Chapters Three and Four presented alternative concepts for finding, recognizing, and defeating elusive maneuver or mobile missile forces. This appendix discusses the technological advances that will be necessary before these concepts can be implemented and describes the current state of the art in deployed systems, ongoing R&D efforts, and major technical challenges to be overcome.

Starting from the ground and moving up, we discuss unattended ground sensors (UGS); automatic target recognition (ATR); micro, small, and large unmanned aerial vehicles (UAVs); advanced radars; hyperspectral image processing; and hypersonic weapons.

UNATTENDED GROUND SENSORS

In principle, unattended ground sensors are simpler and more affordable than most of the other sensors and sensor platforms of interest to the U.S. Air Force (USAF). However, because its focus is on aerospace operations, the USAF’s recent practice has been to use UGS primarily for force protection—for example, the Tactical Automated Security System (TASS), used for air-base perimeter and flight-line protection. (A very notable historical exception was the Igloo White program, which was a major Air Force operation to detect enemy activity along the Ho Chi Minh Trail during the Vietnam War.¹) Nevertheless, UGS have the potential to be an excellent

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complement to airborne and spaceborne sensors, especially during operations against elusive enemy ground forces operating in the absence of friendly ground forces.

UGS can employ one or more sensing phenomenologies, including, but not limited to, acoustic, seismic, magnetic, electro-optical (EO) imaging, imaging infrared (IIR), pressure, radio-frequency (RF) resonance, chemical/biological/nuclear, olfactory, mechanical and infrared (IR) tripwire, and weather. This book focused primarily on integrated acoustic-seismic UGS, since the technology base is fairly mature and these sensors promise useful capabilities against elusive enemy ground forces. While more complex to build and employ, imaging UGS also may be useful to aerospace forces and are discussed briefly. In addition, the U.S. government is conducting extensive research on the development of sensors to detect, recognize, and alert friendly forces of chemical and biological weapons attacks, remotely monitor weather patterns, and protect U.S. facilities. Such applications are not the focus of this study, and their associated technologies will not be addressed in this appendix.2

UGS have many attributes that make them natural complements to airborne and spaceborne sensors. With the possible exception of Low Probability of Intercept (LPI) detection alert and status report transmissions, most UGS will operate passively (receiving only), resulting in low power requirements and reducing their likelihood of detection. Modern battery technology enables most designs to operate autonomously for months. UGS affordability should make it feasible to deploy vast networks of UGS. Further, while various environmental conditions will affect the performance of some UGS, generally they would continue to operate in most weather conditions and would be virtually unaffected by the low cloud ceilings that frequently preclude visual and IR-band imaging from medium- and high-altitude UAVs, manned aircraft, and satellites. Finally, their small size and fixed locations make UGS difficult to detect visually.

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In the next several pages, we discuss acoustic UGS, seismic UGS, advantages associated with combined acoustic-seismic UGS, and imaging UGS.

**Integrated Acoustic and Seismic UGS**

Acoustic and seismic sensors have been used for many years for civilian and military purposes. Used as unattended sensors, both phenomenologies are passive, and neither is dependent upon direct line of sight to the target being sensed. These attributes contribute to the sensor’s covertness and low power requirements, and relax requirements for sensor placement. In addition, since neither acoustic nor seismic sensors need light to operate, they are fully effective at night, providing a good complement to visual-band imagers.

**Acoustic Sensors.** Multiple-microphone acoustic UGS can usually provide a rough indication of the bearing to a detected target. However, because UGS are passive devices, data from an individual sensor does not reveal the range. Assuming the target is traveling along a road, fusing a sensor’s bearing data with the road’s known location can define the approximate target location. Further, if an array of acoustic UGS is deployed with overlapping coverage, beamforming\(^3\) can enhance the network’s detection, recognition, and location-estimating performance; triangulation in addition to beamforming or even instead of it can reveal target location, potentially to within targeting accuracy. However, if multiple vehicles are present, their combined signals and the timing of the signals arriving at separated receiver locations will complicate attempts to localize individual targets. Unresolved ambiguities can arise when there is moderate to heavy traffic.

Beamforming can help to resolve these ambiguities in the following way. Once one sensor detects a target, the array would scan a section

\(^3\text{Beamforming}\) is a process used to improve the signal-to-noise ratio (SNR) and the directionality of an array of sensors. Fundamentally, beamforming is accomplished by collecting the signals from all the array’s elements that are capable of sensing in the direction of interest, delaying the signals of individual sensors to correct for the varying lengths of time required for the sound to travel from a target source, and summing the synchronized signals. Greg Allen provides an illustrated tutorial on beamforming techniques, as well as a short list of related references, at “What Is Beamforming,” http://www.ece.utexas.edu/~allen/Beamforming/, last visited August 22, 2000.
of road by picking one point on the road at a time and thereby knowing the distance from the point to each sensor involved. The UGS would send their signals to a central processor (possibly in one of the UGS that is acting as the central node at a given time). The processor would consider acoustic data from the microphones of appropriate UGS, which are listening in the direction of the point on the road being considered. The processor would use an algorithm to synchronize the signals by delaying the employed microphones’ data by the time it would take for the signals to travel from the point in question to each sensor. The processor could systematically march along the road (or across an area) by repeating this process, sequentially considering several discrete points along the road being surveyed. One clear drawback to this approach is the need to transmit signals, which would use battery power and would emit a signal that the enemy might be able to detect. Of course, the data for a short period of time need only be transmitted once; for each point considered, the processor can select the appropriate microphone’s data and timing.

The effective target-detection range of acoustic sensors is typically on the order of one kilometer (1 km) when the target is a large moving vehicle; when the target is a pedestrian, it is tens of meters to 100 meters (m). The primary range-limiting effect is the spherical spreading of the sound waves, which causes the signal strength to attenuate in proportion to the square of the range to the target. However, acoustic sensor ranges also vary greatly as a function of environmental conditions, sensor placement within the terrain, and target activity. For example, wind distorts and turns sound waves, reducing the sensing range for targets downwind of the sensor and possibly increasing the sensing range for upwind targets. Similarly, thermal gradients in the atmosphere will refract the sound waves upward for normal atmospheric thermal gradients, where the air temperature drops with altitude; they will refract sound waves downward for thermal inversions. Thus, at night, when thermal inversions are fairly common, acoustic ground sensors tend to have greater effective ranges. While acoustic sensors do not require line of sight to a target, placing them out of a direct path for sound waves, such as behind a building, in a ravine, or behind a hill, can reduce the signal strength reaching the sensor to such an extent that the signal-to-noise ratio (SNR) is below the sensor’s operating limits.
Seismic Sensors. Seismic sensors generally have less effective range than acoustic sensors. Erteza et al. have demonstrated that the characteristics of the ground between the target and the UGS will affect the geophone’s performance. For example, igneous rocks have about ten times the propensity to transmit seismic waves as do unconsolidated sediments. However, seismic sensors do not exhibit as much range variability with changing weather conditions as do acoustic sensors. As Wellman et al. have pointed out, seismic signatures can be used to detect and sometimes to classify and recognize vehicles, especially tracked vehicles. However, seismic sensors are generally not useful for determining range or bearing to a target, and for the near term probably should be trusted with the roles of detection and very basic classification.

Integrated Acoustic-Seismic Sensors. The combination of acoustic and seismic sensors is a good choice for detecting moving vehicles. Acoustic sensors have a greater range than seismic sensors. Assuming acceptable SNRs for each sensor, the acoustic signal would contain more usable information than would the seismic signal. Therefore, the advantage of integrating acoustic and seismic sensors is primarily twofold.

First, seismic signals provide confirmation of acoustic detections and recognitions. Since acoustic and seismic phenomenologies are independent, spurious simultaneous detection alarms are unlikely to occur coincidentally or as a result of activity by entities that are dissimilar from valid targets. This confirming function would help reduce acoustic false alarms caused by natural events or by small civilian vehicles. In addition, the combination of phenomenologies complicates enemy deception efforts. For example, playing back a high-quality tape recording of a transporter-erector-launcher (TEL) or tank that contained all relevant portions of the acoustic spectrum would not produce the corresponding seismic signature.


Second, if the acoustic-detection range is severely limited by the UGS’s landing in a crevasse, or being covered by snow, or landing upwind of the target, the seismic geophone may have significantly greater detection range than the acoustic microphones.

One limitation common to acoustic and seismic UGS is their general inability to assess the potential for collateral damage in the vicinity of a detected target. Therefore, depending upon the rules of engagement (ROE), the nature of the region being monitored, and the conflict, an engagement controller may need to call for EO or IR imagery prior to directing a strike.

**Description of an Acoustic-Seismic UGS System.** An effective air-deployed acoustic-seismic UGS would consist of microphones, geophones, a GPS receiver, a communications system, a clock, a computer processor, a hardened ground-penetrating and aerodynamic body, aerodynamic control surfaces, aircraft pylon attachment lugs and/or electrical connector, batteries, and a camouflage scheme, along with flight control, ATR, and diagnostic and communications software. The flight control subsystems are recommended for keeping the circular error probable (CEP) well within the minimum effective radii of the seismic and acoustic sensor ranges. Since the CEP requirements would be similar, the UGS’s flight control software, actuators, and control surfaces could reasonably be a miniaturized adaptation of the Joint Direct Attack Munition’s (JDAM’s) flight control system. The integrated sensor network would also require remote ground control and communications relay systems, as well as synthesis systems to integrate and analyze reports from multiple UGS and to fuse processed UGS network data with other intelligence, surveillance, and reconnaissance (ISR) and intelligence preparation of the battlespace (IPB) data.

The DoD continues to develop and test UGS technologies and systems. Recent Advanced Concept Technology Demonstrations include the Rapid Force Projection Initiative, which investigated the use of Textron Systems Corporation’s Air Deliverable Acoustic Sensor (ADAS) UGS, and the Unattended Ground Sensors, which demon-

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strated the Sandia National Laboratory–designed “Steel Eagle.” The Air Force has transitioned the Steel Eagle, which is an air-deployable acoustic and seismic UGS, to a development program entitled Advanced Remote Ground Unattended Sensor (ARGUS).\(^7\) With the Initial Operational Concept (IOC) scheduled for 2003, plans for ARGUS are to continue to improve the system’s capability and add other sensor phenomenologies as new technologies mature after the initial design freeze and fielding.

This UGS is being developed for F-15, F-16, and A-10 carriage and deployment, and the Electronic Systems Center’s ARGUS program office is considering extending the list of delivery platforms to include medium- and high-altitude UAVs. ARGUS’s minimum performance specifications require finding, fixing, and tracking targets within 500 m of the sensor and recognizing them within 200 m, and set desired objectives for these tasks at 2,000 m and 500 m, respectively.\(^8\) The tested prototype design weighs 84 pounds (lb). For production, this weight is being reduced by integrating advanced batteries and miniaturized electronics into a smaller body.\(^9\) Another noteworthy characteristic of the ARGUS is its capability for updating the target signature database after deployment, which should allow operators to remotely enhance ATR performance after new targets are sensed by the UGS and analyzed by intelligence analysts. Assuming affordable production costs, good fusion with other ISR data, and strong ATR performance including a low probability of false alarm, the ARGUS could provide a good complement to airborne and spaceborne sensors. A very useful enhancement would be the integration of an onboard Global Positioning System and Inertial Navigation System (GPS-INS)-guided flight control system to ensure CEPs are limited to tens of meters. Figure A.1 shows the configuration of the baseline ARGUS UGS.

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\(^9\) Personal interview with 2nd Lt Shelly Reade, ARGUS Program Manager, June 7, 2000.
Distribution of Integrated Systems. Acoustic-seismic UGS could be arrayed in various configurations, including individually, in a uniform grid over the entire area that the commander’s IPB indicates is trafficable, or in clusters.

A uniform array could be used to monitor all traffic and track targets in a region, both on roads and off, assuming the signal processing could distinguish between the valid targets and any other vehicles in the region. The extreme weather-dependent variation in the effective range of each acoustic sensor could make selecting the UGS’s uniform grid spacing a challenge. However, our analysis of target-detection rates as a function of varying sensor effective ranges shows that a uniform array’s effectiveness will degrade slowly and gracefully, even when sensor ranges drop significantly. Figure A.2 shows the results of an analysis of a grid of 100 acoustic sensors configured as a hexagonally arrayed $10 \times 10$ grid. For this analysis, targets moved through this grid along 210 representative straight paths; on successive runs, acoustic-sensor effective ranges were incrementally decreased. As illustrated, even when the ratio of the sensors’ effective ranges to grid sensor characteristic spacing drops to 30 percent of the range required to provide 100-percent coverage within the grid, over 80 percent of the representative targets were detected by at least three of the UGS. In fact, to avoid detection, the target must travel very nearly parallel to, and directly between, rows of UGS in the grid, which is unlikely without prior knowledge of the grid’s specific configuration.
Figure A.2—Graceful Degradation of Unattended Ground Sensor Uniform Grids with Reductions in Sensor Effective Range. Sensor detections are of targets moving on straight paths through a $10 \times 10$ hexagonally arrayed UGS grid.

With a fraction of the number of UGS that would be required for a uniform grid, these sensors could be distributed in clusters in inconspicuous locations along roads, yet where the enemy’s routing alternatives are few to nonexistent. Such clustering would enable friendly forces to remotely monitor traffic, “recognizing” those military targets that have been included in the UGS’s acoustic signature database. Deploying these clusters with overlapping coverage between individual UGS would allow beamforming, triangulation, and redundancy.

In addition, requiring simultaneous consistent target recognitions by multiple UGS in a cluster would provide a strong false-alarm filter. False alarms, which are sensor reports of targets when no target, or a different target, is present, have the potential to negate the effectiveness of an UGS surveillance system. Since civilian vehicles or unimportant military vehicles often greatly outnumber more-significant military targets, there is the potential for false alarms to
overwhelm intelligence analysts, engagement controllers, and imaging systems. If the false-alarm frequency is high enough, the alarms cannot all be investigated, and the engagement controllers and intelligence analysts may choose to turn off the UGS network in order to maintain their effectiveness and sanity. Clearly, the allowable false-alarm rate for an UGS network will depend upon the ratio of confusers to targets, the strictness of the ROE, the importance of finding and striking the real targets, and the number of imaging systems and analysts available to respond to UGS reports. It may be possible to tighten the ATR algorithm’s requirements for issuing an alarm, thereby limiting false alarms, at the expense of a lower probability of valid target recognition.

If the probability of false alarm for an UGS design cannot be kept sufficiently low by developing very capable acoustic ATR algorithms, alternative measures are available to manage the false-alarm rate. For example, the UGS network’s fusion software can be designed so that alarms are sounded only when a designated number of UGS in a cluster are simultaneously or sequentially issuing consistent recognition reports and/or when seismic geophones confirm vehicular traffic. If seismic confirmation is employed, the UGS must be placed several tens of meters away from the road to keep the sensors within the effective geophone range and yet far enough from the road to avoid easy visual detection.

This approach reinforces the argument for an integrated GPS-INS–guided delivery system to keep UGS delivery CEPs low. If, for example, clusters of UGS were placed along a major highway, they might be implanted 50 m from the road to provide high probability of target vehicle detection by a seismic sensor and yet low probability of visual detection of the sensor by enemy personnel in vehicles traveling along the road. A delivery CEP of 10 m would place the majority of the sensors in the band between 40 and 60 m from the road, which should provide near-optimal performance. Alternatively, reasonable ballistic drop CEPs of around 200 m would likely place some sensors out of seismic range on both sides of the road and some within easy visual detection, including on the road.

It is reasonable to assume that if even one UGS lands on or near the road, the entire cluster will be compromised when the enemy finds that wayward sensor and as a result combs the area for the entire
cluster. Furthermore, wind could greatly increase an uncontrolled UGS’s CEP, causing it to drift far from the intended delivery point if it were dropped from medium altitudes (above the MANPADS threat) or from a high-altitude endurance (HAE) UAV at 65,000 feet (ft). This problem would be eliminated by including a GPS-INS–guided delivery system.

**Imaging UGS**

Electro-optic or imaging infrared (IIR)-based UGS would have several advantages over their acoustic-seismic counterparts in providing enduring surveillance of key enemy lines of communication (LOCs), troop concentrations, or other key targets. For example, beyond recognition of targets, engagement controllers and intelligence analysts could use imaging systems to assess collateral-damage potential. Except during periods of inclement weather, well-placed, compact, ground-based imaging systems can be effective at ranges of hundreds or thousands of meters, which would permit fairly wide-area surveillance by each sensor, greater standoff ranges to avoid detection, and fewer restrictions on each UGS’s size and cost than on acoustic-seismic UGS. Furthermore, when used in conjunction with acoustic-seismic UGS, these systems can make it more difficult for the enemy to counter U.S. sensors. However, the development and employment of these systems would be significantly more complicated than for acoustic-seismic UGS.

**Development.** For example, the imaging UGS would have to be positioned within the line of sight to the areas to be surveyed—a difficult proposition in most environments: A bush, rock, mound, or building could limit or negate an imaging UGS’s effectiveness. Because the imaging UGS needs a lens with unobstructed views of the potential target locations, the system’s optics and associated support hardware may be more easily detected by the human eye than by its acoustic-seismic cousin. Designs would have to balance the need for light weight and low power with the requirement for optics of sufficient size to provide adequate resolution for distinguishing targets. In addition, hardening imaging sensors to survive the impact of air-drop could be quite challenging. Moreover, to be useful at night, visual-band sensors would have to incorporate image intensifiers on video cameras or low-light-level (LLL) charge-coupled devices. The
limitations of onboard power supplies would mean that enduring IIR UGS would have to use uncooled detector arrays, and both IIR and EO imaging UGS may have to be cued by a remote engagement controller or by another sensor (e.g., acoustic UGS) to operate only when a suspected target is sensed. Because imaging UGS have a relatively narrow optical beamwidth, these external cues would have to include target-location data so that the imaging UGS could point at the suspected targets. Therefore, the imaging UGS design would need to include a two-axis rotational capability for the optics.

**Deployment.** One means to deploy imaging UGS would involve a rotary-wing miniature air vehicle with hovering capability. A remote “UGS pilot” could use the onboard imaging system to guide the sensor platform to an acceptable observation site, free of visual obstruction and away from likely detection. The hovering systems could also land the UGS gently, precluding the requirement for highly ruggedized optics and sensors. This self-deployed UGS could be large enough to include imaging sensors, flight control, lift/propulsion, batteries, and solar panel subsystems, without being readily detectable. Clearly, the alternative of having friendly ground forces place the imaging UGS would permit simpler designs, but this alternative may not be available in some future operations.

As for acoustic-seismic sensor systems, robust automatic target recognition systems will be critical to the application of acoustic UGS. They will be needed for judiciously cuing imaging UGS, other sensor systems, and engagement controllers. The following section describes how ATR software works and considers some of the technical challenges.

**AUTOMATIC TARGET RECOGNITION**

Faster and more-capable computers, communications, and weapon systems contribute to the faster pace in the battlespace and to the requirements for more-rapid decisionmaking. The proliferation of battlefield sensors provides the opportunity to create a detailed, integrated picture of the battlespace that could enhance and accelerate combat decisionmaking at all levels of command. However, throughout the history of warfare, human senses and reasoning have been the predominant tools used to discriminate friendly forces from targets, and to prioritize and direct strikes against the targets.
Even as collection platforms and bandwidth have multiplied, the human remains the key link in the targeting and target-approval process: The human aims the gun, remotely guides the EO weapon to the target, picks the target to designate with a laser, studies imagery to single out the military targets, and selects and/or confirms the GPS coordinates for the JDAM. Yet, the ever-accelerating pace of warfare and the burgeoning proliferation of sensors—especially imaging sensors—are bringing U.S. forces to a crossroads. With the volume of ISR data threatening to overwhelm both the intelligence analyst and the engagement controller, some relief or assistance is needed to screen data, thereby reducing the requirement for humans to analyze data and make decisions.

Automatic target recognition, or ATR, appears to offer the unique potential for exploiting the snowballing volume of military sensor data by computationally discriminating between detected signatures before a human intervenes. Ideally, ATR algorithms, integrated with high-resolution sensor data and appropriate communications links, would provide engagement controllers with a continuously updated digital list of recognized targets, along with sufficient data to access the associated fratricide and collateral-damage potential. These engagement controllers could then integrate and prioritize targets within their tactical planning process and task strike aircraft immediately or at a later time, as appropriate.

Development of ATR Algorithms

However, in reality the development of robust ATR algorithms is an extraordinarily difficult challenge. The ATR development community generally acknowledges three levels of target categorization: classification, recognition, and identification. Classification groups targets into categories, such as tanks, TELs, and trucks. Recognition refines this grouping to distinguish between specific types or models within each classification, such as T-62, T-72, and M-1A tanks. Identification extends the fidelity a major step further by identifying which M-1A by serial number, license-plate number, or other cataloging scheme. While often inadequate for targeting purposes, classification can perform the critical function of filtering large volumes of civilian traffic from military vehicles. For military targeting purposes, high-confidence target recognition is usually necessary,
with specific identification seldom adding any value. Despite the
distinction between recognition and identification, the literature of-
ten uses these terms interchangeably.

ATR algorithms can be developed to exploit various sensor phe-
nomenologies or combinations of phenomenologies. For example,
U.S. and international researchers are developing ATR algorithms for
EO, IR, millimeter-wave, and synthetic aperture radar (SAR) imaging;
hyperspectral imaging (HSI); acoustic; and chemical/biological sen-
sor data. Although each of these phenomenologies has unique po-
tential, challenges, and limitations, virtually all ATR algorithms refer-
ence appropriate databases of target signatures or characteristics.

**Acoustic ATR**

Acoustic ATR schemes analyze the acoustic spectra of aircraft and
vehicles, “looking” for the unique sound-wave signatures of specific
systems. For example, the exhaust of all vehicles and the rear cog-
wheels of tracked vehicles produce sounds unique to individual ve-
hicle designs, permitting recognition of specific vehicle types, such
as a T-72 tank. One clear advantage of acoustic ATR is its capability
to recognize targets without sensor line of sight to the target.

However, acoustic ATR development also has many obstacles. The
ability of sound waves to propagate to, and reflect from, areas out of
the sensor’s line of sight of the target can lead to multipath complex-
ities. Multipath complexities are created when sound waves and
echoes from earlier sound waves arrive at the sensor at approxi-
mately the same time and from different directions. Similarly, wind,
atmospheric thermal gradients, and other weather effects can turn,
attenuate, and shift the frequency of sound waves. Multiple audible
targets (e.g., from a military convoy) traveling together will also
complicate ATR processing.

While challenging, acoustic ATR is probably the most mature ATR
approach today. Installing the ATR algorithms onboard Air Force
UGS will likely reduce required communications bandwidths, since,
usually only target vehicle location (bearing or approximate location,
if determined), type, and quantity would need to be transmitted to
the engagement control element, as opposed to relaying all sensed
acoustic data.
Imaging ATR

The challenges associated with imaging ATR are, in most respects, more difficult than with acoustic methods, because an infinite variety of images may be encountered from any target. For example, a sensor may capture an image of a target from any azimuth, elevation, and range, relative to the target. Further, the articulation of major components—such as turret rotation, gun elevation, missile rail erection, and radar antenna look angle—may cause the appearance of some targets to vary. Smaller differences, such as hatch openings, paint colors, and cleanliness of the target, along with the addition of fuel barrels, ammunition, or equipment strapped onto vehicle exteriors, are usually referred to as target image variation. Similarly, the infinite combinations of terrain, foliage, man-made structures, weather, and lightning/illumination effects on the image, including partial or complete obscuration, make up the environmental variation in the target image. Finally, the enemy can and likely will use camouflage, concealment, and deception to intentionally complicate this already-daunting ATR challenge. Therefore, it is unrealistic to attempt to create databases of all possible images, which would permit precise image (or silhouette) matching, and a more creative and robust approach must be pursued.

Artificial Neural Networks

Much of ATR research and development is focused on the application of artificial neural network (ANN) algorithms that can recognize distinctive physical features of known targets, thereby automatically recognizing these targets. In addition, corresponding databases of targets are being assembled within the United States, foreign nations, and collaboratively among the NATO nations.

Artificial neural networks are based on the construct of biological neural networks and are able to learn, remember, and associate new information. Like their more complicated biological counterparts, these systems are collections of individual, but interconnected, neurons. Some neurons receive input stimuli from the environment.

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and give output to other neurons; some are stimulated by other neurons and provide output to the environment; still others are isolated from the environment and interact only with other neurons. ANNs are trained to provide appropriate responses to stimuli by adjusting the individual neuron’s positively or negatively weighted responses to input from each other.

Klerfors provides a more detailed tutorial on ANNs and their potential applications, pointing out that the most successful applications of artificial neural networks are in categorization and pattern recognition. Dudgeon\textsuperscript{12} contends that the inclusion of contextual data, including terrain maps and target TTP (tactics, techniques, and procedures), in ATR processing would add complexity to the ATR algorithm, but has the potential to improve recognition performance. For example, knowing the location of roads and other geographic features, and that the desired targets’ operations are limited to certain types of terrain, could be used to focus a search or eliminate false alarms.

**Radar ATR**

The USAF is also developing ATR technologies for use with advanced airborne radar (see the “Space-Based Surveillance” section of this appendix for a brief tutorial on radar). The Radar Technology Improvement Program (RTIP) was originally planned as an upgrade to the Air Force’s E-8 Joint Surveillance and Target Attack Radar System (Joint STARS). However, the USAF has recently redirected this effort. The new Multi-Platform RTIP (MP-RTIP) will be capable of being scaled and integrated on airborne platforms, including Joint STARS, Global Hawk, and other systems; however, at this time, which USAF platforms will receive the upgrade has yet to be decided.\textsuperscript{13}

This system will have the potential to employ ATR to filter detections

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\textsuperscript{13}Interview with Dr. Chris Bowie, Northrop-Grumman Corporation, Rosslyn, Va., November 30, 2000.
and more selectively cue engagement controllers to task additional sensors or weapons. MP-RTIP’s high range resolution (HRR) ground moving-target indicator (GMTI) radar will have sufficient resolution to distinguish large (TEL-sized) vehicles from smaller vehicles. These TEL-sized target detections would serve as cues to the new inverse synthetic aperture radar (ISAR), which has the ability to image moving targets. Similarly, when GMTI indicates a target has stopped, the upgraded SAR can be used to image the target. The resulting SAR and ISAR images of recognized targets could be automatically handed off to engagement controllers for target confirmation and possible prosecution.14

**ATR and Smart Weapons**

ATR systems are also being developed for various precision weapons and could be employed autonomously in the near term, in situations in which the ROE are sufficiently relaxed.15 A discussion of LOCAAS is included later in this chapter because of its strong potential to conduct low-level surveillance as an expendable unmanned aerial vehicle (UAV) and/or to attack moving or stationary enemy forces.

**Realizing the Benefits of ATR**

The difficulties associated with the implementation of ATR in U.S. weapon systems, as well as the reluctance to eliminate human intervention in target selection and strike decisions, will likely result in ATR algorithms being used to screen detections, rather than to automatically direct strikes against recognized targets. While not achieving the full potential of ATR, this mode of operations will allow large amounts of sensor data to be exploited and will make controllers more efficient and responsive by eliminating the need to scan massive quantities of data.

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15For brief descriptions of ATR algorithms being developed for Low Cost Autonomous Attack Systems (LOCAAS), SLAM ER, Storm Shadow, Hellfire, and other weapon systems and development programs, along with their respective conops, see the Armada International Web site at http://www.armada.ch/e/3-98/001outline.htm, last visited September 5, 2000.
UNMANNED AERIAL VEHICLES

UAVs are gaining wide acceptance and are playing an increasing role in USAF operations. Kosovo became an excellent proving ground for the USAF’s Predator medium-altitude endurance (MAE) UAV, which provided valuable imagery during its 24-hour missions. The USAF is addressing weaknesses identified in this new, first-generation UAV and has several enhancements in progress, including adding a laser to conduct range finding and target designation. The Global Hawk high-altitude endurance (HAE) UAV, currently an Advanced Concept Technology Demonstration, is expected to enter service in the next few years.16 MAE and HAE UAVs are suitable platforms for EO, IR, and radar systems, including the FoPen17 and HSI systems described later. In addition, UAVs can be used to carry SIGINT collection systems and communications relay devices. As an extension of these capabilities, either type of UAV could be adapted to carry and deploy GPS-guided UGS, small UAVs, and/or miniature munitions. Examples of miniature munitions include 100- or 250-lb GPS-INS-guided Small Smart Bombs (SSB), or the LOCAAS. The Air Force Research Laboratory’s (AFRL’s) Munitions Directorate is working with industry to develop these and other miniature munitions and their associated technologies.

The medium- and high-altitude UAVs, combined with manned ISR aircraft and constellations of space-based collectors, will provide the USAF’s suite of sensing capabilities at the altitudes above the proliferating Man-Portable Air Defense (MANPAD) threat. However, even with the enhanced airborne and space-based systems described in this book, it is still often necessary to get under the weather and up close to a target to obtain sufficient situational awareness to authorize a strike. This is especially true in an environment of strict ROE and in the absence of friendly ground forces.

Figure A.3 illustrates the weather challenge with weather data from the Prizren region of Kosovo. Ceilings vary with the season. On

17A VHF-band FoPen radar antenna would be quite large and therefore difficult to integrate into a Predator-size UAV.
Figure A.3—Prizren Region (a) Average Cloud Ceilings and (b) Visibility by Month
average, a surveillance platform would have to fly below 4,000 ft to have an 80-percent chance of having a cloud-free view of the ground. Air-deployed unattended ground sensors and smaller, expendable UAVs can fill this gap, to form a seamless web of collection capabilities from the ground through space.

Micro–Air Vehicles

The Defense Advanced Research Projects Agency (DARPA) is developing micro–air vehicles (MAVs), which it defines as UAVs with maximum physical dimensions under 15 centimeters (cm). At this tiny scale, MAVs have the advantages of being man-portable and may eventually be able to navigate in confined areas, such as under forest canopies, in urban canyons, and inside buildings. However, their small size will limit MAVs to fairly short-range and endurance missions, very small sensor apertures, and low-power transmissions. In addition, with typical flight speeds of 5 to 10 meters per second (mps), moderate winds will greatly affect their range, ground speeds, and maneuvering capability. Despite these limitations, MAVs will fill an important void in the U.S. military capability to find enemy forces hiding under trees or in buildings and to conduct immediate BDA or tag targets in these environments.

MAV systems will require the application of several existing technologies and some new technologies. For example, these small air vehicles operate beneath the envelope of most USAF flight experience. Therefore, DARPA’s MAV program includes research in the field of low-Reynolds-number aerodynamics for fixed- and rotary-
wing MAVs. In addition, volume and weight limitations make propulsive efficiency a prime design consideration. DARPA is studying battery-powered, propeller-driven MAVs, as well as miniature jet and rocket engines. Miniatuated guidance systems, sensors, communications systems, aerodynamic control surfaces, and actuators are also being developed and integrated. Although MAVs’ small sizes will contribute to covertness, maneuverability, and transportability, design trades may drive production MAVs to be somewhat larger than DARPA’s goal of 15 cm.

**Deployment.** To employ MAVs as a means of finding hiders in forests or in urban environments, the USAF must have a way of inserting these sensor platforms into the vicinity of the target to be sensed and must have a datalink to the engagement controller. Large UAVs or manned aircraft flying above the surface-to-air threat could facilitate both of these actions in many scenarios. An individual MAV or clusters of MAVs can be carried and dropped from these larger air vehicles in a pod or missile, which would fly to the area of interest and then slow to the MAV’s flight regime before releasing them. Commands from the engagement controller and sensor data from the MAV could then be relayed through the launch aircraft or UAV. If the insertion point is at long range, the MAV may be able to use a satellite’s datalink, or the delivery missile could deploy a separate datalink on a small UAV.

**Designing for Obstacle Avoidance.** The operating requirements associated with flight under forest canopies and in buildings will drive the designs of MAVs intended for those purposes. At this point, battery-powered, shrouded rotary-wing designs appear best suited for flight and imaging in these confined and complex environments. Further, these MAVs’ guidance packages must include search algorithms with obstacle-avoidance subroutines and the system’s sensors will have the additional duty of detecting obstacles that must be avoided. Passive imaging sensors may be the MAV’s primary

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(e.g., the chord of the wing measured from the leading edge to the trailing edge), and \( \mu \) is the viscosity of the flowing fluid (e.g., air is less viscous than honey or motor oil). Since \( \rho \) and \( \mu \) are approximately the same for all aircraft at a given altitude, the MAV’s uniquely low Reynolds numbers stem from their slow flight speeds and small physical dimensions. Assuming the maximum MAV dimension of 15 cm for \( L \) and a flight speed of 6 mps, a MAV’s \( Re \) would be approximately 1/1,000 of a small private aircraft and 1/10,000 of a large cargo aircraft or airliner.
means for target detection/ recognition and for fratricide/ collateral- damage prognosis, but small radar or bat-like ultrasonic echoed- locating sensors may be needed to provide target and obstacle proximity data. Alternatively, a single active sensor, such as a small imaging laser radar, may accomplish both tasks. The guidance systems should be capable of either autonomous searches or remote-controlled flight. Automatic target recognition algorithms will have the challenging task of recognizing targets, as well as natural and man-made obstacles, in these complex environments.

For these reasons, these obstacle-avoidance MAV variants will probably lag the simpler remotely piloted MAVs by many years. However, Draper Laboratory is working on a hovering MAV called the Kolibri, which is to include the obstacle-avoidance algorithms, autonomous and datalinked remote-control systems, miniaturized INS-GPS, and sensors. The Kolibri weighs 320 grams (0.7 lb), is propelled by a miniature diesel engine, and promises an impressive 30 min of endurance.22 Figure A.4 illustrates two shrouded rotary-wing MAVs flying and hovering beneath a forest canopy to image a hiding TEL.

DARPA is also working on an extension to MAV capabilities in their Controlled Biological and Biomimetic Systems program. Studying biological organisms to understand and exploit their means of locomotion, navigation, sensory fusion, and target recognition, this program is developing insect-like sentinels that could be deployed to gather information for the warfighter.23

Small UAVs

Filling the capability gap between MAE UAVs and MAVs, small USAF UAVs will fly close to the enemy, as do MAVs, making them vulnera-
Figure A.4—Micro–Air Vehicles Flying Below the Forest Canopy to Image a Hiding TEL

ble to attack by ground forces. And they will have relatively short ranges. In the absence of friendly ground forces to launch them, they will need to be inexpensive one-time-use vehicles and will have to be delivered to the target vicinity by a manned aircraft, larger UAV, artillery round, or missile. Even so, by flying at several tens or even hundreds of kilometers per hour, these air vehicles may be able to search tens to hundreds of square kilometers during a mission. Flying at hundreds of meters above the ground, they will operate under most cloud cover but will generally not be small enough to maneuver under forest canopies.

These systems will need to be able to transmit both images and the GPS coordinates of targets. Their onboard cameras will have to be small and lightweight, have low power consumption, yet be able to produce image quality at National Imagery Interpretability Rating Scale (NIIRS)\(^{24}\) levels 7, 8 or 9, depending upon the mission and ROE.

\(^{24}\)Image analysts use NIIRS scales (0 to 9) to quantitatively assess an image’s quality, or *interpretability*, which is a function of many factors, including illumination, sharpness, contrast, and picture size. NIIRS scales exist for the visible spectrum, as well as
A small UAV may calculate a target's location using an onboard active sensor's ranging capabilities and extrapolating from the small UAV's GPS coordinates, or it may solve this geometry problem using an IPB-supplied digital terrain map of the region, along with its own GPS coordinates and an onboard passive imaging sensor's look angle. Many small UAVs have been designed and flown, and a wealth of experience is available from the model-airplane industry, sister services, and others.25

The U.S. Army defines small UAVs as having a range of 20 to 25 km, an endurance of 1 to 2 hr, a maximum wingspan of 4 ft, and a maximum weight of 25 lb.26 However, many small-UAV designs vary in some aspects of this description. AeroVironment’s Pointer D-2 is an example of a very lightweight small UAV. This 8-lb platform can operate for 1.25 hr using a lithium battery, has a 9-ft wingspan, and can carry LLL TV, forward-looking infrared, or chemical sensors. However, lightweight airframes such as the Pointer D-2 are designed to be hand-launched and are too fragile for captive carriage under the wing of a combat aircraft. Small-UAV designs can be strengthened and designed with pop-out wings to permit low-drag carriage and deployment from larger air vehicles.

It is possible to design a completely new small UAV for USAF use; however, it might be faster, cheaper, and lower risk to adapt existing small air vehicles, such as DARPA’s Miniature Air-Launched Decoy (MALD)27 or the USAF’s LOCAAS, both of which can be captive-
carried and deployed from larger air vehicles, and are designed to cost approximately $30,000. The MALD has a flight speed of Mach 0.9 and a range of over 550 km.28

The LOCAAS’ speed and range are lower than those of the MALD, but it already has a capable imaging and ranging sensor integrated with an ATR, and high speed may not be necessary or desired when collecting imagery at fairly close range. Therefore, we have chosen to employ LOCAAS and variants of LOCAAS for our concepts of engagement, extending this system’s search and strike capability to accomplish the dual roles of attack and surveillance.

Low-Cost Autonomous Attack System

The Low-Cost Autonomous Attack System, or LOCAAS, is a one-time-use folding-wing air-launched miniature cruise missile that can be deployed from aircraft, UAVs, missiles, or munitions canisters. As represented in Figure A.5, it has a 4-ft wingspan, weighs 85 lb, and is propelled by a miniature turbojet engine.29 LOCAAS searches or cruises at 120 mps (Mach 0.35) for 30 min, giving it a range of 185 km, a search area capability of 50 sq km, or some combination of the two. AFRL has developed LOCAAS to autonomously search for, detect, recognize, and kill critical mobile targets such as tanks, TELs, and mobile SAM launchers. Using a laser radar (Ladar) seeker, it sweeps the search area with an infrared-wavelength laser beam, sensing the reflected light to detect, image, and range targets.

The Ladar produces imagery with sufficient resolution for ATR processing. The system’s ATR compares the Ladar image of the suspected target to its target database in an attempt to recognize the vehicle. This capability includes some target-variation robustness, including turret and gun articulation. However, clouds and precipitation rapidly attenuate IR wavelengths. Although its search altitude of 225 m AGL will usually keep LOCAAS flying beneath the cloud

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layers, LOCAAS will likely have difficulty imaging targets while flying through precipitation or fog.

**LOCAAS Operation.** When LOCAAS detects and recognizes an object as a valid target, it enters an engagement mode. In this mode, it flies a glideslope from its 225-m search altitude to a point directly over the target. As it passes over the target, it fires a self-forging warhead in one of three modes. For hard targets, it fires in the “stretching rod” mode, which is optimized to penetrate a tank’s turret. If the weapon is fired from a greater height above the tank, the warhead forms an “aerostable slug,” which is designed to maintain its integrity for these longer ranges and still penetrate the armored turret. If the target is softer, such as a TEL, the warhead will fire a directed fragmentation-blast pattern.
This multi-mode device not only provides a robust killing capability but also greatly limits the potential for collateral damage by restricting the strike to the target—a stark contrast from the potential effects of most gravity bombs and cluster munitions.

**LOCAAS Plus: Adding a Datalink.** A LOCAAS-like weapon would offer a strong addition to the USAF’s capability to defeat critical mobile targets. However, a modest design enhancement on some of the LOCAAS weapons may provide much more robust capabilities and flexibility against elusive targets than are now planned. Specifically, we recommend adding a two-way datalink from the LOCAAS to the strike aircraft and airborne command element, and adding a LLL visual-spectrum motion-picture camera, slaved to the LOCAAS Ladar’s field of view. Rather than eliminating the system’s autonomous capability, these modifications would complement it by providing for optional remote interaction. The datalink would transmit visual imagery to an engagement controller and remote-control commands to the LOCAAS, enabling many new concepts of operation with this hybrid small UAV–cruise missile.

For example, when a LOCAAS has detected and recognized a target and is closing in for the kill, the engagement controller can view the imagery to determine whether to proceed with the attack or terminate it. Unlike a terminal-phase no-go decision for an AGM-130, the LOCAAS would not be lost. It would simply revert to its search pattern, go around for another pass, or respond to other commands from the engagement controller. The datalink could also provide a variety of other capabilities. When the appropriate search pattern is not clear, one or a few LOCAAS could be remotely piloted to hunt for a target and then could be returned to autonomous operation for the final strike sequence against the designated target. Similarly, a remote operator could observe the imagery during a standard autonomous search pattern, but alter the search pattern if she notices suspicious activity, such as a distinct vehicle trail, dust cloud, target being covered by netting, or a new target of opportunity. If one LOCAAS has just fired at the desired target with unknown results or if the engagement controller has confirmation of a camouflaged target at a specific GPS coordinate, she could direct one or several LOCAAS to abandon their searches, fly directly to the target, and either re-acquire and strike, or simply strike the target’s GPS coordinates using a specified warhead mode. In this case, as each LOCAAS approaches
the target area, its imagery could permit BDA of preceding LOCAAS strikes.

The flexibility provided by this range of operating modes would make the LOCAAS much more robust against a variety of targets. It would also add significantly to the enemy’s challenge of countering the system, since its operation would be much less predictable and since options for counter-counter measures would be more plentiful. Further, this capability could free the LOCAAS to be used with supervision in situations that ROE would otherwise make off-limits. An example of this added engagement freedom might be striking a tank in a convoy for which intermingling of civilians had not otherwise been ruled out. Similarly, the visual-band sensor would provide sufficient resolution to allow the engagement controller to recognize personnel and thereby gain confidence that groups of individuals are enemy soldiers, rather than friendly soldiers, human shields, or otherwise intermingled civilians. One uncertainty that may limit such movement to a man-in-the-loop LOCAAS is cost, which could be driven up substantially by putting a stabilized TV or IR sensor on LOCAAS. If so, then perhaps only a small percentage of LOCAAS would have that feature for situations where it was essential.

Another alternative would be to produce a reconnaissance version of LOCAAS whose sole purpose would be ISR and BDA. By replacing the warhead with additional fuel, this configuration would form a small, expendable UAV, which could have hours of on-station endurance. This system could provide continuous imagery surveillance under cloud cover and/or at night to help fill the gap between endurance UAVs and ground sensors. It could also be used to search for targets, provide target images with GPS coordinates, and then provide BDA imagery immediately after conventional LOCAAS or other weapons have attacked the target.30 In addition, if the LOCAAS’ datalink transmissions are not sufficiently powerful to reach the launch platform, an appropriate communications satellite, or the Airborne Command Element, it may be necessary to use this ISR LOCAAS or another LOCAAS to relay the data.

30Wall and Fulghum (2000, p. 78) recommend a similar design modification, replacing the warhead with a camera.
ADVANCED RADAR

Radar is an active sensor methodology that can exploit many portions of the electromagnetic (EM) spectrum. Most radar systems are designed to use portions of the EM spectrum from UHF through Ka band (300–40,000 MHz). Some systems—including LOCAAS’ higher-frequency IR-band Ladar and the lower-frequency VHF Foliage-Penetrating (FoPen) radar system (described below)—operate outside this range to exploit the unusual attributes of higher or lower frequencies. Because most weather is transparent to the commonly used frequencies and because radar provides its own illumination, radars can be designed to be effective in nearly all weather conditions and at night.

In principle, a radar is a device that actively illuminates objects with EM radiation and measures the frequency, amplitude, and timing of the reflected radiation to determine the ranges and attributes of objects. By also recording the precise angle from the radar to the objects, the radar can be used to determine the relative positions of the objects. As with other active sensors, radars require power for generating their illuminating pulses, and these pulses can reveal their own presence and location. Very high-payoff capabilities for reconnaissance and surveillance radar systems include moving-target indicator (MTI) and synthetic aperture radar (SAR), and in some cases, FoPen radar.

Moving-Target Indicator Radar

Moving-target indicator radar systems can be designed to detect and track moving airborne (AMTI) or ground (GMTI) targets. The fundamental difference between these two systems’ functions is the speed of the targets. As a radar pulse reflects off of a moving target, its frequency shifts slightly, by a magnitude related to the velocity of the target. MTI systems use this Doppler shift in frequency to distinguish moving objects from their stationary surroundings. Emerging GMTI radar capabilities should provide waveforms that can permit some degree of classification of detected targets. Assuming that the desired targets are vehicles with distinct characteristics, this classification process may be able to filter out the vast majority of civilian traffic from consideration. The GMTI system can then cue a SAR to
image the remaining targets in order to continue the filtering and recognition process.

**Synthetic Aperture Radar**

Synthetic aperture radar exploits its own platform’s forward motion to permit the radar’s antenna to collect reflected radiation over a predetermined distance along the platform’s flight path, as if it had an antenna that was as long as that distance. The data collected by this large virtual, or *synthetic*, aperture is then processed to create an image of the area or objects being illuminated. A SAR can be used to create a digital terrain map of a region, survey a large area, or, in a “spotlight” mode, to scrutinize an area with higher resolution by employing a larger synthetic aperture.

Digital terrain maps are useful for IPB development, mission planning, precision targeting, placing ground sensors and interpreting their results, and providing a baseline for change-detection processes. A SAR variation called interferometric SAR (IFSAR) significantly improves terrain height measurements. A single-pass IFSAR employs two antennas in proximity but offset slightly on the cross-track plane (perpendicular to the direction to the target), resulting in very slight differences in distance from the target to each antenna. By comparing the phase differences of the signals received by each antenna and resolving the associated geometry, terrain heights can be measured with a precision approaching the wavelength of microwaves.³¹

SAR imaging complements GMTI by providing a higher-resolution image of the area of interest, but it can only image stationary targets. A variation, called inverse SAR (ISAR), exploits a target’s motion to image it. ISAR is a set of techniques for forming a SAR image of a moving target, in which the motions of both the radar and the vehicle are compensated to cohere the synthetic aperture. The relative motion (not just the sensor platform motion) is employed to sweep out the aperture. To cohere is to adjust the target-to-radar phase relationships from pulse to pulse along the synthetic array to match

those that prevail along the usual kind of static phased array. As with a static phased array, the deviations cannot exceed a fraction of a wavelength without degrading the resolution and blurring the image. At X-band, this would require compensating for platform and target motion down to less than a centimeter. On the platform, modern inertial navigation systems are adequate, even if imaging is done at 0.3-m resolution (requiring about 14 sec for a satellite to traverse a 100-km aperture at 2,000-km range).

Target-motion compensation is more problematic. Conceptually, a vehicle is tracked in an attempt to develop a rough motion estimate, then an image is formed at low resolution (where there is likely to be less smearing) to localize one or more large scattering centers. Next, a simple parametric model of the vehicle dynamics may be developed to try to solve for the model’s free parameters by adjusting the phase corrections until the strong scattering centers are well resolved. Objective measures of goodness for the image can be defined, and these may be used to automate this “autofocus” operation. More-sophisticated versions of this conceptual scheme exist, of course, but they share a fundamental inability to fully compensate for random motions from pulse to pulse. Substantial image degradation should be expected on unpaved rural roads, such as those that mobile missiles might use in rural China.

So far, we have discussed the ISAR case, in which the radar platform supplies the motion used to sweep out the synthetic aperture. If the target moves along a curved portion of roadway, such that the target aspect changes rapidly by several degrees, then the synthetic aperture can be formed much more rapidly. This may help with the problem of road roughness, since it is more likely a short stretch of smooth road can be found than a long stretch. For example, if the several-degree turn takes 2 sec at 40 knots, only 40 m of smooth road is required.

The Joint STARS program has looked extensively at this question and has used maps of road networks to identify appropriately curved portions of roads where ISAR could be performed more effectively. Presumably, if IPB data were to be collected over an extended pe-
ISAR techniques could be tested on vehicles traversing these stretches to determine which were sufficiently smooth to produce good images. Then, if targets are tracked for long intervals during a conflict, eventually they will pass over these smooth stretches or stop somewhere and can be imaged at high resolution with ISAR or SAR.33

Foliage-Penetrating Radar and the Change-Detection Process

In many parts of the world, foliage is one of the most abundant and most effective concealment resources available to military forces. Forests (both tropical and temperate) allowed U.S. adversaries in Vietnam and Kosovo to conduct substantive military combat and re-supply operations, despite extraordinary efforts to stop them. One potential solution to the problem of finding forces hiding under forest canopies is to have sensors that can peer through these canopies to detect and distinguish military targets. Although foliage is fairly transparent to some sensors, physics presents a number of challenges to practical implementation.

For example, campers in a thick forest would not expect direct sunlight in their camp, but they would expect their radios to work, assuming that the campsite was within range of a transmitter: AM and FM radio transmissions, which lie in the UHF, VHF, and lower-frequency bands of the EM spectrum, penetrate foliage with relatively little attenuation,34 as Figure A.6 indicates. It is possible to design radar systems to sense these relatively long wavelengths through forest canopies. As an added benefit, these wavelengths also defeat most camouflage netting, including netting designed to counter the more common, higher-frequency radar transmissions. Using 1- to 10-meter-long EM waves of the very high-frequency (VHF) band, foliage penetration is good and the antenna sizes are

32 Ideally, this IPB would be done during peacetime. Standoff airborne platforms could do some IPB. However, for really large denied areas, such as interior China, a space-based system would be needed.

33 We are indebted to RAND colleague Joel Kvitky for providing this technical discussion of ISAR.

34 VHF = 30–300 MHz; UHF = 300–3,000 MHz; AM radio = 0.55–1.72 MHz; FM radio = 88–108 MHz; television = 45–890 MHz.
manageable aboard aircraft. However, the resolution possible from VHF radar is typically no better than a few meters. In contrast, excellent sensor resolution is available by using very short wavelengths, such as the visual (electro-optical [EO]) or infrared (IR) bands of the EM spectrum. However, these wavelengths are almost completely absorbed or reflected by foliage. The ultra-high-frequency (UHF) band provides some foliage penetration while offering somewhat better resolution than VHF frequencies.

**Developing FoPen Technologies.** Technologies for detecting large vehicles under forest canopies are the goal of a program the AFRL Sensors Directorate is teamed on with the Army, DARPA, and Lockheed-Martin, entitled “FoPen SAR for Global Hawk.” Such
technologies would have a probability of detection of at least 80 percent and a maximum false-alarm rate of 0.1 per square kilometer.\textsuperscript{35}

In the program, a VHF FoPen SAR (25–88 MHz) is used to detect large objects under trees. Unfortunately, the VHF SAR’s coarse, 2–3-m, resolution makes it impossible to recognize targets from these radars’ returns; even classification is limited to the general characteristics of large man-made metallic objects. The VHF FoPen detections will likely also include many false alarms, since other man-made objects, some configurations of clustered trees, and a variety of terrain features can produce target-like radar returns. Therefore, these VHF-detected potential targets act as cues for a wider-band UHF SAR (150–572 MHz), which filters out many false alarms by conducting localized searches in the immediate vicinity of the cues. The UHF SAR will have poorer foliage-penetration capabilities than the VHF SAR; however, it should be adequate for localized searches, and the UHF’s sub-meter resolution should permit the discrimination of individual trees, as well as the scattering centers that are typical of man-made objects. This system will transmit UHF SAR images of the 35 × 35 meter areas around suspected targets to an engagement controller and his support team for further filtering and tasking of higher-resolution sensors.

AFRL’s employment concept includes substituting Global Hawk’s planned X-band (8,000–12,500 MHz) SAR with FoPen VHF and UHF SARs. Their current design is already 85-percent form-fit-function–compatible with the Global Hawk.\textsuperscript{36} This Global Hawk–based VHF SAR will be able to search up to 1,400 sq km/hr. Unlike some large-area surveillance systems, such as Joint STARS, that can function effectively at single-digit look-down angles, FoPen systems must maintain much greater look-down angles—30 to 60 degrees is the ideal range—to avoid excessive interference by obstructions such as

\textsuperscript{35}Personal interviews with Ms. Laurie Fenstermacher, Mr. Ed Hamilton, Mr. Zdzislaw Lewantowicz, Mr. Dennis Mukai, Mr. Steve Sawtelle, Lt Col Steve Suddarth, Mr. Vincent Velten, and Mr. Edmund Zelnio at AFRL/SN, Wright-Patterson AFB, Ohio, February 29, 2000.

\textsuperscript{36}Since a FoPen’s long VHF wavelengths would be susceptible to refraction by the ionosphere if the FoPen SARs were space-based, FoPen systems will be limited to airborne platforms until this technical challenge can be overcome. Personal interview, Mr. Dennis Mukai, Wright-Patterson AFB, Ohio, July 5, 2000.
tree trunks. Therefore, airborne FoPen platforms will not be able to stand off as far as Joint STARS does.

**Change Detection.** Following Operation Allied Force, the Chief of Staff of the Air Force asked AFRL to identify a near-term solution to the problem of finding critical mobile targets hiding under forest canopies. In response, the Information, Munitions, and Sensors Directorates are working together on a program entitled “Tanks Under Trees” (TUT). TUT exploits the capabilities of the VHF and UHF FoPen systems described above in a process called *change detection*. At its current state of maturity, the VHF FoPen system may generate many more false alarms than the number of actual targets. Therefore, rather than attempting to determine the nature of every detection, the change-detection process requires the VHF SAR system to map the same areas periodically, and essentially subtracts a previous digital map from the most recent map to reveal changes in the returns from these large objects, using the rationale that vehicles that have moved from one location to another may have caused the detected changes.

Assuming that the change-detection process eliminates the majority of the VHF SAR’s false alarms, the remaining detections serve as cues for the UHF SAR. In addition, the detected changes will cue searches of other relevant sensor databases. For example, a variety of ISR systems may have historical databases that could be reviewed to look for clues about targets moving into or out of a location where a change has been detected. If an engagement controller determines that a change was probably caused by enemy activity, he could task various sensors to take a closer look. For example, UAVs, manned aircraft, or a satellite could image the target from various aspect angles. The controller might also task airborne or space-based GMTI systems to monitor the vicinity for further indications of vehicles entering or leaving their hides.

While TUT’s FoPen-based change-detection system will not provide instantaneous detection and recognition, it appears to offer the greatest near-term potential for detecting large military vehicles hiding in forests and is a good complement to GMTI capabilities.
HYPERSPECTRAL IMAGING

Offering strong and complementary capabilities to other current and planned sensor systems, hyperspectral imaging (HSI) sensors produce images that normally include information from the visible as well as the infrared spectrum, and they provide a spectral characterization of the electromagnetic radiation incident on each of the sensor’s pixels. Like other imaging systems that operate at these short wavelengths, HSI systems detect EM radiation that is reflected or emitted primarily from the surfaces of objects. Each surface material has a unique spectral signature. Given sufficient spatial and spectral resolution, HSI systems can often reveal man-made objects—even those that would be overlooked by an image analyst scanning a high-resolution photograph. HSI data can be used sequentially, first to detect and analyze suspicious (non-natural) spectral fingerprints and then to provide images of the suspected target and its surroundings to an engagement controller.

The visible and infrared portions of the EM spectrum are conventionally divided into the visible (0.38–0.76 micrometers [µm]), very near infrared (VNIR: 0.76–1.0 µm), near infrared (NIR: 1–3 µm), middle infrared (MIR: 3–8 µm), longwave infrared (LWIR: 8–14 µm), and far infrared (FIR: 14–50 µm) bands. Hyperspectral imaging sensors can be designed to use any of these wavelengths, and many exploit segments of the visible, VNIR, NIR, MIR and LWIR bands, dividing them into much smaller segments to obtain spectral resolution on the order of 10 nanometers (nm). Most current HSI designs use tens to hundreds of small spectral bands. This detailed spectral analysis of each image essentially multiplies the quantity of sensor data relative to a comparable photograph, and the supporting...

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37 Dr. David Lewis points out that the next step in this lineage of sensing is ultraspectral imaging, which will have sufficient resolution to detect emissions or absorption from the atmosphere. Clearly, this improvement goes beyond sensing emissions from the surfaces of objects. Personal communiqué with Dr. David Lewis, AFRL Space Vehicles Directorate, Albuquerque, N.M., October 24, 2000.


39 One meter = 10^3 mm = 10^6 µm = 10^9 nm.

40 Similar devices that employ a few, much broader, frequency bands are called multispectral imagers.
datalink bandwidth and/or processing power requirements scale proportionately.

Advantages of HSI Systems

Examining the spectral content within a given pixel, the HSI system can detect distinctive spectral fingerprints that reveal specific objects, including camouflage nets and paint, and metal surfaces. In fact, a target that subtends a small fraction of a pixel can still be detected, given sufficient SNR and spectral contrast. In addition, because HSI analysis algorithms sense spectral signatures rather than vehicle silhouettes or major features—as do most other imaging-system ATR algorithms—partially obscured targets can be detected and, under some conditions, distinctive spectral content in light scattered by a forest canopy can reveal the presence of targets beneath the canopy.

Another advantage of HSI ATR processing is that it requires databases of one-dimensional spectral signatures, rather than the two- or three-dimensional database elements used by some other image ATR systems. This advantage would tend to offset the added demands of having to examine every pixel. Further, while the visual and shorter-wavelength IR bands’ signatures are greatly reduced at night, the MIR and LWIR bands remain effective. However, both visible and IR bands are absorbed and/or scattered by clouds and precipitation.

Components of HSI Systems

HSI sensor systems consist primarily of optics, a spectral dispersing device (similar to a sophisticated prism to divide the light across the spectrum), a sensing component, recording and transmitting devices, a power supply, a processor, and processing algorithms. Because the wavelengths are shorter than those of most radar systems, the aperture (optical lens) can be as small as a few inches for a low-flying UAV. Therefore, these sensor systems can fit on a

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41 Personal interview with Mr. Mike Eismann at AFRL/SN, Wright-Patterson AFB, Ohio, February 29, 2000.
LOCAAS-size UAV. Most space-based HSI systems would have proportionately larger lenses to retain resolution and SNR from orbital ranges. The high speed at which their sensing elements can be charged and discharged to capture sequential images make charge-coupled devices the sensing instruments of choice for most HSI systems. A charge-coupled device, which is also the sensing instrument in a digital camera, is an array of very small semi-conducting chips that are charged by incident radiation. Because HSI systems are passive collectors, their power requirements are relatively low.

**Operational Use**

Operationally, HSI systems could be used independently to search for targets along LOCs, or they could be cued by wide-area surveillance systems to investigate suspected hiding areas. For example, when a FoPen radar detects a change in an area that IPB indicates is a likely target operating area, the engagement controller could cue an HSI system on a UAV or satellite to investigate the potential target.

**SPACE-BASED SURVEILLANCE**

Orbiting satellites are practical platforms for many types of sensors. Space-based sensors can remain in orbit for years, are difficult to attack, do not put U.S. warfighters in harm’s way, and do not require extensive logistics support in the combat theater. Moreover, their altitude allows them to overfly any country without entering sovereign airspace. This altitude, combined with their velocity, results in greater and dynamic diversity of perspective and mitigates some of the masking problems caused by terrain, trees, or buildings. These attributes offer the potential for conducting detailed digital mapping and photography for observing military training, preparations, massing, or other operations.

Most of the sensor phenomenologies that are effectively employed by airborne sensors are also useful from space. Infrared and electro-optical systems, including hyperspectral imagers, SIGINT sensors, and a variety of radar systems can all provide valuable data. With the
exception of HSI, the United States currently employs these phenomenologies from space, but improved coverage is needed.

**SBIRS Satellites**

The Defense Support Program uses IR sensors in geosynchronous orbit to detect and track missile launches and recognize missile types. Analyzing a missile’s trajectory reveals the approximate launch location and destination. This constellation is scheduled to be replaced by the Space Based Infrared System (SBIRS), which will provide similar, but enhanced, capabilities, including battlespace characterization and tactical intelligence. SBIRS will consist of four satellites in geosynchronous orbit, two in highly elliptical orbits, several in low earth orbits, and an integrated network of ground stations.

**Satellite Radar Systems**

If they prove feasible, advanced space-based radar systems could contribute immensely to the Air Force’s warfighting capabilities. The deployed constellations might include AMTI, GMTI, and SAR (conventional SAR, ISAR, and IFSAR) capabilities, as described above.

Satellite constellation design factors include required coverage rates, orbital altitudes and periods, solar radiation exposure, satellite/sensor power requirements, and acquisition/launch costs. One less-obvious factor relates to the fields of regard of SAR and MTI radar systems. The background clutter directly below a satellite reduces the signal-to-interference ratio to unusable levels for MTI systems. Therefore, spaceborne MTI radars are designed with a toroidal (donut-shaped) field of regard, which excludes the region directly below the radar. Similarly, a SAR’s ground range resolution is in-
versely proportional to the cosine of the radar beam’s depression angle, creating a region of very poor resolution near the nadir, the line on the Earth’s surface directly below the radar’s flight path. As well, the azimuthal resolution in the forward and rear directions relative to the aircraft’s flight path is degraded as a result of the diminished projection of the synthetic aperture baseline in those directions. Consequently, the SAR’s field of regard is in the shape of a pair of unfolded butterfly’s wings.

Despite these complicating geometric considerations, satellite constellations can be configured to provide any level of coverage desired, from intermittent through redundant coverage, which reduces the coverage problem to one of cost. While it might seem that near-continuous coverage would result in only a slight operational compromise as compared with complete coverage, actual coverage gaps are effectively extended by the time required to reacquire a target’s track. In the near term, it is unlikely that a robust system can be developed to rapidly and reliably reacquire target tracks lost during gaps in GMTI coverage. Thus, continuous GMTI coverage and complementary ISAR coverage are desirable, facilitating smooth handoffs of target tracks from one satellite to the next and imaging suspected targets rapidly, especially in an environment with heavy civilian traffic, significant obscuration, or complex terrain.

We should note, however, that the cost of a GMTI constellation sufficiently large to provide near-continuous coverage of China could be huge: over $40 billion by a recent RAND study’s estimates. That study concludes that high-altitude stealthy UAVs carrying GMTI radars could actually be survivable against advanced SAMs, but would be highly vulnerable to attacks from fighter aircraft. If some means were found to protect UAVs from fighter attack, they might offer a cost-effective alternative, or complement, to space-based GMTI.44

The USAF is developing advanced space-based radar technologies. The Discover II program was a USAF, DARPA, and National Reconnaissance Office program to develop and demonstrate affordable space-based radar, including GMTI and SAR-ISAR capabilities. As

44Glenn Buchan et al., “Intelligence, Surveillance and Reconnaissance (ISR) Force Mix Study: Summary Briefing,” Santa Monica, Calif.: RAND.
this report was being written, concerns over the maturity of the technology and questions about which service should steward the DoD’s future large-constellation space-based radar system caused Congress to eliminate funding for this program.\textsuperscript{45} However, applicable technology programs continue in government laboratories and industry.

**HYPERSONIC MISSILES FOR RAPID RESPONSE STRIKES**

Today’s cruise missiles can be launched from ground-, sea-, or air-based platforms. Most existing cruise missiles fly at subsonic speeds. The Russian Sunburn and French ASMP are examples of ramjet-powered supersonic cruise missiles. In the 1960s and early 1970s, the USAF inventories included ramjet-powered Mach 3+ BOMARC surface-to-air missiles. In the 1980s, the USAF successfully flight-tested the prototype Mach 4+ Advanced Strategic Air-Launched Missile (ASALM).

*Hypersonic flight* is usually defined as atmospheric flight at speeds above Mach 5. To date, the world’s experience with manned hypersonic flight is limited to brief flights of rocket-powered test vehicles, such as the X-15 and X-24, and transitory flight of space launch vehicles ascending through, or spacecraft reentering through, the upper atmosphere. However, several nations are developing technologies to permit sustained hypersonic flight. The United States, Russia, and France have the most mature technology bases.

**Technology Challenge: Air-Breathing Propulsion and Fuel Systems**

The integrated air-breathing propulsion and fuel system poses the primary technology challenge for sustained hypersonic flight. Air-breathing engines, rather than rockets, will be used for sustained (cruising) atmospheric flight, owing to their greater fuel efficiency. By definition, rockets carry their fuel oxidizer onboard; air-breathing engines use the atmosphere as their oxidizer source. As a result, rockets are a good choice when the flight vehicle’s design requirement is for short duration but very high thrust-to-weight-ratio

propulsion; air-breathers are appropriate for efficient, sustained acceleration, and/or cruising flight.

The USAF, U.S. Navy, DARPA, and NASA\textsuperscript{46} are working with industry to advance the technology base for supersonic combustion ramjet (scramjet) engines.

Ramjets and scramjets differ from the more common turbojet and turbofan air-breathing engines found in current U.S. civilian and military aircraft and missiles in the way they compress air prior to combustion. Turbojets and turbofans use rotating turbomachinery components called fans and compressors to compress air, and use similar rotating components called turbines to drive the fans and compressors. In contrast, ramjets and scramjets use the \textit{ram} effect created by their high speed to compress the air needed by their combustor, precluding the need for expensive rotating turbomachinery. However, this compression process also limits ramjets and scramjets to efficient operation at supersonic and hypersonic speeds, respectively. Therefore, these systems must be boosted to their operating speeds by rockets or by combining these high-speed cycles with a low-speed cycle to form a rocket-based combined cycle or a turbo-ramjet or turboscramjet combined cycle.

A scramjet is similar to a ramjet in concept, except that the ramjet engine slows the inlet air to subsonic speeds in preparation for the combustion process. Scramjets slow the inlet air from its initial hypersonic speed to supersonic speeds prior to entering the engine’s combustor, which is why the class of engines is called “supersonic combustion ramjet.” Keeping the flow through the combustor su-

\textsuperscript{46}NASA is conducting an independent, yet complementary, hypersonic technology development and flight demonstration program focused on hydrogen-fueled vehicles. NASA is scheduled to fly three X-43, Hyper-X, test vehicles at Mach 7 and 10, within the next two years. (The first of these test flights failed in 2001 when the boost vehicle went out of control.) The X-43 is a 12-ft, one-time-use flight-test vehicle with a hydrogen-fueled scramjet engine. Because this scramjet is not thermally protected, it will operate for only a few seconds during its flight. However, during that time, the United States should learn valuable lessons regarding hypersonic aerodynamics, flight control, propulsion, and flight testing. A combined Langley Research Center–Dryden Research Center team manages the Hyper-X program. Langley is responsible for hypersonic technology development, and Dryden is responsible for the program’s flight testing. MicroCraft Inc. is the X-43 prime contractor. NASA has offered to integrate the USAF Hypersonic Technology (HyTech) engine on its Hyper-X vehicle as the follow-on X-43 test program.
personic prevents the engine from melting and the generally undesirable high-temperature effects known as disassociation and ionization are retarded. However, leaving the flow above the speed of sound during its entire transit time through the engine limits the time available to slow the air, mix the air and fuel, burn the mixture, and reaccelerate the combustion products, to around 1 millisecond. Because the engine’s efficiency is heavily dependent upon the vehicle’s ability to minimize shock-wave losses, hypersonic vehicle designs are carefully integrated and typically use the airframe’s forebody to form the engine inlet and the aftbody to form the expansion ramp for the engine’s propulsive nozzle.

The Air Force Research Laboratory’s Hypersonic Technology (HyTech) program is developing a missile-sized scramjet engine, which has growth potential for larger, reusable, and/or manned vehicle applications. This engine is designed to accelerate from Mach 4+ to any Mach number up to Mach 8, and then cruise for several minutes. It burns standard jet propellant (JP) fuels. However, before it is injected into the combustion chamber, the scramjet’s fuel flows through the engine walls’ catalyst-lined cooling passages, thereby cooling the engine and breaking down the fuel into hydrogen and simple hydrocarbons, such as methane, ethane, propane, and ethylene. These heated, simpler constituents will burn much more readily than will the complex hydrocarbon molecules in JP fuels. A fuel-cooled engine structure may seem too expensive for an expendable missile; in fact, it should cost less than the turbine engines used in subsonic cruise missiles. DARPA estimates that the scramjet engine will also cost significantly less than the simple solid rockets that would boost a cruise missile to scramjet-takeover speeds.

The U.S. Navy, through its relationship with Johns Hopkins University’s Applied Physics Laboratory, is developing another missile-sized, JP-fueled engine called the Dual-Combustor Ramjet. This engine employs a fuel-rich ramjet combustor flowing one-third of the engine’s total inlet air as a pilot for the scramjet combustor. Since neither the pilot nor the scramjet combustor is actively cooled, the engine has a maximum Mach number limit of 6.5.47

47 For further background on the physics and engineering issues related to hypersonic flight and propulsion, see William Heiser and David Pratt, *Hypersonic Airbreathing*
Other Technology Challenges

The other key technology challenges for hypersonic cruise missiles include flight-testing an integrated air-breathing hypersonic vehicle and possibly improving high-temperature materials.

Thermal Protection. The temperatures and thermal loads at these flight speeds far exceed those experienced by current U.S. aircraft and cruise missile airframes. However, they are not as high over the entire vehicle as one might think. The stagnation temperature of a flow increases as the square of the Mach number, with some relief due to vibrational modes, dissociation, and ionization of the atmosphere’s molecules at high Mach numbers. However, if the flow is not stagnated or slowed to subsonic speeds near the vehicle, the air’s temperature will not rise to the stagnation temperature and will not create the extreme heat loads on that portion of the vehicle. The hottest regions on air-breathing Mach 8 flight vehicles will be uncooled portions of the engine combustor and nozzle, which could reach 5,500°F; the inlet duct, at up to 4,000°F; and any unswept leading edges, which could reach 3,500°F. Most other components remain well below 2,000°F. By way of reference, the temperature of the air and high-stress turbomachinery just upstream of the combustor in a modern high-performance fighter engine is also between 1,000 and 2,000°F, and the combustor and downstream components must be actively cooled and/or thermally isolated to keep these components well below the temperature of the combustion products. Similarly, cooling the hypersonic missile’s hottest components will require active cooling techniques (cooling fluid flowing through heat exchangers or a similar approach), ablatives, or high-temperature structures.

The U.S. space program has accumulated extensive experience with thermally protecting structures: regeneratively cooling rocket noz-
zles and adding a layer of ablative tiles to protect vehicle skins. The active-cooling techniques and thermal-barrier coatings used in conventional jet engines, along with a variety of other cooled or thermally protected devices, add to this experience base. Therefore, advances in materials technologies are not required to produce an affordable, expendable, unmanned hypersonic missile, although they could enhance the design and further reduce the cost.

Apart from the main airframe and engine structural components, one potential application for advanced materials is high-temperature apertures for sensors. For example, today an EO sensor on a Mach 8 vehicle would probably require a sapphire window, whose cost may now be acceptable for an expendable cruise missile application. The dual-use applicability of sapphire for high-temperature windows, as well as for bar-code scanner apertures, fiber-optics, and transducers, has brought down its costs. Nonetheless, current missile concepts employ GPS-INS guidance, and deploy lower-speed smart submunitions if terminal sensing is required.50

**Flight Testing.** The requirements for hypersonic flight testing stem primarily from unforeseen system and operational-level issues that occur when new technologies are integrated into complex devices to be operated in new environments. These flight tests should reveal remaining technical issues and help guide the field of hypersonics as it moves from expendable missiles to larger, reusable, and manned cruise and space launch vehicles. Again, our nation’s space programs and previous flight-test programs, such as the rocket-powered X-15, will provide a good foundation for scramjet-powered vehicle flight tests.

DARPA’s Affordable Rapid Response Missile Demonstrator (ARRMD) program may flight test a prototype hypersonic cruise missile in the next few years. ARRMD competitively selected the two JP-fueled en-

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50 Operating concepts must also be carefully considered prior to committing the resources to integrate an imaging sensor into a hypersonic weapon. By the time a hypersonic weapon is close enough to image a target with a useful resolution, the missile will likely be within a few seconds of target impact—probably not sufficient time for an imaging ATR or a human to analyze the image and provide heading corrections, and for the aerodynamic control surfaces to accomplish terminal maneuvers prior to impact. However, offboard sensors could update GPS coordinate targeting information earlier in the missile’s flight.
gines described above, along with corresponding airframe configurations, as parallel design paths. Budget constraints caused DARPA to make an early decision to focus solely on the Air Force missile/engine configuration. Subsequently, further budget constraints forced DARPA to put the program on hold, and the Office of the Secretary of Defense has asked the services, DARPA, and NASA to develop a National Hypersonics Plan to be completed in fiscal year 2001. A revived ARRMD program is a potential near-term element of this plan.

DARPA’s ARRM (USAF variant), at 168 in., is sized for carriage on current USAF and U.S. Navy strike aircraft, including fighters and bombers. Its strap-on rocket boosters accelerate the cruise missile to around Mach 5, at which point the empty rocket cases jettison and the JP-fueled scramjet takes over to propel the missile to its cruise condition and on to the target. DARPA specified a requirement for cruise at Mach 6 for risk mitigation and competitive purposes, but the missile’s design flight envelope extends through Mach 8. The missile will be GPS-INS–guided and is designed to deliver a variety of payloads up to 250 lb. These payloads include a unitary penetrator, small-smart bomb, fléchettes, or two LOCAAS or BAT (Brilliant Anti-Tank) smart submunitions. The missile is designed to attack targets at ranges up to and beyond 1,000 km. Since the majority of the fuel will be used to accelerate the missile to Mach 8, the cruise range could readily be extended by increasing the fuel load slightly or by cruising at a lower hypersonic Mach number.

Boeing is the airframe manufacturer and missile integrator; Pratt & Whitney is developing the engine. DARPA has established affordability as ARRMD’s top priority and has set a cost goal of $200K per missile, assuming a production run of 3,000 missiles. However, given the current design’s maturity, DARPA believes the unit cost would be nearly $250K. AFRL developed a preliminary design for a similar, slightly larger missile called the Fast Reaction Standoff Weapon, which would be capable of carrying larger payloads (e.g., four

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51 DARPA has a second variant of ARRM designed with a tandem booster for launch from ship-based canisters and vertical-launch tubes.
52 Personal interview with Lt Col Walter Price, DARPA ARRMD Program Manager, July 31, 2000.
LOCAAS). Figure A.7 is an artist’s concept of an F-15 launching AFRL’s Fast Reaction Standoff Weapon. In the configuration shown, this weapon integrates a piggyback booster to accelerate the missile to its scramjet engine takeover speed of Mach 4.5.

Illustration courtesy of the Air Force Research Laboratory.

Figure A.7—Mach 8, Fast Reaction Standoff Weapon Being Launched from an F-15