Chapter 5

TECHNOLOGY AND THE FUTURE EVOLUTION OF THE ATC SYSTEM

Photo credit: Federal Aviation Administration

Air traffic control

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Chapter 5

TECHNOLOGY AND THE FUTURE EVOLUTION OF THE ATC SYSTEM

INTRODUCTION

The present air traffic control (ATC) system has evolved over several decades from the one that was first put in place in the 1930's. The operational characteristics and organization of the original system were determined largely by the technologies then available—radio for navigation and air/ground communication, and telephone and teletype networks for distribution of information among ATC ground facilities. New technologies—such as surveillance radar, Air Traffic Control Radar Beacon System (ATCRBS) transponders, microwave relays, and electronic data processing—were added as demand increased and the state of the art progressed after World War II, but they did not change the essential characteristics of the earlier generation of air traffic control—a ground-based, labor-intensive, and increasingly centralized system.

Advanced data-processing and communication technologies have been introduced to meet the growing demand for ATC services* and to provide the controller with the information needed to make the decisions required for the safe and efficient movement of aircraft. However, these technologies were applied largely to improve the acquisition, integration, and display of information, or to speed its dissemination among ATC facilities. Recently, the automated transmission of certain types of information to pilots has also been introduced, e.g., weather and terminal area briefings. However, the making of ATC decisions and transmission of ATC messages have remained essentially a human function.

As the air transportation network grows and evolves in response to economic conditions, market forces, and changing Government regulation, the requirements for the ATC system will be affected in turn. In addition, new technological developments will make possible new functions and modes of operation that would have been impossible with older equipment and resources. The extent to which the system must grow depends primarily on the rate at which the level of air traffic and the demand for ATC services increase. There is considerable uncertainty on this score. The direction in which the system evolves will be influenced by what services are offered, how they are delivered, and how they are **paid for.** The answers to these questions, too, are subject to great uncertainty. Budgetary constraints and the continuing effects of the air traffic controllers' strike have introduced further complications. In addition, the evolution of the ATC system takes place slowly: some of the modernization programs now reaching fruition were first conceived a decade or more ago. During this period new technologies have become available, and there has been continuing controversy regarding the technical choices that will determine the character of the future ATC system.

This chapter presents an overview of some of the technologies and technological issues that are of concern in decisions that will soon be made about the future development of the ATC system. It is not a detailed treatment of the technological and engineering complexities of the subject, nor does it attempt to resolve any of the related economic and funding controversies. Instead, this discussion is intended to provide decisionmakers and the public with useful information about the implications of some of the advances in technology that have occurred or which are on the horizon. This information forms a background against which to assess FAA's 1982 revision of the National Airspace System (NAS) Plan.

* These technologies have also found use in the cockpit where RNAV and other systems have provided capabilities that have indirectly affected the ATC system.

GOALS AND SERVICES OF THE ATC SYSTEM

In order to accomplish the goals of safety, efficiency, and cost-effective operation, the present ATC system offers the following services to the aviation community:

- *separation* assurance—tracking aircraft in flight, primarily with surveillance radars on the ground and airborne transponders, in order to ensure that adequate separation is maintained and to detect and resolve conflicts as they arise;
- *navigation aids*—maintaining a system of defined airways and aids to navigation and establishing procedures for their use;
- *weather and flight information*— informing users of the conditions that may be expected along the intended route so they may plan a safe and efficient flight;
- *traffic management-processing* and comparing the flight plans, distributing flight plans to allow controllers to keep track of intended routes and anticipate potential conflicts, and ensuring the smooth and efficient flow of traffic in order to minimize costly congestion and delays; and
- *landing* services-operating airport control towers; instrument landing systems, and other aids that facilitate the movement of air traffic in the vicinity of airports and runways, particularly during peak periods or bad weather that might affect safety or capacity.

These services together comprise an integrated program, no part of which can be fully effective without the others. Flight plans must take into account weather and traffic, for instance, and traffic must be routed to destinations so that it arrives on time and can be handled at the airport with a minimum of delay. Similarly, clearances have to be modified so that traffic can be routed around severe weather or away from bottlenecks that develop in the system. In a practical sense, the aircrew and ground controllers cooperate as a team using various human and electronic resources to maintain safety and to move traffic expeditiously. While the ultimate responsibility for safety of flight rests with the pilot, he remains dependent in many ways on data or decisions from the ground.

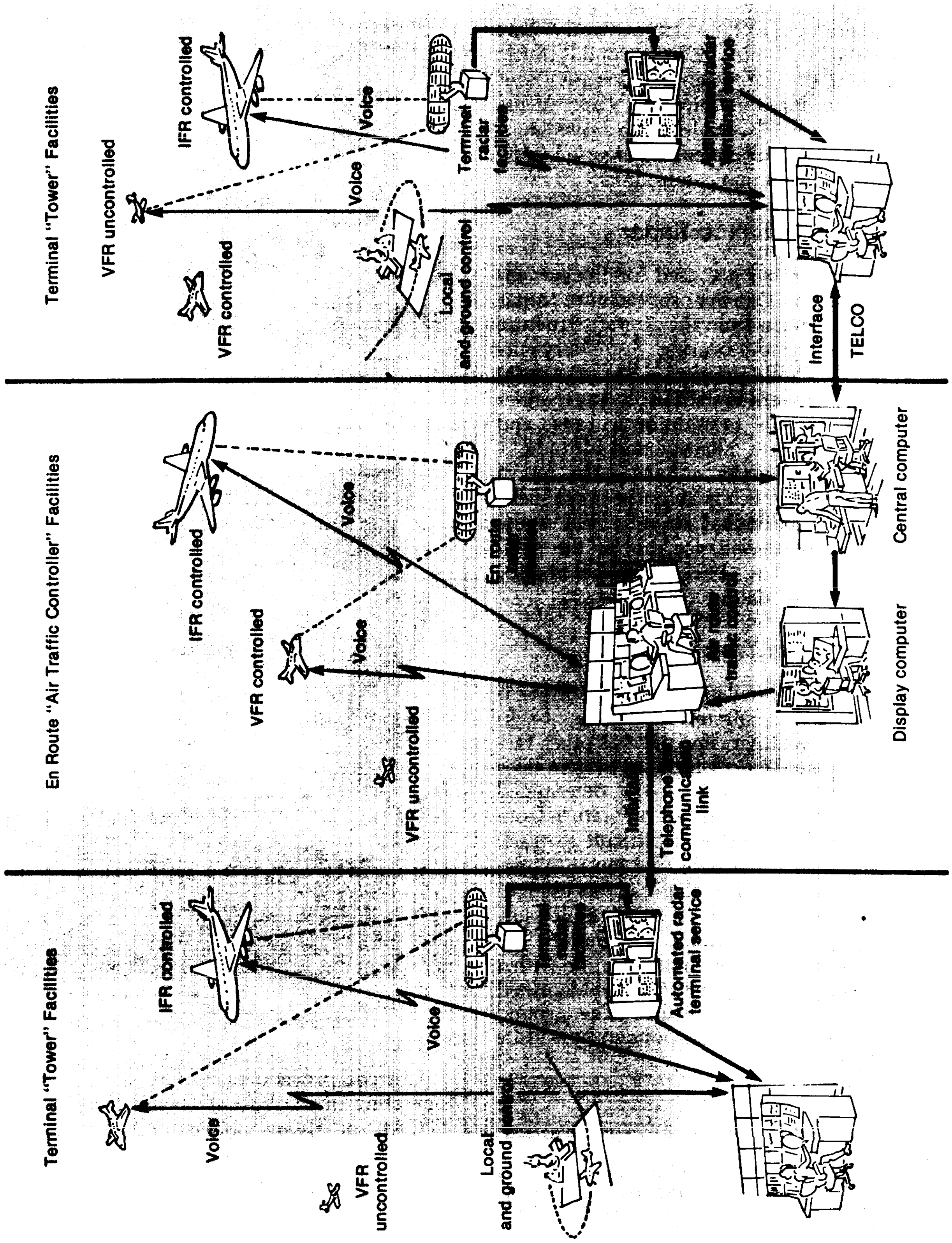
Photo credit: Federal Aviation Administration

One of the Nation's first air controllers—1929

MAJOR COMPONENTS OF THE EXISTING ATC SYSTEM

The present ATC system can be divided into two major subsystems: en route and terminal area (see fig. 23). The en route subsystem is primarily concerned with aircraft moving along the airway network, generally cruising at higher altitudes. To an increasing degree, it is also concerned with traffic flying point-to-point without following the airway network. The terminal

Figure 23.—National Airspace System



SOURCE: U.S. Senate Committee on Appropriations; FAA's En Route Air Traffic Control Computer System.

area subsystem handles aircraft flying at lower speeds and altitudes as they arrive at and depart from airports, but it must also control IFR traffic that is passing through a terminal area without landing. * The major equipment components that support these ATC facilities are surveillance radar, airborne transponders, navigation aids, computers, and communication links.

Surveillance Radar

Two types of radar are used for the surveillance of aircraft. Primary surveillance radar (PSR) uses the return from the aircraft structure to determine range and bearing. Secondary surveillance radar (SSR), triggers **a** response from aircraft equipped with an ATCRBS transponder and is able to obtain, in addition to range and bearing, the aircraft's identity and altitude.** Because the transponder enhances the return from primary radar, it improves the controller's ability to track individual aircraft. SSR is the principal aircraft surveillance tool of the ATC system; PSR is used as a backup for SSR and for long-range weather data.

Airborne Transponders

The returns to surveillance radar vary considerably with range, aircraft structure, background clutter, weather, and several other factors. In addition, the present radar system does not permit aircraft altitude to be determined from the ground on the basis of raw return from primary radar. This makes it difficult to track specific aircraft using a reflective return alone, although computer processing can be used to isolate a moving aircraft from background clutter. Transponders are radio transmitters designed to respond to ground interrogation with a strong signal that can easily be distinguished from a purely reflective return. The ground equipment and airborne transponders constitute the ATCRBS.

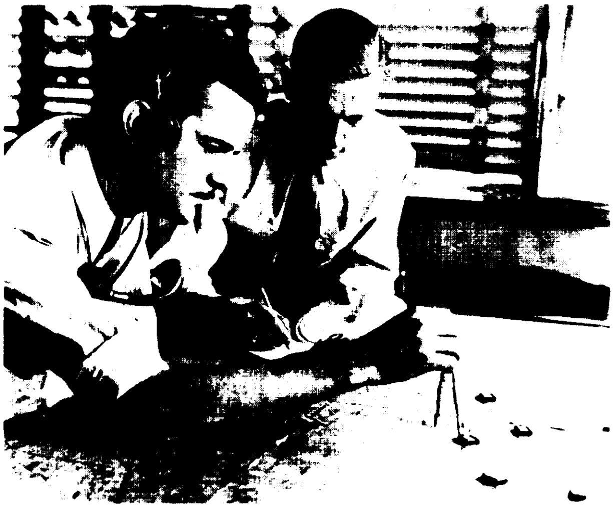


Photo credit: Federal Aviation Administration

Air control in the 1940's using table top plots

Photo credit: Federal Aviation Administration

Air control using a modern console

Current procedures require that all aircraft operating in the busiest terminal control areas (TCA), or flying above 12,500 ft must be equipped with a transponder capable of reporting both an aircraft identification code and altitude, Modes A and C, respectively. These devices respond to a Mode C inquiry from an

● In a terminal control area, all traffic is controlled by the ATC system.

**Altitude data is available only from aircraft equipped with a transponder having Mode C and an encoding altimeter. Only about one-third of the transponder-equipped aircraft have altitude reporting capability.

ATCRBS interrogator by giving the altitude of the aircraft, reported to the nearest 100 ft as sensed by an onboard barometric altimeter. Transponders also have the ability to transmit one of *4,096* different identity codes in response to a Mode A query from an ATCRBS interrogator. Under Instrument Flight Rules (IFR) the code to be used is specified for each aircraft by the ground controller; for all VFR aircraft equipped with a transponder a common identifier code (1200) is used. Some blocks of numbers within the 4,096 identity codes are reserved for classifying traffic such as coast-to-coast flights. Other codes have been set aside for emergency purposes—aircraft that have lost radio communication, aircraft in distress, or hijacked flights.

Navigation

Navigation aids are another important element of the ATC system. Although they are not traffic control devices per se, they do have an influence on the structure and the operation of the system. * As described in chapter 3, the primary radio navigation aid is the very high frequency omnidirectional range (VOR) system that operates in the VHF band immediately below the frequencies used for voice communication. VOR ground stations provide coverage of nearly all the continental United States and adjacent offshore areas, and most aircraft that have communication transceivers also are equipped to use VOR for navigation. VOR equipment enables the aircrew to determine the bearing to the ground station. Distance measuring equipment (DME), colocated with VORS, emits signals that allow the aircrew to determine the distance to the station as well. A station where VOR and TACAN, the military navigation system that is functionally equivalent to VOR/DME but more accurate, are colocated is called a VORTAC. Other navigation systems that are available are listed in chapter 3.

Many large commercial transports, military aircraft, and a growing number of corporate, general aviation (GA) aircraft are equipped with inertial navigation systems (INSs) that permit them to navigate without primary reference to ground-based radio transmitters. INS-equipped aircraft are not completely independent of ground aids since VOR/DME, LORAN-C, or OMEGA navigation signals are used for periodic crosschecks of INS accuracy and realinement of inertial platforms.

A growing number of commercial and GA aircraft are being equipped with navigational computers that enable them to operate off VOR-defined airways along direct origin-to-destination routes. This capability for area navigation **(RNAV) can be achieved either with** an INS or with equipment that uses VOR/DME, OMEGA or other navigation aids as the primary reference. The ability to fly RNAV makes it possible to achieve considerable savings in time and fuel consumption, and also allows aircraft to avoid the congestion that sometimes occurs at VOR airway intersections. FAA has begun publishing RNAV routes for use by suitably equipped aircraft. At present, however, controllers grant direct clearances only to the extent that they do not conflict with traffic along airways or affect adequate separation. While FAA is making an effort to accommodate the increasing demand for RNAV clearances, there are still cases in which the limitations imposed by the present VOR airways system prevent users from realizing the full benefit of installed RNAV equipment.

Computers

Computers are used extensively throughout the ATC system to process flight plans, to correlate radar and transponder returns, to filter out extraneous signals that could obscure controlled aircraft, and to generate displays on the controller's console. All control decisions, however, are made by human operators. In the busiest terminal areas, an ARTS II or ARTS III computer system combines SSR data and flight plan information to create a display on an analog terminal (see fig. 23). Displayed alongside the position indicator for each aircraft is a data block that includes the transponder code of the aircraft, its altitude and groundspeed, and the aircraft regis-

*For example, aircraft will follow radials to or from VOR stations. This tends to add some order to the flow of traffic even if it is not operating within the ATC system.

tration number or flight designation *to the extent that they are available,* For example, none of these data will appear for an aircraft flying VFR without an operating transponder unless they are entered manually.

The principal computer used at the 20 en route ATC centers is the IBM 9020, an assemblage of IBM 360 components that have been modified for ATC applications. The technology incorporated in these machines is of 1962 vintage, and there have been considerable advances in the design and construction of computers since they were first built and installed. The IBM 9020s are tied to either IBM or Raytheon digital display subsystems that present radar surveillance and clearance information in a brighter, sharper image than the analog displays used in the terminal control facilities. In addition to driving the controller displays, the IBM 9020s also handle communications with computers in other en route centers and terminal area control facilities as well as other tasks such as flight plan processing.

In case of an IBM 9020 failure, the controllers have a backup system, called Direct Access Radar Channel (DARC), that digitizes the raw data from the secondary surveillance radar to create a comparatively clean image on the control consoles. However, to use DARC, the controllers must manually shift their display screens from the vertical to the horizontal position and make plastic markers ("shrimp boats") to identify the targets on the screen, because the DARC system cannot obtain the clearance data from which to generate a display of the aircraft call sign or intended route. If the DARC system is inoperable, controllers have a second backup, a broad-band system that displays radar data without computer enhancement and thus provides no data

Photo credit: Mitre Corp.

Computers for air traffic control system for aircraft en route block for individual targets. FAA has indicated that it plans to *remove* the broad-band capability when sufficient operational experience with DARC has been established.

FAA is considering the option of installing compatible computer and display systems in the en route and terminal area control facilities. If this were done, much of the line of demarcation between these classes of facilities could be removed.

Communication

Communication is a key element in the present ATC system, and advances in communication technology may open new options for configuring the system in the future. Historically, voice radio has been the primary and almost exclusive means of communicating between aircraft and the ground. Digital communication—the transmission of data in the form of machine-readable binary signals—has come into use for linking ground stations (particularly for computer-to-computer interchanges), but it has not yet been applied for air-ground messages, except in the limited case of transmitting aircraft identity and altitude by means of ATCRBS transponders. In the future, it is expected that an air-ground digital data link will play an increasingly important role as the automation of ATC functions requires more direct communication between airborne and ground-based computers.

Another important advantage of the digital data link is that it permits messages to be transmitted selectively. The present voice-radio method is broadcast—i. e., available to any and all aircraft equipped with an appropriate receiver, regardless of the intended recipient. This "party line" feature has certain advantages, since it permits pilots to develop a sense of what is happening in the surrounding airspace. Nevertheless, a "discrete address" technology that permits messages to be sent to a specific recipient can be more effective than broadcast for processes that require computer-to-computer communication. This is the underlying principle of the Mode S data link (formerly the Discrete Address Beacon System, or DABS), which is an important building block in FAA's plans for future system development.

In the future, with the introduction of a digital data link capable of selective address, two distinct modes of communication can be expected. Broadcast, the mode now used, will continue for voice or digital transmissions of general interest, such as weather, airport status, and traffic advisories. Other transmissions, pertinent only to specific aircraft, will be sent by a discrete-address digital data link that allows isolation of specific receiving stations. However to the extent that communication relative to position and intent uses a discrete address data link rather than broadcast, the side benefits of the party line would be diminished.

The application of a digital data link is not limited to air-ground communication; it could also be used for exchange of messages between aircraft. For instance, most of the air-to-air communication in proposed collision avoidance systems would be digitized; and by allowing airborne computers to direct messages to specific aircraft, maneuvers intended to resolve conflicts could be coordinated between aircraft. Alternative plans for the implementation of a digital data link are discussed later in this chapter.

FUTURE REQUIREMENTS, OPPORTUNITIES, AND CONSTRAINTS

Future Requirements

The evolution of the ATC system will be influenced by changes in user demand, market forces, and regulatory policy, as well as the availability of new technologies and the possibility of applying them to achieve greater effectiveness of the ATC system through higher levels of automation. In many cases there are several ways of meeting specific needs, and the choice of which path to take will reflect a combination of technological, economic, and policy considerations. In general, however, prospective changes in the system will be dictated by three related technical requirements:

- *replacement of obsolete equipment,* which will become increasingly difficult to maintain and repair, with more modern equipment that offers higher reliability and might also provide greater flexibility, higher capacity, or lower costs;
- *increase of system capacity* in order to accommodate growth when and where it occurs, by improving the management of existing resources where feasible and by adding new resources where necessary; and
- *addition of new capabilities* in order to support improvements in efficiency and productivity by automating more functions and by introducing features that make it possible to take advantage of improvements in avionics and other newly available technologies.

Advances in technology have increased the number of options that could meet these requirements. *Computers* will probably assume roles of increasing importance, both in the air and on the ground, because they present opportunities to increase efficiency, productivity, or capacity by relieving human participants in the system of routine tasks, by facilitating human decisions, and by improving the timeliness and quality of information. As a result, the human operator's role will become more that of a manager of system resources than that of a direct controller of aircraft. *Communications* will also be a critical element, and digital communication between machines (computers and various avionic devices) will be at least as important as voice communications between humans. Future systems, therefore, may have to provide for one or more high-speed data links of sufficient capacity to handle the large volumes of data and messages that will be generated. *Collision avoidance* will receive increasing attention as the volume of traffic grows, and both *navigation and landing aids* may need to be upgraded in order to maintain safety and improve the efficiency with which airways and airports are utilized. Specific technical options for each of these functions are discussed in later sections of this chapter. The more general opportunities created by advanced technology are discussed below.

Technological Opportunities

The development of microelectronics has been a primary source of expanded technological opportunities for the ATC system. Data-processing capabilities can now be tailored to meet virtually any computational requirement, hardware costs have fallen significantly, and reliability continues to increase. The ATC system as presently constituted is highly labor-intensive; and since the PATCO walkout, the system has been kept operating with a greatly reduced work force only by administratively limiting traffic. Some observers have suggested that the current situation presents an opportunity to review the basic structure of the system and to apply new technology so as to make it less labor-intensive and less dependent on (or vulnerable to) the actions of any specific group within the work force.

Computer software figures prominently in the present ATC system and will have an even more significant role in the future as the need for new capabilities expands. Many systems related to the safety of flight, both ground based and airborne, will be "software driven, " in that the processing of sensor data and the generation of displays will be more dependent on computer programs than is now the case. Processes running on different computers will communicate directly with one another. There will thus be a need for systems with the ability to identify errors and to take compensator action automatically. * Present ATC software uses a combination of computer languages, but new high-level languages that are now available (like those used for military command and control) and those that will be developed in the future may make it easier and cheaper to implement, modify, and maintain ATC software.

Commitment to a highly automated mode of operation is not without risk. When there is a computer failure in the present system, the controllers can revert to manual methods and keep traffic flowing. However, experiments with

* Systems with this type of capability are within the state of the art and some are available "of f-the-shelf."

more highly automated systems have shown that traffic levels can reach a point that, although well within the capabilities of the automated system, is beyond the point where they can be handled manually. At these traffic levels, controllers experience considerable difficulty in reverting to manual operations during computer outages. ' This suggests that *even* though computer technology offers promise for the future, there may be a point of no return beyond which the commitment to automation is absolute—the only backup system for a highly automated ATC system is another highly automated system.

Decreasing size and costs of computers also mean, however, that data-processing capability can be located anywhere in a system, and that redundancy can be provided where exceptionally high degrees of reliability are required. Microprocessors have become integral elements of aircraft instrumentation, and modern aircraft can and do carry general-purpose computers that can be used for a variety of applications, such as flight management, processing digital communications with the ground or other aircraft, updating the navigation system, developing alternative flight plans, or driving multifunction cockpit displays that replace several electromechanical instruments. The introduction of these airborne capabilities means that ATC functions need no longer be wholly resident in ground-based computers. As a result, it might be possible to improve system operation and safety by redistributing these functions among the various participants in the ATC process. Many of these functions will be critical to the safety of flight and, therefore, the computer based systems that perform them will fall within the airworthiness certification program of FAA.

An ATC system that places more information and functions in the cockpit will also require changes in communication technology. As ATC automation becomes more widespread and more integrated into the system, digital data communication will come into greater use. Transmissions directed to a specific receiver—the principle underlying the proposed Mode S data link described later—would facilitate communication between ground-based and airborne computers. They would also allow a computer to continue with other functions once it determines that it is not the intended recipient, a feature that increases the effective capacity of a processor. The capacity required for data links between ground facilities would also need to increase. While telephone and other ground links are used at present, point-to-point satellite channels might provide an alternative in the future.

Satellites could also be used for aeronautical navigation and surveillance. Singly or in constellations, satellites with accurate sensors and computing capabilities can be used to determine aircraft position and relay the information to other aircraft and ground stations. Satellite-based collision avoidance systems have been suggested. Large satellites that support a number of functions are also being considered for civil aviation, notably in the Aerosat system of the

[1]Leonard Tobias and Paul J. O'Brian, "Real-Time Manned Simulation of Advanced Terminal Area Guidance Concepts for Short Haul Operations, " Ames Research Center, August 1977, NASA-TN-D-B499.

The experiments, conducted in 1971 at the Ames Research Center and jointly sponsored by FAA and NASA, were to determine the comparative utility of 3-D and 4-D RNAV as aids to flying landing approaches. Controllers and pilots were placed in a simulated high traffic environment and required to control traffic and fly approaches in STOL [short takeoff and landing] aircraft equipped with the two onboard navigation aids. Results showed that the performance of both controllers and pilots improved although the controllers were only secondary beneficiaries of the equipment installed in the aircraft.

Generally, when the effects of 4-D RNAV were compared with those of 3-D RNAV, two types of effects were observed. The first related to improvements in the effectiveness of both pilots and controllers. Pilots were able to fly a better track when assigned a route and a time to arrive at a checkpoint. The range of deviations of arrival time at a checkpoint from the time assigned dropped from about 4 minutes to about 30 seconds. Requirements for voice communication between controllers and aircraft under their control were cut by more than half. Traffic flows were more orderly, and the number of aircraft in the system increased by about 25 percent.

A second major conclusion was that there maybe a point in the development of automated systems beyond which it is no longer possible to return to a manual back-up. At higher levels of traffic, it was more difficult for controllers to make the adjustments required to handle an emergency and restore traffic once the emergency had been resolved. Controllers expressed a definite need for more automated support for handling emergencies and restoring traffic afterwards.

From this it seems that automated systems may have to be built so that they are self-diagnosing, self-correcting and/or backed up with other automated systems. Such back-up systems may not offer all of the features of the primary system but would be adequate for an interim period while repairs to the primary system are underway.

European Space Agency. The reliability and longevity of satellites are high and likely to increase in the future. The space shuttle makes it possible to recover, refurbish, and relaunch satellites, or even make repairs while in orbit. However, the leadtimes for scheduling shuttle payloads will preclude its use in responding rapidly to unforeseen emergencies. In addition, frequencies and orbital slots are limited and ATC applications must compete with other potential users of space technology, Both NASA and FAA have spent considerable amounts on R&D for ATC satellite applications, but no significant U.S. program is currently under way. Much of the required technology is available, but it has not yet reached the point of being a cost-effective alternative to ground-based ATC facilities and configurations. At some point in the future, however, this may change and the option of using satellites in ATC applications may have to be reevaluated.

Constraints and Other Factors Affecting Future Evolution

Continuity of Service

ATC is an ongoing activity that cannot be interrupted while a replacement system is put into place. Any changes in the system must therefore be implemented gradually, and new and old equipment will have to be operated in parallel to assure continuity of service throughout the transition period. FAA can reduce the length of this transition period by mandating equipage by certain dates. If installation is voluntary, however, some users will hold off replacing existing equipment until it wears out, and some users might never make the change. At a minimum, parallel operation will be needed for perhaps as long as a decade while users install new equipment. In some cases, it could be in the best interest of all parties to establish a firm date on which existing services will terminate and by which all users will have to be equipped to use the new service.

Timing of Design Decisions and System Implementation

Identifying future needs and installing the facilities to meet those needs take a considerable amount of time. In periods of rapid technological progress, new equipment or facilities may become obsolescent before the implementation phase is completed. Redesigning the system to incorporate newer technologies, however, may take so long that a badly needed function remains unavailable, or that a deteriorating system is kept in place long after it has become inadequate. At some point, therefore, the decision to go ahead with system enhancements must be made, despite the realization that the incorporation of newer technologies will have to be deferred until a later cycle of system modifications.

The design and development of some prospective ATC systems and facilities began over 10 years ago, and it will be late in the present decade or early in the next before implementation can be completed. A substantial portion of the needed ground facilities would have to be installed before users would begin to install the required equipment on their aircraft, since they would see little benefit in spending money for equipment before it is of practical value. The rate of installation of airborne components would also be limited by the rate at which they can be produced, and the avionics industry would be unlikely to commit to production until it foresees a market of sufficient size to assure profitability.

User Costs

FAA is responsible for the design, procurement, installation, operation, and maintenance of equipment used in ATC installations and for establishing standards for the equipment to be carried on aircraft. However, the responsibility for and costs of procuring, installing, operating, and maintaining the airborne equipment rests with the users. Any adverse impacts on aircraft performance resulting from the installation of airborne equipment also translates into increased user costs. Decisions about changes to the ATC system must consider these user costs and the effect that required equipment might have on aircraft performance.

Large aircraft have the space to accommodate new avionics, but in small GA aircraft or densely packed tactical military aircraft space is at a premium, and room for additional equipment to meet the needs of the ATC system may be hard to find. Antenna location, in particular, often involves a tradeoff between aerodynamic and electromagnetic characteristics. For instance, the small blade antenna used for a standard ATCRBS transponder has little effect on aerodynamics, but the larger direction-finding antennas required for some collision avoidance systems may adversely affect aircraft performance or even structural integrity when retrofitted into existing aircraft.

Not all new functions require the replacement of existing equipment. Some experts suggest that the capabilities in existing equipment are ample for future needs and that new or upgraded equipment is not required. Some entrepreneurs have been successful in adapting existing equipment to new purposes without making any fundamental changes. RNAV, as mentioned, uses VOR/DME signals and existing receivers to obtain the data required for navigation outside the defined system of airways. Tri-Modal BCAS, a collision avoidance system, is designed to operate with the installed ATCRBS transponders and interrogators.

In addition, the ATC system serves a broad mix of users who operate aircraft having a wide range of performance characteristics and who use the airspace for a variety of purposes. Over half of all air operations are not under the control of FAA terminal and en route facilities, but the ATC system must recognize the existence of these "off system" activities so that the available airspace and airport facilities are used in a safe, efficient, and equitable manner. The heterogeneity of the user mix complicates both the design and the implementation of new systems, and the GA community is particularly sensitive to the issues of user costs and mandatory equipage.

Locus of Decisionmaking

Decisionmaking in the ATC system is distributed between ground controllers and aircrew. Ultimate responsibility resides with the pilot, but controller-supplied services are particularly important in high-density traffic and at times of poor visibility. Some pilots feel that the amount of ground control is becoming excessive and that they are burdened with the responsibility of operating the aircraft safely without having available the information required to meet that responsibility. Technologies now available or under development could make additional information available to both ground controllers and aircrew and might permit redistribution of the decisionmaking function. These alternative concepts have not yet been validated and tested; but they could lead to an ATC system that is less dependent on ground-based equipment and control decisions.

Freedom of Airspace and Equipage

The passage of time has also brought increasing limitations on the amount of airspace available for VFR operations. The GA community (traditionally vocal in this matter) has been joined by the military services, who believe that access to suitable training areas is becoming excessively restricted. The airlines, faced with high fuel prices and low profitability, have also argued that they should be permitted to fly the most fuel-efficient routes possible between points served.

While FAA has not required all aircraft to be equipped to participate in the ATC system, it has imposed limitations on the operations of aircraft lacking specific pieces of equipment. While the requirements are still minimal, freedom of airspace is already directly affected by the amount of avionics an operator is able and willing to install on an airplane. As more airspace becomes congested, the areas in which unrestricted VFR flight is permitted may have to be reduced, or some other method be found to assure separation and preserve safety of flight. It may not be possible in the future to permit the some degree of flexibility and freedom of airspace use that has been accorded in the past to those operating outside of positive control by the ATC system.

International Requirements

The United States is party to a number of international agreements that affect the operation of the air transportation system. It is legally obligated to provide ATC services that conform to international standards at gateway facilities unless airspace users are notified that particular exceptions are taken to the applicable agreements. Foreign-flag carriers enter U.S. airspace at gateway facilities with the understanding that they will receive full services if they are equipped in accordance with international standards. U.S. aircraft similarly expect a full range of services from foreign controllers. There is no legal obligation to operate the domestic ATC system in conformity with international standards, although many nations (including the United States) find it desirable to do so.

Two international bodies establish standards that affect aeronautical operations. The International Civil Aviation Organization (ICAO) promulgates standards that establish flight procedures and aircraft equipment specifications. For example, one ICAO standard governs the signal format used by each mode of the ATCRBS transponder. Mode S, the signal format of the DABS data link, is currently being considered for establishment as an ICAO standard, without which it cannot be implemented for international operations.

The second organization, the International Telecommunication Union (ITU), also establishes conventions that affect aeronautical operations, but the relationship is not as close as that of ICAO. ITU assigns portions of the radio frequency spectrum to various applications throughout the world. The spectrum is a finite resource, and competitition among alternative applications is intense. Aeronautical radio has been assigned bands that are of sufficient capacity to meet present needs, but it may be difficult to obtain additional spectrum allocations for new aeronautical applications in the future. However, it may be feasible to reduce the channel spacing in bands that are currently allocated and thus increase total effective capacity. One area where there is significant pressure is in the allocation of spectrum to satellite applications; and this may be a factor that could limit the development of ATC services that use satellites.[2]

Military Requirements

The ATC system will be constrained by national security considerations. In time of war the system must meet the needs of the military without aiding an enemy in locating and hitting targets in the United States. In addition, ATC equipment and facilities must not compromise the operational integrity of military equipment. The military is a full participant in the ATC system, and FAA is charged by **law** with ensuring that the system meets both civil and military requirements. Some arrangements for coordinating the activities of FAA and the Department of Defense (DOD) have been established, but these have not been completely formalized.

‘For further information on this subject see OTA's assessment, ***Radio frequency Use and Management: impacts From the World*** *Administrative Radio* ***Conference of*** *1979,* OTA-CIT-163 (Washington, D. C.: U.S. Government Printing Office, January 1982).

TECHNICAL OPTIONS

En Route Computer Replacement

The computer now in use at en route ATC centers is the IBM *9020*, a designation given to a derivative of the IBM *360* line that has been specially modified to perform ATC functions. Although the IBM *9020* was first commissioned by FAA in 1974, it incorporates a technology that is close to **20** years old. It has less speed and capacity, is less reliable, requires more energy and floor space, and is not as easy to maintain as more modern computers that could be used in support of the ATC system.

Growth in the demand for ATC services has exceeded the data-processing capability of the IBM *9020*. Some ARTCCs are already operating at capacity, while others are expected to reach capacity later in this decade. Alleviating capacity problems by acquiring additional IBM *9020* computers is not a practical alternative, since the IBM 360 has been out of production for several years. Buying used IBM *360s* and modifying them to make them IBM 9020s would be expensive in the short term and would provide, at best, only a stopgap solution.

The reliability of the IBM *9020* hardware and software has also been troublesome, giving rise to concern that the cost of repairing and maintaining the system will become excessive. As time passes and existing stocks of spare parts are exhausted, maintenance of the computers could become very expensive because spares would have to be fabricated to order. Similarly, the task of modifying and maintaining software to meet evolving needs is likely to be increasingly difficult to perform. In the future, it will be difficult to recruit and retain programmers capable of maintaining the software because those who are best able to do this job prefer to work on more modern equipment. Further, there is ample demand for their talents outside of FAA.

FAA is now in the process of planning the procurement of a replacement computer system that will overcome present operational problems and provide additional capacity to meet the needs of the en route centers during the last decade of this century and into the next. Plans are to use the increased capacity of the replacement computers to provide a variety of new and improved services, as well as to satisfy the requirements generated by the anticipated increase in aviation activity. Table *6* indicates the range of services and activities FAA expects to support with the replacement computer system. These applications fall in three major areas: control of individual aircraft, conflict alert and resolution, and management of traffic flow.

The basic technical issue is not whether the 9020 system needs to be replaced—there is wide agreement that it does—but what replacement strategy should be pursued.

There are many strategies for replacing the IBM 9020s, but all can be placed in one of three groups:

- replace all hardware and software simultaneously;
- place initial emphasis on the replacement of the hardware; or
- place initial emphasis on the replacement of the software.

The first strategy—total replacement— implies that the present system, with minor modifications needed to keep it operating, will be kept in place until the replacement hardware and software are ready for commissioning. The latter two strategies are incremental approaches that provide for a transition to the new system in comparatively small steps over an extended period. Some believe that either of these strategies, if successful, could provide relief from the most pressing problems within a period of 3 to 5 years, as opposed to the more than *8* years required for the total simultaneous replacement option.

The en route computer replacement strategy has been reviewed as part of the FAA effort to produce a revised NASP. Implicit in past FAA statements is the presumption that the replacement computer, like the IBM 9020s, would have to be uniquely designed for ATC applications. Critics of the full replacement strategy have put forth options that would effect the replacement of the computers incrementally.[3] Generally, these plans envision using off-the-shelf equipment to replace the IBM 9020s rather than obtaining a computer that has been designed or modified specifically for ATC applications.

Total Replacement

The total replacement strategy has much to recommend it. First, FAA has learned from its experiences with the present system and, given the opportunity to make a fresh start, would be in a position to design a replacement that would correct present weaknesses. Second, advances in hardware, software, and communication technologies have created new options that were not available when the present system was installed. **A** complete replacement of the present system

‘*See,* for example, ***FAA Air Traffic Control Computer Modernization,*** Hearings before the Subcommittee on Transportation, Aviation, and Materials of the Committee on Science and Technology, U.S. House of Representatives, June 16-18, 1981.

Table 6.—Perform ATC Automation Processes

Sustain ATC system operation	Assemble system information: • Acquire or negotiate decisions • Collect and analyze system status information
	Calculate state of ATC system: • Calculate system load • Predict system state
	Resolve management actions: • Resolve differences in system state and decisions . Translate resolutions into automation directives
	Manage ATC automation processes performance: • Formulate required processes actions • Monitor processes status and performance • Monitor plan status and performance
Perform ATC planning processes . . .	Assemble planning information: • Assemble trajectory information • Assemble flow information • Create multidimensional profile
	Identify strategic planning problems: • Predict strategic delays • Predict long-term conflicts
	Resolve strategic planning actions: • Absorb strategic delays • Resolve long-term conflicts
	Issue strategic planning actions: • Formulate clearance plan
Perform ATC controlling processes .	Assemble control information: • Assemble control information • Convert to appropriate reference • Apply control conditions
	Identify control problems: • Predict short-term AC/AC conflicts • Predict environmental conflicts • Detect track/trajectory deviations
	Select control actions: • Assess "accept/handoff" situations • Resolve tactical situations • Generate clearances
	Control ATC system: • Perform aircraft accept/handoff • Deliver clearances • Deliver advisories

SOURCE: *ATC Computer Replacement Program System Level Specification (Preliminary). En Route ATC Automation System.* FAA-ER-130-003, May 1981 (draft).

offers the opportunity to explore all of these options fully and to select the one that best suits ATC requirements in terms of both technical characteristics and overall system productivity.

On the other hand, the total replacement option would do little or nothing to relieve the deficiencies of the present system in the short term. If procurement were to start immediately, it is unlikely that the first replacement computers would be in operation before the end of the decade. In the interim, the IBM 9020s would have to be kept in operation to meet the ongoing needs for ATC services—a task that could become increasingly difficult and costly.

Critics of FAA have pointed out that the number of interruptions to service experienced with the present computers constitutes a threat to the safety of flight. ' A more recent study by the Na-

Air Traffic Control Computer Failures, Committee on Government Operations, U.S. House of Representatives, House Report No. 97-137, June 11, 1981.

tional Transportation Safety Board[5] indicates a significant decrease in the number of computer outages since the controller strike in the summer of 1981 due in part to the subsequent reduction in the level of traffic. Concern with the reliability of the ATC computers remains, however, and FAA has pointed out that some of the en route centers were approaching capacity limits at the time of the strike. This last consideration would favor a conversion strategy that will have a positive short-term effect on en route traffic capacity.

Hardware= First Replacement ("Rehosting")

Either of the alternative strategies for the incremental replacement of the computers entails a number of assumptions about the structure and operational characteristics of the present system. For example, a proposal to move some of the functions from the IBM 9020s to an auxiliary computer assumes that it is possible to isolate the software elements that perform those functions from the rest of the IBM 9020 software. A proposal to move the existing software to a new processor assumes that interface problems arising from differences in the internal timing of the machines can be overcome. Such assumptions are critical both to the feasibility of incremental replacement strategies and to the schedule and budget to carry them out.

The second option—incremental replacement with initial emphasis on substituting new hardware—would "rehost" or move the existing software to a new processor capable of supporting the IBM *360* instruction set. Several manufacturers produce machines with this capability, but in every case some modification of the existing software would be required. * At a minimum, some allowance would have to be made for handling the instructions unique to the IBM 9020. Real-time applications, such as the ATC software, are characteristically sensitive to the timing of internal machine operations, and this too could cause severe problems in rehosting the software. There could also be problems in meeting the requirements of the interface between the main processor and the IBM or Raytheon systems that drive the displays used by the controllers. However, there are probably technical solutions to these problems given enough time and resources to work them out.

Even though there may be problems with rehosting the existing software in a new processor, there are several points that recommend this strategy. Some suggest that this approach could be implemented by 1985. Second, once the constraint of machine capacity has been relieved, it would be possible to begin restructuring the software to improve its maintainability and reliability. Finally, the replacement computer could be selected with a view toward providing enough additional capacity to support the new functions and services planned by FAA as part of longer term improvements of the ATC system.

The "hardware-first" approach does not rest on the assumption that the processor to which the ATC software is moved would necessarily be the long-term replacement for the IBM *9020*. It could be viewed as an interim replacement that would serve while FAA proceeded with a procurement program for a totally new hardware and software package, to be commissioned around the turn of the century and intended to serve well beyond the year 2000. On the other hand, the procurement of an interim computer replacement would involve a sizable investment that might, for budgetary reasons, effectively foreclose the option of initiating a second round of computer replacement after the interim system was put in place.

Software-First Replacement ("offloading")

The strategy emphasizing the replacement of the software first would involve separating individual functions of the existing software. This of itself would be beneficial, since it would make it easier to maintain the existing software and provide an opportunity to increase overall operating efficiency. Weaknesses in the software that are known to have contributed to service interruptions could also be corrected during this ini-

[5] ***Air Traffic Control System,*** Special ***Investigative Report, NTSB-SIR-81-7*** (Washington, D. C.: National Transportation Safety Board, December 1981).

*The ability to modify software rests on an understanding of the existing structure and the procedure it executes in performing required functions.

tial reworking of the existing software. Once this initial phase had been completed, the software could either be rehosted intact in a new computer, or some functions could be offloaded from the IBM *9020* to another processor. The offloading approach would free capacity on the IBM *9020,* allowing it to absorb increases in workload due to higher traffic levels.

In the short run, this strategy makes no provision for adding the new functions envisioned by FAA. However, as various functions are moved from the IBM *9020s* to other processors, there would in effect be an incremental replacement of the present computer. This would offer considerable latitude in specifying the replacement processor. It could be a large main-frame processor to which elements of the ATC system could slowly migrate. Alternatively, the migration could be to several smaller processors, so that the system would finally evolve into a network of distributed, modular processors. Compared to the hardware-first strategy, this one offers the opportunity to migrate to a system that has been selected specifically to meet the requirements of the ATC application. Since the software would be designed first, and then a computer configuration suited to supporting it selected, it would be less likely that a second conversion would be required or that the resulting system would be less than optimal in terms of its ability to meet the long-term needs of the ATC system.

A potential disadvantage of this strategy, however, it that it depends on being able to separate specific functions in the existing software. There are indications that the subroutines within the present ATC programs are strongly interdependent, and that it might therefore be very difficult to modularize the present software system. If this is true, then it might be necessary to essentially rebuild the existing software in order to implement this strategy; and the cost of doing this could be prohibitive relative to other available options.

Modularity and Other Concerns

The total system replacement strategy advocated by FAA in the past recognizes the need to replace the controller displays and other peripherals, as well as the *9020* mainframe. ETABS, the electronic display of flight strip information, and other display features planned for the controller suite require replacing not only the main computer but the computers that generate displays as well. In addition, FAA is contemplating eventual replacement of the ARTS II and ARTS 111 computers now used in the terminal areas.

The ATC functions performed by computers in the en route centers and those performed in the terminal areas are similar. Therefore, one might consider procuring a computer for the en route centers that could also be used in the terminal areas. Most manufacturers produce lines of compatible machines with a considerable range of capacity. Thus, the concept of using a smaller version of the en route computer in the terminal areas could be attractive. In fact, such a strategy could reduce the overall costs of software maintenance for the ATC system because there would be fewer software packages in use.

At some point, FAA will incur the cost of replacing the IBM 9020s now installed in the en route centers. Operational factors create considerable pressure to begin doing so in the near term. However, once the initial conversion has been completed, future steps to upgrade or to modify the system could be accomplished at a slower pace. Manufacturers of computers generally design them so as to provide paths by which users can upgrade capabilities incrementally without large-scale rebuilding of software. Such avenues would be available to FAA in the future so long as off-the-shelf hardware was selected to replace the IBM 9020s. If, on the other hand, a unique processor were to be selected, it is likely that second conversion—of a magnitude similar to the one now being undertaken—would be required at some point in the future to support new ATC services and capabilities.

Automated En Route Air Traffic Control

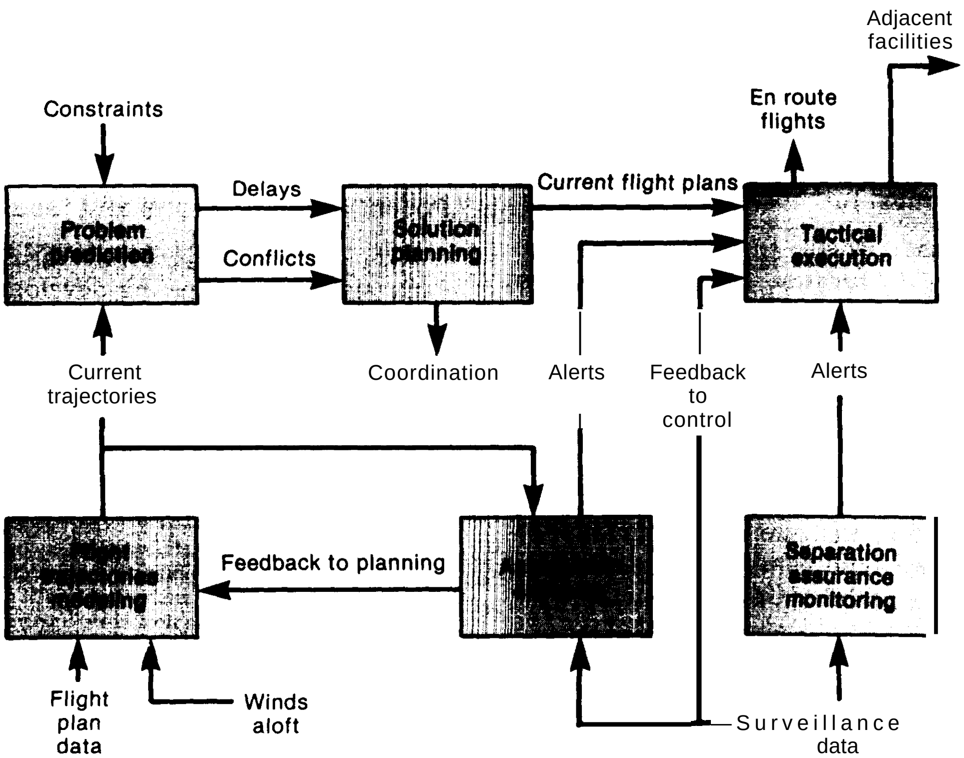
Another factor influencing the selection of the en route computer replacement is its compatibility with the long-term evolution of the ATC system. The future requirements and operational characteristics of the en route portion of the

ATC system are currently defined by FAA under the concept of automated en route air traffic control (AERA).

The essence of FAA's AERA concept is to automate the functions of maintaining aircraft separation, metering traffic flow, delivering clearances, and transmitting ATC messages. These functions would be assigned to computers, thereby relieving the controller of many routine tasks. The controller's role would then be primarily to handle exceptions and emergencies and oversee (manage) the operation of automated ATC equipment. Operationally, AERA would perform four principal functions: 1) automatically produce a clearance for each aircraft operating in positive control airspace that would ensure a conflict-free, fuel-efficient flight path; 2) formulate messages to aircraft needed to execute the planned flight profile and to assure separation; 3) transmit those messages by data link or VHF voice radio; 4) and monitor actual flight movements relative to flight plans, revising those plans and clearances as necessary to ensure continued freedom from conflicts. Major AERA functions are summarized in figure *24*.

As currently envisioned, AERA would be a continuation and extension of the present ground-based ATC system. It could be implemented incrementally over an extended period automating first those functions that are most routine and repetitive for the human controller. Instructions to ensure separation and coordinate traffic flow would still come from ground facilities. However, these instructions would be formulated and issued by computers operating under the supervision of human controllers, Further, the control instructions would be derived from a more extensive data base (geographically broader and covering a greater span of time) than the present system. In effect, the AERA system would operate strategically—planning overall traffic flow as well as individual aircraft movements so that conflicts do not arise—although some form of tactical control would also

Figure 24.–Major AERA Functions



SOURCE: Federal Aviation Administration.

be provided in order to resolve potential conflicts before backup collision avoidance systems would be activated.[6]

While AERA would entail extensive ground-based data-processing capability, detailed analysis of aircraft flight plans, and close surveillance of actual flight paths, it would not necessarily lead to undue restrictions on aircraft movements. As envisioned, AERA could in fact reduce or eliminate many of the procedural constraints now imposed on the use of airspace. It would be a system of management by exception, in which controller intervention would be limited to situations (or localities) where conflicts could not be reliably resolved by computer routines. The controller would not have to visualize or direct overall traffic patterns, as in the present system, because the AERA concept envisions automated planning, monitoring, and metering of traffic flow in a four-dimensional region made up of several airspace sectors over an extended period of time.[7]

Potential Benefits

Initial estimates of the benefits of AERA indicate important savings in two areas: fuel savings due to more direct routings and reduced labor costs. The fuel savings for domestic airlines could be on the order of 3 percent; at present fuel prices, this would amount to a *$250* million reduction in annual fuel costs.

The principal benefit to the Government would come in the form of increased controller productivity and the attendant reduction in operating costs: the volume of airspace assigned to a control team could be greatly enlarged; it might also be possible to reduce the size of the control team by automating the routine tasks of clearance coordination and flight data entry. Preliminary estimates are that controller productivity could be doubled, i.e. that individual en route controllers could handle perhaps twice as many aircraft as with the present system.[8] This in itself would not necessarily increase the capacity of the system, but it could significantly reduce future operating costs. One recent estimate places these savings at $300 million annually (1979 dollars),[9] but these preliminary figures would need to be refined as the AERA program progresses and a more precise picture of its operational characteristics is obtained.

A third advantage of AERA—and a strong part of the rationale for seeking a high level of automation—is that it would help reduce system errors. * In the present ATC system about *60* percent of these errors are attributable to mistakes on the part of controllers: improper coordination between controllers, inattention, forgetting, failure to communicate, poor judgment, and the like.[10] The underlying causes of many of these errors can be traced to the nature of ATC as a work activity—routine, repetitive tasks requiring vigilance and close attention to detail, and often conducted at a forced pace. Computers are ideally suited to this kind of activity; and if the tasks to be automated are judiciously selected and the software carefully designed, an automated system such as AERA could eliminate a major part of system errors, or at least provide a backstop to the shortcomings of human operators. In this sense, AERA is expected to be safer than the present system of traffic control.

Potential Implications and Issues

It must be emphasized that AERA is still in the early stage of engineering development. Extensive effort, over perhaps 5 to 10 years, will be needed to bring AERA to a precise and detailed definition of requirements and equipment specifications. Installation, test, and full operational deployment will take an additional 5 to 8 years.

[6]R. A. Rucker, ***Automated En Route ATC (AERA): Operational Concepts***, MTR 79W00167, The Mitre Corp., May 1979.

[7]L. Goldmuntz, et al., ***The AERA Concept***, Economic and Science Planning, Inc., for the Federal Aviation Administration, December 1980.

[8]Personal communication, S. B. Poritzky, Director, FAA Office of Systems Engineering Management, Dec. 21, 1981.

[9]Goldmuntz, op. cit. This benefit is calculated by taking the $375 million annual expense (1979) to operate ARTCCs, increasing it by a factor of 1.6 to account for traffic growth by the time AERA would become operational taking so percent of that as the benefit due to AERA productivity improvements.

* By FAA definition, a "system error" occurs whenever the actual horizontal or vertical separation between aircraft is less than prescribed minima.

[10]Goldmuntz, op. cit.; and G. C. Kinney, M. J. Spahn, and R. A. Amato, ***The Human Element in ATC: Observations and Analyses of the Performance of Controllers and Supervisors in Providing ATC Services***, MTR-7655, The MITRE Corp., December 1977.

Thus, AERA cannot be expected to replace the present generation of en route ATC until sometime near the end of the century. Similarly, the development costs and subsequent expenditures for facilities and equipment (F&E) have not yet been estimated, except in the most general terms. The latest available projections of R&D expenditures for en route control systems over the coming 10 years, much of which would be for AERA, show a total outlay of *$170* million (1980 dollars).[11] As of the writing of this report, detailed estimates of the required F&E investments and costs to users for avionics appropriate to AERA have not been published.

Three major implications of AERA are already apparent, however. One is that AERA would require computer capacity and software far beyond what is now available in ATC applications, although not beyond the present or foreseeable state of computer technology. Second, AERA will require a two-way data link capable of rapid and high-volume exchange of information between the air and the ground. FAA now envisions that Mode S will provide this data link, and plans for AERA are predicated on the availability and widespread use of Mode S by the early 1990's. (See the discussion of "data link" in the following section.) Third, AERA implies equally extensive automation in terminal areas and in a central flow management facility capable of coordinating traffic throughout the ATC system.

This last point is particularly important both for the immediate plans to replace en route computers and for the design of the entire ATC system over the long term. It implies a modular computer architecture, in which en route and terminal facilities utilize similar hardware and software. This would make possible a flexible system design, in which individual modules would be capable of mutual support and backup in the event of local equipment or software failure. Human controllers would have difficulty operating the ATC system manually in the event of a failure of AERA if adequate automated backup were not provided.

"*National Aviation System Development and Capital Needs for the Decade 1982-1991* (Washington, D. C.: Federal Aviation Administration, December 1980).

The development and implementation of AERA is likely to raise several important issues. Some are technical and concern the reliability and safety of AERA, specifically its vulnerability to undetected software errors or hardware failures, and the adequacy of current hardware and software design techniques. The degree of automation envisioned for AERA may also be controversial, and this could give rise to issues pertaining to the division of tasks between human operators and computers or the design of the man/machine interface. The design will have to include features that keep the controller's attention and insure that he has enough information to deal promptly with anomalous situations as they arise. Acceptance of the system by both controllers and airspace users may prove to be troublesome.

A third set of issues pertains to the costs and benefits of AERA, especially the savings in operational costs ascribed to AERA in comparison with the investments needed to implement the system. A corollary question will be the costs and benefits to various classes of airspace users, especially if AERA entails mandatory equippage with data link or other avionics in order to participate in the automated ATC environment. Resolution of these issues, rather than the somewhat narrower questions of technical feasibility or system design, may prove to be critical to the acceptance and success of the AERA concept.

Data Link

Potential Benefits

Communication is central to the ATC process, and at present voice communication is the primary medium even for messages that involve computers processes. For example, a controller reads data from a computer-generated display, transmits it by voice radio to an aircraft, and the crew then enters the data manually into an onboard computer. This process wastes crew and controller time and is prone to reading or transmission errors. As the ATC system changes to incorporate higher levels of automation, therefore, great benefits could be gained from a digital data link that permits direct communication between automated components. Among these potential benefits are the following:

- Digital messages can include special codes to detect and correct transmission errors.
- Processes that are running on computers can exchange data of little immediate interest to the human participants without human involvement.
- Digital transmissions can be addressed to a specific recipient such as an aircraft without diverting the attention of others to whom the information is not of concern.
- Digital messages can be transmitted, stored by the receiving terminal, and recalled on demand by the recipient.

In the present ATC system, the ATCRBS transponder provides limited data communication, Digital messages are sent by the transponder in reply to interrogations from the ground that request aircraft identity (transponder code) or altitude. Some observers, as discussed later in this section, argue that the inherent capability of the ATCRBS transponder is currently underutilized and that it is capable of meeting many of the future requirements for a digital data link. Others, including FAA and a significant segment of the user community, question this conclusion.

While there is little dispute that a data link is needed for the ATC system of the future, there is considerable discussion on how it would best be implemented. * FAA has suggested the addition of a data link capability—Mode S—to the specifications for the standard ATCRBS transponder. Others have suggested alternatives, and one organization, Aeronautical Radio, Inc. (ARINC), is now operating a nationwide data link that is used by the airlines for administrative communication. These alternatives are described in the sections that follow.

● Data links are also used to connect computers at the various ATC facilities operated by FAA. They use leased commercial telecommunication facilities at the present time; but in the future, satellites might be used to perform this function more efficiently. For this discussion, which will focus on data links for air-to-ground and air-to-air communication, the links between the ground-based computers are not of direct interest.

Mode S

The operating characteristics of the ATCRBS transponder conform to a standard established by the International Civil Aviation Organization (ICAO). For civil aviation, four modes of operation are defined, of which only two are in actual use: Mode A for aircraft identity, and Mode C for aircraft barometric altitude. Interrogation messages are formatted so that the transponder will recognize the mode of the query and reply appropriately. Since the transponder is already the primary link between ATC computers on the ground and aircraft in flight, it is logical to argue that the data link function be incorporated in the transponder.

FAA has suggested adding a fifth mode, Mode S, to the specification for the ATCRBS transponder. ** This mode would provide a general-purpose data link designed to operate in a manner compatible with the existing ATCRBS modes. Mode S was on the agenda at the April 1981 meeting of the ICAO Communications Division, and position papers relating to it have been circulated among members. Great Britain and the Soviet Union have independently developed data link specifications that are compatible with Mode S. As of now, however, no member of ICAO has formally proposed detailed specifications that could be adopted as a Mode S standard.

Mode S permits a digital message to be addressed to a specific recipient. Each aircraft would have a permanently assigned code to identify itself in all ATC-related communications using the data link. When a Mode S interrogation or message is sent, replies from all transponders operating in Modes A and C are suppressed. Thus, during any transition period, interrogations cycles would have to be divided between Mode S interrogations and those in the existing Mode A and Mode C formats.

One of the applications of Mode S is for the surveillance function of the ATC system. When two aircraft are in proximity (i.e. in line or almost in line and differing in range from the inter-

● *Until recently, Mode S was referred to by FAA as DABS (Discrete Address Beacon System).

rogating ground station by 1.5 miles or less), their replies to a Mode A or C interrogation will interfere with one another, creating what is called "synchronous garble." The ability to address the interrogation to a specific aircraft is one method of resolving this difficulty. Other methods, such as computer processing of returns or the use of multiple sensors, can accomplish much the same thing.

A second anticipated benefit from Mode S would be the ability to deliver control messages, such as clearances and en route weather information, to specific aircraft. The data needed to generate onboard displays of traffic could also be transmitted using this technique. Further, a Mode S data link could be useful in an exchange of data between aircraft, allowing them to coordinate conflict-resolution maneuvers (i.e., as an element in a collision avoidance system). Again, however, Mode S is not the only means by which these needs could be met.

Modes B and D

Most of the cost of implementing Mode S would be borne by the users, although some expenditures by FAA for the modification of its computers and software would be required. Some observers, however, consider the expense required for the introduction of Mode S to be unwarranted. They argue that the capability of the present ATCRBS transponder is underutilized. Modes B and D, it is suggested, could be used for some data link purposes, since they have sufficient capacity to meet the needs of the ATC system and would require no change in the existing ICAO specification. In addition, the message format for Modes B and D is shorter than that suggested for Mode S, and therefore less likely to result in the interference that might occur between Mode S transponders replying to simultaneous interrogations from different stations. However, in considering this alternative, one should also note that existing transponders do not include the components needed to process Mode B and D interrogations and would have to be modified (at users' expense) to do so.

VHF Data Link

A second alternative to Mode S is the use of a part of the VHF radiofrequency band assigned to aeronautical voice communication. ARINC, a corporation organized and owned by the airlines to provide communication services, already operates **a** data link of this type, know as ARINC Communication Addressing Reporting System (ACARS), which is being used by airlines for administrative messages. At present, small printers in the cockpit **are** used to record ACARS messages. A future modification could be conversion of the onboard weather radar screen or one of the multipurpose displays used by electronic instrument systems found in some aircraft to double as a display for ACARS messages.

Some critics suggest that ACARS would not meet the requirements for an ATC data link, pointing out that the VHF voice band is already crowded and that the one frequency used by ACARS (although currently underutilized) would not have sufficient capacity to meet the needs of the ATC system. This deficiency could be overcome by assigning multiple frequencies and scanning them automatically to detect incoming messages. There has also been a start (for reasons having little to do with data link) at reducing the current 50 kHz spacing in the VHF band to 25 kHz, effectively doubling the number of channels available. Some of these new channels could be allocated to the data link function.

Potential Implications and Issues

A data link is a primary resource that can be applied in a number of ways, and the benefits obtainable will be a function of the purposes to which it is applied. If the data link is to be used primarily for surveillance, then it would be advantageous to integrate it with the radar beacon system. On the other hand, if it is used primarily for nonsurveillance purposes such as delivering clearances, reporting weather conditions, or sending and receiving advisories, the need to associate it closely with the radar beacon system is less compelling. The balance in traffic between the uplink and downlink is also significant. If the great majority of the message traffic is "up"- from ground to air—the ground station could assume responsibility for allocating time among users. If there is a substantial flow of information in the opposite direction—air to ground, with a large part of it initiated by aircraft—the task of coordinating the activities of the users would become much more difficult. The latter situation would be complicated further by the introduction of substantial amounts of air-to-air traffic, as in the Traffic Alert and Collision Avoidance System (TCAS) concept (described later).

In considering the candidate forms of data link, another important consideration to keep in mind is that the data link is not an isolated subsystem of ATC, nor does it provide any unique service. Some form of data link is indispensable to the future scheme of operation and services envisioned by FAA, such as AERA and the collateral improvements of terminal area control and central flow management. The level of automation and the degree of strategic and tactical control that AERA would bring about requires a high-speed and high-volume flow of information, decisions, and replies between the air and the ground. Thus, even though FAA is committed to Mode S, it is important that all questions about data link be promptly resolved and that the necessary ground facilities and aircraft avionics be put in place so as to keep pace with the parallel computer replacement program. Both of these resources will have to be available within a decade if longer range improvements are to be accomplished in the 1990's.

It is also important to recognize that the data link decision is not one where the United States can act with complete independence. ATC requirements and development programs of other nations must also be considered, and the direction chosen by FAA must be coordinated through ICAO to ensure compatibility of signal format, modes of operation, equipment characteristics, and the like. On balance, a data link system that is compatible with the needs of other ICAO member nations is preferable to one that is unique to the United States.

Another important aspect of the data link decision concerns the avionics equipment that airspace users will have to install in order to take advantage of the services that data link offers. The data link is more than just a special kind of high-speed receiver-transmitter: to make any meaningful use of this capability, aircraft will also have to be equipped with processors to encode and decode messages, and with some kind of input-output device (displays and controls) that presents information to the aircrew and allows them to interact with the onboard processors and ground stations. Such equipment is costly to acquire (about $10,000 for a commercial aircraft, but somewhat less for GA) and would require special maintenance. For commercial and corporate operators the expenses of acquisition and maintenance could be absorbed without great difficulty, and the costs would probably be offset by operating benefits such as fuel savings, avoidance of delay, and greater flexibility of flight planning. For smaller GA operators, on the other hand, the cost-benefit equation may not be as favorable, and they may consequently conclude that the expense is not justified by the improved services or operational savings made available to them.

The matter could become particularly acute for GA if equipage with data link avionics were to be made mandatory for access to airspace or for receipt of essential ATC services. FAA currently envisions a tiered program of services in which users receive progressively more extensive service in relation to the sophistication of the avionics carried on the aircraft. The concern of GA is that the areas in which they will be allowed to operate with only minimal equipment (that is, without a two-way data link) will become so restricted that small GA aircraft will be effectively excluded from the Nation's airspace. The extent to which these concerns are warranted will depend heavily on the type of data link that is selected and how it is to be incorporated in various classes of aircraft.

Collision Avoidance

A primary function of the ATC system is providing separation assurance. Ground-based surveillance equipment and computer software include features that will alert the controller to situations where separation standards have been violated or are about to be violated. Nevertheless, a small number of midair collisions and near misses continues to occur, most of them involving aircraft not under positive control. At the present level of traffic, the probability of collision is very low, but as traffic density increases, so does the threat of collision. The few accidents suffered by commercial carriers have heightened public awareness of the consequences of a midair collision involving large passenger aircraft. This common concern has led to significant public and private efforts to develop collision avoidance systems that would give the aircrew direct warning of the threat of collision.

A collision avoidance system is conceived as a last-resort measure to protect against collisions; it would come into play only after all other means to ensure separation have failed. A collision avoidance system is not intended to be the primary method of ensuring the separation of aircraft. But the extra margin of safety provided by a collision avoidance system could lead to changes in ATC procedures for separation assurance. For example, a reliable collision avoidance system could justify a reduction in separation standards, thus effectively increasing the capacity of the airway and airport system. This section discusses some of the alternative collision avoidance systems that have been proposed over the years in order to give the reader an awareness of their relative merits and implications.

In general, two major classes of collision avoidance systems have been proposed: those that depend on ground facilities; and those that require only airborne equipment. Ground-based collision avoidance systems characteristically require the expenditure of Government funds for facilities and equipment, while airborne systems do not. Some of the so-called airborne systems, however, are in fact passive users of ATC equipment—that is, they "eavesdrop" on replies to ATCRBS interrogations from ground surveillance stations in order to obtain the data needed to locate nearby aircraft. Some systems would be effective only when a large portion of the aircraft in the fleet are equipped, while others would provide some protection regardless of the number of users who install the equipment.

Beacon Collision Avoidance System

The Beacon Collision Avoidance System (BCAS) is one that had been under development by FAA for some time and was nearing the point of implementation when FAA made the decision, in the summer of 1981, to adopt another system that is a derivation of BCAS (see below). The initial version of BCAS, known as Active BCAS, would have been implemented first; and Full BCAS, a more complex version designed to operate in congested airspace, would have followed several years later.

In operation, Active BCAS on board aircraft would emit interrogation pulses to which ATCRBS and Mode S transponders on the other aircraft would reply in the same manner as they would reply to an interrogation from a ground station. The BCAS concept offered immediate protection against aircraft equipped with Mode C ATCRBS transponders and altitude encoders and promised more efficient performance and broader protection against aircraft equipped with Mode S Transponders. The BCAS system used the elapsed time between interrogation and reply to determine the range to other aircraft, and by calculating the rate of closure it determined the potential for collision. If a collision threat were detected, an indicator would advise the pilot whether to climb or descend to resolve the conflict. The DABS data link was to be used to coordinate the maneuvers of two BCAS-equipped aircraft. Active BCAS did not, however, provide the pilot with the relative bearing of the intruder aircraft. * Full BCAS, in addition to originating interrogations, also gathered data by listening to replies to interrogations from the ground and correlated these replies to determine bearing as well as range.

There was little question that BCAS would be effective in low-density airspace, but there was considerable concern that the system would become saturated in areas of high-traffic density where a collision avoidance system is most

* A proposed follow-on version of Active BCAS would have provided direction-finding capability.

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needed. For this reason, FAA planned to install ground equipment (an RBX transmitter) to suppress BCAS and prevent system saturation in areas of high-traffic density where it planned to rely instead on a ground-based system called the Automatic Traffic Advisory and Resolution Service (ATARS) to resolve conflicts. ATARS would use ATCRBS and Mode S interrogations and replies to gather traffic data and convey traffic information to suitably equipped aircraft by means of the Mode S data link; ATARS was designed to provide a turning manuever as well as the climb or descend maneuver of BCAS.

While ATARS would overcome the major weakness of BCAS, however, it would also require considerable expenditure for both ground and airborne equipment. Both BCAS and ATARS planned to use the Mode S transponder as a key element, and both therefore were caught in the debate that surrounded the Mode S data link concept. Some critics have claimed that Full BCAS would be required to support a cockpit display of traffic information (CDTI), since the simpler Active BCAS provided no intruder bearing and thus could not provide the aircrew with a picture of surrounding traffic analogous to that available to ground controllers. In many cases it was difficult to separate the arguments for and against DABS from those pertaining to a collision avoidance system.

Tri-Modal BCAS

Tri-Modal BCAS was one proposed alternative to the BCAS program. It was similar to BCAS in concept but based on the existing ATCRBS transponder rather than the new Mode S capability, and it would operate in three different modes. In areas of high traffic density, Tri-Modal BCAS would operate passively, generating all of the required information by analyzing standard ATCRBS transponder replies to interrogations from ground surveillance stations. In areas without coverage by ground radar, it would operate like Active BCAS. Where coverage was provided by only one ground radar station, it would operate in a semiactive mode to generate its own interrogations while also listening to replies to interrogations from the ground station. The logic used by Tri-Modal BCAS would enable it to determine both range and bearing in airspace adequately covered by ground interrogators and, thus, to generate the data needed to support a CDTI.

Advocates of Tri-Modal BCAS cited the following advantages of this system:

- It does not require the Mode S transponder and provides full protection from all aircraft equipped only with a standard ATCRBS transponder.
- In airspace where the geometry of the distribution of ground-based interrogators is appropriate, it provides bearing without requiring the directional antenna that is needed for TCAS (discussed next) and Full BCAS.
- It requires no change to the ground facilities except for the activation of the north pulse on the secondary surveillance radars now installed.
- It can operate independently of all ground facilities in the same manner as active BCAS.

NASA, with the sponsorship of FAA, successfully tested Tri-Modal BCAS, but its report indicated that the tests were not exhaustive because a working model that included all of the features of the system was not available. However, the developers of the system have continued their work since the NASA tests and claim that their system is ready for certification and operational use.

Traffic Alert and Collision Avoidance System

After supporting the development of BCAS for several years, FAA announced in the summer of 1981 its decision to adopt an enhanced air-to-air version of BCAS, the Traffic Alert and Collision Avoidance System (TCAS). The abruptness of this change has led to controversy in the aviation community, and various observers have questioned both the suitability of TCAS and its superiority to alternative systems.

TCAS is a direct derivative of BCAS and is designed to meet the following criteria:

- It does not require ground-based equipment.
- It is compatible with the present ATC system and a logical extension of it.
- It is more suitable for use in high-density traffic than BCAS.
- It offers a range of capabilities suitable to the needs of various classes of airspace users.

To meet the last criterion, two versions of TCAS have been specified; both include the Mode S data link as an integral component.

TCAS I is designed for use by general aviation and the basic system is estimated by FAA to cost in the range of *$2,500* to *$3,500* per aircraft. TCAS I would indicate to the pilot the presence of a transponder-equipped aircraft without providing either range or bearing information; it would be the responsibility of the pilot to locate the intruder by visual means and to take the appropriate action. An upgraded version of this basic system would provide the pilot with intruder range and bearing and with information describing the maneuver that a TCAS II-equipped aircraft intended to execute. TCAS I estimates range by the strength of the signal received from another aircraft, at best an imprecise measure, and in high-density airspace the proximity-warning indicator tends to be triggered repeatedly, thus minimizing its value as a warning device (if the false alarm rate is high, pilots might tend to ignore the warning). The addition of an altitude stratified in TCAS I, however, appears effective in minimizing high alarm rates.

TCAS II is a more sophisticated version designed for use by air carriers and larger corporate GA aircraft. FAA estimates that the necessary avionics will cost on the order of *$45,000* to $50,000 per aircraft, slightly more than the projected cost of an Active BCAS unit. TCAS II operates in the same way as Active BCAS, but with two major enhancements:

- A directional send-receive antenna that will provide both range and bearing without creating the interference in areas of high traffic density expected with Active BCAS.
- The ability to transmit to TCAS I and other TCAS II aircraft information regarding its relative location and the intended maneuver to resolve a conflict.

Initially, the TCAS 11 antenna will provide bearing information accurate to within 300, sufficient to provide the pilot with an “o’clock” indication of relative bearing and activate a climb or descend indicator. In later versions, FAA plans to specify an antenna with much higher angular resolution (1° to 2°), which would permit the system to generate a command for a horizontal as well as a vertical maneuver. The improved version would also support a CDTI.

FAA has issued a contract for the development of the high resolution antenna to determine if or when an antenna with this degree of resolution, yet suitable for installation on commercial aircraft, can be designed and tested. One early version of the sector scan TCAS II antenna was approximately 18 inches in diameter and extend slightly above the fuselage contour. Mounting such an antenna might require significant modifications of aircraft structure even on a large aircraft; the problem would be more severe in the case of small GA or tactical military aircraft. Further, if a large antenna were to result from the development efforts, it could have detrimental effects on aerodynamics, aircraft performance, and fuel consumption.

The adoption of TCAS means that the DABS transponder remains a key element in FAA plans. However, the fact that TCAS is ground-independent and capable of operating in airspace with high-traffic density puts in question the need for ATARS, one of the key applications heretofore envisioned for DABS. There are strong indications that FAA will drop ATARS from its plans and that, as a result, the level of expenditures on ground equipment will be significantly less than they would have been had the ATARS program been implemented.

FAA has also made a point of leaving the way open for entrepreneurial innovation in the development of TCAS, Thus, it is conceivable that FAA might certify other collision avoidance systems if their capabilities were demonstrated and if they would not interfere with TCAS or other elements of the ATC system.

For instance, TCAS and Tri-Modal BCAS could operate in the same environment because both depend primarily on responses from airborne equipment and neither requires the installation of equipment on the ground. However, as noted above, the TCAS concept contains a provision for coordinating conflict-resolution maneuvers of TCAS-equipped aircraft. Such coordination would not be possible between an aircraft equipped with TCAS and one equipped with Tri-Modal BCAS as these systems are presently designed. On the other hand, the TCAS concept does not assume that it will always be possible to coordinate the maneuvers of aircraft in a conflict situation. Therefore, the inability to coordinate the maneuvers of TCAS and Tri-Modal BCAS aircraft does not present an insurmountable barrier to operation of the two systems in the same environment.

Airborne Collision Avoidance System

All of the alternative collision avoidance systems that have been discussed to this point are capable of providing users some level of protection from aircraft that are not similarly equipped. The Airborne Collision Avoidance System (ACAS), which was developed and demonstrated in the 1970's, was not based on the ATCRBS transponder and could have been made available for about $1,500 per aircraft (1977 dollars), considerably less than the alternatives being considered at that time. A major drawback of this system, however, was that it would not be effective unless a substantial portion of the aircraft operating in a given area were ACAS-equipped.

Conceptually, the operation of the ACAS system was simple. It generated interrogations to which all aircraft within a specified altitude band would respond. Range was determined from the delay between interrogation and reply, and when an aircraft was detected at close range, subsequent interrogations narrowed the altitude band from which a reply was requested in order to determine whether a detected aircraft presented a threat of collision.

ACAS is no longer being actively considered as an alternative collision avoidance system, but it is presented here to illustrate another group of alternatives that have been explored in the past.

Microwave Landing System

Instrument Landing System

Providing precise and reliable guidance for approach and landing in conditions of reduced visibility is a prime consideration for safety of flight, but it also has important implications for the efficient use of terminal area airspace and airport runways. Generally, the highest runway utilization rates are achieved under VFR. When restricted visibility or weather conditions dictate increased separation and the use of instrument approaches, one consequence is a reduction in the number of aircraft that can be landed in a given space of time.

In part, this reduction in airport capacity utilization is a result of the guidance system in use. The present Instrument Landing System (ILS), which has been the standard U.S. system since 1941, provides guidance along a straight path at a fixed slope of 3° or less extending 5 to 7 miles from the runway threshold. All aircraft approaching the airport must merge to follow this path in single file, spaced at intervals dictated by separation minima and the need to avoid wake vortex. Aircraft flying at different speeds along this single fixed path complicate the controllers task in achieving a uniform rate of traffic flow and diminish the capability to use the full capacity of the runway served by ILS.

The runway utilization rate under IFR could come closer to that attainable under VFR if aircraft could be permitted to follow multiple approach paths, descend at different flight angles, fly at different approach speeds, or aim at different touchdown points on the runway—none of which can be done with ILS. If these variations were possible, as they are under VFR, the IFR capacity of the airport would be increased to a limit determined almost solely by the rate at which successive aircraft could touch down, decelerate, and clear the runway. *

● Wake vortex, for example, would remain a constraint on capacity even if MLS with curved and variable glide slope approaches were installed.

Table 7.—Summary of Functional Characteristics of Alternative Collision Avoidance Systems

A/C #1 → / A/C #2 ↓	ATCRBS	ATCRBS ALT ENC	DABS	TCAS I**	TCAS II	BCAS* Active
ATCRBS	None None	None None	None None	Proximity from SSR response for aircraft in radar coverage (bearing) None	Range, range rate, bearing traffic advisory None	Range, range rate, bearing traffic advisory None
ATCRBS ALT ENC	None None	None None	None None	Proximity from SSR response for aircraft in radar coverage, some altitude filtering (bearing) None	Range, range rate, bearing altitude traffic and collision avoidance advisories None	Range, range rate, bearing altitude traffic and collision avoidance advisories None
DABS	None None	None None	None None	Proximity from DABS response and from squitter altitude filtering (bearing) None	Range, range rate, bearing altitude traffic and collision avoidance advisories None	Range, range rate, bearing altitude traffic and collision avoidance advisories None
TCAS I**	None • Proximity from SSR response for aircraft in radar coverage (bearing)	None • Proximity from SSR response, some altitude filtering for aircraft in radar coverage (bearing)	None Proximity from DABS response and squitter altitude filtering (bearing)	• Proximity from DABS response and squitter altitude filtering (bearing) • Proximity from DABS response and squitter altitude filtering (bearing)	Range, range rate, bearing altitude traffic and collision avoidance advisories • Traffic advisory and above-below information from TCAS II	Range, range rate, bearing altitude traffic and collision avoidance advisories Proximity from SSR response and from squitter altitude filtering (bearing)
TCAS II	None • Range, range rate, bearing traffic advisory	None • Range, range, rate, bearing altitude traffic and collision avoidance advisories	None Range, range rate (bearing) altitude traffic and collision avoidance advisories	• Traffic advisory and above-below information from TCAS II • Range, range rate (bearing) altitude traffic and collision avoidance advisories	• Range, range rate bearing altitude traffic and coordinated collision avoidance advisories • Range, range rate (bearing) altitude traffic and coordinated collision avoidance advisories	Range, range rate bearing altitude traffic and coordinated collision avoidance advisories Range, range rate bearing altitude traffic and coordinated collision avoidance advisories
BCAS* Active	None None	None Range, range rate bearing altitude traffic and collision avoidance advisories	None Range, range rate (bearing) altitude traffic and collision avoidance advisories	• Proximity from SSR response and from squitter altitude filtering (bearing) • Range, range rate (bearing) altitude traffic and collision avoidance advisories	Range, range rate, bearing altitude traffic and coordinated collision avoidance advisories Range, range rate (bearing) altitude traffic and coordinated collision avoidance advisories	Range, range rate, bearing altitude traffic and coordinated collision avoidance advisories Range, range rate (bearing) altitude traffic and coordinated collision avoidance advisories

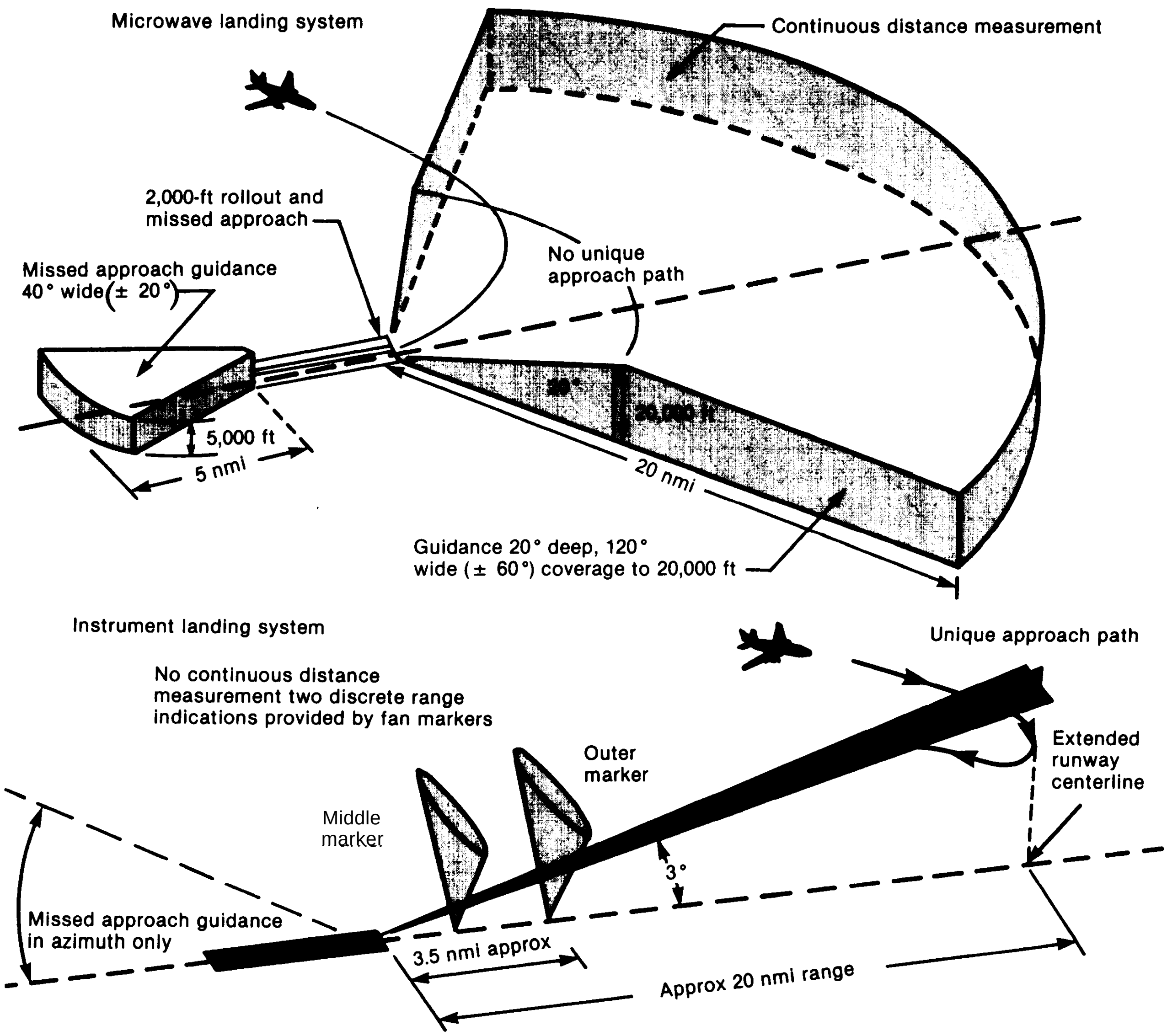
Performance degradation in high density traffic areas.
**Bearing information with optional direction finding antenna provides limited traffic advisories for TCAS I (no range or range rate) and full traffic advisories for active BCAS.
SOURCE: A. Scott Crossfield.

Microwave Landing System

A precision approach and landing system that overcomes these inherent disadvantages of ILS is the Microwave Landing System (MLS). Because MLS uses a scanning beam, rather than a fixed beam like ILS, it allows aircraft to fly any of several approach angles (including two-step glide slopes) and, in the lateral plane, to approach along complex paths that intersect the alinement of the runway at any selected point (see fig. 25). This capability is useful **in avoiding** noise-sensitive areas on approach paths and reducing the impact of the wake vortex problem.

MLS offers other important advantages in comparison with ILS. The reliability of the MLS signal is not influenced by ground-plane effects (snow buildup, soil moisture, tidal effects, etc.); this permits MLS to be installed at sites where ILS will not function properly. Fixed or moving obstacles in the approach zone do not interfere

Figure 25.—Comparison of Microwave Landing System and Instrument Landing System



SOURCE: Federal Aviation Administration.

with MLS signals to the same degree as with ILS. In addition, MLS also provides precision guidance for departures and missed approaches, a feature of particular importance when traffic patterns of closely located airports are in conflict. MLS operates in a frequency band that provides *200* transmission channels; ILS has used only *20* of the *40* channels theoretically available to it, and these are very near saturation in large hubs such as New York and Los Angeles. Finally, ILS does not meet the joint civil/military operational requirement for precision approach, since it does not afford the tactical flexibility needed by military aircraft. MLS does.

For these reasons, FAA has designated MLS as the precision approach guidance system to replace ILS. The MLS transition plan, published by FAA in 1981,12 calls for 1,425 installations to be carried out in three phases over the next 20 years. In the first phase, between 10 and 25 systems will be installed over a period of 2 years at selected airports in order to develop a base of experience and reach an operational confirmation of the benefits that MLS can provide. The second phase will see the installation of 900 additional MLS units at a rate of 100 to 150 per year over a period of 6 to 9 years, with priority given to large and medium hub airports. The third phase involves installation of an additional 300 to *500* units to meet the growth in demand anticipated by the end of this century. FAA estimates the cost of purchasing and installing 1,425 MLS ground units to be $1.332 billion (1981 dollars); the cost to users to equip their aircraft with MLS is estimated to be an additional $895 million, yielding a total cost of roughly $2.2 billion.[13]

In selecting the transition plan, FAA worked in consultation with various user groups under the auspices of Radio Technical Commission for Aeronautics, and considered 10 deployment strategies—9 submitted by FAA and 1 developed by RTCA Special Committee 125. These strategies differed in terms of the order and rate of deployment at various sites, the length of the period of duplicative operation with ILS, and assumed rates of user equipage. Each strategy was analyzed to estimate costs, benefits, and operational effects. All strategies yielded favorable net benefits in the range of *$2.4* billion to $2.7 billion. The costs of the 10 strategies varied narrowly ($1.20 billion to $1.35 billion for ground units), as did the benefits ($3.65 billion to $4.05 billion). These results led FAA to conclude that "there is no clear-cut economic rationale for choosing among the MLS implementation strategies" and that "the choice should be based upon operational considerations or on the special opportunities for improved precision guidance service created by the installation of MLS equipment."[14] The strategy selected by FAA reflects these considerations.

Potential Implications and Issues

There are two factors that may complicate the MLS transition plan, both of them involving the replacement of the existing ILS. As of March 1981 there were 653 ILS units in commission at 458 airports, and an additional 155 units were in various stages of procurement or installation. Thus, the MLS transition plan has to take into account how these ILS sites, many of them recently commissioned and with many years of service life remaining, are to be phased out. ILS and MLS can be colocated and operated simultaneously without signal interference or procedural difficulty, but the length of the period of joint operation and the timing of ILS decommission at specific sites could create difficulties for some classes of airport users. FAA transition plan stipulates that no ILS will be removed until all of the network's Ill-equipped airports have operational MLS and at least 60 percent of the equipped aircraft routinely using the ILS/MLS runway are MLS-equipped. When this occurs however, 40 percent of the regular users of a given airport could lose the precision-landing service, even though they continue to operate with functioning ILS equipment.

The second complication is that, by ICAO agreement, the United States is committed to retain ILS service at international gateway airports through 1995. There are 75 such airports at pres-

''*Microuumw Landing System Transition* **Plan, APO-8 I-I** (Washington, D. C.: Federal Aviation Administration, May 1981).
"Ibid.

[14]*Microwave Landing System* **Transition** *Plan*, op. cit

ent, and generally they are among the busiest U.S. airports. The retention of ILS service at these sites may cause some users to delay purchasing MLS equipment, since the installed ILS equipment will still be usable for another 10 years or more.

Despite the overall favorable benefit-cost ratio of MLS indicated by FAA analysis, the specific benefits and costs to various classes of airspace users remains a subject of controversy. FAA's analysis showed high positive net benefits to air carriers and commuters largely due to the value attributed to passenger time saved. For general aviation as a whole, the costs exceeded the benefits for all 10 deployment strategies, although some classes of GA (notably corporate GA operating multiengined piston and jet aircraft) were shown to derive substantial benefits from MLS. Thus, there is likely to be continued resistance to MLS from some GA operators, probably in the form of opposition to decommissioning ILS at specific sites and reluctance to purchase MLS equipment (at a cost of $5,000 or more) so long as ILS is available.

It is also likely that specific details of the MLS transition plan will continue to arouse debate. Comment received by the FAA during the course of preparing the plan indicates that there are several sensitive points. One potential issue is the priority given to installation of MLS at different types of airports. For example, commuter airlines favor early deployment at small community airports, while the Airline Pilots Association seeks to have MLS first installed at hub airports on runways not now Ill-equipped. Other user groups, for example the Air Transport Association, recommend an installation strategy that would create a network connecting major airports (including many now equipped with ILS), in order to encourage users who fly these routes frequently to install MLS equipment on their aircraft. Another, slightly different, recommendation would involve establishment of a major-city network but with priority also given to installation at sites where it is not possible to locate an ILS and at small community airports that have commercial service but not an ILS.

AS a final point, the MLS transition plan proposed by FAA may encounter administrative and budgetary difficulties. The plan, particularly Phase II, is highly ambitious in that it calls for installation of 900 units at a rate of 100 to 150 per year. It may be technically and administratively difficult to sustain such a pace, and it might be even more difficult to justify the required annual outlay of funds in a time of budget austerity. Implementation of Phase II would entail annual expenditures of $125 million on a 6-year schedule, or $85 million on a 9-year schedule. Stretching out Phase II, in order to hold it within some imposed budgetary limit, is an alternative that may have to be adopted, even though it might increase overall program costs and defer realization of the full benefits of MLS.

ALTERNATIVE ATC PROCESSES

FAA is nearing the end of research and development of several major components of the ATC system and is about to begin operational deployment of these new technologies. Most of the system improvements planned by FAA would continue the present trend toward a ground-based, centralized control system with increasingly more extensive requirements for avionics and more restricted forms of operation. These plans would also entail a major commitment of funds by the Federal Government and the aviation community. It is important that the Congress be satisfied, not only as to the soundness and appropriateness of these prospective system changes, but also as to whether FAA's plans take into account the new alternatives that are being made available by emerging technologies.

There are five aspects of the future ATC system on which new technologies might have an especially important influence in creating new options:

- the role of the human operator;

- tactical v. strategic control;
- autonomy and flexibility of control;
- ground v. satellite basing; and
- levels of service.

Role of the Human Operator

The AERA concept implies that computers will assume many of the controller's routine decisionmaking tasks and, by means of digital data link, many of the communications tasks as well. The immediate consequences would be that fewer human operators would be needed to handle a given volume of traffic and that the human role would evolve toward that of a manager of automated resources.

However, there would also be important consequences for the pilot. The increased level of automation on the ground would bring a corresponding increase in opportunities to employ automation in the cockpit. Aircrew dependency on airborne data processors and displays would increase as more information would be transmitted digitally and the relative importance of the voice channel waned.

Another consequence of automation is that the burden of responsibility for operational reliability would shift. Safety would be assured more and more through the design process and less through the compensatory actions of the human operator.

Tactical v. Strategic Control

A system supported by powerful data processors can collect, analyze, and distribute information on a much wider scale than the present ATC system. This makes it possible to plan and coordinate the movement of traffic over a broader area and a longer span of time. The basic mode of control could therefore become more strategic and anticipatory—relying more on prevention of conflict through planning, and less on tactical or reactive response to actual or imminent violations of separation minima.

For the ground controller, whether human or computer, the principal task would be monitoring aircraft movements to ascertain conformance with a flight plan that, through planning, had been determined to be conflict-free. For the pilot (aided by a flight management computer and onboard ATC systems), the principal task would be to fly from origin to destination without deviating from that flight plan unless unforeseen circumstances (such as weather or deviations of other aircraft) forced rerouting. Tactical control measures would still be available, but they would be called into play only when strategic measures proved inadequate to forestall conflict.

Autonomy and Flexibility of Operation

IFR control is now centralized on the ground because only the ground controller has the information needed to assure separation and an orderly flow of traffic. However, improvements in communication and processing technologies have made it possible to redistribute information among the various participants in the ATC system.

Given greater access to information, aircrew could become more active participants in the ATC process. As the quality and timeliness of the information improves, interaction with ground controllers could become infrequent. However, there is a logical limit to their independence from ground control, because overall strategic control of the flow of traffic will remain a ground-based function.

Ground v. Satellite Basing

Navigation and surveillance functions in the present system are ground-based, as are the facilities for relay of air/ground radio transmissions. The development of space technology makes it possible to consider satellites as alternatives for all three purposes. Satellites could be used in either an active or a passive mode. In the passive mode, they could serve as relay stations for communication between the air and the ground or between ground sites where present methods are limited to line of sight. Satellite-mounted transponders could also provide position reference for airborne navigation systems. In an active mode, data processing capabilities could be installed in satellites to track aircraft and report their location to ground-based control facilities, either replacing or supplementing surveillance radar.

Levels of Service

Under the present ATC system there are only two forms of operation—controlled (corresponding roughly to IFR) and uncontrolled (corresponding roughly to VFR). In the future, improvements in ground-based and airborne technologies could make it possible to provide intermediate levels of ATC services between these two extremes. The level of service could vary according to 1) the density of traffic; 2) the mix of aircraft; 3) the avionics carried by those aircraft; 4) flight conditions; and 5) the ground-based capability for separation assurance and traffic management. The result could be a more varied range of services, more closely tailored to the needs and capabilities of the airspace users, than is now the case.