Chapter 7

Air Traffic System Technologies

Photo credit: Federal Aviation Administration

An FAA Air Route Traffic Control Center

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The Federal Government's major operating responsibility for aviation safety lies in its management of the air traffic system. This system has many individual, interdependent components, each of which affects the safety and capacity of the overall system. Significant components of the current air traffic system are: 1) airports, 2) air route structure, 3) the air traffic control (ATC) system, including hardware, software, and the humans who operate and maintain the system, and 4) communications. Any increase in capacity in one component of the system (e.g., airports) must be accompanied by adequate capacity in the other components for it to have an effect on overall system capacity. In day-to-day operations, the Federal Aviation Administration's (FAA) Central Flow Control uses weather technologies to predict airport capacity, and holds aircraft on the ground when the predicted demand on a destination airport exceeds its capacity in bad weather. Other components of the air traffic system include navigation and surveillance systems, as well as collision avoidance technology currently under development to back up the ATC system.

Recent growth in commercial air traffic has exerted pressures on several parts of the air traffic system. For example, air traffic levels have grown enormously since deregulation without a comparable increase in airport capacity, Moreover, ATC centers must operate using aging equipment and some do not have enough adequately-trained personnel. The hub and spoke system of airline operations has "loaded" hub airports with traffic, causing traffic levels to peak sharply at certain periods during the day and increasing schedule disruption when a flight is canceled or delayed because of weather, equipment malfunction, or any other reason.

If demand for air transportation continues to increase and no actions are taken to address capacity issues, delays will increase and the high level of safety now maintained by the ATC system may deteriorate. Because of the complexity of the system, particularly the human element, it is extremely difficult to determine precisely at what point deterioration would occur.

This chapter examines the potential of technology to mitigate the stresses on the air traffic system and to improve its safety, including technologies or procedures that could increase or better utilize the capacity of the system. It also reviews prospects for technologies to improve communication between pilots and controllers in high-density airspace. Finally, it examines technologies to detect and communicate weather conditions to pilots, training to help pilots use the information effectively, and navigation and surveillance systems for controlling aircraft.

ELEMENTS OF THE AIR TRAFFIC SYSTEM

Models for Evaluating Changes to the Air Traffic System

FAA uses models and other means to evaluate how changes in procedures, facilities, technology, and personnel could affect safety and capacity of the air traffic system. However, the mathematical and computer models described below are rough tools; decisions must still depend on astute judgment of humans familiar with the modeled situation.

Risk Models for Procedural Changes.–FAA normally evaluates the safety impact of procedural changes on the basis of operational judgment, supplemented by models of "worst-case" scenarios and other analytical tools.[1] However, this approach does not always relate procedural changes to any objective measure of accident risk. FAA and the International Civil Aviation Organization have developed mathematical models to estimate an upper

[1]For example, see A.L. Haines and W.J. Swedish, *The MITRE* Corp., "Requirements for Independent and Dependent Parallel Instrument Approaches at Reduced Runway Spacing," Report No. FAA-EM-81-8, prepared for the U.S. Department of Transportation, Federal Aviation Administration, May 1981.

bound to the risk of oceanic collisions and accidents due to obstructions near the airport. The United States is considering a change in separation standards for the North Pacific based partially on the results of risk modeling performed at FAA's Technical Center. Also, traffic levels across the Atlantic are monitored, and if the traffic levels exceed a threshold determined by the risk model, FAA may intervene and change separation standards. The collision risk model for obstructions is used by FAA, for example, in cases when obstacles, such as tall buildings, encroach on airspace close to runways.

Currently, FAA does not have risk models to use in its evaluations of procedural changes in the terminal area, such as the recent reduction in minimum instrument flight rules (IFR) separation standards for certain aircraft types. FAA's monitoring of operations under the new standards has not revealed operational problems that would cause FAA to revert to the original separation standards. However, because aircraft accidents are exceedingly rare, a huge number of observations over a number of years would be necessary to identify a rise in risk because of this change. A risk model for the terminal area would also suffer from lack of data on low-probability events. For this reason, risk models, no matter how well constructed, are not adequate in themselves for evaluating the safety impact of procedural changes in the terminal area. However, quantitative risk models for the terminal area could, if properly developed and used in conjunction with an assessment of the impact of human error, contribute to the evaluation of procedural changes. FAA is beginning to build a terminal area risk model at the Technical Center. Support for development of the model and for thorough external review of the model by risk experts in other industries, such as the nuclear industry, would help make available a potentially useful, but limited, analytical tool.

System Capacity Enhancements

FAA estimates the potential benefits from new terminal airspace control procedures, terminal ATC automation, and construction of new runways based on a model relating total yearly flight delay hours at any airport to the number of air carrier and other operations, IFR and visual flight rules (VFR) capacity, and the percentage of time that IFR conditions prevail during a year. The model was developed from data available from 32 airports for 1983 and 1984, and from 10 airports for 1985. Enhancements are evaluated by estimating the increase in IFR capacity at each airport where the enhancements could be applied using existing FAA models for airport capacity under instrument meteorological conditions. The overall model is then used to estimate total yearly delays, and finally, delays for all 240 airports are considered.[2] The model is not detailed, and estimates delays without regard to airline scheduling, en route ATC procedures, and routing of traffic flows. The model can therefore be used to suggest the approximate magnitude of future capacity problems and effects of airport enhancements only; it is not suitable for comprehensive capacity examination.

SIMMOD is a model which simulates aircraft movements and controller actions. Runways and an airspace configuration are put into the model, airplanes are fed in, and the model keeps track of the statistics of travel times from point-to-point, delays and fuel burn. SIMMOD was originally designed as a fuel-burn model and was only recently adapted for capacity modeling. SIMMOD is a very detailed model, and system capacity can be estimated only by trying to push as many airplanes as possible through the system by trial-and-error. SIMMOD is a useful tool for evaluating airspace reconfiguration, but it is too detailed for a system-wide statistical evaluation.

System-Wide Performance Models.–FAA is currently involved in a modeling effort, called National Airspace System Performance Analysis Capability (NASPAC), to evaluate the system-wide implications of changes in scheduling, airport capacity, airways, and flow control. According to current plans, the models will evaluate airport capacity characteristics, and model traffic flows between airports, keeping track of how delays propagate to later times. If successful, NASPAC could be especially useful as an analytical support tool for FAA at the FAA/Office of the Secretary of Transportation airline scheduling meetings (see chapter 2). Beyond these scheduling meetings, the models could provide guidance for evaluating operational and technological

[2] Transportation Systems Center, "Airport Capacity Enhancement Plan," DOT/FAA/CP-87-3, prepared for the Airport Capacity Program Office, Federal Aviation Administration, 1987.

changes to the National Airspace System (NAS), form the basis for improved real-time capacity management decisions, and support broader policy decisions on demand management as traffic levels increase.

Airports

Although there has been considerable airport expansion in the United States since 1978, the last major commercial airport built in this country was Dallas/Ft. Worth, completed in 1973. Only two new airports are definitely planned for the future; one about 17 miles from Denver to replace Stapleton Airport, and the other in Austin, Texas. The Denver airport would open with a minimum of six runways and would allow simultaneous IFR approach in both the North/South and East/West directions.[3] Commercial airports take many years to construct, so near-term relief for airport congestion must be found in other ways. Runway capacity at existing airports can be constructed more quickly and approximately 18 new runways are currently planned at existing commercial airports. Runways planned for Nashville and Orlando may be completed as early as 1989.[4]

Both departures and arrivals at airports are severely curtailed by bad weather. FAA has set weather criteria for VFR and airlines plan their schedules for VFR weather conditions, although commercial airlines fly under IFR regardless of meteorological conditions. Flights are held on the ground at departure airports by FAA's Central Flow Control Facility when the number of scheduled flights exceeds an airport's capacity to receive them due to bad weather. Most commercial flight delays over 15 minutes are caused by weather;[5] thus, FAA is particularly interested in procedural changes to increase airport capacity under poor weather conditions.

Currently, simultaneous independent use of converging runways is not permitted except when the cloud ceiling is 500 feet or more and visibility is at least 1 mile, because of concern about simultaneous missed approaches by both aircraft. During bad weather, such use of parallel runways is allowed only when the runways are at least 4,300 feet apart; dependent simultaneous use of parallel runways is permitted only when the runways are at least 2,500 feet apart; and triple parallel runways cannot be used simultaneously. Each of these procedural rules is being examined by FAA as part of its Airport Capacity Enhancement Plan; they could potentially be liberalized to allow more operations under instrument meteorological conditions. Reducing requirements on runway spacing for independent parallel IFR approaches would require a precision approach radar and a controller position to monitor the space between the runways–such a controller position is always required for independent parallel IFR approaches.' Not all airports would be affected by these potential changes, because their applicability depends on the runway configuration at the airport.[i]

FAA recently reduced minimum IFR aircraft separation standards for certain aircraft types on final approach from 3 miles to 2.5 miles at airports with taxiways that permit an aircraft to exit a runway within 50 seconds of touchdown and if other conditions are met. The exit time restriction is necessary because no aircraft is permitted to land on a runway already occupied by another aircraft. Twenty-five airports have been approved for the reduced separation standard, and other airports may be eligible in the future if high-speed exits are built for existing runways. However, the reduction is controversial because the 50-second runway time requirement is subject to disagreement, and because the pilot of an aircraft trailing another by 2.5 miles has less time to make altitude or lateral adjustments to avoid the wake vortex of the leading aircraft, a potential problem in bad weather. Moreover, some pilots are uneasy about operating so close behind another aircraft without any means of estimating separation.

Cockpit display of traffic information, applied as a backup to ATC, could mitigate some of these concerns. Nearby traffic has been displayed in the cockpit in tests of the Traffic Alert/Collision Avoidance System (TCAS), although the usefulness of a TCAS

'Wayne]. Barlow, director, Northwest Mountain Region, Federal Aviation Administration, letter to OTA, Dec. 22, 1987.

'Arnold Price, deputy director, Airport Capacity Program Office, Federal Aviation Administration, letter to OTA, Dec. 17, 1987.

[5]Transportation Systems Center, op. cit., footnote 2.

[6]Arnold Price, deputy director, Airport Capacity program Office, Federal Aviation Administration, personal communication, Nov. 13, 1987.

'Transportation Systems Center, op. cit., footnote 2.

display on final approach has not yet been established. FAA plans to test TCAS display use during closely-spaced parallel runway demonstrations in 1988 and 1989. Another option, which may become feasible in the future, is to send surveillance radar data to the cockpit over data link. However, this option raises major operational questions about the roles of pilots and air traffic controllers in maintaining aircraft separation.

Another area of potential gain is in automation of terminal area ATC for more efficient metering of traffic, particularly during bad weather. FAA is starting a program to develop automated terminal systems for eventual implementation around the year 2000.[8]

FAA has estimated the potential benefits from improved terminal airspace control procedures, terminal ATC automation, and construction of new runways (as planned in 1986) using the airport capacity enhancement model described earlier. Although uncertainties remain, the results suggest that the improvement from enhancements cannot compensate for the additional delays caused by projected increases in air traffic levels through 1994. Even with all the enhancements, the projected delay per flight would be 96 percent of its current value. The model projects 114,500 aircraft hours saved compared to a projected increase of 445,000 aircraft hours without enhancements.[9]

Some capacity gains are also possible from the Microwave Landing System (MLS), depending on airport runway configuration and location with respect to topographical features and other airports. However, locally imposed airport noise restrictions may limit the curved and segmented approaches theoretically possible with MLS. Additional airborne computer equipment must still be developed, and MLS will probably not significantly affect airport capacity in the near future because the current Instrument Landing System (ILS) will be widely available until at least 1998, and consequently not all aircraft will convert to MLS. FAA studies suggest difficulties in controlling aircraft making curved or segmented approaches in a mixed ILS/MLS environment.[10]

[8]Ibid.

[9]Ibid.

[10]National Aeronautics and Space Administration and Charles Stafford, "Report on the Simulation of Microwave Landing System Procedures in the New York Terminal Area," unpublished report, 1987.

Greater use of existing military airports for commercial operations instead of building new airports or additional runways can alleviate some airport capacity problems. As of 1984, there were 24 joint-use airports—military airports with agreements to support some commercial operations.[11] However, using these airports for high-volume commercial traffic could produce local noise problems and restrict flexibility for military flights, while security limitations could interfere with efficiency of commercial operations. Furthermore, military airports generally do not have sufficient facilities for conveniently handling large numbers of passengers. Finally, the total additional capacity these airports could add to the system is limited. Thus, military airports are a good choice to relieve congestion in some areas in the near term, but other measures are needed to solve the national capacity problem.

Smaller, less used civil airports could also be used as hubbing centers. In fact, as delays at major hubs increase, some airlines are locating hubs at smaller airports, despite the fact that smaller cities have fewer origin and destination passengers than larger hubs. Smaller airports can relieve some stress on large, crowded hub airports, but, depending on local conditions, may not necessarily assist with airspace congestion. Similar tradeoffs apply to the use of reliever airports to receive some general aviation (GA) traffic that would otherwise fly into busy hub airports.

Noise and congestion problems attendant to airports near big cities have prompted proposals to build large airports far from cities for use as hubbing centers. Using airports strictly as hubbing centers is a radical concept by current standards, because airlines need substantial revenues from origin and destination passengers. This situation could change, however, if traffic levels continue to grow and hubbing persists. FAA is currently exploring high-speed rail or advanced vertical and short take-off and landing aircraft for transporting passengers rapidly from city centers to distant airports.[12] Ad-

[11]The Secretary of Defense and the Secretary of Transportation, "The Plan for Joint Use of Military Airfields," pursuant to section 504(d)(3) of the Airport and Airway Improvement Act of 1982, Public Law 97-248, Mar. 8, 1984, p. 2.

[12]Albert W. Blackburn, associate administrator for Policy and International Aviation, Federal Aviation Administration, reported at the Fifth International Workshop on the Future of Aviation, sponsored by the Transportation Research Board, Oct. 6, 1987.

vanced rapid transit could help keep commuting times to remote airports comparable to commuting times to large hub airports today.

Airspace

The FAA's East Coast Plan and the developing west coast and Midwestern airspace reconfiguration represent attempts to reduce delays by configuring air route structure more efficiently. While such efforts can reduce delays, they have associated costs, including having to change ATC facilities and retrain controllers. For example, the East Coast Plan had a big impact on the Boston Air Route Traffic Control Center (ARTCC), which had to be upgraded and full performance level controllers retrained to work with the new traffic flow configuration. These activities slowed down the training of developmental controllers needed to fill a gap in trained personnel in the Boston Center.[13] Another side effect of the East Coast Plan is that flights in and out of Philadelphia have been routinely delayed because of airspace reconfiguration. This is especially damaging to the commuter airlines who attract customers with frequent, on-time flights.[14]

Airspace reconfiguration require careful analysis to minimize unintended side effects, and FAA is implementing the East Coast Plan in phases. By themselves, such changes cannot compensate for future increases in air traffic levels, since airport capacity is also a limiting factor. According to an FAA estimate based on SIMMOD, the East Coast Plan saves about 27 flight hours per day in the region covered by the Boston ARTCC,[15] or 9,855 flight-hours per year. FAA projects the increase in air carrier delays between 1984 and 1994 at 445,000 aircraft hours, assuming no capacity enhancements,[16]

Widebody aircraft.–Several aircraft manufacturers have forecast a trend towards higher-capacity aircraft in response to the airport congestion problem.[17] The major Japanese airlines (Japan Air Lines and All-Nippon Airways) have adapted some Boeing 747 aircraft for high-capacity short-range travel by reconfiguring the interiors. In the United States, however, the trend following deregulation has been towards smaller aircraft. This could change, however, as demand for air travel increases and if airline operations shift from hub and spoke to point-to-point. Also, even though some airlines are purchasing new aircraft, others are retaining older aircraft, slowing the process of replacing smaller aircraft by larger, more expensive ones. Given the current incentives for purchasing smaller aircraft and continuing to use existing smaller types, it is difficult to predict how much use of larger aircraft will actually relieve congestion. Nonetheless, widespread use of high-capacity aircraft for medium- to long-range routes could increase system capacity significantly, particularly if combined with high-speed ground transportation to major hubs.

[13] Charles Peahl, assistant manager for Training, Boston Air Route Traffic Control Center, Federal Aviation Administration, personal communication, Sept. 9, 1987.

[14] OTA primary research, 1987.

[15] Price, op. cit., footnote 6.

[16] Transportation Systems Center, op. cit., footnote 2.

[17] James Ott, "Industry Foresees Wide-Bodies as Aid to Congested System," *Aviation Week& Space Technology,* Sept. 28, 1987, pp. 36-37.

THE NATIONAL AIRSPACE SYSTEM PLAN

The NAS Plan, developed by FAA and first published in 1981, is a comprehensive plan to modernize and improve airways and aviation facilities. The centerpiece of the NAS Plan is the upgrading of the ATC system to accommodate more traffic with greater efficiency and automation. When it was first presented to Congress, costs for the NAS Plan were projected to be $9 billion over 8 years, but total cost estimates which now include Terminal Doppler Weather Radar, as well as life cycle costs not originally in the NAS Plan, have ballooned to $15.8 billion through the year 2000. NAS Plan financing is described in chapter 3.

All the major programs in the NAS Plan are behind the original schedule by substantial amounts (see table 7-l). Two views as to why the NAS Plan has slipped so far behind schedule are now prevalent. The first view is that Congress has been unwilling to appropriate from the Airport and Airway Trust Fund because the unused fund monies can be applied against the Federal deficit, thereby allowing

Table 7-1.—Status of Major National Airspace System (NAS) Plan Projects

Project	Slippage[a]	Reason for slip
Host Computer	6 months	Contractor delays in software coding and documentation
Advanced Automation System	2 years	Additional requirements added and provision for pre-production testing
Voice Switching and Control System	1 year	Additional requirements (number of operational positions, redundancy) and testing to reduce risk
Flight Service Automation System	2 years	Software development problems
Automated Weather Observing System	2 years	Contractor difficulty complying with Critical Design Review requirements and failure to perform required quality assurance procedures
Central Weather Processor	3 years	Addition of prototype phase, redefinition of statement of work with contractor (NASA/JPL), less than optimum contractor staffing
Long-range radar (Air Route Surveillance Radar: ARSR-4)	4 years	Delay in consummating FAA/USAF agreement on number of systems required and funding
Mode S	4 years	Prototype added, clarification of specifications, revised test plan, contractor late meeting critical design review
Airport Surveillance Radar (ASR-9)	3 years	Delay in completion of critical design review, problems in system integration testing, FAA rejection of inadequate test procedures, contractor problem obtaining critical parts
Microwave Landing System	2 years	Delay in contractor software coding
Radar Microwave Link	1 year	Implementation started in 1986
Terminal Doppler Weather Radar	1 year	Revision of draft project specification, evaluation of impact of various siting options

KEY: NASA/JPL - National Aeronautics and Space Administration/Jet Propulsion Laboratory; FAA = Federal Aviation Administration; USAF = U.S. Air Force
aAmount of slippage in initial implementation comparison 1983 NAS Plan with draft 1987 Plan.

SOURCE: Office of Technology Assessment based on General Accounting Office, 1987 and Federal Aviation Administration, letter to Off Ice of Technology Assessment, Jan. 15, 198S

government funds for other purposes to be appropriated under the Balanced Budget and Emergency Deficit Control Act of 1985. The second view is that FAA has not been able to spend money on NAS Plan procurements because of engineering problems, particularly in software development, and changes in technology requirements caused by unanticipated developments in air transportation since 1981. While both views contain elements of truth, the General Accounting Office (GAO) contends that NAS programs have fallen behind because the original plan did not anticipate the time needed to tailor existing technology to ATC system requirements and did not provide time for adequate development and testing.[18] However, delays and cost increases of the magnitude experienced for the NAS Plan are not unusual for large and complex technological programs throughout the Federal Government.

FAA also maintains a plan for research, development, and engineering to investigate areas of technology not covered in the NAS Plan, and to fully exploit NAS Plan technologies.[19]

Air Traffic Control Hardware and Software

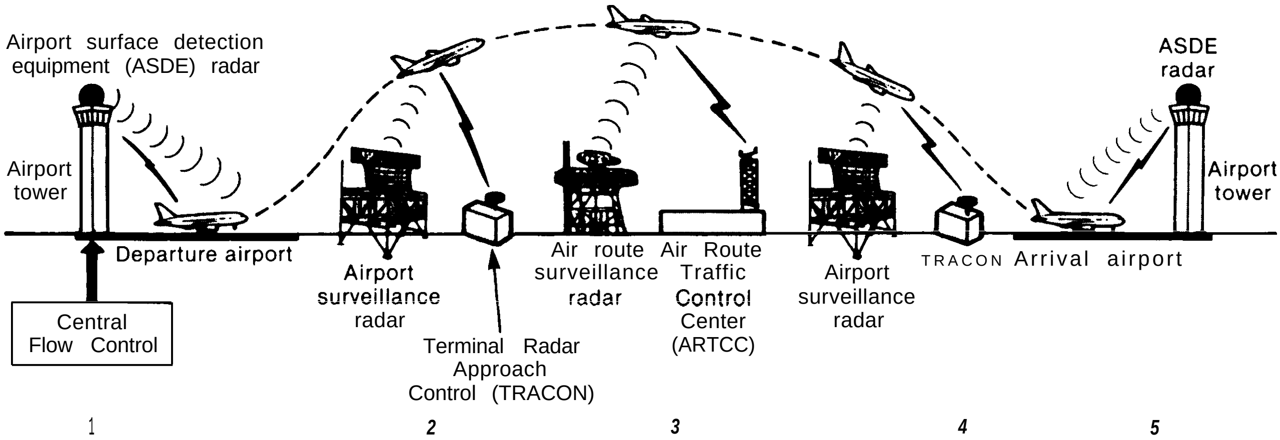
ATC facilities at all levels—airport towers, Terminal Radar Approach Control (TRACON) facilities, ARTCCs, and the Central Flow Control Facility (see figure 7-l)—experience the stresses of high traffic levels. The original version of the NAS Plan called for substantial changes in ATC facilities, including automation, to handle increased traffic by the early 1990s,[20] but most of the major changes are not now expected until the late 1990s and be-

[18]Herbert McLure, associate director, Resources, Community and Economic Development Division, General Accounting Office, "National Airspace System (NAS) Plan Delay s," testimony before U.S. Congress, Senate Committee on Commerce, Science and Transportation, Subcommittee on Aviation, Apr. 8, 1987.

[19]U.S. Department of Transportation, Federal Aviation Administration, "The Federal Aviation Administration Plan for Research, Engineering and Development," vol. 1, draft manuscript, August 1987.

[20]U.S. Department of Transportation, Federal Aviation Administration, *National Airspace System Plan* (Washington, DC: December 1981), pp. III-8, III-9, IV-6, and IV-7.

Figure 7-1 .—Air Traffic Control on a Typical Commercial Flight



KEY

1 The airport tower controls the aircraft on the ground before takeoff and then to about 5 miles from the tower, when the tower transfers aircraft control to a Terminal Radar Approach Control facility (TRACON). Controllers in the airport tower either watch the aircraft without technical aids or use radars—Airport Surface Detection Equipment for aircraft on the surface and airport surveillance radar for those in the air Central Flow Control (in Washington, DC) can order the tower to hold flights on the ground if demand exceeds capacity at the arrival airport.

2. The TRACON, which may be located in the same building as the airport tower, controls aircraft from about 5 miles to about 30 miles from the airport, using aircraft position information from the aircraft surveillance radar. The TRACON then transfers control of the aircraft to an Air Route Traffic Control Center (ARTCC)

3 ARTCCs control aircraft that are en route between departure and arrival airports. Each ARTCC controls a specific region of airspace and control is handed off from one ARTCC to another when a boundary is crossed. Aircraft positions are detected by the air route surveillance radar. The last ARTCC on the flight path transfers control to a TRACON when the flight is about 30 miles from the arrival tower,

4 The TRACON controls the arriving aircraft until it is within about 5 miles of the arrival airport tower, when control is transferred to the tower.

5 The airport tower controls the aircraft on the final portion of its approach to the airport and while it is on the ground.

SOURCE Off Ice of Technology Assessment, 1988

yond.[21] Automated tools for controllers can reduce workload, provide information to reduce the amount of potentially error-prone mental judgments controllers now must make, permit better teamwork, and enhance the working environment. While automation can facilitate safe handling of higher traffic levels, a high degree of automation changes the role of the air traffic controller and may in itself introduce new hazards.

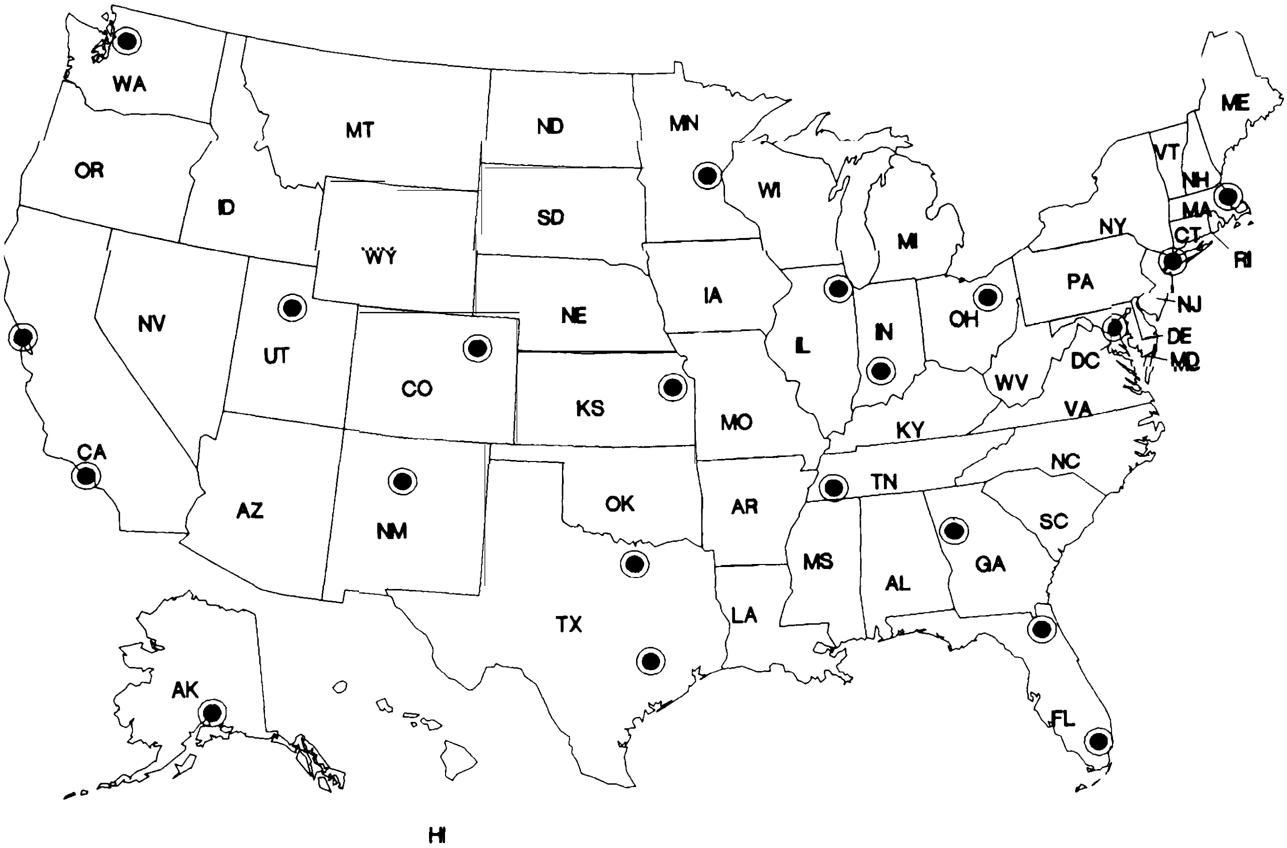
Installation of the Host computer at ARTCCs (see figure 7-2), the first major step in FAA's plan to modernize ATC, is the most significant technology measure taken in recent years to ease capacity problems. The old system would occasionally overload and fail, increasing the risk that other events or human errors could snowball into an accident. The Host computer has much more capacity and speed then the old system, and includes backup by an identical computer system in case of failure.

FAA plans to further modernize ATC equipment and software in a series of steps. According to current plans, the contractor (either Hughes or IBM) for the modernization will be chosen in July 1988. The next major step in the process will be-to replace controller consoles with the Interim Sector Suite System. Then, hardware for the Terminal Advanced Automation System will be installed and software for approach/departure control introduced. Next comes computer hardware and software for en route ATC, called the Area Control Computer Complex. Finally, en route software called Advanced En Route Automation (AERA) will be introduced. The name for the whole system of modernized ATC hardware and software is the Advanced Automation System (AAS). FAA's acquisition strategy for AAS has been criticized by GAO for being too risky; it does not conform with the principles fundamental to Office of Management and Budget Circular A-109 on major systems acquisition.[22] FAA intends to test

[21] U.S. Department of Transportation, Federal Aviation Administration, *National Airspace System Plan* (Washington, DC: April 1987), pp. III-9, III-9, *111-52,* and III-53.

[22] U.S. Congress, General Accounting Office, *Air Traffic Control: FAA Advanced Automation System Acquisition Strategy is* Risky, GAO/IMTEC-86-24 (Washington, DC: July 1986).

Figure 7-2.—Locations of Air Route Traffic Control Centers



SOURCE: Federal Aviation Administration,

the system in partnership with a single prime contractor to take advantage of FAA's ATC and operational experience.

An issue more basic than strict compliance with Circular A-109, however, is whether the process fosters innovative approaches to satisfy real ATC needs in an appropriate time. Emphasis on analytical tools for identifying ATC system needs and on early prototyping and streamlined procurement processes could facilitate timely fielding of new technology [23] and evaluation of alternate approaches to help ensure adequate solutions to ATC problems.

According to current plans, AERA will be implemented in three stages: the first, called AERA-1, will predict the future positions of aircraft using flight plan information and alert controllers when potential conflicts occur between planned flight paths up to approximately 20 minutes into the future. Pilots may also be able to change flight plans en route, and a computer would automatically test the flight plan for potential conflicts with other flights. AERA-2 will provide controllers with several alternate resolutions to potential conflicts and will improve coordination between controllers. AERA-3 is not fully defined, but the basic plan is to have the computer select the proper resolution of conflicts and communicate course and altitude changes directly to aircraft.

FAA's original cost-benefit justification for AAS included benefits from more controller productivity, and fuel and passenger time savings from more efficient routes. However, GAO criticized that original analysis severely. Currently, FAA justification

[23] The President's Blue Ribbon Commission on Defense Management, *A Quest for Excellence: Final Report to the President* (Washington, DC: U.S. Government Printing Office, June 1986), pp. 55-57.

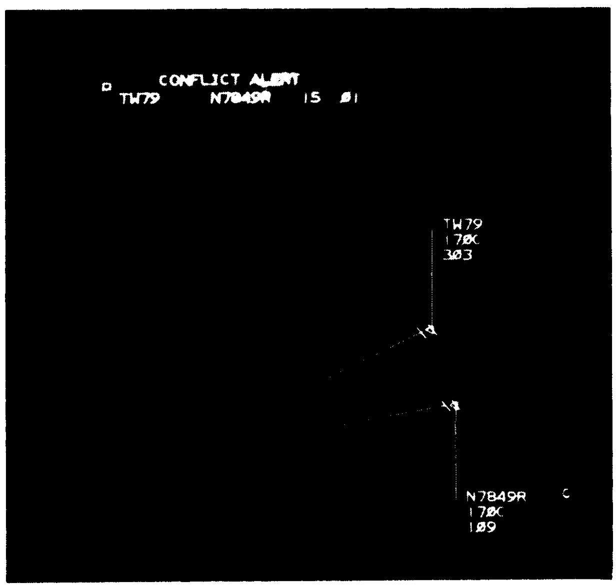
is that traffic levels will increase in the future sufficiently that controllers for en route control sectors will not be able to handle it, and ATC must be automated or more flight delays will occur. Preliminary FAA estimates suggest that flight delays will be substantial after about year 2000. However, the model used to estimate the magnitude of delays assumes the distribution of traffic by time of day is the same as today, This distribution is likely to change significantly because of airport capacity limitations and the changing proportion of nonbusiness travelers. Much more work is needed to identify ATC needs for the future and to evaluate potential approaches to meet the needs.

TRACON Improvements

Current ATC equipment is limited in a number of ways. FAA's original plan was to consolidate ARTCCs and TRACON facilities to form Area Control Facilities, but that concept is being reevaluated. Objections to the consolidation are partly operational and partly due to increased vulnerability of the entire system to military destruction. TRACON facilities, in particular, will be affected by a rule (required by recent legislation) mandating altitude-encoding transponders for all aircraft flying above 6,000 feet and in terminal areas where radar service are required.[24] Locations of these terminal areas are shown in figure 7-3. Relief by AAS is not expected until around the year 2000. The New York TRACON already has overloaded computer equipment, because it is served by more airport surveillance radars than its equipment (called ARTS-IIIA) was designed for. Efforts are under way to upgrade its capabilities in three phases ending in 1990.

However, within a few years, other ARTS-111A TRACONs, whose locations are shown in figure 7-4, will also have increased transponder traffic levels, and their performance could suffer if their capacity is not upgraded. Processing capability at ARTS-111A TRACONs is modular–in the form of up to eight input/output processors (IOPs), although no TRACON except New York has more than four. Each IOP costs about $200,000, and if each of the approximately 60 ARTS-111A TRACONs is upgraded by adding four IOP units, the total cost would be around $50 million plus costs for overhead and installation. Despite the fact that IOP units are 15-year-old technology, production lines could be reopened to permit their re-manufacture to provide near-term capacity increases.

Another improvement for TRACONs would be installation of a Mode C Intruder Alert function, which could warn controllers of potential conflicts between IFR and VFR traffic. The current conflict alert installed in ARTS-111A equipment alerts controllers only of IFR/IFR conflicts, However, Mode C Intruder Alert will produce additional false alarms for the controller, possibly limiting its utility. ARTS-IIIA sites would require additional IOP capacity to handle the Mode C Intruder Alert function in crowded terminal areas, although additional hardware would not be required in less crowded areas. Funding to increase TRACON computer capacity is included in FAA's fiscal year 1989 budget request, and Mode C Intruder Alert for ARTS-111A TRACONS is expected to be included in the 1988 version of the NAS Plan.[25]



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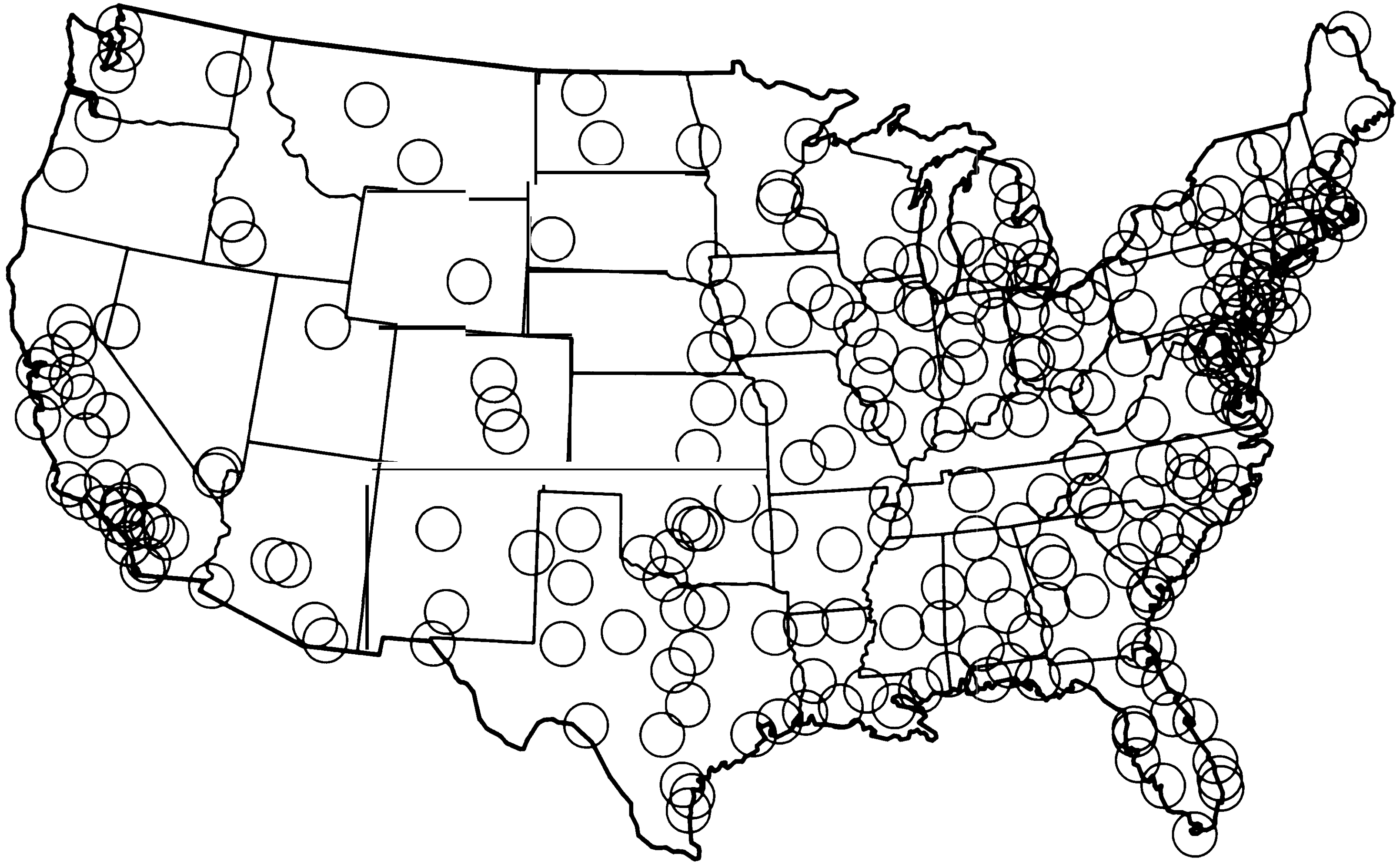
[24] U.S. Department of Transportation, Federal Aviation Administration, "Transponder With Automatic Altitude Reporting Capability Requirement and Controlled Airspace Common Floor, " Notice of Proposed Rulemaking, n.d.

Figure 7-3.—Terminal Areas Where Radar Coverage is Provided

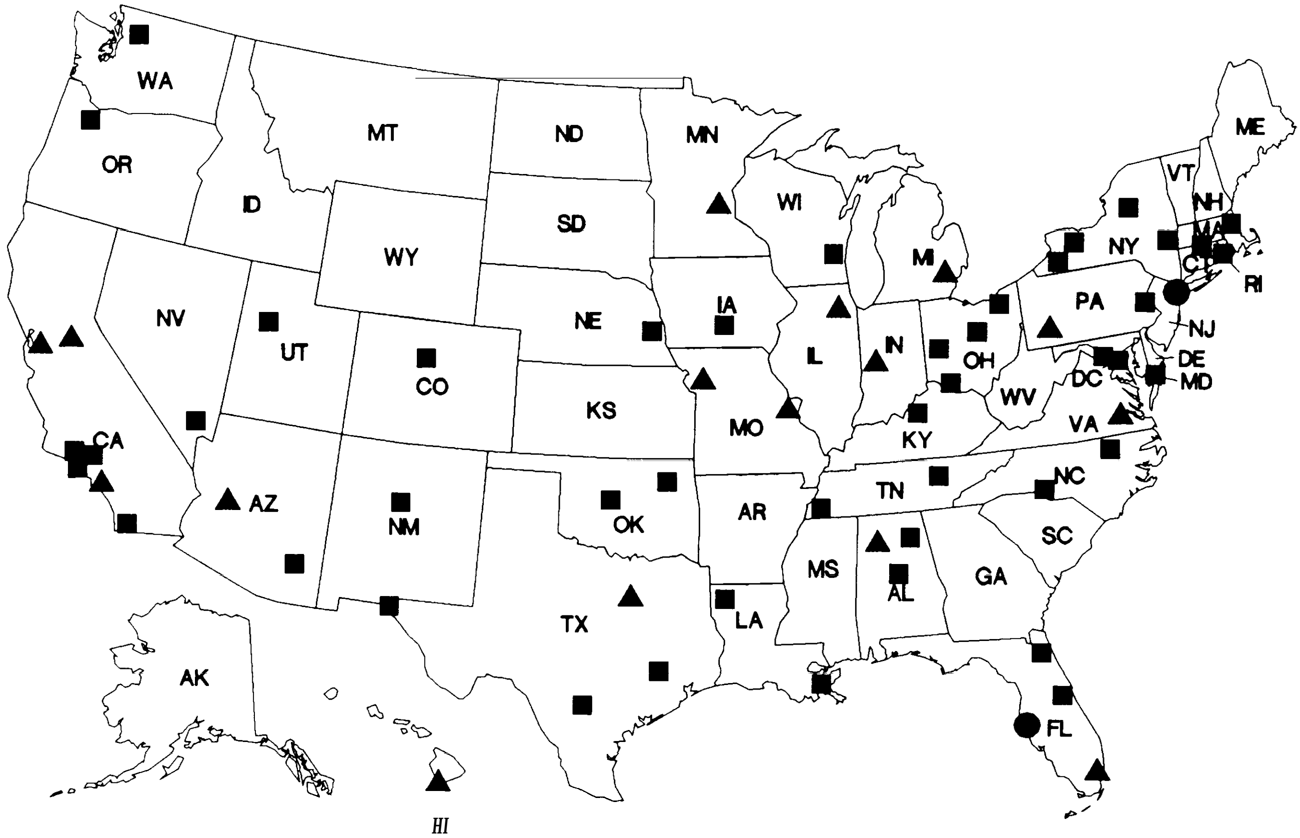


Forty-mile radius circles are shown drawn around each airport.

NOTE: A recent Federal Aviation Administration Notice of Proposed Rulemaking require Mode C transponders in all aircraft operating within the circled area, regardless of altitude.

SOURCE: Federal Aviation Administration.

Figure 7-4.—Locations of TRACONS With ARTS-IIIA and ARTS-IIIE Equipment



■ TRACONS currently operating ARTS-HA equipment,
A TRACONs where ARTS-MIA equipment is not yet operational.
● TRACONs where ARTS-E equipment is planned.

KEY: TRACONS = Terminal Radar Approach Control facility.
SOURCE: Federal Aviation Administration,

Beyond expanding the capacity of TRACONs and installing Mode C Intruder Alert, terminal facilities could be automated to reduce mundane tasks for controllers. Research has been carried out in the United States and Germany on terminal automation and improved controller displays, and FAA's fiscal year 1989 budget request includes increases in funding for terminal automation,[26]

ARTCCs are limited by the number of radar consoles and radars that can be run off the Host computer, limiting expansion possibilities as traffic levels increase. Furthermore, equipment in en route centers is old and is becoming more difficult to replace, and improvements in the basic infrastructure of en route ATC centers are needed. While the general principle of reducing controller workload is sound, other aspects of the cost-benefit analysis for AERA are more questionable. Controllers will be more dependent on automation support if AERA is implemented, and while FAA plans a length_y period of operational evaluation and functional backup for automated aids, the safety hazards of the changes in the controller's role have not been thoroughly evaluated. Currently, the impact of conflict alerts which extend 20 minutes or more into the future

[26]Ibid

are not well understood either from a system safety or an efficiency standpoint. Further examination of the potential hazards and efficiency gains resulting from automation of controller functions could clarify whether AERA would permit safe control of higher traffic levels.

TRAINING AIR TRAFFIC CONTROLLERS

Air traffic controller training is an immediate concern because many ARTCCs and airport towers have a shortage of adequately trained personnel. Some en route facilities report that the current number of personnel is adequate to staff the center, but that many of their controllers need further training to enable them to operate more positions. Training to full performance level at an ARTCC generally requires over 3 years, although sufficient training to operate two positions (at which point the controller is called an operational controller) takes less time.[27] Even if present training needs are met, it is likely that a large number of new controllers will need to be trained in the near future, because many current controllers are approaching retirement age.

Prospective air traffic controllers, called "developmental, " are screened and receive the initial portion of their training at the FAA Academy in Oklahoma City, Oklahoma; then they are sent to an ARTCC or tower for the next stages of training. Only about 60 percent of the developmentals who attend the initial training session at Oklahoma City pass the screening process, which requires them to separate aircraft without radar. A 3-week course at Oklahoma City follows the initial training session for developmental being trained for towers. This course includes training in a scale mock-up of a tower, with small models of aircraft moved around by hand outside the mock-up to simulate airport traffic. Developmentals training for ARTCCs undergo radar training with simulations created through the hardware and software of a system called Dynamic Simulation (DYSIM). DYSIM ties into the operational computer of the ARTCC, presenting the trainee with simulated traffic of limited realism. TRACONs and airport towers with radar have a radar simulator training system similar to DYSIM called Enhanced Target Generator.[28] Beyond simulator and classroom training, ARTCCs, TRACONs, and towers rely heavily on on-the-job training for developmentals.

The Seattle ARTCC uses an upgrade of DYSIM, called Computer Enhanced Radar Training (CERT), which has improved software that more realistically simulates sector traffic. The CERT program emphasizes good use of instructors and the proficiency of operators who simulate pilots. As a result of these improvements, the Seattle ARTCC has cut by over 50 percent the time needed at certain stages of con-- troller training, and has reduced time spent for on-the-job training with live traffic by 18 percent.[29]

The realism of training is limited, because software does not allow simulated traffic to deviate from preferential arrival and departure routes in the live

[27] Peahl, op. cit., footnote 13; Ron Wiest, assistant manager for Training, Chicago ARTCC, Federal Aviation Administration, personal communication, Sept. 10, 1987; Richard Dilley, assistant manager for Training, Los Angeles ARTCC, Federal Aviation Administration, personal communication, Sept. 11, 1987.

[28] Ann Spence, air traffic subject matter expert, Federal Aviation Administration, personal communication, Aug. 27, 1987.

[29] U.S. Department of Transportation, Federal Aviation Administration, "Seattle Center Computer Enhanced Radar Training Staff Study," unpublished manuscript, n.d.

Photo credit: Federal Aviation Administration

Air traffic controller trainees receive instruction at the Seattle Air Route Traffic Control Center's Computer Enhanced Radar Training (CERT) laboratory.

system,[30] and the call signs of simulated traffic must begin with XXX, a pattern never encountered with real traffic. Moreover, some ARTCCs lack sufficient equipment to train all their developmental simultaneously, so developmental spend more time at intermediate levels than may actually be necessary.'[1] In other ARTCCs, on-the-job training of developmental is an additional and taxing task for full performance level controllers.' To deal with these problems, a few ARTCCs have begun sending controllers back to Oklahoma City for site-specific radar training at the Academy.[33] At Oklahoma City, developmental receive increased personal attention and specific remediation, perhaps more important than the Academy's more versatile radar simulation capabilities.[34]

These alternatives point to possibilities for near-term improvements to training capabilities at ARTCCs. For the longer term, airline pilot training could be used as a model, with microcomputers for basic subsystem training and realistic simulators for full operations. Combined with appropriate levels of individual attention, simulator training could reduce or even eliminate the need for on-the-job training of developmental and reduce the time needed to reach operational and full performance levels. FAA is now taking a first step by revising its Instructional Program Guide for en route training to increase site-specific simulator training at each ARTCC.[35]

[30]A.T. Snelson, air traffic manager, Seattle ARTCC, Federal Aviation Administration, personal communication, Aug. 18, 1987.
[31]Peahl, op. cit., footnote 13.
'Dilley, op. cit., footnote 27.
"Dennis Burke, manager, Chicago ARTCC, Federal Aviation Administration, personal communication, Sept. IO, 1987.

[34]B. Keith Potts, Federal Aviation Administration, attachment to letter to OTA, Feb. 22, 1988.
[35]Ibid.

COLLISION AVOIDANCE TECHNOLOGY

Traffic Alert/Collision Avoidance Systems (TCAS) provide independent backup to the ATC system and help pilots fulfill their responsibility to see and avoid other aircraft. Three types of TCAS capability are being developed: TCAS-I, TCAS-II, and TCAS-III. TCAS-I, the least sophisticated of the systems, warns of nearby traffic by giving traffic advisories that indicate the approximate bearing of each threat and the approximate altitude, if the threat aircraft is equipped with an altitude-encoding transponder. TCAS-I is intended for GA use and for small commercial aircraft. TCAS-II and 111 also supply resolution advisories to help the pilot maneuver away from an impending collision or close approach. TCAS-II can advise only vertical maneuvers, while TCAS-III can advise both horizontal and vertical maneuvers. TCAS-II and III are intended for use on large jet aircraft and turbine-powered commuter aircraft.

All three systems require the threat aircraft to have an operating transponder to function in the traffic advisory mode; resolution advisories are generated by TCAS-II and 111 only if the threat aircraft has an operating altitude-encoding transponder. The Mode S data link communications system, now being developed by FAA, will be used for air-to-air interrogation/reply with TCAS-II and III to coordinate maneuvers when two TCAS-equipped aircraft must evade each other.[36]

TCAS-II, the most advanced in development of the three systems, is currently undergoing flight testing scheduled for completion by the end of 1988. TCAS-III has had initial flight tests, but technical challenges remain in collision avoidance logic, human factors, interaction with ATC, certification standards, verification tests, and performance monitoring. TCAS-I development is not as far along as either II or III.[37]

Current TCAS issues include the adequacy of vertical-only maneuvers for collision avoidance, as supplied by TCAS-II. TCAS-III would provide horizontal and vertical maneuvers, but will not be available soon; moreover, it is projected to cost about $20,000 to $30,000 more per copy than TCAS-II.[38] FAA

[36]52 *Federal Register* 32269 (Aug. 26, 1987).
'Joseph Fee, TCAS program manager, Federal Aviation Administration and Dan Tillotson, senior project leader, ARINC Research, Inc., presentation at Air Line Pilots Association 1987 Safety Forum, Aug. 19, 1987.
"Ibid.

Photo credit: Federal Aviation Administration

FAA pilots flight-test a collision avoidance system.

has issued a Notice of Proposed Rulemaking requiring TCAS-II in all Part 121 aircraft and larger Part 135 aircraft with turbine engines, and encouraging manufacturers to build TCAS-II units that can be upgraded to TCAS-III without major changes in hardware. The Airport and Airways Safety and Capacity Expansion Act of 1988 requires development of TCAS-II with standards upgradable to TCAS-III.[39]

GA aircraft operating without transponders will remain problems, since TCAS warns only of aircraft with operating transponders and provides a resolution advisory only if the threat aircraft has an altitude-encoding transponder. FAA rulemaking to require Mode C (i.e., altitude-encoding) transponders on aircraft flying above 6,000 feet and in terminal airspace where radar coverage is provided will induce GA pilots to buy altitude-encoding transponders. Currently, Mode C transponders are required only above 12,500 feet and in Terminal Control Areas. This FAA rulemaking was mandated by Congress as part of a program to reduce the potential for midair collisions. Even with the increased Mode C requirements, a small plane operating without a Mode C transponder could still inadvertently enter terminal airspace with radar coverage. A program to gradually require transponders in all aircraft would provide additional safeguards.

Technical uncertainties still surround TCAS, because the reactions of controllers and air traffic patterns to TCAS-induced altitude changes are relatively untested. The major potential ATC problem is a threat to a third aircraft if an aircraft suddenly changes direction or altitude. Simulations suggest such a problem is extremely unlikely. Because of the complexity of retrofitting TCAS to existing aircraft, it will be gradually introduced, easing potential ATC adjustments.

Ground Collision Avoidance

Although the United States has had few fatalities from collisions on the surface at airports, a number of nonfatal collisions and close calls have occurred. As traffic levels increase the probability of a disastrous ground collision will increase unless compensatory steps are taken. Twelve major airports have Airport Surface Detection Equipment (ASDE-2) radar to present surface traffic information to controllers (see figure 7-5). This equipment is about 25 years old, expensive to maintain, and has performance limitations. Anchorage, Alaska, has a more advanced surface detection radar. FAA plans to replace ASDE-2 with the more advanced ASDE-3 and to field ASDE-3 at some additional airports. ASDE-3 radar can be enhanced by automatic conflict alert and further automated through digital air/ground communications links.

Other fairly simple means to improve ground collision safety include improved signs on the airport surface, control lights at entrances to active runways, and training pilots and controllers to exercise greater vigilance during taxi operations. First, a short-term research and development (R&D) effort to improve sign symbology could provide input for developing consistent standards for taxiway and runway signs at all U.S. airports. Second, radio-controlled light-

[39] Public Law 100-223, Sec. 203(b), Dec. 30, 1987.

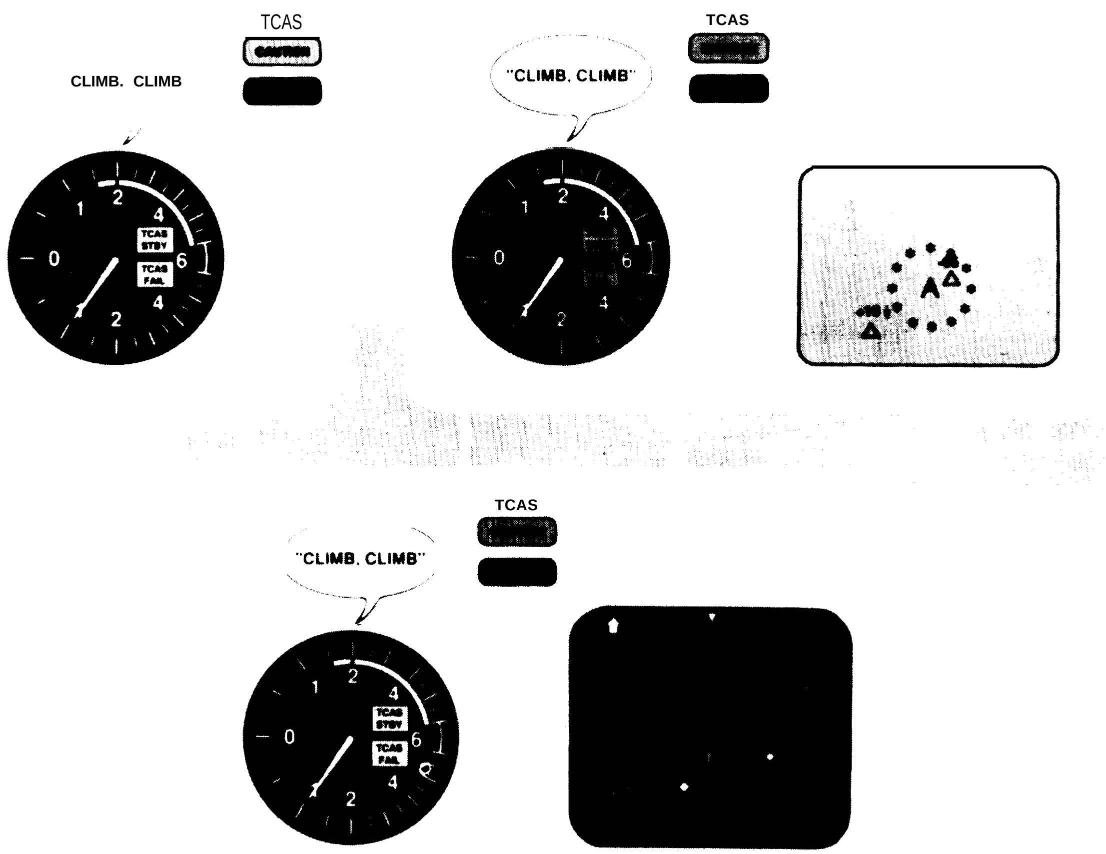


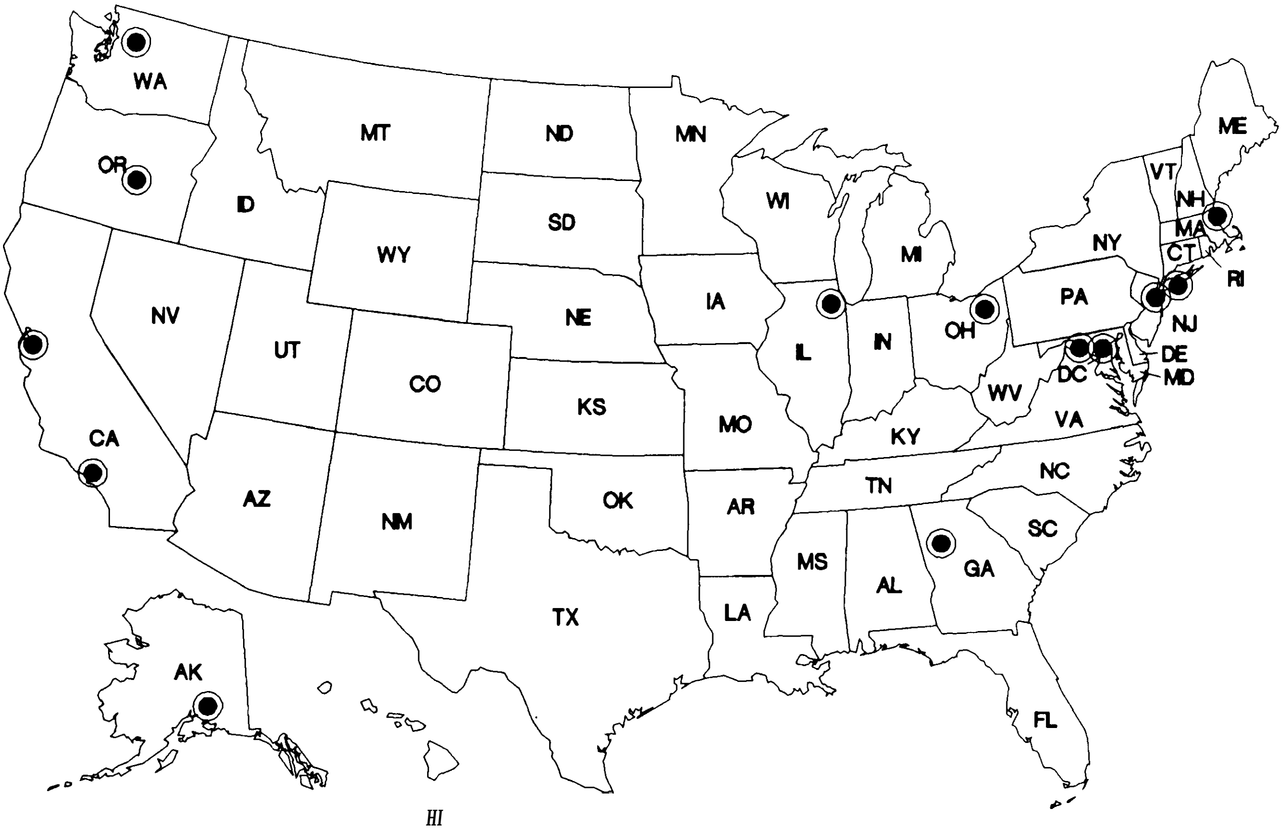
Photo credit. National Aeronauts and Space Administration

Traffic Alert/Collision Avoidance System (TCAS) will provide both visual and aural alerts to the pilot.

ing systems could be installed at entrances to major runways to augment runway clearances from ground controllers. More air traffic controllers for tower operations would be needed to operate the lights. A system of in-pavement stop-bar lights and above-ground signal lights will be tested on 14 runway entrances at JFK Airport (approximately one-quarter of the airport entrances) during 1988. The cost of equipment and installation for the lighting will be about $600,000, but a similar installation at most other major airports would be much more expensive, because, unlike most airports, JFK already has a static bar light system at entrances to runways. Third, training for pilots and controllers on preventing runway incursions could be increased.

For the longer term, work now underway at the FAA Technical Center on sign readability under very low visibility conditions deserves continued support. Also, more advanced sensors for detecting traffic on the airport surface could be developed, along with improved displays for controllers and development of procedures that permit monitoring of the displays as part of a reasonable workload.

Figure 7-5.-Locations of Airport Surface Detection Equipment Radars



NOTE: The ASDE in Anchorage, Alaska is more sophisticated than the systems at the other locations
SOURCE: Federal Aviation Administration.

COMMUNICATIONS

Ground-to-air communications systems are used to transmit ATC, weather, maintenance, and airline administrative information. Existing communications systems include many types: voice and data systems, one-way and two-way systems, and both government and private-owned systems. Analyses have shown that communication problems are significant sources of system safety vulnerability. For example, FAA reports that controller communication with pilots and other controllers was the second most frequent cause of operational errors at ARTCCs and third at TRACONs.[40] The process of communication between ATC and the aircraft crew is also a significant problem according to the National Aeronautics and Space Administration's (NASA) Aviation Safety Reporting System database.[41]

The very-high frequency (VHF) voice system linking pilots to FAA ground facilities is a government system primarily used to transmit ATC and weather information, and for flight plan processing. The voice link between pilots and ATC facilities is also the final backup in case all computers or radars fail.

[40] U.S. Department of Transportation, Federal Aviation Administration, Office of Aviation Safety, *Profile of Operational Errors in the National Airspace System, Calendar Year 1986* (Washington, DC: November 1987), p. 4-55.

[41] David C. Nagel, Chief, Aerospace Human Factors Research Division, National Aeronautics and Space Administration, letter to OTA, Jan. 26, 1988.

An air traffic controller can operate with multiple frequencies, and may have as many as 30 pilots on one frequency. When many pilots are on the same frequency, each must wait for a gap in communications with the other pilots before transmitting a message, slowing communications in busy airspace. While air traffic controllers are required to issue windshear advisories, they provide weather forecast information only as their higher priority functions of separating aircraft and issuing safety alerts allow. Nineteen percent of controllers responding to a 1985 GAO survey reported they often declined to provide weather information to pilots when working peak traffic periods. Another 34 percent said they occasionally decline to give weather advisories.[42] Air/ground communications is the weakest link in transmission of weather information from sensors, observers, or meteorologists to pilots in flight.

One advantage of having many pilots on the same frequency is that all the pilots on the frequency can hear the messages transmitted and received by other pilots. For example, pilots may transmit pilot reports about weather or runway conditions over the VHF voice link. Other messages that are important to pilots on the "party line" include altitude assignments, ATC clearances, and communication frequency changes.

Radio-frequency failures are less common now than in the past for the ground-based VHF voice link, because most of the aging equipment in the field has been replaced by modern, solid-state equipment, including standby equipment in case the primary equipment fails. Nowadays, when a failure occurs, it is more likely to be caused by problems with the leased telephone lines that connect ATC facilities to transmitters and receivers in the field. The national reliability for en route ground-to-air communications, including both FAA equipment and interconnecting links for fiscal year 1987 was 99.6 percent, up from 99.1 in fiscal year 1978.[43] Because a frequency can be blocked if a microphone is stuck in the transmit position, the Radio Technical Commission of America is currently developing standards for devices to alert pilots when this problem occurs. When completed, the standards could be used as a basis for an FAA regulation requiring stuck-microphone alerters in aircraft. Short-term R&D to determine and validate improved ways to utilize analog voice links could enhance current methods.

The government also operates broadcast voice links for transmission of weather and other information to pilots. Services include the Hazardous In-Flight Weather Advisory Service, which is broadcast from selected navigation stations, and the Automated Terminal Information Service (ATIS). ATIS, which is broadcast from navigation stations located on or near airports, is a continuous broadcast of recorded non-ATC information. ATIS relieves airport tower controllers from having to provide certain environmental and runway use information to individual pilots.

VHF radio has limited range, so it cannot be used for transoceanic flight. Instead, high-frequency (HF) radio is used. However, HF communication is not very reliable and long delays sometimes occur before messages can be received. Over land, the secondary surveillance radar system, described later in more detail, communicates altitude data and a code number assigned by ATC for each aircraft from air to ground.

Aeronautical Radio, Inc. (ARINC), a cooperative owned by over 50 airlines and aviation-related companies, owns and manages the ARINC Communications Addressing and Reporting System (ACARS), a terrestrial digital data link for use by airlines. Nearly 75 percent of the commercial fleet is equipped with ACARS, which provides continuous coverage above 20,000 feet in the United States and on-ground coverage at 95 principal airports.[44] ACARS is used primarily for aircraft operational control and administrative communications, as well as for automatic aircraft reporting, such as allowing an aircraft with a system/servicing problem to alert maintenance to have appropriate resources waiting at the airport for its arrival. Weather information prepared by airlines is also transmitted over ACARS, most of it in textual format,[45] although Northwest Air-

[42] U.S. Congress, General Accounting Office, *Aviation Weather: Status of FAA New Hazardous Weather Detection and Dissemination System*, GAO/RCED-87-208 (Washington, DC: September 1987).

[43] Wayne J. Barlow, director, Northwest Mountain Region, Federal Aviation Administration, letter to OTA, Dec. 22, 1987.

[44] R.A. Pickens, vice president, Engineering, Aeronautical Radio, Inc., letter to OTA, July 30, 1987.

[45] Rick Hambly, chief of ACARS section, Aeronautical Radio, Inc., personal communication, Aug. 24, 1987.

lines transmits graphical weather information to pilots of its Boeing 757 aircraft over ACARS.[46]

ACARS is nearing capacity in the northeastern part of the United States, so ARINC has been developing an upgrade. Enhanced ACARS (EACARS) will use up to six separate frequency channels, instead of the single channel of the current system, and will be capable of transmitting at a higher bit rate than ACARS. In addition, the data will be encoded in a format more compatible with transmission of graphical information.[47]

Other privately-owned communication systems used by commercial aviation include the company radio systems of airlines. Northwest Airlines has an eight-frequency analog radio system, over which it transmits graphical weather information to pilots, using audio tones.[48]

Two fundamentally new types of communications systems are currently being developed for aviation use: the government's Mode S data link and industry's satellite communications systems. The expected proliferation of digital communications links raises the possibility of coordinated development to provide air/ground communication that is more reliable and has better coverage and capacity than any of the individual links.

The Mode S data link, part of the NAS Plan, is a subsystem of the Mode S secondary surveillance radar system. Mode S interrogations can be addressed to individual aircraft, and the signal format allows bursts of data to be transmitted from the ground on interrogations and from aircraft on replies. Thus, if an aircraft is equipped with a Mode S data link transponder, two-way air/ground communication is possible.

Future plans include integrating Mode S data link with the Advanced Automation System to provide digital communications between controllers and pilots, as well as weather information through other interfaces. For the near term, however, a relatively limited set of functions is planned, including fairly simple weather messages, pilot advisories, and confirmation of assigned altitudes and communication frequencies.[49]

Mode S implementation is expected to proceed in two phases, with installation of Mode S secondary radars on the ground sufficient to provide nominal coverage down to 12,500 feet above mean sea level in the United States and down to the surface of major airports by 1992 as the first phase. Phase two will involve installation of more Mode S secondary radars on the ground to provide coverage down to 6,000 feet in the United States by 1994.

Mode S data link is robust because of its decentralization and because adjacent ground radars often have overlapping coverage. However, it is basically a line-of-sight system, likely to have coverage gaps near the surface of airports and in mountainous regions, although some additional coverage could be provided by installing extra omnidirectional antennas at airports. Moreover, Mode S will not provide oceanic coverage and is inefficient for broadcast communications, because messages can be received only by aircraft within the main antenna beam of the interrogator (with, perhaps, some exceptions). In addition, information currently available to pilots over the VHF voice party line will be lost with Mode S data link and other discreetly addressed communications systems, unless special provisions are made to transmit that information.

INMARSAT, an international consortium that operates a global satellite system for mobile communications, is working with three groups, including ARINC, to develop aviation satellite services, mainly for oceanic travel.[50] If disputes over frequency allocation can be resolved, the services could be used by U.S. airlines for oceanic ATC, aircraft operational control, and administrative communications, as well as for passenger phone calls in flight, an economically attractive use. Satellite communications systems are relatively expensive to use. Moreover, if all types of aeronautical communications are in the same frequency band, a system must include a feature to override passenger or administrative communications should a safety-critical message

[46] John Dietrich, Meteorology Department, Northwest Airlines, personal communication, Aug. 24, 1987.

[47] Hambly, op. cit., footnote 33.

[48] Dietrich, op. cit., footnote 46.

[49] Joseph Fee, Federal Aviation Administration, personal communication, Sept. 15, 1987.

[50] Jim Clark, Aeronautical Department, Service Development Office, INMARSAT, personal communication, Jan. 6, 1988.

need to be sent. However, a satellite system would provide reliable coverage to the ground over a wide area on the Earth's surface, including oceans, and would be less subject to coverage gaps due to obstructions and multipath effects than terrestrial systems.

The complementary strengths and limitations of Mode S data link, satellite communications systems, and ACARS, point to the value of an integrated approach to aviation communications. Presently, FAA is developing compatibility standards for ground-to-air digital communications systems, using the Open System Interconnection (OSI) model developed by the International Standards Organization. The OSI model, which has been applied in the past to ground-to-ground communications systems, defines communications systems in terms of universal levels which may be common to more than one system. Ideally, if digital communications systems are standardized and integrated, aircraft will not need dedicated hardware for each system. More importantly from a safety standpoint, a pilot could send a message without specifying a particular communications system, and the integrated system would choose the system based on coverage, capacity, and other considerations. Thus, the integrated system would have more coverage and greater reliability than any individual communications system. Although FAA is developing Mode S standards based on the OSI model, and EACARS and the ARINC satellite system are similarly based,[51] FAA and industry have not yet decided to actually attempt to integrate the communications systems. The integrated system concept for air/ground communications systems has attracted the interest of both government and industry representatives on International Civil Aviation Organization committees.[52]

Although digital communications links hold great promise for the future, they will not replace the current air/ground analog voice communications links as the primary system for real-time ATC and weather information until at least well into the 1990s. A great deal of work is still needed to establish and validate a workable set of services for the digital links, and to implement an integrated system into commercial aircraft cockpits and into ground systems. issues of what information to transfer over data links, when to transfer it, and to whom, have not been resolved.

Navigation

Navigation systems help the pilot determine position with respect to points on the ground. instruments on board aircraft use signals from navigation aids or from inertial navigation/reference systems on board to show aircraft position on a display such as a horizontal situation indicator. inertial navigation systems may include special-purpose computers that provide precise Earth latitude and longitude, ground speed, course, and heading. integration of navigation systems with automatic pilot allows automatically controlled flight and landings under low visibility conditions. Using the most advanced integrated navigation/automatic pilot systems now available, a pilot could, in principle, fly an airplane automatically from takeoff to landing, except for control of the landing gear, flaps, and engine reversers.

The NAS Plan includes implementation of MLS to replace the current ILS. MLS has several technical advantages over ILS, because it is not susceptible to unintentional signal reflections from structures or terrain on or near the airport, and it operates at a frequency band that can accommodate more locations than ILS. MLS can provide signal-in-space accuracy exceeding the requirements of Category III ILS (the most stringent requirements). However, initial MLS units will operate only at Category I, whereas some ILS sites now operate to Category III. MLS can be implemented on runways near water or in mountainous terrain where ILS cannot be used effectively, and is operationally compatible with heliports and future tilt-rotor landing areas, which ILS is not. Finally, MLS allows curved and segmented approaches to runways, although curved and segmented approaches at many airports will be restricted by operational and noise constraints. MLS may increase the capacity of some airports and reduce the communications load on air traffic controllers. However, control of a mixed population of MLS and ILS traffic will be difficult, so most aircraft flying into an airport would need

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[51]Rick Hambly, *chief of* ACARS section, Aeronautical Radio, Inc., personal communication, Sept. 18, 1987; Walter J. Gribbin, Aeronautical Radio, Inc., "AvSat, An Aeronautical Satellite Communications System," unpublished manuscript, n.d.

[52]Earnest Lucier, Federal Aviation Administration, personal communication, Sept. 16, 1987.

to be equipped with MLS avionics to realize the maximum capacity gain.[53]

The Loran-C navigation system, which gives bearing relative to radio beacon transmitters, has become more popular as a low-cost navigation system with many pilots, and its coverage is being expanded to include the Midwestern United States. However, Loran-C does not offer redundant coverage in all areas; the loss of a single transmitter means that many aircraft over a wide area lose Loran-C navigation capability. By 1991, however, a satellite-based navigation system, the Global Positioning System, deployed by the Department of Defense, should be operational, and could be used in conjunction with Loran-C to provide redundant coverage. Such redundant coverage could encourage development of new surveillance concepts based on automatic position reports from aircraft in areas not covered adequately by surveillance radars.[54] Automatic position reports would allow much more accurate surveillance of en route oceanic traffic, enhancing air traffic system capacity over oceans.

Surveillance

Two types of surveillance radars detect the positions of aircraft for presentation to air traffic controllers. Primary radar sends out a beam of radiofrequency pulses and measures the distance to aircraft targets by the time it takes to receive the return pulses reflected from the metal surfaces of the aircraft. Secondary radar sends out pulse-coded interrogations on a radio-frequency beam, which are received by transponders on board aircraft. The transponders reply to each interrogation with a coded response. The replies can be encoded with altitude or identification information. This system of ground interrogators and airborne transponders is known as the Air Traffic Control Radar Beacon System (ATCRBS).

Both primary and secondary surveillance radar systems will be upgraded under the NAS Plan. Aging radars at 96 major airports will be replaced by the ASR-9 radar, which offers improved target and weather detection capabilities that do not exist in the current airport radars. The more modern airport surveillance radars (ASR-7s and ASR-8s) already at airports will be transferred from airports receiving ASR-9s to smaller airports. Many en route surveillance radars along the boundaries of the United States will be replaced by the ARSR-4, which is being developed by FAA and the Air Force. The current ATCRBS secondary surveillance radar system will be replaced by Mode S, which also functions as a communications system. Overall, these upgrades in surveillance capabilities will improve the accuracy of surveillance and increase the reliability of the system, as well as provide better weather and ATC information to pilots.

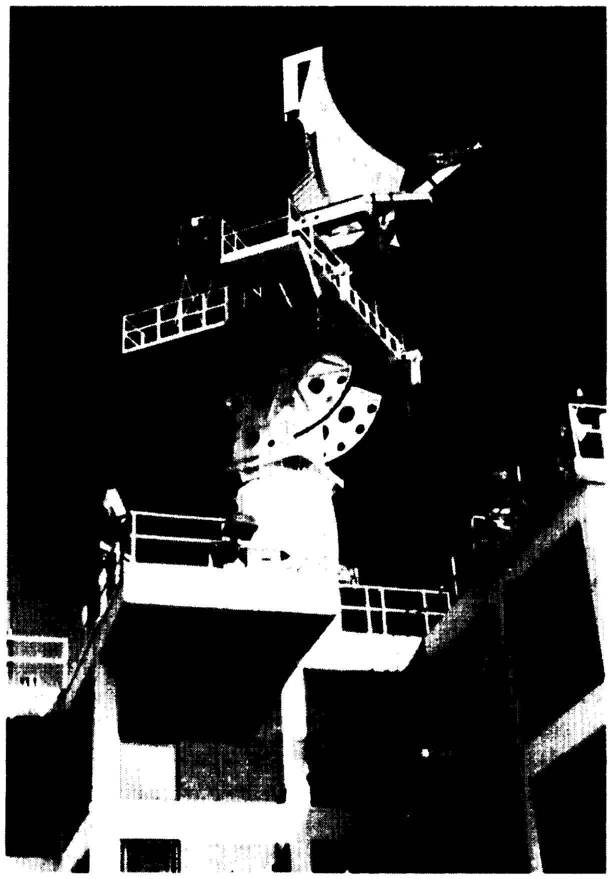

Photo credit: Westinghouse Electric Co.

The first production system of the ASR-9 Airport Surveillance Radar undergoing test at Baltimore-Washington Airport

[53] National Aeronautics and Space Administration and Stafford, op. cit., footnote 10; Joseph M. DelBalzo, director, Eastern Region, Federal Aviation Administration, "MLS Today for More Capacity and Less Noise Tomorrow," presentation at Royal Aeronautical Society, London, February 1988,

[54] Federal Aviation Administration, op. cit., footnote 20, pp. 6-16 through 6-18.

WEATHER TECHNOLOGIES AND TRAINING

The types of weather of most concern to commercial aviation pilots are: current and forecast surface conditions, convective weather and associated precipitation and turbulence, clear air turbulence, icing, winds aloft (although this is rarely a safety factor), and windshear near the surface. Windshear near the surface is particularly significant because, over the past 10 years, windshear contributed to almost one-half of all fatalities resulting from commercial aircraft accidents during takeoff and landing.

Weather technologies include weather sensors, technologies for data interpretation, message formulation and display, and communications technologies. Other technologies deal with the effects of weather, such as de-icing technologies (which are discussed in chapter 8). Some weather technologies are entirely contained within the aircraft, and others are ground-based, with perhaps a ground-to-air communication link to relay the information to the pilot. Many technologies that address weather also have other functions.

Several generic types of weather sensors are commercially available for use on the aircraft, including weather radar, sferics (atmospherics) detectors, and windshear warning systems. Weather radar presents to the pilot radio-frequency reflectivity levels, which suggest precipitation rate, on a map display. Since turbulence is typically a greater hazard to aircraft than precipitation, methods have evolved for using reflectivity data to infer the probable existence of turbulence, Some newer models of airborne weather radar include a Doppler channel for direct detection of turbulence. From the standpoints of engineering approach and use in the cockpit, Doppler radar remains a developing technology.

Neither conventional nor Doppler airborne radar is capable of reliably detecting clear air turbulence, which may appear separate from storms or in the vicinity of storms. Also, airborne weather radars may be attenuated by nearby precipitation or by ice on the radome, although some newer models have a feature that warns pilots when signals are being attenuated. For these and other reasons, proper use of airborne weather radar is by no means straightforward and requires training and experience on the part of the pilot.

Sferics detectors passively detect electrostatic discharges in the atmosphere. The presence of discharges suggests convective activity where turbulence may be present. Sferics detectors derive the range of detected weather statistically from the strength of received signals. As such, the range of detected weather may be significantly in error. The output displays of both weather radar and sferics detectors may be integrated with the horizontal situation indicator in cockpits equipped with CRT displays, so that the pilot sees weather in relation to navigational aids, waypoints, and intended route of flight on a display.

Federal regulations require weather radar for Part 121 operators[55] and for Part 135 operators when operating large, transport category aircraft.[56] Smaller aircraft with at least 10 passenger seats must carry approved thunderstorm detection equipment;[57] these aircraft may carry an approved sferics detector instead of weather radar.

Windshear

Windshear warning systems use the performance of the aircraft itself as a sensor of conditions that indicate the presence of a potentially dangerous windshear. Of all the possible types of windshear, the microburst is usually the most dangerous, and windshear warning systems are optimized to detect the microburst. Visual and audible alarms sound when performance of the aircraft suggests the presence of a windshear. Newer models of windshear warning systems can provide guidance to assist the pilot to escape the windshear, and the warning system can be coupled to the aircraft's autopilot to automatically execute procedures to escape the shear. The weakness of current windshear warning systems is that the aircraft must already have entered the windshear to detect it; this may be too late to escape the most severe shears. Detecting windshear conditions prior to entry represents a significant technological and economic challenge to the aviation industry.

[55] 14 CFR 121.357 (Jan. 1, 1987).
[56] 14 CFR 135.175 (Jan. 1, 1987).
[57] 14 CFR 135.173 (Jan. 1, 1987).

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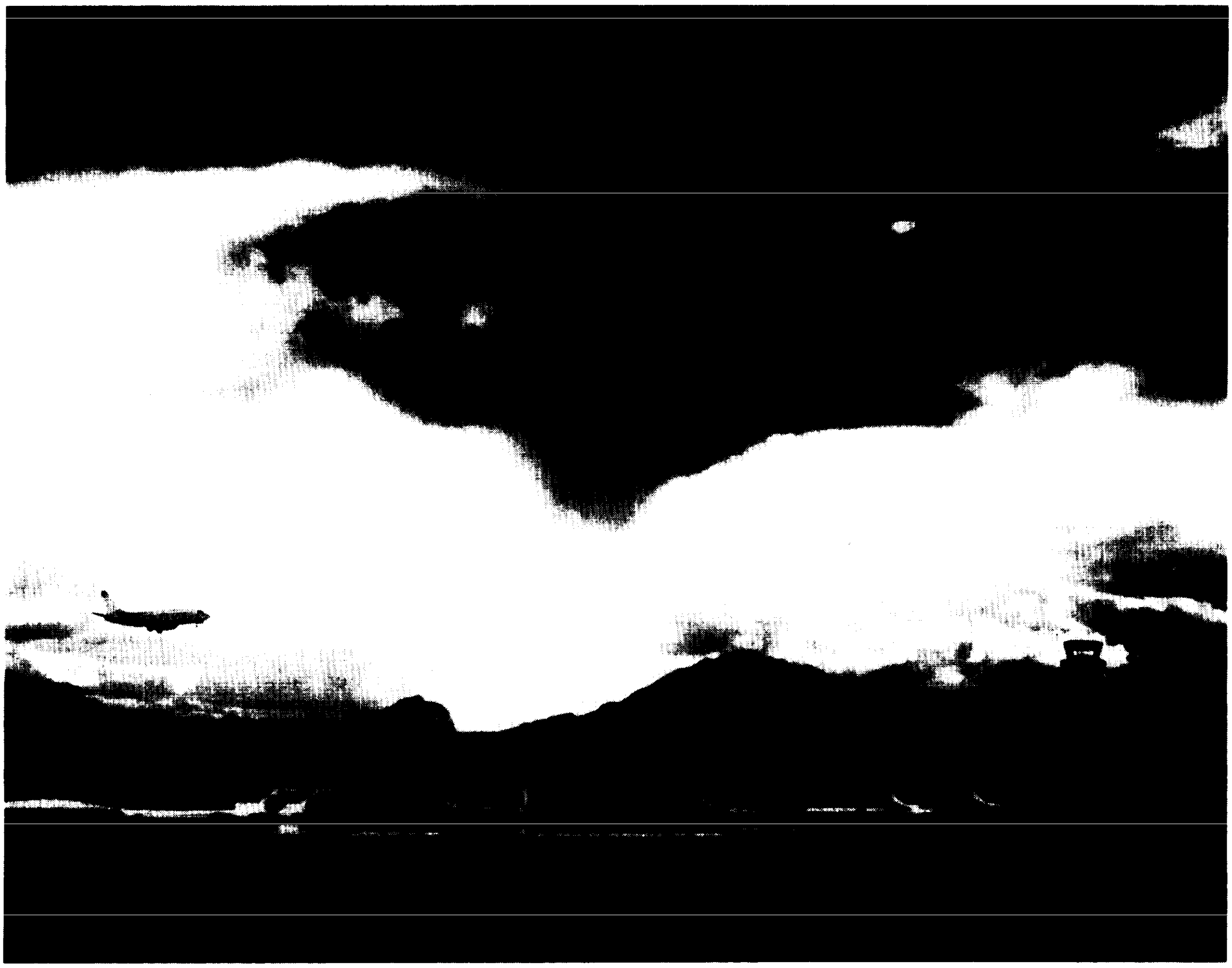


Photo credit: The Sperry Corp.

Windshear near the ground is sometimes accompanied by visual signs.

Windshear warning systems are not currently required in aircraft; however, a recent Notice of Proposed Rulemaking would require windshear warning with flight guidance for Part 121 aircraft, along with training for pilots, and training in windshear avoidance and escape for pilots of Part 135 operations.[58] Many airlines include simulator windshear training to alert flight crews to the indications of incipient windshear and to help them in controlling the aircraft so as to retain sufficient power during escape/avoidance maneuvering.

Because of the many subtleties in the use of cockpit weather sensors, and because of their inherent limitations, adequate, appropriate training is essential for their proper use. The training must involve instruction in the actual use of the equipment, as well as recognition of visual cues for dangerous weather conditions, such as windshear. FAA sponsored joint industry/government development of a windshear training program, called Windshear Training Aid. Completed in February 1987, the program represents the consensus of airlines, manufacturers, pilots, the research community, and government regulatory and safety agencies. The training program is part of the Integrated FAA Wind Shear Program Plan.[59]

[58] 52 *Federal* Register 20559-20571 (June 1, 1987).

[59] E.A. Kupcis, "Windshear Training Aid," *Boeing Airliner,* July-September 1987, pp. 2-7.

Although windshear training is receiving increased attention at this time, training programs for use of weather information in the cockpit are believed by some experts to be inadequate.[60] In particular, many airlines provide minimal pilot training in the use of information such as that available from airborne weather radar. The situation has become more acute as airlines have cut staff and are less equipped to offer professional meteorological help.

National Weather Service

FAA, the National Weather Service (NWS), and some commercial organizations are involved with detecting weather, interpreting the information, and communicating the information to pilots and FAA field personnel. The NWS Aviation Services Branch is in charge of providing aviation weather information, and relies on FAA to stipulate the requirements for the information, Airlines, as well as FAA, use information provided by NWS for functions such as pilot briefings.

NWS operates ground sensors on airports (FAA also operates ground sensors on airports; in fact, more than NWS),[61] Geostationary Operational Environmental Satellites (GOES), upper-air sounding devices, and Weather Service Radars to sense weather for aviation and other users. NWS meteorologists interpret information from the sensors to produce products specifically tailored to aviation needs, such as Terminal Forecasts.

FAA operates Flight Service Stations (FSSs) to provide preflight briefings and in-flight weather information over VHF radio primarily to general aviation pilots, although Part 135 operators use FSSs as well. FSSs are staffed by FAA personnel who are not meteorologists, but who are specifically trained and have access to information from NWS sources, including GOES data, surface observations, and forecasts produced by NWS meteorologists.

Air Traffic Control Role

Air traffic controllers in ARTCCs, TRACONs, and airport towers are an important source of weather information to commercial aviation pilots, although when controllers are busy managing crowded airspace, significant delays occur before weather information is relayed to pilots. Controllers currently receive weather information from pilots in the form of pilot reports, from the weather channel of the en route surveillance radar (and in the future, from ASR-9), from the Center Weather Service Unit (CWSU) meteorologist located in each ARTCC, from NWS products supplied directly to them, from direct observation (in the case of tower cab controllers), and from FAA's Low Level Windshear Alert System (LLWAS). The communication links between the sources of weather information and controllers are often primitive; CWSU meteorologists sometimes leave their CWSU stations to deliver messages by hand to controllers.

Automation and digital air/ground communications could reduce or eliminate the controller's role in the process of providing weather information to pilots. However, controllers themselves need to be aware of bad weather to anticipate when pilots are likely to ask for deviations from their initial flight plans, so they can manage the traffic situation better. Traffic management controllers at ARTCCs and, nationally, Central Flow Control controllers need accurate weather information, so they can adjust traffic flows to the capacity of the system.

LLWAS is a system that employs wind vanes and anemometers in the vicinity of an airport to generate windshear alerts for tower controllers, who are supposed to broadcast the information to pilots under their control. LLWAS was developed in the 1970s before windshear phenomena were understood very well, and is optimized for detecting gust fronts, which are relatively harmless to large aircraft, rather than for detection of deadly microbursts. LLWAS misses some microbursts because the sensors are too widely spaced, produces many false alarms, and its alarms are not timely enough to track the rapid buildup and decay of most microbursts.[62]

[60] John McCarthy, in U.S. Congress, Office of Technology Assessment, "Transcript of Proceedings-OTA Workshop on Technology in Commercial Aviation Safety," unpublished typescript, July 1, 1987, pp. 169-170.

[61] Robert E. Brown, deputy director, Program Engineering Service, Federal Aviation Administration, letter to OTA, n.d.

[62] John McCarthy, National Center for Atmospheric Research, "To Improve the Detection of Hazardous Aviation Weather," testimony before U.S. Congress, House Committee on Public Works and Transportation, Aviation Subcommittee, Oct. 2 and 30, 1985, pp. 23-61.

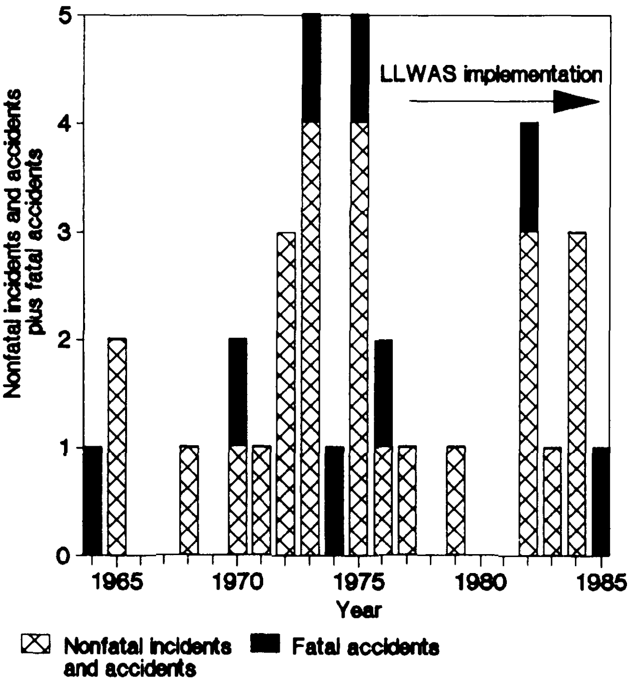
Figure 7-6 plots windshear accidents and incidents for transport category aircraft by year since 1964; no statistical evidence shows that LLWAS has reduced the rate of incidence of windshear-caused accidents.

Weather Research and Development

R&D into windshear sensors falls into two categories, ground-based and airborne, and both categories are being pursued by FAA as part of its integrated Wind Shear Program Plan.[63] Two ground-based windshear detection technologies are being developed: an enhanced version of LLWAS and Terminal Doppler Weather Radar (TDWR). Enhanced LLWAS includes more sensors at each airport and software changes to allow better and more timely detection of microbursts. However even enhanced LLWAS cannot detect microbursts before they hit the ground, which may be too late. TDWR may permit early detection of microbursts, and could be more reliable than enhanced LLWAS, although obstructions on or near the airport surface would limit the coverage of TDWR. One major technological challenge is to develop and validate computer algorithms for automatic detection of microbursts with TDWR.

[63] U S Department of Transportation, Federal Aviation AdrninlStration, *Integrated FAA Wind Shear Program Plan* (Springfield, VA: National Technical Information Service, April 1987).

Figure 7-6.—Windshear Accidents and Incidents Before and After LLWAS Implementation



KEY: LLWAS = Low Level Windshear Alert System.

SOURCE: 52 *Federal Register* 20562-20563 (June 1, 1987); and Federal Aviation Administration, "Integrated FAA Wind Shear Program Plan," DOT/FAA/DL-8711, April 1987.

Originally FAA planned to deploy TDWR at about 100 airports, but the Office of Management and Budget recently restricted the number to 44, based on cost-benefit analysis.[64] An integrated sensor system consisting of both enhanced LLWAS and TDWR may be the best choice at airports where the windshear threat justifies deploying both, but the problem of integrating the sensors to produce a single message to pilots and controllers needs to be solved. Another challenge is to develop a message format and a reliable means of communication of the information to pilots. A message format developed in 1987 by a users' working group has been used at Denver with the enhanced LLWAS, and has been found satisfactory for the TDWR operational demonstration scheduled for summer 1988. Development of ground-based windshear detection technology that is less expensive than TDWR, but more capable than enhanced LLWAS, would help alleviate microburst risk at smaller airports with increasing traffic levels.

Airborne windshear sensors are in a more preliminary stage of development than the ground-based sensors. FAA is underwriting the basic technical and scientific developments in airborne systems to the point where technologies can be developed and marketed commercially. Airborne sensors do not have the coverage limitations of ground sensors, do not rely on a ground-to-air communications link, and provide advance warning. Microwave radar and light detection and ranging technologies are currently undergoing assessment by FAA and a consortia of manufacturers, and at least two companies are independently investigating look-ahead infrared temperature sensors for microburst detection.[65]

[64] Arthur L. Hansen, manager, Weather Radar Staff, Federal Aviation Administration, personal communication, Mar. 3, 1988.

[65] Herb Schlickenmaier, project manager, Airborne Windshear Detection and Avoidance, Federal Aviation Administration, personal communication, Nov. 3, 1987.

FAA, NWS, and the Department of Defense are participating in a joint program, called NEXRAD (next generation weather radar), to upgrade the current system of radars used to map rainfall levels across the United States. NEXRAD is planned to replace the current network of NWS radars, and to provide both reflectivity and velocity dispersion information for determination of turbulence levels. NEXRADS will be sited temporarily at airports where windshear is an especially serious threat to serve as interim terminal weather radars before TDWR is introduced. The issue of how to present NEXRAD information to pilots–through controllers or as a graphical product–has not yet been resolved. Air traffic controllers will receive graphical NEXRAD information.

Automated systems to collect other weather information in the terminal area are being developed by both FAA and NWS. The replacement of human observers by these systems is currently controversial, and message formatting and communication of the information to pilots are unresolved issues. NWS plans to upgrade its capabilities for providing information and making forecasts include replacing the current data analysis and distribution system with a sophisticated network of computing, communications, and display capabilities. Another developing technology is the profiler system to replace current balloon technology for upper atmospheric measurements; the results for aviation include more accurate and timely winds information, hazardous weather warnings, and forecasts for better airspace planning.

Some airlines have meteorology departments that handle preflight briefings, and all airlines are required to have dispatch organizations that transmit weather information to pilots over the company radio system or over ACARS.[66] Some pilots utilize publicly televised weather programs such as "A.M. Weather," or newspapers to obtain weather information.

Improving weather information available to pilots requires better training for NWS forecasters and observers, air traffic controllers, and flight service station specialists in use of weather information and observing weather. Moreover, as new weather sensor technologies are fielded, training for users of the information must be stepped up to ensure safe air travel.

[66] 14 CFR 121.599 and 601 (Jan. 1, 1987).

LIABILITY ISSUES

Liability issues haunt aviation safety because an accident that implicates a safety technology or training program could cost a manufacturer or airline more than it is worthwhile to risk. For example, Boeing nearly backed out of its participation in the Windshear Training Aid program over liability concerns, until the Secretary of Transportation intervened and convinced the manufacturer to continue.[67] The industry-wide endorsement of the results of the program suggest that a valuable product for making commercial aviation safer would have been lost if the project had been abandoned. No other commercial aviation safety technologies or programs have been identified which are in danger of extinction because of liability, but new industry initiatives in the future could be impeded. Liability has had a large impact on the GA industry; while tort actions have produced improvements in areas such as handbooks and crash survivability, the GA industry is in severe financial straits.

[67] Edgars A. Kupcis, New Product Development, Boeing Commercial Airplane Co., personal communication, Aug. 4, 1987.

CONCLUSIONS AND POLICY OPTIONS

While further safety improvements through technology will come at relatively high cost, several technology areas show real promise for improving the current level of safety even as demands increase on the air system.

Some ATC facilities are already severely taxed because of inadequate equipment and unmet controller training needs. Installation of Host computers at en route centers was a major step in bringing up the capabilities of the centers to meet traffic demands.

However, equipment at en route centers, TRACONS, and airport tower cabs is old and difficult to replace; furthermore, the centers have limited expansion capabilities to handle more radars and controller positions. AAS will upgrade capabilities at air traffic facilities, but the system will not be ready in time to head off capacity problems before the mid- to late-1990s.

TRACONs and tower cabs that control traffic around busy airports will face even more responsibilities in the near future when broadened Mode C transponder requirements become effective. Furthermore, many TRACONs would require capacity enhancement to include the Mode C Intruder Alert function. Currently, the New York TRACON equipment is being upgraded for increased capacity, Mode C Intruder Alert, and better displays. OTA finds that other TRACONs will need additional computer capacity to handle expected increases in transponder traffic levels without performance degradation, and still more capacity if the Mode C Intruder Alert feature is included. Funds for increasing equipment capacity at TRACONs are included in FAA's fiscal year 1989 budget request. The Mode C Intruder Alert, which will be used at all ARTCCs, could be used at TRACONs as well, but needs analysis and testing to ensure that its false alarm rate is acceptable. Installation of the Mode C Intruder Alert at TRACONs is expected to be part of the 1988 version of the NAS Plan.

While recent legislation will require broader carriage of Mode C transponders by GA aircraft, some aircraft will still not carry Mode C transponders. An option is to continue to increase altitude-encoding transponder requirements, concurrent with increased ATC equipment capabilities and personnel, to guard against accidental incursions into airspace where radar coverage is provided and to provide the maximum protection through TCAS.

Automation tools for controllers at all facilities– airport tower cabs, TRACONs, ARTCCs, and the Central Flow Control Facility–could assist in the safe handling of higher levels of traffic and reduce pressures on air traffic controllers. In particular, terminal automation development is a potential area for improvement prior to AAS. While terminal automation development has not previously been well funded, additional funding is being sought by FAA for fiscal year 1989. For the longer **term,** ATC problems **may worsen as traffic levels increase unless the infrastructure of the ATC system is upgraded. AAS** is FAA's long-term program **to** avert ATC problems. In the interim, before AAS is fully implemented, support to FAA for analysis to identify emerging operational problems and to establish parameters for solutions to the problems would help facilitate adequate ATC system capabilities as the air transportation system evolves. Timely, cost-effective solutions to ATC problems must include both technological changes and support for related personnel needs. (See chapter 3 for more discussion of ATC personnel problems.) AERA offers potential long-term benefits for en route controllers through automation, but more work is needed to understand both the system safety and efficiency implications of AERA to clarify whether AERA will facilitate safe control of higher traffic levels.

Weather is a contributing factor in many aircraft accidents, and sensors such as TDWR hold great promise for improving safety through rapid detection of dangerous weather. The high cost of TDWR, however, may preclude its use at all but the largest airports, so other lower cost technologies for microburst detection (in addition to enhanced LLWAS) merit further examination. **OTA finds that improved training for pilots in use of weather information available in the cockpit, and R&D to develop message formats and workable air/ground communications for weather information, are at least as important as weather sensor development for improving aviation safety.**

Current air/ground communications are not always adequate to support the needs of pilots for both real-time ATC and real-time weather information. Providing ATC information **to** ensure separation between aircraft and issuing safety alerts are the controllers' first priorities, and controllers sometimes do not have time to transmit weather information to pilots or are distracted from transmitting information by more urgent demands to separate traffic. **For the near term, better pilot training in use of information from on-board weather radar and from visual observations can compensate somewhat for occasional lack of weather information from controllers.** The FAA's Windshear

Training Aid program, developed cooperatively with industry, has features that are a step in this direction. **For the longer term, automation and development of digital air/ground data links can eventually remove controllers from the process of relaying weather information to pilots and can potentially reduce controller workload for ATC messages.** The Mode S data link can be integrated with commercial data links to produce a very reliable system with excellent coverage and capacity. However, in the past, digital communications have been relegated by FAA to the distant future, and commitment is needed to replace the current analog voice system. **OTA concludes that R&D efforts on data link services, human factors, and system integration have a potentially high payoff for efficiency as well as safety.** Both FAA and NASA (which already has personnel, facilities, and equipment to do some of this R&D) have begun work in this area.

TCAS has taken a long time to reach its present stage of readiness for limited installation testing, and whether TCAS introduces unexpected ATC problems and human factors questions remains to be seen. Not all countries are satisfied with TCAS, and requiring its use in the United States will not guarantee its eventual use everywhere. None of these issues appears to be a crucial stumbling block to TCAS.

Although the United States has had few recent fatalities from collisions on the airport surface, a number of nonfatal collisions and close calls have occurred. As air traffic levels increase, the probability of a disastrous ground collision will increase, lacking compensatory measures. The ASDE-3 radar, currently under development, is one such measure, but other means to improve ground collision safety include improved signs on the airport surface, control lights at entrances to active runways, and more vigilance by pilots during taxi operations. **Congress may wish to encourage FAA to expedite increased ground collision safety through technological, procedural, and training approaches, as well as through ASDE~3 development.** Short-term R&D to improve sign symbology could provide the basis for consistent standards for taxiway and runway signs at all U.S. airports. If current tests are successful, stop/go bar lights and signal lights could be installed at entrances to major runways to augment runway clearances from ground controllers. Additional controllers for airport towers would be needed to operate the lights. Procedural rules could be changed to require that both pilots and co-pilots be free of other work while taxiing, and training for pilots and controllers on preventing runway incursions could be increased.

Air traffic controllers at some en route facilities now receive site-specific training at the FAA Academy in Oklahoma City, because of inadequate resources at the en route facilities. **OTA finds that improved simulation training for air traffic com trollers could lead to more cost-effective ATC training, both now and in the future, when further automation is introduced.**

FAA has begun development of system-wide capacity models (NASPAC) to take into account traffic flows between airports. **Continued emphasis on analytical modeling to better understand capacity of the air traffic system would help FAA assume a leadership position in the future when difficult issues regarding capacity, safety, noise, and airline scheduling arise.**

The NAS Plan has suffered because requirements for its technologies have changed since the Plan was created in 1981. FAA, recognizing the emergence of important near-term needs, has established an interim support program. However, FAA has done relatively little near-term or far-term research to support NAS developments. NASPAC and other operations research and analysis efforts could help FAA identify emerging ATC problems and parameters for solutions to the problems. An area for further investigation is the use of modern prototyping and test bed technology to help FAA evaluate alternative technological and operational solutions in a realistic way that encourages innovation and timely fielding of technology.