backup for all of the equipment in (1) through (5), and (7) a VVOR display and control panel.

3.2.3.3.2 Cooperative User - The cooperative user shall be required to carry the following avionics equipment: (1) a surveillance transmitter, (2) two-way digital L-band communications, (3) two-way L-band voice communications, and (4) a VVOR display and control panel.

3.2.3.3.3 Uncontrolled User - The uncontrolled user shall not be considered as participating in the system and has no required avionics equipment.

3.2.4 Airspace Structure

3.2.4.1 Enroute Airspace

Enroute airspace shall consist of controlled, mixed, cooperative, and oceanic regions.

3.2.4.1.1 Controlled Enroute - Controlled enroute airspace shall consist of all airspace above 12,000 ft Mean Sea Level (MSL) over the entire CONUS. The airspace shall be for the use of controlled aircraft only.

3.2.4.1.2 Mixed Enroute - Mixed enroute airspace shall consist of the airspace between 6,000 and 12,000 ft MSL over the CONUS region, except for designated high density terminal regions. Both cooperative and controlled aircraft shall be admitted to this airspace.

3.2.4.1.3 Cooperative Enroute - The cooperative enroute airspace shall extend from ground level to 6,000 ft MSL except for designated high density terminal regions and airport control zones. Only cooperative users shall be allowed into this airspace.

3.2.4.1.4 Oceanic Enroute - Oceanic enroute airspace shall consist of all airspace above MSL outside CONUS.

3.2.4.2 High Density Terminal Airspace

High density terminal regions shall consist of the airspace in the region surrounding a primary aircarrier ACC. Figure 1 shows a typical high density terminal airspace structure.

3.2.4.2.1 Terminal Control Airspace - The Terminal Control Airspace (TCA) shall consist of a cone extending 70 miles from the primary aircarrier airport. The top and bottom of this cone shall be 8° and 6° angles, respectively, from a 3° glide slope 3 mi from the runway. A 4 mi wide sector shall extend to 12,000 ft MSL where the cone shall widen until a 20 mi sector occurs 70 mi from the runway. The TCA shall be restricted to controlled aircraft that intend to land at the primary aircarrier airport.

3.2.4.2.2 Transition Airspace - The region below a TCA cone and above 12,000 ft MSL and extending from 70 to 100 mi from the TCA cone shall be termed transition airspace. This airspace shall be restricted to controlled aircraft awaiting a route assignment in TCA.

3.2.4.2.3 Departure Control and Transition Airspace - Departure transition and control airspace shall be structured similarly to TCA and transition airspace. Runway reversals shall be implemented by reversing the departure/arrival airspaces.

3.2.4.2.4 High Density Mixed Airspace - The high density mixed airspace shall consist of the airspace between 6,000 and 12,000 ft MSL, except for the TCA cone and ACC or airport airspace.

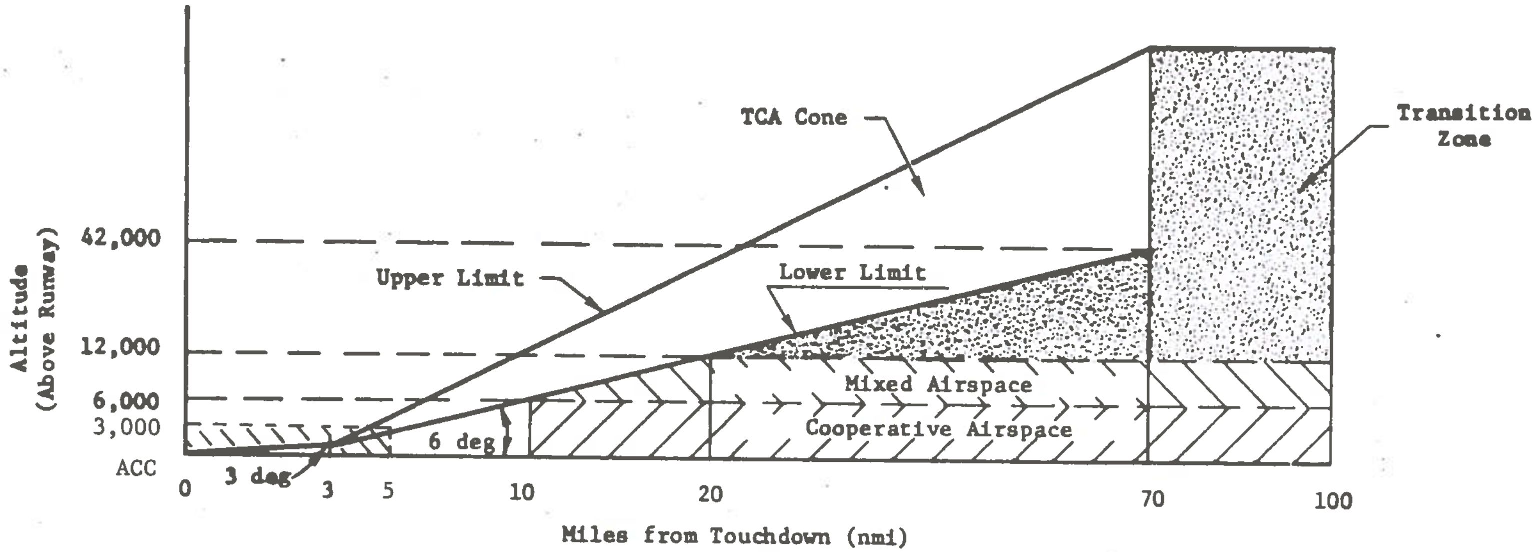
3.2.4.2.5 High Density Cooperative Airspace - High density cooperative airspace shall extend from ground level to 6,000 ft MSL, except for the TCA cone and ACC or airport airspace.

3.2.4.2.6 High Density Uncontrolled Airspace - There shall be no uncontrolled airspace within 20 mi of an ACC.

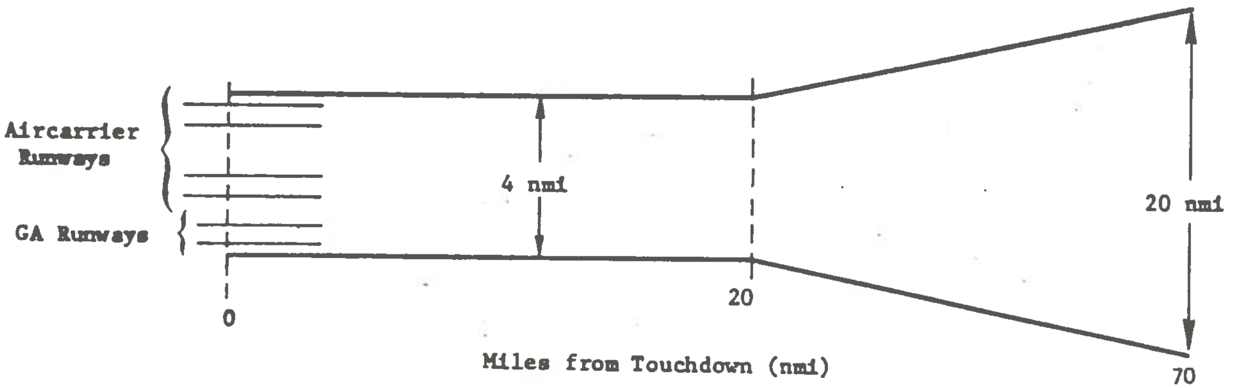
3.2.4.3 Airport Airspace

3.2.4.3.1 Controlled Airports - Primary aircarrier ACC's shall contain segregated aircarrier and General Aviation (GA) runways and shall be designated controlled airports. The jurisdictional boundary shall extend from ground level to 3,000 ft Above Ground Level (AGL) over an area about the runways with approximately a 5 mi radius. The terminal and departure control airspace shall be contiguous to this boundary.

3.2.4.3.2 Mixed/Cooperative Airports - Mixed/cooperative airports shall be defined as those airports with ACC's that are not controlled airports. The ACC jurisdictional boundary shall extend to a 5 mi radius about the runways from ground level to 3,000 ft AGL. Closure of the ACC facilities during low demand period shall change the airport status to an uncontrolled airport configuration.



TCA Profile



TCA Plan View

Figure 1. Terminal Control Airspace

3.2.4.3.3 Uncontrolled Airports - Uncontrolled airports shall be defined as airports without ACC's. The jurisdiction shall extend to a 1 mi radius around the runway from ground level to 1,200 ft AGL.

3.2.5 Management Concept

3.2.5.1 Controlled Airspace

The management concept for controlled airspace shall be as specified in Table 1.

3.2.5.2 Mixed and Cooperative Airspace

The management concept for controlled and cooperative aircraft in mixed airspace with ACC airports and for cooperative aircraft in cooperative airspace with ACC airports shall be as specified in Table 2. The management concept for cooperative aircraft operating in cooperative airspace with non-ACC airports shall be as specified in Table 3.

3.3 System Performance Requirements

3.3.1 Introduction

The system performance requirements shall define the system safety and capacity requirements for the SAATMS.

3.3.2 System Safety

3.3.2.1 Mid-Air Collision

The system design shall provide an equivalent calculated safety level such that no more than one mid-air collision in 10 years will result in controlled or cooperative airspace assuming no human blunder occurs. The model for determining collision risk is specified in Volume IX of the SAATMS Final Report.

3.3.2.2 Near Miss

The system design shall yield an equivalent, calculated safety level such that the probability shall be no less than 99.99% that two user aircraft will not approach closer than 350 ft in controlled or cooperative airspace in the face of a 2 g acceleration blunder by one user. The model for calculating conflict risk is specified in Volume V of the SAATMS Final Report.

3.3.3 System Capacity

3.3.3.1 Instantaneous Airborne Count

The system shall be capable of servicing an Instantaneous Airborne Count (IAC) of 40,000 aircraft from a total fleet of 362,000. Provision for expanded service levels to 100,000 IAC from a fleet of 1,000,000 users shall be provided.

Table 1. Management Concept, Controlled Airspace

Flight Phase	Planning		Path Conformance		Conflict Intervention	
	Prime	Backup	Prime	Backup	Prime	Backup
Preflight	GS - 3D	GS	NA	NA	NA	NA
Departure Taxi	GT - 2D	GT - 2D	A	G	G	A
Takeoff	GT - 2D	GT - 2D	A	G	G	A
Departure	GT - 2D	GT - 2D	A	G	G	G
Departure Transition	GT - 3D	AT - 3D	G	A	G	A
Cruise CONUS	GT - 3D	GT - 3D	A	A	G	A
Cruise Oceanic	GT - 3D	AT - 3D	A	A	A	G Advisories
Arrival Transition	GT - 4D	GT - 4D	G	A	G	A
Arrival	GT - 4D	GT - 4D	A	G	G	A
Approach	GT	AT	A	A	G	A
Landing	GT	AT	A	A	NA	NA
Arrival Taxi	GT	GT	A	G	G	A
Postflight	GT Close Flight Plan	NA	NA	NA	NA	NA

A - Air Managed
G - Ground Managed
S - Strategic Managed
T - Tactical
NA - Not Applicable

Table 2. Management Concept, Mixed Airspace, Secondary and Feeder Airports with Control Towers

Flight Phase	User Class	Planning		Path Conformance		Conflict Intervention	
		Prime	Backup	Prime	Backup	Prime	Backup
Preflight	Controlled	GS	GS	NA	NA	NA	NA
	Cooperative	AS	GS Advisories	NA	NA	NA	NA
Departure Taxi	Controlled	GT	G	A	G	A	G Advisories
	Cooperative	GT	G	A	G	A	G Advisories
Takeoff	Controlled	GT	GT	A	G	A	G Advisories
	Cooperative	GT	GT	A	G	A	G Advisories
Departure	Controlled	GT	GT	A	G	G	A
	Cooperative	AT	NA	A	NA	G	A
Departure Transition	Controlled	GT	AT	A	G	G	A
	Cooperative	NA	NA	NA	NA	NA	NA
Cruise	Controlled	GT	GT	A	A	G	A
	Cooperative	AT	NA	A	NA	G	A
Arrival Transition	Controlled	GS	GT	A	G	G	A
	Cooperative	NA	NA	NA	NA	NA	NA
Arrival	Controlled	GT	GT	A	G	G	A
	Cooperative	GS	AT	A	G	G	A
Approach	Controlled	GS	GT	A	A	A	G Advisories
	Cooperative	GS	GT	A	A	A	G Advisories
Landing	Controlled	GT	AT	A	A	NA	NA
	Cooperative	GT	AT	A	A	NA	NA

A - Air Managed
G - Ground Managed
S - Strategic
T - Tactical
NA - Not Applicable

Table 2. (continued)

Flight Phase	User Class	Planning		Path Conformance		Conflict Intervention	
		Prime	Backup	Prime	Backup	Prime	Backup
Arrival Taxi	Controlled	GT	GT	A	G	A	G Advisories
	Cooperative	GT	GT	A	G	A	G Advisories
Postflight	Controlled	GT	NA	NA	NA	NA	NA
	Cooperative	NA	NA	NA	NA	NA	NA

A - Air Managed
G - Ground Managed
S - Strategic
T - Tactical
NA - Not Applicable

Table 3. Management Concept, Cooperative Aircraft Operating from Airports Without Control Towers

Flight Path	Planning	Path Conformance	Conflict Intervention
Preflight	GS Traffic Pattern; No Clearances Required	NA	NA
Departure Taxi	AT Clearance Required From RCC to Enter System	A	A
Takeoff	GS Traffic Pattern	A	A
Departure	AT	A	A Until Aircraft Crosses 1 nmi Boundary; Then G
Cruise	AT	A	G Prime; A Backup
Arrival	AT	A	G Until Aircraft Enters Pattern; Then A
Approach	GS Traffic Pattern	A	A
Landing	GS Traffic Pattern	A	A
Arrival Taxi	AT	A	A

A - Air Managed
G - Ground Managed
S - Strategic
T - Tactical
NA - Not Applicable

3.3.3.2 System Delay

The system design shall be such that the arrival and departure delays directly attributable to the system shall not exceed 6 min for 50% of user flights, shall not exceed 15 min for 90% of user flights, and shall not exceed 30 min for 99.9% of user flights.

3.4 System Implementation Requirements

3.4.1 Introduction

The system implementation requirements shall consider the quantities and types of facilities that are employed in the SAATMS. The functional and performance requirements of the facilities shall be considered. Specific performance requirements of the subsystems shall be specified in Section 3.5 and supplement the requirements listed herein.

3.4.2 Continental Control Center

3.4.2.1 General Description

The Continental Control Center (CCC) shall be the executive command and control monitor for the SAATMS. The CCC shall have sole responsibility for flow planning and control, some computer processing capability, and shall have the capability to provide system backup in the event of a failure in either or both Regional Control Centers. The major tasks of the CCC shall include interfacing with user and other ground facilities, performing automation tasks, monitoring the system status and reconfiguring the system as the result of functional failur interfacing with control personnel, and maintaining statistical and historical dat on system operation.

3.4.2.2 CCC Functional Requirements

3.4.2.2.1 Site Location - The CCC shall be centrally located in the CONUS region to provide maximal satellite visibility.

3.4.2.2.2 Automated Tasks - The CCC shall have the capability to perform the following automated tasks:

(a) Satellite Ephemeris Estimation
(b) Satellite Ephemeris Prediction
(c) Strategic Flow Planning
(d) Tactical Flow Planning
(e) Acquisition of Newly Entered System Users
(f) Surveillance Tracking
(g) Active Aircraft Status File Maintenance
(h) Conflict Prediction and Avoidance
(i) Intrusion Prediction and Avoidance
(j) Handoff Control
(k) VVOR Navigation Computation
(l) Transition and Arrival Control

(m) Aircraft-to-Ground Communication Decoding
(n) Ground-to-Aircraft Message Formulation
(o) Ground-to-Ground Communication
(p) Display and Man/Machine Processing
(q) System Test
(r) Executive Functions

Items (e) through (n) shall be performed as backup functions for the RCC's. Sufficient processing capability shall be provided to service 100% of the system IAC demand.

3.4.2.2.2.1 Ephemeris Estimation - The CCC shall estimate the ephemeris of each satellite in the SAATMS constellation from data collected by Satellite Tracking Centers (STC).

3.4.2.2.2.2 Ephemeris Prediction - The position of each satellite in the constellation shall be predicted eight hours in advance. The predictions shall be in terms of master time for use by the CCC and RCC surveillance routines and relative to satellite estimated navigation pulse times for satellite navigation usage.

3.4.2.2.2.3 Strategic Flow Planning - The predicted density of future air traffic along the most heavily traveled routes and at major ACC's shall be computed. These data shall be used to prevent scheduled aircraft conflicts and minimize system delays.

3.4.2.2.2.4 Tactical Flow Planning - The CCC tactical flow plan shall be utilized to update the strategic flow plan based on increases or decreases of planned traffic and changing system conditions such as weather or runway closures.

3.4.2.2.2.5 Acquisition of Newly Entered Users - The CCC shall search for and acquire newly entered system users. Assignment to the correct RCC and verification of correct positional location shall be accomplished.

3.4.2.2.2.6 Surveillance Tracking - The CCC surveillance tracking function shall compute the position and velocity of each active user in the CONUS region. The surveillance algorithm shall be a recursive maximum likelihood estimator.

3.4.2.2.2.7 Active Status - The CCC shall maintain a file that contains surveillance data and other data pertinent to the user in the determination of his interaction with the system for each active system user.

3.4.2.2.2.8 Conflict Prediction and Avoidance - The CCC shall test the position and velocity of each active user to predict possible conflicts and compute user control commands required to prevent conflict. These data shall be used to monitor RCC operation during normal CCC operation and shall be used for system operation in backup modes.

3.4.2.2.2.9 Intrusion Prediction and Avoidance - The CCC shall test the position and velocity of each active cooperative user to predict the possible intrusion into controlled airspace and of each active user to predict the possible intrusion into restricted airspace for RCC monitor purposes. The CCC shall compute user control commands as required to prevent intrusion during backup modes of operation.

3.4.2.2.2.10 Handoff Control - The CCC shall determine the jurisdictional location of each active user in the system. These data shall be used for monitor purposes during normal CCC operation and shall be used to accomplish jurisdictional user handoffs during system backup operation.

3.4.2.2.2.11 VVOR Navigation - The CCC shall have the capability of providing surveillance-derived, VVOR navigation commands for transmission to users. This shall be employed during backup modes only.

3.4.2.2.2.12 Transition and Arrival Control - The CCC shall provide four dimensional monitoring and controls for all controlled aircraft within the transition and terminal control airspace. This function shall include merging, spacing, sequencing, and metering as required to minimize system delays and maximize airport capacity. This function shall be employed during system backup only.

3.4.2.2.2.13 Communication Processing - The CCC shall provide decoding for asynchronous aircraft to ground digital data messages and shall provide formatting and formulation algorithms for the generation of ground to aircraft digital data transmissions. These functions shall be provided for system backup only. The CCC shall provide formulation, formatting, and system timing controls for the insertion of navigation ephemeris data into all satellites. The CCC shall provide for master control and assignment of all ground to ground data links. The CCC shall monitor and reconfigure the assignments in the event of system, site, or satellite failures

3.4.2.2.2.14 Display and Man/Machine Processing - The CCC shall provide for the processing of display and man/machine interfaces required to provide for both normal, backup, and contingency system operation.

3.4.2.2.2.15 System Test - The CCC shall provide for automatic monitoring of all major system functions on a continuous basis and shall provide for system maintenance testing on a periodic basis.

3.4.2.2.2.16 Executive Functions - The CCC shall provide for the supervision and management of the overall SAATMS as well as the CCC specific functions. The executive functions shall include allocation of processing equipment, resolution of usage conflicts of equipment, and reconfiguration of system hardware and software as required due to failures or maintenance outages.

3.4.2.2.3 Communications - The CCC shall provide for the following communications functions

(a) Transmission of ground-to-aircraft digital data

(b) Transmission of ground-to-aircraft voice data
(c) Reception of aircraft-to-ground digital data
(d) Reception of aircraft-to-ground voice data
(e) Transmission of navigation ephemeris data to all satellites
(f) Transmission and reception of ground-to-ground digital data
(g) Reception of surveillance data

3.4.2.2.9 Master Timing - The CCC shall contain the master clock for the SAATMS system and shall provide for the synchronization of all RCC and ACC clocks to this master clock.

3.4.2.2.5 Reliability - The CCC shall have sufficient functional and equipment redundancy to preclude single equipment failures from causing loss or degradation of any CCC function.

3.4.2.3 CCC Performance Requirements

3.4.2.3.1 Strategic Flow Planning - The CCC shall compute the strategic flow plan at least once per day utilizing a minimum of 4,000 check points and 100 time intervals.

3.4.2.3.2 Surveillance Data Transmission - The CCC shall transmit the identification and surveillance data of all active users within 20 mi of an ACC to that ACC if the associated RCC function has failed.

3.4.2.3.3 Probability of Intrusion - The CCC shall provide intrusion buffer zones that provide an equivalent calculated maximum intrusion rate of one aircraft per month assuming no user blunder.

3.4.3 Regional Control Centers

3.4.3.1 General Description

The Regional Control Centers (RCC) shall be the primary command and control elements for their assigned jurisdictional regions. The RCC shall have primary surveillance for all active users in their jurisdiction and shall have primary control responsibility for all users in their jurisdictional area except for those users in ACC or airports. The major tasks of the RCC shall be interfacing with the users and with other ground facilities, performing automation tasks, interfacing with control personnel, and controlling the region as directed by the CCC.

3.4.3.2 RCC Functional Requirements

3.4.3.2.1 Site Locations - One RCC shall be located on the eastern edge of CONUS and one on the western edge of CONUS to provide maximal satellite visibility for oceanic aircraft.

3.4.3.2.2 Automated Tasks - The RCC shall have the capability to perform the following tasks automatically:

(a) Acquisition of Newly Entered System Users
(b) Surveillance Tracking
(c) Active Aircraft Status File Maintenace
(d) Conflict Prediction and Avoidance
(e) Intrusion Prediction and Avoidance
(f) Handoff Control
(g) VVOR Navigation
(h) Transition and Arrival Control
(i) Aircraft-to-Ground Communication Decoding
(j) Ground-to-Aircraft Message Formulation
(k) Ground-to-Ground Communication
(l) Display and Man/Machine Processing
(m) System Test
(n) Executive Functions

Sufficient processing capability shall be provided to service approximately 60% of the IAC demand.

3.4.3.2.2.1 Acquisition of Newly Acquired Users - The RCC shall search for and acquire newly entered system user within its jurisdiction.

3.4.3.2.2.2 Surveillance Tracking - The RCC surveillance tracking function shall compute the position and velocity of each active user in the jurisdictional region. The surveillance algorithm shall be a recursive maximum likelihood estimator.

3.4.3.2.2.3 Active Status - The RCC shall maintain a file that contains surveillance data and other data pertinent to the user in the determination of his interaction with the system for each active user in the RCC jurisdiction.

3.4.3.2.2.4 Conflict Prediction and Avoidance - The RCC shall test the position and velocity of each active user in the RCC jurisdiction to predict possible conflicts and shall compute and transmit to users control commands required to prevent conflicts.

3.4.3.2.2.5 Intrusion Prediction and Avoidance - The RCC shall test the position and velocity of each active cooperative user to predict the possible intrusion into controlled airspace and of each controlled and cooperative user to predict the possible intrusion into restricted airspace. The RCC shall compute and transmit control commands as required to prevent intrusions.

3.4.3.2.2.6 Handoff - The RCC shall determine the jurisdictional location of each active user being tracked. These data shall be used for control purposes within the RCC domain and to transfer surveillance responsibility to the other RCC.

3.4.3.2.2.7 VVOR Navigation - The RCC shall compute surveillance-derived VVOR navigation commands for all requesting aircraft in the RCC domain and transmit these commands to the users.

3.4.3.2.2.8 Transition and Arrival Control - The RCC shall provide four dimensional monitoring and control for all controlled aircraft in transition and terminal control airspace within the RCC domain. This function shall include merging, spacing, sequencing, and metering as required to minimize system delays and maximize airport capacity.

3.4.3.2.2.9 Communications Processing - The RCC shall provide decoding for asynchronous aircraft-to-ground digital data messages and shall provide formatting and formulation algorithms for ground-to-aircraft and ground-to-ground digital messages.

3.4.3.2.2.10 Display and Man/Machine Processing - The RCC shall provide for the processing of display and man/machine interfaces required to provide for both normal and contingency system operation.

3.4.3.2.2.11 System Test - The RCC shall provide for automatic monitoring of all major RCC functions and shall provide for system maintenance testing on a periodic basis.

3.4.3.2.2.12 Executive Functions - The RCC shall provide for the supervision and management of the RCC specific functions. The executive functions shall include allocation of processing equipment, resolution of usage conflicts of equipment, and reconfiguration of RCC hardware and software as required due to failures or maintenance outages.

3.4.3.2.3 Communications - The RCC shall provide for the following communications functions:

(a) Transmission of ground-to-aircraft digital data
(b) Transmission of ground-to-aircraft voice data
(c) Reception of aircraft-to-ground digital data
(d) Reception of aircraft-to-ground voice data
(e) Transmission and reception of ground-to-ground digital data
(f) Reception of surveillance data

3.4.3.2.4 Clock - The RCC shall contain a clock which shall be synchronized to the CCC master time. In the event of a CCC master time failure, one RCC clock shall be used for system master timing.

3.4.3.2.5 Reliability - The RCC shall have sufficient functional and equipment redundancy to preclude single equipment failure from causing loss or degradation of any RCC function.

3.4.3.3 RCC Performance Requirements

3.4.3.3.1 Surveillance Transmission - The RCC shall send the identification and surveillance data of all active users within 20 mi of an ACC to that ACC for each of the ACC's in the RCC's domain.

3.4.3.3.2 Probability of Intrusion - The RCC shall provide intrusion buffer zones that provide an equivalent calculated maximum intrusion rate of one aircraft per month assuming no user blunders.

3.4.4 Airport Control Centers

3.4.4.1 General Description

The Airport Control Centers (ACC) shall be the primary command and control elements for their assigned jurisdictional regions. All ground surveillance and control; airport arrival and departure control; and runway, ramp, and gate management control shall be accomplished by the ACC.

3.4.4.2 ACC Functional Requirements

3.4.4.2.1 Site Locations - An ACC shall be located at all primary aircarrier airports and secondary and feeder airports with manned control towers.

3.4.4.2.2 Communications - The ACC shall provide for the following communications functions from ACC directly to the user:

(a) Transmission of ground-to-aircraft digital data
(b) Transmission of ground-to-aircraft voice data
(c) Reception of aircraft-to-ground voice data
(d) Transmission and reception of ground-to-ground digital data

3.4.4.2.3 Surveillance - The ACC shall provide for the reception of the identification and surveillance data for all users within 20 mi of the ACC. These data shall be used for arrival, departure, and runway management.

3.4.4.2.4 Local Surveillance and Control - The ACC shall have a local surveillance and control system to provide for runway, ramp, and gate control and management.

3.4.4.2.5 Instrument Landing System - The ACC shall have an Instrument Landing System to provide for user navigation during approach and landing.

3.4.4.3 ACC Performance Requirements

To be determined.

3.4.5 Satellite Constellation Requirements

3.4.5.1 Introduction

The satellite constellation is employed for relaying digital and voice communication between aircraft and ground, for relaying surveillance pulses from aircraft to the ground, for the transmission of navigation data, and for relaying data between ground sites.

3.4.5.2 Functional Requirements

3.4.5.2.1 Satellite Types - The satellite constellation shall be composed of geostationary satellites with equatorial subsatellite points and geosynchronous satellites. Some geostationary satellites shall be termed communications satellites.

3.4.5.2.2 Constellation Size - A minimum of 10 and a maximum of 18 satellites shall be employed. At least two and at most tour communications satellites shall be included in the constellation.

3.4.5.2.3 Satellite Functions - The satellites shall provide for the following functions:

(a) Relay of ground-to-aircraft digital data
(b) Relay of ground-to-aircraft voice data
(c) Relay of aircraft-to-ground digital data
(d) Relay of aircraft-to-ground voice data
(e) Relay of aircraft-to-ground surveillance data
(f) Generation and transmission of navigation timing pulses
(g) Reception and retransmission of ground generated ephemeris data

In addition, the communication satellites shall provide for the relay of ground-to-ground digital data.

3.4.5.2.3 RF Channels - All satellite to user transmission/reception RF channels shall be in the L-band spectrum (1535-1660 MHz). All satellite to ground transmission/reception RF channels shall be in the C-band spectrum (5000-5280 MHz). Table 4 lists the minimum channel requirements.

3.4.5.2.4 Navigation Timing - Satellite navigation timing pulses shall be transmitted each 3 to 8 seconds. Within 100 μsec of the timing pulse transmission, the satellite ephemeris data associated with the navigation pulse shall be transmitted.

3.4.5.2.5 Navigation Signal Spacing - The satellite design shall be such that navigation data from more than one satellite shall not occur during the same time period. Provisions to maintain a minimum time spacing of 0.15 second between satellite navigation data transmissions from different satellites shall be included.

3.4.5.2.6 Ground-to-Ground Communication - Communication satellite ground to ground channel spectrum allocation shall be the same for all equipped satellites to allow for ground frequency reallocation of channels in the event of a satellite failure.

Table 4 . Satellite RF Channel Minimum Requirements

FUNCTION	DATA	BAND	BAND WIDTH	NUMBER OF CHANNELS	
Transmission	Surveillance Data	C	21 MHz	3 - 6	(1)
	Navigation Timing	L	20 MHz	1	
	Ephemeris Data	L	15 MHz	1	
	A-G Digital Data	C	15 MHz	1	
	G-A Digital Data	L	15 MHz	3 @ 5 MHz	
	A-G Voice Data	C	5 MHz	200 @ 25 KHz	
	G-A Voice Data	L	5 MHz	200 @ 25 KHz	
	G-G Digital Data	C			(2)
Reception	Surveillance Data	L	20 MHz	1	
	Ephemeris Data	C	15 MHz	1	
	A-G Digital Data	L	15 MHz	1	
	G-A Digital Data	C	15 MHz	3 @ 5 MHz	
	A-G Voice Data	L	5 MHz	200 @ 25 KHz	
	G-A Voice Data	C	5 MHz	200 @ 25 KHz	
	G-G Digital Data	C			(2)

NOTES: (1) Satellite-to-ground 20 MHz channels may be spaced out to aid separation of adjacent satellite signals

(2) Band width plus space diversity to yield a minimum of 2000 channels of 5 KHz each.

3.4.5.2.7 Co-channel Interference - The satellite channel allocations shall preclude transmission and reception on the same frequency channels and shall be designed to minimize co-channel interference.

3.4.5.3 Performance Requirements

3.4.5.3.1 Constellation Coverage - The constellation primary coverage area shall be the Continental United States (CONUS) and the contiguous land and oceanic regions within 50 nmi of CONUS. The secondary coverage shall be the additional area bounded by longitudes 170 W and 40 W and latitudes 20 N to 75 N.

3.4.5.3.1.1 Primary Coverage Requirements - Within the primary coverage area, at least seven satellites shall be visible at all times over surveillance and navigation links given nominal system users. For a nominal user, the surveillance, navigation, and communication subsystem performance shall be as given in paragraph 3.5. For a combination of worst-case aircraft bank and low power surveillance transmitter (3 db below nominal), the surveillance degradation shall be no worse than 100%.

3.4.5.3.1.2 Secondary Coverage Requirements - Within the secondary coverage area, at least four satellites shall be visible at all times over surveillance and navigation links given nominal system users. For the nominal user, the surveillance, navigation, and communications shall be as given in paragraph 3.5.

3.4.5.3.1.3 Coverage Redundancy - The CONUS area satellite surveillance and navigation accuracy shall degrade by no more than 50% for any single satellite failure or non-availability, by no more than 75% for any combination of two satellite failures or non-availability, and by no more than 100% for any three satellite failures or non-availabilities.

3.4.5.3.2 Satellite Usable Life - The usable satellite life shall be measured in terms of the satellite reliability and orbit stability.

3.4.5.3.2.1 Orbit Stability - The satellite orbit stability shall be such that no more than 1°/year longitude precession occurs. Incline, eccentric orbit satellite shall be designed such that no more than 2°/year in-plane precession of the perigee point results. Active station keeping to achieve these values shall be permissible.

3.4.5.3.2.2 Reliability - The satellite equipment reliability (and expendable stores, if employed) shall result in a 95% probability that all functions will remain within specified performance limits for a seven year period.

3.4.6 Satellite Tracking Centers

3.4.6.1 General Description

The Satellite Tracking Centers (STC) shall be the primary sites for the collection of the data required to predict and estimate the ephemeris of each satellite in the SAATMS constellation.

3.4.6.2 STC Functional Requirements

3.4.6.2.1 Site Locations - The STC's shall be collocated facilities. The STC's shall be located at CCC, RCC, or ACC facilities as required to provide a minimum of three lines of sight to each satellite for at least 80% of the time each day.

3.4.6.2.2 Measurement Function - The STC's shall receive the navigation timing pulses from each satellite in its visibility range, preprocess the data, and transmit these data to the CCC via the collocated facility ground-to-ground communication link.

3.4.6.3 STC Performance Requirements

3.4.6.3.1 Data Reception - The navigation pulse reception system shall employ multiple antennas to insure a 99.9% probability of receiving each transmitted pulse for all satellites 10° or more above the STC's horizon.

3.4.6.3.2 Preprocessing - The preprocessor shall provide data to the CCC a minimum of 10 and a maximum of 15 times per hour.

3.4.7 Flight Service Station

3.4.7.1 General Description

The Flight Service Stations shall be the primary interface between users and the SAATMS for flight plan submittal and approval. The FSS shall provide weather and system status to the user to aid in flight planning and shall contain provisions for accepting, modifying, and approving flight plans.

3.4.7.2 FSS Functional Requirements

To be determined.

3.4.7.3 FSS Performance Requirements

To be determined.

3.5 Subsystem Requirements

3.5.1 Introduction

The subsystems to be considered shall include the surveillance, navigation, communication, and satellite tracking subsystems. The requirement shall be considered in terms of the individual subsystems functional and performance requirements. The specific site allocation of functional and performance requirement shall be indicated where appropriate.

3.5.2 Surveillance Subsystem

3.5.2.1 Introduction

The surveillance subsystem is employed in identifying and locating all active aircraft within the coverage area of the satellite constellation. The basic functional elements shall be as shown in Figure 2.

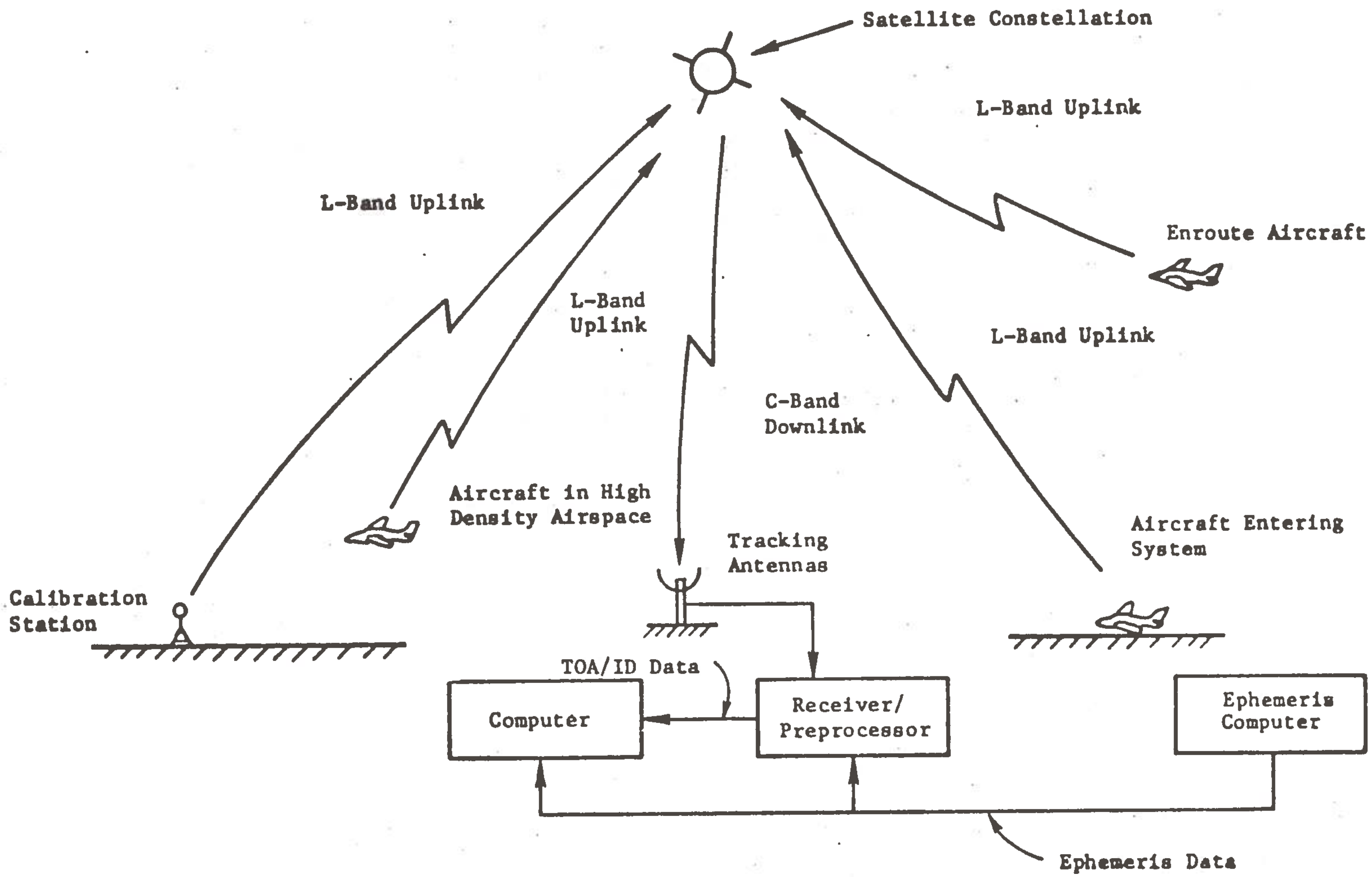


Figure 2. Surveillance Functional Elements

3.5.2.2 Functional Requirements

3.5.2.2.1 Surveillance Transmitters - All active aircraft in the system shall periodically transmit L-band surveillance signals encoded with an individually unique identification code for purposes of position location and identification. The surveillance transmission shall be asynchronous among users.

3.5.2.2.2 Satellite Relays - The individual satellites shall receive the L-band aircraft transmissions and relay the received surveillance data on C-band down links. Maximum efforts to limit the effect of adjacent satellite signal interference shall be employed regardless of satellite constellation temporal effects.

3.5.2.2.3 Signal Reception - C-band tracking antennas shall be provided to receive the retransmitted surveillance data at Regional and Continental Control Centers. Independent reception channels from each visible satellite shall be provided, along with a minimum of two spare tracking antennas and reception channels.

3.5.2.2.4 Surveillance Preprocessing - Provisions for the decoding of surveillance identification codes and measurement of their times of arrivals shall be provided for each reception channel at each control center.

3.5.2.2.5 Surveillance Acquisition - Provisions for the acquisition of newly entering aircraft shall be incorporated at each tracking site. Methods for rejecting false acquisitions shall be incorporated.

3.5.2.2.6 Surveillance Tracking - Provisions for the computation of the position and velocity of each active user shall be provided as a minimum at each tracking control center. Methods for the rejection of false surveillance data shall be incorporated.

3.5.2.2.7 Coding Recognition - Provisions for the rejection of non-issued identification sequences shall be included in each tracking site. Each tracking site shall be responsible for tracking aircraft within its jurisdictional region. All other surveillance signals shall be rejected at each tracking site.

3.5.2.2.8 Calibration Stations - Calibration stations shall be employed in high density regions to increase the absolute accuracy of the surveillance system.

3.5.2.2.9 Acquisition Requirements - Prior to active participation in the system, each newly entered aircraft shall be informed of his successful acquisition. Aircraft flight prior to acquisition shall be prohibited.

3.5.2.3 Surveillance Performance Requirements

3.5.2.3.1 Surveillance Transmission Requirements

3.5.2.3.1.1 Surveillance Coding - The identification coding embedded in the surveillance pulses shall be capable of uniquely identifying each aircraft in a fleet of 1,000,000 aircraft.

3.5.2.3.1.2 Transmission Timing - The surveillance signals shall be transmitted by each user at a minimum rate of once each eight seconds. A two second surveillance transmission rate will be employed for newly entered aircraft to distinguish them from aircraft being tracked.

3.5.2.3.1.8 Surveillance Transmitter Power - Independent of the surveillance mechanization coding scheme employed, the maximum surveillance transmitter power shall be limited to 2 kw peak power.

3.5.2.3.2 Satellite Relays - The satellite relays shall not introduce more than ±10 nsec transit delay from the mean satellite transit delay between reception and retransmission of surveillance data.

3.5.2.3.3 Tracking Site Requirements

3.5.2.3.3.1 Demand Requirements.- Each of the two Regional Control Centers shall have the capability to track a minimum of 20,000 active users. The Continental Control Center shall have the capability to track a minimum of 40,000 active users. The RCC's shall have the capability to handle up to 64,000 users without major equipment modification. The CCC shall have the capability to handle up to 100,000 users without major equipment modifications. The term without major equipment modification is meant to preclude receiver or decoding equipment redesign but will allow reconfiguration of processing equipment.

3.5.2.3.3.2 Acquisition - Each tracking site shall have the capability of acquiring newly entering users at a minimum rate of 50/sec. Acquisition shall require at least two receptions of surveillance pulses and no more than four, given nominal users.

3.5.2.3.4 Subsystem Accuracy

3.5.2.3.4.1 Analysis Baseline - The analysis baseline to be used for surveillance subsystem performance analysis shall consist of a scenario with the following parameters

(a) Flight speed = 400 knots
(b) Flight direction = West
(c) Velocity uncertainty = Random walk with along-track and vertical rms uncertainty of 0.22 $\sqrt{t}$ m/sec and cross-track rms uncertainty of 0.9 $\sqrt{t}$ m/sec.

The accuracy shall be stated in terms of the one sigma rms estimates of position and velocity errors after steady-state errors have been reached.

3.5.2.3.4.2 Accuracy in Primary Coverage Areas - The steady-state absolute errors shall be no more than the following:

Along-Track Position Error	36 m rms
Cross-Track Position Error	115 m rms
Vertical Position Error	48 m rms
Velocity Error	<1 m/sec rms

The steady-state absolute errors within 50 mi of a calibration station and the steady-state relative errors between aircraft with a 50 mi or smaller separation distance shall be no more than the following:

Along-Track Position Error	6 m rms
Cross-Track Position Error	7 m rms
Vertical Position Error	4 m rms
Velocity Error	<1 m/sec rms

3.5.2.3.4.3 Accuracy in Secondary Coverage Areas - The steady-state position and velocity errors shall be no more than four times the error requirements in the primary coverage areas

3.5.3 Navigation Subsystem

3.5.3.1 Introduction

The navigation subsystem provides navigation data to active users in the system so that flight path conformance can be accomplished. Both a satellite based (see Figure 3) and a surveillance derived (Virtual VOR) navigation subsystem are used.

3.5.3.2 Satellite Navigation Functional Requirements

3.5.3.2.1 Navigation Transmission - The navigation data transmissions shall be as specified in paragraph 3.4.5.2.4.

3.5.3.2.2 Aircraft Reception - The aircraft reception of navigation data shall include both precision measurement of the navigation timing pulse time of arrival and the decoding of the associated ephemeris data.

3.5.3.2.3 Navigation Mechanization - The aircraft satellite navigation mechanization shall include provision for estimating both the position and velocity of the aircraft and for synchronizing the user's clock to the ground master time.

3.5.3.3 Satellite Navigation Performance Requirements

3.5.3.3.1 Analysis Baseline - The baseline for navigation analysis shall be the same as for the surveillance analysis as specified in paragraph 5.2.3.4.1.

3.5.3.3.2 Accuracy in Primary Coverage Areas - The steady-state absolute navigation errors shall be no more than as follows:

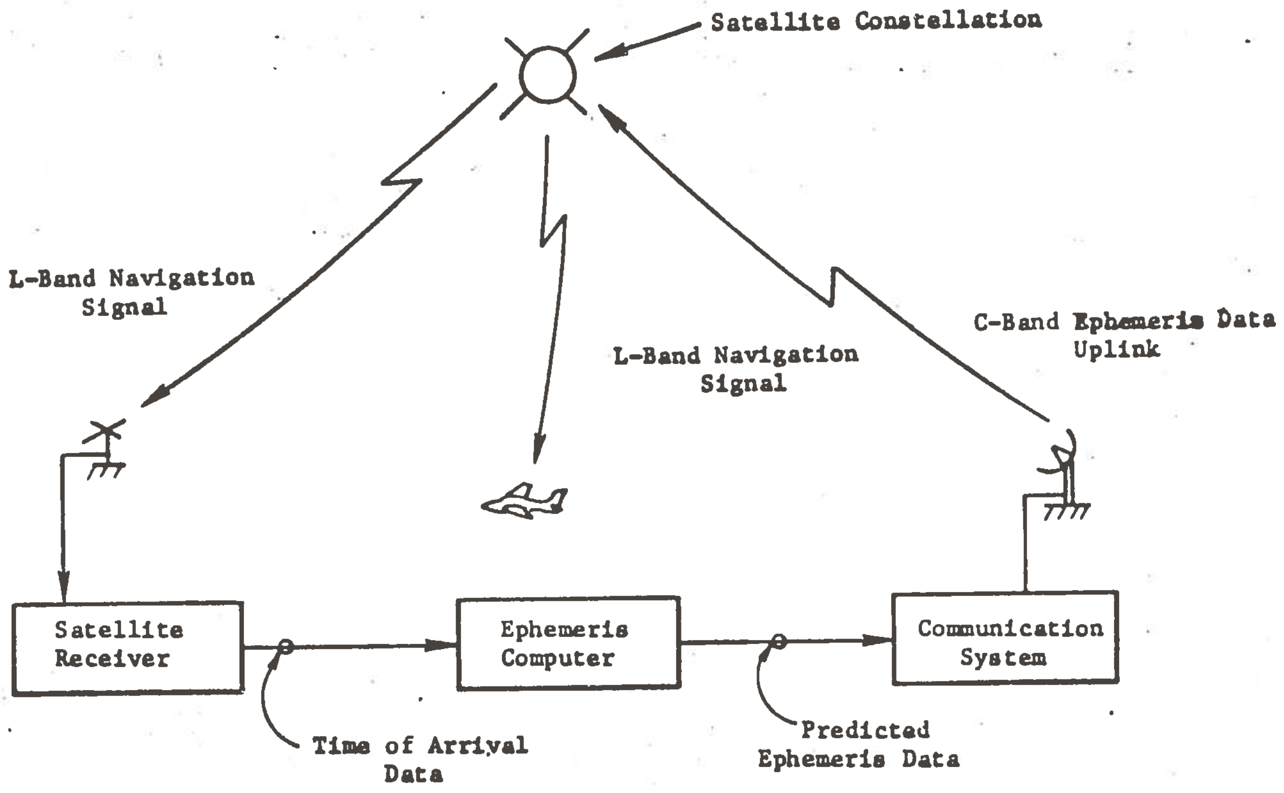


Figure 3. Navigation Functional Elements

Along-Track Position Error	35 m rms
Cross-Track Position Error	70 m rms
Vertical Position Error	35 m rms
Velocity Error	2 m/sec rms

3.5.3.3.3 Accuracy in Secondary Coverage Areas - The steady-state absolute position errors in secondary coverage areas shall be no more than four times the error requirements in primary coverage areas.

3.5.3.4 Virtual VOR (VVOR) Functional Requirements

3.5.3.4.1 Navigation Data Source - The VVOR navigation function shall be based on the user surveillance data and flight plan checkpoint data.

3.4.5.4.2 Navigation Algorithms - Both bearing/range and cross-track deviation/range algorithms shall be provided at the user's option.

3.4.5.4.3 User Interface - The user shall be provided VVOR navigation data via the ground-to-aircraft digital data communications channel.

3.5.3.5 VVOR Performance Requirement

3.5.3.5.1 Data Quantitization - The VVOR data transmission to users shall provide a maximum quantitization of 187 m for range or cross range and 0.1° for bearing angles.

3.5.3.5.2 Update Rate - The VVOR navigation quantities shall be provided at least once each 30 seconds and no more than once each 8 seconds.

3.5.3.5.3 Maximum Course Length - The maximum distance between VVOR check points shall be 500 mi.

3.5.3.5.4 Range Accuracy - The maximum range to-go error shall be

$$\delta R_{TG} = 187 + (V/t)\ \mathrm{m}$$

where

δR_{TG} = Range error in meters

V = User velocity in mph

T = Time between updates

3.5.3.5.5 Cross-Track Deviation Uncertainty - The cross-track deviation uncertainty contribution due to the VVOR system shall be less than 375 m for the cross-track deviation/range algorithm and shall be less than the larger of

$$\delta R_{CT} = 375\ \mathrm{m}$$

$$\delta R_{CT} = 3.37\ (R)\ \mathrm{m}$$

where

δR_{CT} = Cross-track uncertainty

R = Range from VVOR site in meters

3.5.4 Communications Subsystem

3.5.4.1 Introduction

The communications subsystem provides for the interchange of digital data and voice data between the user aircraft and the ground facilities and the interchange of digital data between ground facilities.

3.5.4.2 Communications Functional Requirements

3.5.4.2.1 Aircraft-to-Satellite-to-Ground Digital Data - The aircraft-to-satellite-to-ground digital data link shall employ the basic surveillance identification coding as an integral element of an asynchronous link design.

3.5.4.2.2 Ground-to-Satellite-to-Aircraft Digital Data - The ground-to-satellite-to-aircraft digital data link shall be a time-ordered, specific user addressed link. The ground facility shall direct messages to satellites to optimize user reception based on the user's geographic location and shall include guard times to preclude multiple receptions by users. Three separate channels shall be provided.

3.5.4.2.3 Ground-to-Aircraft Digital Data - A ground-to-aircraft digital data link channel shall be provided. The coding scheme shall be compatible with the ground-to-satellite-to-aircraft digital data link.

3.5.4.2.4 Ground/Aircraft Voice Links - A minimum of 200 ground-to-aircraft voice channels shall be provided through the satellite constellation. A minimum of 400 direct ground to aircraft voice channels shall be provided. These links shall employ narrow band frequency modulation.

3.5.4.2.5 Ground-to-Ground Digital Data Links - A minimum of 2400 digital data channels shall be provided for interchange of ground-to-ground digital data.

3.5.4.2.6 Redundancy - All digital data links shall employ redundant coding or error detecting schemes to aid in message validation.

3.5.4.2.7 User Frequency - All user transmissions and receptions shall be in the L-band spectrum (1535-1660 MHz).

3.5.4.3 Communications Performance Requirements

3.5.4.3.1 Gain Margins - All RF links in the communications system shall provide a minimum of 6 db gain margin.

3.5.4.3.2 Bit Error Rate - The minimum acceptable bit rate error for all digital links shall be 10^{-6}.

3.5.4.3.2 Ground-to-Ground Channel Capacity - The minimum ground-to-ground digital channel capacity shall be 2.4 kbs per channel.

3.5.4.3.3 Ground-to-Aircraft Channel Capacity - The minimum ground-to-aircraft digital channel capacity shall be 90 kbs per channel.

3.5.4.3.4 Aircraft-to-Ground Channel Capacity - The aircraft-to-ground digital channel shall allow a minimum of 50 kbs to be transmitted by the individual user aircraft.

3.5.4.3.5 Spectrum Usage - The communications subsystem shall require no more than 60 MHz of C-band spectrum (5000-5280 MHz) and no more than 50 MHz of L-band spectrum.

3.5.5 Satellite Tracking Subsystem

3.5.5.1 Introduction

The satellite tracking subsystem estimates and predicts the position of each satellite in the constellation. These data are used to derive tracking antenna control commands, to allow surveillance computations to be performed, and to provide ephemeris data for the navigation subsystem.

3.5.5.2 Satellite Tracking Functional Requirements

3.5.5.2.1 Satellite Tracking Centers - Satellite Tracking Centers (STC's) shall be provided at precisely known geographic locations for the reception of L-band navigation pulses. At least three and at most eight STC's shall be employed.

3.5.5.2.2 Preprocessing - Preprocessing of navigation data shall be provided at STC's. Preprocessing shall reduce the number of measurements before the data are transmitted to the CCC.

3.5.5.2.3 Ephemeris Estimation - Ephemeris estimation shall be provided at the CCC. The observation shall be the preprocessed navigation pulse data from the STC. The position, velocity, and navigation pulse time error estimates of each satellite in the constellation shall be formed.

3.5.5.2.4 Ephemeris Prediction - Ephemeris predictions shall be provided in an earth centered fixed orthogonal coordinate set at navigation pulse times and at master times. The former data shall be used for navigation purposes and the latter for surveillance and antenna tracking control.

3.5.5.3 Satellite Tracking Performance Requirements

3.5.5.3.1 Ephemeris Quantitization - Ephemeris position quantitization shall be 1 m in position and 10 nsec in navigation time.

3.5.5.3.2 Satellite Position Error - The satellite position error when predicted for up to 8 hr shall not exceed 10 m rms in radial uncertainty, 50 m rms along the satellite velocity vector and 25 m rms normal to the velocity vector/radial vector plane.

The following sections will be prepared at a later date:

3.6 System Reliability
3.7 Maintainability
3.8 Design and Construction
3.9 Documentation
3.10 Logistics
3.11 Personnel and Training
4.0 Quality Assurance
5.0 Preparation for Delivery (Not Applicable)
6.0 Notes
10.0 Appendix