# IMPROVING THE NATION'S AIR TRAFFIC CONTROL SYSTEM

A Report of the

Ad Hoc Air Traffic Control Panel

of the

President's Science Advisory Committee

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Years of neglect have permitted the problems of air
transportation in America to stack up like aircraft circling
a congested airport.

The challenge confronting us is not one of quality,
or even of technology.  Our air traffic control system
is the best in the world; our airports among the finest
anywhere.  But we simply do not have the capacity in our
airways and airports ample to our present needs or
reflective of the future.

. . . development for the 1980s and beyond cannot
be neglected.  Technology is moving rapidly and its
adaptation to provide future solutions must keep pace.

Richard Nixon

June 1969

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Note:    This report was substantially completed December 1970.
         It has been updated since that time only by editorial
         modifications, including the addition of more recent
         references where that seemed helpful to the reader.

# IMPROVING THE NATION'S AIR TRAFFIC CONTROL SYSTEM

## EXECUTIVE SUMMARY

### BACKGROUND

The air traffic control system in the United States operates
precariously close to saturation. Costly delays develop under peak
traffic loads and there is little flexibility to respond to
perturbations in the system, such as adverse weather, equipment
failures, and minor accidents. Congestion at major terminals has
developed into a national problem forcing short-term remedial
action by the FAA (Federal Aviation Administration) to alleviate
the most critical system deficiencies. Thus, restrictions have
been placed upon the numbers of aircraft movements at a number of
major terminals and a process of dynamic rescheduling of traffic to
respond to extended delays in the system--called flow control
--has been instituted to accommodate the propagation of delay from
one part of the system to other segments that are also operating
close to capacity.

In addition to these weaknesses of the system, the cost of
operation and maintenance has continued to rise--to almost $1
billion annually--in part because the present control process
depends upon manpower to perform tasks that could be automated.

If ATC (air traffic control)* delays and, especially,
increased schedule time caused by lack of an adequate ATC system
cost the airlines nearly $400 million[1] in 1970, as they did in
1969, the elimination of these costs of fuel, crew, and reduced
utilization would have resulted in a profitable year for the air-
carriers* rather than an industry-wide loss.

This saturation of the ATC system did not result from a
dramatic and sudden surge in air traffic, but developed slowly
during the 1960's as a result of increasing air-carrier and general
aviation activity, relatively static airport capacity, and
inadequate productivity increases within the ATC system. The
history of the growth of the ATC problem has been well documented[2].

The growing realization of the need for system improvement led
the DoT (Department of Transportation) to convene the ATCAC (Air
Traffic Control Advisory Committee*) that reported in December
1969[3]. The ATCAC outlined a technical approach to improve system
performance and was intended to provide adequate system capacity
until the late 1980's or mid-1990's. The ATCAC approach was based
upon

(a) improving the present radar-beacon* tracking system,

(b) increasing airport capacity, and

(c) incorporating a collision avoidance system (CAS)* through ground-controlled data-link*--called IPC (intermittent positive control)*.

In addition, the ATCAC urged "an early review ...to determine the new organizational and contractual arrangements necessary to ensure the timely completion of a program of the magnitude and urgent national priority recommended." The FAA has adopted these major recommendations as a basis for its long-range system improvement program. In the short term the FAA will continue the limited automation of radar-beacon tracking and flight plan-following which constitute the initial phase (NAS stage A Enroute System and ARTS III)* of the transition to an automated system.

The ATCAC study provided valuable insight into improvements that might be applied to existing equipment and to extension of the present control philosophy.

The ATCAC recognized, however, that its recommendations for system improvements were likely to lead to "significant deficiencies" under traffic densities predicted to occur before the end of the century. The approach suggested by the ATCAC would have required an ever-growing number of highly-trained controllers (more than 35,000 by 1980, almost a doubling of the current number, at an even greater increase in cost). The ATCAC saw the likelihood of continued system saturation and noted that coverage from navigation and surveillance systems would likely be inadequate for VTOL (vertical takeoff and landing)* and STOL (short takeoff and landing)* air-carrier needs, for general-aviation* and air-carrier needs in remote areas, and (if control services were to be required) for the expected general-aviation traffic in the neighborhood of major terminals. Both satellite systems and full automation of the control functions were recognized as offering the greatest potential for solving these difficulties, but practical application was not considered to be possible before 1990.

One additional recent development bears upon the future mechanism for ATC system improvement. The Airport and Airway Development and Revenue Act of 1970 established the principle that revenues for the support of system improvement will be derived from taxes upon the users of the system. This new Trust Fund is predicted to provide almost $10 billion over the next 10 years for support and expansion of airports and airways.

ESTABLISHMENT OF PANEL

The President's Science Advisory Committee reviewed these developments and the proposed initial steps by the FAA to implement a program to achieve a new level of performance for the a National Aviation System over the next 10 years.

The FAA planning appeared to be an important first step in approaching needed major systems improvements. However, there were deficiencies in several areas, including lack of emphasis on the systems aspect of the problem, inadequate attention to reducing the increasing costs of the ATC system, inadequate funding for research and development activities (projected at that time by FAA at a constant level of $60 million annually for the decade), indications of little coordination with DoD (Department of Defense) on planning of subsystem elements, and limited investigation of alternative technological approaches to various subsystems. In addition, no management structure had been established for carrying out a large-scale research, development, demonstration, test and evaluation program adequate to meet future needs. In general, at that time there was neither the management focus nor the parallel program alternatives necessary for a high-confidence program in this important area.

Therefore, in January 1970, the President's Science Advisory Committee established an _ad_ _hoc_ Panel to examine the needs and opportunities for improving the nation's ATC system and the FAA's plans for proceeding with system development. Particular emphasis was to be given to systems and management aspects, with due consideration of recent previous studies and new legislation, the character of projected demands upon the system, and the potential contributions of advanced technology.

The Panel received and studied information in the form of reports and briefings from a variety of sources. Visits have been made to the Transportation Systems Center, to the National Aviation Facilities Experimental Center, and to operating air traffic control installations. In the course of its activities the Panel heard from: pilots, AOPA (Aircraft Owners and Pilots Association) and ALPA (Air Line Pilots Association International); controllers; business and professional associations, NBAA (National Business Aircraft Association), ATA (Air Transport Association of America); the Civil Aeronautics Board; the FAA; the DoT; and numerous aerospace firms. Some contract support for the Panel activities was obtained from the Rand Corporation, and discussions with representatives of the Mitre Corporation assisted the Panel in defining its views. Continuing contact with the leadership of the FAA and with the Assistant Secretary of Transportation for System Development and Technology has been most helpful in the exchange of information and understanding.

DISCUSSION OF MAJOR ISSUES

Management changes and a broadened approach to technical alternatives have occurred during the course of the Panel's study. In the DoT, the Office of the Assistant Secretary for Systems Development and Technology has been strengthened by the addition of staff positions and a field center, the Transportation Systems Center at Cambridge (formerly the Electronics Research Center of the National Aeronautics and Space Administration), has been established to assist in supporting department activities. Within the FAA, research and development activity has been given increased priority and a new Office of Systems Engineering Management has been established to provide central direction to the program of upgrading the air traffic control system. New efforts are under way to define subsystem alternatives and to prepare realistic budget proposals based upon defined objectives with associated program schedules and costs.

These steps, coupled with an assured continuing base of funding support now available through the Airport and Airway Trust Fund, are as important to the task of defining and implementing an improved ATC system. However, given the complexity of the task and the diverse forces that will press for selection of particular subsystems or equipment, a key question remains concerning the adequacy of the management organization for accomplishing the program. It is the Panel's view that improvement of the ATC system should become a national commitment and that a stronger management structure is required.

Beyond a strengthened management structure, there are additional technical approaches that should be explored, for even if there were no further increase in air traffic there would be a need for system improvement in order to reduce operating cost of air traffic control, to enhance safety, and to increase system capacity so as to reduce the cost of delays and increased scheduled time resulting from the inadequacies of the control system. Projected demands for ATC services over the next decade (a threefold increase) and beyond (eightfold increase by 1995) heighten this need. A major part of the increased traffic will be general-aviation aircraft--a class of user that is expected to grow significantly in number and in sophistication. In addition, the Panel believes there is a growing need for the introduction of VTOL and STOL air-carrier operations for short-haul applications, where flexibility of service is advantageous, and for increasing the capacity of existing airfields by VTOL operations. Projected increases in demand for ATC services are not based upon a large VTOL component, and the Panel's conclusions regarding the ATC system are generally independent of this aspect. Nevertheless, the Panel expects an increasing level of VTOL and STOL operations that will impose special requirements upon the ATC system.

It is apparent to the Panel that a new approach is needed if we are to achieve a system with a high degree of flexibility that

will operate far from capacity. Emphasis must be placed on a vigorous program of research, development, demonstration, and evaluation leading to an overall coordinated system design. Long lead times are required for implementation of new equipment in the ATC system because of the many diverse users and large in-plant investment. For this reason, a new system must be designed to accommodate projected demand over an extended period, implying both a high degree of system flexibility and adoption of system modifications with projected lifetimes adequate to anticipate growth in demand. The time required to select a system approach, with the finite possibility that any given choice will prove to be inadequate, creates the need for parallel exploratory development programs to minimize the likelihood of extensive program delay. For example, this philosophy convinced the panel that technical approaches in addition to development of the discrete address beacon transponder with data-link should be explored for accomplishing the surveillance function during the 1980's.

The Panel believes that automation of the control function based upon strategic-control* of aircraft offers the greatest potential for increasing the capacity and safety of the airways and for reducing future operations costs for the system. Strategic-control implies providing a conflict-free flight path, with the pilot responsible for maintaining the aircraft on the flight plan within time constraints determined for the particular region of flight. Many of the elements for such a highly automated system can be identified, for the basic functions that must be performed in the ATC process remain the same across a broad range of feasible approaches to system design. These include surveillance (determining where aircraft are in three dimensions and in time), navigation (enabling an aircraft to determine its flight path in three dimensions and in time), communication (providing the means of transferring instructions or information between elements of the system), and control.

In each of these functional areas, the Panel has identified subsystems that would be candidate elements of a total system. For example, in order to improve communications capability and to assist in the provision of automated conflict resolution, ground-air-ground data-links appear to offer important advantages over extensions of present voice links. Such data-links would serve to communicate the few stereotyped messages required for IPC, while for aircraft equipped with a printer or some other highly capable display device, data-link could handle additional ATC messages. Many of the components of candidate data-link systems have been demonstrated, but it remains to specify the functions to be performed, interfaces with other ATC system elements, frequency, and the test, evaluation, and implementation plan.

Similarly, the Panel has investigated all-weather landing systems and other aids to navigation, including the potential

contribution of satellite-based systems to both navigation and surveillance functions. The ATCAC considered an ATC satellite system to handle all three tasks of surveillance, navigation, and communication, but they judged it infeasible in the 1980 time period. Indeed, the full ATC communications load exceeds present and foreseeable satellite capabilities, but it has become clear during the Panel investigation that satellites can play an important and cost-effective role in navigation, surveillance, and the limited communication load implied by IPC.

From its review, the Panel is convinced that a satellite-based aircraft surveillance and navigation system could offer a capability superior to that of any ground-based system yet proposed. The Panel is cognizant, however, of the substantial cost required to develop and deploy such a satellite system. It recognizes the possibility that the DoT, on its own, might not be justified in pursuing to completion this alternative. On the other hand, the Panel is also aware of the very real needs of the DoD in this area--needs overlapping those of the DoT. Accordingly, it believes there is an attractive and urgent opportunity for the DoD and the DoT to explore, jointly, the feasibility and desirability of a satellite-based surveillance and navigation system to serve both military and civilian needs. The Panel believes that such a joint system can be available in about six years, if an intensive development program costing about $100 million is executed over the next 3 to 4 years.

In addition to specific subsystem elements performing the basic functions outlined above, the Panel supports adoption of an operational philosophy that includes cooperative surveillance of all aircraft, IPC to insure positive separation for aircraft in controlled-airspace*, tight time control of flight progress in the vicinity of terminals and on low altitude V/STOL (VTOL and STOL) routes with progressively less time control en route, and revised airspace structure to provide better separation between controlled-* and uncontrolled-aircraft*.

It is the Panel's view that, in all areas of ATC activity, reduced cost of operations and of user equipment should be important objectives and that appropriate incentives to this end should be established.

MAJOR_RECOMMENDATIONS

To implement an ATC improvement program at reasonable cost, the Panel recommends the following:

1. At any particular level of ATC services, setting cost reduction as a specific goal.

2. A very substantial augmentation in Airports/Airways research and development funds to develop the means to increase the capacity of the ATC system. For this purpose, the Panel recommends an increase of the Airports/Airways research and development budget to about $150 million annually for the next eight years.

3. Recognition of the value of flexibility in the new ATC system. Similarly, the program for achieving it must not be a rigid single approach but must provide sufficient alternatives to support system choices in a timely fashion.

4. Consideration be given to the establishment within the DoT of a special Executive Agency for Air Traffic Control System Improvement, responsible for the design, verification, and deployment of an improved ATC system. The Director of the Agency would report to the Office of the Secretary of Transportation and would provide a central point of program and budgetary control and direction.

Establishment of a Technical Advisory Committee reporting to the Director of the Agency for Air Traffic Control System Improvement and to the Secretary of Transportation.

Establishment of a User Advisory Group reporting to the Director of the Agency for Air Traffic Control System Improvement.

While details of an improved ATC system certainly cannot be fixed prior to the accomplishment of the recommended research, certain broad elements and characteristics of the system are sufficiently clear that the Panel recommends:

5. Commitment to deployment of an ATC system in which control by the FAA is largely automated and consists of strategic-control of aircraft movements rather than detailed move-by-move tactical-control*, and in which aircraft have adequate on-board capability for adherence to a precise filed flight plan.

6. Extending system automation to include certain terminal and en route functions.

7. Provision of dual-lane-runways* at high-density airports, with high-speed access, egress, and taxiways.

8. Demonstration of technical feasibility and system capabilities of quiet VTOL with ATOL (automatic takeoff and landing) capability as a tool toward the resolution of the airport and runway congestion problem. More intensive use of existing runways and the construction of new runways offer

only limited increases in capacity (by 2-3 times). VTOL, when achieved, offers at least a 10 times increase in capacity of existing airports for shorter-haul traffic.

9.    In view of the benefits available to civil air transport and military forces, joint exploration by DoT and DoD of a Navigation Satellite Service for military and civil aircraft over the United States, with characteristics providing flexible, economic, and precise navigation to air-carriers and other similarly equipped aircraft. The Navigation Satellite Service satellites could also provide a platform for FAA precision surveillance of cooperating aircraft.

## CONCLUSION

The initial commitment to airport and airway improvements has been made in the legislation establishing the Airport and Airway Trust Fund. With strong project leadership and a vigorous research, development, demonstration, and evaluation program in the next decade, the nation can achieve the objective of a greatly improved ATC system. An effective program to meet this objective is necessary to assure continuing growth and high productivity of domestic air transportation services, a resource of major importance to our national life and commerce.

NOTES AND REFERENCES

1.  Including loss of aircraft utilization (see Note 5, page 1-10 of this report).

2.  <u>Problems Confronting FAA in the Development of an Air Traffic Control System for the 1970's</u>, Hearings before Government Activities Subcommittee (Jack Brooks, Chairman) of a Committee on Government Operations, January 27, 1970.

3.  Report of the Department of Transportation Air Traffic Control Advisory Committee, December 1969.

MINI-GLOSSARY FOR EXECUTIVE SUMMARY


Air Carrier                     An aircraft or organization certified
                                by the FAA for the purpose of carrying
                                goods or persons commercially by air.

Air Traffic Control             A service that promotes the safe,
    (ATC)                       orderly, and expeditious flow of
                                air traffic, including airport
                                approach and enroute air traffic
                                control.

Automatic Radar Control         A partially-automated data processing and
Terminal System--               display system that is being added to
Third Generation                existing terminal equipment.
    (ARTS III)

Collision Avoidance             A device that can warn of the presence
System                          of other aircraft similarly equipped,
    (CAS)                        assess a potential collision hazard, and
                                provide appropriate command signals
                                indicating the proper evasive maneuver.

Controlled Airspace             Defined region in which FAA may carry
                                out a control function, specifically
                                traffic separation service.  It may
                                contain controlled and uncontrolled,
                                i.e., VFR aircraft.

Data Link                       Any communication channel or circuit used
                                to transmit data from a sensor to a
                                computer, a readout device, or a storage
                                device.

Dual-Lane Runway                As described in the ATCAC Report, a pair
                                of runways a few hundred feet apart,
                                one used exclusively for takeoffs and
                                the other for landings.  The sequencing
                                of takeoffs and landings in this way is
                                more efficient than on a common runway.

General Aviation                All aircraft that are neither military
                                nor commercial aircraft.

Intermittent Positive           A control concept in which aircraft are
Control                         advised of threats due to other aircraft,
    (IPC)                       weather, airspace boundaries and surface
                                obstacles, and given commands for
                                appropriate evasive maneuvers.  This


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|  | service could be provided to both controlled and uncontrolled aircraft. |
|---|---|
| NAS Stage A En Route System | A partially-automated system of en-route ATC providing alphanumeric information on en-route radar displays and flight data processing. |
| Radar Beacon | A radar receiver-transmitter that transmits a coded signal whenever its receiver is triggered by an inter-rogating radar. The coded reply can be used to determine position in terms of range and bearing from the beacon. Also called beacon or radar transponder. |
| Short Takeoff and Landing STOL | Aircraft that have performance charac-teristics allowing use of considerably shorter runways than standard fixed-wing aircraft. |
| Strategic Control | Strategic control of an aircraft by ATC implies permission to fly a complex, precisely-specified flight path. ATC retains responsibility for authorizing, modifying and monitoring compliance by the aircraft in executing the agreed flight path. A specified flight path may include the complete trajectory with 10-20 precise three-dimensional way-points. Responsibility for executing the agreed flight path would remain with the pilot of the aircraft. |
| Tactical Control | Control of an aircraft flight path through a series of commands, each guiding the aircraft through short segments of its intended flight. |
| Uncontrolled Airspace | Airspace outside the airways, positive controlled airspace, terminal and special purpose areas. |
| Vertical Takeoff and Landing (VTOL) | Aircraft which have performance charac-teristics permitting vertical or almost vertical takeoffs, landings, and climb and descent angles. |

## 1.0 INTRODUCTION

In 1968 and 1969, extensive delays encountered at the nation's largest airports sharpened a growing recognition of the need for major improvements in the ability of the present ATC (air traffic control)* system to accommodate more effectively existing traffic levels. Anticipated continuing sizable growth of air traffic requiring control services promised further deterioration of system performance.

Recommendations for system improvements were put forward by the ATCAC (Air Traffic Control Advisory Committee) of the DoT (Department of Transportation)[1] and by the ATA (Air Transport Association)[2]. In addition, legislation was proposed that would establish a Trust Fund to provide monies for improvement of the nation's airports and airways with revenue obtained from taxes upon the users of the system.

With the necessity of system improvement clearly recognized, and with the basis for continuing and expanded funding support established, a review of FAA (Federal Aviation Administration) plans and the mechanisms for carrying out a program adequate to meet these needs was instituted by the President's Science Advisory Committee (PSAC).

As a result of this preliminary assessment, it appeared that important improvements in the ATC system would result from incremental or evolutionary modifications to the present system but that these modifications were likely to provide only limited relief and would in the longer term result in a re-emergence of present system deficiencies. In particular, the system would continue to operate at high cost, near saturation, and without adequate flexibility to accommodate to the uncertainties of the future.

Thus, in January 1970, the President's Science Advisory Committee established an ad hoc Air Traffic Control Panel to conduct a more thorough investigation and to report on its findings. The Terms of Reference for the Panel are included as Appendix 6.

## 1.1 THE TASK

The Ad Hoc Air Traffic Control Panel of the President's Science Advisory Committee was created to provide overview on a national basis of the nature of an adequate ATC system and the mechanism for its realization. The Panel has discussed ATC status

and plans extensively with the FAA and the Office of the Secretary of Transportation and has benefited from the very valuable reports resulting from recent examinations of air traffic control.

### 1.1.1 Previous Recommendations

The ATCAC report[1] and also the ATA report[2], both published in 1969, contain a wealth of technical and operational material, and important and well-considered recommendations, most of which the Panel supports. For example, we make the following recommendations in agreement with or extending those of the ATCAC report:

-- reduction of the operating costs of the ATC system through automation of the current man-in-the-loop functions, particularly those associated with traffic surveillance, positive-control*, and flight services;

-- treatment of air traffic control as a tightly-integrated total system problem, as opposed to considering the system as a coordination of separately-designed functions of navigation, surveillance, communication, and control;

-- extension of limited ILS (instrument landing system)* capability to airports not possessing an ILS;

-- development of airport improvements, including parallel-* and dual-lane-runways* at high density airports, automated surface control, fog dispersal, wake turbulence avoidance and dissipation, reduction of airport noise and air pollution;

-- a coordinated approach to development of landside improvements in airport access and egress, guidance for land use planning, and terminal building operations.

Some of these programs are being vigorously pursued by the DoT/FAA. We strongly support this essential activity and the increased R&D funding that will be necessary to achieve fruitful results. Still, the Panel concludes from its review of air traffic control that neither the present system nor those recommended by the ATA and the ATCAC is likely to provide the extra margin in system capacity needed for the future, as we see it.

### 1.1.2 Recent DoT/FAA Program Development

The Panel has reviewed DoT/FAA near-term plans, which use the ATCAC recommendations as a starting point for developing an upgraded system to supplement the system currently under development. With strong support from the Assistant Secretary of Transportation for System Development and Technology, the FAA requested a several-fold increase in FY-72 R&D funding to mount the major development program. The Panel supports this substantial increase in R&D funding level as essential to the successful improvement of air traffic control, although we believe development and test of alternative sub-systems are still not adequately included. Further, since the Panel began its review, the Office of the Assistant Secretary of Transportation (which commissioned the ATCAC Report) has begun a program of concept formulation for an advanced ATC system. Still, the Panel believes that improvements in both the management and the content of the present research and development plan for the ATC system will be required if adequate levels of performance, including system flexibility and lowered cost of system operation, are to be achieved.

### 1.1.3    Management_and_Financing

A House Government Activities Subcommittee report[3] of July 1970 correctly emphasized deficiencies of former FAA management and organization as important factors contributing to the present inadequate ATC system. The Subcommittee (and the Project Beacon Report[4] of 1961) noted that committee reports are no substitute for a competent organization to define and execute an improvement program for the ATC system. An early and continuing concern of the Panel, too, has been the structure for managing development of the ATC system. Since the Panel began its study, some strengthening of management has occurred within DoT. The Assistant Secretary for Systems Development and Technology has established the new position of Deputy Assistant Secretary for Systems Engineering, whose duties include the direction of concept development of an advanced ATC system, and provision of Secretary-level guidance to the FAA's development of the upgraded third-generation* ATC system. The FAA has established a new Office of Systems Engineering Management (with some 25 spaces) for the express full-time purpose of developing the upgraded third-generation ATC system. The Director of this Office has been delegated authority for managing and directing this development.

These are significant new steps to strengthen the capability to plan, direct, and implement the new ATC system. Even so, we believe additional steps should be taken. For this reason, we have addressed this important problem in Section 4.

Since publication of the ATCAC and the ATA reports, the Airport and Airway Development and Revenue Act of 1970 has been enacted, providing income to be used for improvement and operation of the ATC system. This Act provides from user taxes not less than $250 million annually for the acquisition, establishment, and improvement of ATC facilities (in addition to research and development), and an additional $295 million annually over the decade for airport assistance. With this new legislation the commitment to support of the ATC system by its users has been made. Details of this support may be changed in the future to enhance internal incentives toward reducing costs and increasing overall effectiveness, in accord with the results of a study mandated by Congress and now in progress.

### 1.1.4 The Need for Air Transport

For many endeavors, no better measure of social benefit has been found than that of demand in a free competitive society under appropriate rules. The availability of air transport, for passengers and freight, at continually lower cost will spread its benefits to a larger fraction of the population, will provide cost reduction for those who now use it, and will allow allocation of some of the savings to social benefits such as quieter airports and lower direct or indirect subsidies for necessary but uneconomic service.

The Panel notes that air transport is an alternative to ground transport and, in many cases, to communication of information by wire or radio. Society may wish to restrain, proscribe, or tax any of these modes in order to reflect and to further societal goals. We believe that such measures should be overt, if adopted. We have, however, concentrated on the technical questions of air traffic control and air transport, noting the existence of as-yet-unquantified social costs and benefits, but not attempting to focus on questions of policy in this new area.

### 1.2 PROBLEMS OF TODAY'S AIR TRAFFIC CONTROL SYSTEM

The ATC system exists to serve the users of the air space --air-carriers*, military-aviation, general-aviation*, and, through them, the public. Its purpose should be to provide for effective, efficient and safe use of the air space. There is consensus that the present ATC system is barely adequate for present and inadequate for future needs. Examples of the consequences of its deficiencies are:

-- inadequate capacity of high-density terminal-areas*, a harbinger of more widespread difficulty as other terminal-areas move into the same range of flight operations;

-- high and rapidly-increasing cost of operation and maintenance of the present ATC system with increased traffic;

-- a significant, and potentially increasing, incidence of mid-air collisions;

-- large numbers of controllers required to operate the system, and the difficulty in obtaining projected numbers of trained controllers to satisfy future needs;

-- large costs to air-carriers and passengers resulting from long scheduled block-times* and long delays beyond these scheduled times;

-- high sensitivity to weather conditions;

-- lack of flexibility of the ATC system that would permit or encourage timely introduction of new systems or new operational techniques, such as area-navigation* or VTOL aircraft.

The deficiencies of the ATC system arise from:

-- excessively slow implementation of the recommendations of the 1961 Beacon Project, which when partially completed in 1974 will be some 7 years behind schedule, behind the need, and far short of what is feasible technically;

-- the failure to create within the FAA a technical capability with the necessary internal priority and personnel resources to implement the Beacon recommendations;

-- inadequate development and investment in training aids for controllers (e.g., via simulation rather than on-the-job practice); and especially,

-- inadequate attention to automation of the control function, contrasted with mechanization of forwarding of flight data or the aided tracking of aircraft;

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    --     finally, the acceptance of inadequate resources for development. This tendency culminated in FAA testimony in 1970 which set $60 million annually as the anticipated R&D needs for the next decade, when substantially greater funds are required. The FAA now estimates a need for $150 million annually in R&D to support its current plan.

The Panel notes with approval initiatives by the FAA and DoT in attacking some of the problems of air traffic control, namely:

    --     the change of procedures in 1969 which introduced a reservation system for landings at the busiest airports, as well as "flow control," which holds aircraft on the ground rather than adding to congestion and hazard by holding them in the air;

    --     strengthening in the FAA of the systems management capability to plan and direct a program for an improved ATC system, and the beginning in the DoT of a competence for analysis, research, and management in support of an improved ATC system as well as of other transportation needs; and

    --     improvement within the FAA of the mechanism for formulating and presenting R&D plans.

## 1.3 THE NEED FOR A NEW APPROACH

Air traffic control is a component of the national aviation system, itself an element of the national transportation system. In principle, such systems could be designed by the following process:

    --     derive sets of values from broad goals;

    --     merge these values with available techniques to form alternative programs;

    --     infer from these programs schedules, costs, and capabilities;

    --     relate these possible results to the original goals.

In this way, alternative system designs could be considered and the best one chosen in terms of the benefits, costs, risks, and current interest rate. We are far from having the data necessary

to carry out this process for the ATC system. This handicap results from a lack of focussed effort to understand goals, values, and the range of possible techniques, as well as the program schedules, costs, and capabilities. While pursuing this more rational approach, in the near term it is necessary to improve the ATC system and the air transport system without the global understanding which might be provided by an overall systems approach.

Indeed, air transport is but a small part of the domestic transportation capability, and a "top-down" systems design in this one area would be of little value without consideration of the various, largely uncontrolled developments in local and short-haul transportation systems. Finally, even the best available alternative may not be adequate unless sufficiently well-motivated and well-funded exploratory developments and demonstrations provide adequate scope for choice.

A significant incentive for change is the present high annual operating cost of the FAA, which has reached almost $1 billion in FY-72, almost entirely in support of air traffic control. In addition to this cost of operation, at least $400 million in losses due to delays are suffered annually by the airlines in the form of additional crew costs, fuel costs, and reduced utilization of aircraft[5]. The overall cost to the economy of such delays is evidently even larger. Beyond the usually-reckoned delay is the increased block-time which has been built into the schedule and is not normally counted as "delay." Increased pollution caused by holding on the ground or in the air is an additional social cost. It is important to adopt a specific goal of eventual cost reduction and improved efficiency with increased capability for air traffic control, because incentives to this end are not automatically provided once the FAA costs are covered by user charges.

1.4 THE PANEL REPORT

The Panel report is structured as follows: Section 2 is a sketch of the air transport system of the future, in the context of the national transportation system, accommodating long-haul CTOL (conventional takeoff and landing) jet aircraft which now predominate in the air-carrier fleet, military aircraft, the rapidly growing and highly variegated general-aviation fleet, and VTOL and STOL aircraft which may fill a need in the future air transport system.

Section 3 describes a future air traffic control system and a system philosophy for air traffic control. The system may be regarded from three points of view:

-- the required airborne equipment and resultant capabilities provided to air-carrier, military, and various general-aviation aircraft;

-- FAA equipment and procedures, with resultant manning, failure modes, etc.; and

-- the content of a program necessary to achieve an improved ATC system.

The Panel has neither specified in detail the elements of an improved ATC system nor estimated definitive costs. In several cases there are viable alternatives on which sufficient work has not yet been done to make a proper choice, which should be investigated, in parallel, in a competitive analysis and demonstration program. Section 3 is not a day-by-day management plan for an improved ATC system. It is an outline, a statement of scope, and a discussion of highlights, with some ordering of priorities. A firm plan can follow only from the efforts described in Section 4.

Finally, Section 4 of the report examines an organization and management structure for providing an improved national ATC system. The Panel's intent is to recommend an organization capable of rapid sequential choices among the interdependent options which will become apparent as the improvement program goes forth. Since its creation in 1966, the DoT has become involved in air traffic control, supplementing the traditional responsibility of the FAA. Indeed, it was the Assistant Secretary of Transportation for Systems Development and Technology who commissioned and staffed the ATCAC study, resulting in a report[1] which is now of central importance in the FAA program for the future. It is important that the combination of DoT and FAA be more effective than the FAA alone, and the management structure must take this into account.

NOTES AND REFERENCES

(1) Report of the Department of Transportation Air Traffic Control Advisory Committee, Vols. I and II, December 1969.

(2) Report, Air Traffic Control Planning Group, Air Transport Association of America, July, 1969, "Recommendations for a National Air Traffic Management System."

(3) Problems Confronting FAA in the Development of an Air Traffic Control System for the 1970's, Hearings before Government Activities Subcommittee (Jack Brooks, Chairman) of a Committee on Government Operations, January 27, 1970.

(4) Project Beacon Report, 1961.

(5) Cost implications of delays were derived from:

   (a) a FAA 1968 study of air carrier terminal delay, which evaluated the cost of 19 million minutes of delay at $118 million, not including losses due to unproductive aircraft, etc.,

   (b) a 1970 Eastern Airlines study which estimated the 1969 cost of ground waiting time at $7.2 million, unproductive airborne time at $10.6 million, and aircraft utilization loss at $33.6 million, and

   (c) extrapolation to the industry, giving total losses for 1969 as approximately $410 million.

   In contrast with this estimate of $410 million costs to air carriers of 1969 terminal delays, the DoT-NASA-Civil Aviation R&D Policy Study (DoT TST-10-4; NASA SP-265), p 5-9, estimates "$158 million in crews, fuel, and vehicle losses." This figure appears not to include aircraft utilization losses. That study also notes that 22 million passenger hours lost account for an additional $90 million, so that if passengers built "as little as one additional hour into their schedule to accommodate unforeseen delays," the cost would increase by an additional $375 million.

## 2.0 THE AIR TRANSPORT SYSTEM OF THE FUTURE

### 2.1 TRENDS IN AIR TRANSPORT

The problems of air traffic control depend in large measure, of course, on the demand for its services. That demand in turn depends in part on the volume of air traffic in the years ahead. The FAA has projected the traffic between now and 1980; the projected increase in the number of IFR (instrument flight rules)* flights, for example, shown in Table 1d is very considerable.

The Panel has not studied in detail the question of volume of traffic during the next years. It has no reason, however, to substitute other projections for those of the FAA. History shows that such projections are often conservative. In 1969, the number of IFR landings and takeoffs at FAA airports was 16.7 million, an increase of 240% over 1958 and far larger than expected a decade earlier.

In the following sections, the Panel notes some factors important in shaping the public demand for air travel. We point out, in particular, the likely need for the introduction of VTOL aircraft as a major component of the air transport fleet. Table 1 does not reflect traffic from these aircraft. The ATCAC noted, further, that if IFR or presumably also CVR (controlled visual rules)* service were extended to all VFR (visual flight rules)* traffic within 30 miles of a primary terminal, the control loads "may increase by a factor of 10 to 15 over today's peaks" rather than the tripling assumed in the projections.

#### 2.1.1    Air Carriers

Internal incentives in the air transport industry are driving the air-carriers toward more intensive utilization of their vehicles. Jumbo jets make more effective use of saturated terminal-areas and runways and have a lower crew cost per passenger than do smaller aircraft.

An important potential is revealed by the success of California intrastate air-carrier operations, initiated by a carrier unregulated by the Civil Aeronautics Board (CAB), which (as of October 1970) operates with some fares as low as $7 and flies 376 miles between Los Angeles and San Francisco for $16. This contrasts with the 225-mile New York-to-Washington trip for $24.

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The FAA Ten Year Plan[1] anticipates future growth of air-carrier, general-aviation and military traffic as shown in Table 1. The Panel emphasizes that this projection does not consider the possibility of the introduction of much lower fares and the market expansion which might ensue. Indeed, that expansion is constrained not only by the high noise levels of existing aircraft, but also by the inability of present runway arrangements (even if expanded to dual-lane-runways at most major airports) to accommodate more than twice the number of present operations, by terminal congestion problems, by high zero-trip-length costs of conventional airline operations, by shortage of passenger parking near airports, and by congestion in ground access to airports.

Productive utilization of aircraft and crew will continue to encourage air-carriers toward all-weather operation at all airports, with full area-navigation capability. Most large jet aircraft will proceed according to an agreed flight plan and will have their adherence to the flight plan verified automatically by the ATC system. (Provisions for contingencies are discussed in Section 3.) Improved technology of airframe construction and advances in engine technology will be used in part to increase the passenger load, in part to reduce operating costs and, in the Panel's opinion, to a very large extent to reduce noise and pollution and thus environmental costs. For conventional aircraft the FAA has advanced the goal of 80 EPNdB (effective perceived noise level measured in decibels)* at certain standard noise-measuring points. For VTOL aircraft the goal is 95 EPNdB at 500 feet. It is technically feasible to build VTOL aircraft to meet this standard. The question is whether the advantages of lowered noise outweigh the increased first cost and operating cost for a given payload.

Experience of major airline activities with STOL and third-level carrier operations with light STOL's and helicopters show the lack of adequate aircraft and of operational experience. Helicopter intra-city operations had direct federal subsidy for some years, but now have none. They use relatively inefficient aircraft, at least one and often two generations old, and serve poorly developed markets. Several of the larger helicopter carriers have gone out of business in the last few years, despite evident ground congestion. Feeder and flight-connecting service in cooperation with the larger fixed-wing common carriers has proved feasible, if not outstandingly successful. Without this private initiative the helicopter carrier situation would be still worse. Despite availability of more efficient, reliable, and maintainable

helicopters, the growth and even survival of these services may depend on government leadership.

Activities of some major carriers in the Northeast Corridor are aimed at establishing STOL service on short air strips at existing major airports, using a terminal ATC system separate from that used for the saturated operation of CTOL aircraft. They also propose special city-center locations or reliever airports. The latter plans have involved extensive efforts to create STOL ports in areas relatively insensitive to noise. Some NASA and military R&D activity, as well as foreign work, aims toward the development of STOL transport aircraft with improved speed, cruise efficiencies, and payloads and low noise levels on takeoff and landing. It remains to be seen how the market for such service will develop, once the availability of improved technology is recognized. A critical element is public acceptance.

The third level carriers, e.g. air taxis, presently operate very limited STOL aircraft services in a few high-traffic density areas. Although these early services using small aircraft and serving few terminals are therefore relatively expensive for the passenger, the growth of this type of operation in the past few years indicates a demand for flexible short-haul service.

The Panel believes that STOL and particularly VTOL operations are likely to contribute to solution of airport congestion problems as well as to the demands on ATC systems. Choice of ATC systems for the future should not restrict the growth of V/STOL service.

2.1.2    General Aviation

General aviation is expected to grow at a rate of 5.5% per year, as indicated in Table 1-a. Even more rapid growth of 12-14% per year is expected in IFR operations of the general-aviation fleet (Table 1-d). If increased aircraft control automation and dependability of operation make private flying available to a wider spectrum of the population, a larger growth rate may develop.

For example, if reliable electronics for cockpit management reduces the level of skill required for instrument operations, and if the ATC system allows direct and convenient flight, there could also be a vast growth of rent-a-plane services supplied by corporations of national character. While we cannot see that it is the business of the government to develop automatic piloting for general-aviation aircraft, we do feel that the regulatory agencies should maintain an open mind toward the proper relation between

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reliable aircraft control automation and required pilot skill, and that the navigation and ATC system provided should not arbitrarily restrict this technical feasibility. There remains the further possibility of revolutionary changes in airplane and control design philosophy which could provide a vastly enlarged market for general-aviation aircraft, particularly if major cost reductions were achieved.

Corporate jet aircraft, classed as general-aviation, can be expected in the future to be equipped like air-carriers. The population of single- and twin-engine light aircraft will continue to grow, and we expect that the reciprocating engine will give way to low-cost turbine-powered propulsion.

### 2.1.3 Military Aircraft

The productive use of high-performance military combat and transport aircraft will probably require that they be equipped with navigation and automatic-piloting equipment comparable with that detailed for air-carriers in Section 3. All military aircraft will carry equipment required for reliable and accurate surveillance by air traffic control, and will have the necessary two-way radio.

Air Force experience in operating a squadron of F-4D aircraft equipped with LORAN-C navigation equipment linked with a digital computer has demonstrated the operational utility of a flexible navigation system achieving few-hundred-feet position accuracy even when not coupled to an altimeter (i.e., a two-dimensional rather than a three-dimensional navigation system). In addition to all-weather mission capabilities, this limited system demonstrated significant operational advantages. Navigation in three dimensions to substantially better position accuracy than is possible with LORAN has been extensively studied in connection with satellite-originated LORAN-like systems. Signals from a constellation of four in-view satellites can give instantaneous position accuracy of tens-of-feet at lower on-board cost than is possible with LORAN. The mission-effectiveness of precise navigation having been demonstrated, the Panel believes it highly likely that a Defense Navigation Satellite Service (DNSS) will be deployed for navigation of aircraft and other vehicles without the necessity to transmit signals from the aircraft. The use of the DNSS in theaters of operation will presuppose a comparable service for training and operational purposes in the domestic United States, a system which has the potential, with proper planning, for use by air-carriers and general-aviation.

Another well-developed trend in military aircraft is toward
VTOL. The United States Army now has some 9000 helicopters, and
operational VTOL attack capability is being pioneered by the Marine
Corps with their first squadron of vectored-thrust "Harrier" jet
attack aircraft which originated in the United Kingdom.

## 2.2  SOME FACTORS AFFECTING THE AIR TRANSPORT SYSTEM OF THE FUTURE

As described in the Introduction, the future air transport
system would benefit from a systems analysis and design extending
from goals to values to programs to implementation. However, the
air transport system is not monolithic. Government-supplied
services and regulations influence but do not completely control
the actions of airlines and manufacturers. With proper emphasis,
leadership, and understanding of the need for extensive discussion,
research, demonstration, and planning, we hope that a more soundly-
based government program may indeed be achieved.

### 2.2.1  Policy Formulation

Several relevant and important studies are worthy of note:

--    The Airport and Airway Development and Revenue Act of
      1970 mandates that by May 1971 the Secretary of
      Transportation, "Shall formulate and recommend to the
      Congress for approval a national transportation policy,"
      and by May 1972 shall conclude a study "respecting the
      appropriate method for allocating the cost of the airport
      and airway system among the various users."

--    A Joint Department of Transportation-NASA Civil Aviation
      R&D Policy Study[2] with the primary objective "to analyze
      the relationship between benefits that accrue to the
      nation from civil aviation and the level of aeronautical
      research and development effort."

The national transportation policy to be formulated by the
Secretary of Transportation, the cost allocation study of the DoT,
and the Civil Aviation Research and Development Policy Study
represent a beginning to the necessary systems approach to the
basic problem. A prime impact of these studies should be to make
clear that disagreements and disputes previously thought to be
doctrinal often arise from differing values. Much public
discussion will be required, not only within the transportation
industry, but also involving the traveling public, those affected
by the environmental consequences of travel, and the taxpayer.

Indeed, in the preparation of the National Airport System Plan, the Secretary of Transportation is directed to consult with and consider the views and recommendations of the Secretary of the Interior; the Secretary of Health, Education, and Welfare; the Secretary of Agriculture; and the President's Council on Environmental Quality, taking into account their recommendations with regard to the preservation of environmental quality to the extent that the Secretary determines to be feasible.

2.2.2    The Need for More Research and Demonstration in Support of the Planning of the National Air Transportation System

Research and development are familiar as a step toward the availability of new vehicles or "hardware." Research and demonstrations to gain the understanding necessary to make proper choices, toward the determination of true costs, or of the dollar equivalent of benefits not ordinarily considered in dollars, are far less familiar, but nonetheless important.

An excellent example is the STOL demonstration conducted by Eastern and American Airlines among Washington, New York and Boston, using the Breguet 941 aircraft and a flexible DECCA* area navigator. From the point of view of the airline and the pilot, this series of flights demonstrated savings in time and cost associated with slower aircraft using separate short runways at busy airfields. They did not address the determination of other costs and benefits, such as public acceptance of the service. In general, such a demonstration may use demonstration hardware and specially-trained personnel.

Similarly, research attempting to quantify in dollars the cost of a noisy and polluted environment, including the degradation of property values and other social costs, would yield valuable data for determining the proper tradeoff point between increased direct operating cost and reduced noise level of conventional or V/STOL aircraft. The variation in operating cost with specified noise level is much better understood. The magnitude of social benefits available may be inferred from an estimate that the area already heavily impacted by noise exposure around Kennedy Airport, Los Angeles International, and O'Hare alone is three times greater than all the land redeveloped during 16 years of urban renewal at a cost of $5 billion[3].

The results of the Northeast Corridor Study, together with the fact that VTOL holds the promise of significantly relieving the

runway acceptance limitation at high-density airports, strongly recommend an operational demonstration to provide a base of understanding to support future planning of the air transport system. This program could establish the marketing elasticity for such service, its acceptance by the community, practicality of groundside and airside operations, all-weather capability, and required aircraft characteristics. Such a program is not dependent upon the availability of an economically viable production aircraft of suitable size, since the objectives could be accomplished with:

-- demonstration aircraft with reduced range and passenger load, accepting higher maintenance costs than would be tolerated for operational aircraft;

-- higher noise levels than would be acceptable from regularly operational aircraft operating from city centers, but still tolerable for operation from existing airports;

-- more expensive interior soundproofing and cabin design;

-- special personnel and procedures in the FAA ATC operation to simulate the environment which would be available for production aircraft, with special emphasis on assuring that noise levels will not be higher than those achievable from regularly operational aircraft from the same terminals.

A realistic evaluation of the market, however, requires that demonstration aircraft be certificated to carry passengers, and not only cargo.

While the benefits to be expected from technology-oriented research and demonstration lie farther in the future than those from development of a particular vehicle, they are of much greater magnitude. Such research and demonstration must be initiated at a level which will provide sufficient information that policy decisions in the air transport field, and more important, those regarding a national transportation system, can be adequately supported. It seems clear that the DoT should extend its work to include detailed system studies of air transport needs as well as the conduct of demonstrations in several parts of the country, including demand patterns, land use, airport access, and environmental effects.

Direct costs and implementation schedules associated with the programs suggested by the Panel can be determined by detailed analysis. There is less certainty regarding softer but nonetheless vitally important questions as to the value of flexibility, market response to transportation systems offering different levels of comfort, the impact of breakdowns and repair time for linear systems as opposed to distributed systems, and public reaction to costs and benefits in terms of changes in the environment (primarily noise and air pollution). One of the major delays in formulating rational policy and in moving toward an optimum transportation system will be the lag in understanding and in response on the part of groups which have for years been concerned only with very limited aspects of the overall problem. Organizational and program innovations will be needed to bridge traditional gaps in understanding and to force consideration of interactions among the modes of the transportation system.

2.2.3     Inter-Modal Problems and the Modal Split   Between Ground and Air Transportation

Inter-modal problems are at the core of the DoT's responsibilities. They form the environment of the FAA, whose planners should also be familiar with them. In the United States, approximately 20% of the Gross National Product (GNP) is spent on passenger and freight transportation, with long-haul common-carrier passenger transport dominated by the airplane, and shorter-haul systems by bus and automobile. The automobile (non-common carrier) dominates both the short- and long-haul passenger transportation market. Some 2% of the GNP goes for civil air transport. As yet, no systematic effort has been made to allocate transportation resources to maximize benefits to passengers and the public. The results are seen in congested access to excellent inter-urban highway systems, and to major airports, even though the enroute road and air space can accommodate substantially more than present traffic. Because of the limited purview of many of the organizations involved, some of the most critical and costly deficiencies affecting the economy and the traveler do not receive proper identification or remedial effort. In fact, congestion in one form or another is associated with every node in the transportation system.

It is essential that the DoT initiate comprehensive studies of overall national transportation requirements and opportunities, including both air and ground transport in all feasible modes. The varied ingredients of economics, legislation and regulation, technical problems of vehicle design, control and guidance,

sociological implications of new transportation modes and their impact on urban development, noise and air pollution and other environmental factors, and the problems of optimizing a network with multiple-commodity flows and cyclic demands, in the face of uncertainty, pose a difficult problem of systems analysis.

This Panel is primarily concerned with air transportation --indeed more with the solution of the problem of airport access from the air than from the ground--but this problem cannot be analyzed entirely out of context with the total transportation problem. For example, we cannot assume that large amounts of federal funds should be spent to reduce air travel time as airport access in most cities becomes more and more time consuming. It would be preferable, from the federal government's point of view, to obtain the maximum reduction in overall trip time by dividing expenditures between ground access and air-related improvements. A solution to the local metropolitan transport problem should also provide tools for the solution of the problem of airport access, since long-haul travel will continue to involve only a small fraction of the population on any given day.

Some partial solutions to the airport access problem--short of improving all metropolitan transport--will also contribute to reduction of congestion in the air and to a decrease in the number of people actually using the airport. One such solution is the provision of short- to medium-haul VTOL feeders for the airport. Systems analysis will show the exact boundary between the utility of such a VTOL system and complementary concepts such as automated highways and demand-scheduled mini-buses. Until such analyses of the total transportation function exist, we shall lack guidelines to direct future research, development, and demonstration programs. Consequently, local transportation authorities may continue to deal only with existing modes, ignoring the potential of advanced technology and innovative organization to resolve our growing transportation problem. However, the introduction of an effective VTOL system need not wait for precise analysis of its ultimate scope. The more efficient system which would result from precise analysis must be contrasted with the earlier benefits of an effective, less-than-ideal, but evolving system. The Panel believes that the transformation of the present elementary VTOL service to a productive mass transport system will require firm government leadership in the provision of adequate ATC coverage and procedures, and in the stimulation of availability of more productive aircraft, with particular attention to environmental suitability, i.e., noise and flight path.

2.2.4    The Influence of the Discount Rate On Program Choice

A 10% annual discount rate on future benefits is now in quite general use for program analysis within the government. Such a discount rate evidently and properly discourages consideration of programs with large fixed costs and heavy capital investment, as compared with programs of higher operating cost and lower fixed investment. As an example, the consequences for VTOL are that:

--    relative to tracked air cushion vehicles or greatly-improved rail, it has the advantage of lower capital costs (air vehicles) and of capital which is immediately productive;

--    relative to STOL in serving densely populated areas, it requires less land, and thus permits less expensive and more flexibly located ports, offsetting a somewhat higher direct operating cost;

A further consequence of the discount rate, for all programs, is the large cost associated with delay of net benefits. The discounted-present-value* of a program, assuming that all benefits and all costs can be expressed in dollars, is the difference between the flow of benefits by year (discounted to the present) and the flow of costs by year, likewise discounted to the present. Discounted present value, weighted by probability of success, should be a primary tool in formal program decision.

2.3  CONCLUSIONS AND RECOMMENDATIONS

Sometimes change comes slowly, but the Panel believes that from now through the 1980's there can be major changes in the air transport system, if the government will provide an environment in which the individual decisions of industry and of consumers can lead to more effective systems. Proven technology and gradual growth are predictable, but it is also likely that innovations will result in the growth of qualitatively new systems.

To remove the inadequacies of the present Airports/Airways system and provide adequate traffic-handling capacity and improved air safety, at reasonable cost to the government and users of the system, is a challenge to government leadership. In meeting this challenge, the ATC system is the key to the future. Accordingly, the Panel recommends that the national program for the development of a new and improved system should focus on:

-- the reduction of airport congestion and airspace saturation, while providing increased capacities needed for projected growth in IFR traffic, especially in business and general-aviation;

-- effective means to reduce the potential growth in mid-air collisions;

-- a significant growth in productivity over the present system both to increase capacity and to reduce operating costs to the government and users of the system.

-- provision of navigation and surveillance capabilities, as well as procedures, which will accommodate the introduction of productive VTOL or STOL service.

Regarding the air transport system in general, the Panel recommends that new policies be studied with respect to:

a) control and distribution of demand (e.g., through new airline schedules);

b) allocation and use of airspace and routes;

c) traffic control procedures and separation standards;

d) national uniformity of system operation from the viewpoint of both the operators and users of the system;

e) possible changes in fare structure and their impact on demand and thus on the ATC system;

f) incentives for the FAA to provide a given ATC-related service at the lowest possible cost.

Further, the air transportation system should be expanded to include all-weather VTOL and STOL systems in order to alleviate the short-haul load on conventional air transport. So doing would improve airport access and reduce congestion and airspace saturation in high-density terminal areas. If there were no other problems in air traffic control, system capacity would still be seriously constrained by runway occupancy. VTOL is one of the cures for that limitation.

Therefore, the Panel recommends:

-- R&D for a productive VTOL-ATOL system should be started now, including systems studies, demonstration of technical feasibility, system demonstrations, community acceptability, etc., because of the high leverage of these expenditures on potential benefits.

Section 3 elaborates on the above points.

TABLE 1

TOTAL TRAFFIC PROJECTIONS, 1968 to 1995*

a -- Aircraft Fleet Size, 1968 to 1995

| User Category | 1968 | 1980 | 1995 |
|---|---|---|---|
| Air Carrier | 2,452 | 3,600 | 6,700 |
| General Aviation | 114,186 | 214,000 | 500,000 |
| Military | 20,000 | 20,000 | 20,000 |
| All Users | 136,638 | 237,600 | 526,700 |

c -- Annual Flights, 1968 to 1995 (in millions)

| Aviation Category | 1968 | 1980 | 1995 |
|---|---|---|---|
| Air Carrier: | | | |
| Itinerant | 5.2 | 9.8 | 14.1 |
| Local | 0.1 | 0.2 | 0.5 |
| Total | 5.3 | 10.0 | 14.6 |
| General Aviation: | | | |
| Itinerant | 16.2 | 34.9 | 93.9 |
| Local | 8.7 | 16.5 | 43.3 |
| Total | 24.9 | 51.4 | 137.2 |
| Military: | | | |
| Itinerant | 2.2 | 1.7 | 1.5 |
| Local | 3.3 | 3.5 | 4.1 |
| Total | 5.5 | 5.2 | 5.6 |
| All Users: | | | |
| Itinerant | 23.6 | 46.4 | 109.5 |
| Local | 12.1 | 20.2 | 47.9 |
| Total | 35.7 | 66.6 | 157.4 |

b -- Peak Airborne Aircraft, 1968 to 1995

| User Category | 1968 | 1980 | 1995 |
|---|---|---|---|
| Air Carrier | 1,300 | 2,100 | 4,600 |
| General Aviation | 8,000 | 16,800 | 46,300 |
| Military | 3,500 | 3,300 | 3,500 |
| All Users | 12,800 | 22,200 | 54,400 |

d -- IFR Aircraft Handled By FAA Air Route
Traffic Control Centers
(in millions)

| Fiscal Year | Total | Air Carrier | General Aviation | Military |
|---|---|---|---|---|
| 1963 | 10.2 | 5.3 | .9 | 3.9 |
| 1969 | 20.6 | 12.6 | 3.2 | 4.7 |
| 1975 | 29.6 | 17.9 | 6.8 | 4.9 |
| 1980 | 42.0 | 22.5 | 14.7 | 4.8 |

NOTE.--Detail may not add to total due to independent rounding.

*Data from Report of the Air Traffic Control Advisory Committee, Vol. I, Chapter 3 (December, 1969)

## NOTES AND REFERENCES

(1) "The National Aviation System Plan, Ten Year Plan -- 1971-1980," Department of Transportation, Federal Aviation Administration (U.S. Government Printing Office, Washington, D. C., 1970); there is also a companion volume "Policy Summary."

(2) Joint DoT-NASA Civil Aviation Research and Development Policy Study, March 1971.

    (a) Report -- DoT TST-10-4 (NASA SP-265)

    (b) Supporting Papers -- DoT TST-10-5 (NASA SP-266)

(3) Ref. 2a, page 5-3.

## 3.0 THE AIR TRAFFIC CONTROL SYSTEM OF THE FUTURE

## 3.1 CONCLUSIONS AND RECOMMENDATIONS

Where no further elaboration is needed, statements in this Section are not repeated in the main body of Section 3.

### 3.1.1 Summary

Conservative estimates indicate that traffic demand on the ATC system will increase threefold by 1980 and eightfold by 1995. This traffic will include a mixture of general-aviation, sophisticated and simple military aircraft, and air-carriers--both conventional and V/STOL aircraft. General-aviation will comprise over 85% of the total flights and 95% of the vehicles; the design of the ATC system will be dominated by the need to take this fact into account. This increased traffic demand and the growth in potential mid-air collisions it will create the need for very extensive modifications or additions to the present ATC system.

Indicative of the national commitment to the air transportation system is the FAA's annual current operations budget of about $1 billion, most of this for air traffic control. This budget will increase significantly by the 1980's if the system continues to evolve in its present form. Similarly, direct losses to the users of the system through flight delays and, especially, decreased aircraft utilization may be four to five times as great in the 1980's as today's losses of over $400 million per year. Loss of life and aircraft in air collisions could potentially be large also.

In the Panel's judgment, automation of the control function offers the greatest leverage per dollar invested for increasing the capacity and safety and for reducing the operations cost of the future ATC system. In the control function, productivity increases of at least one-third in the 1970's and two-thirds in the 1980's can be achieved through the use of new technology. Potential savings of up to $1 billion per year in ATC system operations costs in the 1980's and 1990's and over $1 billion per year to users are possible if an automated system is deployed by 1980[1]. In addition, needed increases in capacity and safety will be achieved. For example, control commands generated automatically by the ground ATC system to aircraft in case of flight conflicts can prevent growth of potential mid-air collisions that can be expected as the density of aircraft increases.

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Even if the savings outlined above are discounted at 10% annual rate to 1970 dollars, benefits-to-cost ratios exceeding 2 to 1 can be achieved through reduced operations costs and user costs if an automated system is implemented.

Accordingly, the Panel recommends:

-- Commitment to deployment of an ATC system in which the strategic-control* of aircraft by the FAA is largely automated, but in which a suitably-equipped aircraft can exercise tactical-control* of its own flight path through the use of accurate 3-D navigation, air-ground data-link*, all-weather landing systems, and suitable aircraft displays.

To achieve the needed safety in such a system and to keep a balance between airport and airways capacities, the Panel endorses many of the ATCAC recommendations, for example:

-- Use of the IPC (intermittent positive control)* concept to guarantee separation in mixed-airspace*.

-- Use of parallel and dual-runways at high-density airports.

To achieve a safe, automated system, it is necessary that the ATC system have reliable and accurate position data on all aircraft at all times.

Therefore, the Panel recommends:

-- Make mandatory the use of cooperative equipment in all aircraft in order to provide cooperative surveillance of all airspace.

-- Establish incentives in the form of improved services and procedures for those users who invest in airborne equipment (e.g., area navigation) for tactical control of their flight path in a manner compatible with overall strategic control from the ground ATC system.

Further, the following airspace structure should be employed:

-- "High-density-control" airspace within the terminal area for sophisticated users, with tight time-control area-navigation routes.

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--    "Positive-control" airspace for less dense regions, including both IFR and CVR.

--    "Mixed-airspace" for VFR and IFR, where IFR density is low.

--    "Uncontrolled-airspace"* for VFR only.

There is need to have national uniformity of operation in an automated system. Therefore, the Panel believes that the large degree of autonomy in the regional structure of the current ATC system must be reduced particularly as applied to procedures, standards, and operational control techniques and equipments.

A program of near-term improvements for early deployment is needed to alleviate present deficiencies in ATC system capacity until a system for the long term is deployed in the 1980 time period.

The Panel recommends for the near term:

--    Improvements of the ground-based elements of the present radar-beacon* system (e.g., more directive antenna, monopulse*-on-receive, improved ground-based interrogator discipline, etc.).

--    Improvement of precision of the present VOR (Very High Frequency Radio Omnirange)* and DME (Distance Measuring Equipment)* navigation aids for continued use by some general-aviation aircraft and for interim use by air-carriers, the military and others until a satellite based navigation system is deployed.

--    Accelerated installation at many more airports of a limited ILS both for general-aviation and air-carrier use.

--    Formulation of an operational design for utilization of area-navigation both in the enroute and terminal approach areas. The design should look at both long-term (most users equipped) and short-term (few users equipped) layouts with considerable emphasis on providing short-term benefits to encourage further user participation. The design should be simulated and verified first for an area such as the Northeast Corridor.

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-- Further automation of the FAA's current national flow control function to reduce the response time of the system to changes in traffic and weather conditions.

-- Rapid deployment of NAS Stage A Enroute System* and ARTS III (Automatic Radar Control Terminal System)* to provide an adequate base for an automated control system.

-- Development of a traffic sequencing and spacing capability for the ARTS III, including automatic tracking and multiple-runway feeding, with emphasis on early deployment in the present 5 to 8 high-density areas.

-- Improvement in reliability of ground-based radar and communications equipment and telephone lines.

Finally, the Panel believes that a system meeting future requirements at reduced operations costs and user costs can be achieved, but only if a broader range of technical capabilities and alternatives are considered than have been addressed to date. Specifically, both immediate improvements to the current system and the design of the future system must consider greater application of automation and of satellites. Towards this end, a sustained and broadly based RDD&E (Research, Development, Demonstration, and Evaluation) program for the next eight to ten years should be planned and started now to provide both near-term improvements for early deployment in the ATC system and new technology for the long-term for use in: control automation; data acquisition, navigation, landing, and communication subsystems; airports (both the airside and landside); and airborne equipment, primarily to reduce cost to the user.

The Panel therefore recommends:

-- Increase the RDD&E budget of the FAA from the 1972 level of $115 million to a level of about $150 million and maintain that budgetary level for about the next eight years--with the primary purpose of increasing the capacity and safety of the ATC system. This contrasts with FAA RDD&E budgets of only $70 million as recently as 1971. The major and critical parts of this $150 million annual program are described below.

This RDD&E program will make available equipment of advanced capabilities. Acquisition of this equipment will require capital investments of about $300 million annually starting in the mid-

1970's and continuing for about seven years. This expenditure follows that for facilities and equipment needed in the early 1970's to upgrade the current ATC system.

Improved demand forecasting techniques, system evaluation tools, and performance measures are needed to aid in planning, analyzing and managing this complex effort of developing a new ATC system.

The_Panel_recommends:

-- Formulation of a system design, analysis, and simulation program to compare the magnitude of the required capital expenditures for new system options of the future, (differentiated by investments in airports and air transportation system improvements), and the benefits to be derived therefrom in capacity, safety, and reduced operations and maintenance costs from these capital investments in order to be able to assess priorities and investment decisions.

-- Preparation of an implementation, training and phasing plan by the FAA for the acquisition and operational introduction of the mainstream subsystems over the next ten years that is kept up-to-date annually with costs, schedules, and descriptions of system capabilities and benefits over time. This will enable: (1) needs to be met in the order of their priority and (2) operational phasing of new subsystems to be accomplished with minimum disruption of current operations and with minimum impact on personnel due to automation programs.

## 3.1.2    Functional Elements

The conclusions and recommendations for the various functional elements described below comprise the specific program needed to implement the general recommendations outlined above for the overall system.

### 3.1.2.1    Control Automation

The control function will be difficult to automate using present technology, especially for unusual situations such as hazardous weather and ground-system failures (e.g., power, computer, communications). System failures, especially those

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impacting large geographical areas, must be expected and the system designed to degrade softly.

In the control area, the Panel recommends:

-- Development of automated network concepts and techniques that will reduce the number of control centers needed by a factor 2 to 5 in relation to today's system, as dictated by the requirements of economy and system reliability.

-- Development of the hardware, software, procedures, and man-machine techniques needed to: (1) automate the normal functions of traffic planning and scheduling; enroute and terminal-area control (i.e., metering, sequencing and spacing); safety commands; flow control; and (2) adapt to and cope safely and efficiently with dynamic situations.

-- Development of control concepts and the associated avionics and aircraft displays to allow a suitably-equipped aircraft to execute precisely an agreed flight path.

-- Examination of the feasibility of remote manning of the hundreds of small airport control towers.

-- Development of further automation of the function of flight service stations (FSS)*.

-- Development of high-reliability, large computer/communications systems through high-component reliability and the use of distributed and redundant system elements.

-- Development of techniques to sense and predict hazardous weather in a timely way.

-- Use of enroute and terminal-area system test centers to focus the overall development effort, to test and evaluate experimental systems and to verify designs which can be introduced confidently into the operating system. Likely places to establish these test centers are the FAA National Aviation Facilities Experimental Center at Atlantic City, New Jersey, and/or FAA facilities at Dulles Airport and the Leesburg, Virginia, Center. It is important that funds be programmed now to initiate experimental activities and to provide the facilities,

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displays, computers and communications equipments, and
simulation software to be used in these system test
centers. The highest priority should be given to this
control automation development program.


### 3.1.2.2 Surveillance and Communications

Effective air traffic control depends upon a close integration
of surveillance, navigation, communications, and control. In
particular, the parameters and needs of individual subsystems
interact strongly with one another and with the control concept in
the design of a new system. Flexibility and capacity must
characterize the improved ATC system, but different technical
approaches link the subsystems in different ways. For instance,
the ATCAC-recommended discrete-address evolution of the present
beacon transponder can naturally serve as a data-link, with certain
strengths and limitations. In contrast, the addition of
surveillance capability to a satellite system designed for
navigation could be accomplished for approximately 20% increase in
satellite costs. In this Section, we choose, somewhat arbitrarily,
to summarize both the surveillance and the communication subsystems
(particularly appropriate to the ATCAC-recommended approach),
remembering the close link of surveillance and navigation in the
case of a satellite based system.

The choice now of surveillance, communications and navigation
subsystems for long-term national deployment is complicated by the
interrelation of the ATC functions that these subsystems support;
technological uncertainty and risk; and uncertainties in ground and
airborne equipment costs, acquisition schedules, and operational
phasing--including introduction of new user equipment in all
aircraft. A number of desirable options should be pursued through
program definition, development and test before subsystems in these
areas are selected for national deployment. This course of action
will certainly save money and time in the future.

The ATCAC report recognizes the need for new surveillance and
communication subsystems for domestic use. The Panel believes
there is not a clear-cut choice for national deployment of these
new subsystems at the present time, and therefore recommends that
over the next 2 to 3 years the DoT/FAA:

-- Develop the phased-array* interrogator and the
   addressable-beacon* and data-link features of the ATCRBS
   (Air Traffic Control Radar Beacon System).


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--  Develop techniques for a high capacity VHF (Very High Frequency)* data-link. (See Appendix 2.)

--  Conduct an exploratory development program for a satellite-based surveillance system. This should be done in conjunction with DoD (as part of the Defense Navigation Satellite Service Program) if mutual cost savings are expected and mutually agreeable program schedules can be arranged. A particularly close coupling exists to the Air Force Defense Navigation Satellite Program. (See Appendix 3.)

--  Define, cost, and demonstrate user equipment for all these options.

Based on technical and cost data from these parallel development programs, a system development decision for surveillance and communication subsystems can be made in about 2 to 3 years without delaying attainment of the capability ultimately chosen, and with increased assurance of having indeed selected the best system.

### 3.1.2.3  Navigation

While present VOR and DME installations and planned modifications are necessary to support the needs of aviation throughout the 1970's, the short line-of-sight range at low altitudes and the angular inaccuracy of the VOR will require either substantial cockpit attention to the sequencing and switching of VOR receivers or else the installation of a computer for that purpose. Additionally, even upgraded VOR and DME will probably not provide adequate navigation accuracy to permit control automation with the capacity and safety that a new surveillance system will be capable of handling.

A passive system in the aircraft, computing aircraft position from signals received from synchronous navigation satellites could provide air-carriers, military-aircraft, and advanced general aviation aircraft a navigation system of universal domestic coverage. While it would be unwise to deny present aircraft the benefit of improved navigation and the greater safety and capacity which improved VOR and DME systems can offer, especially when combined with inertial navigation, it would also be unwise to penalize additional hundreds of thousands of aircraft to be built in the 1980's by denying them a better system (and for general-aviation aircraft, a less expensive system of navigation by data-

link communication of precise position derived from a surveillance
system of universal coverage).

For these reasons, the Panel recommends:

-- Joint exploration by the DoT and the DoD of the
feasibility and desirability of a Navigation Satellite
Service. Surch service could be initially available
within about six years for civil and military aircraft
over the United States, with characteristics providing
flexible, economic, and precise 3-D navigation to
suitably-equipped aircraft. To achieve this schedule, an
intensive program costing about $100 million is
necessary, through initial deployment, and an intensive
effort should be carried out to define system
characteristics and gain ICAO concurrence for them.

-- Development of this capability in conjunction with the
exploratory development effort recommended above for a
satellite based cooperative surveillance system.

-- Integration of surveillance and navigation capabilities
into the same Satellite Service if the surveillance
capability proves feasible and cost-effective.

3.1.2.4    Landing Systems

The Panel supports the extension of existing VHF ILS
capability to many airports not possessing an ILS. This will
provide aid to instrument-equipped aircraft both in good weather
and in IFR conditions.

However, as pointed out in the ATCAC report, the need for an
improved ILS is clearly indicated.

Microwave ILS systems are in use by the military and provide
improved performance over the standard ILS. To make effective use
of an all-azimuth and multi-glide-slope* type of Microwave ILS will
require a degree of cockpit automation which will be present in
aircraft in the 1980's and beyond in order to take advantage of
flexible area navigation, three-dimensional navigation systems,
precise control over flight paths, etc. Alternatively, a satellite
navigation system should provide sufficiently accurate position
information for all guidance needed up to the final touchdown onto
the runway and thus offers another solution to the all-azimuth
approach for aircraft equipped with such an on-board computer.

Further, accuracy and coverage of a single microwave ILS is not adequate to guide aircraft to touchdowns on the multiple runways and runway ends of a large airfield.

Therefore, the Panel recommends:

-- That the FAA pursue a broadly based design definition and development program over the next three to five years to produce a set of prototypes and production specifications for a modular ILS system with capabilities ranging from a single glide-slope to a multiple scanning-beam system.

-- In the interim, a simple microwave ILS based on current military technology and compatible with the existing VHF ILS system in format should be widely deployed soon at those airports needing a landing aid no more capable than the present ILS.

### 3.1.2.5 Airports

The federal government has provided over one billion dollars of aid to airports in the past decade with little R&D to determine how to spend this money most effectively. An RDD&E program to improve airport throughput capability should be undertaken by the FAA in proper balance with the system capacity increase to be provided in the airways system.

The Panel recommends:

-- Development of the improvements recommended by the ATCAC, including parallel- and dual-runways at high-density airports, automated surface control, fog dispersal, wake turbulence avoidance and dissipation, airport noise and air pollution reduction, and crash handling and safety support.

-- In coordination with HUD and local authorities, development of suitable planning guidance for implementation of landside improvements in airport access and egress, land use planning, and terminal building operations. Funding of such improvements would not be through the FAA or DoT.

-- Development of new concepts and designs for V/STOL ports, both at busy airports and at independent sites, with proper regard for traffic capacity.

-- Simulation of a demonstration airport region as a whole and development of alternative system plans for increasing airport capacity.

-- Implementation of a demonstration program in one to three airport areas to validate the improvements developed.

-- Widespread dissemination of these improvements through an aid-to-airports program.

### 3.1.3     System Phase-Over

The Panel has considered implicitly some of the problems of phase-over in making its recommendations, although it has not attempted to attach a dollar value to the cost of phase-over other than the projected cost of new equipment for the ATC system.

Phase-over entails problems for the ATC user--change or addition to airborne equipment--and for the ATC system itself, since ATC service must remain uninterrupted. Phase-over involves two types of costs: (1) direct costs for new or additional equipment which can, presumably, be estimated with reasonable accuracy, and (2) a second type of cost--one much harder to predict--which has to do with the nature of the phase-over process itself. Does it occur gradually in time? Is it to be introduced regionally or over the United States? Should both old and new system be operated simultaneously for a while and, if so, for how long? What new equipments and facilities are needed? The answer to some of these questions depends, of course, very much on the nature of the new system itself. For example, a phase-over to a new surveillance system based on satellites will entail different problems than would phase-over to a system based on the new ATCRBS. On the other hand, an aircraft equipped for satellite navigation can use that system anywhere in the nation from the first day of operation, in contrast with an improved ground system that spreads relatively slowly over the region. Other problems of phase-over involve user acceptance and resistance, operations personnel training and conversion, etc.--factors which are hard to predict without detailed analysis of alternatives. Phase-over to operational use, therefore, needs to be considered intensively by the FAA in its development program and deployment decisions.

## 3.2  SUBSYSTEM ELEMENTS AND RDD&E PROGRAMS

In this Section are discussed major subsystem elements and specific RDD&E programs needed to implement recommendations presented in the previous section.

### 3.2.1    Control Automation

With respect to an overall control system philosophy and concept, the Panel believes that the present DoT/FAA National Airspace System Program must, of necessity, be continued during the near-future years to keep pace with air traffic demands.

For the future, the overall control concept that we see for high-density traffic begins with strategic flow-control planning to maintain the enroute and terminal system far from saturation. This function is applied to high-density airports through a national flow control facility which balances traffic demand against airport capacity by issuing confirmed reservations and by dynamically adjusting departure release times or requesting enroute slow-down or other change of flight plan in case of runway closure, accident, or hazardous weather. An aircraft will typically fly enroute for 1 to 6 hours with rare control commands for separation, and possibly some enroute slow-down when a major change in capacity affects its destination airport. We do not see tight enroute time control as a necessity since the long-haul enroute system is maintained far from saturation, and conflicts are few.

When the aircraft approaches its destination airport, it will be subjected to enroute metering, i.e., the process of dynamically adjusting average arrival rate to current capacity of the airport via speed reductions and/or path adjustments. This process also includes provision for transition of aircraft from their enroute altitudes to their approach altitudes. The next step in the process is the terminal metering and spacing function which precisely schedules aircraft to waypoints and to specific runways and issues control commands to deliver aircraft to the landing system properly spaced relative to other aircraft. Finally, the aircraft is turned over to the landing system which provides guidance for the final approach and landing. This, then, is a process in which tighter and tighter time control of an aircraft's position in space occurs as it approaches its destination, with the aircraft itself exercising tactical control of its flight path. Tight coupling of the aircraft to its filed flight path or to the ATC system helps to isolate different terminal-areas from one another.

An adequate solution to the general-aviation problem in high-density terminals will require a greater degree of integration with the ATC system than is the case today for general-aviation. This increased integration will require development of low-cost (in the range from a few hundreds to a few thousands of dollars per unit) general-aviation avionics systems, which should be required for all aircraft operating in high-density airspace. These systems will provide a general-aviation flight capability more nearly comparable to that of air-carriers, without increasing the level of general-aviation pilot skills now needed. Such systems would certainly include:

    -- cooperative surveillance equipment;

and might include:

    -- ATC command data-link;

    -- autopilot-coupled approach navigation.

Current FAA automation programs (NAS Stage A and ARTS III) are taking the first basic and necessary steps in using digital computers to perform functions previously performed manually--aircraft tracking, flight plan processing, and alphanumeric display of data. However, the present NAS/ARTS conceptual design is nearly 10 years old. Little significant research and development in automation of the ATC function has been done for over 5 years. A study and development program is urgently needed with emphasis in the following functional areas:

- National Flow Control

    automation of the function of strategic planning and scheduling of traffic flow nationwide.

- Enroute and Terminal-Area Control

    -- flow metering between enroute and terminal-areas;

    -- arrival and departure control--i.e., dynamic sequencing and spacing in terminal-areas;

    -- conflict prediction and resolution for IFR-IFR situations;

-- IPC for IFR-VFR and VFR-VFR situations in controlled-airspace.

To achieve these capabilities will require a broad application of new subsystems, such as digital data-link; area-navigation; landing systems with curved approaches and steeper descents; accurate 3-D surveillance and navigation; airborne computers and displays; on-board flight management systems for tactical control of the aircraft flight plan; parallel- and dual-runways (with due consideration of wake-turbulence effects); airport surface control; tower displays; weather sensing and prediction.

• This will also make possible:

-- automatic weather rerouting;

-- four-dimensional navigation (x, y, z, and time);

-- new airspace structures to separate IFR and VFR traffic;

-- reduced separation standards;

-- procedures for abatement of noise and pollution;

• and require emphasis in the development of:

-- high system reliability for large computer systems;

-- proper man-machine interfaces; and

-- low-cost avionics.

• Problems in Achieving Control Automation

The above capabilities, even under "routine" conditions, are difficult to automate, principally because the control problem is characterized by three-dimensional flow patterns with:

-- a multiplicity of origins/destinations, and many different low-utilization routes interacting with high-density routes;

-- a multiplicity of aircraft and pilot-performance capabilities;

-- a dynamic environment which includes hazardous weather and variable winds.

Furthermore there are problems of reducing the cost of avionics (data-link, cooperative surveillance, navigation) required for participation in an automated system and the difficulty of achieving automated control for unusual situations. These include, for example, hazardous weather and ground system failures (power, computers, communications, etc.). The problem is to sense hazardous weather in a timely way, and then design a system sufficiently adapative to cope with the resulting dynamic situation. System failures, especially those impacting large geographical areas, must be anticipated, and the system designed to degrade softly. Automation tends to centralize functions, and thus makes the system more vulnerable to large-area failure. Regardless of theoretical efficiency considerations, most existing complex large-scale systems (e.g., power nets, telephone systems) utilize highly distributed and redundant subsystems to minimize vulnerability to wide-spread failures. We would extend these concepts to the current and future ATC system.

To include all the above concepts in a system design for automated air traffic control, it is urgently necessary to carry out an intensive and integrated program of systems analysis and development of high-reliability hardware and software, leading to verified designs that can be introduced with confidence into the operating system.

- ### Test and Evaluation

To focus this development program on a system level, the FAA needs facilities in which to test and evaluate experimental enroute and terminal-area systems. Funds should be programmed now to provide facilities, computers, communications-interface hardware, and simulation software as a base for a systems analysis and development program in control automation.

- ### Funding

The Panel estimates[2] that about $50 million is needed for facilities, equipment, software, and people over a two-year period to initiate the long-term program in control automation outlined above, and about $15 to $20 million per year thereafter for at least 5 years if productivity increases of 3 to 1 or more are to be achieved by the late 1970's and the 1980's.

In the next two years, the most important needs in control automation are modest programs to develop interim computer-aided flow control, terminal-area sequencing and spacing, and a prototype IPC capability. These initial development programs can be executed for a few million dollars at existing facilities.

### 3.2.2    Surveillance and Communications

#### 3.2.2.1    System Alternatives

##### A.    Cooperative Systems

As pointed out in the ATCAC Report, the system now being used to gather surveillance data for air traffic control--the radar beacon system--is already exhibiting overload in some of the busiest areas. Studies show that saturation of the system will increase throughout the country in the next decade. In addition, accuracy, resolution, and data rate of the system are inadequate to sustain automated control and safety in terminal-areas of the kind described previously. The need for an improved surveillance system is clearly indicated.

Many system approaches to surveillance and communications have been proposed; several have been designed and tested. Four system categories have recently been examined in some detail:

- i) Range and angle (rho-theta)* systems based upon the present ATCRBS;

- ii) Trilateration* systems using one-way ranging by a network of ground stations;

- iii) Trilateration systems using two-way ranging from a network of ground stations;

- iv) Systems using a constellation of satellites for trilateration or time-difference-of-arrival measurement of aircraft position.

Since maximum data rate and accuracy requirements are largely determined by needs of the surveillance system controlling aircraft on final approach to close-spaced runways, the foregoing systems can be combined with the following:

> deriving surveillance information from the landing system used by aircraft to navigate to touchdown, thus easing

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accuracy and data rate requirements on the general surveillance sytem.

This alternative needs more study in connection with the choice of a new surveillance data-acquisition system and before a new landing system is developed.

Each of these system alternatives is discussed in greater detail.

### i)   A New ATCRBS

The ATCAC Report[3] has recommended development of a rho-theta system for the upgraded Third Generation ATC System--"a discrete-address ATCRBS that incorporates an integral data-link (of varying sophistication, depending on the aircraft) and that employs phased-array ground interrogators."

This ATCAC-recommended surveillance system evolves from the current ATCRBS. It resembles the current system in that coverage would be provided by a network of interrogators operating on a common channel. Replies from aircraft would provide azimuth and range information as well as identity and altitude codes. Most aircraft would be on a discrete address roll-call and receive ground-derived control information. These aircraft could transmit data-link information back to the ground. Some aircraft would continue to use only standard transponders and voice communications. They would be interrogated in the same way as the present ATCRBS. The system would measure position from a single site, with redundant coverage to aid system reliability.

The Panel has reviewed this system in detail. Costs and schedule for phase-in of the superbeacon are compared in Appendix 4 with those for a satellite surveillance and navigation system. Because of limited coverage and unavailability of data-link except in areas served by new interrogators, the Panel does not recommend a commitment at this time to deploy the superbeacon. Rather we recommend its development and design verification so that a program choice can be made in about two years without losing valuable time and with the results of parallel development programs in hand.

### ii and iii)   Ground-Based Trilateration Systems

Ground based trilateration systems have been proposed by a number of groups for an ATC surveillance system. The ATCAC

eliminated these systems as candidates because of siting costs and problems with multipath*, accuracy, and line-of-sight coverage.

In particular, such ground based systems do not provide altitude information to an accuracy useful for the ATC surveillance function. Thus altitude must be carried on the transmission from each aircraft. Further, the radio propagation path from each of the ground sites typically makes an angle of only a few degrees with the horizon, thus constraining site location and introducing problems with reflection and multipath. If the system were required to continue to operate in the presence of a single failure, many redundant stations would have to be provided. Since an aircraft must be capable of receiving signals from at least three and sometimes four stations, siting problems are severe, as is the burden of continued maintenance of such a dispersed network.

While the Panel does not believe it desirable to base a surveillance system upon ground-based trilateration systems, a few such receiving sites in areas of dense traffic, working in conjunction with the satellite system described in the next paragraph, can increase the robustness of the surveillance system. Further, for blind landing, the critical navigation accuracy in altitude and cross-track may best be obtained by supplementing satellite-based transmitters with one or two low-power transmitters broadcasting a similar navigation system and sited on the airfield (see Appendix 3). Further, it is clearly possible to do simulation and system refinement of satellite-based systems by the use of at least some ground-based transmitters and receivers as indicated in Appendices 4 and 5.

Transmission frequencies and formats suitable for use with satellite-based navigation and surveillance systems can be used unchanged for ground-based supplements, although they might not be optimum for a completely ground-based trilateration system. Therefore, the Panel recommends continued consideration of ground-based supplement, as indicated here, to the satellite-based systems discussed in the next section.

### iv) Satellite Based Systems

Satellite based systems for surveillance compute on the ground either by trilateration via one or two-way ranging or by relative-arrival-time computations (i.e., time-difference of arrival) using a constellation of several satellites (e.g., 4 to 6) which receive coded transmissions from each aircraft every second or so*. These

same satellites could also provide universal 3-D navigation function to suitably equipped aircraft.

A satellite based surveillance system has potential capabilities not available to ATCRBS, among them an independent measurement of aircraft altitude, and essentially universal coverage of the airspace. In contrast to the ATCRBS, the addition of a navigation capability would enhance system flexibility by providing independent sensors of aircraft altitude, one for navigation and one for surveillance.

Three problems are evident with a satellite based system:

-- Vulnerability of the system to intentional jamming of the satellite receivers by high-gain, high-power antennas mounted off-shore, in foreign countries, or in the United States. This is a technical issue with political content that needs to be investigated and policy established, as in the case of oceanic satellites for airborne communications and air traffic control.

-- Possible delays in reacquisition of the positions of many thousands of aircraft if the system fails because of either hardware or software problems, or in regaining track on an individual aircraft if signal dropout occurs because of aircraft antenna orientation and/or destructive interference due to multipath.

-- Possible complexity in signal formatting (codes) and ground-receiver processing which may be required to reduce mutual interference to acceptable levels. This problem may limit the number of aircraft which may be handled on any one channel in the steady-state condition.

The two latter problems are technical ones on which some progress has been made and which might yield to a research, development and test program and proper system design.

The ATCAC reported on the use of satellites for domestic air traffic control in the context of a satellite-based system providing all three functions of surveillance, communication, and navigation[5]. The specific function of communicating via satellite to one hundred thousand or more users involves large amounts of radiated power. For this reason, and because the specific satellite sytems investigated were not well suited to the task,

their deployment for use in domestic air traffic control was relegated by the ATCAC to the post-1990 period.

On the other hand, if a satellite based system designed to do part of the ATC job demonstrated significant cost-reduction possibilities compared with alternative schemes, and/or improved benefits (including airborne equipment costs), then satellite subsystems should be considered for earlier deployment in competition with any part of the entire complex of ground-based systems. The Panel's review has revealed the likelihood that satellites are indeed well suited to provide universal surveillance, an accurate navigation capability and a candidate data link for IPC, without being able to handle the totality of data-link or voice communications necessary for air traffic control. The probability of success, and the combined benefits of this satellite system (described in Appendix 3) leads us to recommend the initiation of a program to define the system and to resolve the remaining uncertainties, with a choice between the satellite approach and the superbeacon approach possible in about two years, without loss of valuable time.

B.  Primary Radars

Primary radars are now used to supplement beacon radars for data acquisition. The Panel recommends that primary radar eventually be phased out of the ATC system both for enroute and terminal surveillance. Since current radar does not determine aircraft altitude, radar returns from uncontrolled-aircraft* provide only limited information for control and collision avoidance of aircraft under FAA control. Moreover, a radar which would provide altitude would be expensive in development, procurement, and probably operation. The Panel recommends that only those R&D efforts be performed that will yield worthwhile improved operation of current radars within their remaining useful life in terms of reduced maintenance costs and higher reliability.

A future ATC system operating without primary radar must rely on cooperative surveillance aids in all aircraft. Even so, allowance must be made for in-flight failure of the surveillance aid. As noted by the ATCAC, there is a procedural response to occasional failure of the surveillance aid, which would be rendered even more effective by a requirement that the aircraft be acknowledged by the surveillance system before it takes off. Large aircraft would normally carry redundant surveillance aids.

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Aside from the situation of equipment failure when the aircraft is under surveillance by the ATC system, there is the possibility of an intruder--an aircraft which for one reason or another has intentionally not equipped itself with, or not operated, the surveillance aid. Such threats must be put in the context of other threats to civil aviation. The present system under which the FAA forwards primary radar surveillance data to the Air Defense Command evidently inhibits FAA transition to a completely cooperative system. While direct costs of forwarding of data may be reimbursed by the DoD to the FAA, it is the public and civil users who pay for retaining a more costly and less effective air traffic control system incorporating primary radars. The Panel suggests that surveillance of non-cooperative targets (remaining after ATC-tracked aircraft are deleted from the radar) is a responsibility of the Air Defense Command, and that such data be forwarded to the FAA for avoidance and action.

### 3.2.2.2    Recommended R&D Programs for Surveillance

Because of the impact of surveillance and communication subsystems on investment and operating costs of the user community and on success of the control automation program, the Panel feels it prudent that various system options for data acquisition be intensively studied and compared over the next two to three years. This should be done on the basis of system costs (ground and airborne), coverage, reliability, and operational phasing before a choice is made for long-term national deployment. Given adequate funding, such a comparison of the following system options should not delay operational deployment schedules:

Option 1)  A next-generation radar beacon system network (ATCRBS) having two-way data-link and a discrete-address capability for air traffic control, acceptable operationally and economically to the full range of users.

Option 2)  A discrete-address beacon system (ATCRBS) to provide improved surveillance, but with a separate VHF data-link to meet airline as well as ATC requirements.

Option 3)  A satellite based surveillance system that is acceptable operationally and economically to the full range of users while providing greatly improved service in terms of both performance characteristics and acceptable O&M (operation and maintenance) costs for the FAA. The system may have two-way data-link (for IPC and command/control). A

hybrid surveillance and communication system may be preferable, with one or both portions of the two-way data-link furnished by a separate ground based system, e.g., at VHF. These digital-data-link options also need to be investigated as part of an R&D program for a new communication subsystem.

Any of these surveillance systems can serve as a source of position data to be communicated to aircraft from the ground system on demand via data-link, the navigation data thus obtained in Option 3 being clearly superior in accuracy and data rate to either of the others.

The primary need for pursuing these options before a national deployment decision is made is due not so much to technological uncertainty, but to uncertainties in ground and airborne system costs, system design, acquisition schedules, and operational phasing and benefit for each option. A two-to-three year, adequately-supported development and evaluation program should resolve these uncertainties and save money in the long term, without delaying operational capability.

First, we discuss near-term improvements needed now in surveillance and communication, and then long-term improvements.

A.    Near-Term Improvements

To alleviate existing problems of azimuth accuracy, data rate, resolution, and interference in the present beacon system, thereby providing increased capacity and improved separation control, a near-term improvement program should be implemented over the next two years.  This program should include development of:

   --    a more directive (i.e., larger) interrogator antenna
         (mechanical and/or phased array);

   --    a monopulse-on-receive capability with:
             single-pulse azimuth-estimation,
             side-lobe    suppression-on-receive    to    reduce
             interference,
             lower interrogation rates to reduce transponder
             overload;

   --    a more sophisticated digital detector-estimator to de-
         interleave range overlaps;

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-- designation of prime interrogators, sharing prime-
interrogation data, re-siting of prime interrogators, and
turning off other interrogators; in general,
establishment of an improved ground-based interrogator
environment;

-- frequent monitoring by the FAA of interrogator discipline
in dense areas.

The Panel estimates that about a $5 million development and
test program for about 1 to 2 years is needed to provide these
near-term capabilities. Interrogators in the field can probably be
retrofitted for between $250,000 and $500,000 each, depending on
the level of capability needed at each particular site. A few
sites in high-density areas may require more extensive
modifications of up to $1 million. All these changes can be made
by the FAA without affecting user equipment and can therefore be
available and contributing to air traffic control long before the
estimated 1978 service date for a discrete-address beacon system.

B.  Long-Term Improvements

Among the recommended surveillance systems, the satellite-
based approach requires a development effort of special magnitude
and complexity. For this reason, Appendix 4 describes a
comprehensive RDD&E program for a representative satellite-based
system and compares this approach with the upgraded ATCRBS in terms
of phasing (both ground system and users) and life-cycle costs
including R&D, capital and O&M costs taken over a 15-year period.
These costs do not include the savings that would be possible in
achieving a satellite-based surveillance system by incrementally
adding this capability to a Defense Navigation Satellite System.

Assuming successful development of any new system, a primary
problem is phasing-over civil and military users of the ATC system
and the ATC ground environment to the new system.

The following sections summarize the detailed material in
Appendix 4.

(1)  Satellite-Based System R&D Program, Including Data-Link
Studies

We envision a four-phase program of R&D that would focus early
on key areas to demonstrate system feasibility and provide a well-
developed data base for further concept synthesis and refinement.

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Assuming that a desirable system concept is feasible, the complete R&D effort, including a prototype initial-operating-capability for the domestic United States, could involve an expenditure of $220 to $270 million over an 8 year period.

The four-phase program would consist of the following:

| | | |
|---|---|---|
| -- | Exploratory Development | $30 to $40 million |
| -- | System Design and Verification | $20 to $40 million |
| -- | Prototype Development | $165 million |
| -- | Operational Test | $12 to $25 million |

In the Exploratory Development Phase over the next three years, three categories--Signal Design and Transmitter/Receiver Processing, Satellite Technology, and Data Processing Methods --would be explored with the hope of achieving significantly improved capabilities. A "break-through" in either of the first two categories could have a significant effect on both user equipment cost and ground cost for both surveillance and data-link portions of the system. For example, in the area of surveillance, a great cost reduction in high-power coherent transmitters on the aircraft would allow the use of combined time-frequency and phase codes which may have good performance in the presence of fading, and would facilitate rapid reacquisition if track was lost briefly. In satellite technology, development of multiple large-aperture antennas or optimum processing of large arrays could greatly reduce the user equipment and ground system costs, both for communications and surveillance.

A major portion of the Exploratory Development costs are attributable to the need for an early satellite experiment. Fortunately, a great deal of cooperation could be available for this work from both NASA and DoD. Satellites of the NASA ATS variety as well as satellite systems proposed by DoD for defense navigation and tactical communications purposes (e.g., Defense Navigation Satellite System, Interim Defense Communication Satellite Program, Lincoln Laboratory Experimental Satellites) could be shared for this work. The possibility exists, given an L-band capability, for using oceanic ATC satellites as well[6]. Similar cooperative arrangements might be available for satellite technology and aircraft antennas. The remainder of the exploratory development work is of a somewhat specialized study and simulation character, but of more modest cost. Of the total exploratory development effort, at least $11 million might be assignable to the DoT/FAA, the remainder to existing programs in NASA and DoD.

The results of this phase, if successful, would be a greatly improved R&D data base which would allow several viable system concepts to be synthesized and compared in the System Design Verification Phase. Using the common exploratory data available, each concept should be fully simulated and its cost and feasibility proven. This will involve limited user equipment and ground system hardware construction. The Design Verification Phase will be complete when one or two of the concepts have been found to be sufficiently sound and promising to encourage detailed prototype specifications to be written for ground, user and space-craft equipment.

The Prototype Development Phase would carry one such concept through full-scale testing. During the latter portion of this phase, a minimally useful number of satellites would be launched. Satellite life-time could be such that an interim-operating-capability would be available following operational test; in this way maximum utility would be obtained from the large expenditure for prototype development. Likewise, a ground complex could be constructed (including data distribution and conversion) sufficient to handle the operational test as well as a non-redundant operating capability. If a prototype Defense Navigation Satellite Service were deployed, given adequate program coordination, satellite facilities for domestic civil navigation and ATC surveillance system could probably be incorporated for about 10% to 20% increase in satellite cost of the defense program.

(2)  VHF Data Link

To determine the role of VHF data-link in air traffic control, a review of IPC and ATC data link needs was made for an area such as the Los Angeles basin in 1995 with a traffic load of about 150 IFR and 1200 VFR aircraft[7]. Based on a preliminary analysis described in Appendix 2, a reasonable VHF uplink, where one is not constrained to use current aircraft equipment, can consist for example of two 1200-bit/sec links multiplexed into each adjacent 5 kHz sub-band of a 50 kHz VHF channel allocation. Assuming dedicated data-link equipment in the aircraft, a 78-bit address and 120-bits of message require about 0.2 sec of transmission time. Acknowledgement by transmission of check bits (not parroting) will require about 0.02 sec on the downlink channel, allowing 4 messages per second per subchannel (peak)--a rate which may be closely approached with computer-managed queuing.

Without requiring human acknowledgement, an ATC channel burden of about 10 command/control commands per second and 1 IPC command

per second will occupy (11/4)=3 subchannels of the 20 available in a single 50 kHz VHF channel. For the IPC commands to VFR aircraft, about 6 additional commands per second, or 2 subchannels, are required.

An alternative implementation of the VHF data-link would use a single 50 kHz VHF channel without subchannelization, transmitting at a data rate of 24,000 or 48,000 bits per second in a completely time multiplexed fashion. This implementation would be significantly less expensive and would be preferable if thorough experimentation shows that it is operable in the presence of multipath.

It seems reasonable to assign 2 adjacent VHF channels to data link--one ground-to-air and one air-to-ground, with aircraft equipped with fixed-tuned receivers and transmitters to take part in the system.

The critical items needed to develop in this data-link are:

i)   establish data requirements for IPC, ATC, and airlines use, establish signal format;

ii)  establish and minimize the cost of user equipment; and

iii) develop hardware and software for the ground system to use the data link. The VHF data-link can then be compared with the ATCRBS link on the basis of user costs and system performance.

(3)  ATCRBS System RDT&E Program

A new ATCRBS system requires an RDT&E effort of about $40 million over a three-to-four year period. The program would involve radio-frequency environment and signal-format studies, deployment analyses and construction and test of several prototype systems. The ATCAC Report has described this program in some detail, so it will not be repeated here.

The most important and critical area that needs to be investigated in the next 18 months for an upgraded ATCRBS is the addressable beacon and data link feature. A modest $5 to $6 million effort should be initiated now in this area to:

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-- conduct a study of addressable beacon systems, including a requirements analysis, coding concepts, equipment design, and system-implementation needs and costs;

-- prepare a set of operational specifications;

-- fabricate a breadboard model, including ground and airborne equipment;

-- conduct a flight test program to demonstrate the feasibility of the addressable beacon and data link system and to gather and analyze data on the effects of interference and multipath.

The ATCAC recommended RDT&E program, in conjunction with the satellite-based system RDT&E effort, should provide the technical and cost data needed to make a system deployment decision in about 2 to 3 years without delaying attainment of the capability ultimately chosen.

(4) Estimated Costs and Phasing of a New Surveillance and Communications System

For the satellite-based system we have estimated that about $235 million for RDT&E would provide a prototype system with an initial operating capability. An additional $100 million capital cost would allow for: upgrading of the prototype ground complexes to have full interim operational capability ($30 million); launching 4 more satellites ($60 million); the completion of a data dissemination network; and the launching of additional satellite replacements each year ($25 million). About $15 million per year would be needed to maintain the ground environment (10% of $150 million capital costs). The cost of the ground complex might be reduced by innovations not considered at this time.

Assuming a successful development and deployment phaseover beginning in 1978, cumulative FAA costs for the satellite-based system are about $900 million through 1985. Yearly spending would peak in 1980 at roughly $100 million. O&M cost remains relatively constant at $45 million following completion of the transition period. Cost savings attributable to a Satellite System that may also be used for navigation by suitably-equipped users are not taken into account here.

As noted in Appendix 4.3, sharing satellites with a Defense Navigation Satellite Service but paying all incremental satellite

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and total ground system costs would reduce this $900 million cumulative cost to some $740 million. A more rapid phasing out of the then-redundant ATCRBS would save about $140 million more in O&M, bringing the total for this approach to $600 million through 1985.

As noted earlier, the RDT&E costs for the new ATCRBS are about $40 million. Cumulative FAA costs through 1985 for a fully deployed beacon system (all new units) are about $820 million. These costs assume new beacon system deployment beginning in 1975, including integral data link.

The cost to the FAA of development, deployment, and operation through 1985 of the surveillance/navigation satellite capability ($600 million to $900 million) is thus entirely comparable with that for the superbeacon system ($820 million).

### 3.2.3    Aircraft Navigation and Landing

#### 3.2.3.1    Present System

The chief domestic civil-aircraft navigation systems are VOR and DME for enroute guidance, and ILS systems for landing. At present, 289 ILS systems are operational, and FAA plans to increase the number of installations to 890 by 1980.

The existing VOR system provides point-to-point (VOR to VOR) two-dimensional guidance throughout the contiguous United States with implementation of this system essentially complete (approximately 900 installations). The accuracy of guidance (angular accuracy of 2 to 4 degrees provided to a point on the earth's surface, the VOR ground station) is such that airways are not generally located with less than a 15 degree angle of intersection at the VOR to preclude airways intersecting at near-parallel angles. This limitation does not allow a flexible airways structure.

To supplement the VOR system, the DME system (co-located with a VOR) provides the slant range between an aircraft and a VOR by means of a transponder at the DME site. Approximately 580 VOR's are presently equipped with DME capability. The remaining VOR's are to be equipped prior to 1980. A developing problem associated with the DME system is the inability of any particular DME ground station to service more than about one hundred user aircraft simultaneously because of power limitations.

The existing VOR and DME enroute navigation systems provide sufficient information for area navigation. The main reason that aircraft today navigate along line segments, formed by radials from VOR stations, is the general lack of airborne computation and display capability. Many airlines are now equipping their fleets with area-navigation equipment. However, improved guidance signals are needed to reduce the VOR and DME deficiencies noted above. These signals in turn will allow greater area-navigation capacity--i.e., for great-circle routes, random creation of routes, and most importantly, the use of many parallel routes in high-density areas. However, terrain and local distortions of the VOR pattern make off-airway navigation by VOR and DME inadvisable and not certified except where specific area-navigation airways have been surveyed.

### 3.2.3.2   Near-Term Improvements

A.   VOR and DME:  In the early 1960's, prototype equipment demonstrated that the existing VOR system could be upgraded in a compatible manner to provide six- to ten-fold improvement in navigation accuracy for equipped aircraft, particularly where optimum siting is not available. This improvement requires addition of a new subcarrier to give a second phase measurement, which reduces multipath effects, and an improved ground antenna. With these improvements the best angular accuracy will be a few tenths of a degree. (For the aircraft which does not upgrade its navigation equipment, some improvement will also occur.) Estimated cost for each such precision VOR ground system is approximately $105,000. Existing FAA plans are to provide this improved service at approximately 10% of the VOR ground stations located within sixty major terminal areas to permit the establishment of more area navigation and point-to-point routes in that airspace.

The expected increased utilization of area navigation generally requires two precision VOR's, a precision VOR and a DME, or two DME's to be usable by an aircraft simultaneously. As a consequence, DME utilization is expected to increase, and ground and aircraft modifications will be necessary to increase the number of aircraft which can be handled simultaneously by each DME.

For the near-term there should be an upgrading of the existing VOR and DME networks and some expansion of the existing ILS for the following reasons:

--   The FAA will gain increased high-density airport and terminal capacity where and when needed with increased safety, minimal technical risk, and a gradual capital

expenditure for the PVOR and DME and the expanded VHF-UHF ILS installation.

-- General-aviation will obtain increased navigation capability without avionics modification (about 90% of fleet has VOR capability) and a still further increase in navigation capability with minimal modification of aircraft avionics. The existing ILS system will be implemented at many smaller airports for general-aviation use.

-- Air-carriers will gain a reduction in operating cost through reduced delays, and greater assurance of all-weather operation in the near-term through the use of area navigation at high-density airports.

The FAA needs to study how best to integrate area-navigation into the ATC system to allow maximum cost and safety benefits to the users. This study is needed particularly in regard to siting of PVOR and DME stations and the creation of high-density routes.

B. Landing Systems: The ATCAC report pointed out that the present instrument landing system must be replaced eventually to allow the increased capacity, made possible by reduced parallel-runway separations, actually to be realized at the high density airport locations. In addition, there are many sites, particularly in mountainous areas, where components (primarily glide-slope) of the present system cannot be commissioned because of severe multipath. Multipath errors at some airfields and total lack of glide-slope information at others make it difficult to achieve terminal capacity and maintain adequate safety in many terminal areas. Need for an improved instrument landing system is clearly indicated.

In the 1960's, demonstrations established feasibility of utilizing pulsed, microwave guidance for instrument landings. These tests have demonstrated significant improvements in signal integrity, large reduction in degradation of the ILS system by airport obstructions, increased capability for blind landings, and ability to provide guidance simultaneously along multiple (steeper-descent) curved-paths. Present FAA plans are to install sixty Microwave ILS systems at high density airports prior to 1980 at an estimated cost of $500,000 each.

Microwave landing aids are in use by the U.S. military to provide small, readily deployable systems of higher accuracy than

the normal ILS and to accommodate glide-slopes of varying angles. Microwave ILS's, in principle, are of three types listed in order of complexity:

-- fixed glide-slope and single azimuth,

-- arbitary glide-slope and single azimuth,

-- arbitary glide-slope and multiple azimuth, e.g., 120- or 360-degree coverage.

Systems of the first two types could readily be integrated into the present ATC system requiring only installation of microwave receivers and ILS data-link on general-aviation and air-carrier craft, which could then use the new microwave as well as the old ILS system. Such an improvement would provide a better quality ILS approach for blind touchdown, and it would also permit higher-angle approaches, for those airplanes capable of using them, to minimize noise under the approach path. Large reductions in noise, and improvements in airport capacity under IFR conditions, would accompany deployment and use of the third type of microwave ILS system. An aircraft to use the third type must be equipped with an on-board flight-management computer which we believe will be installed on many aircraft of the future. Given the likelihood that the sophisticated ILS will be of use only with an advanced, computer-managed area-navigation and tactical-control system, which has already been shown to be adequate in itself for curved approaches and letdown on the final approach, we believe that the desirability of deployment of the more sophisticated multiple-azimuth microwave ILS is not a foregone conclusion. In particular, it seems likely that computer-managed area-navigation systems, particularly those using navigation satellites, supplemented with two small transmitters on the airfield or a single glide-slope ILS for CTOL aircraft, might provide high quality ILS approach at a much lower investment per additional airport served.

There is a further uncertainty about the Microwave ILS program. Since accuracy and data rate of the surveillance system described by the ATCAC derives largely from the necessity to monitor simultaneous approaches on close-spaced parallel-runways, it seems perfectly feasible to design the microwave ILS system with a two-way capability to work with beacons or corner-reflectors on the aircraft to provide especially accurate and frequent surveillance of the aircraft in this high-density, time-critical area.

Therefore, the Panel recommends that the FAA pursue:

--   A broadly based design definition and development program
     over the next three to five years to produce a set of
     functional prototypes and production specifications for
     a modular ILS system with capabilities ranging from a
     single glide-slope to a multiple scanning-beam system.
     Such a program will provide system options for national
     deployment which need to be evaluated with respect to
     operational flexibility, ground system complexity, and
     airborne equipment cost and complexity. These system
     options include: (1) use of a multiple scanning-beam
     microwave ILS for curved approach and landing in
     conjunction with TVOR (terminal VOR) and DME for
     terminal-area navigation, and (2) use of a satellite
     based system for terminal-area navigation and curved
     approach with straight-in microwave ILS guidance during
     landing.

--   In the interim, a simple straight-in microwave ILS based
     on current military technology and compatible with the
     existing VHF ILS system in format should be deployed at
     those airports needing a landing aid no more
     sophisticated than the VHF ILS provides. This interim
     microwave ILS should be of a single type in order to
     provide economy of acquisition and maintenance.

### 3.2.3.3   Long-Term Improvements

     Even when all of the above near-term system improvements are
implemented, a number of deficiences in the system will remain.
These include lack of:

--   An independent measure of altitude, and possibly
     velocity, throughout the system.

--   An "ILS"-type navigation capability at thousands of
     airports that will not be equipped with any ILS at all.

--   Accurate low-altitude coverage for high-density terminal
     areas and routes to accommodate V/STOL aircraft flying in
     and out of centrally located V/STOL ports. (The existing
     VOR-DME provides coverage over the entire U.S. at high
     altitude, but siting and shadowing of the transmitters do
     not permit universal use of the system even at altitude
     without expensive aerial survey.)

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Navigation needs and possibly the landing capability might be met by a satellite multilateration navigation system in the time frame of interest and for this reason research and development activities necessary to determine system realizability and cost should be pursued in conjunction with DoD in the intervening years as outlined previously in the section on surveillance.

Other improvements might include DECCA and LORAN, widely used by military aircraft since they provide navigation down to ground level. LORAN is also used by transatlantic carriers. However, both of these systems suffer from the inability to provide vertical navigation guidance to aircraft. In addition, user equipment for these systems is complex and potentially as costly as a satellite multilateration navigation system receiver.

Inertial navigation of course provides very useful capability for oceanic navigation, but its accuracy and cost will not allow it to compete effectively against a satellite receiver-computer if a satellite navigation system were available. Some of the benefits usually ascribed to an inertial system stem from the use of an onboard computer and will be available with any area-navigation system. For aircraft in international service in areas in which adequate navigation aids are not available, or where excessive charges might be made for their use, inertial navigation will remain uniquely valuable.

In summary, while these present installations and projected modifications are necessary to support aviation needs throughout the 1970's, only if both navigation and surveillance systems have greatly improved accuracy can airspace requirements be minimized, and deviations from conflict-free trajectories be monitored sufficiently closely to provide IPC service with a minimum of commands. We believe that a passive system in the aircraft, computing aircraft position from signals received from synchronous[8] navigation satellites, could provide a valuable domestic system of universal coverage usable by air-carriers, military-aircraft, and some general-aviation aircraft. The remainder of general aviation may well use position determined by the surveillance system and communicated to the aircraft via data-link periodically or on demand. This navigation-via-satellite system is far more accurate and probably less expensive than a full set of VOR and DME equipment and its coverage (the intersection of surveillance coverage and data-link communication coverage) would extend to all regions in which data-link is available.

If the U.S. Defense Department undertakes to develop and deploy a navigation satellite system to provide highly-accurate, three-dimensional, world-wide position fixing, then adding civil-user navigation capabilities to this system would probably increase the cost of the satellites and their ground support by only a very small amount.

Thus, the most attractive navigation system of the future for highly productive vehicles, either military or civilian (and later, perhaps general aviation), is the navigation satellite, providing universal coverage down to ground level and three-dimensional accuracy, improving with sophistication of airborne equipment, on the order of 100 feet. Satellite navigation using on-board computers requires no transmission from the aircraft. The cost of such a computer-receiver combination at present would be less than $50,000, and still lower in the 1980's and 1990's. The same computer-receiver might be used in the neighborhood of airports to provide few-foot accuracy (assuming local airport calibration) for touchdown guidance and even for guidance on the taxi-way. This is an important possibility that deserves study.

We have outlined above the overlapping and competing capabilities of ground-based area-navigation systems, simple and complex microwave ILS, and satellite multilateration navigation systems (with or without precision enhancement at airports). A one-to-two year adequately-supported program of analysis, development, and evaluation should lead to a better grasp of technical feasibility, ground and airborne systems costs, system design and functional interaction, acquisition schedules, and operational phasing for the various options and combinations of options. Such a program would be well worthwhile to resolve uncertainties and need not delay operational capability.

### 3.2.4    Use of the Airspace

#### 3.2.4.1    Structure

The structure of the airspace is dynamically determined by the interactions between the FAA and the airspace users, military, general aviation, and air carrier. There is a substantial demand for effective segregation of airspace, particularly in the terminal areas, which has been met in a fashion apparently unsatisfactory both to general aviation and to the air carriers by the FAA Terminal Control Area scheme. The wider use of simulation to choose among alternative structures of the terminal air space should avoid incidents like the afternoon of August 20, 1970, when

Terminal Control Area operation was introduced at Washington National Airport and withdrawn a few hours later. If the FAA maintained an adequate and flexible simulation capability, the Terminal Control Area concept proposed jointly by the air carriers and by general aviation could have been simulated and compared with the simulated FAA Terminal Control Area. We recommend that more extensive use of this simulation of new modifications to airspace structure be carried out in the future.

We envisage the following types of airspace outside the terminal area:

-- Uncontrolled air space, in which the only requirement is for the airplane to have an operating surveillance aid to allow air traffic control to ensure that the aircraft remains within uncontrolled airspace.

-- Positive-control air space, in which aircraft must be equipped with two-way radio and navigation aids, in addition to the surveillance aid, in order to ensure that the aircraft will under all conditions of visibility be able to maintain its specified flight plan.

-- Mixed air space in which aircraft under positive control and flying IFR are present at the same time as aircraft flying VFR. In this airspace, IPC will be used to guard against collisions and near collisions between IFR and VFR aircraft and among VFR aircraft.

### 3.2.4.2    Integration of General Aviation

General aviation unquestionably contributes to congestion in high-density terminal areas, prompting suggestions that our air traffic problems would be solved if general aviation were simply banned. The general aviation fleet consists of both aircraft and pilots of a very wide range of capability, the best of which are fully the equal of those used by the air carriers, the simplest of which are unsophisticated indeed. Distribution of general aviation traffic is inhomogenous in space and in time, contributing least to traffic density at times and places where the congestion is worst. Of approximately 10,000 airports in the country, some 500 are served by air carriers and the rest exclusively by general aviation. The busiest airports in the country already have de facto separation of air carrier and general aviation traffic. The busiest general aviation airports have well over 95% general aviation operations, while the busiest air carrier airports such as

Chicago's O'Hare and New York's Kennedy have the ratio nearly reversed. Even the small percentage of general aviation at these busy airports tends to be from the more sophisticated fraction of the general aviation fleet, such as air taxi or corporate aircraft. Further, air carrier congestion is worst in instrument weather, which tends to ground all but the better equipped and more capable part of the general aviation fleet.

The Panel concludes that it is essential to extend mandatory surveillance to general aviation aircraft in the whole of the air space as described elsewhere in this report, but that simple exclusion of general aviation from terminal areas cannot be a long-term solution to the ATC problem.

It is quite true that an ATC system to handle only air-carrier operations could look quite different from that which will handle both air-carrier and general-aviation. It is not at all clear to what extent complexity and cost of the latter system can be ascribed to the necessity to protect air-carriers against general-aviation or whether it is due largely to services provided to general-aviation itself.

What is clear, however, and has been demonstrated by analysis repeatedly over the last decade, is that the total cost to the government of providing ATC services would be much reduced and the quality and safety of service increased for all participants, if general-aviation aircraft were to carry a cooperative surveillance aid[9]. Considering potential savings in cost of primary-radar* alone, the discounted benefit-to-cost ratio appears to range from slightly over one if the government gives or lends the surveillance aid to every aircraft operator, to more than 8 if the operator buys the aid at no cost to the government. Consideration of other FAA costs related to lack of cooperative surveillance is likely to improve these benefit-to-cost ratios by an additional factor 3 or more. Net benefits to the government must not be lost simply because in gaining these benefits the government might provide equipment to general-aviation. There is room for imaginative solutions, such as a requirement that all aircraft carry surveillance aids, which might be satisfied by hourly lease of adequate equipment, to be plugged into an adapter in the aircraft. Allocation of ATC costs among the various users of the system is being addressed in a special study chartered by the Secretary of Transportation and will not be discussed here.

### 3.2.4.3 "Controlled Visual Rules"--CVR

At present general-aviation aircraft equipped with navigation, radio, transponder and other instruments have the option of filing an IFR flight plan and participating fully in the ATC system. If on the other hand, these aircraft elect to fly VFR, thus reducing the burden on air traffic control, the FAA policy is currently to issue traffic advisories in mixed airspace on a "workload permitting" basis. This often results in no service to the VFR craft. Further, fewer than 20% of private pilots have an instrument rating, so that the great majority are precluded from participating in the control system, although their aircraft are suitably equipped, simply because they are not certified capable to control the aircraft by instruments alone.

The Beacon Committee in 1961 considered this problem and noted that participation in the control system and ability to fly an airplane by instrument reference can be separated. They recommended the adoption of a third set of rules, CVR, which would permit a non-instrument-rated pilot to enter the control system completely, and be treated in this context as if he were on an instrument flight plan. This would open participation in the control system to a much wider class of pilots, though one might still wish to test participating pilots for their competence in radio navigation and in their ability to communicate effectively and expeditiously with air traffic control, perhaps through introduction of a new CVR rating, often proposed and not yet implemented.

Although the Panel recognizes the increased work load which would result from introduction of CVR, it recommends this concept for reconsideration.

### 3.2.5    Airports

The government has provided over one billion dollars in aid to airports in the past decade with little R&D to determine where to spend this money most effectively. Therefore, to balance the system capacity increase provided in the airways system a major RDD&E program to improve airport throughput capability should be undertaken by the FAA to guide the $2.5 billion in federal expenditures over the next decade, provided by the Airport and Airway Development and Revenue Act. This R&D program should include airside improvements and in cooperation with other Federal or civil authorities, should include development of planning guidance for the landside parts of airports.

### 3.2.5.1    Airside

As described by the ATCAC, on the airside:

-- ILS and runway operations, including use of parallel and dual-runways at high-density airports;

-- forecasting of windshifts;

-- wake turbulence avoidance and dissipation;

-- fog dispersal;

-- airport surface control systems to detect, identify and guide aircraft from runways to ramps;

-- airport noise and air pollution reduction;

-- crash handling and safety support;

-- ramp and gate design;

-- servicing support to reduce turn-around time.

3.2.5.2. Landside

On the landside:

-- terminal building operations--baggage and passenger handling and ticketing;

-- land use planning;

-- airport access.

New concepts and designs in the use of:

-- satellite terminals for ticketing, baggage handling;

-- separate V/STOL ports;

-- interchange airports for use by passengers going from a long-haul to a short-haul system or in establishing an efficient multi-point system.

In addition to study and development of techniques and subsystems in these areas, an airport region as a whole (e.g., New

York area) should be simulated and analyzed as a system, and several alternative plans for increasing airport capacity developed and costed.

We agree with the ATCAC that an FAA RDD&E program of about $15 to $20 million per year is needed in the airports area, the major portion of which would be devoted to the airside problems outlined above. A demonstration program should be implemented in one to three airport areas to validate the improvements developed. Airport runway and surface-traffic control should be emphasized because of their importance to system throughput capacity. Similarly, special attention should be given to the means by which multiple VTOL landing-and-loading areas would be incorporated into the airport land and air complex.

The Panel recommends that the DoT/FAA take the lead in stimulating the necessary R&D to ease landside congestion problems.

### 3.2.6    Oceanic Air Traffic Control

Unlike domestic air traffic control, the problem of oceanic air traffic control is characterized by low density enroute traffic, long distance navigation, lack of reliable communications, and lack of surveillance coverage. A detailed description of the problem may be found in Appendix 5. The phased assumption of navigation and surveillance functions by a domestic-satellite compatible system is discussed (only as an example) in Appendix 3. For reasons of RDD&E funding economy and to gain an understanding of the applicability of oceanic ATC techniques to the domestic ATC problem, the RDD&E and deployment of a new ocean ATC system should be done in close consort with the program for domestic air traffic control.

## 3.3 AIRBORNE USERS

This section describes the new ATC system from the viewpoint of the users. The system should be structured so that the user obtains more benefits if he makes a greater investment, providing a short-term, local, individual initiative. Further, there must be adequate incentive and mechanisms for the users--air-carriers, general-aviation, and military--to take actions over the long run resulting in lower costs for air traffic control overall by increasing efficiencies and by wise use of technology in the ATC system.

The system user, by investment in equipment and acceptance of constraints, should be able to increase his efficiency and improve his safety to any desired extent, so far as air traffic control is concerned. We believe that there should also be room in the system for those without great interest in efficiency, but that this should not result in reduced **efficiency and impaired** safety to other users of the system.

- User Equipment

For convenience, we shall classify aircraft in the system as follows:

-- air-carriers, private jets and other sophisticated private aircraft;

-- military aircraft;

-- general-aviation.

3.3.1    Air Carrier and Private Jets

1)    On-board, accurate navigation. The desire of the air-carrier for efficient use of expensive aircraft and crews, and the value to the passenger of shorter trip-time, will impel the air carrier to install computer-driven three-dimensional area-navigation systems. Such systems allow the aircraft to follow a three-dimensional path accurately in space either automatically or by signaling the pilot through indications on the conventional flight director. These systems can guide the aircraft from takeoff through climb, turns, and cruise, and to the runway approach. With sufficient accuracy, they could provide blind-landing capability as well. Considering the need for air traffic control to provide separation between aircraft, it seems highly likely that the accurate navigation system may also be used in a 4-D mode, in which the aircraft makes good a given schedule along its agreed 3-D track. Aircraft equipped with such on-board navigators will put a substantially smaller communication and control load on the ATC system, since communication between air and ground need only be of a strategic nature, rather than continuing receipt of positive-control commands as at present.

2)    Accurate surveillance and flight-plan following. These aircraft will also carry equipment to provide information to the ATC data acquisition system in order to allow the system to detect, very early, any deviations from the agreed flight plan. The ground

system will of course have to be capable of following arbitrary 3-D and 4-D flight plans. If, for example, the aircraft under normal circumstances can guarantee to follow its agreed flight plan to an accuracy of 1000 feet and 5 seconds, the ATC system will undertake communication with the aircraft only if it deviates by that amount from its flight plan. The data acquisition system must be precise enough to give such an indication and must also have adequate coverage if air-carriers are to be guaranteed separation in all phases of flight.

3) Flight Plans. Airline-requested, largely-prearranged flight plans will for the most part be approved by the ATC system, which will follow the aircraft's progress along this flight plan. To the greatest possible extent, multiple flight plans will be stored and called out by number when needed. Since only conflict-free flight plans will have been approved, the ATC system might alert the controller only in exceptional cases.

4) Air-carriers will have equipment to cooperate with airfield surveillance and surface guidance equipment.

5) Air-carriers will have all-weather landing capabilities useful at many airfields. The following are candidate systems:

-- microwave ILS, either simple fixed glide slope or of a more capable, more flexible and more expensive type;

-- for VTOL aircraft, on-board equipment working with the on-board computer and measuring (from an omnidirectional beacon at the desired touchdown point) by means of an on-board beacon-only radar, the declination and heading of the beacon in the aircraft coordinate system, together with the range to the beacon;

-- airport-based omnidirectional transponders for improving the local accuracy of on-board systems primarily working with navigation satellites.

In all-weather landing, the navigation system will make use of flight-quality gyros and accelerometers for smoothing data and for damping short term disturbances.

6) VTOL aircraft are expected to be of great importance in increasing airfield access, and in improving airfield capacity for the short-to-medium haul. They will be equipped with automatic takeoff and landing, ATOL, oriented toward the landing pad. VTOL

aircraft with ATOL capability intensify the need for Items (1), (2), (3), and (5) above and will also require accurate low-altitude navigation and surveillance coverage at other than major airfields.

7) Over the long-term, on-board navigation equipment will work with navigation satellites deployed for military as well as civil purposes. Given the above-designated equipment, the accommodation of navigation-satellite systems to provide universal, accurate navigation can be expected to cost less than $10,000 extra per aircraft.

8) Exchange of information between aircraft and ground will be for the most part via data-link; however,

9) IPC signals may normally be transmitted as a few information bits (in some cases a single physical pulse without necessity of address bits) in connection with the surveillance beacon or transmitter.

### 3.3.2 Military Aircraft

We distinguish two types of military-aircraft by the terms sophisticated and simple, with the break-point at perhaps $1 million per aircraft.

### 1) Sophisticated Military Aircraft

The sophisticated military-aircraft which must operate in all portions of the world with high operational effectiveness and readiness will be equipped in a manner analogous to air-carriers. In addition to the world-wide satellite navigation system described for air-carrier use, in which the aircraft computer-receiver processes signals from the satellites, military-aircraft will presumably have a secure navigation capability providing substantial resistance to enemy jamming and also greater accuracy than is available from the civil system. Military-aircraft will be able to accomplish terrain avoidance by accurate navigation, and by programming altitude with respect to local ground elevation obtained from a contour map stored within the aircraft.

So far as FAA ATC system is concerned, sophisticated military aircraft will behave like air-carriers. In addition, of course, they will have specifically military equipment.

### 2) Low-Cost Military Aircraft

Low-cost aircraft, such as small helicopters or forward-air-controller aircraft, benefit substantially from the availability of accurate navigation systems in coordinating their work with other aircraft and with ground troops. However, the cost of such systems may be excessive, for instance, in a utility helicopter. These low-cost vehicles will be equipped like general-aviation aircraft insofar as the U.S. domestic ATC system is concerned.

### 3.3.3    General Aviation

Service provided by the FAA to general-aviation will depend upon the level of equipment installed in the general-aviation aircraft.

1)    Surveillance Aid.    All general-aviation aircraft will carry equipment adequate for precise surveillance data acquisition for the ATC system.    Not only air taxis, corporate aircraft, private fliers, but also crop dusters would be required to carry and operate when aloft a simple beacon or transmitter which would provide highly reliable, accurate location information to the ATC system.

2)    Communication Equipment. All general-aviation aircraft which might enter into controlled airspace must also be equipped with operating two-way VHF voice communications and IPC capability. They may, of course, have an optional command data-link for ATC purposes.

3)    Navigation. Navigation under VFR conditions in mixed airspace can well be by pilotage. Separation from air-carriers could then be maintained by the IPC technique described in the ATCAC Report. General-aviation aircraft flying IFR will have to be equipped with navigation equipment suitable to the task, such as VOR-DME, and may of course carry area-navigation equipment or data-link to allow navigation-by-surveillance.

## NOTES AND REFERENCES

(1) On the assumption that the projected operations cost of about $3 billion per year at that time can be reduced to $2 billion by a factor of 1/3 increase in productivity.

(2) Costs estimated in this report were for the most part derived from DoT/FAA plans or from Contractor-Consultant studies for the Panel. These costs are not intended for programming or budgeting estimates or as a set of complete R&D costs, but only for the understanding needed to assess the possible magnitude of the expenditure for particularly critical areas. Definitive costs can only be determined by substantial program definition efforts conducted in the course of program development, as described in Section 3.

Most of the costs discussed in this report are estimated on the basis of 1970 technology, while the system is sized to deal with the 1995 expected traffic. Indeed, equipment for a new-generation ATC system will be produced in 1975 or 1980, and it is evident from increasing reliability and decreasing cost of consumer electronic equipment that medium- and large-scale integration is having a very substantial impact. The comparison between electronic systems is less sensitive to this overall scale of costs, but it should be noted that the cost of elements of air traffic control and of mandatory surveillance can be reduced significantly in the next few years as a consequence of progress in medium- and large-scale integration of electronic circuits. By comparison with costs of aircraft and personnel, investment in onboard and ground equipment will become even more favorable than is evident from present costs.

(3) See ATCAC Report, 63-70.

(4) See Appendix 3 for a detailed description of a representative satellite-based data-acquisition system.

(5) See ATCAC Report, pp. 379-399.

(6) See Appendix 3.6.

(7) See ATCAC Report, p. 51.

(8)  Since the area of the United States is approximately 5 million
     square miles and that of the entire earth surface some 200
     million square miles, and since synchronous satellites can
     have their field of view focussed 80% - 100% of the time on
     the United States, compared with some 5/200 or 2% of the time
     for satellites orbiting at medium altitude, such loweraltitude
     satellites have a large disadvantage which is only partially
     overcome by smaller launch cost. Aside from cost, such
     systems could perform in a manner similar to the synchronous
     satellite systems. For a world-wide system, rather than a
     domestic system, the choice is not so overwhelmingly clear.

(9)  DoT-NASA Civil Aviation R&D Policy Study--(Supporting Papers-
     -DoT TST-10-5; NASA SP-266), p 4-31.

## 4.0 ORGANIZATION AND MANAGEMENT FOR INTRODUCTION OF AN IMPROVED AIR TRAFFIC CONTROL SYSTEM

### 4.1 INTRODUCTION

Improvement of the national ATC system will require new airport facilities, new air vehicles, and a variety of new electronic control systems, together with operational concepts which are significantly different from those now current. Many of these additions and changes can be based on present technology and will require, primarily, choice and product development. For the longer term, new technical solutions must be found. A thorough systems design and analysis must be undertaken to (a) define the desired next generation system and (b) identify and guide the research, advanced development, and demonstration required for realization of such a system. Large sums--on the order of billions of dollars--will eventually be required to design, develop, and deploy the new system. A properly designed system will be able to accommodate growth in air traffic, and at the same time reduce operation and maintenance costs, even discounted to the present. This entire effort must be established on a sound basis and accomplished in an expeditious manner.

The Panel believes that it is absolutely essential to the success of the ATC improvement program that strong and efficient management be provided. It believes further that the necessary combination of program and fiscal authority, responsibility, and dispatch are not likely to be achieved by assigning parts of the program piecemeal among various offices within the existing FAA and DoT organizations. Essential considerations in determining the desired management approach are that:

-- It should be a _full-time_ assignment of the individuals involved.

-- The _management_ _should_ _report_ _at_ _a_ _sufficiently_ _high_ _level_ to command the authority and exercise the responsibility required by the task. This task is of such magnitude and complexity as to require the individual energies of a management with strong executive power. It is a job which cannot be handled by a committee of individuals, no matter how highly placed, who devote only a portion of their attention to it.

-- A single manager should have program and budgetary control for all aspects of development and initial deployment of the new system.

-- There should be a supporting staff to provide technical and management direction to in-house activities as well as to industrial contractors. Some of this support staff function can also be obtained on contract.

-- There should be an adequate mechanism for phasing tested improvements into the operational system on an appropriate schedule, and further, the management structure itself must have the flexibility to change according to the needs and phases of the improvement program.

● Experience with Large Government Project-Type Organizations

The management approach required to implement a program for improving the ATC system has the characteristics of a large-scale, centralized project organization. Some outstanding examples of such organizations, though of much greater size and national commitment, that have been successful in completing complex programs of national concern are:

-- the Manhattan Project of World War II for development of nuclear weapons,

-- the Air Force Western Development Division of the 1950's for development and deployment of intercontinental ballistic missiles,

-- the Special Projects Office of the U.S. Navy for development and deployment of the Polaris submarine-launched ballistic missile system.

Given extraordinary powers, the management of such a project organization is charged with great responsibility. Those responsible for carrying out the program are clearly identified, and decisions needed to respond to changing demands and technical problems can be obtained in the shortest possible time. Through efficient control of resources, an operational capability becomes available years earlier, and in our experience at lower cost, than with normal management and budgetary procedures. On the debit

side, the continuing claim of first priority may work to the disadvantage of other programs within the department.

## 4.2 ORGANIZATION

According to current DoT/FAA plans (December 1970), responsibility for the upgraded "third generation" ATC system will reside in the Office of System Engineering Management. This office reports to the Associate Administrator for Engineering and Development of the FAA. The responsibility for the "fourth or next generation" system would reside in the office of the Deputy Assistant Secretary for Systems Engineering, Office of the Assistant Secretary for Systems Development and Technology, DoT.

The structure of the DoT and of its air-modal administration, the FAA, are shown in Figure 1. Those elements which are involved in the decision and approval process for design, development, and deployment of an improved ATC system are indicated by means of a heavy vertical bar. The element that has concern solely for an improved ATC system is also dark-bordered. The Panel believes that the present organization of the DoT and FAA (with planned changes as stated above) is not adequate for effectively managing a large, complex program for improving the national ATC system. This program includes both upgrading the present system and developing a completely new or fourth generation system. While operational and procedural elements of the FAA have much information and experience which is valuable for the design of an improved ATC system, we believe that needed improvement has been delayed by too strong an operational influence. Specifically, these factors highlight the need for a revised management concept:

-- responsibility is too widely dispersed and resides too far down in the organizational structure of the DoT;

-- with the present structure, although the DoT will be able to pursue promising approaches, there will be great difficulty in implementing them.

After reviewing a number of alternatives, including the current organization, establishment of a public or semi-public corporation, or establishment of a Joint System Project Office, the Panel has selected for elaboration in Appendix 7 the establishment of a new Executive Agency within the DoT as a management structure which satisfies the criteria stated at the beginning of this Section for successful conduct of this program.

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## 4.3 THE PROCESS TO BE MANAGED

The overall task can be simply stated as that of defining the need and benefits, determining the alternatives, planning the program, obtaining the funds, carrying out the development, evaluating the system, training the people, deploying the initial system, and turning over control to the operators. The task is complicated by

(a)   the requirement that there must be a near-certainty of success,

(b)   the changing technology which makes available improvements to the present alternatives,

(c)   the long time normally required to go through this process,

(d)   the need to introduce the new system without interference with operation of the current system, and the need to bring the system operators into each stage of the development and deployment process,

(e)   the need for the management structure to modify itself according to the phase of the improvement program.

### 4.3.1   Iterative Nature of the Task

In Section 1 of this report, it was emphasized that the improvement of the ATC system is an iterative task. The types of aircraft operating within the system and the uses they make of it are dependent upon the benefits they derive from it and on the requirements of air traffic control. These interrelationships indicate that no plan will remain unchanged during the development and deployment program, nor can a plan simply be followed step-by-step to achieve the desired end. The dynamic nature of technology, and continuing recognition of difficulties and opportunities, require an unusually compact, rapidly reacting management for the design, development, and implementation of this complex, highly interacting system. The management and budgetary procedures adequate for operating an ATC system are inappropriate for the development and introduction of a new system.

### 4.3.2   Systems Engineering and Integration

To support the ATC program director adequately, it is necessary that a highly competent and integrated Systems Engineering group be established as part of his in-house organization. Generally, the responsibilities of this group would be to:

-- translate policy and program objectives into system performance requirements and then into system design;

-- conduct or manage technical and cost trade-offs of various system concepts;

-- define interfaces and sub-system requirements to assure compatibility between major elements;

-- initiate appropriate back-up programs;

-- plan, control, and evaluate system and sub-system operational tests;

-- initiate and direct sub-system developments to obtain technology required to support engineering development of the desired system.

One result of systems engineering and integration efforts will be technical reports and demonstrations. These will form the basis for planning and management decisions and must be sufficiently sound to stand inevitable criticism regarding choice of a particular approach or decision.

How well the ATC program director succeeds will be largely determined by the direct control which the Systems Engineering and Integration group can exert at the initiation of, and during, the overall program.

### 4.3.3    Operational Procedures Development

No ATC system can be specified independent of the operational procedures to be used. IPC, mixed-airspace, high-density control areas, and corridors must be examined by analysis and simulation to determine compatible mixes of air space, equipment, procedures, etc. Choice and development of new operational procedures for the improved ATC system should be a responsibility of the program management for ATC improvement in coordination with the Associate Administrator (FAA) for operations. For each class of air space, the acceptable range of traffic densities and missions must be

determined, together with estimated requirements on controllers or other ATC personnel. Detailed airspace design and simulation must be performed in order to validate the concepts. Plans must be formulated for phasing proven developments into the operating system, including relative phasing of interdependent equipment, training requirements for controllers, manpower phasing, etc.

### 4.3.4 Program Phasing--Short Term/Long Term

The program recommended in Section 3 of this report consists of distinct but overlapping sets of activity. Improvement of the present system should be continued. To the greatest extent possible, this near-term improvement program should concentrate on FAA-funded ground-based modifications, even if the cost is somewhat greater than could be achieved with a new generation of airborne equipment. Concurrent with this effort, studies for an improved system must be initiated to serve as the basis for exploratory and advanced development to obtain the broad data base and experience necessary for engineering development of the next system.

Three phases of activity will be required in development of an improved ATC system. It would be a great mistake to delay initiation of the longer-term phases in order to accomplish near-term phases. In order to avoid this pitfall we list the three phases, emphasizing that the priority of funding is in the order listed.

1. Phase 1, which must be initiated immediately, would lay the foundation after some years for better decisions in air traffic control. It would feed larger-scale decisions concerning the national transportation system. Here we have in mind the funding of research in system demand, concept studies, preliminary design programs, and simulation for both air transport and air-transport-connected transportation systems, since the characteristics of the air transport system are determined by tradeoffs with these ground-transport systems. In this phase, work would be conducted at universities, in-house laboratories, and industry on control automation procedures, on new types of air traffic control, and on the potential of highly reliable avionics and its impact on aircraft and ATC system design.

2. Phase 2 consists of effort devoted to those candidates for deployment which require further analysis of sub-

system development before actual experimental verification can take place. Comparative analyses and design tradeoffs are required here, together with some exploratory development including development of interface equipment which would not necessarily be used in an operating system. For instance, the government has responsibility for the central data acquisition system for determining position and identity of aircraft. However, to verify anticipated performance of a data acquisition system would require preliminary development and prototype manufacture of airborne beacons or interface equipment which would not be a continuing FAA responsibility. Other candidates are:

-- IPC,

-- VFR highways,

-- ATC data-link,

-- Satellite navigation and surveillance systems,

-- Full automation of air traffic control,

-- All-weather landing,

-- Automatic piloting from ground-to-ground,

-- New airport configurations,

-- Four-dimensional navigation,

-- VTOL aircraft with ATOL capability.

These programs have longer lead times than those in Phase 3 and also have great potential. They should be initiated now at a level which could properly be determined by the anticipated discounted return on investment combined with an estimated probability of success. Lacking the data to make such decisions formally, relative effort will have to be a matter of judgment on the part of the Director of the Executive Agency.

3.  Phase 3 consists of those capabilities which can be implemented on the basis of previous development, requiring only verification, detailed choice, and perhaps contractor selection. New ground-based or

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airborne sub-systems    are    not    required.    These
improvements  could proceed directly to a system test and
evaluation stage.    Among   these   important   capabilities
are:

--    Central flow control,

--    Terminal flow metering,

--    Automated sequencing and final spacing,

--    Automated departure control,

--    Ground-based proximity warning.

## 4.4  CONCLUSIONS

We   reemphasize   that   the   organizational   style   which   is
appropriate  for  operation of an ATC system is not appropriate for
initiation and management of a  sophisticated  development  program
which  requires  centralized  direction  and  control,  at  a  high
organizational level, to make decisions and provide direction  with
a  minimum  number of layers of management.  We believe that it may
be desirable to establish a special project management organization
for the development of an improved ATC system.

As a suggested organization we have examined the establishment
of a  new  Executive  Agency  for  ATC  System  Improvement,  whose
Director  reports to the office of the Secretary of Transportation.
The organization would have full-time responsibility and  authority
for  the ATC system improvement plan, utilizing the best aspects of
the project system for reducing lead time,  making  most  efficient
use  of personnel, while placing as much of the routine performance
as possible on  existing  bureaus  and  offices.   Outside  support
should  also  be  obtained  from industry, non-profit institutions,
universities, and government laboratories.   A   Technical   Advisory
Committee  would  be  appointed to counsel the Executive Agency for
ATC System Improvement and the Secretary of Transportation,  and  a
User  Advisory  Group would be established to interface between the
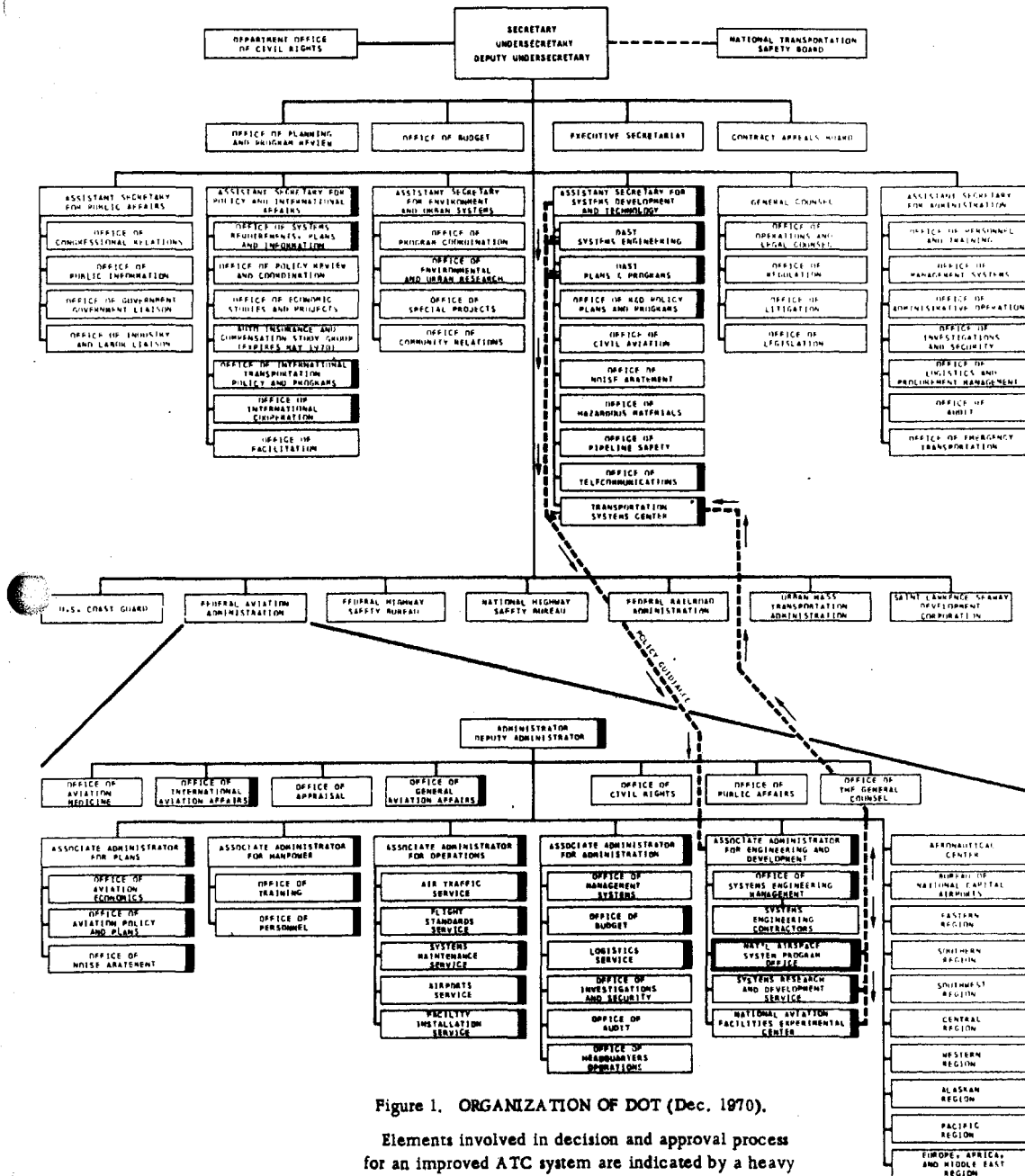Agency and the user community.

Figure 1. ORGANIZATION OF DOT (Dec. 1970).

Elements involved in decision and approval process for an improved ATC system are indicated by a heavy vertical bar. The element that has concern solely for an improved ATC system is dark bordered.

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APPENDIX 1

## THE ROLE OF VERTICAL AND SHORT TAKEOFF AND LANDING
## AIRCRAFT IN THE AIR TRANSPORT SYSTEM OF THE FUTURE

VTOL appears to have the potential airfield acceptance rate and all-weather capability to provide the basis for a short-haul air transport system economically competitive and functionally complementary with both surface transport and conventional air. A VTOL system with ATOL (automatic takeoff and landing) capability based on a precision 3-dimensional navigation system and an on-board computer, probably making use of an omni-directional transponder on the landing pad to provide flexible automatic approach, will have the capability for touchdown in all weather from any direction. A beacon-only radar on the aircraft would provide precise measurements of elevation, azimuth, and range to the assigned landing point and would permit automatic guidance of the aircraft from wing-borne flight to touch-down all while locked on the radar beacon. We are confident that this system is feasible and that it will provide, on existing airports, a very high airfield acceptance rate independent of and additive to the acceptance rate for conventional operations. It would also provide a capability to serve, at low additional investment cost, VTOL ports and emergency fields over the service area determined by aircraft range of about 500 miles. Such a system with its small penalty in cost or time for takeoff and landing appears to make feasible the concept of interchange airports and even extension of aircraft range by touchdown at a refueling stop.

One of the most recent analyses of the utility of VTOL is contained in the report of the Northeast Corridor Transportation Project[1]. Although the project was initiated primarily to review and to provide a foundation for decisions in regard to high-speed ground transportation within the Northeast Corridor, the results of initial simulation runs for STOL and VTOL are very revealing.

As shown in Table 1, the passenger mile costs for STOL and VTOL nearly match the costs for a type of High Speed Rail transport and Tracked Air Cushion Vehicle. In addition, the air modes earn a return on capital in competition with automobiles and buses, while these ground modes lose money. In part, this is due to the lower trip time possible with the air modes.

Table 1**

(All Values in Millions of 1970 Dollars)

| MODE | OPERATOR INVESTMENT | | ANNUAL COSTS | | ANNUAL REVENUE | COST PER PASS. MILE |
|------|------|------|------|------|------|------|
| DEMO | 69 | (1) | 61 | (4) | 144 | 3.4 |
| HSRA | 1590 | (1) | 240 | | 213 | 9.6 |
| HSRC | 2600 | | 335 | | 288 | 10.5 |
| TACV | 3340 | | 452 | | 349 | 11.3 |
| STOL | 195 | (2,3) | 244 | | 244 | 9.6 |
| VTOL | 1060 | (3) | 318 | | 318 | 11.0 |

1.  DEMO and HSRA not charged for present right of way
2.  STOL not charged for present airports
3.  STOL and VTOL not charged for air traffic control
4.  Costs include amortization and return on investment

**From "Multi-Modal Transportation System Planning," C. A.
  Zraket and R. D. Nutter, AIAA 7th Annual Meeting and
  Technical Display, Houston, Texas, October 1970.

    The costs for full  operation  of  the  present  Demonstration
Metroliner  and  Turbotrain systems (DEMO) are nearly all operating
costs, since the DEMO investment only  includes  rolling  stock  in
proportion to demand.   Investments in the other three surface modes
include  trackwork, stations, land, etc.   The capital cost for VTOL
includes an arbitrary amount of $0.75  billion  in  terminal  land,
structure and fixed equipment, while no such costs are included for
STOL,  since  they are assumed to use existing airfields.  Further,
a rather crude helicopter  VTOL  was  used,  with  relatively  high
maintenance  costs  and a top speed of about 265 miles per hour, in
comparison with STOL speed of 370 miles per hour.   It seems  likely
that had these restrictions been removed, VTOL would have dominated
STOL patronage.

    Another  result  of  the  simulations  is diversion of the air
terminal load from CTOL to STOL.  Considering,  for  instance,  New
York  in  the  absence  of STOL, and for trips within the Northeast
Corridor, the daily passenger movement by conventional air in  1975
would  have been 10,700.  With the provision of the STOL (or VTOL),
the total movement rose to 20,100, of which CTOL takes  only  2700.

Thus, the number of passengers moving by air is doubled (in free competition with ground modes), while the number taking aircraft occupying conventional runways and utilizing conventional takeoff, landing and enroute ATC services is reduced to 25 per cent of the previous value.

A great attraction of STOL and VTOL vs new high-speed ground transport is the possibility of capital investment to fit the demand rather than the requirement for building an entire line before the first passengers can move. Further, since STOL-VTOL can use a system of dispersed airports, and the vehicle paths themselves do not create impediments to ground transport, with resulting high social costs, access to terminals from home or place of business can be substantially quicker than for high-speed or conventional air transport.

It should be noted that a successful VTOL system put into use for the Northeast Corridor or other dense areas could be expected to stimulate production of an aircraft which could provide service without further development and without large fixed capital cost in other less densely populated areas of the country, although a productive aircraft does not, in itself, guarantee a viable service. Indeed, foreign sales could reduce the average cost of these aircraft purchased for domestic use.

The Panel believes there is a near-term need for efficient VTOL aircraft with ATOL capabilities, operating initially from airport to airport outside the present runway system and traffic pattern. Such an aircraft, designed and built from the first to operate with automatic capability, could be optimized at a somewhat lower hover efficiency than one built for manual landing. It could thus have better propulsive efficiency, higher speed, and be more competitive with CTOL over the mid-range (up to about 500 nautical miles). The airport-to-airport market already exists and is severely constrained in many areas by terminal congestion. VTOL-ATOL, because of the availability of nearby emergency landing facilities in any weather, can be designed with lower reserve fuel requirements, and ATOL provides lower fuel consumption on landing than is necessary with more familiar VTOL concepts. After introduction of the VTOL-ATOL with acceptable noise characteristics in airport-to-airport service, a fleet of such aircraft could absorb some of the demand between city centers and satellite airports, further relieving main operating airports and existing ground transportation from congestion, and saving trip time for a substantial fraction of the passengers. Development of such a VTOL-ATOL would provide a marketable product for operation in the

densely populated, poor weather, land-scarce countries of Western Europe.

Such VTOL craft could operate out of suburban ports and, if designed for adequately low noise level, from the city center. Initiated for the purpose of airport access, such a system could in the end generate sufficient point-to-point demand of its own to make this its major function. Therefore, especially initially, it might be desirable to design VTOL hub airports for high vehicle acceptance and convenient passenger interchange in order to promote the twin virtues of multiple terminals and high frequency of service connecting any two points. Under such circumstances, the long-haul airport becomes simply another node in the system to be serviced like any other center of population. Once fully developed, such a VTOL transport system would also allow the development of long-haul airports far from centers of population, thereby reducing the cost of airport land and of noise-compatible usage. Recent studies suggest that high-speed VTOL aircraft can be used for short-haul airlinks, operating frequently from locations in the city center and the suburbs, linking these points and transfer hubs. For instance, plant parking lots or those at major public facilities are good candidates for VTOL terminals.

Two advances are necessary for the success of VTOL--reduced direct operating cost, in part through better maintainability than has been achieved on the helicopters now operating as VTOL; and reduced zero-trip length cost, including reservations and boarding. With the British-built Harrier jet-lift fighter entering service with the US Marine Corps, substantial experience should become available on a relatively modern VTOL craft. This aircraft could serve as a test vehicle to examine the value and problems of ATOL, ride-quality improvement mechanisms, all-weather operations, and integration with existing and simulated future ATC systems.

Medium-haul service of airports and airport access by VTOL will require independent guidance of the aircraft away from runways. If medium size VTOL's are not to contribute substantially to airport surface traffic problems, they should and could take off and land at their terminals with little or no taxiing, by the use of an all-weather ATOL system. Unlike STOL craft, for which a single strip presents approach pattern, runway occupancy, and ground taxi problems similar to those impeding conventional planes at major terminals, VTOL craft can land from any direction on individual terminal spots, thus increasing the airfield acceptance rate. At low speeds VTOL aircraft are far more controllable in gusts or cross winds than are STOL.

Handling a half-million passenger trips a day in 100-passenger vehicles in an urban area could require several hundred vehicles to be air-borne simultaneously. For this short-haul system, the preferred operating philosophy would appear to be one in which a proposed flight plan is:

-- filed automatically by the operator;

-- cleared when no other filed flight plan conflicts; and

-- executed precisely to few-second accuracy by on-board automatic equipment while the aircraft is tracked by the ATC surveillance system.

As described in Section 3 of this report, such operation is entirely feasible with a 1980+ universal surveillance and navigation system providing position accuracy to within a few hundred feet. The procedure would speed ground trips in urban areas and reduce airport congestion both on the ground and in the air. It would allow substantial freedom in decentralization of urban centers and would add an element of flexibility now lacking in air transport systems.

# REFERENCES

1.  The Northeast Corridor Transportation Project report is an
    interim report and the results of the simulation runs are
    strongly dependent on the assumptions used in deriving the
    models and the input data. For this reason, the results of
    the simulations should be interpreted with care.

# APPENDIX 2

## DATA-LINK REQUIREMENTS AND
## THE CAPABILITIES OF VHF DATA-LINKS

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# APPENDIX 2

## DATA-LINK REQUIREMENTS AND
## THE CAPABILITIES OF VHF DATA-LINKS

## INTRODUCTION

This appendix presents a brief sketch of an analysis of data-link requirements for a dense region like the Los Angeles Basin in the 1995 time period. Two classes of data-link are discussed:

1.  A VHF data-link for air carriers and general-aviation using subchannelization of a few of the 50 kHz VHF voice channels, with separate up- and down-channels and with capability and redundancy of the airborne box increasing with its cost. Minimum capability would be 1200 bits/second.

2.  Data-link integral with a new discrete-address ATCRBS and communicating with a new electronically-scanned phased-array ATCRBS interrogator on the ground.

Channel requirements of the compatible VHF data-link can be determined for the Los Angeles Basin and compared to the data-link system recommended by ATCAC, in which digital commands are transmitted as an integral part of discrete-address ATCRBS. A third class of data-link using the present VHF voice transceiver was judged to impose excessive operational problems and to be too costly for the service provided.

## A2.1 DATA-LINK REQUIREMENTS

Here the data-link capacity requirements are developed for both the IPC data-link, providing separation commands to VFR aircraft and for the ATC data-link (commands to IFR aircraft for both separation and normal control, e.g., altitude changes). These requirements are based on a demand model of a dense region--the Los Angeles Basin--in the 1995 time period.

### A2.1.1    Intermittent Positive Control

The IPC data-link as recommended by the ATCAC would have the following operational applications:

1.  "Do" and "Don't" commands to avoid collisions between IFR and VFR aircraft in mixed-airspace.

2.  "Do" and "Don't" commands to avoid collisions between VFR aircraft.

3.  Commands to keep VFR aircraft in airspace allocated to VFR highways.

4.  Commands to keep VFR aircraft away from hazardous weather and physical obstacles.

The command rates for the first two applications were derived as part of the ATCAC studies[1]. The following assumptions were made relating to the Los Angeles Basin in 1995:

Extent of Airspace   60 nm x 120 nm x 10,000 feet

Number of IFR        145

Number of VFR        1220 (50% at 200 knots and
                           50% at 100 knots)

If we further specify that the airspace protection volumes are such as to provide for a 3 degree per second aircraft turn rate and a thirty-second warning time, then the referenced document shows that the following average hourly commands would occur per VFR aircraft:

IFR/VFR Commands          3.73 per hour per aircraft

VFR/VFR Commands          13.94 per hour per aircraft

Based on the assumed number of VFR aircraft (1200), the average number of commands per second would then be (for the entire Los Angeles Basin):

IFR/VFR                   1.26 commands per second

VFR/VFR                   4.72 commands per second

Depending upon the actual implementation, the capacity of the data channel must be increased due to three factors:

1.  peaking of messages,

2.    message retransmission if no pilot acknowledgement is received,

3.    message re-transmission in case of detected error.

A detailed analysis of the peaking would include the imposition of the constraint that the probability of message delay exceeding a certain value (e.g., 3 seconds) be less than, say, 1%. The analysis is further complicated but the requirement is eased by the fact that certain messages (e.g., "don't" commands) are not so time critical as are "do" commands, and thus priorities can be given to critical messages.

### A2.1.2    Air Traffic Control Commands

Table 1 derives the number of ATC commands which would be needed in an en route center with 2500 instantaneous airborne aircraft (11.3 commands/sec). This estimate is based upon data collected and analyzed for the Chicago Air Route Traffic Control Center plus assumed rates for other commands. Thus, it conservatively assumes that automation of the data-link function must support the present command rate per aircraft typical of a manual system. It is likely that fewer commands would be needed for a highly automated system. The en route commands have not been included in the level for the Los Angeles Basin. Their inclusion might raise the ATC requirements an additional 10%.

Tables 2 through 6 indicate that for a high density terminal area with a very high IFR operations rate (1160 arrivals and 1160 departures per hour or 580 instantaneous airborne aircraft) there is a requirement for about 10.2 up-link messages per second and 10.5 down-link messages per second, or an average of 10.35 two-way message sequences per second. The above rates assume a sophisticated ground-based system which derives heading, speed, and altitude commands to control precisely arrival and departure of aircraft to and from high density airports. The ATC system proposed in the Panel report, in which on-board equipment assumes tactical-control, will require fewer messages.

### A2.1.3    Data-Link Requirements Summary

Table 7 gives 18 per second for the total data-link command rate requirements for a dense region like the Los Angeles Basin in 1995. Further sections will translate these requirements into communication channel requirements.

## A2.2 DATA-LINK CHARACTERISTICS

### A2.2.1 VHF Data-Link

The VHF data-link in any area could use a single present 50 kHz VHF voice allocation for data up-link, and a single 50 kHz allocation for down-link. Within the 50 kHz channel we might put 10 carriers, each four-phase modulated at a total bit rate of 2400 bit/sec. Thus within 50 kHz we have 20 independent 1200 bit/sec data channels. At 5 kHz channel separation in 100 MHz (50 parts per million), the transceivers would require frequency stability of 5 parts per million, which could be accomplished with crystal oscillators or by offset from an up-link-broadcast reference tone, whichever proves the less expensive alternative. An aircraft would be permanently assigned to a single subchannel and would have its down-link frequency at fixed offset to the up-link.

Upon receipt of an up-link message, the airborne VHF data-link box would perform message error detection and/or correction. If an error-free or correctable message had been received, the aircraft would immediately (e.g., within 0.01 sec) transmit on the down-link the check bits for that message, modified by the identification number of the aircraft. Knowing the procedure for generating the check bits, as well as the identification of the aircraft, the ground station will count the message as received if the down-link carries at the proper time the expected check bits (perhaps 20 bits).

The ground-based demodulator which handles on the average more than one down-link message per second should evidently be more capable and more expensive than the up-link demodulator on the aircraft, which handles a message each thousand seconds. This increased capability is reflected then in the absence of synchronizing bits on the down-link message. Note that no specific address or identification block is necessary in the down-link message. Since the down-link messages are much shorter than those on the up-link, and since pilot-initiated messages will be relatively rare, the down-link check bits should be received without garble more than 95% of the time. Message re-transmissions as a result of detected error or non-receipt of check bits on the down-link will require some additional up-link capacity, say 5-10%.

The modem could accommodate pilot acknowledgment of the message by re-transmitting the same check bits (e.g., at 5.00 seconds after receipt of message or again at 10.00 seconds) if the pilot depressed the "acknowledge" button at any time in the

interval. The ground computer then would know when to look for the "acknowledge" message in the down-link, without the necessity of polling the aircraft.

The air-carrier version of the VHF data-link would have more capable displays, probably a printer, and might incorporate reception on a peak-shaving overflow channel to reduce the (already small) probability of message unavailability at a critical time. This version might have a greater capability for aircraft-initiated messages, e.g., change of proposed flight plan.

Either version would transmit short, pilot-initiated messages without interference with the up-link. The data-link is shown in Figure 1.

This system data format is similar to that of the ARINC (Aeronautical Radio, Inc.) experimental system, although separate VHF frequencies are used for air-ground and ground-air directions. These frequencies are dedicated for digital data transmission (no voice). Modulation on a given channel could be bi-phase at roughly a 1200 bit/second rate. A complete message might consist of

(a) synchronization (50 bits),

(b) 7-character aircraft address (63 bits),

(c) aircraft address block error check (15 bits),

(d) aircraft control command of 5-20 characters (45-180 bits),

(e) control command block error check (15 bits).

The complete message ranges from 188 bits to 323 bits, depending on control command length. Transmission at the 1200 bit/second rate requires, on the average, about 0.2 seconds. Decoding of the message by the aircraft follows. The aircraft must then switch from receive to transmit mode (requiring, for a new data transceiver, about 0.01 seconds) and transmission of the modem acknowledgment follows (an additional 0.02 seconds). The aircraft may indicate a detected error, and request re-transmission by the ground on the same message, or new data may be sent to the ground, depending on the command type originally sent to the aircraft.

• Channel Requirements for VHF Data-Link

The computation of channel requirement has two parts: (a) determine the messages/per second/per channel capacity for the VHF data-link, and (b) given the commands/second requirements developed earlier in this paper, and a polling factor given the average number of messages required per command, compute the number of channels:

Number of Subchannels = $\dfrac{\text{(commands/second)(messages/command)}}{\text{(messages/second/subchannel)}}$

In Figure 1 are shown the time budget for each message and the average bits per message, including overhead. Using the raw bit rate of the modem, 1200 bits/second, and assuming a data peaking factor of 1.33 for this computer-managed up-link, the channel capacity is 3 message/second/ subchannel.

Taking these capabilities together with the Los Angeles Basin requirements developed earlier, the channel requirements are as shown in Table 8.

In data-link systems like the VHF described here, using omni-directional antennas at either end, adequate protection must be provided against noise and fading. Little development work is required for this type of VHF data-link. Broad-band approaches seem more uncertain at this time although potentially less costly. VHF data-links of performance similar to the candidate described above have been flown extensively, and the risks seem minimal.

- Cost Estimates for VHF Data-Link

The VHF ground station cost for the Los Angeles Basin can be estimated conservatively for the full 20 subchannel case as follows (remembering that even in 1995 only 6 of the 20 up-link subchannels are expected to be filled):

| | |
|---|---|
| Transmitters | $5000 x 10 |
| Receivers | $2000 x 10 |
| MODEMS | $1000 x 10 |
| Message Switching Computer | $100,000 |
| | $180,000 |

If 60 such installations are required in the United States, the investment will be about $10 million.

The most important system cost elements of VHF data-link are thus the cost of airborne user equipment, and the cost to air transportation and to air traffic control of the delay in implementing data-link.

Conservative cost estimates for the airborne VHF data-link box are:

| MITRE Numbers: | | RAND Numbers: |
|---|---|---|
| MODEM | $1000 | VHF data transceiver with |
| Receiver | $ 300 | discrete address, IPC data- |
| Transmitter | $ 400 | link and acknowledge: $1000 |
| Display | $ 100 | As above, plus ATC data-link |
| | | including 10-12 digit display |
| | | $1250 |

$1800

- Fully Time-Multiplexed VHF Data-Link

Substantial simplification and economy, and a better fit to digital implementation, can be obtained from a fully time-multiplexed 24,000-bit-per-second VHF data-link occupying a single 50-kHz VHF channel allocation. The uplink would be computer managed, while the downlink, in a separate 50-kHz channel, would provide at least 98 per cent immediate transmission probability for pilot-originated messages, as contrasted with 95 per cent immediate transmission capability for a subchannelized VHF data-link, both for 1995 aircraft populations. Although this higher data rate system is somewhat more susceptible to multipath distortion than the subchannelized 1200-bit-per-second link, it is possible that detailed analysis and experiment will show that it is adequate in this respect and superior over all.

A2.2.2    New Air Traffic Control Radar Beacon System ("Superbeacon")

The new ATCRBS will be discussed for comparison purposes. Illustrated in Figure 2 is a proposed configuration having three independent directional send/receive beams. On a given beam, two-way data is handled using separate up- and down-link frequencies. With this system all users are polled on each positional update

cycle (1 second in dense terminal regions). Modulation consists of simple on-off pulse modulation of the carrier frequency. The basic bit rate of the "modem" (transponder) is 600,000 bits/second. Such a high basic bit rate is possible because the directional ground-station antenna provides protection against multipath while giving high signal strength, resulting in favorable signal-to-total-interference ratio. In the omni-omni case (VHF) (non-directional ground and airborne antenna) on the other hand, extensive coding would be required for the same data reliability--as well as greater ground transmitter power.

The up-link message format of the system (large message lengths are assumed in this example for comparison purposes. In actuality, about 20-24 bits of address would be sufficient in the ATCRBS design) consists of an address of 7 characters plus 15 bits block-check (78 bits), a standard interrogation character (9 bits), and a command of 5-20 characters plus 15 bits block-check (60-195 bits) for a total of between 87 and 284 bits, the average message being 185 bits. Shorter message lengths are possible. This is considered an upper bound (e.g., address characters and error block check can be handled in less than 78 bits). The messages/second capability of the ATCRBS is computed in the same manner as for the VHF data-link, with the exception that messages are now packed in a range-ordered way, to take maximum advantage of message length relative to propagation time. Consider a compatible ATCRBS configuration having 100 nm range. At maximum range, choice of a PRF of 300/sec (interrogation rate) allows a conventional mode 3/A or C interrogation as well as up to 600 microseconds of data-link message content per interrogation. Using the basic "modem" bit rate of $600 \times 10^3$ bits/second and an average message length of 185 bits, the average number of messages transmitted per basic pulse repetition interval (per antenna beam) is 1.8. The combined capacity of 3 beams over the one-second cycle in which 900 pulse repetition intervals are transmitted is 1620 (for the worst case range distribution).

This capability of ATCRBS allows for many future applications of data-link, without fear of overload. In addition, it should be capable of incorporating pilot-initiated messages, although with a delay of 1 to 6 seconds because the data-link operates only when the aircraft position is being updated by the surveillance system.

A recent "Report of the Department of Defense Beacon Analysis Committee" (July 1970) reviews the impact of the superbeacon on military aircraft and operations with respect to both data acquisition (surveillance) and IPC data-link. The report strongly

recommends "diversity operation" with two antennas on the aircraft
and indicates that the superbeacon (without display and without
digital altimeter) could be procured for some $3000. For military
aircraft, installation costs may far exceed the procurement cost,
but it may be expected that the total installed cost for general-
aviation will be less than the $3000 quoted. The report
perceptively addresses many of the questions which must be answered
to convert the superbeacon from a concept to a plan, for instance
the critical question of whether the 1030/1090 MHz present
allocation is viable or whether the superbeacon must move to the
1600 MHz band while retaining the capability to operate in the
present mode on 1030/1090 MHz.

A2.3 COMPARATIVE EVALUATION AND SUMMARY OF VHF DATA-LINK AND
SUPERBEACON

No data-peaking factor is involved with the discrete-address
data-link ATCRES, since all users are handled each system cycle.
The three-beam ATCRBS handles 1620 messages/sec in a bandwidth of
4 MHz, or 400 messages/sec/MHz. The VHF data-link described here
handles 3 messages per subchannel per second, with 20 subchannels
in a 50 KHz voice allocation, or 1200 messages/sec/MHz. If one
provides an equal amount of VHF frequency spectrum for down-link,
the VHF capacity is 600 messages/sec/MHz.

Thus, both the ATCRBS data-link and an independent VHF data-
link appear to offer satisfactory capability for IPC and control
functions. The choice between VHF data-link and superbeacon should
not, however, be be made on the basis of data-link capability
alone; but rather in connection with understanding of the planned
phased improvement of the data acquisition system. The extent of
coverage is important, as is the possible phased implementation of
the data-link system to reduce spectrum congestion, quite apart
from the relation to surveillance or IPC.

The Panel concludes that VHF data-link appears to be a
technically feasible approach to provision of IPC and ATC commands
to general-aviation, air-carrier, and military aircraft. New
dedicated equipment on the aircraft should be used, and a
reasonable system might use two 1200 bit/sec data channels
modulated on the two phases of each of 10 carriers within a 50 kHz
VHF voice allocation. The system cost is dominated by the
equipment cost to the airborne user.

If new discrete-address ATCRBS were installed, together with
phased-array ground-based interrogators, adequate data-link could

certainly be provided via the beacon to aircraft in flight and in
direct line of sight of the phased-array interrogators. The Panel
has seen no analysis, however, of broader application of the ATCRBS
associated data-link, such as by aircraft on the airfield or at
their loading gates.

TABLE 1**

EN ROUTE UP-LINK COMMANDS FOR IFR FLIGHTS

| COMMAND | ARRIVALS | DEPARTURES | OVERS | WITHINS |
|---|---|---|---|---|
| ENTER HOLD | .25 | - | - | - |
| LEAVE HOLD | .25 | - | - | .25 |
| ROUTE ASSIGNMENT | 1.0 | 1.0 | - | 2.0 |
| ROUTE CHANGES | .2* | .3* | .2* | .4* |
| CHANGE SPEED | .8* | - | - | .2* |
| TAKE UP HEADING | 3.0 | 3.0 | - | 6.0 |
| CHANGE VOICE FREQUENCY | 2.5* | 2.5* | 3.4* | 3.0* |
| CHANGE ALTITUDE | 3.9* | 1.5* | .8* | 3.1* |
| CLEARED FOR TAKEOFF | -- | .3 | -- | .3 |
| TOTAL | 11.9 | 8.6 | 4.4 | 15.5 |
| TRAFFIC DISTRIBUTION | 34.9% | 24.8% | 16.3% | 24.0% |
| CONTROL LIFE | 33.1 MIN | 40.2 MIN | 59.3 MIN | 46.8 MIN |
| MESSAGES PER HOUR FOR IAC = 2500 | 18,940 | 7,970 | 1,815 | 11,920 |
| AVERAGE NUMBER OF MESSAGES PER SECOND | 5.3 | 2.2 | .5 | 3.3 |

*BASED ON PEAK DAY CHICAGO ARTCC DECEMBER 1968

**Data from Table 1-2, "Computer Sizing of En Route Command and Control for the ATC Advisory Committee," MITRE WP-8272).

TABLE 2*

TERMINAL UP DATA-LINK COMMANDS FOR NORMAL FLIGHTS

FREQUENCY PER FLIGHT

| COMMAND | ARRIVAL | DEPARTURE | CONTENT |
|---|---|---|---|
| ENTER HOLD | .25 | | Position: Lat/Long, FIX ID, FIX/Radial/ Distance, "now" Indicator |
| LEAVE HOLD | .25 | 1.0 | Time 0-59.59 |
| TRACK ASSIGNMENT | 1.0 | 1.0 | Track ID: aa, aaa |
| CHANGE SPEED | 4.0 | 2.0 | Knots: 1 - 2048 |
| TAKE UP HEADING | 6.0 | 2.0 | Degrees 1 - 360 |
| CHANGE VOICE FREQUENCY | 4.0 | 2.0 | Frequency 121.65 |
| INTERCEPT LANDING SYSTEM | 1.0 | | |
| CHANGE ALTITUDE | 4.0 | 2.0 | 100's of feet 1 - 999 |
| POSITION FOR TAKEOFF | | 1.0 | |
| CLEARED FOR TAKEOFF | ----- | -- | |
| | 20.5 | 11.0 | |

*Data from Table 2-3, "Computer Sizing of Terminal Area Command and Control for the ATC Advisory Committee," MITRE WP-8266.

TABLE 3**

ADDITIONAL UP DATA-LINK COMMANDS FOR

AIRCRAFT EXECUTING MISSED APPROACHES

| COMMAND | FREQUENCY PER MISSED APPROACH |
|---|---|
| Execute Missed Approach | 1 |
| Take Up Heading | 8 |
| Change Speed | 4 |
| Change Altitude | 2 |
| Enter Hold | 1 |
| Leave Hold | 1 |
| Intercept Landing System | 1 |
| | 18 |

NUMBER OF MESSAGES PER HOUR

Los Angeles Basin High Density Airports*
   (1160) (0.01) (18)                     208 Messages per hour

*Assumes probability of missed approach is 0.01.

**Data from Table 2-4, "Computer Sizing of Terminal Area Command and Control for the ATC Advisory Committee," MITRE WP-8266.

# TABLE 4**

## SPECIAL DATA LINK COMMANDS FOR

## AIRBORNE COMPUTER EQUIPPED AIRCRAFT

| COMMAND | FREQUENCY PER FLIGHT | CONTENT |
|---|---|---|
| Leave Hold at Time T | 0.25 | Time: 0-59.59 |
| Control Points and Times (7 points with times and altitudes) | 2.0* | Lat/long Time Altitude, lat/long time altitude, etc. |

*Assumes one update per flight.

**Data from Table 2-5, "Computer Sizing of Terminal Area Command and Control for the ATC Advisory Committee," MITRE WP-8266.

TABLE 5**


DOWN-LINK COMMANDS


| COMMAND | FREQUENCY PER FLIGHT | CONTENT |
|---|---|---|
| Final Approach Speed | 1 | Speed knots   1-200 knots |
| Acknowledgements | 1 per uplink command | |
| Descent Rate | 1 | 0-10,000 feet per minute in 100's of feet |
| Missed Approach | - | Message Type |
| Pilot Observed Weather Reports | - | ? |


**Data from Table 2-5, "Computer Sizing of Terminal Area Command and Control for the ATC Advisory Committee," MITRE WP-8266.

TABLE 6**


SUMMARY OF DATA-LINK COMMANDS


NUMBER_OF_UP_LINK_COMMANDS*

| | | | |
|---|---|---|---|
| Normal arrivals per hour | (1160) | (20.5) | = 23,800 |
| Normal departures per hour | (1160) | (11) | = 12,760 |
| Missed Approach Messages | | | ___208 |

    Total Up-Link Messages
       per hour                                         36,768

    Average Up-Link Messages
       per second                                        10.2 Messages


NUMBER_OF_DOWN-LINK_COMMANDS

| | |
|---|---|
| Up-Link Acknowledgements Per Hour | 36,768 |
| Final Approach Speed | _1,160 |
| Total Down-Link Messages per hour | 37,928 |
| Average Down-Link Messages per second | 10.5 Messages |
| Average Number of Up and Down Data-Link Messages per second | 20.7 Messages |


*Assumes sophisticated airborne about same as normal aircraft.

**Data from Table 2-5, "Computer Sizing of Terminal Area Command and Control for the ATC Advisory Committee, MITRE WP-8266.

TABLE 7

SUMMARY OF COMMAND RATES FOR
ENTIRE LOS ANGELES BASIN 1995


IPC_DATA-LINK                          COMMAND_RATE

IFR/VFR                                1.26 per second

VFR/VFR                                4.72 per second

                                       5.98



ATC_DATA-LINK

Command and Control                    10.35 per second
IPC Commands                            1.26 per second

                                       11.61

            ----------------------------


GRAND TOTAL                            17.59 per second
  (ENTIRE 1995 IA Basin)

TABLE 8

DATA-LINK REQUIREMENTS AND
THE CAPABILITIES OF VHF DATA-LINKS**

| APPLICATION | COMMAND RATE | SUB-CHANNELS AIR-CARRIER (VHF) | SUB-CHANNELS GEN. AVIATION (VHF) | R.F. BAND |
|---|---|---|---|---|
| IPC DATA-LINK | | | | |
| IFR/VFR | 1.26 Comm/Sec | - | 0.4 | |
| VFR/VFR | 4.72 Comm/Sec | - | 1.6 | |
| | | | 2.0 | 5kHz |
| ATC DATA-LINK* | | | | |
| Command and Control | 10.35 Comm/Sec | 3.5 | - | |
| IPC Commands | 1.26 Comm/Sec | 0.4 | - | |
| | | 3.9 | | 10kHz |

\* Does not include such services as weather, initial clearance, approach information.
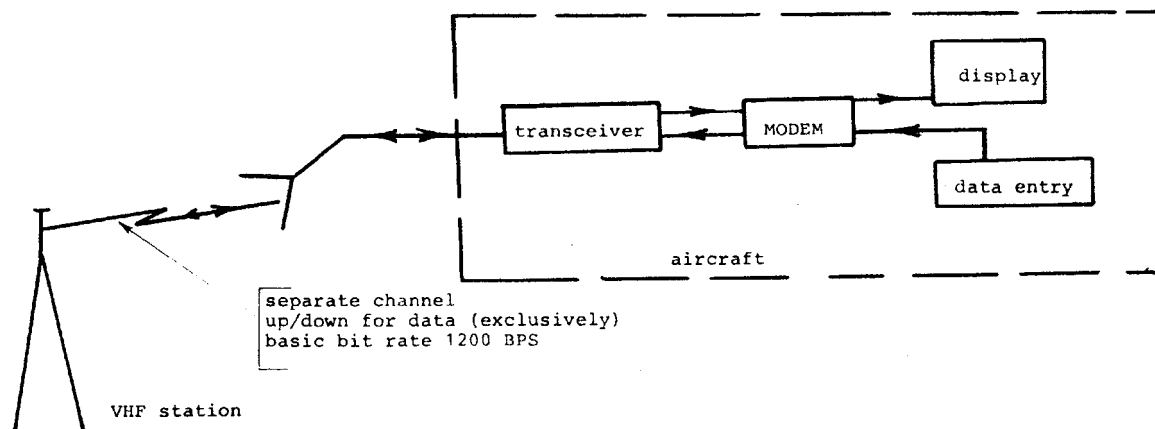
\** Does not include en route IFR above 10,100 feet.

Footnote to Table 8

Note: There are two 1200 bit/sec subchannels spaced at 5 kHz within a single 50 kHz VHF allocation, giving a total of 20 independent subchannel up-links in a single present VHF channel.

FIGURE 1                        VHF DATA LINK



separate channel
up/down for data (exclusively)
basic bit rate 1200 BPS

VHF station

| Message Format (Uplink) | Round Trip Message Time | Uplink Message Capacity |
|---|---|---|
| 1. MODEM sync = 50 bits | 1. uplink ≈0.20 sec | |
| 2. address (7 ch. + 15 bits) = 78 bits block check | 2. transmit dead time ≈0.01 sec 3. down link confirm ≈0.02 sec | 4 msg/sec/subchannel (maximum) |
| 3. message (5-20 ch. prs. + 15 bits) = 60-195 bits block check 188-323 total | 0.23 sec total | 3 msg/sec/subchannel (average) |

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FIGURE 2 - New ATCRBS



3 directional send/receive fan beams
separate up and down frequencies
basic bit rate 600 K bits/sec
(1.45 μs pulse spacing)
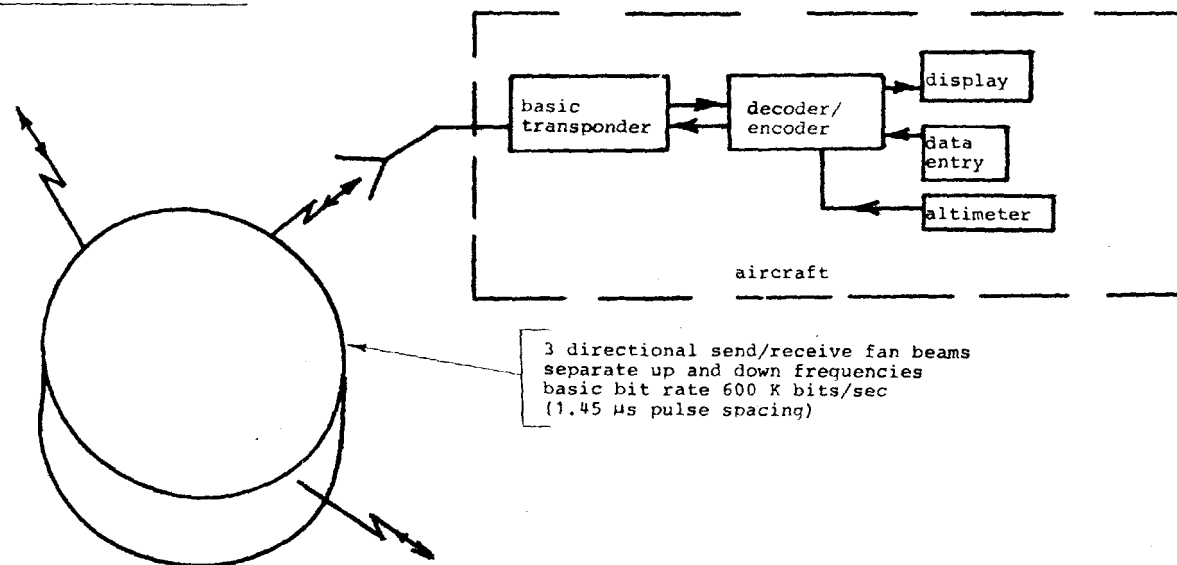
## Message Format (Data Acq. & ATC Data Link)

1. address 78 bits

2. message up
   -standard int.          9 bits
   -command           60-195 bits
                      _____
                      87-284 bits
3. message down
   -address             78 bits
   -altitude            12 bits
   -command         60-195 bits
    parrot

## Message Capacity

time/PRI = 600 x $10^{-6}$ sec (usable for data)
average message/PRI = 1.8
total PRF/ATCRBS = 900/sec (3 beams)*
maximum message rate = 1620 msg/sec/ATCRBS
minimum message rate =  900 msg/sec/ATCRBS**
                        (no polling necessary because
                         of automatic D/A update)
*   terminal PRF 300 at 100-mile range
**  one message per PRF

Note:  "PRI= pulse-repetition interval"

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REFERENCES

(1)  Report of Department of  Transportation  Air  Traffic  Control
     Advisory  Committee,  Volumes 1 and 2, December 1969 (see, for
     instance, Vol. 1, p. 51.

APPENDIX 3


A CANDIDATE NEAR-TERM SATELLITE SYSTEM
FOR DOMESTIC AIR TRAFFIC CONTROL


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APPENDIX 3


A CANDIDATE NEAR-TERM SATELLITE SYSTEM
FOR DOMESTIC AIR TRAFFIC CONTROL


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## A CANDIDATE NEAR-TERM SATELLITE SYSTEM
## FOR DOMESTIC AIR TRAFFIC CONTROL

With communication satellites in daily productive use relaying television programs as well as data and voice communications, the question has long been asked as to the utility of such satellites to aid in air traffic control. Oceanic applications of satellites are discussed in Appendix 5 of this report; here we concentrate on the application to domestic air traffic control.

The ATC task differs from the normal communication task in that ATC participants are users with vastly different requirements and capabilities, both natural and technical. There is no question of satellites doing the "entire ATC job"--there will still be in any case management and actual control tasks required--the question is what fraction of the ATC job, from the point of view of performance and economy, should be accomplished with the aid of satellites.

The Intelsat 4 series of satellites under construction (costing $72 million for the first set of 4 and $34 million for the second set of 4) are stabilized with respect to the earth and have antennas which cover a small fraction of the earth's surface. Similar techniques are also available for air traffic control. However, low-cost general-aviation aircraft cannot have highly directional antennas as are common for those ground terminals communicating with satellites such as Intelsat 4, and in what follows all aircraft antennas will be assumed to have hemispherical coverage. However experience with operation and on-orbit life times of communication satellites provides assurance of similar performance for ATC oriented satellites.

A3.1    DISTINCTIONS AMONG DOMESTIC SATELLITES, OCEANIC SATELLITES, AND SATELLITES FOR STRICTLY MILITARY PURPOSES

It is important to note the differences between a satellite aiding in domestic air traffic control and one used for oceanic or military navigation purposes. The oceanic satellite for the foreseeable future never needs to handle more than 500 aircraft simultaneously in flight, each of which costs more than $5 million

and which is producing revenue at a rate of several thousand dollars per hour. By definition, the ATC problem is an enroute problem in the oceanic areas, and the airlines would be highly satisfied with surveillance and navigation accuracy of a few nautical miles. In the oceanic areas, the airlines' expressed need is for communications more than for navigation or surveillance. Moreover, communications, navigation, and surveillance in the oceanic task can all have delays on the order of a minute or more, quite different from the domestic task. Thus, it would not be an exaggeration to say that the domestic system must operate on a time scale of 1 second as contrasted with 1 minute or more for the oceanic, at the same time that the domestic system must accommodate 50,000 airborne aircraft while the oceanic system accommodates 500. Further, by 1995 the domestic system must work with a fleet of 500,000 general-aviation aircraft, some of them with a sales price below $10,000, while the oceanic system deals mainly with aircraft costing $5-$20 million or more.

However, it turns out that techniques which make satellites useful for domestic air traffic control can also serve to do the oceanic task economically. The converse is obviously not true.

Satellites are well suited to provide a universal and highly accurate navigation system for military aircraft, ground forces, and naval vessels. Substantial government and industry participation in the Air Force-sponsored system 621B and DNSS studies have provided much detail and concrete data on satellite size, navigation accuracies, etc. One concern of military navigation satellites is to provide navigation information which has substantial insensitivity to enemy counter-measures, a capability which is reflected in the cost of user equipment. Indeed, the 621B concept has a Clear channel as well as a Protected channel, the first one being used for acquiring the second and also for low-cost navigation purposes of lesser accuracy. When the ATCAC considered a satellite-aided surveillance system, doing also the communication and navigation jobs for air traffic control[1], it was natural that this was based on the navigation signal for 621B and included two-way ranging with aircraft linked to the 621B system. Such a technique uses a correlator in the master ground station for each airborne aircraft, resulting in a substantial cost to the ATC system, while each aircraft, in order to provide surveillance information, must have a highly reliable sensitive receiver to tell it when to transmit its special code. Such a system can be very useful and perhaps even optimum for a constellation of military aircraft or of air-carrier aircraft, but it is too expensive for the general-aviation fleet. In effect, it

requires each of the participating aircraft to have much of the
equipment necessary for precision satellite navigation, even if
that aircraft's interest is only in cooperating with the
surveillance system.

More recently, during the period of this Panel's activity, we
have seen a substantial recognition of the possibility and
desirability of separating participation in the cooperative
surveillance function from the navigation function, although both
can still be provided via the same satellite. In arriving at this
judgment we have made use of technical analyses of the systems
described below[2][3].

A3.2    FUNCTIONS PERFORMED BY THE CANDIDATE SYSTEMS

We believe it likely that satellites can provide effectively
and economically

   --    universal surveillance of aircraft within the United
         States,

   --    autonomous accurate navigation capability within the
         United States and indeed over most of the hemisphere
         viewed by the satellite system,

   --    data-link to aircraft for IPC commands, and

   --    signaling link from aircraft to ground stations via
         satellite for one of a very few stereotyped messages.

We emphasize that, for the foreseeable future, there will continue
to be a need for VHF voice communication between aircraft and the
present VHF ground stations, and we recommend that this link be
supplemented by extensive use of VHF data-link as indicated in
Appendix 2.

Provision of a few voice channels in an oceanic satellite can
accommodate the expected small population of aircraft, but when
(for domestic use) the population served is increased by a factor
of a hundred and aircraft must be monitored in critical regimes of
flight rather than enroute, voice communication places too great a
demand for power on the satellite. For this reason, it is unlikely
that satellites can be used in the near term to assume the ATC load
of voice communication to each individual airborne aircraft within
the United States.

A3.2.1    Surveillance

A constellation of four or more satellites which relay to a central ground station pulses received from an individual aircraft, and whose positions are accurately known, thus determines from the relative delay in the arrival of the pulses at the ground station (together with the known velocity of radio signals) the range differences from the satellites to the aircraft. The constellations and frequencies chosen will give worst-case position errors on the order of 100 to 200 feet.

Accuracy of position determination is dependent upon the short-time structure of the transmitted pulse; a physical pulse 0.1 microsecond long (light travels 100 feet in 0.1 microsecond) gives the accuracies stated above. However, since a given pulse energy is required for detectability above noise, the peak transmitter power can be reduced by using a longer, internally modulated pulse. Duration of such a pulse is limited by Doppler shift due to aircraft velocity and by frequency drift of the transmitter. The frequency of radio transmission is limited on the low side by disturbance of propagation due to electrons in the ionosphere and on the high side by steeply rising power requirements. Although 1000 MHz seems ideal (and there is a TACAN band which could be pre-empted in part for this purpose), there is an aeronautical satellite band at 1600 MHz which we shall use in the calculations that follow. As a result of extensive calculations[2], a pulse length of about 50 microseconds seems optimum. A single aircraft transmitting a pulse of 50 microsecond length with approximately 500 0.1 microsecond length chips* coded by phase reversal of the carrier or otherwise, at a peak transmitter power of some 3000 watts, would provide a signal in the ground station from which the aircraft's position could be determined to an accuracy of approximately 100 feet. The ground station would have 4 microwave antennas (one for each satellite), preamplifiers, amplifiers, and tapped-delay-line matched filters which would linearly compress the 50 microsecond pulses to 0.1 microseconds. At that point they would be timed against a standard, and the time of arrival inserted into a computer. For a surveillance system dealing with a single aircraft, identification need not be provided, nor is there a problem of interference from the pulses of other aircraft. The question of necessary frequency of identification is raised in Section A3.5.1. That of interference between pulses has been addressed, but not settled, in recent months and is referred to in that same section. If many aircraft were to emit, in concept, 0.1 microsecond pulses at random, it would be difficult for the ground computer to sort out from one satellite channel the pulses which

correlated with those in another channel for that same aircraft.
Therefore, one system concept makes use of some number, perhaps
1000, discrete pulse repetition periods (PRP), spaced in 100
microsecond steps from 1.0 second to 1.1 seconds. In addition,
there may be N individual pulse categories assigned to the aircraft
population, corresponding either to different pseudo-random noise
codings inside the 50 microsecond pulse or, alternatively, to some
small number, say 4, identically-coded 50 microsecond pulses
emitted sequentially within 250 microseconds and carrying for a
given aircraft some fixed pulse delays relative to the first pulse.
Alternatively, a set of four different but common 50 microsecond
pulses in a similar manner could distinguish among categories by a
fixed set of pulse delays. It is possible using reasonable
computer systems with a total capacity of about 60 million
instructions per second[3] to keep track of 100,000 aircraft
simultaneously over the United States, to look for conflicts, and
once per second to pass routinely to ATC centers the few hundred
conflicts requiring IPC intervention.

The detailed mode of correlation between satellites of a given
transmission is covered in A3.5.1, while the question of computer
sizing is touched upon in A3.3.3. In summary, to participate in
the surveillance system each airborne aircraft will be required to
carry and operate while airborne a transmitter which has some fixed
period in the range 1 to 1.1 seconds and transmits on a near omni-
directional antenna a single (or a few) 50-microsecond pulses at a
peak power level of approximately 3 kilowatts at a frequency of
1600 MHz. The central computer will utilize this signal to
determine the position of the individual aircraft to an accuracy of
a few hundred feet.

A3.2.2    Navigation

Just as a single aircraft transmitting a single pulse to a
single ground station via four or more satellites in known
locations provides sufficient range difference information for the
ground station to determine the aircraft position, so the ground
station can broadcast a single pulse via the four satellites to
allow any aircraft with knowledge of the satellite positions to
determine range differences from the satellites and thus its
position in three-dimensions. The aircraft need not radiate any
signals in order to obtain its position, and this navigation
function is not subject to system-wide interference from jamming.
For domestic air traffic control, these navigation data can be used
in several ways.

## • Broadcast Signals for Onboard Computers

Since navigation system signals are broadcast by satellites and not addressed specifically to each aircraft, there is little penalty associated with broadcasting them every 0.1 seconds, allowing any aircraft to update its position to an accuracy of 100 feet (or in some cases to an accuracy of some tens of feet or better) at intervals of 0.1 seconds. Continuous pseudo-random noise sequences have been most studied for this navigation function, but it is perfectly clear that individual pulses like those specified above for surveillance will perform equally well for navigation, and may result in user equipment at lower cost. This point is raised again in Section A3.5.5. In what follows we shall assume that navigation signals are broadcast in a band near 1600 MHz and received by those aircraft so equipped on the same antenna used for cooperative surveillance or on a similar antenna. Signals from the ground station to the satellites can in fact be staggered in time in such a way that there is no ambiguity at any aircraft about which satellite signal comes first. Precise measurement of arrival time then gives range differences from which aircraft can determine position, using ephemeris data and aid-to-computation constants broadcast by the satellites. By use of flight-quality heading references and strapped-down accelerometers, (not the more costly inertial navigation systems as usually known) an aircraft then has the information to make precision approaches as well as to navigate in three-dimensions throughout the air space. In this mechanization, the most expensive part of the navigation system is the onboard computer, which must have a memory of about 5000 words. Total cost estimates for commercial equipment for satellite navigation range from $5000 to $50,000, substantially less than the cost of inertial navigation units of far lesser performance.

## • Navigation by Surveillance

Under normal circumstances, the ATC surveillance system via satellite, described in A3.2.1, would know the precise position of each aircraft. In view of the capacity of the VHF data-link described in Appendix 2, there is evidently no bar to transmission of present aircraft position as determined by the surveillance system to each aircraft every few minutes, even in the densest areas, if the aircraft is equipped with VHF data-link. There is also the capability to transmit position data to the aircraft, either routinely or on demand, by computer-generated voice, although there is not enough communication capacity (because of the inefficiency of voice communications) to update each aircraft

position in this way as frequently as once per minute. On the other hand, it seems reasonable to ask whether an aircraft could not be charged by individual voice transmission (a "toll call") whenever it requests voice communication of its position. It should be noted that the surveillance box itself can provide the mechanism for requesting such a navigation fix as well as for acknowledging a transmission from the ground. It need only incorporate a button, which when depressed would delay the next two surveillance pulses by some fixed time, say, one microsecond. This would not interfere in the least with precision of position determination, nor significantly with tracking the aircraft, but it would be recognized and decoded as an acknowledgement or as a request for a navigation fix, depending upon the precise amount of the delay. It should be recognized that no partial failure of the surveillance transmitter on the aircraft could falsify the position information obtained by the ATC system. A total failure of the transmitter would simply deny position data. The question of redundancy of the overall system is touched upon in Section A3.3.3.

- **Navigation by Re-Transmission to Ground Stations**

It is evidently possible for an aircraft which does not have an operating onboard computer to receive navigation pulses from satellites, time them against an onboard crystal oscillator and transmit these arrival times via VHF data-link to an ATC center. There position computation can be done for that aircraft, and the result returned via data-link. This capability could be imagined as a back-up against failure of the onboard computer, although "navigation by surveillance" would seem to insure adequately against that. It also could be used to provide surveillance information to the ground system, for aircraft so equipped, in case of deliberate jamming of the satellite surveillance system or of catastrophe at the ground tracking center. It is not clear whether this added capability is worth the expense of the on-board equipment. That can only be determined via proper system design, taking into account the possibility of jamming of the surveillance system and the degree of desirability of such a fallback to surveillance-by-navigation.

A3.2.3    **Data-Link for Intermittent Positive Control and for Other Signaling**

The surveillance scheme described in A3.2.1 and in more detail in A3.5.1 requires only a single pulse from an aircraft for each position determination. Although the pulse may be 50 microseconds long rather than 0.1 microsecond, it is coherently added in the

pulse compression process and is the equivalent of a 0.1 microsecond pulse. Aircraft identity is then determined on a second-to-second basis by the pulse repetition period (if there are one thousand pulse repetition periods and fifty thousand airborne aircraft, the surveillance scheme with common pulses identifies the aircraft at each position as belonging to a class of some fifty aircraft), and on a longer time scale by correlation with data-link or voice messages. Alternatively, a burst of surveillance-type pulses can be transmitted routinely as described in Section A3.5.1. In general, this surveillance scheme which does not rely upon each aircraft broadcasting its full identity (some fifty bits or more) at each transmission thereby saves a factor 50 in aircraft radiated power and a similar factor in spectrum utilization.

A similar saving can be made in this system in transmission of a simple command to the individual aircraft. This is achieved again by capitalizing upon the ATC system's precise knowledge of aircraft position. In the data-link discussion of Appendix 2, each message contains 78 bits of address. The transmitter power and message duration is determined in large part by this long address, and the airborne receiver must have an address recognizer in order to insure that the aircraft receives only its own messages. In the satellite surveillance system, one has four or more satellites in line-of-sight communications with the aircraft. This makes possible a "spatial-address" mode of communication to individual aircraft, which for short messages needed for IPC can reduce power requirements on the satellite by a factor 10 to 20. It is also important to remember that the ground station knows the precise time of the next transmission of each aircraft, to an accuracy comparable with 0.1 microsecond, simply by having tracked the pulse repetition period of the aircraft. Thus, when the ground station receives a message to be transmitted to an individual aircraft, it can launch pulses toward the individual satellites at such a time that the pulse relayed from that satellite on a frequency near 1600 MHz will arrive at the aircraft a specified time after the next surveillance pulse is emitted by that aircraft.

In fact, the four pulses from the four satellites can either be on different frequencies within the band and be detected simultaneously by the aircraft receiver, thereby alerting the receiver that an information pulse is to follow, or, more simply, be on the same frequency and be timed to arrive at the aircraft in ripple fashion at equal spacing of say, 0.1 to 0.5 microseconds. Receipt of this sequence then alerts the receiver to accept the following information pulse. The IPC information itself can be carried by position modulation of 1 or 2 pulses from one of the

satellites, or in a pulse-code-modulation chain of 3 or 4 pulses. In any case, the aircraft can receive IPC data in this way, uniquely addressed, with the satellites having transmitted only 5 to 8 pulses as compared with 80 or more for the normal addressing schemes. If all 50,000 peak airborne aircraft were in such congested areas as the Los Angeles Basin, the IPC command rate of Appendix 2 would correspond to about 200 IPC messages per second, about 1200 pulses per second from the whole satellite constellation, or about 300 pulses per second for each satellite. The average radiated power is then about 40 watts, a perfectly reasonable value.

In principle, the satellite could radiate this power as 300 0.1 microsecond pulses, which would require a 1.5 megawatt peak power transmitting tube in the satellite. It is more reasonable to equip the satellite with the same type of 3 kW output tube as is carried by the aircraft for generation of the surveillance pulse (perhaps with on-line spares to meet the reliability requirement), and to equip each of the aircraft with the pulse-compression matched filter needed to compress the received pulse to 0.1 microsecond. Such matched filters might now be built with acoustic surface wave delay lines.

The IPC data-link might be used to transmit about 10 standardized messages. One of these messages could request the pilot to initiate voice transmission on VHF with air traffic control. Specific uses of such low-capacity data-links has barely been considered.

- • Alternative Implementation of Satellite-to-Aircraft Intermittent Positive Control Link

Confidence in the promise and flexibility of this approach may be enhanced by the following indication of an alternative implementation of the IPC link via satellite to the aircraft. This scheme retains the spatial address feature and has the following characteristics:

-- Single receiver in the aircraft.

-- Satellite pulses which are distinguishable to eliminate the possibility of spatial addressing by pulses arriving in the wrong order (e.g., by multipath) although analysis does not thus far indicate that this is necessary.

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--    No pulse compression filter or long shift registers in the aircraft.

--    Large processing gain to allow good time resolution with low peak power in satellites.

This implementation uses the fundamental concept of spatial address, taking advantage of the fact that the ATC computer on the ground which tracks the aircraft in space also tracks its pulse emission in time and can direct pulses from the satellites to arrive at the aircraft with a time error much less than a microsecond, although the aircraft clock is stabilized only by a simple inexpensive crystal oscillator, and in the presence of Doppler shifts, etc.

Thus it becomes possible to use a "parallel-search" pulse correlator. Imagine that each of the four active addressing satellites transmits a pulse of length, say, 51.1 microseconds, containing 511 0.1 microsecond chips. These pulses could perfectly well be generated by a shift register sequence, and since the number of IPC messages per second is on the order of 50 and the number of individual pulses thus on the order of 500, as compared with the 50,000 we have assumed in the surveillance example above, no difficult cross-correlation or autocorrelation requirements need be imposed on the IPC pulse code. Further, links from the multiple satellites to a single aircraft are likely to be significantly more similar in gain than links from various aircraft and locations to a single satellite.

The pulses would be timed to arrive at the selected aircraft in successive 51.1 microsecond blocks, to an accuracy much better than 1 microsecond with respect to one another and with respect to the "gate" time of the selected aircraft as predicted by the ground computer.

Each aircraft, say, 500 microseconds before the transmission of its surveillance pulse, would "enable" its receiver for the reception of IPC commands. At the same time, it would initiate the local generation of a sequence of, say, 2048, 0.1 microsecond chips via a small shift register (11 bits long). This sequence would be the same for every aircraft in the system, and the first 511 chips of the same sequence would be used by the ground station as the first spatial address pulse, to be transmitted by satellite A. The second, third, and fourth 511 chip segments would be transmitted by three other satellites B, C, and D. The four pulses, A, B, C, and

D, would be timed to arrive at the aircraft in successive 51.1 microsecond intervals.

The locally-generated pseudo-random-noise chip sequence would be used to detect coherently each 51.1 microsecond pulse, although individual 51.1 microsecond segments would be incoherent with respect to one another. Thus, the output of the sequence generator modulating a local oscillator would, in principle, be multiplied (gated) by the received signal and the product accumulated on a storage capacitor. In fact, since the received carrier can be in phase or in quadrature with respect to any reference, two such multiplications and accumulations are required--a total of four if a positive output indication is required rather than either positive or negative. This process would be quasi-linear. To allow for a time window up to 1 microsecond, rather than 0.1 microsecond or less, the four bi-phase modulator-integrators would be replicated 10 times. Thus, after the first 51.1 microseconds of the sequence, a logic unit would determine whether any of the 40 integrators contained a pulse and if so would count pulse A as having been received. The integrators would be reset, the next 511 chips of the shift register sequence would be mixed with the incoming signal in order to detect the B pulse, and so on for the C and D pulses.

The information pulse can then be carried in the time difference between the D pulse and an E pulse to be radiated by the D satellite and to be shifted in time by 0.1 microsecond intervals over a 1 microsecond range. Alternatively, E, F, and G pulses could be transmitted from satellite D, carrying a digital message by pulse position modulation. Still another alternative would be to have the E pulse repeated, say, 8 times and be either present or not--thus allowing receipt of an 8-bit signal by the spatially-addressed aircraft. This signal could include internal error detection.

It should be emphasized that the airborne code generator, with perhaps 40 bi-phase modulators, integrators, and detection logic readily fit on a chip currently producible by medium scale integration techniques and sold for a few dollars.

This IPC link appears to be a hybrid between pure spatial address and a correlator addressing scheme. In fact, it provides a baseline for performance and cost. Simplifications and compromises might be made from this baseline in the interest of lower cost. It should be noted that it is quite unnecessary for every satellite pulse to be received in order for the aircraft to

count itself as addressed. It is also possible, within the power
budget, to repeat IPC messages either routinely or if
unacknowledged. A more detailed analysis is required to decide
between a necessary window of 1 microsecond width (40 integrators)
or 0.2 microseconds (8 integrators).

## A3.3    STRUCTURE OF SATELLITE SYSTEMS

In the paragraphs above we have described a technique for
surveillance, navigation, and IPC that in the near future might be
fulfilled effectively and economically by a satellite system. The
following sections describe in slightly more detail the structure
of that system.

### A3.3.1    Satellite Orbits and Satellite Characteristics

Extensive studies have been made of the errors of such a
navigation or surveillance system as a function of the orbit of the
synchronous satellite. A stationary synchronous satellite at 100
degrees west longitude and three or more in orbits with a near
circular ground track centered on the 100 degree west subsatellite
point seems near optimum. Orbital inclinations of about 20 degrees
give coverage of the entire United States and, with 4 satellites in
the ring and 2 stationary satellites, allow operation with any
single satellite out. The question of redundancy of the satellite
constellation is touched upon further in Section A3.3.3. Probably
the best cost and weight estimates for the satellites come from Air
Force-sponsored 621B studies, which give spacecraft weights of 1300
pounds and a five year program cost of $270 million, leading to
four fully operational satellites in orbit (of a type meeting
specific military requirements of vulnerability, anti-jam features,
etc.). An estimate[3] for development costs needed to add
surveillance and IPC features to such satellites (without any
coupling to the 621B features) is $2.5 million for development and
$1.1 million additional for each satellite, raising the weight to
1560 pounds. The resulting satellites would have near-
hemispherical coverage for the navigation signal, and coverage of
the continental United States with the antennas for ATC
surveillance and IPC.

Obviously, should the 621B-type navigational features of the
system be reduced to those required to demonstrate operational
utility of navigation satellites, and to work in precisely the
operational manner with airborne equipment (i.e., replacing on-
board clocks and signal generation equipment by transparent
repeaters with ground-generated navigation signals), the weight and

cost of the spacecraft could be substantially reduced. Indeed, a program has been defined to build 5, and launch 4 such satellites for a total four-year program cost below $120 million, including navigation and surveillance functions, a single ground station, and 100 sets of airborne user equipment.

### A3.3.2    Airborne User Equipment

As emphasized in the body of the report, it is expected that in the future all aircraft would be required to carry a cooperative surveillance aid. For the satellite system, this would be an L-band transmitter with a fixed pulse repetition period between 1 and 1.1 seconds, radiating an appropriate 50 microsecond pulse internally coded with 0.1 microsecond chips. Beyond that, optional equipment may be carried as summarized below.

- ### General-Aviation

General aviation desiring to enter controlled-airspace would be required to carry an operational IPC addition to the surveillance transmitter box, as well as two-way voice radio. The latter is already required in many areas. Optional beyond that would be a VHF data-link that could be used routinely to obtain ATC navigation-through-surveillance data without posing a significant burden to the ATC or communication system.

- ### Air-Carrier

We expect all airline aircraft to be required to carry the equipment described as optional for general-aviation. Most airliners would elect to carry on-board navigation equipment which would allow real time derivation of the aircraft position to accuracy in the 100-foot range from navigation signals broadcast by satellites. Eventually, most air-carriers could be expected to employ a system in which navigation data are used to provide three-dimensional control of the aircraft in normal circumstances. Essential parts of the equipment would be duplexed for reliability. An alternative at a cost that probably can not be afforded by most general-aviation, and one which guards against large-scale failure of the surveillance sorting means, is to provide apparatus for timing arrival of the navigation signals and transmitting these times via data-link to the ground ATC system, whence aircraft position can be computed and returned to the aircraft by VHF data-link. Not only does this provide a capability redundant to the on-board computer, but it guards against certain other contingencies as well. If, as suggested in paragraph A3.7, a beacon on the

airfield allows NAVSAT-equipped air-carriers to perform ILS approaches and landings, then it is to be expected that many air-carriers would be equipped in this way.

- **Military**

Military aircraft are expected to be equipped either like general-aviation or air-carriers. More use is expected to be made of the ILS-like capability which can be derived from a beacon on the air base, together with the NAVSAT system. Further, military craft could of course carry specific mission equipment, such as terrain avoidance and following by means of a stored terrain altitude map. This, together with precision position information derived from the navigation satellite system allows the aircraft to program its altitude or horizontal path in order to follow or clear the terrain, without the use of expensive, bulky, heavy, and radiating terrain-following radars.

### A3.3.3 Ground Equipment

- **Central Computers**

The computers used for "data acquisition," that is for deriving accurate position information from the streams of pulses from the satellites, have been considered, together with detailed algorithms for performing this function. The normal tracking function is a small part of the total process for any advanced ATC system[4]. Reference 4 starts from various algorithms and instruction requirements and works out the price of computers to be delivered in 1980 to do the job of a major enroute and terminal center handling a total of 8000 aircraft. The results include a degradation of a factor 2 in relating the instruction time to the fastest instruction time, a further factor 2 for executive overhead, and a further factor 3 for "high level language" degradation. Beyond this factor 12, reference 4 applies a factor 4 to 8 to the manufacturer's cost to obtain the purchase price of the computer. Total costs for one enroute and one terminal center handling 8000 aircraft are then $19 to $36 million. For a system having 50,000 peak airborne aircraft in 1995, the total system cost of computers purchased in 1975 for delivery in 1980 would thus be some $84 to $210 million. In fact, of course, full computer capacity would not be purchased in 1975 for the 1995 task, but that is irrelevant for our discussions of the near-term contribution of satellites.

If the central computer has to start from scratch in the satellite surveillance scheme described here, an upper limit can be obtained to the number of instructions required to recover essentially all tracks and identities in 2 seconds. In the worst case, if all 50,000 aircraft used the same coded pulse, then the track initiation program consists of "de-interleaving" those pulses in each satellite stream which correspond to any constant pulse repetition rate. For each of the 50,000 pulses detected in the first second, a region from 1.0 to 1.1 seconds later must be scanned for pulses, and those pulses falling within some tolerance (say 5 microseconds full window) of a multiple of 100 microseconds spacing of possible pulse repetition periods must be selected as candidates for a pulse train. About 5000 pulses will appear in this 0.1 second interval, of which approximately 250 will thus be possible candidates. For every pulse in the first second, 250 possible pulse trains are started. Received pulses are again inspected at an equal time later. If timing accuracies necessitate a 1 microsecond window for this third pulse, the probability of an accidental coincidence is 1/20, so only 12 accidental pulses will survive, in addition to the real ones. One more second of projection will then eliminate on the average all of the false sequences, leaving the real one. Thus the great burden on the computer is to look at the 250 times 50,000 or 12 million possible 5 microsecond windows. This might be done in 2 seconds for all 4 satellites without exceeding computer capability installed for other purposes. It should be emphasized that such a contingency of abrupt start should be extremely rare, and that there is no need to recover track on all aircraft so very quickly.

Should the individual aircraft transmissions contain identity information as suggested in A3.2.1, the number of instructions required under this algorithm is reduced by the number of codes employed. Indeed, if there are 1000 pulse repetition periods and 1000 codes, so that on the average 50 aircraft are present with one code, an entirely different algorithm proves superior, which associates a given transmission received on one satellite with a transmission of the same code received on another satellite within the five milliseconds allowable time difference caused by the aircraft's unknown position within the United States. On the average there will be only one identical code within the allowable time, reducing the track initiation problem to negligible proportions.

- Command, Tracking, and Calibration

For tracking the satellite, a 15 foot ground antenna operating at C band can be used to receive information relayed by the satellites from aircraft surveillance transmitters. The same antenna can be used with an up-link at a slightly lower frequency to command the satellite for orbit-adjust purposes, phasing of the transmission, and to provide the IPC pulse to be radiated by the satellite as described above. These functions are standard, and the antennas cost about $75,000 each, with transmitter, receiver, etc. The satellite orbits can be determined either from a standard satellite tracking network or better from a number of aircraft-like surveillance transmitters located on the runway or control tower of a number of airports around the United States. Apparent motion of these transmitters as deduced by the central computer, provides data for rapidly refining the orbits of the satellites in a standard least-squares fashion. Since transmitters for airborne use cost between $500 to $1000, the total cost for a set of 10 to 100 calibration transmitters is negligible, and the system does not depend on the continued operation of any number of them.

- **Backup to Ground Stations**

A single ground station with tracking antennas, receivers, transmitters, and a single set of large-scale computers is adequate to derive position information from the surveillance scheme described above, and also to initiate navigation signals and IPC transmissions in response to ATC-supplied messages. The existing twenty enroute ATC centers would have no place in data acquisition, but it would be unthinkable to rely on a single ground station, if only because of its physical vulnerability. Aside from natural hazards such as tornado, fire, flood, and earthquake, there are man-made dangers, such as airplane crashes, insurrection, etc. No matter how thoroughly redundant the equipment is at a center, there is always the possibility of losing the entire center for an extended period due to physical damage. Therefore, there must be at least one additional center, physically separated from the first and capable of performing all of its functions. Indeed, the same statement can be made about the second center, when it is carrying out the operation after failure of the first. Actually, what is needed is a thorough analysis, without preconceptions about the necessity for reliable equipment at individual centers, based upon provision of any desired assurance of continuous operations for any given period, such as thirty years. Prime input to such an analysis will be the probability of occurrence of disabling damage to an installation, the time to repair, and the desired assurance of continuous operation. A consequence of the need for backup centers will probably be a reduced requirement on reliability of

the individual center, since transfer to the backup is by definition at least as effective as transfer to redundant equipment at the individual center. The backup centers will have high-performance computer equipment which can be doing other jobs related to air traffic control or indeed other jobs for the federal government of lesser urgency tnan surveillance for air traffic control, so that these jobs can be dropped if the primary responsibility devolved upon the particular center. It would take us too far afield here to detail the communication system required for productive use of backup centers in non-ATC-related tasks, but that should be part of the program for determining the cost of the satellite system described above.

It is a very small job to provide backup capabilities for managing the navigation portion of the satellite system, and that should be done. If the navigation signals are present, air-carriers and military aircraft can use the technique of navigation by re-transmission described in Section A3.2.2 as an additional backup means.

- Satellites for Exchange of Data Among Traffic Control Sites

With the Intelsat 4 series of satellites, the cost of a repeater channel in a communication satellite has rapidly decreased. The possibility of switching large amounts of communication load from one control center to another is necessary to maintain ATC capability in the presence of contingencies that are required not only for data acquisition but also for the control function. For this purpose and for reliability, a communication satellite used in its traditional role with directional antennas on the ground can provide the FAA with new capabilities at lower costs than the present ground-based communication system. Quite independent of the use of satellites in connection with aircraft, the FAA should look on an urgent basis to the use of one or more of the 24 transponders available on the Intelsat 4 type of satellite to determine how this capability might best serve its needs, e.g., with a frequency-division multiple-access or a time-division-multiple-access system. Experience in recent years, in which at times a substantial fraction of the New York terminal area control was provided from Boston or Washington indicates that this flexibility in managing resources will serve the FAA well.

A3.3.4    Interface with Air Traffic Control

The satellite system described here provides position information to the ATC system, and to those aircraft properly equipped. It does not control aircraft. It can provide conflict prediction and candidate aircraft pairs for IPC action. In the other direction, it takes IPC messages from the FAA and translates them into the peculiar time structure desired for implementation in the system. To the extent that aircraft are equipped with VHF air-ground data-links, the position information can be transmitted to the aircraft periodically or on request. As noted previously, the same information can be provided at substantially higher cost to the system, via VHF voice.

A3.4        PRESENT STATUS OF SATELLITE SYSTEMS FOR DOMESTIC AIR TRAFFIC CONTROL

Technology is in hand from Intelsat and other stabilized satellite programs on the one hand, and from the 621B technology programs on the other, to give assurance of adequate performance of satellites required for this system. What is lacking is a definition of the total system in a program context. 621B has been an Air Force navigation satellite program. Only recently has a surveillance task been considered for those same satellites, really a FAA/DoT responsibility. Beginning in January 1971, a flight test and evaluation will be performed at White Sands using ground-based transmitters to simulate the navigation satellite and an airborne receiver on an F-4 aircraft. In addition, some work is being performed using the NASA ATS 5, together with a 621B receiver.

An advanced development plan for the 621B navigation satellite system has been prepared but not approved. Discussions between the DoT/FAA and the DoD have only begun, although a combined surveillance/navigation system would be far more valuable than either alone. It seems likely that the functional prototype system at $120 million program cost (described in A3.3.1) can serve as a timely vehicle for collaboration.

A3.5 SPECIFIC TECHNICAL QUESTIONS TO BE ANSWERED IN A PROGRAM CONTEXT

In any field, continued work in technology results in a wider choice for the ultimate system, and particularly in less expensive and more effective options. This is true for the upgraded radar beacon as well as for the use of satellites in air traffic control. It holds also for improvements in airplanes and engines. However, when the existing technology is in general adequate to support an operational system which competes sucessfully with other choices,

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it is time, without necessarily stopping technology improvement, to incorporate what exists into a system. At that time, as indicated in Section 4 of this report, various program choices must be made. To guide these program choices, certain questions must be investigated in more depth than is natural in a broad technology program. Some comments on these choices follow.

### A3.5.1 Degree of Identification to be Required and Utilized in the Surveillance Link

As noted previously, candidate satellite surveillance systems range from those in which each aircraft emits about once per second at a fixed repetition rate a single common pulse of some 50 microsecond length compressible to 0.1 microsecond, to those in which each aircraft emits a set of 4 different but common pulses with its own fixed pulse position code modulated upon them, thus conveying substantial identity information on a "single pulse" basis.

- ### Single Compressible Pulse

In this case, the question to be investigated is not so much the ability of the surveillance system to track individual aircraft but rather the precise algorithm by which it will do so and the size of computer required. Further, there are questions about how identification of the tracks thus resulting will be established, whether by occasional interrogation of the aircraft via the spaital-address IPC link above, by requiring the aircraft to identify themselves before entering the system, or in other ways. With 1000 pulse repetition rates and 50,000 aircraft airborne, there will be at any time about 50 aircraft using the same pulse repetition rate. It may be desirable to introduce a programmed long-term stagger of the pulse repetition rate in order to provide identity over a period of many seconds, together with the aid to tracking provided by short-term constancy of the pulse repetition interval. More simply, an occasional burst of surveillance-type pulses with fixed coded delay can supply identity to the continuing track.

The radiation of a single physical pulse of 0.1 microseconds width by each aircraft is the ultimate in this non-identified common pulse. It would have the advantage of infinitesimal time side lobes and would arouse least doubt regarding operability of the system in the presence of antenna pattern variations, power output variations, etc. It has been shown[5] that the common 50-microsecond compressible pulse also can have its side lobes removed

in a linear fashion to any desired level (by employing a somewhat
mismatched filter), but it is not yet known whether this is
possible in systems which use several or many compressible pulse
types.

* Pulse-Position-Coded Zero-Side-Lobe Compressible Pulse

If one employs a single slightly mismatched filter in the
ground station for the purpose of removing side lobes from the
common compressible pulse, then the situation is the same as if
aircraft were able to transmit physical 0.1 microsecond pulses of
adequate power. In this case, every 10 or 20 seconds an aircraft
might transmit its standard surveillance aid pulse, followed by
three more at intervals of approximately 51 microseconds, but with
its own identity class (1 of 1,000) impressed upon these pulses by
a position modulation of the starting delay of each pulse. If
there are 10 possible starting delays for each, then 1,000 pulse
position codes and 1,000 pulse repetition rates for the
surveillance signal provide unique identification to any of one
million aircraft, more than are expected through the year 2000.
The probability of finding no interfering pulse within one
microsecond on either side of the four pulses used for
identification is approximately 70 per cent, so that the
probability is high of identifying each aircraft track within less
than 10 seconds. If the surveillance signal fails for a few
seconds, track identity will be carried forward from before the
failure. These considerations must be refined in order to
determine whether the repeated compressible pulse is a viable
modulation format. Naturally, identity may be verified and the
track preserved even if one or more digits in the pulse modulation
code are ambiguous due to a neighboring independent pulse.

* Pulse Position Modulation of Four Compressible Pulses

As indicated above, a single pulse can be provided with a mis-
matched filter in the ground station that will reduce its side
lobes below the system noise. It is not yet known whether it is
possible to reduce the cross-correlation function among pulses in
this way. Nevertheless, pulse sequences are known with side-lobe
levels and cross-lobe levels which seem adequate to define a
system. Such a system could use the 1,000 pulse repetition periods
indicated above, combined with four compressible pulses, A, B, C
and D, radiated by each aircraft at its standard transmission rate,
with the time of the last three pulses relative to the first fixed
for each aircraft but variable across the fleet. In this way, if
there are ten possible starting positions in each of the three

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pulses at intervals of 0.1 microseconds, an assembly of four matched filters in each satellite channel in the ground station, together with software or hardware delay lines, will allow instantaneous assignment of each transmission to one class out of 1,000, permitting immediate correlation with the (rarely more than one) similar code in the other satellite streams. The technical question here is determination of an optimum set of four or perhaps five such pulses, considering the penalty of increased pulse energy in the transmission band as the number of pulses is increased, as opposed to the benefits of increased redundancy in the reading and tracking of the code with more pulses. Further, there is the question of the best side-lobe levels which can be obtained by a search among pulses of known modulation format, by the introduction of four-phase modulation, and by the possible application of so-called "complementary" sequences[6] in which the side-lobes are canceled in a deterministic fashion. Another question is the extent to which those side-lobes can be maintained, at a sufficiently low level, for words of the assumed 50 microseconds duration in the presence of Doppler shift and tolerable crystal oscillator drift.

### A3.5.2    Available Technology for Pulse Compression

Tapped delay lines of 500 chips length are not readily realizable with inductors and capacitors at room temperature. Since only a single delay line is necessary in the ground station for each satellite output stream, the cost of delay lines will not significantly affect overall cost of the ground stations. Three definable candidates present themselves for this ground application.

First, it is perfectly possible to use normal lumped-constant electro-magnetic delay lines in which the inductors and capacitors are superconducting and maintained at liquid helium temperature. Many satellite communications terminals operate with liquid-helium-cooled parametric amplifiers, and reliable and relatively inexpensive refrigerators have been developed for this specific purpose. The lowest development risk and total program cost is probably associated with this choice of linear pulse compressor, even though its unit cost is greater than others discussed below.

Second, acoustic surface wave matched filters can be built with 500 chips. The temperature coefficient and environmental accuracy requirement remain to be demonstrated, as does the necessary accuracy of fabrication. Simultaneous use of the same transmission medium for several pulses, and the use of Golay

complementary pulses have been demonstrated in acoustic surface wave processors[6]. The manufacturing cost of acoustic surface wave delay lines might be below $100, fitting them for use as pulse compression receivers in aircraft, and, of course, allowing their use in elaborate temperature-regulated oven enclosures, if that were necessary, on the ground. Like the superconducting delay line, the acoustic delay line is also a strictly linear element and would handle any number of overlapped pulses, due consideration being given only to the resulting individual side-lobes.

Third, there is the possiblity of digitizing on the ground the pulse stream from a satellite either at the intermediate frequency or after being heterodyned with in-phase and quadrature-phase local oscillator signals at the carrier frequency. In radar terminology, this is known as an "all-range decoder" and is discussed, for instance, in Reference 5, p. 476. If the digitizing consists only of polarity detection (one-bit accuracy) there is a loss due to limiting and quantization of about 2dB. This loss is rapidly recovered if two- or three-bit quantization is used. The quantized signal would then be sent to a number of parallel shift-register delay lines operating on a clock frequency of two or three steps per pulse, two such 1,000-bit shift registers being required per satellite stream.

Neither the superconductive electromagnetic delay line nor the integrated circuit quantization-and-shift-register matched filter presents any significant development risk or cost exposure to a satellite surveillance program. On the other hand, work should go on in connection with acoustic surface wave processors and other analog pulse compression means in order to refine the costs and to choose the best for airborne application in connection with the satellite-to-aircraft link. There is no need in this latter case to use compression ratios as high as 500, since the problem is not so much discrimination against unwanted or overlapping pulses as it is coherent integration to allow substantial signal energy with limited peak power.

- ## Achievable Side-Lobe Levels

While pseudorandom noise bi-phase coded pulses of length $N$ chips have a peak-to-side lobe (power) ratio of $N$ (27 dB for a 511-chip pulse), and while this may be inadequate or barely adequate for a single channel carrying the full 1995 surveillance load, much better pulse patterns are known. In particular, the technique of Paragraph A3.5.1, a mismatched filter applied to a 13-chip Barker pulse, provides a peak signal-to-residual peak side lobe ratio of

22.3 dB for a matched filter, 32.4 dB for a 13-tap weighted filter which eliminates the first six side lobes, and 45.6 dB for a 25-tap weighted filter which eliminates the first twelve side lobes.   The weighted filter would be used in the ground station, and the peak-to-side-lobe ratio for the Barker code, thus filtered, is far more than adequate for the surveillance job.   Such a short code, however, would require uneconomically large peak transmitter power on the aircraft.   The use of such code groups as elements in a Barker-squared code reduces the required power to reasonable magnitude and shows promise of RMS side lobes low enough for the surveillance job.

Further freedom is to be found in the polyphase codes, such as the Frank code. A Frank code of length 256 encoded in sixteen phases has a peak-to-RMS-side-lobe ratio of 46 dB, with the maximum side lobe 33 dB below the zero-offset peak.   Four-phase approximations to the Frank codes gives significantly worse results, but this performance might be improved without complicating the transmitter by adding a weighted network to the pulse compression mechanism in the receiver on the ground.

There is thus reason for optimism that an adequate code can be found for surveillance use in those techniques which require a single common code with good autocorrelation properties. It is an open question whether codes can be found with cross-correlation properties to support the potentially more convenient systems using several coded pulses on a single channel.

In addition to the compression techniques described in Section A3.5.2, using analog addition in the transversal filter, fully digital techniques are now available.[7]

A3.5.3   Specific Communication Capabilities to be Provided on the Surveillance Transmission Channel

• Uses to be Made of this Capability

We have previously discussed a satellite-to-aircraft link, spatially-addressed, to provide the few-bit messages needed for intermittent positive control, without the overhead of the usual 50 to 80 bits of address. Also discussed above is "navigation by surveillance", making available to the aircraft via VHF data-link or via computer-generated voice from the ground the precise position known to the surveillance system.  It is also possible for the satellite to provide this information to an instantaneous peak-user set of 50,000 aircraft via the IPC link and an expanded

display. Reference 3 (page 5-18) provides cost estimates as follows for the airborne equipment required to emit cooperative surveillance pulses, to accept the IPC message and, optionally, to accept and display navigation-by-surveillance data transmitted directly from the satellite to the individual aircraft.

## Civil User Equipment Costs

| | ATC | ATC + Nav. | Airline Quality ATC + Nav. |
|---|---|---|---|
| Transceiver | $ 900 | $ 900 | $2100 |
| Antenna and Duplexer | 200 | 200 | 500 |
| Display | 200 | 700 | 1500 |
| Total | $1300 | $1800 | $4100 |
| Production: | 10,000 units | 10,000 units | 2,000 units |

Such navigation data would not have a refresh rate required for maneuvering an aircraft in a terminal area, but it would be adequate for long portions of the flight and, in particular, more than adequate for oceanic surveillance and navigation.

It would also be possible to allocate one of the IPC-type messages to instruct the pilot to initiate a voice transmission with the ground or to begin operation in some backup mode.

- **Specific Means of Aircraft-to-Satellite Signaling Without Increasing Transmission Burden**

There is a need for pilot acknowledgement of the IPC command and perhaps a need to allow aircraft to request a navigation fix from the ground either via the satellite or via the VHF data-link or computer-generated voice, depending upon the aircraft equipment. Without providing any additional transmission equipment, the aircraft can make use of its surveillance pulse for signalling, since the ground system knows to 0.1 microsecond accuracy when to expect the next pulse. Such accuracy is possible in the face of crystal-oscillator inaccuracies and drifts in the one part per million range because the ground station has tracked the pulses for some time and has a better knowledge of the oscillator frequency,

even in the presence of Doppler shift, than does the aircraft. Thus, an intentional delay of the time of transmission of the pulse by a fraction of a microsecond is noticeable to the ground station and can be used as a specific message by the aircraft. One of several delays could be chosen by the use of a switch and command button on the airborne box and could correspond, for instance, to request for a navigation fix, acknowledgement of a transmitted message, and any other agreed signals.

### A3.5.4 Sizing of the Computation Requirements

As indicated above, Reference 4 applied safety factors of 12 to a particular computational algorithm for multilateration in order to determine the size of the computer necessary to track 50,000 aircraft simultaneously. In Reference 3, there is a more recent calculation, taking into account simplifications in position determination in order to reduce computational load. That same reference contains an analysis associated with the computational load due to the IPC function. For a system operational in 1978 or 1980, both calculations use estimates of cost and performance of 1975 large general-purpose digital computers. Total ground station equipment costs in Reference 3 are given as $0.3 million total for four tracking antennas, transmitters, receivers, etc.; $9 million total for three 1975 large general-purpose digital computers; and $2 million for one 1975 large special-purpose computer; totaling $11.3 million. These costs are additional to the building, timing, tracking, and ground station costs of the 621B navigation systems, which themselves are greater than would be required for an all-civil system.

For instance, the 621B navigation satellite, to work in the presence of jamming, must not depend on the existence of a surveillance up-link. Therefore, the precision orbit determination by "surveillance" of ground-emplaced aircraft-like transmitters is not available to 621B.

Some of the difference between the $11 million estimate of Reference 3 and the $80 million estimate of Reference 4 is due to different "safety factors" applied for overhead due to the software executive program, to writing in a high-level language, etc., but some is due also to an advance in the algorithm used for position determination and for IPC filtering. These differences are under investigation.

### A3.5.5 Minimization of the Cost of Airborne Equipment

Competitive design and production of airborne equipment in the free market place is probably the best assurance of low cost. Equipment manufacturers cannot, however, choose their own satellite system--they must design airborne equipment to fit a system defined by government leadership. Substantial differences in estimated costs at present are due in part to differing experience, and assumptions on the use of medium- and large-scale integration, as well as, at times, different assumptions about whether the navigation function, for instance, is performed on board with received signals or is obtained by relay of surveillance information via ground or satellite. However, for making a program decision it is necessary to estimate now the minimum cost of equipment which will be available to the airborne user in the 1978+ period. This requires a more fundamental approach than is often employed in cost estimating, and requires design and testing of several laboratory generations of developmental equipment in order that the techniques employed can be used as a basis for estimates of production cost, not necessarily by designers but by manufacturers who have proven their ability to compete in offering low-cost equipment to the general-aviation market.

A3.6 AN OCEANIC SATELLITE AIR TRAFFIC CONTROL SYSTEM TO SERVE AS A PRECURSOR TO A DOMESTIC SATELLITE SYSTEM

It is of interest to note that the candidate satellite system discussed here for air traffic control within the United States can provide, with a smaller constellation, important service to aircraft over the oceans. At the same time at which it is operating in this oceanic mode with degraded performance, the full performance of the ultimate satellite system can be realized and operational experience gained by the use of ground-based receivers along the shores, which for aircraft closer than 100 to 200 miles will allow a reasonable test of the operational nature of a full domestic system. Appendix 5 discusses in greater detail the needs of oceanic air traffic control.

For the small population of high-value aircraft involved in oceanic travel, there is no problem in the use of round-trip ranging, and there is time and spectrum available to allow each aircraft to transmit its altitude to the satellite on the reply. With altitude and range, rather than range differences and no altitude, only two satellites are necessary to provide normal two-dimensional navigation and surveillance information to the aircraft, as compared with the four satellites required for three-dimensional information in the candidate domestic system.

Such an oceanic system could use two stationary synchronous satellites, one of which polls the aircraft which have previously been assigned a standard time offset from receipt of the poll. If slots are spaced at ten millisecond intervals, a ten second poll will allow 1000 slots and receipt of the pulses at the satellites without possibility of overlap. The 579th aircraft, for instance, simply counts precisely 5.790000 seconds after it receives the poll and then transmits its surveillance pulse identical with that discussed for the domestic satellite system. This pulse is received by the two satellites and relayed to a ground center. The ground center determines the time of arrival at the two satellites, subtracts the offset of 5.79 seconds assigned to that aircraft, and thus knows the range from the satellites. The aircraft should have a surveillance aid capable of higher duty cycle than the domestic aircraft and can use this coded pulse, if desired, for transmission of altitude and identity information. In this way, the ground station would be able to determine position of the aircraft to an accuracy limited by the altitude uncertainty, which might be reflected in a 2000-foot error in position. The aircraft can readily receive its position information from the surveillance system, or it could carry the on-board computer described for the domestic role and determine its position instantaneously from ranging signals transmitted by the satellites.

As a third satellite is launched, the aircraft position can be determined for surveillance purposes either by dropping the requirement of polling or by eliminating the requirement to transmit altitude. A fourth satellite would convert the system into the domestic ATC satellite system described earlier in this Appendix.

Even with a single satellite, three shore-based ground stations near the busy terminus of the Atlantic air routes would provide substantial experience relative to a domestic surveillance and satellite navigation system. A satellite is required because ground-based receivers do not provide adequate accuracy of altitude determination.

## A3.7 USE OF NAVIGATION FOR INSTRUMENT LANDING

Typical ranging accuracy of about 40 feet rms in the candidate system is reflected in a position uncertainty on the order of 100 to 200 feet on a single pulse basis because of geometric dilution of position. Once an aircraft has a satellite navigation receiver computer on board, it can navigate very accurately with respect to satellite-like relays deployed on an airfield on which the aircraft

wishes to land. Analytical studies show that one or two transmitters deployed on such an airfield can result in accuracies of position location perpendicular to the runway on the order of 10 feet, comparable with that required for a high precision ILS approach. No scanning beam is required, and the transmitters are omni-directional, inexpensive, and, with the satellite system to aid in the determination of altitude, can probably serve for blind landing of conventional aircraft at airfields not equipped with any other kind of instrument landing system.

Aircraft not equipped with on-board navigation computers could have their position determined to ILS accuracy by such transceivers, and the position or the off-track errors transmitted to the aircraft by the local VHF data-link. This concept and the service thus provided should be explored in greater detail.

## References

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3. "Satellite Element for a Fourth Generation Air Traffic Control System," I. Rider, Aerospace Corporation Report No. ATR-71 (8109)-3; April 15, 1971.

4. Report of the Department of Transportation Air Traffic Control Advisory Committee, December 1969, Appendix D-1.

5. F. E. Nathanson, Radar Design Principles, McGraw-Hill 1969, pp 489 ff (Side Lobe Suppression of Phase-Coded Words).

6. S. C. Tseng, "Signal Multiplexing in Surface Wave Delay Lines Using Orthogonal Pair of Golay's Complementary Sequences," to be published in IEEE Transaction on Sonics and Ultrasonics (April 1971).

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# APPENDIX 4


## SATELLITE AIR TRAFFIC SURVEILLANCE AND NAVIGATION R&D PROGRAM AND PHASE-IN COMPARISONS


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APPENDIX 4

SATELLITE AIR TRAFFIC SURVEILLANCE AND NAVIGATION R&D PROGRAM
AND PHASE-IN COMPARISONS


INTRODUCTION

The satellite-based surveillance approach requires a development effort of special magnitude and complexity. Here a comprehensive RDD&E program for a representative satellite-based system is developed and this approach compared with a new ATCRBS in terms of phasing (both ground system and users) and life-cycle costs including R&D, capital and operation and maintenance (O&M) costs taken over a 15-year period.

A4.1 GOALS OF THE RESEARCH, DEMONSTRATION, DEVELOPMENT, AND ENGINEERING PROGRAM

Briefly stated, the RDD&E program must yield with high assurance the knowledge, techniques, equipments, and experience to permit a confident decision on the feasibility of a space-based surveillance system that would be acceptable to the full range of users while providing greatly improved service (both performance characteristics and reduced operations and maintenance costs) for the operating agency and the users. The final system concept should embody, if possible:

1. Good availability of surveillance position data during all modes of aircraft operation.

2. Low probability of system failure and quick restart.

3. Navigation capability acceptable to as broad a community as possible.

4. Two-way air-ground data-link with acceptable access properties and error rate. Hybrid data-link approaches, i.e., those having one or both paths independent of the satellite system are, of course, eligible.

5. A balance of subsystem complexity and costs among ground complex, avionics and space segment such that the sum of the following is minimized:

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a.  Capital expenditures for a new system.

b.  Transition period O&M costs due to overlap
    (satellite system, ATCRBS as well as certain
    navigation aids). This component is controlled
    strongly by transition period duration, which is
    directly related to user equipment cost and
    acceptance, particularly by general-aviation.

c.  Long-term system O&M costs, for ground complex and
    space segment.

## A4.2 DEVELOPMENT PHASES

A possible approach for achieving the above in a prudent but
aggressive fashion is shown in Figure 1 with a cost breakdown in
Table 1. The program would focus, early, on key areas in an
Exploratory Development Phase to (1) demonstrate conclusively
whether such a system concept is feasible and (2) provide a well
developed data base for further concept synthesis and refinement.
Assuming that such system concepts can be found that are
demonstrably feasible, completion of the RDD&E effort and initial
deployment could involve an expenditure of, perhaps, $250 million
over eight years. The output would be a tested system concept
(with some interim operating capability) or, at the very least, an
exhaustion of possibilities in a conclusive and orderly way at the
earliest possible time and at a cost of perhaps $50 million. In a
properly managed program, it would be highly unlikely to have a
major program failure beyond the design and verification stage.

### A4.2.1    Exploratory Development

An outline of this portion of the program is given in Table 2
with time phasing shown in Figure 2. The effort has been
categorized in five portions. Of these, the first three: (A)
Signal Design and Transmitter/Receiver Processing, (B) Satellite
Technology, and (C) Data Processing Methods are explored with the
hope of achieving significantly improved capabilities in these
areas, whereas the (D) and (E) areas require refinement and
verification. A major advance in any of the sub-categories under
(A) and (B) could have a significant effect on user equipment cost
and ground cost for both surveillance and data-link portions of the
system. For example, in (A), a substantial cost reduction in high-
power coherent waveform generation on the aircraft would allow the
use of codes having excellent properties in the presence of fading
together with rapid reacquisition. In satellite technology,

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development of multiple feeds for large-aperture antennas or optimum processing of large arrays could greatly reduce user equipment and ground system costs, both for communications and surveillance.

The exploratory development program could cost, roughly, between $30 and $50 million. A major portion is attributable to early satellite experiments. Fortunately, there is a large overlap in interest and program with both NASA and DoD. Satellites of the NASA ATS type as well as satellites proposed for defense navigation and tactical communications purposes could be shared for this work. The possibility exists of using oceanic ATC satellites as well, if they have a capability to operate in the 1000 MHz range. Indeed, early oceanic air traffic communications satellites can, with foresight and at little additional cost, be made entirely compatible functionally with later domestic ATC satellites which serve primarily for surveillance and navigation. This foresight would then be reflected in aircraft equipment which would be compatible with the future domestic satellite system and would yield valuable operational experience as indicated in Section 3.6. Similar cooperative arrangements might also be available in the satellite technology and aircraft antenna areas. The remainder of the exploratory development work is of a somewhat specialized study and simulation character, but of more modest cost. Of the total exploratory development effort, about $11 million might be assignable to the DoT/FAA.

The result of the exploratory development phase would be a greatly improved data base which would allow several viable system concepts to be synthesized and compared in the following phase.

### A4.2.2    System Design and Verification

The system design and verification phase would overlap the exploratory development phase and would proceed along several (perhaps three or four) parallel paths. At this time it would be speculative to label the various paths, each representing a system class. At present there are at least two concepts (see Appendix 3, e.g., the round-trip continuous pseudo-random noise method of Reference 1 and the pulsed one-way scheme of Reference 2, adopted as a candidate system in Appendix 3). Hybrid approaches are possible; and each of these could be divided into sub-branches according to the particular signal basis used (e.g., time-frequency hop, multiphase). Further, separate surveillance and data-link approaches could be combined, provided total user and ground cost is carefully evaluated together with system performance.

Using the common exploratory data available, each promising concept should be fully simulated and its cost and feasibility proven. This phase would also involve limited user equipment and ground system hardware construction.

The system design and verification phase would be complete when at least one of the concepts has been found to be sufficiently sound and promising, so that detailed prototype specifications could be written for ground, user, and spacecraft equipment.

A4.2.3    Prototype Development

This phase carries the most promising concept through full-scale testing. During the latter portion a minimally useful number of satellites would be launched. The anticipated 5-7 year satellite life would provide an interim operating capability following operational test; in this way the large expenditure for prototype development could be retrieved through operational use. Likewise, the ground complex might be constructed (including data distribution and conversion) sufficient to handle the operational test as well as a limited operating capability. Additional capacity and redundancy would be added as needed.

Table 1 provides an estimate of $167 million for prototype development and deployment of one concept of Satellite Surveillance and Navigation System. This one-way multilateration surveillance technique considered as a candidate system in Appendix 3, at present has the technical risk that the problem of finding adequate codes may not be solved in the exploratory development stage. The least-expensive user box for cooperative surveillance might cost $500-$1000 for the one-way system without data-link. Total RDD&E cost for this system is estimated as $236 million, resulting in an interim operational capability.

If a prototype DNSS were deployed, it appears likely that given adequate program coordination, satellite facilities for domestic civil navigation and ATC surveillance system could be incorporated for perhaps 10% to 20% increase in program cost. In that case, the total incremental satellite-related cost of satisfying ATC needs could be as low as $100 million through 1985, as contrasted with nearly $400 million if no DNSS were provided, or if it were delayed for a few years so that collaboration would not be possible.

A4.3 PHASE-IN COST COMPARISONS FOR TWO APPROACHES

The two most promising approaches to development of new data acquisition and air-ground data-link systems for the future are:

1. A new discrete-address ATCRBS which may or may not be compatible with present airborne transponders and present interrogators and has an air-ground data-link function.

2. A new satellite-based system, which provides a surveillance capability for all aircraft together with an independent ground-based VHF air-ground data-link, maintains the present ATCRBS airborne transponders until the satellite system is phased into service, but improves the ground-based interrogators as described in Section 3.2.2.2A, "Near-Term Improvements."

Tables 3 and 4 summarize the phasing assumptions for the two approaches:

## Approach 1: New ATCRBS Including Data-Link

This approach utilizes, exclusively, the new ATCRBS (superbeacon), for meeting the surveillance and all air-ground data-link requirements. The detailed phase-in plan (Table 3) assumes the following:

-- The low, moderate and high-service requirements are met using the appropriate level of new ATCRBS interrogator, if required in that time period.

-- If, in a given region of coverage, the service level increases and that region is already equipped with a new ATCRBS interrogator, a new higher-level ATCRBS interrogator must be installed but the ATCRBS interrogator already there may be employed at some other site now requiring the previous level of new ATCRBS service (i.e., conservation of new ATCRBS interrogator is assumed).

-- In new regions requiring coverage for the first time, a new ATCRBS interrogator will be installed even if the service level does not require it at the time.

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**Approach 2: Improved ATCRBS Interrogators with VHF Data-Link for the Near-Term, with Phaseover to Satellite System**

This approach depends on a near-term ATCRBS interrogator improvement program together with a VHF data-link capability, to enable a smooth phaseover to a satellite-based system by the early 1980's. The detailed phase-in plan (Table 4) assumes the following:

-- All requirements given in Table 3 for the pre-1980 time period are met utilizing improved ATCRBS interrogrators with VHF data-link. The appropriate level of improved ATCRBS interrogator is used in each case.

-- All regions requiring service for the first time are equipped with the improved interrogator system.

-- Transition to the satellite system begins in the late 1970's and continues until 1985 when all airborne users are assumed to be equipped with a satellite-system transponder and the ATCRBS interrogators are completely phased out. The beacon system continues in operation until 1985 at an annual O&M cost of about $20 million.

The phasing plans in Tables 3 and 4 have been used to estimate the overall system costs (exclusive of user costs) until 1985 for the two approaches. Table 5 summarizes the assumed costs for research, development, demonstration, and evaluation (RDD&E), capital costs (F&E) and operation and maintenance (O&M) for the two approaches. For example, the RDD&E for all the versions of the new ATCRBS has been estimated to cost about $40 million over 4 years. The capital costs for the three versions of new ATCRBS interrogator are estimated to be $3.0, $1.0, and $0.5 million per system (All three new interrogators provide discrete address and data-link capability, $3 million buying a 3-simultaneous-beam, electronically-scanned phased-array; $0.5 million buying a similar mechanical-scan system of lower data rate). Finally, the annual O&M costs for the three levels were estimated to be 10% of the capital costs. Similar estimates are made for the modifications needed to improve the beacon system to support the increased NAS/ARTS automation and to cope with the increased number of users while the satellite system is being developed and made operational.

The current ATCRBS interrogators have been assumed to cost $50,000 per year each to operate and maintain. These O&M costs are

applied to all current ATCRBS that remain in service in both Approach 1 and 2.

The improved ATCRBS costs cover development of the improvements ($10 million) discussed in Section 3.2.2.2A and the cost of modifying existing and future ATCRBS interrogators ($1.0 million, $0.5 million, and $0.25 million for the high, medium, and low density systems).

A VHF data-link based upon a subchannelized 1200 bit/sec link could be developed for $2-$3 million over two years with an expected cost for the ground station of $100,000. One of these stations would be installed together with each high density interrogator (e.g., 75 in 1985) to provide service comparable with Approach 1. Data-link service could be extended to the entire area where there is radio communication at a cost of some $80 million, thus facilitating extensive automation.

The satellite-based system might cost about $235 million to develop and perhaps $100 million to upgrade the development system into a fully operational system. The O&M costs of $45 million per year are based upon an assumed replenishment cost of $25 million per year and an additional $15 million per year to maintain the ground complexes. It should be noted that the replenishment cost could drop to $12 million annually, if the NASA Space Shuttle (Space Transportation System) program were operational at that time.

Based upon individual cost estimates in Table 5 and the phasing plans in Table 3, the yearly costs for Approach 1--new ATCRBS-based system--(Figure 3) indicate an annual expenditure of about $60 to $80 million and roughly a total of $800 million over the time period from 1970 to 1985.

Similarly, based upon the individual cost estimates of Table 5 and the phasing plan in Table 4, the overall costs for Approach 2--satellite-based system--(Figure 4) total about $950 million by 1985. Of this total, $100 million is for continued operation of ATCRBS in parallel with a completely functional satellite system in the period 1980-1985, and attention should be given to a more rapid phasing out of this redundant capability. Further, as suggested in Section 3.2.2.2B, if a DNSS were deployed, the additional cost of satellite capabilities for domestic civil navigation and surveillance would be only about 10-20% of that included in the $900 million figure above. Thus, still assuming and paying for parallel operation of ATCRBS through 1985, the cumulative cost for

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the satellite plus VHF-data-link plus improved ATCRBS approach
would be about $740 million through 1985 if the satellite were
supplied by a DNSS and only incremental costs (and all costs of
ground stations) were paid by the FAA.

A4.4 SUMMARY AND DISCUSSION

In summary, it appears possible that, in non-discounted
dollars, the new ATCRBS with data link would cost the government
about $50-150 million less than a space-based approach, in terms of
total dollars up to 1985. The O&M costs of the ATCRBS in 1985 are
about $40 million as compared to the $45 million of the satellite-
based system, but the service is not entirely comparable. As
indicated earlier, almost $210 million program cost could be pared
from the space-based approach by joint occupancy of satellites with
a DNSS, and $140 million more by a more rapid phase down of
redundant ATCRBS capability.

It should also be pointed out that for a short period before
1980, the new ATCRBS approach offers superior performance over the
improved ATCRBS (e.g., elimination of synchronous garble and better
resolution through the use of discrete-address), although the
satellite approach offers at a much earlier date improved beacon
data and wide use of data-link, and later a surveillance and
navigation system of better accuracy and coverage.

Lastly, cost to the user (particularly general-aviation) would
be an important consideration in making any decision between the
two approaches. A brief survey of the relative user equipment
costs shows that for Approach 1, new ATCRBS including data-link,
the general-aviation user cost would be $1000-1600 for the new
discrete-address transponder with air-ground data-link plus $500 to
$1000 for the altitude reporting capability, totaling some $1500 to
$2600, whereas for Approach 2, satellite-based system with VHF
data-link, the general-aviation user cost would be about $1500-
$2800 ($500 to $1000 for satellite surveillance transmitter box and
$1000 to $1800 for a new high capacity VHF data-link box).

The services available to the user and to the FAA are far from
comparable in the two approaches. The satellite system will make
available reliable precision surveillance down to ground level to
a properly equipped aircraft anywhere in the United States as early
as 1978, providing automatically, for instance, precision location
of downed aircraft and obviating the need for "crash-locator
beacons." The satellite system will likewise provide a uniform
navigation system universally available within the United States to

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air-carrier aircraft, of precision and reliability far superior to the VOR-DME which is the only planned FAA navigation aid. Availability of precision navigation-by-surveillance data on demand via the VHF data-link would make it _less_ expensive for general-aviation to install the VHF data-link than to buy VOR-DME on-board equipment. Navigation-by-surveillance could also be considered for the new ATCRES, but the coverage and accuracy would clearly not completely displace VOR-DME.

On the other hand, the superbeacon approach provides needed improvement in the densest areas at lower initial cost to the FAA. It will result initially in data-link being available only in those areas and may lead to a proliferation of data-links of different technology for other uses.

To decide _at_ _present_ to deploy a satellite surveillance and navigation system of the one-way type would be to assume a considerable technical risk which can be removed by the first two phases of the program defined in Table 7 at a cost to the DoT/FAA between $50 million (if no NASA or DoD help were forthcoming) and $25 million. To decide at present _not_ to deploy a satellite system in the near future would be to close the door to system flexibility and to deny benefits for which there is no counterpart in the competing systems.

TABLE 1

RDD&E FUNDING BREAKDOWN


EXPLORATORY DEVELOPMENT

A.  Signal design and transmitter/receiver
    processing                                            5 million*

B.  Satellite technology                                 10 million*

C.  Data processing methods                               5 million

D.  Aircraft antennas                                     5 million*

E.  Early satellite experiments                        _7-12_million

                                                       $30-40 million
                                                       ($35 million average,
                                                       including
                                                       $10 million DoT/FAA)



SYSTEM DESIGN & VERIFICATION


    Cost for   Per System Design & Verification
               Effort                                  _5-10_million

    Total Cost For the Verification of
               Two Concepts                            $10-20 million
                                                       ($15 million average)


*A great deal of overlap exists in those areas with NASA and DoD
programs, and assuming full cooperation, the cost assignable to the
DoT/FAA could be as low as $10 million.



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TABLE_1 (Continued)

PROTOTYPE_DEVELOPMENT_&_DEPLOYMENT*

Four satellites in orbit                                    $120 million

One computer complex usable
for IOC                                                       25 million

Ground signal processing,
usable for IOC                                                20 million

Data dissemination, to one en route
center, one high density terminal,
one low density terminal                                 ____2 million

                                                         $167 million


OPERATIONAL_TEST

User equipment production                               $ 1-  2 million

Test fleet costs                                           5- 10 million

Data reduction and analysis                               5- 10 million

Special ATC displays and equipment                      __1-__3 million

                                                        $12- 25 million
                                                        ($19 million average)


*In this category of Development and Deployment of a prototype
satellite-based data acquisition and navigation system, the costs
are indicative of a one-way multilateration approach as considered
in Appendix 3 of this Report. In the other three categories, the
cost ranges are due to uncertainty and to the desired degree of
assurance and optimization, rather than to a difference in system
choice. In the further use of these numbers, average values will

be used for the costs of Exploratory Development, System Design and
Verification, and Operational Test.

TABLE 2

EXPLORATORY DEVELOPMENT PHASE

A.  SIGNAL DESIGN & TRANSMITTER/RECEIVER PROCESSING   ($5 million)

    1.  Economic and reliable generation and processing of large time-bandwidth signals.

        a.  Oscillator stability/cost studies.

        b.  High power coherent transmitter techniques.

        c.  Matched-filter/correlator implementation.

    2.  Waveforms for comprehensive and reliable surveillance, communications and navigation.

        a.  Acquisition and ranging properties of time-freqency, multiphase and hybrid modulations (both pulsed and C.W.).

        b.  Codes and bases useful for polled and time-ordered communication.

        c.  Integrated (surveillance, data, navigation) modulation approaches.

B.  SATELLITE TECHNOLOGY   ($10 million)

    1.  Large in-orbit radio-frequency power.

        a.  Methods of long-term generation.

        b.  Power dissipation techniques.

    2.  Antenna system studies

        a.  Multiple large-aperture antennas.

        b.  Optimum processing and steering of antenna arrays.

C.   EFFICIENT DATA PROCESSING METHODS ($5 million)

1.   Surveillance and communication

    a.   Multilateration computation.

    b.   Optimal tracking.

    c.   Data filtering methods.

    d.   Message decoding and error correction methods.

    e.   Anti-jamming detection and rejection.

2.   Data Distribution.

    a.   Study of data network organization.

    b.   Channel capacity requirements analysis.

3.   Large Scale Computer reliability analysis and  redundancy
     techniques.

D.   AIRCRAFT ANTENNAS   ($5 million)

1.   Development of wide-coverage high-gain antenna types  and
     subsystems.

    a.   Analytical and scale modeling of patterns.

    b.   Analysis of pattern variation.

    c.   "Usable satellites in view" simulations.

    d.   Spatial diversity techniques.

2.   Installation feasibility/cost analysis.

3.   Measurement program (see satellite experiments).

E.   EARLY SATELLITE EXPERIMENTS   ($7-$12 million)

1.   Calibration techniques

a.  High altitude satellite tracking and orbit smoothing.

b.  Development and experimental validation of ionospheric error model and correction methods.

c.  Development and experimental validation of tropospheric correction methods.

d.  L-band scintillation effects measurement.

2.  Satellite-aircraft link experiments.

a.  Multipath.

b.  Received signal variation.

TABLE 3

PHASING PLAN FOR NEW ATCRBS -- APPROACH #1

| SERVICE LEVEL | NUMBER OF INSTALLED ATCRBS SYSTEMS | | | | | |
|---|---|---|---|---|---|---|
| | 1975 | | 1980 | | 1985 | |
| | NEW | TOTAL IN-SERVICE | NEW | TOTAL IN-SERVICE | NEW | TOTAL IN-SERVICE |
| LOW-DENSITY | 0 | 100 | 60 | 140 | 190 | 190 |
| MODERATE DENSITY | 0 | 90 | 100 | 100 | 110 | 110 |
| HIGH DENSITY | 25 | 25 | 35 | 35 | 75 | 75 |
| TOTAL SYSTEMS | 25 | 215 | 195 | 275 | 375 | 375 |

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TABLE 4

ATCRBS PHASING PLAN FOR NEW SATELLITE SYSTEM -- APPROACH #2

| | NUMBER OF INSTALLED ATCRBS INTERROGATOR SYSTEMS | | | | | |
|---|---|---|---|---|---|---|
| SERVICE LEVEL | 1975 | | 1980 | | 1985 | |
| | IMPROVED | TOTAL IN-SERVICE | IMPROVED | TOTAL IN-SERVICE | IMPROVED | TOTAL IN-SERVICE |
| LOW-DENSITY | 0 | 100 | 50 | 140 | 0 | 0 |
| MODERATE DENSITY | 0 | 90 | 100 | 100 | 0 | 0 |
| HIGH DENSITY | 25 | 25 | 35 | 35 | 0 | 0 |
| TOTAL SYSTEMS | 25 | 215 | 185 | 255 | 0 | 0 |

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TABLE 5

BASIC SURVEILLANCE COSTS ($ MILLIONS)

| SYSTEM | | RDD&E | | CAPITAL PER FAC. | O & M PER FAC./YEAR |
| | | TOTAL $ | YEARS | | |
|---|---|---|---|---|---|
| NEW ATCRBS | H | ↑ | ↑ | 3. | .3 |
| WITH DATA | M | 35 | 4 | 1. | .1 |
| LINK | L | ↓ | ↓ | .5 | .05 |
| CURRENT ATCRBS | | -- | -- | -- | .1 |
| IMPROVED | H | ↑ | ↑ | 1. | .05 |
| ATCRBS | M | 10 | 1 to 2 | .5 | .05 |
| | L | ↓ | ↓ | .25 | .025 |
| VHF DATA LINK | | 2-3 | 2 | .1 | .01 |
| SATELLITE SYSTEM WITH DATA-LINK | | $236 | 6-8 | $100 total | 40 total |

FOR APPROACH #1

FOR APPROACH #2

FIGURE 1

SURVEILLANCE RDD&E PROGRAM

$30-40 million

EXPLORATORY DEVELOPMENT

$10-20 million

SYSTEM DESIGN &
VERIFICATION

$165 million

PROTOTYPE DEVELOPMENT
& DEPLOYMENT

$12-25 million

OPERATIONAL TEST

0     1     2     3     4     5     6     7

YEARS

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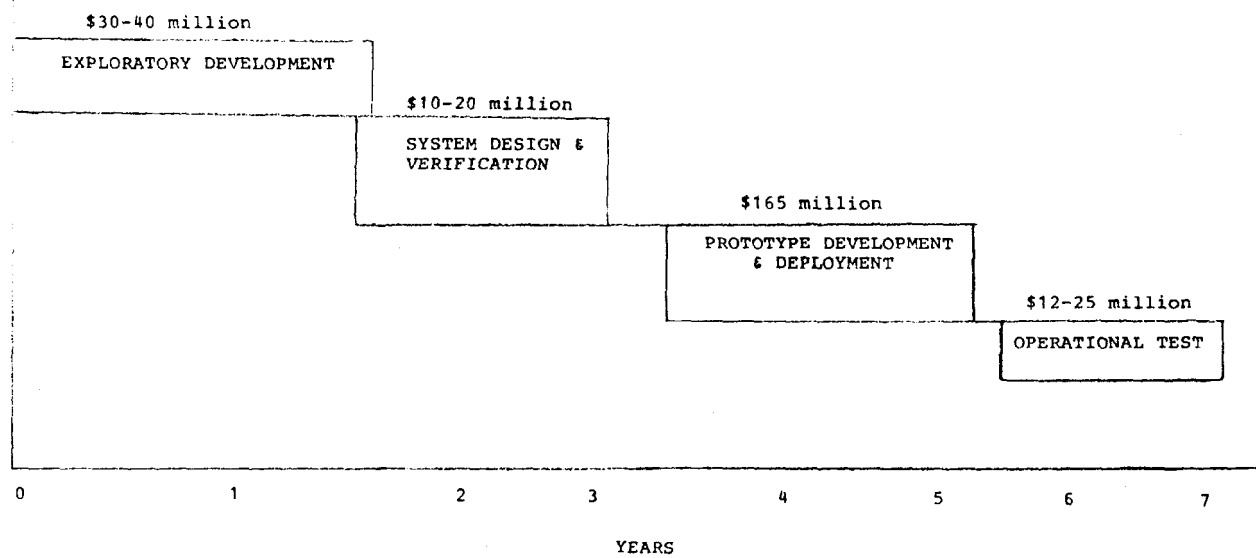
# FIGURE 2

## EXPLORATORY DEVELOPMENT PHASE*

| | | | |
|---|---|---|---|
| A. Signal Design and Transmitter/ Receiver Processing | $1 million | $3 million | $1 million |
| B. Satellite Technology | $3 m | $3 m | $3 m |
| C. Data Processing Methods | $1 m | $3 m | $1 m |
| D. Aircraft Antennas | $2 m | $2 m | $1 m |
| E. Early Satellite Experiments | $2-5 m | $5-10 m | |
| | 1 | 2 | 3 |
| FUNDING | $9-12 million | $16-21 million | $6 million |

*Considering NASA and DoD interests and possible programs, the FAA share of this total might be reduced to some $10 million.

FIGURE 3

COSTS:  NEW ATCRBS INCLUDING DATA-LINK

FIGURE 4

COSTS: IMPROVED ATCRBS WITH VHF
DATA-LINK + SATELLITE SYSTEM INCLUDING DATA-LINK

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APPENDIX 5


OCEANIC AIR TRAFFIC CONTROL
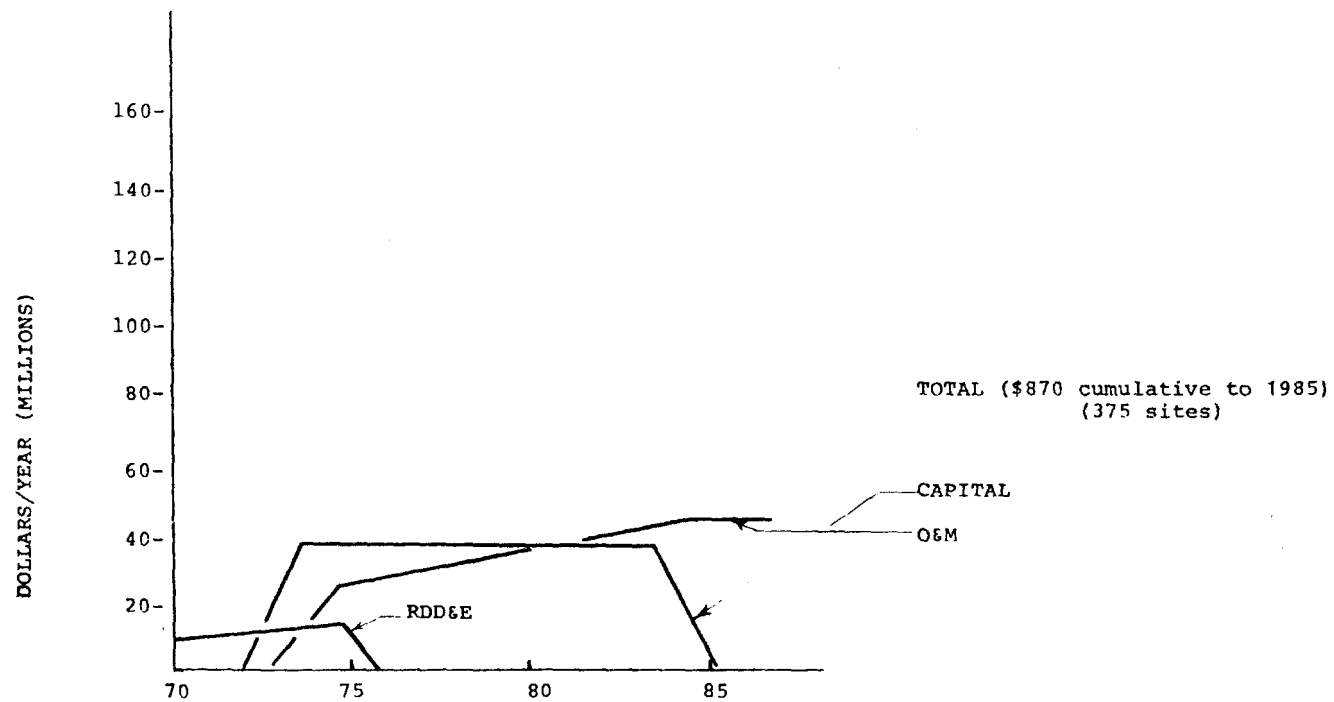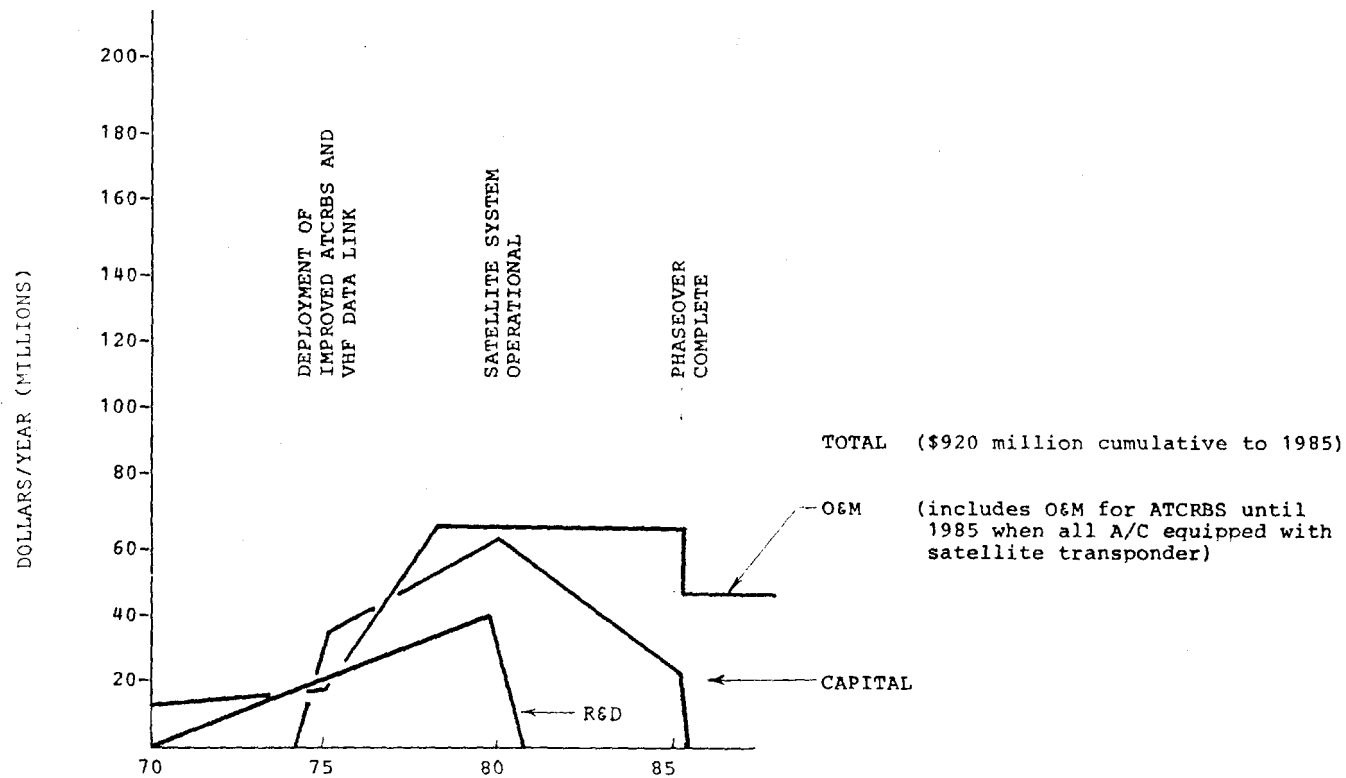

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OCEANIC AIR TRAFFIC CONTROL

## A5.1 PRESENT SITUATION

The advent of long-range, high-speed jet transport and the resulting growth in air traffic over the ocean have increasingly stressed ATC procedures and communications in these areas. As an example, in the North Atlantic air traffic flows along parallel multi-altitude routes terminating at Gander, Newfoundland, and Prestwick, Scotland. East-West flow and West-East flow are assigned on routes North and South, respectively, of a daily established datum line corresponding to a nominal minimum-time route (determined by weather conditions, primarily wind).

Aircraft are beyond surveillance coverage except near the start and finish of passage. Position reports are unavailable for roughly an hour to an hour and a half depending on current VHF and HF radio conditions, and when received reflect navigation system drift plus pilot error. These factors have led to conservative separation procedures on the over-ocean portion of these routes.

Projected peak traffic insertion rates for the 1973 period are 50 aircraft per hour, sustained for approximately six hours. The average flight time penalty incurred using the existing route structure will amount to roughly thirty minutes during these peak traffic periods. The resulting economic penalties due to added fuel consumption and revenue loss incurred by fuel-displaced cargo have been estimated at $100 million over the peak summer months of 1973. Losses due to reduced productive utilization of aircraft and crews contribute at least as much.

Higher traffic density on the low-flight-time routes can recoup a significant percentage of these losses, but greater utilization of the "best" routes can be achieved only through some method of control based on surveillance (central or otherwise), reliable communication and navigation of accuracy suited to the spacing, through use of inertial systems, Doppler, improved radio aids, or some combination thereof.

The formulation of ATC concepts and development programs for oceanic employment is clearly simpler than for the continental United States, since (a) user density is low, (b) user population

can support more costly equipment, and (c) the oceanic "control system" presently in being is simpler and more easily modified than the domestic system; thus a fresh approach is not penalized on grounds of incompatibility or of outmoding present investment. On the other hand, the oceanic system can serve as a test-bed for CONUS-capable systems, and the extent to which it should do so must be decided soon.

## A5.2 POSSIBLE ROUTE STRUCTURES

Considering again the North Atlantic, one can conceive of multiple non-parallel routes from many (rather than single) terminal points on each coast. This more general approach could certainly be utilized with the advent of improved oceanic air traffic control. However, closer spacing on the existing parallel route structure can in itself provide greatly increased capacity, realizing most of the cost savings. For example, the present plan to interleave nearby routes and reduce altitude separation from 2000 to 1000 feet and route spacing assignments to 60 nm rather than 120 nm would improve capacity on a given route and thereby reduce the incremental cost penalty for those users overflowing the central-most routes.

## A5.3 CONTROL CONCEPTS

Control techniques may be grouped into two classes depending on air-derived control commands (aircraft-managed systems) or on ground-generated commands. Hybrid techniques, or control via one system with backup provided by the other, may be desirable to achieve a reasonable balance between user equipment complexity and safety. More probably, a replicated system would require less change in operation on switchover to the backup system.

- Aircraft-Controlled

  In this concept, aircraft route assignment and sequencing would be initially established by ground control centers at each end.

  A station-keeping function would be provided by a between-aircraft ranging and data-link system. This element plus navigation with low cross-track error would provide the control function. No central surveillance subsystem would be involved although flight progress might be reported via a satellite communication link.

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Navigation would be via passive navigation satellite and/or Doppler/inertial systems.

- Ground-Controlled

    The addition of a surveillance function (independent of other subsystems or not) would allow generation of spacing and warning commands in a central computer. The ground central computer would process flight plans, perform sequencing and routing of aircraft, determine position and issue control commands and advisories. Further, overall surveillance would permit improved estimates of upper-air wind conditions. Each aircraft would be equipped with a navigation satellite receiver and/or Doppler/inertial system and interface equipment for satellite communications and surveillance.

    For this multiple-aircraft control problem, work is needed to relate the allowable deviation from flight plan before corrective action must be taken to the surveillance interval, surveillance accuracy, navigation accuracy and system delay.

    Stability of the control system from the viewpoint of the users, under all conditions of wind and subsystem failure, must be guaranteed for the close-spaced route-structure concept discussed earlier.

    Design of the specific control strategy and cooperating subsystems are dependent on (a) time selected for employment, and hence the level of technology usable (e.g., space-based power, aircraft antennas and knowledge of the ionosphere); and, perhaps most importantly, (b) the degree of international and interdepartmental agreement needed.

## A5.4 SUBSYSTEMS

Given a specific control strategy, there is interaction among requirements for surveillance, communication and navigation. For example, less-frequent surveillance update rate necessitates more stringent control of navigation errors. Cost tradeoffs (including O&M) must be considered across all three subsystem areas, including user equipment. Choice of best subsystem parameters is complicated not only because requirements interact but, in the case of

subsystems which share common components, subsystem designs interact.

- Surveillance: For oceanic use, an adequate surveillance system need have only moderate accuracy (0.5-1.0 nm) and modest update rate (1-5 minutes). Surveillance should be nearly independent of on-board equipment. Practically, the choice is limited to various space-based systems. Further, if full-time, geographically-limited coverage is required, synchronous satellites are most economical. The choices are a roll-call system (in which round-trip ranging or transmission of computed position by the user is accomplished on command from the ground) or a free-running relative-arrival-time system. The final choice should be based not only upon total user and satellite system equipment cost, including communication and navigation elements, but also upon contribution of the operational oceanic system to techniques needed in domestic air traffic control. Indeed, Appendix 3 (Section A3.6) describes an example in which on-board equipment is gradually simplified and reliability improved as additional satellites are deployed, although both navigation and surveillance are obtained from the first two satellites.

  Key technological factors are the degree to which ionospheric error may be corrected at VHF frequencies, comparative antenna problems at UHF and VHF, and launch vehicles available in a given weight range.

- Communications: For effective air traffic control, both conventional voice as well as digital data-links will be required, with reasonable access time (several seconds) in both directions for a relatively small aircraft population (several hundred). In addition, it would be desirable to supply limited marine channels. A limiting factor in the communication area is the ability to design high-power spacecraft which have a long mean-time-to-failure. Greater satellite power will allow more communication channels with user equipment of a given quality (cost) or will give the same capacity using somewhat cheaper user equipment (receiver and antenna). However, satellite costs and launch costs depend primarily upon satellite transmitter power requirements, and these costs can be significant considering the small user population. The choice of operating frequency is

also important because of variations in propagation characteristics at different frequencies. Further, multipath problems may be of importance, particularly at low elevation angles, and close attention must be paid not only to choice of carrier frequency but also to modulation techniques.

- **Navigation**: It has been traditional that pilot flight-plan-following (navigation) should be independent of any elements used for ATC flight monitoring (surveillance). Use of current inertial systems (1-2 nm/hour drift) will provide sufficient accuracy to allow reasonable flexibility in specification of surveillance and communication elements. However, synchronization signals from space-based surveillance elements can be used for highly accurate passive navigation. Even if such fixes were used infrequently during a flight, they could greatly ease the stability and/or maintenance requirements of inertial or Doppler navigation components. Further study is required to understand the impact on ATC reliability of common, highly-reliable satellite navigation and surveillance elements which would allow elimination of expensive inertial systems and their replacement by strapped-down smoothing systems.

## A5.6 DISCUSSION

The RDD&E and operational employment of a new oceanic ATC system needs to be carried out in close consort with the program for domestic air traffic control if money to be saved in RDD&E and experience to be gained from the oceanic system is to be applied to design of a domestic system.

Further, needs of the various anticipated user groups should be determined to guide: (1) the overall design and cost of the system; (2) the sharing of development, production, launch, operations and maintenance costs of the space segments of the system; and (3) management and budgeting.

There are several technically satisfactory and cost-effective approaches to oceanic air traffic control. Since any of these solutions will save airlines far more than the sum of the costs of required on-board equipment and satellite system, the choice among detailed concepts should weigh

-- earliest date of operational capability,

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-- the degree to which on-board equipment and satellites will contribute to the choice and early operational capability of a domestic ATC system,

-- utility of on-board equipment for use in a future domestic ATC system, and

-- minimization of overall costs.

TERMS OF REFERENCE
FOR THE
PSAC AD HOC AIR TRAFFIC CONTROL PANEL

The Panel will review the present status of the ATC system and the program of the FAA to upgrade it. It will review the recommended program of the ATCAC and the DoT and FAA time-phased implementation plan for that program.

The Panel will independently review the validity of the approach recommended by the ATCAC. Beyond that, with the help of the DoT and the FAA, it will attempt to estimate the cost of program implementation and continued manning for the ATCAC recommended program.

The ATCAC program is an evolutionary program. In contrast to this evolutionary approach, the ATCAC noted the existence of revolutionary approaches, which, if sufficiently desirable and inexpensive, might be instituted independently of the present NAS, allowing a change-over at some time in the future. The Panel will attempt to identify one of the best of such revolutionary approaches and will determine a time-phased implementation, together with costs and benefits.

The purpose of this second approach is to determine whether the evolutionary approach, although feasible, might not imply much higher costs through the 1980's than a revolutionary approach. If this were true, then it might be desirable to proceed as well on the more revolutionary approach.

The Panel will review the potential for V/STOL aircraft and their interaction with the projected ATC system in order to determine whether a combined ATC-V/STOL approach has merit for solving real problems of the air transport system.

The Panel will review the needs and programs of the Department of Defense which bear upon air traffic control in order to

determine the relationship among the future air traffic control of military aircraft, air-carriers, and general-aviation.

A review of relevant NASA resources and programs will also be made to determine the potential contribution of NASA to the timely solutions of the ATC problem within reasonable cost.

APPENDIX 7


A PROPOSAL FOR A NEW EXECUTIVE AGENCY
WITHIN THE DEPARTMENT OF TRANSPORTATION


The sole mission of a new Executive Agency would be to define and carry out the ATC improvement program. The Agency would be staffed by people from the FAA, DoT, and the Transportation Systems Center, as well as by new employees, and would include extensive contractor support. The Director of the Agency should report directly to the Office of the Secretary of Transportation, to ensure the appropriate level of authority and responsibility. We believe that such an organization would have a high probability of success. One of its major advantages would be flexibility in staffing key positions, a need which has been noted by the Blue Ribbon Panel in connection with the DoD, and by the House Government Activities Subcommittee.

The Executive Agency would be responsible for planning and directing the overall development effort for a system of improved airports and airways. It would obtain support for its purchasing, accounting, etc., from within the DoT, providing satisfactory response time can be achieved. All decisions would occur within the Executive Agency. Costs, training, and operational problems associated with phase-over to the new system would be a primary concern during systems design.

The Agency's Director would have a staff of technical and administrative assistants, along with authority to procure both in-house and outside support, using streamlined contracting procedures. An organization of this type would be highly effective because of centralization of both program and fiscal control without multiple layers of management. Its authority to disburse funds, as contrasted with annual budget review by a staff organization, would shorten the time required for the improvement program. Its responsiveness would be assured by the requirement that its Director report to the Office of the Secretary of Transportation. The Agency would be aided by a Technical Advisory Committee and a User Advisory Group, to be described in later paragraphs.

The Executive Agency would require a highly competent technical staff of sufficient size to perform the functions

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outlined in Section 4.3 below, including procurement of in-house and outside support, encompassing development, test, and evaluation. All personnel assigned to the Agency would work full time on the project with no other assigned tasks. The Agency's Director would have delegated authority, granted to the Secretary of Transportation by the Airport and Airway Development Act of 1970, to negotiate certain purchases and contracts (with annual ex post facto reporting to the Congress).

Rapid reaction by other organizations to requests of the Executive Agency could be assured by providing it with funds which could be transferred to other agencies or departments of the government. In this way, one could avoid the budgetary and reprogramming process in these other departments in support of what is essentially a responsibility of the DoT. In the use of internal governmental resources within DoT or DoD, the Executive Agency could fund this effort under specific task orders, and provide technical direction for the effort by an appropriate monitoring and review mechanism. The Executive Agency might contract with a technical organization which would have the major responsibility for system engineering and integration. Subsystem feasibility investigations and advanced development and demonstration would be contracted to industry, universities, and non-profit organizations as well as to government laboratories.

### A7.1      Technical Advisory Committee and User Advisory Group

A project organization of the type recommended in this section is desirable when there is a well-defined task of critical importance. Since such an organization would lack some of the normal bureaucratic checks and controls, special means are needed to ensure that the project is conducted in an effective and responsive manner. For this purpose, the Panel suggests that a Technical Advisory Committee be established to serve the Director of the Executive Agency and the Secretary of Transportation. This Advisory Committee would consist primarily of technically competent individuals with understanding of air traffic control as well as experience in managing large complex programs. The Committee would have a strictly advisory function in providing support to the project management by assessing recommended options as well as technical status and back-up efforts in case of contingencies. The Technical Advisory Committee could meet two days, bimonthly, with the project management. In addition, semi-annual meetings with the Secretary of Transportation could be held to bring to his attention necessary actions for him to take        --or to request of higher authority--in connection with demands of, or on, other

agencies or departments within the government. The Technical
Advisory Committee, together with the normal staff of the Secretary
of Transportation, would provide him continuing assurance of the
adequacy of his national stewardship in the ATC field.

The project will have to operate very openly, with full
realization that a single program will evolve which will certainly
not satisfy all the preferred ideas or existing capabilities of
different users or suppliers. A mechanism is necessary to allow
the views of outside organizations to be heard by the head of the
project. Therefore, in addition to the Technical Advisory
Committee a User Advisory Group with responsible technical
membership from affected user organizations should be established
and should report to the head of the project. User groups clearly
affected by air traffic control and its evolution are

(a) the ATA (Air Transport Association) and the ALPA (Airline
Pilots Association), both representing the air carriers,

(b) the AOPA (Aircraft Owners and Pilots Association) and the
NBAA (National Business Aviation Association)
representing the general aviation sector,

(c) the DoD, representing the military,

(d) AOCI (Airport Operators Council International)
representing the airport operators, and

(e) the ICAO (International Civil Aeronautics Organization).

To the extent that these groups can set up counterpart full-time
project organizations, they can provide useful liaison with the
project to assure that views of the operators are considered during
design and development of changes to the system.

A7.2    Advantages_of_the_Proposed_Organization

On the basis of its experience with similar tasks, the Panel
believes that the present FAA and DoT organization, despite recent
modifications, may not be appropriate for the job of designing,
developing, and deploying an effective and economical ATC system by
1980. Of the alternatives considered, the Panel has confidence
that a new Executive Agency, established by Presidential direction
within the DoT to carry out a task of national importance and
provided with streamlined fiscal and mangement tools, would
accomplish the task. The Executive Agency would have the

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advantages of national prominence and strong executive authority as a result of its high organizational status. With a strong executive director, and with the charter and reporting channels described above, it could do the job essential to continued operability and growth of air transport.

# GLOSSARY

| | |
|---|---|
| Addressable Beacon | An airborne radar beacon or transponder which responds to a discrete address transmitted by an interrogating radar. |
| Air Carrier | An aircraft or organization certified by the FAA for the purpose of carrying goods or persons commercially by air. |
| Air Traffic Control (ATC) | A service that promotes the safe, orderly, and expeditious flow of air traffic, including airport approach and enroute air traffic control. |
| Approach Sequence | The order in which aircraft are positioned while awaiting approach clearance or while on approach. |
| Area Navigation | Two-dimensional navigation using VOR/DME or other references. |
| Automatic Radar Control Terminal System-- Third Generation (ARTS III) | A partially-automated data processing and display system that is being added to existing terminal equipment. |
| Block Times | Total time allocated to travel from gate to gate including any expected delays. |
| Category I Weather (CAT I) | Weather allowing a forward visibility of 1/2 mile.  Under Category I, the pilot should be able to see the runway from an altitude not in excess of 200 feet. |
| Category II Weather (CAT II) | Weather allowing a forward visibility of 1/4 mile.  The pilot should be able to see the runway from an altitude not in excess of 100 feet. |
| Category III Weather (CAT III) | Runway effectively not visible from any altitude and all landing decisions are left to the pilot.  Category III breaks down into three subcategories: |

IIIA.  Forward visibility is 700 feet,
a distance sufficient for a landing abort.
IIIB.  Forward visibility is 150 feet,
a distance sufficient to permit taxiing.
IIIC.  Zero forward visibility.

Chip
In an internally coded pulse, an element
of constant frequency and amplitude.
Thus one might speak of a bi-phase coded
pulse of 511 0.1-microsecond chips (total
pulse duration 51.1 microseconds) in
which each chip has the same amplitude
and frequency but represents a choice of
carrier phase either plus or minus.

Collision Avoidance
System
   (CAS)
A device that can warn of the presence
of other aircraft similarly equipped,
assess a potential collision hazard,
and provide appropriate command signals
indicating the proper evasive maneuver.

Controlled Aircraft
Aircraft participating in and receiving
traffic separation service from the ATC
system.

Controlled Airspace
Defined region in which FAA may carry out
a control function, specifically traffic
separation service.  It may contain
controlled and uncontrolled, i.e, VFR
aircraft.

Controlled Visual
Flight Rules
   (CVR)
Visual flights in which avoidance of
collision with all other aircraft is
assured by the ATC system.

Corner Reflector
A retrodirective reflector that reflects
radio energy back to the source along the
incident path for a range of angles of
incidence.

Data Link
Any communication channel or circuit used
to transmit data from a sensor to a

|  | computer, a readout device, or a storage device. |
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| DECCA Navigation | A form of hyperbolic navigation using low-frequency continuous-wave signals in which a master station normally operates with two slave stations. |
| Discounted Present Value | Dollar amounts, A, of benefits or costs N years hence are reflected in present value as A exp(-ND), where D is the annual discount rate of say 0.10(10%). |
| Distance Measuring Equipment (DME) | Airborne and ground equipment used to allow an aircraft to measure its distance from a radio navigation aid. |
| DME Fix | A geographical position determined by reference to a radio navigation aid that provides distance and azimuth information; this position is defined by a specified distance in nautical miles and a radial in degrees referenced to magnetic North from that aid. |
| Dual-Lane Runway | As described in the ATCAC Report, a pair of runways a few hundred feet apart, one used exclusively for takeoffs and the other for landings. The sequencing of takeoffs and landings in this way is more efficient than on a common runway. |
| EPNdB | Effective Perceived Noise Level measured in decibels. A unit which has been defined to provide a scale for judging aircraft noise which includes weighting factors for both duration and discrete tones. |
| Flight Service Stations (FSS) | A facility operated by the FAA to provide flight assistance service. |

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| Fourth Generation System | A future ATC system, not yet defined, to supplant the Third Generation System that was recommended by Project Beacon in 1961 and is now being implemented. |
| General Aviation | All aircraft that are neither military nor commercial aircraft. |
| Glide Slope | Vertical guidance portion of an instrument landing system used to establish a desired angle of descent during final approach. |
| Instrument Flight Rules (IFR) | At present, flight in which the ATC system assures collision avoidance between aircraft operating in accordance with IFR and CVR in Positive Control Airspace. Pilot responsibility with respect to collision avoidance differs according to flight weather conditions. |
| Instrument Landing Systems (ILS) | A runway approach system for unfavorable weather conditions consisting of equipment both on the aircraft and on the ground: the localizer, which broadcasts an electronic extension of the runway; the glide slope, a signal which defines the altitude limits within which the aircraft must be for proper approach; and the extended centerline marker signal. |
| Intermittent Positive Control (IPC) | A control concept in which aircraft are advised of threats due to other aircraft, weather, airspace boundaries, and surface obstacles, and given commands for appropriate evasive maneuvers. This service could be provided to both controlled and uncontrolled aircraft. |
| L-Band | A band of radio frequencies extending from 390 to 1550 Mega-Hertz. |
| Mixed Airspace | Airspace containing aircraft flying |

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| | under either VFR or IFR. |
| Modem | An electronic apparatus used for modulation and demodulation; that is, the conversion of signal levels designating zeros and ones into a form suitable for radio transmission, such as phase-shift signaling, amplitude modulation, frequency modulation, etc. |
| Monopulse | The use of sum and difference patterns to obtain on a single pulse a measurement of the angle off-boresight. |
| Multipath | Electromagnetic energy arrival at a receiver via indirect path(s) from the source as a result of reflections from either the ground or from other external reflectors such as another aircraft, an aircraft's own structure, or buildings. |
| NAS Stage A En Route System | A partially-automated system of en-route ATC providing alphanumeric information on en-route radar displays and flight data processing. |
| Parallel Runways | As described in the ATCAC report, two independent IFR runways separated by 2500 feet (at present 5000 feet). |
| Phased Array | An antenna having a beam that can be electronically scanned in azimuth or elevation. |
| PNdB | Perceived noise level measured in decibels. A measure of aircraft noise weighted for the sensitivity of the ear at various frequencies but not for discrete tones or duration of the signal. |
| Positive Control | Provision of assured separation service between all aircraft. |

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| Primary Radar | The form of radar that depends upon the reception of reflected electromagnetic energy for the detection of objects in the area under surveillance. |
| Proximity (Pilot) Warning Indicator (PWI) | A pilot warning instrument which, in its most simple form, is an airborne device whose function is to warn a pilot of the proximity of other aircraft. It may also provide other information to assist the pilot in evaluating the situation, such as relative bearing and bearing rate of other aircraft, relative altitude, range, or combinations of these parameters. |
| Radar Beacon | A radar receiver-transmitter that transmits a coded signal whenever its receiver is triggered by an interrogating radar. The coded reply can be used to determine position in terms of range and bearing from the beacon. Also called beacon or radar transponder. |
| Rho-Theta System | A navigation system based on azimuth (theta) and range (rho) relative to a fixed point. |
| Short Takeoff and Landing (STOL) | Aircraft that have performance characteristics allowing use of considerably shorter runways than standard fixed-wing aircraft. |
| Strategic Control | Strategic control of an aircraft by ATC implies permission to fly a complex, precisely-specified flight path. ATC retains responsibility for authorizing, modifying, and monitoring compliance by the aircraft in executing the agreed flight path. A specified flight path may include the complete trajectory with 10-20 precise three-dimensional |

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|  | way-points.  Responsibility for executing the agreed flight path would remain with the pilot of the aircraft. |
| TACAN | A radio navigation system providing range and bearing information from a ground station to properly equipped aircraft. |
| Tactical Control | Control of an aircraft flight path through a series of commands, each guiding the aircraft through a short segment of its intended flight. |
| Terminal Area | Airspace and surface area within a pre-designated boundary and up to a pre-designated altitude above the surface surrounding one or more airports. |
| Third Generation System | The semiautomatic ATC system recommended by Project Beacon in 1961 and now being implemented. |
| Transponder | See radar beacon. |
| Trilateration | A system by which an aircraft is located by measuring its distance from three separate known locations. |
| Ultra High Frequency | A band of radio frequencies extending from 300 MHz to 3 GHz. |
| Uncontrolled Aircraft | Those aircraft not participating in or receiving traffic separation service from the ATC system. |
| Uncontrolled Airspace | Airspace outside the airways, positive controlled airspace, terminal and special purpose areas. |
| Vertical Takeoff and Landing (VTOL) | Aircraft which have performance charac-teristics permitting vertical or almost vertical takeoffs, landings, and climb |

|  | and descent angles. |
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| Very High Frequency (VHF) | A band of radio frequencies extending from 30 to 300 MHz. |
| Very High Frequency Radio Omnirange (VOR) | A radio navigation aid providing bearing information relative to the VOR station to properly equipped aircraft. |
| Visual Flight Rules (VFR) | Flight in which avoidance of collision with other aircraft is dependent upon every pilot seeing other aircraft and avoiding them. |
| VOR | VHF omnirange equipment providing bearing from the VOR referenced to magnetic North to properly equipped aircraft. |
| VORTAC | An air navigation system combining VHF omnirange (VOR) and TACAN equipment. |

## LIST OF ABBREVIATIONS

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| AIAA | American Institute of Aeronautics & Astronautics |
| ALPA | Air Line Pilots Association |
| AOCI | Airport Operators Council International |
| AOPA | Aircraft Owners and Pilots Association |
| ARINC | Aeronautical Radio, Inc. |
| ARTS III | Automatic Radar Control Terminal System, Third Generation |
| ATA | Air Transport Association of America |
| ATC | Air Traffic Control |
| ATCAC | Air Traffic Control Advisory Committee, Department of Transportation |
| ATCRBS | Air Traffic Control Radar Beacon System |
| ATOL | Automatic Takeoff and Landing |
| ATS | Applications Technology Satellite |
| CAS | Collision Avoidance System |
| CONUS | The Continental United States |
| CTOL | Conventional Takeoff and Landing Aircraft |
| CVR | Controlled Visual Flight Rules |
| DEMO | Demonstration Metroliner and Turbotrain System |
| DME | Distance Measuring Equipment |
| DNSS | Defense Navigation Satellite Service |
| DoD | Department of Defense |
| DoT | Department of Transportation |
| EPNdB | Effective Perceived Noise Level measured in decibels |
| FAA | Federal Aviation Administration |
| FSS | Flight Service Station |
| HSRA | High Speed Rail "A" (150 mph) on existing right-of-way |
| HSRC | High Speed Rail "C" (200 mph) on new right-of-way |
| ICAO | International Civil Aviation Organization |
| IDCSP | Interim Defense Communication Satellite Program |
| IFR | Instrument Flight Rules |
| ILS | Instrument Landing Systems |
| IPC | Internmittent Positive Control |
| LES | Lincoln Laboratory Experimental Satellites |
| LORAN | Long Range Navigation |
| NAS | National Airspace System |
| NAVSAT | Navigation Satellite |
| NBAA | National Business Aviation Association |

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| PSAC | President's Science Avisory Committee |
| PVOR | Precision VHF Omnirange |
| RDD&E | Research, Development, Demonstration, and Evaluation |
| RDT&E | Research, Development, Test, and Evaluation |
| STOL | Short Takeoff and Landing |
| TACAN | Tactical Air Navigation |
| TACV | Tracked Air Cushion Vehicle |
| TVOR | Terminal VHF Omnirange |
| UHF | Ultra High Frequency |
| VFR | Visual Flight Rules |
| VHF | Very High Frequency |
| VOR | VHF Omnirange |
| V/STOL | VTOL and STOL |
| VTOL | Vertical Takeoff and Landing |

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