History of Lincoln Laboratory at the Reagan Test Site

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In 2012, MIT Lincoln Laboratory celebrates 50 years of continuous service on the Kwajalein Atoll. Since the first Laboratory staff arrived on the atoll in 1962 to take on the responsibilities of scientific director to Project PRESS (Pacific Range Electromagnetic Signature Studies), personnel from the Laboratory have been supporting technology development and operations at the Reagan Test Site (RTS), formerly known as Kwajalein Missile Range. With the technical support of Lincoln Laboratory, now serving as scientific advisor to the site, the RTS has been a critical contributor to the ballistic missile defense and space situational awareness national missions. In addition, many important technologies had their beginnings and many science experiments leading to improved understanding of the Earth and our universe have been carried out at RTS and the Kiernan Reentry Measurements Site.

» **The Reagan Test Site (RTS), as it is** known today, is the United States' premier missile range. Located on Kwajalein Atoll in the Pacific, RTS has played a major role during the past 50 years in intercontinental ballistic missile (ICBM) testing, missile defense development and testing, space-object tracking and identification, new foreign launch monitoring, sensor technology development, and scientific research. MIT Lincoln Laboratory has filled the technical leadership role at RTS since 1962 when the first instrumentation radar, Target Resolution and Discrimination Experiment (TRADEX), became operational. The year 2012 marks 50 years of operation of TRADEX and 50 years of continuous presence and service of Lincoln Laboratory at Kwajalein. During those 50 years, the Laboratory has been responsible for keeping the RTS instrumentation at state-of-the-art levels by continuously developing and inserting advanced technology. As a result, the RTS major support areas expanded and evolved over time in line with the enhanced sensor capabilities.

Lincoln Laboratory, initially under the sponsorship of the Advanced Research Projects Agency (ARPA), a Department of Defense agency, and since 1968 under sponsorship of the U.S. Army, serves as scientific director of the Kiernan Reentry Measurements Site (KREMS), and since 1996 as the scientific advisor for all RTS instrumentation. KREMS is that portion of the RTS that contains a suite of the world's most powerful and precise instrumentation radars. KREMS is named after U.S. Army Lieutenant Colonel Joseph M. Kiernan, who, as an ARPA engineer, oversaw the early radar design and development during a period of rapid growth from 1963

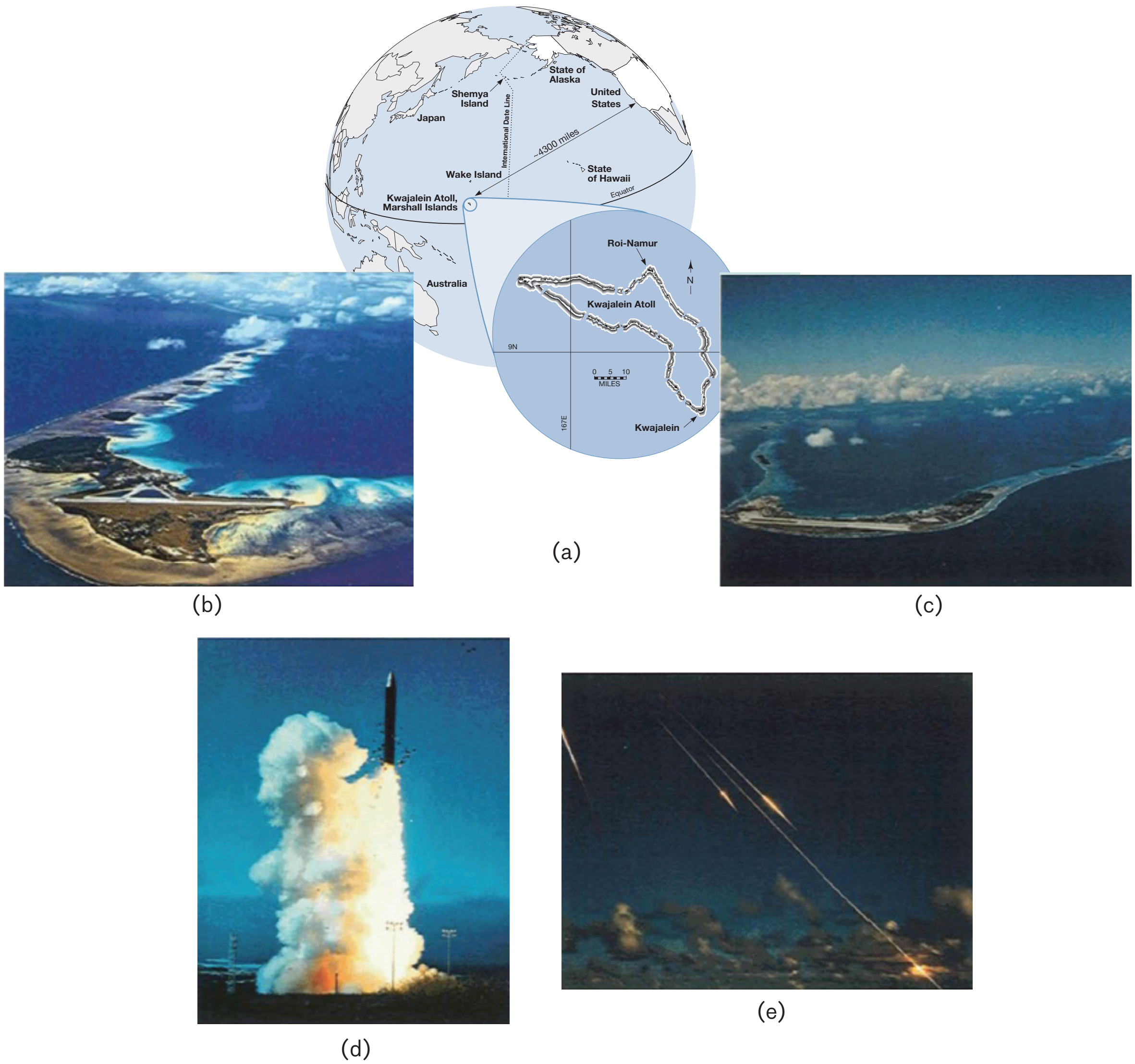


FIGURE 1. The Reagan Test Site is located in the central Pacific on the world's largest atoll. This atoll is about equidistant from Hawaii, Australia, and the Philippines (a). The world's most sophisticated instrumentation radars are located on Roi-Namur island (b) at the northern extent of the atoll. Most personnel manning the site continue to reside on the southernmost Kwajalein Island (c). In a typical missile test, a launch occurs remotely, in this case shown at Vandenberg Air Force Base in California (d), and the parts of the test that requires detailed data collection occur near Kwajalein, in this case a multiple reentry event (e).

to 1966. LTC Kiernan later served as Commander of the 1st Engineer Battalion of the 1st Infantry Division in Vietnam, where he was killed in 1967.

Kwajalein Atoll, lying 9° north of the equator and 3500 km southwest of Hawaii, is a necklace-like collection of remote islands in the Pacific Ocean. Situated 7000 km downrange from Vandenberg Air Force Base in California, Kwajalein Atoll is the home of the Reagan Test Site with the KREMS radar suite located on Roi-Namur Island, the northernmost island in the atoll. In addition to KREMS, RTS also includes a wide array of other systems, including optical-data-collection sensors, telemetry data-collection instrumentation, and range safety systems, all of which are integrated and controlled through a mission-coordination center that interfaces to the instrumentation. Figure 1 provides a synopsis of RTS location information.

Over the 50-year period, RTS has undergone a number of name and government organizational changes. Table 1 lays out the dates of the RTS evolution.

Today, KREMS includes four unique, high-power, precision radars: TRADEX, which became operational

Honoring LTC Kiernan

Lieutenant Colonel Joseph M. Kiernan Jr., the son of a captain in the U.S. Navy, was commissioned in the Army after his graduation from the U.S. Military Academy at West Point. The top graduating senior in the class of 1948, he was assigned to the 1st Engineering Battalion of the 1st Infantry Division (nicknamed the Big Red One). After earning a master's degree at the California Institute of Technology, Kiernan was assigned to the Missiles and Space Division of the Office of the Chief of Research and Development. His expertise in missile technology led to his Pentagon assignment in the Advanced Research Projects Agency (ARPA) and to Project PRESS.

During a critical three-year period of growth and consolidation, 1963–66, Project PRESS was energized by the leadership and presence of LTC Kiernan. Under his personable, energetic, and knowledgeable guidance, both the ARPA Long-Range Tracking and Instrumentation Radar (ALTAIR) and ARPA-Lincoln C-band Observables Radar (ALCOR) radar designs were conceived. These powerful radar systems have contributed significantly to the collection of important data on ballistic missiles and satellites.

Upon completing his tour of duty at Project PRESS, Kiernan volunteered for assignment in Vietnam so that he could return to the Big Red One as Commander. Not long after his tour began, he was killed in a helicopter accident in 1967. Kiernan was a highly decorated soldier, having received numerous awards and decorations including the Silver Star with Oak Leaf Cluster, the Legion of Merit, the Distinguished Flying Cross, the Bronze Star Medal with V for Valor Device, the Air Medal with seven Oak Leaf Clusters, and the Purple Heart Medal. In recognition of his contribution to the defense efforts of the United States, the instrumentation complex at Roi-Namur was renamed the Kiernan Reentry Measurements Site (KREMS) in 1969.

in 1962, ALTAIR (ARPA Long-Range Tracking and Instrumentation Radar), and ALCOR (ARPA-Lincoln C-band Observables Radar) both of which have been operating since 1970, and the MMW (Millimeter-Wave) radar, which began operations in 1983. Over the years, the Laboratory has repeatedly upgraded and modernized the electronics and most of the other hardware, except the antennas and pedestals, and all four radars remain today as state-of-the-art radar systems. Figure 2 shows the island of Roi-Namur as it exists today with the four KREMS radars, and Table 2 gives some of the important parameters for each of the radars.

RTS also contains an extensive suite of additional instrumentation, including two MPS 36 skin and beacon-tracking radars located on Kwajalein Island; a variety of optical data-collection systems, including fixed-mount

Table 1. Reagan Test Site name changes

Name	Era
Naval Station Kwajalein	Post WWII–1959
Pacific Missile Range Facility, Kwajalein, managed by the U.S. Navy	1959–1964
Kwajalein Test Site managed by U.S. Army Nike-X project office	1964–1968
Kwajalein Missile Range managed by U.S. Army Kwajalein Missile Range Directorate	1968–1986
Kiernan Reentry Measurements Site (KREMS) at Roi-Namur	1969–Present
United States Army Kwajalein Atoll (USAKA) lead on-island command	1986–Present
Kwajalein Missile Range, subordinate command, responsible for all technical instrumentation	1986–1999
Ronald Reagan Ballistic Missile Defense Test Site (RTS), responsible for all technical instrumentation	1999–Present

staring cameras and several telescopes installed on high-performance tracking mounts, located on several islands around the atoll; a large number of telemetry antennas for receiving in-flight position and housekeeping data on test vehicles; and a ship-based range-safety command-destruct system. Since 1993, Lincoln Laboratory, in concert with the government and with the support of the RTS operations and maintenance technical contractor, has provided technical leadership for the design, development, and execution of major upgrades and technology improvements to all of these RTS systems.

The Laboratory has also been and remains responsible for the development and upgrade of the mission coordination center, which orchestrates the integration and control of all of the RTS sensors. Finally, the Laboratory is heavily involved in planning how the sensors are to be utilized during test operations, and following a test, verifies the proper operation of the sensors and analyzes and interprets the data that have been gathered.

RTS is a premier element in the Department of Defense's (DoD) Major Range Test Facility Base (MRTFB) suite of test and evaluation national ranges. RTS contributions have been primarily in the five following major areas:

- U.S. Air Force missile system development and operational testing
- Space surveillance, tracking, and object identification
- Ballistic missile defense (BMD) research and system testing
- Sensor and command and control advanced technology development
- Scientific research

The first area involves collection of data on U.S. strategic missile system components, such as the Air Force Minuteman and Peacekeeper systems. These components include reentry vehicles (RV) and associated objects. Recently, this mission area has transitioned to become part of the U.S. global strike system. The U.S. Air Force continues to test its strategic missile arsenal at Kwajalein by conducting at least three or four tests per year. A new hypersonic glide vehicle is in its early development stage, and the first successful flight test occurred at Kwajalein in November 2011.

Table 2. Specifications for the KREMS radars

	ALTAIR		TRADEX		ALCOR	MMW
Frequency band	VHF	UHF	L band	S band	C band	Ka band
Center frequency (GHz)	0.162	0.422	1.320	2.95	(NB) 5.664 (WB) 5.672	35.0
Antenna diameter (m)	45.7 (150 ft)		25.6 (84 ft)		12.2 (40 ft)	13.7 (45 ft)
Beamwidth (°) (6 dB 2-way)	2.8	1.1	0.61	0.3	0.3	0.0435
Peak transmit power (MW)	6	6	2.0	2.0	2.25	0.060

FIGURE 2. The island of Roi-Namur at the northern extreme of the Kwajalein Atoll is the location of the four primary KREMS radars. Looking southwest from the ocean side reef, ALCOR in seen in the lower left corner, TRADEX in the center foreground, MMW in the center background, and ALTAIR in the upper right corner.

The U.S. space situational awareness operational mission had its beginning in the late 1970s and includes detecting and tracking new foreign launches, imaging near-Earth satellites (space-object identification, or SOI, activity), tracking high-priority near-Earth satellites, and tracking deep-space and geosynchronous satellites (Satellite Catalog Maintenance). RTS, a supporter of the NASA Space Shuttle Program since the program's inception, has also tracked shuttles and imaged payloads during deployment and subsequent orbit transfers. The KREMS radars have also supported NASA by gathering data on space debris, especially at low inclination angles, during extended data-collection campaigns. A detailed article describing the space mission at RTS is contained within this issue.

The third area, BMD research and system testing, covers collection and exploitation of data to understand BMD signature phenomenology, to assess BMD system and component performance, and to develop decision support, target identification, and discrimination techniques. In this capacity, RTS plays a major role in the national BMD discrimination research program by providing the live-fire test capability to exercise candidate waveforms, signal processing concepts, and tracking, target identification, and decision support algorithms.

The U.S. ballistic missile database consists largely of KREMS data generated from over 900 missile tests during the past 50 years. During the 1970s, RTS collected and recorded relevant data for the development of the Safeguard system and System Technology Radar programs. Beginning in the 1980s, the radar system collected and recorded data that characterized target vehicles, assessed interceptor miss distances, and analyzed post-impact debris for intercept tests, such as the Homing Overlay Experiments (HOE) and the Delta experiments of the Strategic Defense Initiative (SDI) during the 1980s. More recently, RTS collected data and provided performance assessment for the Exoatmospheric Reentry Interceptor System (ERIS) program, the National Missile Defense (NMD) program, the Ballistic Missile Defense Organization (BMDO), the Missile Defense Agency (MDA) ground-based midcourse defense (GMD) effort, and a number of important theater missile defense and countermeasures assessment programs.

The fourth area of support is the advanced technology that has been developed to support and enhance the above mission areas. Much of the advanced technology developed at Kwajalein has made its way into other DoD systems through technology transfer. Key examples include wideband radar systems, open system and net-centric architectures, numerous real-time technology demonstrations, waveform and signal processing advances, and data-exploitation techniques such as radar imaging.

The fifth area falls under the broad category of scientific research to study various natural phenomena. RTS has performed extensive multifrequency sea-clutter backscatter measurements that helped the Navy characterize and model the sea-clutter environment. Multifrequency measurements of aircraft wakes have been carried out for the Air Force. RTS has gathered ionospheric scintillation and electron-density profile data that help the Defense Nuclear Agency and the scientific community improve their models of the ionosphere. A companion article on ionospheric modeling appears later in this special issue. The RTS sensors have also contributed to studies of the movement of the Earth's tectonic plates, meteor trails, and various weather-related phenomena.

In the remainder of this article, many of the major advances and contributions at RTS will be highlighted and described during three time phases:

- The early development years beginning in the 1960s and continuing until the mid-1970s
- The middle years of continued development and growth of new sensors and mission areas, extending from the mid-1970s into the early 1990s
- The most recent 20 or so years of continued technology insertion and demonstration, growth in new capabilities, and also consolidation to bring efficiencies and reduced operating costs for RTS

In order to keep the length of this article at a manageable level, not all five support areas described above will be discussed within each of the three time periods. However, it is hoped that enough detail is provided that the reader will have a good appreciation for how the support areas have evolved at RTS.

Figure 3 provides a historical timeline of some of the major developments that have occurred at RTS. A more detailed historical timeline of the most significant RTS developments is provided in the following article in this *Journal*.

Early Development (1958–1975)

Project PRESS and TRADEX

In 1958, the Advanced Research Projects Agency (ARPA) was created by the DoD in response to the Soviet Union's 1957 launch of the first intercontinental ballistic missile (ICBM) and the launch of the first artificial Earth satellite (Sputnik 1). ARPA (which has since been renamed DARPA, Defense Advanced Research Projects Agency) was given broad jurisdiction over ballistic missile and space systems research and development. Since little was known at the time about the physics and phenomenology of ballistic missile reentry into the Earth's atmosphere, ARPA initiated a measurements and research program called Project PRESS (Pacific Range Electromagnetic Signature Studies) and named Lincoln Laboratory as scientific director of the project. The lofty goals of the program were to determine the effects of the ionization produced by a reentering body on the body's electromagnetic scattering characteristics, and to develop adequate theoretical models to explain the experimentally observed phenomena. The need to make measurements on in-flight ballistic missiles was recognized and led to the need for a remote site to target ICBM reentry vehicles and to locate measurement sensors.

In 1959, ARPA chose Kwajalein Atoll because the Air Force was already using the site as a target for its ICBMs being launched from Vandenberg Air Force Base in California and because the Army had recently decided to use Kwajalein to develop and test the Nike-Zeus antiballistic missile system. The Nike-Zeus system, designed by Bell Laboratories, contained three radars, an ultra-high-frequency (UHF) acquisition radar, an L-band discrimination radar, and a C-band target-tracking radar, all located on Kwajalein Island at the southern end of the atoll.

In 1962, the Laboratory began work on the design, development, testing, and evaluation of countermeasures. The objective of the program was to examine the effectiveness of various countermeasures against postulated Soviet BMD systems. Work of this nature continued at the Laboratory until well into the 1970s. During this period, various countermeasure devices were fabricated at the

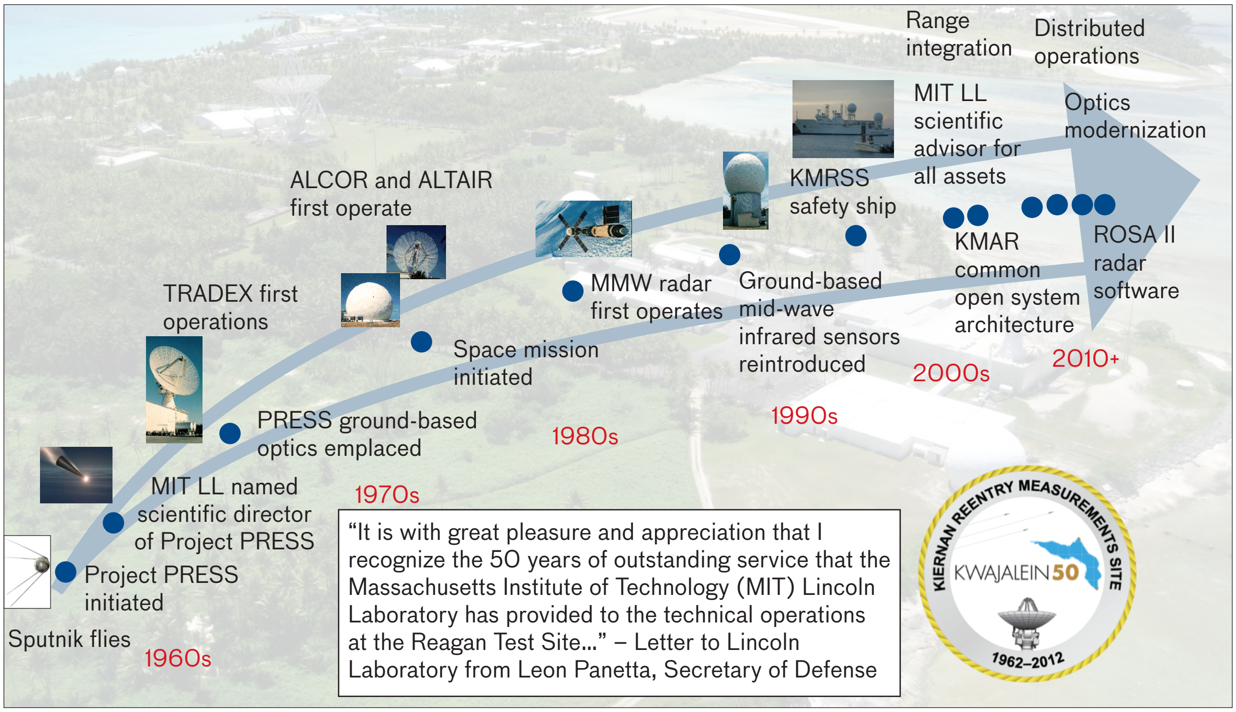


FIGURE 3. A technology timeline for RTS shows some of the key events in the development of the highly sophisticated equipment now stationed at Kwajalein.

Laboratory and flight-tested at Kwajalein. Among them were the first inflatable replica decoys and compact radar jammers. The flight tests conducted at RTS were invaluable in helping to determine the veracity of the various countermeasure techniques.

In early 1960, a site on Roi-Namur, the northernmost island, was selected by Lincoln Laboratory for the TRADEX radar, an advanced derivative of the UHF radars that made up the Ballistic Missile Early Warning System (BMEWS). ARPA selected the RCA Corporation to build and install TRADEX. TRADEX originally operated as a UHF tracker and an L-band illuminator.

In the spring of 1962, the first Lincoln Laboratory personnel arrived to live on Kwajalein in order to provide technical supervision during the final testing and initial operation of TRADEX, and to prepare to take over the radar once it was accepted by ARPA. TRADEX successfully tracked its first ICBM, an Atlas missile launched from Vandenberg Air Force Base on 26 June 1962. ARPA accepted TRADEX and turned it over to Lincoln Laboratory on 1 December 1962. From the outset, ARPA expected Roi-Namur to be a research site manned by scientists and engineers.

At about the same time, the U.S. Air Force was interested in how U.S. ICBMs would perform against an enemy defensive system. They began an effort to minimize the radar cross section of their warheads and to develop decoys and other penetration aids to confuse and defeat the defense. The Air Force also held discussions with Lincoln Laboratory and selected the Laboratory to lead their Advanced Ballistic Missile Reentry Systems (ABRES) Program. To test their systems, the Air Force needed the same type of measurement radars and analysis techniques that ARPA was working to develop at Kwajalein.

Figure 4a shows the TRADEX antenna under construction at Roi-Namur during 1962. Figure 4b shows the TRADEX antenna on Roi-Namur as it exists today. TRADEX was one of the earliest radars to use pulse compression, utilizing a 1 MHz linear frequency modulation "chirped" transmit pulse to achieve high sensitivity, while achieving a range resolution of approximately 200 m. With an 84 ft antenna and high peak power, the TRADEX system was able 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 waveforms capable

(a) (b)

FIGURE 4. The TRADEX antenna was the first radar installed on the island of Roi-Namur on Kwajalein Atoll in the Marshall Islands in the central Pacific: (a) TRADEX is shown during construction in 1962, (b) as it exists today.

of operating at a variety of pulse-repetition frequencies (PRF). High PRFs provided excellent Doppler resolution for wake measurements, while low PRFs were needed to view very widely spaced target complexes. A memorable feature of the early TRADEX radar was the intermediate-frequency (IF) tape recorder (shown in Figure 5), an analog recorder with 3 ft diameter reels. This tape recorder achieved sufficient bandwidth to record the IF signals and collect the essential radar pulse amplitude and phase information, but it did so with very high tape speeds that occasionally caused the tape to break, resulting in spectacular chaos.

When the Laboratory assumed control of the TRADEX radar, the first change was to install a pulse-burst waveform to provide improved range and Doppler measurement capability. The burst waveform provided a range resolution of approximately 15 m, which allowed the analysts to examine the amplitude and velocity spectrum of the wake as a function of distance behind the body. The modification of the transmitter to pass this waveform and a digital recording system that could handle its high data rates were designed and built at Lincoln Laboratory. The decision was also made to add a third frequency, VHF (very high frequency), to TRADEX, and in 1964 this added capability became operational.

During the 1960s, because the developers of both ballistic missiles and ballistic missile defense systems were firing missiles into Kwajalein, TRADEX became the primary source of data for reentry phenomenology and discrimination research.

TRADEX L- and S-Band Modification

In 1970, the TRADEX radar was shut down for a major redesign. The UHF capability was removed, a new dual-frequency feed was added to make it an L-band range and angle tracker, and an all-new S-band illumination capability 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 Nike system. The redesigned TRADEX system became a workhorse for the development of discrimination techniques. In the 1970s, everyone in the BMD community had a favorite discrimination waveform, and essentially all of them were implemented and tried on TRADEX. Clearly, ARPA's vision of a continuously evolving and improving research facility had been fully realized. For the benefit of this and subsequent discussions, Figure 6 shows a comparison of the frequencies of the wavebands used by the KREMS radars today.

ALTAIR

In the early 1960s, the United States was surprised to find that the Soviet Union was developing very large VHF and UHF radars (nicknamed Henhouse and Doghouse), 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. As a result, the second Project PRESS radar development was initiated, and called the ARPA Long-Range Tracking and Instrumentation Radar (ALTAIR). It was designed to range and angle track at VHF and collect UHF data, with both greater sensitivity and resolution than the results provided by the original TRADEX radar.

A very large antenna and high-power transmitters were specified to achieve high sensitivity. As a consequence of these design factors, ALTAIR can consistently acquire targets launched from Vandenberg Air Force Base as they break the horizon at a range of over 3500 km. The ALTAIR antenna is a very agile system given its large size. As shown in Figure 7, the 150 ft diameter antenna rotates on a 110 ft diameter circular track. To achieve the rates and accelerations necessary to track vehicles during deep reentry, the antenna is far stiffer than most 150 ft dishes. The rotating portion of the antenna weighs almost a million pounds. Although perhaps not realized at the time, 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 about 10 years with loading more than 10 times as high as the worst-case loads used by the railroad industry before the original wheels and rails had to be replaced. Transmitter powers of 100 kW average at VHF and 120 kW average at UHF were specified and demonstrated. Originally, three different transmit pulse lengths were provided 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 32 m at VHF and 15 m at UHF. Initial control of the system was performed by a Honeywell computer that had only 16 kilobytes of "core" memory!

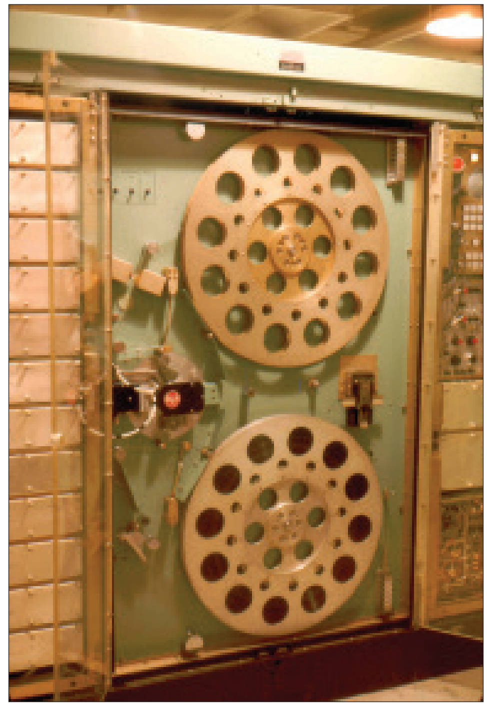


FIGURE 5. The early TRADEX radar saved its data on this analog intermediate-frequency tape recorder.

The ALTAIR signature recording system was built by Lincoln Laboratory and interfaced to the radar at its intermediate-frequency stage. With its relatively broad beamwidth of 3° at VHF, ALTAIR illuminates an entire typical ICBM target complex from just before horizon break (because the atmosphere refracts the radar beam) until well into reentry. The initial system provided the ability to simultaneously track and record extensive signature data on up to 14 targets at each frequency. Because the data rate was far too great for computer tape drives of the time, multiple 14-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 standard digital computer tapes for further processing.

ALCOR

In the late 1960s, Lincoln Laboratory analysts became interested in wideband radar waveforms for ballistic missile discrimination. Wide-bandwidth radars provide the means of measuring the length of objects and examining details of individual scattering centers on the bodies. With short pulses on a static range, length was easily measured, but the effects of the reentry plasma sheath on the mea-

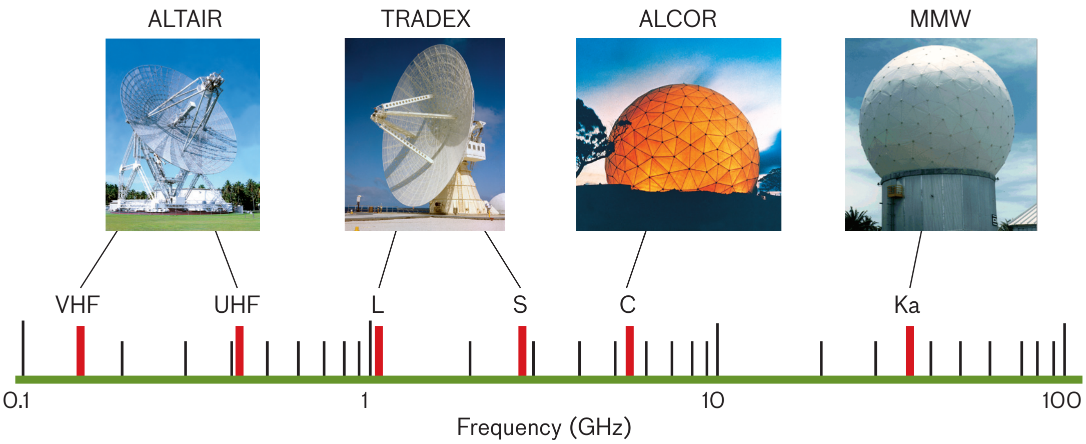


FIGURE 6. The four radars at KREMS utilize the wavebands shown in this simplified frequency scale.

surement capability were difficult to predict. In addition, the generation and processing of wideband waveforms with sufficient energy to obtain length measurements on targets at long range 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 several other smaller contractors. ALCOR became operational in January 1970. Figure 8 shows the antenna and radome during installation on Roi-Namur and as it looks today. The original waveforms were 10 μsec chirped pulses of 6 MHz and 512 MHz bandwidth operating at a peak power of 3 MW. The key to processing the 500 MHz waveform was "stretch" processing or time-bandwidth exchange. An unusual feature of the original ALCOR, which reduced the system cost and ensured the match between all receiver channels, was the multiplexing of all the signals with delay lines and passing the signals sequentially through a single set of signal processing hardware. Many of the components, including tapped-delay line compression networks, analog-to-digital converters, and the control computer, were the same as those used on ALTAIR.

(a)

(b)

FIGURE 7. The ARPA Long-Range Tracking and Instrumentation Radar (ALTAIR) is shown in its initial configuration (a) and as currently in operation (b).

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. Surface-acoustic-wave technology found wide application for analog pulse compression and was later used at TRADEX and ALTAIR. Transponder waveforms (to interrogate beacons carried on in-flight vehicles and for transponder reply tracking), pulse pair waveforms (for measuring reentry vehicle wake velocity), and multiple range windows were added to ALCOR in the early 1970s.

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 an indispensable feature in today's BMD systems. Even though the space surveillance mission at Kwajalein did not formally get under way until the late 1970s, it was recognized in the early 1970s that coherent wideband radars could also be used to image space-borne objects. In 1971, ALCOR became the first radar to effectively use inverse synthetic aperture radar (ISAR) imaging techniques on orbiting satellites. As a result, ALCOR's impact on space-object identification has been profound. Early radar imaging experiments with ALCOR led to the later development of much higher resolution radars both at RTS and Millstone Hill in Westford, Massachusetts. Today, high-resolution imaging of space objects remains an essential component of our nation's space surveillance system.

Project PRESS Optical Systems

In the early 1960s as part of Project PRESS, ARPA also assigned Lincoln Laboratory the task of developing and managing a ground-based and airborne optical measurements program at Kwajalein. The first ground-based optical instruments deployed by the Laboratory were three ballistic cameras and a Recording Optical Tracking Instrument (ROTI), Mark II at the Kwajalein Test Site. The ROTI was a Newtonian telescope with a 24-inch aperture and 100-inch focal length, on an azimuth-elevation mount, recording images on an attached 70 mm photographic film transport. Three ground locations were employed for the ballistic cameras to enhance RV trajectory determination. These locations were the islands of Roi-Namur, Kwajalein, and Ennylabegan. The 12-inch focal length, *f*/2.5 ballistic cameras were mounted in squinting pairs, and they recorded (on 9-inch × 12-inch glass photographic plates) the reentry against the stellar background at each location with a total field of view of 40° × 100°. The last instrument of the initial ground optics deployment was a Baker-Nunn slitless cinespectrograph, emplaced during March 1963 at the Kwajalein Optical Station. The Baker-Nunn telescope had a 20-inch aperture and focal length, but operated at *f*/2.5 because of internal obstructions. The spectrograph was mounted in a three-axis mount, and the prism assembly azimuth in the aperture was remotely controlled so that

(a) (b)

FIGURE 8. The third radar installed on Roi-Namur was the ARPA-Lincoln C-band Observables Radar (ALCOR). Above are the antenna and radome during installation (a) and the radome today (b).

the dispersion direction could be maintained normal to the reentry vehicle's wake.

Driven by a need to position optical sensors above as much atmosphere and cloud cover as possible, Lincoln Laboratory began planning for a PRESS airborne optics system in early 1962. The primary sensor, known as Skyscraper, was a 20-inch aperture telescope and tracking flat coupled to tracking and spectrograph optics. It was mounted in an open cavity on a KC-135 aircraft looking out the side of the airplane fuselage. Real-time pointing coordinates were relayed from the PRESS Control Center to the airplane to assist in target acquisition. The last data-gathering mission for the KC-135 aircraft was in June 1972.

PRESS Control Center Development

The need for a central control center to serve as the interface between the sensors was recognized early on. The role of the PRESS Control Center was to accommodate the exchange of track information. Track information from all three radars as well as external sources, such as the airborne optics system, was stored, smoothed, extrapolated, and redistributed as needed to provide a designation source for target acquisition.

The PRESS Control Center, shown in Figure 9, helped the narrow-beam optical sensors and the ALCOR radar, with its one-third of a degree beamwidth, acquire targets by providing very accurate pointing information. The control center provided directing data based on a combination of stored pre-mission target trajectories and satellite ephemerides, up-range track data, and smoothed and extrapolated track data from the TRADEX and ALTAIR radars.

During initial operation of the radars by the control center, it quickly became apparent that there were other important advantages in having an integrated command-and-control system. With data from all the sensors, the control center was able to more readily identify specific targets in the missile complex. In addition, non-nominal target deployments, sensor tracking issues, and operator errors were more apparent to the PRESS Control Center operators than they were to the individual sensor operators. PRESS Control Center personnel were able to specify corrective action and save valuable data on the one-of-a-kind missions typically performed at Kwajalein. When the site was named KREMS in 1969, the PRESS Control Center was renamed the KREMS Control Center (KCC). As the KCC role grew, the computers were upgraded a number of times. Other 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.

Early BMD development

In the late 1950s and early 1960s, the ICBM was thought of as the "ultimate weapon"—a device that could rain destruction down upon an enemy from a distant location. Since the Soviet Union was clearly developing ICBMs and planning to stockpile them, it was manifest that defensive measures needed to be taken. The task of developing BMD systems was initially the responsibility of the U.S. Army and of ARPA. The Army was responsible for building and testing BMD system components and eventually deploying them. ARPA was responsible for concentrating on major technical problems, such as discrimination, whose solutions were to be integrated into the Army's BMD systems. As discussed earlier, the U.S. Army began developing the Nike-Zeus system in the late 1950s to defend U.S. cities against ICBMs. The first successful live intercept occurred at Kwajalein in July 1962. This early BMD system was basically a variation on existing air defense systems, the Nike-Ajax and Nike-Hercules, that were emplaced earlier in the 1950s to guard U.S. cities and installations against strategic bomber attacks.

A key difference between air defense and ballistic missile defense is the speed of the incoming threat objects. The higher speeds of ICBMs compress the "battle space" and shorten the defense's timeline for taking effective action against an approaching threat object. To help compensate for this challenge, the defense must detect ballistic missiles at extremely long ranges, which requires more powerful sensors, and must automate such critical functions as target identification, weapons allocation, and fire control.

Another key difference between air defense and BMD is the more prominent role of countermeasures in BMD. The process of tracking bodies in the presence of clutter and then discriminating (that is, identifying and selecting) the warhead from all other objects is one of the most difficult and most important technical problems faced by BMD system designers. The Nike-Zeus system employed

FIGURE 9. The KREMS Control Center, depicted here, managed all three radars, while providing cross-platform correlative and corroborative data.

separate dish radars for surveillance, target tracking, and interceptor guidance. The system suffered from two major deficiencies: a limited ability to handle large numbers of objects in a target complex and an inability to discriminate warheads from decoys and other objects at high altitudes.

Furthermore, in order to defend soft targets such as cities, intercepts must occur at high altitudes to limit the residual damage created by nuclear detonations in the atmosphere. Therefore, in the mid 1960s, the Army began the development of a new, longer-range BMD system called Nike-X. Nike-X, as well as its later versions, Sentinel and Safeguard, was designed primarily for city defense. The system used two electronically scanned phased-array radars for its operations, and two types of interceptors: a long-range interceptor (called Spartan) able to destroy warheads during the midcourse phase of flight, and a high-acceleration, short-range interceptor (called Sprint) that waited to engage the reentry vehicle until the atmosphere had effectively filtered out all objects except the warhead. Both interceptors were tipped with nuclear warheads (5 megatons and a few kilotons, respectively) that could destroy all objects within their lethal radius. The Nike-X phased-array radars, which could redirect their beams in microseconds instead of seconds, significantly improved the handling of target complexes with large numbers of objects (called traffic). The system was tested extensively at Kwajalein during the late 1960s and early 1970s. The first successful Spartan launch at Kwajalein occurred in March 1968, and the first successful Sprint launch occurred in March 1972. These initial launches, as well as the large number of follow-on tests, were observed by the KREMS sensors at Roi-Namur.

In the early 1970s, the BMD focus began to shift from urban defense to defense of our silo-based Minuteman system. The discrimination requirements for dedicated silo defense differed significantly from those for urban defense. The site defense radar, which was to be hardened and deployed near the interceptors, operated at relatively short ranges, and the defense battle space shifted to lower altitudes than for Safeguard. Against a massive attack with sophisticated warheads and penetration aids, the defense would rely on the atmosphere to filter out much of the missile debris and light decoys, leaving only the warheads and high-ballistic-coefficient reentry decoys to be discriminated.

Reentry Designation and Discrimination Experiment

In the early 1970s, the Army Ballistic Missile Defense Agency (ABMDA) asked the Laboratory to develop a real-time discrimination capability on the Kwajalein radars to be used as a test bed for systems such as Safeguard and Site Defense. The implementation, which was termed the Reentry Designation and Discrimination Experiment (REDD), became operational in 1972. Its purpose was to test and demonstrate (on live-fire missile tests) real-time ballistic missile defense algorithms for signal processing of wideband waveforms and coherent-burst waveforms. The algorithms were run on a stand-alone CDC-6600 computer system that received and processed metric and signature data from the KREMS radars. TRADEX was the first radar incorporated into REDD. Shortly after its initial operational date, ALCOR was incorporated into REDD for real-time testing of various length-measurement algorithms. An identical computer with identical software was also installed at the Laboratory in Lexington, Massachusetts, where algorithms were developed and tested on recorded KREMS radar data. The promising algorithms were then demonstrated on the REDD system in real time during actual missile flights at Kwajalein. In this manner, a number of tracking, length-measurement, and wake-discrimination algorithms were fully tested. The algorithms that performed well were installed on the Site Defense system's missile site radar (MSR), a prototype of which was being fielded at that time on Meck Island. Several Laboratory staff were assigned to work with the MSR at Meck to aide in the integration and testing of its discrimination architecture.

SIMPAR

The large UHF search radar of the Safeguard system, the Perimeter Acquisition Radar (PAR), was deployed in North Dakota, where it was not possible to fly threat-like targets for testing the radar. A prototype of the entire radar was never built at Kwajalein because of the high construction cost. However, it was possible to test the PAR software at Kwajalein using the ALTAIR radar as a surrogate system. The PAR software contained a large body of target acquisition, tracking, discrimination, and impact-prediction algorithms that were installed at ALTAIR and tested against simulated threat targets. This program was known as SIMPAR, short for Simulation of PAR.

The ALTAIR UHF system was modified in 1973 to produce PAR-like data, and the PAR real-time program was run on the REDD system computer installed at Roi-Namur. The ALTAIR hardware modifications were extensive: new Cassegrainian feed, microwave system, receivers, and pulse-compression channels were added to provide independent angle tracking at UHF. A frequency-selective subreflector, 22 ft in diameter, was developed and installed at the focal point to allow the system to angle track at either UHF or VHF. The PAR waveforms proved a challenge to simulate. To operate at PAR pulse-repetition rates, the relatively low-duty-cycle ALTAIR transmitter could transmit only a 40 msec expanded pulse. A digital tapped-delay line pulse-compression system was designed and built at Lincoln Laboratory. The system operated well, and consequent tests of the PAR software produced excellent results.

In 1972, the United States signed the Anti-Ballistic Missile (ABM) defense treaty with the Soviet Union, which allowed only one BMD site for each country. In October 1975, shortly after Safeguard achieved an initial operating capability, the U.S. Congress voted to deactivate the system.

U.S. Strategic Missile Development

The Laboratory had also been involved since the late 1960s in examining the effectiveness of Air Force and Navy long-range strategic missiles. To that end, measurements of operational ICBMs and submarine-launched ballistic missiles (SLBMs) impacting in the vicinity of RTS were analyzed. Studies at different levels of complexity contributed to the determination of the effectiveness of these missiles in different offense-defense scenarios. RTS is regularly the target of Air Force strategic missile tests and helps to ensure the missile performance, accuracy, and veracity that is necessary to maintain a credible deterrent. The Laboratory's BMD expertise coupled with these strategic testing activities enabled it to view both sides of a complex offense-defense interaction.

During the 1960s, the Laboratory also conducted several countermeasure-related flight tests at Kwajalein (known as the Have Jeep flight tests) using low-cost sounding rockets. The purpose of these tests was to collect data for discrimination algorithm development. By the end of the period, an extensive database of high-quality radar signature data had been assembled on the plasma bow shock and wake of warhead-like targets.

Propagation Studies

Since the RTS radars collect position, velocity, and radar cross-section data on objects that traverse the troposphere (the lower atmosphere) and the ionosphere (above 90 km altitude), metric data analysts and atmospheric scientists were able to develop space and time-dependent radio-frequency (RF) signal-propagation models capable of mitigating atmospheric-based signal-degradation effects. These models consist of two main components: the space and time-varying nature of the index of refraction in each region of the atmosphere and the corresponding RF signal-propagation effects themselves.

The radars at KREMS collect extremely accurate metric and radar cross-section data to characterize missiles traversing space as well as the atmosphere. Above an altitude of approximately 90 km, the gases are strongly ionized by solar radiation. This region is the ionosphere where free electrons and ions (both molecular and atomic) are present in roughly equal numbers. The distribution and dynamics of these particles in the ionosphere affect the propagation of electromagnetic waves and the corresponding radar measurements of objects within (up to 2000 km altitude) or above the ionosphere. The propagation of radar (and radio) waves is affected by the electron density. In addition, there are detailed anomalies in the ionosphere related to the Earth's magnetic field and, in some instances, the seasons.

Since the amount of refraction in an ionized layer depends strongly on the frequency of the electromagnetic wave traversing the layer, it is expected that large differences in refraction will be observed between frequencies. With ALTAIR VHF, significant refraction can take place. With ALTAIR UHF, much less refraction is noted. The refraction effects of the ionosphere at VHF are nearly 100 times greater than at L band (TRADEX). This differential refraction phenomenon results in a *range delay* between UHF and VHF when range is measured on the same target at the same time. When ALTAIR views satellites at the horizon, the VHF range delay can be as large as 5 km because of the increased amount of atmosphere present along the radar wave's line of propagation.

During the 1960s and the early 1970s, an effort was initiated to model the effects of the changing atmosphere (space weather effects for the ionosphere and terrestrial weather effects for the neutral atmosphere) on RTS radar measurements. The goal was to improve the accuracy of the radar data. The models developed for both the ionosphere and the neutral atmosphere were designed to create a better estimate of target position by removing the atmospheric effects that produce a distorted apparent target position. RF propagation effects include elevation-angle bending, range delay, Doppler frequency shifts, polarization rotation, frequency spreading, and rapid amplitude and phase scintillation. The RTS atmospheric models focused on correcting for the effects that are responsible for radar-range (time delay) and elevation-angle bias errors. Ionospheric modeling is discussed in greater detail in another article in this issue.

The Middle Period (1975–1992)

Millimeter-Wave Radar

In 1977, discussions between Lincoln Laboratory and the Army's Ballistic Missile Defense Advanced Technology Center (BMDATC) 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 radar development. The radar (shown under construction at Roi-Namur Island and as it exists today in Figure 10) had a variety of goals and offered many challenges. The Army was using millimeter-wave seekers in interceptors, such as the Patriot, and wanted to collect a signature database on ballistic missiles. There was also interest in developing components for operation at short radar wavelengths. BMDATC and the space community 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 sufficient 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.

FIGURE 10. The radome surrounding the MMW radar is being erected around the radar during construction. The right image shows the radar as it appears today surrounded by its radome.

Particularly at 95 GHz, the high loss of RF power per unit length of waveguide presented severe problems. Combining the output of two tubes proved impractical because the loss of the combining network nearly equaled the power enhancement 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 excessively high.

A second major challenge was the design of the antenna. With the limited power of the system, a large 13.7 m antenna was needed to achieve the required sensitivity. The antenna was designed to be an extremely rigid structure, and great attention was paid to maintaining it at a uniform temperature in order to achieve adequate surface tolerances. The MMW radar beamwidths (0.043° and 0.014°, respectively) are very small even compared to the narrow ALCOR beam, which itself had proved difficult to point. With the advances in trajectory-extrapolation algorithms and calibration that took place, the millimeter-wave radar was able to acquire targets very reliably and achieve angle accuracy typical of a good optical telescope.

The MMW radar became operational in 1983. Soon thereafter, the radar became the premier imaging system at RTS and, as discussed later in this article, continues to be heavily used by the space-object identification community. Its short wavelength greatly increases the number of scattering centers visible on tracked objects and contributes to the superb detail of the images. Its ability to measure miss distance or impact point on intercept tests also became very important to the BMD users.

By the late 1980s, radar signal processing technology had advanced enough to permit significant performance improvements to the MMW radar. Faster computers and digital signal processing equipment allowed full PRF real-time compression of the wideband pulses and real-time coherent integration to provide significant improvement in sensitivity.

In the early 1990s, the application of new quasi-optical techniques provided an outstanding sensitivity improvement to the 35 GHz microwave system. By moving the radiating horn close to the tube and then directing and refocusing the beam through free space 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 was also achieved. Figure 11 illustrates the configuration of the 35 GHz beam-waveguide system.

Other KREMS Upgrades

In 1983, a multistatic measurements system (MMS) was added to TRADEX. Remote receiving antennas were installed on the islands of Illeginni and Gellinam, about 40 km from Roi-Namur. Precise timing was established between the three sites by using phase for alignment, and extremely accurate tristatic measurements of range were obtained on reentry vehicles as they reentered the atmosphere. Absolute metric accuracies at RV pierce point (120 km altitude) as good as 12 m in position, 0.1 m/s in velocity, and 0.2 g in acceleration were demonstrated. L-band and UHF multistatic signature data were also obtained. The MMS system operated for 10 years and was shut down permanently in 1994.

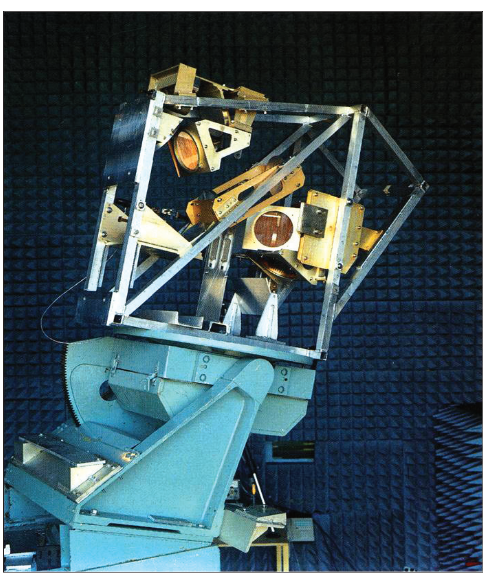
At TRADEX, pseudorandom, phase-modulated noise waveforms were added at S band in 1986 to emulate Soviet BMD radars. Real-time coherent integration and long continuous-wave waveforms were added at L band in the late 1980s for long-range acquisition and for tracking of deep-space satellites. A multitarget real-time tracker became operational in 1991.

In 1984, ALTAIR's original UHF klystron transmitter was replaced with an array of 24 traveling-wave-tube (TWT) transmitters that were combined through a series of hybrids, each consisting of eight in-parallel TWTs. As a result of the upgrade, the average power at UHF was more than doubled, greatly increasing the sensitivity of the system and enhancing the deep-space tracking capability.

In 1987, real-time ALCOR and MMW wideband imaging of reentry vehicles was demonstrated with the addition of the Kwajalein Discrimination System (KDS). KDS was a noninvasive stand-alone system consisting of a special-purpose signal processor that could generate as many as 60 images per second. The images were then provided to a set of candidate algorithms for discriminating reentry vehicles from other nonthreatening objects. A duplicate system existed at the Laboratory, known as the Lexington Discrimination System. The system in Lexington was run on ALCOR and MMW recorded data following the mission.

Army Optical Station

In the early 1970s, the Laboratory championed the creation of an Army Optical Station (AOS) at Roi-Namur. The AOS initially consisted of three passive infrared (IR) sensors and one laser radar. The passive IR sensors,



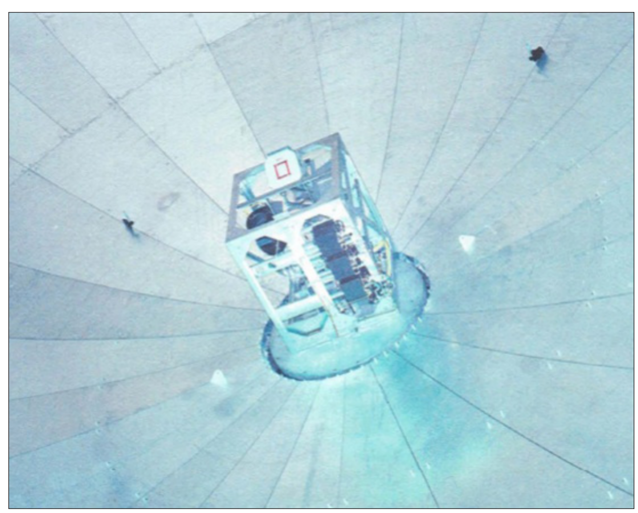


FIGURE 11. The MMW optical beam waveguide is shown being tested in the anechoic chamber at Lincoln Laboratory (left) and after installation on the radar (right).

Samso/Lincoln Tracking and Acquisition Infrared Experiment (SOLITAIRE) and GBM (Ground-Based Measurement), were originally fielded at White Sands Missile Range in New Mexico. Each was extensively reworked (SOLITAIRE by the Laboratory and GBM by General Electric) and installed in the AOS at Roi-Namur. Operations for both systems began in the mid 1970s. SOLITAIRE operated in the 8–12 μm band. GBM operated at 4 and 10 μm. The third passive sensor, a long-wavelength IR wideband radiometer, known as the Wide Angle Sensor, was also installed at Roi-Namur as part of the AOS.

The Laser Infrared Tracking Experiment (LITE) was a neodymium-doped yttrium aluminum garnet (Nd:YAG) laser radar operating at a wavelength of 1.064 μm. LITE began operations at Roi-Namur in 1977. The LITE system utilized direct detection and operated at a fixed 10-pulse per second pulse-repetition frequency. The main receiving optic was a 56 cm diameter aperture Cassegrain telescope with a 15% obscuration factor. The laser receiver used a silicon avalanche photodiode with an effective field of view of 325 microradians. The system had a range resolution of 3 m and angular resolution of 30 microradians. The system was housed in a 5.5 m dome. Figure 12 contains a photo of the Army Optical Station as it existed in the late 1970s. The LITE system was operated at Roi-Namur through June 1981. Laser radar cross-section data were obtained on a number of reentry vehicles during the four years of operation.

Circa 1980, Photo-Sonics Inc. built the Super Recording Automatic Digital Optical Tracker (Super RADOT) system, one of the most capable tracking optics mounts ever built, for the Reagan Test Site. Six of these extremely agile, heavy-duty optical tracking mounts were built for RTS, each with a 1000 lb sensor payload capacity, making the Super RADOT well-suited to a wide variety of sensor configurations. The Super RADOT systems were strategically dispersed to islands around the Kwajalein Atoll to achieve geometrically diverse viewing. Each site's optical measurements fed a triangulated optics solution that provided RTS customers, such as the U.S. Air Force ICBM test program, extremely accurate reentry vehicle trajectory reconstructions that were used to assess the accuracy of the ICBM arsenal.

FIGURE 12. The Army Optical Station, shown here as it existed in the late 1970s, complemented the four radars on Roi-Namur.

Space Mission

In 1977, U.S. Space Command began to consider a network of radars in the Pacific Ocean, known as the Pacific Barrier, to detect and track new Russian and Chinese satellite launches on their initial revolution. Lincoln Laboratory proposed that ALTAIR, with its large power-aperture product, become the centerpiece of this system. U.S. Space Command, however, was unsure of both the surveillance scan that was proposed and the reliability of the system under 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 in November 1977 using a new, unique 75° bow-tie scan for acquisition of new foreign launches. During the three-month test period, ALTAIR tracked more than 6000 resident space objects and was found to be far more successful at detecting and tracking new foreign launches than the Air Force had thought possible.

Because of these excellent results, ALTAIR was modified to conduct deep-space tracking and detection of new foreign launches for U.S. Space Command. New computers, waveforms, and signal processing techniques were installed as part of these modifications. To this day, ALTAIR continues to be the most heavily utilized radar at RTS, supporting space activities for 128 hours per week. In addition, ALTAIR is prepared twenty-four/seven for detecting and tracking new foreign launches from Asia.

The value of wideband data for identification of space objects was recognized by the space surveillance community in the early 1970s after ALCOR generated its first satellite image on the Soviet Union's *Salyut* satellite. By collecting wideband data and forming ISAR images, Lincoln Laboratory was able to provide size and shape information on resident space objects at ranges much greater than the best diffraction-limited optical telescopes. By 1986, ALCOR was able to generate images of orbiting satellites in near real time. By 1988, MMW had demonstrated even higher-resolution near-real-time imaging. In the mid-1980s, over 60 image sets per year on high-interest satellites were generated at KREMS and transmitted via an encrypted link to the Air Force Space Command at Cheyenne Mountain, Colorado. Today, of course, images can be generated in real time and more than 300 image sets are provided per year. As will be discussed in the next section, MMW is the primary satellite-imaging sensor because of its vastly improved resolution over ALCOR. Figure 13 depicts the relative location of objects in space and the role of the KREMS sensors in monitoring these objects.

In the early 1990s, the RTS sensors successfully participated in several space-debris measurement campaigns in support of the effort to determine the debris population and characterize debris objects not contained in the Space Surveillance Network catalog. A much more comprehensive look at the space mission at Kwajalein appears in an accompanying article in this *Journal*.

Another key use of the KREMS radars, in particular ALTAIR, in the space application has been to provide detailed understanding and modeling of the ionosphere. As ALTAIR single-frequency tracking requirements expanded for space surveillance purposes, a first-order vertical ionospheric range-delay model was developed. Later, a more accurate ionospheric correction model was developed using a two-frequency track at VHF and UHF. In the 1990s, an even more precise model driven by inputs from real-time Global Positioning System (GPS) measurements was developed and remains in use today. Ionospheric modeling is discussed in more detail in an accompanying article in this issue.

The Strategic Defense Initiative Era

In 1983, President Reagan announced the beginning of the Strategic Defense Initiative (SDI). His thesis was that international stability could be better achieved by deploying a leak-proof BMD system than by continuing along the path of mutually assured destruction. To accomplish this formidable task, he directed the beginning of a long-term research and development effort. Large amounts of funding were provided to reinvigorate the missile defense effort and a new organization, the Strategic Defense Initiative Organization (SDIO), was formed in January 1984 to manage and direct the program. To help lay out SDIO's course of action, BMD's Defensive Technologies Study (DTS) was conducted with strong participation from several Laboratory staff members. The DTS resulted in two major recommendations. First, a multilayer defense should be used to achieve low leakage. Second, to complicate the design and use of countermeasures, several different types of sensors (microwave radars, laser radars, and passive IR sensors) should be employed for detection, tracking, and discrimination. The DTS then recommended a long-term research and development effort that would down-select the most promising technologies, which in turn would be the basis for future BMD architectures.

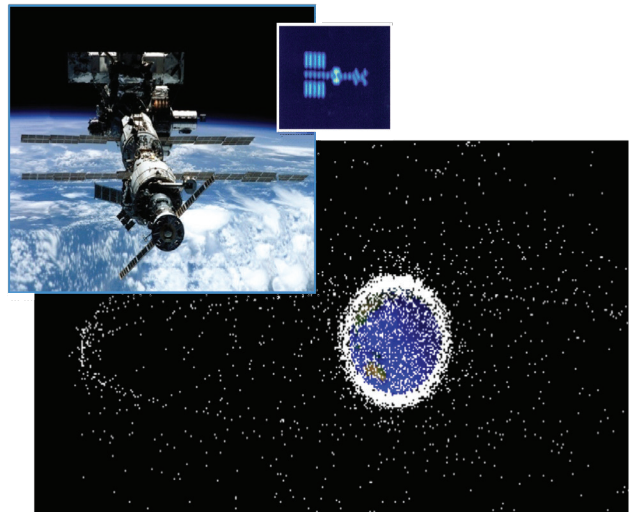


FIGURE 13. ALTAIR and TRADEX are used for determining and following the orbits of resident space objects while MMW and ALCOR, with their wider bandwidths, are used for identifying the objects by using radar-imaging techniques. The location of space objects, including active and defunct satellites as well as debris pieces, are cataloged and studied by using the RTS sensors. The insets show the International Space Station along with its simulated radar image.

Renewed attention was given to discrimination, and emphasis was placed on space-based sensors and directed-energy weapons. Now missiles were to be discriminated during boost phase, while separating from their booster, and during their entire midcourse flight as well as in reentry. These long timelines would allow radars to image objects and measure their motion with great precision. For resolved targets, space-based IR telescopes would measure thermal properties. At about the same time, the United States adopted a doctrine not to use nuclear-tipped interceptors. This doctrine significantly reduced an interceptor's lethal radius and required precision guidance of the non-nuclear interceptors.

Toward the end of the SDI era, two major events occurred that would change the direction of future BMD efforts. The first was the theater ballistic missile attacks launched by Iraq upon U.S. and allied forces as well as upon Israel during the Persian Gulf War in 1990. The second was the dissolution of the Soviet Union in December 1991. The main threat changed from a massive ICBM attack upon the U.S. mainland from the Soviet Union to a limited attack from any of several countries and to a theater attack upon U.S. and allied expeditionary forces. The shift in direction was made explicit by the Missile Defense Act passed by Congress in 1991. The act directed the Pentagon to develop and deploy theater BMD systems and to include participation of the Army, Air Force, and Navy in these systems. It also directed the Pentagon to pursue the development of an ABM treaty-compliant national missile defense (NMD) system. The ABM treaty, enacted in 1972, had limited the deployment of BMD systems to 100 interceptors located at a single site.

The Modern Period (1993–present)

KREMS Upgrades

Although no new radars have been put in place since the early 1990s, the KREMS radars have continued to evolve, and many new capabilities have been implemented. Major examples are discussed in the following paragraphs.

By the early 1990s, radar signal processing technology had advanced enough to permit continued performance improvement of the MMW radar. In 1994, continuing development of coupled-cavity TWTs allowed Varian to produce 35 GHz transmitter tubes with 50 kW peak power and 2 GHz bandwidth. In addition, two tubes could be operated in parallel for added sensitivity. At this same time, the 95.5 GHz capability was removed because of the difficulty in getting losses in the transmit system below acceptable levels and because of difficulties with atmospheric absorption in the 100 GHz frequency regime.

By the early 2000s, MMW required updates to many of its critical components. Its radome, which was no longer shedding water effectively nor drying quickly, caused increased losses at 35 GHz. Transmitter tubes were in short supply and, paradoxically, showed poorer performance when used units were replaced by newly manufactured units supposedly of the same design. To solve these difficulties, the radome was replaced with a unit made from new, low-loss, Gore-Tex® material, and an effort was instituted at Varian, the tube manufacturer, to develop a more robust design. The effort with Varian was highly successful, yielding a tube that not only was 4 dB better in efficiency, but was capable of 4 GHz bandwidth operation. To take advantage of this tube design, Lincoln Laboratory upgraded much of the RF circuitry to allow the entire system to operate at 4 GHz. Full operation at 4 GHz was realized in 2011. This very innovative work is described in a companion article in this issue.

In 1994, ALCOR's high-power amplifier was replaced with an extended-interaction klystron design. In addition, the replacement of ALCOR's original timing and data unit increased its PRF from 200 to 323 pulses per second, provided a second independent range tracker and sampling window, and enabled the implementation of real-time coherent integration.

In 1995, the ALTAIR UHF transmitter was upgraded from 24 to 32 TWTs, increasing its average power to 300 kW. As a result, ALTAIR was able to reduce the coherent integration time required to track deep-space targets and increase the overall number of satellites it could track in a given interval of time. In 1998, a major set of modifications to the ALTAIR VHF system was completed. A major measurements campaign has over the years made extensive use of these ALTAIR modifications.

Noteworthy upgrades at TRADEX include the following:

- In 1995, a stare-and-chase mode was added in support of a NASA study of space debris.
- The capability to do deep-space tracking was added so that TRADEX could be used as a backup to ALTAIR during ALTAIR down times.
- In 1998, TRADEX was officially recognized by Air Force Space Command as a Space Surveillance Network contributing sensor. TRADEX is now dedicated to deep-space tracking for at least 10 hours each week.
- In 1997, an S-band frequency-jump burst waveform was added to TRADEX in order to replicate a new syn-

thetic wideband waveform that was planned for a BMD upgrade to the U.S. Navy Aegis system. The data collected at TRADEX proved the utility and value of the new waveform, which has since been integrated into the Aegis BMD system.

In accordance with ARPA's original vision, the KREMS radars have undergone a continuous process of technology improvement and upgrade since they were constructed. The Lincoln Laboratory site personnel have traditionally included a cadre of radar and optical system engineers to support the effort to sustain the sensors at the forefront of technology. All of the KREMS radars have had their computers, recording and display systems, and much of the other hardware upgraded repeatedly with new technical capabilities over the years. For the most part, only the antennas and mounts remain unchanged from the as-built systems. The frequency coverage of the complete set of KREMS radars as they operate today is shown in Figure 6.

Kwajalein Mission Control Center

Prior to the 1990s, two separate control centers operated at Kwajalein, one controlling the KREMS sensors at Roi-Namur and the second, located on the island of Kwajalein, controlling the other KMR sensors. A microwave link between Roi-Namur and Kwajalein allowed the control centers to communicate with one another. In the early 1990s, the U.S. Army requested that Lincoln Laboratory assist them in integrating activities at the Kwajalein Missile Range by designing a single control center for both KREMS and the other sensors and systems of the range. In addition, an undersea fiber-optic ring was put in place between Roi-Namur and Kwajalein. The new control center, shown in Figure 14, named the Kwajalein Mission Control Center, was located on the main island of Kwajalein. It provided the capability to monitor the status of the mission, the local weather, and all of the KMR sensors, and to control all the radars, optical systems, and telemetry assets located within KMR.

FIGURE 14. Because of the success of the Kwajalein Mission Control Center project, shown above, Lincoln Laboratory was asked to serve as scientific advisor for the entire range. This role included responsibility for not only the KREMS radars but also the full suite of range optical sensors, the FPQ-19 and MPS-36 radars located on Kwajalein Island, and the telemetry sites located on Roi-Namur and Carlos Islands.

FIGURE 15. The Kwajalein Mobile Range Safety System monitors theater-class missile launches from its ship-based platforms.

Kwajalein Mobile Range Safety System

The need for a ship-based mobile range safety system at Kwajalein was recognized in the early 1990s as testing of theater-class ballistic missiles began. The Kwajalein Mobile Range Safety System (KMRSS) became fully operational in July 1996 (see Figure 15). The system was developed at Kwajalein under Laboratory supervision and enabled the range to safely conduct extensive testing of theater-class missiles launched from Wake Island or nearby atolls. The KMRSS contains two fully redundant command destruct systems capable of monitoring the missile flight path and initiating vehicle-destruct commands if the vehicle wanders too far off the nominal flight path. In addition, the KMRSS contains three telemetry collection antennas for gathering vehicle in-flight data from onboard sensors such as accelerometers.

Kwajalein Modernization and Remoting

The KREMS radars led the state of the art when developed and have been kept at the forefront of technology ever since. KREMS has truly been the remote research laboratory that was originally envisioned by ARPA, but the excellent performance was achieved with a large investment and operating cost. The original systems, which contained several hundred racks of custom hardware, were extremely complex and required substantial numbers of highly skilled engineering personnel to operate and maintain them. Supporting those personnel and their families at a remote island was too costly in an era of shrinking defense budgets.

In 1997, a major five-year effort, led by Lincoln Laboratory and based on the Laboratory's Radar Open System Architecture (ROSA) concept, was undertaken to rectify the situation. By using the ROSA architecture, the RTS radars were modernized, remotely operated from Kwajalein Island, and automated to reduce their operations and maintenance cost. For the KREMS radars, the transmitters, antennas, and receiver front ends were retained, but interfaced with new modular and open controllers based largely upon commercially available components and general-purpose computers. Built-in diagnostics were provided to remotely detect and isolate faults to the circuit-board level. Therefore, the capabilities of the new technology greatly reduced the required number and skill level of maintenance personnel. The hundreds of racks of custom hardware at each radar were replaced with eleven identical racks of mostly commercial off-the-shelf hardware, as shown in Figure 16.

Enforcing a common design for all the radars reduced the implementation costs and facilitated maintenance by a matrixed operations and maintenance organization. Remoting the operations and diagnostics from Roi-Namur to the main island of Kwajalein reduced intra-atoll transportation costs and further facilitated a matrix support organization. Software development was relocated to Lexington to allow additional reduction in support personnel.

Furthermore, the automated radars were capable of being driven by a script, which is generated by test planners located in the continental United States (CONUS), many of whom reside at Lincoln Laboratory. An extensive high-fidelity simulation capability, built into each radar, facilitates testing of the mission scripts. A complete development system, minus transmitter and antenna but with high-fidelity simulated targets, is maintained at the Laboratory and used to develop future block upgrades, troubleshoot problems observed at Kwajalein, and test repaired or replacement components and subsystems.

The first system upgrade was for ALCOR and was completed in 1999. Four weeks after the system's arrival at RTS, the ROSA components were installed and interfaced to the antenna and transmitter, and ALCOR was tracking satellites with its new "back end." The MMW system upgrade was delivered to site in October 2000, and MMW was able to track satellites only three weeks later. ALTAIR and TRADEX upgrades followed and became operational in 2002.

The final radars to be upgraded at RTS with the ROSA back end were the two MPS-36 radars. This upgrade, which was not considered part of the KMAR project, was completed in 2004.

Telemetry Consolidation

Prior to 2002, several telemetry receiving antennas were located on remote islands such as Ennylabegan. The location of these antennas increased the cost of operating and maintaining the systems because of the need to provide electrical power and marine or helicopter transportation for personnel who serviced and maintained the systems. Furthermore, most of the systems were in serious need of modernization and replacement. As a cost-savings measure, all the telemetry systems were consolidated on the islands of Kwajalein and Roi-Namur. The systems were entirely revamped, and new antennas and higher-sensitivity receivers were procured. Four fixed systems were installed on Roi-Namur and three fixed plus two transportable systems were positioned on Kwajalein. Real-time data decommutation was implemented so that the data could be used to improve situational awareness during operations. Data from all the systems were sent over fiber to a new centralized telemetry control center located on Kwajalein Island.

FIGURE 16. Reduced complexity and reduced costs were realized by having a common set of eleven racks for each radar.

Real-Time Open System Architecture

In 2006, the Laboratory began an effort to refresh its ROSA concept to include support for highly modular software, phased-array radar control, and flexibility to be used with optical sensors. The result of this effort is referred to as ROSA II*, a sensor-agnostic, Real-Time Open System Architecture that uses modern software middleware, component-based models, and modern software-development techniques. Abstraction of specific details of hardware and operating systems allows ROSA II to easily use different types of machines for control and signal processing, and to easily interface with a wide variety of existing hardware and software. System designers are able to use inexpensive commodity computers, rugged space- and power-efficient computers, or the traditional high-performance symmetric multiprocessing computers as appropriate for their application.

ROSA II has since been used to develop a number of test beds for operational systems, including an airborne, optical telescope real-time control and data processing system. Currently, this evolutional technology is being reapplied to the RTS radars by a Lincoln Laboratory team. In 2011, MMW performed its first mission using this new technology, and the other radars are in the process of being upgraded with ROSA II.

Net-Centric Architectures

Over the past several years, the Laboratory has focused significant attention on the development of net-centric, service-oriented software and hardware architectures

* The reader should note the change in the meaning of the ROSA acronym from Radar Open System Architecture to Real-Time Open System Architecture. This change reflects the transition from ROSA compatibility with only radar systems to its broadened usage to include other types of sensors, for example optical systems.

for use across multiple mission domains. The KREMS sensors, through the use of *sidecars,* which are discussed later in the MDA section of this article, have played an extremely important role in this development.

In 2006, the Laboratory began a three-year Extended Space Sensors Architecture (ESSA) advanced concepts technology demonstration (ACTD) to build and demonstrate a net-centric architecture using operational space surveillance network sensors, such as the KREMS sensors. One of the real-time demonstrations involved passing data from the ALTAIR and MMW radars to a central data-fusion node that hosted a set of net-centric services that ingested data and produced higher-level, fused information for monitoring deep-space satellites. This demonstration marked the first use of Net-Centric Enterprise Services for messaging to publish data from ESSA nodes and for consumption through user subscription.

In November 2008, the Laboratory carried out a first-of-its-kind demonstration on an Air Force Minuteman test. The demonstration cut across both the BMD and space situational awareness disciplines in order to illustrate how sensors and weapon systems can be integrated in a global context. The exercise demonstrated the ability to use net-centric services to expose and share sensor data and to broker in real time the control of sensors between multiple domains via machine-to-machine tasking. The actual experiment used a KREMS sensor that was conducting space surveillance activities, retasked it in real time to track a new missile launch, and then afterwards returned it to its original space surveillance task. More complex net-centric demonstrations have been carried out at KREMS in recent years.

RTS Distributed Operations

In 2006, Lincoln Laboratory led an effort to develop and deploy distributed-operation technology to allow control of RTS sensors and processes from remote locations in CONUS. It was called the RTS Distributed Operations program and its goal was to transform the range from a locally operated entity to a globally accessible national asset. A fundamental technical aspect of the program involved the distribution of mission operation tasks among remote locations, allowing the control center, sensors, and space operations to be run remotely. The key location for distributed operations was to be Huntsville, Alabama, where the headquarters of RTS's parent organization, the U.S. Army Space and Missile Defense Command/Army Forces Strategic Command (SMDC-ARSTRAT), is located.

Initial operational capability was declared in December 2011, and the range control facility in Huntsville is now operational for space surveillance activities and missile tests. The first reentry mission taken from the CONUS Huntsville control center was conducted in early 2012. This comprehensive effort is described in detail in a companion article in this issue.

Optical Sensors

By the 1990s, emphasis on flight testing began evolving toward Ronald Reagan's Strategic Defense Initiative missile defense testing. For the optical sensors, the mission support strategy naturally shifted toward supporting the needed phenomenology characterization of hypervelocity kinetic interceptor tests. The Super RADOT systems, put in place in the 1980s, were well-suited to this new role. In 1995, Lincoln Laboratory began a campaign to modernize and improve the optical sensors at RTS so that higher-quality and more period-relevant optical data could be collected.

New cameras and optical mount control systems (computer back ends) were installed at the sites around the atoll. The mid-wave infrared (MWIR) data-collection capability, which had been lost with the closure of the Army Optical Site in the 1980s, was restored with the deployment of two MWIR telescopes built by the Laboratory and a subcontractor. A high-speed, 1000-frame-per-second, visible camera was also deployed to the range. These enhancements made possible important optical data collects of high quality on the theater missile defense (TMD) phenomenology and intercept experiments that were conducted at RTS during the mid-to-late 1990s. In addition, the Laboratory also undertook to modernize the optical data processing for these sensors. The optical data processing was transitioned to Lexington by using a suite of software-based optical processing algorithms and infrastructure based upon general-purpose computers.

In the late 2000s, it was recognized that another refresh of the aging RTS optical instrumentation was needed, and in 2007 a multiyear optics modernization program was initiated. The optics modernization program's major technical objectives included enabling net-centric distributed sensor operation, upgrading optical sensors by eliminating optics obsolescence and analog media, reducing maintenance and sustainment costs, and upgrading planning and analysis tools. The project implemented a complete overhaul to the Super RADOT and ballistic camera optical systems. The upgrade included new ROSA II-based back-end control and data-acquisition software and computers for the optical sites, new digital cameras and telescopes, modern domes (see Figure 17), weather detection and protection capability for remote opening and closure of the domes, and remote operation for the optics sensors so that they may be controlled from CONUS. The optics modernization effort is nearing completion, and the first system has been accepted and declared operational. Slated for completion in 2013, the project delivers a fully modernized, state-of-the-art, optical sensor suite to RTS that will support demanding mission requirements for the coming decade.

Ballistic Missile Defense Organization Era

By 1992, the USSR had collapsed, USSR and U.S. strategic missile arsenals were reduced under Strategic Arms Reduction Treaties (START 1 and START 2), and theater missile proliferation was becoming rampant. The Scud missile, a derivative of the World War II German V-2s that had been further developed by the Soviets, had become the third-world weapon of choice. Scuds and Scud derivatives were used during the Middle East War of 1973, later in large numbers during the War of the Cities between Iran and Iraq, and extensively during the Persian Gulf War in 1990.

By 1993, there was a major redefinition of the goals of BMD and a consequent restructuring of the program. The BMD effort was redirected to deal with more limited threats against the territory of our nation and our allies and against deployed troops involved in theater engagements. The new goals were to (1) place primary emphasis on the development and acquisition of TMD for the protection of expeditionary forces, and (2) restructure National Missile Defense to a technology readiness program. Consequently, the program office was restructured and its name changed from the SDIO to the Ballistic Missile Defense Organization (BMDO). Research and development funding was reduced in accordance with these goals. The discrimination problem, although not fully solved, became more tractable because short-range missiles used in theater engagements generally do not carry light decoys. The ICBM threat was more limited in terms of numbers, and technology had surged ahead during the SDI years. But challenges in theater defense remained. Short timelines and the need to defend simultaneously against air-breathing threats (cruise missiles) make TMD problematic and difficult, even against short-range missiles.

Because ballistic missile attacks upon expeditionary forces can occur in a variety of geographic locations, no single armed service can develop a TMD system that is effective for all situations. Both land-based and sea-based systems are required. Thus, both the Army and the Navy became involved in TMD. Both services began developing systems that would operate at low altitudes as well as at high altitudes. To investigate signatures of putative countermeasures, the Laboratory, beginning in 1993,

FIGURE 17. The Super RADOT optical sites at Kwajalein are being upgraded with new domes and camera systems.

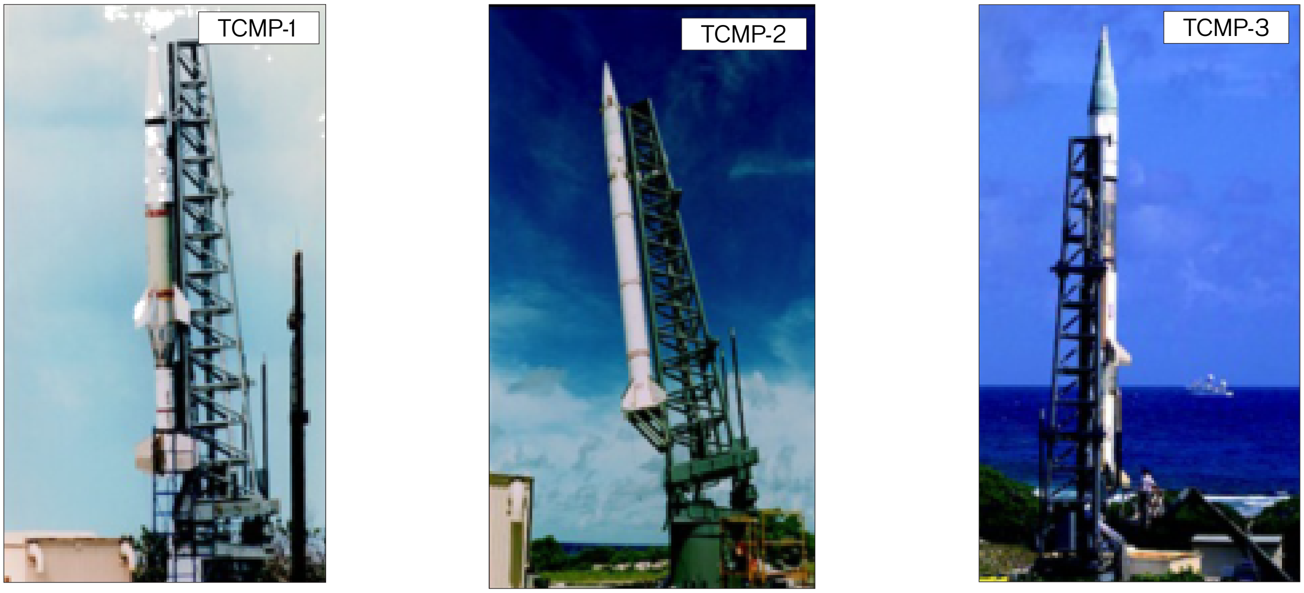


FIGURE 18. Theater Missile Defense (TMD) Critical Measurements Program (TCMP) missiles are launched from Wake Island. Here the missiles await launch on their rails.

conducted a series of well-instrumented threat-representative TMD field tests at RTS. The tests were known as the Theater Critical Measurements Program. Three campaigns consisting of two or three flights each were conducted. Figure 18 shows the TCMP missiles on the launch rail at Wake Island. The devices flown on these tests were designed and built by the Laboratory. The analysis of the test data led to new discrimination approaches.

The national missile defense effort was restructured into a technology readiness effort in the early 1990s, and to that end many tests were conducted at RTS with Lincoln Laboratory participation in the test planning, radar and optical data collection, data analysis, and performance evaluation. This work started during this period with the Exoatmospheric RV Interceptor System (ERIS) tests, continued later in the decade with intercept tests at Kwajalein of the Ground-Based Interceptor (GBI) system, and continued into the 2000s with exoatmospheric kill vehicle (EKV) interceptors fired from RTS's Meck island. One such EKV launch from March 2002 is shown in Figure 19.

Missile Defense Agency Era

In 2002, the BMDO was redesignated by the Secretary of Defense as the Missile Defense Agency (MDA) and given the task of deploying a single integrated Ballistic Missile Defense System (BMDS) with the capability to intercept missiles in all phases of flight, against all ranges of threats. An initial rudimentary version of the BMDS was deployed at the end of 2004. Current BMD technology provides powerful high-frequency, wideband, phased-array radars; infrared seekers; light, non-nuclear, hit-to-kill interceptors; and integrated command and control. Many additional flight tests were conducted throughout the 2000s at RTS to verify the appropriateness of interceptor designs and validate their performance in preparation for operational deployment of the systems. During these activities, RTS continued to be the primary location for collection of relevant data.

A tool kit of discrimination algorithms, under development since the 1960s, was assembled and tested. The challenge for discrimination is to design an architecture of discrimination algorithms that is sufficiently flexible and resilient to deal with evolving threats and countermeasures. With the advent of hit-to-kill interceptors, end-game discrimination is also needed. Discrimination information from a ground-based radar and from space-based IR sensors must be handed over to the interceptor seeker in a form it can interpret and fuse with its own discrimination data. The interceptor seeker must aim at a specific hit point on the missile in order to destroy it, and the ground-based radar and space-based IR sensors must assess the effectiveness of the intercept. The collection and analysis of performance data during combat to identify enhancements quickly are also needed.

In the early 2000s, RTS pioneered the use of sensor sidecars. These adjunct processors were initially installed on the KREMS radars for BMD research purposes. They were capable of tapping off radar data from the associated sensor in real time and running BMD processes and algorithms on the data in real time, without interfering with the operational in-line sensor processing. Many BMD radar data processing and feature extraction algorithms were tested and proven in a real-time environment by using this approach. After RTS validated the veracity and value of the sidecar approach, these devices were installed on other BMD relevant sensors, such as the forward-based radar test bed.

The implementation of sidecars on the KREMS sensors enabled sensor-fusion, real-time demonstrations to be conducted. The BMD fusion test bed (BFT) was created by networking the KREMS sidecars together with sidecars on other sensors, such as MDA's HALO-II optical aircraft. A system-level node, which received data from individual sidecars during live-fire missions, was created at the Laboratory in Lexington, and system-level decision architectures were demonstrated. Between 2002 and 2009, the BFT was used on more than 23 missions and served to demonstrate many fusion algorithms and architecture concepts.

FIGURE 19. An exoatmospheric kill vehicle (EKV) launch from Meck Island on Integrated Flight Test 8 was conducted on 16 March 2002.

Meteor Studies

Roughly a billion meteors, generated from comets heated by the sun, enter Earth's atmosphere daily, and their potential impact on spacecraft is of high interest to the space community. RTS radar systems, because of their high sensitivity and precise calibration, contributed new information on meteor phenomena in 1998 by gathering observations on the Perseid and Leonid meteor showers. These identified events take their names from the constellations from which they appeared to emanate.

Perseid data were collected by ALTAIR (at the request of the U.S. Air Force Office of Scientific Research) for the purpose of detecting head echoes (returns from the meteor itself combined with the ionized plasma around the head as it transfers energy into atmospheric heating). Later in the same year, after the Perseid observations demonstrated ALTAIR's capabilities for meteor detection, Leonid data were simultaneously collected by using ALTAIR and other Kwajalein sensors at both microwave and optical frequencies.

Most of these detected particles were small meteoroids (i.e., meteors in solar orbit), typically the size of a grain of sand, which are captured by Earth's gravitational field and destroyed in the atmosphere before they reach the Earth's surface. The collision of a meteoroid and a satellite can result in significant damage, including cratering of the satellite surface or plasma and electromagnetic pulse generation, which can lead to electronic noise, sudden current and voltage spikes, and onboard computer anomalies.

When meteoroids enter Earth's atmosphere, they ionize neutral air molecules and atoms, creating localized plasma regions. Ionization takes place in the ionosphere between approximately 80 and 140 km in altitude. Meteor ionization in the ionosphere is classified into two categories—the ionized meteor trail and a localized spherical ionized region surrounding the meteoroids, the head. The trail is cylindrical in shape and can be kilometers in length and meters in diameter. The trails are stationary and typically last for about one second. The localized spherical ionization surrounding the meteor produces a much weaker type of reflection known as the head echo, with radar cross sections that depend on the size and shape of the meteor.

For the Perseid meteor shower, data were recorded at ALTAIR with the antenna pointed in the direction of the oncoming shower. About 700 head echoes of oncoming meteors were detected in 11 minutes of observation. The detection altitude, velocity along the line of sight, and radar cross section were noted for each meteor, and histograms of these quantities were produced. The histograms were in good agreement with earlier published data, with the exception of the radar cross-section data. The distribution of cross sections was skewed lower than other results in the literature because ALTAIR has extraordinary sensitivity and was able to detect a greater number of smaller-diameter meteors.

Summary

The rich history of accomplishments discussed above, illustrate that Lincoln Laboratory's work at RTS has indeed been pioneering and cutting-edge. Over the 50 years of the Laboratory's involvement, the focus of the efforts at Kwajalein has continued to evolve and adapt to the changing needs and priorities of the Department of Defense and of the test and space communities. Throughout these changing times, the pursuit of innovation has remained steadfast, leaving in place a strong legacy of technical achievements. Many advances in technology had their origins at RTS, and these advances have not only benefited the government but also found their way into other applications and the private sector.

In the future, significant changes and technical challenges will emerge at RTS, and the Laboratory is prepared to address them with great enthusiasm. As the RTS program begins its sixth decade, the Laboratory has strong confidence that these challenges will result in a new round of significant technical achievement.

Over 400 Laboratory scientists and engineers have served at Kwajalein during the past 50 years. Many are among the most accomplished in our nation. The opportunity to gain hands-on experience with large sensor systems has indeed provided unique career-advancing benefits. Many have used a tour of duty at Kwajalein as the stepping-off point for long and illustrious technical careers at the Laboratory, within the government, and within industry. The contributions of those that have served at Kwajalein in the past will inspire the next generation of Laboratory staff to serve at RTS and to address the future challenges.

Acknowledgment

In compiling the 50 year history of the Lincoln Laboratory involvement at the Reagan Test Site, the authors drew heavily and freely from past publications pertaining to the Laboratory's work at Kwajalein, specifically from the publications referenced below. In many cases, much more detail on the Laboratory's work at Kwajalein can be found in these documents. ■

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Kenneth R. Roth is a principal staff member assigned to the Air and Missile Defense Technology Division. Prior to this position, he was the head of the division, overseeing the Navy air defense programs, all aspects of the Laboratory's broad range of ballistic missile defense activities, and the Reagan Test Site program. He received bachelor's, master's, and doctorate degrees in aeronautical and astronautical engineering from the University of Illinois. When he joined Lincoln Laboratory in 1968, the focus of his work was the analysis of radar observables and the development of ballistic missile defense discrimination techniques. In 1980, he became the leader of the Analysis Techniques and Interpretation Group, responsible for exploitation of radar intelligence data from sensors such as Cobra Dane and Cobra Judy. In 1993, he was appointed associate head of the Ballistic Missile Defense Technology Division, responsible for a broad range of activities relating to test and evaluation, intelligence data exploitation, sensor and flight test hardware design and development, sensor test planning and data collection, and data analysis and interpretation. He served two tours at the Reagan Test Site, the first as a staff member from 1971 to 1974 and the second as the Lincoln Laboratory site manager from 1985 to 1990.