Long-Range UHF Radars for Ground Control of Airborne Interceptors

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■ The standard Air Force radars available in the early 1950s had major shortcomings for air-battle management in the face of plausible threats. At that time Lincoln Laboratory was achieving impressive success in developing UHF radars for airborne early warning with moving-target indication by changing from shorter to longer operating wavelengths. It appeared that similar innovations would also yield major performance improvements for radars devoted to the ground control of airborne interceptors. Lincoln Laboratory developed and fielded two different UHF radars that showed that this promise could be fulfilled. Both had quite large antennas rotating in azimuth. A narrowband radar operating near 425 MHz was built on Jug Handle Hill near West Bath, Maine; it became a primary sensor for the Cape Cod System and the Experimental SAGE Subsector. A broadband radar operating across the 400-to-450-MHz band was built atop Boston Hill near North Andover, Massachusetts. This radar was designed as a test bed for the development of techniques to combat active electronic jamming and passive countermeasures such as chaff dispensed by hostile aircraft. These radars paved the way for subsequent Air Force efforts to achieve frequency diversity in its air-defense network.

STANDARD AIR FORCE L-BAND AND S-BAND radars provided the primary input data for ground control of intercepts (GCI) in the Cape Cod System, which was Lincoln Laboratory's early demonstration of air-battle management by a central computer. By 1954, it became apparent that these sensors, only marginally more capable than radars developed by the end of World War II, displayed an unacceptable amount of clutter on their plan position indicators (PPIs). The circuits intended to cancel out echoes from fixed and slowly moving targets and to display only those from high-speed targets such as airplanes in flight were not fully effective. The uncanceled echoes from mountains, buildings, precipitation, and occasional flocks of birds produced numerous false targets that had to be identified and eliminated (mapped out) before the airborne targets of interest could be tracked from their digitized coordinates. The proportion of the radars' coverage that had to be sacrificed in this way was unacceptably large. Could anything be done about these problems?

Deficiencies also existed in the vertical coverage provided by these radars. They had been designed to detect aircraft powered by piston engines. Such aircraft do not routinely operate much above 20,000 ft. The advent of heavy bombers and interceptors powered by jet engines meant that an airborne threat would soon be able to escape radar detection by flying over the radars' coverage volumes.

As a result of the 1952 Summer Study at MIT in Cambridge, Massachusetts, Lincoln Laboratory began developing and testing UHF airborne-early-warning (AEW) radar systems with airborne-moving-target-indication (AMTI) capability [1]. These radars demonstrated in flight tests some of the advantages of operating at lower frequencies (longer wavelengths), which are discussed in the article entitled "Displaced-Phase-Center Antenna Technique," by Charles Edward Muehe and Melvin Labitt, in this issue. For example, echoes from precipitation and birds were reduced because the scatterers were smaller in terms of wavelength. The success of the AEW program led radar designers to believe that operating GCI radars at longer wavelengths could solve many of the problems that radars experienced at higher-frequency L- and S-bands. Of course, the horizontal aperture of the rotating radar antenna needed to be wider in proportion to the wavelength ratio to maintain the same resolution in azimuth. Keeping the vertical dimension of the antenna about the same meant that the vertical beamwidth was broader so that the coverage in elevation angle extended to correspondingly—and gratifyingly—higher altitudes. The resolution in range could be preserved by using transmitted pulses of the same length as before.

Other benefits were associated with the move to longer wavelengths. Engineers realized by this time that—all other things being equal—the effectiveness of a pulsed radar in searching for targets at unknown positions throughout a given volume is proportional to the product of the average power of its transmitter and the aperture area of its receiving antenna, independent of the wavelength at which the radar operates. Thus using longer wavelengths would increase the effectiveness of a pulsed radar by increasing the horizontal aperture of the rotating antenna. Transmitters with higher peak and average powers at longer wavelengths would be easier to build than those at shorter wavelengths because the physical dimensions of the radio-frequency (RF) components would be larger. Increasing the size of the RF components would reduce the likelihood of breakdown within them because of high electromagnetic-field strengths.

Longer wavelengths also facilitated efforts to resist jamming, an unanticipated vulnerability of radar operations. In the early years of World War II, radar developers such as those at the "RadLab," MIT's Radiation Laboratory [2, 3], were elated just to get their equipment to work properly in the field. They had enough problems to solve without also considering that an enemy might try to jam the radars' operation with electronic countermeasures. Just as the radar developers did not initially anticipate jamming techniques, the Axis forces, especially submarine crews, were initially unaware that they were vulnerable to detection by airborne radars. Soon enough, on all sides researchers began to invent measures to counter or reduce the effectiveness of their opponents' radars.

For example, the Radio Research Laboratory [3] at Harvard University worked hard to develop active electronic jamming and passive countermeasures (dropping chaff) to interfere with radars like the ones under development about a mile down the street at the MIT Radiation Laboratory. It therefore became necessary for the radar developers to devise counter-countermeasures (CCMs) for their equipment.

With substantial electronic jamming of radio transmissions from the western world already in effect, there was no doubt that the Soviet Union would employ radar countermeasures. The standard Air Force GCI radars that were available in the early 1950s offered little in the way of CCM capability. A new generation of GCI radars needed the flexibility to accommodate emerging CCM techniques to operate in assorted frequency bands. They also required the ability to burn through wideband noise jamming and provide coverage on airborne targets of interest out to a useful extended range. The sidebar entitled "The Air Force Frequency-Diversity Radar Program" describes how these requirements were incorporated in new radars. An incoming bomber force facing an array of frequency-diverse air-defense radars needed to carry an equally diverse collection of active and passive countermeasures, adding to the complexity of the aircraft and reducing their combined useful payload of bombs.

Lincoln Laboratory's contributions to this effort were made at a practical level. Two different large UHF GCI radars were developed and put into operation at field sites in New England.

Jug Handle Hill, West Bath, Maine

In 1954 Lincoln Laboratory undertook to cobble together a demonstration UHF GCI radar in a hurry.

THE AIR FORCE FREQUENCY-DIVERSITY RADAR PROGRAM

IN JUNE 1955 Rome Air Development Center, Griffiss Air Force Base, New York, let design-study contracts for six new ground control of intercepts (GCI) radars, each to operate in a segment of the frequency range 214 to 5900 MHz. At that time, Air Force GCI radars were moving through attrition toward occupancy of only two frequency bands: the AN/FPS-7 surveillance and height-finding radar with stacked beams operated at 1300 MHz, and the AN/FPS-6 height-finding radar operated at 2900 MHz. These two radars, lineal descendants of radars developed during World War II, constituted what amounted to a single-frequency air-defense radar system. The frequency-diversity (FD) radar program was to reverse that trend.

The spread of operating frequencies to be provided by the FD radar program promised to make it more costly in terms of payload for an airborne intruder to penetrate and survive in the defensive radar environment, as discussed in the main text. At the same time, the new program would enhance the Air Force's GCI capabilities, in particular its ability to feed high-quality data to the Semi-Automatic Ground Environment (SAGE) air-defense system. Table 1, on the following page, shows the characteristics of the Air Force frequency-diversity radars.

Five of the six proposed radars were selected for prototype development, and four were produced in quantity. These five systems in their prototype forms were installed for testing and evaluation at operational Air Force sites in Alabama, Louisiana, and Mississippi, part of the Mobile, Alabama, Air-Defense Sector. Their test programs began in 1959.

In addition, the AN/GLA-8 signal processing system, built by Airborne Instrument Laboratory, was an important common adjunct to each frequency-diversity radar. This equipment included a special antijamming console used by the radar's human counter-countermeasures (CCMs) operator. As discussed in the main text, CCMs such as frequency hopping and PRF jitter/stagger are useful in reducing the effectiveness of both passive countermeasures (chaff, for example) and active countermeasures (spot and noise jamming, and signal repeaters). The wise use of the many features of a highly flexible FD radar required special skills and sophisticated technological support.

The Jug Handle Hill radar began operation in October 1955. Without question, the measure of success it achieved despite the bearing problems of its gargantuan rotating antenna paved the way for the three lower-frequency FD radars.

The Boston Hill radar, which began operation in 1959, was contemporary with the AN/FPS-35 but had quite a different design. They should not be confused. Four AN/FPS-35s were procured by Rome Air Development Center under a prototype contract for early installation at field sites and operation by Air Force crews. Boston Hill, on the other hand, was intended to serve as Lincoln Laboratory's long-term test bed for development and evaluation of CCM techniques, hence its formal name, CCM Radar Mark I.

Its characteristics were spelled out by midyear. The antenna, 120 ft wide by 16 ft high, was not expected to be a great construction challenge. Its mechanical tolerances in terms of wavelength were no more stringent than those of the ≈1300-MHz AN/FPS-3, then a standard Air Force heavy radar for fixed GCI installations, which had a 40-ft-wide by 16-ft-high antenna reflector. Both yielded approximately 1.5°-wide radar beams and blips on their PPI displays. Rotating the UHF GCI radar antenna at 6 rpm would make its data-output characteristics essentially the same as those of the AN/FPS-3. The new radar promised to

Table 1. Characteristics of the Air Force Frequency-Diversity Radars

Function	*Frequency Range (MHz)*	*Equipment Designator*	*Contractor*
Surveillance	214–236	AN/FPS-24	GE
Surveillance	400–450	AN/FPS-35	Sperry
Surveillance	510–690	AN/FPS-28*	Raytheon
Surveillance and height finding (stacked beams)	2320–2680	AN/FPS-27	Westinghouse
Height finding (nodding beam)	5400–5900	AN/FPS-26	AVCO Manufacturing Co., Crosley Division

*Not produced in quantity

be a prime input sensor for the Cape Cod System and later for the Experimental Semi-Automatic Ground Environment (SAGE) Subsector.

The design of the electronics for the new radar was taken directly from that of the AN/APS-70, Lincoln Laboratory's UHF AEW radar with AMTI, which was then undergoing development and testing (see the article entitled "Displaced-Phase-Center Antenna Technique," by Charles Edward Muehe and Melvin Labitt, in this issue). The moving-target-indicator (MTI) circuitry of the UHF GCI radar was simpler.

Adopting the magnetron-based transmitter design of the AN/APS-70 was a compromise decision. Although the transmitter and its associated circuitry could be readily copied from the AEW-radar equipment, the transmitter was not very powerful. Any magnetron has a random start-up phase on each pulse, making the radar's signal processing equipment more complicated. We would have preferred to build a fully coherent radar of the master-oscillator/power-amplifier family (see the article "Early Advances in Radar Technology for Aircraft Detection," by Donald L. Clark, in this issue). That approach would have required using a high-power amplifier such as a triode, tetrode, klystron, or amplitron, but no suitable tube was immediately available. Furthermore, the 2% instantaneous RF bandwidth of the magnetron could not accommodate the rapid changes of transmitted frequency—perhaps even pulse to pulse—required for some radar CCM techniques.

Work on this UHF GCI radar, ultimately designated the AN/FPS-31 (XD-1), got under way in the fall of 1954. Figure 1 shows the transmitter and QK-508 magnetron for the AN/FPS-31 (XD-1) radar. A site near the Maine coast on Jug Handle Hill, West Bath, was selected to serve as a counterpart to the shoreline GCI radars at South Truro on Cape Cod, Massachusetts, and Montauk Point on Long Island, New York, that were already integrated into the Cape Cod System. The radar began operation in October

FIGURE 1. Transmitter of the AN/FPS-31 (XD-1) UHF ground control of intercepts (GCI) radar. The QK-508 magnetron (middle) fits into a pulse transformer and is powered by the modulator cabinet on the right. The high-power RF output pulses travel from the magnetron through a section of 3-1/8-in flexible coaxial transmission line (at the left) to the vertical waveguide run (see also Figures 2 and 3). Note the windlass (essential when changing magnetrons) and the arrangements for liquid cooling of the magnetron.

FIGURE 2. The AN/FPS-31 (XD-1) UHF radar at Jug Handle Hill, West Bath, Maine. The vertical waveguide runs from the equipment building to the rotary-joint housing beneath the antenna atop the tower. Note the stairway for scale.

FIGURE 3. Another view of the tower and antenna assembly of the AN/FPS-31 (XD-1) UHF GCI radar. The feed (in the center at the top of the picture) is at the focus of the parabolic-cylinder antenna reflector.

1955. The 120-ft-wide antenna shown in Figures 2 and 3, painted with broad vertical white and international-orange stripes, was an impressive sight when rotating at 6 rpm.

The Jug Handle Hill site was ultimately equipped with two standard Air Force AN/FPS-6 S-band nodding-beam height finders to give it full GCI capability. A dual-channel AN/FST-1 Slowed-Down-Video (SDV) system, later replaced by an AN/FST-2 fine-grained-data system, was installed at the site to relay data from the three radars and the Mark X identification-friend-or-foe (IFF) equipment to the Experimental SAGE Subsector's central computer at Lexington, Massachusetts.

The fabrication, installation, and operation of a full suite of transmitting, receiving, and MTI signal processing circuitry for the AN/FPS-31 radar was a straightforward task. There were some interesting aspects to it, however. Ignition noise from vehicles driving by the radar site, which was just seaward of U.S. Route 1, jammed the radar. AN/APN-1 FM radar altimeters, carried by military aircraft passing through the radar's coverage volume, caused interference. There was pulsed RF interference from AEW aircraft—carrying experimental UHF AEW radars built by Lincoln Laboratory—when they operated within line of sight of the AN/FPS-31. All of these disruptions had to be mitigated.

The radar interference was eliminated by replacing the fixed-tuned magnetron in the transmitter of Figure 1 by a tunable one. Of course, the radar receiver had to be tuned to match the frequency of the magnetron. An arrangement for "one-knob" tuning control of the complete radar was developed.

The unique subsystem in the AN/FPS-31 radar was its large antenna, together with the tower to support it and the bearing arrangements and drive machinery to rotate it in azimuth, as shown in Figures 2 and 3. The bearing caused many headaches. The original design called for the heavy rotating mass to be carried on sets of bogie wheels at the ends of a three-armed spider that rolled on a smooth, level circular track at the top of the tower. This installation gave trouble from the start. The track had not been made sufficiently smooth to begin with, and the wheels soon wore out.

Further design studies and tests showed that this bearing arrangement could be perfected. However, the pressure from the SAGE development schedule to get the AN/FPS-31 radar into full operation speedily led to the decision to abandon the original design and go to a large central ball bearing upon which the entire rotating assembly would ride. This modification proved to have its own problems. There was a shutdown of several months while the bearing was re-

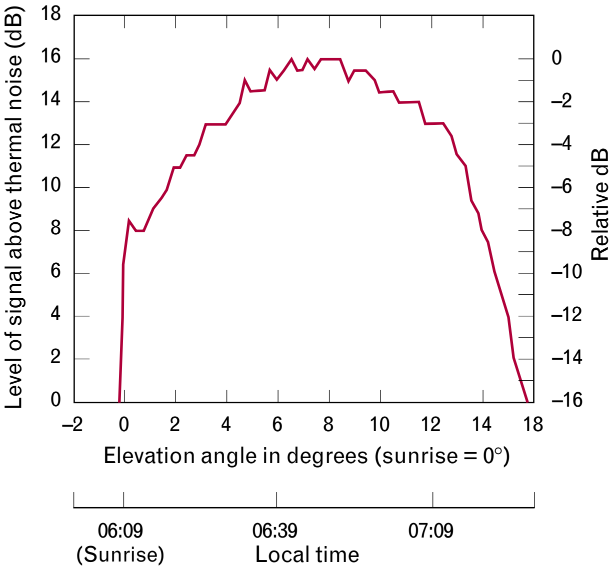

FIGURE 4. Vertical pattern of the AN/FPS-31 (XD-1) antenna using the sun as a source of RF noise.

worked. These mechanical problems were eventually solved to achieve reliable operation of the large rotating antenna assembly. The experience that Lincoln Laboratory gained in solving such problems was shared with others and led to subsequent successful designs of the Counter-Countermeasure (CCM) Radar Mark I at Boston Hill, Massachusetts, the Millstone Hill radar, the AN/FPS-49 Ballistic Missile Early Warning System (BMEWS) tracking radars, and other radars.

Although the performance of the AN/FPS-31 radar was impressive, it did not meet expectations established by scaling from the demonstrated performance of UHF AEW radars operating at lower power and with smaller antennas. Improper orientation of the feedhorn proved to be the source of the problem. The peak of the approximately 18°-vertical-width main beam was 8° above the horizon. For best coverage, the 3-dB-down point of the vertical lobe should have been on the horizon, putting the peak 4° above it. This point was proved convincingly with the aid of antenna patterns measured at sunrise and at sunset as the rotation of the earth moved the antenna beam across the disk of the sun, as shown in Figure 4 [4]. A new feedhorn was ultimately procured and installed, with gratifying results.

In April 1956 the AN/FPS-31 radar was found to display clutter of an unexpected sort, shown in Figure 5. Echoes resembling returns from storms were observed, but they had unusual characteristics: high scatterer velocities, sharply defined azimuth boundaries, and consistent occurrence in the same general azimuth direction—magnetic north. Consultation with personnel from the Communications and Components division yielded the suggestion that the AN/FPS-31 radar was receiving echoes from the aurora borealis. This surmise was verified when it was possible to correlate these 425-MHz observations in Maine with those from a 50-MHz radar located at Ottawa, Canada. Correlation of the radar data with the occurrence of solar flares and sudden ionospheric disturbances led to the conclusion that auroral clutter showed up on the AN/FPS-31 radar about 48 hours after a solar flare.

Despite the rare occurrence of auroral activity in New England skies, the AN/FPS-31 radar was powerful enough to produce pulse echoes that backscattered from the actual aurora (high above the atmosphere and far to the north) and reached the radar at the same time as did echoes from later pulses returned by the much closer targets of interest. This auroral clutter could overlie any part of the radar's unambiguous range. The velocity distribution of the ionized particles comprising the aurora was so broad that there

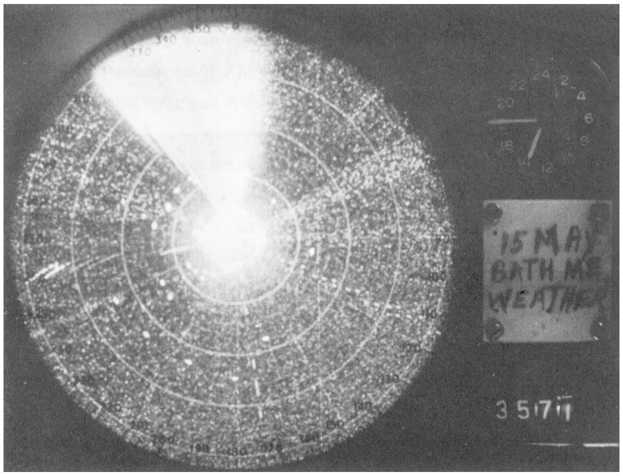

FIGURE 5. Auroral echoes on the AN/FPS-31 (XD-1) radar at Bath, Maine. The range of the echoes was seen the "second time around." The distance between range marks is 50 miles. The clock face and grease-pencil notes on the white tablet represent how test data were recorded at that time.

FIGURE 6. The remains of the Jug Handle Hill radar, circa 1998. Courtesy of Harold Heggestad and Chester Kurys.

was no hope of eliminating the backscattered signals by the techniques of moving-target indication. It had to be mapped out when it occurred.

It had not been generally believed beforehand that auroral echoes could be observed above 200 MHz. The AN/FPS-31 detected strong auroral echoes at 425 MHz, and the Sentinel radar, the AN/FPS-30, did so at 600 MHz. This surprise is reminiscent of something that happened at the MIT Radiation Laboratory during World War II. The newly developed microwave radars at 3-cm wavelength were so successful that researchers decided to develop systems at 1.25-cm wavelength, providing finer angular resolution for a given antenna aperture. When they did so, they discovered that the new radars, which operated near the peak of the curve of water-vapor absorption in the atmosphere, had disappointing performance. In the Radiation Laboratory incident, the cause of the problem was obvious by hindsight. The auroral-backscatter problem was less obvious.

Ultimately, the MITRE Corporation, incorporated on 21 July 1958, took over responsibility for the Jug Handle Hill site along with everything else in the Experimental SAGE Subsector. They closed the site in November 1962. Figure 6 shows what was left of this radar in the summer of 1998. The rotating antenna assembly is long gone. The tower still stands, festooned with assorted communication antennas for mobile communications and data links. This old sword has been beaten into a modern plowshare.

Boston Hill, North Andover, Massachusetts

After the UHF GCI radar at Jug Handle Hill became an operational element of the Experimental SAGE Subsector, it could no longer be available for the development and testing of new radar techniques. Consequently, Lincoln Laboratory undertook to build an improved version of it, dubbed the Experimental CCM Radar Mark I. It was installed atop Boston Hill, west of Route 114 in North Andover, Massachusetts. A comprehensive description of the so-called Boston Hill radar has been published [5].

The aerial view of Boston Hill in Figure 7 shows the radar and its associated facilities. The reflector of the rotating radar antenna was 120 ft wide and 30 ft high. The low building to the right of the radar tower housed the AN/FST-2 fine-grained-data signal processing equipment needed to transform the analog output signal from the radar receiver into a digital data stream suitable for transmission to the AN/FSQ-7 SAGE central computer.

Figure 8 shows the Boston Hill radar. The L-band

FIGURE 7. Aerial view of Boston Hill, North Andover, Massachusetts, showing the experimental Counter-Countermeasure (CCM) Radar Mark I and its facilities.

IFF antenna is mounted atop the reflector at its center. The ball bearing that carries the 55-ton rotating load is 13.5 ft in diameter. The radiated E-field polarization of the radar is horizontal. Both horizontal and vertical polarizations can be received for study of the depolarization characteristics of aircraft, chaff, precipitation, and aurora. At UHF, linearly polarized signals reflected from targets such as sounding rockets, missiles, and satellites at long range within or above the ionosphere are almost certain to have undergone a significant amount of Faraday rotation, so polarization diversity is essential for their best reception.

It was originally planned to build a two-frequency radar, the feedhorn and reflector serving at both 200 and 400 MHz. The lower frequency was not implemented, however. All subsystems of the radar were housed within and atop the tower.

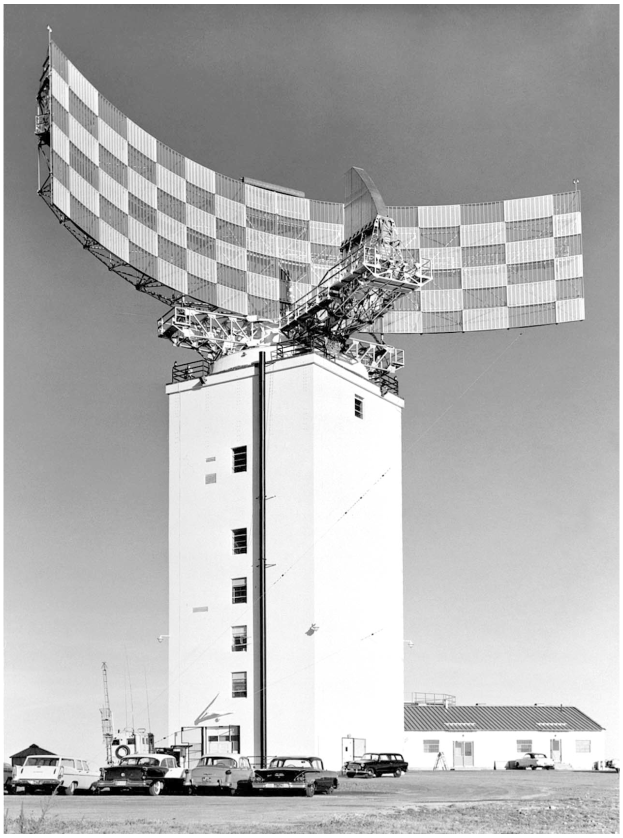

FIGURE 8. UHF GCI/CCM (Boston Hill) radar. The principal subsystems of the radar are housed on separate floors in the tower building beneath the antenna. The feed is at the focus of the parabolic-cylinder antenna reflector. Note the "hog-trough" identification-friend-or-foe (IFF) antenna atop the reflector at its center.

This radar was designed to provide broadband operation over the range 400 to 450 MHz [6]. The transmitter was a klystron amplifier, shown in Figures 9 and 10, rather than a magnetron oscillator. It produced higher output power and provided more control over the transmitted waveform. It allowed fully coherent operation, since the receiver's local oscillators were derived from the same frequency source that powered the transmitter. The first klystrons, VA-812s, had 2% instantaneous bandwidth. The klystron vendor, Varian, later produced VA-812B tubes with 12% instantaneous bandwidth.

The antenna was designed to have low sidelobe levels to minimize the enemy's ability to conceal aircraft by sidelobe jamming. Figure 11 shows a full azimuth cut of the radar antenna pattern at 430 MHz, at an elevation angle of about 0°. A central pedestal about 200° wide has peaks ranging from 19 to 27 dB below the observed beam peak. This observed beam peak lies about 4.5° in elevation angle below the true peak, which had a gain of about 32 dBi [7]. The remainder of the azimuth scan beyond this 200° pedestal is about 37 dB below the observed peak.

The Boston Hill radar was about twenty miles from the Millstone Hill radar, and no significant terrain obstructions existed between the two facilities. In that era Millstone Hill was operating near 440 MHz. It was decided to restrict the broadband operation of the Boston Hill radar to frequencies suitably distant from 440 MHz. That measure minimized RF interference (RFI) to Millstone Hill.

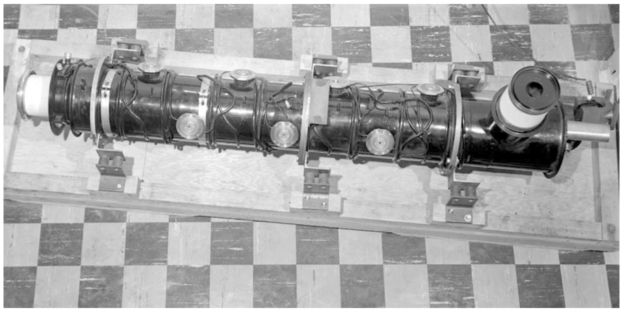

FIGURE 9. Varian VA-812 klystron for the transmitter of the UHF GCI/CCM radar. Its rating is 8-MW peak power, 28-kW average power, 2% instantaneous bandwidth. The cathode is on the left and is operated below ground potential. The anode is on the right along with the cylindrical RF output window. The klystron measures nearly ten feet long.

FIGURE 10. Dummy RF load for the transmitter of the UHF GCI/CCM radar. The transmitter is on the floor below; the rotary joint and antenna mount are on the floor above. A waveguide switch allows for operating with the dummy load (right) or the antenna (upstairs). For scale reference, each floor tile measures 9 × 9 in.

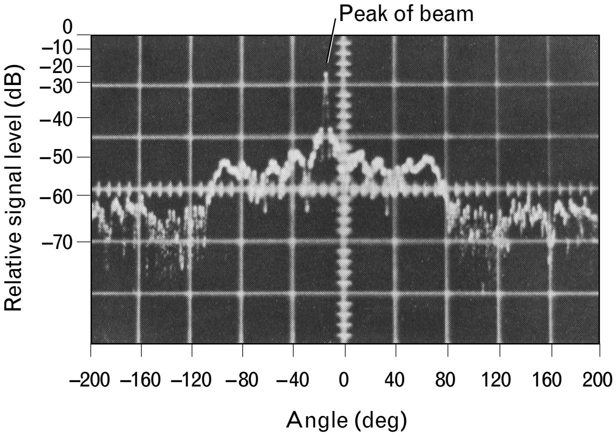

FIGURE 11. An azimuth cut at an elevation angle of about 0° through the 430-MHz antenna pattern of the Boston Hill radar. A central region about 200° wide contains peaks ranging from 19 to 27 dB below the observed beam peak. This observed beam peak lies about 4.5° in elevation angle below the true peak, which had a gain of about 32 dBi.

There was justifiable concern about placing a UHF ground/air communication terminal (an important part of the SAGE system concept) at the same site as a large VHF or UHF radar such as the AN/FPS-24 or AN/FPS-35. The Boston Hill radar provided a good experimental facility for the investigation of these potential RFI problems.

A number of radar-evaluation, antijam, and CCM techniques were tested at Boston Hill. We briefly discuss seven of them.

Determining a Radar's Detection-Range Capability

Directly measuring the performance of a high-capability radar against a small airborne target can be difficult because of horizon effects and the target's altitude limitations. Tests involving an F-86 fighter aircraft had to be run at reduced transmitter power and with a 16-dB attenuator in the receiver line in order to determine an experimental value for the detection range. These results were then scaled to the condition of full transmitter power and no receiver attenuator. Figure 12 shows the radar's coverage diagram.

Adapting Sea-Clutter-Cancellation Techniques

Consider a cloud of chaff in an environment of constant-velocity winds, observed by a ground-based radar. The echo signals from this cloud behave in some ways like the sea-clutter returns seen by an airborne radar. The Time-Averaged Clutter-Coherent Airborne Radar (TACCAR) AMTI system succeeded in reducing sea clutter by causing the zero-response notch of the IF velocity filter to track the radial component of sea-surface velocity relative to the airborne platform (see the article "Displaced-Phase-Center Antenna Technique," by Charles Edward Muehe and Melvin Labitt, in this issue). The sliding-notch IF canceler (SNIFCAN), developed for the Boston Hill radar, was an application of the same idea to reduce echoes from chaff, and it was tested at the Boston Hill radar.

Chaff-Canceling Techniques

A fully coherent frequency-hopping radar can overcome the frequency sensitivity of the motions of a chaff cloud by making the radar echoes noncoherent. Just after the chaff bundle is dispensed by an enemy aircraft the echo from it looks like that from a strong point target, but as time passes the chaff slows down and disperses in position and in velocity. The echo from it in each of the radar's resolution volumes becomes weaker and noiselike. The radar's problem then becomes that of detecting the echo signal from aircraft targets immersed in the noisy echoes from the chaff cloud.

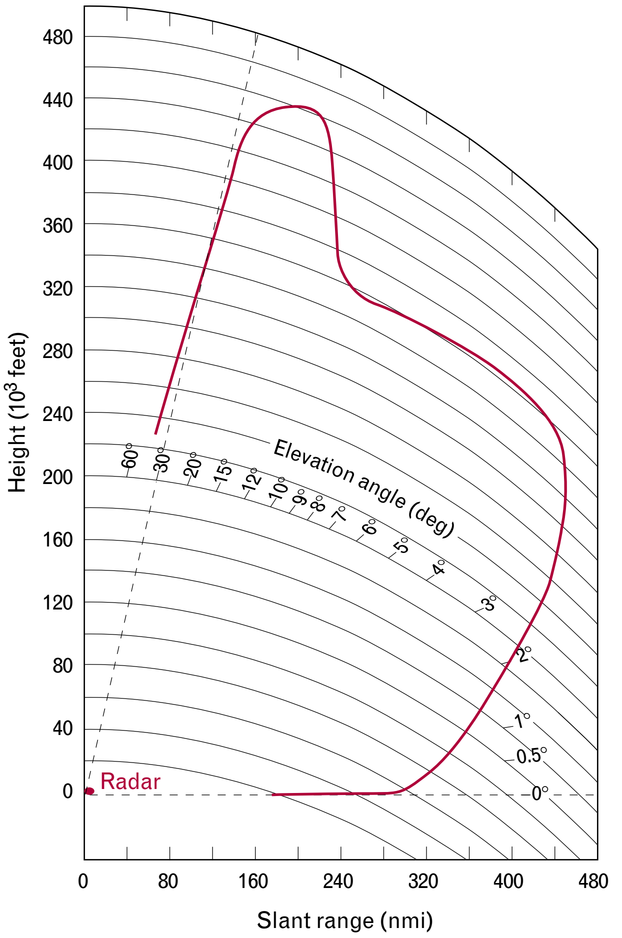

FIGURE 12. Boston Hill UHF radar coverage diagram on an F-86 fighter aircraft for 50% blip-scan ratio (the radar operator on average sees the blip every other scan). The radio horizon is 4/3 the radius of the earth.

The broadband characteristics of the Boston Hill radar made it practical to demonstrate the efficacy of pulse-to-pulse frequency hopping in the minimization of echoes from distributed targets such as weather and chaff.

More about Pulse-to-Pulse Frequency Hopping

Pulse-to-pulse frequency hopping has the further advantage of transforming ground-clutter echoes into noiselike signals also, unless a particular piece of clutter corresponds to a large physical point target. Of course, frequency hopping adds complexity to the radar's MTI circuitry.

The incorporation of frequency coding in the frequency-hopping pattern made pulse-interval expansion possible at the Boston Hill radar. A target (a missile, for example) in a distant and specific interpulse range interval could be detected without its having to compete with echo signals from targets in other intervals. The addition of instantaneous-frequency-correlation (IFC) constant-false-alarm-rate (CFAR) circuitry to the radar's frequency-hopping receiver greatly reduced or eliminated the echoes from weather and chaff. The echoes from auroral ionization were also reduced, but it was found that pulse-to-pulse frequency hopping was not necessary; the relatively simple IFC CFAR circuitry sufficed.

Jittered Pulse-Repetition Frequency

The Boston Hill radar was capable of jittering its pulse-repetition frequency (PRF). That CCM technique can be employed to prevent a pulse-repeater jammer, carried by an aircraft, from jamming echoes from targets that are closer to the radar than it is. Outside that range the repeated pulse signals fall into the same range box as the authentic signals when received at the radar. Inside that range they fall into randomly distributed range boxes, depending on how the PRF jitter is programmed. They do not simulate echoes from a nonexistent aircraft, so they cause less confusion to the radar signal processing circuitry.

Sidelobe Cancellation, Jammer-Strobing Systems

A system installed in the Boston Hill radar could indicate unambiguously the azimuth (or "strobe") of a jammer, even when the latter was within its self-screening region. The operating principle involved comparing the signal received by an omnidirectional antenna with the signal received by the main radar antenna. The output of the system was a PPI strobe, of angular width roughly equal to the antenna beamwidth at its sidelobe level, pointing directly toward the azimuth of the jammer. This system was an outgrowth of Lincoln Laboratory's Project Cross Over. It was satisfactorily tested in the course of several U.S. Air Force jamming exercises.

Another jammer-strobing method was developed in the course of Lincoln Laboratory's program to develop electronic counter-countermeasures for AEW radars. This method requires only a Clark/Dicke-Fix IF channel in the radar receiver and provisions for inserting pulsed RF signals ahead of it. For a discussion of the Dicke Fix, a counter-countermeasure, see the article entitled "Early Advances in Radar Technology for Aircraft Detection," by Donald L. Clark, in this issue. Comparison of the two jammer-strobing methods revealed essentially the same basic limitations for both.

Observing Objects in Space

An interesting experiment was carried out on 29 October 1959, when NASA launched a 100-ft-diameter metallized-plastic balloon called *Shotput 1* on a sounding rocket from Wallops Island, Virginia, some 400 to 500 miles south of Boston Hill. The balloon was inflated after launch. This preliminary test was followed by the successful launch to orbit of the *Echo 1* balloon from Cape Canaveral, Florida, on 12 August 1960. In the *Shotput 1* test, the balloon rose to an elevation angle of about 25°, as seen from the radar, and it could be seen with the naked eye. The echoes from it were strong. The signals dropped out during the higher-altitude portions of the balloon's flight, probably because it had then risen above the main lobe of the radar's antenna pattern. The signals reappeared a few minutes later, when the balloon fell back into the antenna beam. The Boston Hill radar also supported NASA's *Shotput 2* test on 16 January 1960. This radar was not well suited to the observation of orbiting satellites; attempts to detect them were unsuccessful.

The Boston Hill radar reached its full operating capability in late 1959, just about the time when Lincoln Laboratory changed the thrust of its radar programs. Although by no means had all of the problems presented by airborne threats been solved, Lincoln Laboratory's efforts in radar research and development were to be concentrated on ballistic missile threats until the late 1960s. At that time Lincoln Laboratory began its FAA-sponsored program in air traffic control. Also at that time there was resurgence of interest in tactical radar applications, engendered by the Vietnam War. These two disparate influences led to the broad range of radar technology that is chronicled in other articles in this issue of the *Lincoln Laboratory Journal.*

On 1 April 1960 responsibility for the Boston Hill radar was transferred to the MITRE Corporation, just as was done earlier for the Jug Handle Hill radar. Several years later the antenna of the Boston Hill radar was demounted and used to replace an AN/FPS-35 antenna that had been damaged by high winds at an operational Air Force site. One of the authors, visiting Boston Hill in the early 1990s, found the tower still standing. It, like the tower of the Jug Handle Hill radar (Figure 6), had become an antenna farm.

Acknowledgments

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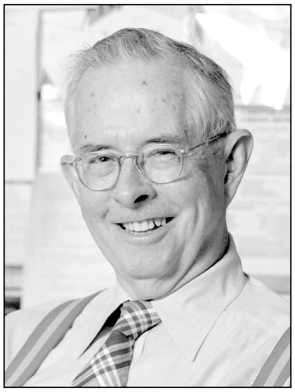
REFERENCES

1. J.R. Zacharias and A.G. Hill, *Final Report of 1952 Summer Study Group,* vol. 2, Lincoln Laboratory (10 Feb. 1953).
2. "Five Years at the Radiation Laboratory," *1991 IEEE MTT-S Int. Microwave Symp., Boston, 10–14 June 1991* (originally published 1946).
3. R. Buderi, *The Invention That Changed the World: How a Small Group of Radar Pioneers Won the Second World War and Launched a Technological Revolution* (Simon & Schuster, New York, 1996).
4. J. Aarons, "Antenna and Receiver Measurements by Solar and Cosmic Noise," *Proc. IRE* **42** (5), 1954, pp. 810–815.
5. P.A. Northrop, "Boston Hill UHF Radar," *Technical Report 243,* Lincoln Laboratory (6 July 1961), DTIC #AD-325634.
6. The Jug Handle Hill radar was narrowband but tunable over the same frequency range.
7. The nose of the antenna beam was designed to be about 4.5° above the local horizontal at the radar, to improve its coverage of airborne targets.



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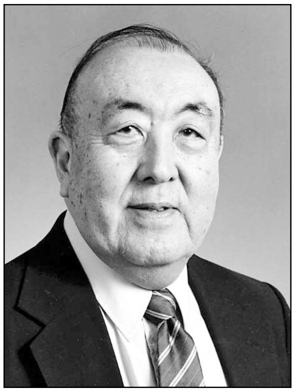
was born in Texas in 1924. During World War II, he served in the U.S. Army Signal Corps, where he installed, maintained, and repaired cryptographic equipment in the Pacific Theater of Operations. He received a B.S. degree from Texas A&M College, and M.S. and Ph.D. degrees from California Institute of 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 FLTSATs 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 Lincoln 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 Aerospace and Electronic Systems Society.



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joined Project Lincoln in June 1951 after completing his Doctor of Science degree (electron optics) at Harvard University. In 1954 Dr. Naka became associate leader of the Special Radars group. In 1956 he became the leader of the Heavy Radars group, where he led the development of the Boston Hill radar and was a member of the Air Force's Frequency Diversity Advisory group. In 1959 Bob joined the MITRE Corporation, which had been established a year earlier to head the Radar Systems and Techniques department. Subsequently he became associate technical director, then technical director of MITRE's Applied Science Laboratories. In 1969 Bob became chief scientist of the MITRE Corporation. That same year, he reported to the Pentagon to become deputy director of the National Reconnaissance Office. In 1972 he joined Raytheon to be director of Detection and Instrumentation Systems, and in 1975 returned to the Pentagon to become Air Force chief scientist. In 1978 he joined Science Applications, Inc. as corporate vice president, and in 1982 he joined GTE Government Systems Corporation as vice president, Engineering and Planning, from which he retired in 1988. He now runs a small business, CERA, Inc., specializing in electromagnetic technology, as its president. He is a registered professional engineer in Massachusetts. Bob's honors include Member of the National Academy of Engineering, Fellow of the Explorers Club, and member of the honorary societies Sigma Xi, Tau Beta Pi, and the Druids (Omicron Delta Kappa) of the University of Missouri. He has received the U.S. Air Force's Exceptional Service Award four times. The University of Missouri bestowed an Honor Award for Engineering and the Faculty Alumni Award.