Radars for the Detection and Tracking of Cruise Missiles

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The advent of the modern cruise missile, with reduced radar observables and the capability to fly at low altitudes with accurate navigation, placed an enormous burden on all defense weapon systems. Every element of the engagement process, referred to as the kill chain, from detection to target kill assessment, was affected. While the United States held the low-observable-technology advantage in the late 1970s, that early lead was quickly challenged by advancements in foreign technology and proliferation of cruise missiles to unfriendly nations. Lincoln Laboratory's response to the various offense/defense trade-offs has taken the form of two programs, the Air Vehicle Survivability Evaluation program and the Radar Surveillance Technology program. The radar developments produced by these two programs, which became national assets with many notable firsts, is the subject of this article.

In 1977, the Defense Advance Research Projects Agency (DARPA) requested that Lincoln Laboratory develop and lead a new program in air defense against cruise missiles. The initial focus of the work at Lincoln Laboratory was to quantitatively assess and verify the capability of U.S. cruise missiles to penetrate Soviet air defenses. Two principal areas of technological concentration emerged from this study: (1) understanding and modeling the environmental factors, such as propagation and clutter, that directly affect a defensive system's capability to detect and engage a low-altitude, low-observable air vehicle; and (2) measuring, developing, and demonstrating the radar and infrared detection technologies required to address this difficult threat. Between 1982 and 1986 the program sponsorship was transferred from DARPA to the U.S. Air Force, and in 1983 this program was renamed the Air Vehicle Survivability Evaluation program (AVSE), which continues to this day. This article gives a short history of the AVSE program and several of the radar developments that resulted from the program, including the Airborne Seeker Test Bed.

In 1983 the U.S. Navy (particularly the Naval Sea Systems Command and the Office of Naval Research) began sponsorship of a Lincoln Laboratory program, complementary to the AVSE program, which was originally focused on the U.S. ship-based defense against foreign antiship cruise missiles. The major development of this program, called Radar Surveillance Technology, was the Radar Surveillance Technology Experimental Radar (RSTER). Recently, the RSTER mission was modified to address issues related to the operation of airborne radars, including applications to the Air-Directed Surface-to-Air Missile (ADSAM) concept. A later section of this article gives a short history of the Radar Surveillance Technology program and describes the development of the RSTER system.

Radar Development: Air Vehicle Survivability Evaluation

The purpose of the AVSE program is to understand and predict the survivability of U.S. air vehicles against existing or new enemy air defenses. A process, illustrated in Figure 1, was developed early in the program to provide these predictions of air-vehicle survivability. Close ties with the intelligence community helped to define the enemy air-defense-system pa-

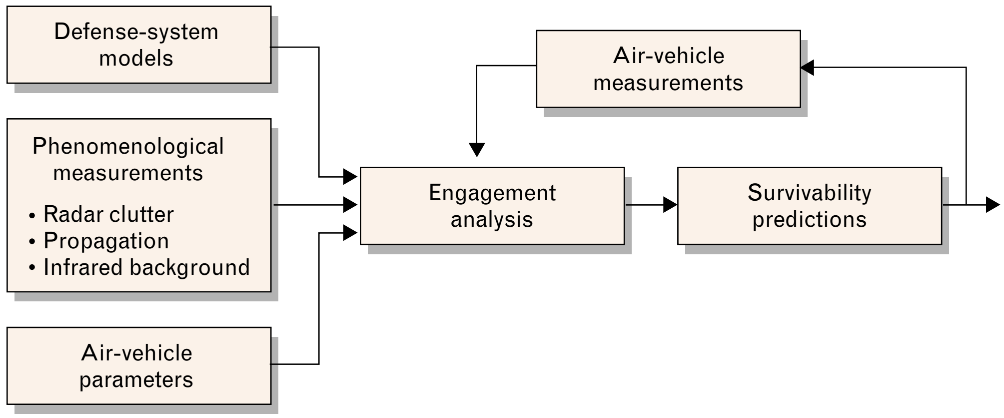

FIGURE 1. Air-vehicle-survivability prediction process. The engagement-analysis computer program combines the measurement data and defense-system models to predict the survivability of the air vehicle in the defense-system engagement scenario. The accuracy of the prediction is verified by using airborne experimental captive-carry tests.

rameters; vehicle radar cross-section measurements and models were generally provided by the U.S. industrial developers via their government sponsors. Lincoln Laboratory's role was to build phenomenological models and predictive survivability models, as needed. Over the years this role has necessitated the need to develop instrumentation systems and to use these systems and sensors in air-vehicle measurements. These measurements are key to a confident prediction process since they are subsequently compared with system-analysis predictions. Over the last twenty years the system-analysis models and methodology that have been developed have greatly benefited from the corrective process afforded by these measurements. Much of the effort of the AVSE program is classified, however, and that portion is not discussed in this article.

The effectiveness of defense against cruise missiles is highly dependent on the radar cross section of an air vehicle versus frequency. Figure 2 presents a notional representation of the variation in radar cross section of an air vehicle versus frequency. Note that the radar cross section of an air vehicle is lower at S-band and X-band (the track/kill portion of the kill chain) than at HF, VHF, and UHF (the surveillance portion of the kill chain). Modern methods, such as airframe shaping and the use of absorbing material, have been used to considerably reduce the cross sections of air vehicles. These techniques are particularly effective at higher frequencies. The effect of an air vehicle's reduced radar cross section is a reduction in the air defense's effective battle space. Reduced radar cross section also lends itself to the employment of various electronic countermeasures.

The early years of the AVSE program tended to focus on phenomenology and analytic modeling of Soviet defenses; the middle years saw growing efforts in field instrumentation and field testing. Most of the recent work has emphasized missile seekers, countermeasure and counter-countermeasure issues, and infrared systems. The Lincoln Laboratory infrared sys-

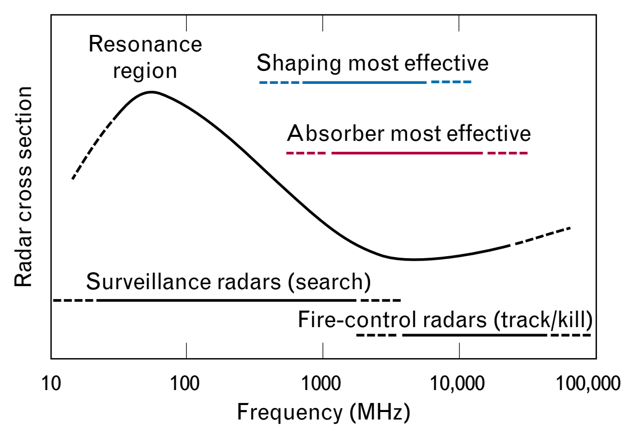

FIGURE 2. Variation with frequency of the radar cross section of a typical air vehicle. The dashed extensions suggest the cross-section behavior for very low and very high frequencies, where radar wavelength becomes much longer or much shorter, respectively, than the physical length of the air vehicle. The figure also shows the frequency domains occupied by most surveillance and fire-control radars.

FIGURE 3. Phase Zero radar equipment in Dundurn, Saskatchewan, Canada. X-band clutter surveys were performed at more than one hundred sites.

tems associated with the AVSE program, namely, the ground-based infrared measurement sensor and the pod-mounted airborne infrared imager, are mentioned here for completeness but are not discussed extensively in this article (since the focus here is on radar). Chronologically, the AVSE program first emphasized the surveillance aspect of air defense, then the fire control (target tracking) aspect, and currently the target intercept (kill) aspect.

Monostatic Clutter Measurement
(Phase Zero and Phase One Radars)

An initial AVSE program objective was to accurately predict the performance of surface-sited radars against low-altitude targets. This capability required a greatly improved understanding of clutter phenomenology, which led to plans for a major new program of ground-clutter measurements.

This new program occurred in two phases: Phase Zero, a pilot phase that involved a small noncoherent X-band radar; followed by Phase One, the full-scale coherent-radar data-collection program at five frequencies (VHF, UHF, L-band, S-band, and X-band). Figure 3 shows a photograph of the Phase Zero measurement instrumentation, and Figure 4 shows a photograph of the Phase One measurement instrumentation. The Phase One radar was a computer-controlled instrumentation radar specifically designed for ground-clutter measurements. It had high data-rate recording capability and could maintain coherence and stability sufficient for 60-dB two-pulse-canceler clutter attenuation in post-processing.

Because Soviet-type terrains were of principal interest, and the prairie provinces of Canada provided a good analog of this terrain, measurements were primarily made in Canada with the assistance of the Canadian government. In addition, measurements were made at selected sites in the United States for a total of forty-two Phase One sites. These measurements resulted in a large land-clutter measurement database. This calibrated clutter database was used to develop an empirically based clutter-modeling capability. A new site-specific approach was adopted in model development, based on the use of digitized terrain elevation data to distinguish between visible and masked regions to the radar. Extensive analysis of the new clutter-measurement database led to a progression of increasingly accurate statistical clutter models for laying down the clutter strengths in visible regions of clutter occurrence [1, 2].

Figure 5 shows mean and median clutter reflectivity as a function of depression angle at the radar

FIGURE 4. Phase One radar equipment at Lethbridge, Alberta, Canada. Clutter surveys at five different frequencies were performed at forty-two different sites.

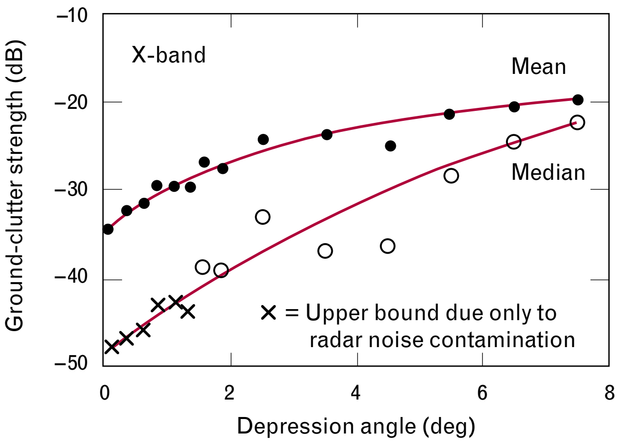

FIGURE 5. General variation of ground-clutter strength with depression angle.

antenna for typical rural terrain, observed at X-band frequency with horizontal transmit and receive polarizations. Each plotted point is the result of a combination of many similar measurements (e.g., on the order of hundreds) in general rural terrain. It is only by means of such extensive averaging that the ground-clutter dependencies with angle emerge empirically to provide a general predictive capability. Both mean and median are observed to rise monotonically with increasing depression angle, and the spread in low-angle clutter-amplitude statistics is defined by the mean-to-median ratio that decreases rapidly with increasing depression angle. The curves in Figure 5 illustrate that at low depression angles near grazing incidence, clutter is a widespread spikey process dominated by discrete sources, but with increasing angle, spread diminishes and the process gradually begins to transition to one of homogeneous Rayleigh statistics, which are more typical of clutter observed from airborne regimes. (Airborne clutter measurements were made by Lincoln Laboratory in 1980 by utilizing an airborne X-band and L-band synthetic-aperture radar system from the Environmental Research Institute of Michigan. These measurements are not detailed in this article.)

Low-Angle Propagation Measurements

Propagation of radar signals can affect radar target and clutter returns, especially at low frequencies (e.g. VHF). In 1982, to understand this phenomenon better and to improve prediction models, Lincoln Laboratory built a propagation measurement instrumentation module that could be conveniently carried on a helicopter. In a typical experiment, the helicopter-borne instruments recorded received signal strength versus height from the radar of interest, at various ranges and azimuths around the radar. Measured terrain profiles were used in conjunction with reflection and diffraction theory to deduce the relative importance of each effect. The principal insights of the propagation work are incorporated in the Lincoln Laboratory Spherical Earth with Knife Edge (SEKE) model [3], which is used along with some more exact models in AVSE system analyses.

Fire-Control Experiments

In the early 1980s many defense planners were interested in the performance of fire-control radars, especially the Soviet SA-10 Flap Lid radar, against low-flying cruise missiles. This interest led to Lincoln Laboratory's involvement in two X-band tracking systems: the L-X radar and the FLEXAR radar. The AN/TPN-19 aircraft-approach radar, derived from the Raytheon prototype Hostile Weapons Location System, was modified for Lincoln Laboratory and delivered in 1982 as the L-X radar. It was a dual-frequency instrumentation system that collected signature and metric data on a variety of targets, and participated in twelve air-launched and ground-launched cruise-missile tests at the Dugway, Utah, test range in 1983 and 1984. Of special note was the vertically polarized X-band system that employed a reflector, a small phased array, and a monopulse feed, and formed a pencil beam (2° azimuth, 1.5° elevation angle).

There was much debate on how well the SA-10 Flap Lid's receiver performed in canceling ground clutter, and this capability was a significant factor in the system's ability to track low-altitude, low-observable targets. Since the United States had no direct access to the SA-10, the next best thing was to look for existing U.S. systems to evaluate the technology limits. The Hughes Aircraft Company had developed an experimental X-band, phased-array, fire-control radar for Navy shipboard applications. This radar, called FLEXAR, had state-of-the-art clutter-rejection capability. The Laboratory conducted field experiments with the FLEXAR system from 1983 to 1986.

FLEXAR was first used to characterize the clutter-rejection capability of high- and medium-pulse-repetition-frequency ground radars, and it added much needed real-world data to the Flap Lid clutter-cancellation debate. It was later used at Eglin Air Force Base, Florida, and at the China Lake, California, test range to evaluate U.S. electronic countermeasures against Soviet radars.

Another asset used to investigate the Flap Lid type of radar was the Waveform Simulator (WFS), which was originally developed by the Georgia Tech Research Institute for the Army Missile System Intelligence Command's CROSSBOW office, now called the Threat Systems Office. The WFS was then transferred to Lincoln Laboratory in 1990, where it has been used extensively as an illuminator for the Airborne Seeker Test Bed (ASTB) and in conjunction with the ASTB to evaluate the SA-10's potential system performance in clutter.

VHF Instrumentation Radar

Even before the development of the modern cruise missile, the Soviets had deployed thousands of VHF ground radars for aircraft surveillance and early warning. In 1983 the Laboratory initiated a competitive procurement for a VHF test-range instrument, in order to have an instrumentation-quality VHF radar to investigate the issues associated with low-frequency surveillance. General Dynamics of Fort Worth, Texas, delivered this VHF radar in 1985. It is a substantial but transportable radar featuring a 150-ft-wide antenna, as shown in Figure 6, and it can emulate Russian VHF radars such as Tall King and Spoon Rest (although it has superior electronic performance). What is particularly interesting, especially for clutter and electronic-countermeasure measurements, is that the VHF instrumentation radar can selectively transmit in horizontal and vertical polarizations and receive in both polarizations simultaneously. The radar has undergone a number of modifications and upgrades, including extensive waveform changes and the addition of a sidelobe canceler, to enhance its usefulness to the test community.

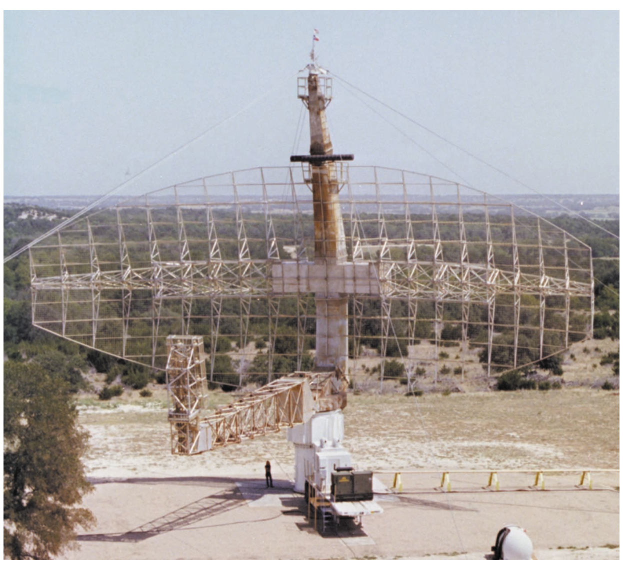

FIGURE 6. The VHF instrumentation-quality radar used as a test bed to investigate problems in low-frequency surveillance, including target detection, clutter, and electronic-countermeasure performance. The person standing to the left of the pedestal indicates the very large size of this radar.

The principal contribution of the VHF instrumentation radar has been the development of realistic appraisals of VHF radar capability against low-observable air vehicles. VHF-radar performance predictions are rich in phenomenological questions relating to low-elevation-angle propagation and ground-clutter effects, and this radar was a national test bed to explore and define these effects.

Airborne Seeker Test Bed

The Airborne Seeker Test Bed (ASTB) is an aircraft-mounted instrumentation system used for developing and evaluating missile-seeker technology. Since the initial flight in March 1990, the ASTB has been used on 550 flights to collect radar and infrared data critical for understanding air-defense issues.

The impetus for the ASTB came from a controversy within the defense community, including Lincoln Laboratory and Raytheon, over the performance of the improved HAWK surface-to-air missiles and Sparrow air-to-air missiles in live firings against U.S. cruise missiles in the early 1980s. The expense of missile live firings does not permit the collection of a sufficiently large database to completely assess the effectiveness of missile seekers in all scenarios of interest. Furthermore, it is challenging to represent the performance of a seeker in a realistic electromagnetic environment through computer modeling or hardwarein-the-loop hybrid simulations. A key challenge is to capture the effects of propagation and clutter, and the interaction of electronic countermeasures with these phenomena. Therefore, Lincoln Laboratory specified an airborne missile-seeker instrumentation platform to directly capture the performance of missile seekers in complex environments, and to record instrumentation-quality data to support the development of more realistic computer models of seeker performance and the environment.

Construction of this instrumentation platform began in 1986 with the award of a contract to Raytheon Missile Systems Division in Bedford, Massachusetts, to build the primary sensor—a calibrated, dual-polarization, eight-channel, X-band, semiactive instrumentation system. The Laboratory developed the airborne data-recording and processing system, and added additional measurement support systems, including an 8-to-12-μm infrared camera, a Global Positioning System (GPS) receiver, and a pod-mounted C-band beacon tracker. By providing information on the angular position of the X-band seeker antenna, the position of the ASTB aircraft, and the position of a C-band beacon-equipped target, these auxiliary systems bring an element of scientific control to airborne missile-seeker measurements. By March 1990 the system was fully integrated into a Dassault Falcon-20 twin-engine jet aircraft, shown in Figure 7.

The purpose of the ASTB was to produce high-fidelity test data related to semiactive radar-seeker phenomenology, target scattering characteristics, electronic countermeasures, electronic-counter-countermeasure technique development, and missile-seeker acquisition and tracking performance [4]. The ASTB radar receiver operates with ground-based radars such as the HAWK missile illuminator, the special-purpose WFS radar, or modern airborne radars, including those on the F-15 and F-16 aircraft. These radars track the target aircraft and provide the illuminating radar signal received by the ASTB. Typically, the ASTB climbs or dives toward a target aircraft on a proportional navigation collision course. The effects of target cross section, ground clutter, and electronic countermeasures have been evaluated in intercept scenarios for a variety of air vehicles at national test ranges, including White Sands Missile Range, New Mexico; Eglin Air Force Base, Florida; the Utah Test and Training Range, Nellis Air Force Base, Nevada; Edwards Air Force Base, California; and the Naval Air Warfare Center's Weapons Division Test Ranges at China Lake and Point Mugu, California.

FIGURE 7. Dassault Falcon-20 twin-engine jet aircraft. This platform was the original Airborne Seeker Test Bed (ASTB).

In the study of cruise-missile offensive and defensive interactions, such as semiactive missile intercepts and towed-decoy and terrain-bounce electronic countermeasures, it is desirable to understand not only the monostatic clutter but also the bistatic clutter characteristics and their effects on radars and radar seekers. In the development of the bistatic clutter models, however, neither the existing bistatic clutter data nor the theoretical bistatic clutter models were found to be adequate. The main reason is that the bistatic clutter is more difficult to investigate than the monostatic clutter because of additional complexities such as transmitter/receiver clutter-cell geometry and increased number of bistatic angular variables, resulting in increased efforts and costs for measurements.

In 1990, as interest increased on the development of the bistatic clutter models in order to understand the operation of missile seekers against low-flying missiles, Lincoln Laboratory, with DARPA sponsorship, carried out extensive bistatic clutter measurements by using advanced test assets and supporting equipment. The ASTB was used in conjunction with the WFS or with a terrain-bounce antenna mounted on a Lear Jet as a transmitter to gather bistatic clutter over a wide range of bistatic angles and in a variety of terrain types.

The ASTB was instrumented to properly guide the aircraft position and antenna pointing during the measurements with a GPS satellite and a C-band beacon-tracking radar in range and angle. Both the GPS and beacon-tracking radar data were used in post-mission analyses to reconstruct target position as well as antenna position and pointing. With these test assets and a systematic test plan to cover the bistatic angles of interest, it was possible to gather bistatic measurement data for the development of the bistatic clutter models.

From these measurements the X-band bistatic clutter models were developed. As examples, Figure 8 shows a land-clutter model of a rough desert terrain from White Sands Missile Range and a sea-clutter model (sea state 3) from the Point Mugu Naval Air Warfare Center test range. These models may be used to predict the clutter effects on the operation of missile seekers against low-flying cruise missiles.

Electronic countermeasures, known as endgame countermeasures (EGCM), can be used against missile seekers during the last few seconds before target intercept. Techniques known as counter-endgame countermeasures (CEGCM) have been postulated to allow a missile to continue to guide to the target. The ASTB has been used to collect bistatic radar target and clutter data, as discussed in previous sections, and to support the development of CEGCM concepts. In December 1995, a high-speed digital signal processor was added to the ASTB to process radar returns and control the pointing of the instrumentation seeker. This effort culminated in the first real-time demonstration of a class of radio-frequency (RF) CEGCM techniques in June 1996 at White Sands.

The success of the ASTB led the U.S. Air Force sponsor to request the expansion of system capability. In late 1993, the ASTB performed its last mission on the Falcon-20 aircraft, and the system was installed on a Gulfstream II twin-engine jet in fall 1994. The Gulfstream II is a more capable aircraft in terms of payload and endurance. Up to five external sensor pods can be carried on the aircraft, and it has room for additional sensor operators. Figure 9 shows the configuration of the ASTB on the Gulfstream II aircraft. Modifications have been recently made to extend the frequency of operation of the ASTB, and several additional RF and infrared seekers are being prepared for future tests.

In May 1995, the ASTB mission was augmented to collect data on infrared-seeker phenomenology

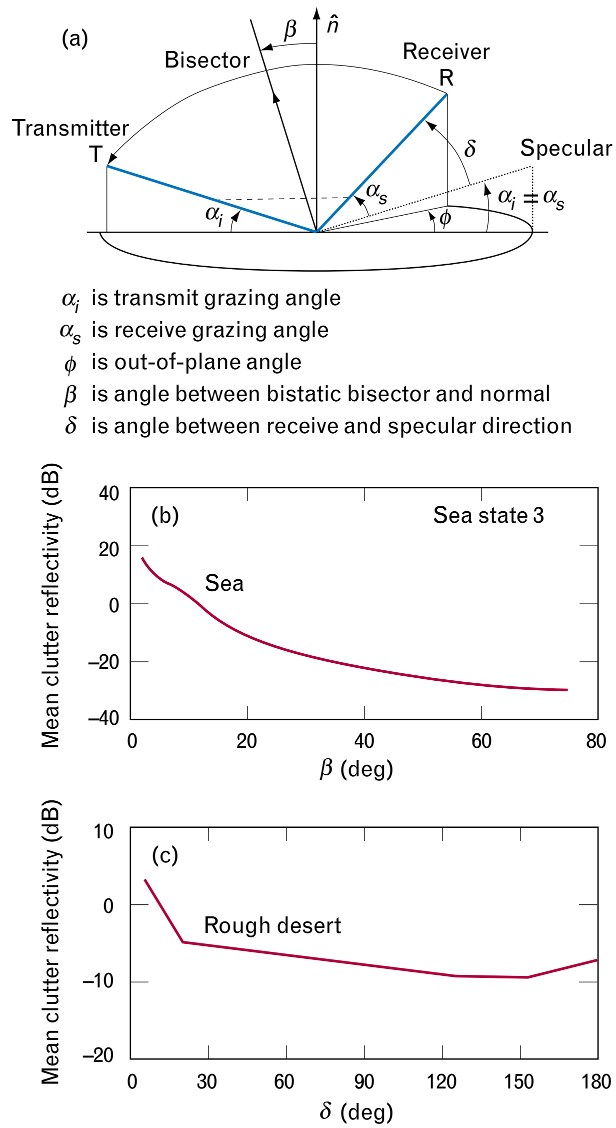

FIGURE 8. (a) Bistatic clutter-measurement geometry, (b) mean normalized clutter reflectivity versus β, and (c) mean normalized clutter reflectivity versus δ, a measure of angular distance from the specular direction. The bistatic clutter models specify measurements of mean clutter reflectivity at X-band, with vertical polarization.

(infrared clutter, atmospheric propagation), target infrared signatures, and infrared-seeker acquisition and tracking performance. Adding a pod-mounted airborne infrared-imager system accomplished this task. From a missile-seeker-technology point of view, the role of the airborne infrared-imager system is analogous to the role of the X-band instrumentation head. The dual-band, radiometrically calibrated infrared camera is used to evaluate current and proposed infra-

FIGURE 9. Current version of the ASTB. The ASTB is a fully instrumented, highly calibrated, airborne data-collection system. The Gulfstream II platform carries an assortment of sensor pods (e.g., an RF seeker, the airborne infrared imager, and an AIM-9M seeker), a C-band beacon-tracker subsystem that is used to point the sensor pods at beacon-carrying targets, and nose-mounted advanced array antennas. Data from the sensors and support equipment are recorded on a wideband digital recorder for post-mission data analysis and interpretation.

red seekers. A pod-mounted infrared missile seeker (Sidewinder or AIM-9M) is carried by the aircraft to evaluate the performance of current U.S. infrared missiles, especially in clutter background.

Radar Development: Radar Surveillance Technology

The initial focus of the Radar Surveillance Technology program, as discussed earlier, was the U.S. ship-based defense against foreign antiship cruise missiles. A later focus was on the radar detection and track of a low-flying cruise missile by the naval fleet-surveillance airborne-radar system, the E-2C. The concept presented in Figure 1 for the air-vehicle-survivability prediction process can also be applied to the Radar Surveillance Technology program. Here the air vehicle is a foreign cruise missile, the defense system is the U.S. Navy's Aegis air-defense system or its E-2C airborne surveillance radar systems, and the phenomenological measurements and the air-vehicle measurements are accomplished by the program's Radar Surveillance Technology Experimental Radar (RSTER). The same concept of prediction using available measurements and models and closing the prediction loop by using measurements on air vehicles is, of course, valid in these scenarios.

Radar Surveillance Technology Experimental Radar

The RSTER is a UHF, phased-array, moving-target-indicator system capable of detecting targets in the presence of heavy clutter and jamming interference. The interference is mitigated through the use of adaptive-nulling capability in elevation angle and ultralow sidelobes in azimuth. Development of the RSTER system began in 1983. During the first two years of the program, the antiship-missile threat characteristics were established, and engagement analyses were performed. Radar design studies were conducted that took into account the target platform's capabilities and the threat environment. These studies of clutter

FIGURE 10. Radar Surveillance Technology Experimental Radar (RSTER), as originally deployed at Lincoln Laboratory. The 5-m-high × 10-m-wide, 14-channel antenna is connected to the transmitter and receiver subsystems via a 33-channel rotary coupler. Signals from the individual channels are digitized and processed to achieve adaptive digital beamforming (in elevation), pulse compression, Doppler filtering, constant false-alarm-rate detection, multitarget tracking, synthetic displays, data recording, and target track-file generation. The last capability is required to direct other sensors and weapon systems. All the radar subsystems are contained in the two forty-foot trailers shown at the base of the tower.

levels, radar performance, and radar equipment configurations led to a RSTER system design in 1986.

After the initial design, technology development began on the antenna, transmitter, and digital adaptive beamformer. A contract was awarded to Westinghouse to develop an ultralow-sidelobe vertically polarized phased-array antenna that was five by ten meters and consisted of fourteen channels of antenna elements. During 1991 and 1992, the spatially adaptive digital signal processor was designed and built at Lincoln Laboratory. Following the completion of the signal processor, the assembly of the RSTER system was concluded, and system-level testing was conducted during the first half of 1992. Figure 10 shows RSTER as first installed at the Laboratory. Each channel had twenty-four elements connected to a precision corporate feed that applied a fixed Chebyshev amplitude taper. The corporate feed design produced azimuth sidelobes that were more than 60 dB below the main lobe, as shown in Figure 11. The antenna was steered mechanically in azimuth and electronically in elevation angle and was designed to be used over the 400-to-500-MHz band. Westinghouse was also commissioned to build the very stable fourteen-channel solid state transmitter. The transmitter had a pulse-repetition-frequency range of 300 to 1500 Hz and produced 10 kW of peak power in each of the fourteen channels, for a total peak power of 140 kW [5].

Following initial tests, RSTER was shipped to Wallops Island, Virginia, where—acting as an Aegis adjunct radar—it participated in exercises involving jamming and clutter, including heavy chaff. RSTER successfully detected and tracked high-flying, low-radar-cross-section targets in real time and designated the targets to the AN/SPY-1B radar. The RSTER system met or exceeded all its design goals with regard to azimuth sidelobes, moving-target-indicator (MTI) performance, and adaptive-null depth in these tests and demonstrations. Figure 12 shows an adaptive-nulling result involving detection of a Lear Jet in the

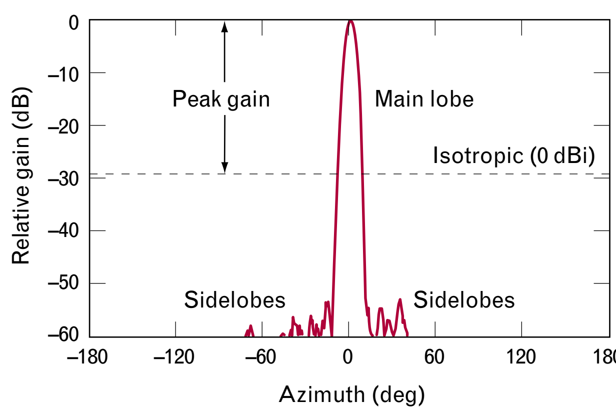

FIGURE 11. RSTER ultralow-sidelobe array azimuth principal plane. The array beam in the azimuth (horizontal) plane is formed within the array by using precision analog techniques. The gain of the antenna is the ratio of the peak of the beam to the isotropic level, and is within a very small percentage of achieving the theoretical maximum. Sidelobes away from the main beam are governed in amplitude by array fundamentals, weighting tapers, and electronic phase and amplitude errors. The RSTER array's sidelobe levels suggest performance levels rarely achieved in a laboratory, but which are demonstrated here in a fielded experimental radar.

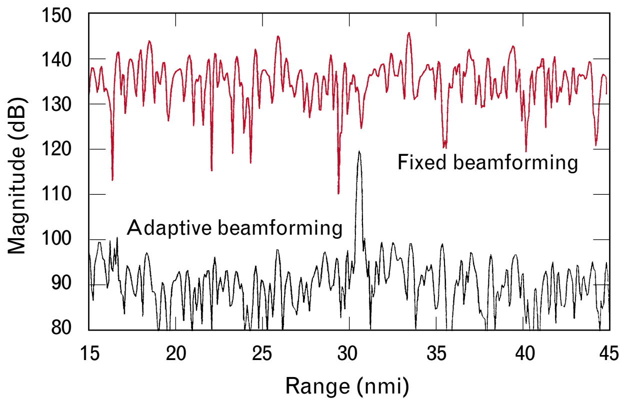

FIGURE 12. RSTER detection of an inbound (at 8° elevation angle) Lear Jet in the presence of a jammer with and without adaptive nulling (jammer-to-noise ratio of 64 dB).

FIGURE 13. Aerial view of the Makaha Ridge site at the Pacific Missile Range Facility, Kauai, Hawaii.

presence of a strong jammer. RSTER's adaptive null provides about a 45-dB reduction in the jamming noise level.

As part of the Mountaintop program, RSTER was shipped to the Pacific Missile Range Facility at Makaha Ridge on Kauai, Hawaii, in July 1994. Figure 13 shows an aerial view of the Makaha Ridge site. In 1995, the radar was moved to Kokee Park on Kauai to act as a simulated airborne radar in the U.S. Navy's Cruise-Missile-Defense Advanced Concept Technology Demonstration (ACTD). The goal of the ACTD was to provide over-the-horizon detection and engagement of low-flying targets by using a sensor suite at the 3800-ft Mountaintop site, which served as a surrogate airborne radar; this scenario, illustrated in Figure 14, demonstrated the air-directed surface-to-air missile (ADSAM) system concept in the Mountaintop test venues. The elevated site consisted of RSTER providing surveillance and acquisition and an MK-74 fire-control system providing precision tracking and target illumination. The Mountaintop sensors were interconnected to each

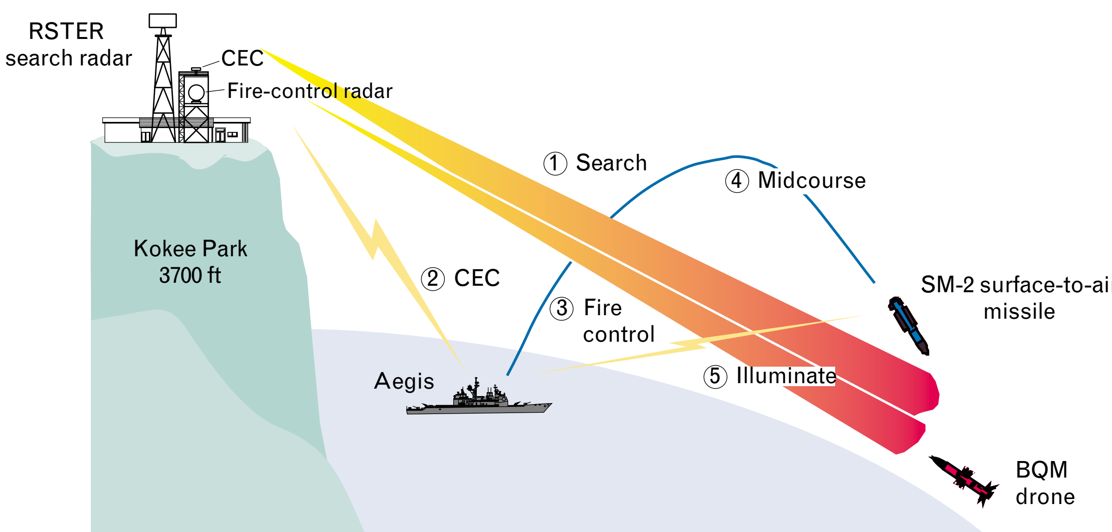

FIGURE 14. U.S. Navy Cruise-Missile-Defense Advanced Concept Technology Demonstration (ACTD) on the Kokee Park mountaintop on Kauai, Hawaii. Multiple radar sensors were netted via the Cooperative Engagement Capability (CEC) communication system to detect, track, launch against, and destroy a low-flying surrogate cruise missile (the BQM drone) that was flying beyond the line of sight of the surface-based Aegis missile system. The test demonstrated the air-directed surface-to-air missile (ADSAM) system concept in the Mountaintop test venues.

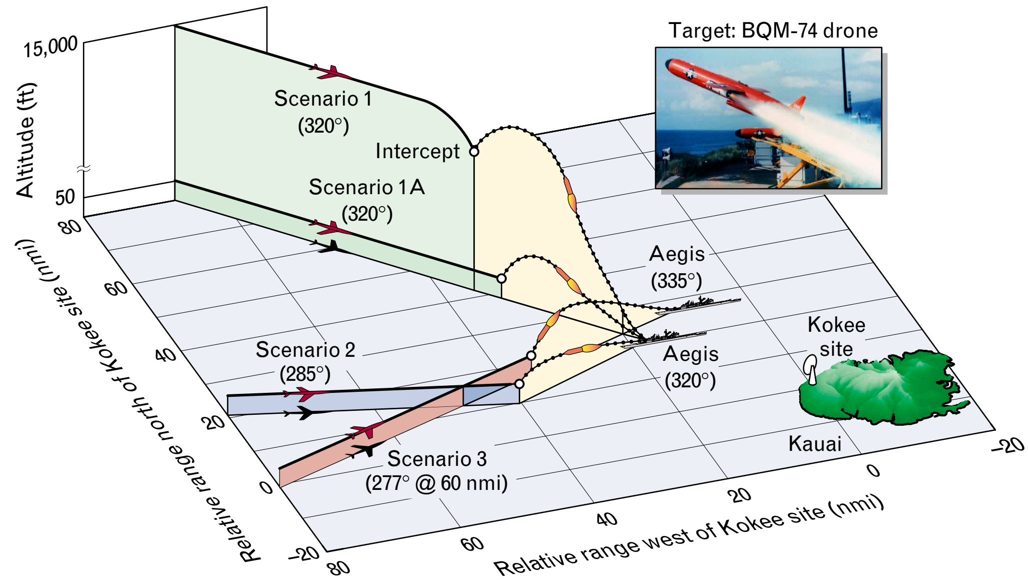

FIGURE 15. ACTD scenarios with RSTER as the surveillance sensor. A single high-altitude calibration scenario and three missile-firing low-altitude intercept scenarios were performed as the test complement for the Mountaintop ACTD. Success was achieved for all the scenarios, which brought the U.S. Navy closer to the ADSAM capability needed for future littoral warfare.

other and to an Aegis Cruiser (CG 70-USS *Lake Erie*) by using the U.S. Navy's Cooperative Engagement Capability (CEC). BQM-74E drones flying at close to Mach 1 were used as surrogate low-altitude cruise missiles. The drones were engaged by the modified Aegis SM-2 surface-to-air missile.

After several months of integration testing, highly successful live-fire concept demonstrations were accomplished in January 1996. Figure 15 illustrates the four different flight scenarios that were flown. In scenario 1 the drone was inbound at an altitude of 15,000 ft. In the other three scenarios the drones were flown inbound at an altitude of fifty feet. The principal measure of success for the ACTD was intercept (to within a lethal radius) in all three low-flying scenarios beyond the 18-nm radar horizon of the ship's AN/SPY-1B radar to the BQM-74E at an altitude of fifty feet. The tests were all completed successfully.

The Future

Cruise missiles will continue to be improved in all aspects of their performance, and they will continue to proliferate to many nations of the world. Lincoln Laboratory will continue to work on behalf of the Department of Defense to pursue the system constructs, technology developments, and proof-of-concept demonstrations that are required to maintain the preeminent position the United States holds in low-observable air defense and low-observable air vehicles. Radar sensors such as those developed for the ASTB and RSTER programs will provide the legacy for future detection and tracking of cruise missiles.

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