D6-60105

EXPERIMENTAL L-BAND SST SATELLITE COMMUNICATIONS/SURVEILLANCE TERMINAL STUDY

VOLUME I

STUDY SUMMARY

by

Thomas K. Foley

and

Robert W. Sutton

November 1968

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Prepared under Contract No. NAS 12-621 by

BOEING

COMMERCIAL AIRPLANE DIVISION
RENTON, WASHINGTON

for

Electronics Research Center

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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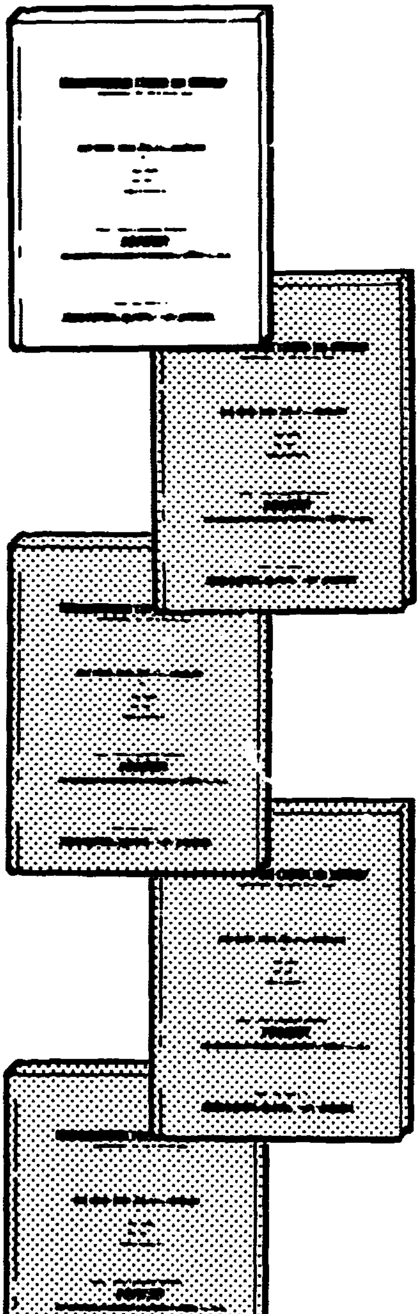


VOLUME I
STUDY SUMMARY

VOLUME II
OPERATIONAL REQUIREMENTS STUDY

VOLUME III
COMMUNICATIONS/SURVEILLANCE ANALYSIS

VOLUME IV
AIRCRAFT ANTENNA STUDIES

VOLUME V
AIRCRAFT TERMINAL DEFINITION

CONTENTS

CONTENTS–Concluded

Page

FIGURES

TABLES

EXPERIMENTAL L-BAND SST SATELLITE COMMUNICATIONS/SURVEILLANCE TERMINAL STUDY

VOLUME I: STUDY SUMMARY

By Thomas K. Foley and Robert W. Sutton
The Boeing Company

SUMMARY

A program definition study was carried out for NASA/ERC under contract NAS 12-621 on the design of an experimental L-band SST communications/surveillance terminal. The terminal, in conjunction with a satellite system, would demonstrate the capability of extending air traffic control (ATC) surveillance and communications functions over the North Atlantic area on a full-time basis. The study includes development of the operational requirements imposed on both satellite and aircraft terminals. Aircraft traffic forecasts for 1975 through 1980 are developed and the peak loading estimates are used as a basis for deriving specific surveillance and communications requirements. It is concluded that a system designed to meet the derived requirements (1-n.mi. surveillance accuracy) would allow reduction of the current 120-n.mi. lane-separation standards to a goal of 30 n.mi. for an SST equipped with an inertial navigation system (INS). In addition, six voice channels are shown to be adequate for ATC/aircraft message requirements under such loading conditions.

The study highlights are summarized for the various analysis tasks conducted in developing the performance requirements and the specific terminal baseline design. These tasks included evaluation of alternate satellite configurations for surveillance and communication functions and the evaluation of different modulation techniques for each function. In addition, L-band propagation effects are analyzed and the inherent aircraft radio noise environment is investigated. Aircraft antenna techniques are also evaluated, because of the severe gain/power limitations on the system satellite/aircraft voice links and the flush-mounted antenna constraint imposed by the SST. The results of the analysis tasks and a comprehensive state-of-the-art equipment survey form the basis for the specific aircraft terminal design selection and functional description for both experimental and operational programs.

1.0 INTRODUCTION

In March 1968, the Electronics Research Center of NASA awarded the Boeing Company contract NAS12-621. The objective of the contract was to conduct a program definition study of an experimental L-band communications terminal for use on the supersonic transport (SST). The contract covered the first phase of a five-phase program defined in Boeing's original proposal (ref. 1). The five phases and the associated program schedule are depicted in fig. 1. As seen in the program schedule, the overall goal is to design, develop, install, and flight test an L-band terminal aboard the SST prototype. The experimental design defined in this report is compatible with the SST but is also easily adaptable to other airborne test platforms, such as a subsonic 707-series aircraft. This flexibility is desirable in the event the schedules of an experimental satellite and the SST prototype are not properly phased.

1.1 Background

The study approach in the current contract is divided into the following three broad categories:

(1) Development of operational and functional requirements for the experimental terminal based on the projected communications, traffic control, and navigation requirements for the SST aircraft

(2) Analysis of parameters associated with the communications link performance between the satellites and aircraft, and evaluation of alternate techniques to meet the system performance requirements

(3) Development and evaluation of candidate aircraft-terminal hardware concepts and selection of a preferred design for the experimental program

Under terms of the contract, the cost-effectiveness of systems using frequencies other than L-band (1540 to 1660 MHz) was not examined. For example, the impact of L-band terminal equipment upon the airlines' inventory and maintenance costs should be carefully considered before final commitment to an operational system is made.

In addition to the Boeing study contract for the aircraft terminal, NASA/ERC funded two system contractors–TRW (contract NAS12-595) and RCA (contract NAS12-596)–to conduct concurrent system studies. These studies, entitled "Navigation/Traffic Control Satellite Mission Study," consider the overall requirements and constraints of air traffic control (ATC), primarily in the North Atlantic. Candidate satellite concepts were traded off, which led to a recommended system design that best satisfies all the requirements of the ATC environment–including ground, satellite, and aircraft. The system studies considered VHF, L-band, and C-band for operating frequencies, and the conclusions available indicate a recommendation of L-band for both voice and surveillance functions.

During the contract period, three technical briefings were held with NASA/ERC. At these briefings, interim progress reports were made and discussions about remaining work items were held with the Technical Monitor. The Technical Monitor also provided status reports on the evolving system-contractor designs in the areas where they impacted the aircraft terminal design. In addition, Boeing held periodic technical interchange meetings with RCA and TRW, who were conducting broad system studies into all aspects of ATC. These

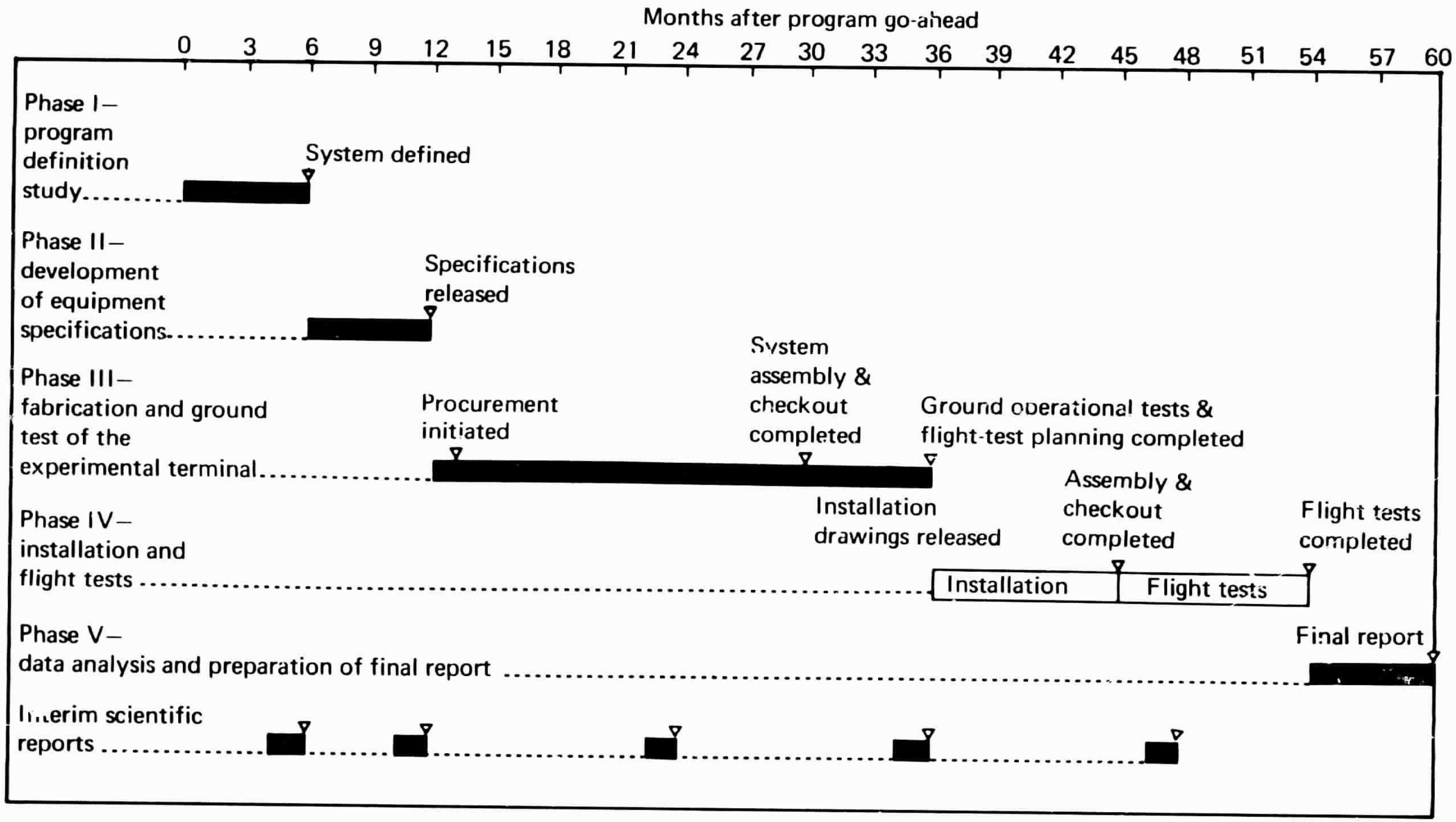


FIGURE 1.— PROGRAM SCHEDULE

meetings revealed that critical design features of a recommended ATC satellite system would be developed by the system contractors too late for Boeing to incorporate them into the airborne terminal design. Therefore, to develop the required information, Boeing independently investigated relevant operational and system requirements.

1.2 Report Organization

The final technical report is submitted in five volumes. The areas of investigation reported in the different volumes are as follows:

(1) *Volume I* contains an overall summary of the study, including the technical highlights and the results of the tradeoff analysis.

(2) *Volume II* presents the operational requirements study for ATC in the North Atlantic through 1980. Passenger and aircraft traffic forecasts are established, and the required communications capacity, aircraft position accuracy, and surveillance fix rates are determined to support reduced separation standards.

(3) *Volume III* gives the analysis supporting the major communications/surveillance tradeoffs. Included are alternate satellite techniques for air traffic control, performance analysis of candidate surveillance and voice modulation techniques, and analysis of both propagation anomalies and sources of aircraft-terminal radio noise. In addition, a set of system performance criteria is developed.

(4) *Volume IV* consists of analysis and performance tradeoffs accomplished in evaluating potential aircraft antenna techniques. Low-gain hemispherical-coverage antennas are evaluated with supporting pattern data. An analysis is presented on different methods of developing a high-gain, steered-beam antenna design compatible with the SST configuration. Both mechanically steered and electronically steered arrays are analyzed.

(5) *Volume V* develops the specific aircraft-terminal definition for the experimental program. The design is based on the performance parameters developed in the analysis volumes as well as on the results of a hardware state-of-the-art survey. Included is a detailed functional description of the recommended terminal design and preliminary definition of the testing program.

A strong team effort was involved in conducting the overall study effort for NASA/ERC. Credits for individual contributions are given in the appropriate volume. Mr. A. F. Norwood, Technology Chief–Electronics, provided invaluable consultant support during the study effort. Overall management direction and technical reviews were accomplished by Mr. R. W. Sutton. Significant contributions to the overall management and technical direction of the study were made by the following personnel:

Study management technical direction	R. W. Sutton, Program Manager
Technical direction of operational requirements analysis	J. T. Burghart

Technical direction of communications/surveillance analysis and aircraft terminal definition	T. K. Foley
Technical direction of aircraft antenna analysis and testing	W. V. Kiskaddon

2.0 OPERATIONAL REQUIREMENTS FOR NORTH ATLANTIC AIR TRAFFIC CONTROL

One of the major tasks undertaken in the current study was development of the operational requirements for a satellite system performing full-time air traffic control (ATC) of the North Atlantic airlanes. The current oceanic ATC procedures and traffic are considered, and an evaluation is made to show the benefits of a satellite system to handle the expected airplane and passenger traffic growth through 1980. Figure 2 gives the relationships of the major analyses used to develop the operational requirements. The three major analysis tasks consist of evaluating (1) the airplane traffic growth, (2) the surveillance requirements, and (3) the voice communications requirements. The specific details and supporting tradeoff analysis for the results given are contained in vol. II.

2.1 ATC Environment and Trends

Current operation on North Atlantic crossings consists of both active ATC when aircraft are near or over land masses and semiautonomous ATC monitoring in the open ocean areas. Active ATC is accomplished during the initial and terminal flight phases through use of land-based surveillance radars, VHF communications, and VOR navigation aids. Generally, these facilities are located along the seacoast (fig. 3) such that control service for jet aircraft at cruise altitudes is available out to about 200 miles. These limits thus help define the open-ocean principal area between longitudes 10°W and 50°W. Without radar surveillance, the oceanic controllers rely on filed flight plans, aircraft position reports via HF from the pilots, and extensive lane-separation standards. To ensure flight safety, the current lateral-separation standard in use is 120 n.mi.

The extensive increase in future oceanic traffic would result in many aircraft being assigned tracks far removed from the minimum-distance path (MDP). A significant economic penalty can thus be incurred by the airlines due to the increased flight distances. This situation will be particularly important with the introduction of the SST, because for probable traffic density the optimum flight characteristics dictate lateral separations primarily, with minimum altitude stacking. Boeing has evaluated (ref. 2) the economic benefits involved in reducing the lateral-separation standards for SST aircraft. The results are shown in fig. 4, where the average dollar cost increase per crossing is plotted versus the required number of lateral lanes for different separation standards. The costs will increase with time, because the higher traffic in later years forces more frequent use of tracks farther off the MDP. For example, the reduction in separation standards from 120 n.mi. to 30 n.mi. for SST's can mean an average savings of $1000 per crossing for traffic requiring use of 15 lateral lanes.

Thus, the reduction in separation standards not only achieves better utilization of the limited airspace but also has a definite economic benefit for the airlines.

The development of the operational requirements to permit such a reduction with safety is based on the ATC satellite system model shown in fig. 5. The basic ground ATC real-time surveillance range capability is extended throughout the principal area by use of a system of synchronous satellites. The satellites, which are visible to both ground and aircraft terminals, act as relay points for the surveillance and voice signals between terminals.

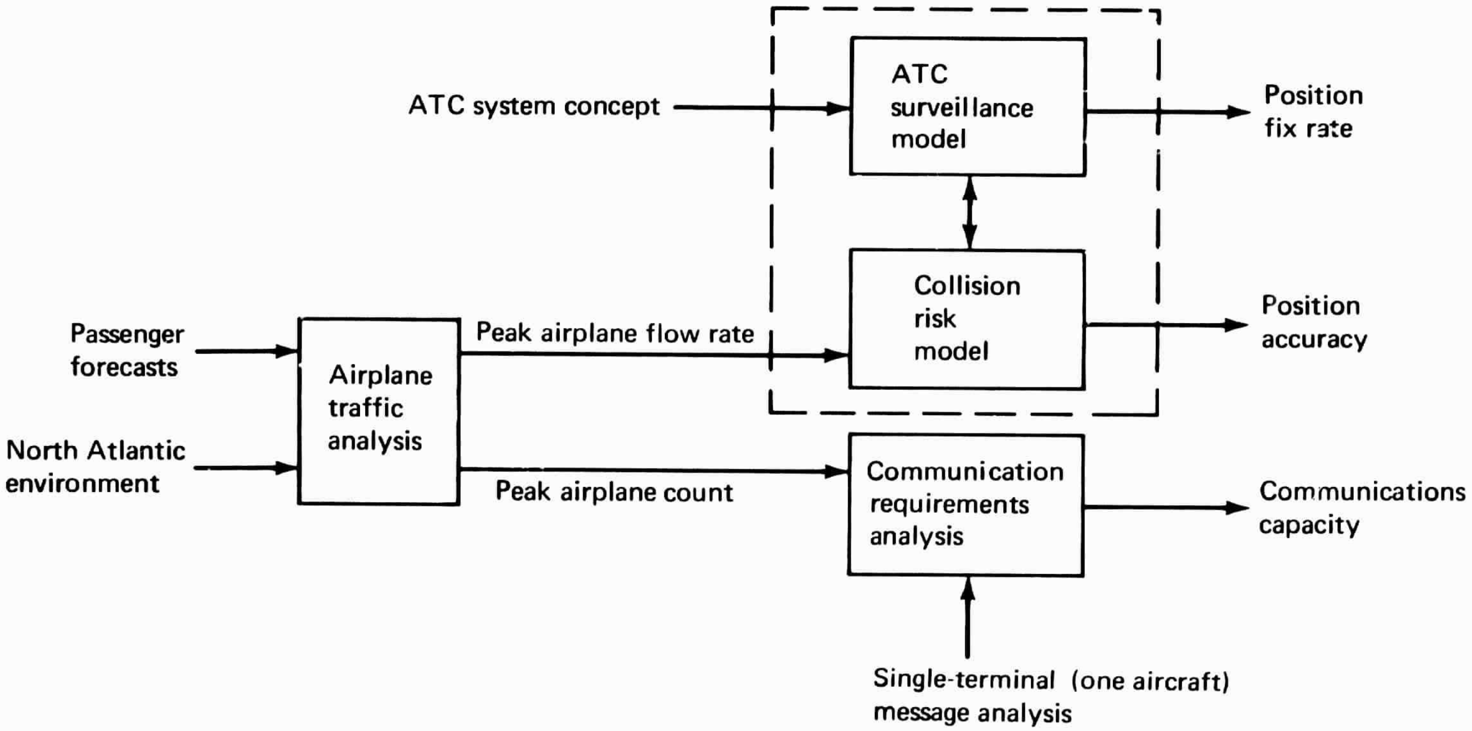


FIGURE 2.– OPERATIONAL REQUIREMENTS ANALYSIS FLOW

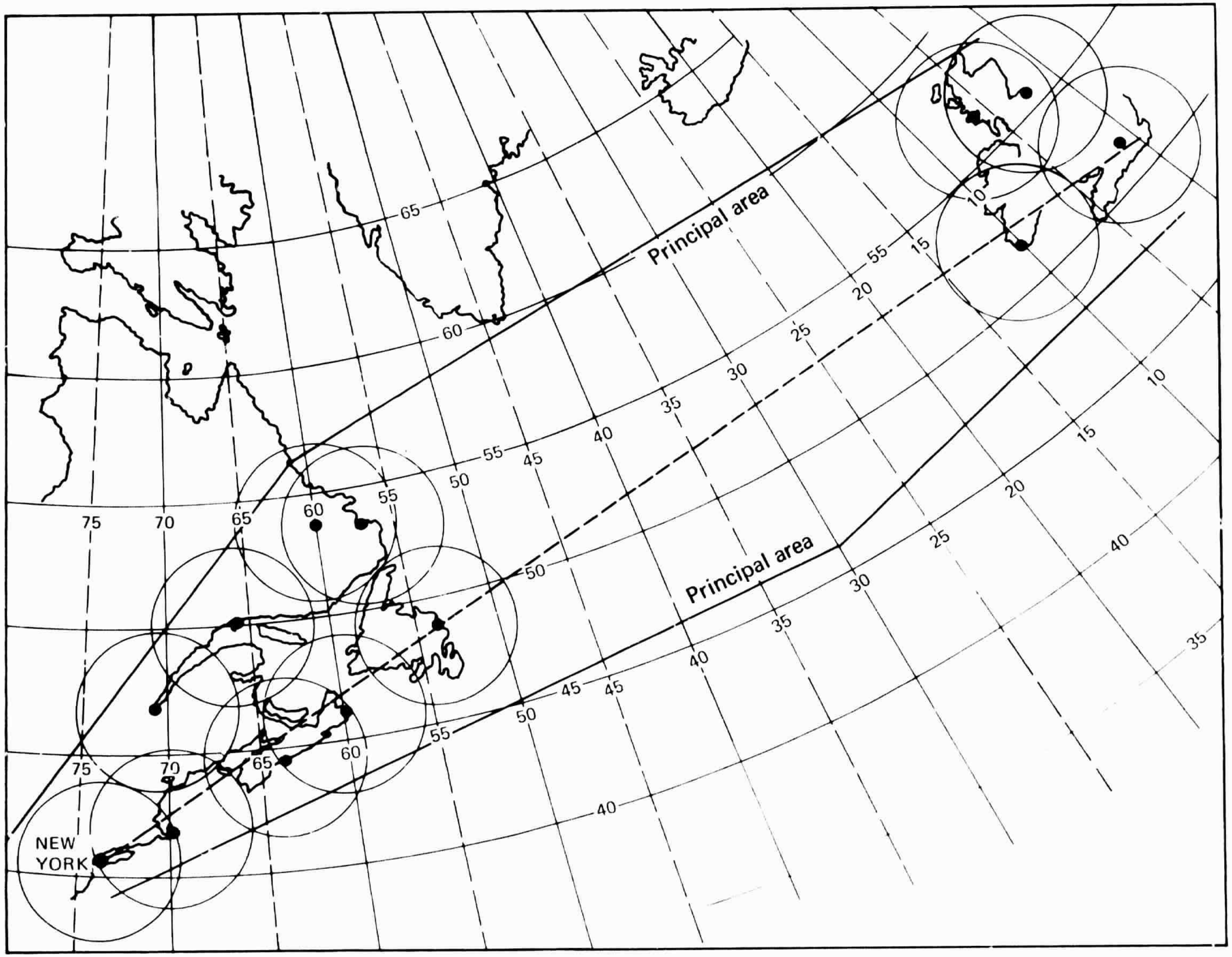


FIGURE 3.– PRESENT-DAY SURVEILLANCE COVERAGE

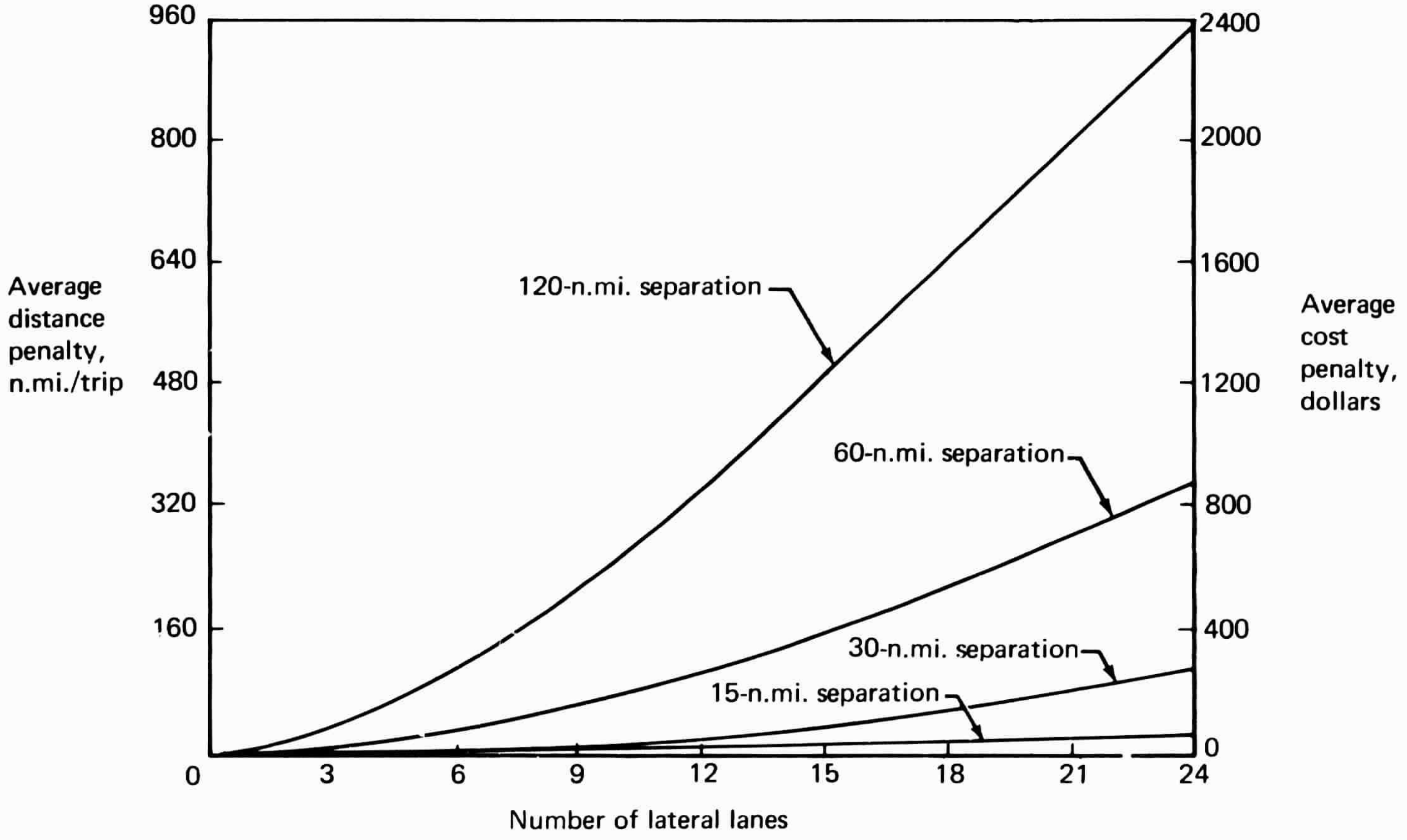


FIGURE 4.– COST PENALTY DUE TO SEPARATION STANDARDS

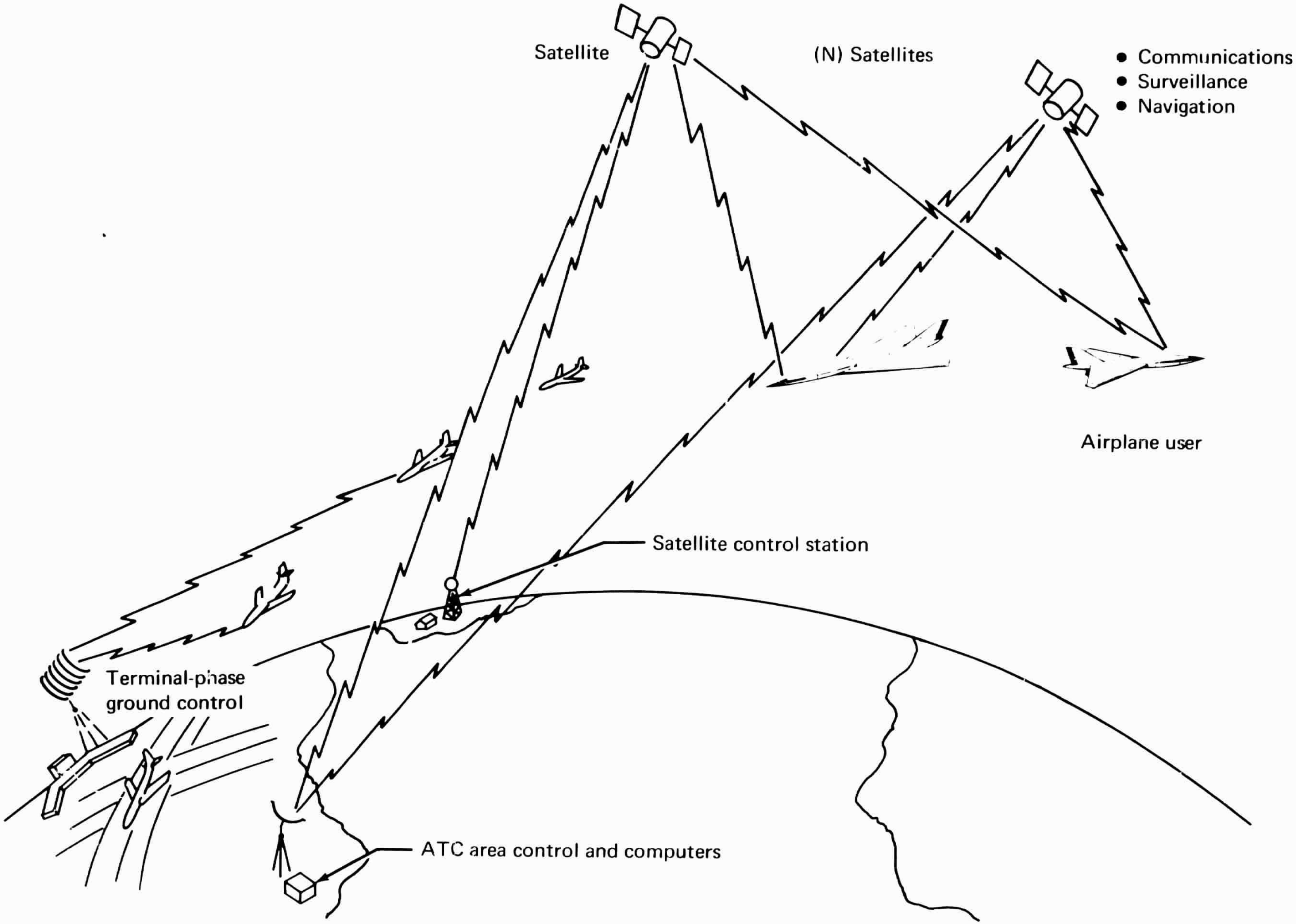


FIGURE 5.– ATC SYSTEM

The following sections summarize the traffic growth through 1980 and the requirements that both the satellite and aircraft terminals must satisfy to support the reduction in separation standards in terms of (1) surveillance position-fix accuracy, (2) fix rate, and (3) voice channel capacity.

2.2 Airplane Traffic Analysis

The area of primary interest was determined to be the North Atlantic bounded approximately by latitudes 40° N and 60° N. The critical communications and navigation/surveillance area in this region is between the 10° W and 50° W meridians.

The desired form of the traffic output is the number of flights of the various types of aircraft and the spatial distribution for peak loading conditions. To obtain this for the 1975-1980 time period, a prediction of passenger crossings was required. The passenger demand was converted to the required flight data using known and postulated rules about airplane load factors, passenger preferences–both for departure hours and airplane types–airplane delivery schedules, seating capacities, and cargo flights.

The greatest variation in the approach arises from the passenger-projection input. Predictions of future North Atlantic travel demand are subject to great uncertainty. The usual approach is to examine past travel growth rates and postulate the future demand based on these rates. A typical projection (from FAA data, ref. 3) is shown in the first column of table 1. The other set of data (shown in the second column) is a more conservative traffic projection based on a correlation of passenger flow between North Atlantic country pairs and gross national product. Gross national product growth has been more predictable in the past and for that reason is a useful basis for projection. The two projections were made to determine the bounds of the possible traffic; the conservative traffic estimate was used to determine a possible minimum-capability system. In all other feasible systems considered, including the preferred configuration, the maximum traffic predictions were used.

The spatial distribution of the maximum instantaneous airborne count (IAC) of aircraft is shown in table 2. A preferred communications capability in the North Atlantic communications-gap area between longitudes 10° W and 50° W would accommodate 131 airplanes. The peak hourly subsonic and supersonic flow rates were also developed using the high traffic estimates for use in the surveillance analysis.

2.3 Communications Analysis

The airplane traffic load was combined with the single-terminal (individual aircraft) message load using a queueing-type computer simulation model to determine the satellite communications capacity requirement. The model generates message traffic based on peak-hour airplane loading and postulated message-type distributions. The output is message-delay statistics by category.

The message traffic model used in the study is shown in table 3. Classification of messages by category (priority), the typical time duration of each type of message, and the number of messages expected during a busy-season peak hour for two operational concepts are shown. The first concept assumes current North Atlantic message loads and procedures: namely, voice position reports for every 10° of longitude (adjusted for 1980 traffic). This concept implies flight following via the voice position reports, rather than a separate surveillance system, with the result that reduction in separation standards may be limited.

TABLE 1.–PROJECTED NORTH ATLANTIC PASSENGER CROSSINGS

Year	Typical forecast (a)	Conservative forecast
1975	14 024 000	8 454 000
1976	16 045 000	8 978 000
1977	18 371 000	9 515 000
1978	21 100 000	10 061 000
1979	24 000 000	10 621 000
1980	27 300 000	11 243 000

[a] 1978-1980 data extrapolated from 1968-1977 forecast

TABLE 2.—NORTH ATLANTIC TRAFFIC SPATIAL DISTRIBUTION

Region	Longitude	Number of airplanes[a]		
		Subsonic	Supersonic	Total
Polar (60°N to 90°N)	- - - -	10	4	14
Principal area (40°N to 60°N)	0°W to 10°W	12	19	31
	10°W to 20°W	20	16	36
	20°W to 30°W	16	15	31
	30°W to 40°W	16	16	32
	40°W to 50°W	16	16	32
	50°W to 60°W	14	37	51
	60°W to 70°W	10	35	45
Other (0°N to 40°N)	- - - -	26	9	35
Total		140	167	307

} 131 aircraft

[a]For 1980, transoceanic traffic, peak busy summer day, instantaneous count

TABLE 3.–COMMUNICATIONS REQUIREMENTS

Message category	Message type	Average duration of contact, seconds	Information bits (a)	Number of messages (peak-hour loading)	
				Present procedures (b)	Comm/Surv satellite system (c)
First priority	Emergency	30	900	10	10
	Conflict resolution	30	600	35	70
	Other	30	750	- -	60
ATC messages	Position report	45	225	300	- -
	Clearance control	15	60	100	100
	Vectoring messages	10	60	- -	100
Advisory messages	Aircraft traffic	10	250	- -	30
	Airport status	5	100	- -	5
	Weather advisory	10	200	50	100
Unclassified	Non-ATC	20	600	50	200
	Miscellaneous	20	500	60	70

[a] ATC messages formatted. Other messages transmitted with elimination of voice redundancy.

[b] 1980 traffic with 10° position reports (present-day North Atlantic message load)

[c] 1980 traffic with 20 position samples per hour and typical U. S. message load

The second concept involves a separate surveillance system without voice position reports and a message load based on U.S. domestic procedures and the 1980 traffic forecast.

These two concepts, along with several variations, are evaluated in detail in vol. II. The results for each concept are summarized in table 4, which shows the required number of channels, percent channel utilization, and the associated message delay characteristics. The last entry of the table is the preferred operational concept, selected on the basis of a cost-benefit analysis and subjective reasoning, that will provide the ATC capability to handle the North Atlantic traffic with a message load equivalent to U.S. domestic operations. The preferred concept would support a peak-hour load of 745 messages with a breakdown by type as given in table 3. The message load can be handled with 5 voice channels at a peak channel utilization of 77.7%. The message delay characteristics for peak-season/peak-hour loading are as follows:

Average delay (all messages)	2.8 seconds
Average delay (first priority)	0.2 second
Maximum delay (first priority)	9.6 seconds

After review of the data, it was decided to provide a sixth open (zero-delay) channel reserved exclusively for those first-priority messages relating to an imminent catastrophic emergency. This decision is based on concern for controlling the priority access and on ease of implementing the additional channel in a two-satellite system where the voice channels are equally divided between the satellites.

2.4 ATC Surveillance Analysis

Both a collision-risk model and an ATC surveillance model were developed for the ATC surveillance analysis (fig. 2). The collision-risk model (based on work done by the Royal Aircraft Establishment) was used to determine an acceptable probability of overlap. Certain limitations are recognized, such as the model does not include the ability of the pilot or a collision-avoidance system to reduce collision risk. However, the surveillance parameters obtained are conservative and suitable for developing terminal requirements. Probability of overlap is defined as the probability that two aircraft (with planned separation in one dimension only) are actually in conflict in that dimension. The overlap is not the collision risk but is related to the collision risk by the parameters of the model (traffic, airplane dimensions, probability of conflict in the other dimensions, etc.). The "acceptable" collision risk is an input to the model. The resultant acceptable probability of overlap is an input to the ATC surveillance model that incorporates the airplane navigation and surveillance accuracies, the position reporting rates, and the separation standards. These are the design parameters of most interest in the study.

As a result of this analysis, the following are specified as the required surveillance parameters:

System accuracy	1.0 n.mi. (one sigma)
Reporting rate	20 position reports per hour per airplane
Separation standard	30 n.mi.

TABLE 4.–SUMMARY OF CHANNEL REQUIREMENTS

Operational concepts	Channel requirements				Average delay, seconds by message category				Maximum delay, seconds (b)	Comments
	Voice		Digital (a)							
	Number cf channels	Channel utilization, %	Number of channels	Channel utilization, %	1	2	3	4	First priority	
All voice–minimum capability	4	56	- - -	- - -	0.6	1.4	3.0	5.1	10.6	
All voice–preferred capability	7	77	- - -	- - -	0.5	3.5	14.5	24.9	9.3	
All voice–increased position reports	9	86.6	- - -	- - -	0.3	4.6	27.0	46.2	7.5	
Automatic digital position reports	3	46	3	52.7	- -	2.9	- -	- -	- -	For digital messages
					0.2	0.6	1.1	2.3	6.0	For voice messages
All-digital system–U. S. message load	1	Emergency only	4	75	0.4	1.6	3.6	5.2	6.9	For digital messages
Surveillance function added–present procedures	3	46	- - -	- - -	0.2	0.6	1.1	2.3	6.0	
Surveillance function added–U. S. ATC message load	5	77.7	- - -	- - -	0.2	0.7	1.8	6.3	9.6	

[a] 100 bits/sec data rate

[b] Maximum delay is the average delay for the worst delayed message of each run (100 or more runs).

Alarm threshold	10 n.mi.
Alarm rate	3 per hour

The alarm threshold is defined as the perpendicular distance from the center of the track that an aircraft can stray before corrective action is necessary. The alarm rate is defined as the number of airplanes per hour that require corrective action.

3.0 ANALYSIS OF MAJOR COMMUNICATIONS/SURVEILLANCE SYSTEM TRADEOFFS

Analysis of an ATC system using satellites can be divided into two broad categories: surveillance and communications. The purpose of this section is to examine the results of the major tradeoffs for implementing these functions into an ATC system. One primary concern is the impact that proposed systems may have on the aircraft-terminal design requirements. Particular emphasis is given to a system designed to service anticipated North Atlantic traffic through 1980.

The surveillance function is considered first in the following sections. Surveillance is considered as a entity distinct from navigation. In this study, surveillance is defined as a function that permits the ATC system to check on the aircraft navigation system. As such, surveillance must be implemented independent of the aircraft navigation system and, as far as practical, be independent of all aircraft equipment. Thus, the theoretical goal is to remove the aircraft hardware and human-error environment from the ATC surveillance accuracy capability.

Different system approaches to implementing a satellite surveillance capability for the ATC system are examined first. The information presented is extrapolated from data available from the system contractors (RCA and TRW) and from other industry-proposed systems. Two competitive candidate satellite systems are selected, and a detailed analysis is made of the performance capability of each system.

The satellite communications function in the North Atlantic ATC environment is the other major area of analysis. The principal items considered include the impact of alternate satellite designs on the aircraft terminal requirements, propagation effects on the rf signals, the aircraft radio-noise environment, analysis of different voice modulation techniques for improved threshold performance, and a definitive link analysis to establish the satellite and aircraft parameter tradeoffs to support the voice links. A set of performance criteria is established to measure how well a selected design satisfies the desired communications function.

3.1 Surveillance Considerations

The requirements study of Sec. 2.0 showed the operational and cost benefits of implementing a satellite surveillance capability for an ATC system that could handle the increasing North Atlantic traffic loads after 1975. The use of such a system permits reduction of separation standards while maintaining or even lowering the currently acceptable collision probabilities.

The tradeoffs for implementing an ATC satellite surveillance function can be divided into two study areas. The first study analyzes different satellite systems for performing surveillance. After definition of specific satellite systems, the second study area then pertains to the selection of a specific modulation technique and to its associated performance evaluation.

3.1.1 Surveillance system alternates.– The system contractors (TRW and RCA) at the inception of the current contracts were given the task of analyzing several candidate satellite systems that might have potential for an ATC surveillance system. The techniques considered are based on the following parameters, used singly or in combination: range, range rate, range differences, interferometer angle measurements, and aircraft altitude. The satellite systems can be classified into the two major categories of single-satellite or multiple-satellite systems. The specific techniques for single-satellite systems are:

(1) Active user, two-axis interferometer

(2) Passive two-axis interferometer

(3) Passive polar coordinate

(4) Active one-axis spinning interferometer

(5) Swept fan beam

The techniques for multiple-satellite systems are:

(1) Active range measurement

(2) Passive range differencing

For all of these types, "passive" implies nontransponding users whereas "active" implies transponding users. "Passive" in reference to an ATC surveillance function is a misnomer, because it is incumbent on the user to respond to the ATC automatically. This response may simply be a turnaround of a forward-link signal or the return of the results of an onboard position determination made from the forward-link signal. The latter case is dependent also on a data link to the aircraft to provide appropriate satellite ephemeris data.

The evaluation results of the system contractors and a limited amount of the selection rationale were made available to the Boeing study group. The data were reviewed and Boeing agreed with the contractors that the single-satellite systems were not competitive. The major differences between the two system contractors' recommendations are the specific type of multiple-satellite system to be used and the modulation technique to be employed. RCA is recommending an active tone-ranging system based on the SPOT concept developed during a NASA/ERC study (ref. 4). TRW is recommending a range-differencing system based on the NAVSTAR system developed during a previous NASA/ERC navigation satellite study (ref. 5). It was in this modulation-technique-selection area that Boeing felt it could make a significant contribution by conducting an independent analysis.

3.1.2 Active ranging.– The active-ranging technique is sketched in fig. 6. The ATC center initiates a multiple-tone forward surveillance signal S_f through a satellite in view of the user aircraft. (The specific characteristics of the signal are detailed in a later section.) The user, after acquisition and recognition of a unique address, returns the received signal via the return surveillance paths S_{r1}, S_{r2} through two satellites in view of the user back to the ATC center. The return signal also contains aircraft-derived altitude data. The ATC center makes a tone-phase comparison between the original forward signal and the return signals and calculates the aircraft range to each satellite. The ATC center can also determine the satellite positions so that three spherical surfaces can be generated about three known points, namely the two satellite positions and the center of the earth. The radii of the

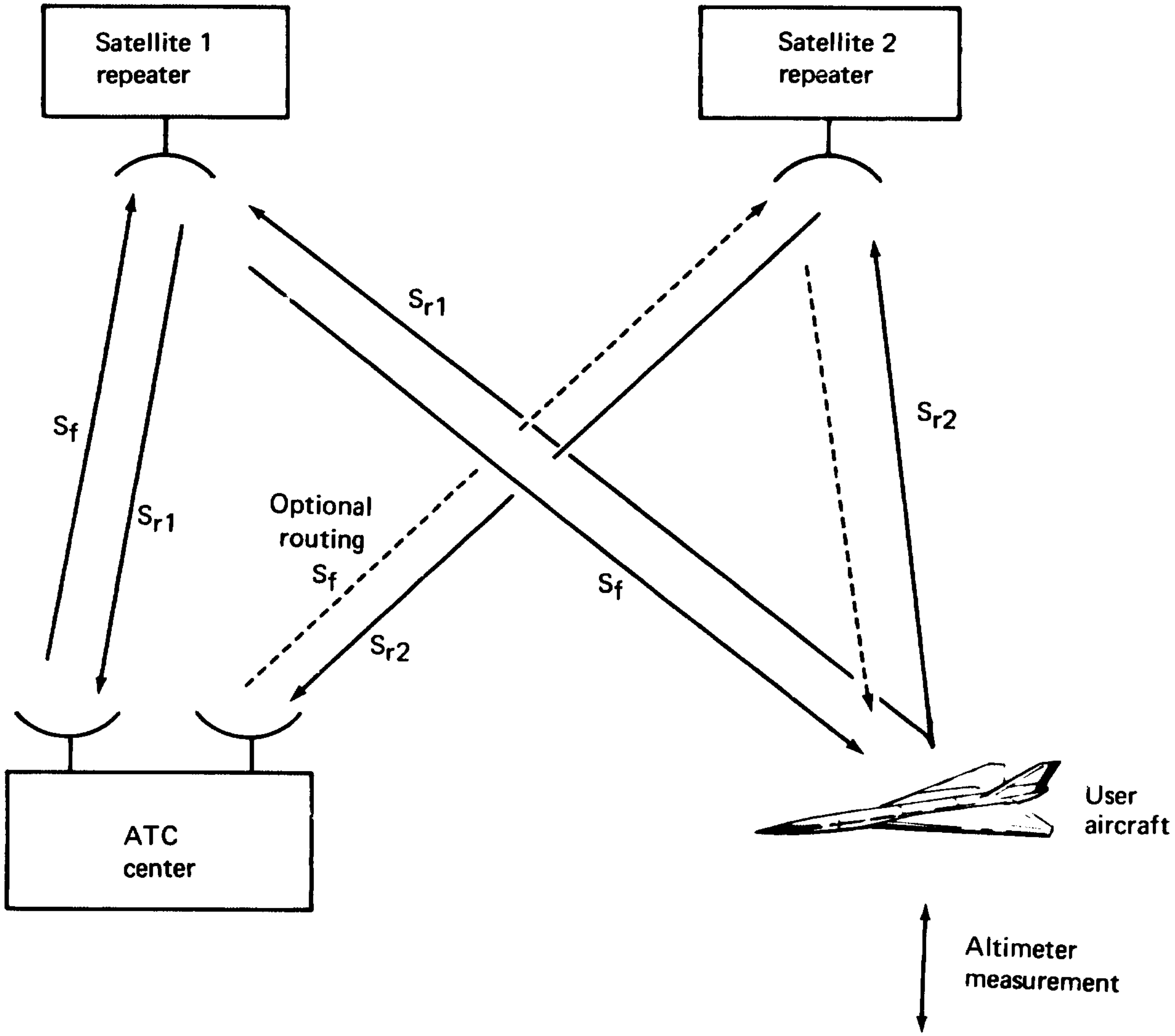


FIGURE 6.— ACTIVE-RANGING SURVEILLANCE SYSTEM

spheres are the two range measurements and the earth-radius-plus-aircraft-altitude distance. The point of intersection of the spheres is the aircraft position. Since this technique measures absolute range and employs aircraft-altitude readback, a maximum of two satellites would be required to serve the North Atlantic traffic.

3.1.2.1 Accuracy requirements: To determine the required performance and design parameters for the tone-ranging system, it is first necessary to evaluate parametrically the required accuracies of the system (both in terms of the overall surveillance accuracy of aircraft-position determination and the ranging accuracy of each range measurement from which position determination is made). Inaccuracies in measured ranges, in addition to inaccuracies of satellite positions, result in an overall uncertainty in aircraft position. A computer program was developed based on a mathematical model derived by Kulik for the FAA (ref. 6) to relate these inaccuracies to overall position-determination inaccuracy for the two-satellite-plus-altimeter scheme under consideration. The results are shown in fig. 7, where the overall aircraft surveillance accuracy σ_μ achieved at the ATC is plotted versus the required measurement accuracy σ_R of the aircraft-to-satellite range.

The data in fig. 7 were developed for a worst-case aircraft position in the North Atlantic area and satellite position uncertainties of 300 feet (1 σ). For overall surveillance system accuracies of 1 n.mi.–determined from the previous traffic analysis–it is seen that a ranging accuracy of 3600 feet is required for determining the satellite-to-aircraft range. In addition, the required surveillance accuracy is seen to be relatively insensitive to the aircraft altimeter accuracy over the range of parameters and geographic areas under consideration.

The satellite-to-aircraft range accuracy σ_R is the actual measurement accuracy required by ATC and must be obtained in the presence of all the contributing error sources that affect the ranging signal. These error sources include (1) overall system noise σ_N, both thermal and additive, (2) propagation effects due to transmission media, (3) phase distortion due to multipath, (4) oscillator instabilities, (5) equipment time delays, and (6) uncertainty in speed of light. These error sources are summarized in table 5.

The errors can be assumed random and the root-sum-squared (rss) total set equal to σ_R. The design value for σ_N in the ground tone-tracking loops is then found for the desired σ_R. For example, to support a 30-n.mi. separation standard, a σ_R of 3600 feet is required and the resultant value of σ_N is 2785 feet.

3.1.2.2 Signal characteristics: With the loop threshold noise level selected, the remaining tradeoff is the choice of actual tone frequencies and threshold loop signal-to-noise ratio (S/N). A five-tone ranging system has been selected in this study consisting of tones at 31.25 Hz, 125 Hz, 500 Hz, 2000 Hz, and 10 000 Hz. The tones were selected using conservative integer tone multiples of four and five. The lower tones are used for ambiguity resolution and provide a coarse range measurement if desired. The high tone, at 10 kHz, is used for the fine range measurement. Figure 8 shows the tradeoffs between tone frequency, loop S/N, and σ_N. As seen, a measurement accuracy on the 10-kHz tone to 2785 feet (which supports a 30-n.mi. separation standard) requires a loop S/N of only +7 dB. Additional design margin has been provided in the link analysis by using a more conservative value of +10 dB.

The results of this study show that the best active-ranging system combines the ranging signal with a digital data channel. The specific subcarriers used on the surveillance link are the five ranging tones mentioned plus a PCM/PSK data subcarrier. The combined baseband is phase modulated onto the L-band carrier. This approach minimizes the

Notes:
1. Aircraft position—worst case for North Atlantic quadrant, 40° N, 70° W
2. Satellite positions—equatorial, 10° W, 50° W
3. Satellite position accuracies $\sigma_{S_1} = \sigma_{S_2} = 300$ ft

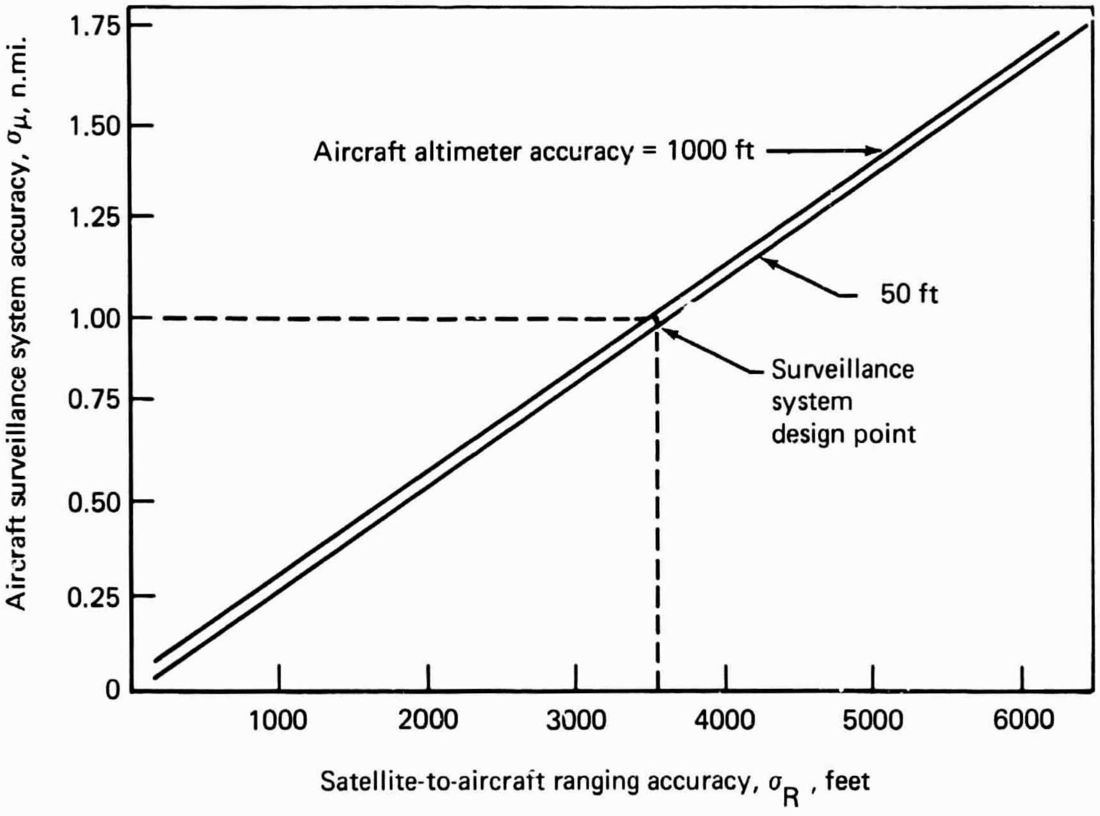


FIGURE 7.– SURVEILLANCE SYSTEM ACCURACY VERSUS SATELLITE-TO-AIRCRAFT RANGING ACCURACY

TABLE 5.– TONE RANGING ERROR SOURCES

Source	Error value
System noise	σ_N
Atmospheric errors	890 feet
Multipath phase distortion	500 feet
Oscillator instability	Negligible
Equipment time delays	1970 feet
Speed-of-light error	532 feet

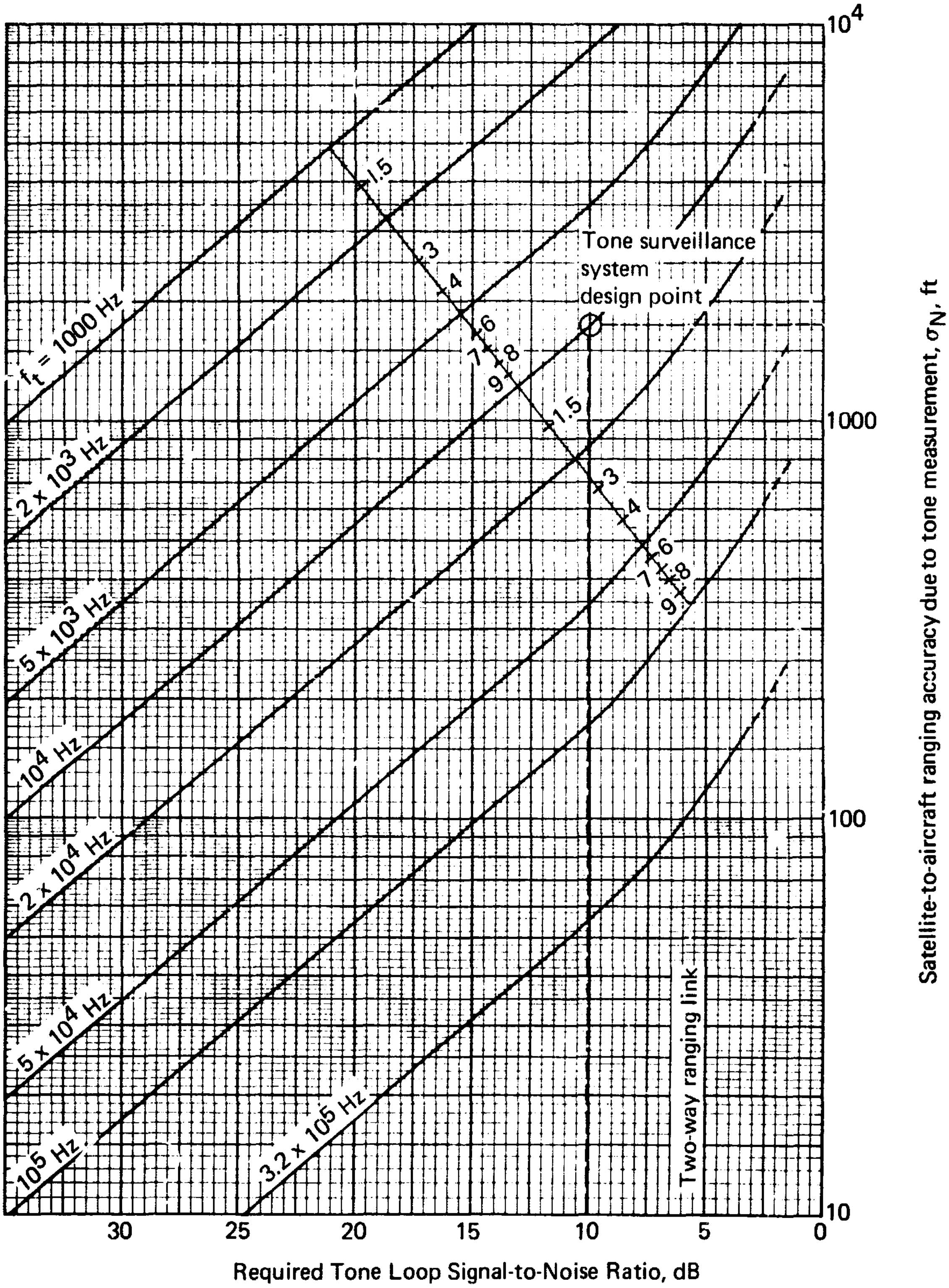


FIGURE 8.– REQUIRED TONE LOOP SIGNAL-TO-NOISE RATIO VERSUS ACCURACY

complexity of the aircraft receiving system, since all aircraft continually receive and track the phase-modulated carrier and perform demodulation of the data subcarrier. Thus, all aircraft are continually and coherently locked to the ATC center so that there is no need for continuous reacquisition in the aircraft receiver. When a particular aircraft detects its address in the data frame, it activates gate circuitry to output the received tone signals and a return data subcarrier back to the ATC center.

Acquisition problems are more severe for the return link, since extremely rapid carrier, data, and tone acquisitions are required at the ATC center as the response from each aircraft is received. The traffic analysis showed that surveillance-fix rates of once every 3 minutes are required to reduce separation standards to 30 n.mi. Since worst-case traffic estimates (peak season, peak hour) are for 131 aircraft in the principal North Atlantic region, a surveillance-fix response from each aircraft must be accomplished in about 1-second total time. During this time, carrier acquisition, tone acquisitions, phase measurements, and data demodulation and synchronization must be performed. The carrier acquisition problem is the most critical, since a frequency uncertainty of up to ±8.8 kHz exists on the incoming carrier. Fortunately, the uncertainty is almost entirely comprised of doppler shift, since frequency coherence is maintained by the very stable ATC master oscillator. Therefore, in the normal operations mode, most of the frequency uncertainty can be predicted since the approximate location, bearing, and speed of each aircraft are known from the previous surveillance fixes. Calculations of doppler shift can be made by the ATC computer just as positions are calculated with each fix; consequently, an accurate estimate can be made of the incoming carrier frequency from each aircraft as it responds to the ATC. A much smaller sweep range is made possible for each carrier acquisition, permitting fast lockup on each response. As each aircraft is interrogated, predicted values of the received carrier frequency would be routed to the two ATC receivers (one for each satellite) where the carrier sweep-circuitry VCO would be reset to the proper value. A short sweep would then be made as the carrier is received.

An aircraft entering the control system with an unknown doppler shift may require a wider-sweep, longer-than-normal acquisition sequence (e.g. 5 seconds). The duration of the aircraft response would be controlled by a signal sent along with the aircraft address code on the forward surveillance link. Even at peak loading with 131 aircraft, responses of 1 second every 3 minutes still allow about 50 seconds for the surveillance response with the longer acquisition mode. In addition, the available time margins permit "spotlight" surveillance of any critical aircraft situation. This capability could be implemented by ATC computer software permitting higher-rate surveillance interrogations and resultant position fixes on selected aircraft.

The 1 second allowed for the aircraft response in the normal mode of operations permits carrier acquisition (with a 3σ acquisition probability) to be accomplished in 0.4 second. This leaves the remaining time for tone acquisitions and measurements, and data demodulation and synchronization—all of which can occur only after carrier acquisition is made. The time breakdown chosen is near optimum from link carrier-to-noise-density considerations, providing sufficient carrier acquisition time with a moderate carrier tracking bandwidth and sufficient data transmission time. Tone acquisition will occur rapidly (0.2 second), since an unswept tracking loop can be used due to only minor tone frequency uncertainties. Similarly, data subcarrier acquisition and demodulation, using one of the locked-up tones for reference, present no significant problems because demodulation and bit synchronization will take only a few tenths of a second.

3.1.2.3 Link performance parameters: Evaluation of the surveillance system for the active tone ranging scheme was made with a detailed worst-case analysis for the four links shown in fig. 6. It was necessary to determine the forward- and return-link noise-degradation effects caused by both the satellite repeater and the aircraft tone-turnaround equipment. The characteristics of the assumed hard-limiting satellite repeater also give rise to signal suppression effects. This suppression is due both to the presence of input noise and other signals competing for the available power as well as to intermodulation products. The magnitude of these effects depends on the levels of the different signals. It was found that acceptable (0.3 dB) degradation on the power-limited satellite-to-aircraft link occurs when the repeater input levels are designed to provide a repeater output S/N of +12.0 dB for the forward signal and an output S/N of -4.2 dB for the return signal. These values are in the repeater noise bandwidth for each signal.

The results of the detailed link analysis for the forward and return surveillance channels between the satellite and the aircraft are shown in fig. 9. Required transmitter power (both satellite and aircraft) is plotted versus aircraft antenna gain for both an earth-coverage and regional-coverage satellite antenna. Included in the link budget was a +2-dB multipath fade margin to ensure a link time availability of 99% in the North Atlantic. A -1-dB aircraft antenna gain was selected as the design point. This choice is based both on a broad-coverage requirement to ensure view of both satellites simultaneously and the strong need to minimize the aircraft terminal design requirements and resultant costs. For this antenna and an earth-coverage satellite antenna, the required satellite and aircraft transmitter powers are 43 watts and 700 watts, respectively. The use of a regional-coverage satellite antenna is dictated by the voice-channel requirements discussed in a later section. The latter antenna reduces the required transmitter powers to 7 watts and 110 watts, respectively.

A similar link analysis was carried out for the less critical links between the ATC center and the satellites. The results show that an adequate forward surveillance signal can be sent from the ATC center using a 5-foot-diameter antenna and a 10-watt transmitter. Using the same antenna for reception of the return surveillance signal requires less than 1 watt of satellite transmitter power to meet threshold performance levels.

3.1.3 Range differencing.– The NAVSTAR concept developed by TRW is the second potential technique to provide a surveillance function for ATC. The concept was originally developed to provide a worldwide, highly accurate satellite navigation system to serve numerous types of users.

3.1.3.1 System characteristics: Figure 10 is a simplified sketch of the NAVSTAR system modified for ATC surveillance. The BINOR coded ranging signals are originated sequentially in the individual satellites, with timing and frequency adjustments made periodically by the ground site. This approach differs from the previous tone system where the ranging signals are originated by the ground site and the satellite is a simple repeater.

Also shown is the addition of interrogation and reply links that permit the ATC to interrogate all aircraft and to receive, sequentially, position-report information. This information may be specific geographic position reports (as derived onboard from the received BINOR signals) plus aircraft altitude. The other alternative is to return to the ATC center the raw time-delay data from the received satellite signals together with aircraft altitude; the actual position of the aircraft is determined by the ATC center. The first approach has the strongest impact on the aircraft terminal (fig. 11). The equipment required includes both the basic BINOR receiver and the preprocessor used to determine the time-delay range parameters, as well as a computer capability to determine aircraft position. The computer calculates position from the satellite time-delay range data, satellite ephemeris data (position, oscillator drift, timing), and aircraft altitude. The aircraft terminal requirements are considerably simplified when only raw time-delay data are derived onboard and position

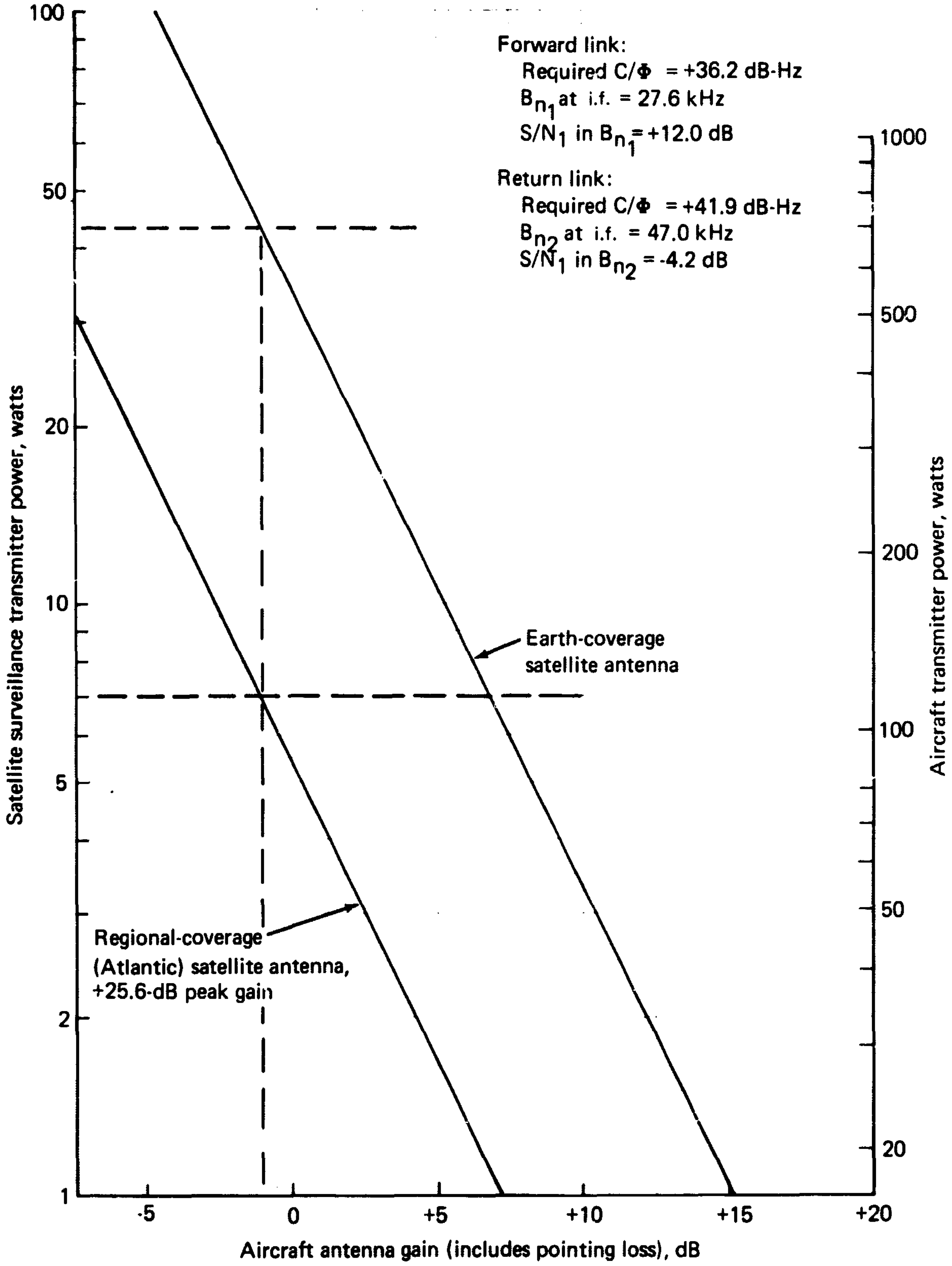


FIGURE 9.– TONE SURVEILLANCE LINK PERFORMANCE

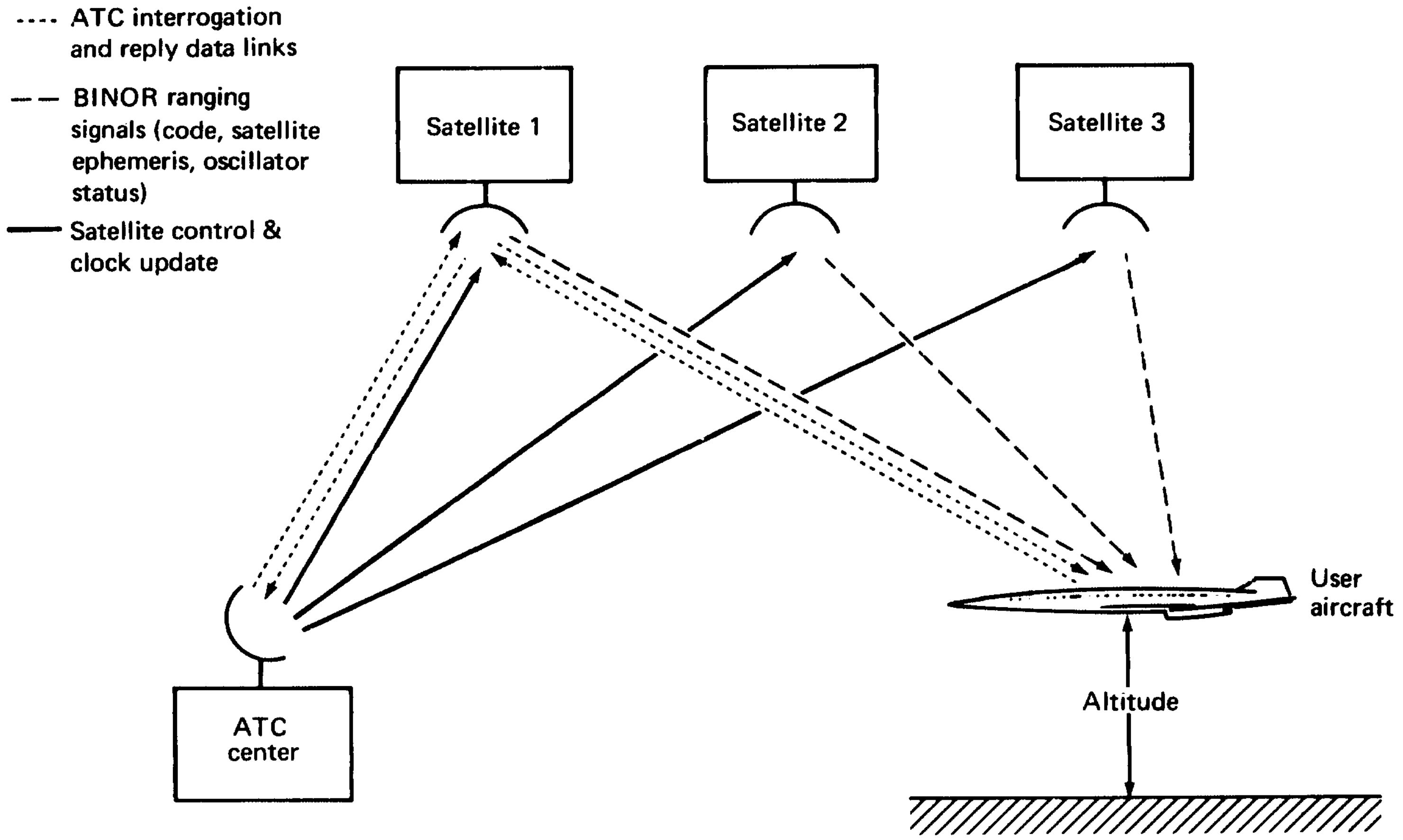
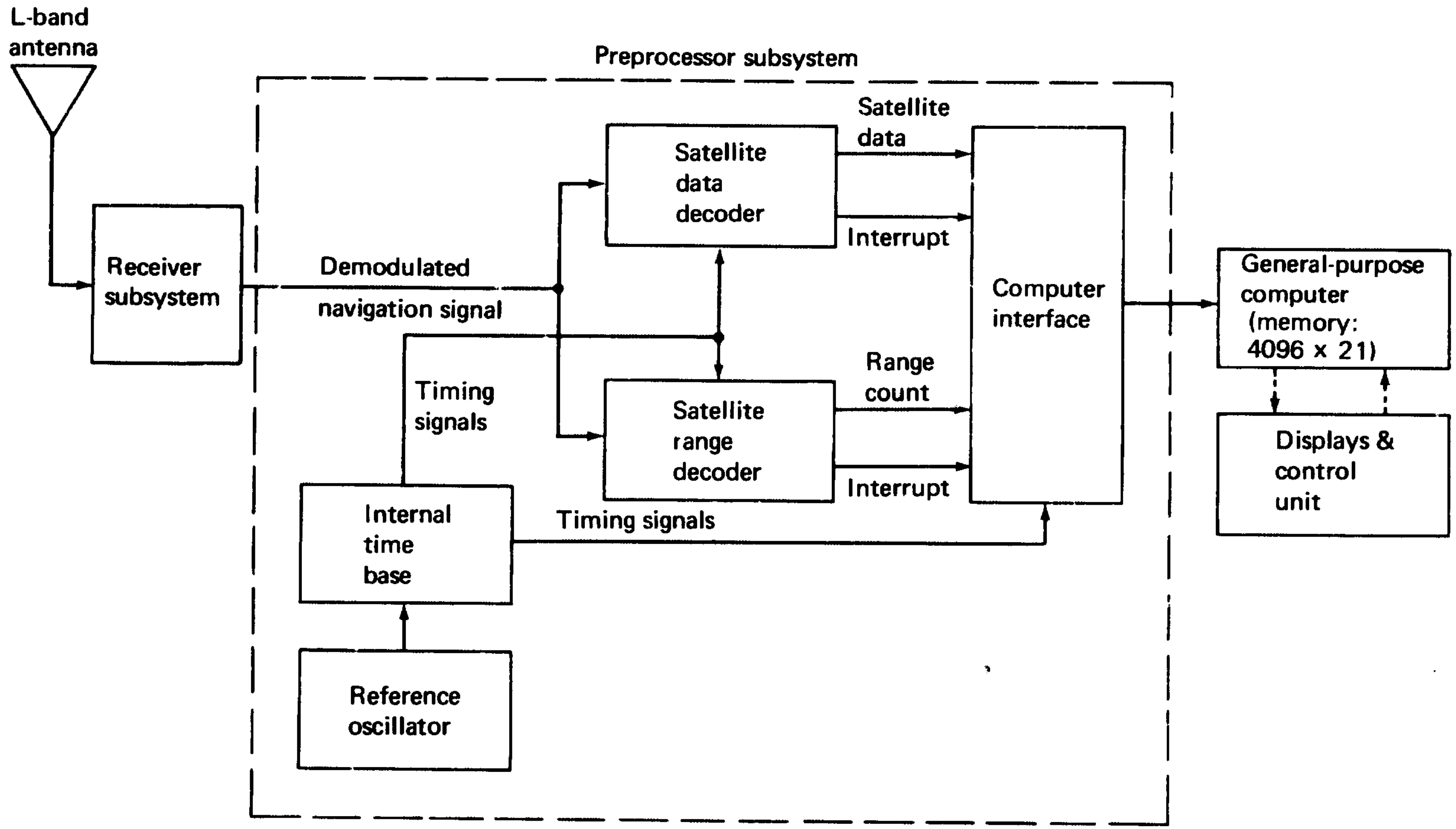


FIGURE 10.– ATC SURVEILLANCE WITH NAVSTAR



From ref. 5

FIGURE 11.– BLOCK DIAGRAM OF NAVSTAR USER EQUIPMENT CONFIGURATION A (AUTOMATIC, SELF-CONTAINED COMPUTATION FOR SUPERSONIC AIRCRAFT)

determination is done at the ATC. The BINOR receiver is still required, but the need for an onboard computer vanishes, and the preprocessor is simplified since satellite ephemeris need not be received and decoded.

Estimates of hardware costs for the aircraft-terminal equipment were also presented by TRW. These costs for the five major subsystems are shown in table 6 and are derived based on production runs of 100 (which is realistic for SST-type aircraft). As seen, total terminal cost would be about $70 000 per aircraft.

In the BINOR system approaches above, the user can either make absolute time measurement (ranging) of each arriving satellite signal against a precision onboard clock or can simply measure the time differences (range differencing) between the incoming signals. The latter technique relaxes the requirement for a precise clock on the aircraft, but raises by one the number of satellites required to make a position fix. The choice of ranging versus range differencing is part of the surveillance system selection task being carried out by the system contractors concurrently with the terminal study contract. TRW, in the earlier NAVSTAR study (ref. 5), had recommended absolute range measurement for supersonic aircraft using a precision clock onboard, as shown in fig. 11. The short-term stability of the clock is $\pm 10^{-9}$ to support the ranging-accuracy potential of NAVSTAR ($<$ 100 feet). Recent contacts with TRW indicated the possibility of using range differencing for the SST-user application, and this approach is reflected in the aircraft terminal design.

It should be noted that the precise accuracy of the NAVSTAR system is much greater than that required for ATC surveillance of aircraft in the North Atlantic area. However, included in the contractor's system-design capability is the use of the NAVSTAR to provide surveillance of aircraft for local-airport operations. The accuracy required for that application is more commensurate with the system capability. It is in this area that the terminal study and the system study have different goals. The Boeing goal is to study aircraft terminal equipment designs for operation in the North Atlantic oceanic area. Thus, the goal does not include study of a system capable of replacing or augmenting the current domestic surveillance radar and VHF voice-communications complex. The TRW approach may be hard to sell to the airline customers as cost effective for the North Atlantic. This is particularly true for operators of both SST and 747 aircraft, which are being delivered with a self-contained triply-redundant inertial navigation system (INS). The analysis of vol. II shows that 30-n.mi.-separation standards can be safely implemented in the North Atlantic when aircraft are equipped with an INS characterized by a track-keeping accuracy of 2 n.mi. per hour (1 σ). Recent informal discussions with NASA/ERC indicate that TRW is preparing an ATC addendum to the earlier NAVSTAR study. This addendum was not available at the time of writing this report and could significantly modify the above comments.

3.1.3.2 Performance parameters: The NAVSTAR system is considered in a configuration providing an ATC surveillance capability. The parameters required to support the BINOR ranging signal on the satellite-to-aircraft link have been determined in TRW's report. The key parameters are listed in table 7 for a satellite with an earth-coverage antenna. It should be noted that when the TRW satellite parameters are adjusted to the regional-coverage antenna and a zero-dB worst-case margin as used in the tone system link analysis, the two techniques are competitive in terms of link performance. After modifying the one-way data shown for the BINOR scheme by a factor of two, the ranging accuracy of 30 [illegible] is found to be in agreement with the data of fig. 8 for the BINOR clock frequency of 320 kHz and the clock loop S/N of +21 dB.

TABLE 6.–NAVSTAR HARDWARE COSTS FOR SST TERMINAL

Subsystem	Cost per unit (a)
Antenna	$ 325
Receiver	7 130
Preprocessor	11 630
Computing	35 700
Display/control	15 000
Total	$ 69 785

[a]Based on 100 units

TABLE 7.–BINOR LINK PARAMETERS

Parameter	Value
Satellite transmitter power	50 watts
Satellite antenna gain	+16 dB
Aircraft antenna gain	0 dB
Carrier loop bandwidth	
Acquisition (S/N = 6 dB)	1650 Hz
Tracking with modulation (C/N = 10 dB)	50 Hz
Clock loop bandwidth	26 Hz
Clock loop S/N (range acc. = 30 ft)	+21 dB
Data rate	625 bps
Data channel ST/(N/B)	+9.5 dB

The remaining link parameters requiring definition are those associated with the forward-interrogation and return-position data links. These links are analogous to the forward and return links associated with the active-tone surveillance system discussed in Sec. 3.1.2. The difference is the reduced power requirements, since the tone signals are not required for the BINOR scheme. The forward link, for interrogating the aircraft, is assumed to have the same carrier and data characteristics as the tone-surveillance case. A continuous forward link is used, and all aircraft are continuously and coherently locked to the ATC signal. When the unique address of the particular aircraft is received in the interrogation sequence, the aircraft outputs the latest BINOR position data on the return link. This response may be either raw range-difference data or actual derived position data, depending on the sophistication of the aircraft terminal equipment.

A carrier phase modulated by a single data channel was postulated for both the forward and return links. A link evaluation shows that the forward-link power requirements are about 5-dB lower than for the tone case, since no tones are required. Satellite-power requirements for surveillance interrogation are minor in comparison to those of the BINOR code link and the individual voice links. For the return data link, a response cycle similar to that for the tone system was assumed. The resultant data rate was found to be 550 bps or 250 bps based on the message lengths given by TRW for the return of either raw time-differencing data or actual position data, respectively. Since these data rates are higher than for the tone response (which includes both data and turnaround tones), system performance is nearly identical for the return link in both cases. However, power requirements at the aircraft and satellite are again small in comparison to those of the voice links.

3.1.4 Surveillance conclusions.– The analysis that was conducted established the characteristics and performance capability of both an active tone-ranging system and TRW's NAVSTAR range-differencing techniques. The evaluation emphasized an ATC surveillance function for control of aircraft in the North Atlantic oceanic area. The results show that the NAVSTAR concept, modified to provide surveillance, can achieve very precise position accuracy (< 100 feet) compared to an active turnaround-tone ranging system (< 1 n.mi.) for the same link performance capability. The precise NAVSTAR accuracy capability, however, is not dictated by ATC surveillance requirements in the North Atlantic, which can be met with the relatively coarse accuracy of the tone technique. The choice of a specific technique is not in the domain of this study and the aircraft experimental-terminal design presented reflects both options.

3.2 Communications Considerations

Major communications-analysis tasks are summarized in this section. The results are the basis for the design parameters of the selected aircraft terminal. Principal tasks include the consideration of alternate satellite routing schemes, the impact of propagation effects, and the determination of the aircraft radio-noise environment. In addition, the critical power limitations of the voice links leads to an evaluation of different voice modulation techniques that can provide improved threshold performance. The characteristics of the selected voice technique are then used in a link analysis to develop the performance tradeoffs between the satellite and aircraft terminal.

3.2.1 Alternate design concepts.– Several items related to the overall communications and surveillance functions are considered in terms of alternate design concepts. These include signal routing alternates through the satellite, digital-data channel requirements, and the methods a pilot might use to access a voice circuit.

3.2.1.1 Signal routing alternates: Three alternate system configurations were postulated with respect to voice- and surveillance-signal routing through the satellites to determine the overall impact on the aircraft terminal design for an operational system. These alternates are:

(1) Alternate 1–Separate voice and surveillance repeaters, unequal loading
(2) Alternate 2–Separate voice and surveillance repeaters, equal loading
(3) Alternate 3–Integrated voice and surveillance repeater, equal loading

In a system with equal loading, the available voice channels are divided equally among the several satellites, whereas with unequal loading, all voice channels are routed through one satellite.

The three alternates were individually evaluated in terms of six criteria. The results are summarized in table 8. As seen, the three criteria most critical to system operation (aircraft EIRP, satellite prime power, and aircraft equipment complexity) favor alternate 2. For this reason, alternate 2 was chosen as the best scheme for routing the voice and surveillance links for an operational system. A simplified system diagram of this alternate is shown in fig. 12. By dividing the required voice links between the two available satellites, the prime-power requirements imposed on the satellites are reduced from the case where one satellite must support all voice links. This advantage is significant in an operational (multichannel) system, since prime-power requirements for voice channels are expected to comprise a high proportion of the total satellite power available. Operationally, this system may occasionally require reorienting the aircraft antenna to the second satellite with certain voice channel selections. If either satellite or its voice-link repeater fails, the equal loading provides operation of one-half the total channels through the remaining satellite for the degraded mode of operations.

3.2.1.2 Digital-data channel: The requirements of a limited digital-data channel used in conjunction with the forward and return surveillance functions were evaluated. With all aircraft locked to the forward-link signal, a digital-data channel can be continually received and demodulated. This technique permits the system to forward both "all-aircraft" data and discrete data for individual aircraft. One example of "all-aircraft" data is the voice-channel status-display update discussed in the next section. Discrete data is the unique address sent to each aircraft (in rollcall order) to respond to the forward-link surveillance signal. The discrete addressing of the surveillance interrogation can also be used effectively for "spotlight" surveillance of aircraft in critical situations; the ATC computer software can be implemented to issue interrogations to these aircraft at a higher rate than the normal rollcall rate.

A data-frame format for the forward and return link was developed with attention given to frame and bit sync requirements, address detection, data transfer, and command capability. The data-frame formats selected for a minimum capability on the experimental system are shown in fig. 13. One important item is to ensure that an aircraft responds only when it receives its own address, since dual responses can mask the return of the intended aircraft and disrupt the surveillance rollcall. The use of the 8-bit address code, repeated three times, results in a probability of false response equal to about 10^{-7} for the link random bit error rate of 10^{-4}. Another consideration is the selection of a frame synchronization pattern to ensure fast, accurate frame acquisition. A 17-bit Legendre code is chosen for this capability; the key acquisition characteristics of this selected frame sync code are given in table 9.

3.2.1.3 Voice channel access: The implementation of a busy-signal indication is one problem associated with a system of relatively low-power mobile users accessing a channel repeater. The user is unable to hear another aircraft user already on the channel, although it

TABLE 8.—ROUTING ALTERNATE COMPARISON

Criteria	Alternate 1	Alternate 2	Alternate 3
EIRP required by aircraft	Highest	Lowest	Higher
Satellite prime power	Highest (+3-dB min.)	Nominal	Nominal
Aircraft equipment complexity	Nominal	Nominal	Higher
Spectrum allocation bandwidth	Higher	Lowest	Higher
Satellite equipment complexity	Highest	Higher	Lowest
Degraded system capability[a]	All voice links	1/2 of voice links	1/2 of voice links

[a] One of two satellites fails; surveillance function seriously degraded

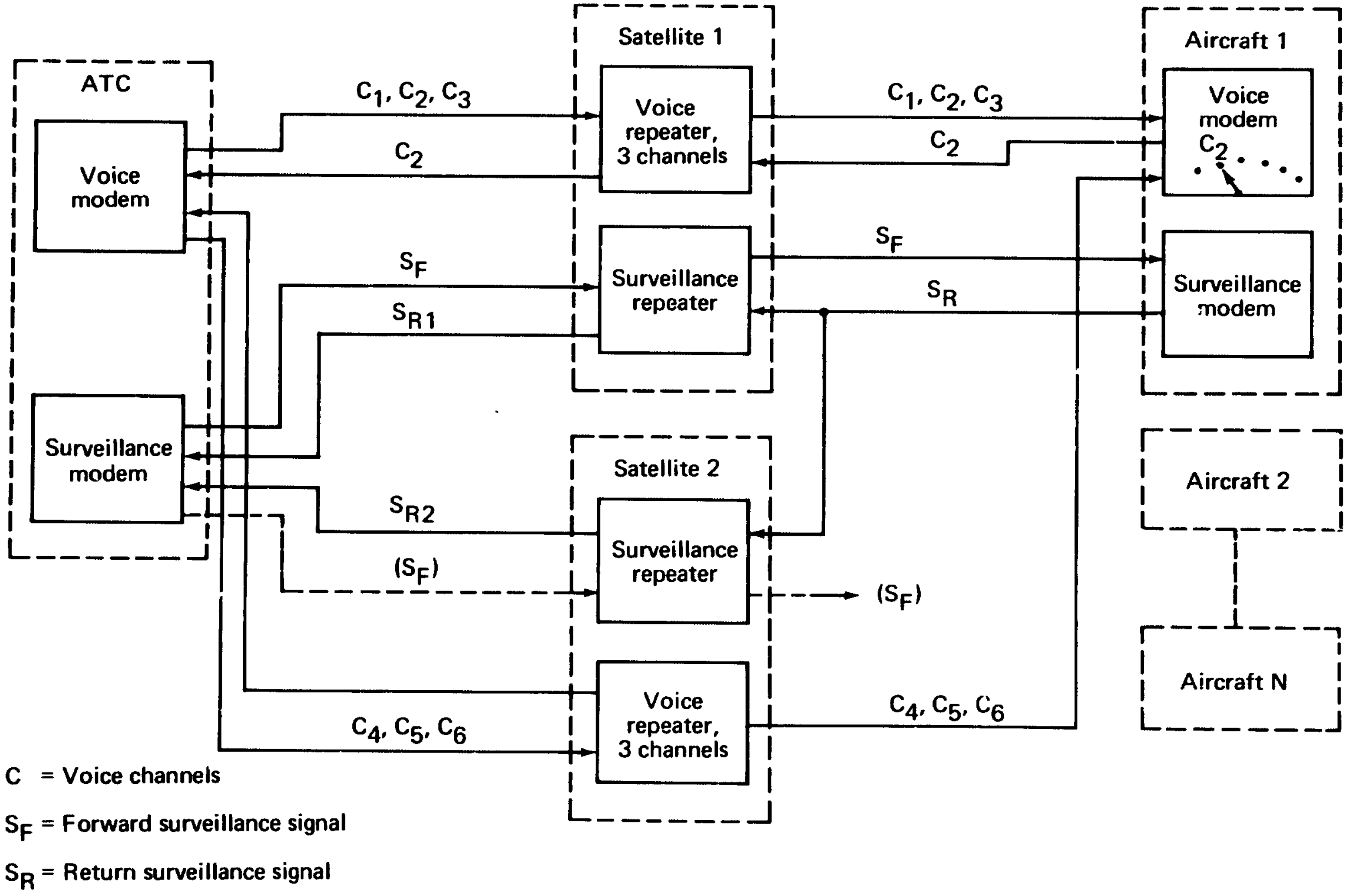


FIGURE 12.– ALTERNATE 2: SEPARATE VOICE AND SURVEILLANCE, EQUAL LOADING

Frame sync	Address	Address	Address	Command	Channel status

where:

Frame sync	a 17-bit Legendre code
Address (3 times)	an 8-bit address code
Override command	a 7-bit command for extended return-link reply
Channel status	a 7-bit voice-channel-status word
Frame length	55 bits
Bit rate	55 bps

(a) Forward link

Bit Sync	Frame Sync	Address	Altimeter	Voice request (optional)

where:

Frame sync	a 17-bit Legendre code
Address	a 9-bit code
Altimeter data	an 11-bit data word
Voice request	a 3-bit code (optional)
Bit rate	202 or 210 bps

(b) Return link

FIGURE 13.– DATA FRAME FORMATS

TABLE 9.–FRAME SYNC PROBABILITY

Sync probabilities	Forward link	Return link
Probability of false sync (one frame)	0.007	0.004
Probability of true sync (one frame)	0.992	0.992
Probability of no sync (in k frames)	3×10^{-3}(k = 1) 8.1×10^{-11}(k = 4)	0.003 (k = 1)

is possible to hear the forward link used by the ATC controller. To minimize conflicts in accessing a channel, both ground-controlled-access and random-access techniques for the voice channels were developed. The significant characteristics of each technique are given in figs. 14 and 15.

The random-access technique is preferred for the experimental program, at this time. The primary reason for its selection is that the 3-minute access delay for the controlled-access technique described is excessive. Furthermore, equipment complexity aboard the aircraft and on the ground is less for the random-access technique.

3.2.2 Propagation effects.– The direct propagation path between the satellite and the airplane terminal includes free space, the ionosphere, and the troposphere. An extensive computer simulation model was used to evaluate the media effects on signals transmitted between the terminals. A brief summary of results is given in the following paragraphs.

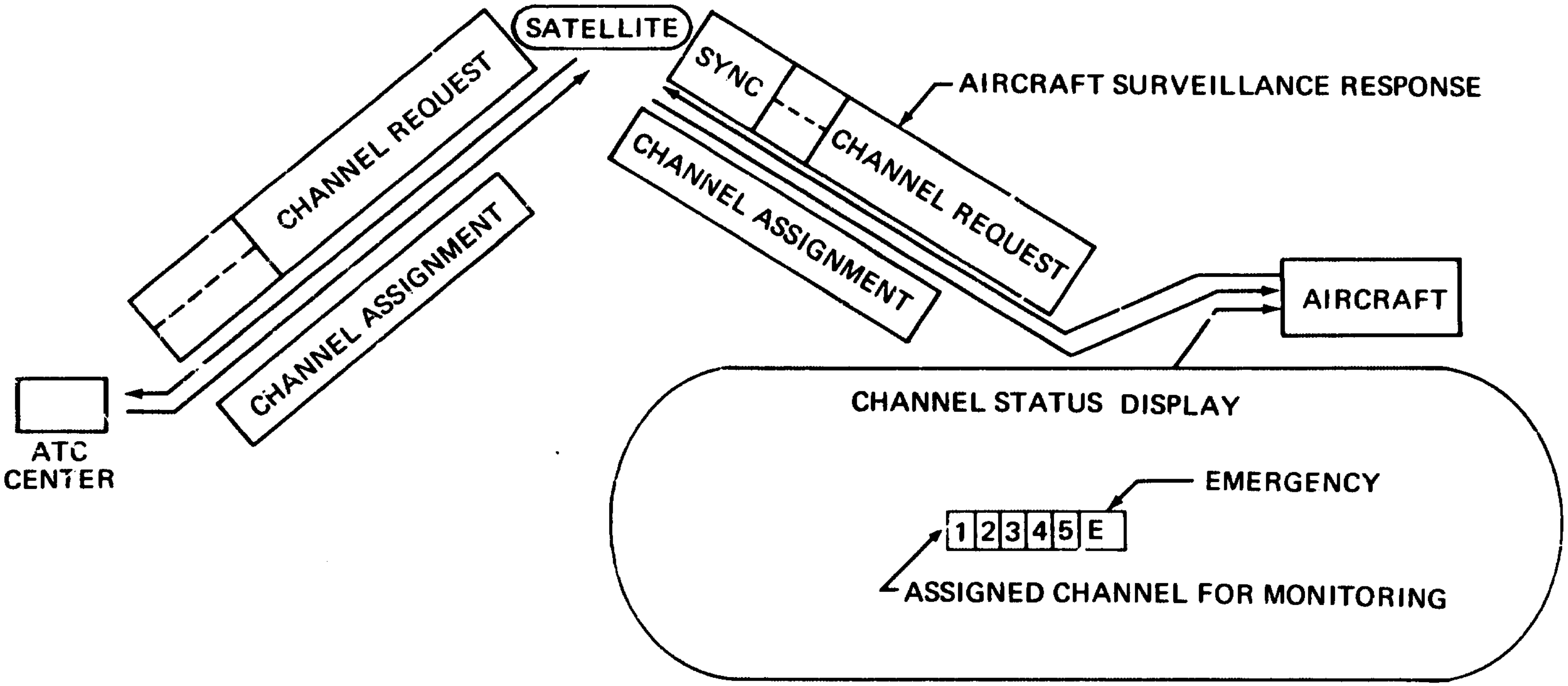
Both the troposphere and the ionosphere will produce significant time-delay effects (both group delay and bending delay) upon the direct wave which represent a source of error in the range measurements. The total time delay for the direct wave, due to the combined effect of the ionosphere and the troposphere, has been calculated as a function of satellite elevation angle. Results of the analysis indicate that the bending delay due to both the troposphere and the ionosphere is less than 235 feet at all satellite elevation angles above 10°. A curve showing bending delay as a function of satellite-elevation angle is presented in fig. 16. The attenuation effects of the ionosphere and troposphere upon the direct wave were determined to be negligible.

In addition to the direct propagation path between the aircraft terminal and the satellite, there is a second propagation path which exists because of reflection from the surface of the earth. The resultant multipath fading effects, caused by interference between the direct and earth-reflected waves, have a significant impact upon system performance. A curve showing required multipath fade margin as a function of satellite elevation angle is presented in fig. 17. The curve was derived under the assumptions that (1) the airplane terminal employs a typical low-gain antenna installation atop the fuselage, (2) sea state 1 (smooth sea) conditions exist (worst-case multipath), and (3) the system time availability criterion is 95% or 99%. The data indicate that the maximum multipath-fade-margin requirement is less than 2 dB for all elevation angles above 10°.

The performance parameters for a typical North Atlantic operational air route between New York and London are shown in table 10. These tabulated data represent a summary of the various propagation effects that could be encountered in an operational environment.

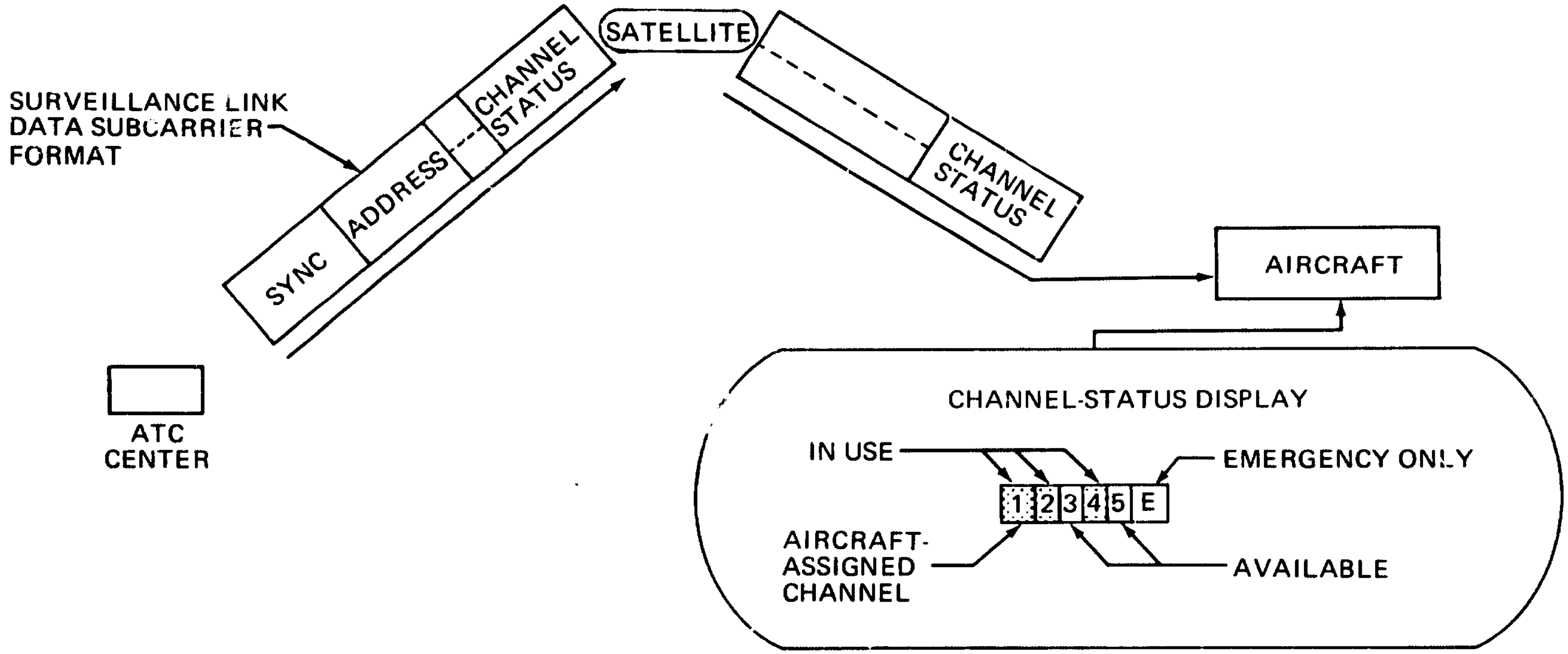
3.2.3 Aircraft radio noise environment.– One critical parameter that may limit the performance level realizable in the SST L-band aircraft terminal is the effective radio noise temperature of the receiving system. Contributions to this receiver noise temperature arise from inherent thermal sources within the receiver front end; ohmic losses in the transmission line between the receiver and receiving antenna; ohmic losses due to impedance mismatches at each end of the line; ohmic losses in the antenna itself; onboard self-generated equipment radio frequency interference (RFI); aircraft thermal sources external to the antenna (i.e. aircraft-skin aerodynamic heating); external atmospheric sources (absorption, P-static, sferics); and external terrestrial and extraterrestrial sources, such as discrete bodies (Earth, Sun, Moon, planets, radio stars), the galaxy, and interstellar hydrogen.

The extent and characteristics of radio noise from these sources were analyzed to define the total aircraft radio noise environment likely to be encountered by the aircraft



1. Pilot requests voice channel via surveillance reply
2. ATC gives go-ahead based on call-in order and message priority
3. Alternate channel assignment requires ATC-to-aircraft link with discrete address and command capability
4. Channel-access delay determined by surveillance fix period (3 min)
5. Emergency channel available without delay (random access)

FIGURE 14.— GROUND-CONTROLLED VOICE-CHANNEL ACCESS



1. Channel status continuously known to pilot via surveillance data subcarrier
2. Pilot normally uses assigned channel for transmission and reception
3. If assigned channel is occupied, pilot waits or switches transmitter and receiver to unoccupied channel to initiate message
4. Flight-status exchange required between ATC controllers when aircraft uses alternate channel
5. Channel-status display lags about 1.5 sec behind actual channel usage

FIGURE 15.– RANDOM VOICE-CHANNEL ACCESS

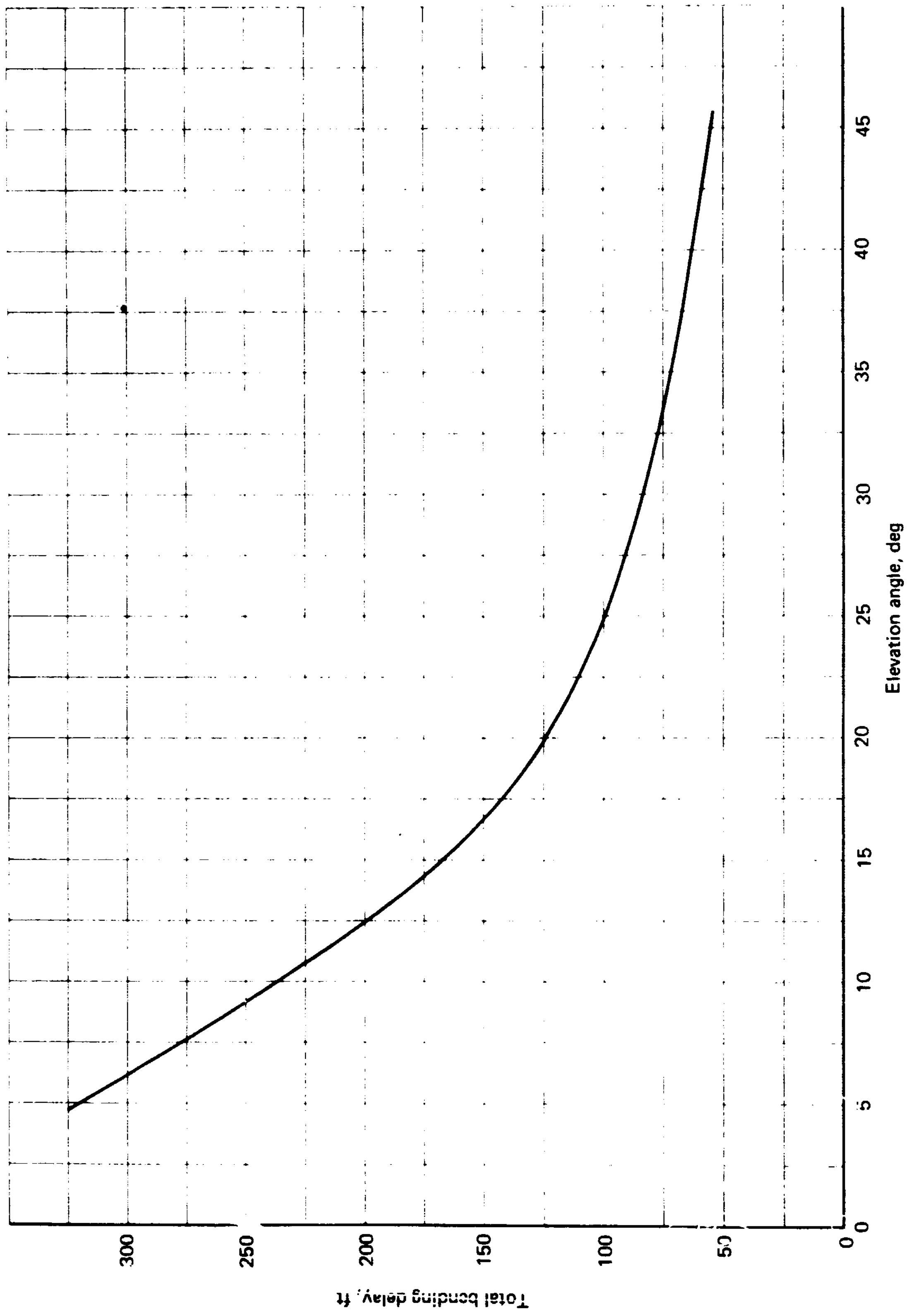


FIGURE 16.– TOTAL BENDING DELAY AS A FUNCTION OF ELEVATION ANGLE FOR 1620 MHz

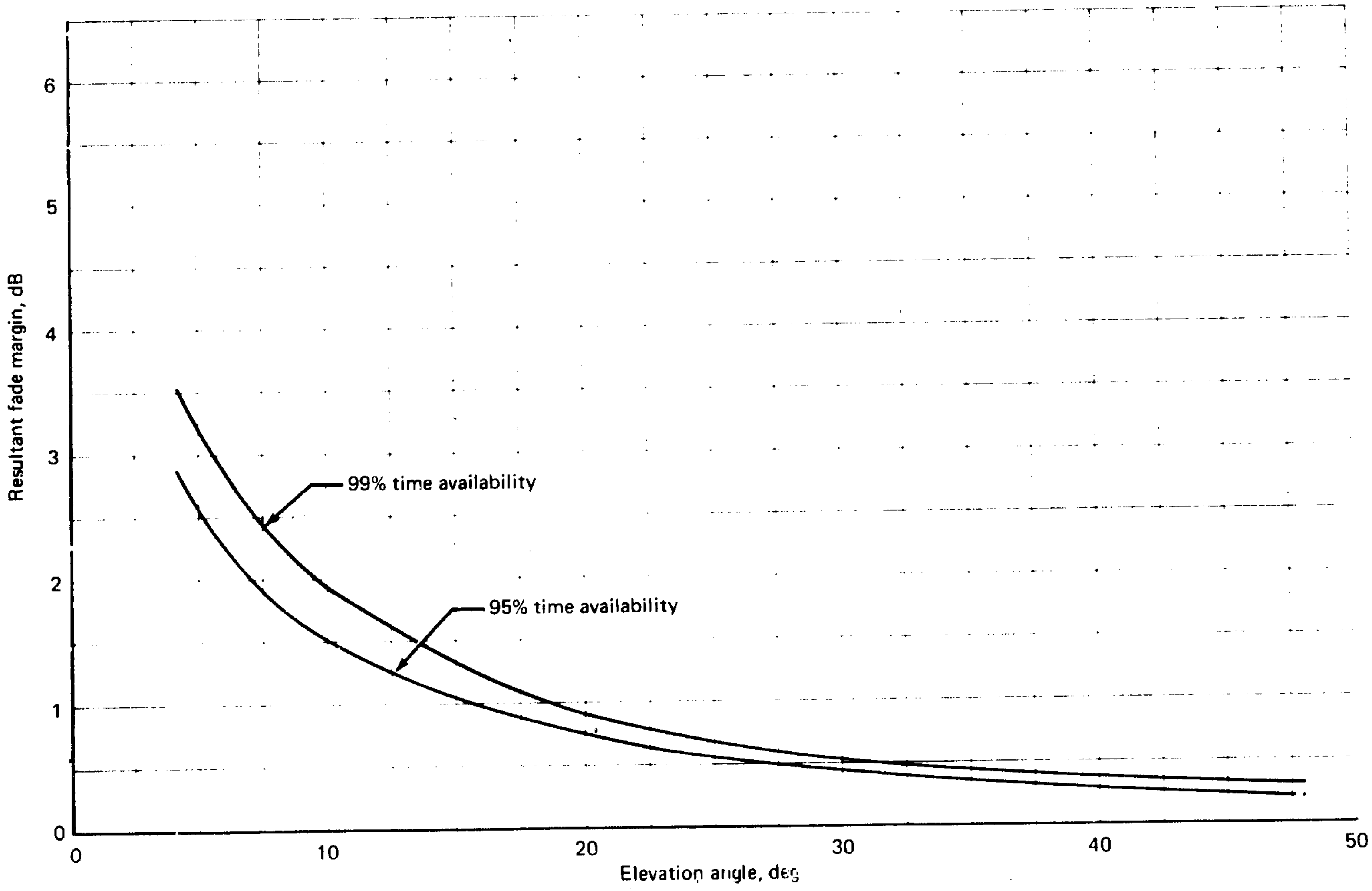


FIGURE 17.– REQUIRED MULTIPATH FADE MARGIN AS A FUNCTION OF SATELLITE ELEVATION ANGLE FOR SEA STATE 1

TABLE 10.– TYPICAL OPERATIONAL SYSTEM PROPAGATION PARAMETERS

Airplane position ⟶	42.15° N–71.16° W		47.57° N–59.32° W		52.21° N–41.30° W		53.64° N–29.90° W		52.75° N–8.30° W	
Satellite position ⟶	0°N–10° W	0°N–50°W	0°N–10°W	0°N–50°W	0°N–10° W	0°N–50° W	0°N–10° W	0°N–50° W	0°N–10° W	0°N–50° W
Fade depth, dB	1.3	0.4	1.1	0.5	0.7	0.5	0.6	0.7	0.5	1.2
Total direct ionospheric group delay, feet	39.7	21.6	34.1	22.6	28.5	24.5	26.6	28.2	24.5	34.1
Total reflected ionospheric group delay, feet	37.7	21.6	32.8	22.6	28.2	24.6	25.9	27.9	24.6	33.5
Total direct tropospheric group delay, feet	0.98	0.32	0.65	0.32	0.32	0.32	0.32	0.32	0.32	0.65
Total reflected tropospheric group delay, feet	61.3	21.9	43.9	23.3	33.8	26.2	32.1	32.5	26.6	44.1
Total ionospheric and tropospheric bending delay, satellite to ground, feet	183.7	72.1	146.2	73.8	106.6	86.9	91.8	100.7	85.3	148.3
Bearing angle of satellite from airplane heading	57.2	96.9	60.9	106.0	67.1	115.8	73.3	121.8	82.2	127.4
Elevation angle of satellite with respect to airplane	12.43°	36.75°	17.78°	34.56°	23.57°	29.71	27.2	24.54	30.06	17.03
Distance from airplane subpoint to reflection point, n.mi.	54.4	17.5	39.1	18.9	29.4	22.7	25.1	28.1	22.4	40.8

receiver. Particular emphasis is given to those sources specifically contributing to the apparent antenna noise temperature.

The results are shown in table 11, which summarizes the significant contributions to apparent antenna noise temperature for both low-gain and high-gain aircraft antennas. Total temperatures at both residual and transient levels are given. Since transient contributions probably will occur less than 0.1% of the SST flight time over the oceanic area, only the residual totals are considered as realistic estimates for use in the systems analysis.

3.2.4 Voice modulation analysis.– The choice of voice modulation technique can have a significant design impact because of the peak-power-limited nature of the satellite-to-aircraft link. An evaluation of different modulation techniques was therefore performed to determine which has the best potential for improved threshold performance. The improvement achieved can lead to a reduction in satellite EIRP or a reduction in aircraft antenna gain.

The basic characteristics of speech were discussed (including the voice spectrum distribution) as were measurement parameters of voice intelligibility, articulation index, and associated S/N requirements. Different speech processing methods were evaluated, such as clipping, emphasis, and various vocoder applications. The modulation techniques examined included the common types of amplitude and angle modulation (with variations) as well as a few unusual approaches. The latter included both the low-energy speech transmission (LEST) concept developed by G.E. and the frequency-and-amplitude-modulation concept (FRENA) conceived by the Phillips Company of the Netherlands.

The results of the voice modulation study are depicted in fig. 18 for several of the more promising modulation techniques. The quality measures of articulation index (AI) and percent word intelligibility are plotted versus the required link threshold carrier-to-noise-density ratio C/Φ at the aircraft terminal. The technique recommended as most suitable for the experimental terminal is narrowband frequency modulation (NBFM) with the following characteristics:

Voice baseband	200 to 3200 Hz
RF bandwidth	13 kHz
Modulator input ratio	6 dB peak-to-rms
Threshold C/Φ	+ 50.0 dB-Hz
Frequency deviation (max.)	± 3.2 kHz

The design point chosen for the link analysis was an AI of 0.6, corresponding to a word intelligibility of 95%. This high, rather conservative value was used since the voice link is the medium for command instruction to the pilot when the ATC surveillance system detects a conflict. At present there are no voice intelligibility criteria officially established for ATC voice channels. However, the FAA Systems Research and Development Services (SRDS), in cooperation with the USAF Cambridge Research Laboratories (AFCRL), has been attempting to develop applicable criteria. The FAA/AFCRL program employs a technique known as Speech Communication Intelligibility Measurement (SCIM) to determine the voice intelligibility realized on operational ATC voice channels. The SCIM technique consists of transmitting a simulated speech signal over a voice communication channel and, through suitable data reduction techniques, determining the voice intelligibility of the channel. This study has not been completed to date; however, conversations with SRDS personnel indicated that, pending results from the SCIM study, they feel that the operator-to-operator grade-of-service criterion (90% intelligibility of unrelated words) established by CCIR Report 339 is probably very adequate for ATC voice communication channels. Using

TABLE 11.–TOTAL APPARENT ANTENNA NOISE TEMPERATURE, °K

Contributer	Low-gain antenna on TCL (a)	Low-gain antenna 30° to 40° off TCL (a)	High-gain antenna +10-dB peak gain
"Hot" radome	5.75	5.75	5.75
"Hot" skin	72.50	72.50	7.25
Atmospheric absorption	10.00 (max.)	10.00 (max.)	10.00 (max.)
Terrestrial (sea)	45.1	102.00	5.00
Galactic (average)	0.1	0.1	1.00
TOTAL RESIDUAL[b]	133.45	190.35	29.00
Precipitation corona	2.26	2.26	2.26
Galactic (max.)	10.00	10.00	100.00
TOTAL TRANSIENT[c]	12.26	12.26	102.26
GRAND TOTAL	145.71	202.61	131.26

[a] Top centerline of fuselage

[b] Values used in analysis

[c] <0.1% of operating time

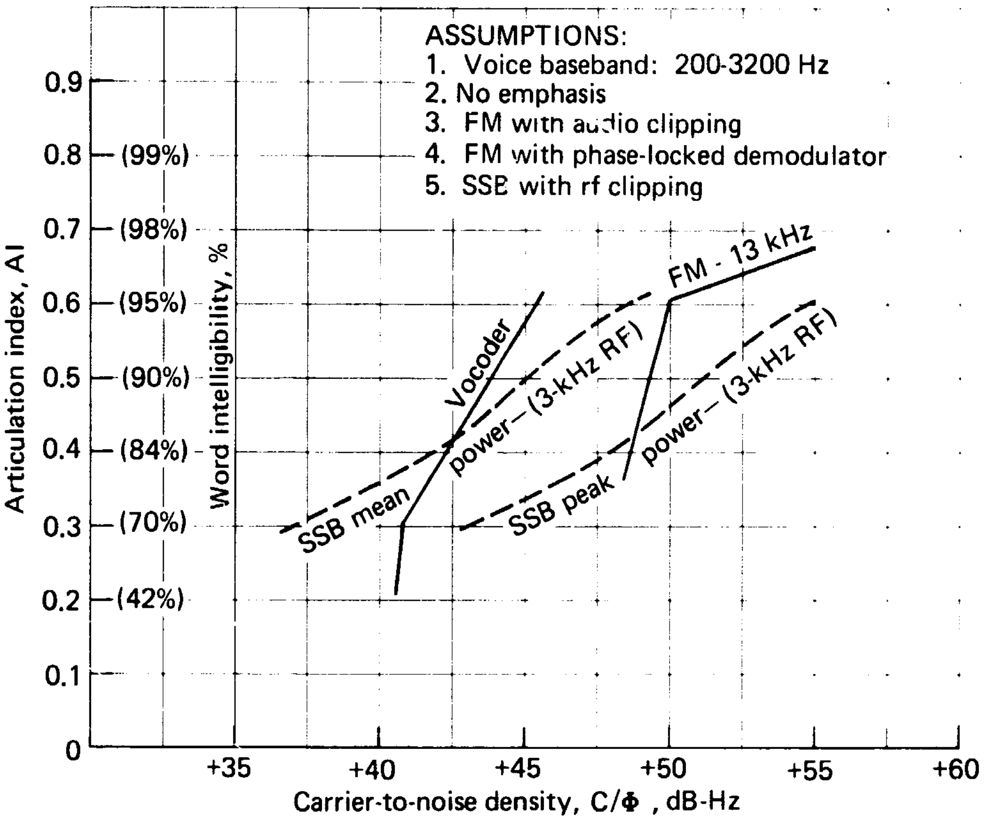


FIGURE 18.– VOICE MODULATION CHARACTERISTICS

this criterion, the data in fig. 18 for NBFM shows a 1-dB improvement in the C/Φ required for the voice link (+49 dB-Hz).

In addition, Philco, in a recent paper (ref. 7) reported study results that show that a word intelligibility criterion of 95% can be met with a C/Φ of only +46 dB-Hz using clipped NBFM and a phase-locked demodulator. The ability to meet this low threshold value should be demonstrated experimentally in a typical aircraft environment. Thus, while the more conservative C/Φ value of +50 dB-Hz is used in the link design, a potential 4-dB improvement in threshold performance remains.

3.2.5 Voice link performance.– The voice channels for the ATC satellite L-band system make the major demands on the system due to (1) the combination of power and antenna-gain limitations at the satellite and aircraft coupled with (2) the large carrier-to-noise-density ratio C/Φ required for acceptable link quality. A link analysis was accomplished for the recommended NBFM modulation technique described in the previous section assuming a phase-locked demodulator at the aircraft receiver and a required threshold C/Φ of +50 dB-Hz (AI of 0.6). The analysis was done for L-band (1540 to 1660 MHz) with the links operated in a simplex mode, for both a single-channel and multichannel satellite repeater. The results for both cases are shown in the performance-tradeoff graph of fig. 19, for a regional-coverage satellite antenna.

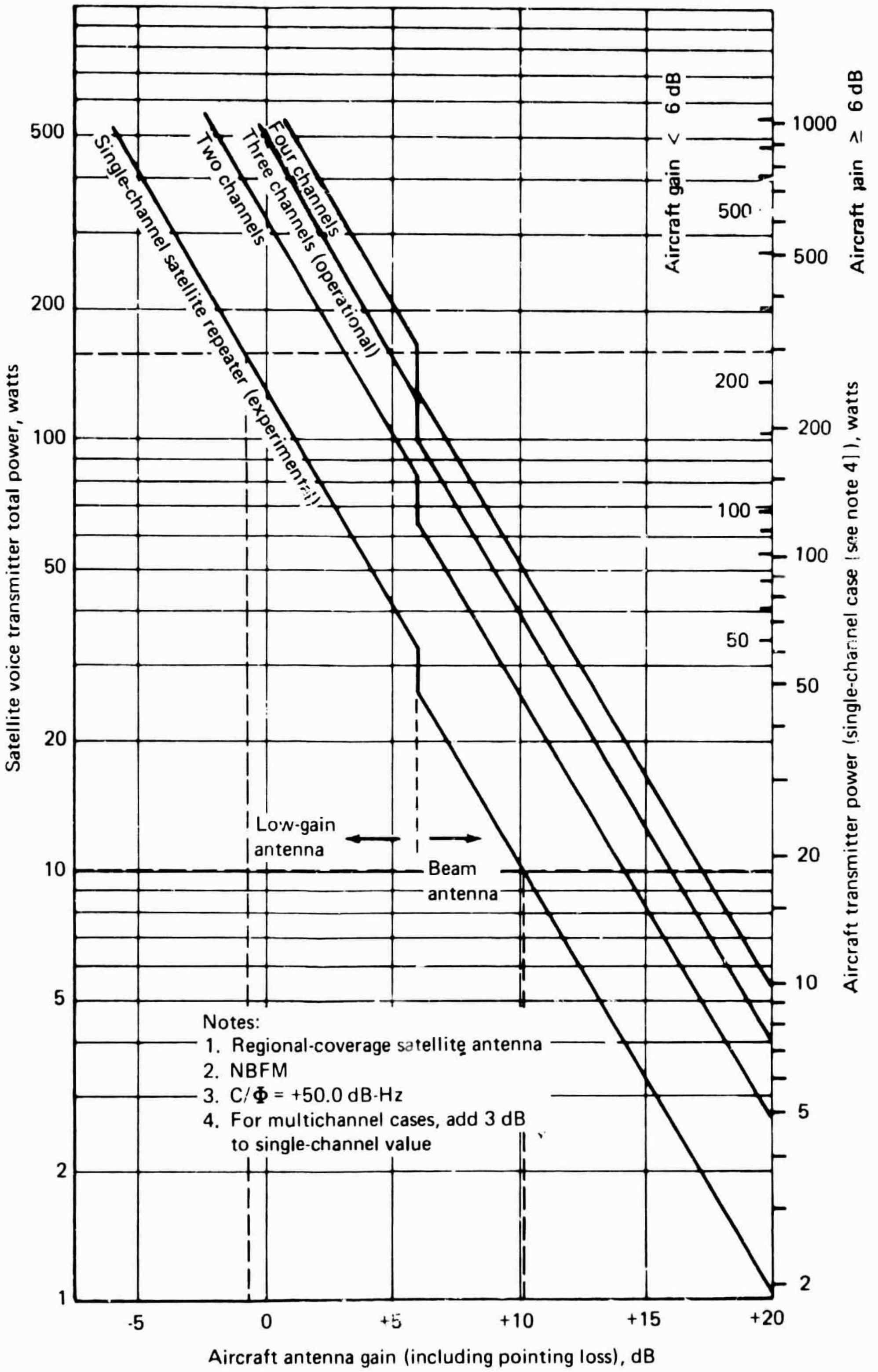
The results show that the use of a -1-dB antenna (a desirable operational system feature) on the aircraft, in conjunction with a regional-coverage satellite antenna, would require a satellite transmitter power of over 150 watts. If, on the other hand, the power of the experimental satellite was limited to 10 watts, then the required aircraft antenna gain would rise to +10 dB. This gain would lead to use of a steerable directive-beam antenna on the experimental aircraft. The corresponding aircraft uplink transmitter power is also shown on the graph. The required power for the two examples above would be 240 watts and 19 watts, respectively.

3.3 System Performance Criteria

During the course of the study, a set of performance criteria was developed to evaluate the expected performance of the recommended design. Included in these criteria are qualitative factors related to link reliability, economics, system responsiveness, growth potential, compatibility, and capacity.

The reliability criteria that were assumed are given in table 12 for the voice, tone surveillance, and digital channels.

The economic criteria are qualitative at this time, because overall system cost studies are not part of this contract. Economic evaluation must include initial costs, payload costs for weight of airborne equipment, maintenance, logistics, channel-utilization charges, and the cost of flight delays due to malfunctions of the aircraft terminal equipment. In addition, there is a recognized need to trade off the satellite EIRP versus the aircraft-terminal performance to find the optimum combination to achieve minimum overall cost for the system.



Notes:
1. Regional-coverage satellite antenna
2. NBFM
3. $C/\Phi = +50.0$ dB-Hz
4. For multichannel cases, add 3 dB to single-channel value

FIGURE 19.– MULTICHANNEL VOICE LINK PERFORMANCE

The responsiveness criterion for the surveillance function is a reply to the ATC once every 3 minutes. The voice channel maximum-delay criteria are:

Emergency message	0 second
Air traffic control message	20 seconds
Advisory message	30 seconds
Other messages	90 seconds

The criteria represent maximum tolerable message-delay times. The average message-delay times have been calculated to be 1, 2, and 7 seconds, respectively, for the latter three categories, using 5 voice channels plus one emergency channel.

TABLE 12.–LINK RELIABILITY CRITERIA

Criteria	Channel		
	Voice	Surveillance	Digital
Grade of service	95% word intelligibility	S/N = 10dB (accuracy = 1 n.mi., 1 σ)	Probability of bit error = 10^{-4}
Time availability	99%	99%	99%
Service probability	98%	98%	98%

The growth criterion is postulated as the ability for the basic design to be extended to global coverage up to latitude 70° N. The design must also be able to accept advanced data systems, including the digital transfer requirements associated with the Aircraft Integrated Data System (AIDS) and Automated Flight Management (AFM) concepts.

The compatibility criterion implies that the satellite and aircraft terminal system must have the ability to be integrated into the current ATC environment in a smooth manner. The postulated aircraft terminal design must (1) be capable of interfacing with the existing on-board electronic equipment (as required) and (2) be compatible with the structural characteristics of the aircraft. In particular, the terminal installation must not degrade the aircraft's performance capability.

The final criterion is capacity. A minimum capacity given for the system was established as 150 airborne terminals during peak traffic periods in the principal area (10° W to 50° W) through 1980. In addition, the system must have the capacity to handle a minimum of 750 messages per hour during the busy-season peak-traffic hours. A voice-channel utilization factor of 80% is also established.

4.0 ANALYSIS OF AIRCRAFT ANTENNA TECHNIQUES

It has been recognized from the inception of this program that the requirements established for an airborne terminal antenna would be among the most significant outputs of the study. The results of the analytical and experimental efforts on the airborne antenna that have been performed during the course of this study are presented in vol. IV. Preliminary analysis of the system requirements led to the conclusion that both low-gain fixed-beam antennas and steerable medium-gain antennas should be considered for the experimental terminal. The critical importance of weight and drag on a supersonic airplane led to the study of flush-mounted antenna configurations.

4.1 Antenna System Requirements

The specific airborne terminal antenna requirements evolved during the study are based on results of the system analysis tasks and tradeoff studies. The requirements include basic antenna parameters and required antenna coverage, gain, and multipath discrimination characteristics.

4.1.1 Basic antenna parameters.– The basic antenna parameters include operating frequency, polarization, impedance, and the expected physical environment. The frequency assignment is L-band, where the aircraft terminal will receive in the 1540- to 1560-MHz band and transmit in the 1640- to 1660-MHz band.

To avoid the possible complete loss of signal due to polarization misalignment resulting from relative attitude variations between the satellite and aircraft antennas, use of circularly polarized satellite antennas was assumed. In addition, circularly polarized aircraft antennas were emphasized in the study to avoid the inherent 3-dB polarization loss incurred in signal propagation between circularly and linearly polarized antennas.

The impedance characteristics of the terminal antenna are such that the voltage standing-wave ratio (VSWR)does not exceed 1.5:1 at any frequency in the transmit or receive bands. This VSWR ensures that the system loss attributable to mismatch between the antenna and its transmission line does not exceed 0.2 dB.

The environmental criteria shown in table 13 are typical of those to which the SST will be developed. Specifically, the terminal, including the antenna system, must be capable of operation at altitudes to 75 000 feet and satisfy the physical requirements shown in the table. Although this environment is considerably more severe than that experienced by present commercial aircraft, flush-mounted, L-band, annular-slot antennas have been qualified for similar environments for military aircraft.

4.1.2 Antenna coverage requirements.– The computer program used in the propagation-effects study was also used to develop the antenna coverage requirements. Examples of the bearing and elevation angles from the aircraft to the satellite are shown in figs. 20 and 21 for a typical New York-to-London SST flight. Satellite positions are shown from longitude 0° W to 70° W.

For surveillance with satellites at longitudes 10° W and 50° W, the antenna system must look from the right side of the airplane simultaneously at: (1) 14° elevation, 31° forward of broadside and (2) 36° elevation, 10° aft of broadside when near New York; and

TABLE 13.– TYPICAL SST ENVIRONMENTAL CRITERIA

Parameter	Extreme Values
Maximum noise level in external acoustic environment	165 dB
Peak level in external acoustic environment (spectra at takeoff)	144 dB at 42.5 Hz
Acoustic noise environment in unconditioned compartments	MIN: 80 dB at 53 Hz MAX: 143 dB at 425 Hz
Acoustic noise environment in conditioned compartments	MIN: 75 dB at 53 Hz MAX: 128 dB at 850 Hz
Vibration envelope – Power spectral density (g^2/Hz) vs frequency	MIN: 1.8×10^{-4} at 53 Hz MAX: 10 at 150 Hz
Ambient flight temperature	MIN: -123° F MAX: 102° F
Equilibrium skin temperature	MIN: 410° F MAX: 480° F Stagnation: 500 ° F
Temperature in unconditioned compartments	MIN: -50° F MAX: 480° F

From ref. 8

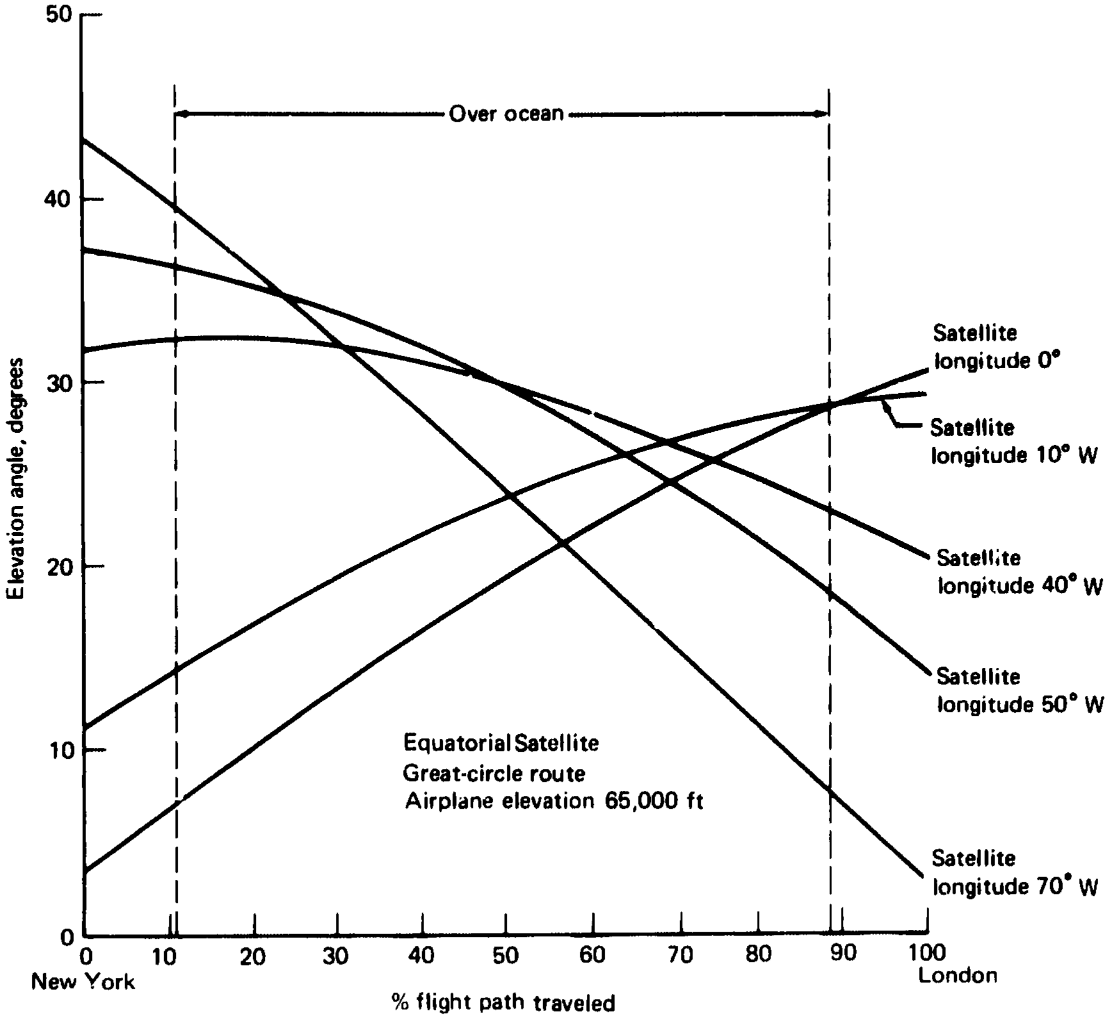


FIGURE 20.– ELEVATION ANGLE TO SATELLITE: NEW YORK TO LONDON

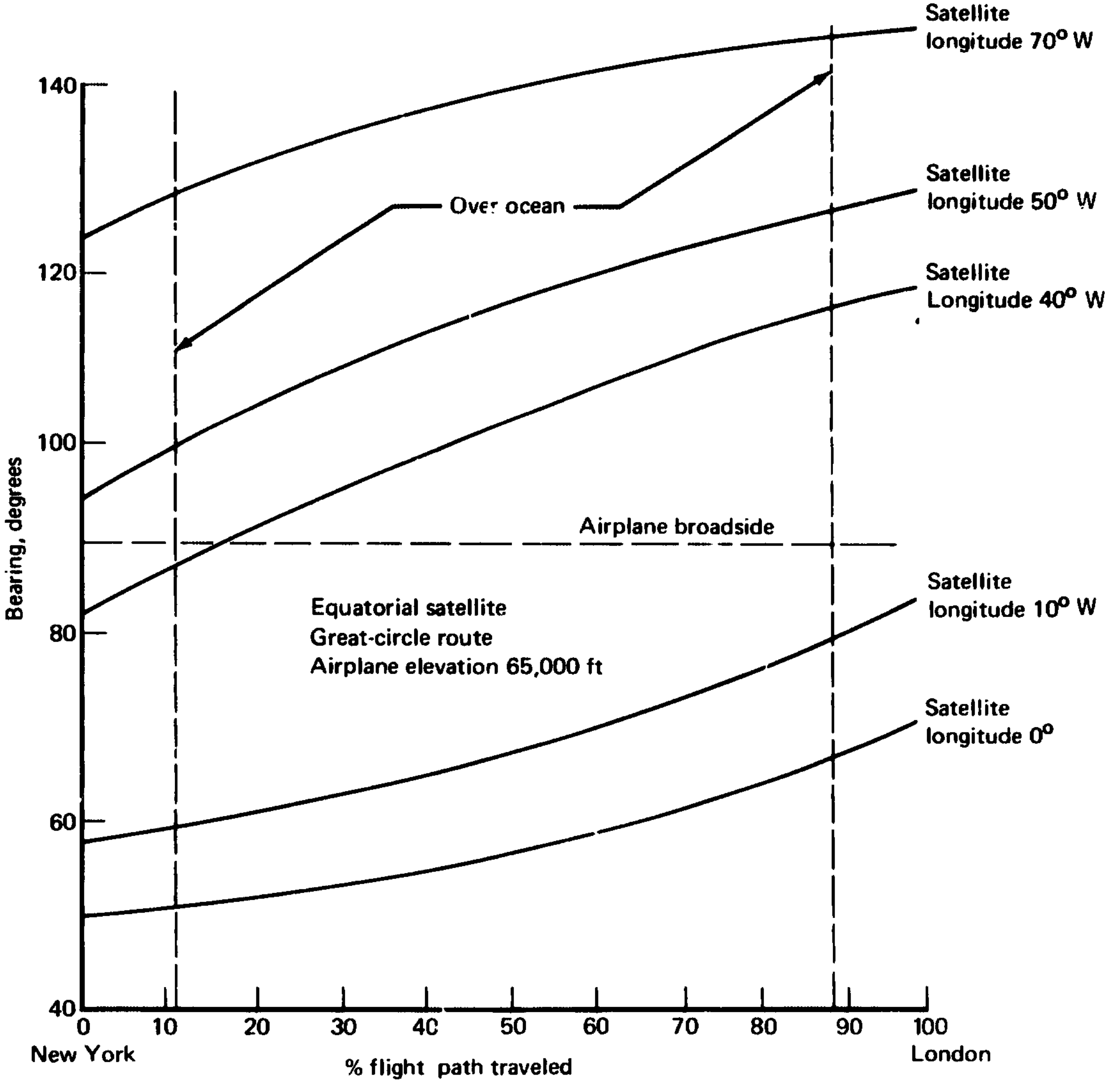


FIGURE 21.– BEARING TO SATELLITE: NEW YORK TO LONDON

at: (1) 29° elevation, 10° forward of broadside and (2) 19° elevation, 33° aft of broadside when near London. The voice communications antenna is required to look only at one satellite at a time. On the return trip, corresponding coverage on the left side of the airplane is necessary. The resulting minimum sector-coverage requirements for the terminal antenna are a minimum sector width of 26° in elevation and 66° in azimuth.

4.1.3 Experimental-terminal antenna gain requirements.– The communications/surveillance link analysis described previously developed a set of link tradeoff charts. Figures 9 and 19 are examples that were used to establish the final aircraft antenna-gain requirements. The interrelationship of satellite EIRP, aircraft antenna gain, and aircraft transmitter power are shown for a multichannel experimental voice link and a tone surveillance link. In particular, the voice performance graph (fig. 19) shows the significant tradeoffs that can be made between satellite EIRP and aircraft antenna gain. These tradeoffs are discussed later in Sec. 5.0 when the aircraft terminal design is selected At the initiation of the antenna studies, these tradeoffs were not complete and the assumptions were made that antenna gain requirements might range from a low of zero dB to as much as 20 dB; therefore, antenna configurations with gains in this range were studied. Similarly, an assumption was made that the antenna design selected has a power-handling capability ranging from 100 to 1000 watts.

4.1.4 Multipath discrimination requirements.– A complete discussion of multipath effects is given in vol. III, where it is concluded that, in general, the required multipath discrimination capability of the antenna must increase for look angles near the horizon. The ratio of the direct-wave gain to the reflected-wave gain at a particular angle of arrival is defined as the multipath discrimination factor. For a circularly polarized antenna system, this multipath discrimination factor is maximized by an aircraft antenna pattern that is nearly circularly polarized for the direct path and has a high axial ratio for the reflected-wave path.

Because of the interrelation of ellipticity and gain at the angle of interest, both must be considered in defining a requirement for the antenna system. The differences in gain and ellipticity ratio for the angles corresponding to the direct- and reflected-ray paths are important. The antenna requirements to provide a given fade margin for an elevation angle of 10° above the horizon can be found from fig. 22 for a 99% communications-time availability.

The link calculations used to develop the curves shown in figs. 9 and 19 assume a maximum multipath fade margin of 2 dB. If the antenna axial ratio difference between the direct and reflected paths is 6 dB, the required antenna multipath discrimination factor for 10° above the horizon is 6 dB (fig. 22).

4.2 Candidate Low-Gain Antennas

During the study, two low-gain antenna designs were examined in depth. The first design was an adaptation of an existing Boeing-developed dual-mode, cavity-backed, four-arm planar log-spiral antenna. This antenna has good coverage characteristics but has a relatively complex feed and mode switching network. The second design, which was selected for an experimental feasibility demonstration, is the orthogonal TE_{11}-mode cavity antenna. This antenna is small, is relatively simple in design, and has good low-angle coverage because of its small aperture.

The orthogonal-mode-cavity antenna consists of a right-circular cylindrical section (about 0.7 wavelength in diameter) in which orthogonal TE_{11} circular-waveguide modes are

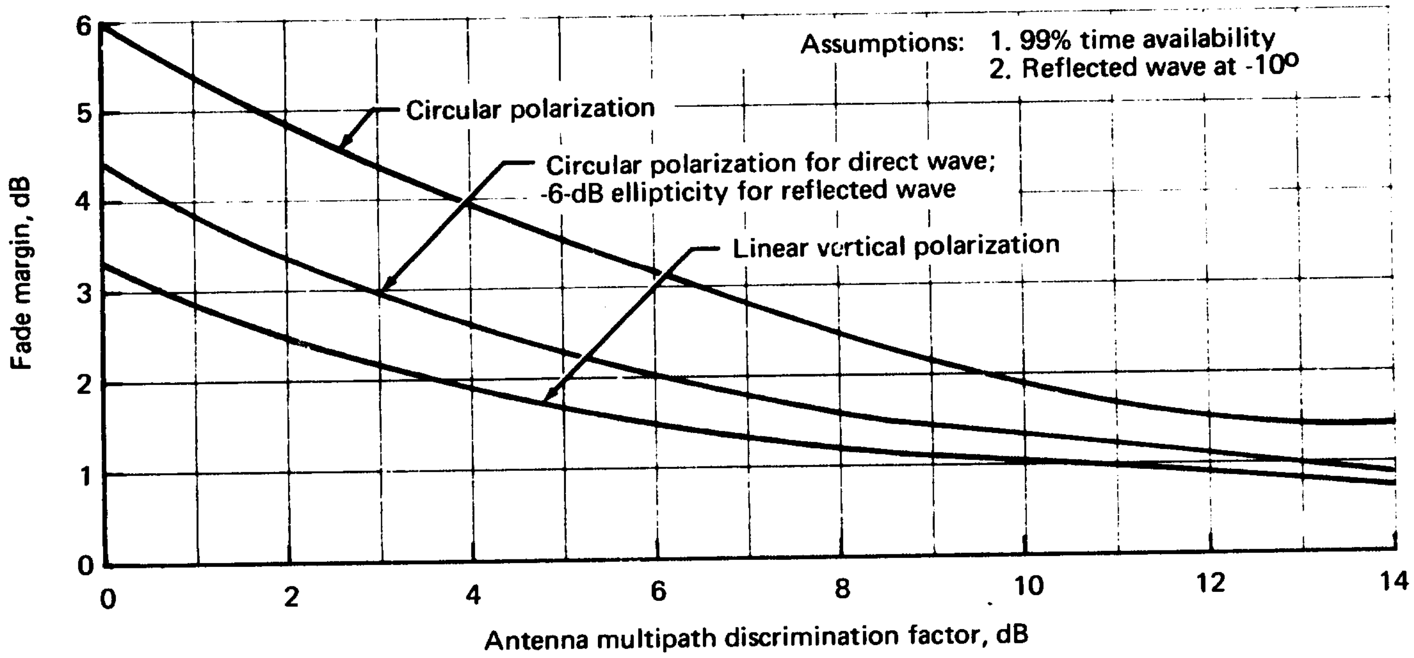


FIGURE 22.– EFFECT OF ANTENNA DISCRIMINATION ON MULTIPATH FADING: 10° ELEVATION ANGLE

excited 90° out of time phase to provide circular polarization. The aperture size is reduced to slightly less than 0.5 wavelength by an annular iris so that a broader pattern can be obtained. A 90°, 3-dB stripline hybrid that is mounted on the bottom of the cavity is used to provide the proper phase and power division for circular polarization.

Radiation-pattern data was obtained from experiments on a 1/6-scale model of this antenna (scale frequency of 9.6 GHz) mounted on a 2-foot-diameter, 12-foot-long cylinder. This diameter approximates that of a 1/6-scale fuselage section for SST-size aircraft. The principal plane pitch ($\phi = 0°$, θ variable) and roll ($\phi = 90°$, θ variable) patterns for the predominant circular polarization are shown in fig. 23. Angle ϕ is measured counterclockwise in the wing plane when looking down at the aircraft and angle θ is measured from the zenith point above the aircraft. The maximum directivity D_{max} was +7.2 dB as measured with respect to a circularly polarized reference. Based on past experience, the antenna losses are not expected to exceed 1.2 dB. Thus, the maximum gain of the orthogonal-mode cavity is +6 dB. The ellipticity as a function of azimuth angle is shown in fig. 24 for zenith angles θ of 40°, 60°, and 80°.

4.3 Mechanically Steered Antennas

A mechanically steered antenna is one in which coverage is achieved by the physical movement of the antenna structure by an electromechanical drive system. The antenna beam is generally narrow in one or both planes; hence, relatively high gain is possible. The large aperture and pointing excursions combined with a typical parabolic-dish antenna require a prohibitively large swept volume in the aircraft. The outstanding exception is the weather radar antenna in commercial aircraft where aerodynamic, structural, and antenna-pointing requirements are harmonious.

The feasibility of an unique mechanically steered antenna was experimentally demonstrated during the study. This antenna is the geodesic Luneberg Lens, which offers several features appropriate to an SST application. These include flush-mounting, hemispherical-scan capability, and appropriate beam and gain characteristics. The evolution of the nonplanar, two-dimensional lens from the conventional Luneberg Lens is shown in fig. 25. Since this class of lens has circular symmetry, the beam may be scanned in aximuth by rotation of the feed mechanism. This lens is strictly in focus for only one radial-feed-point location; nevertheless, approximate focus can be obtained at radial-feed-point positions other than the focal radius, which results in a new elevation beam position for each feed position. Hence, it is possible to scan over the required hemispherical coverage by a combination of feed switching and mechanical azimuth scan.

A prototype antenna was fabricated to demonstrate its properties. The dimensions of the prototype are 24 inches in diameter and 9 inches in depth with a 1-inch plate separation for the test frequency of 1700 MHz. The measured gain for the model antenna was +10.3 dB.

The predicted gain of the lens was +15.0 dB. This was not achieved because of unexpected problems in the design of the feed and apparent phase errors in the model that resulted in a defocussed split elevation beam. Because of the limited success with the laboratory model of the geodesic Luneberg Lens, further development would be required before it could be considered a serious candidate.

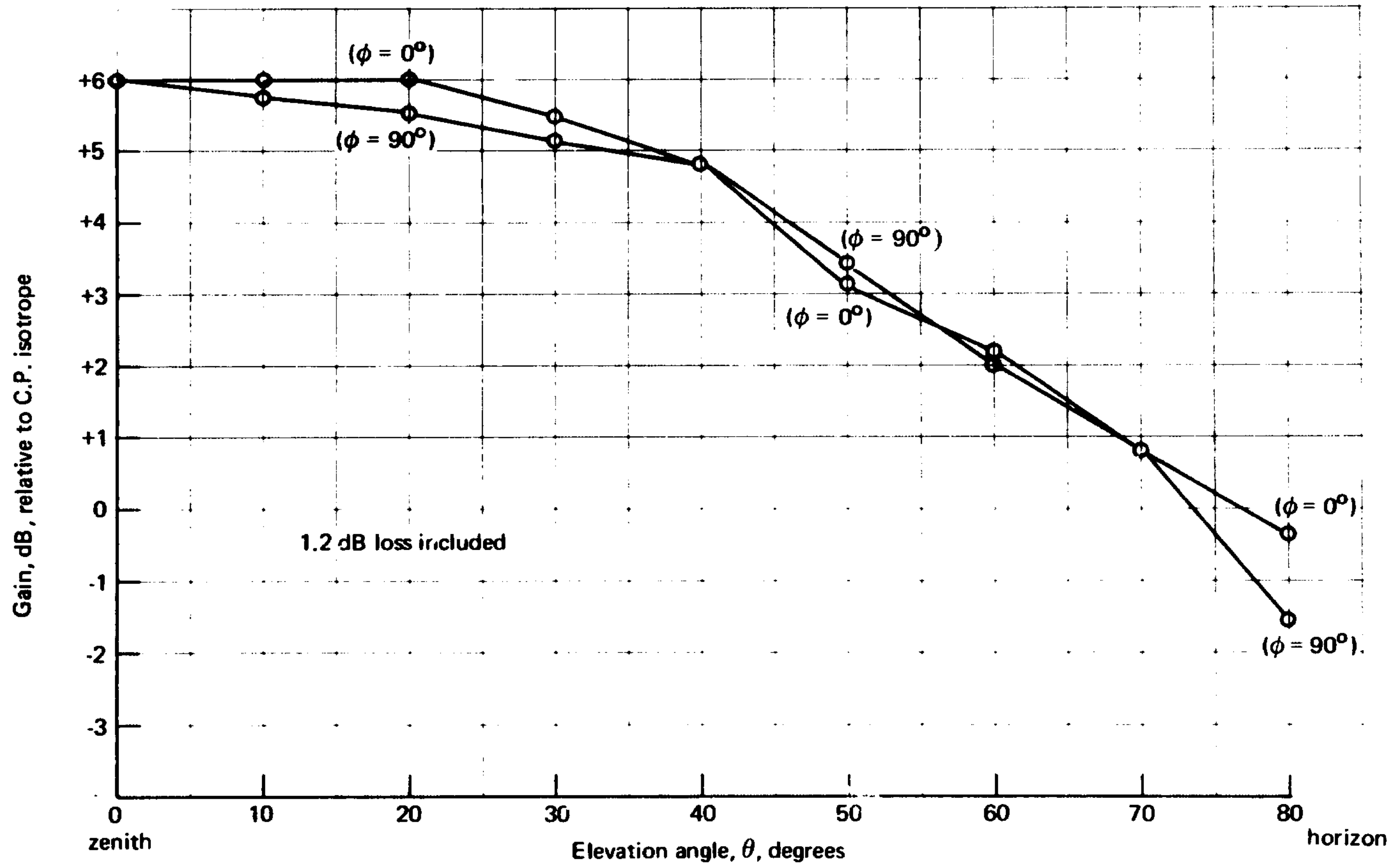


FIGURE 23.– PRINCIPAL PLANE PATTERNS OF ORTHOGONAL-MODE-CAVITY ANTENNA

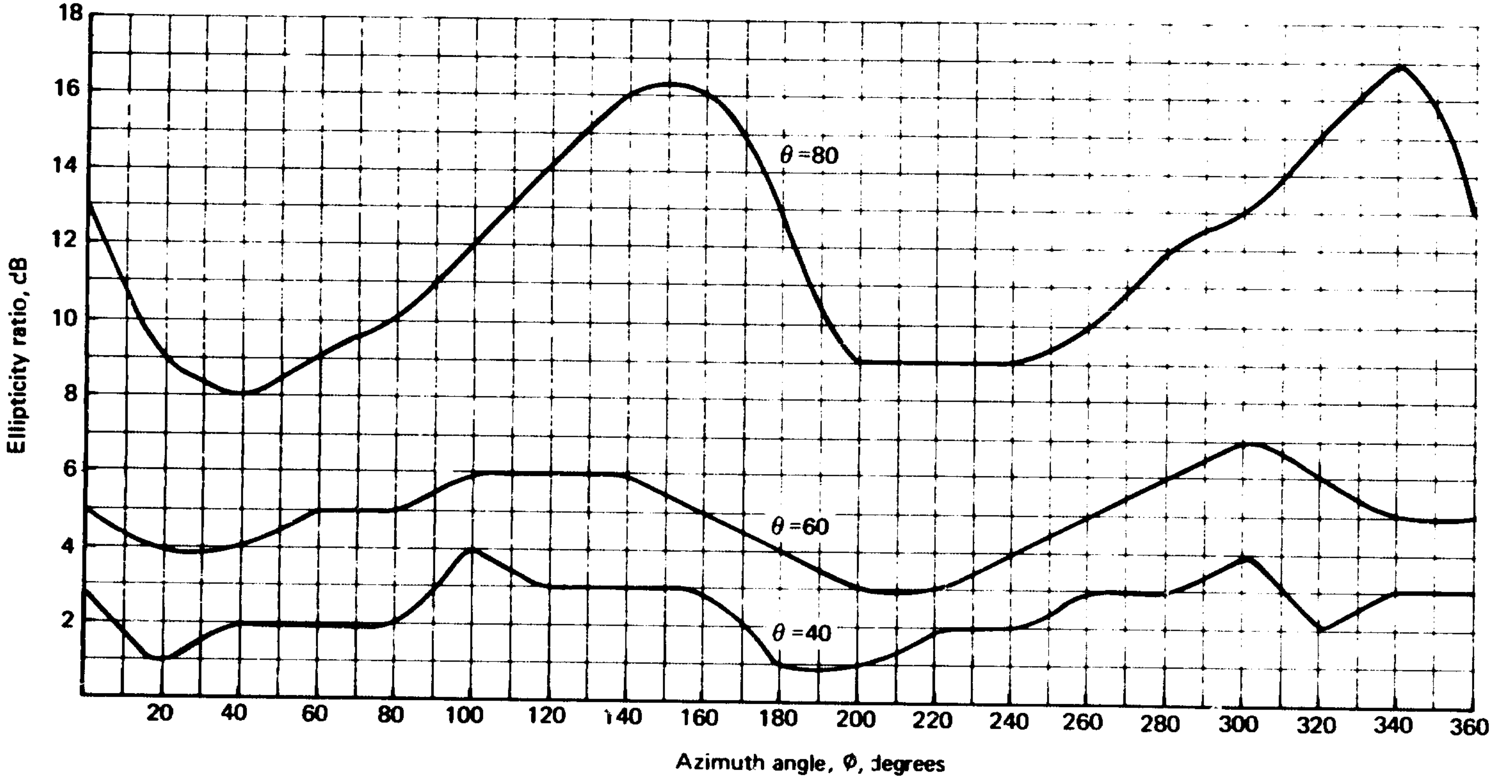
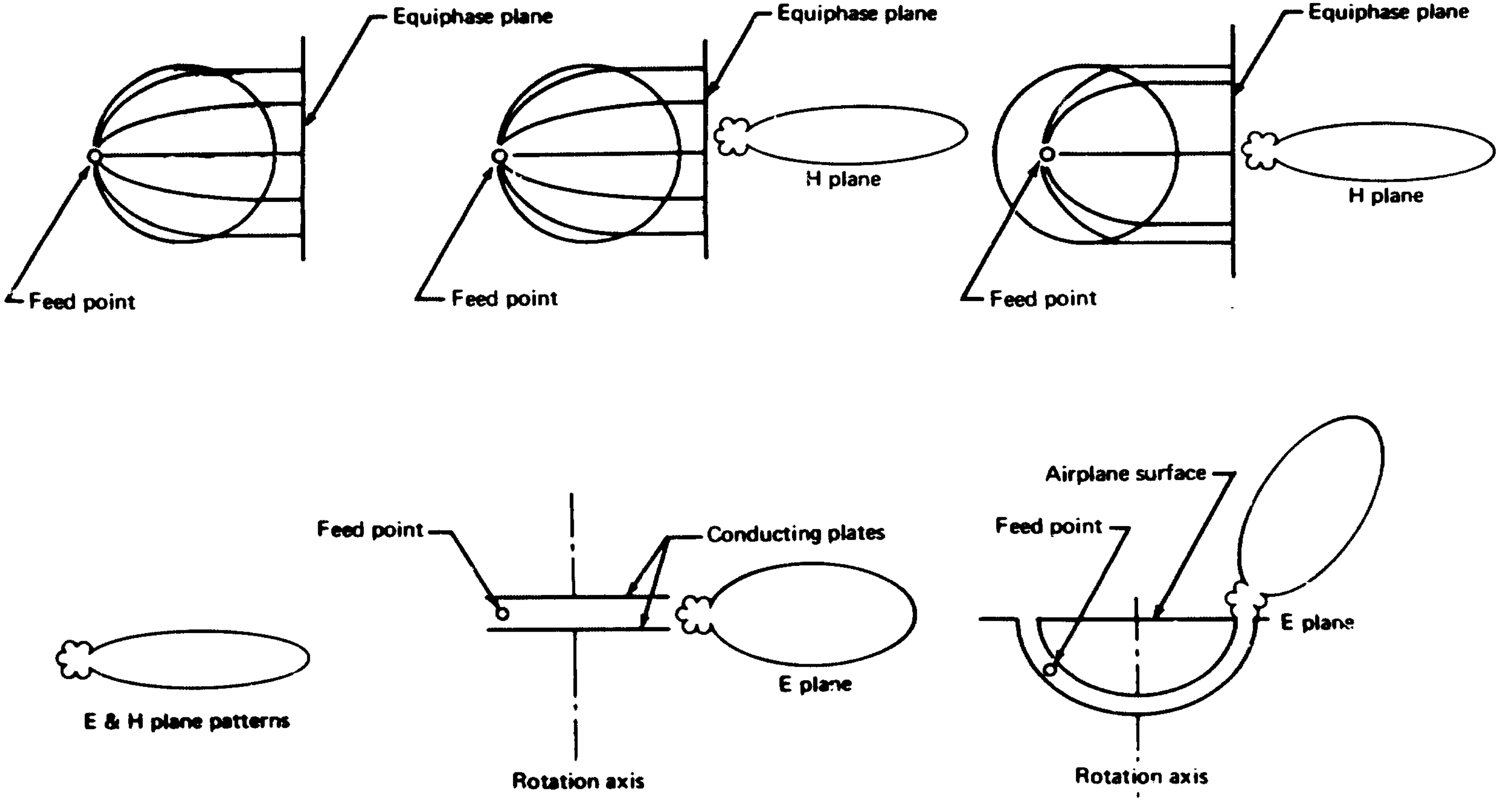


FIGURE 24.– ELLIPTICITY OF ORTHOGONAL-MODE-CAVITY ANTENNA



(a) Conventional Luneberg Lens (b) Two-dimensional Luneberg Lens (c) Geodesic Luneberg Lens

FIGURE 25 – EVOLUTION OF UNIT–INDEX LUNEBERG LENS

4.4 Electronically Steered Antennas

Electronically steered antennas can be flush mounted and offer potential of providing high gain and inertialess beam steering. However, these features are accompanied by increased complexity and a natural decrease in gain as the beam is scanned away from the array broadside.

The electrical performance of a phased-array antenna is determined by the array geometry, the number and types of array elements, and the method of exciting the array. The main beamwidth is determined by the size of the array, whereas the sidelobe structure, polarization, gain, impedance characteristics, and the change of characteristics with scan are affected by the element spacing within the array, the number of elements, the type and size of elements, the means of exciting the elements, and the mutual coupling effects between the elements.

4.4.1 Array elements.– The relative spacing of elements of a phased array must be less than 0.54 wavelength for scanning to ±60° off the array normal without grating lobes. The ideal individual element pattern is $\cos^{1/2}\theta$. The element should be circularly polarized with the ability to operate throughout the 1540- to 1660-MHz frequency range. If a linear array is needed, the 0.54-wavelength spacing requirement and pattern requirement will hold in one plane only. However, the dimension of the element aperture perpendicular to the line of the array must be kept small so that the pattern in the orthogonal plane is as broad as possible.

Cavity-backed crossed slots, cavity-backed spirals, and circular-waveguide orthogonal-mode cavity elements are examples of flush-mounted circularly polarized elements for a phased-array antenna. Crossed dipoles mounted one-quarter wavelength above a ground plane and fed in the proper phase for circular polarization approach the pattern of an ideal element and are desirable for applications where flush mounting is not necessary.

An example of a typical circular waveguide element with a sleeve dielectric is shown in fig. 26. Use of a sleeve dielectric provides desirable bandwidth characteristics. The patterns and performance of this antenna are similar to that of the orthogonal-mode circular cavity described in Sec. 4.2, where the diameter of the cavity was made larger so that no dielectric loading is necessary.

4.4.2 Beam steering methods.– There are three basic methods of beam steering. One is to provide computer-controlled phase shifters in series with each element of the array. The second is to switch between fixed multiple beams formed by a passive feed matrix. The third is to accomplish beam steering by using a pilot tone from the other end of the communications link.

An example of an eight-element series feed with analog hybrid phase shifters is shown in fig. 27. The proper couplers to provide uniform distribution (assuming lossless transmission lines) are shown. Beam steering is accomplished simply by providing the same dc control voltage to each diode. This type of system is limited to small arrays because of the necessary power-splitting ratio of the couplers and the cumulative phase errors that are inherent in a series feed.

Another simple means of beam steering is to switch between the outputs of a Butler-fed matrix. A two-dimensional Butler matrix will connect an N x M planer array and will provide N x M independent simultaneous beams. Each beam will have the full gain of the

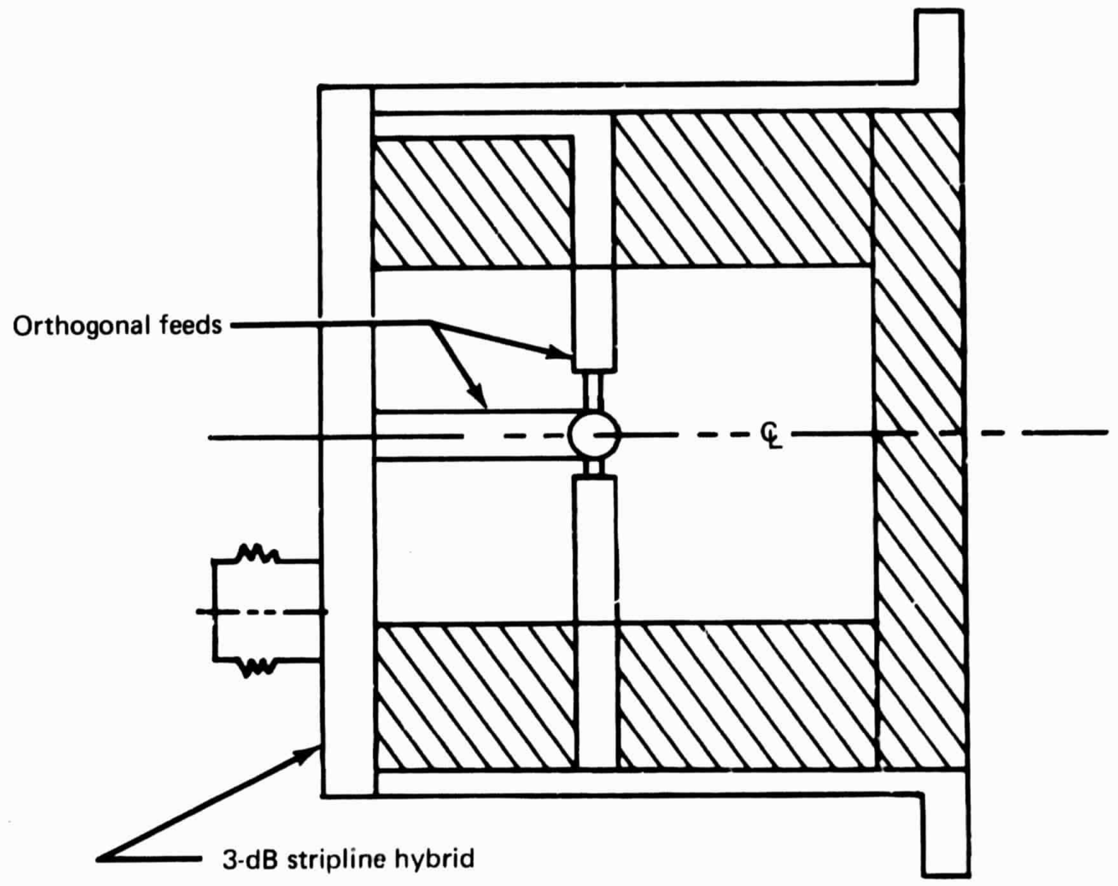


FIGURE 26.– SLEEVE-DIELECTRIC-LOADED ORTHOGONAL-MODE-CAVITY ELEMENT

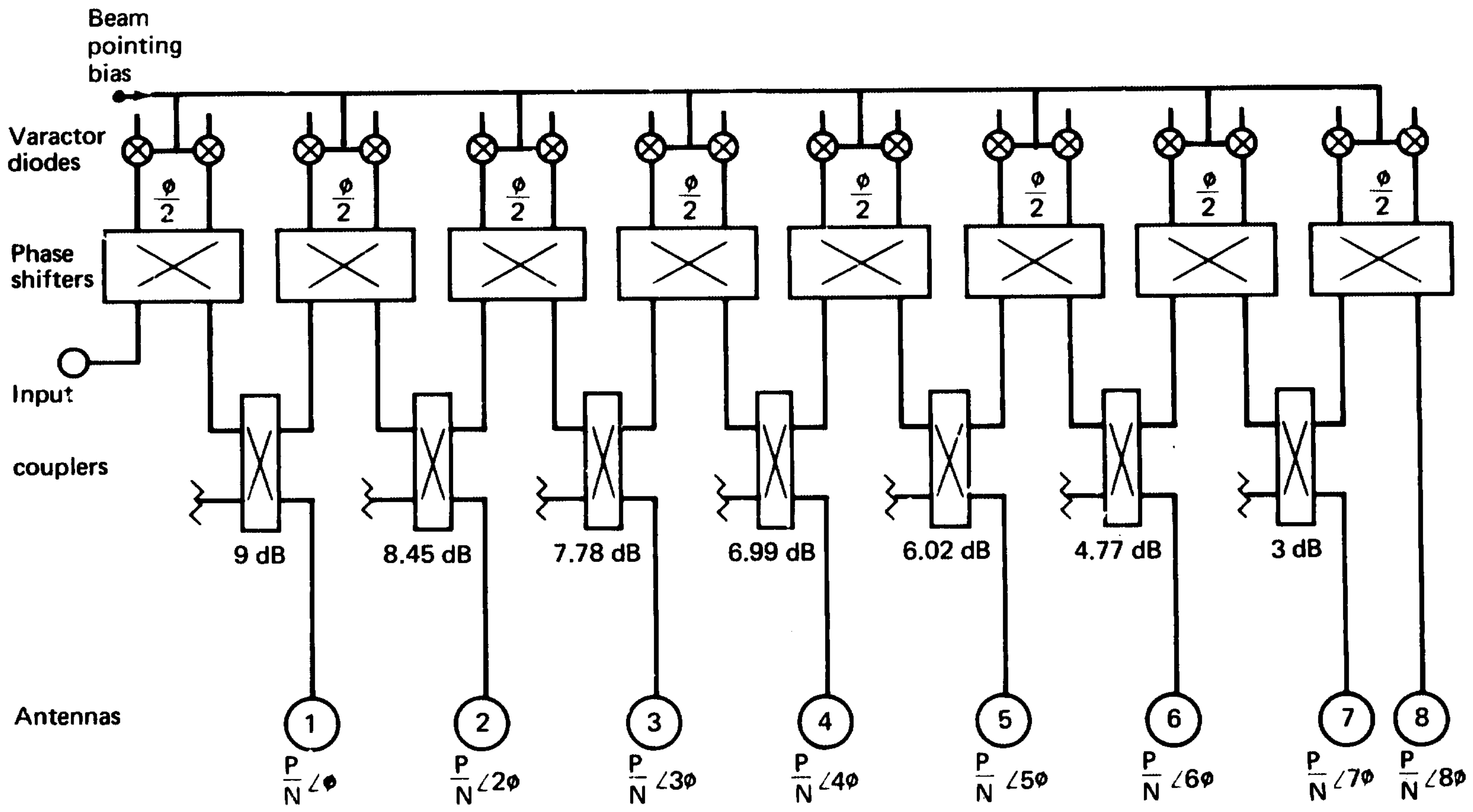


FIGURE 27.– ANTENNA-ARRAY SERIES FEED

aperture. The outputs of the matrix can be switched by diodes having capability to handle up to 200 watts cw power. The matrix is completely passive and can be manufactured in stripline with the loss in the feed limited to 0.3 dB for an eight-element matrix. Operation to 500° F is possible by using a ceramic dielectric. The gain of a Butler-matrix-fed array varies with pointing angle as the beams are fixed in space with approximately -4-dB gain degradation at the crossover points.

4.4.3 Modular arrays.– There has been an industry-wide research and development effort to design integrated phased-array elements. Each element contains an antenna, a transmit-receive switch, a solid-state transmitter, a receiver, a mixer, and a phase-shifting mechanism. Texas Instruments' MERA (Molecular Electronic Radar Array) development and RCA's Blue Chip programs were among the first developments. Ryan, Dalmo Victor, Motorola, AEL, Sanders Associates, and IBM Federal Systems Division (which were all visited during the state-of-the-art survey) indicated that they are working on integrated-circuit phased arrays but that the details were proprietary. A Boeing-developed prototype module is discussed in Sec. 5.4 of vol. IV as an example of modular technology.

A major problem of a modular antenna for use on the SST is that cooling must be provided at the antenna. The active components have an upper operating-temperature limit of about 150°F, whereas the array surface will experience temperatures near 450°F. An example of one type of element that can be used with high surface temperatures is the disk-loaded circular waveguide shown in fig. 28. The complete receiver-transmitter microstrip circuitry can be contained in a one- or two-layer printed-circuit module at the bottom of the element. The dielectric disks can be constructed of ceramic material (alumina, for example) having excellent resistance to heat and good thermal conduction properties. The spaces between the disks can be low-density, high-temperature foam disks that have excellent insulation properties. Thus, cooling of the metal waveguide will provide protection for the circuit elements.

4.5 Experimental-Terminal Antenna System Configurations

The choice of an aircraft antenna system for the experimental program will be determined by the EIRP characteristics of the satellite available for the experimental program. Since the satellite configuration is not known, systems with high-, medium-, and low-gain antennas were considered. Potential locations for mechanically-steered antennas and phased arrays were studied. It was concluded that arrays mounted on the side of the forward fuselage should be recommended for the experimental terminal.

Antenna configurations that can satisfy various minimum-gain requirements over the required coverage area were synthesized. A summary of these configurations is given in table 14. The single top-mounted element, the simplest possible antenna system, provides about -1 dB gain. Left-right switching is required for an antenna gain greater than -1 dB. The single element mounted 60° above the horizon requires an increased multipath fade margin, which results in an equivalent gain of only +1 dB rather than the expected 3 to 3.5 dB. A two-element array mounted 38° above the horizon will support a 2-dB multipath fade margin. Any array of three elements or more will provide adequate multipath protection.

Beam steering is necessary to meet the minimum sector coverage requirements for the New York-to-London route for all arrays of four elements or more. The additional complexity of two-dimensional beam steering is necessary for all of the two-dimensional arrays.

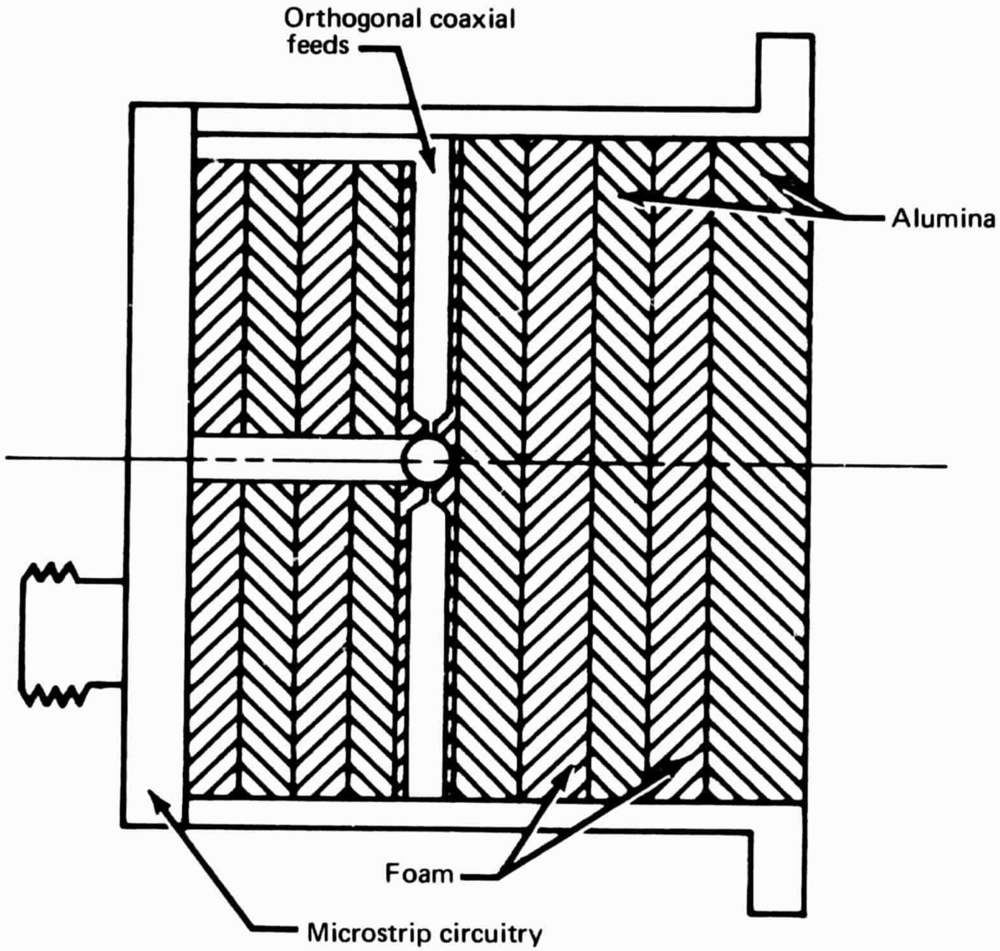


FIGURE 28.— ORTHOGONAL-MODE-CAVITY MODULAR ELEMENT

TABLE 14.– ANTENNA CHARACTERISTICS

Antenna	Antenna normal axis (degrees above horizon)	Antenna size, inches	Assumed loss (feed and dielectric), dB	Maximum gain, dB	Minimum gain over required experimental coverage area, dB	Required multipath fade margin, dB	Remarks
One element	90°	7 dia x 3	1.2	6	-1.5 to -0.5	1.9	Upper-hemisphere coverage
One element	60°	7 dia x 3	1.2	6	3 to 3.5	4.2	Equivalent to +1 dB gain over elevation angles -10° -and-above
1 x 2 array	38°	6 x 10 x 4	1.5	7.5	3	1.8	Elevation coverage to 67° above horizon
1 x 3 array	30°	6 x 14 x 4	1.5	9.0	3	1 to 1.5	Elevation coverage to 51° above horizon
1 x 3 array	25°	6 x 14 x 4	1.5	9.0	5.3	1	
1 x 4 array	25°	6 x 18.5 x 4	3.0	9.0	8.0	1	One-dimensional beam steering required
1 x 8 matrix Fed array	25°	6 x 35 x 4	1.5	12.3	7.0	1	Fixed multiple beams with 4 dB cross-over points
2 x 8 array	25°	10 x 35 x 4	3.0	14.5	13.5	1	Two-dimensional-beam steering required
2 x 9 array	0°	10 x 39 x 4	3.0	15.0	13.3	1	Two-dimensional beam steering required
4 x 4 array	25°	18.5 x 18.5 x 4	3.0	14.5	13.5	1	Two-dimensional beam steering required
4 x 5 array	0°	18.5 x 22.5 x 4	3.0	15.5	13.8	1	Two-dimensional beam steering required
6 x 8 array	25°	26.5 x 35 x 4	3.0	19.2	18.2	1	Two-dimensional beam steering required
6 x 9 array	0°	26.5 x 39 x 4	3.0	19.7	18.0	1	Two-dimensional beam steering required

5.0 AIRCRAFT EXPERIMENTAL TERMINAL DEFINITION

The previous sections summarized the various tradeoffs leading to the specific requirements and constraints that are established for an aircraft terminal designed to operate with a satellite system for ATC. The purpose of this section is to present the proposed aircraft terminal design for the experimental program. The complete details and rationale leading to the selection are contained in vol. V of this report.

The terminal design is discussed both in terms of the equipment state of the art and the performance requirements established previously. The goal of the terminal-design selection is to provide good flexibility in test options during the experimental program.

5.1 Equipment State-Of-The-Art Summary

Throughout the study, close contact was maintained with potential suppliers of L-band systems and components. Near the half-way point in the study program, many potential vendors were visited to determine their interest, capabilities, and previous research and development experience in areas applicable to this study. The particular components of interest were power amplifiers and low-noise receiver front ends. The goal of the survey was to establish the development status and preliminary cost estimates of L-band devices appropriate for the terminal design. The L-band frequency assignments assumed were 1640 MHz to 1660 MHz for the uplinks to the satellite and 1540 MHz to 1560 MHz for the corresponding downlinks (based on FAA data, ref. 9).

Specific choices of device or vendor should not be inferred in the following sections, because the final selection will be made in phase II after evaluation of vendor responses to detailed procurement specifications.

5.1.1 Power amplifier devices.– A survey was made of traveling-wave tubes (TWT's), klystrons, crossed-field devices, negative-grid devices, and solid-state device technology. A number of off-the-shelf devices (primarily broadband TWT's) were found that met the power output requirements of the preliminary terminal design. Device technology for electrostatically focused klystrons (ESFK's) and crossed-field devices was found to be far enough advanced to support tube development programs aimed toward satisfying the operational terminal requirements.

Table 15 contains a representative sample of current device technology for power amplifiers. The experimental-terminal transmitter power-output requirement is from 100 to 300 watts; consequently, a TWT may be the recommended power amplifier device. Typical tubes suitable for this application are the Varian VA-624C and the Microwave Electronics Corporation M5477. Of these two tubes, the M5477 has the best form factor for airborne packaging. The quoted TWT efficiencies are based on broadband operation from 1 GHz to 2 GHz (typically). However, with the narrowband requirements of the terminal, it is possible to design a tube to provide double the beam efficiencies shown. The 100-watt S-band tube being developed by Watkins-Johnson under contract to NASA/JPL is a good example of this type of TWT.

Solid-state power amplifiers are not recommended for the experimental terminal due to present power output limitations. However, such devices could be competitive for the operational system as device technology progresses.

TABLE 15.– REPRESENTATIVE 1.65-GHz POWER OUTPUT DEVICES AVAILABLE OFF THE SHELF[a]

Device	Type	Power output	Beam efficiency, %	Gain, dB	Instantaneous bandwidth, MHz	Weight, lb	Size, inches	Remarks
Varian 4K3SL	Magnetic-focused Klystron	1 kW	~ 33	>30	9	85	18 x 14 dia	Too large for ARINC 404 box
Hughes 551H	Solenoid-focused TWT	1 kW	14 to 16	≥30	Sufficient	20	20 x 3 dia	2- to 4-GHz tube – Hughes feels it may work down to 1.65 GHz
Microwave Associates MA 2032	Solenoid-focused TWT	800 W	~14	25	Sufficient	21	18 x 4 dia	
MEC M5477 (modified)	PPM-focused TWT	300 W	14	≥30	Sufficient	8	21 x 3 dia	100-watt tube also available, same size
Varian VA-624C	PPM-focused TWT	160 W	10 to 15	30	Sufficient	9.5	24 x 2-1/2 dia	Too long for ARINC 404 box

[a]Within 90 days

5.1.2 Low-noise receiver front-ends.– Both an uncooled parametric amplifier (paramp) and a low-noise transistor amplifier are recommended for use as low-noise preamplifiers for the experimental-terminal receiver. The paramp with a noise temperature of 50° K provides significant performance improvement to compensate for the expected low-power experimental satellite. This choice permits voice-link evaluation with aircraft antenna gains held to values applicable to an operational terminal where higher satellite powers are expected. A transistorized preamplifier is recommended to demonstrate the operational capability for surveillance by using it in conjunction with the low-gain antenna. The transistorized preamplifier is recommended for the operational voice and surveillance receiver from both economic and maintenance considerations. Typical cost tradeoffs are given in fig. 29, which shows the paramp priced a factor of ten higher than the transistor preamplifier.

5.2 Experimental-Terminal Design

The initial hardware phase of the L-band communications/surveillance SST terminal program will be directed at development, testing, and demonstration of an experimental version of the operational system to prove concept feasibility and provide data on system performance. The design goal of the selected experimental-terminal concept is to provide a high degree of flexibility during the demonstration program.

The terminal design was selected on the basis of providing this test flexibility as well as the ability to meet the established terminal requirements and constraints. Requirements and constraints for the terminal design are based on the results of the previously described studies on operational requirements, communications/surveillance analysis tasks, and the aircraft antenna evaluations. In addition, the experimental-terminal design was predicated on existing hardware technology and on the ability to adjust to the evolving satellite design. The choice of satellite EIRP, which is a design factor external to this contract, has a strong impact on both the experimental and operational aircraft terminal configuration. These factors and the selected experimental-terminal design are discussed in the following sections. Flight-test considerations are also discussed.

5.2.1 Terminal requirements and constraints.– The SST aircraft-terminal design for use with an ATC satellite system has been divided functionally into four subsystems. These are the rf subsystem, the surveillance and data subsystem, the voice subsystem, and the BINOR subsystem. The BINOR subsystem represents the components required to implement a capability to receive and process signals from the NAVSTAR system postulated by TRW. The details of the subsystems are described in a later section. The specific requirements and constraints established for each subsystem are given in fig. 30. There will undoubtedly be changes to some of these requirements as the overall system concept is selected, because the final system selection will consider the results of the parallel system studies done by RCA and TRW as well as the results of Boeing's terminal study.

5.2.2 Terminal rf performance tradeoffs.– There are significant tradeoffs possible at the aircraft terminal based both on (1) the satellite performance capability, and (2) the choice of the terminal-antenna design and receiver noise threshold. To aid in developing the performance criteria of the aircraft terminal, several satellite configuration alternates were developed. The characteristics of these alternates are shown in table 16 and represent the possible extremes in satellite EIRP (effective isotropic radiated power). EIRP is the product of satellite transmitter power and the antenna gain along the line-of-sight vector, divided by the rf circuit loss. This definition is consistent with CCIR recommendations.

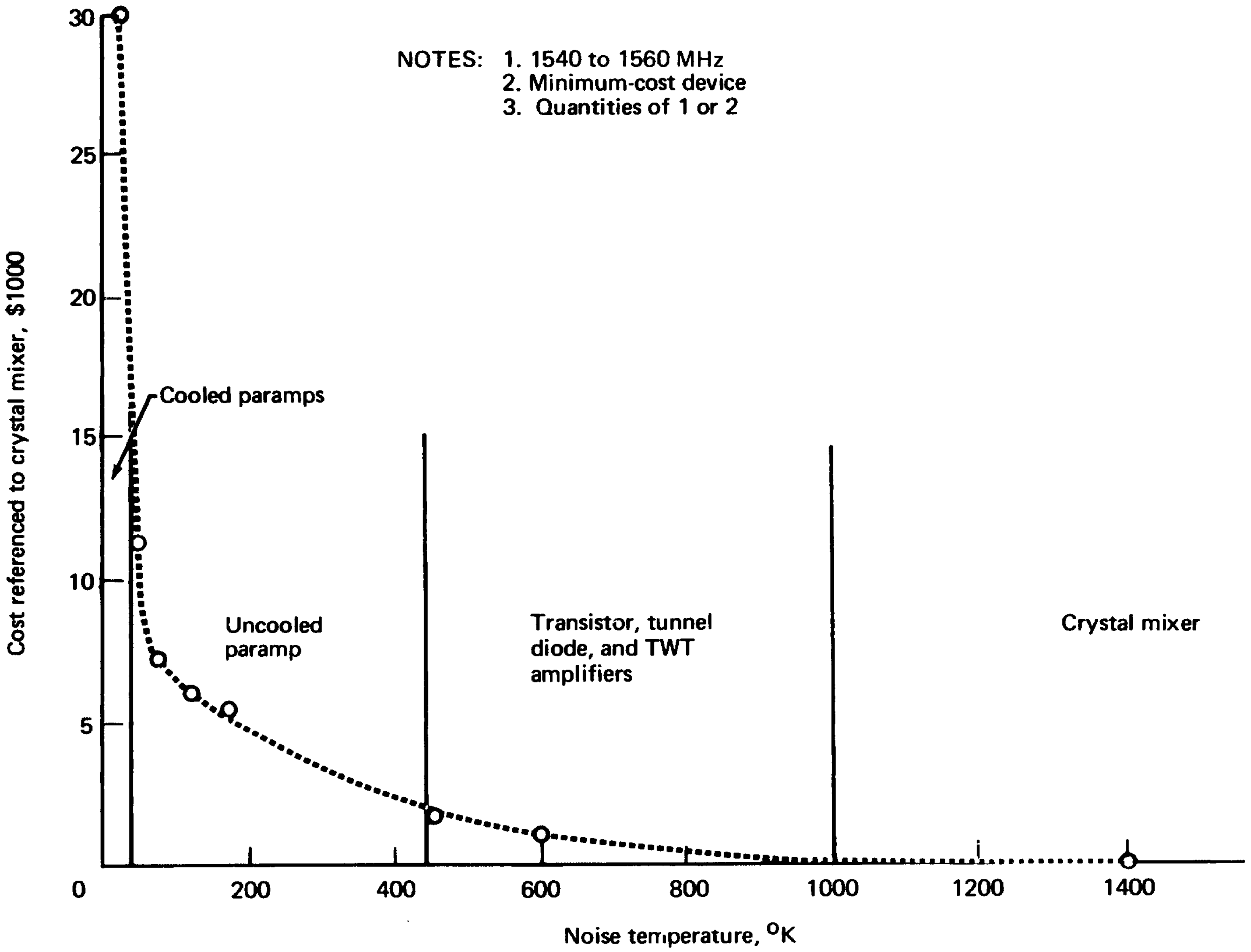


FIGURE 29.— COST OF LOW-NOISE PREAMPLIFIERS

RF subsystem

- Provide antennas for reception of voice & surveillance
- Use same antennas for transmission of voice & surveillance
- Provide sufficient amplification of received and transmitted signals
- Translation to and from i.f. frequencies
- Isolation—received and transmitted signals
- Isolation—rf and other subsystems

Surveillance and data subsystem

- Coherently demodulate surveillance carrier and subcarrier
- Establish bit and frame sync
- Provide tracking reference for voice demod.
- Detect received address, command, and voice channel status
- Initiate correct response:
  1. PSK modulation of return data subcarrier
  2. Turnaround of ranging tones
  3. Phase modulation of return-link carrier by tones and data
- Compatibility with BINOR surveillance function in BINOR scheme
- Maintain isolation between surveillance/data subsystem and other subsystems

Voice subsystem

- Receive and demodulate NBFM channels (1 through 6)
- Provide sufficient conditioning of received and transmitted audio signals
- Insure compatibility of receiver and aircraft audio equipment
- Process pilot's voice signals
- Transmit on 1 of 6 NBFM voice channels
- Maintain isolation between voice subsystem and other subsystems

BINOR subsystem

- Provide BINOR reception, demodulation, code acquisition, and preprocessing functions
- Provide for surveillance response, either
  1. Computed position data
  2. Unprocessed time-difference data

FIGURE 30.– AIRCRAFT TERMINAL REQUIREMENTS AND CONSTRAINTS

TABLE 16.–SATELLITE CONFIGURATION ALTERNATES

Alternate	Transmitter power, watts	Antenna	EIRP (d)
1	10	Earth coverage [a]	+24.1 dBW
2	20 to 75	Regional coverage [b]	+34.9 to +40.6 dBW
3	75	Area coverage [c]	+52.2 dBW

[a] Peak gain = +19.6 dB; edge gain, includes pointing losses = +15.6 dB

[b] Peak gain = +25.6 dB; edge gain = +23.4 dB

[c] Edge gain ≈ +35 dB; 2.8° HPBW, 1100-n.mi.-diameter area

[d] Includes 1.5 dB of rf circuit loss

Alternate 1 represents current L-band capability with 10 watts of satellite repeater power and an earth-coverage antenna pointed to local vertical (i.e. the center of the earth). Alternate 2 corresponds to the next level of satellite development, which represents 1970 capabilities for greater satellite repeater powers (on the order of 20 to 75 watts) and a more sophisticated regional-coverage antenna. This antenna has 6-dB greater peak gain than the earth-coverage antenna and is capable of being pointed to the center of the desired North Atlantic coverage area. Regional-coverage narrowbeam satellite antennas are within the present state of the art, as evidenced by the planned replacement satellites for the Interim Defense Communication Satellite Program (IDCSP) that will be implemented with antennas having 1000- to 2000-mile regional-coverage areas (12 dB to 18 dB greater gain than earth coverage). Alternate 3, as proposed, represents a later-generation satellite incorporating repeater power of 75 watts or greater and a multiple-beam antenna system having beamwidths on the order of 1° to 3° for illumination of areas several hundred to about a thousand n.mi. in diameter. Area-coverage capability could be implemented using the developing multiple-beam phased-array satellite antenna technology. Examples of this technology are the Boeing APPA concept discussed in Sec. 9.1 of vol. IV and RCA's evolving design of a steerable satellite antenna. Discussions with RCA indicated such an antenna may be recommended for the L-band voice circuits in their final report. Current information on ATS-F and G designs shows that a 30-foot antenna is planned that would provide EIRP's consistent with satellite alternate 2 and 3 levels.

The transmitter power, antenna gain, and receiver threshold requirements of the experimental aircraft terminal for each of the various satellite configuration alternates were established using the results of the detailed link analysis. The resultant aircraft-terminal parameter requirements, in terms of each satellite alternate, are given in table 17. The requirements are shown for both a transistor (450° K) and an uncooled paramp (50° K) as the receiver low-noise preamplifier. The paramp is presented as a possible candidate for the experimental terminal, particularly where limited satellite capability can be compensated for with the improved noise performance of the paramp. The operational system, on the other hand, would incorporate the transistor preamplifier, which is recommended from factors of cost, reliability, and maintainability.

The terminal requirements shown to support the surveillance function can accommodate either tone ranging or the BINOR technique. The voice-link requirements shown in table 17 are for both single and multiple channels, depending on the satellite configuration. Satellite alternate 1 and the lower transmitter power capability (20 watts) of alternate 2, for example, can support single-channel voice transmission, whereas the 75-watt capability of alternate 2 and alternate 3 (more representative of an operational system) can support a three-channel voice capability per satellite. Satisfactory performance of the voice links requires substantially higher satellite EIRP and/or aircraft antenna gain than do the surveillance links. The minimum-capability satellite (alternate 1 for example) requires +18 dB of aircraft antenna gain for threshold performance of a single-channel voice link using a transistor preamplifier; this can be compared to a paramp, which requires +13.5-dB aircraft antenna gain. Satellite alternate 2, on the other hand, requires only +8-dB antenna gain using a transistor preamplifier and +3.5-dB antenna gain using a paramp for single-voice-channel capability. Should the upper limit of satellite transmitter power (75 watts) be available for alternate 2, a three-channel operational system voice capability could be demonstrated with the same aircraft antenna gains as those for the single-voice-channel system. For alternate 3 satellite capability, the required aircraft antenna gain is minimal for a three-channel operational-type system with a -1-dB gain figure being sufficient over the upper hemisphere of the aircraft.

Required aircraft transmitter power for voice-link operation is not excessive for any of the satellite alternates. Table 17 shows that a maximum of 160 watts is required for a three-channel system and an alternate 2 satellite. (Required aircraft transmitter power is increased by 3 dB, over single-channel requirements, for a three-channel system to compensate for satellite hard-limiter degradation effects.)

TABLE 17.–AIRCRAFT EXPERIMENTAL-TERMINAL REQUIREMENTS

Satellite			Aircraft				
				Surveillance		Voice	
Alternate	Total transmitter power/antenna	EIRP, dBW	Preamplifier device	Antenna gain, dB	Transmitter power, watts	Antenna gain, dB	Transmitter power, watts
1	10-watt/earth coverage[a]	+24.1	Transistor	+5.2	165	+18.0	19
			Paramp	+0.7	475	+13.5	55
2	20-watt/regional coverage[b]	+34.9	Transistor	-1	110	+ 8.0	27
			Paramp	-1	110	+ 3.5	80
	75-watt/regional coverage[c]	+40.6	Transistor	-1	110	+ 8.0	54
			Paramp	-1	110	+ 3.5	160
3	75-watt/area coverage[c]	+52.2	Transistor	-1	7.5	- 1	32
			Paramp	-1	7.5	- 1	32

[a] Nonsimultaneous repeater operation: surveillance or single-channel voice

[b] Simultaneous operation: surveillance and single-channel voice

[c] Simultaneous operation: surveillance and three-channel voice

Based on the aircraft antenna requirements, the satellite for the experimental program should preferably be an alternate 2 type. If only an alternate 1 satellite is available (of limited EIRP), aircraft antenna gains of +13.5 or +18 dB are required; this necessitates a rather complex phased-array implementation. Such an antenna not only would be expensive to develop and implement for the experimental phase of the program but would also not be representative of the operational system (since for the latter a higher-EIRP satellite is expected). It is thus desirable (if possible) to conduct the experimental program using aircraft antennas of the type and gain expected for operational use and thereby obtain applicable performance data on their characteristics.

5.2.3 Experimental-terminal configuration.- The proposed aircraft-terminal baseline design is presented in fig. 31. The terminal design is functionally divided into the rf subsystem, the surveillance and data subsystem, the voice subsystem, and the BINOR subsystem. Maximum flexibility is provided to demonstrate and test all required system functions under a variety of terminal component implementations and satellite capabilities. The flexibility is obtained by providing several aircraft antennas—in conjunction with two preamplifier devices and a power amplifier with variable-attenuation input power control—to demonstrate the voice and surveillance functions. It is desirable to demonstrate as far as possible the performance characteristics of an operational system. For this reason, the proposed experimental aircraft terminal is configured assuming the availability of at least the lower capability of an alternate 2 satellite (i.e. 20 watts of total transmitter power and a regional-coverage antenna). Should a full-capability alternate 2 satellite (75 watts) be available, even further experimental capability would exist.

The features of the proposed experimental aircraft terminal are as follows:

(1) Demonstrate forward- and return-link surveillance via the -1-dB low-gain antenna (LGA) and the transistor or paramp preamplifier

(2) Demonstrate two-way, single-channel voice via a directional antenna and the transistor or paramp preamplifier

(3) Demonstrate two-way three-channel voice via a directional antenna and the paramp preamplifier

(4) Demonstrate simultaneously both surveillance and single-channel voice via a directional antenna and the paramp preamplifier

(5) Demonstrate simultaneously both surveillance and three-channel voice via a directional antenna and the paramp preamplifier

(6) Permit testing of multichannel voice performance for both balanced power ratios and various strong/weak signal combinations in the satellite repeater to determine the resultant effects on system performance

(7) Permit testing of satellite repeater intermodulation degradation effects on the voice circuits for three-channel operation

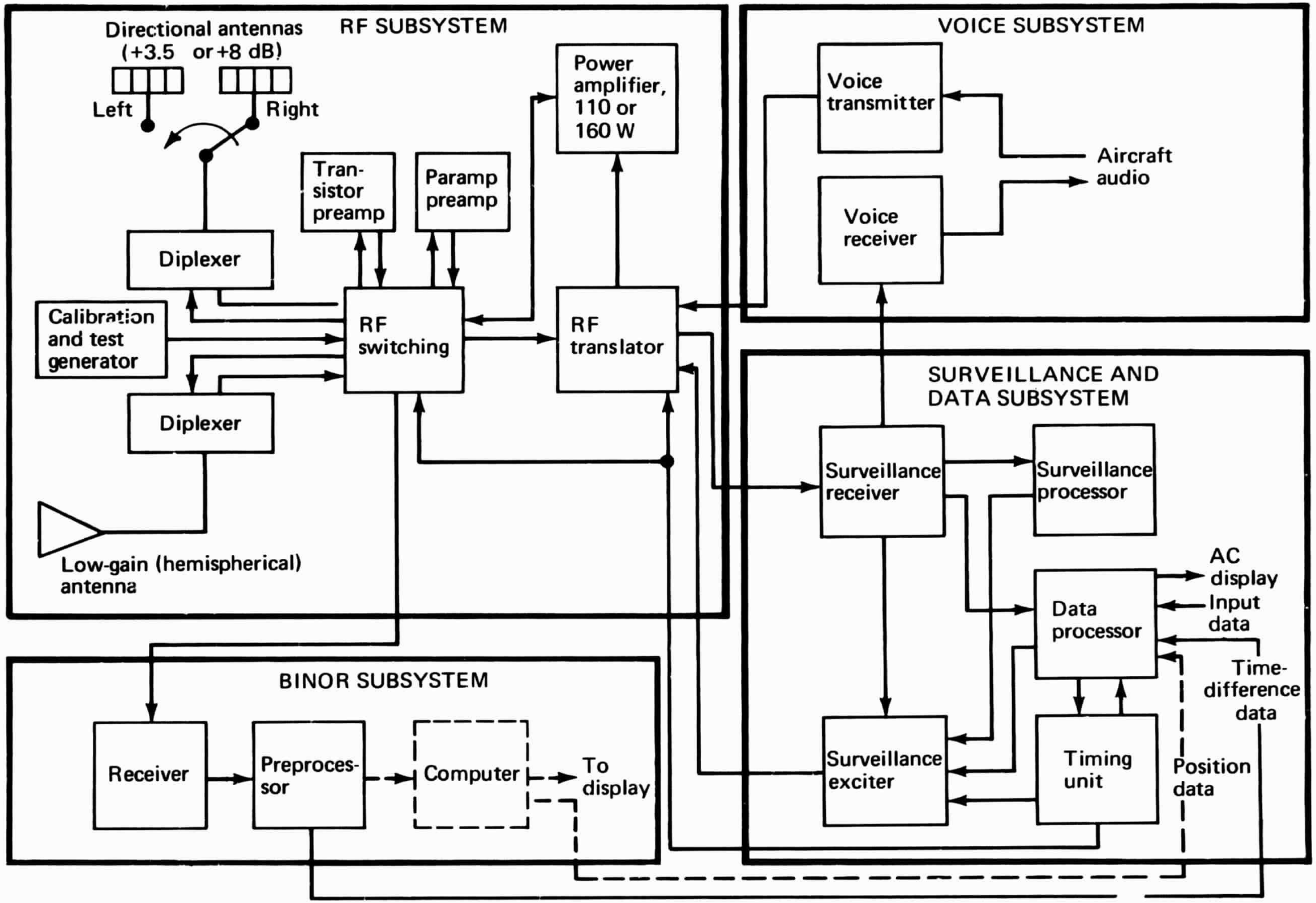


FIGURE 31.— AIRCRAFT EXPERIMENTAL-TERMINAL FUNCTIONAL DIAGRAM

For a maximum-power (75 watts) alternate 2 satellite, the terminal capabilities would be identical to those enumerated above, but would in addition:

(8) Demonstrate two-way single-channel voice via the LGA and paramp preamplifier

(9) Demonstrate simultaneously both surveillance and single-channel voice via the LGA and paramp preamplifier

This final capability is significant because it represents the ultimate aim of the operational aircraft terminal to provide both surveillance and voice functions over a low-gain hemispherical-coverage antenna at the aircraft. In an operational system, such capability would be realized with a transistor preamplifier at the aircraft terminal and a multichannel mode of voice operations, with the required link margin being accommodated by greater satellite EIRP.

The rf subsystem parameters of antenna gain and transmitter power associated with the proposed terminal in fig. 31 are dependent upon which satellite is available. The recommended antenna system for the experimental terminal consists of both low-gain and medium-gain antenna systems that can be switched as desired. The low-gain antenna system consists of a single circularly polarized top-mounted orthogonal-mode-cavity antenna. The antenna is 6 inches in diameter and about 3 inches deep. The maximum gain of the antenna is 6 dB. The 3-dB beamwidth is 110°, and the gain is -1 dB at a 10° elevation angle.

The medium-gain antenna system consists of left-right-switched circular-polarized linear-phased arrays mounted on the side of the fuselage. If the 20-watt satellite is used, a flush-mounted four- to eight-element steerable-beam array of dielectric-loaded orthogonal-mode cavities providing +8-dB gain is recommended. The actual choice of array will depend on the locations on the fuselage selected for the antennas (to be determined in phase II). Each array is 6 inches wide, 4 inches deep, and 16 to 33 inches long. The corresponding aircraft transmitter power is 110 watts.

If the 75-watt satellite is used, the medium-gain antenna system can be simplified to a nonsteerable array of two dielectric-loaded cavity-backed elements that will provide +3.5-dB gain and sufficient multipath discrimination throughout the required coverage volume. The arrays are mounted so that the antenna normal points 38° above the horizon, and each array would be 6 by 4 by 10 inches. The aircraft transmitter power for the lower-gain array would rise to 160 watts.

The switching functions performed by the rf switching network are necessary for connecting the various components of the rf subsystem for performance testing. The capability for switching, or interconnection, will exist for:

(1) Switching between antennas (left or right) of the directional-beam antenna configuration (+3.5- or +8-dB gain)

(2) Routing of either antenna input (low-gain or directional) through either preamplifier (transistor or paramp) to the rf translator

(3) Connection of calibration and test generators to all devices in the terminal

(4) Routing of the power-amplifier output to either antenna (low-gain or directional) for transmission

The received signals are routed to the rf translator, where translation is made to i.f. for the voice and surveillance signals. The i.f. output is then routed to the surveillance and data subsystem for further down-conversion and subsequent demodulation in the surveillance and data or voice subsystems. For the return voice and surveillance links, the output from the rf translator is provided to the power amplifier and then routed via appropriate switching to the desired antenna for transmission. A calibration and test generator set is also included in the design to check out and calibrate the system prior to each demonstration test.

The surveillance and data subsystem is composed of five components for operation with a tone surveillance scheme. These include a receiver, surveillance processor, data processor, timing unit, and exciter. The receiver coherently tracks and demodulates the surveillance carrier and demodulates the data subcarrier. In addition, the receiver also provides the second mixer down-converter for the received voice signals and provides a doppler-corrected output to the voice subsystem. The surveillance processor filters the received tones for the turnaround transmission on the reply links. The data processor decommutates the received data, detects the aircraft address code, and formats the surveillance reply data. The timing unit actuates and sequences the aircraft response when the correct address code is detected in the data processor. The exciter uses a coherent multiple of the received carrier for return transmission and remodulates it with the turnaround tones and the return data subcarrier.

For operation with a BINOR surveillance scheme, the surveillance and data subsystem is comprised of only four components: receiver, data processor, timing unit, and exciter. The surveillance processor is excluded since no tones are now present for turnaround transmission. The exciter is altered to eliminate modulation of the tones on the return carrier, whereas the data processor is implemented to receive time-difference or position data from the BINOR subsystem for inclusion in the aircraft surveillance data frame response when interrogated by ATC.

The BINOR subsystem was not treated in depth during this study because of the extensive design work done by TRW in the earlier NAVSTAR study (ref. 5). In a discussion with NASA/ERC, it was learned that evaluation testing later this year is planned for components of this subsystem. The results of this testing will provide the design parameters for the BINOR subsystem for possible implementation in the experimental terminal.

The voice subsystem consists of a voice receiver and transmitter operating in the HF and VHF frequency ranges. The voice receiver gets an input derived from the second mixer of the surveillance receiver at about 12 MHz. The narrowband FM voice signal is then further down-converted and detected by a phase-locked demodulator. The output of the audio section is available for routing to the aircraft interphone or speaker system. The return-link voice signal from the aircraft is processed by the voice transmitter. The transmitter accepts the input voice signal and provides the required clipping, truncation, and narrowband frequency modulation on the selected operating channel. The output at VHF (110 MHz) is then sent to the rf subsystem for final frequency multiplication to L-band. The signal is routed through the power amplifier to the selected antenna.

5.2.4 Terminal physical characteristics.– Weight, power, and volume are not major constraining factors for the experimental terminal, although they are quite important in an operational system. The final selection of the terminal components for the operational system will be based on considerations of maintainability, cost, weight, volume, and power. Typical weight, power, and volume requirements for an experimental flight-test aircraft terminal are given in table 18.

TABLE 18.–PHYSICAL CHARACTERISTICS OF EXPERIMENTAL TERMINAL

Component	Weight, lb	Power, watts	Volume, in^3
Transmitter (power amplifier, transmitter power supply, output filter, driver/multiplier, voice exciter)	40.0	1650	1611
Receiver (rf section, voice receiver, surveillance/data receiver, surveillance processor, timing unit, data processor, surveillance exciter)	25.0	50	1510
BINOR subsystem package	58.5	200	2570
Preamplifiers	16.5	200	420
Diplexers	15.0	- - - -	310
Feedline	9.0	- - - -	- - - -
Antenna	17.0	- - - -	1840
Total	181.0	2100	8261

There are several physical installation constraints imposed by the SST configuration and environment that must be carefully considered in the design of the L-band terminal. The antenna must be mounted flush with the fuselage surface to be compatible with aerodynamic requirements, and it must withstand the high skin temperatures (500° F) caused by aerodynamic heating. Also basic to the design of the antenna is the structural integrity of the fuselage, which limits the extent of structural modification that can be done to accommodate the antenna installation. The antenna must thus integrate with the airframe and be fully compatible without affecting the primary structure. The potential of installing the array antennas in the aircraft service door for the experimental program is under consideration.

The L-band terminal electronics packages must also be compatible with the aircraft configuration. For the experimental terminal installation, the power amplifier and other modem packages will probably be installed in a special flight-test electronics rack that will be temporarily mounted in a convenient location in the SST passenger compartment relatively close to the antenna. The L-band terminal equipment for a production SST would be installed in an allocated electronics-equipment compartment. The operational equipment would then be required to conform to the appropriate environmental and packaging specifications.

5.2.5 Flight-test instrumentation.– Flight-test evaluation of the experimental L-band satcom SST terminal will require test instrumentation compatible with flight and environmental parameters of the test-bed aircraft (one of the SST prototypes). Interim terminal testing may also be accomplished on a subsonic test-bed aircraft prior to availability of the SST prototype. It is anticipated that initial flight testing of the L-band satcom system will take place within the framework of a program providing only one satellite with an L-band frequency-translation repeater. Complete evaluation of system surveillance performance, which functionally requires at least two satellites for the cw tone ranging and possibly three for BINOR ranging, will therefore require simulating the second and possibly third satellites at ground positions (preferably near the ground control terminal that originates the ranging signal, and by flying the test-bed aircraft within line-of-sight propagation distance from that terminal).

The following paragraphs give the results of a preliminary evaluation of the flight-test instrumentation requirements and constraints. In addition, a summary is given of potential interim experiments that could be performed to determine the extent of L-band airborne radio noise and to evaluate multipath effects over oceanic waters. A complete definition of the L-band terminal flight-test program is to be carried out in phase III.

5.2.5.1 Flight-test requirements and constraints: The testing of the L-band terminal aboard the prototype SST would be subjected to the following set of initial requirements and constraints:

(1) The second SST prototype would be proposed as the test-bed aircraft

(2) Supersonic flights would be confined to the instrumented Pacific Coast offshore flight-test corridors or the Edwards flight-test corridor

(3) Subsonic flights would be in the same areas or in the Puget Sound test corridors used by Boeing in northwest Washington State

(4) L-band tests would be conducted on a noninterference basis with the primary SST flight-test program

(5) The flight-test corridors mentioned constrain the experimental-satellite geostationary location to be between longitudes 90° W and 150° W

In addition to the above requirements and constraints, a tentative list of measurement parameters is given in Sec. 4.1 of vol. V. These include the aircraft flight parameters, external environmental parameters, and the L-band system parameters required for evaluation of the surveillance and communications functions.

5.2.5.2 Interim experiments: Several potential interim experiments that could be conducted prior to actual flight testing of the L-band terminal have been defined (vol. V, Sec. 4.3). It is felt these experiments would provide valuable data to aid in designing the terminal. The first of these tests is the measurement of ambient L-band radio-noise temperatures onboard the aircraft to obtain significant low-noise-level data previously unavailable and to pinpoint possible problem areas from typical onboard interference sources. The second of these tests is the detailed measurement of L-band multipath propagation characteristics to substantiate the analytical results derived during this study. In addition, an evaluation of the recommended voice modulation technique should be performed. This test would evaluate the effects of baseband clipping and truncation on the attainable voice articulation index, would verify experimentally the threshold performance of the proposed voice phase-locked demodulator, and would establish the specific threshold C/N required to meet different intelligibility levels.

In defining the interim experiments, it was assumed that they would be conducted prior to the orbiting of an L-band satellite and the flight testing of SST prototypes (i.e. during 1969-1970). Consequently, the experiments were configured to utilize ground-based implementation (where practical) and subsonic airborne platforms if needed. The instrumentation components would be selected from commercially available units so that they could be utilized later in the implementation of the experimental airborne L-band terminal.

5.3 Growth to an Operational Terminal

The characteristics of the aircraft terminal to be used with the operational ATC satellite system represent a modification to the aircraft terminal developed for the experimental program. The reasons for the modification stem both from the expected change in satellite capability and the somewhat different goals of the experimental and operational program. The design goal of the experimental terminal is to provide a maximum amount of test flexibility during the demonstration program. The design goal of the operational terminal, however, must be to provide a cost-effective minimum-complexity aircraft terminal amenable to integration into the airlines' fleet inventory.

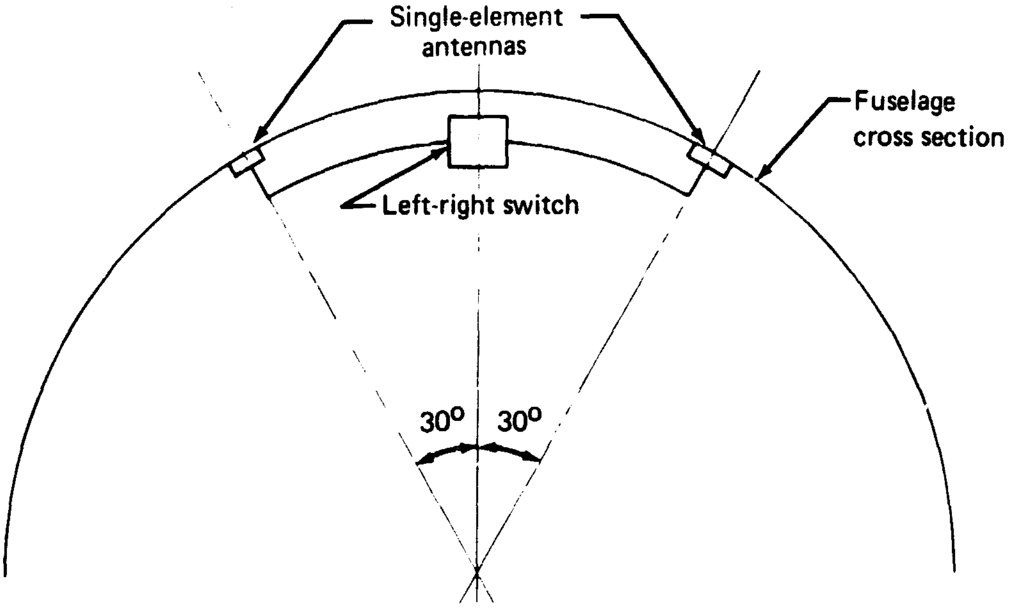
5.3.1 Expected operational satellite characteristics.– In developing the required rf parameters for the experimental terminal program, it was recognized that the associated satellite available for the tests would have a lower EIRP than the satellite developed for an operational system. For example, if the demonstration program is done with one of the later ATS-series satellites, the L-band tests would be just one of several experiments. The resultant satellite design would thus be a compromise to satisfy the particular requirements of each experiment, and its capability also would represent the state of the art for an earlier time period (1972) than that of the operational system (1975-1980). In addition, tradeoff of satellite and aircraft performances to obtain a minimum-cost system must be treated differently in the experimental and operational programs.

In the experimental program, one satellite and a few aircraft terminals are available (possibly only the one on the prototype SST); thus, it is cost effective to put more emphasis on developing the performance capability and associated complexity of the aircraft terminal than that of the satellite terminal. The additional dollars-per-pound cost of developing and orbiting the added satellite performance capability is thereby avoided. In the operational system, however, the cost tradeoff is significantly changed, because the system would consist of a few satellites and possibly several hundred aircraft terminal installations. Although the overall system cost study has not been done, it is intuitive that there should be a shift in emphasis that would place increased performance capability and complexity into the operational satellite. The results of such a design approach should minimize the overall system cost and give the airlines a terminal design of reasonable cost and a minimum amount of operational and maintenance complexity.

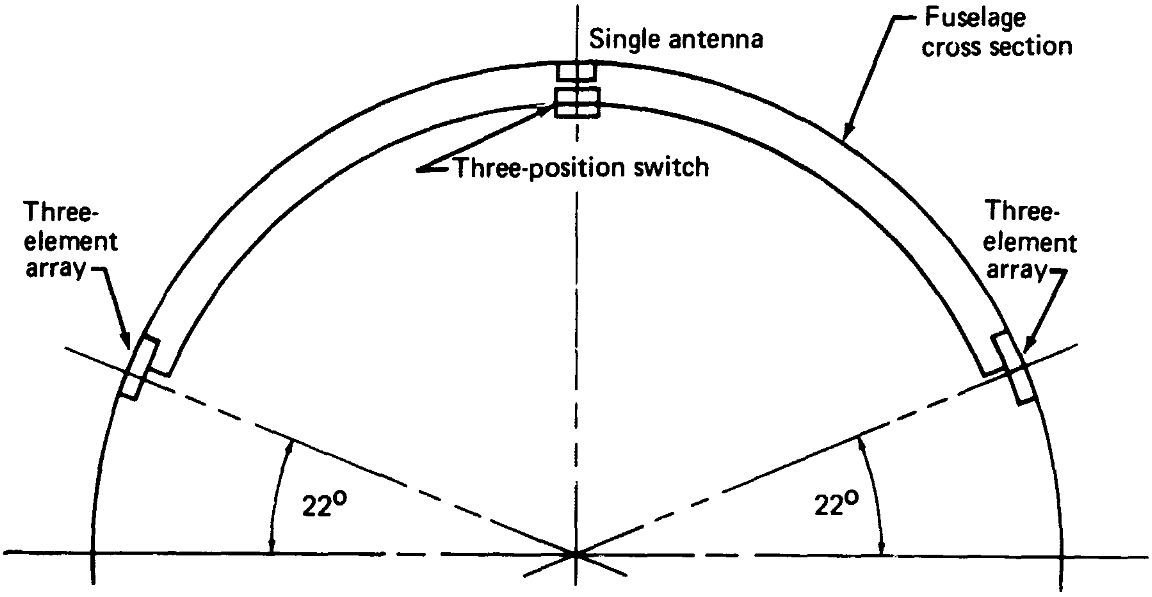
It is therefore assumed that the operational ATC satellite system must provide a capability to permit the aircraft terminal to operate both surveillance and voice channels through a low-gain fixed-beam antenna system. The results of the antenna tradeoff analysis (Sec. 9.2 of vol. IV) indicate that either of the two low-gain aircraft antenna systems shown in fig. 32 are good candidates for the operational system. The first system consists of three antennas: (1) two three-element fixed-beam-array antennas, each mounted 22° off the top centerline and (2) a third single-element antenna on the top centerline. One of the three antennas is selected, depending on the existing aircraft-to-satellite geometry. The three-element arrays provide fan beams with +3-dB gain at the 5° elevation angle and give multipath discrimination commensurate with the 2-dB fade margin used in the earlier link analysis. The second system consists of two single-element low-gain antennas, each mounted 30° off the top centerline of the fuselage with a simple left-right switch. Each single-element antenna provides +3-dB gain at the 10° elevation angle, but has slightly poorer multipath-discrimination characteristics than the three-antenna system.

To define the required satellite characteristics, the simpler two-antenna system is assumed. The previous link analysis was scaled for the +3-dB aircraft antenna gain, modified by a 2-dB increase required in fade margin. The results show that a satellite EIRP of +47.6 dBW is required to support three voice channels and the forward and return surveillance links. If the satellite transmitter is assumed limited to 75 watts in the operational time period, the satellite antenna gain must be +30.4 dB to meet the EIRP requirement. Such an antenna would have a HPBW of 4.7° and would illuminate an earth surface area of about 2000 n.mi. A better approach to the satellite design is a phased-array antenna such as the Boeing APPA concept of multiple simultaneous steerable beams, wherein the power amplifiers are low-power devices integrated with the array elements.

5.3.2 Operational aircraft terminal characteristics.– The conceptual operational terminal design (fig. 33) is compatible with the satellite characteristics of the previous section. Forward-link ATC voice and surveillance signals are received from the satellite through the selected low-gain antenna. The performance parameters permit use of an economical transistor preamplifier and a 50-watt power amplifier. The latter may well be a solid-state device based on 1975 state-of-the-art technology. As the block diagram shows, the system approach is quite similar to the experimental terminal design. The received surveillance and data carrier is continuously tracked and used for the coherent reference for the reply surveillance signal. It also provides doppler correction to the input voice carrier signal to aid in optimizing the voice-channel demodulation. The forward-link data subcarrier is continuously demodulated to provide output data to the aircraft. These data permit updating the voice-channel status display to show the pilot which channels are currently in use. In addition, growth capability is provided to handle an expanded digital data link that would be useful in



(a) Two-antenna system



(b) Three-antenna system

FIGURE 32.– POSSIBLE OPERATIONAL ANTENNA CONFIGURATIONS

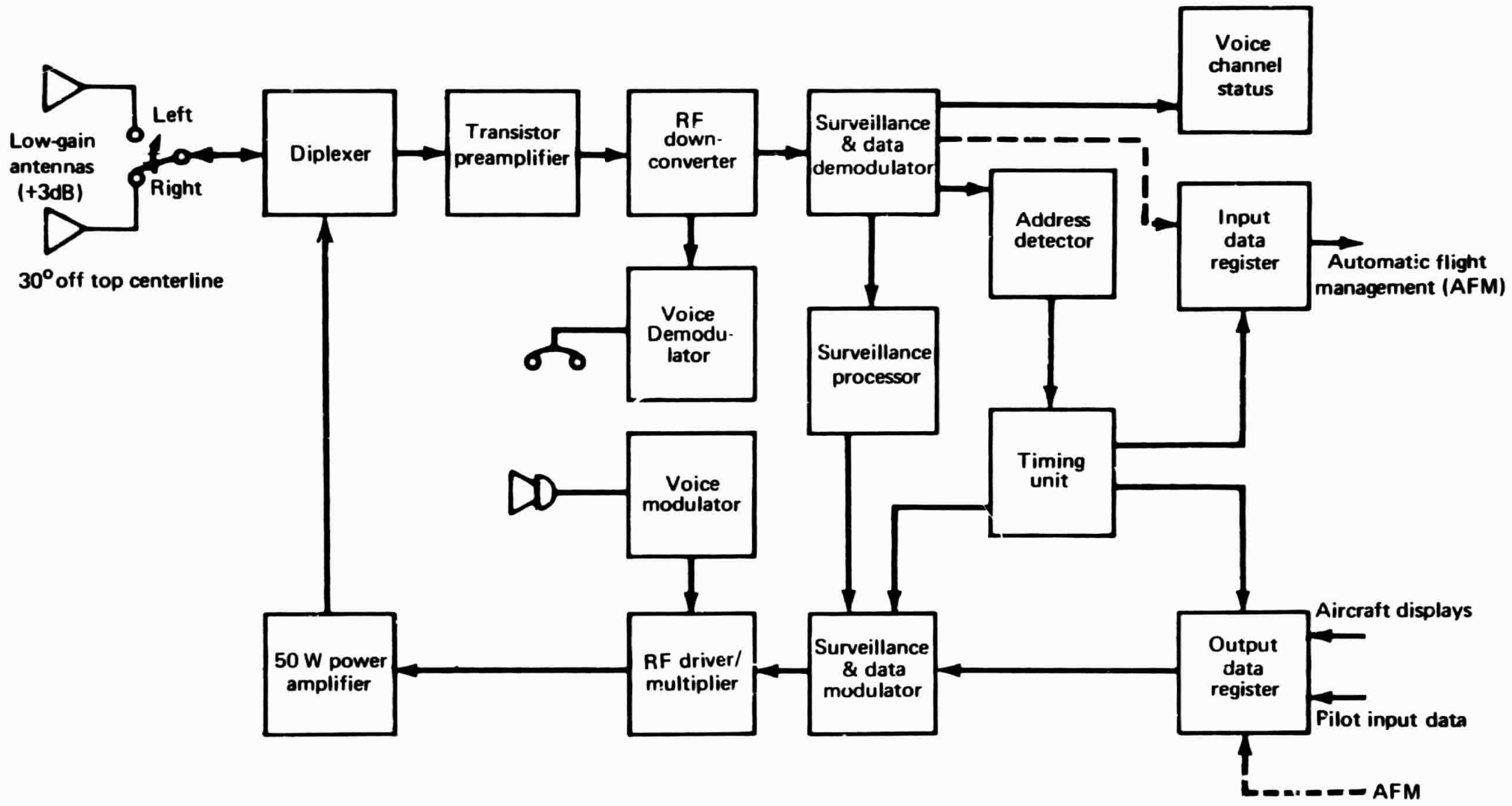


FIGURE 33.– CONCEPTUAL OPERATIONAL AIRCRAFT L-BAND TERMINAL

implementing an automatic flight management (AFM) system. The address in each cycle of the forward surveillance signal is checked in the address detector and, when the unique address for an individual aircraft is detected, the surveillance reply link to the ATC is activated for 1 second. The reply link includes both a data channel and the surveillance signal. The latter signal can be either turnaround tones or the position information associated with the processed BINOR signal. The data channel includes aircraft identification and altitude data; growth capability is provided to return both AFM-type data and additional pilot-inserted data.

6.0 CONCLUSIONS AND RECOMMENDATIONS

The overall report has described the results obtained in conducting the program definition phase for an experimental L-band communications/surveillance terminal to be used onboard the prototype SST. This summary volume has presented the highlights of the different analysis and configuration-selection tasks. These tasks include evaluation of the operational requirements for the expected North Atlantic traffic for the 1975-1980 period and analysis of the surveillance and communications systems. The results of the different tasks were used to define the design parameters for the aircraft terminal.

6.1 Study Conclusions

Results of the operational requirements study showed that a properly designed satellite communications/surveillance capability would permit reduction of the current 120-n.mi. separation standards to a goal of 30 n.mi. for an INS-equipped SST and to a goal of 60 n.mi. for current subsonic jet aircraft without INS. These reductions can be achieved while maintaining or improving the existing North Atlantic safety standards. The ATC system implemented—including the effects of the ground, satellite, and aircraft terminals—must provide the following minimum capabilities:

(1) Aircraft position accuracy of 1 n.mi. (1σ)

(2) Individual aircraft position fix once every 3 minutes

(3) Position determination independent of aircraft navigation

(4) Six voice channels between the ATC center and the aircraft

(5) Average time delays of zero and 1 second for emergency and routine ATC messages, respectively

The surveillance study tasks showed that a multisatellite ranging system is favored. The choice of a specific modulation technique depends on the selection of either a tone-ranging two-satellite system or the BINOR range-differencing three-satellite system. Both are candidates for the experimental demonstration program; the final choice rests with NASA and other government agencies (U.S. and foreign) after consultation with the user airlines.

A variety of communications study tasks were also undertaken to evaluate the impact of the system design on the aircraft terminal configuration. Briefly, the conclusions are as follows:

(1) Separate voice and surveillance repeaters should be provided in each satellite with equal division of voice channels between satellites.

(2) Forward and return data links should be implemented for surveillance interrogation, voice-channel status information, and aircraft altitude reporting.

(3) Narrowband FM should be used for voice transmission with baseband clipping to provide a 6-dB peak-to-rms ratio into the modulator.

(4) A 2-dB link fade margin is required at L-band (1540 to 1660 MHz) under worst-case sea conditions (sea-state 1) based on a 99% time availability criterion.

An L-band aircraft terminal design was developed for the experimental program providing considerable flexibility to allow a maximum of demonstration test options. In addition, a preliminary operational terminal was developed. The hardware-configuration tradeoffs, coupled with detailed link analyses, established these conclusions:

(1) The experimental satellite should have a regional-coverage antenna and 20 to 75 watts of transmitter power (EIRP of +34.9 to +40.6 dBW).

(2) Dependent on the satellite transmitter power, the experimental terminal antenna for voice reception should be either a 4- to 8-element flush-mounted phased array with beam steering or a 2- to 3-element fixed-beam array. In addition, a hemispherical-coverage low-gain antenna should be provided for surveillance demonstration.

(3) The operational satellite should have an area-coverage antenna (2000-n.mi coverage) providing an EIRP of +47.6 dBW.

(4) The corresponding operational aircraft antenna system for the voice and surveillance signals should be two or three low-gain elements with a simple left-right switch.

(5) The aircraft terminal design is capable of incorporating both the tone and the BINOR surveillance system equipment for demonstration.

(6) The experimental terminal design includes a 160-watt TWT power amplifier and both a transistor preamplifier (450° K noise temperature) and an uncooled paramp preamplifier (50° K).

(7) The operational aircraft terminal would use a 50-watt solid-state power amplifier and the more economical transistor preamplifier in conjunction with the higher-capability satellite.

6.2 Study Recommendations

The work carried out indicates there are no major technology constraints that would restrict implementation of an experimental or operational aircraft terminal for ATC satellite surveillance and communications functions in the North Atlantic. However, under terms of the contract, the cost effectiveness of systems using VHF or other frequencies was not compared to that of an L-band system. The following specific recommendations are made as a result of the study:

(1) Initiate the phase II effort of aircraft terminal development in accordance with the program schedule of fig. 1.

(2) Conduct the interim tests described in Sec. 5.2.5.2 before the SST prototype is available. These tests include the following:

- Measure the aircraft radio noise environment at L-band.
- Perform an experimental test to verify the analytical multipath predictions.
- Evaluate experimentally the effects of the proposed clipping and spectrum truncation on the required voice intelligibility.
- Verify experimentally the threshold performance of the proposed voice phase-lock demodulator and establish the specific threshold carrier-to-noise-density ratios required to meet different voice intelligibility levels.

The phase II program is primarily oriented to develop the detailed equipment specifications; the proposed technical task flow is shown in fig. 34. The results of the current study and recommendations of NASA and the system contractors form the basis for selecting the final terminal design concept. A detailed design would be developed commensurate with the electrical and mechanical environment of the evolving SST design. Each element of the final design would be subjected to a make-or-buy decision, and the output of phase II would be the specific procurement or manufacturing specifications.

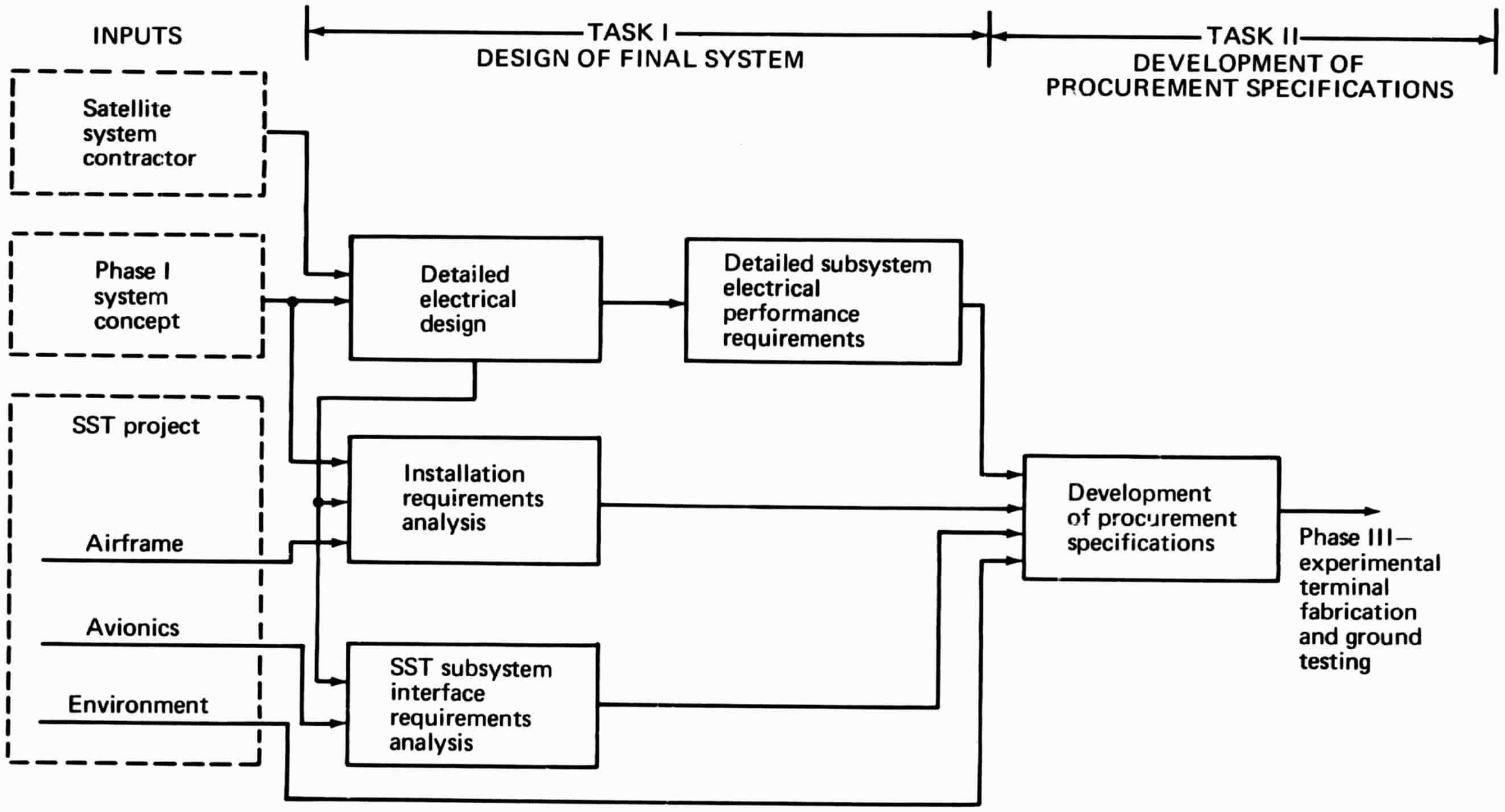


FIGURE 34.– PHASE II–DEVELOPMENT OF EQUIPMENT SPECIFICATIONS

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