Radar Development at Lincoln Laboratory: An Overview of the First Fifty Years

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■ **This article provides an overview of the first fifty years of radar development at Lincoln Laboratory. It begins by reviewing early Laboratory efforts in North American air defense, which quickly branched into efforts in missile defense and space surveillance as the Soviet Union developed missiles and launched satellites into space. In the 1970s, two other radar-intensive activities began at the Laboratory: a program in tactical surveillance arose out of the challenges of the Vietnam War, and a program in air traffic control responded to the need to modernize systems for control of civilian aircraft. Research in advanced air defense also returned to the Laboratory with the advent of the modern cruise missile. This article summarizes these major Laboratory radar programs in a synoptic fashion, which can serve the reader as a road map to the ensuing fourteen articles, each of which provides a more in-depth view of the Laboratory's radar developments.**

THE MASSACHUSETTS INSTITUTE OF TECHNOLOGY has been involved in radar development since 1940, when the security challenges of World War II inspired the development of working military radars based on ideas and crude experiments of earlier decades. The MIT Radiation Laboratory was a focal point for much of the Allied development of microwave radar, and astounding progress was made during the Radiation Laboratory era, which spanned 1940 to 1945 [1, 2]. The Radiation Laboratory ceased operations in 1945, but many of the talented researchers who worked on radar development remained in the New England area.

The threat of attack on the United States by long-range Soviet bombers carrying nuclear weapons led to the formation of Lincoln Laboratory (originally Project Lincoln) in 1951. From its start, the Laboratory was heavily involved in radar development [3], and that involvement has continued to the present. Typically, fifty percent of today's programs at the Laboratory directly involve radar development, technology, or experimentation.

Fifty Years of Radar Development

The cartoon "tree" of Figure 1 is a simple graphic way to convey a macroscopic view of radar developments at Lincoln Laboratory. The roots of the tree represent the pioneering work performed at the Radiation Laboratory during World War II. The branches of the tree are the major radar program areas that have evolved at Lincoln Laboratory over time. Lincoln Laboratory's initial charter was to support the development of a North American air-defense system called SAGE, for Semi-Automatic Ground Environment. The SAGE system used ground-based radars, sea-based radars on ocean platforms called Texas Towers, and airborne radars to detect enemy aircraft. Digital communication links conveyed this information to command centers, where the first large real-time digital processors—novelties at that time—

tracked the radar targets and guided fighter-interceptors to engage the intruding aircraft. Although Lincoln Laboratory's primary responsibility was to invent the needed command-and-control processes by using the newly emerging technology of digital computers, many developments in radar technology were also needed to provide the "clean" data demanded by the computer.

The tree of radar development shown in Figure 1 quickly branched in the late 1950s to include missile defense, and then branched again to include space surveillance, fields driven by the Soviet Union's rapid development of ballistic missiles and satellites. The Vietnam conflict of the late 1960s occasioned further branching into radar technology for tactical battlefield applications. This activity was followed in the early 1970s by the branching into air traffic control with the advent of a major program for the Federal Aviation Administration. The last major branch in the tree occurred in the late 1970s in response to the development of the modern cruise missile and the renewed air-defense concerns it caused.

Figure 2 puts more of the "twigs and leaves" on the tree of Figure 1. The dates are approximate and the numerous abbreviations are explained throughout this issue. By no means did Lincoln Laboratory have sole responsibility for every project depicted in Figure 2. This was an era of significant collaboration among industry, government, and laboratory researchers, and we acknowledge the contributions of a great number of organizations. For example, industry was the main performer in radar systems such as BMEWS, Cobra Dane, and Cobra Judy. Lincoln Laboratory played a significant but supporting role in these projects. Also, much of the Laboratory's contribution to radar was not in the development of specific radars but in the development of advanced radar techniques, associated technology, and the understanding of radar phenomenology. These topics are the focus of many of the articles in this special issue.

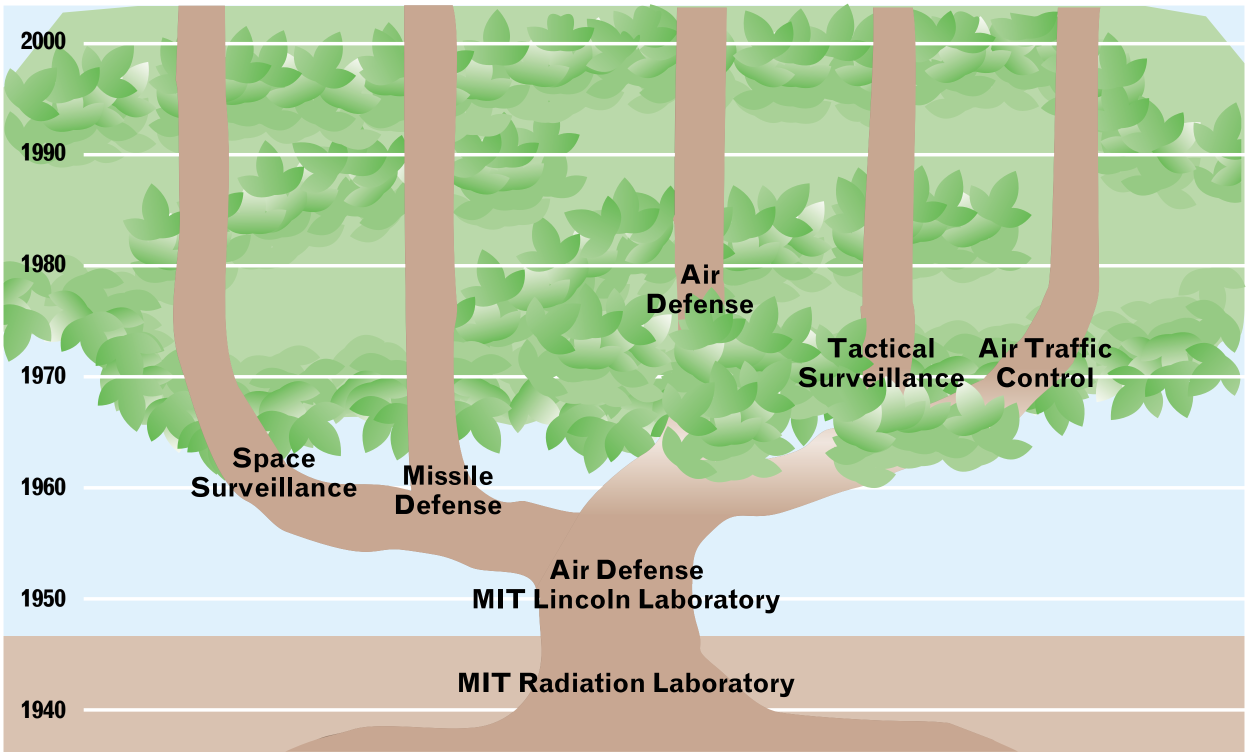

FIGURE 1. A conceptual radar "tree," illustrating the five main areas of radar activity at Lincoln Laboratory. Research in radar at the MIT Radiation Laboratory during World War II provided the foundation for early Lincoln Laboratory work on an air-defense system called SAGE, or Semi-Automatic Ground Environment. Over time, this work branched into areas of missile defense and air defense, which then branched further into additional programs in space surveillance, air traffic control, and tactical surveillance.

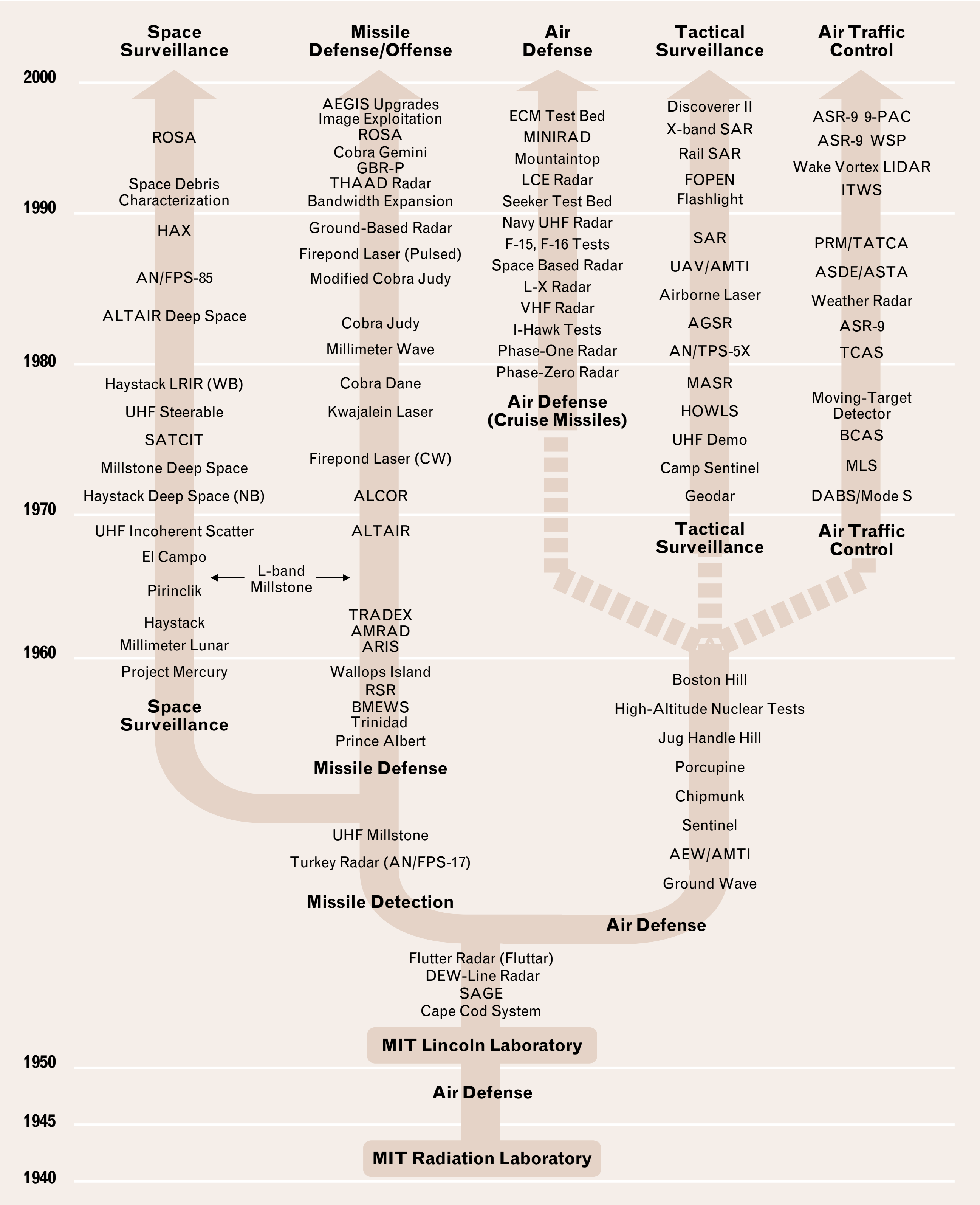

FIGURE 2. The expanded radar "tree." Lincoln Laboratory had varying degrees of involvement in the nearly one hundred radar activities illustrated here. In most instances, the Laboratory was the principal developer. In some instances, U.S. industry was the lead developer, and the Laboratory played a supporting role.

Air Defense—The First Years

The story of the development of SAGE and its early experimental model, the Cape Cod System, has been told in detail elsewhere [4–6]. The first major Lincoln Laboratory effort in air defense, the Cape Cod System, was designed to integrate a surveillance net consisting of large search radars, height-finding radars, and gap-filler radars with a central digital computer (called Whirlwind) by using telephone lines for data transfer. The computer accepted target data from the radars and created tracks showing the positions and movements of the enemy aircraft. The computer then formulated a response and sent messages to the fighter aircraft so that they could intercept the target aircraft.

The first version of the Cape Cod System was fully operational in September 1953, and it demonstrated that air battles could be managed with such a system. The next step was the augmentation of the Cape Cod System to form the Experimental SAGE Subsector, which covered more of New England. The Experimental SAGE Subsector included more radars, better data processing at the radar sites, a more capable central computer (the AN/FSQ-7), and improved display and control consoles for the human operators who were an integral part of the SAGE system. Figure 3 shows operations at a SAGE Direction Center at Lincoln Laboratory. The AN/FSQ-7 computer had a processing rate of about 100,000 instructions per second, which is much less processing power than today's least expensive laptops—talk about efficient software!

The first radar development needed to make SAGE work was to improve the performance of moving-target-indicator circuitry, which separates the echoes of the fast-moving objects of interest, namely, airplanes in flight, from echoes of slow-moving objects such as waves on the ocean and birds, and nonmoving objects such as buildings and mountains. The second radar development came from an urgent need to strengthen the ability of radars to extract information despite radio-frequency interference and jamming. Both of these developments profited from the enlarged understanding of communication theory, of which radar theory is a special case, that had flowered after the end of World War II. Underlying these advances was the important development of processing

FIGURE 3. Console operations at the Experimental SAGE Subsector Direction Center at Lincoln Laboratory in 1957.

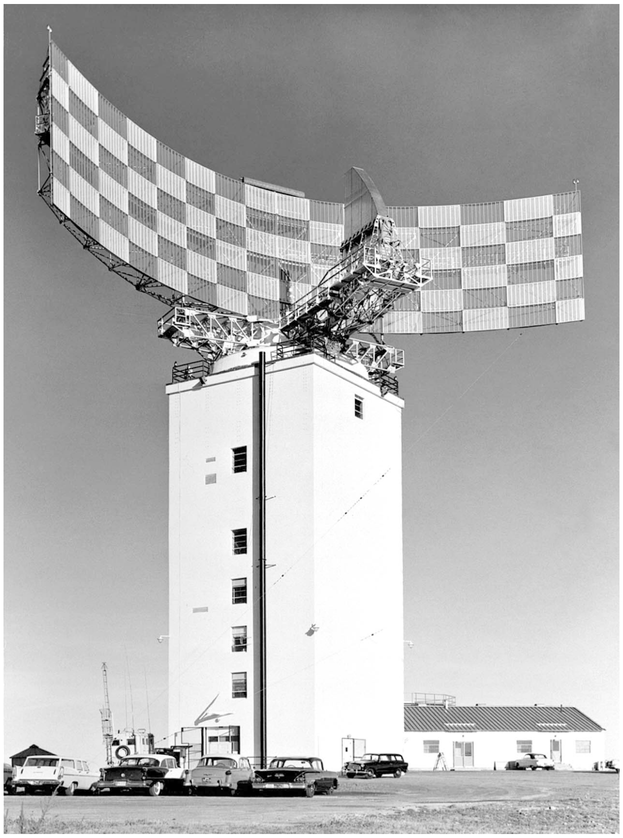

FIGURE 4. The UHF radar at Boston Hill, North Andover, Massachusetts, in the late 1950s. Operating from 400 to 450 MHz, this radar combined impressive performance for ground control of intercepts with sophisticated counter-countermeasure capabilities.

devices to digitize data at the remote radar sites and send it error-free to large central computers. SAGE was a large, distributed, digital, real-time, surveillance, communication, and command-and-control system. It was the world's first such system, and the impact of its successful development spread far beyond its role in air defense of the United States. Some historians of science and technology consider SAGE to have been the launching pad of that economic marvel, the Boston-area electronics industry [7].

Laying the foundation for Lincoln Laboratory's program of radar development for air defense was the Summer Study of 1952 [8]. One conclusion of this study was the need for a barrier line of radars across Canada to give early warning of the approach of bombers from the Soviet Union. The most significant result that emerged from the Summer Study was the Distant Early Warning Line, or DEW Line, which included reliance on automated detection of radar echoes in low-traffic situations. Another major conclusion of this study was that radar development, which had moved to microwave frequencies at the Radiation Laboratory and elsewhere, could profitably reverse course for some applications and return to lower frequencies, where initial efforts in radar had begun decades earlier. Going from centimeter-wavelength microwave radars to meter-wavelength lower-frequency radars made the moving-target-indicator task easier, particularly when the surveillance radar was itself airborne. It was also possible to increase the absolute performance of large ground-based radars for surveillance and ground control of intercepts. Examples of these lower-frequency ground-based radars include the Laboratory-based Sentinel radar at 600 MHz, and the radars at Jug Handle Hill near West Bath, Maine, and at Boston Hill near North Andover, Massachusetts, both at 425 MHz. Figure 4 shows a photograph of the Boston Hill radar in the late 1950s.

Lincoln Laboratory investigated many radar possibilities in those days of frenzied activity to counter the perceived strategic airborne threat posed by the Soviet Union. Fluttar was a system of bistatic gap-filler radars, numerous and comparatively cheap, that were designed to augment the DEW Line of search radars. Other possibilities such as ground-wave radar were also investigated; these lower-frequency radars were the forerunners of the high-frequency over-the-horizon backscatter radars that were later developed by other laboratories. Chipmunk, a portable radar that could be carried by one person, showed how small a search radar could be made at that time. The Porcupine weapon system demonstrated Laboratory advances in pulse-Doppler radar when it helped to shoot down a drone B-17 bomber in a California test.

In this same 1950s era, Lincoln Laboratory developed UHF airborne-early-warning radars for detection of aircraft hidden in terrain or sea clutter; the radars were demonstrated on a variety of four-engine aircraft and airships. These developments led to the U.S. Air Force's AN/APS-95 radar and the U.S. Navy's APS-96 radar and its successors, currently deployed on Navy E-2C carrier-based aircraft [9].

Two of Lincoln Laboratory's UHF airborne-early-warning radars took part in Operation HARDTACK in 1958, during which thermonuclear weapons were exploded high above Johnston Island in the Pacific Ocean. The radar data recorded during those tests helped characterize the reflection and propagation of signals through the diverse phenomena that accompany such detonations.

Lincoln Laboratory developed the UHF scatter-communications system to convey the DEW Line data to the Air Defense Command Center in Colorado Springs, Colorado. Also, in the early years of air-defense research, the Laboratory led the development of rigid radomes, which culminated in the construction of the 150-ft-diameter Haystack radome in Tyngsboro, Massachusetts.

The development of air-defense radar at Lincoln Laboratory diminished in the late 1950s with the transfer of major responsibilities for ongoing support of SAGE to the newly formed MITRE Corporation in Bedford, Massachusetts. Lincoln Laboratory's radar efforts were then directed to the problem of defense against attack by intercontinental ballistic missiles, or ICBMs. However, air-defense activity would spring back to vigorous life in 1977 with research programs in defense against cruise missiles, as is discussed later.

Detection of and Defense against Intercontinental Ballistic Missiles

The first branching in the Lincoln Laboratory radar tree occurred in the mid-1950s in response to the rapid advances in ICBMs that the Soviet Union achieved [10]. Lincoln Laboratory played a key role in shaping the architecture and choosing the radar approaches used in the Ballistic Missile Early Warning System, or BMEWS, which was installed at three sites: Thule, Greenland; Clear, Alaska; and Fylingdales Moor, United Kingdom.

Lincoln Laboratory's phase-coded pulse-modulation receiver/exciter for the VHF AN/FPS-17 radar, built at a site in eastern Turkey by the General Electric Company, allowed U.S. observers to monitor missile test launches from Kapustin Yar, deep within the Soviet Union. Subsequent installation of one or more AN/FPS-17 radars on Shemya, a western island in the chain of Aleutian Islands off Alaska, made it possible for U.S. observers to monitor Soviet missile test flights to the Kamchatka peninsula. The AN/FPS-17 radar was the first demonstration of pulse compression in an operational radar system [11].

FIGURE 5. An early photograph of the antenna and supporting pedestal of the long-range UHF missile- and satellite-tracking radar on Millstone Hill in Westford, Massachusetts.

The 440-MHz UHF Millstone Hill radar, built by Lincoln Laboratory at Westford, Massachusetts, came into service in time to observe *Sputnik I*, the world's first artificial satellite, which was launched by the Soviet Union on 4 October 1957. The race between the United States and the Soviet Union to demonstrate achievements in space was on. The Laboratory's programs in space surveillance, satellite tracking, and space-object identification started at this time, and they continue to this day.

The UHF Millstone Hill radar, which is shown in its original form in Figure 5 (and on the cover of this issue of the *Journal*), served as the model for several high-power, long-range radars built for the detection and tracking of ballistic missiles and for the collection of related data. One of these radars, installed at Prince

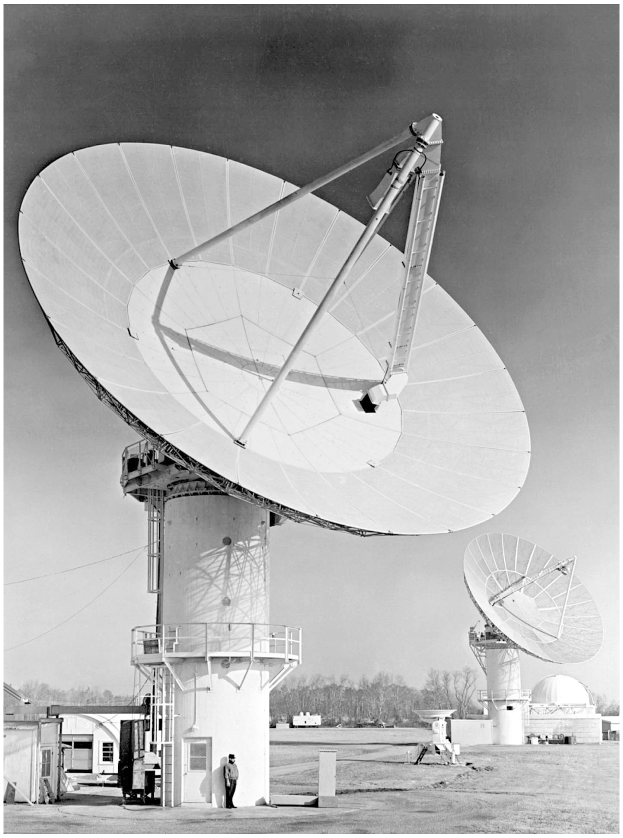

FIGURE 6. Radars at the Laboratory field site at Arbuckle Neck, on Wallops Island, Virginia. These radars were used to study physical phenomena observed during reentry.

Albert, Saskatchewan, Canada, was used to study auroral echoes, which are often encountered when a radar looks for ICBMs passing over arctic regions. Another such radar was installed on the island of Trinidad in the Caribbean, where it could observe missiles launched from Cape Canaveral, Florida. This radar served as the prototype for the missile trackers of BMEWS.

By the early 1960s, the United States had embarked on its ballistic-missile-defense course, which continues to this day. The threat posed by Soviet ICBMs in this early era led to major radar developments by many other organizations, including the Bell Telephone Laboratories, Western Electric, the General Electric Company, and the Radio Corporation of America.

Lincoln Laboratory's research and development role in ballistic missile defense was concentrated on the problem of target discrimination during the reentry phase. The formidable task facing the defense was to identify the real warheads amidst the clutter of accompanying objects that can be part of an attack by ICBMs, and to perform this identification despite any countermeasures employed by the offense.

The Laboratory's approach to ballistic missile defense evolved in three directions. First, a reentry-simulation range was built on Katahdin Hill, adjacent to the main Laboratory buildings in Lexington, Massachusetts. Small objects, a few centimeters in size, of different materials were fired at ICBM reentry velocities by light-gas guns. The phenomena associated with the passage of these objects through the controlled atmospheres inside the test chambers were measured by radar and optical instrumentation. Analysis of the collected data provided a start on a scientific understanding of the physics of reentry [12].

Second, at Wallops Island, Virginia, test objects of a few tens of centimeters in size were fired back into the atmosphere after having been launched above it by Trailblazer sounding rockets. Radar and optical instrumentation on the ground at Wallops Island, such as the radars shown in Figure 6, observed the accompanying physical phenomena during reentry [13]. The Laboratory also developed and initially operated the Advanced Research Projects Agency (ARPA) Measurements Radar at White Sands Missile Range, New Mexico. That instrument was used to observe the reentry at ICBM speeds of larger objects fired back into the atmosphere by Athena sounding rockets launched from Green River, Utah.

Third, the Department of Defense decided to establish a national center for ballistic missile testing at the Kwajalein Atoll in the middle of the Pacific Ocean. The U.S. Army and Bell Telephone Laboratories had already installed on Kwajalein a prototype version of the Nike-Zeus weapon system for defense against ICBMs. Long-range ballistic missiles could be launched to Kwajalein from Vandenberg Air Force Base on the west coast of California, about 7000 km away. Short-range missiles could be launched to Kwajalein from submarines and from Wake Island, about 1100 km north of Kwajalein.

Lincoln Laboratory became the Scientific Director of Project PRESS (Pacific Range Electromagnetic Signature Studies), which was part of ARPA's Project De-

FIGURE 7. The UHF/L-band TRADEX radar on Roi-Namur Island, Kwajalein Atoll, Marshall Islands. This sensor combined outstanding performance capability with great flexibility in transmitted waveforms, tracking, and data recording.

FIGURE 8. The VHF/UHF ALTAIR radar on Roi-Namur Island, Kwajalein Atoll, Marshall Islands. ALTAIR is a prime sensor for satellite tracking as well as for support of ballistic missile tests. After ALTAIR became an operational radar the UHF subsystems of the TRADEX radar were replaced by S-band subsystems.

fender. Under the Laboratory's leadership, additional radar and optical instrumentation was installed on the island of Roi-Namur, on the northern tip of Kwajalein Atoll. The Laboratory operated the instrumentation radar and optics complex on Roi-Namur, analyzed the reentry data gathered during many launches, and distributed the results widely to the ballistic-missile-defense community.

Lincoln Laboratory also developed and operated airborne optical instrumentation to observe the terminal phase of ballistic missile tests. Data gathered by this collection of tracking and measuring sensors were combined to provide a comprehensive understanding of the behavior of a reentering ICBM payload complex, which might typically include multiple warheads, decoys, and booster hardware. Attaining that understanding was critical for the development of effective ballistic-missile-defense systems. It was also critical to U.S. Air Force and U.S. Navy developers of ballistic missiles, wherein the steps to assure successful penetration of Soviet ballistic-missile-defense systems could be evaluated in a full-scale environment.

The UHF/L-band TRADEX radar shown in Figure 7 was the first radar constructed at Roi-Namur Island. It was built by RCA under the technical direction of Lincoln Laboratory. TRADEX was followed by the VHF/UHF ALTAIR radar, shown in Figure 8, which was built by Sylvania, also under the technical direction of Lincoln Laboratory. These two radars were followed shortly by the C-band ALCOR radar, shown in Figure 9, which was built by Lincoln Laboratory with support from industry. ALCOR provided the nation's first long-range wideband radar capability, and in the early 1970s it demonstrated the first high-resolution range-Doppler imaging of satellites. ALTAIR now has a space-surveillance mission as well as its ballistic-missile-defense role. These radars, operating at conventional radar frequencies, were later joined by millimeter-wave and laser radars.

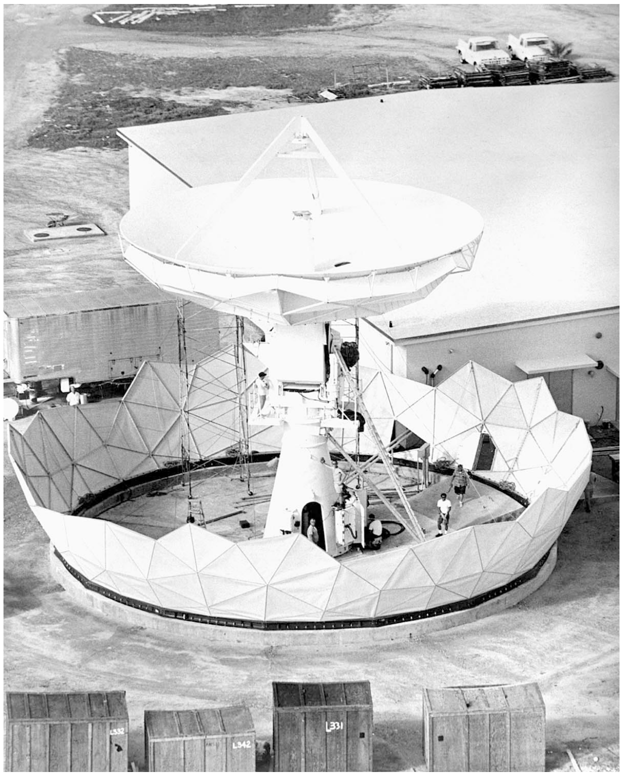

FIGURE 9. Construction of the C-band ALCOR radar, Roi-Namur Island, Kwajalein Atoll, Marshall Islands. ALCOR was the first U.S. radar designed for imaging reentry vehicles and low-altitude satellites.

Not all ICBM launches of interest to the United States were aimed at Kwajalein Atoll. Early in the U.S. ICBM test program, radars were installed on ships that were stationed downrange from Cape Canaveral, Florida, to observe physical phenomena during reentry in the vicinity of the impact area. Seaborne radars such as these prefigured the Cobra Judy S-band phased-array radar shown in Figure 10, which was built by the Raytheon Corporation and installed on the USNS *Observation Island* in 1981. This potent resource could be moved wherever it was needed, such as to Kwajalein Atoll or to international waters off the Kamchatka Peninsula to observe the terminal phase of Soviet missile test flights [14]. Lincoln Laboratory provided support to the Cobra Judy system in its developmental phase, and later became one of the principal analyzers of the data from this capable intelligence-collection radar.

In 1996, in response to the needs of the U.S. theater-missile-defense community, Lincoln Laboratory designed and built a prototype transportable instrumentation radar, called Cobra Gemini. This radar system features wideband S-band and X-band radars that are packaged in air-transportable containers. Operational capability was achieved in March 1999 when the radar was installed on a Navy T-AGOS-class ship, the USNS *Invincible*, shown in Figure 11.

There were a large number of ancillary developments related to missile defense that cannot be covered in this short review. One development that deserves an acknowledgment is the work on very high-power microwave components and high-power tubes. The Laboratory maintained a high-power test facility in the 1960s that contributed substantially to high-power microwave component and klystron development.

FIGURE 10. The Cobra Judy phased-array radar (far right) in its sea-based configuration on the USNS *Observation Island*. Putting a radar such as Cobra Judy on a mobile platform adds greatly to a radar's flexibility and utility.

FIGURE 11. The Cobra Gemini radar antenna (inside the large radome) in its sea-based configuration on a T-AGOS-class ship, the USNS *Invincible*. The flexibility of a mobile platform allows Cobra Gemini, like Cobra Judy, to be deployed where it is needed and when it is needed.

Space Surveillance and Space-Object Identification

The UHF Millstone Hill radar shown in Figure 5 (and also featured on the cover of this issue of the *Journal*) was originally built with missile detection and tracking as its principal mission, although the radar's founding father, Herbert G. Weiss, foresaw that other uses for it would surely arise [15]. Another use arose almost immediately when Millstone was the first radar to detect radar signals reflected by the Soviet satellite *Sputnik I* soon after its launch, and the first radar to track this satellite in range, azimuth, and elevation angle. From the beginning, the Millstone Hill radar was clearly an important U.S. resource for monitoring satellite launches and for keeping track of objects in orbit. The upgrading of Millstone to L-band in 1962 provided greater capability for space-related operations.

In the early 1970s the Millstone Hill radar was equipped with signal processing hardware and software so that a large number of echo signals from an object of interest could be added coherently over tens of thousands of interpulse periods. This technological advance made it possible for Millstone to provide high-quality metric and cross-section data on satellites in deep space and, in particular, at the 36,000-km altitude of the heavily utilized geostationary orbit.

The ALTAIR radar, on Roi-Namur Island in the Kwajalein Atoll, was subsequently enhanced by the addition of similar capabilities so that it also serves as a deep-space satellite sensor in addition to its missile-defense research mission [16].

When the Millstone Hill radar was upgraded to operate at L-band, its UHF transmitter and receiver were retained and were connected to a 220-ft-aperture-diameter fixed zenith-pointing paraboloid. This radar has been used extensively for scientific research on the properties of the ionosphere. A 150-ft-diameter steerable paraboloidal antenna that was no longer needed to support research at a U.S. Air Force facility was moved to Millstone Hill. This antenna has also operated as part of a UHF radar, sharing the same radio-frequency equipment with the zenith-pointing UHF antenna. Other Lincoln Laboratory radars with primarily scientific uses included the 38-MHz instrument at El Campo, Texas, which was used to study the sun in 1961, and a radar atop Building D at Lincoln Laboratory that detected echoes from the moon at 35 GHz.

Millstone's original 84-ft-diameter UHF antenna was moved to Dyarbakir/Pirinclik in eastern Turkey, where the addition of UHF transmitting, receiving, and signal processing equipment made it a useful sensor for tracking space objects. The addition of long-duration coherent integration to Pirinclik gave it deep-space capability.

The U.S. Air Force's UHF AN/FPS-85 phased-array radar at Eglin Air Force Base, Florida, was originally designed by the Bendix Corporation to search

FIGURE 12. The Haystack Hill facility in Tyngsboro, Massachusetts. The large antenna within the radome has been a fertile source of advances in radio astronomy, radar astronomy, satellite imaging out to geostationary-orbit altitudes, and characterization of orbital debris.

for and track satellites at low-to-intermediate altitudes. Lincoln Laboratory supported the application of coherent-integration techniques for this radar to perform the same function for satellites at geostationary altitude.

Figure 12 shows the Haystack facility [17, 18], located in Tyngsboro, Massachusetts, which was originally constructed as a prototype for large 8-GHz space-communication terminals. The 120-ft-diameter paraboloidal antenna inside a 150-ft-equatorial-diameter metal-space-frame radome, sensitive receiving system, and powerful transmitter gave Haystack tremendous potential radar capability as well. The designers of Haystack had the foresight to provide for interchangeable room-size equipment boxes to be installed at the vertex of the paraboloid, so that the antenna could be used in communication modes, radar modes, or radio-astronomy modes. The addition to Haystack of an X-band transmitter of increased bandwidth provided enough capability so that imaging of satellites at geostationary altitude could be accomplished. Haystack became the mainstay in the nation's capability to image spacecraft [19].

The Haystack Auxiliary Radar, or HAX, came online in 1993. Operating at approximately 16 GHz, HAX provides potent satellite-imaging capability that can be used when the larger Haystack antenna must operate in a radio-astronomy mode. Both Haystack and HAX contribute data to a NASA-sponsored survey of orbital debris. The increasing amount of space junk in earth orbit constitutes a hazard to satellites and in particular to manned spacecraft such as shuttles and space stations.

Radars for Tactical Battlefield Surveillance

In 1967 events related to the war in Vietnam pressed the major national laboratories into contributing to the solution of tactical battlefield problems. Lincoln Laboratory's involvement began with the development of a ground radar to penetrate jungle foliage and detect intruders moving at short range.

This first major effort in tactical radar was called the Camp Sentinel radar. It was developed, tested, and then deployed with U.S. combat forces in Vietnam in 1968, as shown in Figure 13. This radar operated in UHF band and successfully met its goals of detecting moving enemy troops under foliage.

In the late 1960s, the Laboratory's attention turned to the challenging surveillance problem of using airborne radars to detect moving enemy ground vehicles. A variety of development efforts in airborne radar eventually led to the Multiple-Antenna Surveillance Radar, shown in Figure 14, which in 1975 demonstrated the application of the displaced-phase-center antenna technique for canceling ground clutter to allow the detection of slow-moving ground vehicles. This technique, with progressive refinements, made

FIGURE 13. The Camp Sentinel radar installed at the Lai Khe base in the battle zone in Vietnam.

FIGURE 14. Flight test of the Multiple-Antenna Surveillance Radar on a Twin Otter aircraft. The rectangular displaced-phase-center antenna can be seen on the fuselage behind the wing.

possible the current Joint Surveillance Target Attack Radar System, or Joint STARS, which is an airborne radar for ground surveillance.

In 1975, the Laboratory began to focus on the problem of using airborne radars to detect and identify stationary targets. The initial development effort for the Defense Advanced Research Projects Agency (DARPA) and the U.S. Army led to a K_u-band airborne radar to locate and identify indirect-fire weapons. While stationary targets in the open could be detected, the detection suffered from a high false-alarm rate from natural and cultural clutter. Experiments with this radar pointed to the need for sharper angle and range resolution, and suggested the value of a multiple-polarization radar to reduce false-alarm rates.

In 1987, a high-resolution, multiple-polarization, K_a-band synthetic-aperture radar (SAR), called the Advanced Detection Technology Sensor (ADTS), was developed under DARPA sponsorship. This radar was built by the Goodyear Aerospace Company and over its eleven-year lifetime provided high-resolution, fully polarimetric SAR data to a large number of Department of Defense users. Figure 15 shows the ADTS mounted under a Gulfstream aircraft. The Laboratory's main focus in this program was the collection of SAR data on strategic and tactical targets for the development of target detection and recognition algorithms for stationary targets. In 1997, the radar was upgraded to include high-resolution SAR modes at both X-band and K_u-band. Later, in 1997 and 1998, the radar helped pioneer high-resolution imaging of moving ground targets.

In the 1980s, the Laboratory also developed a moving-target surveillance radar to be mounted on a small unmanned air vehicle (UAV). The radar was small and lightweight, and it featured a high-performance onboard signal and data processor. The radar, built in a UAV fuselage and mounted on an aircraft, as shown in Figure 16, demonstrated a 20-km range, and provided reliable moving-target detection, multiple-target tracking, and classification of moving ground vehicles and low-flying aircraft. All target reports were processed onboard the UAV, thereby reducing the data-link bandwidth requirement by three orders of magnitude.

In 1990 this 110-lb K_u-band radar-and-processor combination convincingly demonstrated detection, tracking, and identification of moving military vehicles in a comprehensive series of field tests at Fort Sill, Oklahoma. The UAV development program ended with this technology demonstration, but the results of the program convinced the U.S. Army of the feasibility of battlefield-surveillance radar for small-to-medium-size UAVs.

In between these ground-radar and airborne-radar developments the Laboratory demonstrated the successful SAGE-like netting of several ground radars and an airborne radar at a major military exercise at

FIGURE 15. The Advanced Detection Technology Sensor (ADTS) airborne radar, a fully polarimetric, high-resolution synthetic-aperture radar (SAR) mounted below the fuselage of a Grumman Gulfstream aircraft.

FIGURE 16. The unmanned-air-vehicle (UAV) moving-target-indicator radar system mounted in an Amber UAV fuselage attached to a Twin Otter aircraft. The radome has been removed from the UAV to show the radar antenna.

Fort Sill in 1978. This netting greatly expanded the battlefield coverage and improved the tracking of moving ground vehicles. Enhanced communications between the radar tracking units and the artillery units decreased the response time after detection and allowed fire units to react quickly to advancing threats. One particularly dramatic demonstration featured a command-and-control console in the Pentagon successfully controlling and directing artillery fire on moving target vehicles at Fort Sill—all in real time.

Lincoln Laboratory's efforts in tactical battlefield surveillance also led to the development and demonstration of advanced airborne laser radars. Between 1975 and 1985 the Laboratory explored the application of lasers to the identification of military targets such as tanks, trucks, and artillery. These efforts culminated in the Infrared Airborne Radar, which was mounted in a Gulfstream aircraft. Extensive testing with this system demonstrated the value of the very high spatial and Doppler resolutions available from modern coherent laser radars.

A major challenge in tactical battlefield surveillance is the detection and identification of targets under foliage. The United States had mounted several development efforts on foliage-penetration radar during the Vietnam war. The Laboratory recognized the continuing importance of foliage-penetration techniques, and in 1989 launched a major successful research effort to produce images of military targets under foliage cover. A variety of low-frequency (50 MHz to 1000 MHz) airborne radars from a variety of agencies have been utilized in a series of experiments to demonstrate and refine the imaging of targets under foliage. The major Lincoln Laboratory experiments over the years have led to a substantial U.S. program in foliage penetration.

Air-Vehicle Survivability and Air Defense

Air defense has played a prominent role in Lincoln Laboratory's history. The Laboratory was founded to address the problem of North American air defense, but that work diminished significantly with the completion of the Laboratory's role in SAGE activity in 1958. Nearly twenty years later, in 1977, the United States' development of the modern cruise missile led to a new role for the Laboratory in air defense. The new effort was initially not the development of an air-defense system itself, but the corollary task of developing insights, techniques, models, and experiments that would help to ensure that U.S. cruise missiles could penetrate enemy air defenses. The Soviet Union already had a formidable national air-defense system in the mid-1970s, and the initial task at the Laboratory in 1977 was to characterize these enemy air defenses and the ability of U.S. cruise missiles to defeat them. In the mid-1980s the program was expanded to include the additional role of developing air-defense technologies useful against enemy cruise missiles. These two component activities—air-vehicle survivability and air defense—grew in size so that in 1997 the air-vehicle research effort was the largest program in the Laboratory.

A major Laboratory contribution to air-vehicle survivability has been in the area of radar clutter. The low-flying cruise missile's ability to hide in clutter is a major survivability tactic. In 1980 the Laboratory undertook an extensive empirical effort to characterize low-grazing-angle ground clutter, probably the most intensive and coherent effort ever carried out in this phenomenological area. Because Soviet-type terrains were of principal interest, and the prairie provinces of Canada provided a good geographic analog to the Soviet Union, DARPA instituted a joint measurement program with the Canadian government. As a result,

FIGURE 17. The VHF test-range instrumentation radar that was used to emulate Soviet Union VHF air-defense radars in U.S. cruise-missile survivability tests. To appreciate the size of this radar, note the person standing just to the left of the radar's pedestal.

the Laboratory conducted multifrequency VHF-to-X-band clutter and signal-propagation experiments at a variety of sites in Canada and the United States. These ground-based measurements of clutter and propagation, along with airborne clutter measurements at L-band and X-band, allowed the Laboratory to develop a phenomenological model that effectively captured the wide variations in the amplitude of ground clutter [20].

Field experimentation has played a critical role throughout the twenty-year history of the air-vehicle survivability and air-defense programs. For example, VHF radars are an important factor in the survivability of U.S. cruise missiles because the Soviet Union has deployed thousands of VHF ground radars. A particular concern to the United States was that cruise-missile signatures tended to be higher at VHF than at microwave frequencies, which might make the cruise missiles more visible to Soviet radars. In 1983 the Laboratory procured a substantial VHF test-range instrument from General Dynamics of Fort Worth, Texas. This radar, shown in Figure 17, can emulate Soviet VHF radars such as Tall King and Spoon Rest, which made it extremely useful for missile survivability testing. The radar has had a number of modifications and upgrades to enhance its continuing usefulness to the air-defense test community.

Another important field activity was the experimental characterization of the premier Soviet surface-to-air missile system, the SA-10, by using developmental U.S. radar systems to emulate its radar guidance scheme. Additionally, the ability of Soviet fighter aircraft to engage U.S. cruise missiles was investigated by characterizing the similar ability of U.S. F-15 and F-16 fighters to accomplish this challenging task.

Assessing the performance limits of missile seekers is an important part of the air-vehicle survivability program at Lincoln Laboratory. Early experimental work analyzing the improved Hawk surface-to-air-missile live firings and the Sparrow air-to-air-missile live firings against cruise missiles pointed to the need for an experimental mechanism to investigate missile-seeker performance. Because firing actual missiles against test targets would be an expensive and cumbersome way to gain this insight, an effort was started to develop the Airborne Seeker Test Bed, or ASTB.

The ASTB, shown in Figure 18, is a jet aircraft configured to represent a missile. The nose of the jet carries the missile-seeker instrumentation, and the fuselage carries processing electronics and other antennas needed to emulate a surface-to-air or air-to-air missile, thus making the ASTB essentially a flying missile-seeker laboratory. In 1986, the Raytheon Missile Systems Division built the first major ASTB sensor, an X-band semiactive homing instrumentation seeker, which was installed in a Dassault Falcon 20

FIGURE 18. The Airborne Seeker Test Bed, or ASTB, installed in the nose and under the fuselage of a Gulfstream jet aircraft. The ASTB allowed researchers to emulate a surface-to-air missile or an air-to-air missile, thus making the ASTB essentially a flying missile-seeker laboratory.

twin-engine jet aircraft, and later, in 1996, in a Gulfstream II jet aircraft.

Early experimentation with the ASTB focused on clutter and target-scattering issues of importance in modeling missile-seeker capability. The ASTB has also been used to evaluate the vulnerability of a variety of U.S. air vehicles to missile attack. Since 1990, the ASTB has played a key role in the scientific characterization of countermeasure techniques—particularly endgame countermeasures—that operate in the last few seconds of an interceptor missile's engagement of the target.

The Air Vehicle Survivability program between 1977 and 1984 focused almost exclusively on understanding and modeling the survivability of U.S. cruise missiles against existing or possible new Soviet air defenses. These in-depth investigations gave the Laboratory a substantial head start on the complementary question: how to develop advanced U.S. air defenses to counter enemy cruise missiles. A number of classified activities in this area began in the mid-1980s, and the Laboratory has played an important part in their definition and execution.

One major air-defense activity at this time involved the investigation and demonstration of the technologies necessary for a space-based wide-area-surveillance radar for the detection of airborne and moving ground targets. The basic concept was that a network of satellite radars could provide global surveillance of enemy air and ground activity and furnish warning and cueing information to the U.S. military forces. Although no operational military space-based radar surveillance system has been deployed, this Lincoln Laboratory program helped lay the system and technology groundwork for a recent initiative (by the U.S. Air Force, the National Reconnaissance Office, and DARPA) called Discoverer II, a concept for a large constellation of space-based radars for ground surveillance.

Another major advanced air-defense-radar effort had its origins in the U.S. Navy. The radar developed here has a most interesting travel history! The Navy was well aware of the threat of enemy cruise missiles because a number of nations had deployed a variety of such antiship missiles. In 1984 the U.S. Navy initiated a radar development program centered on a sensitive, high-power shipboard radar that could survey the full airspace around a ship and detect medium-to-high-altitude, low-observable cruise missiles. The radar was designed with an extraordinary amount of jamming resistance and clutter rejection. Lincoln Laboratory's design featured a UHF radar with an ultralow-sidelobe array antenna, which could adaptively null jammers in elevation angle, and an all-solid-state transmitter. The Westinghouse Company built the radar itself, and Lincoln Laboratory designed and built the signal-processing and data-processing subsystems.

FIGURE 19. The ultralow-sidelobe UHF radar antenna under test on Katahdin Hill, Lexington, Massachusetts. This antenna is 5 × 10 m in size.

In 1991 the entire radar, shown in Figure 19, was completed. Tests showed the radar to have extraordinarily low sidelobes and an impressive ability to null jammers near the main beam. In 1992 the radar was moved to a U.S. Navy test site at Wallops Island, Virginia, for an extensive series of detection, tracking, and jamming tests. This site emulated a shipboard environment. The Wallops Island tests were successful, and in 1993 the radar was transferred to DARPA and moved to the White Sands Missile Range to begin a new life, not as a shipborne radar but as an advanced airborne-radar research and development tool in the so-called Mountaintop program.

FIGURE 20. The Mountaintop radar under construction at Makaha Ridge, Kauai, Hawaii.

The concept of the Mountaintop program was to use the UHF experimental radar on a mountaintop to emulate an airborne radar. By using a technique developed at Lincoln Laboratory, researchers showed that stationary ground clutter seen in the radar sidelobes could be made to appear to be moving at airplane velocities. Thus much of the initial experimentation on advanced techniques for airborne radar-clutter mitigation was able to proceed without the cost burden of a large radar on a large aircraft.

Experimentation on adaptive space-time clutter processing and jammer-mitigation techniques was carried out on a mountaintop called Oscura Peak at White Sands in 1993. During 1994 the radar was moved again, this time to Makaha Ridge on the island of Kauai, Hawaii, for a continuing series of tests with U.S. Navy assets. Figure 20 shows the Mountaintop radar under construction on Kauai. In 1996 a major test with the Mountaintop radar demonstrated detection, fire control, and interception of low-flying drones by Navy interceptor missiles fired in a beyond-the-ship's-horizon mode.

In summary, Lincoln Laboratory was challenged in 1977 to provide a strong scientific foundation in air-vehicle survivability to support the design and development of the modern version of the cruise missile. This activity continues today, and has expanded to address the additional challenge of developing advanced air defenses against enemy cruise missiles.

Air Traffic Control

The program in air traffic control (ATC) for the Federal Aviation Administration (FAA) has been the foremost non–Department of Defense program at Lincoln Laboratory. In effect, the SAGE system developed during the Laboratory's early years was an ATC system for air-battle management. The earlier work in radars, computers, digital communication, and signal processing that made SAGE feasible provided substantial background for many of the more sophisticated recent developments in ATC [21–23].

Lincoln Laboratory's first task in this area, which formally began in 1971, was to develop and field-test a next-generation aircraft beacon system that was operationally compatible with the FAA's existing ATC Radar Beacon System, or ATCRBS. This new system was initially called the Discrete Address Beacon System, but is now known internationally as Mode S. Mode S uses existing beacon channels to provide enhanced surveillance and an air/ground data-link communications capability between individual aircraft and ATC centers.

Mode S achieves these improvements through its ability to assign a unique address to every aircraft in the world, and through the use of off-boresight monopulse processing that permits operation of the beacon at a much lower interrogation rate than earlier ATCRBS beacon radars. Mode S is now widely implemented in the United States, and plans are in place to implement Mode S in Europe early in this decade.

In the 1970s Lincoln Laboratory's expertise in ATC beacon surveillance allowed it to address another aviation-safety problem: the avoidance of midair collisions. The Beacon Collision Avoidance System (BCAS) was based on ATCRBS technology. BCAS led to the Traffic Advisory and Collision Avoidance System (TCAS), in which there is automatic cockpit-to-cockpit digital communication independent of the ground-based ATC system.

The origin of TCAS came from a proposal in the mid-1970s to develop an airborne collision-avoidance system based on existing beacon transponders. If such a system could be practical, it would provide a major benefit relative to several existing collision-avoidance system designs, all of which would have required separate transponders to be installed on all participating aircraft. A major question in the beginning of the TCAS program was the extent to which air-to-air multipathing (transponder signals reflected from the ground) would interfere with reception, especially given the constraint to use the existing beacon signal formats. These transponder signals were originally developed for surveillance of aircraft from the ground, using directional narrow-beam antennas. Using the same signals for air-to-air surveillance might have been much more difficult because of the multipath effects.

Initially, Lincoln Laboratory conducted airborne measurements to quantitatively characterize air-to-air multipath effects. The results showed that air-to-air multipathing is indeed a serious disturbance. Subsequently, the Laboratory built a flexible test bed for airborne experiments. Researchers conducted tests on a number of techniques that would enable a collision-avoidance system to tolerate multipath effects. The first reliable air-to-air surveillance was demonstrated in these tests. The favorable test results led to a decision by the FAA to use TCAS as the national basis for collision avoidance, and furthermore to modify the design of TCAS to accommodate the highest foreseeable densities of aircraft in the future. As a result, the Laboratory developed enhancements to the basic design of TCAS, giving it the capability of operating in all environments. Beginning in the 1980s, standards were developed so that TCAS could be used internationally. Later in the 1980s, Congress enacted a law requiring TCAS on all air carriers in the United States, following a transition period. Currently, all airliners operating in the U.S. airspace, both domestic and foreign, are equipped with TCAS transponders.

One Lincoln Laboratory development under FAA sponsorship led to a revolution in the design of air-surveillance radars. The digital moving-target detector not only enhanced the use of primary, or skin-tracking, radars for ATC, but it almost instantly changed the way military surveillance radars were designed [24]. The engineers who developed the moving-target detector put together a number of diverse digital techniques to solve moving weather-clutter and ground-clutter problems that had limited radars since the inception of the moving-target indicator during World War II.

Weather data from airport surveillance radars, or ASRs, are a vital part of the information provided to air traffic controllers; approximately 130 ASR-9 surveillance radars are deployed at major airports across the United States. In the 1990s, Lincoln Laboratory developed a processor augmentation card for the ASR-9 called the 9-PAC, which addresses challenging performance problems observed over the first five years of this radar's operation. Beacon problems that affected the ASR-9's post-processing of merged skin-tracked and beacon-tracked targets included the detection of "phantom" aircraft caused by the reflection of the beacon interrogation signals off buildings and other aircraft, and poor surveillance of parallel runway approaches due to garbling of reply pulses from beacons on closely spaced aircraft. Skin-track radar problems included loss of tracks during parallel approaches and departures, the inability to track highly maneuverable military aircraft during high-G turns, radar clutter caused by automobile traffic and weather, and system overloading as a result of signal returns from flocks of migrating birds.

The 9-PAC processor augmentation card addresses these problems by using significantly more capable radar post-processing algorithms, hosted on contemporary data-processing hardware. The production version of 9-PAC is under manufacture as of this writing and will be deployed nationally by the end of this decade.

Severe weather—especially microbursts, with their associated low-altitude wind shear—has been a major cause of fatal aviation accidents during recent decades. Starting in 1984, Lincoln Laboratory has conducted a major radar investigation into the detection of hazardous weather. A capable microwave test-bed radar was assembled and operated near the Memphis, Orlando, and Denver airports to characterize the microburst phenomena in a variety of environments and climatologies. Figure 21 shows the test-bed radar at the Memphis airport. Figure 22 shows a radar-derived map of the weather velocity field in an area containing microbursts.

Signal-processing and data-processing algorithms were developed and tested to demonstrate that

FIGURE 21. Microwave test-bed radar at the Memphis, Tennessee, airport. This radar allows airport controllers to characterize microburst phenomena in a variety of environments and climatologies.

microbursts could be reliably detected early in their development cycle so that adequate alerting could be given to nearby aircraft. The success of this substantial multiyear investigation has led to the current deployment of a national network of terminal Doppler weather radars. The radars were produced for the FAA by the Raytheon Corporation; the processing for detecting hazardous weather with these radars was initially developed at Lincoln Laboratory.

The Laboratory's current ATC program includes developments for managing airplanes while they are moving on the ground, and taxiing between gates and runways. The Global Positioning System (GPS) is having a profound impact in many areas, of which ATC is one. During recent years, Lincoln Laboratory has worked to evaluate GPS and GLONASS, a similar satellite-based global positioning system deployed by Russia, so that manufacturers can produce airborne receivers capable of capitalizing on both of these systems.

Summary

A myriad of radar and radar-related programs have been carried out at Lincoln Laboratory since it was established in 1951, close to fifty years ago. Many of these programs, but not all, are summarized in the time-line diagram of Figure 2. Some activities involving significant technology innovations remain classified and are not included in the figure or mentioned in this article.

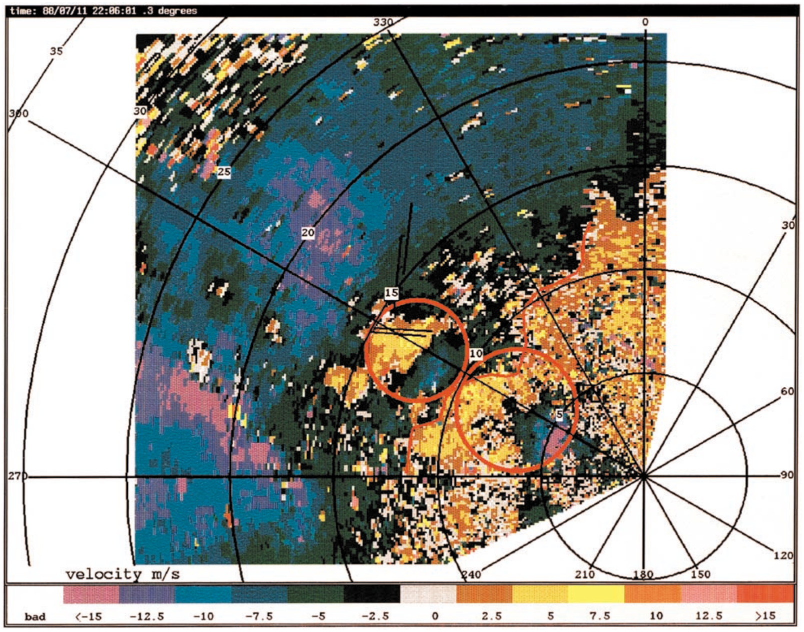

FIGURE 22. Radar-derived map of the weather velocity field indicating the presence of microbursts in the vicinity of an airport.

The reader can now turn to the following articles in this issue, which describe many interesting radar programs in greater detail. The choice of programs for these articles reflected a consensus of opinions from those whom we surveyed. We commiserate with those whose favorite programs are not included, but the final article in this issue of the *Lincoln Laboratory Journal* may provide some consolation: it is a photo album of interesting special radar hardware from the past fifty years.

Lincoln Laboratory is justifiably proud of its first half-century of radar development. We confidently look forward to the next half-century—well into the new millennium—for continuing challenges and continuing fun developing new and better radars.

Acknowledgments

The editors and authors of this special issue acknowledge the enormous contributions from literally thousands of Lincoln Laboratory engineers, scientists, technicians, and support staff whose radar accomplishments over a fifty-year span are chronicled in this issue of the *Journal*. These people are far too numerous to cite individually. Their innovation, creativity, and dedication to improving the nation's radar capability are to be greatly admired. Perusing this issue places one in awe of what they have accomplished!

We also wish to acknowledge all those who helped us create this special issue, particularly the *Lincoln Laboratory Journal* staff, the Lincoln Laboratory Publications group, the Laboratory Library, and especially the Library's archivists. The daunting task of getting these many articles released for public distribution was handled most capably by Barbara Raymond.

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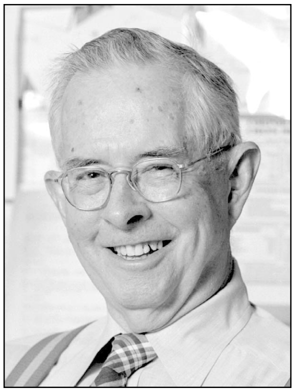
WILLIAM P. DELANEY came to Lincoln Laboratory in 1957 after graduation from the RCA Institutes and Rensselaer Polytechnic Institute. In 1959 he received an S.M.E.E. degree from MIT, where he became involved in radar with a thesis topic on UHF power amplifiers for phased-array radars. His early research at the Laboratory involved the development of antenna and beamforming techniques for phased arrays. Phased-array work of that era naturally migrated to ballistic-missile-defense techniques, and he became heavily involved in analysis of missile defense systems. From 1968 to 1970, at the Kwajalein Atoll in the Pacific Ocean, he served with and then led the team that built and initially operated the ALCOR wideband radar. Returning to the Laboratory in 1970, he held a variety of management positions of increasing responsibility in missile defense, air defense, air traffic control, and battlefield surveillance, all involving radar systems. He was appointed an assistant director of the Laboratory in 1987. Along the way, he spent a three-and-a-half-year tour in the Office of the Secretary of Defense (1973–1976), where he had responsibilities for research and development in strategic air, missile, and space defense systems. In 1995, he maneuvered himself into what he considers the best job at Lincoln Laboratory, Director's Office Fellow. His external responsibilities include support to major Department of Defense studies and committees such as the Defense Science Board. He "pays his dues" internally by taking on chores such as the co-editorship of this special issue of the *Lincoln Laboratory Journal.* He has served on many government committees, including the Air Force Scientific Advisory Board and the Defense Science Board, and he has chaired a number of Defense Science Board task forces. In 1976 he received the Secretary of Defense Meritorious Civilian Service Medal, in 1991 he was elected a Fellow of the IEEE, and in 1994 he was awarded the Air Force Exceptional Civilian Service Medal. His recreational interests include tennis and cross-country skiing, but his dominant pursuit is fly fishing for smallmouth bass and striped bass in New England and for more exotic fishes around the globe in far-flung places such as Christmas Island, Patagonia, and the Kola Peninsula of Russia, where he catches fish so large he does not have to lie about them!



WILLIAM W. WARD was born in Texas in 1924. During World War II he served in the U.S. Army Signal Corps, where he installed, operated, maintained, and repaired cryptographic equipment in the Pacific Theater of Operations. He received a B.S. degree from Texas A&M College, and M.S. and Ph.D. degrees from California Institute of Technology, all in electrical engineering. In 1952 he joined Lincoln Laboratory, where his first thirteen years were devoted to radar system engineering, including airborne-early-warning and ground-based surveillance radars, and space tracking and range instrumentation for NASA's Project Mercury and for ballistic missile testing. In 1965 he switched from struggling to solve problems that involve $(\text{range})^{-4}$ to working on more tractable problems involving $(\text{range})^{-2}$. That work has been in space communication, primarily in the development of systems that serve the diverse needs of the military and civil user communities by means of reliable links through satellites. He has helped to design, build, test, and operate in orbit Lincoln Experimental Satellites 5, 6, 8, 9, and two EHF packages carried by host satellites FLTSAT 7 and 8. He has also contributed to the development of the operations centers associated with these satellites. Being blessed with a retentive memory, and having the collecting habits of a pack rat, he helped to prepare *MIT Lincoln Laboratory: Technology in the National Interest,* an illustrated history of the Laboratory published in 1995. He retired from the Laboratory in 1994 after long service as Manager of Satellite Operations ("Keeper of Old Satellites"). He now putters around with a few old satellites that refuse to die, consults, writes, lectures, and raises vegetables in the summertime. He is a registered professional engineer in Massachusetts, a member of several professional societies, and currently a Distinguished Lecturer for the IEEE's Aerospace and Electronic Systems Society.