# Tactical Radars for Ground Surveillance

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**Battlefield awareness is the key to battlefield dominance. The field commander who knows the enemy's location and the types of forces being deployed enjoys a great tactical advantage. The problem of detecting and classifying ground targets presents substantial technical challenges, which Lincoln Laboratory has addressed for nearly three decades in its Tactical Technology program. Substantial progress has been made in many aspects of ground surveillance since the mid-1960s, but many challenges remain. These challenges include sensor development, signal processing, and target-recognition technology. Among its successes, the Laboratory has provided the foundation for operational national assets such as the Joint Surveillance Target Attack Radar System (Joint STARS) airborne surveillance system. This article describes in chronological order several important Laboratory tactical-radar programs and the technologies that were developed for both airborne and ground-based surface surveillance.**

Lincoln Laboratory's involvement in the arena of tactical battlefield surveillance began in 1967 with a program to develop a radar system that would penetrate jungle foliage and detect moving hostile intruders. This effort arose during the war in Vietnam, when major national laboratories were called upon to contribute solutions to tactical battlefield surveillance involving ground-based and airborne-based sensors.

Ground-based sensors can be loosely grouped into two categories. Special ground-penetrating radar sensors are used to detect mines and other explosives as well as hidden tunnels and buried stores. Other ground-based radar systems are used to survey large regions of terrain within the sensors' fields of view in order to detect and identify fixed ground targets and to detect, identify, and track moving ground targets. Airborne sensors designed for tactical battlefield surveillance require the ability to survey large areas on the ground in a timely manner in order to detect and identify both fixed and moving surface targets that may be hidden in ground clutter or protected by countermeasures. Lincoln Laboratory has developed a broad understanding of the technology and the phenomenology of target detection; the Laboratory has also developed a variety of remote sensors, communication strategies, digital processors, signal-processing algorithms, and data-processing techniques to address the concerns of different surface-surveillance systems. This article describes some of the significant Laboratory radar programs and the technologies that were developed for these ground-based and airborne systems. For more information on these and other programs at the Laboratory, see the articles entitled "Displaced-Phase-Center Antenna Technique," by Charles Edward Muehe and Melvin Labitt, and "Development of Coherent Laser Radar at Lincoln Laboratory," by Alfred B. Gschwendtner and William E. Keicher, both in this issue.

### Foliage-Penetrating Radar (1967–1972)

Field reports from American troops in Vietnam revealed that foliage played a major role in concealing the enemy in most tactical engagements. As a result, Lincoln Laboratory began an investigation of a surveillance system that offered a foliage-penetration capability. A preliminary Laboratory study in 1966 concluded that radar would be able to detect people and vehicles moving through dense foliage.

*The Camp Sentinel Radar*

The foliage-penetration radar program, supported originally by the Defense Advanced Research Projects Agency (DARPA) and subsequently by the U.S. Air Force, began in January 1967 [1]. The objective was the development of a ground-based radar that could detect intruders moving into a small encampment. This ground-based system was named the Camp Sentinel Radar. Deployed in Vietnam after an eighteen-month crash development program, it protected American troops throughout the rest of the war.

At the inception of the Camp Sentinel Radar program, there was little information on which to base the radar design. The technical literature provided minimal data on electromagnetic attenuation in tropical foliage, but it did suggest that the best operating frequencies were between 20 and 500 MHz. A frequency (435 MHz) near the upper end was chosen in order to localize any detections to a small azimuthal region with an antenna small enough for tactical deployment.

Three critical questions had to be answered about the propagation of radar signals within relatively dense foliage: (1) How much does the moving foliage spread the frequency spectrum of a signal reflected from a target? (2) What is the frequency spectrum of clutter signals reflected from windblown foliage? (3) What is the effect of multipath propagation on range and azimuth resolution and on subclutter visibility?

Lincoln Laboratory built two radar systems to answer these questions. The initial system, called the Camp Sentinel Radar-I, took measurements at a site local to Lincoln Laboratory. This system worked well, and it was used in demonstrations to military observers in the fall of 1967. A second version was mounted in a van and sent to Bisley, Puerto Rico, where foliage closely simulated the conditions in Vietnam. By January 1968, enough measurement data had been accumulated to go ahead with a more advanced radar, called the Camp Sentinel Radar-II.

The design of the Camp Sentinel Radar-II incorporated unique and innovative concepts. The antenna was mounted high above the ground on a rapidly deployable tower so the electromagnetic waves could reach a target by propagating over the tops of the trees and then be diffracted to the ground, rather than by propagating directly through the foliage. An electronically scanned cylindrical array sequentially stepped the antenna beam through thirty-two positions in azimuth to cover 360°. The transmit/receive beams were stepped so rapidly in azimuth that the signal processing functioned as if there had been thirty-two individual radars, each with stationary azimuth coverage and all operating simultaneously. The processors were able to execute the critical algorithms needed to detect small, slow-moving human infiltrators from the high-level clutter background created by the windblown tropical foliage.

The radar control was designed to allow an operator to construct two intrusion fences. These fences could be made irregular in shape, to match them to the desired defense perimeter. The operator did not need to monitor the radar unless an alarm sounded. If a detection occurred, the operator simply checked the display to see which range/azimuth sector contained the intruder and whether the target was incoming or outgoing. After a short local testing period, the first Laboratory-built Camp Sentinel Radar-II was

**FIGURE 1.** The Camp Sentinel Radar-II was first installed and operated in Lai Khe, Vietnam, in 1968. The system was situated on the perimeter of the U.S. Army camp, with the radar antenna mounted on top of the tower. The remainder of the radar system was located in a bunker behind the hill in this picture, where the machine-gun tower was located.

**FIGURE 2.** Field operation of the Geodar ground-penetrating radar system. Initial testing of this system consisted of dragging the antenna over a known test area to detect tunnel-like voids under the surface. The antenna was connected to the radar equipment in the jeep by a cable.

shipped to Vietnam in August 1968. Laboratory employees Leonard Bowles and David Rogers spent two months in Vietnam, introducing the radar to the Third Brigade, 1st Infantry Division, and instructing Army personnel in its operation and maintenance. The radar, shown in Figure 1, received immediate acceptance, and the Army used it until the end of the war.

The U.S. Army's Harry Diamond Laboratory carried out additional development work. The improved version, called the Camp Sentinel Radar-III, included a more powerful transmitter to increase the detection range and to provide an additional number of display options. Six of these radars were manufactured and sent to Vietnam, where they remained until U.S. combat troops were withdrawn.

### Geodar: Ground-Penetrating Radar (1966–1967)

American forces operating in Vietnam needed a sensor system that could detect tunnels. In 1966, after discussions with other laboratories working on this problem, Robert Lerner of Lincoln Laboratory concluded that a ground-penetrating radar offered possibilities, and the Geodar (ground echo detection and ranging) program was initiated to investigate the concept under DARPA sponsorship. The distinguishing feature of the Geodar concept was that electromagnetic energy was radiated directly into the ground.

Because the soil-penetration properties of radar were not known with any precision, it was decided to use a wide band of frequencies, from 50 to 150 MHz, within the generally applicable frequency range. A flat rectangular-shaped antenna of transmission-line design, operating close to the ground surface, radiated electromagnetic energy in compact packets of 3-to-5-nsec duration. The antenna, shown in Figure 2, with an effective area of about 3/4 of a square meter, was drawn over the ground on a Teflon sled structure.

A first experimental system was quickly assembled in 1966, and proof-of-concept tests were made at a simple tunnel test range at Lincoln Laboratory. The tests proved that tunnel-like voids in the ground could be detected. A formal program was then established to develop a demonstration system for a field test. The first system, Geodar Mark I, was completed in March 1967, and an improved version, Geodar Mark II, was completed a few months later [2].

The Geodar systems were tested on tunnels at Fort Belvoir, Virginia, and at Raleigh, North Carolina, as well as on voids implanted in a second Laboratory test range constructed at Millstone Hill in Westford, Massachusetts. The test results indicated that the Geodar systems could locate tunnels of two to three feet in diameter at depths of up to approximately twenty feet in most alluvial, glacial, and loessial soils.

Several sets of Geodar Mark II were fabricated by Sylvania West, and Lerner went with them to Vietnam. Demonstrations there corroborated the earlier test data and predictions. For a time, the Geodar system was deployed for perimeter tunnel surveillance around a U.S. Army Headquarters installation.

### Hostile Weapons Location System (1974–1981)

The joint DARPA–U.S. Army Hostile Weapons Location System (HOWLS) program, which began in 1974, focused on the development of techniques to locate and classify stationary indirect-fire weapons in background clutter. In December 1974, the General Electric Company was selected to build the HOWLS airborne radar. The HOWLS system consisted of a $K_u$-band (16 GHz) array radar mounted in a twin-engine aircraft, a ground-station recording system, and an off-line processing system in a van [3]. The azimuth resolution (real-beam) was 0.5° and the range resolution was ten meters, which was a high-resolution system at that time. The program addressed two major issues: solve the automatic-target-detection problem, and implement this solution on a miniature unmanned air vehicle (UAV) radar.

Figure 3 shows the airborne and ground-station components of the HOWLS experimental radar system. Figure 3(a) shows the HOWLS radar antenna mounted under the fuselage of a twin-engine Piper Navajo aircraft. The radar was a $K_u$-band system with a 500-MHz radio-frequency (RF) bandwidth. The maximum coherent-pulse bandwidth was 18 MHz (corresponding to a resolution of ten meters), and the center frequency could be stepped across the RF bandwidth in sixty-four steps. The system was used to develop stationary-ground-target detection techniques with a spatial resolution of 10 × 10 m and a single polarization. Figure 3(b) shows the interior of the ground-station van with the signal-processing and recording system. The HOWLS system provided the information needed to design a lightweight and low-cost radar appropriate for mini-UAV applications.


**FIGURE 3.** (a) The airborne component of the DARPA–U.S. Army Hostile Weapons Location System (HOWLS) installed in a twin-engine Piper Navajo aircraft with the array antenna mounted below the fuselage. (b) Data from this sensor were linked to a ground-station van for signal processing, recording, and display.

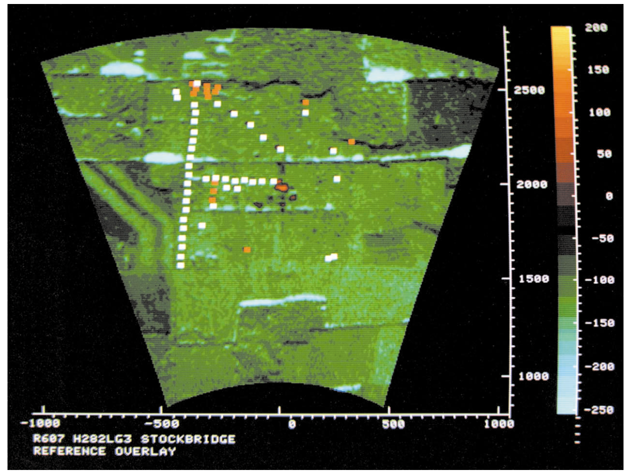


**FIGURE 4.** A HOWLS radar map of the ground at Stockbridge, New York. The white squares are returns from a calibration array, while the red squares are detections of targets such as eight-inch guns and armored vehicles.

Figure 4 shows a HOWLS ground-radar map of Stockbridge, New York, at 10 × 10-m resolution with target detections overlaid. The white squares form a calibration array, while the red squares are detections of targets such as eight-inch guns and armored vehicles. Speckle in the image was reduced by noncoherently averaging over sixteen independent frequencies. Targets in relatively open areas could be detected, but the false-alarm rate was high from natural and man-made clutter. Resolution was still inadequate for acceptable classification of stationary tactical targets.

One major accomplishment of HOWLS was the development of a new theory of target detection that more accurately predicted the detection performance of moderate-resolution radar systems [4]. Earlier theories that used noise models to represent ground clutter gave very optimistic detection results, which were in error by one to two orders of magnitude. The new theory correctly took clutter inhomogeneity into account, leading to more accurate predictions of performance. Figure 5 plots the probability of detection of armored targets against the number of false alarms expected per square kilometer. The dashed black line is the fit to the experimental data; the average target-

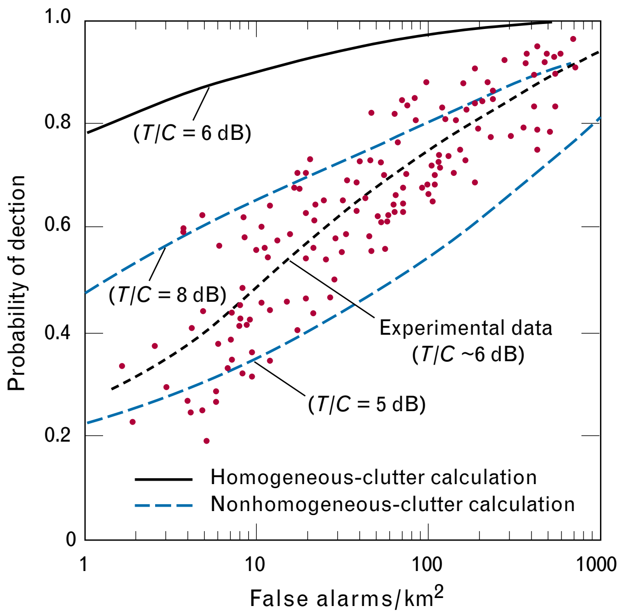


**FIGURE 5.** Detection performance of HOWLS against stationary targets in clutter. The assumption of a homogeneous ground-clutter model predicts very optimistic results, as shown in the upper black curve for a target-to-clutter ratio ($T/C$) of 6 dB. The HOWLS radar data from experiments in Stockbridge, New York, shown as red points, show the probability of detection of armored targets versus the number of false alarms per square kilometer. The curve-fit HOWLS data, shown as a black dashed line, indicate a much less optimistic performance for this medium-resolution radar than the homogeneous-clutter model, an error of about two orders of magnitude. A new theory developed by Leslie M. Novak at Lincoln Laboratory assumes a nonhomogeneous-clutter model, and predictions from this theory bracket the experimental results quite well, as shown by the blue dashed lines for $T/C$ = 5 dB and $T/C$ = 8 dB [4].

to-clutter ratio ($T/C$) was 6 dB. The theoretical curves for $T/C$ = 5 dB and $T/C$ = 8 dB nicely bracket the curve for the experimental data. The homogeneous-clutter model (the top curve in Figure 5) predicts 2 false alarms/km$^2$ for a detection probability of 0.8 and a $T/C$ = 6 dB, while the experimental-data curve shows 200 false alarms/km$^2$ for the same conditions—an error of two orders of magnitude. The HOWLS program demonstrated the potential of both automatic-target-detection techniques for stationary targets and the utility of mini-UAV radar systems with their excellent terrain visibility.

The HOWLS program was a pioneering wide-area battlefield-surveillance effort. It proved that a sensor with good resolution like the HOWLS radar would be inadequate for target detection because the sensor would be swamped with false alarms if it were set to achieve realistic target-detection probabilities. To achieve the higher detection probabilities with a significantly lower false-alarm density required much better resolution, such as that achievable with a synthetic-aperture radar (SAR) and a polarimetric-measurement capability to further distinguish targets from natural and cultural clutter. The performance that can be realized with such a system is discussed later in this article in the section entitled "Stationary-Target Detection Employing High Resolution and Polarization."

## Netted Radar Program (1976–1981)

The Netted Radar Program began in 1976 to address the moving-target detection problem and to demonstrate that an operational system of distributed radars connected by a multiple-user network would provide for the first time a comprehensive view of the battlefield. In addition, the program showed that the U.S. Army's AN/PPS-5 ground radars could be vastly improved by adding modern digital signal-processing techniques originally developed by Lincoln Laboratory for use in air-traffic control.

Figure 6 illustrates the Netted Radar System as demonstrated at Fort Sill, Oklahoma. The network utilized an airborne radar (a modified version of the HOWLS radar called the Advanced Airborne Radar with moving-target detection and tracking capability [5]), two modified AN/PPS-5 ground-based radars, and a U.S. Army AN/TPQ-36 ground-based artillery-locating radar. The AN/PPS-5 radars were equipped with modern signal-processing capabilities implemented by Lincoln Laboratory, and were renamed AN/TPS-5X radars [6]. Figure 7(a) shows an AN/TPS-5X antenna looking over Fort Sill, Oklahoma, from nearby Mount Scott. The AN/TPS-5X radar could detect and track tank-sized targets out to a range of about twenty kilometers. In addition to detecting moving ground vehicles, the AN/TPS-5X radar also detected low-flying aircraft, rotating antennas, moving personnel, and artillery shell bursts. It could also estimate the azimuth positions of noise jammers.

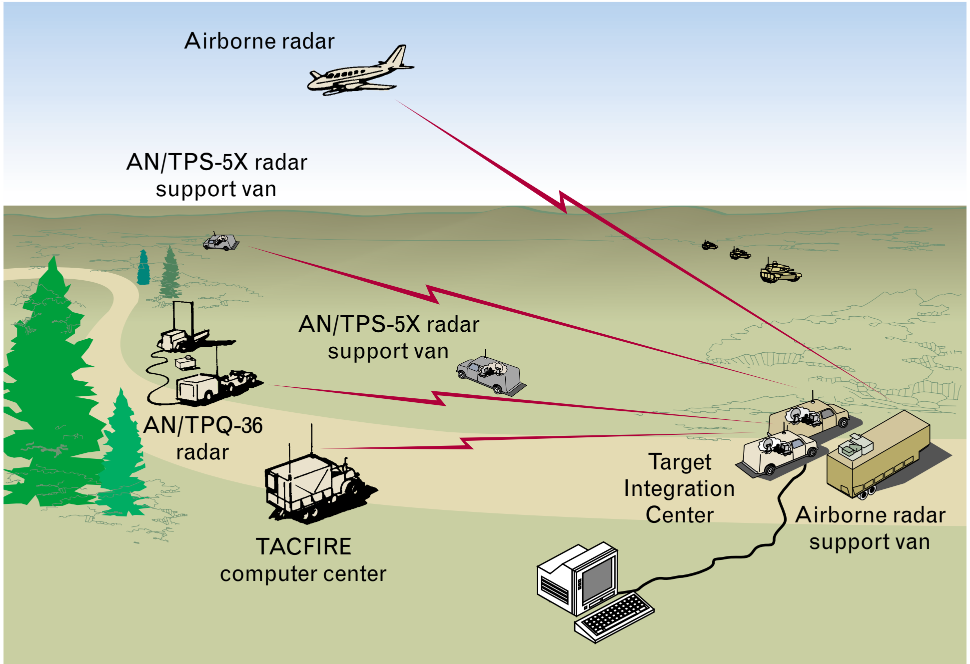


**FIGURE 6.** Elements of the Netted Radar Program demonstration of moving-target detection. Data from the single airborne radar and three ground-based radars were sent over narrowband VHF links to the Target Integration Center, where they were integrated with the Army's Tactical Artillery Fire Direction System (TACFIRE) computer center. Fire missions then brought artillery fire against designated moving targets on roads in real time.

All radars were netted together through a Target Integration Center, which in turn was connected to the Army's Tactical Artillery Fire Direction System (TACFIRE) computer center. The system provided exceptional coverage of the battlefield and greatly reduced the delay between target detection and artillery fire on the target. This demonstration clearly showed the Army the advantages of tracking and reporting moving targets with an automatic real-time system, compared to the Army's established "man-in-the-loop" methods.

Figure 7(b) illustrates the operator display for the Netted Radar Demonstration. Each tracked target is automatically assigned a target number that can be accessed to give the target's location and velocity. For instance, target 17 is a ground object moving at 12 m/sec, while target 16 is a helicopter in the air. The system also provided jammer location and artillery-fire registration by using range and azimuth triangulation techniques.

The Fort Sill demonstration clearly showed the advantages of an airborne radar for terrain visibility. Even in the moderately level terrain of Oklahoma, terrain masking was a serious problem for ground-based sensors, while virtually all targets were visible to the airborne radar. The airborne radar component of the Fort Sill demonstration pointed to the value of UAV radar with moving-target detection and tracking capability.

In addition to rapid target acquisition, the advantages of combining target information with rapid dissemination to artillery units were demonstrated in real time. As an example of the speed and accuracy of the networked system, a tank, fortified to withstand hits with inert artillery rounds, was tracked by the radar network as it moved along a roadway in the East Range target area at Fort Sill. A firing time was computed at the Target Integration Center on the basis of (1) the predicted arrival time of the tank at the predetermined aim point on the road, and (2) the estimated flight time of the projectile from gun to aim point. Because the artillery had been zeroed in on the aim point, and because the predicted projectile time of arrival derived from the real-time measurements

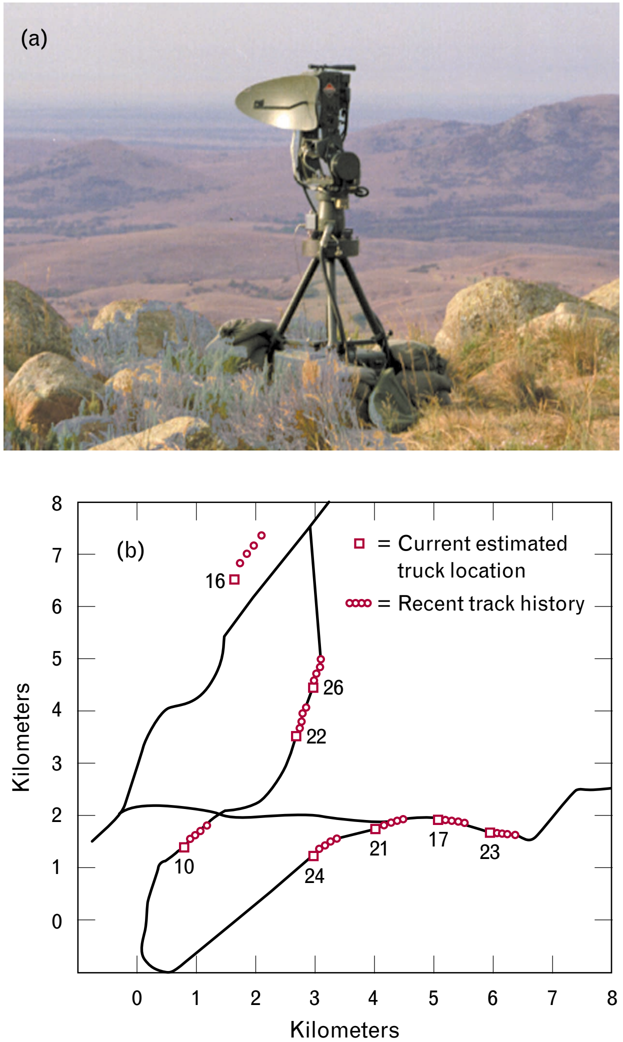


**FIGURE 7.** (a) The radio-frequency (RF) portion of a U.S. Army AN/TPS-5X radar looking over Fort Sill, Oklahoma, from Mount Scott. A nearby radar support van housed the signal-processing and data-processing equipment. (b) An illustration of the operator display used in the Netted Radar Demonstration. The Fort Sill demonstration clearly showed the advantages of an airborne radar for significantly reducing terrain masking.

was very accurate, the inert round hit the tank and damaged one of the tank treads. This convincing result demonstrated the improved performance of the AN/TPS-5X radars, the automatic target-acquisition and tracking functions, the feasibility of radar netting, and the potential to provide for more accurate artillery-fire adjustment.

The basic objective of the Netted Radar Program was to develop the technology for the netting of battlefield radars. The AN/TPS-5X radars had several limitations: they could not serve multiple users in a dynamic situation, they were easily detected by their scan motion, and the VHF radio system was not jam-resistant enough for a tactical configuration.

For these reasons, Lincoln Laboratory developed the Advanced Ground Surveillance Radar (AGSR), which was incorporated as a parallel element of the Netted Radar Program. The AGSR was a moving-target-indicator (MTI) radar. It featured a C-band cylindrical array antenna, which was electronically steerable in azimuth over 360° and capable of simultaneous multimode radar operation together with an integral data link. [7] The fully coherent MTI AGSR was demonstrated at Fort Sill from November 1980 through January 1981, where it automatically tracked ground vehicles, walking troops, and helicopters. It also detected and accurately located artillery shell bursts.

The achievement of the Netted Radar Program was the completely automated fusion of a number of surveillance radars in U.S. Army exercises under various field conditions. The system developed under this program was conceptually similar to the Laboratory's SAGE (Semi-Automatic Ground Environment) air-defense system developed in the 1950s [8]. The success of this program set the stage for the netting of other operational military surveillance radars.

## Unmanned-Air-Vehicle Radar Program (1982–1991)

In 1982, under DARPA and U.S. Army sponsorship, Lincoln Laboratory began a UAV-radar development program to detect and classify moving targets with a low-power, lightweight radar designed for a UAV platform. The system provided either a specific angular sector or full 360° surveillance of moving ground vehicles and low-flying helicopters, as illustrated in Figure 8. MTI data were first processed onboard the UAV. Low-bandwidth data were then linked to a ground station where precision track, location, and classification of moving targets were performed and the results were displayed [9].

Lincoln Laboratory researchers designed the UAV radar, using commercially available components for the RF parts of the radar such as the transmitter, re-

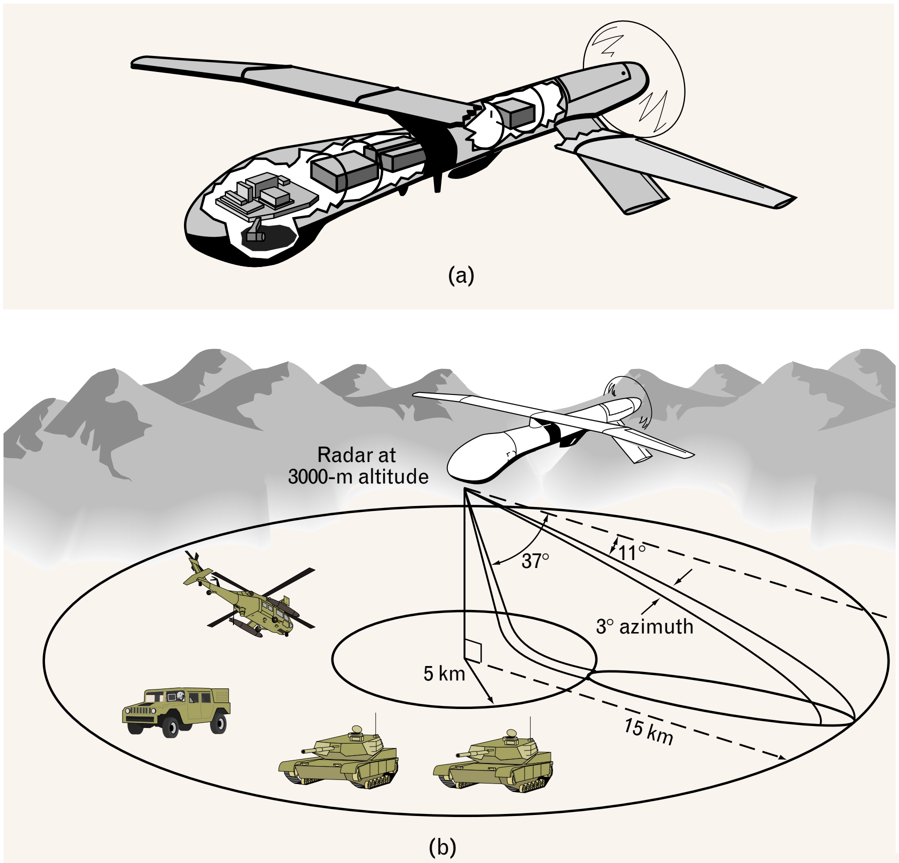


**FIGURE 8.** The unmanned-air-vehicle (UAV) surveillance and tracking radar concept. (a) The remotely controlled UAV carries a small coherent moving-target detection radar that provides surveillance of a large area of the surrounding terrain and sends moving-target reports, generated by an onboard processor, via data link to a ground station for display and target tracking. UAV position estimates are provided by a Global Positioning System (GPS) receiver and are used to update an inertial-navigation system that provides filtered UAV position (two dimensions), altitude, and aircraft attitude information. (b) With high look-down angles, the UAV radar has an excellent view of the surrounding terrain for detection and tracking. With its small visible signature and low radar cross section, the UAV is difficult to locate and destroy with surface-fired weapons.

ceiver, and antenna. One important issue was to provide onboard MTI processing and to provide a low-bandwidth communication link to send the target reports to a ground station for classification and real-time display. Since a suitable commercial processor was not available at that time, the Laboratory developed a state-of-the-art processor together with the necessary signal-processing and data-processing algorithms. Figure 9 shows the equipment as mounted in an Amber UAV fuselage. Figure 10 shows how the entire system was form-fitted in the UAV fuselage and captive-carried on a Twin Otter aircraft for testing and evaluation. The radar could be operated from the ground station or independently by an operator in the aircraft. The complex radar data were recorded on a 13-MB/sec recorder, so missions could be flown beyond the reach of the ground station.

In the spring of 1990, a field demonstration was conducted at Fort Sill and evaluated by the U.S. Army's Intelligence School. As an example of real-time wide-area surveillance, Figure 11 shows the detection of virtually all of the moving targets found in less than three minutes within a 900-km$^2$ area surrounding Fort Sill (above center in the figure) and the town of Lawton, Oklahoma (just below center). The density of moving targets is clearly visible from the number of MTI detections overlaid on the digitized road map. Notice the absence of detections or false

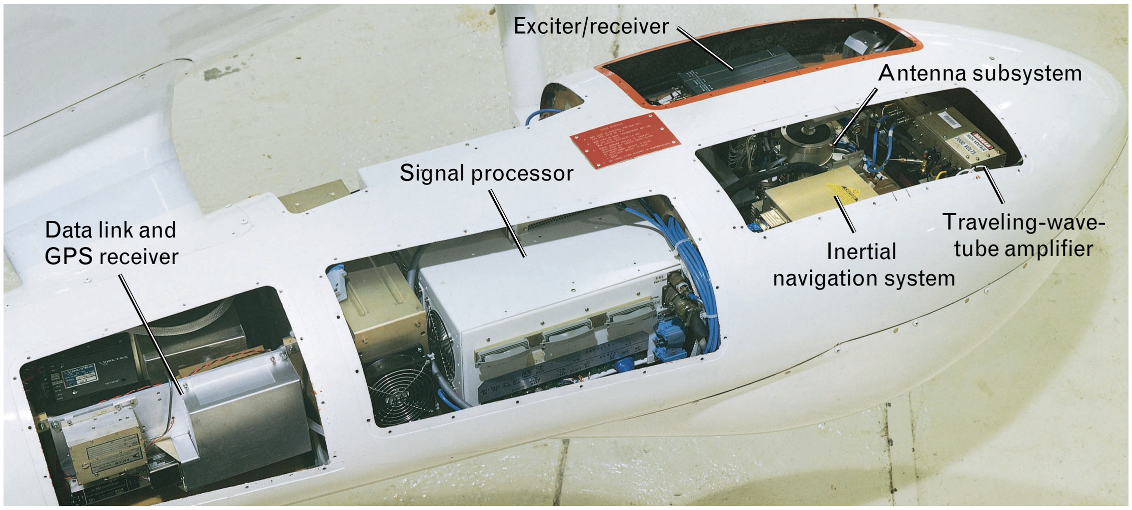


**FIGURE 9.** The moving-target-indicator (MTI) radar mounted in the UAV fuselage. The open panels show the location of the radar components within the fuselage. The UAV, with a twenty-foot wing span, was developed by Leading Systems, Irvine, California, under DARPA sponsorship, and was identified by the name "Amber."

alarms in the (restricted access) artillery ranges to the northeast and northwest. The accuracy of target placement can be qualitatively measured by how closely detections match the underlying road grid.

The radar was also required to supply moving-target reports and tracks against a background map of the Fort Sill area. During a blind test, the radar operator was asked to determine the number of vehicles, the speed, and the mix of wheeled and tracked vehicles in the convoys sent out by the evaluation team. The radar successfully reported location, speed, and composition of the convoys out to ranges of sixteen kilometers. The field demonstrations were conducted jointly with the Army Research Laboratory. The combined efforts and the demonstration results convinced Army users of the value of such an MTI radar on a UAV. The Joint UAV Program Office is now considering such applications.

**FIGURE 10.** The UAV-radar captive-carry flight-test configuration. The UAV fuselage was attached, without wings, tail, or engine, to a Twin Otter aircraft for testing. All the UAV radar equipment was contained within the UAV's fuselage. The Twin Otter aircraft flies at a speed comparable to that of the UAV.

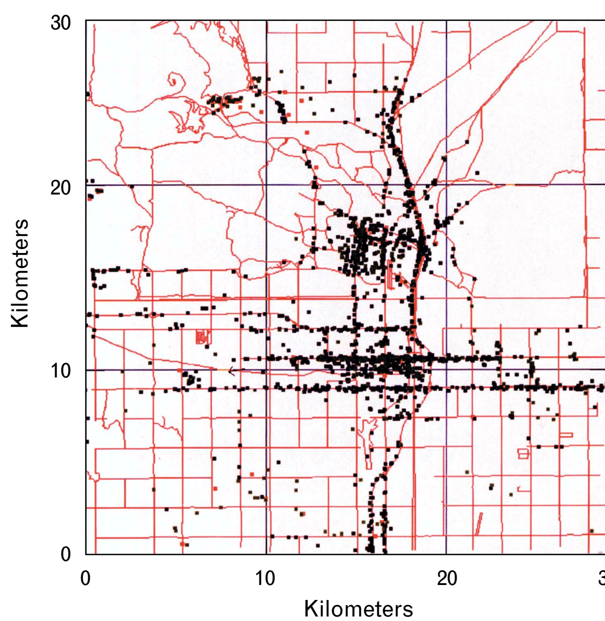


**FIGURE 11.** UAV-radar wide-area MTI surveillance at Fort Sill, Oklahoma. An activity map of moving vehicles shows the vehicular traffic near Fort Sill and the town of Lawton, Oklahoma. This map represents moving-target detections obtained from several 360° scans of the antenna.

Lincoln Laboratory has made many significant contributions to the improvement of airborne MTI systems. Much of the pioneering work in the area of surface surveillance has contributed directly to the development of national assets such as the U.S. Air Force Joint Surveillance Target Attack Radar System (Joint STARS) airborne surveillance system. This work included the development of improvements to MTI target-detection techniques, SAR imaging, and fixed-target detection, as discussed in this article. A major contribution in the area of airborne MTI clutter cancellation and target angle estimation was made with the concept of the displaced-phase-center antenna (DPCA), which introduced the multiple-phase-center array concept. The details of DPCA are covered in the article entitled "Displaced-Phase-Center Antenna Technique," by Charles Edward Muehe and Melvin Labitt, in this issue.

Joint STARS is a long-range surface-surveillance multiple-aperture array radar carried by U.S. Air Force E-8C aircraft. The wide-area surveillance and moving-target indicator (WAS/MTI) are the radar's fundamental operating modes. WAS/MTI is designed to detect, locate, and identify slow-moving targets. Synthetic-aperture radar/fixed-target indicator (SAR/FTI) provides high-resolution SAR imaging for stationary-target detection and identification.

## Stationary-Target Detection Employing High Resolution and Polarization (1982–1996)

In parallel with the UAV MTI work, some of the Laboratory's effort in tactical technology shifted to developing more capable techniques for stationary-target detection and understanding the performance limits of these techniques. The Laboratory began the Advanced Detection Technology (ADT) program in 1982 under DARPA sponsorship in response to a Department of Defense need to examine the potential of MTI radar for use in "smart weapons." A very capable instrumentation radar, called the Advanced Detection Technology Sensor (ADTS), was built for Lincoln Laboratory by Goodyear Aerospace. The Laboratory used this dual-polarized sensor to capture the full dimensionality of the radar signal. The radar, mounted in a Gulfstream II aircraft as shown in Figure 12, provided well-calibrated, high-resolution, fully polarimetric, real or synthetic-aperture data. Originally built for $K_a$-band (33 GHz) operation [10], the radar was later modified to include X and $K_u$-bands together with a bistatic capability as well.

This radar and the associated research programs have played a vital role in the national effort to develop automatic target recognition (ATR) of stationary ground targets. The airborne data acquired by the radar in Figure 12 have been a principal source for development in the ATR research community. For example, the high-resolution SAR map of the site in Stockbridge, New York, displayed in Figure 13(a) shows targets in typical background clutter. Figure 13(b) shows the declared detections that result from processing the data represented in Figure 13(a). Figure 13(c) shows the results of an end-to-end performance study using a baseline SAR ATR algorithm suite. These results have formed the fundamental understanding of the value of SAR resolution and multiple polarizations in ATR.

Figure 13(c) summarizes the fundamental tradeoffs between false-alarm density versus probability of

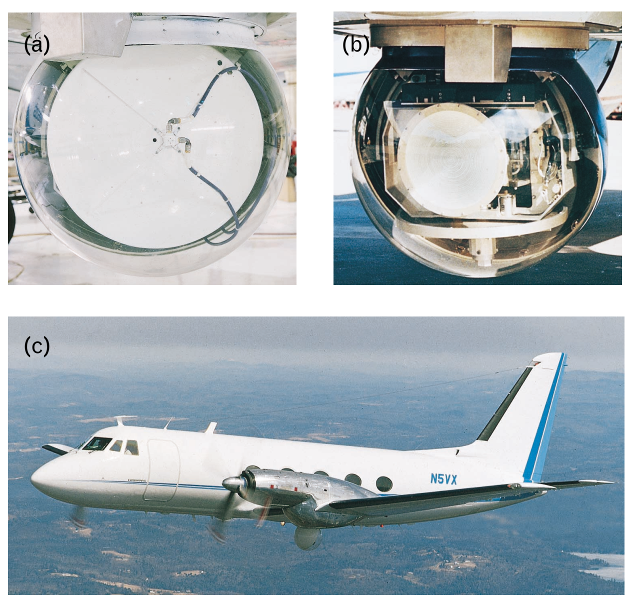


**FIGURE 12.** The Lincoln Laboratory airborne Advanced Detection Technology Sensor (ADTS) had X-band, $K_u$-band, and $K_a$-band (monostatic and bistatic) synthetic-aperture radar (SAR) modes. Either (a) the dual-band (X and $K_u$) antenna (reflector type) or (b) the $K_a$-band horn antenna is mounted in (c) the radome below the Gulfstream II aircraft fuselage, depending on the data-collection requirements.

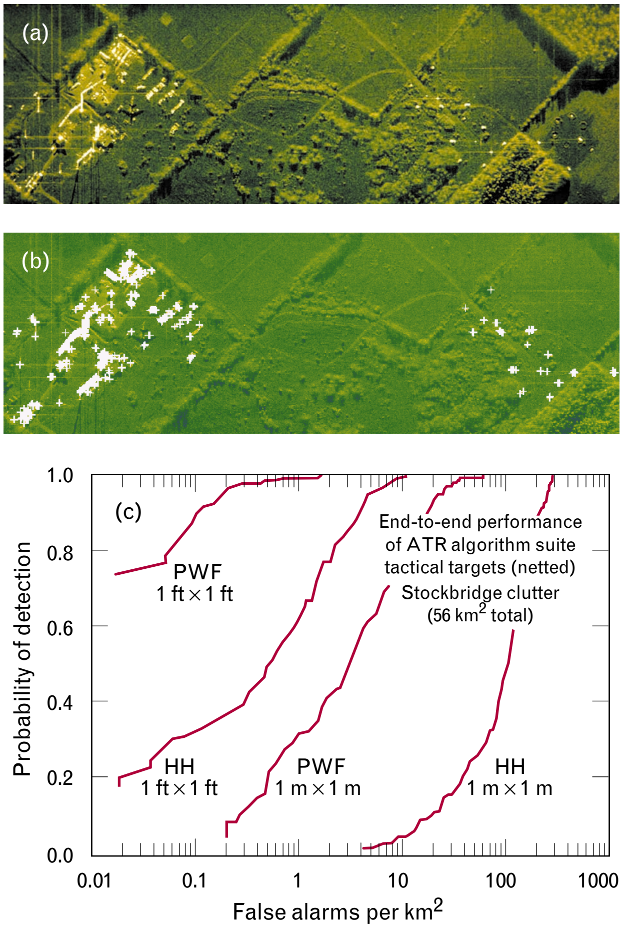


**FIGURE 13.** (a) The ADTS high-resolution SAR map of the Stockbridge, New York, site covered approximately the same geographical area of natural and cultural clutter as shown in the low-resolution map in Figure 4. In this high-resolution SAR map, light pixels indicate strong radar reflections. Located on the right side of the image is a region containing various tactical targets. On the left side of the image is a large maintenance area containing buildings, vehicles, aircraft, and other man-made objects. (b) Declared detections are indicated as white markers on the ADTS SAR map of the Stockbridge site. Note the relative absence of false detections in the natural-clutter areas. (c) SAR automatic-target-recognition (ATR) detection performance results versus polarization and resolution for the Stockbridge site. HH represents horizontal polarization (on both transmit and receive), and PWF represents the polarimetric whitening filter.

detection for single and multiple polarizations (optimally combined) and for various resolutions [11, 12]. Algorithms developed under these programs were used in the DARPA Semi-Automated IMINT (Image Intelligence) Program, or SAIP.

Over four hundred data-collection missions were flown with the ADTS aircraft, satisfying a variety of mission objectives relating to (1) detection and classification of stationary tactical targets, (2) internal seawave detection for antisubmarine warfare, (3) bistatic phenomenology for missile-seeker applications, and (4) SAR for moving-target imaging. Following an active and productive lifetime, operations with the ADTS sensor ended in late 1998.

### Synthetic-Aperture Foliage-Penetration Radars (1987–1996)

Synthetic-aperture foliage-penetration (FOPEN) radars have been developed because of the need to find stationary tactical targets located in deep foliage and natural camouflage, which hide these targets from conventional microwave surveillance sensors. During the Vietnam era, as noted earlier, military personnel successfully used the Camp Sentinel ground-based radar to detect enemy soldiers and vehicles moving in foliage. To locate stationary targets, researchers also needed to develop a low-frequency foliage-penetration SAR imaging capability with sufficient resolution to differentiate targets from clutter. Unfortunately, no reliable target-recognition algorithms were available at that time to reduce false alarms. Many of the currently successful ATR and cueing techniques for detecting moving and stationary targets have been developed to be used only for targets in the open.

Since the late 1980s, Lincoln Laboratory, under DARPA and U.S. Air Force sponsorship, has planned and conducted a number of experiments and data-collection programs utilizing a variety of industry-built sensors to evaluate the use of low-frequency radar to detect and identify tactical targets hidden by foliage. The results from these efforts have been used to develop the current automatic target-detection and cueing algorithms that operate on UHF and VHF SAR data. When we use a SAR system to detect objects hidden or obscured by foliage, detection is degraded in three ways for the higher microwave frequencies (>100 MHz). First, the foliage contributes to the clutter return. Second, the foliage attenuates signal propagation through it. And third, the moving foliage induces fluctuations in the amplitude and phase of the radar signal, which distort the SAR image of the target. These fluctuations affect the image-

**FIGURE 14.** The NASA/Jet Propulsion Laboratory AIRSAR aircraft containing the UHF, L-band, and C-band SAR radars. This aircraft was used to measure and characterize radar attenuation and backscatter caused by foliage in heavily forested areas.

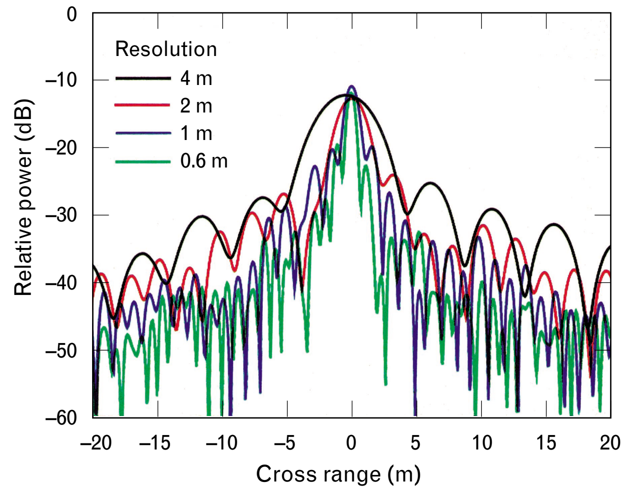


**FIGURE 15.** Foliage-penetration (FOPEN) results demonstrate that SAR azimuthal patterns can be generated with increasing resolution as small as 0.6 m, which indicates the ability of FOPEN systems to form accurate SAR beams through foliage.

focusing quality and the detection performance of SAR for targets hidden by foliage.

To obtain a better understanding of the foliage effects, researchers needed an accurate quantitative assessment of these issues. In 1990, Lincoln Laboratory conducted a definitive experiment to measure foliage attenuation and backscatter of heavily forested areas. This experiment was conducted with the NASA/Jet Propulsion Laboratory AIRSAR aircraft, which has UHF, L-band, and C-band SAR radars. Figure 14 shows this aircraft equipped with these systems.

The Laboratory conducted tests by overflying a forest site in northern Maine. The site had been carefully mapped and implemented with a variety of calibration reflectors and devices. Phase and amplitude data from the experiment were coherently integrated to create synthetic-aperture azimuthal patterns that would result when imaging a point target obscured by the foliage. The effects of synthetic-aperture length, frequency, and polarization on the attenuation and azimuthal synthetic beam pattern were investigated. Measurements also showed that less than a one-meter resolution for foliage penetration could be achieved at UHF frequencies. The results, shown in Figure 15, demonstrate the well-defined synthetic-aperture azimuthal patterns that can be generated even down to resolutions as small as 0.6 meters. This result was certainly a surprise to the conventional wisdom of the time, and it launched a major Department of Defense effort in FOPEN radar technology.

In the past decade, this FOPEN work has been extended to develop a phenomenological understanding of foliage penetration and to develop advanced automatic-target-detection and recognition techniques. Additional foliage-penetration measurements were made in 1993 in tropical rain forest and northern U.S. forest environments by using the Swedish 3-m-resolution Coherent All Radio Band Sensor (CARABAS) and the Stanford Research Institute ultrawideband (UWB) SAR sensor collecting horizontal-polarization VHF and UHF data. The data collected in these experiments were processed into calibrated SAR imagery, and foliage-induced attenuation for all frequency bands was calculated by comparison of echoes from test reflectors in foliage and those in the open [13–15].

In support of the current DARPA-sponsored foliage-penetration SAR project, Lincoln Laboratory is currently developing automatic-target-detection and cueing algorithms for VHF and UHF radar. With the detection of targets now possible with our existing foliage-penetration capability, the remaining issue becomes the identification of threatening targets from all of the many detections that are reported. Two false-alarm-mitigation techniques—change detection and group detection—have been used to reduce these false alarms substantially.

Wideband FOPEN systems are needed to detect targets reliably in the presence of foliage, radio interference, and cultural clutter. This requirement has motivated the development of a UWB SAR operating over 215 to 730 MHz. Its resolution is 0.3 m in range and 0.6 m in cross-range; and it has a full range of polarizations. The radar was built by the Environmental Research Institute of Michigan and installed on a U.S. Navy P-3 aircraft controlled by the Naval Air Warfare Center. This test-bed sensor, funded by the Air Force Wright Laboratory, was flown in 1995 to collect data on tactical targets in geographically diverse foliage over some 1500 $km^2$ of foliated terrain. Lincoln Laboratory has analyzed these data to determine the system requirements for an operational system and to identify suitable concepts to be employed with a tactical platform. Preliminary results from the UWB data suggest that a resolution finer than one meter is required to reduce false alarms from trees and to provide a sufficient number of independent pixels for recognition of potential targets in a radar image. At UHF frequencies, this requirement implies we need SAR azimuth integration angles greater than 35° with correspondingly long integration times. Lincoln Laboratory has also designed a new coherent classifier to use the complex polarimetric UHF data. The classifier performs well on targets in the open, and it correctly classifies a significant portion of targets hidden under foliage.

Recently, many researchers have been interested in the use of an airborne SAR for detection of underground targets, large and small, such as mines and trucks hidden in underground bunkers. In support of this interest, a ground-penetration experiment was conducted in 1993 near Yuma, Arizona. Again, a variety of radars were used, covering the RF band from 20 to 500 MHz. Data from this test helped researchers to develop a phenomenological understanding of soil-penetration losses and clutter backscatter, and to investigate the signatures of buried targets [16].

## Summary

Lincoln Laboratory has had a major influence over the past thirty years on the science and technology of battlefield surveillance for stationary and moving targets. Major developments and tests of airborne and ground sensors have been accomplished.

In all these efforts the goals have been to (1) understand the fundamental radar and processing issues involved, (2) determine the theoretical performance limits based on scientific principles and state-of-the-art technology, and (3) confirm those limits with field demonstrations. Many problems still remain in battlefield surveillance, and the ongoing program at the Laboratory continues to address these challenges.

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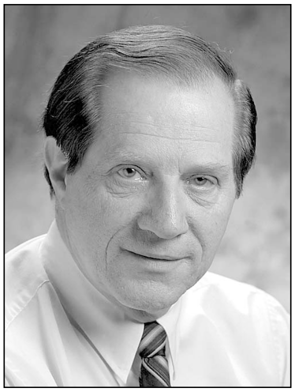

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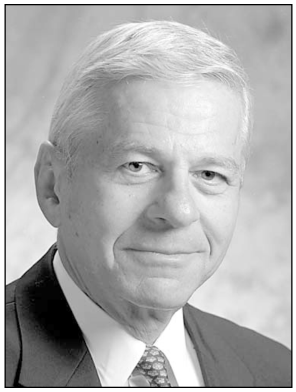

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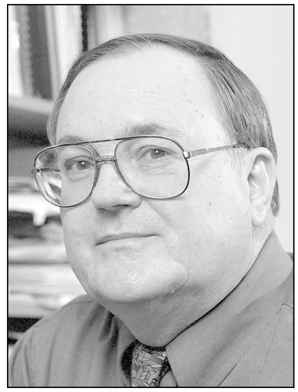

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