Paul R. Drouilhet, Jr.

Air Traffic Control Development at Lincoln Laboratory

For nearly two decades Lincoln Laboratory has carried out a series of major programs in air traffic control for the Federal Aviation Administration. The programs have developed systems that improve surveillance, communications, collision avoidance, and severe-weather sensing. These systems are now beginning to be installed at airports around the country in support of air traffic control. Recently, major new programs have been initiated to enhance the efficiency and capacity of aircraft operations in the terminal area and on the airport surface.

Since its founding in 1951, Lincoln Laboratory has worked primarily on problems relating to national defense. In the late 1960s, three factors led to an expansion of the Laboratory's scope of activity to include work in a few nondefense areas. The largest of these areas, and the only one that continues at a substantial level today, is civil air traffic control.

The factors that brought about this activity were (1) an important national need; (2) an opportunity, manifested in the willingness of the Laboratory's Department of Defense (DoD) sponsors to see a fraction of the Laboratory's efforts and facilities devoted to nondefense problems; and (3) an interest on the part of members of the Laboratory staff to work on such problems.

The need was clear. In the late 1960s the U.S. air traffic control (ATC) system faced a crisis. The introduction of jet aircraft beginning in the late 1950s had led to a rapid expansion of air carrier traffic. The greater demand placed on ATC by the higher speeds and greater fuel consumption of these jet aircraft compounded the impact of the expansion. Likewise, a booming economy stimulated the rapid growth of general aviation. Flight delays increased, and the current system appeared to many to be on the verge of breakdown. The projected growth of aviation required substantial improvements in the quality and efficiency of air traffic control.

There was also a perception in the country at that time that the United States placed too much national research and development effort into defense-related areas, and neglected important needs in the civilian economy. This perception led to an active interest within the DoD to demonstrate the applicability of DoD-developed technology and resources to critical nondefense problems. In particular, the Air Force, the principal Laboratory sponsor, encouraged the Laboratory to use some Air Force general research funding as seed money to develop programs in selected nondefense areas. ATC was particularly appropriate, since the Air Force had decided to reduce its own ATC research and development and give the responsibility for joint-use ATC/air-defense sensors to the FAA.

Finally, air-traffic-control-related problems interested many Laboratory personnel, both as engineers and as travelers frustrated by frequent flight delays. The Laboratory had been established in 1951 to work on a form of air traffic control—detecting enemy aircraft and vectoring fighters to intercept them. While the Laboratory's program had broadened substantially over the years, and in fact no longer included air-defense-related activities, considerable interest and expertise in air traffic control remained among Laboratory personnel.

The central focus for this interest at the Laboratory was the development of a concept proposed by Herbert Weiss, then head of the Radar Division, for a new air traffic control system structure [1]. Weiss's "spaghetti tube" concept for en route traffic management, and the ATC interest it stimulated, led to the formation in late 1968 of an Ad Hoc Committee on Air Traffic Control within the Laboratory. The Committee was charged to carry out a broad study of the air traffic control system and its problems, and to recommend a program to develop solutions. The committee met over a period of several months, and in May 1969 published its report, including a proposal for a Laboratory program in the ATC area, based generally on Weiss's concept.

In September 1969 a study group chaired by Walter E. Morrow, Jr., then Assistant Director of Lincoln Laboratory, was convened to examine further the possibility of new programs in Air Traffic Control. In addition to Lincoln Laboratory personnel, members of this group were drawn from the MIT Flight Transportation Laboratory in the Department of Aeronautics and Astronautics, the Electronic Systems Laboratory, the Measurement Systems Laboratory, and the Draper Laboratory, then part of MIT. Over a three-month period the study provided for its participants a broad education in the various disciplines related to ATC, and validated the idea that an ATC program should be pursued.

Both the committee and the study group concluded that the Laboratory had the right mix of capabilities to make a unique contribution to ATC research and development. These capabilities included the development and analysis of new concepts, the design and construction of evaluation hardware and software, and the planning and execution of field test programs. To provide a defined focus for the development of an ATC program at the Laboratory, the Radar Division was restructured in early 1970, and renamed the Air Traffic Control Division. Ongoing defense-related activities were moved to other divisions, and the Air Traffic Control Division became the nucleus for the development of an ATC program. A small number of interested staff members (including the author) from other parts of the Laboratory joined the ATC Division at this time to work with Herb Weiss on the development of an ATC program.

Air Traffic Control Advisory Committee

During the same time period, the Department of Transportation formed a national committee, the Department of Transportation Air Traffic Control Advisory Committee (ATCAC), to examine all aspects of the national air traffic control system, to project the demands on the system for at least a 20-year period, and to develop a recommended national program for air traffic control to meet these projected demands. This committee reviewed and was influenced by the Lincoln Laboratory study, but proceeded independently and with broader scope. The ATCAC report, dated December 1969, proposed an architecture for an evolving system to meet the projected needs of air traffic control, and outlined a development program to realize the proposed architecture [2].

A key element of the ATCAC plan was an upgrade to the existing Air Traffic Control Radar Beacon System (ATCRBS) to give it improved surveillance capability and an integral data link for two-way communication between air traffic control facilities and aircraft under control. The upgraded beacon surveillance system, which came to be called "super-beacon," would support an automatic ground-based collision avoidance concept called Intermittent Positive Control (IPC). IPC ground facilities would track otherwise uncontrolled aircraft, and issue conflict-resolution commands via the data-link portion of super-beacon to resolve potential conflicts.

The principal technologies—radar, signal processing, digital communications, data processing—necessary to bring the super-beacon concept to reality were well matched to the capabilities and interests of the Laboratory. Thus super-beacon, or the Discrete Address Beacon System (DABS) as it came to be officially known, became the focus of the Laboratory's initial foray into air traffic control.

The Early Years

Discrete Address Beacon System

In early 1971 the FAA established its first sponsored program at the Laboratory, a six-month effort to prepare a technical development plan for DABS. The successful completion of this effort led, in turn, to a greatly expanded effort to develop, test, and demonstrate DABS and its associated IPC capability. The execution of this program included the development of a DABS experimental facility adjacent to the Laboratory, and a transportable measurement facility for

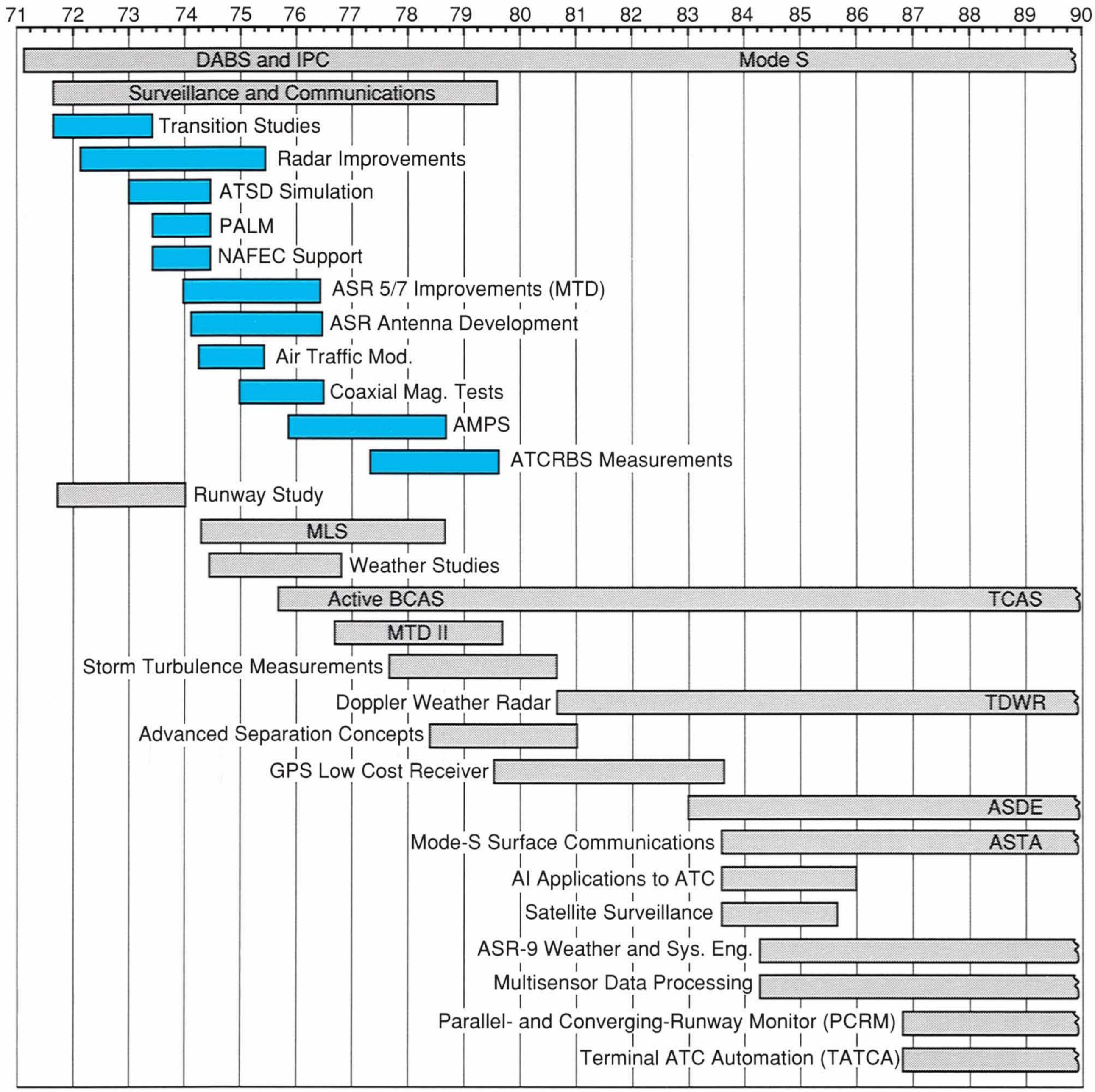

Fig. 1—Principal Lincoln Laboratory programs for the FAA from 1971 to the present. The colored efforts are sub-tasks of the Surveillance and Communications program.

testing the DABS concept in many locations around the country. Several test aircraft were also outfitted to make airborne measurements and to test the IPC concept. A number of pilots from the local community, as well as airline flight crews, participated in these flight-test activities.

The basic design of DABS was largely complete by the mid-1970s. Since that time, the Laboratory has assisted the FAA in the refinement, development, and testing of three prototype systems manufactured by Texas Instruments, and in the currently ongoing procurement of 137 systems from a joint venture of Westinghouse and Unisys. DABS, or Mode S as it was officially named in 1983, will begin to be deployed at the nation's airports and en route surveillance facilities in 1991.

In addition to supporting these procurement activities, the Laboratory has participated in the development of international standards for Mode S. Over the next one to two decades, Mode S will be implemented in high-traffic-density areas throughout the world for air traffic surveillance and data-link communications. A companion paper by Vincent Orlando, on page 345, presents a detailed description of the development program and features of Mode S.

Fig. 3—Early testing of DABS/Mode S, using the Transportable Measurement Facility (TMF) at Logan Airport, Boston.

Surveillance and Communication

During the course of the DABS development, Laboratory personnel became increasingly familiar with the then current FAA surveillance and communications system. Numerous opportunities appeared for interim improvements in system operation prior to the introduction of

Fig. 2—DABS/Mode-S experimental facility with two experimental radars in the background.

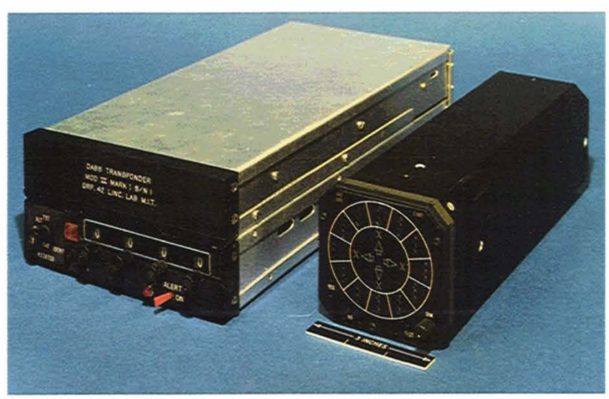

Fig. 4—First DABS/Mode-S transponder and IPC display.

Fig. 5—Aircraft used in early IPC and DABS/Mode-S flight tests, in front of Lincoln Laboratory Flight Facility. (The large aircraft at the left rear is a Twin Otter used for a DoD radar program.)

DABS/Mode S. To make the improvements, a separate multitask surveillance and communications program was initiated. This program led to the development and adoption of many techniques for improving existing primary-radar and secondary-radar (beacon) systems in the United States and abroad.

The most enduring results of these efforts have been the application of monopulse techniques to ATCRBS, and the development of an improved primary-radar signal processor, called the Moving Target Detector (MTD).

The use of monopulse for ATCRBS improves surveillance accuracy and reliability, and allows the use of substantially reduced interrogation rates, thereby reducing self-interference. To provide improved air traffic surveillance prior to the introduction of Mode S, a number of foreign countries (e.g., Canada, France, and the United Kingdom) have implemented monopulse. The United States, however, decided not to implement monopulse, but to proceed directly to the introduction of Mode S.

The MTD enhances the detection of aircraft in the presence of various forms of radar clutter, such as ground, weather, and birds. The resulting radar display is nearly as clean as the display provided by beacon surveillance (ATCRBS and Mode S), but without the identity and altitude features. The radar also includes a digital weather channel. The processor overcomes ground-clutter and storm-velocity-filtering

Fig. 6—Larry Giusti and Dorothy Zanni monitor early IPC tests.

Fig. 7—The ASR-7 radar at Burlington, Vt., used for testing the Moving Target Detector (MTD). The surrounding hills provided a high-clutter environment to test and demonstrate the clutter reduction capability of the MTD.

problems to develop timely reports of storm reflectivity for display to controllers. Many U.S. and foreign radar systems have adopted MTD and its derivatives for both civil and military application. MTD is the basis for the latest generation of FAA airport surveillance radar, the ASR-9, which is manufactured for the FAA by Westinghouse. A companion paper by Melvin Stone and J.R. Anderson, on page 363, describes the advances in airport-surveillance radar technology.

Broadening the Program

After passing the peak of activity on DABS development, the Laboratory program expanded into other ATC-related activities. These other activities were built on the foundation of increasing familiarity with ATC problems and techniques.

Microwave Landing System

During the 1960s and early 1970s, in the United States and abroad, a new Microwave Landing System (MLS) had been under development as a replacement for the venerable Instrument Landing System (ILS). MLS was motivated by the desire for improved performance (i.e., better accuracy and less susceptibility to multi-

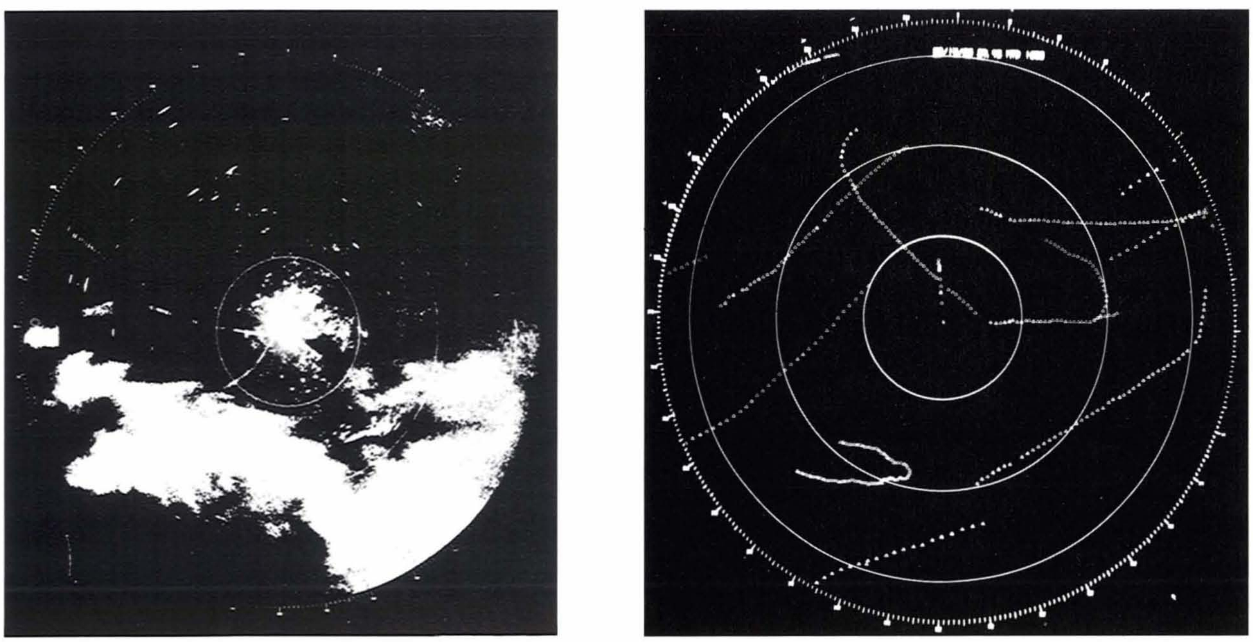

Fig. 8—Comparison of conventional and MTD radar performance in heavy rain. The conventional video image is on the left, and the MTD radar tracker output is on the right.

path interference), greater flexibility (such as the ability to support curved approaches), and operation in a new part of the frequency spectrum where many more channels would be available. An additional key motivation was the need for economical precision-landing guidance at airports such as Aspen, Colo., where special terrain features make the use of conventional ILS difficult and/or expensive.

In the mid-1970s a concerted international program developed to select a single MLS technique among the various contenders, complete its development and test, and define standards for international deployment. The field quickly narrowed to a small number of similar contenders. One of the discriminants used in the selection process was the sensitivity of the various techniques to multipath interference. The FAA asked Lincoln Laboratory, because of its experience in related programs, to undertake a program of analysis, simulation, and experimentation to assess the relative susceptibility of the proposed MLS techniques to multipath interference.

The two principal contenders were the Doppler technique, sponsored by the United Kingdom, and the Time-Reference Scanning-Beam (TRSB) technique, sponsored jointly by Australia and the United States. Because the two techniques were so similar in other respects, their relative susceptibility to multipath became a key issue in the selection. The Laboratory and its project personnel found themselves in a highly charged techno-political arena. After extensive analysis and experimentation, the TRSB showed a small but significant performance advantage in multipath susceptibility, and was selected as the international standard for MLS.

Weather Radar

Severe weather—especially low-altitude wind shear—has been a principal cause of fatal avia-

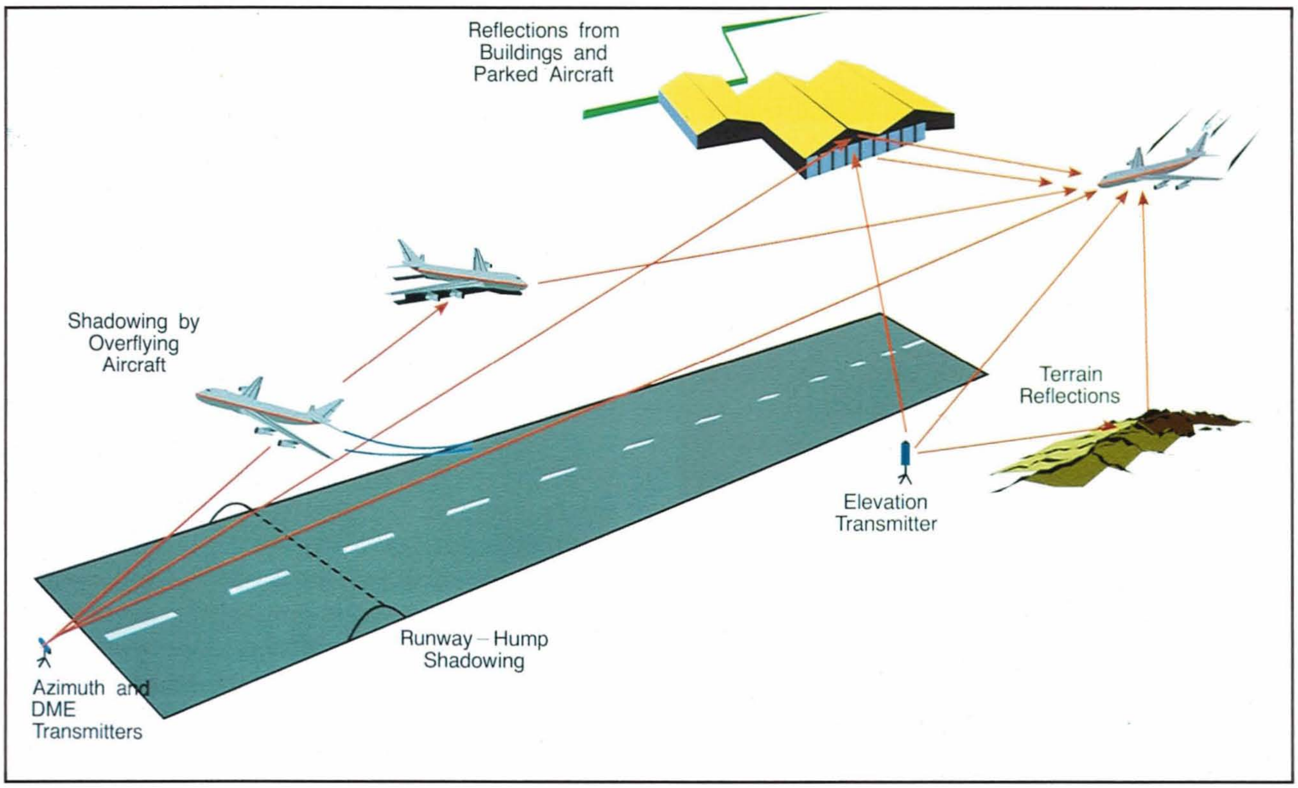

Fig. 9—Response to multipath and shadowing was a key factor in the selection of a Microwave Landing System (MLS) technique.

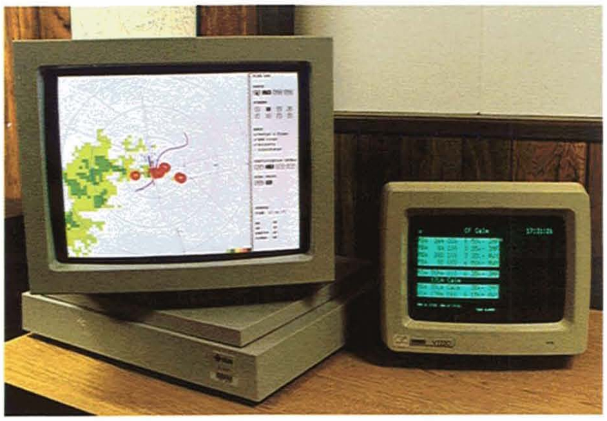

Fig. 10—Graphic and alphanumeric displays of microburst winds detected by an experimental TDWR.

tion accidents in the past 20 years. While the MTD radar processor rejects weather-induced clutter, and thus allows the radar to detect aircraft targets in the presence of heavy precipitation, the processing techniques embodied in the MTD also allow the radar to provide more information on the weather itself than conventional weather radars provide. In particular, the Doppler processing techniques provide information on turbulence and windshear. These capabilities led to a program to develop the radar processing technology that could detect and thereby warn of severe-weather phenomena hazardous to aviation. Early results of these efforts influenced the Next-Generation Weather Radar (NEXRAD) program, a tri-agency (FAA, National Weather Service, and DoD) program to develop and deploy a national network of next-generation weather radars.

In the past several years, the weather-radar program has focused principally on the detection of microbursts and other severe low-level windshear in the terminal areas. The ongoing

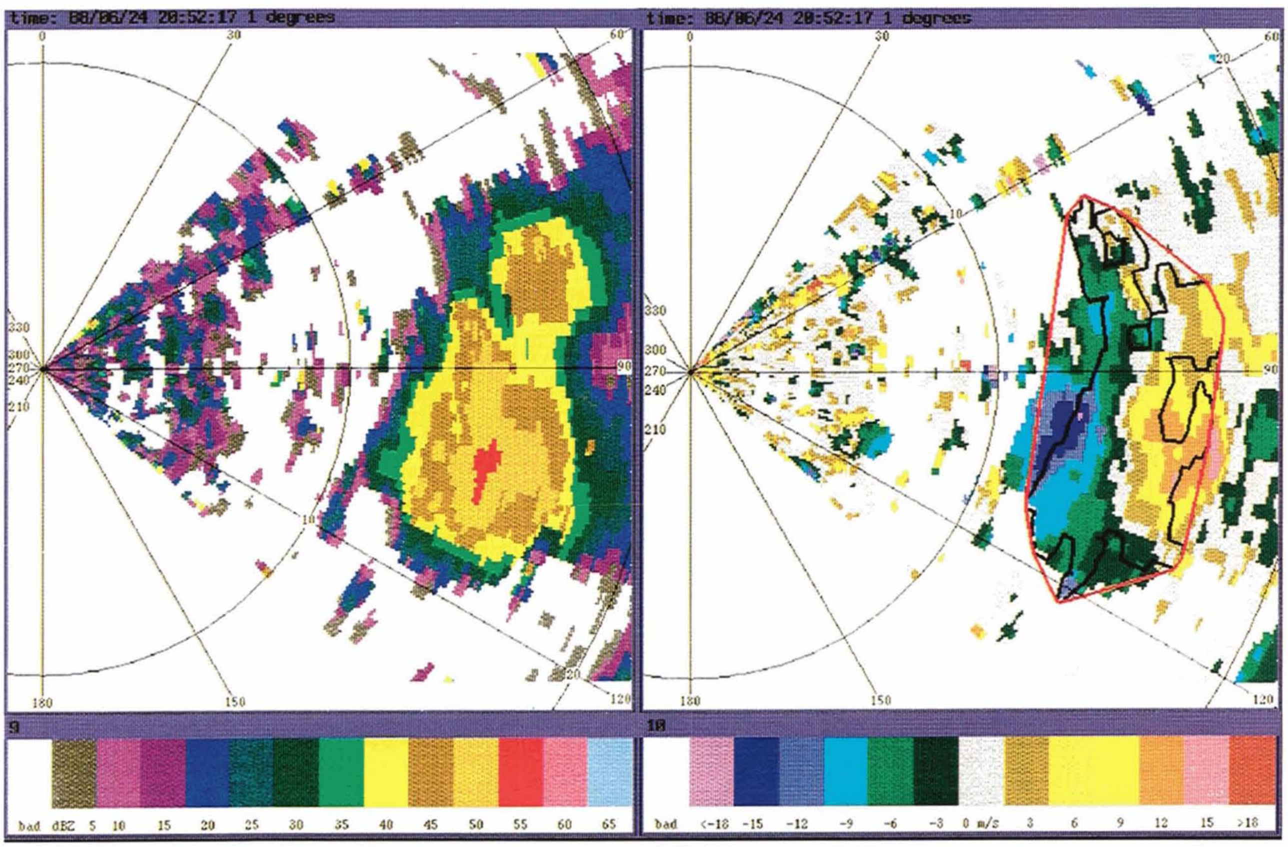

Fig. 11—A microburst-producing thunderstorm as observed by an ASR-type radar at Huntsville, Ala. The left side is the reflectivity image and the right side is the radial velocity image.

activity, described in a companion paper on page 483 by Mark Merritt, Diana Klingle-Wilson, and Steven Campbell, has led to the specification and procurement by the FAA of a NEXRAD-derivative Terminal Doppler Weather Radar (TDWR). A contract for the procurement of 47 TDWR radars, for installation at airports starting in 1992, was recently awarded to the Raytheon Corporation. To create an earlier capability to detect microbursts, Lincoln Laboratory is providing algorithms for the interim use of 16 NEXRAD radars as terminal sensors starting in 1990.

A modified ASR can to a limited degree also detect microbursts and windshear. It is not as effective as a dedicated weather radar, but it can bring a useful safety function to airports that do not qualify for a dedicated TDWR. An extension of the Laboratory's support for the FAA ASR-9 development program is investigating how well such a modified system can perform microburst and windshear detection, and is specifying the necessary modifications to the ASR to accomplish it. A companion paper by Mark Weber and Terri Noyes, on page 511, describes this effort.

BCAS/TCAS

Interest in an Airborne Collision Avoidance System (ACAS) to complement and back up the separation service provided by air traffic control dates back to the 1950s. Several ACAS approaches were proposed at that time, and some were carried through to limited testing.

In the mid-1970s different manufacturers proposed three principal competing ACAS systems. Each contender, however, suffered from the same defect. For an ACAS aircraft to be protected against an intruding aircraft, the intruder also had to be equipped with a similar ACAS, or a special ACAS transponder. The first aircraft to equip would receive essentially no protection. And even if all air carrier and other high-cost aircraft were ultimately equipped, they would receive no protection from the large number of small aircraft whose operators would be very reluctant to equip with a transponder whose only function was to make the small aircraft visible to ACAS-equipped aircraft.

Most desirable would be a system that did not require a special piece of equipment on the other aircraft. A compromise would be to use the ATCRBS transponder that most aircraft already carried. This approach led to the concept of a Beacon Collision Avoidance System (BCAS), in which an aircraft desiring collision avoidance system protection carries a special interrogator that elicits replies from the ATCRBS transponders on nearby aircraft, and coordinates avoidance maneuvers with other BCAS-equipped aircraft.

While attractive in concept, BCAS faced many practical difficulties. The ATCRBS interrogation and reply waveforms were not designed for air-to-air links. Interference, multipath, and synchronous garble (overlapping replies from aircraft at nearly the same range) presented severe technical difficulties. However, the potential advantage of such a system was so great that the FAA initiated a program at Lincoln Laboratory to see if these difficulties could be overcome and a workable solution achieved. Building on the beacon signal processing technology developed in the DABS program, and augmented by the whisper-shout interrogation scheme (a scheme originally proposed by MITRE Corporation engi-

Fig. 12—A TCAS display of conflicting traffic, using modified digital weather radar. The display shows level traffic 600 ft below our own aircraft and ahead at a range of 1.5 mi, along with an aircraft 400 ft above and descending 3 mi ahead at 1 o'clock.

Fig. 13—TCAS testing. This photo was taken from the cockpit of a Lincoln Laboratory test aircraft during controlled encounters with a FAA Boeing 727 aircraft.

neers), a BCAS system was devised that could provide reliable detection, tracking, and threat warning.

BCAS (and most of the ACAS versions) warned the pilot of the equipped aircraft that he was in a threatening encounter, and provided the pilot with a *climb* or *descend* command to resolve the encounter. Tests showed, however, that many pilots were uncomfortable with a command to execute an avoidance maneuver without understanding the conflict situation that led to that maneuver. To alleviate this problem, a traffic display was added to BCAS that provides the pilot with a picture of the range, bearing, and relative altitude of nearby aircraft. With this addition, and with enhancements necessary to operate the system in the highest projected traffic densities in U.S. air space, the system was renamed the Traffic Advisory and Collision Avoidance System, or TCAS.

The BCAS/TCAS program has been a cooperative effort between Lincoln Laboratory and the Washington division of the MITRE Corporation. Lincoln Laboratory has been responsible for the development of the surveillance and communication subsystem, which detects and tracks nearby aircraft and exchanges information with other TCAS-equipped aircraft. MITRE has been responsible for the conflict-resolution subsystem, which acts upon the surveillance data to determine what warnings and commands should be given to the pilots to alert them to the conflict, and suggests appropriate complementary avoidance maneuvers.

Throughout the early years of the BCAS program, the development of IPC, discussed above, proceeded in parallel. BCAS was seen as a service primarily for air carrier and similar high-cost/high-performance aircraft, and IPC was seen as a service primarily for general aviation aircraft. In 1981, then FAA Administrator Lynn Helms discontinued the development of IPC, and selected TCAS (which operates independently of the ground-based ATC system) as the single FAA-supported backup to the air traffic control system.

Lincoln Laboratory has supported the BCAS/TCAS development throughout its inception, its initial design and test, the development by industry of prototype systems, the recently completed limited implementation program testing, and the development of international standards. TCAS is currently in the final phases of development and standardization. Several avionics manufacturers are beginning to produce equipment to meet the Congressionally mandated airline equipage date of 30 December 1991. (As of August 1989, a modified schedule is being considered, requiring 20% equipage by the end of 1990, 50% equipage by the end of 1991, and 100% equipage by the end of 1993.) A companion paper by William Harman, on page 437, describes in detail the development of TCAS.

Advanced Separation Concepts

The Air Traffic Control Advisory Committee also considered a fourth-generation system, which could be a totally new structure, not necessarily an architecture that evolved gradually from the existing system. Most of the proposed fourth-generation architectures utilized satellites for one or more of the functions of communications, navigation, and surveillance.

However, ATCAC finally recommended an evolutionary system, and deferred consideration of fourth-generation systems.

In the late 1970s, the Department of Transportation's Transportation System Center undertook a reexamination of satellite-based ATC system architectures. Lincoln Laboratory participated in this effort by examining the application of satellites to each of the principal ATC functions. The study concluded that consideration of satellites for the communications and surveillance functions of air traffic control in the continental United States was premature (although over-ocean applications may soon develop). Satellite-based air navigation, however, will compete with ground-based systems in the not too distant future.

Data-Link Applications

DABS/Mode S provides a data link between the air traffic control system and each equipped aircraft. Services provided to the aircraft over this data link are expected to encourage general aviation pilots to replace their ATCRBS transponders with Mode-S transponders. To understand better the feasibility and utility of various data-link services, the Laboratory has been carrying out a data-link applications program as part of the DABS/Mode-S development effort. Data-link services being examined include

(1) the transmission of various forms of weather information to the aircraft, either in response to a pilot request or as a ground-initiated warning of severe-weather phenomena;
(2) automatic traffic advisories to alert non-TCAS-equipped aircraft of the presence of other aircraft in the immediate vicinity;
(3) alerts and warnings to assist pilots in avoiding restricted air space;
(4) automatic assistance to pilots in an emergency situation—for example, location and navigation assistance to a lost pilot.

The data-link applications effort includes flight tests of the proposed services so that they can be evaluated by pilots with various skill levels.

A principal result of this effort will be the development of signal standards for the selected data-link services. These standards will allow the independent development of the ground equipment providing the data-link service and the aircraft equipment needed to receive it, the former by the FAA and the latter by various avionics manufacturers.

Fig. 14—Mode-S data-link presentation of weather information in the cockpit of a test aircraft.

The Current Program

The first 15 years of the Lincoln Laboratory program for the FAA focused primarily on issues of surveillance. The major efforts were DABS/Mode S, TCAS, ASR-9, and TDWR. While considerable work remains to be completed before a nationwide operational capability is achieved, the role of the Laboratory in these activities is reaching fruition.

In parallel with the results from the Laboratory programs, other aviation support systems are in the process of development and implementation. These systems include the advanced automation system, MLS, GPS (the satellite-based global positioning system), NEXRAD, and advanced flight-management systems on aircraft.

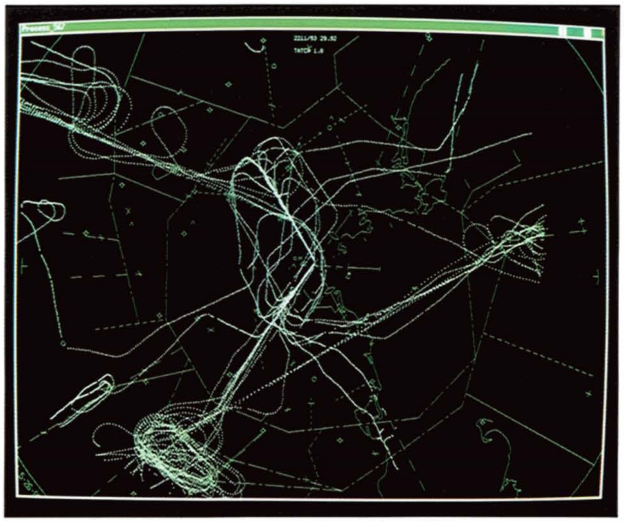

Fig. 15—Composite tracks of arriving aircraft during approximately one hour at Logan Airport on 15 December 1987. TATCA will assist controllers to schedule arrivals, reduce arrival delays, and increase the average landing rate.

Taken together, these new systems provide an impressive set of tools for improved ATC. The central issue now becomes how to use this array of tools to make the aviation system more efficient, safe, and productive.

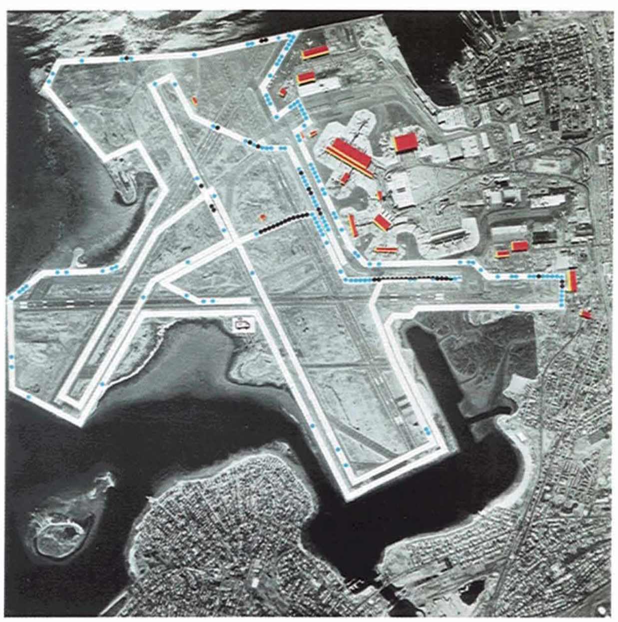

Fig. 16—Test of Mode-S round reliability at Logan Airport. The white areas are greater than 90%, the blue areas represent 50% to 90%, and the black areas represent less than 50%.

TATCA and ASTA

To address this challenge, Lincoln Laboratory in the last few years shifted its focus from the development of surveillance and communications systems to the development of techniques and algorithms used to improve air traffic management. The Laboratory initiated, with FAA support, two major new programs that will provide a principal focus for the ongoing ATC activities. These programs, directed at increasing the efficiency and capacity of aircraft operations in the terminal area, are the Terminal Air Traffic Control Automation (TATCA) program and the Airport Surface Traffic Automation (ASTA) program.

TATCA focuses on the development of computer-based aids that will allow the controller to utilize new surveillance, communications, navigation, and control capabilities to increase the efficiency of terminal area operations, i.e., to get maximum use out of the available runways. A companion paper by David Spencer, John Andrews, and Jerry Welch, on page 527, describes the major elements of the TATCA program.

ASTA focuses on the surface of the airport. The program will develop and implement improved surface surveillance and communication, along with the associated automation aids that enhance the safety and efficiency of surface operations, especially during periods of bad weather and limited visibility. The ASTA program includes (*a*) an upgrade of the capabilities of the ASDE (airport surface detection equipment) radar to include tracking and enhanced target identification; (*b*) Mode-S-based surveillance and communication to provide automatic identification of radar-tracked targets on the surface; (*c*) data-link communication to all Mode-S-equipped aircraft on the airport surface; and (*d*) automation aids to assist the controller in efficiently controlling traffic movements on the airport surface.

The TATCA and ASTA activities are highly complementary, since improved efficiency in airborne operations increases the pressure for effective ground operations, and vice versa.

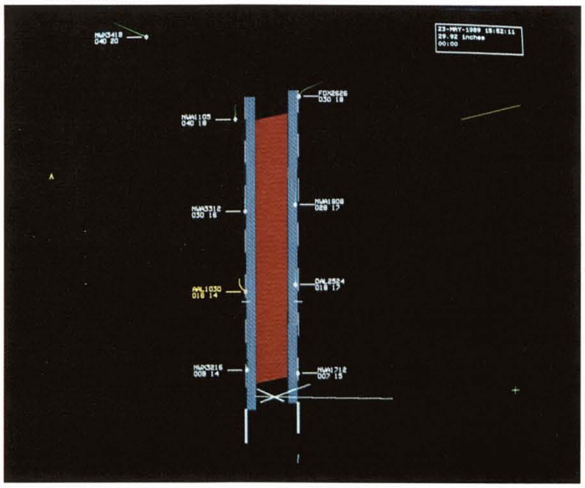

Fig. 17—A display of aircraft arriving on parallel runways at Memphis, Tenn.

Parallel and Converging Runway Monitor

Runway configurations at many U.S. airports allow simultaneous operations—landings and takeoffs—in clear weather, but restrict operations in limited visibility. Parallel runways are of particular concern. Current ATC procedures allow independent operation of parallel runways under instrument meteorological conditions (IMC), i.e., reduced visibility, only when the lateral spacing between the runways is 4,300 ft or greater. More closely spaced runways are restricted to dependent operation. Thus those airports with parallel runways closer than 4,300 ft suffer a severe capacity loss when the weather becomes IMC. With current surveillance technology and manual blunder detection (a controller watching the radar display), runway spacings closer than 4,300 ft do not give the controller adequate time to detect that an aircraft is blundering—i.e., straying from its intended approach path—and to provide a warning to the threatened aircraft in time for it to react.

To alleviate this problem the FAA initiated the Parallel and Converging Runway Monitor (PCRM) program. The PCRM goal is to extend independent operations in IMC to runway spacings of 3,400 ft or less by using high-update-rate, high-accuracy sensors augmented by computer-assisted blunder detection.

The Laboratory has doubled the update rate of a transportable monopulse beacon sensor, originally used in Mode-S experiments, by using back-to-back antennas. With improved displays and computer-assisted blunder detection, the sensor is in use at Memphis International Airport to evaluate the feasibility of independent parallel runway operation at a spacing of 3,400 ft.

A successful outcome of this effort would improve the IMC capacity of 7 to 10 airports in the United States, depending on the runway spacing actually achieved. In addition, construction of parallel runways would be allowed at additional airports that do not have room for runways spaced according to the current criteria. A paper by Raymond LaFrey, on page 411, describes the PCRM program more fully.

Summary

For almost twenty years Lincoln Laboratory has carried out a program of research and development for the FAA. Major outputs of this program are reaching fruition and beginning to enter nationwide service in support of air traffic control. These outputs include systems to provide improved surveillance, communications, collision avoidance, and severe-weather sensing.

As the current programs are completed, a new set of programs are being undertaken that focus on the use of these and other new technical capabilities to enhance the efficiency and capacity of aircraft operations in the terminal area and on the airport surface. Through these programs, Lincoln Laboratory will continue to play a major role in providing the FAA with technology to meet the critical air traffic control needs in the coming years.

Acknowledgment

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In 1970 he helped establish a program in the development of air traffic control technology for the FAA, and was appointed Group Leader of the newly formed Air Traffic Control Group. He led the development of two major new surveillance systems for the FAA: the Discrete Address Beacon System, now known as Mode S; and the Moving Target Detector Doppler radar system, now known as ASR-9. These systems will soon be deployed at over 100 sites in the United States. In 1972 he was appointed Associate Division Head of the Air Traffic Control Division. Under his leadership the Air Traffic Control program expanded to include the development of an airborne traffic alert and collision avoidance system (TCAS) capable of reliably performing air-to-air surveillance with existing commercial ATC radar beacon transponders.

In 1978 Paul was appointed Head of the Surveillance and Control Division with responsibility for ATC activities and a number of major Laboratory programs in tactical battlefield surveillance, target identification, signal intercept, advanced IFF systems, and advanced air defense. In 1985 he was appointed Assistant Director of the Laboratory, with principal responsibility for the Laboratory's programs in surveillance and control technology and air traffic control. In July 1987 he assumed responsibility for the Laboratory's programs in ballistic missile offense and defense technology and in adaptive optics for high-energy laser systems.

Paul is a member of Eta Kappa Nu, Tau Beta Pi, and Sigma Xi. He was elected a Fellow of the IEEE in 1986 for his contributions to air traffic control systems.

In addition to his professional interests, Paul has had a long-standing avocational interest in aviation. He has been an active general aviation pilot since 1958, and holds Airline Transport Pilot and Flight Instructor ratings.