Wideband Radar for Ballistic Missile Defense and Range-Doppler Imaging of Satellites

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Lincoln Laboratory led the nation in the development of high-power wideband radar with a unique capability for resolving target scattering centers and producing three-dimensional images of individual targets. The Laboratory fielded the first wideband radar, called ALCOR, in 1970 at Kwajalein Atoll. Since 1970 the Laboratory has developed and fielded several other wideband radars for use in ballistic-missile-defense research and space-object identification. In parallel with these radar systems, the Laboratory has developed high-capacity, high-speed signal and data processing techniques and algorithms that permit generation of target images and derivation of other target features in near real time. It has also pioneered new ways to realize improved resolution and scatterer-feature identification in wideband radars by the development and application of advanced signal processing techniques. Through the analysis of dynamic target images and other wideband observables, we can acquire knowledge of target form, structure, materials, motion, mass distribution, identifying features, and function. Such capability is of great benefit in ballistic missile decoy discrimination and in space-object identification.

The impetus at Lincoln Laboratory for the development of wideband radar systems was rooted in the success of high-power instrumentation radars for research in ballistic missile defense (BMD) and satellite surveillance. In 1962 the Target Resolution and Discrimination Experiment (TRADEX) radar, which was modeled in part after the Millstone Hill radar in Westford, Massachusetts, and built by RCA, became operational at Kwajalein Atoll in the Marshall Islands. This UHF and L-band radar was the primary sensor for the Advance Research Projects Agency (ARPA)–sponsored Pacific Range Electromagnetic Signature Studies (PRESS) project, which Lincoln Laboratory managed for the U.S. Army in support of its BMD program [1].

Project PRESS emphasized the use of radar and optical sensors for the observation, tracking, measurement, and characterization of a full-scale intercontinental ballistic missile (ICBM) targets. A major effort of BMD research at Lincoln Laboratory was the development of techniques to discriminate warheads from penetration aids, or *penaids*. These penaids, which accompany warheads in a ballistic missile reentry complex, are devices designed to confuse, blind, overwhelm, or otherwise prevent defense systems from identifying and destroying the warheads. The Laboratory worked both on the development of penaids for U.S. missile systems and on techniques for real-time discrimination of potential enemy penaids that could be used against U.S. defense systems. A major penetration aid at that time was the decoy, a device that looked to the radar like a real warhead.

Decoys could be quite sophisticated and complex, but they all conformed to the basic requirement of being light in weight compared to the weight of a warhead. Thus the fundamental approach to warhead identification was to discriminate between warheads and penaids on the basis of motion, size, and shape differences caused by these weight constraints. In the early days these decoys were designed to mimic the dynamics and sensor signatures of warheads, and they would challenge a defense radar's ability to discriminate between similar targets in reentry. A second approach to warhead discrimination involved traffic decoys, which consisted of a large number of smaller objects designed to overwhelm and confuse a BMD system. To defeat traffic decoys, the radar needed to dismiss a large number of less credible objects quickly. Wideband radar operation helped with both of these discrimination tasks [2].

By the mid-1960s the TRADEX radar had proven invaluable as a sensor capable of highly accurate tracking of ballistic missile components from horizon break through midcourse and reentry. It could also identify characteristic signatures of such components through processing of radar returns from reentry bodies and their accompanying ionized wakes. During this same era many other field radars and laboratory research facilities were gathering volumes of data on real and simulated ballistic missile components and reentry wakes. As these data were analyzed, it became clear that low-range-resolution radar systems operating at the then-available frequencies were inadequate to unambiguously identify target signatures suitable for discrimination in a BMD environment.

In particular, effective discrimination against strategic threats requires a means of dealing with potentially large numbers of small decoys and penaids at high altitudes well beyond the level where atmospheric deceleration becomes a discriminator between heavy and lightweight objects. This need was especially acute in the 1960s, when BMD emphasis was on wide-area defense of cities. It was recognized that discrimination radars with wide bandwidth and the corresponding fine range resolution would be able to measure the lengths of objects, and quickly identify and eliminate radar targets substantially smaller than warheads from consideration as threats. Furthermore, the high operating frequencies required for wide-bandwidth radars would be of added benefit over those available in Nike Zeus and TRADEX (both at L-band). Bandwidths that are 10% of the radar's carrier frequency are reasonably straightforward to implement (e.g., 500 MHz at C-band or 1000 MHz at X-band). At the higher frequencies required for wide-bandwidth sensing, there is greater potential to characterize the radar target's physical features, thus providing another level of capability for discovering attempts to disguise a target's true nature. In addition, higher operating frequencies are less vulnerable than lower frequencies to the effects of nuclear blackout.

Given these considerations, Lincoln Laboratory initiated programs in the 1960s for the development of wideband high-resolution, high-power radars operating at high microwave frequencies. The first radar to be deployed was the ARPA-Lincoln C-band Observables Radar, or ALCOR. It was designed as an instrumentation radar to support research in BMD wideband discrimination techniques, and it achieved operational status in 1970 at Kwajalein Atoll [3].

Another major thrust at Lincoln Laboratory in the late 1950s and 1960s—an effort that eventually led to specialized wideband radar systems—was in the area of satellite surveillance. During this era the space-defense establishment and NASA grew concerned about the plethora of satellites and debris orbiting the earth. Lincoln Laboratory and others recognized that radar sensors beyond the capabilities of existing systems would be needed for space-object identification. The use of wideband techniques could allow specific scattering centers to be identified. These techniques, coupled with the development of high pulse-repetition-frequency coherent waveforms, would make the generation of detailed radar images of orbiting space objects possible.

The truth of this claim became abundantly clear shortly after ALCOR came on line. The space-surveillance community had arranged to enlist ALCOR in tracking satellites on a noninterference basis. Then in 1970 China launched its first satellite, which was observed by ALCOR. Analysis of ALCOR images of the booster rocket body revealed the dimensions of this object. This information was of great interest to the Department of Defense because it gave insight into the size and payload capacity of the forthcoming Chinese ICBMs. This observation, which was a historic first for the defense establishment, resulted in satellite imaging missions becoming an integral part of ALCOR operations.

More recently, the use of wideband phased-array radars has greatly facilitated the transition of BMD weapons systems from nuclear to non-nuclear, hit-to-kill interception techniques. These radars use modern solid state microwave technology and high-capacity high-speed computers and signal processors, all of which permit near-real-time imaging and discrimination processing on a large number of targets.

Wideband Observables

The distinguishing characteristic of a wideband radar is its fine range resolution, which is inversely proportional to the operating bandwidth. Such a radar system has a range resolution that is a fraction of the linear dimensions of its intended targets. These radars generally operate at high frequencies, where wide-bandwidth waveforms are easier to implement. With range resolution fine enough to encompass a target in a significant number of resolution cells, it becomes possible to distinguish individual scattering centers, which occur at regions of physical discontinuity. A ballistic missile warhead, for example, exhibits radar reflections from the nose, body joints, and base, as well as other points of discontinuity such as antenna ports. To observe radar reflections from smaller discontinuities, the radar must be able to operate at short wavelengths, since discontinuities much smaller than a wavelength will in general produce low-intensity reflected signals from the target. In addition, a short wavelength is desirable for observing curved surfaces, because when the wavelength is short compared to the radius of curvature, the radar reflection is dominated by specular reflection, thus allowing a finer determination of the size and shape of corresponding surfaces.

For an object that reenters the atmosphere and generates an ionized wake, fine range resolution allows examination of the wake in thin slices, which results in the separation of reflections from different atmospheric phenomena around the hard body, such as the plasma layer at the nose or leading surface, the plasma sheath around the body, the boundary layers, the shock fronts, and the development of turbulent regions at the rear of the body. Such observations are of great value in deriving information about a target's physical parameters, structural and heat-shield materials, and the function of reentering objects, all of which aid the discrimination process of distinguishing warheads from decoys.

In the above scenario, the radar produces a one-dimensional range profile of the target. However, if the target is rotating about an axis that has a component perpendicular to the radar line of sight, such that some scattering centers are moving toward the radar with respect to others that are moving away from it, we can construct a one-dimensional cross-range profile for each range cell through Doppler processing of the radar returns. The range and cross-range profiles can then be combined to produce a two-dimensional range-Doppler image of the complete body. We can analyze this image to yield body size, body shape, the position and nature of scattering centers, the presence of internal reflections, the rotation rates, and the rotation axes for the object. In addition, these images can provide valuable information on the nature of the materials used in constructing the body, and information about antennas, apertures, and interior structures of such an object.

Three-dimensional images can be generated from the two-dimensional images by using a technique called extended coherent processing. With this technique a series of range-Doppler images are collected over a time period when the target presents different look angles to the radar. The series of range-Doppler images is then coherently processed and referenced to a particular look angle. The resulting three-dimensional images produce even greater detail of target features than the two-dimensional range-Doppler images. The image of the damaged *Skylab* orbiting laboratory shown in Figure 1 is an example of this kind of processing.

More recent advances in signal processing hardware and computational speed have led to the generation and measurement of wideband observables in real time. These observables, which can be used for real-time BMD discrimination, include determination of body length, feature identification, and radar images. Doppler processing and coherent phase-derived range techniques permit real-time indications of

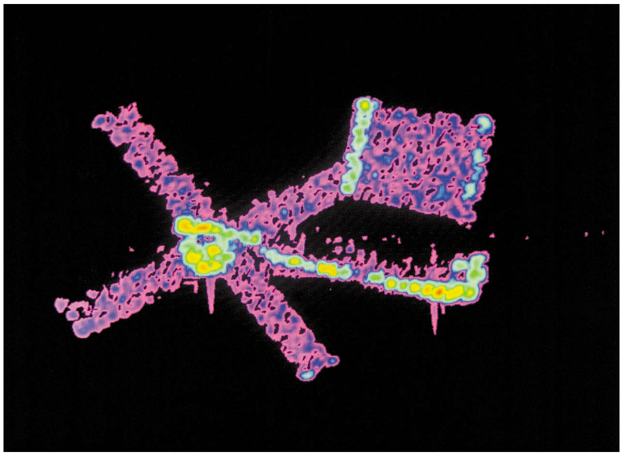


FIGURE 1. Simulated radar image (actual radar images of satellites remain classified) of the NASA *Skylab* orbiting laboratory, with a damaged solar panel on one side and a partially deployed solar panel on the other.

macro- and micro-dynamic body motion, which may offer clues to mass and mass distribution. Advances in wideband phased-array radar design now make it possible to exploit wideband observables on multiple objects in a missile complex.

ALCOR

The initial wideband radar research at Lincoln Laboratory was embodied in a program called Wideband Observables. Initial objectives of this program were to verify the nature of wideband returns from realistic targets and investigate technology challenges that might arise in developing full-scale wideband radar systems. To this end the Laboratory constructed a ground-based static radar range that included a small wideband radar and facilities for mounting and rotating real, replica, and simulated targets. The promising results of this program and the pressing need for a fine range-resolution instrumentation radar at Kwajalein led to the decision to develop the ARPA-Lincoln C-band Observables Radar, or ALCOR.

ALCOR, shown in Figure 2, was the first high-power, long-range, wideband field radar system. Lincoln Laboratory was the prime contractor for ALCOR; a variety of industrial firms provided major subsystems and hardware (such as Hughes, Westinghouse, Honeywell, and RCA). It became operational at Kwajalein Atoll in 1970, and was probably the first wideband radar in the world to reach that status, although research in this field was under way elsewhere during the 1960s, most notably at Rome Air Development Center. ALCOR was designed to have as large a bandwidth, sensitivity, range coverage, and tracking agility as contemporary technology would reasonably allow, to support its role in BMD research. It was located next to the TRADEX radar on Roi-Namur Island in the Kwajalein Atoll. Figure 2(a) shows the sixty-eight-foot-diameter ALCOR radome, and Figure 2(b) shows the forty-foot ALCOR antenna and its pedestal inside the radome.

ALCOR operates at C-band (5672 MHz) with a signal bandwidth of 512 MHz that yields a range resolution of 0.5 m. (The ALCOR signal was heavily weighted to produce low range sidelobes with the concurrent broadening of the resolution.) Its wide-bandwidth waveform is a 10-μsec pulse linearly swept over the 512-MHz frequency range. High signal-to-noise ratio of 23 dB per pulse on a one-square-meter target at a range of a thousand kilometers is achieved with a high-power transmitter (3 MW peak and 6 kW average) and a forty-foot-diameter antenna. Cross-range resolution comparable to range resolution is achievable with Doppler processing for targets rotating at least 3° in the observation time. The pulse-repetition frequency of this waveform is two hundred pulses per second.

Processing 500-MHz-bandwidth signals in some conventional pulse-compression scheme was not feasible with the technology available at the time of ALCOR's inception. Consequently, it was necessary to greatly reduce signal bandwidth while preserving range resolution. This is accomplished in a time-bandwidth exchange technique (originated at the Airborne Instrument Laboratory, in Mineola, New York) called stretch processing [4], which retains range resolution but restricts range coverage to a narrow thirty-meter window. In order to acquire and track targets and designate desired targets to the thirty-meter wideband window, ALCOR has a narrowband waveform with a duration of 10.2 μsec and bandwidth of 6 MHz. This narrowband waveform has a much larger 2.5-km range data window.

The ALCOR beamwidth is 5.2 milliradians, or 0.3°. This beamwidth, together with a high-performance antenna mount, enables ALCOR to produce precision target trajectories and provide high-quality designation data to the other Kwajalein radars. This very narrow beam also caused some real challenges in target search and acquisition. Searching with a 5.2-milliradians beam is akin to looking through a two-hundred-foot-long pipe that is only one foot in diameter. Fortunately, ALCOR was located next to TRADEX and ALTAIR, which are much bigger radars with great search capability.

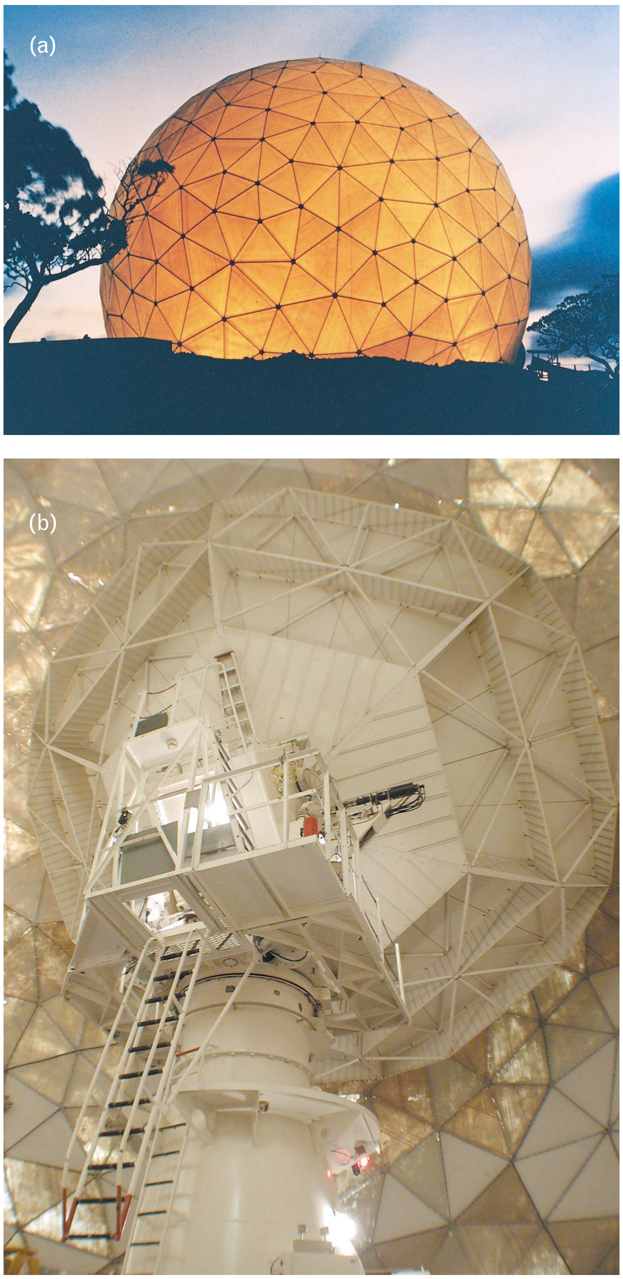


FIGURE 2. (a) The sixty-eight-foot-diameter ALCOR radome and (b) the forty-foot-diameter ALCOR antenna and its pedestal. ALCOR, which became operational at Kwajalein Atoll in 1970, was the first high-power, long-range, wideband field radar.

The more difficult technical challenges included construction of the analog 10-μsec, 512-MHz-bandwidth linear-FM-ramp generator. It required a high degree of timing stability, phase coherence, and frequency linearity to control range sidelobes to a level of at least 35 dB below the peak response. The timing generator for controlling ramp triggering likewise required a high degree of precision and stability to limit target tracking jitter to a small fraction of a range-resolution cell.

Also, phase distortion in the transmitter and microwave systems is held to a low level through careful design and matching of components, in order to realize low range sidelobes. Residual distortion is compensated by transversal equalizers in the wideband receiver channels. Another feature that is part of the ALCOR radar design and unique to wideband systems is compensation for waveguide dispersion.

ALCOR is one of the earliest radars to incorporate computers running real-time programs as an integral part of radar operations. Major radar control and timing functions are under computer control, and the range and angle-tracking loops are closed through the computer. In recent years advances in signal processing technology applied to ALCOR have made it possible to generate wideband images of multiple targets in multiple range windows in near real time. [3, 5]

TRADEX S-Band

In 1972 the TRADEX UHF radar was replaced by an S-band system (built by RCA under the direction of Lincoln Laboratory) while retaining its L-band capability. Although TRADEX S-band was the second wideband radar system to be brought on line by Lincoln Laboratory, the approach taken to achieve fine range resolution was substantially different from that taken in ALCOR and later wideband systems. The S-band wideband waveform grew out of research on frequency-jumped pulses conducted by the Laboratory in the 1960s. The new set of S-band waveforms includes one with a signal bandwidth of 250 MHz. This bandwidth is achieved by transmitting a string, or burst, of 3-μsec pulses; each pulse has a different center frequency such that the bandwidth spanned by the burst is 250 MHz. The spacing and number of pulses in a burst is variable and the maximum repetition rate is one hundred bursts per second. Coherent integration of a burst yields a range resolution of one meter. Processing of this frequency-jumped-burst type waveform at S-band is implemented post-mission. Wideband target profiles have been constructed post-mission and have helped demonstrate the utility of wideband observables for use as a target discriminant at S-band.

The Haystack Long-Range Imaging Radar

From its earliest days of operation ALCOR was called upon to track and image satellites, both domestic and foreign. ALCOR's historic imaging of the booster rocket body of China's first orbiting satellite in 1970 was followed by similar success in imaging the USSR's *Salyut-1* space station in 1971. The demonstration of such imaging capability led to the establishment of the Space Object Identification program at Lincoln Laboratory. One of the many successes of this program was the imaging of NASA's troubled *Skylab* orbiting laboratory shortly after its launch in 1973, as shown in Figure 1. Telemetry data from *Skylab* showed that something was wrong with the deployment of the solar panels. ALCOR images showed that one solar panel was missing and the other panel was only partially deployed, and there was no evidence of the presence of the micrometeorite shield. This information was extremely useful to NASA in determining how to recover from this mishap and successfully continue the *Skylab* mission.

As the Space Object Identification program continued, the capability to image satellites out to deep-space ranges soon became an important requirement. The limited sensitivity of ALCOR allowed the observation of satellites only out to intermediate altitudes. At the same time, researchers wanted to improve range resolution, extend range-window coverage, and achieve higher pulse-repetition frequencies in order to eliminate cross-range ambiguities in the images of rapidly rotating space objects. Concurrent advances in signal processing technology gave promise that such improvements in radar techniques could readily be accommodated. After exploring a number of options, researchers determined that a high-performance long-range radar imaging capability could be provided by a new radar system added to Haystack, the Lincoln Laboratory–built radio-astronomy, communication, and radar research facility located in Tyngsboro, Massachusetts. The development of this new radar capability for Haystack was sponsored by ARPA. After the facility was completed in 1978, operations were supported by the U.S. Air Force.

The Haystack system has a number of features that rendered this option extremely attractive. It has a large diameter (120 ft) antenna needed to achieve deep-space ranges. The antenna was designed with Cassegrainian optics and could accommodate plug-in radio-frequency (RF) boxes at the vertex of the paraboloidal dish. These boxes supported various communications, radio astronomy, and radar functions. The interchangeable boxes are $8 \times 8 \times 12$ ft, which is large enough for the high-power (400 kW peak and 200 kW average) new transmitter and associated microwave plumbing, feedhorns, and low-noise receivers needed for the long-range imaging radar.[1] The Haystack antenna surface tolerance allows efficient operation up to 50 GHz, thus readily supporting operating at X-band (10 GHz) with a bandwidth of 1024 MHz, and a resulting range resolution of 0.25 m. A system for interchanging ground-based electronics and power sources supporting the various RF boxes was already in place. Using an established facility with existing antenna and prime power sources greatly reduced the cost of the new system, known as the Long Range Imaging Radar, or LRIR [6].

The LRIR, which was completed in 1978, is capable of detecting, tracking, and imaging satellites out to synchronous-orbit altitudes, approximately 40,000 km. The range resolution of 0.25 m is matched by a cross-range resolution of 0.25 m for targets that rotate at least 3.44° during the Doppler-processing interval. The wideband waveform is 256 μsec

[1] Over the years several modifications have been made to the Haystack transmitter to make it more reliable. These have affected the radar's average power and maximum pulse width. Currently, the maximum average power of the radar is 140 kW and the maximum pulse width is 5 msec. With these values the radar continues to perform all of its required missions.

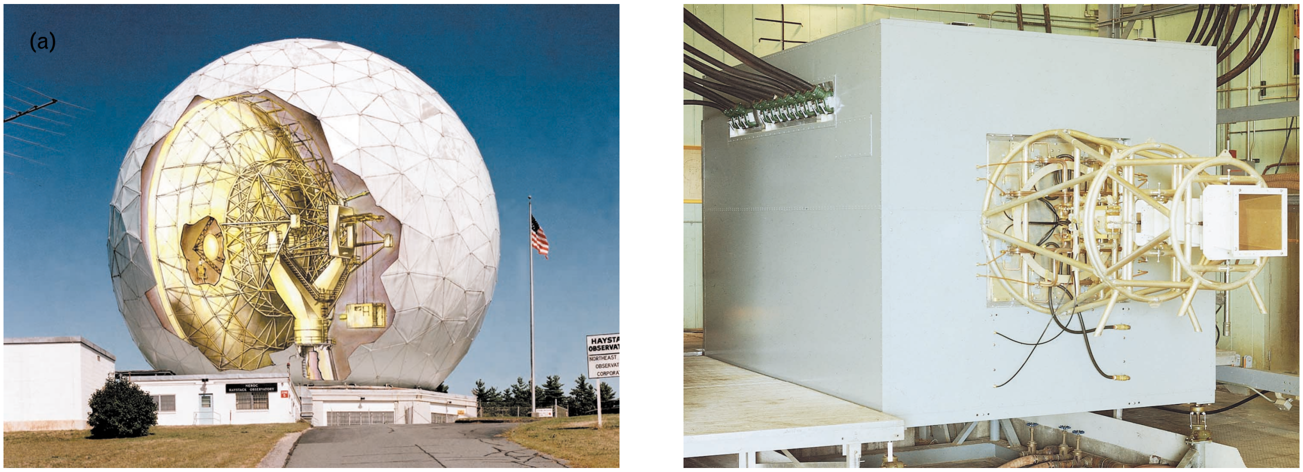


FIGURE 3. (a) Artist's rendition of the 120-foot Haystack antenna in its 150-foot radome; (b) the long-range imaging radar (LRIR) feed horn and transmitter/receiver radio-frequency (RF) box in its test dock in the Haystack radome.

long and the bandwidth of 1024 MHz is generated by linear frequency modulation. The pulse-repetition frequency is 1200 pulses per second. The LRIR employs a time-bandwidth exchange process similar to that of ALCOR to reduce signal bandwidth from 1024 MHz to a maximum of 4 MHz, corresponding to a range window of 120 m, while preserving the range resolution of 0.25 m. To place a target in the wideband window, we first acquire the target with a continuous-wave acquisition pulse that is variable in length from 256 μsec (for short-range targets) to 50 msec (for long-range targets). An acquired target is then placed in active tracking by using 10-MHz-bandwidth chirped pulses, again of variable length, from 256 μsec to 50 msec. The wideband window is then designated to the target. Antenna beamwidth is 0.05°. Figure 3(a) shows an artist's rendition of the 120-foot Haystack antenna in its 150-foot radome; Figure 3(b) shows a photograph of the LRIR feed horn and transmitter/receiver RF box in the Haystack radome.

The LRIR design and construction at Haystack required special attention to waveform distortion, phase control, phase stability, timing precision, and timing stability (as did ALCOR). With the longer wideband pulse width and advances in digital signal processor and computer technology, however, much of the signal processing and compensation has been accomplished with digital hardware under computer control.

The transmitter and microwave subsystems also presented design challenges. To achieve maximum sensitivity the transmitter used four traveling-wave tubes (TWT) operating in parallel. Each TWT high-power amplifier developed by Varian for LRIR generates 100 kW peak and 50 kW average X-band power. Combining and balancing the TWT outputs through the myriad of required microwave components while controlling phase errors was a major challenge.

The front-end receiver amplifiers developed by Airborne Instrument Laboratory are cryogenically cooled parametric amplifiers, or *paramps*. These efficient paramps are major contributors to Haystack's high radar sensitivity, achieving a system noise temperature of 35 K.

Although not a directly related part of the research and development of LRIR, the Haystack antenna and its protective radome are impressive engineering accomplishments. The Haystack 150-ft-diameter radome, at the time it was built in the early 1960s, was the largest rigid radome in the world. It was designed by the ESSCO Company of Concord, Massachusetts, to survive 130-mph winds.

The Haystack antenna was also considered an engineering feat at the time of its construction. It was the first large structure designed by computer with a finite-element representation of every strut in its structure. North American Aviation and the MIT Civil Engineering Department accomplished this significant first.

The Haystack Auxiliary Radar

When the LRIR became operational in 1978, the Haystack facility was being operated by a university consortium known as the Northeast Radio Observatory Corporation, or NEROC. The primary mission of Haystack was radio astronomy. Lincoln Laboratory contracted with NEROC to use the facility for satellite tracking and imaging for a thousand hours per year. Eventually, U.S. Space Command and NASA recognized that this arrangement for sharing Haystack was too restrictive to satisfy their needs. The restriction was especially limiting when there was an immediate need to assess new or unexpected foreign launches, or when space debris needed to be catalogued.

The Haystack Auxiliary Radar (HAX) system, shown in Figure 4, was conceived to eliminate this restriction on observation time, and simultaneously further improve range resolution and pulse-repetition frequency. HAX operates at K_u-band with its own forty-foot antenna, transmitter, RF hardware, and receiver, but it shares the LRIR control and signal and data processing systems with Haystack. HAX, which began operation in 1993, is the first radar to have a signal bandwidth of 2000 MHz, which improves the range resolution to 0.12 m. HAX represents a significant advance in radar imaging capability, producing finer and sharper images of satellites than the Haystack LRIR. It is also extremely useful in producing detailed information for NASA on the locations, orbits, and characteristics of space debris.

FIGURE 4. The Haystack radar site in Tyngsboro, Massachusetts. The 150-foot LRIR Haystack radome and 120-foot antenna are on the left, and the fifty-foot Haystack Auxiliary Radar (HAX) radome, forty-foot HAX antenna, and equipment building are on the right.

The Millimeter Wave Radar

The Millimeter Wave Radar, or MMW, was built at Kwajalein by Lincoln Laboratory (with significant contributions by the University of Massachusetts, RCA, and Raytheon) to extend the general imaging and tracking capabilities of ALCOR and to develop millimeter-wavelength signatures of ballistic missile components. The MMW, shown in Figure 5, became operational at K_a-band (35 GHz) in 1983, and W-band (95.48 GHz) in 1985, sharing a paraboloidal antenna with a diameter of forty-five feet. Both systems initially featured wideband waveforms of 1000-MHz spread generated by linear FM, and achieved 0.28-m range resolution. The transmitted pulse width is 50 μsec at a maximum pulse-repetition rate of 2000 pulses per second. The initial peak power at K_a-band was 60 kW and at W-band was 1.6 kW.

A major thrust in the evolution of the MMW radar has been to demonstrate the feasibility of candidate real-time discrimination algorithms required for fire control and guidance of hit-to-kill BMD interceptors. To this end, the radar was designed with a rigid mount and narrow beam to provide precise angle metric accuracy ($\leq$50 μradians). Several contractors assisted the Laboratory in the development of the MMW radar, among them researchers at the University of Massachusetts, RCA (now Lockheed Martin), and Raytheon. The combination of metric accuracy, wide bandwidth, and high Doppler-resolution capabilities makes MMW an excellent sensor for a real-time discrimination test bed. It provides extremely accurate estimates of motion differences caused by mass imbalances on real and threat-like targets and other feature-identification processing. Such a real-time test bed, called the Kwajalein Discrimination System, was implemented and exercised at MMW from 1988 through 1992. This system has demonstrated the feasibility of numerous real-time wideband discrimination algorithms. Following this successful demonstration, many of these processing

FIGURE 5. The forty-five-foot millimeter-wave (MMW) antenna and its sixty-eight-foot radome under construction on Roi-Namur Island at Kwajalein. The MMW radar was built to extend the general imaging and tracking capabilities of ALCOR and to develop millimeter-wavelength signatures of ballistic missile components.

algorithms have been subsequently implemented permanently into the MMW real-time system.

Beginning in the late 1980s, a significant effort was carried out to further enhance the capabilities of the MMW radar. Advances in computer technology reached the point where real-time pulse compression at high pulse-repetition frequencies was possible. This capability results in improved sensitivity realized from real-time coherent and noncoherent pulse integration at 35 GHz. In 1989 researchers implemented a digital pulse-compression system that compresses every pulse in real time and subsequently improves coherent processing at higher tracking rates. A state-of-the-art beam-waveguide antenna feed replaced the more lossy conventional microwave-waveguide plumbing. A second 35-GHz tube was also added, which doubled the average transmitted power. These modifications increased the signal pulse detection range on a one-square-meter target to over two thousand kilometers. System bandwidth was also increased to 2 GHz, resulting in a range resolution of about 0.10 m.

The 95-GHz MMW system is now undergoing a major upgrade. Recent advances in MMW solid state technology, combined with state-of-the-art quasioptical feed elements, have resulted in significant increases in system sensitivity. Mixer diodes capable of cryogenic operation have led to a reduction in the receiver noise figure, and a Gunn-effect diode intermediate-power amplifier has boosted transmit power by driving the final TWT into saturation. Application of beam-waveguide optics techniques to the antenna has resulted in a reduction in transmit and receive losses, while simultaneously increasing transmit and receive isolation and power-handling capability. In all, these improvements provide a sensitivity improvement of almost two orders of magnitude, yielding the higher capability for metric tracking and range-Doppler imaging on a variety of important targets. When these modifications are completed, the robust combination of 35-GHz and 95-GHz wideband capability on a single sensor will ensure MMW's place as one of the world's premier wideband-imaging systems [7, 8].

Cobra Dane and Cobra Judy

Two of the most important sensors in the evolution of wideband BMD architecture and technology are the Cobra Dane and Cobra Judy wideband phased-array radars. Both of these radars were built by the Raytheon Corporation under support of the U.S. Air Force and U.S. Army. Lincoln Laboratory played a supporting role in the development of these phased-array sensors, and it continues to provide essential support in upgrades and data processing. The Laboratory has also been heavily involved in the analysis of data. Developed to collect data on strategic ballistic missiles, these sensors were at the forefront of wideband phased-array technology. Cobra Dane, shown in Figure 6, was the first sensor to become operational, in 1976. Located on the island of Shemya, Alaska, in the western end of the Aleutian chain, Cobra Dane can observe the exo-atmospheric portions of Russian missile flights into the Kamchatka Peninsula and the Pacific Ocean.

The Cobra Judy mobile S-band phased-array radar, located on the U.S. Naval ship *Observation Island*, was subsequently developed and became operational in 1981 to provide improved global ballistic missile data collection on a mobile sea-based platform. An X-band wideband dish radar added to Cobra Judy became operational in 1984. The shift to X-band was to enhance resolution and imaging capability relative to S-band, and subsequently to

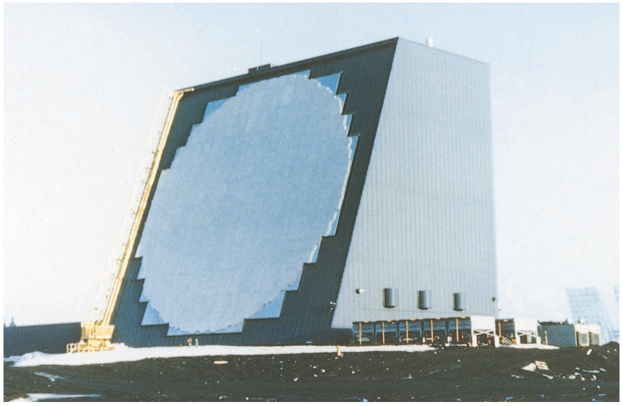


FIGURE 6. The wideband phased-array Cobra Dane radar, located on the island of Shemya, Alaska, in the western end of the Aleutian chain. In this location, Cobra Dane can observe the exo-atmospheric portions of Russian missile flights into the Kamchatka Peninsula and the Pacific Ocean.

support the BMD community in developing a national missile defense system that would incorporate an X-band phased array for interceptor fire control. Cobra Judy, shown in Figure 7, remains to this date the world's largest mobile phased-array sensor.

Lincoln Laboratory's support of the development and use of these high-quality instrumentation radars involved a number of significant contributions. Specifically, Lincoln Laboratory (a) developed the requirements and specifications for each of the sensors and validated sensor performance after deployment; (b) developed the data processing and data distribution architecture, including calibrations and the data processing software and methodology; (c) developed and applied key analysis tools tailored for BMD data exploitation; and (d) continues to participate in the operational use of these sensors. Some of the analysis tools tailored for BMD data exploitation are synthetic bandwidth expansion for enhanced range resolution, extended coherent processing for three-dimensional imaging, macro- and micro-motion-dynamics processing techniques, and enhanced spectral estimation for feature identification. The Laboratory continues to participate in the operational use of these sensors through Cobra Judy mission planning, ballistic missile profile development and operator training, Cobra Judy upgrades and enhancements, and the development of data interpretation and analysis techniques.

Development of the Cobra Dane and Cobra Judy sensors required advances in two key technology areas: wideband wide-angle phased-array scanning coverage, and automated target classification and data collection.

Cobra Gemini

Over the past few years, many nations have begun to obtain tactical ballistic missiles. The recent Gulf War illustrated that these missiles can be important political weapons when equipped with explosive warheads.

FIGURE 7. The wideband phased-array Cobra Judy radar on the U.S. Naval ship *Observation Island*. The S-band phased-array radar is at the stern of the ship; the mechanically scanned dish just forward of it is the X-band radar antenna. The Cobra Judy is the world's largest mobile phased-array sensor.

If these missiles are coupled with a chemical, bacteriological, or nuclear weapons capability, they present an extremely threatening weapons system. Current development of theater-missile defense systems such as Theater High Altitude Area Defense requires data on these tactical missile systems for use in fire-control-radar discrimination functions.

In 1996, to meet the defense community's global requirements for radar signature data for theater-missile defense, Lincoln Laboratory, with sponsorship from the U.S. Air Force Electronic Systems Center, initiated development of an operational prototype of a transportable instrumentation radar called Cobra Gemini. Cobra Gemini is a sensor designed to collect metric and signature data on tactical theater-ballistic-missile targets. Since an operational radar must respond to a wide variety of launch locations, a sensor like the Cobra Gemini must be both air- and ground-transportable. It must also be capable of worldwide operation on land and deck-mounted operation on ships at sea. Figure 8 shows the Cobra Gemini radar implemented in a sea-based configuration on the *Invincible,* a U.S. Naval T-AGOS ship.

The signature data collection requirements include wideband and narrowband radar data at both S-band and X-band. High pulse-repetition-rate, wide-bandwidth data are collected at both X-band and S-band frequencies to support detailed analysis of tactical missile dynamics as well as the characterization of objects in the missile threat complex.

The Cobra Gemini radar was designed to acquire a –5-dBsm (decibels relative to one square meter) target at a range of a thousand kilometers over a 20°-wide horizon-surveillance fence. The thousand-kilometer requirement for detection range is adequate for detecting tactical ballistic missiles over a wide range of scenarios. Surveillance and target acquisition are performed at S-band by using the radar's mechanical scanning dish antenna, which has a fifteen-foot aperture. The radar has 50 kW of average power at S-band and 35 kW at X-band. The antenna uses a dual-band feed to transmit both S-band and X-band energy from the same dish. After acquisition, tracked objects are classified in real time so that high-resolution data can be collected on high-priority objects. In the wideband mode, the radar has a bandwidth of 1 GHz at X-band and 300 MHz at S-band. These bandwidths correspond to range resolutions of approximately 0.25 m and 0.80 m, respectively.

The purpose of the Cobra Gemini program was to produce a prototype radar with a short delivery schedule and low risk of delays in development. Additional radars of this type can then be more confidently produced by industry with this baseline design. The Cobra Gemini prototype completed its ground-based test and evaluation in July 1998. The

FIGURE 8. The Cobra Gemini radar (large radome) in its sea-based configuration on the *Invincible,* a U.S. Naval T-AGOS ship. A transportable sensor such as Cobra Gemini is designed to assist in the detection and discrimination of tactical theater ballistic missiles.

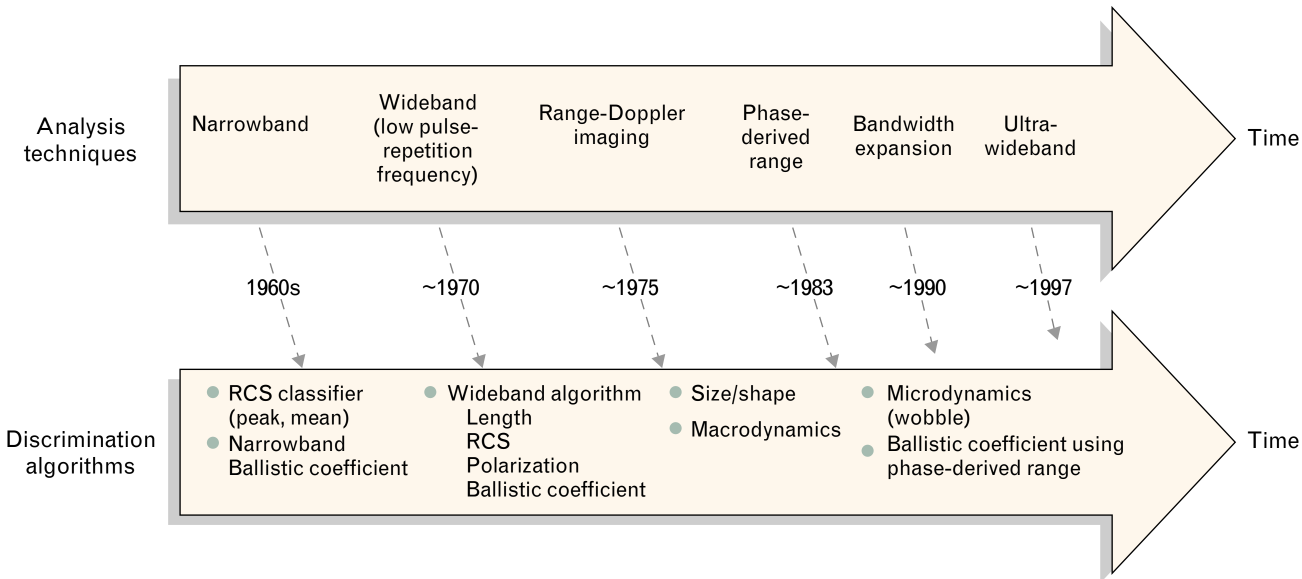


FIGURE 9. The evolution of wideband radar data-analysis techniques and their relationship to the development of ballistic-missile-defense discrimination algorithms. As wideband radar technology has evolved, providing higher pulse-repetition frequencies, wider bandwidths, and higher operating frequencies, the analyst's ability to infer more information about a target under observation by the radar has increased significantly.

radar was then installed on the *Invincible*. The prototype achieved operational capability on 1 March 1999 after successful completion of its sea-based test and evaluation.

Advances in Wideband Data Analysis

Lincoln Laboratory has played a major role in the development of data-analysis techniques for use in exploiting data collected by wideband radars on strategic and theatre ballistic missiles. The evolution in complexity of discrimination technology has directly followed the evolution of capability in computer processing. Figure 9 illustrates this evolution of analysis techniques over time and their relationship to the development of discrimination algorithms. As wideband radar technology has evolved, providing higher pulse-repetition frequencies, wider bandwidth, and higher RF operating frequencies, the analyst's ability to infer more information about a target under interrogation by the radar has increased significantly. Developments in computer processing have led to subsequent real-time implementation of algorithms based on these analysis techniques.

More recently, Lincoln Laboratory has developed and exploited several techniques for improving the resolution of wideband coherent radar data. The first technique uses modern spectral-analysis methods for improving resolution relative to the restrictions of conventional Fourier processing. These spectral methods extrapolate signals in a radar-frequency dimension by a process called bandwidth extrapolation. Each wideband pulse return includes the target frequency response over the chirped bandwidth. Modern spectral-estimation techniques are then applied to extend this frequency response synthetically outside this band to a factor ranging from two to three times the bandwidth. This expanded pulse return is then recompressed to provide finer range resolution (for practical signal-to-noise ratios, an improvement of a factor of two to three in resolution is generally realized), and when applied to radar imaging, it provides much improved sharpness in the radar image [9].

The second technique uses signal processing models that correspond to rotating-point motion. The models allow extended coherent processing over wide target-rotation angles, resulting in improved Doppler (cross-range) resolution [10]. For sufficiently large resolution angles and for constant-amplitude scattering centers, extended coherent processing also improves the range resolution. Extended coherent processing essentially aligns and stores radar pulses obtained over longer time spans as compared to conventional imaging. When combined with bandwidth extrapolation, extended coherent processing can achieve enhanced resolution in both range and Doppler (cross-range) spaces. For targets where the radar viewing angle is at a constant aspect angle to the target's angular-momentum vector, extended coherent processing provides high-quality three-dimensional radar images.

More recently, the Laboratory has explored the possibility of achieving ultrawideband resolution by using data only over sparse subbands of the full ultrawide bandwidth. We can view this technique as a generalization of bandwidth extrapolation to multiple bands [10]. Ultrawideband's potential as a discrimination tool is much more robust, as scatterer-feature identification on a specific target is inherently more accurate when observed over a much wider bandwidth.

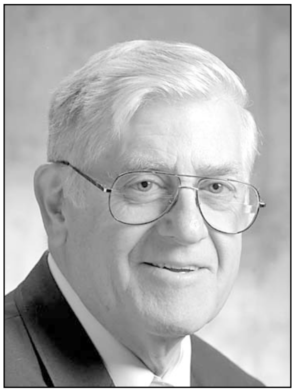
Summary

Lincoln Laboratory has played a pioneering and dominant role in the development of high-power wideband radar systems and technology. As the capability of wideband radars has progressed, the Laboratory has continued to develop high-speed signal processing devices and systems, and more sophisticated analysis techniques. These new developments permit the formation of dynamic three-dimensional images of multiple targets in near real time, and have resulted in the development of discrimination algorithms applied to real-time ballistic missile defense.

As a result of the Laboratory's research and development efforts in wideband radar, signal processors, and data analysis, the original promise of wideband systems has been fulfilled to an extent unforeseen thirty years ago. Today's wideband systems reveal information across the full spectrum of physical attributes of observed targets. The true test of the value of this Lincoln Laboratory development is that today's ballistic-missile-defense radars, such as the Theater High Altitude Area Defense radar and the National Missile Defense Ground-Based Radar Prototype, feature substantial wideband capabilities that are critical to meeting their challenging missions.

REFERENCES

1. M.L. Stone and G.P. Banner, "Radars for the Detection and Tracking of Ballistic Missiles, Satellites, and Planets," *Linc. Lab. J.,* in this issue.
2. P.A. Ingwersen and W.Z. Lemnios, "Radars for Ballistic Missile Defense Research," *Linc. Lab. J.*, in this issue.
3. M. Axelbank, W.W. Camp, V.L. Lynn, and J. Margolin, "ALCOR—A High-Sensitivity Radar with One-Half-Meter Range Resolution," *IEEE 71 International Conv. Dig., New York, 22–25 Mar. 1971,* pp. 112–113.
4. M.I. Skolnik, *Introduction to Radar Systems,* 2nd ed. (McGraw-Hill, New York, 1980), p. 432.
5. R.K. Avent, J.D. Shelton, and P. Brown, "The ALCOR C-Band Imaging Radar," *IEEE Antennas Propag. Mag.* **38** (3), 1996, pp. 16–27.
6. E.C. Freeman, ed., *MIT Lincoln Laboratory: Technology in the National Interest* (Lincoln Laboratory, Lexington, Mass., 1995), pp. 118–119.
7. M.D. Abouzahra and R.K. Avent, "The 100-kW Millimeter-Wave Radar at the Kwajalein Atoll," *IEEE Antennas Propag. Mag.* **36** (2), 1994, pp. 7–19.
8. J.C. McHarg, M.D. Abouzahra, and R.F. Lucey, "95-Ghz Millimeter Wave Radar," *SPIE* **2842,** 1996, pp. 494–500.
9. K.M. Cuomo, "A Bandwidth Extrapolation Technique for Improved Range Resolution of Coherent Radar Data," *Project Report CJP-60, Rev. 1,* Lincoln Laboratory (4 Dec. 1992), DTIC #ADA-258462.
10. K.M. Cuomo, J.E. Piou, and J.T. Mayhan, "Ultra-Wideband Coherent Processing," *Linc. Lab. J.* **10** (2), 1997, pp. 203–222.



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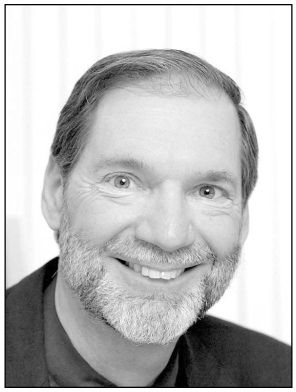

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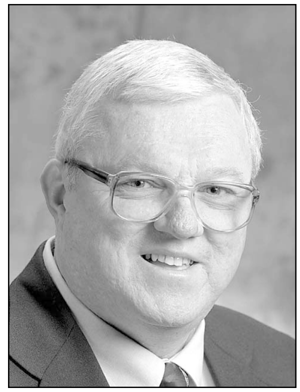

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