Radars for Ballistic Missile Defense Research

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■ **Lincoln Laboratory's involvement in ballistic missile defense began over forty years ago at the time of the first launches of ICBMs and satellites by the Soviet Union and the formation of the Advanced Research Projects Agency (ARPA). The Reentry Physics Program, started in 1958 and sponsored by ARPA, set out to understand the behavior of hypervelocity objects reentering the atmosphere, with the expectation that this research would lead to a means of discriminating between warheads and decoys. The program, which combined theoretical analysis, laboratory experiments, and field measurements, provided a foundation that soon led to other similar programs. The U.S. Air Force, interested in the performance of its own ICBMs against enemy defense systems, also initiated a program of radar development and measurements similar to that of ARPA. As a consequence, the Laboratory became heavily involved in ARPA's Project PRESS (Pacific Range Electromagnetic Signature Studies) and ARPAT (ARPA Terminal) programs and the Air Force Penetration Aids program. By 1963 these three large programs, combined with related efforts in the development of radar technology, occupied approximately half of Lincoln Laboratory's staff. Fifteen large sensitive radars designed for signature measurements were built as a result, and Lincoln Laboratory had some role in the development of each. This article traces the history of the measurement radars and the technology programs that supported them. It concentrates on the four major radars at the Kwajalein Missile Range. These radars continue to play a major role in the development of ballistic-missile-defense systems and discrimination techniques.**

In 1953 a modest program in what was then called AICBM began at Lincoln Laboratory. The initial goal was to study the detection and tracking of enemy intercontinental ballistic missiles (ICBM) in order to gain early warning of an enemy attack. The Millstone radar (see the article entitled "Radars for the Detection and Tracking of Ballistic Missiles, Satellites, and Planets," by Melvin L. Stone and Gerald P. Banner, in this issue) was also started in 1956 as a prototype of an early-warning radar. Two events in 1957 resulted in the acceleration of efforts by the United States to develop systems capable of countering attacks by enemy ICBMs. First, on 26 August 1957, the Soviet Union announced that it had successfully tested an ICBM. Second, on 4 October 1957, the world was shocked to hear the beeping of *Sputnik I*, the first artificial satellite. The Department of Defense reacted swiftly to these two events and formed the Advanced Research Projects Agency (ARPA) in early 1958. ARPA was given broad jurisdiction over research and development of space projects and antimissile systems. ARPA's principal program, called DEFENDER, focused on solving what was perceived to be the most difficult antimissile problem, namely, discrimination between warheads and the debris and countermeasures expected to accompany the warhead.

In the vacuum of space, objects such as chaff, bal-

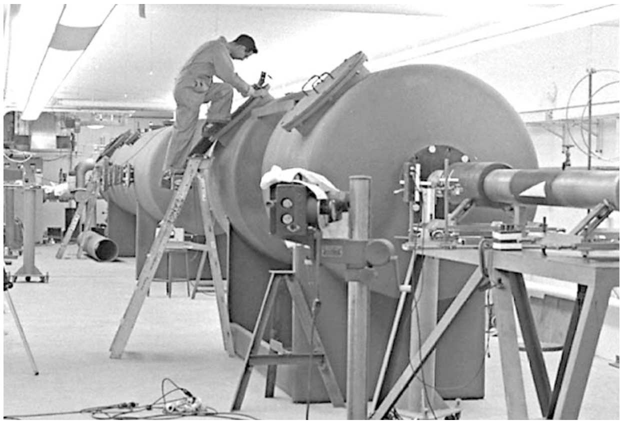

FIGURE 1. The two expansion chambers and the experimental chamber (in the rear) of the Reentry Simulating Range (RSR) constructed by Lincoln Laboratory in 1960. This facility utilized high-velocity pellets to simulate and measure the physics of atmospheric reentry. Pellets entering from the right in the picture pass through the two cylindrical expansion tanks in the foreground to dissipate the combustion products of the gun before entering the experimental chamber in the background. This large system could be evacuated to a pressure of fifty microns of mercury in only five minutes.

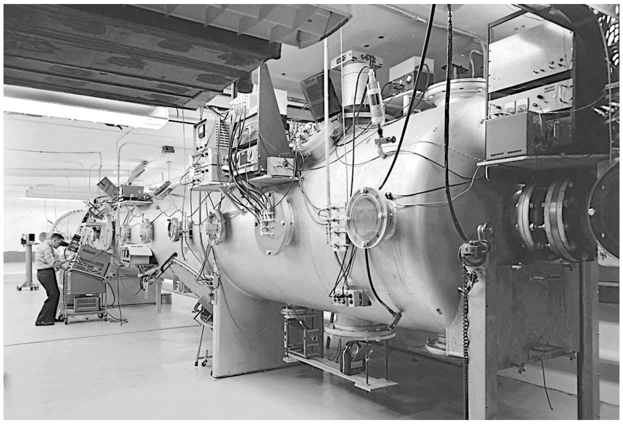

FIGURE 2. The experimental chamber of the RSR was large enough to accommodate multiple optical and microwave measurement instruments. The principal instruments were schlieren cameras and a cavity resonant at UHF, which provided quantitative measurements of electron density and wake diameter.

loon-like replica decoys, and fragments of the launch vehicle move at the same velocity as the warhead. Chaff can hide the warhead, while balloon-like replica decoys and fragments of the launch vehicle can have radar signatures sufficiently similar to that of the warhead to make discrimination quite difficult. Tracking all these objects and assigning interceptors to them when discrimination is not possible can easily exhaust the radar and interceptor resources of a defense system. As atmospheric drag is encountered in reentry, the lighter objects slow down and fall back to reveal the threatening heavier vehicles, including the warheads. The lower the altitude at which the slowdown occurs, the less time there is for defense-system reaction and interceptor launch and fly-out. Thus one of the more stressing countermeasures for the defense system to overcome is the reentry decoy, a small, heavy object that can match the radar cross section and deceleration characteristics of the warhead all the way down to low altitudes. Learning how to perform discrimination between warheads and reentry decoys at as high an altitude as possible was a major goal of ARPA and the DEFENDER program.

Hypervelocity objects encounter increasing drag as they enter the atmosphere. The kinetic energy they lose heats and ionizes the surrounding air, leaving an ionized trail. From studies of meteors, scientists knew that this ionized wake could be detected at radar wavelengths as well as in the visible spectrum. They reasoned that the energy of the wake should be related to the mass of the object that produced it, and thus radar measurements of the ionized wake should yield a means of discriminating between the heavy warheads and the lighter reentry decoys. Building radars that had the sensitivity, coherence, and resolution in both range and range rate to make the required measurements was a challenging task that required many advances in the state of the art. The DEFENDER program set out to solve the problems, and Lincoln Laboratory was given the opportunity to work on many of them.

Reentry Physics Program

In July 1958 the ARPA-sponsored Reentry Physics program started at the Laboratory under the technical direction of Daniel E. Dustin, then a group leader, and his assistants, Glen F. Pippert and Leo J. Sullivan. The lofty goal of the program was "to determine the effects of the ionization produced by a reentering body on the electromagnetic scattering characteristics of the body," and "to develop adequate theoretical models to explain the experimentally observed phe-

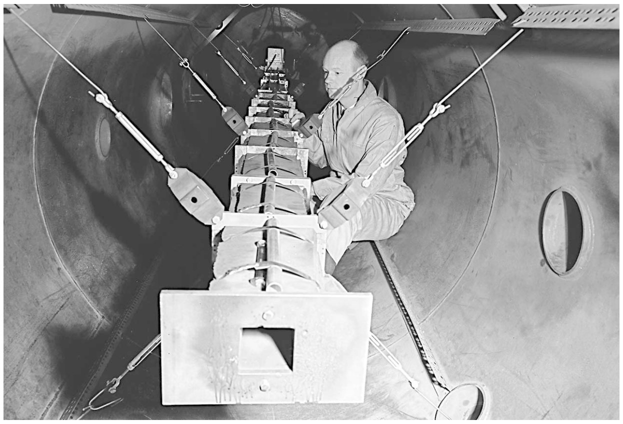

FIGURE 3. The inside of the RSR experimental chamber is shown with an L-band waveguide experiment that was used to measure the transmission and reflection properties of the ionized medium. The experimenter is Melvin A. Herlin, the leader of the group responsible for the RSR.

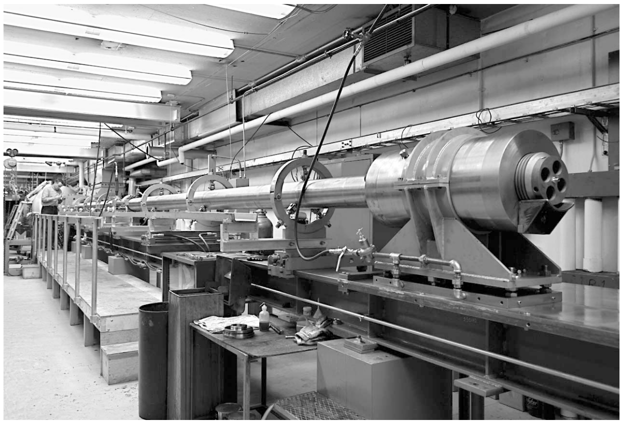

FIGURE 4. The light-gas gun used to fire pellets at ICBM velocities. This gun routinely achieved pellet velocities of over 20,000 ft/sec. On one occasion a hydrogen leak caused a pellet to be fired at 32,000 ft/sec.

nomena" [1]. Laboratory measurements were to be made on small pellets at a number of hypervelocity test facilities, including one to be built at Lincoln Laboratory. Field measurements of somewhat larger reentry objects would be provided by radars at Arbuckle Neck, Virginia, observing vehicles launched from Wallops Island, Virginia.

Reentry Simulating Range

In 1960 a Reentry Simulating Range (RSR) was constructed near the Laboratory and equipped with a conventional powder gun that could fire 0.5-inch-diameter projectiles at velocities up to 9200 ft/sec, and a light-gas gun that could fire 0.186-inch-diameter spherical pellets at velocities of over 20,000 ft/sec. The light-gas gun fired a three-inch-diameter projectile to compress hydrogen in a barrel blocked with a frangible window. When the window broke, the compressed gas was released into a smaller barrel, where it accelerated the pellet to ICBM velocities. Figure 1 shows the expansion tanks and experimental chamber of the RSR; Figures 2 and 3 show the experimental chamber in more detail. Figure 4 shows the light-gas gun that fired pellets at ICBM velocities, and Figure 5 shows some of the pellets that were used by both of the guns.

The RSR experimental chamber accommodated multiple optical and microwave measurement instruments; schlieren cameras and a resonant UHF cavity were the principal instruments [2]. Figure 6 shows an example of the photographs made with these instruments. These photographs provided an excellent qualitative picture of the projectile's flight, the bow shock wave, the growth of the wake diameter as a function of distance behind the object, and the location of the point at which the wake flow changed from laminar to turbulent. The resonant UHF cavity provided a time history of the pellet's passage, and thus measurements of the atmospheric ionization as function of distance behind the body. Amplitude and phase measurements could be interpreted in terms of wake diameter and electron density, and changes in the wake's growth rate were used to determine the position of the transition from laminar to turbulent flow. Because of its ability to perform a large number of experiments in a relatively short period, the RSR proved invaluable for determining the effects of pressure, velocity, and materials on the wake properties. It was used until 1970.

Arbuckle Neck Radars

Lincoln Laboratory's first two reentry-measurement radars were designed and built at the Laboratory in 1959 and installed at Arbuckle Neck, Virginia, to observe *Trailblazer I* and *Trailblazer II* vehicles launched by NASA from Wallops Island, Virginia [3].

The *Trailblazer I* was a six-stage missile that used three stages to boost its velocity package to an altitude

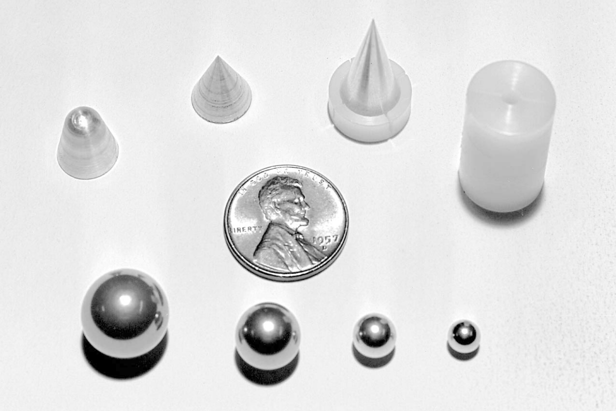

FIGURE 5. Assorted pellets used at the RSR. The 0.5-inch projectiles, including all the non-spherical objects, could be fired only by the conventional powder gun. The spherical pellets smaller than 0.5 inches were fired only by the higher-velocity light-gas gun. True ICBM velocities were achieved only with the 0.186-inch-diameter pellets.

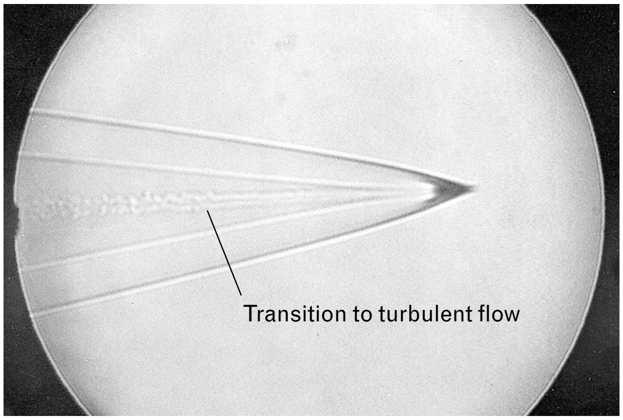

FIGURE 6. A schlieren photograph of a 12.5° half-angle cone travelling at 5700 ft/sec. The photographs provided a qualitative measure of reentry events, which aided the interpretation of the more quantitative microwave measurements. The pointer in the image indicates the approximate position of the transition from laminar to turbulent flow.

of approximately two hundred miles and the remaining three stages to accelerate the payload back toward Wallops Island. The system achieved a reentry velocity of 20,000 ft/sec with a two-pound payload. Between March 1959 and July 1962, fourteen of the *Trailblazer I* vehicles were flown, the majority with five-inch spherical reentry bodies of various materials and coatings. In order to fly larger vehicles, more representative of warheads, NASA designed the *Trailblazer II*, which was a four-stage rocket that could achieve a velocity of 20,000 ft/sec with a thirty-five-pound payload. Firings commenced in 1963 and continued through the end of the Laboratory's operations at the site in 1965.

The first of the two reentry-measurement radars at Arbuckle Neck, the S-band tracker, was built in a little over one year, in time to successfully track the 1 December 1959 launch of the third *Trailblazer I*. To meet the accelerated schedule, Laboratory researchers assembled the system primarily from available parts. The antenna was a sixty-foot dish on a surplus U.S. Navy five-inch gun mount. The transmitter was from an AN/FPS-6 radar and utilized an S-band magnetron capable of 4.5-MW peak power at a pulse width of 2 μsec. Tracking hardware was from an SCR-584, a World War II fire-control radar for antiaircraft guns. The system used conical-scan angle tracking and a single receiver channel with a cooled parametric amplifier designed and built at Lincoln Laboratory. The conical scan was used because at that time it was not possible to build parametric amplifiers with the stability required for a three-channel monopulse system.

The second radar at Arbuckle Neck, also utilizing a surplus U.S. Navy gun mount and a sixty-foot dish, had diplexed UHF and X-band systems that were slaved to the S-band tracker to form the first integrated multiwavelength data-gathering system. With

FIGURE 7. Radar antennas at the Lincoln Laboratory field site at Arbuckle Neck, Virginia, located near the Wallops Island, Virginia, launch facility. Site instrumentation consists of (from right to left) the S-band tracking radar, the multiplexed UHF and X-band cross-section measurements radar, and the SPANDAR (Space Range Radar) long-range trajectory and range-safety radar designed and built by Lincoln Laboratory for NASA.

Table 1. Approximate System Parameters for the Reentry-Measurement Radars at Arbuckle Neck, Virginia

	UHF	*S-band*	*X-band*
Frequency (MHz)	400	2800	9000
Output power (peak in MW)	8	5	1
Pulse width (μsec)	6	2	2
Pulse-repetition frequency (Hz)	320	320	320
Antenna gain (dB)	35	53	60
Beamwidth (degrees)	2.9	0.3	0.12
Reflector diameter (ft)	60	60	60
Antenna efficiency assumed (percent)	50	50	40
Intermediate-frequency signal-to-noise ratio for a five-inch sphere at a distance of 200 nautical miles, neglecting losses.			
Using conventional receivers (dB):	8	13	10
Improvement expected with low-noise preamplifier (dB):	4* with parametric amplifier	10* with parametric amplifier	10* with maser

* These approximate signal-to-noise ratios are on a per-pulse basis with no integration. A system noise temperature of 300K, corresponding to a conventional noise figure of 2 (or 3 dB), is assumed achievable at each frequency with the parametric amplifier or the maser.

little knowledge of what wake cross section to expect, the designers built the UHF system to transmit alternating 1-μsec and 6-μsec pulses. The transmitter used a version of the VA-812 klystron developed for the Boston Hill radar (see the article entitled “Long-Range UHF Radar for Ground Control of Airborne Interceptors,” by William W. Ward and F. Robert Naka, in this issue) and used again for the ARPA Long Range Tracking and Instrumentation Radar (ALTAIR). Although the transmitter chain was coherent, only amplitude detection was used. The system transmitted a vertically polarized signal and received both linear polarizations. The X-band system had the world’s first X-band maser preamplifier, which was designed and built at Lincoln Laboratory. The careful wording of Table 1, copied from the first Semiannual Technical Summary Report of the Reentry Physics Program [1], indicates the uncertainty about the performance that would be achieved by the low-noise preamplifiers. The report also raised concerns about the feasibility of making a sixty-foot paraboloid of sufficient accuracy for operation at X-band. In the end, only the central portion of the dish was used at X-band in order to have a broad enough beam to keep the target illuminated in the slaved mode of operation. Figure 7 shows the Lincoln Laboratory S-band and UHF/X-band radars built for ARPA at Arbuckle Neck, and a third system called SPANDAR (Space Range Radar) that was built by Lincoln Laboratory for NASA. SPANDAR, which operated at S-band, also had a sixty-foot dish, but used the superior mount design of the Millstone radar. It was designed and used as a range-safety radar for missile launches and for satellite tracking.

The emphasis on digital recording, which became a hallmark of the Lincoln Laboratory measurement radars, and the practice of recording digital data at field sites and bringing it back to Lexington for analysis, were first established with these sensors. In this case, the data consisted of time, range, azimuth, and elevation angle, and one range-gated amplitude sample from each pulse.

Much reentry phenomenology, the knowledge of which we now take for granted, was first observed by these radars and came as a surprise. The cross-section dip that occurs in early reentry, the very large cross section of the turbulent wake, and the large cross section of the orthogonally polarized return are examples. The Millstone radar in Westford, Massachusetts, some seven hundred kilometers from Arbuckle Neck, also observed the *Trailblazer* launches and provided the coherent data that first showed how rapidly the mean wake velocity decays. In 1965, with data on full-scale vehicles available from the Target Resolution and Discrimination Experiment (TRADEX) radar at the Kwajalein Atoll in the Pacific Ocean, Lincoln Laboratory ceased operations at Arbuckle Neck and transferred the radars to NASA. For more details on the Arbuckle Neck sensors, the vehicles, and the results, see the article by Sullivan in the summer 1991 issue of the *Lincoln Laboratory Journal* [3].

ARPA Radar Technology Program

In July 1959 a second ARPA-sponsored effort started at Lincoln Laboratory. Called the Radar Techniques Study, the program had an extremely broad work statement designed "to allow researchers to develop ideas with a minimum of direction" [4]. Topics included, but were not limited to, high-power radio-frequency (RF) sources, high-resolution techniques, improved radar accuracy, low-noise receivers, and extraction and utilization of information in radar signals. Detection of signals in non-Gaussian noise and radiometry were two of the initial areas studied. In 1960 a larger effort called Microwave Power was started at the Laboratory for ARPA. The tasks included the design of high-power duplexers and basic work on vacuum voltage breakdown and electron optics, which was needed to design improved RF amplifiers and modulator switch tubes. The first computer code to model the saturated gain of a klystron was one of the results.

U.S. Air Force Interests

The U.S. Air Force, interested in how U.S. ICBMs would perform against an enemy defense system, wanted to minimize the cross sections of their warheads and to develop decoys and other penetration aids. To test their systems, they needed the same type of measurement radars and analysis techniques that ARPA was developing. The Air Force planned to test ICBMs in the Atlantic by using sensors on Ascension Island and on the Mobile Atlantic Range Station (MARS) ships. During 1960 both ARPA and the Air Force were holding discussions with Lincoln Laboratory about enlarged programs. On 29 August 1960 the Director of Defense Research and Engineering directed ARPA and the military services to execute a single integrated program in penetration aids, target identification, and reentry physics. Lincoln Laboratory was requested to provide scientific direction. As a result, the Laboratory assumed responsibility for ARPA's Project PRESS (Pacific Range Electromagnetic Signature Studies), and a multifaceted Air Force program called Penetration Aids was initiated under the leadership of V. Alexander Nedzel. The scope of the program included the following three elements: (1) participation, with responsible Air Force agencies and their contractors, in preparing general concepts and detailed plans for testing and evaluating ICBM reentry vehicles and penetration aids, in forecasting instrumentation needs, in monitoring test operations, and in evaluating the test results; (2) research and development on advanced range instrumentation and associated equipment as indicated by anticipated needs; and (3) exploratory research on ICBM penetration problems for the purpose of generating and testing ideas that might contribute to advanced concepts and techniques.

Initial work on the first element of the program was concentrated on assisting the Air Force in the procurement of the MARS ships and an assessment of the other instrumentation on the Atlantic Missile Range. The initial view was that the L-band, C-band, and X-band radars of the first two ships would not have adequate sensitivity for measurements on low-cross-section reentry vehicles, and that a third ship with advanced capabilities would be required. Lin-

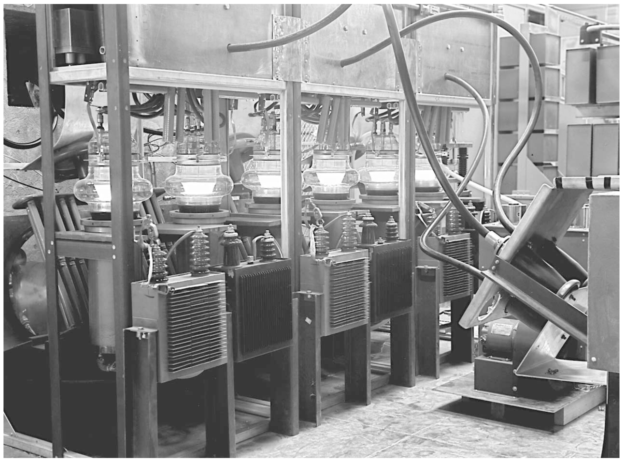

FIGURE 8. The hard-tube modulator at the Radar Transmitter Research Facility (RTRF) at Lincoln Laboratory. Operating singly, the Westinghouse triode switch tubes could generate 50-kV, 500-A pulses with rise times of 0.5 μsec. Derating was necessary when they were operated in parallel. A pulse transformer stepped the voltage up to the 300 kV required by the klystron.

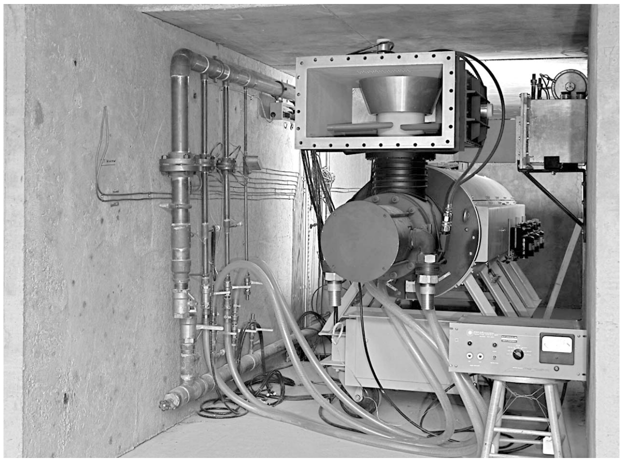

FIGURE 9. A UHF klystron designed for horizontal operation at 60-MW peak power is shown in the RTRF test stand. The heavy concrete walls provided necessary shielding against the intense X-rays generated by these tubes.

coln Laboratory recommended changes that would increase the initial capability of the radars and pave the way for future system upgrades.

Under the second element, Lincoln Laboratory initiated a program at Litton Industries to develop a high-power L-band klystron amplifier while a plan was being developed for other transmitter research. Sidelobe suppression, the coherence of compressed waveforms, and the design of burst waveforms to achieve good range and Doppler resolution were signal-design issues of immediate concern.

In slightly more than one year, the ships became Advanced Range Instrumentation Ships (ARIS), the program became Ballistic Missile Reentry Systems (BMRS), and the ARPA and Air Force technology development efforts were well integrated. A burst-waveform generator—to be utilized in the ARPA Measurements Radar (AMRAD) and the TRADEX radar—was developed under the BMRS program.

With limitations on antenna size due to shipboard installations, high power was even more important to the Air Force than it was to ARPA. Under the BMRS program, the Laboratory sponsored tube development programs at Varian, Litton, and Westinghouse for later application in the measurement radars. Lincoln Laboratory's Building V, then known as the Radar Transmitter Research Facility (RTRF), was constructed to investigate ways to build transmitters with greater waveform flexibility and to provide modulators, power supplies, and cooling with which to test the new tubes to higher power levels than the vendors could achieve.

The Laboratory designed a hard-tube modulator, shown in Figure 8, which when operated with eight tubes (six tubes are shown in the photo) could provide pulses of up to 180-MW peak power and 2-MW average power. It became the prototype for the ALTAIR transmitter and was used to test UHF tubes for ARIS and ALTAIR and at a later date the tubes that would be used for the L & S-band modifications of the TRADEX radar. The UHF klystron shown in Figure 9 was destined for use in the advanced ARIS ships and ALTAIR, but it never achieved its design goals of 60-MW peak power and 300-kW average power. As a result, ALTAIR used a version of the VA-812 klystron developed for the Boston Hill radar, while the ARIS systems used a transmitter with twenty-four traveling wave tubes operating in parallel. Some twenty years later the ARIS ships were retired from service, and Varian announced that it would no longer maintain the facilities needed to build the large VA-812 klystron. ALTAIR acquired the ARIS traveling-wave-tube transmitters and is using them to this day.

The RTRF was also equipped with a very high-voltage power supply of more modest average power, as shown in Figure 10, in order to test tubes with modulating anodes.

Project PRESS

Project PRESS (Pacific Range Electromagnetic Signature Studies) was ARPA's most ambitious DEFENDER program. It was to include the PINCUSHION S-band radar, the TRADEX radar, airborne optical sensors installed in a KC-135 and Navy A3D aircraft, and numerous ground-based optical sensors. All the sensors were to be interconnected and controlled by a central IBM 7094 computer.

In February 1959 the Army decided to site its Nike Zeus antiballistic missile system at the Kwajalein Atoll, where it could be tested against missile targets launched from Johnston Island or Vandenberg Air Force Base in California. The Zeus system, designed by Bell Laboratories, consisted of the UHF Zeus Acquisition Radar, the L-band Discrimination Radar, and the C-band Target Tracking Radar, all located on Kwajalein Island, the southernmost island in the atoll. In order to take advantage of the Zeus targets for reentry measurements, ARPA decided to locate its instruments there as well. A site on Roi-Namur, the northernmost island, was selected for the TRADEX radar by Lincoln Laboratory's Glen F. Pippert in early 1960 [5]. From the outset, ARPA expected the installation to be a research site manned by scientists and engineers. Figure 11 shows Kwajalein Atoll viewed from the north. The island in the foreground is Roi-Namur, where all the KREMS radars are located [6].

As the result of a study requested by ARPA and conducted by the Laboratory in 1960, work on the PINCUSHION S-band radar ceased and Lincoln Laboratory was given responsibility for the PRESS program.

TRADEX

The TRADEX radar, already under construction by RCA when Lincoln Laboratory assumed responsibility for PRESS, was a derivative of the UHF trackers RCA had built for the Ballistic Missile Early Warning System (BMEWS), but with an L-band range-track-

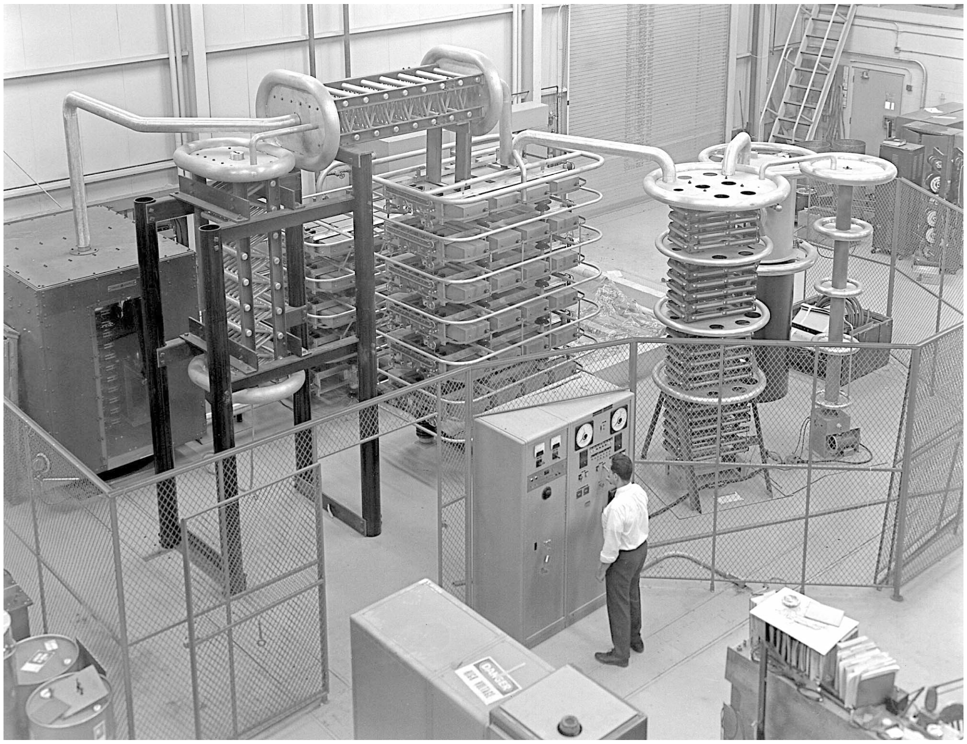

FIGURE 10. A 350-kV, 1-A power supply used to test tubes with modulating anodes at the RTRF.

FIGURE 11. A view of the northern tip of Kwajalein Atoll looking south. The island in the foreground is Roi-Namur, the site of all the KREMS radars, which can be seen at the extreme left edge of the photograph. The brown areas in the picture are the coral reef, exposed at low tide but under three to six feet of water at high tide.

ing and data-gathering capability. With the aid of personnel from the Laboratory and RCA, the radar was installed and checked out in time to successfully track the first Atlas ICBM launched to Kwajalein on 26 June 1962. Figure 12 shows the TRADEX antenna on Roi-Namur.

TRADEX was one of the earlier radars to use pulse compression, utilizing a 50-μsec, 1-MHz linear frequency modulation, or "chirped," transmit pulse to achieve high sensitivity, while achieving a range resolution of approximately two hundred meters. With an eighty-four-foot antenna and 2-MW peak power, the TRADEX L-band system achieved a single-pulse signal-to-noise ratio of 28 dB on a one-square-meter target at a range of a thousand kilometers, easily enough to detect warheads as they came over the Earth's horizon in the vicinity of Hawaii. From the beginning, the system was coherent and featured an unusually broad range of pulse-repetition frequencies (PRF). High PRFs provided excellent Doppler reso-

FIGURE 12. The TRADEX antenna, located on the island of Roi-Namur in the Kwajalein Atoll.

lution for wake measurements, while low PRFs were needed to view very long target complexes. As installed, the radar used all-analog circuitry, but it was modified over time to provide ever-increasing use of the IBM 7094 computer for control, recording, and trajectory extrapolation. A memorable feature of the early TRADEX radar was the intermediate-frequency (IF) tape recorder, an analog recorder with three-foot-diameter reels. This tape recorder achieved sufficient bandwidth to record the IF signals and collect the vital phase information, but it did so with very high tape speeds that resulted in spectacular displays whenever the tape broke.

When the Laboratory assumed control of the TRADEX radar, the first change was to add a pulse-burst waveform to provide improved range and Doppler measurements. The burst subpulses were 2-μsec chirps of 20-MHz bandwidth, providing range resolution of approximately fifteen meters and allowing the analysts to examine the amplitude and velocity spectrum of the wake as a function of distance behind the body. The subpulse spacing of 14 or 28 μsec provided quite high Doppler ambiguities, while the 32-pulse duration of the burst provided good Doppler resolution. Major modifications to the transmitter to pass this waveform and a digital recording system that could handle its high data rates were required. They were designed and built at Lincoln Laboratory.

During the 1960s, with the developers of both ballistic missiles and ballistic-missile-defense systems firing missiles into the Kwajalein Missile Range, TRADEX became the primary source of data for reentry discrimination work. At a time when most people still thought of radar only as a means of measuring range, azimuth, and elevation angle, seeing what TRADEX could measure on their vehicles changed the thinking of many of the users.

TRADEX L & S-Band Modification

In 1970 the TRADEX radar was shut down for a major redesign. The UHF capability was removed, a new feed and additional channels were added to make it an L-band tracker, and an all-new S-band radar was added. The Missile Site Radar of the Nike-X ballistic-missile-defense system (which later became the SAFEGUARD system) operated at S-band, and an S-band database was needed in order to design discrimination techniques for the system.

Two new transmitter output tubes were developed by Varian for TRADEX and tested at Lexington. The L-band klystron operated very well at 4-MW peak power and 300-kW average. The S-band klystron, a derivative of the Missile Site Radar tube, had 250-MHz bandwidth and operated successfully at 4 MW and 120 kW. The tube is so conservatively designed that three of the four original tubes are still in use.

All of the receiver, signal processing, and recording electronics were new. With a Sigma V computer, a powerful real-time computer for the time, the system achieved a remarkable level of flexibility. The S-band radar started with only two basic pulses, a 3-μsec, 60-MHz chirp, and a 9-μsec, 17.6-MHz chirp. The system design allowed the pulses to be used in many combinations, including trains, bursts, pairs, long pulse bursts, and frequency-jumped bursts, which provide a range resolution of one meter. The pulse scheduler allowed mixing many of these waveforms in a single 0.1-sec interval and changing the mix every 0.1 sec. The redesigned TRADEX system remained the workhorse for the development of discrimination techniques. In the 1970s everyone in the ballistic-missile-defense (BMD) community had a favorite discrimination waveform, and TRADEX tried them all.

The TRADEX system to date has covered 545 ICBM missions, approximately a hundred experiments with interceptors and other locally launched vehicles, innumerable satellite tracks, orbital-debris data-gathering missions, and a host of other experiments, such as ionospheric-effects measurements, sea-clutter characterization, and tectonic-plate movement. Clearly, ARPA's vision of a continuously developing and improving research facility has been fully realized.

Measurements at White Sands Missile Range

At the same time the TRADEX system was being developed, two other major efforts started. ARPA was considering a next-generation terminal-defense system and a radar that would serve as a technology testbed for the system. The system was the ARPA Terminal (ARPAT) and the radar was called the ARPA

Measurements Radar, or AMRAD. Lincoln Laboratory performed several studies of the ARPAT system for ARPA under the Radar Techniques Study program. As a result ARPA requested the Laboratory to assume responsibility for the ARPAT program, and the Radar Discrimination Technology (RDT) program emerged. Its goal was (1) to determine the feasibility of performing designation and discrimination by using the radar-observed reentry phenomenology from the Reentry Physics program and the PRESS program, (2) to study conceptual defense systems using radar sensors, and (3) to build a prototype terminal-defense system.

Special Test Vehicle Program

As experiments for the BMRS program were planned it quickly became apparent that the Atlantic Ocean and Pacific Ocean ICBM tests would not begin to provide enough payload space for all the planned measurement programs, and that the cost of performing all the tests with ICBM vehicles would be prohibitive. The Air Force determined that a vehicle similar to the *Trailblazer* could be used as an economical means of flying test targets at ICBM velocities. After examination of the instrumentation, range-safety issues, and security at Wallops Island, Virginia, Eglin Air Force Base, Florida, Point Mugu, California, and White Sands Missile Range, New Mexico, White Sands was selected as the site for the BMRS experimental program. The security of the inland location and the prospect of using Nike Zeus test targets and obtaining data from the Zeus prototype radars at White Sands were major factors in the decision.

The Special Test Vehicle program was formed to perform the BMRS experiments. It included the launch vehicles and new instrumentation at White Sands. The tests were performed with a mix of sounding rockets, which could be fired within the boundaries of the White Sands Missile Range, and with the four-stage *Athena* rocket, which like *Trailblazer II* used two stages to boost the vehicle to altitude and the remaining two stages to accelerate the test target into reentry at ICBM velocities. Unlike the *Trailblazer*, *Athena* could not be flown on an “out and back” trajectory because of the expected impact points of the initial stages. It was launched instead from Green River, Utah, some four hundred miles north of White Sands, and overflew privately owned land. The sounding rockets achieved a reentry velocity of 4000 ft/sec with a fifty-pound to seventy-pound payload, while the *Athena* rocket achieved a velocity of 22,000 ft/sec with a nominal seventy-pound payload. The *Athena* could carry vehicles as large as 26 inches in diameter and 72 inches long. The initial plan called for twenty sounding rocket flights and eighty-two *Athena* launches. To perform measurements on the vehicles required a large upgrade of the White Sands instrumentation. A sophisticated S-band radar system, named RAMPART, derived from the earlier PINCUSHION system, and a UHF and L-band radar system called RAM were installed near the impact area on the southern end of the range. A similar UHF/L-band system that included a VHF measurement capability was installed at the more northerly Stallion site to provide high-aspect-angle data. Because the Special Test Vehicle program offered ARPA an excellent chance to test AMRAD and its discrimination techniques, White Sands was selected as the site for that radar.

AMRAD

The ARPA Measurements Radar, or AMRAD, was built by the Raytheon Corporation to Lincoln Laboratory specifications. An L-band system with a sixty-foot dish, it exploited technologies different from those of TRADEX in many areas with the expectation that each radar would be upgraded with successful features of the other. While TRADEX experimented with pulse compression, AMRAD used burst waveforms to produce the high Doppler ambiguities needed for wake-velocity measurements. The initial waveform consisted of a precursor pulse of 0.1 to 8.0 μsec in duration followed by up to thirty 0.2-μsec subpulses with spacings of ten to fifty μsec. To generate the fast rise time needed, the transmitter used a new device, a klystron with a magnetron injection gun and a modulating anode with a gain of four. By reconfiguring the waveguide, the system could transmit linear or circular polarization, but received only orthogonal linear polarizations. The receiver preamplifiers were Lincoln Laboratory–built cooled varactor-diode parametric amplifiers, which provided a

FIGURE 13. The ARPA Measurements Radar (AMRAD) with its clutter fence at the White Sands Missile Range, New Mexico (U. S. Army photograph). In this picture the 60-ft-diameter AMRAD antenna is aimed through a gap in the 104-ft-tall fence in order to work with radio-frequency (RF) calibration instrumentation on a boresight tower on a hill a few kilometers away. In actual missile-test operations the antenna is rotated about 180° in azimuth and raised in elevation angle, its beam pointing over the fence at the incoming target complex. The fence keeps the antenna's sidelobes from illuminating the mountain ranges that border the Tularosa Valley, where AMRAD is placed, on its east and west sides. Before the fence was installed, strong clutter echoes from these mountains in the same range interval as the target complex made the collection of useful data difficult.

system noise temperature of 180 K. Work on the radar began in 1961, and it was turned over to Lincoln Laboratory in December 1963 [7].

The AMRAD contract did not include any recording capability. Raytheon, under a separate contract from Lincoln Laboratory, designed and built a digital signal processor for AMRAD. In addition to performing all the digital sampling, tracking, and recording for the radar, the processor served as the synchronizer, providing clocks and frequency sources for other subsystems and all the RF and video start and stop pulses. Logarithmic amplifiers and quadrature phase detectors were used with 6-bit A/D converters. To provide 10-MHz sampling with 4-MHz analog-to-digital converters, three of these units sequentially sampled the video signal. A phase-shifted 10-MHz clock provided a sampling granularity of 1.5 nsec. The system recorded amplitude and phase samples on the orthogonal-sum channels and angle-error channels with up to twenty-one samples on each burst subpulse. It also collected the metric data, mode information, and samples of the transmitted phase. All of this was accomplished without a computer! This system represented a great advance from the primitive recording system used on the Arbuckle Neck radars, and it became the model for systems later installed at TRADEX and ALTAIR.

A highly visible feature of AMRAD was its clutter fence. Detecting very-low-cross-section wakes at the AMRAD site, which was surrounded by mountains of up to 8000-ft elevation, proved impossible without the addition of a clutter fence. The required fence, designed by John Ruze of Lincoln Laboratory, was 104 ft tall and triangular in shape with a perimeter of 2000 ft. The clutter suppression it provided matched theoretical predictions exactly. Figure 13 shows a photograph of AMRAD and its clutter fence, "the biggest corral in New Mexico" [8].

Both TRADEX and AMRAD evolved through the 1960s; researchers at each system frequently applied techniques and hardware developed for the other system. Pulse compression was added at AMRAD and bursts at TRADEX. RCA-furnished analog recording was installed at AMRAD, while a digital system was installed at TRADEX. When it was discovered that the wake velocities decayed much more rapidly than expected behind the vehicles, the burst parameters were modified to provide improved Doppler resolution at the expense of lower Doppler ambiguities.

By 1963 the PRESS, BMRS, and Radar Discrimination Technology programs employed 246 members of the Laboratory technical staff. Laboratory management started looking for ways to decrease the BMD involvement in order to support other areas of research. Turning the Arbuckle Neck radars over to NASA was the first step. As a second step, the Laboratory asked ARPA to be relieved from operating AMRAD. On 17 February 1966 the responsibility for AMRAD was transferred to the Columbia University Electronics Research Laboratory, later to become the Riverside Research Institute.

ALTAIR

In the early 1960s, the United States was surprised to find that the Soviet Union was developing very large VHF and UHF radars (called Henhouse and Doghouse), presumably intended for ballistic missile defense and space surveillance. In order to understand how U.S. strategic weapons would fare against such radars, it was necessary to test these weapon systems against radars of similar capability. The second Project PRESS radar was initiated, the ARPA Long Range Tracking and Instrumentation Radar (ALTAIR). It was specified to track at VHF and collect UHF data with greater sensitivity and spatial resolution than that provided by the TRADEX radar. A very large antenna and high-power transmitters were specified to achieve high sensitivity. As a consequence of these design factors, ALTAIR routinely acquires targets launched from Vandenberg Air Force Base in California as they come over the horizon at a range of 3500 kilometers.

The ALTAIR antenna is unusual for its size and agility. As shown in Figure 14, the 150-ft diameter antenna rotates on a 110-ft diameter circular track. To achieve the rates and accelerations necessary to track reentry vehicles, the antenna is far stiffer than most 150-ft dishes. The rotating portion weighs almost a million pounds. Perhaps this fact was not realized at the time, but the system was designed with a record-setting load on the wheels and track. With extremely hard steel and meticulous alignment, ALTAIR operated successfully for many years with loading more than ten times as high as the worst-case loads used by the railroad industry. Redesigned bogies with twice the number of wheels have since been installed to insure long life even with the twenty-four-hour-per-day utilization of the antenna needed for SPACETRACK satellite-tracking operations. To this day, seeing the antenna operating at its full 2°/sec^2 acceleration and 10°/sec velocity is impressive.

Transmitter powers of 10 MW peak and 120 kW average at VHF and 20 MW peak and 120 kW average at UHF were specified and demonstrated. Originally, three different transmit pulse lengths were pro-

FIGURE 14. The ARPA Long Range Tracking and Instrumentation Radar (ALTAIR) on the island of Roi-Namur, Kwajalein Atoll, Marshall Islands.

vided at each wavelength to furnish pulse-repetition rates as high as 3 kHz. The bandwidth of all three waveforms was the same, providing range resolution of thirty meters at VHF and fifteen meters at UHF. Control of the system was performed by a Honeywell DDP-224 computer that had only sixteen kilobytes of core memory!

The study to determine the radar specifications was completed in early 1965. The competitive contract to build ALTAIR was awarded to Sylvania. Installation and checkout of the system occurred in the late 1960s and it became operational in May 1970. In order to obtain some VHF data at an earlier date, researchers modified the TRADEX radar to add a 60-MHz radar and then a 149-MHz capability, which was dubbed "SMALLTAIR."

The ALTAIR contract, like that for AMRAD, did not include a signature-data-recording capability. The ALTAIR recording system was built by Lincoln Laboratory and interfaced to the radar at its IF output. With its relatively broad beamwidth of 3° at VHF, ALTAIR illuminates an entire ICBM complex from a few degrees below the horizon until well into reentry. The recording system provided the ability to range-track and collect extensive signature data on up to fourteen targets at each frequency. Because the data rate was far too great for computer tape drives of the time, multiple fourteen-channel instrumentation recorders were used for data recording. After a mission, the tapes were laboriously played back with an 8:1 slowdown to transcribe the data to computer tapes for further processing. By the late 1960s, when the system was designed, sidelobes of more than 30 dB down were readily achievable for the 17.6-MHz-bandwidth waveforms with analog pulse-compression equipment, and reliable 7-bit 10-MHz analog-to-digital converters were available. Control, tracking, and auxiliary data recording were performed by a pair of DDP 224 computers.

SIMPAR

The large UHF search radar of the SAFEGUARD system, the Perimeter Acquisition Radar (PAR) was not installed or tested at Kwajalein. The PAR software contained a large body of target acquisition, tracking, and impact-prediction software that could not be tested against realistic targets at the radar's North Dakota location. The Simulation of PAR (SIMPAR) program was initiated to test the software. The ALTAIR UHF system was modified to produce PAR-like data, and the PAR real-time program was run on a Control Data Corporation CDC 6600 computer installed at Kwajalein.

The ALTAIR modifications installed in 1973 were extensive. A new Cassegrainian feed, microwave system, receivers, and pulse-compression channels were added to provide angle tracking at UHF. A frequency-selective subreflector, twenty-two feet in diameter, was developed and installed at the focal point to allow the system to angle-track at either UHF or VHF. The "coarse or fine" angle-tracking capability thus provided is unique and has been important for many of the missions ALTAIR has been asked to perform over the years. Figure 15 shows the ALTAIR feed.

FIGURE 15. The VHF and UHF feeds of the ALTAIR radar. The white "teacup" (notice its size relative to that of the man standing below it) is the cover of the conventional five-horn focal-point feed of the VHF system. The "saucer" is the dichroic secondary reflector of the UHF Cassegrainian system with a multimode horn at the vertex. The reflector is composed of two layers of crossed dipoles that are resonant at UHF, making it an excellent reflector at UHF and almost transparent at VHF. The system angle-tracks at both frequencies, and either frequency can drive the antenna-servo system. (A similar frequency-selective subreflector was installed on the Millstone Hill radar; see the article by Stone and Banner in this issue.)

The PAR waveforms proved difficult to simulate. To operate at PAR pulse-repetition rates, the relatively low-duty-cycle ALTAIR transmitter could transmit only a 40-μsec expanded pulse. With the required chirp bandwidths of only 115 kHz and 690 kHz, the time-bandwidth product of the pulses was too low to be compressed efficiently by the analog techniques of the early 1970s. A digital tapped-delay-line pulse-compression system was designed and built at Lincoln Laboratory to solve this problem. This system provided excellent sidelobe performance. The system operated well, and the PAR software produced good results. The modifications installed were invaluable for the next ALTAIR modification.

SPACETRACK Modifications

In 1977, U.S. Space Command began to consider a network of radars in the Pacific Ocean to detect and track new Russian and Chinese satellite launches on their initial revolutions. Lincoln Laboratory proposed that ALTAIR, with its large power-aperture product, could do an excellent job. U.S. Space Command, however, was unsure of both the surveillance scan that was proposed and the reliability of the system with the heavy usage expected. A trial period was arranged, and with heroic effort and good use of the SIMPAR software and hardware, ALTAIR began operations by November 1977 with its unique 75° bow-tie scan. During the three-month test period, ALTAIR tracked 6121 objects out of 6396 assigned, and was far more successful at detecting and tracking newly launched objects than the Air Force thought possible.

Because of these excellent results, ALTAIR was modified to provide support to U.S. Space Command for both deep-space tracking and the detection of new foreign launches. New computers, waveforms, and signal processing techniques were required as part of these modifications. Details on the modifications and ALTAIR's continuing role as a space-surveillance sensor are found in the previously mentioned article by Stone and Banner in this issue.

ALTAIR continues to be the most heavily utilized radar at the Kwajalein Missile Range. During the 128 hours per week that ALTAIR works for U.S. Space Command it performs more than 35,000 deep-space tracks per year and 2500 high-priority near-earth tracks. For ICBM and interceptor missions ALTAIR is Kwajalein's primary long-range search and acquisition sensor. Its broad beam and high sensitivity allow it to detect all the targets in a target complex, and its long wavelength facilitates the identification of the significant objects in the complex.

ALCOR

In the late 1960s Lincoln Laboratory analysts became interested in wideband radar waveforms for ballistic missile discrimination. The rationale for this interest is explained in more detail in the article entitled "Wideband Radar for Ballistic Missile Defense and Range-Doppler Imaging of Satellites," by William W. Camp et al., in this issue. In short, wide-bandwidth radars provide a means of measuring the length of warheads and decoys. With short pulses on a static range, length was easily measured, but the effects of the reentry plasma sheath on the measurement capability were difficult to predict. In addition, the generation and processing of wideband waveforms with sufficient energy to make a practical BMD radar was a challenging task. In response to a Lincoln Laboratory proposal in mid-1965, ARPA authorized the Laboratory to build the ARPA Lincoln C-band Observables Radar (ALCOR). Acting as the prime contractor, Lincoln Laboratory built the radar with assistance from RCA, Westinghouse, Hughes, Honeywell, and numerous smaller contractors. ALCOR became operational in January 1970. Figure 16 shows the antenna and radome during installation of ALCOR on Roi-Namur.

The original waveforms were 10-μsec chirped pulses of 6 MHz and 512-MHz bandwidth operating at a peak power of 4 MW. The key to processing the 500-MHz waveforms was stretch processing or time-bandwidth exchange. The stretch-processing technique and additional details about ALCOR's wideband performance are discussed in the previously mentioned article on wideband radar by Camp et al. in this issue. An unusual feature of ALCOR, which reduced the system cost and insured the match between all receiver channels, was to multiplex all the signals with delay lines and pass them sequentially through a single set of signal processing hardware. Many of the components, including tapped-delay-


FIGURE 16. The ARPA Lincoln C-band Observables Radar (ALCOR) antenna and radome during installation on Roi-Namur. At C-band frequencies the forty-foot antenna provides a beamwidth of one-third of a degree, which is excellent for sensitivity and angular accuracy but difficult to point accurately.

line compression networks, analog-to-digital converters, and the control computer, were the same as those used on ALTAIR.

With its beamwidth of only one-third of a degree and limited range window, ALCOR needed very accurate pointing information to acquire targets. ALTAIR and TRADEX were excellent sources of such information. The role of the PRESS Control Center and its IBM 7094 computer was expanded to accommodate the new radars. Files from all three radars as well as external sources were stored, smoothed, extrapolated, and redistributed to the radars as needed to provide designation. Another ALCOR first was the use of surface-acoustic-wave devices built by the Laboratory to provide all-range compression of the 500-MHz pulses. (See the article entitled “Radar Signal Processing,” by Robert J. Purdy et al., in this issue.) Surface-acoustic-wave technology found wide application for analog pulse compression and was later used at TRADEX and ALTAIR.

ALCOR was the nation’s first high-power, long-range wideband radar. It played a pivotal role in introducing the BMD community to the discrimination potential of wideband systems. As a consequence, wideband capability is a key feature in today’s BMD systems. ALCOR’s impact on space-object identification has been equally profound. Early experiments with ALCOR led to the nation’s impressive capabilities to create high-resolution images of satellites at great distances.

The Formation of KREMS

In the late 1960s, as offensive-weapon testing increased at the Kwajalein Missile Range, the Director of Defense Research and Engineering, John Foster, insisted that the sensors at Kwajalein, including ARPA’s PRESS, be treated as a national facility. He directed that the PRESS complex be transferred to the U.S. Army, and that the sensors be kept abreast of, or lead, advances in state-of-the-art radar technology. The Army submitted a support plan that included the required assurances. In 1969 TRADEX and the PRESS complex were transferred to the U.S. Army; ALTAIR and ALCOR followed as soon as they were declared operational. In a formal ceremony at the Pentagon, the Kwajalein radar complex was renamed the Kiernan Reentry Measurement Site (KREMS) in honor of Lt. Col. Joseph M. Kiernan, U.S. Army, a visionary ARPA PRESS program manager who died in action in Vietnam. Kiernan managed the program from 1963 until 1966 and led the studies that resulted in ALTAIR and ALCOR.

Real-Time Experiments

Using recorded data, analysts had shown that ballistic missile discrimination during reentry was possible, but there was concern in the BMD community about the practicability of the solutions being proposed. Could the job be done without human intervention, and were the computers powerful enough to perform discrimination in real time? To answer these questions, Lincoln Laboratory proposed the Reentry Designation and Discrimination (REDD) system. Using a CDC 6600 computer, the Laboratory developed real-time discrimination algorithms, incorporated them into a complete discrimination logic (schema), and tested them on preprocessed recorded data. The schema was then installed in a second system at Roi-

Namur for true real-time tests on ICBM targets. The second system included a CDC 6600 and special-purpose hardware that tapped into the data from TRADEX and ALTAIR and performed the preprocessing that had been done in software at Lexington. The REDD system was used in many ICBM tests at Kwajalein with good success, and it alleviated many of the concerns about real-time discrimination.

Control Center Development

The initial goal of the PRESS Control Center was to assist the narrowbeam optical sensors and the ALCOR radar in acquiring targets by providing directing data based on stored target trajectories and satellite ephemerides, up-range track data, and smoothed and extrapolated track data from TRADEX and ALTAIR. In operation, it quickly became apparent that there were other important advantages in operating an integrated system. With data from all the sensors, non-nominal target deployments and sensor problems and mistakes were more apparent to the PRESS Control Center operators than they had been to the sensor operators. PRESS Control Center personnel were able to direct corrective action that saved valuable data on the one-of-a-kind missions typically performed at Kwajalein.

Working together and using each other's tracks for designation, ALTAIR and TRADEX could step through the target complex and identify the important objects far more rapidly than when they tried to perform the job independently. ALCOR beacon tracks that provided positive identification of a few objects in a target complex proved valuable in understanding the deployment of the whole complex. A mission goal of determining how UHF chaff deployed around the dispensing vehicle was easily met by beacon-tracking the dispenser with ALCOR and slaving ALTAIR's recording window to the ALCOR track. When a millimeter-wave radar was added to the system at a later date, its ability to provide real-time images became an important tool to help in understanding the target-complex deployment.

When the site was named KREMS, the PRESS Control Center was renamed the KREMS Control Center (KCC). As the KCC role grew, the IBM 7094 was replaced first with the CDC 6600 and then with multiprocessor Digital Equipment Corporation Alpha computers. Changes included the application of detailed sensor-bias models and logic to determine the best source of directing data for each object in the complex. Metric data to and from the sensors and status and cross-section data from the sensors to the KCC were passed via an Ethernet network connection at an update rate of 20 Hz.

As the power of computer-generated graphics increased, a number of site-wide displays were also designed and the KCC provided the data to update the displays at the sensors via a second Ethernet network connection.

In 1990 the U.S. Army requested that Lincoln Laboratory assist them in integrating activities at the Kwajalein Missile Range by designing a control center for both KREMS and the other sensors and systems of the Range. The Kwajalein Mission Control Center (KMCC) was the result. It is located on the main island of Kwajalein and provides the capability to monitor the status of the mission, weather, and all Kwajalein sensors, and to control all the radars, optical systems, and telemetry assets of the Kwajalein Missile Range.

Millimeter-Wave Radar

Discussions between Lincoln Laboratory and the Army's Ballistic Missile Defense Advanced Technology Center (BMDATC) in 1977 led to a decision to build a dual-frequency millimeter-wave radar operating at 35 GHz and 95.5 GHz with 1000-MHz bandwidth waveforms. Lincoln Laboratory was the prime contractor for the development of this radar. The radar had a variety of goals and offered many challenges. BMDATC was interested in using millimeter-wave seekers in interceptors and wanted to develop components for operation at the short wavelengths in addition to collecting a signature database on ballistic missiles. BMDATC and SOI (Space Object Identification) personnel were also interested in the discrimination and imaging possibilities of the short wavelength and 0.25-m range resolution.

A major challenge in the development of millimeter-wave radar was the generation and transmission of microwave power. The selected peak powers of 30 kW and 6 kW at the two frequencies resulted in extremely high power densities in the very small waveguide and RF structures used at these frequencies. Varian, the transmitter-tube developer, went through many iterations of geometry, materials, and processing before producing guns and focusing structures that could provide the current density needed. Particularly at 95 GHz, the high loss of RF power per unit length of the waveguide presented problems. Combining the output of two tubes proved impractical because the loss of the combining network almost equaled the benefit of the second tube. Even with the transmitters and receivers mounted on the antenna as close to the feed as possible, the RF losses were high.

A second challenge was the design of the antenna. With the limited power of the system, a large 13.7-m antenna was required to achieve the required sensitivity. The antenna was designed to be an extremely rigid structure, and great attention was placed on maintaining it at a uniform temperature, in order to achieve adequate surface tolerances on such a large dish. The antenna beamwidths (0.042° and 0.014°) are very small compared to the ALCOR beam, which had proven difficult to point. With the advances in trajectory-extrapolation algorithms and calibration that have taken place, the millimeter-wave (MMW) radar acquires targets very reliably and achieves angle accuracy typical of a good optical telescope, approximately 40 μrad. Figure 17 is a photograph of the MMW radar antenna, taken as the radome was being installed.

As expected, the MMW radar has become the premier imaging radar of the Kwajalein Missile Range and is heavily used by the SOI community. Its short wavelength effectively increases the number of scatterers visible on objects being observed and contributes to the superb detail of the images. Its ability to measure miss distance or impact point on intercepts is increasingly important to the BMD users. Additional details on the MMW radar and its uses appear in the previously mentioned article on wideband radars by Camp et al. in this issue.

Evolution of KREMS

Ballistic missile defense has always been a rapidly changing process, driven by changing threats, missions, and technological opportunities for improved capability. In accordance with ARPA's and John Foster's vision, the four KREMS radars have undergone a continuous process of modification and upgrade since they were constructed. The site manning has traditionally included a cadre of radar-system design engineers to support the effort to stay at the forefront of technology.

FIGURE 17. Construction of the MMW (millimeter-wave) radar and radome on Roi-Namur, Marshall Islands. The heavy structure of the dish is needed to achieve the surface tolerance required for the short wavelengths of the radar.

All of the KREMS radars have had their computers, recording, and display systems upgraded several times and added coherent integration capability to assist in acquiring targets at longer ranges.

At TRADEX, long continuous-wave and pseudorandom phase-modulated noise waveforms were added at S-band to emulate Soviet BMD radars. A narrowband 565-μsec pulse was added at L-band for long-range acquisition and deep-space tracking. A 50-μsec, 20-MHz chirp waveform provides improved range resolution for complex multitarget missions, and a multitarget tracker provides noncoherent integration, target detection, acquisition, and target identification aids on up to sixty-four targets. Most re-

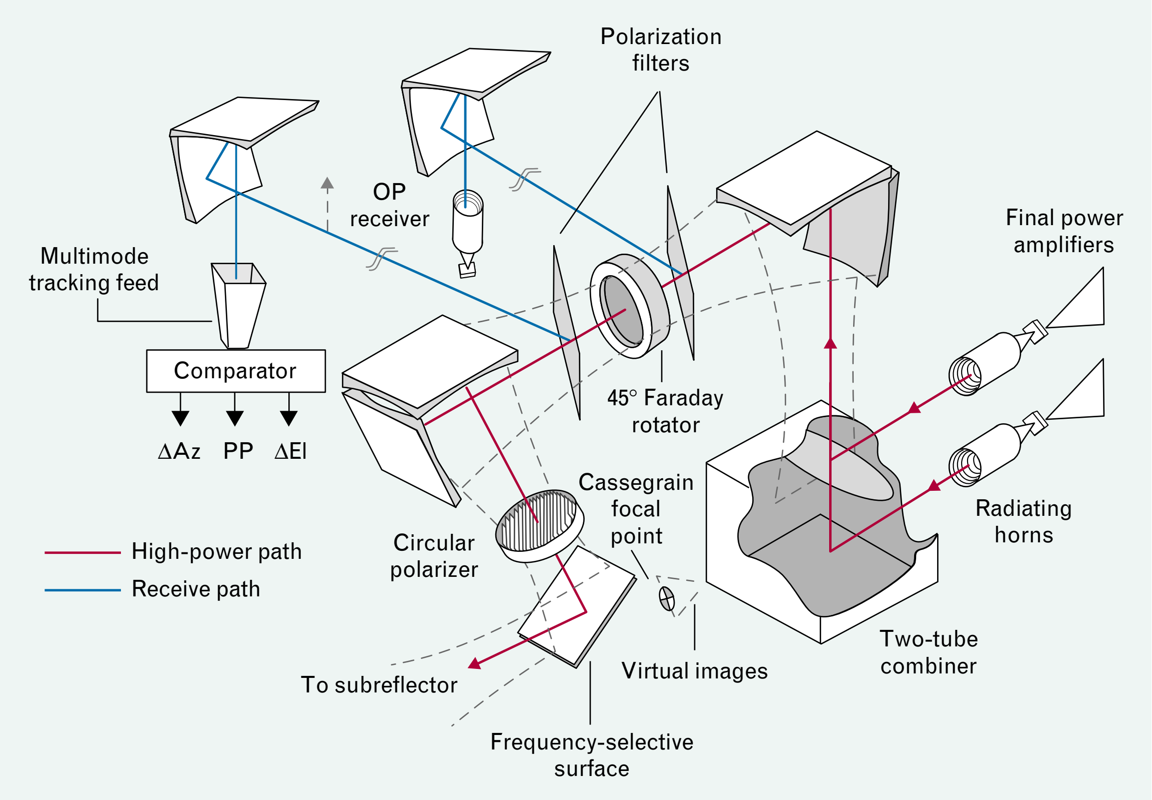

FIGURE 18. Configuration of the 35-GHz beam-waveguide system.

cently, a new frequency-jumped burst that simulates a waveform being considered for the U.S. Navy Aegis system has been added.

In addition to the SIMPAR and SPACETRACK modifications, ALTAIR has seen many other major changes. The UHF transmitter replacement, necessitated by the vendor's inability to make replacements for the 20-MW, 115-kW klystron, proved so beneficial that when the second ARIS traveling-wave-tube (TWT) transmitter became available, ALTAIR acquired it to augment the transmitter with an additional eight TWTs to reach an average power of 330 kW. For deep-space tracking doubling the average power halves the coherent integration time required and thus doubles the number of targets the radar can track in an interval of time. The TWT transmitter is more efficient than the old klystron transmitter. With around-the-clock operations, the savings on the power bill are impressive.

To fully utilize the capability of the transmitter, which has a peak power rating of only 6.5 MW, ALTAIR needed a number of new, longer UHF pulses. A very large finite-impulse-response (FIR) digital signal processor was implemented to generate and compress the new waveforms and replace all the existing pulse-compression hardware and software. The 3000-tap-per-channel FIR filter required a "world-record" gate-array chip to be designed. With the new design, eight racks of equipment—one per receiver channel—replaced twenty-four racks of analog hardware.

The most recent ALTAIR modification provides the capability to change the VHF transmit polarization in real time so that the full scattering matrix of a target can be explored. The modification also provides polarization and other waveform changes on a pulse-by-pulse basis.

At ALCOR, beacon tracking, pulse pairs, and multiple range windows were added in the 1970s. With the additional computer power available in the 1990s, ALCOR has doubled its PRF and added a second independent range tracker.

By the late 1980s, radar signal processing technology had advanced enough to permit significant performance improvement of the MMW radar. Improved computers and digital signal processing equipment allowed full PRF real-time compression of the wideband pulses and coherent integration to provide significant improvement in sensitivity. Continuing development of coupled-cavity TWTs allowed Varian to produce 35-GHz transmitter tubes with 50-kW peak power and 2-GHz bandwidth.

The application of new quasi-optical techniques provided an outstanding improvement in the microwave system [9]. By moving the radiating horn close to the tube and then directing and refocusing the beam with a series of mirrors, Laboratory researchers designed and implemented a beam-waveguide system with excellent properties. Microwave losses were reduced by more than 3 dB, and the power-handling capability was greatly increased. Better antenna illumination with lower sidelobes, deeper monopulse nulls, better polarization isolation, and bandwidth well over 2 GHz were all achieved. With transmitter and microwave systems capable of 2-GHz bandwidth, the rest of the system is now being modified to provide 2-GHz waveforms and a second independent range window, which will provide more precise measurements of interceptor hit point or miss distance.

FIGURE 19. The scalar, or ridged, horns used for the 95-GHz radar. This small horn launches an almost perfect Gaussian beam that, with a properly designed optical system, provides excellent illumination of the 13.7-m primary reflector. The system provides higher power capability, broader bandwidth, lower losses, and better antenna patterns than a conventional waveguide system could at shorter wavelengths.

Figure 18 illustrates the configuration of the 35-GHz beam-waveguide system. Figure 19 is a photograph of the 95-GHz scalar or ridged horn feeds. These very small horns launch an almost perfect Gaussian beam. After refocusing with the mirrors of the beam-waveguide system, excellent illumination of the 13.7-m MMW radar antenna is achieved. The contrast in the size of these feeds and those of ALTAIR is a reminder of the very broad spectral band that is covered by the KREMS radars.

The Future

While new technology has been applied at KREMS to improve capability and replace unsupportable obsolete equipment, it has not been used specifically to reduce operating costs. The present systems are complex and require substantial numbers of highly skilled personnel to operate and maintain them. Supporting those personnel and their families at a remote island is too costly in a time of shrinking defense budgets. A major effort is under way to deal with this challenge. The systems are being modernized, remoted, and automated to reduce their operations and maintenance costs. Replacement of special-purpose processors and one-of-a-kind electronics with powerful general-purpose computers and commercial off-the-shelf digital hardware will simplify the systems. Coupled with built-in diagnostics to detect and isolate faults to the circuit-board level, the capabilities of the new technology will greatly reduce the required number and skill level of maintenance personnel. Enforcing a common design for all the radars will facilitate maintenance by a matrixed operations and maintenance organization, and reduce the implementation costs as well. Remoting the operations and diagnostics from Roi-Namur to the main island of Kwajalein will reduce intra-atoll transportation costs and further facilitate the matrixed support organization. Remoting software development to the continental United States will allow additional reductions in island personnel. Finally, the systems will be more tightly integrated and automated to reduce the demands on operators and increase the capability to handle the complex multiple-target-multiple-interceptor missions expected in the 21st century. The overall goal of this modernization program is to make the Kwajalein Missile Range sensors operate as a single multibeam, multispectral sensor with operating costs reduced by as much as 50%.

Summary

Lincoln Laboratory entered the field of ballistic missile defense in the mid-1950s at the inception of the ICBM. In the ensuing forty years, Laboratory engineers and scientists, aided by an active and innovative program in the development of radar systems and measurement techniques, have led the nation in the field of ballistic missile discrimination. The discrimination techniques and radar advances developed by Lincoln Laboratory undergird the missile-defense systems being developed today. The four radars of the KREMS complex, which have contributed most heavily to our understanding of the field, continue to play a vital role. With the modifications now being introduced, they will continue to do so well into the twenty-first century.

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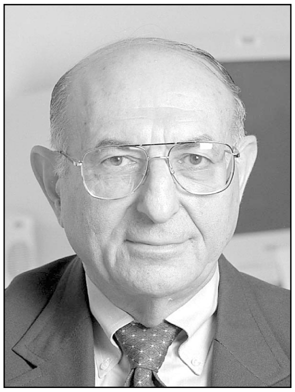

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