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ACCESS CONTROL AND PROCESSING STUDIES FOR GROUND-SATELLITE MOBILE COMMUNICATIONS/SURVEILLANCE SYSTEMS

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FINAL REPORT

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16. Abstract

The report synthesizes a set of satellite communications systems configurations to provide services to aircraft flying oceanic routes. These configurations are combined with access control methods to form complete systems. These systems are analyzed using a simulation and their performance is presented in terms of avionics complexity and cost, queuing delays, pilot workload, and operational considerations. A preferred system is selected and recommendations are made.

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PREFACE

The control subsystem of any satellite communication system is a major unifying force in its operation and its considerations permeate the system design in many ways. It is therefore important to investigate its design at an early stage in system development.

This report examines and compares the performance of several communication access control subsystems potentially applicable to the Aerosat System.

Throughout the study, Robert M. Snow and Leslie Klein, Transportation Systems Center, have continuously supplied guidance and unstinting support for which we express our appreciation.

Additionally, helpful comments and review at various times during the study have been provided by the following personnel:

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SECTION 1 - INTRODUCTION

This is the final report on Contract No. DOT-TSC-565, "Access Control and Processing Studies for Ground-Satellite Mobile Communications/Surveillance Systems." Access control, the major subject of this study, is the fundamental unifying system concept around which other considerations must be organized; in a sense, then, specifying the access control subsystem is tantamount to describing system operation. An Interim Report was issued in August, 1973, which presented interim results obtained. Considerable details regarding background and analysis were given in that report. This Final Report makes liberal reference to the Interim Report.

This report is organized as follows:

- Section 1 is a brief introduction to the use of aeronautical satellite systems.
- Section 2 briefly reviews the constraints faced by the aeronautical satellite system designer, defines the problem addressed, and presents the guidelines adopted and the approach followed in the study.
- Section 3 summarizes the five systems synthesized for analysis purposes and describes their access control doctrines and operational procedures.
- Section 4 presents the results of the analyses conducted in three major areas:
  - Signal design modulation, multipath, acquisition, and poll channel design
  - Avionics design, configuration, and relative cost
  - Access control simulations delays, operational aspects, and conclusions.
- Section 5 discusses the conclusions made on the basis of the results obtained and presents a number of recommendations for consideration.

The need for improved overocean services in the 1975-to-1985 decade has been widely recognized by the FAA, Office of Telecommunications Policy (OTP), and the various foreign nations involved with the United States in providing aeronautical services for the Atlantic and Pacific oceanic areas. The intense international interest in aeronautical satellites that has developed in the past few years is an obvious indication of that recognition. Satellites have been of particular interest because they afford the opportunity to substantially upgrade the available communications and provide air traffic control (ATC) related surveillance.

Several factors have combined in recent years to cause an interest in significant modifications to the existing oceanic support systems. These factors can be divided into two broad categories: increased requirements and the availability of new approaches to meeting requirements. The increased requirements involve such things as traffic growth and the introduction of new aircraft types. The new approaches include communication satellites, new methods of navigation, and the use of computers for system automation.

The future air traffic environment will have a twofold impact on support services requirements. The future traffic will change quantities of services needed as well as the nature and quality of these services. Defined in terms of information exchanges, the change in the number of aircraft in the air at a given time is the fundamental driving force behind changes in the volume (i.e., quantity) of information exchanged. However, the new traffic environment also produces changes in the content, transmission format, frequency of occurrence, length, and perhaps priority of the information transfers involving an individual aircraft. These changes are primarily deviations in the nature and quality of individual information transfers, and they reflect a significant evolution in the aeronautical support services being provided.

Higher traffic volume obviously indicates an increased communications demand regardless of the exact means employed for providing the various aeronautical services. However, more importantly, it will bring pressure for a reduction in permissible aircraft separation standards without adversely affecting safety.

Depending upon its origin and destination, the weather, and various other factors, each aircraft has an optimal flight path. If the flight is short, the cost penalty for deviation from the optimal path may be outweighed by other factors. However, if the flight is long, the cost penalty for deviation from the optimal path is significant.

Oceanic ATC generally operates by clearing each aircraft in advance for operation on a conflict-free path. The mechanism of clearance is the flight plan. There is presently no independent surveillance to detect deviation from the flight path; thus, the system provides for large horizontal separation distances so that conflicts may be avoided under "worst-case" inaccuracy of navigation equipment. If the traffic is light there will be little potential conflict, and an aircraft will generally be cleared for its requested plan. If the traffic is sufficiently heavy, an organized track system will be used. Under such a system, the aircraft is cleared for the best available track; however, as the traffic grows, increasing numbers of aircraft are required to accept the penalties of using nonoptimal paths.

The overall cost penalty could be lessened by reducing the required separation distances. This approach, however, alters the requirement placed on the communications system. At present the traffic is largely of an advisory or status nature rather than of the type involved in active control. From the time an aircraft has been cleared for a flight path until it leaves the oceanic ATC area, the primary communication between the aircraft and ATC consists of an hourly position/status report which informs ATC of the flight progress.

To reduce aircraft separation standards, a number of the international aviation support services must be improved. Aircraft navigation systems must be upgraded to provide greater navigational accuracies, and aircraft surveillance must be improved, necessitating improved communications regardless of whether it is dependent or independent surveillance.

Better communications will also improve the reliability and response times for executing ground-to-air control commands. In addition, reduced separation standards may make it necessary to increase the accuracy, amount, and geographical extent of the meteorological data collected.

New routing and new airports are associated features of the future air traffic environment. Some routing changes are likely to occur even without any changes in available airports. Additional routing changes may result from new airport locations. The probable effect of these changes will be more complex routing patterns in the future, including a much greater number of route crossings and midocean mergings. Thus, improved navigation, communications, and meteorological data collection systems will be required.

The introduction of the new types of aircraft, such as the SST, could have substantial effect on ATC and navigational services. The widespread introduction of new widebody jets with their higher optimum airspeeds compared to the older jets (e.g., Mach 0.84 versus Mach 0.82) will also produce some changes. However, these changes can very likely be refined to create relatively minor adjustments in ATC procedures.

Major areas of technology pertinent to future aeronautical support services include satellites, improved navigational systems, digital transmission, and computers. Satellites offer the potential for improved aeronautical mobile communications, more accurate aircraft surveillance for ATC purposes, and more precise aircraft navigation. Improved navigational systems include the use of satellites and various other techniques, such as inertial navigation. The upgraded position location afforded by these techniques would allow aircraft separation standards to be reduced, thereby providing operational economies. Converting from analog voice to digital data transmission offers potentially reduced demands for communications capacity and shorter response times. Such digital transmission could increase the need for greater automation. Greater automation would reduce system response times, increase the volume of traffic that could be handled satisfactorily, and free personnel from many clerical tasks, allowing them to concentrate on decisionmaking.

Satellites would improve aeronautical mobile communications by offering increased capacity and high reliability service that would be available over the entire Atlantic and Pacific oceanic regions. Aeronautical satellites offer the potential for improved ATC knowledge of aircraft positions by making continuous independent surveillance possible. Even if dependent surveillance were used, the improved communications capability made available by satellites would upgrade the surveillance system by allowing more frequent, reliable transmissions.

The plan as presented in the AEROSAT specification* for implementing an aeronautical satellite system calls for placing experimental satellites into service over the Atlantic Ocean. These satellites will be employed for experimentation and evaluation of system concepts and aircraft equipment.

When aeronautical satellites are placed into service, the trend toward greater use of digital communications will be accelerated. A teletypewriter channel provides a 100-word per minute (wpm) information rate with a 75-bps channel, compared with the 100 to 150 wps achieved in a 4-kHz wide voice channel. Thus, many routine, nonperishable, and machine-oriented messages should and will be digitized. On the other hand, the audio communication system (voice and ears) of the human "machine", unlike the hands and eyes, is not heavily used in the course of aircraft operation. Consequently, there will always be a residue of voice traffic requirement for real-time communications (e.g., between pilot and controller). However, these individuals should not serve as mere input-output devices or transducers. Automation can therefore remove such data transfer requirements from the voice communication system. Further, computers offer the potential for even greater reductions in the communications capacities and response times required by performing source encoding (message formatting) to take advantage of redundancy in the information transmitted. Source encoding in many cases can lead to dramatic reductions in the number of information bits required per message.

Computers have potential applications in handling oceanic control center ATC operations and in supporting aircraft operating agency activities. The ATC computer could handle a wide variety of operations, including message encoding/decoding, storing flight plans and determining clearances, storing weather data and making updated forecasts, determining minimum time paths and establishing tracks in organized track systems, tracking airborne aircraft and determining potential conflicts, and providing updated displays of system status for controller personnel. An airline computer might

*"AEROSAT Performance Specification," Draft, January 11, 1973.

handle passenger and cargo reservations, develop flight plans, keep records on aircraft maintenance materials and equipment to expedite air fleet maintenance, and administer cargo and passenger processing. The airborne computer could provide message encoding/decoding, monitoring of aircraft flight path and weather data to generate updated predictions of flight progress, and performance checks of onboard equipment to give assistance in maintenance and repair activities.

The primary driving force behind the trend toward greater use of digital transmission and automation is the expanding volume of air traffic. This increased demand for service will force the use of these more efficient techniques. Generally, the adoption of these techniques will occur separately at individual airports and in individual airline fleets as the need arises on particular routes and in specific geographic areas.

The AEROSAT System, the access control techniques, the terminal equipment and software, and the initial phases of the testing or experimentation might all be expected to progress and improve in an evolutionary manner. Maintaining a smooth evolutionary progression is considered an important constraint upon access control and equipment development.

Flexibility to respond to system evolution is necessary for another reason. Oceanic satellite service may give rise to new or different uses and applications. Even the transmission of data is different from anything done at present. Eventually the users may discover and decide that such a capability can be used for a variety of functions. Changes in the voice data mix, allowable delays, and similar parameters can have significant impact on the design of appropriate access control systems and accompanying hardware. A similar evolutionary factor arises in considering revision of the flight information regions (FIRs) and control areas (CTAs).* Ultimately, when satellite transmission becomes the primary oceanic communication technique, there will be no logical reason for maintaining the present FIR/CTA boundaries. The existing

*Although they actually refer to different jurisdictions, the terms control area (CTA) and flight information region (FIR) are often used interchangeably. This report will refer to both as CTAs.

configuration of oceanic ATC CTAs was developed in response to the technical characteristics of the existing methods of oceanic aviation support and communications. The facilities within the individual CTAs are substantially responsible for all communication with aircraft within their assigned areas. This factor, combined with others (e.g., proximity to busy routes and ocean areas; coordination with appropriate CTAs and terminal areas (TMAs); and other economic, technical, and political factors involved in supplying the support services); has produced the existing organization of CTA boundaries.

The technical basis for the existing CTA configuration will be altered at a future time by the introduction of satellite communications and the automation of ground facility procedures and equipment. Once again, a flexible approach is necessary to allow for such changes in the system configuration.

Lastly, one would desire orderly evolution from the AEROSAT preoperational system into an operational system. This smooth transition, without expensive modification or discarding of equipment, is the ideal. Whether or not it can be achieved is problematic; for example, the history of many satellite and avionics programs is not encouraging. But at the least this study will attempt to minimize the planned obsolescence in the access control system and equipment.

SECTION 2 - DEFINITION OF PROBLEM AND APPROACH TO SOLUTION

2.1 INTRODUCTION

This section briefly reviews the constraints of satellite communication systems applied to aircraft in oceanic airspace, defines the problem which this study addresses, and presents the guidelines of the study and the general approach followed in its pursuit.

2.2 SATELLITE SYSTEM DISCUSSION

The designer of a satellite communications system for aircraft users generally must consider the following:

- Large number of aircraft users
- Low communication duty cycle per user
- Limited satellite capacity in ground-to-air direction
- Low gain user antenna
- Potential multibeam satellite antenna
- Desire to keep down avionics cost and crew workload
- Potential requirement for independent surveillance
- Relatively severe Doppler environment.

The first three points provide the basis for the problem addressed in this study - namely, the provision of a method of controlling the access of the many aircraft to the limited communication capacity of the system. The other points have a major impact on how this might be done, and directly affect the capacity of the system in some cases.

The choice of access control method is affected by system configuration (i. e., the existence of multiple beams), the system capacity, the type of information to be sent (digital or analog messages), the frequency and regularity of transmission, the allowable waiting time between requiring a message transmission and consumating its transmission, and whether independent surveillance is provided in the system.

These factors and others have been considered in arriving at the recommended access control methods.

2.3 SYSTEM DEFINITIONS

This paragraph defines the various components of an ATC system. The ATC system definitions are included to formalize the terminology to be used in reporting the results of this study.

2.3.1 Oceanic Aviation Support Services

The range of services required for international aviation includes the general categories of airports, air traffic services, communications, meteorology, search and rescue, aeronautical information, and aeronautical navigation. The principal categories affected by a satellite system are those of air traffic services and communications. Meteorology and search and rescue are affected to the extent they are influenced by the organization of the communications system.

Air traffic services will be affected by the improved communications and surveillance capability introduced by the AEROSAT Satellite System. This additional capability will permit greater use of automation and will result in an improvement in the air traffic services provided. Satellite surveillance and communications will permit the introduction of ATC techniques and equipments formerly restricted to regions in which the aircraft is in the line of sight of an appropriate ground facility (such as a radar or VHF communications station).

In general, these improvements will involve an overall increase in the levels of service provided. These include, for example, reduced separation standards and a capability for more active controller involvement in situations where such control activity would be beneficial. The present oceanic system is primarily a manual system. The AEROSAT Satellite System will facilitate the use of computers and other equipment in the Air Traffic Control Center (ATCC), and will remove the restriction that the ATCC be located near the oceanic area being controlled.

It is anticipated that in the future oceanic system, control will be generally tactical rather than strategic. The system will utilize surveillance data displayed to the controller in a manner similar to the present use of radar in the domestic system. Interaction between controller and pilot will occur on a closer basis than in the present oceanic system. However, the larger separation standards, lower traffic loads, and longer intervals between changes of flight status (e. g., sector changes) will permit a lower level of procedural and communications activity than would be required in the domestic system. The oceanic procedures and their related communications requirements will tend to combine features of both the present and future domestic systems and the present oceanic system.

Aeronautical communications in the oceanic region consist of the fixed, mobile, and broadcasting services. The principal direct impact of a satellite system will be on the mobile and broadcasting services, since these services will utilize the ground-to-air links which are the principal contribution of the satellite system. However, there may be substantial impact on the ground-to-ground (fixed) system.

The present ground-to-ground system includes the Aeronautical Fixed Telecommunications Network (AFTN), the Air Traffic Service (ATS) Direct Speech Network, dedicated meteorological links, and the communications support for search and rescue. The AFTN handles record traffic (i. e., formatted messages) between all types of facilities and offices. The ATS Direct Speech Network is a system of voice links between control centers and is used for real-time coordination.

The future communications requirements can be categorized as:

- Ground-to-air communication, including any necessary ground-to-ground relay due to facility locations
- Coordination between oceanic centers
- Coordination between oceanic centers and other ATS units

- Record traffic (including meteorological) between facilities other than oceanic centers
- Search and rescue communication.

2.3.2 Oceanic System Facilities

The oceanic system facilities relevant to the areas of consideration in this study include a space segment, a mobile segment, and a ground segment. The space segment consists of the satellite and its associated boosters. The mobile segment includes all appropriately equipped aircraft within the coverage region of the system. The ground segment involves a number of facilities, which may be distinct or may be collocated, together with a communications network linking these facilities. The ground facilities are as follows:

1. The Air Traffic Control Center (ATCC)

   The ATCC includes the air traffic controllers and their displays, computers, and other associated support equipment. The ATCC exercises control over a CTA.

2. The Aeronautical Services Earth Terminal (ASET)

   The ASET provides connectivity from the ground facilities to the mobile segment via the satellite. As a minimum it consists of an appropriate antenna, transmitter, receiver, and related equipment. The necessary baseband and control functions are provided by the ASET in conjunction with the aeronautical satellite communication center (ASCC). An ASET does not necessarily serve only a single ATCC. In fact, if there is more than one ATCC in the ocean area, it has been found to be technically effective to share a single ASET rather than to provide an ASET to each ATCC.* There may, however, be other administrative considerations which constrain the situation.

* "Adaptive Multibeam Concepts for Traffic Satellite Systems," CSC Report No. 4126-1, Prepared for NASA Goddard Space Flight Center, February 1972.

3. Aeronautical Satellite Communications Center (ASCC)

   The ASCC represents a function rather than a necessarily distinct facility. This function includes the areas of computation, interface, and system control. The precise allocation of this function is one area to be considered in the analysis.

4. Spacecraft Control Facility (SCF)

   The SCF consists of a spacecraft control center (SCC) and a spacecraft control earth terminal (SCET). The SCC maintains control of the space segment with a command capability by monitoring and analyzing the tracking and telemetry data. If spacecraft reconfiguration is necessary, it will be accomplished by coordination between the SCC and the ATCC. The SCET may be collocated with an ASET.

5. Company Communications Facility (CCF)

   The CCF acts as a control, coordination, and interface facility for aircraft operator traffic. It interfaces with the ASCC function and may include portions of that function exclusively related to aircraft operator traffic.

These facilities are linked to each other and to other ATC facilities by means of a communications system. This communications system may use either the common carrier system or the satellite, in accordance with decisions to be made during the process of system design.

2.3.3 Guidelines

A number of guidelines established at the outset served to focus and bound the overall study:

1. The study would concentrate on reasonably complete synthesis and analysis of a number of complete systems, including access control doctrine, based essentially on the AEROSAT specification dated January 11, 1973. This guideline led directly to the approach described in the next paragraphs.

2. Emphasis would be placed on the satellite-to-aircraft portions of the systems. The ground subsystem would be considered only to the extent that its possible configuration would affect the design of the satellite-to-aircraft portions.

3. Although results of analysis would necessarily apply only to specific systems, the access control doctrines should be applicable to other than those systems specifically synthesized and analyzed.

4. The study would accept to the maximum extent possible the coverage areas and capacity requirements defined in the AEROSAT specification. There is no reason at this point to conclude that another set of coverage areas would be more suited to potential system design. Furthermore, since these coverage areas have also been selected on the basis of operational considerations, they should be used as defined. The capacity requirements represent a realistic goal for the size of satellite being considered.

5. It was assumed that a power-limited satellite with approximately 9 "units" of power would suffice (one unit was found to be equal to about 30W RF). This guideline is reasonable, in that a 9-unit satellite has approximately the maximum capacity that can be launched by the Delta 2914 * vehicle.

6. It was assumed that all ground-to-air channels will be established at their lowest C/N_o (i. e., 43 dB-Hz), and, therefore, that a maximum number of channels will be controlled. The systems are being given the maximum resources available for apportionment among system users at the lowest reasonable channel quality. This places the maximum burden on the access control subsystem.

7. Spacecraft implementation feasibility should be considered only to the extent that it affects the parameters of this study. That is, the equipment needed to implement the specific antenna coverages as defined, the transmitter-repeater combinations, etc., should be studied only to ensure feasibility.

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* Current plans are to use a Delta 3914, using the excess capacity over the 2914 to provide a VHF capability.

8. Aircraft implementation feasibility should not extend to the design of antenna systems that have desired discrimination capabilities. Based upon segments of our study, we would attempt to establish these desired capabilities, but not to pursue the point further. Power budgets should assume a 4-dB antenna gain and the need for a 5-dB margin as per the AEROSAT specification.

9. The aircraft interface is defined as the output of the voice channel demodulator and the data channel demodulator in the case of single channel per carrier frequency division multiple access (FDMA) systems, and as the voice baseband and reformatted data output lines in the case of time division multiplex (TDM) or time division multiple access (TDMA) systems. Further routing (including potential multiple destination distribution), and processing (such as providing refresh memory capability), are beyond this interface.

10. The access control methods selected for study in each system configuration should not require significantly different avionics equipment when the ground facility relationships are varied, i. e., multiple ASET/ASCC/ATCC complexes versus a single complex, primary-secondary responsibility switches, etc.

11. Necessary access control signals can use either all or portions of the defined communication channels (ground-to-air and air-to-ground), or be provided via separate, specially designed supervisory channels, as appropriate.

12. The functions of and inclusion of the SCF should be considered only to the extent that the SCF interfaces with the access control subsystem. That is, any satellite reconfiguration, frequency switching, or other satellite commands necessary to effect access or channel control should be included.

13. Failure and backup modes of access control must be considered. These include provisions for high priority communications, long messages, emergency situations relating to the aircraft, satellite failures, and alterations necessitated by locally poor communication performance due to natural causes.

14. Overall system configurations generated should use the fully loaded mode which, for the purposes of this study, includes a number of controllers/companies and control centers, three to four ASET/ASCCs, a variable number of channels (two to 12), and a large number of aircraft (400 to 500).

15. The access control methods devised must be capable of operating with either a two-satellite system or a single-satellite system and without avionics modification.

16. Provision must be made for handling less than full satellite eclipse capability.

2.3.4 Approach

When the viable system configurations and access control doctrines were laid out in detail, it immediately became evident that an exhaustive analysis of all combinations was impossible within the constraints of this study. The approach taken, therefore, was to synthesize five basic system configurations described in terms of their satellite antenna beam configuration, equivalent ground-to-air communication capacities, and, in some cases, modulation and multiple access characteristics. Then, depending on their inherent capabilities, combinations of the available access control doctrines were synthesized and matched to the system configurations to comprise workable systems.

These systems were further refined, particularly with respect to modulation and multiple access design, using the results of simulation analyses conducted in parallel.

Each system was finally incorporated into an overall oceanic communication simulation in order to obtain quantitative information on its performance in a postulated traffic and communications environment. The environment was derived from work done on previous contracts and from a brief requirements study which bounded communications traffic from two sides: one considering all traffic to be analog (i.e., voice) and the other considering all traffic to be digital (i.e., data).

Finally, on the basis of simulation results obtained, a number of the systems were modified to obtain better performance.

A number of side studies were conducted to support the system studies. These included:

- Avionics configuration study
- Signal design (acquisition and tracking in a multipath environment) study
- Automatic Repeat Request (ARQ) analyses.

SECTION 3 - SUMMARY OF SYSTEMS ANALYZED

3.1 INTRODUCTION

The approach taken in this study was to synthesize, within the study guidelines, five system configurations. These configurations were defined primarily in terms of their satellite antenna coverage patterns since these patterns (along with other factors) determine the capacity, connectivity, and certain access control constraints. The configurations were augmented with multiple access and modulation approaches and finally were matched to access control doctrines to form complete systems.

These systems were then subjected to the performance simulations using the methods described in the Interim Report.

After the simulation analyses were conducted, these systems were modified as deemed appropriate.

The original systems and their subsequent modifications, along with the appropriate operational procedures for each, are described in this section. Results of the analyses conducted and the reasoning behind the modifications made are discussed in Section 4.

3.2 SYSTEM CONFIGURATIONS

Within the guidelines established, the following five system configurations in the ground-to-air direction were devised:

Configuration	Satellite Antenna Coverage
A	Global coverage antenna beam
B	Three beams - Beamwidths of 8°, 13.2°, and 13.2° - covering AEROSAT zones A, B, C and D
C	Seven beam cluster providing global coverage
B-1	B plus global beam
C-1	C plus global beam

Coverage obtained from configuration B at the 3-dB points is shown in Figures 3-1 and 3-2 for satellites located at 10^{o} and 40^{o} West longitude. This configuration was selected for four major reasons:

1. The beams each cover one coverage area defined in the AEROSAT specification; hence, all channels assigned to a specific coverage area are available to all of it.

2. The major East-West routes and the major North-South routes are each in one beam. Therefore, enroute handovers are not necessary for most traffic.

3. The beams and their relatively high crossover levels can be feasibly generated from a single 2-meter aperture.

4. The same coverage configuration serves the coverage areas for satellite locations between 10^{o} and 40^{o} West longitude. An East-West shift in boresight of the antenna cluster of up to 3 degrees is necessary depending on satellite location. This is easily done with either a spin or a three-axis stabilized spacecraft.

The feasibility of this antenna configuration was demonstrated by an analysis presented in the Interim Report, Section 4.

Coverage obtained from configuration C at the 3-dB points is shown in Figure 3-3. The 7-beam cluster is oriented so that the East-West routes in the NAT region and the North-South routes in the Caribbean are each largely covered by a single beam, thus avoiding beam handovers enroute. The antenna required for this coverage pattern, which was investigated under a previous contract,* is based on minimizing the gain over the entire surface of the earth. Each beam is 7.2 degrees wide at the 3-dB points. The beams cross over at the 3.2- and 4.3-dB points. An antenna 2 meters in diameter is required. Higher order antenna systems (up to 49 beams) were also investigated in the past, but the 7-beam system appears appropriate for AEROSAT consideration because of its relative simplicity.

*"Adaptive Multibeam Concepts for Traffic Management Satellite Systems," Final Report Under Contract NAS5-21590, CSC Report No. 4126-2, March 1973.

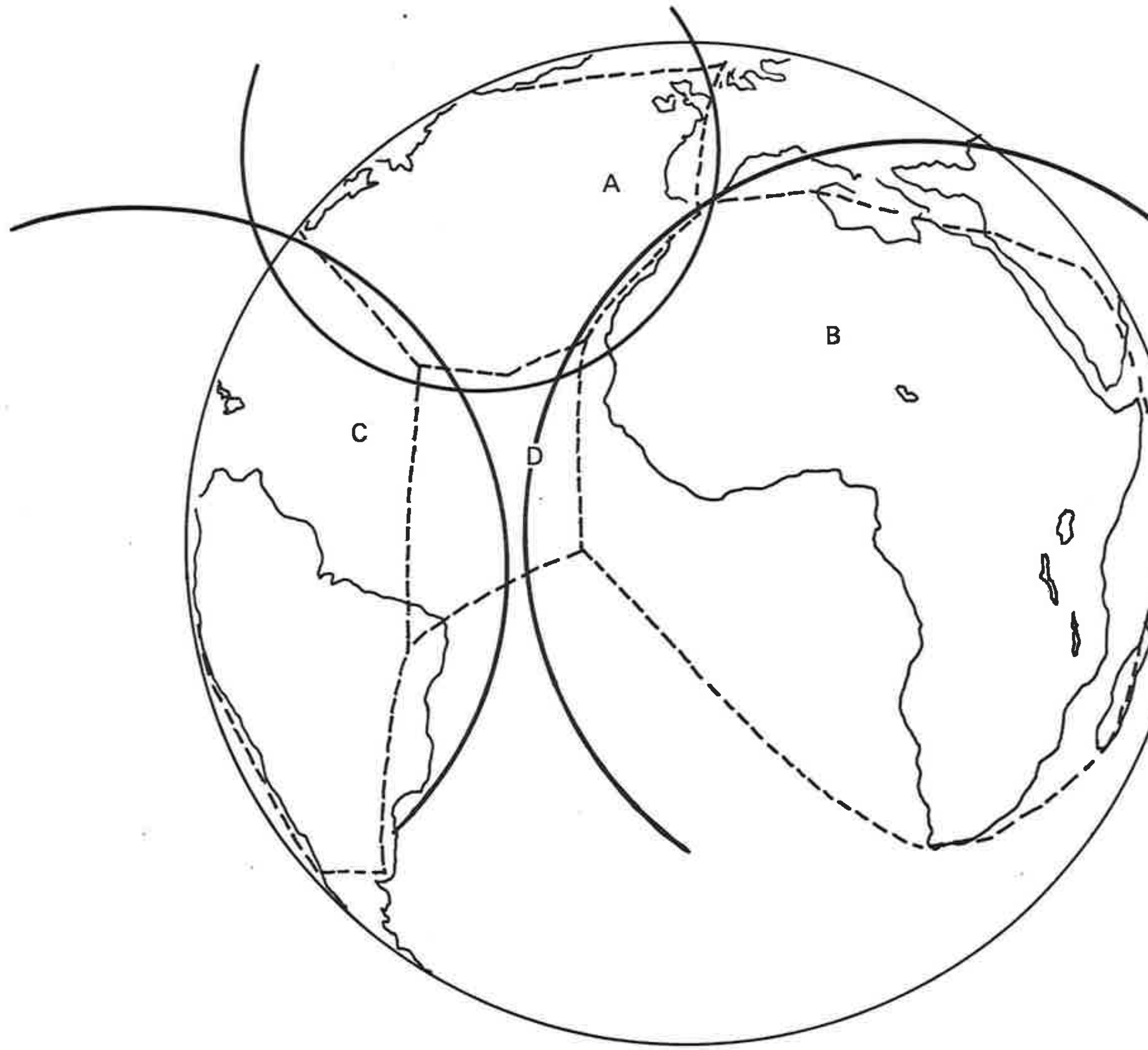

Figure 3-1. Configuration B Satellite Antenna Coverage for 10°W Longitude

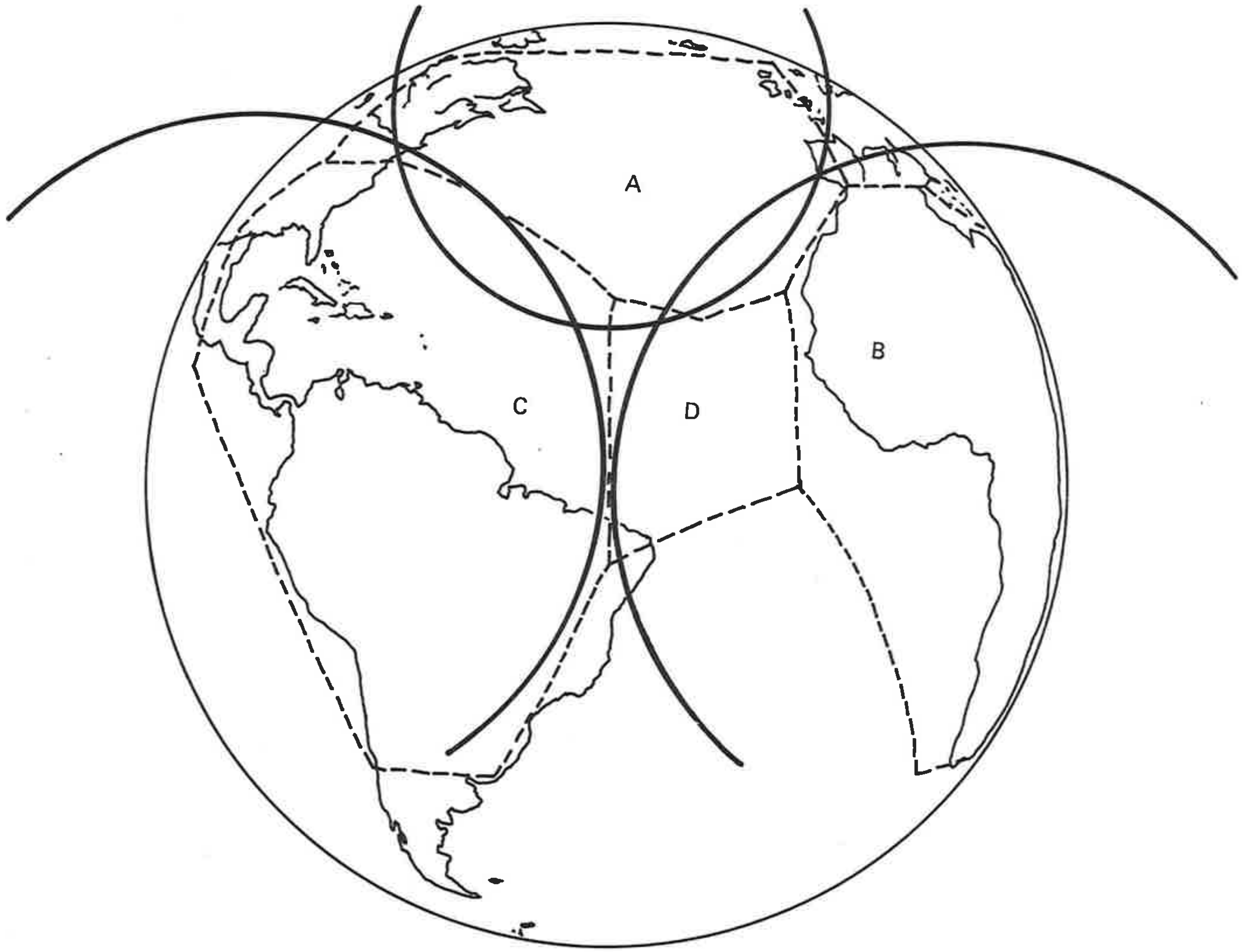

Figure 3-2. Configuration B Satellite Antenna Coverage for 40^{o}W Longitude

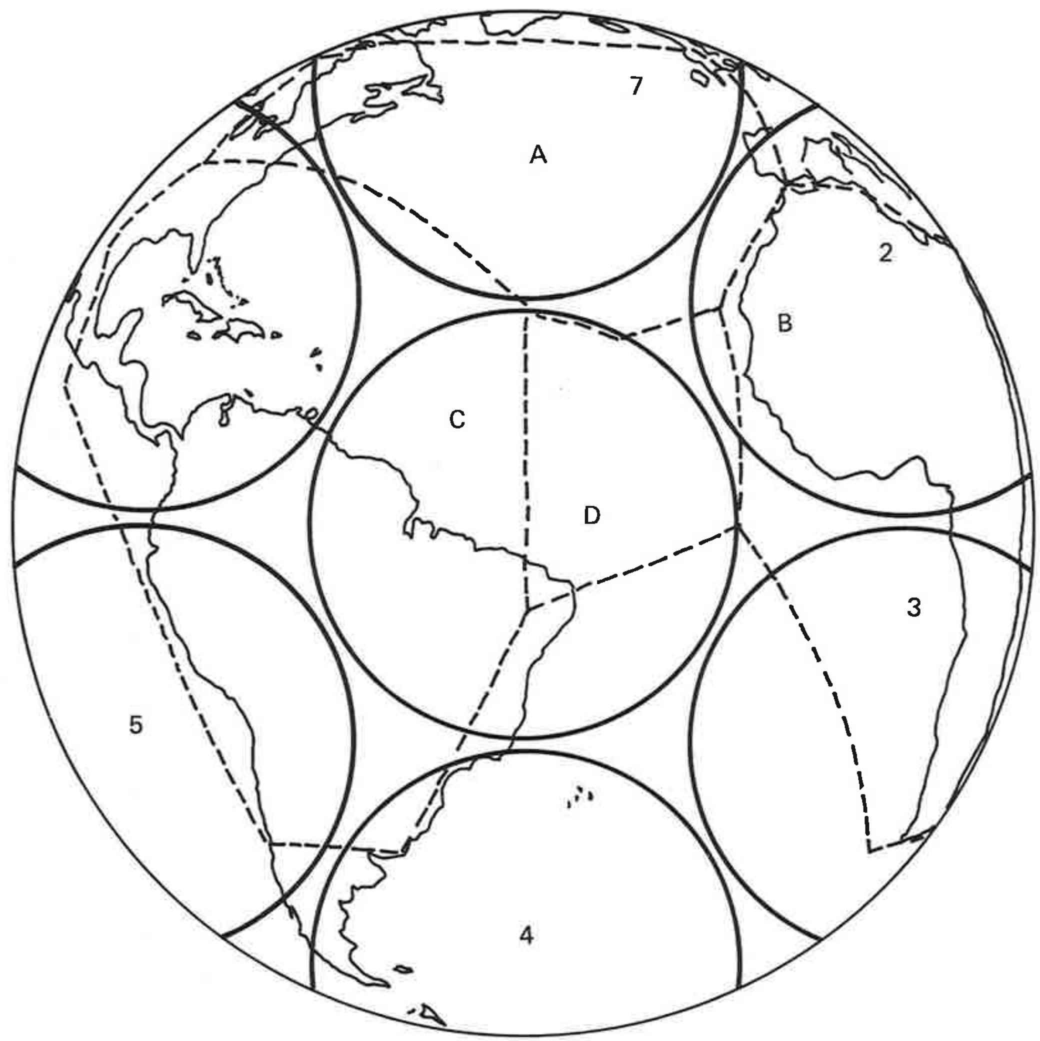

Figure 3-3. Configuration C Satellite Antenna Coverage for 40° W Longitude

Configuration C is unique in that, although the antenna beams could be simultaneously illuminated with information-carrying signals, they are sequentially operated using a TDMA in the time division channel format (actually ground-to-satellite links).

Based upon the feasibility analyses conducted, the minimum antenna gains available for each configuration are:

A	16 dB
B	8^{o} beam: 21 dB
	13.2^{o} beams: 19 dB
C	22.5 dB
B-1	A and B above
C-1	A and C above

3.3 GROUND-TO-AIR COMMUNICATION CAPACITY ESTIMATES

3.3.1 Reference Power Budget

The satellite-to-aircraft reference power budget for configuration A is given in Table 3-1.

For ease of manipulation, the AEROSAT specification has adopted a measure of RF power and has expressed required satellite power in terms of that measure. The "power unit" is the adopted measure. The specification states that an earth coverage channel with $C/N_0 = 43$ dB-Hz requires 3 power units. A power unit therefore is equivalent to approximately 30 RF watts.

Finally, the number of units required to sustain a 43-dB-Hz channel for each configuration antenna is shown in Table 3-2.

3.3.2 Capacity Estimate

Using configuration B as a baseline, an 11-unit satellite is required to provide the AEROSAT capacity requirement of three channels into area A and two channels into each of areas B and C. Including a global channel (configuration B-1), the requirement

Table 3-1. Reference Power Budget, Satellite to Aircraft - Configuration A

Item	Amount
RF Power (dBW) (1 W assumed)	0
Transmitter to Antenna Loss (dB)	-1.5
S/C Antenna Gain (dB)	$G_{s/c}$
EIRP (dBW) per W of RF Power	$G_{s/c}$ -1.5
Free Space Loss (dB)	-188.4
Margin (dB)	-5.0
Added Polarization Loss (dB) (assuming 6- and 2-dB axial ratios)	-0.4
$G_{a/c}$ (dB)	+4.0
Received Power (dBW) per W of RF Power	$G_{s/c}$ -191.3
N_o (dBW/Hz) (1000°K)	-198.6
Received C/N_o (dB-Hz) per W of RF Power	$G_{s/c}$ +7.3
Required RF for C/N_o = 43 (dB-Hz)	35.7 - $G_{s/c}$
For Configuration A ($G^*_{s/c}$ = 16.0 dB) P_{r-f}	19.7 dBW (100 W)

Table 3-2. Power Units Required per Channel

Antenna Beamwidth	Gain Available (dB)	RF Power/Channel (W)	Units/Channel
8°	21.0	30	1
13.2°	19.0	50	2
Global	16.0	100	3
Seven-beam Cluster	22.5	22	3/4

* Earth coverage antenna typical minimum gain

is raised to 14 units. Both of these are unattainable with a Delta 2914* without advanced technology.

A nominal 9-unit satellite, attainable with a Delta 2914*, can provide the capacities and coverages shown in Table 3-3.

In configuration A, all channels are available globally; i.e., to any point visible to the satellite. In configuration B, the channels assigned to each beam are available only to points within those beams; therefore, their availability is restricted.** The channel assignments were made on the basis of known traffic distributions. A similar situation exists in configuration B-1, the difference there being that one channel is available globally and may be used whenever needed. In this sense configuration B-1 is no worse, and is in a sense better, than configuration B.

In configuration C, all channels are available globally; that is, they may be spread out or concentrated within any one beam. Modeling in the ground-to-air direction can therefore proceed with the assumption of a global coverage antenna. In addition, the twelfth channel is reserved for ground-to-air supervisory functions and is not available for communications.

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* Or with the portion of a Delta 3914 allocated to L-band communications.

**The ability to transfer power between beams in order to tailor beam capacity to demand was investigated by CSC under contract NAS5-21590, and was found to be of marginal value. Intrabeam adaptability (link power control) was, however, found to be of significant value.

Table 3-3. Candidate Capacity/Coverage Estimates

Configuration		Capacity/Coverage
A	Global (9 units)	Three Channels - Globally Available
B	Triple Beam (9 units)	Three Channels in 8° Beam (Area A) One Channel into 13.2° E. Beam (Area B) Two Channels into 13.2° W. Beam (Area C)
C	Seven Beam (9 units)	Eleven Channels into Globally Available (another is reserved for zone supervision)
B-1	Triple Beam with Global Beam (9 units)	Four Channels into 8° Beam (Area A) No Channels into 13.2° E. Beam (Area B) One Channel into 13.2° W. Beam (Area C) (not including the global beam channel)
C-1	Seven Beam with Global Beam (9 units)	Eight Channels (not including the global beam channel)

3.4 COMMUNICATION CHANNEL DEMAND ACCESS CONTROL METHODS

3.4.1 Introduction

The access control problem addressed by this study involves the efficient management of the ground-to-air capacity of the various system configurations in the user environment. A general discussion of this problem is presented in the Interim Report. A brief review is given here. First, two definitions:

- Access control refers to the process involved in the allocation of the communication resources of the system. This process provides a similar function whether the communication channels are to be full-time assigned or demand assigned. The access control subsystem of a communication system is responsible for controlling the capacity of the system by use of an efficient and ordered set of techniques.

- Multiple access on the other hand, refers to the signal design techniques used to achieve efficient generation of the communication capacity of a system in such a way that some portion is available to each of a set of users. Examples of multiple access techniques are time division multiple access (TDMA), frequency division multiple access (FDMA), and a variety of quasi-orthogonal multiple access (QOMA) methods. These techniques are used to structure the available time-frequency-amplitude space for potential users. One or more multiple access techniques may be used in the design of an access control subsystem.

A demand (or allocated) access philosophy is attractive for an aeronautical services satellite system because of the low-duty cycle of the users. Within this philosophy, users are provided communication capacity when they need it (on demand) and they return this capacity to a common pool when they are through. Although full-time access systems are attractive from a system control, equipment complexity, and user workload standpoint, the low duty cycle of the aeronautical user results in inefficient bandwidth utilization in the case of FDMA and in inefficient bandwidth and power use (assuming a peak power limited satellite transmitting device) in the case of TDMA. This paragraph describes a number of candidate approaches to controlling the access to a demand access system.

For the purposes of this study, access control applies to two areas:

- The problem of properly delivering ground-originated traffic to the appropriate aircraft
- The problem of providing each aircraft with the opportunity of delivering its traffic.

In both cases, we assume the conceptual existence of a central point (not necessarily physically available) from which ground-to-air traffic originates and to which air-to-ground traffic is delivered for further distribution.

Methods of access control for ground- and air-originated traffic are difficult to completely describe separately because they interact to a large extent. That is, the choice of one method for ground access to aircraft may imply the existence of signals which would essentially dictate or at least influence the choice of access control for air-originated traffic. Also, the desire to include dependent or independent surveillance makes certain access control methods potentially more attractive than others. In spite of these factors, access control methods will be separated in this paragraph as a beginning point for synthesis.

3.4.2 Access Control Methods for Ground-Originated Traffic

There are three methods for access control when the need to establish communication contact originates on the ground:

- Semipermanent channel assignment
- Channel scanning
- Supervisory channel assignment.

3.4.2.1 Semipermanent Channel Assignment

In the first method, each aircraft is assigned a communication channel to monitor continuously (i.e., a party line operation). All messages for an aircraft are sent over that channel using a header containing its address. These may be true messages, or a poll, or both. A return channel may be permanently paired with this channel for duplex traffic or poll responses. If a particular channel becomes heavily loaded, changes in channel assignments can be made using the channel itself. The communication channel provides its own supervisory functions.* Because voice and data must be interchanged over any channel, the header must also contain additional information to switch in the appropriate aircraft modems. In the case of data messages, a block format with an ARQ strategy might be used via the return channel. In the case of voice, acknowledgment of header receipt before the voice conversation begins would be necessary using the return communication channel.

3.4.2.2 Channel Scanning

In the channel scanning method, all aircraft continuously scan across all communications channels looking for their address in a header. This is applicable to systems using either FDMA or TDMA, but FDMA presents reliability problems since the header and channel dwell times must be appropriately oversized to assure reliable detection. Channel scanning is most appropriate to TDMA (configuration C and C-1) systems. Upon receipt by an aircraft of its address and a channel identification code, the system proceeds as in the semipermanent assignment case.

3.4.2.3 Supervisory Channel Assignment

This method uses a supervisory channel apart from the communication channels which all aircraft monitor. Aircraft are addressed over this channel and are told over which channel a message is coming and the message type (voice or data). It is also possible to include within the supervisory channel, at the expense of channel capacity, short messages. In this case, an ARQ strategy could be used via a return supervisory channel. After aircraft tuning is accomplished, the aircraft transmits

* In-band or out of band signalling similar to SELCAL can be used.

an acknowledgment over the paired return communication channel, and either voice or data (possibly using a block ARQ strategy) transmission commences.

3.4.2.4 Method Selection

The choice of these methods depends upon:

- The particular system configuration; i.e., whether multibeam or not, whether a global coverage antenna is available
- The multiple access method (e.g., configuration C can easily incorporate a channel scanning doctrine)
- The expected message length distribution
- Whether or not surveillance is included in the system
- The channel and resulting constraints imposed on message block length due to burst errors.

3.4.3 Access Control Methods for Air-Originated Traffic

Table 3-4 presents a number of methods by which a field of aircraft users can gain access to the capacity of a satellite system. These methods apply mainly to access of two-way channels. In this table, a message consists of a transmission of information to be transferred (with routing information) or a signal designed only to cause a route connection to be made at the ground complex (e.g., to set up a voice conversation). On the other hand, a call is a transmission designed to enter the desire to establish communications into a system control function. In some of the methods in Table 3-4, both messages and calls relating to other messages (for example, voice or long data messages) can be combined. This will be shown during the system tradeoff analyses.

The methods are broken into two groups: those which permit direct communication channel entry and those which use an access control or calling channel to indicate a desire to communicate.

Table 3-4. Communication Channel Access - Control Methods for Aircraft-Originated Traffic

METHOD	DOCTRINE	OPERATIONAL IMPLICATIONS	COMMENTS
<u>Seizure Methods</u>			
Channel Seizure Without Observation	Aircraft seizes and transmits message on any channel selected at random without regard to occupancy of channel.	Simple method, but interference probability is high for a heavily loaded system. Therefore, inefficient channel usage is necessary for acceptable performance.	This method will not be considered.
Channel Seizure With Observation - Type 1	Channel occupancy observations are made by tuning through received channels. User then transmits message on an unused channel. Acknowledgment or response comes by some forward channel.* Cross band repeater implementation may require introduction of an occupancy signal on forward half of channel or A-G message turnaround or equivalent.	Simple, but workload on operator is greater unless tuning can be automated (i.e., a scanning receiver). Interference probability is still high for a heavily loaded system where users are waiting to access system due to the round trip propagation delay.	This method is most easily applied to Configuration C and C-1 TDMA approaches because channel scanning is inherent in the system, and a relatively large number of channels are available.
Channel Seizure With Observation - Type 2	Channel occupancy indicators are included in a broadcast transmission. User chooses a clear channel at random and transmits message. Acknowledgment or response comes by some forward channel.	This obviates need for automated receiver scan but interference problem is the same as Type 1. The broadcast transmission can be used to resolve interference problems.	The broadcast transmission requires satellite power, whereas the Type 1 occupancy signal uses unused communication channel access.
<u>Calling Methods</u>			
Random Calling	Aircraft enters a calling channel at random with a short calling message. Acknowledgment and channel assignments come by forward channel.*	If random channel is properly designed, waiting time to introduce call can be made to approach channel delay. If a forward supervisory channel is used, random calling minimizes its load for channel supervision.	Call must be short and relatively infrequent for random channel to work acceptably. Particularly useful for emergency channel access.
Ordered Calling - Type 1	All aircraft periodically enter the calling channel with a calling message designating whether or not a channel is needed.	Interval between calls determines maximum time to introduce a call. Of interest when surveillance is included because surveillance report or waveform sample can be combined with calling message.	A synchronization method is needed which, in general, can be derived from a forward supervisory channel. Means can be devised to make calling interval flexible for some limited fraction of the aircraft; particularly useful for surveillance purposes.
Ordered Calling - Type 2 (Poll)	Same as Type 1 except that the calling message is generated in answer to a forward poll.	The interval between polls determines maximum time to introduce a call. Also of interest for surveillance applications. Polling channel usage is low because of low-duty cycle of users (i.e., answer to poll is no most of time). If poll interval is lengthened to reduce percentage of "no's," waiting time to introduce a call increases.	The forward poll serves as the synchronization waveform needed in Type 1. This inherent ground control of synchronization leads to significant flexibility in calling interval, surveillance update, etc.

*Depending on how ground-originated access control is organized.

Acknowledgment of a message or response to a desire to establish two-way communications (for example, voice) in the seizure approaches, and response to a call in the calling approaches, would use a forward communication channel or supervision channel, depending on how the ground-originated access control is organized. In the calling approaches, this response could include channel assignment or estimated waiting time. The latter gives the aircraft the option of waiting or requesting again under a higher priority.

In the calling approaches, the call may include channel-type needed (one-way or two-way) message type (voice or data), and message priority (routine or urgent), in addition to addressee and originator identifications.

It is possible to use hybrid methods wherein approaches are combined and/or augmented with certain features of each other. Some of these possibilities will be explored during the system tradeoff analyses.

3.5 BASELINE ACCESS CONTROL DOCTRINES FOR SYSTEM CONFIGURATION

3.5.1 Introduction

The table on page 3-1 and Paragraph 3.4 described the five candidate system configurations with their capacities and possible access control methods. This paragraph synthesizes a set of baseline systems, drawing from the two previous paragraphs and the signal phase acquisition work* described in the Interim Report. Specific access control doctrines were matched to system configurations on the basis of the following considerations:

1. The lower capacity system configurations need tight control to be operationally acceptable.

2. The highest capacity system (C) might work under a looser seizure-type doctrine because of generally lighter channel loading.

3. The requirements study (Appendix D of the Interim Report) indicated a predominance of relatively short messages of both one-way and two-way types. The requirements study has also considered two approaches to channel management for two-way interchanges:

   - Where the two-way channel is assigned and held for the full duration of the interchange, including reaction (thinking, processing, researching, etc.) times. This is characteristic of all voice conversations and some data transactions.

   - Where the two-way channel is used only during the time when information is being transferred and relinquished to other transactions during reaction times. This is characteristic of many record transactions.

4. A poll, with or without major message content, is a potentially attractive means of access control for both ground- and air-originated traffic if the polling interval does not become too long.

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*Assuming use of some form of PSK.

5. Some access control methods can inherently accommodate either dependent or independent surveillance, or both.

Consideration is given only to access to system capacity by aircraft and by the ground environment (as an entity) to aircraft.

All of the synthesized systems are starting points for analysis using our queuing simulation model, and represent an attempt to reduce the number of analysis possibilities.

Table 3-5 presents the basic system configuration characteristics along with additional characteristics derived from studies conducted and discussed in the Interim Report. TDMA for System B has been eliminated because of the Doppler acquisition problem,* but it is retained for System B-1 since the global coverage broadcast channel available in that configuration can potentially provide a Doppler correction capability in the avionics.

3.5.2 Modulation/Detection

The modulation/detection choices in Table 3-5 reflect the analyses conducted and discussed in Section 6 of the Interim Report and assume that coherent modulation and detection are feasible over the channel.** Since all the FDMA approaches and the global beam channels use continuous communication signals, avionics phase acquisition must occur on a fully modulated signal. Even in the face of worst-case Mach 3 Doppler, this is not a major problem.

It must be assumed that the receiver is faced with acquisition upon the sudden appearance of a signal. This can occur during beam changing or satellite switching transitions. However, the signal may increase gradually, in which case acquisition will have occurred long before a useful signal level for reliable detection will have been reached.

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* TDMA is feasible for system C because the considerably higher bit rate permits wider bandwidth tracking loops in the avionics (See Table 4-1).

** Multipath simulations conducted during this study and discussed in Section 4 support this assumption.

Table 3-5. Systems Analyzed

	Satellite Transmit Coverage	Multiple Access	G → A Capacity	Modulation/ Detection	Surveillance* Capability
A	Global Beam	FDMA	3	DPSK**/Costas	Dependent Independent
B	Triple 8 x 13 x 13 Beam	FDMA	3 → 8° Zone 1 → 13° E. 2 → 13° W.	DPSK/Costas	Dependent Independent
C	Three Beam - 8°, 13.2° and 13.2°	TDMA	11 + 1	Carrier Burst/ Mod. Costas and DPSK/Costas	Dependent Independent
B-1	Global + B	FDMA or TDMA	4 → 8° Zone 0 → 13° E. 1 → 13° W.	Same as B	Dependent Independent
C-1	Global + C	TDMA	8	Same as A and C	Dependent Independent

*This is the assumed requirement. The provision of independent surveillance in configuration C requires more study.

**This will be referred to as differentially-encoded PSK (DEPSK) to distinguish it from the scheme where carrier phase during a bit is used as a detection reference for the following bit.

The acquisition results obtained indicate that for a 1200-bps channel, a pure phase-locked loop needs an acquisition time of about 0.12 second when working on a pure carrier when frequency search is used, and about 3.2 seconds if the loop is left to acquire on its own in a worst-case Mach 3 environment. (These estimates are 0.05 and 0.35 second for Mach 1.) A Costas loop, which is needed for detection with differentially encoded phase-shift keying (DEPSK), will require about four times the self-acquisition value for this large Doppler value, or about 13 seconds (1.4 seconds at Mach 1)* This is not unreasonable, but the application of frequency search will considerably reduce the acquisition time for the Costas loop.

Systems C and C-1 use TDMA. Since burst-independent TDMA is used, completely independent acquisition and synchronization must be achieved quickly on

* The self-acquisition performance of a Costas loop used for DEPSK is given in Table 4-2 of this report. A qualitative performance discussion is included in Paragraph 6.2 of the Interim Report.

each burst to avoid the expenditure of inordinate amounts of overhead that would either make the system inefficient or would require very long burst lengths. The latter results in the need for large buffer storage on the aircraft and ground, long delays in the transmission, and more inefficient usage of the burst by shorter messages.

Carrier synchronization in this case may be efficiently achieved through the use of a pure burst of carrier at the beginning of each TDMA burst. The Costas loop used is modified by clamping the I channel so that it operates similarly to a phase-locked loop on a pure carrier. For the 12 channels available from this configuration (symbol rate ≈ 16 kbps), the acquisition results indicate that an allowance of 1.5 milliseconds (24 symbols) will be sufficient in a Mach 3 environment to permit phase acquisition. After acquisition, the I channel is unclamped and phase tracking continues on the DEPSK signal while bit synchronization is achieved over the remainder of the burst. The use of continuous tracking during the entire burst is preferable to an approach which develops a phase estimate only during the carrier synchronization burst and holds it during the remainder of the burst in light of the expected multipath environment.

Independent surveillance capability can be provided in all systems having a global supervisory channel (Systems A, B-1, and C-1) by multiplexing a ranging signal on the supervisory channel. This can also be done on System B using the communication channels themselves since all aircraft continuously monitor one channel. The return ranging signal (assuming a return via two satellites in a "one out-two back" ranging configuration with altitude reporting) can be multiplexed with a poll response or handled in a manner similar to dependent surveillance information or any other periodically transmitted air-to-ground information. This reporting integrates nicely with the access control methods using ordered calling (see Table 3-4). In System C, dependent surveillance can be implemented using the twelfth reserved ground-to-air channel for polling the aircraft. Independent surveillance may be difficult and must be studied further before conclusions can be drawn.

3.5.3 System Configuration Commonalities

All system configurations have certain points in common. These are:

1. All air-to-ground channels use FDMA at the satellite, sometimes into global coverage antennas and sometimes into narrow beam antennas.

2. All ground-to-air channels (whether TDMA or FDMA) are two-way and are paired with one air-to-ground FDMA channel. *

3. Except for the ground-to-air (TDMA) direction of Systems C and C-1, all voice is narrow band frequency modulation (NBFM) at 43 dB-Hz C/N_o and all data is 1200 bps (150 ASCII characters per second) at 10^{-5} error rate. (C/N_o = 43 dB-Hz.)

4. A number of unpaired one-way air-to-ground channels are provided in each system. As a first cut, it is assumed that twice as many one-way air-to-ground channels than two-way channels are provided.

5. All systems use a random access calling channel for high priority access and for use in pop-up entry procedures. This channel (or channels) is entered by aircraft using a short message. The channel duty cycle is extremely low so that the probability of interference from other aircraft transmissions is extremely low. A complete description of this technique and the analysis method used is given in Appendix B of the Interim Report. Results obtained are summarized in Section 4 of this report.

*This is not a major point and a more flexible arrangement could be used wherein all air-to-ground channels are pooled and assigned to ground-to-air channels as needed. However, in light of the relatively insignificant satellite power demand of air-to-ground channels and the desirability of providing acknowledgement of ground-to-air digital messages, this concept is postulated. In some of the modified systems discussed in Section 4, several air-to-ground channels are associated with one ground-to-air polling channel.

3.5.4 Access Control Methods and Procedures

With five system configurations and the many possible access control methods available, the number of combinations is very large. Therefore, to provide a starting point for analysis, the system doctrines described in Table 3-6 were developed. Additional iterations were made as performance results become available; these are discussed in Section 4.

3.5.4.1 System A

With only three channels available, a regimented approach appears desirable. The system operates as follows:

1. Operation

   Two of the three 43 dB-Hz ground-to-air channels are reserved as supervisory polling channels* which can also handle short data messages,** and the third is held for voice and long data traffic. During early stages of system implementation when voice may be predominant, one polling channel and two voice channels might provide a better balance. Each aircraft acquires and monitors one of the polling channels when it enters the system. This channel will normally be semipermanently assigned before takeoff, but it can be assigned in flight using one of the channels designated by system doctrine to handle entry assignments (see the paragraph on Aircraft Entry below).

   Aircraft are periodically polled by address and sent short data messages. The length of the data block to be provided was optimized using the requirements analysis as an input; results are discussed in Section 4. The nominal polling interval is, of course, dependent on message block size and the number of aircraft in the poll. The polls to successive aircraft are separated

*Two-way simultaneous operation is used because of delay to the satellite.
**This is referred to as a poll with information in Section 4.

Table 3-6. Access Control Doctrine for Systems Analyzed

Configuration	A/C Receiver Operation	Ground-Air Method/ Signal Received	Info. on Poll	High Priority A/C Access	Air-Ground Method	Comments	Satellite Beam for A-G Signals			Satellite Beam for G-A Polling Signals
							Poll Response	Communi-cation	Random Access	
A	Semipermanent assigned to one of two channels	Poll with response on return channel	Relatively short mes-sages (80 char.)	Random	Response to poll with short mes-sages	Long messages and voice use third channel	EC	EC	EC	EC
B	Semipermanent assigned to one of N channels	Addressed messages in block format	N/A	Random	Random	Channel held until voice or message com-pleted	NB	NB	EC	NB
C	Scans through all comm. channels	Addressed messages in block format	No	Random	Seizure with ob-servation. Poll in 0 capacity beams		NB	NB	EC	Not applicable*
B-1	Assigned to supervisory channel	Poll with response on return channel	Channel assignment, Comm. to 13°E	Random	Response to poll		NB	NB	EC	EC
C-1	Assigned to supervisory channel	Poll with response on return channel	Channel assignment	Random	Response to poll		NB	NB	EC	EC

EC - earth coverage

NB - narrow beam

*Except for the single supervisory time slot used as a poll in zero capacity beams.

at the transmitter by 40 milliseconds (the two-way differential satellite-to-aircraft delay) so that the aircraft responses on the paired air-to-ground channel never overlap. The alternative of range-ordering the interrogations appears to be both restrictive and unnecessary.

The aircraft responds to the poll using the paired air-to-ground channel. All aircraft use the same fixed processing delay. (A few counts in the bit clock will probably suffice.) Air-to-ground messages include:

- Aircraft address
- ACK/NAK of ground-to-air message (assumed to be error detection encoded for ARQ)
- Position report (for dependent surveillance)
- Other air-to-ground messages (see requirements study in Appendix D of the Interim Report)
- Request to access long-message channel for voice or data
- Request to access one-way air-to-ground channels. *

A header is used at the beginning of the poll response to permit ground receiver phase acquisition and bit, character, and message synchronization. In addition, message routing information is included for automatic routing on the ground. Finally, error detection check bits are appended.

The ground-to-air message includes:

- Aircraft address
- ACK/NAK of previous poll response or one-way/two-way message sent
- Long-message or one-way channel switch command (on, off, or selection)

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*The avionics substudy has shown that the use of the supervisory channel to obtain Doppler correction information for the one-way air-to-ground transmissions is feasible.

- Other ground-to-air messages up to some predetermined length (see Section 4 for the analysis results).

The header contains bit, character, and message synchronization information. Carrier synchronization is not provided because the polling channel is continuous and fully modulated at all times. An aircraft entering the system must therefore acquire the channel using a Costas detector (to derive a carrier reference). This was previously discussed.

2. Aircraft Entry

Aircraft enter the system in either of two ways: flight plan assignment or pop-up assignment. In the former, the polling channel to be monitored is preassigned. In the latter, the aircraft indicate their presence by transmitting on the random access channel provided while temporarily monitoring the polling channel previously designated for entry assignment. This channel then provides the aircraft's semipermanent channel assignment.

In a two-satellite system, the random access channel of either satellite can be used during eclipse. If a response via the designated assignment polling channel does not occur, the aircraft will assume that the satellite has failed and try the remaining one.

Information contained on the system access call includes:

- Identity/aircraft type
- Position
- Access message.

3. Emergency Procedures

An emergency message is transmitted from ground to air or the voice channel is assigned for emergency purposes by interrupting the normal periodic poll. This also permits more frequent position updates when necessary. An air-to-ground emergency message can be sent on the regular poll or can be immediately transmitted over the random access channel. If the emergency warrants it, upon receipt of the air-to-ground emergency message the ground controller can immediately poll the aircraft, send a return message, and/or assign the voice channel, thereby preempting all other communications. If the channel is already assigned, the aircraft using it will be polled first and commanded off the channel.

3.5.4.2 System B

The capacity of the beams in System B varies between three channels and one channel. Access control of the three-channel beam could be made identical to that of System A, but the single channel beam would have to be different. Since it is operationally desirable to use a single method throughout the system, another method must be used. This system must contend with the additional problem of beam handover even though most flights will not cross beam boundaries. In reality, the impact is little different from satellite handover. In this system, all communications (including responses) use one of the three narrow beams.

1. Operation

Each aircraft monitors one of the available channels for an addressed call. In the multichannel beams, the aircraft can be reassigned to monitor another channel if the load on one channel becomes too high.

Following the call and appropriate indicators, a ground-to-air message (single or multiblock) can be sent. One indicator used will signal a voice transaction, which will switch in the appropriate demodulator in the aircraft. In the case of a digital message, it will be block encoded and an ACK/NAK message will be periodically transmitted from the aircraft in a manner similar to that used in the polling scheme of System A. Message lengths and types sent over the assigned channel to each aircraft are completely flexible and are not constrained as they are over the polling channel of System A.

Since there is no periodic interrogation of each aircraft, regular surveillance is not indicated. However, it is possible to incorporate a simultaneous synchronization waveform and/or a ranging waveform to permit either dependent or independent surveillance.

Aircraft request access to a communication channel (either two-way or one-way) by transmitting an access message on the random access channel(s)* separate from the emergency random access channel. Acknowledgment and channel assignment (for one-way channel requests) are received over the ground-to-air channel monitored by that aircraft.

Header and synchronization information included in the transmissions is similar to that of System A. The problems are also similar. One major difference, however, is that after a voice transaction (using NBFM) is completed on a channel, each aircraft assigned to monitor that channel must reacquire before another aircraft can be addressed. A related operational problem, potentially serious, is that while a voice transaction is taking place on a channel, no other aircraft assigned to that channel can receive any but emergency messages. Interruption is easily accomplished if the ground is transmitting (in which case all receivers but the one involved in the voice conversation will acquire).

2. Aircraft Entry

The pop-up entry of aircraft is handled the same as in System A by random access transmission via the earth coverage receive antenna. The aircraft pilot, however, must know the beam he is in (not a severe problem) to enable him to monitor the channel designated for assignment purposes.

3. Emergency Procedures

Emergency messages are transmitted ground-to-air over the channel the particular aircraft is monitoring by interrupting communications on that

*This channel (or channels) does not pass communication traffic but only provides the means of signalling a desire to communicate air-to-ground.

channel. Air-to-ground emergency messages use the global coverage random access channel.

3.5.4.3 System C

The inherent independent burst TDMA structure of the ground-to-air links of System C and its higher capacity make the "channel seizure with observation-type 1" method of access control for air-originated traffic (see Table 3-4) both easy to implement and viable. (The queueing simulations will assess the latter point.)

1. Operation

   All aircraft monitor all channels assigned to their beam. The channel burst structure contains channel identity (to permit automatic transmit frequency selection) and occupancy information, as well as aircraft address, if an aircraft is being called or if the channel is occupied. Access to aircraft for ground-originated messages uses the address to call an aircraft. If the aircraft being called is not in a beam which has capacity assigned to it, or if all capacity assigned in the beam is used and the message cannot wait, a command must be sent to the satellite to alter the channel-beam assignments. This is not expected to take place very often, except for the one supervisory time-channel reserved.

   Access to the satellite for air-originated traffic located in beams which are assigned capacity is accomplished by monitoring each channel and seizing it by transmitting an access request on the appropriate FDMA half of the channel when it is observed to be vacant. This request triggers an addressed acknowledgment on the seized ground-to-air channel. On rare occasions two or more aircraft will attempt to seize a channel simultaneously and none will get an acknowledgment. In this case, we rely on repeated trials by each aircraft to eventually succeed in accessing the system. If an emergency exists onboard one aircraft, it can use the emergency random access channel.

Air-originated traffic located in beams which have no capacity assigned have no ground-to-air transmission to monitor. These aircraft are individually polled by the supervisory channel and access the system in this manner. It is felt that most aircraft will be in beams having channels assigned to them and thus the poll will involve relatively few aircraft. ACK/NAK of ground-to-air messages uses the paired FDMA channel as in System B.

2. Aircraft Entry

Pop-up entry is handled somewhat as in System B, with the aircraft transmitting through a global coverage random access channel but monitoring all ground-to-air channels for an acknowledgmment. A two-satellite system requires that the aircraft receiver be tunable to receive the second satellite TDMA signal if the first tried does not acknowledge the call.

3. Emergency Procedures

Emergency messages are sent ground-to-air merely by seizing a channel and diverting it into the beam covering the desired aircraft. An air-to-ground emergency message will use the global random access channel.

3.5.4.4 System B-1

The use of the global channel as a supervisory channel appears attractive for this system. The supervision information and ranging waveforms (for independent surveillance) will be multiplexed on a single carrier, probably using one form of orthogonal multiplexing [quadriphase shift keying (QPSK) and Interplex are candidates].

1. Operation

All aircraft in the system are periodically polled on the global supervisory channel. A minimum of information is contained in the poll, (i.e., messages are not normally permitted). This permits a higher average poll rate than in System A. Poll acknowledgment is returned from each aircraft over its associated narrow beam. Aircraft poll transmit frequency changes are automatically commanded over the poll channel in the occasional instance when they are needed. Channel assignment for the receipt of ground-to-air messages is sent over the poll channels and automatically sets the receiver and transmitter frequency. ACK/NAK responses are sent over the air-to-ground portion of the ground-to-air channel used.

Aircraft indicate a channel need (one-way or two-way) in their poll response. In addition, either a position report or ranging waveform sample is simultaneously returned. Acknowledgments and channel assignments are made over the ground-to-air poll channel.

Since, in this configuration, permanent communication capacity is not available in one of the 13.2°-beams, the polling channel will be used to send ground-to-air messages and provide voice communications to aircraft in this beam. The 13.2°E-beam will be active on receive, however, to enable aircraft air-to-ground transmissions to use it.

2. Aircraft Entry

Pop-up entry of aircraft is handled by the aircraft transmitting an access call on a random access channel and monitoring the global polling channel for acknowledgment that the A/C has been acquired into the system.

3. Emergency Procedure

Emergency ground-to-air messages will be permitted on the normally message-free poll channel if the aircraft being addressed is not communicating. If the aircraft is communicating, the ground-to-air message will be sent over the channel being used if the ground-to-air portion is active (i.e., preempting), and either over the ground-to-air portion or over the polling channel (depending on how the avionics is configured) if the air-to-ground portion is active.

Emergency air-to-ground messages will use the random access channel with communication channel preemption following, if warranted, as in System A.

3.5.4.5 System C-1

System C-1 has a smaller capacity than does System C because of the power consumed by the 43-dB-Hz global channel. Therefore, a more ordered doctrine than a seizure one was felt to be desirable as a baseline for this system. A polling scheme similar to that used in System B-1 is therefore used.

1. Operation

   All aircraft in the system are periodically polled on the global supervisory channel. Each aircraft is also monitoring all communication channels as in System C. As in System B-1, a minimum of information is contained in the poll. Poll acknowledgment is returned from each aircraft over its associated narrow beam/poll response channel, whose frequency is automatically controlled over the poll channel. The poll is used mainly for surveillance interrogation (dependent or independent) and for triggering aircraft access requests for air-to-ground messages and aircraft-originated two-way communication interchanges.

   Access to aircraft for ground-to-air messages and for ground-originated calls to establish two-way communications are handled over the communications channels themselves, as in System C. This unloads the polling channel somewhat. Acknowledgment to an aircraft call occurs over the assigned channel if the request is for a two-way channel and it is available. If the channel is not available or if the request is for a one-way air-to-ground channel, the acknowledgment is sent over the poll.

2. Aircraft Entry

   Pop-up entry of aircraft is handled exactly as in System B-1.

3. Emergency Procedures

   Emergency ground-to-air messages sent over the poll have priority if they are short and require no significant iteration. Longer ground-initiated contacts will be established by direct addressing on one of the communication channels.

Emergency air-to-ground contacts will be established using the random access channel, followed by preemption of a two-way channel, if warranted.

SECTION 4 - SUMMARY OF RESULTS

This section presents a summary of the most significant results obtained during the course of this study. These results can have an important effect on the design and performance of aeronautical systems. The summary is divided into three major components: signal design, avionics, and access control.

The signal design summary gives the results of the analytic and computer simulation modulation and tracking analyses in order to determine the error performance capabilities of selected modulation techniques in the aeronautical environment. The major purpose of this substudy was to draw conclusions regarding the communication channel capacities of the candidate system and the necessary aircraft discrimination.

The avionics summary gives the results of a preliminary substudy conducted to determine the impact upon aircraft equipment of the various system configurations developed in this study. The avionics substudy is restricted to the original five system configurations (i.e., A, B, C, B-1, and C-1) developed for this study. Study has not been given to the impact of modifications and additions made to these systems.

The access control simulations summary presents the results of the various system configuration performance tests, and gives the results of the intra- and inter-system tradeoff analyses. The purpose of this part of the study was to determine how each system configuration, with associated access control subsystem, performed with respect to delay and blocking, given the fixed satellite power resource.

Additional results, not specifically discussed here, are given in the Interim Report. These results will be expressed in terms of the conclusions drawn from them and presented in Section 5.

4.1 SIGNAL DESIGN SUMMARY

This paragraph presents a summary of the results obtained from analytic and computer simulation analyses conducted to investigate the nature of the signal structures that are applicable to aeronautical systems. The type of signalling used in the system greatly influences system performance. Consequently, it is of concern in the design of the access control subsystem. Furthermore, signal design of the access control subsystem itself is related to system performance. In the aircraft-to-satellite environment, transmissions are subject to degradation caused by surface-scattered multipath. This degradation in performance manifests itself in a number of areas of system design analysis. First, there is the obvious evaluation of error rate of performance of various modulation and multiplexing techniques. That is, should one attempt to track the received signal with a coherent scheme, or just accept the envelope with a noncoherent scheme? A subset of this question is whether a coherent receiver can track a received signal in the aircraft-to-satellite environment. If so, can it acquire in this environment? Furthermore, can a coherent receiver properly operate with the velocity Doppler and Doppler acceleration expected from commercial aircraft? Given the relative performance estimates of the candidate techniques, one is also interested in the methods that can be employed to improve performance.

Specifically, this portion of the study concerned itself with determining whether C/N_0 values of 43 to 46 dB-Hz, as specified in the AEROSAT specification, were sufficient to achieve the 10^{-5} error rate (P_e) desired. If so, then available communication channel capacities can be determined for the candidate system configurations in accordance with the specification. If not, appropriate modifications must be implemented. The evaluation of this type of problem requires the analysis of not only the error rate performance capabilities of a given modulation technique, but also its acquisition and tracking performance capabilities, and the applicability of error control techniques.

4.1.1 Modulation Analysis Summary

The analytic and computer simulation analyses that were performed in support of the access control tradeoff study are reported in detail in the Interim Report. The basic results are presented in Section 6 of that report, along with supporting information in Appendices E, F, G, H, and I.

The basic AEROSAT-related questions that were addressed during this portion of the study were:

1. How much acquisition time must be allocated in the presence of multipath Doppler spread?

2. What bit tracking capabilities are required in the presence of multipath?

3. What error rate performances can be expected for the various modulation techniques in the presence of additive Gaussian noise and multiplicative multipath noise?

4. How much multipath discrimination must the aircraft-to-satellite link have in order to achieve the desired level of performance?

Since the answers to these questions are basic to the design of the system, their resolution was approached as follows:

Questions 1 and 2 were answered via full scale simulations of the communication link. Performance estimates were obtained as a function of the following:

- Modulation technique
- E_b/N_o
- Multipath power
- Multipath Doppler spread
- Desired system reliability
- Average error rate.

The answers to questions 1 and 2 were used to parameterize the computer simulation in order to analyze the fine grain error performance of the system (i.e., question 3).

Question 4 was not answered directly in this study. The amount of multipath discrimination required for the AEROSAT System is dependent upon the methods available for mitigating the effects of the multipath degradation. For example, if one desires a $P_e = 10^{-5}$ and obtains a $P_e = 10^{-3}$ for a given set of system parameters, the question arises: Is it valid to demand sufficient additional aircraft antenna discrimination to improve performance; does one demand more transmitter power to satisfy the need; or does the system designer include some form of error control to resolve the issue? Considering the fact that the discrimination properties of aircraft antennas are not well understood, this question is not easily answered. Demanding sufficient antenna discrimination may be unreasonable. Similarly, advocating some error control technique, say a stop-and-wait ARQ scheme, may achieve the performance level desired at the expense of an intolerably low throughput.

Since our purpose in analyzing modulation techniques in the aircraft-to-satellite environment is to answer some basic questions regarding performance, we did not feel that is was necessary to analyze a wide variety of geometric situations. Rather, the analyses performed were based on a set of physical conditions designed to ensure a strong multipath environment. Consequently, a set of representative aircraft flight parameters was selected, along with a representative analytic multipath model. From these were calculated the necessary parameters that were used in the simulation multipath model. The details of these procedures are given in Paragraph 6.1.6 of the Interim Report. Statistically significant simulation runs were made for FSK, PSK, and DEPSK modulations with E_b/N_o, signal-to-multipath power ratios (S/Is), and the noise tracking bandwidth (B_L) of the coherent receiver as independent variables. As previously stated, the purposes of these simulations were to determine coherent and noncoherent modulation performance capabilities, to compare FSK and DEPSK error rate performances, and to determine coherent receiver noise tracking capabilities.

The results of the FSK simulation for a R_s = 1200 bps data rate at three values of E_b/N_o are shown in Figure 4-1. Supporting theoretical results have been calculated in Appendix I of the Interim Report and are shown in Figure I-1. The simulations and theoretical exercises show that FSK performance in the multipath environment can be successfully predicted by the analytic expressions developed in Appendix I. Figure I-1 also shows that the error rate performance of a TDMA system design will be poorer than that of the equivalent FDMA system design, due to the differential delay structure

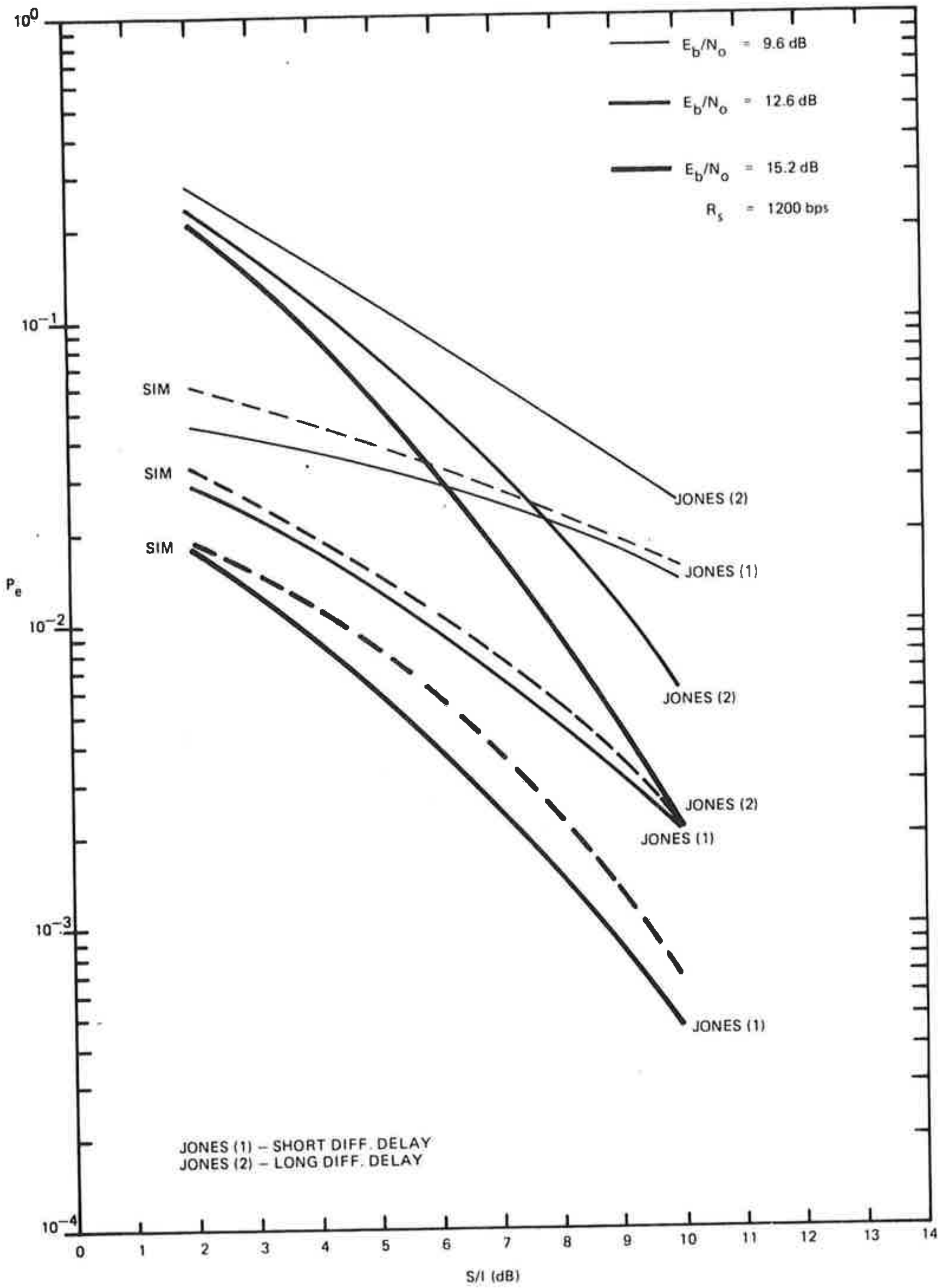

Figure 4-1. Simulated and Theoretical FSK Error Rate Performance Results

of the aircraft-to-satellite multipath. For example, for System C, which is a 12-channel communication system, the data rate for TDMA is R_s = 16.8 kbps, rather than the R_s = 1200 bps associated with an equivalent FDMA configuration. The error rate for an S/I = 6 dB and E_b/N_o = 15.2 dB is $P_e = 5 \times 10^{-3}$ for FDMA and $P_e = 2.5 \times 10^{-2}$ for TDMA. The 2.5 times increase in error rate is due to increased differential delay and its attendant effects on the performance of an incoherent FSK detector. The most significant result obtained from the FSK analyses is that an error rate of $P_e = 10^{-5}$, even for FDMA applications, cannot be obtained unless S/I >15 dB and E_b/N_o = 15.2 dB (i.e., C/N_o = 46 dB-Hz). If the nominal E_b/N_o = 12.2 dB (i.e., C/N = 43 dB-Hz) and/or TDMA is employed, the S/I required for $P_e = 10^{-5}$ will rise accordingly.

The results of the DEPSK simulations and theoretical analyses are given in Figure 4-2 of this Final Report and Figure I-3 of the Interim Report, respectively. These results show that there is not very good agreement between the theoretical and simulated results.* Therefore, we will only use the simulation results for comparison analyses. The simulation results indicate that a $P_e = 10^{-5}$ can be obtained for FDMA applications with E_b/N_o = 15.2 dB and S/I = 12 dB.

A direct comparison of the performance capabilities of the frequency-shift keying (FSK) and DEPSK modulations reveals that, for E_b/N_o = 9.6 dB (i.e., C/N_o = 40.4 dB-Hz) and R_s = 1200 bps, for S/I < 2.5 dB we see that the FSK modulation has better performance results than does the DEPSK, although the S/I is so low that both techniques perform poorly. Figure 6-6 of the Interim Report shows plots of the relative advantage, in terms of E_b/N_o, of DEPSK over FSK as a function of S/I. For an E_b/N_o = 9.6 dB, we see that FSK is better than DEPSK for low values of S/I, and that the theoretically assumed 3-dB advantage of coherent over incoherent techniques is not realized until S/I >8 dB. For the E_b/N_o = 15.2 dB case, however, DEPSK is always better than FSK, and its relative advantage reaches 3 dB for S/I >4 dB.

From these sets of results we may conclude that DEPSK will have superior performance capabilities as compared to FSK for reasonably large values of E_b/N_o. Certainly for C/N_o = 43 and 46 dB-Hz, DEPSK will have significantly better performance

* The theoretical work considers DPSK, whereas the simulation results were obtained for DEPSK. It is expected that the theoretical error rate performance of DPSK and DEPSK are nearly identical at these levels for additive white Gaussian noise environments.

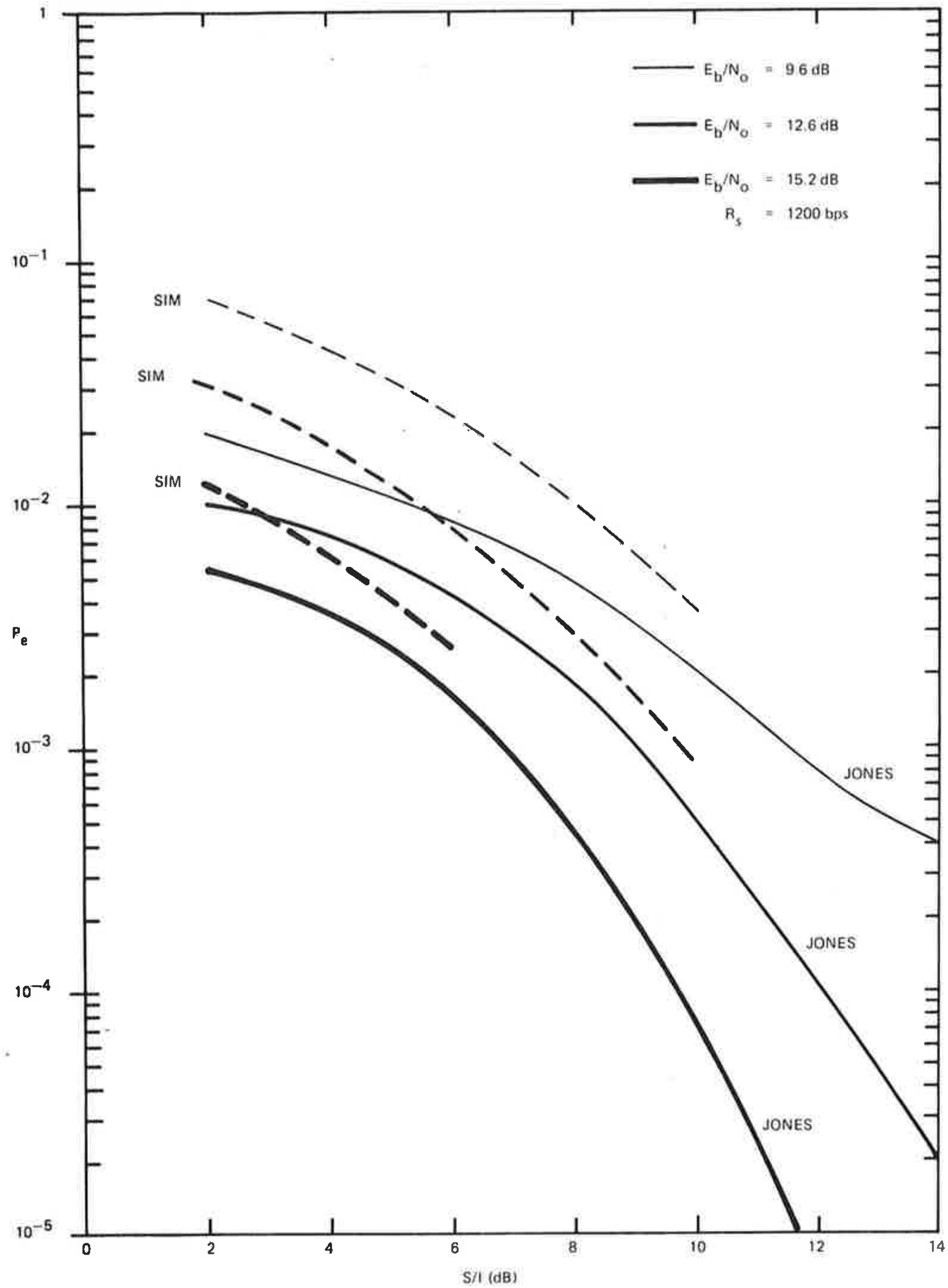

Figure 4-2. Simulated and Theoretical DEPSK Error Rate Performance Results

results than FSK for expected values of S/I. For S/I values in the 8- to 12-dB range, one can expect $2.0 \times 10^{-4} < P < 8.0 \times 10^{-4}$ for the DEPSK technique.

PSK modulation error performance is on the order of twice as good as DEPSK performance with respect to error rate. It would seem, therefore, that we should recommend PSK over DEPSK. There is a problem associated with PSK modulation that precludes making such a recommendation; i.e., PSK is subject to a π radian ambiguity. So, if a chance multipath should cause a cycle slip, the error rates of the PSK technique will go from P_e to $1-P_e$, where $P_e \ll 1$. DEPSK, however, is not subject to the cycle slip phenomenon due to its encoding. A π radian phase shift will merely result in a paired error, and then the system will automatically adjust. Furthermore, it can only be rectified by another chance cycle slip or a resynchronization. For a real system, this amounts to a dropout and requires resynchronization.

Given that DEPSK techniques are to be used for the system, questions arise as to the ability of a coherent receiver to acquire in a multipath Doppler spread environment and to track in the same. Figure 4-2 shows the simulation results obtained for the DEPSK modulation technique. For an $R_s = 1200$ bps and an $E_b/N_o = 9.6$ dB, we have obtained P_e as a function of the noise bandwidth, B_L, of a second-order phase-locked tracking loop. The results are presented for two values of S/I. Both the relatively low E_b/N_o and the low S/I provide a good test setup to obtain acquisition and tracking characteristics of a coherent receiver in the presence of multipath Doppler spread. For each set of simulations, the results indicate that little degradation is to be expected for values of $B_L < 100$ Hz. In fact, even for $B_L = 300$ Hz (i.e., $B_L = R_s/4$), the degradation only amounts to a doubling of the error rate over that obtained for a very narrow loop bandwidth.

As the noise bandwidth of the loop gets wider than $R_s/4$, there is a dramatic degradation in tracking performance (see Figure 4-3). The cause of this phenomenon is two-fold. First, the loop bandwidth is now so wide that the receiver is tracking the multipath phase fades on a one-to-one basis. The wide noise bandwidth has also allowed the signal-to-noise ratio (S/N) in the loop to approach the critical threshold of 10 dB. Now, when a multipath phase fade causes the composite received signal vector to be reduced in magnitude such that the S/N < 10 dB momentarily, the receiver cannot

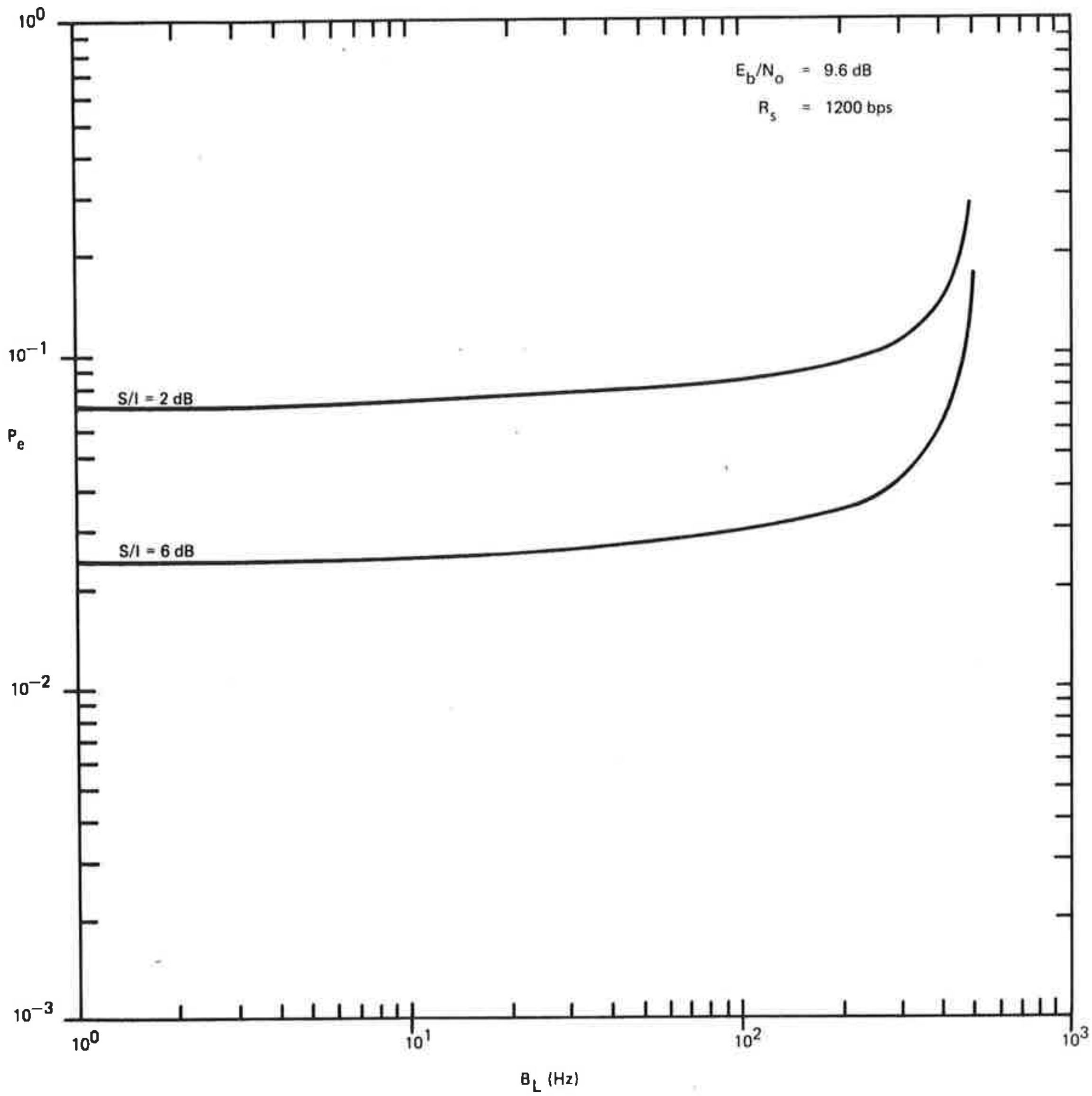

Figure 4-3. Simulation Results of Error Rate Performance Versus Loop Noise Bandwidth DEPSK Receiver

obtain a good phase estimate, and the large amount of Gaussian noise (i.e., N_oB_L) causes burst errors to occur. The simulation of the PSK technique resulted in a large number of cycle clips under these conditions. Although the DEPSK technique is not subject to such ambiguities, the cycle slip density was high enough to cause poor error rate performance.

In summary, the following are important results of the modulation analysis:

1. An error rate of 10^{-5} can be achieved with incoherent FSK modulation operating at C/N_o = 46 dB-Hz and R_s = 1200 bps only if $S/I > 15$ dB.
2. The same error rate can be achieved with coherent DEPSK with a $S/I \cong 12$ dB.
3. The DEPSK technique is better than the FSK technique, in terms of $\Delta(E_b/N_o)$, by 3 dB for error rates of interest for AEROSAT applications.
4. The loop noise bandwidth, B_L, of the DEPSK receiver can be operated up to $B_L = R_s/4$ without serious detection degradation. As shall be summarized immediately below, this value of B_L is sufficient to correct Doppler offset and acceleration tracking errors.

4.1.2 Acquisition Summary

Coherent detection requires the availability of a local replica of the carrier waveform for the received transmission. A carrier synchronizer is the device that is used to obtain an estimate of the frequency and phase of the carrier so that a replica may be produced at the receiver. Usually, the carrier synchronizer tracks the frequency and phase of a residual (unmodulated) component of the transmission, or derives the reference from a suppressed-carrier transmission. Whereas the detection performance is affected by the tracking mode of the carrier synchronizer, it is first necessary for the acquisition of carrier synchronization. Because both modes of synchronization are related to the noise bandwidth of the synchronizer, acquisition and tracking are dependent functions.

Carrier synchronization is adversely affected by several conditions, such as Doppler, Doppler rate, multipath Doppler spread, and Doppler spread velocity. A second-order phase-locked loop (PLL) is ordinarily used for carrier synchronization so that Doppler may be tracked. The loop bandwidth must be adequate to avoid significant tracking errors from the maximum Doppler rate. In most cases, the loop parameters are selected based on a communications channel with additive white Gaussian noise (AWGN). Since narrow bandwidths are suitable for filtering the noise in the tracking mode, while wide bandwidths allow rapid acquisition, the optimum bandwidth is a tradeoff between the conflicting requirements in tracking and acquisition. The introduction of variable multipath transmissions further complicates the synchronization analysis so that the optimum bandwidth is most readily determined experimentally, i.e., by simulation. Such simulation has been discussed in Paragraph 4.1.1, and the results indicate that a design point can be ascertained from an analysis that does not include the multipath case, since an adequate noise bandwidth can be tolerated in the multipath environment.

The results of this analysis are presented in Tables 4-1 and 4-2. Table 4-2 shows that for DEPSK modulation a modified Costas loop can be used for carrier detection. The Costas is modified to look like a PLL during acquisition by clamping the I channel output to one. Once acquisition is achieved, it is returned to the normal PLL mode. Table 4-1 shows that for frequency offset values $\leq R_s/4$, only 10 bits are required for 1.5-kHz Doppler offsets (i.e., Mach 1 operation) for System C operation. The loop bandwidth required for this is $B_L = R_s/4$, which is compatible with the conclusions obtained in Paragraph 4.1.1. The acquisition performance of System C-1 will be similar to that of System C, and will present little acquisition delay difficulty.

The nature of the access control doctrines of Systems A, B, and B-1 are such that carrier acquisition is not a major problem. Systems A and B-1 have permanent poll channels (thus allowing reasonably long acquisition times) and System B has the semipermanent assignment doctrine on the ground-to-air channels.

4.1.3 Automatic Repeat Request (ARQ) Summary

The use of some form of ARQ should be considered for error control on the multipath fading channel. The Interim Report presents the results of an analysis

Table 4-1. Acquisition Requirements

System	Frequency Offset F (Hz)	R_S Sym/Sec	m: Technique I PLL	m: Technique II Frequency Scan
C	1.5 K	24.0 K	8	N/A
		18.0 K	10	N/A
		12.0 K	10	N/A
	3.0 K	24.0 K	10	N/A
		18.0 K	15	N/A
		12.0 K	23	16
	4.5 K	24.0 K	15	N/A
		18.0 K	23	16
		12.0 K	34	20
B	1.5 K	3.6 K	48	22
		2.4 K	110	28
	3.0 K	3.6 K	202	35
		2.4 K	418	48
	4.5 K	3.6 K	418	48
		2.4 K	930	68

Table 4-2. Summary of Acquisition/Tracking Techniques

Modulation	Carrier Detector	Carrier Synch. Waveform	Carrier Acquisition Operation	Acquisition Performance	Comments
BPSK (Antipodal)	Phase-Locked Loop	Pure Carrier Burst	Straight Frequency and Phase Acquisition or Frequency Search Using $B_L \approx R_s/4$	Given by tabular values	No phase acquisition ambiguity. No tracking during data transmission - poor in dynamic environment.
Residual Carrier PSK ($\Delta\phi \approx 72°$)*	Phase-Locked Loop (Switched Mode)	Pure Carrier Burst	Straight Frequency and Phase Acquisition or Frequency Search using $B_L \approx R_s/4$	Given by tabular values	After acquisition, when data is added, the PLL bandwidth is reduced by a factor of 10 in order to maintain a good phase reference. Transient performance after switch uncertain.
Differentially Encoded PSK (DEPSK)	Costas Loop	Pure Carrier Burst or Modulated Carrier	Straight Frequency and Phase Acquisition using $B_L \approx R_s/4$	If frequency offset is less than R_s but greater than $R_s/4$, acquisition time is approximately four times worse than PLL. Between $R_s/4$ and 0.02 R_s, two times worse; and less than 0.02 R_s, about equal.	Partially simultaneous carrier and bit synch. possible, but savings not as great as time loss incurred.
	Modified Costas Loop	Pure Carrier Burst	Costas modified to look like PLL (During Acquisition, Clamp I channel output to one). Then same as PLL.	Given by tabular values if frequency offset is on order of $R_s/4$.**	

*Carrier 10 dB down.
**Previous analysis indicates that this is the only practical case.

conducted to compare the performance of three types of ARQ techniques; namely, stop-and-wait ARQ, continuous ARQ, and a polling scheme. Comparisons of these ARQ schemes are made in terms of throughput and mean message delivery time.

ARQ is a practical means of achieving low undetected error rates with modest encoder/decoder cost and complexity. Its use is being considered for application for two reasons:

1. No matter how well the system may perform with respect to error rate, those errors that do occur must be accounted for in a simple yet efficient manner.
2. If insufficient S/I proves to be practical in order to achieve $P_e \leq 10^{-5}$, as called for in the AEROSAT specification, ARQ represents a viable form of error control.

The results of the ARQ analysis indicate that none of the three forms of ARQ applies directly to the system. Rather, a modified form of either the polling scheme, or stop-and-wait ARQ with acknowledgement delay, is applicable. For those systems with polling channels (i.e., A, B-1, and C-1) the ACK or NAK message can be returned via the air-to-ground poll. If a NAK is returned, the system controller preempts the very next ground-to-air poll slot and repeats the message. Therefore, no propagation or framing delay is incurred in the event of a NAK. For those systems with demand access channels (i.e., B, C, B-1, and C-1), the ground-to-air message is transmitted for a given user and the system simply goes on to other users. When an ACK is received via the return ARQ channels, no further action is taken; if, however, a NAK is received, the original message is retransmitted at the next available time interval. For both forms of this modified ARQ technique, no delay is incurred due to propagation time, and the communication channels are not held idle waiting for ARQ acknowledgements.

The efficiency of the modified ARQ technique, measured in terms of throughput, is given in Figure 4-4 for an AWGN channel. The AWGN channel represents a worst-case design baseline. Figure 4-4 shows that for message sizes of > 80 characters

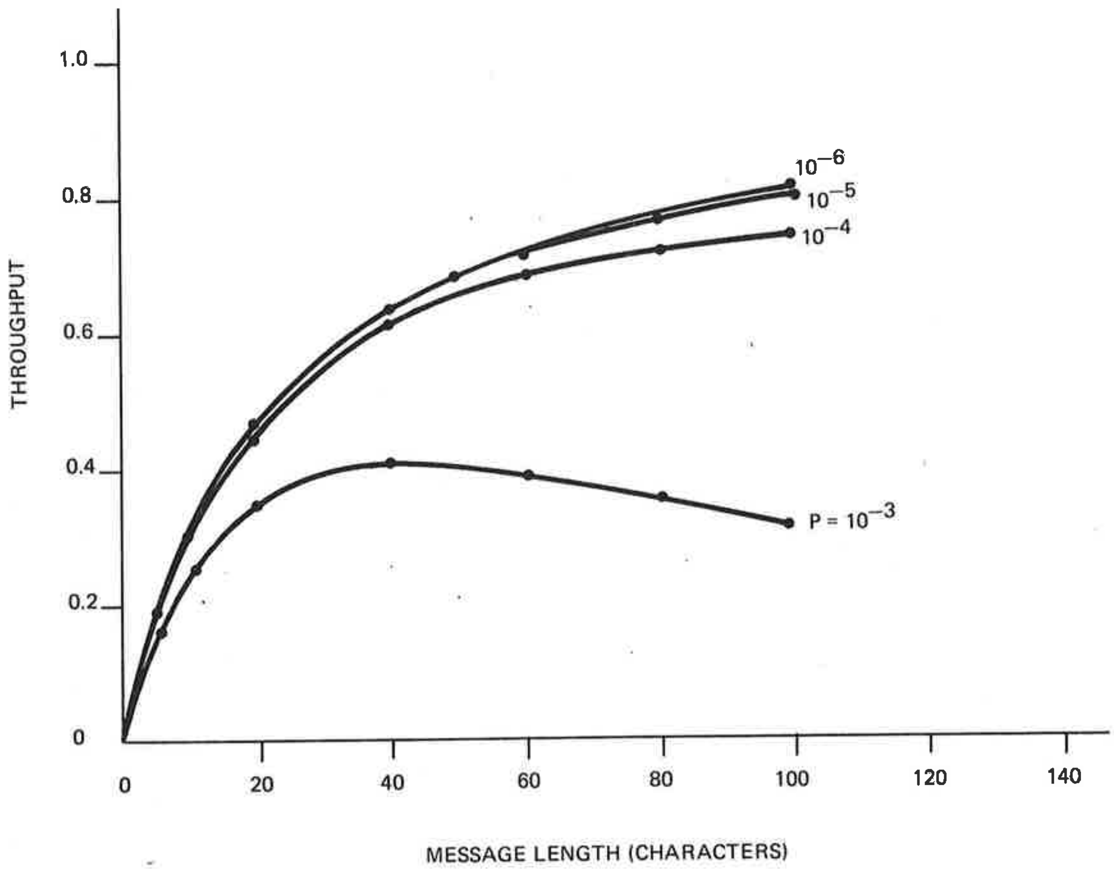

Figure 4-4. Throughput of Polling Channel Versus Message Length and Bit Error Probability (P)

and values of $P_e \leq 10^{-4}$, the throughput of the modified ARQ approaches the overhead efficiency of the burst itself (i.e., >80 percent). Therefore, the modified ARQ technique does not lower the delay or throughput of the channel to any significant extent, yet it provides the necessary error control function.

4.1.4 Poll Channel Design

Systems A, B-1, and C-1 have global coverage polling channels for ground-to-air message traffic, air-to-ground message traffic, and/or access control of other communication channels. System A uses the channel(s) for all three functions. Systems B-1 and C-1 use it for the access control functions only. In addition, System B, which interleaves all communications on a channel, will use the same header information at the beginning of a transmission. Some of these systems currently require independent surveillance as well, and thus require a broadcast ranging waveform.

The limited ground environment studies done on this contract have shown that:

1. Each polling channel in the system must be capable of being accessed by more than one ASET. This can be done at little penalty if each ASET's poll is contiguous so that only a single carrier burst for phase acquisition must be provided by each ASET at the beginning of its poll interval.

2. The system should be capable of having each ASET perform independent surveillance of its assigned aircraft.

The inclusion of these two features, along with multiple access of the communication channels, provides a design which is largely independent of the ground system configuration.

Each ASET polls its own aircraft over the assumed common polling channel at 1200 bps (150 characters/second). Since the system operates as a two-way channel, the system can support air-to-ground responses at the same time that ground-to-air polls are occurring. Therefore, the ground-to-air polls will be separated by 40 milliseconds (worst-case two-way differential satellite-to-aircraft delay) from each other and the air-to-ground poll responses will be the same length as the ground-to-air polls.

This prevents the responses from overlapping without using special poll sequence algorithms. Specifically required polling sequences constrained by such considerations are not desirable because they negate the complete flexibility needed in the surveillance system.

Aircraft perform an error detection check on the received poll data and respond at 150 characters/second as part of their response with either ACK or NAK. If a NAK is received, the message is repeated at a convenient time later in the polling sequence (not necessarily a full frame interval later). This is equivalent to an ARQ scheme without feedback delay, as was discussed in the previous paragraph.

For systems using a poll with information, a message block length of about 80 characters appears to be a reasonable choice. A polling interval of about 6 minutes results if all aircraft are in one poll and are receiving messages. This, of course, can be halved if two channels are used as in System A. A throughput of 72 to 80 percent can be achieved for error rates between 10^{-4} and 10^{-6}, but message delivery reliability may require 10^{-5} to achieve 99 percent reliability. Finally, 80 characters or fewer will handle about half of the projected messages without resorting to multiblock transmissions. Of course, longer messages can also be handled as multiblock messages.

For systems using a poll without information, polling intervals as low as 1 minute are possible with a single earth coverage channel.

The previous results were used as inputs to the simulation analyses discussed in Paragraph 4.3.

4.2 AVIONICS SUMMARY

The results of the preliminary analysis leading to the determination of the overall avionics equipment profile for the system are presented in Appendix A. Two areas should be considered:

- Equipment configuration/performance requirements associated with the system configuration, its operating requirements, and the intrasystem interface parameters.
- User-oriented considerations.

For the AEROSAT Avionics equipment the major interface areas are:

1. Satellite-to-aircraft (forward and return) links
2. Ground terminal control function to aircraft communications subsystem interface (via the satellite links)
3. User input/output device end-to-end interface, specifically the intermediate requirements imposed to support end-to-end traffic
4. Onboard interface requirements between the AEROSAT Avionics equipment and the aircraft input/output devices.

These interfaces are determined by individual or combined requirements relating to system configuration, service mix, and specific user needs.

The specific functional breakdown is shown in Figure A-2 of Appendix A, and a tabulation of the first-order impacting requirements on each function is presented in Table 4-3. The generalized functional components were mapped against the various system configurations (i.e., A, B, C, B-1, and C-1). From this mapping, sensitivities were obtained for each of the major interface areas. The major results indicate that the ground-to-air link is limited by the receiving noise temperature; the air-to-ground link is transmitter power limited, subject to the satellite antenna beam gain characteristics.

Table 4-3. Impacting Requirements on AEROSAT Avionics Basic Functions

Function	Requirements Impacting Design/Performance
Antenna Subsystem	• Fixed Constraint (+4 dB gain) from RAI requirements
Receiver	• Noise performance determined by support technology. Specific bandwidth and tunability requirements defined by choice of FDMA/TDMA system. Equipment configuration determined by aircraft installation requirements.
Transmitter	• Determined by choice of satellite antenna receive configuration. Number/type of transmitters determined by user service needs.
Modem (Forward)	• Demodulator design determined by forward link modulation (i.e., FSK, PSK, DPSK and FDMA/TDMA choice). Number of demodulators and mix determined by simultaneous service needs and mix.
(Return)	• Fixed by choice of FDMA return link and return link modulation. FDMA choice based on satellite return link repeater considerations.
Communications Processor	• Determined by FDMA/TDMA choice, simultaneous service mix and use of supervisory signaling channels. Outputting format design dictated by user I/O device choices.
Frequency Generation & Control	• Form determined by FDMA/TDMA choice and service requirements (including supervisory signaling channels).

Table 4-3. Impacting Requirements on AEROSAT Avionics Basic Functions (Cont'd)

Function	Requirements Impacting Design/Performance
System Control Function	• Dictated by system control regime and user needs relating to cockpit automation
Equipment Control Function and Operator Control	• Established by system control functions

In order to ensure a reasonable and uniform base for evaluating equipment for the various system configurations, a number of baseline assumptions were considered:

- Size of user market and potential equipment production runs
- Effective utilization of available technology
- Characteristics of potential user aircraft
- Built-in test equipment considerations
- Equipment design requirements.

These five factors were taken into account in the types of tradeoffs that were conducted, as well as in the design of the candidate equipment configurations and the costing of the recommended equipment configurations.

4.2.1 Major Tradeoff Summary

Two major tradeoffs which are essentially independent of the system configuration have been identified:

- Service need, relating to the requirement of simultaneous voice/data or any simultaneous two-channel transmission from the aircraft
- The equipment form factor (packaging) necessary to support the receiving system noise temperature specified for the reference avionics interface.

In addition, two other tradeoff areas applicable to several possible configurations, depending on specific signal design on operational methods choice, are identified:

- Simultaneous versus alternate two-way communications
- Doppler-corrected versus uncorrected return link transmission from the aircraft.

The simultaneous two-channel transmission from the aircraft can be provided by either multiple transmitters or a single transmitter with multichannel capacity. Consideration of six transmitter arrangements that can provide the required service has resulted in the conclusion that although a single quasilinear transmitter appears to be a viable approach, the prime power considerations and the cooling system load may impose higher installation costs for the equipment (even though the equipment itself is less costly than in alternative approaches). Thus, the two-transmitter approach is recommended. One further argument that may be advanced in favor of two transmitter installations is that redundant transmitters would normally be required in any case. Thus, the use of a single transmitter for two-channel output capacity would be more costly in the case of an operational installation.

The equipment form factor tradeoff of distributed versus consolidated arrangements resulted in the conclusion that, from a practical standpoint, it appears that the most desirable configuration is a distributed equipment with RF preamplification at the antenna, but with the transmitter(s) located in the aircraft equipment bay. This represents a reasonable compromise between serviceability/maintainability and cost/performance considerations. From this, a proposed arrangement of black boxes or line replaceable units (LRUs), described in Paragraph A.3.5.2 of Appendix A, was evolved. This arrangement appears to be well suited to design and construction practices.

One area in which a significant equipment hardware impact is experienced is in the method by which the transmitter and receiver share a common receiver port. One of the two following approaches may be used:

1. The use of a diplexer-filter that provides simultaneous transmit and receive capability. This approach can be used only when the transmit and receive frequencies are different, since the design of the diplexer depends on:

   - Presenting an open circuit at the transmitter output at the receive frequency

   - Presenting an open circuit at the receiver input at the transmit frequency.

   Since the forward and return links in the AEROSAT are frequency separated (by about 6-1/2 percent), this approach is applicable to the AEROSAT System.

2. The use of an antenna changeover switch that alternately connects the receiver or transmitter to the aircraft antenna for transmission or reception, but not both simultaneously.

For our purposes, the use of a diplexer-filter appears to be the best choice since it will readily accommodate the requirements of any system configuration and, even where not initially needed, will provide an equipment which is readily adaptable to evolutionary expansion of AEROSAT services.

Because the air-to-ground link proposed for all systems will use an FDMA approach (with a requirement for rapid acquisition in some cases), each individual aircraft addressing a particular frequency channel will be offset at the avionics terminal from the channel center frequency by an amount corresponding to the sum of the frequency uncertainty of the aircraft frequency source and the Doppler frequency due to that aircraft's relative motion with respect to the satellite. To avoid the need for a separate frequency-phase acquisition for each aircraft's message at the ground terminal, it is desirable to apply Doppler correction to the return link frequency at the aircraft.

Several techniques are available for application of Doppler correction at the aircraft. The exact method and detailed implementation techniques depend, to a degree, on the precise system configuration. For example, if a full-time supervisory signalling channel is available, the Doppler offset may be measured continuously from the supervisory channel carrier, and a scaling factor may be applied (corresponding to the receive-to-transmit frequency ratio) to the transmitted signal frequency. Alternatively, if the forward link is TDMA only (as in the System C configuration), the Doppler estimate must be derived from a sample of the carrier detector loop. It is important to note that if the system is planned to incorporate Doppler correction at the aircraft and no acquisition search is provided at the ground terminal, then entry of an aircraft into the system (i.e., via the air-to-ground link) must be preceded by carrier acquisition in the ground-to-air link. We have assumed that the operational implications of Doppler correction at the aircraft are accommodated by system/procedural design.

The results indicate that two methods are readily apparent for application to the air-to-ground link:

- Inverting the sense of the Doppler frequency at the input to the receiver carrier detector loop, and using the detector loop voltage-controlled oscillator (VCO) output directly to drive the equipment monitor. This method provides exact Doppler correction, but it doubles the frequency error due to local oscillator (LO) frequency uncertainty.

- Sensing the loop error voltage at the receiver carrier detector loop and, with suitable error voltage scaling, applying the error voltage to the transmitter modulator frequency control oscillator [nominally a voltage-controlled crystal oscillator (VCXO)]. As in the preceding case, frequency error due to LO frequency uncertainty is doubled; however, the choice of receiver LO frequencies (and use of high side versus low side mixing) is not as critical as with the first scheme.

From a design standpoint, the first approach is most straightforward and should be employed if there are no problems encountered in receiver image or LO spurious response placement. A block diagram for the functional implementation of the first approach is presented in Figure 4-5.

4.2.2 Candidate Equipment Configuration Summary

Based upon the previously reported considerations and the five possible system configurations (A through C-1), a matrix of service mix versus system configuration was developed. This matrix is presented in Table 4-4. From this matrix, it was found that for a given service mix, the same equipment functional configuration could be applied to all systems employing a FDMA multiple access method - Systems A, B, and B-1. The actual differences from system to system would be in transmitter size (as determined from the system link budgets and some relatively minor factors in the detailed implementation of the equipment control function). Five separate FDMA equipment functional configurations were developed; these are described in detail in Appendix

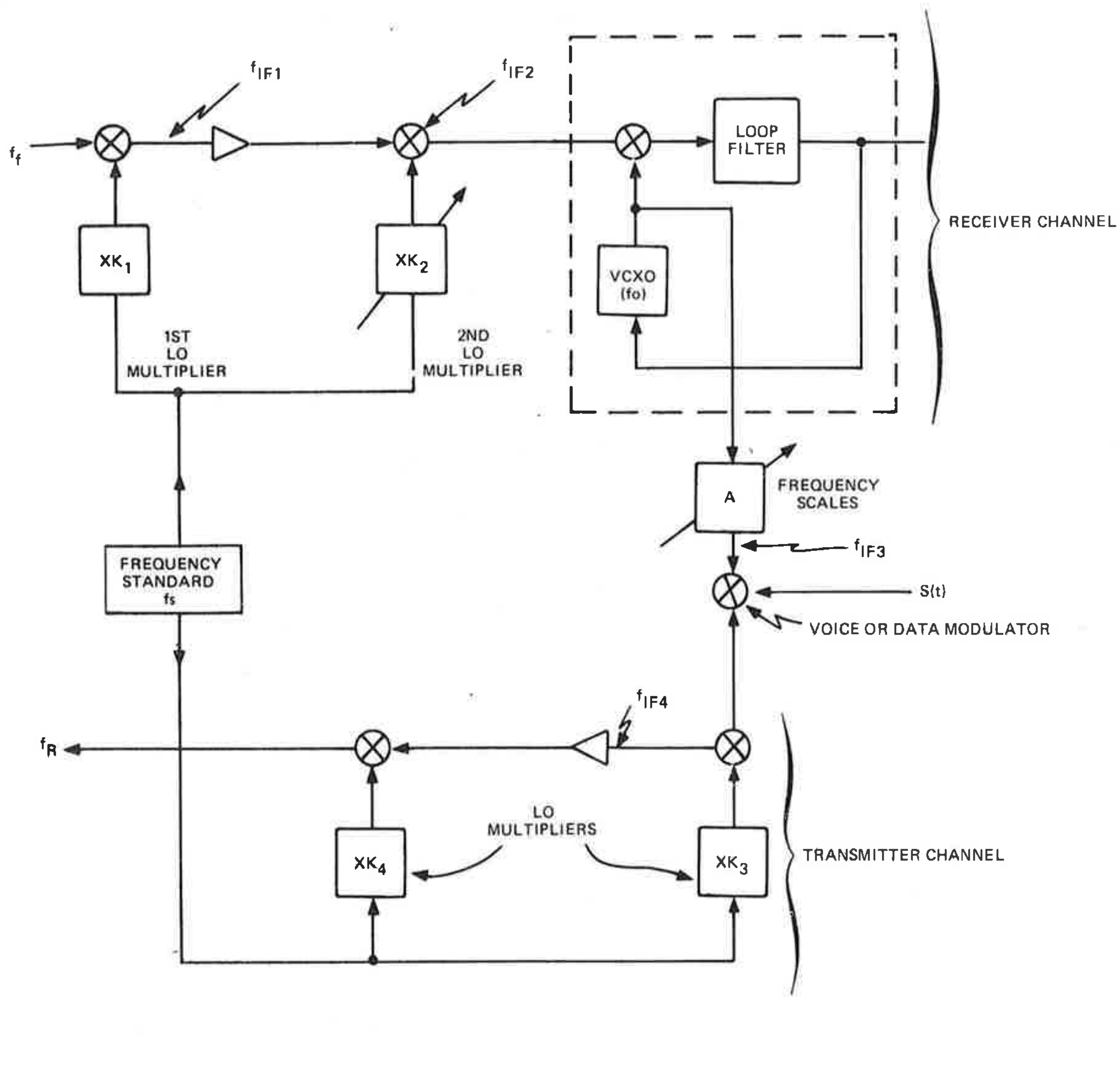

Figure 4-5. Functional Block Diagram for Doppler Correction in Avionics Equipment

Table 4-4. Equipment Configuration as a Function of System and Service Provisions

System Type	Satellite Antenna Configuration	Multiplexing (Forward Link)	Service Provided[1] V/D	O/W	Ind. Surv.	Comb. O/W-Surv.	Equipment Functional Configurations	Remarks
A	Global	FDMA	X				1	Basic voice/data capability only
			X	X			2, 2A	See Note 2
			X	X	X		3	
			X			X	4	
B	Triple Beam	FDMA	X				1	
			X	X			2, 2A	
			X	X	X		3	
			X			X	4	
B-1	Global & Triple Beam	FDMA	X				1	
			X	X			2, 2A	
			X	X	X		3	
			X			X	4	
C	Multiple Narrow Beam	TDMA	X				5	
			X	X			6	
C-1	Global and Multiple Narrow Beam	TDMA on Narrow Beam w/Global Coverage FDM w/ TDM Channels	X	Global			7	Receiver designs incorporate both TDMA and FDM provisions (applies to 7, 8, 9)
			X	Nar. Beam	Global		8	
			X			Global	9	

NOTES:

1. O/W: Orderwire or supervisory signalling channel capacity
   Ind. Surv.: Independent Surveillance channel capability
   Comb. O/W-Surv.: Combined - common channel supervisory signalling and independent surveillance
2. Configuration 2 produces totally independent supervisory signalling while 2A requires voice or data interrupt for supervisory signalling

A. Of these configurations, either equipment configuration 2 or 2A is appropriate for system configuration A, equipment configuration 1 is applicable to system configuration B, equipment configuration 2 is applicable to system configuration B-1 without independent surveillance, or equipment configuration 4 is applicable to system configuration B-1 with independent surveillance.

For the TDMA systems (C and C-1), a total of five additional equipment configurations were identified; these are given in Appendix A. Of these equipment configurations, numbers 5 and 6 are designed for TDMA - system configuration C only. The remaining equipment configurations (numbers 7 through 9) incorporate provisions for both TDMA reception in the multiple narrow satellite beam with FDM reception of earth coverage supervisory signalling, and/or independent surveillance channel(s) of system configuration C-1. Of these, the viable equipment configuration candidates are configuration 5 for System C, configuration 7 for System C-1 with dependent surveillance, and configuration 9 for System C-1 with independent surveillance.

4.2.3 Relative Equipment Cost Summary

Table 4-5 shows the relative equipment cost results determined for the recommended equipments of Paragraph 4.2.2. The cost estimates are given relative to a unity cost figure for the baseline equipment, configuration 1.

Table 4-5. Recommended Equipment Configuration Cost Index Comaarisons

System	Equipment Configuration									
	1	2	2A	3	4	5	6	7	8	9
A	1.00*	1.27	1.25							
B	0.92									
C						1.08				
B-1		1.19			1.35					
C-1								1.42		1.49

*Configuration 1 for System A is the reference point for all other cost estimates. It is not recommended for System A.

4.3 ACCESS CONTROL SIMULATION SUMMARY

This paragraph presents a summary of the results obtained from the computer simulations of the five candidate system configurations introduced in the Interim Report and discussed in Section 3 of this Final Report. In addition, results are presented for additional system configurations, not included among the original five, that are an outgrowth of additional conceptualization. Specifically, the results for two additional forms of system configuration A are reported, as are the results of a complete analysis of the performance capabilities of System C as a function of communication channel capacity.

In all cases, the main criterion of system performance has been total time delay. This is defined as the total elapsed time between initial user request and completion of message. From Section 7 of the Interim Report, we see that there are three main forms of delay that combine to form the total delay. These are:

- Access control delay
- Waiting delay
- Service delay.

The access control delay is that delay incurred in obtaining a control-acknowledged user request. This type of delay is a function of the access doctrine. On a poll, this delay is defined as the elapsed time between a user desire to communicate and the appearance of his assigned slot in the poll frame. Once a request is acknowledged, the waiting-delay is that elapsed time associated with queuing up for the next available communication channel. The service delay is associated with the elapsed time during which the assigned communication channel is actually being utilized.

The delay criterion has been supplemented in the following paragraphs by detailed available knowledge of the three delay times discussed above and the population sizes of the access control, waiting, and service queues. In addition, system performance can be analyzed on a beam-by-beam basis, rather than on a systemwide basis.

The detailed description of the access control simulation is presented in the Interim Report and will not be repeated herein. Appendix K of the Interim Report presents a description of the aircraft traffic simulation model used as part of the access control simulation. Although the traffic model can simulate aircraft route traffic for any time of day, the time of 1600 GMT was selected for the access control simulations because it represents the peak daily traffic hour.

4.3.1 System A Summary

The results from System A (which provides a polling with information access control/communication doctrine) were obtained for three separate technique variations. In all variations the system consisted of two polling channels and one "clear" (i.e., used for voice and long data messages) channel in the ground-to-air direction, and four polling channels and one clear channel in the air-to-ground direction. Briefly, the three technique variations were:

1. A rigid poll with each potential user preassigned a slot. If a given user does not wish to use the system, his assigned slot must still be held available.

2. A "two-step"poll with each potential user preassigned a slot. If a given user does not wish to use the system he is assigned a "short" slot (i.e., in the ground-to-air direction), otherwise he is assigned a "long" slot. From Figure 7-5 of the Interim Report, it is seen that short slots require 193 milliseconds, whereas long slots are variable. For the two-step poll, a fixed length for the long slots has been selected.

3. A variable poll with each potential user preassigned a slot. This technique is similar to the two-step poll with the exception that the long slot can now be dynamically sized according to the individual's current communication needs.

The design of the polling frame in all cases was dependent upon the amount of message space allocated to a user within a frame. Using the rigid poll as an example, one can allocate sufficient message space in each user slot such that almost all users will be guaranteed complete message transmission within one polling frame. Such a selection is not wise since the individual slots will be underutilized and the frame size will be unacceptably long. Making the frame size as short as possible will result in almost no slot message capability, and will thereby constrain the user to deliver his message over many frames. So, the message capability of a user slot must be a compromise between the time delay to initiate communication and the time delay between initiation and complete message delivery.

The System A configuration was set up such that all analog communications and the longest digital messages will use the clear channel. The service distributions of these two types of requirements are discussed in Appendix D of the Interim Report. By eliminating these two classes of message lengths, the design of the poll slots is relieved of the constraint of being required to handle long messages. The length of the message that determined the maximum allowable service time on the poll was obtained by normal procedures using the general simulation model. The criterion used was that messages greater than a given threshold would be allowed on the clear channel as long as the queue for that channel was not unacceptably long. So, a threshold of an infinity of seconds was initially set and a simulation was run to determine the stochastic steady-state queue size. The threshold was then lowered and the simulation rerun. This procedure was repeated until a complete curve of threshold setting versus queue size was obtained. The results, shown in Figure 4-6, clearly indicate a preferable threshold number. Assuming that no more than one user is allowed in the queue at a given time, it appears that the service time corresponding to this queue size, as obtained from Appendix D of the Interim Report, is approximately the 0.9 probability event. Therefore, the 10 percent longest digital messages were delegated to the clear channel.

Since no analog messages can appear on a poll, by definition, the next question to answer is: How much of the user communication traffic on System A can be allowed to be analog? Running the simulation with a mixture of analog and digital message

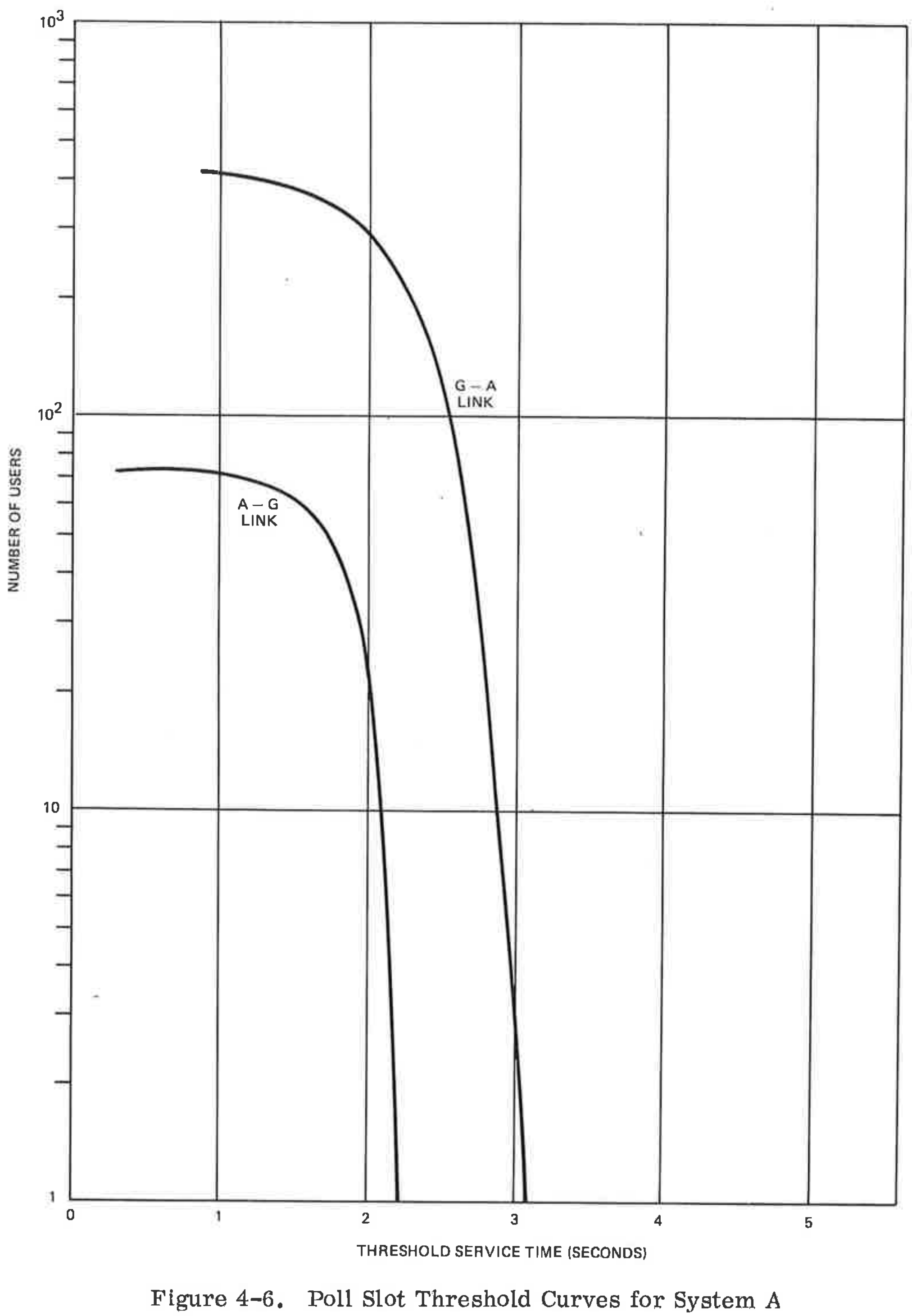

Figure 4-6. Poll Slot Threshold Curves for System A With Digital Requirements

requirements, and with all analog and 10 percent of the longest digital messages on the clear channel, we obtained the results shown in Table 4-6. Considering that the maximum possible number of system users is 462, Table 4-6 clearly shows that System A can successfully handle less than 1 percent analog traffic.

Table 4-6. Effect of Analog Requirements on System A

% Analog Messages	Number of Users in "Clear" Channel Queue (G-A Direction)
20	428
10	406
2	221
1	110
0.2	0

The next step in the design of System A is to determine the size of the poll slots. As discussed, we have a choice between delay to initiate message delivery and delay to deliver a message after initiation has occurred. Again, a number of approaches were examined. The simulation was run with various slot times to ascertain the minimum total delay time. Figure 4-7 is a plot of queue size versus total delay time. The queue consists of users waiting for their slots to appear initially and/or users waiting for enough frames to complete a message transmission. As can be seen, there is a clear minimum to the curves of Figure 4-7. It turns out that the optimum slot size corresponds to the median service time of the digital requirements, discussed in Appendix D of the Interim Report. That is, exactly half the messages can be delivered in one frame and half will take at least two frame durations. Such a result is fundamental in that the median of any probability distribution is independent of the shape of that distribution. Therefore, no matter what the user requirement service distribution may be, the slot size of a rigid poll should be large enough to accommodate the median message size.

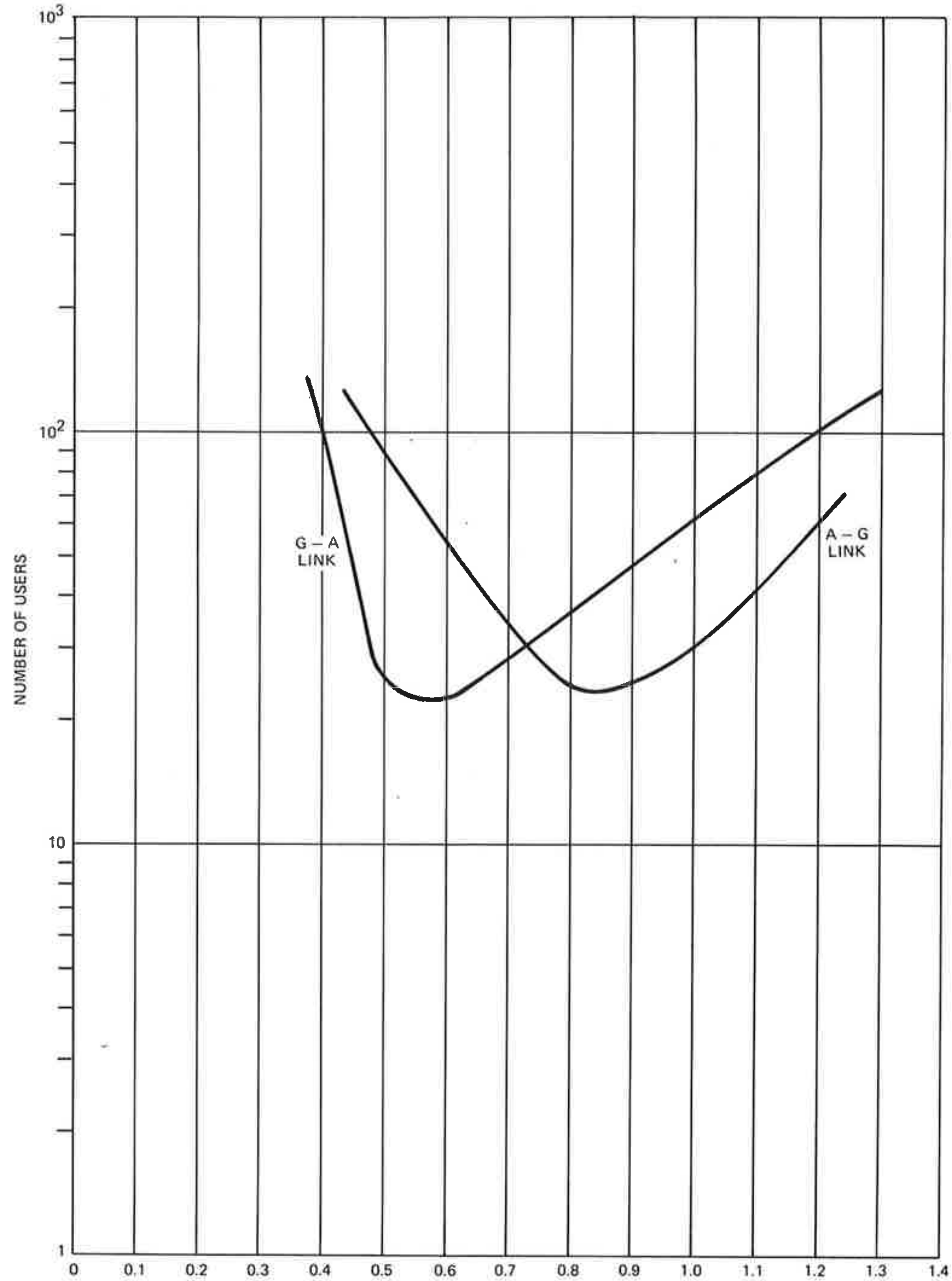

Figure 4-7. Poll Slot Message Size Versus Population for System A With Digital Requirements

The slot sizes of the rigid poll turned out to be 680 milliseconds. Thus, all slots of the rigid poll are 680 milliseconds, as are the long slots of the two-step poll. Each of the three technique versions of System A were simulated for both ground-to-air and air-to-ground directions, and the results are summarized in Table 4-7. Specifically, the median and 0.9 probabilities of total user delay are shown. Note that the availability of two air-to-ground channels for each ground-to-air channel improves the performance of the rigid technique in the air-to-ground direction relative to the ground-to-air direction, but is of no consequence in the other two techniques. This is because of their design, as has been discussed in Section 3. Note also that while there is some system performance improvement by using the two-step rather than the rigid technique, there is little improvement by going to the variable technique. In fact, taking into consideration the potential problems associated with timing and error control of variable block sizes, it appears that the two-step poll technique is best suited for aeronautical mobile application.

Table 4-7. System A Performance Results

Poll Type	Delay (Seconds)				Poll Frame Size (Seconds)
	Median		0.90 Point		
	G-A	A-G	G-A	A-G	
Rigid	114	58	210	160	228
"Two-Step"	81	81	85	85	81 (Median)
Variable	75	75	---	---	150 (Median)

The advantages of both the two-step and variable techniques over the rigid techniques are based upon lower user usage of a given poll frame. For a set of user requirements that is different than used in this study (i.e., high user usage) there may be little advantage to implementing an adaptive poll. Table 4-8 shows the poll population probabilities for the rigid poll as determined by simulation. Here we see that less than 40 percent of the rigid poll slots actually carry messages at any given time.

Table 4-8 . System A Poll Population Probabilities

Probability that User Population/ Frame is as Shown or Less	G-A Direction	% of Total Population	A-G Direction	% of Total Population
0.2	110	0.238	115	0.248
0.3	121	0.262	125	0.270
0.5	146	0.315	148	0.320
0.75	154	0.333	160	0.346
0.9	160	0.346	175	0.379
1.0	174	0.376	184	0.398

Thus, some form of poll adaptation is clearly in order to improve System A performance.

From the results of the performance of System A with polling, it appears that the total delay time associated with a user obtaining any sort of service from AEROSAT may be unacceptable.* Three communication channels, no matter how well organized and controlled, are clearly insufficient for this application.

4.3.2 System B Summary

The results from the simulations of System B indicate the significant differences in performance to be obtained from a given system configuration using different quantities of user requirements and different types of access control doctrines. Specifically, System B was simulated utilizing both the analog and digital requirements, the semipermanent aircraft channel assignment doctrine on the ground-to-air links, and the random access supervisory channel with demand access channel assignment doctrine on the air-to-ground links.

The design of the random access channel for the air-to-ground direction is dependent upon the user request arrival rate, the length of the request burst (τ seconds), and the potential update rate (T seconds) of the request burst. The details of random

* Using the requirements and traffic model described in the Interim Report.

access control signalling are discussed in detail in Appendix B of the Interim Report. In brief, each aircraft wishing to use the communication system sends a request burst of τ seconds every T seconds over his designated orderwire until an acknowledgment is received from the controller via his semipermanent ground-to-air channel. Bearing in mind that mutual interference among bursts is the main reason for burst repetition (i.e., non-acknowledgment), and given a fixed value of τ, a value of T can be selected that minimizes the probability of mutual interference. Should this probability be unacceptably high, more than one orderwire channel can be utilized, with proportionately fewer aircraft assigned to each channel. With regard to the selected value of T per channel, it can be seen that for $T \rightarrow 0$ mutual interference will always occur, whereas for $T \rightarrow \infty$ an individual request will never get acknowledged if at least one mutual interference does occur.

The results of the simulation design of the System B air-to-ground random access supervisory channel are shown in Figure 4-8, which shows the quantity of users in the access control subsystem as a function of T for one, two, and four channels. For one or two channels the best value of T results in an unacceptable number of unacknowledged users, whereas four channels allow for a selection of T whereby only three users are in each channel at a given time for T = 5 seconds. Since it is likely that all or some of these users are transmitting their initial requests, four random access channels on the air-to-ground System B link represents an acceptable design for $\tau = 187$ milliseconds.

The results of the System B simulations are given in Table 4-9. The criterion of performance is total user delay in seconds. As before, we present the median and 0.9 probability delays. Two observations are apparent from these results:

- The service times associated with the two types of requirements result in dramatically different performances of the B System. It will be seen that this observation is also valid for Systems C, B, and B-1, which merely verifies the sensitivity of the performance of a given system to user requirements.

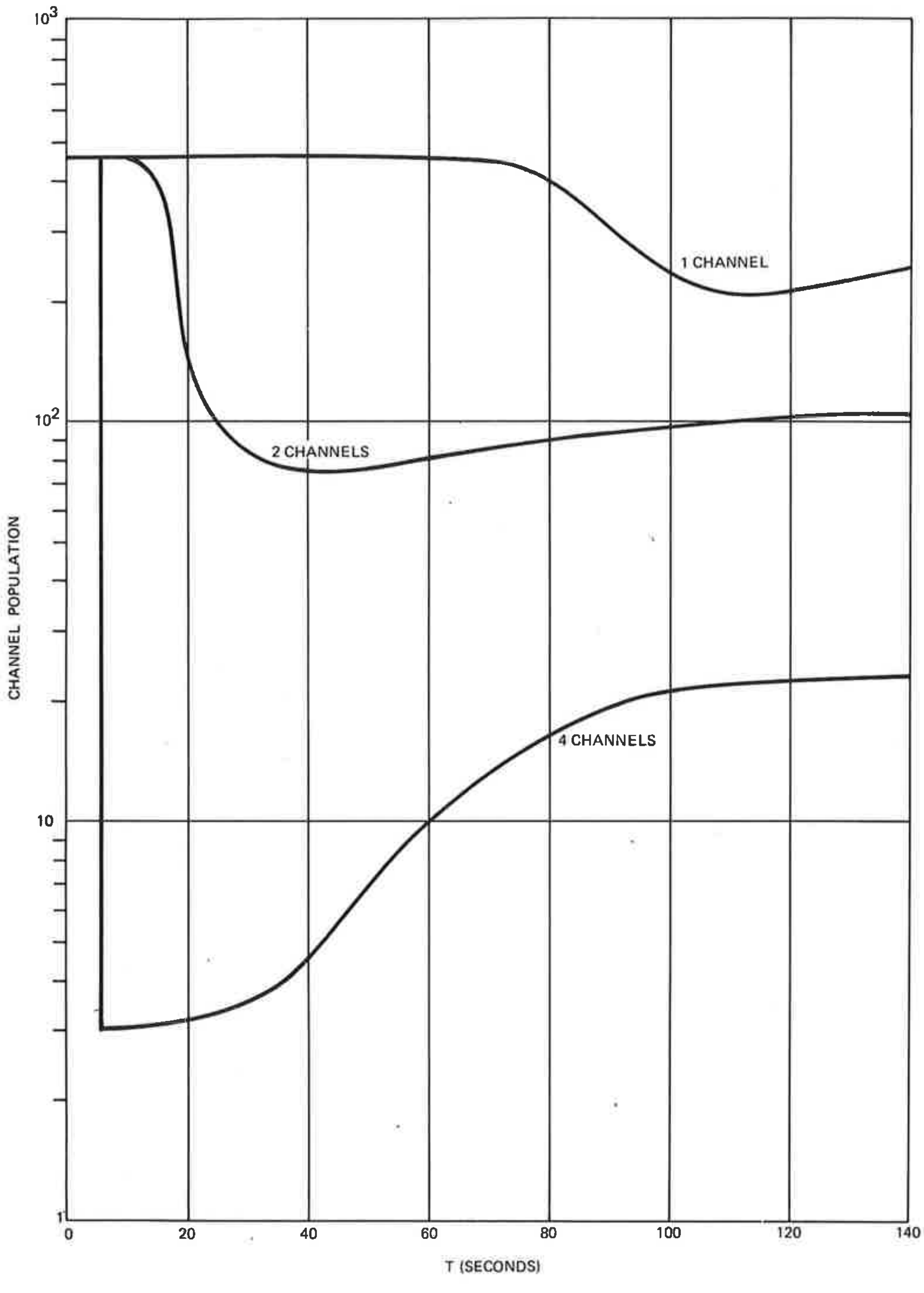

Figure 4-8. Random Access Control Channel Design Curves

Table 4-9 . System B Performance Results

Requirements	Delay (Seconds)			
	Median		90% Point	
	G-A	A-G	G-A	A-G
Analog	325	15	455	18
Digital	< 1	< 1	< 1	6

- The management of the resources of System B is far better accomplished by an efficient supervisory channel and communication demand access doctrine than a more restricted semipermanent assignment doctrine.

Note that the air-to-ground link of System B with analog requirements has acceptable delays, whereas the ground-to-air link does not. Part of this difference can be attributed to the larger number of air-to-ground communication channels, but most is the result of a superior management doctrine, i.e., the random access calling channels used.

4.3.3 System C Summary

The performance results obtained from the simulations of System C indicate the improved capability that can be attained by taking a given satellite resource and using it in a more efficient manner. As already discussed, System C attains a total of 11 communication channels in the ground-to-air direction and 22 channels in the air-to-ground direction by the use of TDMA beam-hopping techniques. Because this channel capacity is considerably greater than that of System B, it was felt that acceptable levels of performance might be attained even with relatively inefficient access control doctrines. Consequently, random seizure with observation was utilized as the doctrine for ground-to-air channels.

The results of the System C simulations are shown in Table 4-10 in the same format as has been used previously. The delay indicated is for the total delay incurred

Table 4-10. System C Performance Results

Requirements	Delay (Seconds)			
	Median		90% Point	
	G-A	A-G	G-A	A-G
Analog	79	10	170	19
Digital	< 1	2	5	8

for a user to access the system and utilize its communication facilities. Again we see a great difference in the performance of this system when we compare the analog and digital requirements in the ground-to-air direction. That is, even with 11 flexible communication channels available to the system, delay performance is unacceptable for the analog requirements. However, the 22 channels on the air-to-ground link appear to be adequate to yield acceptable delay performance. It may well be that the ground-to-air direction of System C can yield acceptable performance with analog requirements if the access control doctrine is more efficient in traffic management than the random seizure with observation doctrine. We shall see one such result for System C-1. Regardless, it can be seen that the delay performance results for System C, with the digital requirements, is excellent and provides acceptable performance standards for oceanic aeronautical communications.

In order to ascertain the minimum number of communication channels required for acceptable delay performance of the C System, simulations were conducted for System C with variable numbers of communication channels. The results are shown in Figure 4-9 for analog requirements in the ground-to-air direction. Plotted is total delay in seconds versus number of available communication channels for the median and 90 percent probabilities. Note that the portions of the curves greater than 11 channels cannot be designed in the System C configuration with the assumed Delta 2914 launch vehicle. An appropriate System C configuration for up to 20 channels can be attained by a 13- or 19-spot beam satellite antenna scheme. In general, the number of available communication channels is a function the number of spot beams,

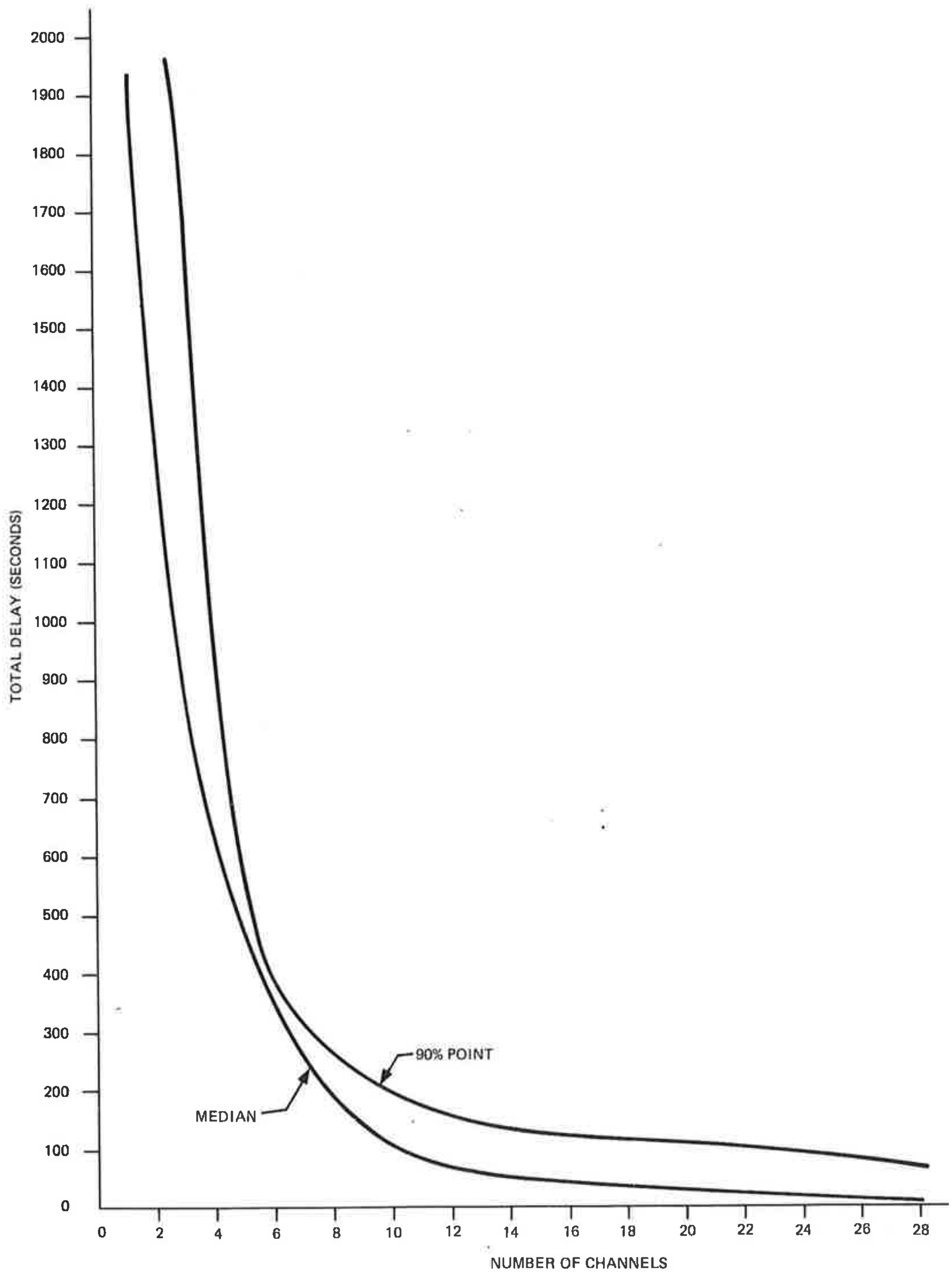

Figure 4-9. System C Ground-to-Air Access Delay Versus Capacity Analog Requirements

as has been previously shown.* Returning to Figure 4-9, we see that approximately 30 channels are required in order to attain total delays that approach the analog service delays. This requires a 37-beam configuration. Even with a 16-beam configuration, the median total delay is excessive. Of course, an alternative to increasing spot beams for System C is to increase prime satellite power.

4.3.4 System B-1 Summary

The large delays associated with the analog requirements in the ground-to-air direction of System B suggest that a more efficient access control doctrine than semipermanent assignment may lead to improved delay performance. Furthermore, since much of the traffic is in the North Atlantic beam, increased numbers of available communication channels over the three used in System B may also improve delay performance. Consequently, System B-1 was configured with four channels available in the North Atlantic beam and one in the Caribbean beam. A strict poll without message information was selected as the access control doctrine. As before, there are two air-to-ground communications channels available for each ground-to-air channel. Of course, there is only one air-to-ground poll via the global beam.

The results of the System B-1 simulations are shown in Table 4-11. These results indicate three important facts:

Table 4-11. System B-1 Performance Results

Requirements	Delay (Seconds)			
	Median		90% Point	
	G-A	A-G	G-A	A-G
Analog	275	64	442	105
Digital	46	46	82	82

*Final Report on Contract NAS5-21590, "Adaptive Multibeam Concepts for Traffic Management Satellite Systems," Computer Sciences Corporation, March 1973.

- The analog requirements performance results are unacceptable and inferior to those obtained via the digital requirements.
- There is considerable performance improvement of System B-1 analog requirements performance in the ground-to-air direction as compared to System B.
- The digital results are inferior to those obtained for System B.

Although System B-1 has better delay performance results than does System B for the ground-to-air direction with analog requirements, it appears that the use of a nonadaptive poll without information deteriorates the performance of System B-1 relative to System B for the air-to-ground analog and ground-to-air, air-to-ground digital requirements. The poll frame size is at an absolute minimum and nothing can be done except to provide multiple polls or to not address each user on every frame. The latter does not represent intelligent operational practice, whereas the former concept requires a scarce resource to be shifted from communication capabilities to control doctrine. A two-poll digital System B-1 will have only two available communication channels, with median poll delays still on the order of 20 to 25 seconds.

4.3.5 System C-1 Summary

Given the encouraging delay performance results of System C, particularly with the digital requirements, it appeared possible that a system with fewer available communication channels than System C, but with a more organized access control doctrine, would yield acceptable delay performance results. Consequently, System C-1, with eight universally available communication channels and a poll without information access control doctrine, was devised and tested. System C-1 is similar to System B-1, with the exception that C-1 has more communication capability.

The results of the System C-1 simulations are shown in Table 4-12. These results show the same type of performance results that have been obtained from the other systems, namely:

Table 4-12. System C-1 Performance Results

Requirements	Delay (Seconds)			
	Median		90% Point	
	G-A	A-G	G-A	A-G
Analog	210	50	260	87
Digital	46	46	82	82

- The analog results are unacceptable and provide much more total delay in the ground-to-air direction than do the results obtained from the digital requirements.
- The poll without information access control doctrine ultimately limits the delay performance capability of System C-1 at an unacceptable value of delay. In fact, note that the digital requirements delay results of System C-1 are no better than those obtained from System B-1 even though the communication capability of System C-1 is far greater than that of System B-1.

This last point can be best amplified by revealing that the satellite population analyses of both Systems B-1 and C-1 for digital requirements in the ground-to-air direction show that no more than three communication channels are ever simultaneously in use (see page 7-57 of the Interim Report). Furthermore, the probability that more than two channels are simultaneously in use is only 0.02. Thus, of the eight available communication channels, five to six of them are not needed for the digital requirements. By comparison, the ground-to-air analog requirements are such that all eight communication channels are almost always required (i.e., there is always a nonzero queue in the system).

4.3.6 System Comparisons

The summaries of results presented above were intended to facilitate intra-system performance comparisons. This paragraph summarizes the intersystem performance comparison results based upon the access control/system configuration simulations.

The results of all the simulations of the basic systems described in Section 3 are presented in Table 4-13. Total delay in seconds is presented as a function of communication direction, type of requirements, and type of system for two statistical points. The variations of the basic systems, such as the adaptive poll of System A, have little bearing on the intersystem comparisons and will be included in the discussion only as required.

A study of the results obtained using the assumed analog requirements reveals the following observations:

1. All delay performance results in the ground-to-air direction represent operationally unacceptable delay times to access and use the facilities of the system. This even holds for System C.

2. Systems B and C have marginally acceptable delay times in the air-to-ground direction, whereas Systems B-1 and C-1 have unacceptable delay times.

3. As the satellite capacity increases from three channels in the North Atlantic beam of System B, to four channels in System B-1, to eight universally available channels in System C-1, to 11 in System C, we see the almost fourfold increase in system delay performance in the ground-to-air direction. Considering the fact that the direction from System B → B-1 → C-1 → C is inversely proportional to access control doctrine efficiency (i.e., semipermanent assignment → poll → poll → random seizure), the improved performance trend indicates that the assumed analog requirements exceed the communication capabilities of the Delta 2414-launched AEROSAT.

4. The excessive delay times of Systems B-1 and C-1 in the air-to-ground direction are primarily associated with the poll. The poll frame length

Table 4-13. Access Control Delay Performance Comparisons

		Total Delay (Seconds)			
		Median		90% Point	
	System	G-A	A-G	G-A	A-G
Analog Requirements					
	A	---	--	---	---
	B	325	10	455	18
	C	79	15	170	19
	B-1	275	64	442	105
	C-1	210	50	260	87
Digital Requirements					
	A	114	58	210	106
	B	<1	<1	<1	6
	C	<1	2	5	8
	B-1	46	46	82	82
	C-1	46	46	82	82

is 91 seconds, yielding a median delay of 45.5 seconds. Add to this the median service delay of about 1 second in the air-to-ground direction, and it can be seen that System C-1 has almost no queueing delay (i.e., waiting for the next available satellite channel), whereas only about one third of the System B-1 total delay can be attributed to the queueing delay. From page 7-52 of the Interim Report, we see that the full 16-channel air-to-ground capacity of the C-1 system configuration was required less than 1 percent of the time, with the median carried traffic load being about seven channels. From page 7-43 of the Interim Report, we see that the shared 10-channel air-to-ground capacity of the B-1 system configuration was required about 45 percent of the time, with the median load being about eight channels.

5. The channel capacities of Systems B, C, B-1, and C-1 appear to be adequate enough to handle the assumed air-to-ground analog requirements, although the access control doctrine of Systems B-1 and C-1 does not yield acceptable performance with respect to delay. However, both the random access (System B) and random seizure (System C) doctrines give acceptable results. The random access doctrine gives better absolute results than does the random seizure doctrine, even though the latter is on a system that has considerably greater capacity than is available for the system of the former.

A study of the results obtained using the assumed digital requirements reveals the following observations:

1. System A yields the longest total delay results. From Table 4-7 we see that the two-step and fully variable polls improve the delay results markedly. It appears, however, that the low capacity of System A precludes it from being seriously considered for Aerosat.

2. Systems B and C show performance delay times that indicate that little or no delay is incurred in accessing the system or waiting for an available satellite channel. Almost all the delay is associated with the service distributions. In fact, from the population analysis results, neither system ever requires more than three satellite channels simultaneously. Thus, System B, and particularly System C, have excess satellite capacity to meet the assumed requirements.

3. Systems B-1 and C-1 also have excess satellite channel capacity since System B-1 has more than three available ground-to-air channels in the North Atlantic beam and System C-1 has eight universally available ground-to-air satellite channels. From Table 4-13 we see that the median total delay of both systems is 46 seconds. About 0.5 second of this results from the digital requirements service distributions, and almost all the remainder occurs as a result of the delay incurred in accessing the system via the polls.

4. The results of the digital requirements simulations indicate that, with the possible exception of the ground-to-air direction of System A, all other systems tested (i.e., B, C, B-1, and C-1) have adequate or excess capacity to handle the offered traffic load.

5. The results of the digital requirements simulations further indicate that the random access, random seizure access, and semipermanent assignment access control doctrines provide equally acceptable system delay performance, whereas polling with, or without, message information does not provide acceptable system delay performance.

Of all the access control subsystems conceptualized and of those actually tested via computer simulations, the random access, random seizure, and semipermanent assignment doctrines are best suited for aeronautical mobile application. The random seizure doctrine is well suited to large capacity system configurations, such as System C; but may not work well for smaller capacity system configurations, such as Systems B, B-1, and C-1; due to the possibility of mutual interference on the communication channels. A properly designed random access control subsystem will slightly out-perform a random seizure access control subsystem, particularly with a small communication channel capacity system.

Due to the total available knowledge of the ground controller, neither random seizure nor random access apply to the ground-to-air direction. Semipermanent assignment doctrines are, therefore, best suited to the ground-to-air direction of the system. For Systems B-1, C-1, and C, where TDMA is feasible, semipermanent assignment doctrines can easily be extended to an all-channel scanning doctrine. We have not tested the improvement in delay performance when using all channel scanning as compared to semipermanent assignment, but it can be argued that the difference is not great, with the former yielding superior results. For Systems A and B and possibly B-1, where FDMA is required, semipermanent doctrines can only be extended to all channel scanning doctrines with an attendant increase in avionics equipment cost and complexity. Therefore, it appears that semipermanent assignment doctrines are best suited for the ground-to-air directions of the FDMA systems. (This assumes that the operational problem discussed in Paragraph A.1.3.2 of Appendix A is ignored.)

Since the global channel of Systems B-1 and C-1 are not needed for air-to-ground access control purposes with a random access channel(s) serving this function, and may only be used "as needed" for ground-to-air access control, their main purpose can be relegated to the surveillance functions.

In summary, the five basic system configurations tested in this study are best suited for aeronautical mobile applications with revised access doctrines as shown in Table 4-14. The systems are listed in ascending order of delay performance capabilities.

Table 4-14. Revised System Access Control Doctrines

System	Multiple Access	Access Control Doctrine G-A	Access Control Doctrine A-G	Remarks
A	FDMA	Semi-Perm Assignment	Random Access	
B	FDMA	Semi-Perm Assignment	Random Access	
B-1	FDMA	Semi-Perm Assignment	Random Access	EC Poll for Surveillance & G-A Access Control
B-1	TDMA	All-Channel Monitoring	Random Access	EC Poll for Surveillance
C-1	TDMA	All-Channel Monitoring	Random Access	EC Poll for Surveillance
C	TDMA	All-Channel Monitoring	Random Monitoring	

SECTION 5 - CONCLUSIONS AND RECOMMENDATIONS

The conclusions and recommendations presented in this section are based on results described in Section 4 and in various sections of the Interim Report. The conclusions are grouped into three study areas:

- Signal design
- Avionics
- Access control/systems.

5.1 CONCLUSIONS

5.1.1 Signal Design

1. FSK error rate performance estimates in the AEROSAT environment can be predicted from theory (i.e., see Appendix I of the Interim Report).

2. DEPSK error rate performance estimates in the AEROSAT environment cannot be accurately predicted from theory. Event-by-event computer simulation or empirical methods must be used.

3. For practical users of the AEROSAT System, DEPSK performs better than does FSK. In the normal operating range of the system, where one wishes to achieve a $P_e = 10^{-5}$, DEPSK is 3 dB better than FSK in terms of $\Delta(E_b/N_o)$.

4. The link C/N_o used to size the system capacity was 43 dB-Hz with a 5-dB-Hz margin. Assuming that 3 dB is reserved for multipath, the "free space" C/N_o per link is 46 dB-Hz. This results in an E_b/N_o of 15.2 dB at a data rate of 1200 bps. From the simulation results, we conclude that an error probability of 10^{-5} can be obtained at this C/N_o if the signal-to-multipath ratio is at least 12 dB at the receiver input. The necessary multipath discrimination must be achieved as a combination of utilizing the natural properties of the scatter process itself and the aircraft antenna system gain patterns.

5. DEPSK is a better choice of modulation than PSK. The latter enjoys a better error rate, but is subject to the so-called cycle slip phenomenon. The former is protected against such an effect by the differential encoding.

6. The coherent receiver associated with DEPSK modulation is capable of successfully tracking multipath perturbed signals in the AEROSAT environment with $B_L \leq R_s/r$, without significant degradation in P_e. A $B_L = R_S/4$ for values of R_S associated with AEROSAT applications is adequate to correct Doppler offset and acceleration tracking errors within a small number of overhead bits (i.e., less than ten for TDMA applications).

7. Carrier acquisition in a TDMA AEROSAT environment can be obtained for DEPSK modulation via a modified Costas loop, with $B_L = R_S/4$, in less than ten bits. The FDMA AEROSAT configurations obtain carrier acquisition for all users via continuously operating poll and/or semipermanent assignment channels.

8. A modified form of stop-and-wait or polling ARQ is applicable as an efficient method of error control for the aircraft-to-satellite AEROSAT environment. The efficiency of this method approaches the overhead efficiency of the burst itself for moderate error rates, and the delay is held to that incurred waiting for the next available communication channel (i.e., no propagation delay).

9. Polling channels and associated avionics should be designed using TDMA on a poll-block basis. That is, every ASET in the system must be capable of successively polling all aircraft within its jurisdiction before relinquishing the channel to another ASET. This provides maximum satellite power efficiency and makes the avionics independent of the ground configuration.

5.1.2 Avionics

1. The two-aircraft transmitter configuration is recommended for simultaneous two-channel transmission. A single, quasilinear transmitter will not be cost effective with respect to power, cooling, and redundancy.

2. A distributed equipment form factor is selected, with the RF preamplification at the antenna and the transmitters and balance of the avionics located in the equipment bay.

3. For common transmitter and receiver port sharing, the use of a diplexer-filter is the best choice to permit simultaneous two-way operation.

4. Aircraft transmission Doppler correction can be achieved by having the inverted input Doppler frequency signal drive the equipment monitor via the output of the detector loop VCO. This is necessary to permit rapid acquisition in the ASET of the random access and poll response transmissions.

5. The recommended matchups of the candidate system configurations and the corresponding equipment configurations are as follows:*

System	Equipment**
A	2 or 2A
B	1
C	5
B-1	2 or 4
C-1	7 or 9

6. The avionics study showed that avionics cost can be a major consideration in the selection of access control methods. The base cost of the avionics package (transmitter, receiver, etc.) is such that the worst-case access control methods can add up to 50 percent to the base cost. For the more reasonable methods, between 10 and 20 percent is the probable cost penalty.

7. The avionics study also showed that, to a large extent, pilot workload is not a significant factor in access control method selection. All can be automated at reasonable cost to reduce the workload to insignificant proportions.

8. The use of a poll or similar continuous signal in the avionics can be a valuable aid to system self-checking and fault isolation.

*Analysis has not been conducted for the additional modified system configurations.
**See Appendix A for discussion.

5.1.3 Access Control/Systems

5.1.3.1 Access Control

1. The polling access doctrines investigated incurred long access delays for both analog and digital air-to-ground traffic.

2. The use of random access calling channels for air-originated air-to-ground traffic results in high reliability and in insignificantly low access times if signaling is properly optimized.

3. The semipermanent assignment and channel scanning methods for use on ground-to-air channels are equivalent to single-server and multiserver queues, respectively, with the ability to dynamically aportion the user population. Thus, in the long term steady state, their performances are equal. The additional overhead involved in reassigning users to channels in the semipermanent assignment is not expected to be significant.

4. The seizure with observation doctrine simulated in System C apparently does result in a significant number of simultaneous seizures by aircraft desiring to gain access for the requirements assumed.

5. Semipermanent assignment, when used with the simplest avionics package, locks out the aircraft communicating on the channel under certain circumstances and requires all aircraft assigned to the channel to reacquire after a narrow band frequency modulation voice transaction.

6. The use of a two-step poll significantly lowers the access time for air-to-ground traffic when used with System A. This procedure provides a better match of slot length to message length distribution (assumed), and performs almost as well as a fully variable slot.

5.1.3.2 Systems Conclusions

Access control performance and estimated relative avionics cost for each system originally synthesized are summarized in Table 5-1.

Table 5-1. Access Control Delay Performance Comparisons

		Total Delay (Seconds)				Relative Cost of Avionics*
		Median		90% Point		
	System	G-A	A-G	G-A	A-G	
Analog Requirements						
	A	---	--	---	---	1.25-1.27
	B	325	10	455	18	0.92
	C	79	15	170	19	1.08
	B-1	275	64	442	105	1.19-1.35
	C-1	210	50	260	87	1.42-1.49
Digital Requirements						
	A	114	58	210	106	1.25-1.27
	B	<1	<1	<1	6	0.92
	C	<1	2	5	8	1.08
	B-1	46	46	82	82	1.19-1.35
	C-1	46	46	82	82	1.42-1.49

*See Table 4-5 for definition of reference cost.

5.1.3.2.1 System A

System A does not present any major technical problems in access control. However, because of the assumed launch vehicle constraint, the capacity is low and it is felt that the access delays incurred in this system (for the requirements used) would seriously jeopardize the eventual operational acceptability of the system. Even a fully variable slot length results in a median access delay of 75 seconds. A two-step poll, which is much simpler to implement and is recommended, increases the access delay only slightly.

5.1.3.2.2 System B

System B requires a minimum and therefore the least expensive avionics package. A single channel receiver and a switched (not diplexed) antenna are sufficient. Because the ground-to-air channels themselves are used for management purposes, the analog requirements result in extremely long delays in delivering ground-to-air messages to the aircraft users. The use of four random access supervisory channels in the air-to-ground direction results in significantly lower, and probably acceptable, access delays for air-to-ground analog messages. Digital traffic can be adequately handled in both directions with this management doctrine and the resources available from System B.

System B also suffers from a number of operational disadvantages which further discourage its adoption:

1. Independent surveillance waveforms must be provided on all channels, thereby increasing ground station and satellite costs (since each waveform must be generated, relayed in the air-go-ground direction, and phase compared at the ground facility).

2. Since a number of aircraft are monitoring each channel for both access information and messages during voice transmissions, no other aircraft can receive any but emergency messages.

3. After each voice transaction on a channel (assuming NBFM) every aircraft assigned must reacquire phase for address recognition purposes.

4. In the lower capacity beams, the failure of a satellite channel amplifier may cause severe access delays (or no capacity at all) in that beam. The use of a global coverage pattern with some minimum capacity provides backup in such cases.

5.1.3.2.3 System C

Even though System C has a large capacity, its analog access performance in the ground-to-air direction is poor. This can only be attributed to the high message arrival rate dictated by the requirements used and the seizure access doctrine used in this system. As in System B, the absence of a global beam on the satellite compromises its reliability if any normal beam fails. In the case of System C, the beam switching mechanism on the satellite might be most susceptable to failure.*

5.1.3.2.4 System B-1

Since in System B-1 both the ground-to-air and air-to-ground channels are controlled by using the poll, the access delay is dominated by the poll interval. For the requirements assumed, the analog delays are unacceptable in both the ground-to-air and air-to-ground directions. The overall performance of this system would be improved, and the system would be preferred over all others studied, if the access control performance could be improved.

5.1.3.2.5 System C-1

Similar conclusions can be drawn for System C-1 as for B-1 with the additional observation that advances in satellite and overall system technology must be made before this type of system can be actively pursued and fully evaluated operationally. *

5.1.3.3 Preferred Method

When all the results of this study are considered, assuming that independent surveillance is required, it appears that the most desirable system uses system configuration B-1 (i. e., multiple beams for most communications and a global beam) with the access control procedure described below. Each of the communication beams have from one to four channels, depending on the geography they cover, and the global

* Aerosat is an experimental system but it is felt that most experimentation will be concerned with the technical aspects of communication and the operational aspects of system control and usage rather than the development of satellite technology per se.

beam provides a supervisory channel which all aircraft monitor. This channel also provides coverage to areas not covered by the multiple beams (if there are any) and provides backup communication coverage to areas if satellite failures occur. The narrow multiple beams are used by the aircraft for all air-to-ground transmissions except for the random access calling channel(s) described below. The satellite equipment serving this channel(s) is made redundant to ensure extremely high reliability.

The access control procedure uses:

- Semipermanent assignment of ground-to-air communication channels
- Random access calling channels to signal for access by aircraft-originated traffic
- A global broadcast supervisory channel also used as a reference to aid acquisition of assigned channels and for Doppler correction of all aircraft transmissions.

In most instances, the channel assignment to each aircraft is made well in advance of the need, either before takeoff or via other than satellite means (for example, VHF). If not, the supervisory channel can be used.

To obtain access to a channel (one way or two way) an aircraft proceeds as follows. One of the random access calling channels (any one) is entered with a short pulsed transmission (containing identification and channel type needed), repeated every few seconds until acknowledged as follows:

1. If a two-way channel is requested:
   - The aircraft is called over its assigned channel (if available or if the wait is not too long), or
   - It is called on the global supervisory channel and told either the waiting time or to tune to another channel (change in assignment) over which it is called after acknowledging change over random access channel
   - ACK/NAK for digital transmission is received over the paired communication channel for both directions.

2. If a one-way air-to-ground channel is requested:

- The aircraft is called over the global supervisory channel and told which one-way air-to-ground channel to use
- ACK/NAK comes over the global supervisory channel.

For the ground system, to access one particular aircraft:

- The aircraft is called on its assigned channel, or
- It is called on the global supervisory channel and an assignment change is made.

The global supervisory channel is also used for:

- Requesting surveillance returns from aircraft
- Synchronizing periodic data reporting transmissions (including position reports and surveillance returns)
- Emergency calling when assigned channel cannot be used or preempted
- General broadcast messages through the use of appropriate message labels in the addressed transmission.

Other rules are:

- Aircraft in flight enter the system using the random access channel, after acquiring the global supervisory channel, and are acknowledged and assigned their channel and satellite over the supervisory channel.
- The supervisory channel being monitored is used as an indication of satellite health. If it fails, the crew assumes the satellite has failed and manually switches to the backup satellite.
- The satellite supervisory channel to be monitored is assigned along with channel assignment. In the case of pop-up or in-flight system entry, the crew randomly selects a satellite and is told to change if necessary.

- If only the supervisory channel of a satellite fails, the satellite is operated in a backup mode with all supervisory channel functions picked up on one channel in each beam. This channel is cleared and operation continues as before.
- If all random access channels of a satellite fail (which is highly unlikely because the simulations indicated that two per satellite are required), all aircraft will use the second satellite, thereby slightly increasing its random access load and access delay characteristics.

Almost all receiver functions are accomplished automatically either in response to signals/commands on the global supervisory channel or its carrier, signals/commands generated internally to the receiver, or those received over the assigned communications channel. The aircraft crew initiates only communication need (if not an automatic report), desire to enter the system, the message itself (if not an automatic report), and the global supervisory channel to be monitored (which depends on satellite assignment).

5.2 RECOMMENDATIONS

The following recommendations are made as a result of this study:

1. System B-1, as modified, should be seriously considered as a prime candidate for the AEROSAT System.
2. The above system, as well as any others proposed, should be subjected to more rigorous simulation activity to further explore its communication and access control performance and the detailed reasons for its performance. The simulation programs used in the performance of this contract offer an excellent base for such activity, but should be improved by using updated communication requirements and oceanic traffic data.
3. All systems, as modified, should be further evaluated using simulation (with updated data) in order to further assess the sensitivity of their performance to input requirements and to realistic evolutionary mixes of analog voice and data.

4. The design of signalling for random access calling channels should be studied further. In particular, the impact on ASET design, complexity, and cost must be determined.

5. More sophisticated signalling and formatting for the polling channels should be explored in an attempt to reduce the polling interval if these approaches are contemplated.

6. A complete design study for the ASCC/ASET complex and the equivalent ground access control problem should be undertaken. The current simulations can be expanded to include this capability.

7. The impact of the system modifications recommended on the avionics packages should be assessed.

APPENDIX A - AVIONICS CONSIDERATIONS

A.1 GENERAL

The general approach to determining the overall avionics equipment profile for a future AEROSAT system considers two major requirements areas. The first is equipment configuration/performance requirements associated with the system configuration, its operating requirements (e.g., access control, operating regimes, etc.) and the intrasystem interface parameters. The second requirements area is user-oriented considerations, which include the form factors, environmental considerations, operator interface and compatibility with existing or planned aircraft equipments which will directly or indirectly interface with the AEROSAT Avionics equipment.

The critical interfaces within the system are shown in Figure A-1. For the AEROSAT Avionics equipment (referring to Figure A-1) the major interface areas are:

1. Satellite-to-aircraft (forward and return) links
2. Ground terminal control function to aircraft communications subsystem interface (via the satellite links)
3. User input/output (I/O) device end-to-end interface, specifically the intermediate requirements imposed to support end-to-end traffic
4. Onboard interface requirements between the AEROSAT Avionics equipment and the aircraft I/O devices.

These interfaces are determined by individual or combined requirements relating to system configuration, service mix and specific user needs.

For the purposes of this study, a common functional breakdown of the equipment was developed, as indicated in Figure A-2. This breakdown shows the basic functions which are applicable to all systems and serves as a reference point for assessing the impact of system, operational and user imposed requirements on the equipment. Two assumptions are made:

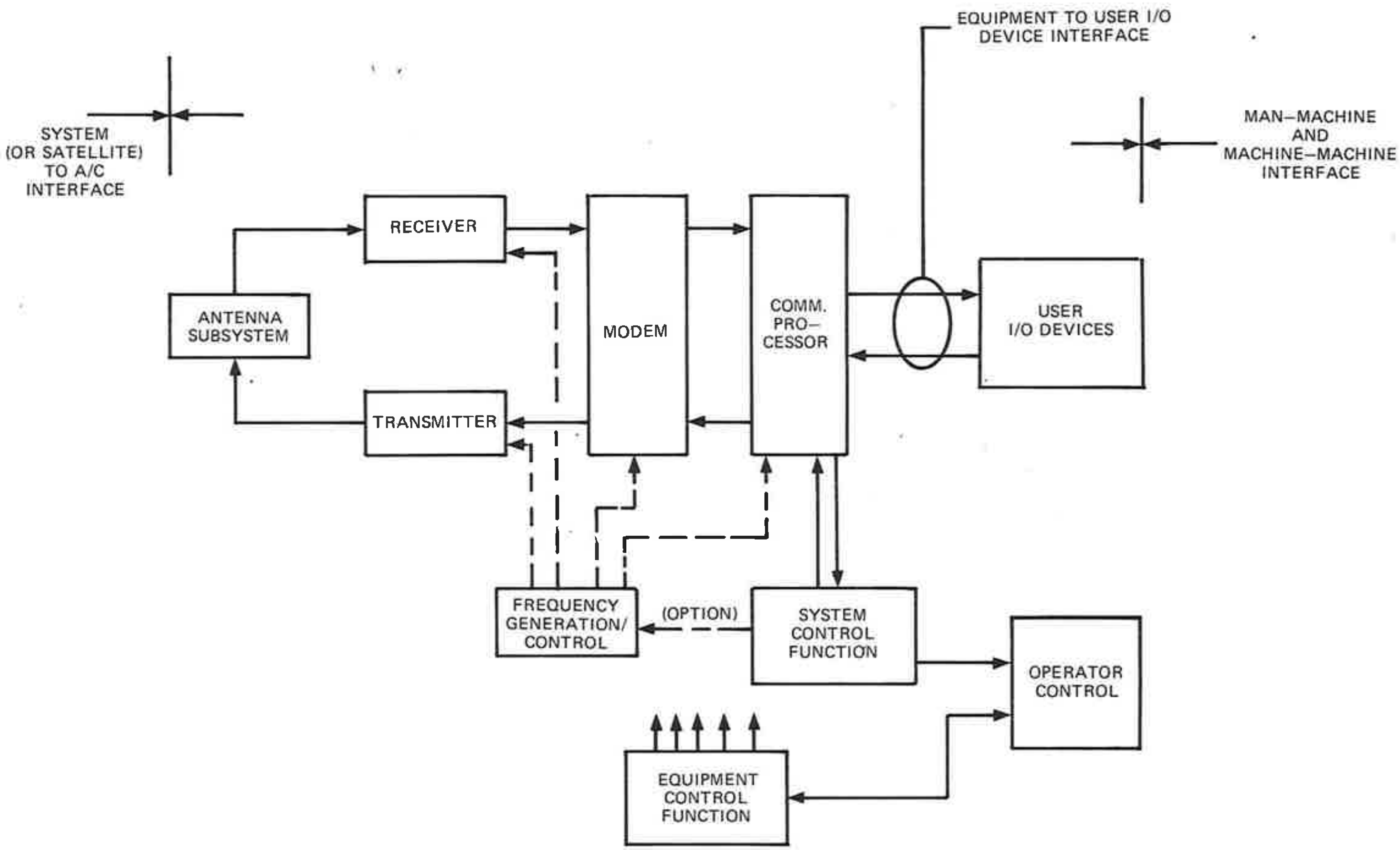

Figure A-1. Basic Functions for all Systems

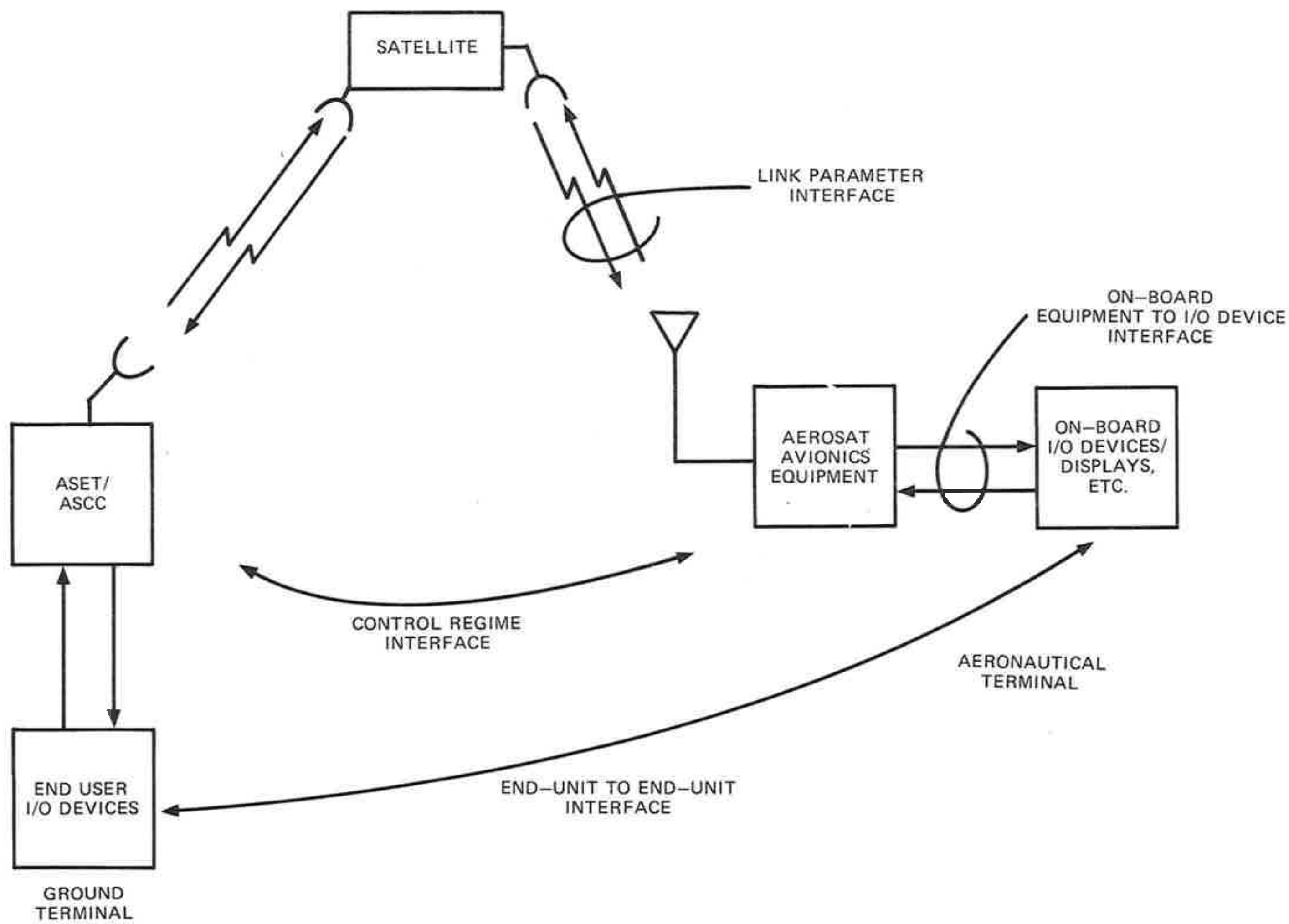

Figure A-2. AEROSAT Avionics Equipment Interface

1. The antenna subsystem employed meets the Reference Avionics Interface (RAI) requirements in providing a minimum gain over the coverage volume (measured at the antenna radiator) of +4 dB. Any functions associated with the control, steering or switching of the radiator element are not incorporated as a part of the AEROSAT Avionics equipment except for a receive-transmit diplexer, or an antenna changeover relay, which provides the "antenna" part of the AEROSAT Avionics.

2. The output end of the equipment is at the interface between the onboard I/O device(s) and the communications processor. The equipment, in itself, does not contain formatting, decoding or other functions required to drive specific terminal equipments (e.g., teleprinters or n character displays).

For the specific functional breakdown shown in Figure A-2 a tabulation of the first order impacting requirements on each function is presented in Table A-1.

It should be noted that the functional breakdown of Figure A-2 and Table A-1 does not represent a particular configuration of equipment "black boxes" or line replaceable units (LRUs), but rather a definition of classed functions. These functions, in practice, may be grouped in a single equipment package or distributed among a number of equipment packages according to other considerations. In some cases, a function (e.g., the equipment control function) may be distributed throughout several equipment packages for circuit design or interwiring convenience.

A.2 EQUIPMENT CONFIGURATION SENSITIVITIES

As a starting point, the generalized functional configuration of Figure A-2 and the information in Table A-1 were mapped against the various system configurations (A through C-1). From this mapping, the following sensitivities are found.

A.2.1 System Parameters

A.2.1.1 Forward (Satellite-to-Aircraft) Link

The principal sensitivity in this link is dictated primarily by technology limitations. That is, assuming a fixed aircraft antenna gain (+4 dB at the antenna radiator port), the receiving system noise temperature is the dominant factor.

Table A-1. Impacting Requirements on AEROSAT Avionics Basic Functions

Function	Requirements Impacting Design/Performance
Antenna Subsystem	• Fixed Constraint (+4 dB gain) from RAI requirements
Receiver	• Noise performance determined by support technology. Specific bandwidth and tunability requirements defined by choice of FDMA/TDMA system. Equipment configuration determined by aircraft installation requirements.
Transmitter	• Determined by choice of satellite antenna receive configuration. Number/type of transmitters determined by user service needs.
Modem (Forward)	• Demodulator design determined by forward link modulation (i.e., FSK, PSK, DPSK and FDMA/TDMA choice). Number of demodulators and mix determined by simultaneous service needs and mix.
(Return)	• Fixed by choice of FDMA return link and return link modulation. FDMA choice based on satellite return link repeater considerations.
Communications Processor	• Determined by FDMA/TDMA choice, simultaneous service mix and use of supervisory signaling channels. Outputting format design dictated by user I/O device choices.
Frequency Generation & Control	• Form determined by FDMA/TDMA choice and service requirements (including supervisory signaling channels).

Table A-1. Impacting Requirements on AEROSAT Avionics Basic Functions (Cont'd)

Function	Requirements Impacting Design/Performance
System Control Function	• Dictated by system control regime and user needs relating to cockpit automation
Equipment Control Function and Operator Control	• Established by system control functions

The effect of receiving system noise temperature impacts all systems equally in that the penalty directly affects forward channel capacity. For this reason, the Reference Avionics Interface (RAI) requirement in the AEROSAT specification is applied to all system configurations. A 1000° K maximum receiving system noise temperature is assumed. This is achievable in current advanced technology with transistor amplifiers. To achieve a satisfactory noise temperature, however, it is necessary to minimize the losses preceding the receiver RF preamplifier. This will be necessary with either a transistor amplifier or with a more sophisticated parametric amplifier. Thus, there appears to be no particular advantage in opting for a more sophisticated RF preamplifier since the major concern, ultimately, will be to minimize the RF loss between the antenna and the RF preamplifier, and proper installation will be more critical than the specific choice of the amplifier type used. This is more thoroughly detailed in Paragraph A.2.2.

A.2.1.2 Return (Aircraft-to-Satellite) Link

In the return direction the relative transmitter size is determined by the satellite receiving antenna configuration. Link budgets for each of the five system configurations are presented in Table A-2. For this table, a net loss of 3.6 dB between the transmitter (power output stage) and the antenna radiator element is assumed.[1] This is justified in Paragraph A.4.2. In addition, a design margin of +1.8 dB is added to the required transmitter power output to allow for design tolerances, adjustment, and service degradation. The advantage of the multibeam system is readily evident when comparing a design center requirement of 83 W for the multibeam (C and C-1) systems to the 148-W requirement for the triple beam (B and B-1) system and a 296-W requirement for global coverage (A) system.

[1]The net loss of 3.6 dB is predicated on the use of a diplexer-filter in the receive-transmit function rather than a simple antenna changeover relay. The choice of a diplexer as opposed to the changeover relay is treated as a separate tradeoff. However, operational considerations indicate that the diplexer, which provides simultaneous receive and transmit capability, will be mandatory in practically all cases.

Table A-2. Aircraft Transmitter Sizing for Various Satellite Antenna Configurations

Parameter	Satellite Antenna Receive Configuration		
	A Earth Coverage	B&B-1 Triple Beam[1]	C&C-1 Seven Beam
Recd Link Quality at Reference ASET	← 44.0 dB-Hz C/No →		
at Satellite[2]	← 44.4 dB-Hz C/No →		
No at Satellite (Tr 800° K)	← -199.5 dBW/Hz →		
Satellite Antenna Gain	+16.0 dB	+19.0 dB	+22.5 dB
Path Loss (1650 MHz)	← -189.0 dB →		
Propagation Loss Margin	← -5.0 dB →		
Polarization Loss	← -0.4 dB →		
EIRP required at aircraft	+23.3 dBW	+20.3 dBW	+16.8 dBW
Aircraft Antenna Gain	← +4.0 dB →		
RF Losses - Transmitter to Antenna	← -3.6 dB →		
Transmitter Power Output Received	+22.9 dBW	+19.9 dBW	+16.4 dBW
Equipment Design/Service Margin	← -0; + 1.8 dB →		
Design Center for Transmitter	+24.7 dBW (296 W)	+21.7 dBW (148 W)	+19.2 dBW (83 W)

(1) Applies to low gain (13°) beams

(2) Assumes 55 dB-Hz C/No satellite-to-ground link

Aside from the obvious cost implications of the higher powered transmitters, cooling requirements, prime power load, and reliability considerations favor the lowest transmitter power.

A.2.1.3 Modulation Schemes Requiring Coherent Detection

In system configurations requiring coherent detection of both the forward and return link, design of the power subsystem in the Avionics equipment will be of critical importance. The principal area of concern will be elimination of phase/frequency transients in the receiver and transmitter due to aircraft prime power variations/ transients. Because the aircraft prime power characteristics, as defined in ARINC specification and MIL-STD-708, indicate that relatively long duration disturbances are experienced in the aircraft prime power source, certain portions of the equipment (particular oscillators and coherent detection loops) will require an uninterruptable power source to avoid long dropout or frequent reacquisition requirements due to prime power interruptions.

A.2.2 User Needs/Cockpit Automation

Equipment sensitivity to user needs/cockpit automation requirements poses a broad range of impact on the equipment cost and complexity and must be evaluated on a case by case basis. Two factors are of concern:

1. The service and service mix to be accommodated and its attendant I/O device requirements
2. Cockpit workload and system procedural requirements needed to support this service.

Some of the major items considered in these two categories are presented in Table A-3, with the probable order of impact.

A.2.3 Access Control/Channel Management Techniques

The selection of a particular access control/channel management technique, as user needs and cockpit automation requirements, can pose a broad range of impact on

Table A-3. User Need/Cockpit Automation Considerations

Item	Considerations	Equipment Impact
Multichannel Reception	Individually or Simultaneously	Number of Detectors and Processor Capacity. Agility of Aircraft Frequency Control Function.
Multichannel Transmission	Individually or Simultaneously	Agility of Aircraft Frequency Control Function.
Voice/Data Service		Requires separate voice/data modulators or separate (digital) voice processing. Also requires separate processing on receive side.
Surveillance Service		Requires separate detector and processor functions (and possibly a separate modulator).
Channel Status Indication (eg: Channel Busy)	Used for seizure with observation	Simple decoding function in communications processor.
Channel Scan	Used for seizure with observation	Same as above plus automatic channel selection in frequency control position of equipment.
Automatic Channel Tuning (on receive)	Used where assignment is made via supervisory signaling channel.	Decoder in communications processor plus automatic channel selection in frequency control portion of equipment.
Transmit/Receive Channel Pairing		Channel pairing register in frequency control portion of equipment.
Automatic Selection of I/O Devices	Automatic voice/data select or selection of multiple data output devices	Decoder and signal routing logic in communications processor.

equipment cost/complexity. The alternatives range from no measurable impact, where access control and channel management procedures are exercised on the normal communications channels, to a full-time dedicated supervisory system.

Because the range of alternatives is so extensive, it is necessary to identify viable candidate approaches and analyze the impact on a case by case basis. This will be reported in the latter paragraphs of this section.

A.2.4 Experimental Versus Operational System

Because the initial AEROSAT Avionics equipment will operate in a "preoperational" or experimental system, it is expected that early versions of the equipment will be provided with facilities which will not be used in the fully operational configuration. A realistic cost/complexity assessment, however, cannot be based on these peculiar requirements. For this reason, equipment functions and performance requirements contained in the AEROSAT specification which relate to experimental requirements are deliberately omitted in this analysis. It is recognized, however, that these requirements will impact the design of early versions of the equipment, but are not pertinent to determination of the cost/complexity associated with a fully operational system.

A.3 BASELINE CONSIDERATIONS

To ensure a reasonable and uniform base for evaluating equipment for the various system configurations, a number of baseline assumptions are made. These follow.

A.3.1 Size of Market and Potential Equipment Runs

Based on an optimistic 1980-1985 air traffic estimate, it is expected that a maximum of 1500 U.S. and foreign aircraft will be equipped for operation in a fully operational AEROSAT System. Assuming a 5-year operational implementation period, with uniform demand, the production requirements for AEROSAT Avionics equipment will be on the order of 300 equipments per year. It is expected that this market will be addressed by 5 to 7 domestic and foriegn suppliers. With a field of 5 suppliers, a typical manufacturer could expect to supply about 60 equipments per year to the air carrier industry, at a production rate in the vicinity of 5 equipments per month.

Under this assumption, it is anticipated that the design and production techniques employed will reflect practices of a "semi-custom" or low-volume product line. Capital investment will tend to be limited, as will nonrecurring costs associated with design, production and testing facilities. It also appears that the low volume will discourage entry of new firms into the business, limiting the market to firms which have the skills, experience and facilities which are supported by similar or compatible product lines.

A.3.2 Technology Utilization

Because of the relatively low production volume with its attendant minimization of capital and nonrecurring costs, AEROSAT Avionics equipment will be designed and fabricated using available, or off-the-shelf, technology. Any advanced technology used will result from developments evolving from higher volume base needs.

In particular, three areas are of importance:

1. Digital Processing and supporting semiconductor integrated circuit technology. It is expected that most signal processing will employ digital (or switching) circuits, with most processing done using standard logic techniques. This includes the use of digital phase detectors, digital phase locked loops (e.g., for carrier detection) and digital frequency synthesis for channel frequency control in lieu of analog circuit techniques. This choice is primarily dictated by price and availability of a wide range of standard digital integrated circuit functions. The use of Large Scale Integration (LSI) will probably be restricted to standard or programmable functions [e.g., Programmable Read Only Memories (ROM)] rather than custom fabricated LSI devices.

2. Receiver Technology in which developments aimed at a general (and fragmented) communications market will be used.

3. L-Band Transmitter Technology, which similarly will depend on developments specifically directed to other application areas or to a general market.

Since the transmitter design will be highly dependent on duty factors, it is important to establish a realistic bound based on message traffic where a high dependency on voice/data service mix will be exhibited. For example, in current VHF A-G-A equipment, the transmitter must be designed for continuous duty. This is necessary even though the transmitter may have long idle periods (thereby giving the transmitter a low average duty cycle) since, when used, the short-term duty factor is high and the durations of the short-term high-duty cycle use exceeds the thermal time constant for the equipment. This condition may preclude the use of L-Band transmitter designs that will be developed for ATCRBS/DABS and TACAN/DME equipment.

A. 3. 3 Aircraft Considerations - Present and Future

Within the implementation time frame for the operational AEROSAT System (1980-85) user aircraft will consist of existing in-service types and several new types currently in the intermediate design phases. For transoceanic service, there are the U.S.-built Boeing 707, Convair CV-880/990 and McDonnell-Douglas DC-8 and several competitive foreign types for standard (large) aircraft and the Boeing 747 in the heavy aircraft class. In addition, such aircraft as the DC-10-30 and versions of the Lockheed 1011 may also be in service along with the planned Boeing 7X7 (4 engine) and similar competitor aircraft. With the relatively low predicted number of SST aircraft, it is therefore expected that the major numbers of aircraft which are potential AEROSAT System users will be of current generation airframe design techniques (at least so far as Avionics equipment installation criteria are concerned). Thus, the AEROSAT Avionics equipment will be designed to conform to current environment, racking and packaging practices (with minor updates to accommodate design technology changes). These design requirements are presented in Paragraph A. 3. 5.

A. 3. 4 Built-In-Test Equipment (BITE) Considerations

A. 3. 4. 1 Introduction

Because of the complexity and quality of equipments in the normal aircraft complement, there has been a growing trend to provide functions in the individual equipments to facilitate operational and maintenance tests. Although there are no detailed guides as to the extent of the built-in test facilities, many current generation military equipments are designed to provide three levels of test functions. These are:

1. A cockpit-level status indication (OK - or Fault) based on either a manually initiated or automatic end-to-end test of the equipment.

2. A Line Replaceable Unit (LRU) status indication indicating the status of each individual "black-box" in an equipment set on a go/no-go basis. This permits immediate identification and replacement of a defective unit on the flight line. The individual "black box" tests are a necessary part of the end-to-end test, and are performed as part of the overall status check.

3. Augmented LRU Testing, usually accomplished by interfacing to external test equipment via an umbilical cord. Such Augmented LRU Testing can usually be done while the equipment is installed in the aircraft, but is usually performed on the bench since this level testing is generally performed to isolate faults to the equipment subassembly or circuit level. The level of detail in augmented testing varies considerably. In simple cases, a plug is provided for a specially configured test set (usually a voltmeter with appropriate multipliers) to isolate common faults; e.g., power supply failure, receiver crystal current for mixer diode failures, etc. In more complete arrangements, e.g., VAST, the goal of the augmented test is to fault isolate to the component level for 90 - 95 percent of the circuits involved in the equipment.

The question of extent to which these test facilities should be provided cannot be answered on a general basis; however, for most military equipments it appears that 20 percent in terms of cost/complexity is an acceptable figure. For operational performance testing (i.e., nonaugmented testing) the cost/complexity of built-in test facilities must be weighed against safety and in-flight operating costs.[1] The augmented test facilities, on the other hand, impact maintenance, logistics and support requirements. As such, the concern with augmented test facilities in the equipment design is directly related to the user's ground support philosophy and its associated costs.

For the AEROSAT Avionics, BITE will be considered only at the first two levels; that is, system status test and LRU test. In addition, test arrangements for the various equipment configurations will be considered for control of reconfiguration and backup mode operation.

A. 3. 4. 2 Specific Considerations

Some basic decisions must be made in establishing an overall test philosophy, as well as how it is applied in a specific system configuration. For the AEROSAT Avionics equipment the following conditions are considered appropriate:

1. At the cockpit level - test indicators should show fault or no-go conditions.

2. Tests should be performed continuously and automatically. In addition, a manual override, permitting pilot-initiated test to provide an essentially instantaneous status indication, shall be incorporated. Time interval between automatically initiated tests shall be consistent with safety vs. pilot need-to-know criteria. For oceanic operations, this is estimated to be in the range of 5 to 30 minutes, depending on separation standards and the amount of real-time control exercised over the traffic.

3. For systems employing continuous coverage such as a full-time supervisory channel in the forward link direction (or alternatively, employing active

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[1] Particularly since an acceptable equipment cost penalty of 20 percent for the military is weighed against "mission-readiness" requirements and not operating cost on safety factors per se.

surveillance), portions of the test can rely on available downlink signals. Each system arrangement must map these considerations into detailed equipment configurations applicable to the particular system configuration.

A. 3. 5 Baseline Equipment Design Requirements

Because the aircraft design and equipment installation practices that will be employed during the operational implementation of the AEROSAT System are expected to be similar to current practices, design and environmental specifications may be applied directly from current documentation. Three areas of specific interest are:

1. The packaging, installation and racking requirements (i.e., mechanical form factor and installation detail).
2. The environmental conditions over which the equipment must be designed to perform.
3. The characteristics of the aircraft prime power system which the equipment use and over the range the equipment must provide proper performance.

The specification requirements arising from these three areas will be applied to equipment configured for each system arrangement as defined in the following paragraphs.

A. 3. 5. 1 Equipment Cases, Installation and Racking Requirements

Preliminary analysis based on considerations to be presented in Paragraph A. 4. 2 indicate that the physical equipment packaging will consist of four equipment cases (LRUs) and a control box as indicated in Figure A-3. This arrangement reflects the need for remote (at the antenna) installation of the receiver RF preamplifier as described in Paragraph A. 4. 2 and permits simplification of installation of two transmitters for simultaneous voice/data or redundant transmitter operation as described in Paragraph A. 4. 1.

The particular partitioning of the equipment is based on the use of equipment case sizes, defined in ARINC Specification 404, minimization of equipment intrawiring

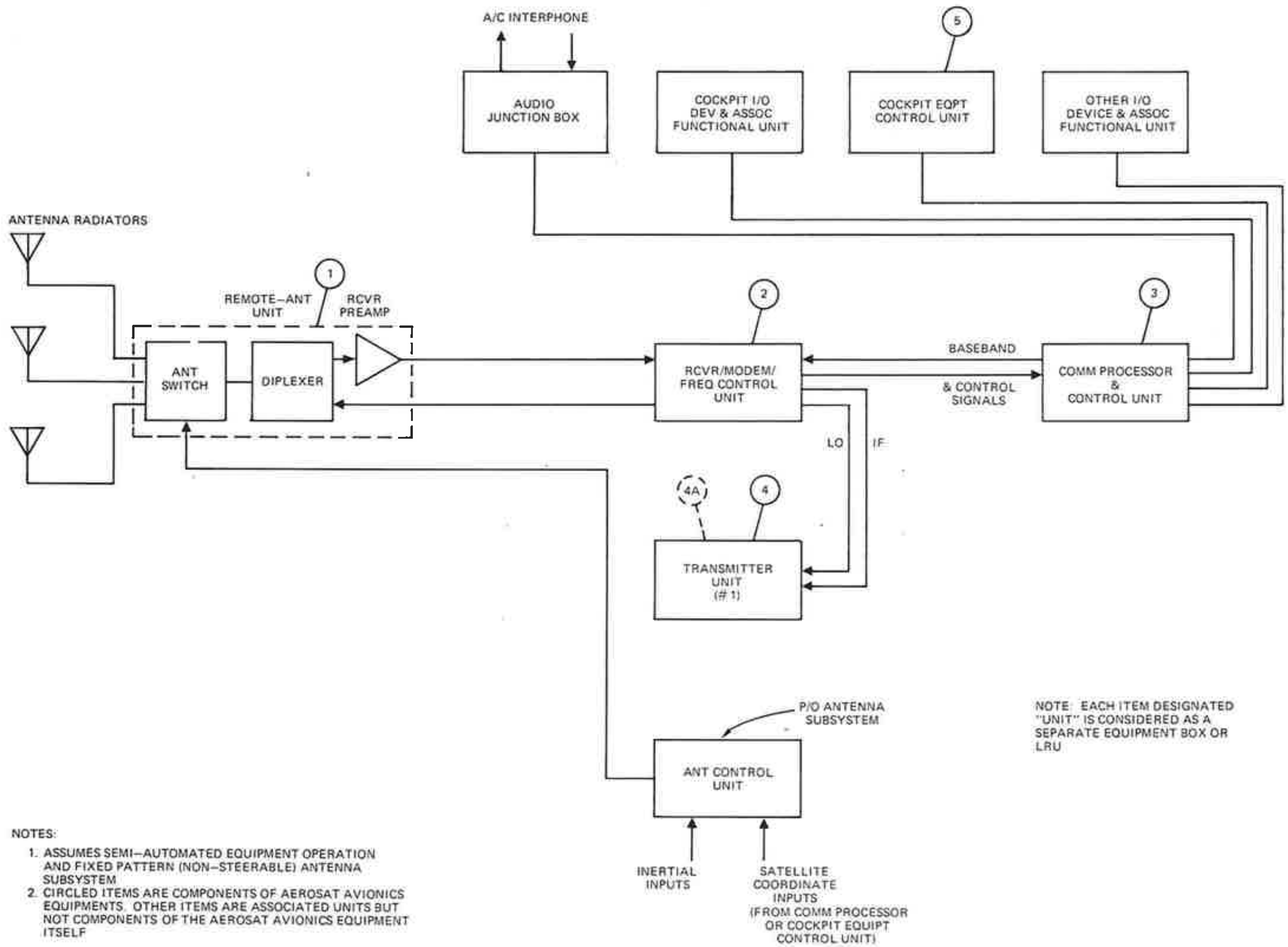

Figure A-3. AEROSAT Avionics Probable Configuration of Equipment Packages[1] requirements, ease of service and logistics and thermal considerations. To the extent practical, the arrangement groups functions having similar circuit functions and component makeup and, in addition, isolates critical equipment functions from heat sources.

From an arrangement, such as shown in Figure A-3, the individual equipment cases include:

1. Unit 1 - Remote Antenna Unit, using a packaging configuration specifically suited for mounting on the aircraft fuselage in the vicinity of the antenna radiator elements (i.e., nonstandard packaging in terms of ARINC Specification 404). This unit would contain the receiver RF preamplifier, the diplexer-filter (or alternatively R-T antenna changeover relay) and the antenna switch used to select the antenna radiator element. (The antenna switch is not part of the AEROSAT Avionics equipment, but rather is part of the antenna subsystem. For weight minimization, maintenance and reliability, however, this switch should be included in the Avionics Equipment Remote Antenna Unit.)

2. Unit 2 - Receiver/Modem and Frequency Control Unit, which would be located in the aircraft equipment bay. This unit would contain all of the low-level RF - IF functions of the equipment and the basic bit synchronization - detection functions. This unit would also contain a separate uninterruptable power supply to meet the transient elimination requirements associated with coherent detection requirements. For any system configuration chosen, these functions could probably be contained in a long 3/4 ATR Case (1120 IN^3) with a maximum weight on the order of 32 lbs. Prime input power (115V-400 Hz) would be on the order of 40 to 50W and simple conduction-convection cooling could be used.

3. Unit 3 - Communications Processor and Control Unit, which would be similarly located in the aircraft equipment bay. This unit would primarily contain digital/logic functions associated with processing and interfacing of message traffic to

and from the various input/output devices on the aircraft (both voice and data) and would contain the control functions associated with access control, channel management and overall equipment automation, management and control. In cases where supervisory signaling channels and/or surveillance functions are provided, the necessary equipment functions would be included in this unit. Because of the wide range of service mix, system configurations, automation criteria and I/O device complement, a gross assessment of the physical characteristics of this unit cannot be made. The range of possibilities extends from a short 3/8 ATR case for the simplist nonautomated arrangement through to 1-1/2 ATR case for the most complex arrangement. Internal construction for any type will be of the "card file" arrangement and simple conduction-convection cooling will be employed.

4. Unit 4 - Transmitter Unit, which will be located in the aircraft equipment bay. This will contain the power amplifier-driver chain with all stages operating at moderate to high RF power levels. For intrawiring convenience, input to this unit will be at an IF (in the 60- to 70-MHz range) and the necessary upconversions will be performed in the unit. A LO multiplier chain will probably also be included to avoid intraconnection of units with UHF LO lines.

   Because of the wide range of transmitter powers required for each of the system configurations and the volumetric requirements for differing power amplifier approaches (i.e., transistor PA vs. triode-cavity vs. TWTA) a gross estimate of size and power requirements cannot be made. However, because of the high dissipation density of the transmitter power amplifier (regardless of the particular type used), it is highly probable that simple conduction-convection cooling will not be enough for this unit and that some form of air cooling will be required [either due to equipment reliability considerations or, more directly, due to maximum temperature limits on the active device(s) in the power amplifier].

5. Unit 5 - Cockpit Equipment Control Unit, located in the aircraft cockpit to provide operator (pilot) control and indications for the equipment. This unit will be designed for installation in the 5.75 "DZUS" rail spacing in the cockpit. The physical panel area will be dictated by the equipment control and indicator requirement for each particular system configuration. Maximum depth of the Cockpit Equipment Control Unit is limited to 4.0 inches as dictated by the maximum clearance below the "DZUS" rails provided by most airframe manufacturers.

   Since the Cockpit Equipment Control Unit will probably not contain any dissipative sources, no thermal control problems will be experienced in this unit.

A.3.5.2 Environmental Conditions

Because aircraft environmental conditions are not expected to experience radical changes over the implementation time frame of the AEROSAT System, the environmental categories contained in the current RTCA DO-138 document[1] can be applied. For the equipment partitioning defined in Paragraph A.3.5.1 the equipment environmental categories for each unit are as indicated in Table A-4. These categories are based on installation in turbojet aircraft. Test procedures for qualification of equipment to these categories are described in the appropriate sections of RTCA DO-138.

The major implication in the selection of these categories lies in the imposition of both electrical and mechanical design requirements on the equipment, although it does not dictate the design approach which must be taken by any equipment contractor.

These environmental condition requirements are not sensitive to the particular system configuration chosen, but rather by the physical environment imposed by the aircraft.

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[1] Environmental Conditions and Test Procedures for Airborne Electronic/Electrical Equipment and Instruments; Radio Technical Commission for Aeronautics (RTCA) Document D-138, June 17, 1968 with Change Notice Number 1, July 1, 1969.

Table A-4. Environmental Categories for AEROSAT Avionics Equipment

UNIT \ CATEGORY	Temperature and Altitude Test Category	Humidity Test Category	Vibration Test Category	Audio-Frequency Magnetic Field Susceptibility Test Category	Radio-Frequency Susceptibility Test Category	Emission of Spurious Radio Frequency Energy Test Category	Explosion Test Category	Waterproofness Test Category	Hydraulic Fluid Test Category	Sand and Dust Test Category	Fungus Resistance Test Category	Salt Spray Test Category
UNIT 1. Remote Antenna Unit (mounted on aircraft fuselage at antenna)	*	A	J	A	Z	A	X	W	H	X	X	X
UNIT 2. Receiver-Modern and Frequency Control Unit (mounted in aircraft equipment bay)	G	A	O	A	Z	A	X	X	X	X	X	X
UNIT 3. Communications Processor and Control Unit (mounted in aircraft equipment bay)	G	A	O	A	Z	A	X	X	X	X	X	X
UNIT 4. Transmitter Unit (mounted in aircraft equipment bay)	G	A	O	A	Z	A	X	X	X	X	X	X
UNIT 5. Cockpit Equipment Control Unit (located in aircraft cockpit)	D or G	A	K	A	Z	A	X	X	X	X	X	X

*Category A for standard aircraft; may require upgrading to category K, L, P or Q for SST type aircraft.

A.3.5.3 Aircraft Prime Power Source Conditions

The equipment will be designed to operate from the standard 115 V–400 Hz aircraft power source. The characteristics of this source (for air carrier aircraft) are detailed in ARINC Specification No. 413, which in turn represents an industry-coordinated interpretation and updating of MIL-STD-704.

Test procedures for qualification of equipments over the range of power input and transients are defined in Sections 9 and 10 of the RTCA-DO-138 document, respectively.

With regard to the aircraft prime power system, the current generation variable speed constant frequency (VSCF) systems employing hydraulic converters are used on most operational aircraft. Later aircraft may employ chopper/synthesizer systems (ARINC Specification 413); however, this move will result primarily in simplified maintenance and service requirements rather than in improved power system performance and transient elimination.

As in the case of environmental conditions, the aircraft power system characteristics impose specific design requirements on the equipment designer and are a function of the aircraft itself.

A.4 MAJOR TRADEOFF AREAS

Two major tradeoffs which are essentially independent of the system configuration have been identified. These are:

1. Service need, relating to the requirement of simultaneous voice/data or any simultaneous two-channel transmission from the aircraft

2. The equipment form factor (packaging) necessary to support the receiving system noise temperature specified for the RAI.

In addition, two other tradeoff areas, applicable to several possible configurations, depending on specific signal design on operational methods choice, are identified. These are:

1. Simultaneous versus alternate two-way communications

2. Doppler corrected versus uncorrected return link transmission from the aircraft.

These four items are discussed in the following paragraphs.

A.4.1 Simultaneous Two-Channel Transmission from the Aircraft

If service requirements necessitate multiple-simultaneous transmissions from the aircraft, suitable provisions must be made in the initial equipment design. Two possibilities exist:

1. Multiple transmitters may be provided

2. A single transmitter with multichannel capacity may be used.

Within these possibilities, four arrangements are possible with the two-transmitter configuration and two arrangements are possible for the single transmitter configuration. These are depicted in Figures A-4 and A-5, respectively. A tabulation of the impacting results of each choice is presented in Table A-5. The tradeoffs become significant when the transmitter power output capabilities for each system are considered.

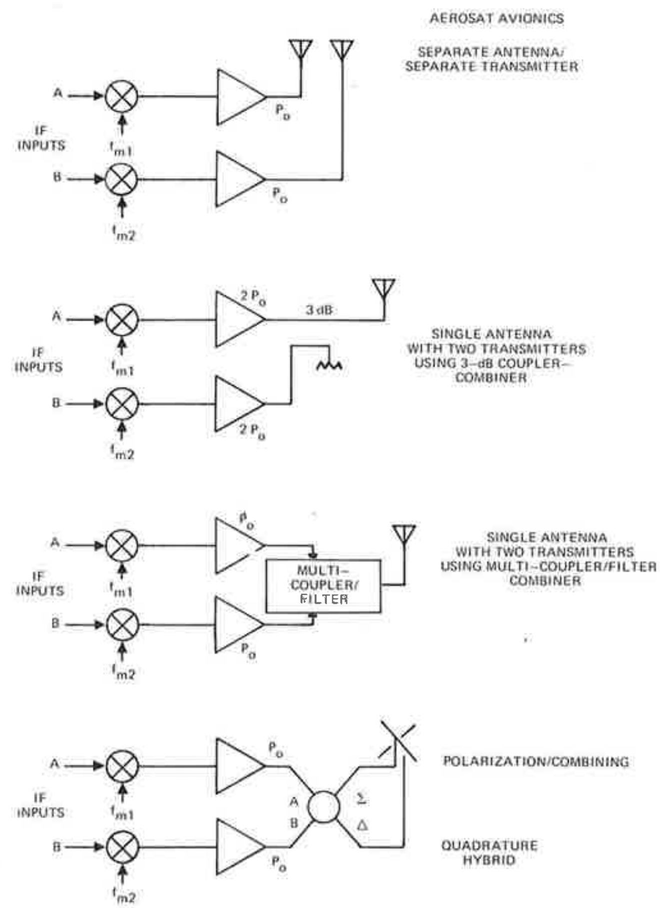


Figure A-4. Two-Transmitter Arrangements

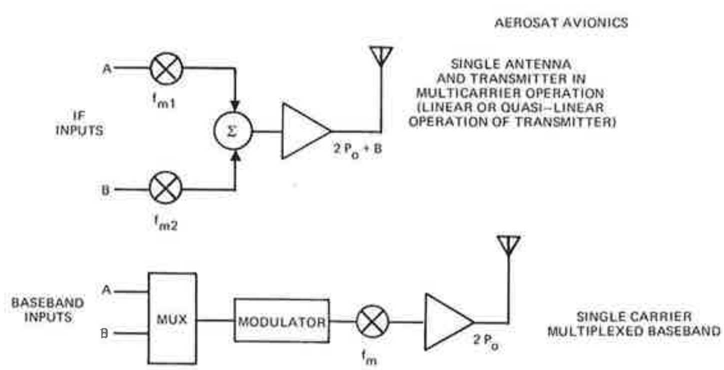


Figure A-5. Single Antenna and Transmitter in Multicarrier Operation (Linear or Quasilinear Operation of Transmitter)

Table A-5. Results of Two-Transmitter and Single Transmitter Arrangements

	Two Transmitter Arrangements				Single Transmitter Arrangements	
	Two Antenna/Two Transmitter	Single Antenna/2 Transmitter w/ 3 dB Coupler	Single Antenna/1 Transmitter w/ Multicoupler/Filter	Polarization Combining	Multicarrier Operation	Multiplexed Baseband-Single-Carrier Operation
General:	Transmitter Redundancy Provided (at cost of Loss of Simultaneous V/D Capability)					
Aircraft Antenna System	Two Separate Systems	One System	One System	Complex Antenna System	One System	One System
Transmitter Operation	(2) Class C – (Saturated)	(2) Class C – (Saturated)	(2) Class C – (Saturated)	(2) Class C – (Saturated)	(1) in Class C (Saturated) or Quasi-Linear Mode	(1) Class C – (Saturated)
Transmitter Power	(2) at P_o	(2) at P_o	(2) at P_o	(2) at P_o	(1) ranging from $2\ P_o$ to $2\ P_o$ + Backoff *	(1) at $2\ P_o$
Component Complexity	Standard Functions	Standard Functions	Complex Multicoupler	Standard Functions	Standard Functions	Complex Multiplexer
Frequency Plan	Independent V/D Ch. Good spectrum use	Independent V/D Ch. Good spectrum use	Min V/D Ch. separation depends on multicoupler design	Independent V/D Ch. Good spectrum use	Frequency planning required to avoid IM products from falling into adjacent channels. Voice and data channel assignments dependent. Poor spectrum use.	Requires pairing of voice and data channel assignment at aircraft. Poor spectrum use
Impact on Satellite	None	None	None	Requires reception of LHCP and RHCP at satellite (complex antenna) plus combining	None	None
Avionics Cost Impact for Transmitter Only[1]						
System A	3.4	5.2	4.0[2]	3.4	~3.4	2.6[3]
System B & B1	2.4	3.4	3.1[2]	2.4	2.3	1.7[3]
System C & C1	1.9	2.5	2.5[2]	1.9	1.7	1.3[3]

[1] From normalized cost curve – Figure 5–6.
[2] Including multicoupler-filter.
[3] Does not include cost of complex multiplexer-modulator.

* Backoff required is estimated at 3.4 dB from simulations described in Interim Report.

Using a normalized cost curve as presented in Figure A-6 (probable cost), the cost impact for the transmitter only is presented on the last three lines of Table A-5. For the quasilinear single transmitter operating under multicarrier conditions, the backoff for linearization (b) is taken as 3.4 dB.

From the transmitter cost comparison presented in Table A-5, the use of a single quasilinear transmitter appears to be a viable approach. However, for System A, a 1.2-kW transmitter will be required and both prime power considerations and the cooling system load may impose higher installation costs for the equipment (even though the equipment itself is less costly than in alternative approaches). One further argument that may be advanced in favor of two-transmitter installations is that redundant transmitters would normally be required in any case. Thus, the use of a single transmitter for two-channel output capacity would be more costly in the case of an operational installation.

A.4.2 Equipment Form Factor - Distributed Versus Consolidated Arrangements

Because early calculations indicated that some difficulty would be experienced in achieving the RAI requirement of a 1000° K receiving system noise temperature, possible installation configurations were examined. In particular, consideration was given to minimizing the RF losses between the receiver RF preamplifier and the antenna radiator elements. As a starting point, the following is assumed:

1. From RAI
   - G_{ANT} = 4.0 dB (including polarization loss)
   - EIRP = 23.0 dBW (assumed min.)
   - T_s = 1000° K (including service degradation)

2. Practical Factors

   a. Distance from A/C equipment bay to antenna station on A/C is assumed to be 75 feet (cable run length) and for multielement antennas, the distance between C-to-L and C-to-R element is 16 feet.

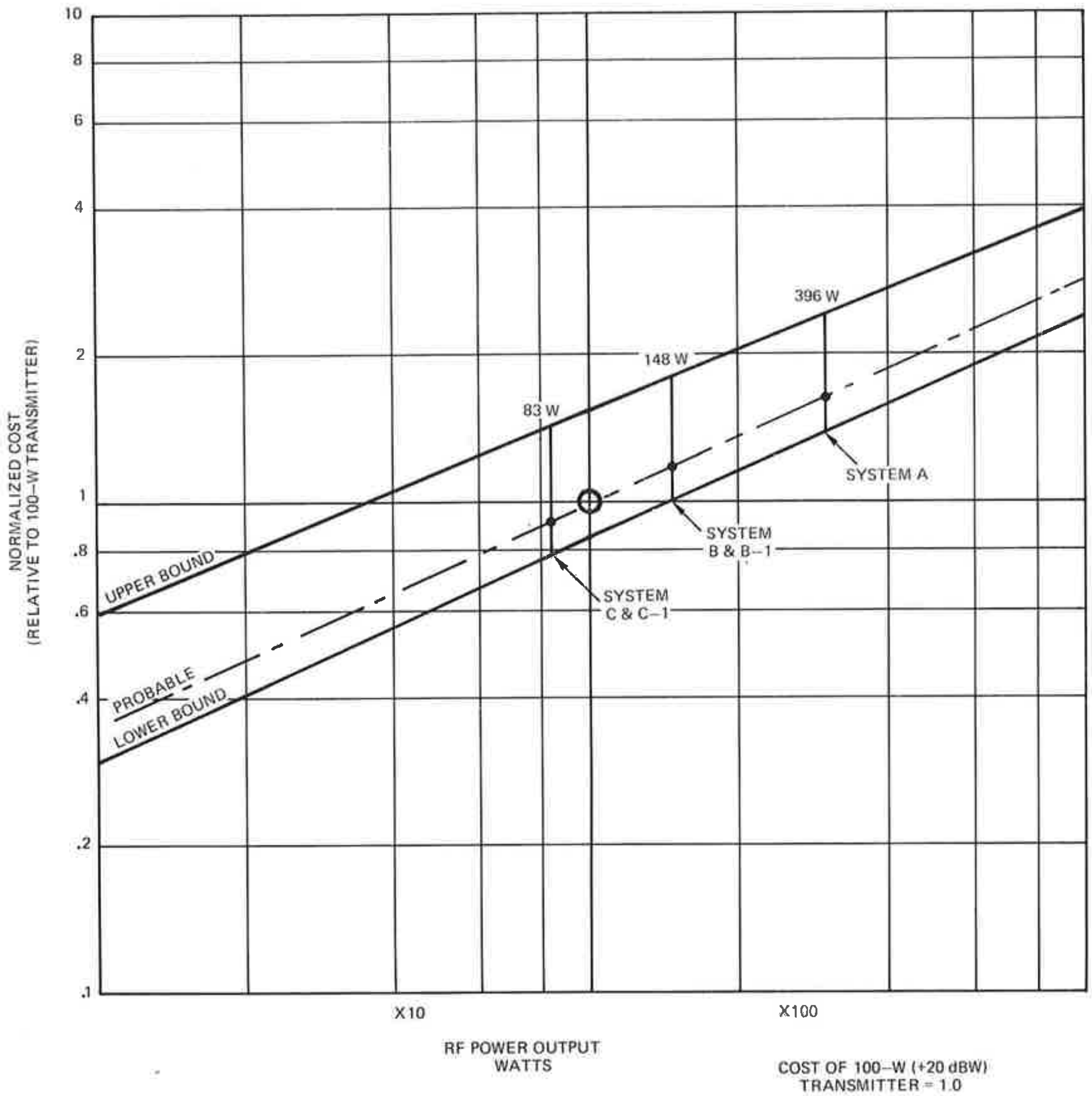


Figure A-6. Normalized Cost Trend Curve for L-Band Transmitter (Including Power Supply and Cooling)

b. Available semirigid foam-filled or semiair dielectric lines exhibit a loss of 2.0 dB/100 feet for 7/8-inch-diameter line at 25° C and 2.2 dB/100 feet at 70° C (0.022 dB/ft.), at 1.5 GHz.

c. Each connector in the line will produce a loss of 0.05 dB.

d. The best available bipolar or FET transistor amplifiers at 1.5 GHz exhibit noise temperatures of 150° K (at room temperature and under optimum operating conditions), corresponding to F = 1.8 dB. For practical avionics, production design, and tolerance and degradation, a worst-case preamplifier noise temperature of 200° K will be assumed.

From a practical standpoint, a transistor RF preamplifier represents the most attractive approach in the receiver design. The incremental cost of the transistor preamplifier in the equipment is small compared to a direct mixer input (which cannot provide the desired noise performance). Improved noise performance could be achieved with a noncryogenic parametric amplifier; however, the paramp is more costly, bulkier and more difficult to maintain. Further, even with the improved noise performance of the paramp (up to 1 dB better than a transistor amplifier), overall receiver noise considerations would still dictate that the paramp be physically located at the diplexer. Performance of current state-of-the art receiver front end assemblies is given for reference in Figure A-7.*

Using these assumptions, a typical installation diagram as shown in Figure A-8 was developed, and several possible variations were considered in placement of the receiver RF preamplifier and transmitter. These variations include a consolidated equipment configuration in which all equipment items are contained in the aircraft equipment bay and two distributed configurations. The distributed configurations provide RF preamplification at the antenna radiator element (Form A) and a version with both the transmitter and RF preamplifier at the antenna radiator element (Form B). The

*Okean, H.C., and Lombardo, P.P., "Noise Performance of M/W and MM Wave Receivers," Microwave Journal, January 1973.

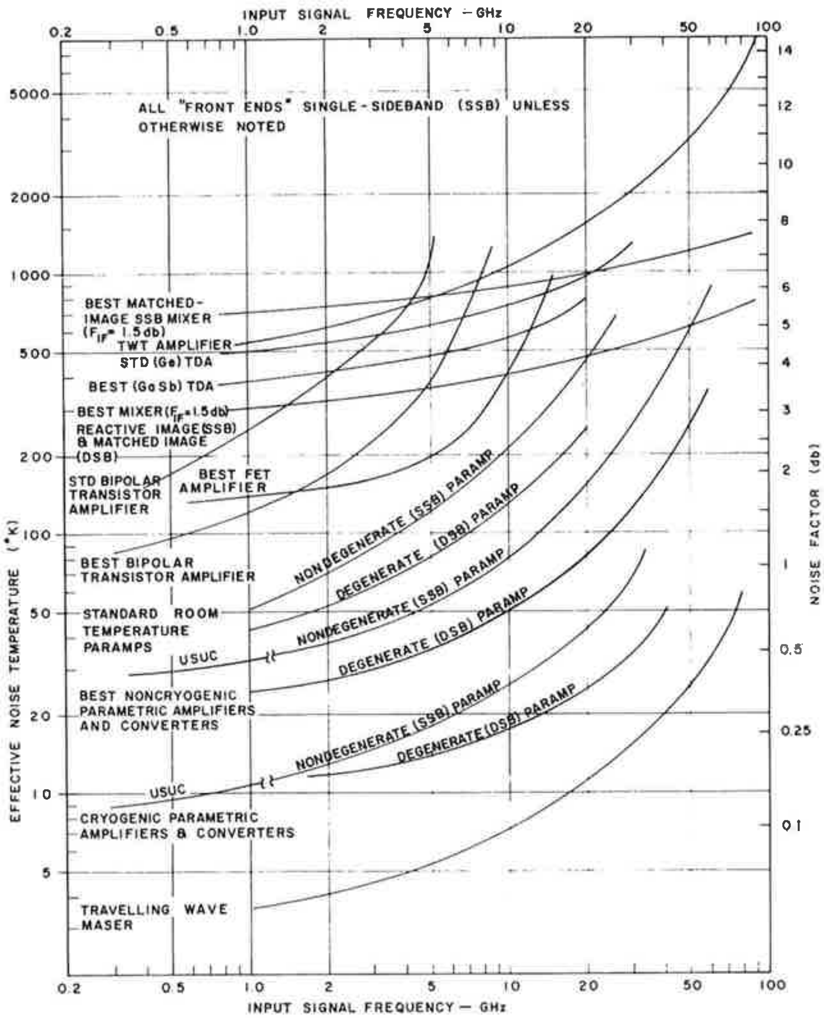
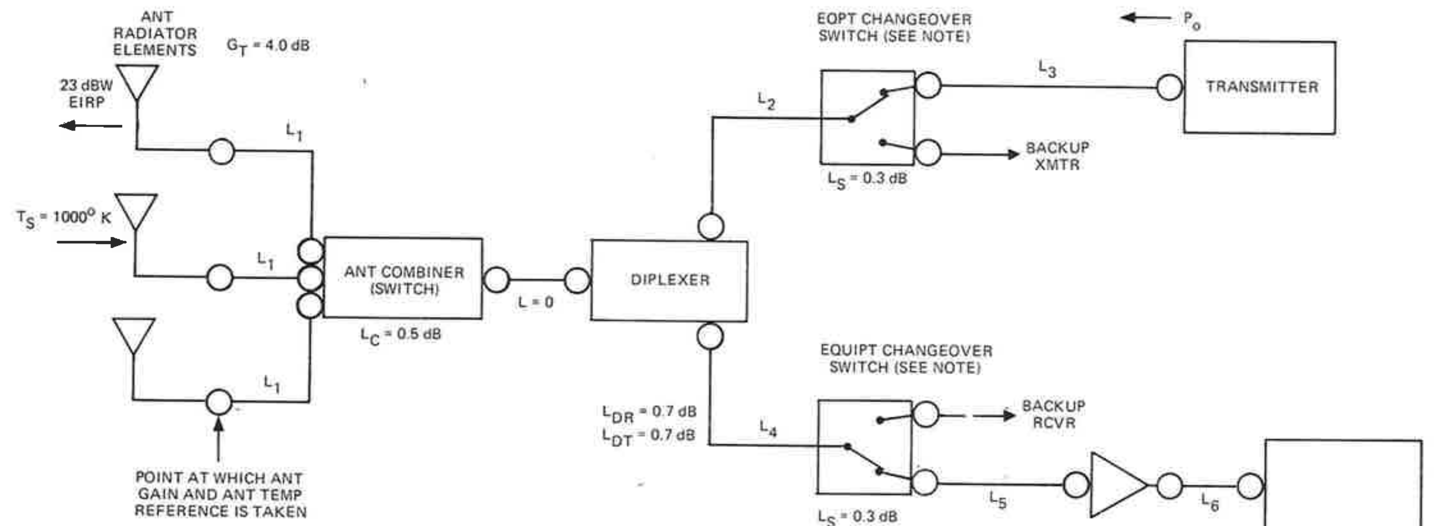


Figure A-7. Receiver Front-end Noise Performance as a Function of Input Signal Frequency - State of the Art



NOTE: AN EQUIPMENT CHANGE–OVER SWITCH IS CONSIDERED AN ESSENTIAL FUNCTION FOR AIR CARRIER A/C INSTALLATION (ALTHOUGH IT IS NOT NEEDED FOR SYSTEM OPERATION) TO PERMIT SWITCH IN OF REDUNDANT OR BACKUP UNITS.

Figure A-8. AEROSAT Avionics Practical RF Subsystem Interconnect equipment performance requirements, based on an installation similar to that shown in Figure A-8, are presented in Table A-6. Specific considerations associated with each configuration are presented in Table A-7.

From a practical standpoint, it appears that the most desirable configuration is a distributed equipment with RF preamplification at the antenna, but with the transmitter(s) located in the aircraft equipment bay. This represents a reasonable compromise between serviceability/maintainability and cost/performance considerations. From this, a proposed arrangement of black boxes or LRUs, described in Paragraph A. 3. 5. 2, was evolved. This arrangement appears to be well suited to design and construction practices.

A. 4. 3 Simultaneous Versus Alternate Two-Way Communications

One area in which a significant equipment hardware impact is experienced is in the method by which the transmitter and receiver share a common receiver port. One of the two following approaches may be used:

1. The use of a diplexer-filter that provides simultaneous transmit and receive capability. This approach can be used only when the transmit and receive frequencies are different, since the design of the diplexer depends on:

    a. Presenting an open circuit at the transmitter output at the receive frequency

    b. Presenting an open circuit at the receiver input at the transmit frequency.

    Since the forward and return links in the AEROSAT are frequency separated (by about 6-1/2 percent), this approach is applicable to the AEROSAT System.

2. The use of an antenna changeover switch that alternately connects the receiver or transmitter to the aircraft antenna for transmission or reception but not both simultaneously.

    The principal disadvantages of the diplexer-filter arrangement are:

    a. Cost and physical size

Table A-6. AEROSAT Avionics - Transmitter Sizing and Receiver Performance for Various Equipment Configurations (To Meet RAI Requirements)

	Ideal	Consolidated	Distributed(2) A	Distributed(2) B
1. TRANSMITTER				
G_{ANT} (transmit)	+4.0 dB	+4.0 dB	+4.0 dB	+4.0 dB
L_1	0	(incl in L_2)	-0.35 dB	-0.35 dB
L_C	-0.5 dB	-0.5 dB	-0.5 dB	-0.5 dB
L_{DT}	-0.7 dB	-0.7 dB	-0.7 dB	-0.7 dB
L_2	0	-2.0 dB	-1.65 dB	-0.1 dB
L_S	-0.3 dB	-0.3 dB	-0.3 dB	-0.3 dB
L_3	0	-0.1	-0.1 dB	-0.1 dB
Net Gain (XMTR to Antenna)	+2.5 dB	+0.4 dB	+0.4 dB	+1.9 dB
EIRP Required	←	+23.0 dBW	→	
Transmitter Power Required (RAI Spec.)	+20.5 dBW (112.0 W)	+22.6 dBW (183.0 W)	+22.6 dBW (183.0 W)	+21.1 dBW (128.0W)
2. RECEIVER				
T_{ANT}	290° K	290°K	290°K	290°K
L_6	0	-0.1 dB	-1.65 dB	-1.65 dB
T_e at Preamp Input	210° K	~210° K	~216° K	~216°K
F at Preamp Input	2.36 dB	2.36 dB	2.42 dB	2.42 dB
Loss Preceding Preamp	1.5 dB	3.7 dB	1.85 dB	1.85 dB
F at Reference	3.86 dB	6.06 dB	4.27 dB	4.27 dB
T_r	418° K	842° K	485° K	485°K
T_s	708° K	1132° K(1)	775° K	775°K

(1) Exceeds RAI spec requirement.

(2) Distributed Column A, XMTR in equipment bay, RCVR front-end at ANT combining switch.

Distributed Column B, both XMTR and RCVR are at ANT combining switch.

Table A-7. Factors Affecting Choice of Consolidated Versus Distributed Equipment Configuration

<u>Consolidated Equipment Configuration</u>

All equipment functions (except antenna radiator elements) contained in aircraft equipment bay

- Ease of installation, maintenance and servicing of equipment (desired by user)
- No customized equipment design needed to meet peculiar aircraft installation requirements
- Backup & multiple installations easily accommodated
- Problems - 1) reasonable receiving system noise temperature ($< 1000°K$) difficult or impossible to achieve; 2) transmitter power output capability must be increased by ~ 3.6 dB to overcome link losses

<u>Distributed Equipment Configuration (Form A)</u>

All equipment functions except antenna RF switching, diplexing and receiver preamplifier are located in equipment bay. Excepted functions located at antenna radiator station(s)

- Reference system noise temperature $\leq 1000°K$ easily achieved (reduced EIRP requirement from satellite)
- Remote installation items are (relatively) high reliability-low maintenance items: have low power & control requirements
- Bulk of equipment - and higher maintenance requirement items are located for easy installation, maintenance and service
- Problems - 1) remote items difficult to install, service and maintain; 2) design of remote items will require more severe environmental specs. and in addition may need to be "customized" for specific aircraft installations and for specific user needs (e.g., multiple installations); 3) transmitter power requirements same as for consolidated configuration

<u>Distributed Equipment Configuration (Form B)</u>

Similar to Form A except transmitter(s) are also located at antenna radiator stations

- Same advantages as Form A, plus transmitter power output requirements are reduced by approximately 1.9 dB
- Problems - 1) same as Form A, plus increased power supply and dissipation requirements introduced by transmitter; 2) lower reliability of transmitter increases service access problem associated with remote installation

b. The filters must be tunable for manufacturing purposes, thereby introducing possible additional service adjustment points in the operational equipment.

c. The diplexer-filter will have a higher insertion loss than a simple changeover switch (i.e., 1.0 to 1.5 dB, opposed to 0.3 to 0.5 dB). (The insertion loss of the diplexer-filter may be reduced by increasing the physical size of the filter resonators - leading to a higher unloaded Q, but electrical constraints limit the maximum dimensions, hence minimum insertion loss which may be achieved.)

These disadvantages are, however, weighed against two major advantages:

a. Simultaneous transmit-receive capability is achieved. Thus, in systems employing a supervisory signaling channel or employing a surveillance/ranging signal, the system is not disabled during transmission. Simultaneous two-channel (i.e., voice/data) operation can also be achieved with a single receiver.

b. The diplexer-filter is entirely passive, and thus does not require periodic preventive maintenance service and does not contain any inherent wear-out or failure mechanisms.

In the case of the antenna changeover switch, the principal advantage lies in lower cost and low insertion loss in the antenna line. The disadvantage lies in the inability to provide simultaneous transmission and reception capability (which may make it impossible to use a changeover switch in certain operating schemes and for certain service mixes). Further, if the changeover switch is a mechanical relay, the response time will influence minimum turnaround time and, in addition, will impose serious reliability limitations in the equipment. If the switch is of solid-state design, insertion loss will tend to be higher than for a mechanical relay, and driver/switch sequencing controls must be added to the equipment to achieve proper and reliable operation of the switch.

For our purposes, the use of a diplexer-filter appears to be the best choice since it will readily accommodate the requirements of any system configuration and, even where not initially needed, would provide an equipment which is readily adaptable to evolutionary expansion of AEROSAT services.

A. 4. 4 Doppler Correction Provisions

Because the return link (aircraft-to-ground) proposed for all system approaches will use an FDMA approach, each individual aircraft addressing a particular frequency channel will be offset at the ground terminal from the channel center frequency by an amount corresponding to the sum of the frequency uncertainty of the aircraft frequency source and the Doppler frequency due to that aircraft's relative motion with respect to the satellite. To avoid the need for a separate frequency-phase acquisition for each aircraft's message at the ground terminal, it is desirable to apply Doppler correction to the return link frequency at the aircraft. A detailed discussion of these correction requirements (and the supporting return link message format) is presented in Section 6.

Several techniques are available for application of Doppler correction at the aircraft. The exact method and detailed implementation techniques depend, to a degree, on the precise system configuration. For example, if a full-time supervisory signaling channel is available, the Doppler offset may be measured continuously from the supervisory channel carrier, and a scaling factor applied (corresponding to the receive-to-transmit frequency ratio) to the transmitted signal frequency. Alternatively, if the forward link is TDMA only (as in the System C configuration) the Doppler estimate must be derived from a sample of the carrier detector loop. It is important to note that if the system is planned to incorporate Doppler correction at the aircraft and no acquisition search is provided at the ground terminal, then entry of an aircraft

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* For example, an initial system providing only communications service may be configured to operate with an antenna changeover switch, but the future addition of a surveillance/navigation function would require extensive retrofit to incorporate simultaneous receive-transmit capability.

into the system (i.e., via the air-to-ground on return link) must be preceded by carrier acquisition in the forward link.*

Under the assumption that the operational implications of Doppler correction at the aircraft are accommodated by system/procedural design, the following considerations presented in the succeeding paragraphs are applied to the AEROSAT Avionics equipment.

A.4.4.1 Local Oscillator Choice - Receiver and Transmitter (Upconverter)

Where Doppler correction is applied, the choice of upper or lower sideband selection of mixer outputs cannot be arbitrarily made. Consider for example the case of a signal $(f_o + \delta)$, where f_o is the channel center frequency and δ is the Doppler frequency. For high side mixing (i.e., $f_{Lo} > f_o$), the IF output is the lower sideband of the mixing process; i.e.:

$$f_{IF} = f_{Lo} - (f_o + \delta) = f_{Lo} - f_o - \delta \tag{4-1}$$

and the Doppler component has reversed sense.

However, if low side mixing is used (i.e.: $f_{Lo} < f_o$), the upper sideband is the IF output:

$$f_{If} = (f_o + \delta) - f_{Lo} \tag{4-2}$$

and the Doppler component is not inverted in sense. Note, however, that if the local oscillator has a frequency uncertainty (u):

$$f_{Lo} = (f_s + u). \tag{4-3}$$

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*This may imply that an emergency or special calling channel must contain ground terminal provisions for frequency search. In addition, an emergency message format generated at the aircraft would be required to contain an adequate preamble to allow for ground terminal acquisition. This, of course, assumes that under emergency conditions (or in case of receiver failure) the forward link signal may not be acquired at the aircraft.

The uncertainty would be added in the case of high side mixing, but subtracted in the case of low side mixing. Thus, the sense of the frequency uncertainty of the LO source is always opposite to the sense of the Doppler component of the incoming signal.

For a double conversion process (such as would be used in the AEROSAT Avionics receiver) the sense of the Doppler frequency error and LO frequency source error are as shown in Table A-8.

Table A-8. Sense of the Doppler Frequency Error and LO Frequency Error

1st Mixer LO	2nd Mixer LO	Doppler Sense at IF Output	LO Error Sense at IF Output
Low side	Low side	$+\delta$	$-u$
High side	Low side	$-\delta$	$+u$
Low side	High side	$-\delta$	$+u$
High side	High side	$+\delta$	$-u$

Thus, the choice of LO frequencies and the use of high side versus low side mixing must be made based on obtaining the proper sense of Doppler offset at the IF output and consistent with avoiding detrimental image frequency or internally generated LO frequency components in the equipment (for example, choosing a plan which would place the receiver image in the uplink frequency band on having an LO harmonic falling within the downlink frequency hand).

A. 4. 4. 2 Methods of Applying Doppler Correction

Two méthods are readily apparent for application of Doppler correction to the return link:

1. Inverting the sense of the Doppler frequency at the input to the receiver carrier detector loop and using the detector loop VCO output directly to drive the equipment modulator (after suitable frequency scaling). This method provides exact Doppler correction but doubles the frequency error due to LO frequency uncertainty.

2. Sensing the loop error voltage at the receiver carrier detector loop and, with suitable error voltage scaling, applying the error voltage to the transmitter modulator frequency control oscillator (nominally a VCXO). As in the preceding case, frequency error due to LO frequency uncertainty is doubled; however, the choice of receiver LO frequencies (and use of high side versus low side mixing) is not as critical as with the first scheme.

From a design standpoint, the first approach is most straightforward and should be employed if there are no problems encountered in receiver image or LO spurious response placement. A block diagram for the functional implementation of the first approach is presented in Figure A-9.

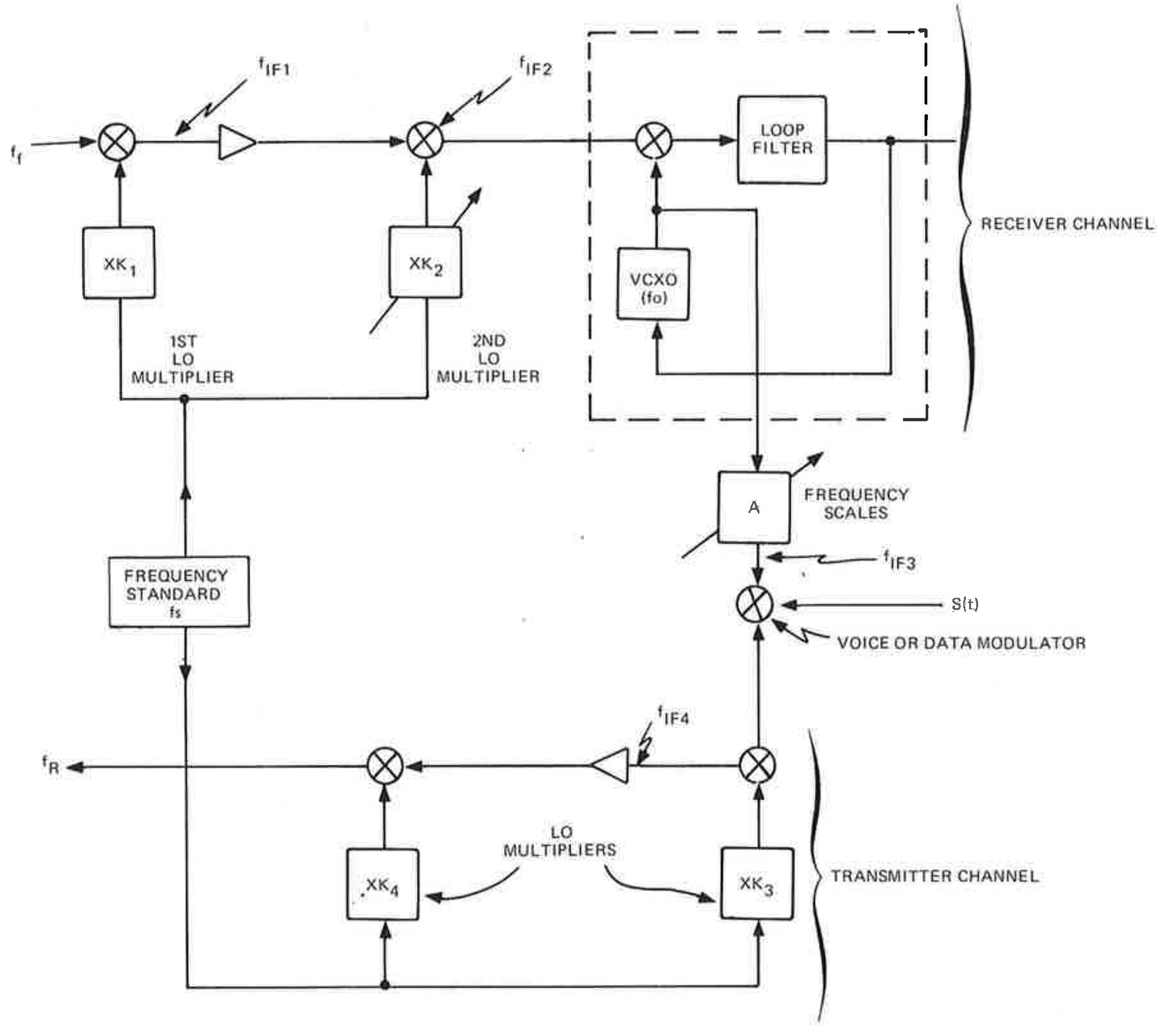

Figure A-9. Functional Block Diagram for Doppler Correction in Avionics Equipment

A.5 CANDIDATE EQUIPMENT CONFIGURATIONS

From the five possible system configurations (A through C-1) a matrix of service mix versus system configuration was developed. This matrix is presented in Table A-9. From this matrix, it was found that for a given service mix, the same equipment functional configuration could be applied to all systems employing a FDMA multiple access method - that is, Systems A, B and B-1. The actual differences from system to system would be in transmitter size (as determined from the system link budgets and some relatively minor factors in the detailed implementation of the equipment control function). Five separate FDMA equipment functional configurations were developed. These are presented in Figures A-10 through A-19. Of these configurations:

1. Either equipment configuration 2 or 2A, with one or two transmitters, is appropriate for system configuration A
2. Equipment configuration 1 is applicable to system configuration B
3. Equipment configuration 2 is applicable to system configuration B-1 without independent surveillance, or equipment configuration 4 is applicable to system configuration B-1 with independent surveillance considerations.

For the TDMA Systems (C and C-1), a total of five additional equipment configurations were identified, as shown in Figures A-11 through A-18. Of these, equipment configurations 5 and 6 are designed for TDMA - system configuration C only. The remaining equipment configurations (7-9) incorporate provisions for both TDMA reception in the multiple narrow satellite beam with FDM reception of earth coverage supervisory signaling and/or independent surveillance channel(s) of system configuration C-1. Of these, the viable equipment configuration candidates are configuration 5 for System C, configuration 7 for System C-1 with dependent surveillance, and configuration 9 for System C-1 with independent surveillance. These configurations are presented in Figures A-15 through A-19.

Table A-9. Equipment Configuration as a Function of System

System Type	Satellite Antenna Configuration	Multiplexing (Forward Link)	Service Provided[1] V/D	O/W	Ind. Surv.	Comb. O/W-Surv.	Equipment Functional Configurations	Remarks
A	Global	FDMA	X				1	Basic voice/data capability only
			X	X			2, 2A	See Note 2
			X	X	X		3	
			X			X	4	
B	Triple Beam	FDMA	X				1	
			X	X			2, 2A	
			X	X	X		3	
			X			X	4	
B-1	Global & Triple Beam	FDMA	X				1	
			X	X			2, 2A	
			X	X	X		3	
			X			X	4	
C	Multiple Narrow Beam	TDMA	X				5	
			X	X			6	
C-1	Global and Multiple Narrow Beam	TDMA on Narrow Beam w/Global Coverage FDM w/ TDM Channels	X	Global			7	Receiver designs incorporate both TDMA and FDM provisions
			X	Nar. Beam	Global		8	
			X			Global	9	

NOTES:

1. O/W: Orderwire or supervisory signalling channel capacity
   Ind. Surv.: Independent Surveillance channel capability
   Comb. O/W-Surv.: Combined - common channel supervisory signalling and independent surveillance
2. Configuration 2 produces totally independent supervisory signalling while 2A requires voice or data interrupt for supervisory signalling

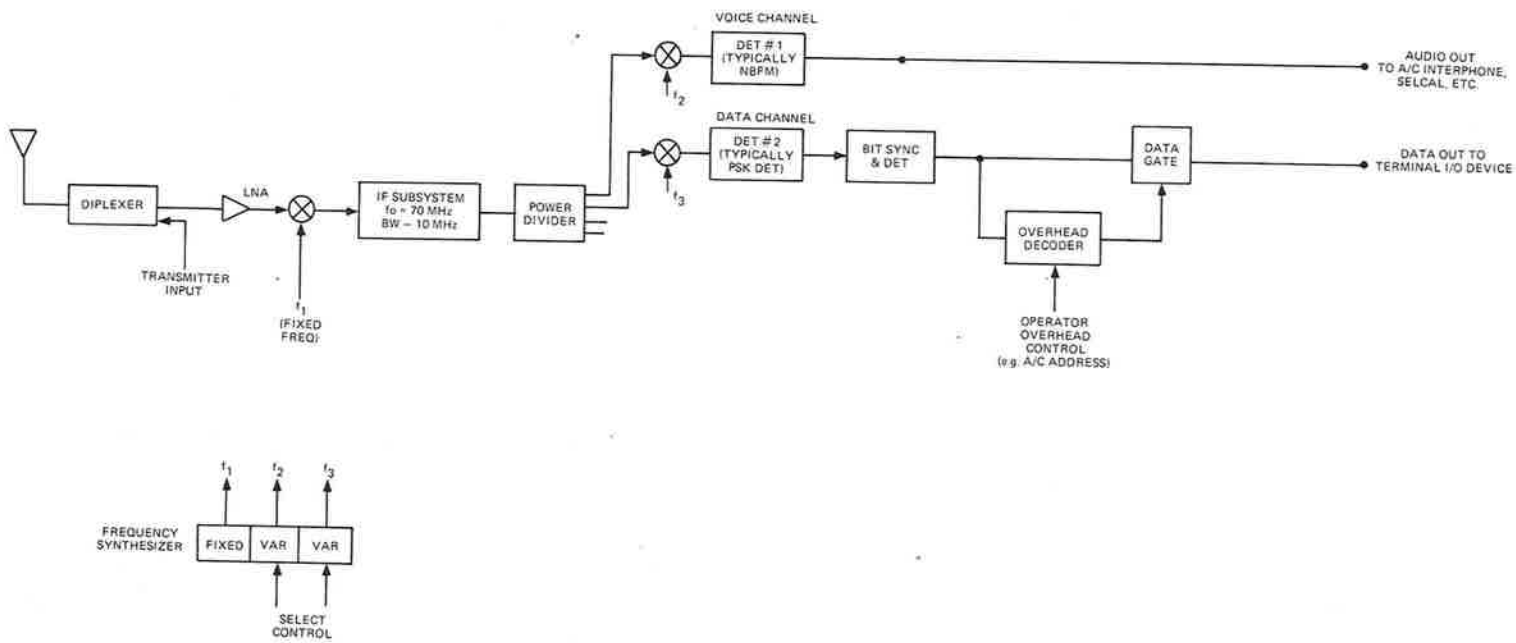

Figure A-10. AEROSAT Avionics Configuration 1 FDMA Receiver With Voice/Digital Capability Only

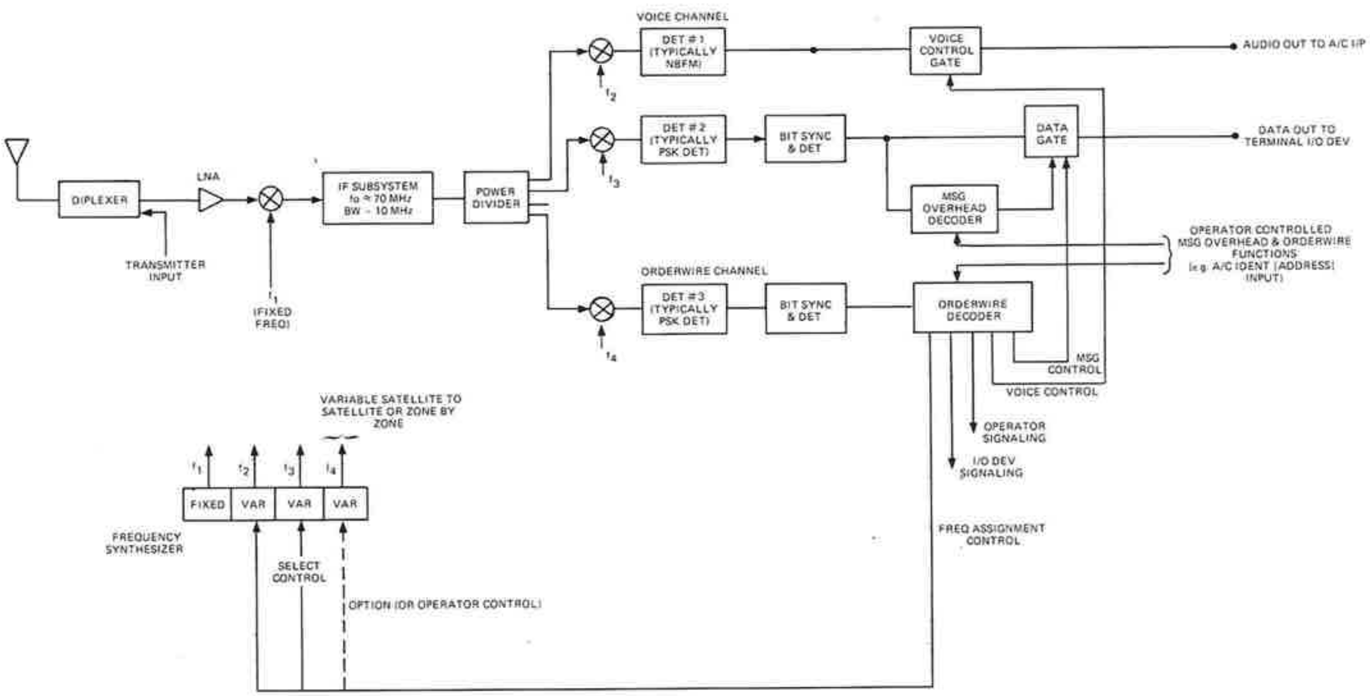

Figure A-11. AEROSAT Avionics Configuration 2 FDMA Receiver with Voice/Digital and Separate Orderwire Channel (Independent) Operation

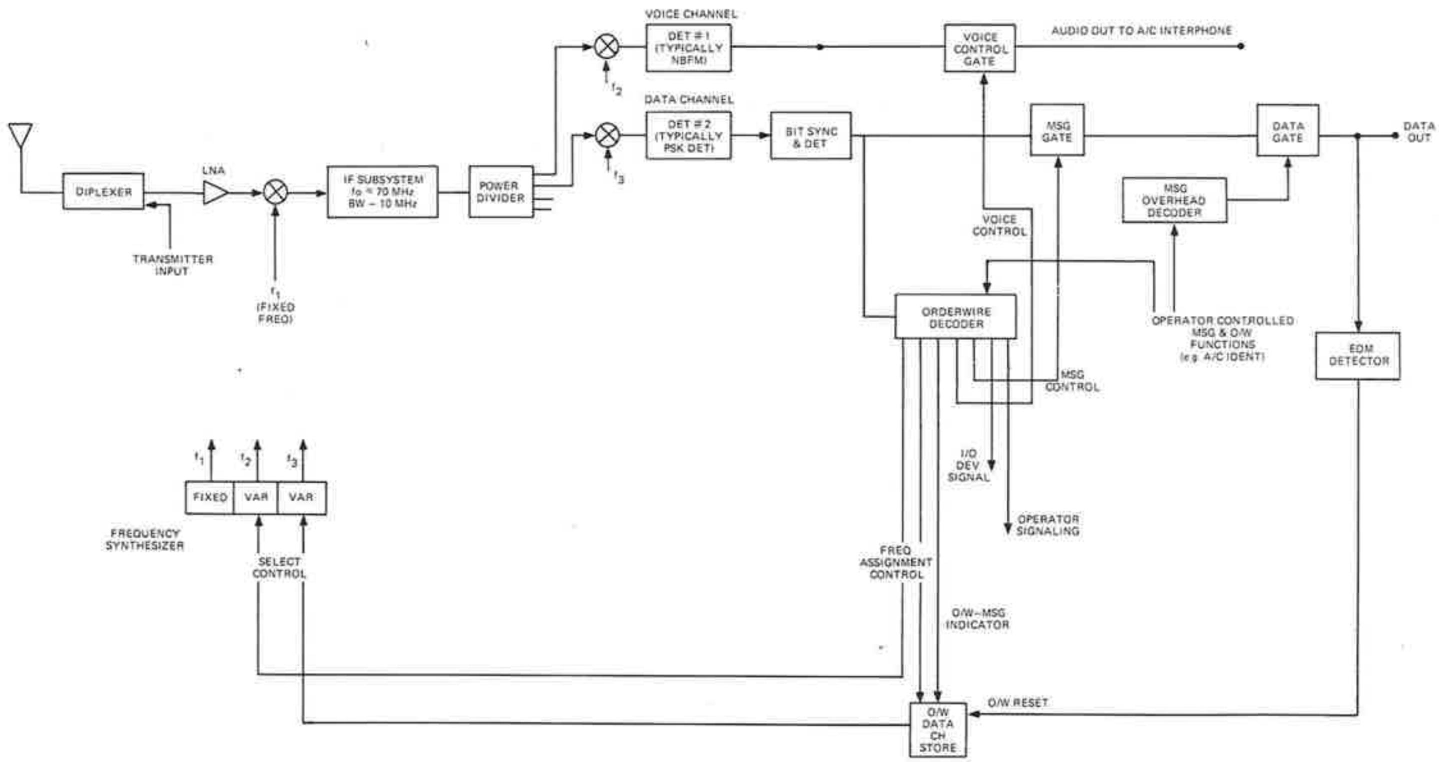

Figure A-12. AEROSAT Avionics Configuration 2-A FDMA Receiver with Voice/Digital and O/W Shared with Data Detection

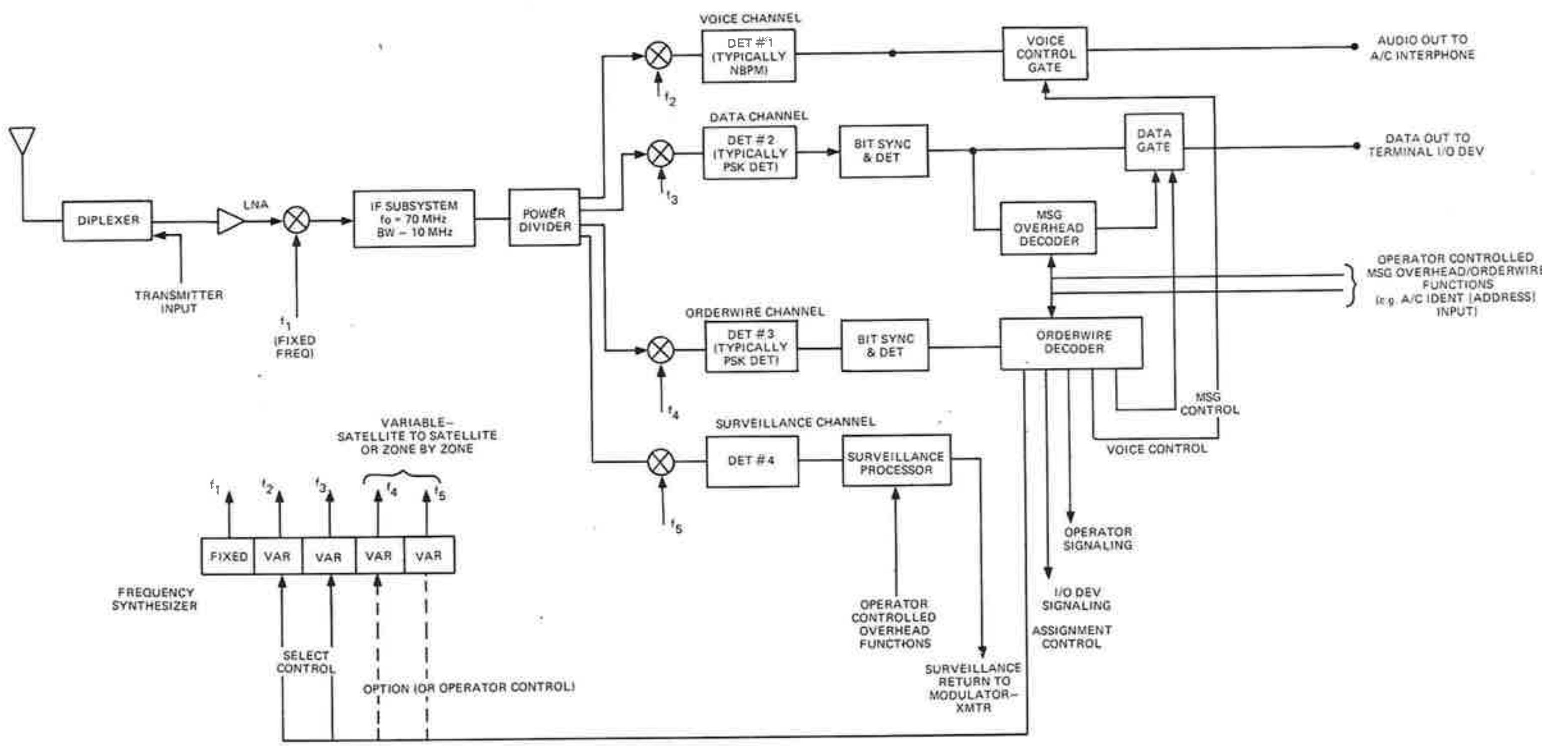

Figure A-13. AEROSAT Avionics Configuration 3 FDMA Receiver With Voice/Digital and Separate Orderwire Channel (Independent) Operation and Separate Surveillance Channel

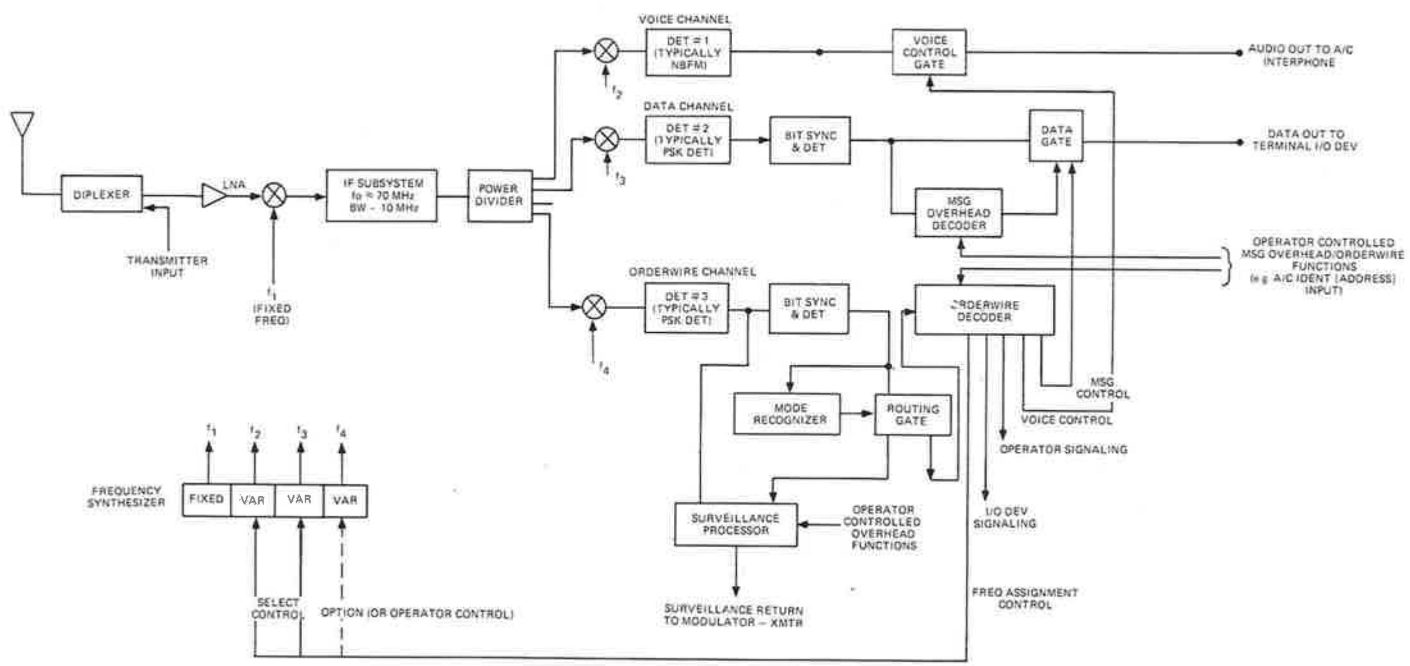

Figure A-14. AEROSAT Avionics Configuration 4 FDMA Receiver with Voice/Digital and Combined O/W - Surveillance Channel

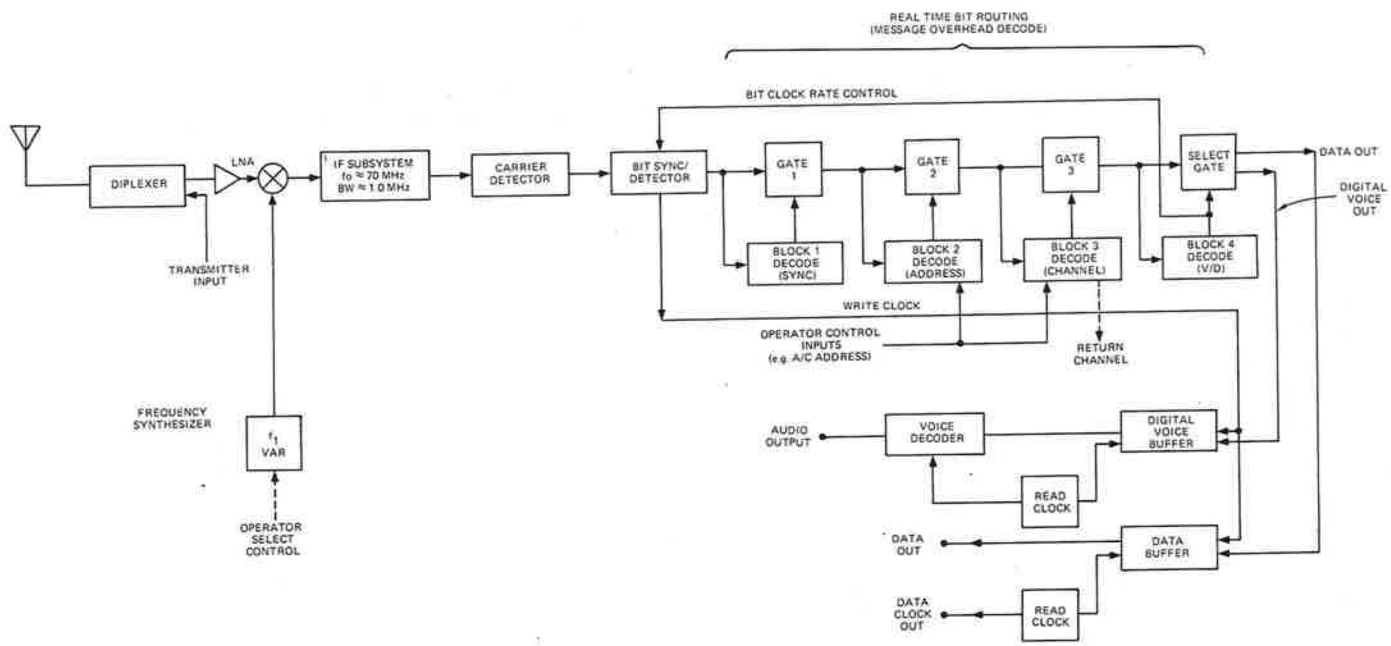

Figure A-15. AEROSAT Avionics Configuration 5 TDMA (Independent Burst) Receiver with Voice/Digital Capability Only

Table A-10. AEROSAT Avionics - Internal Frequency Generation/Control Selections

Item	Symbol	Function	Determination	Probable Range
1	f_1	1st Mixer L.O.	Determined by choice of 1st IF frequency (f_{IF1}) (and receive frequency).	1450-1650 MHz
2	f_{IF1}	1st IF Frequency	Chosen sufficiently low to permit high out of band signal rejection (high filter Q) but high enough to permit high (> 60 dB) image rejection by diplexer-preselector filter.	50-100 MHz
3	f_2	2nd Mixer L.O.	Determined by 1st IF frequency and choice of 2nd IF frequency (and receive frequency).	40-90 MHz
4	f_{IF2}	2nd IF Frequency	Chosen sufficiently low to permit high adjacent channel signal rejection (high filter Q) but high enough to avoid image within acquisition or pull-in range of carrier detector loop.	5-15 MHz
5	VCO #1	Carrier Det.	VCO frequency centered on 2nd IF frequency.	5-15 MHz
6	VCO #2	Receive Bit Clock	VCO frequency centered on received (forward link) bit rate.	1200 bps - FDMA 500 kHz (max) TDMA
7	01	Local Bit Clock	Used for on-board data synchronization at standard bit rate (e.g., 1200 - 2400 bps).	1200 bps - data 19.4 kbps - digital voice
8	02	Transmit Bit Clock	Synchronizes/converts local bit rate to transmit bit rate suitable for return link transmission.	1200 bps
9	f_B	Modulator Drive	Based on choice of f_{IFA} and transmit frequency.*	5-15 MHz and 40-90 MHz
10	f_{IFA}	Transmitter IF Input	Chosen low enough to permit implementation of modulator, but sufficiently high to avoid image from falling in bandpass of Xmtr-power amplifier.	40-90 MHz
11	f_B	Upconverter Mixer L.O.	Based on choice of f_{IFA} and transmit frequency.	1550-1700 MHz

*May require double upconversion process, hence 2 frequency choices.

Table A-11. Channel Separation/Selection Requirements as a Function of Satellite Antenna Configuration

Satellite Antenna Configuration	Multiple Access Method	Service Provided: V/D	Service Provided: O/W	Service Provided: Ind. Surv.	Service Provided: Comb. O/W-Surv.	Channel Separation	Channel Outputs	Channel Selection
Global (A) (Equipment Configurations 1, 2, 2A, 3, 4)	FDMA	X X X X	 X X 	 X 	 X	Multiple 2nd Mixer FDM Receiver	2 2 or 3(1) 3 or 4(1) 4	2nd Mixer L.O. Tuning ($1 \leq N \leq 320$) 2 x 320 discrete channels (2 x 320) or 2 x 320 + 1 x N discrete channels (2 x 320 + 1 x N) or 2 x 320 + 1 x N_1 + 1 x N_2 discrete channels 2 x 320 + 1 x N discrete channels
Triple Beam (B) (Equipment Configurations 1, 2, 2A, 3, 4)	FDMA	X X X X	 X X 	 X 	 X	Multiple 2nd Mixer FDM Receiver	2 2 or 3(1) 3 or 4(1) 4	2nd Mixer L.O. Tuning ($3 \leq N \leq 320$) 2 x 320 discrete channels (2 x 320) or 2 x 320 + 1 x N discrete channels (2 x 320 + 1 x N) or 2 x 320 + 1 x N_1 + 1 x N_2 discrete channels 2 x 320 + 1 x N discrete channels
Global & Triple Beam (B-1) (Equipment Configurations 1, 2, 2A, 3, 4)	FDMA	X X X X	 X X 	 X 	 X	Multiple 2nd Mixer FDM Receiver	2 2 or 3(1) 3 or 4(1) 4	2nd Mixer L.O. Tuning ($3 \leq N \leq 320$) 2 x 320 discrete channels (2 x 320) or 2 x 320 + 1 x N discrete channels (2 x 320 + 1 x N) or 2 x 320 + 1 x N_1 + 1 x N_2 discrete channels 2 x 320 + 1 x N discrete channels
Multiple Narrow Beam (C) (Equipment Configurations 5, 6)	TDMA	X X	 X			Routing Logic w/ Multiple Buffers	3(2) 3	Requires Band Selection Q Bands (Tuning 1st or 2nd L.O.) Plus Time Decoding (via routing logic) Same as Above
Global and Multiple Narrow Beam (C-1) (Equipment Configurations 7, 8, 9)	TDMA on Narrow Beam w/Global Coverage FDM w/ TDM Channels	X X X	Global Nar. Beam	Global	Global	Same as Above plus Separate Freq. Channel for Global	3(2) 3 4 4	Q Selectable Bands (tuning 1st or 2nd L.O.) plus Time Decoding with Predetermined FDM/TDM Frequency Allocations

Notes: 1) Lower number of channel outputs (separators) needed if voice/data interrupt is permitted for O/W operation.
2) TDM receiver contains limited (but necessary) overhead or orderwire functions in the message structure.
3) O/W or surveillance channel(s) may be global or narrow beam without impact to avionics receiver.

APPENDIX B - REPORT OF INVENTIONS

After a diligent review of the work performed and results obtained under this contract, it has been determined that no inventions, innovations or new products have been developed.