INTRODUCTION

Aerospace forces have made important contributions to urban operations from World War II to the present (see Appendix D). Chapter Three identified some important limitations on the use of these forces in situations with very strict ROE and tight political/legal constraints. Although many would not even consider the use of aerospace forces for some of these operations, Chapter Five illustrated many ways that such forces could accomplish tasks that today can only be done by putting ground forces into very risky situations. With the right investments, DoD and the USAF can develop new capabilities that will allow the United States to achieve key objectives in urban operations more efficiently, minimizing risks to friendly forces in the process.

Six technology areas have promise for improving the contribution of aerospace forces to urban operations:

- Three-dimensional modeling of urban environments
- Communication and navigation systems
- Sensor technologies
- Sensor fusion
- Air-launched sensor platforms
- Limited-effects munitions.
In this chapter, we discuss both the latest advances in these areas and the technical hurdles that must be overcome to make the capabilities explored in Chapter Five a reality.

THREE-DIMENSIONAL MODELING OF THE URBAN ENVIRONMENT

Key Functions and the Scope of Air Force Involvement

Building high-quality 3-D maps and effectively integrating them with geospatial information represent a serious challenge for the Air Force, but one with a potentially great consequence for both air and ground operations in urban areas. The challenge can be divided into four key elements:

- Acquiring and processing data—acquiring current 3-D maps of urban areas and producing raw Digital Elevation Models (DEMs) of areas of interest
- Extracting terrain and surface object features for classification
- Associating feature data with geospatial information
- Updating the scene with dynamic information.

Air Force decisionmakers must tailor their technological investments in proportion to the extent and nature of their participation in each of these four key elements. The USAF needs to determine which, if any, of these elements are most appropriate for investment, and also how to address the division of responsibilities with organizations such as the National Imagery and Mapping Agency (NIMA). Of particular concern is the extent to which it is appropriate and necessary for the Air Force to undertake these activities independently rather than rely on other agencies for critical products. These issues, while not strictly technological, are central to understanding the relevance of different technology options.

The first phase of the urban modeling effort is building the baseline map for the area of operations, a task usually done and updated by NIMA in the course of normal tasking requirements. A Digital
Elevation Model consists of sets of latitudes and longitudes, along with height information relative to a standard geodetic datum.\textsuperscript{1} High-fidelity DEMs have postings every few meters.\textsuperscript{2} A typical DEM will have a portion reflecting the estimated contour of the underlying terrain, and a second portion containing a model of features, both natural and man-made, that overlie the terrain. Because the data acquisition-phase requires specialized collection platforms and sensors, it usually attracts the most attention.

A geospatial information system (GIS)\textsuperscript{3} can be used to store the DEMs, along with other data of interest, and thereby greatly increase the value of what is collected by specialized assets. For instance, having a DEM with just the observed elevation (terrain with features) is useful for many applications such as route planning for low-altitude aircraft and missiles. However, when the data are married to other geospatial information (e.g., whether the object on top of the terrain is a stand of trees or a building, the object’s function, street address, type of construction), the value of the data increases dramatically, along with the number of potential users.

The value of the data is increased further when dynamic information is added to the static data in the GIS, providing a current situational picture. This addition involves sensing dynamic and emerging static elements (obstructions in roadways, damaged buildings, etc.) as in the first stage, updating DEMs with information on feature changes and alterations of objects on the surface, then inserting transitory elements such as personnel and vehicles.

Most of the activities outlined above are classic intelligence-collection functions. Building the initial DEMs, compiling basic information on the area of operations, and populating the GIS fall within the domain of the intelligence community, with some division of responsibility between national and theater components.

\textsuperscript{1}For a good introduction to mapping issues, see Defense Mapping Agency (now NIMA) \textit{Geodesy for the Layman}, DMA TR 80-083, which is available at ftp://ftp.nima.mil/pub/gg/geo4layman/Geo4lay.pdf
\textsuperscript{2}A posting is an average of elevation readings within a given area.
\textsuperscript{3}A GIS comprises maps and data associated with particular locations. For example, in a real estate GIS, clicking on a home icon (on a map screen) may bring up the number of rooms, square footage, date built, assessed value, and other information.
Obtaining updates on features in the DEMs, adding dynamic elements, and ensuring the connection with both weapon systems and command and control elements is the business of the services. Capabilities overlap, particularly in building DEMs. If feature changes over a significantly broad area are to be included for purposes of mission planning and weapon employment, then many of the data-collection and -processing elements necessary for basic DEM construction could either be under the control of the service or levied on the national intelligence and mapping agencies as additional requirements for timely updates. Failure to clearly spell out responsibilities and funding obligations increases the likelihood that gaps will develop. Moreover, some technologies, if properly deployed, can be used to bridge potential gaps in capabilities.

In the next six sections, we describe three techniques for collecting data to construct 3-D urban models—laser radar mapping, stereoscopic electro-optical imaging, and interferometric synthetic aperture radar (InSAR); compare the three techniques; discuss trade-offs involved in selecting collection platforms; and describe the computer software the warfighter needs to display and manipulate the models.

### Laser Radar Mapping

Used for decades in the civilian sector for conducting airborne surveys, laser radars currently dominate the imaging field. Laser radars are similar to conventional pulsed radars, except that light pulses are emitted instead of radio-frequency pulses. Typical commercial laser radar systems, including ancillary equipment, weigh between 100 and 250 lb.\(^4\)\(^5\) The laser is mounted pointing downward from a stabilized platform on the aircraft. The aircraft position is established to within a fraction of a meter, using differential GPS.\(^5\) The laser transmitters are usually solid-state neodymium yttrium aluminum


\(^6\)Differential GPS is a way of increasing the accuracy of the GPS signal by transmitting a signal containing correction information derived from a receiver at a surveyed location on the ground.
garnet (Nd:YAG) devices operating in the band just above 1 µm, which lies just outside the visible band, in the IR. At this wavelength, there are minimum-altitude guidelines\(^7\) to avoid damaging eyesight on the ground; techniques are being introduced into military systems to shift the wavelength to the eye-safe band near 1.6 µm. In principle, other forms of aided GPS could be used, such as the pseudolites discussed later in this chapter.

The narrow laser beam scans a swath below the aircraft, precisely measuring the range to the ground and the angle of deflection of the beam as it sweeps to the left and right of the aircraft’s nadir spot.\(^8\) In some systems, multiple beams are transmitted simultaneously to increase the swath width. Assuming typical commercial parameters—e.g., a swath angle of 20˚, aircraft altitude of 1 km, and speed of 250 kt, we obtain a ground swath 730 m wide and an area sweep rate of 330 km\(^2\) per hour. The aircraft will traverse many parallel swaths if a large area is to be covered. At the stated rate, the city of Los Angeles could be mapped in 3 to 4 hours. The range and angle data are recorded digitally and are combined with the aircraft’s position record to yield a digital elevation map of the terrain. Typical elevation accuracy is 0.05–0.15 m.\(^9\) (See Figure 6.1 for a sample image produced by laser radar mapping.)

Ideally, archival urban models could be compiled during peacetime and accessed as needed for military purposes. However, updates during wartime or other emergencies may be required, because urban areas are in constant flux and the programmed refresh rate of the database will not always maintain adequate currency. In light of the potential urban threats discussed earlier in this report, it would be desirable to collect data from high-altitude UAVs.

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\(^7\) Laser radars are routinely used by private-sector mapping companies to produce 3-D maps of cities. The radar-equipped aircraft must fly above certain minimum altitudes to avoid the risk that anyone on the ground might have their eyes exposed to dangerous levels/frequencies of laser energy.


\(^9\) This level of accuracy is achieved by processing out the GPS bias.
The ability to collect from high altitude is perhaps best illustrated by the Mars Orbiter Laser Altimeter (MOLA), carried aboard NASA’s Mars Global Surveyor. In March and April 1999, MOLA collected 27 million laser measurements of the Martian surface through the thin Martian atmosphere, to form a 3-D map of much of the planet. To operate at the orbital altitude of 400 km, the laser receiver was equipped with a large, 50-cm-diameter, parabolic mirror and a sensitive silicon-avalanche photodiode detector.\textsuperscript{10,11}


\textsuperscript{11}Silicon photodiodes are one type of semiconductor device used as an element in CCD arrays, which are commonly used in focal planes for commercial digital cameras. Avalanche photodiodes are even more sensitive than the photodiodes ordinarily used in cameras. They have some of the properties of image intensifiers, such as the ability to detect smaller numbers of photons by amplifying the electrical signals produced by the photons impinging on the detector.
The main impediments to high-altitude operation are weather and degraded angular resolution, which results in degraded horizontal resolution for the map. If the MOLA laser, with its beam divergence of 0.46 milliradians (mr),\(^\text{12}\) were used for mapping from Global Hawk at 60,000 ft, the spot size on the ground would be 8.5 m.\(^\text{13}\) Measurement accuracy, e.g., for obtaining GPS coordinates of a building’s corners, can be improved if the laser samples are spaced only a fraction of the spot size apart. An improvement factor of 2 to 3 seems attainable, which would be adequate for the more-demanding applications of guiding weapons up to the terminal phase.

**Stereoscopic Electro-Optical Imaging**

Stereoscopic imaging is the basis for human depth perception. When we view a nearby object, the observation angle from each of our two eyes is slightly different, an effect known as *parallax*. The amount of parallax displacement depends on the range to the object and the separation between our eyes. Without our having to think consciously about it, our brains are able to convert the parallax offset into an estimate of range, which we perceive as depth. But, how are the two “eye views” seamlessly combined into one? Conceptually, the eyevies are warped until every point is remapped into a single, unified picture. The amount of warping required to match up a point is a measure of its parallax. The tricky part is that identifying corresponding points sometimes requires paying attention to the *content* of the image, which is easy for brains but hard for computers.

An image collected by a single spaceborne electro-optical (EO) sensor contains only two-dimensional information, analogous to a single human eye. It is possible to recover the third dimension by measuring parallax between images obtained from two satellite or aircraft locations, but the positions and pointing directions of the optics must be known precisely.

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\(^{12}\)A milliradian, abbreviated mr, is approximately 0.0573°. At a range of 1 km, an angle of 1 mr subtends exactly 1 m, i.e., 1/1000th of the range—a convenient unit.

\(^{13}\) The smaller the spot size, the higher the resolution.
Intensive research is under way to completely automate the process of extracting depth from stereo imagery. Currently, however, smart workstations and software tools exercised under human supervision are relied on for such extraction. The near-real-time production of urban models that laser radars can offer today may not be possible with EO for some time.

Nonetheless, EO can provide higher-resolution information on exterior details of buildings, e.g., the placement of windows, thickness of walls, and construction materials, than can laser radar. Typical large EO sensors used for reconnaissance have ground resolution of 0.6 to 0.3 m from the Global Hawk altitude of 60,000 ft. Spaceborne EO sensors could have ground resolution as good or better than this from a 600-km orbit.

**Interferometric Synthetic Aperture Radar**

Interferometric synthetic aperture radar (InSAR) is a technique for coherently combining two SAR images taken from two slightly offset positions, either simultaneously with two or more antennas, or separated in time with one antenna (see Figure 6.2). The coherence property refers to preserving the phase information in the image, which stems from the wavelike nature of electromagnetic signals. When SAR images are first synthesized, each resolution cell has associated with it an amplitude and a phase angle between 0 and 360°; when displayed, the phase information is usually suppressed. The phase is a measure, but an ambiguous measure, of the two-way distance, \( d \), between the antenna and the point on the ground.

Consider two SAR images of the ground obtained with antennas displaced along the cross-track direction from one another. The two-

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15 If the distance is a perfect multiple of the wavelength, the phase is zero. If the distance is \( N \) wavelengths plus a half-wavelength, the phase is 180°, i.e., halfway between 0 and 360°. In general, if the distance is \( N \) wavelengths plus a fraction, \( F \), of the wavelength, the phase is \( 360\times F \). Phase is spoken of as being related to the distance, *modulo the wavelength*. 
way distance \( T_2 \) from the top antenna to some resolution cell on the ground is slightly longer, by an amount \( \Delta d \), than the two-way distance to the bottom antenna, \( T_1 \). If we subtract the phases between the two SAR images, producing a phase-difference map, this resolution cell will have the phase corresponding to \( \Delta d \).

If, instead of the ground, the resolution cell in question contains a raised structure, the difference in distance from the two antennas to the roof of the structure will not be \( \Delta d \) but some other value, \( \Delta d' \), depending on the height of the structure. In this way, the phase-difference map encodes information about a third dimension—elevation—that is not available in a single SAR image (see Figure 6.3).\(^{16}\)

\(^{16}\)There is a slight hitch, however. The phase is related to \( \Delta d \) ambiguously: Adding (or subtracting) integer multiples of the wavelength to (from) \( \Delta d \) yields the same value of phase. But, to compute the height, precisely how many wavelengths must be known. This number can be determined by looking at the trend of phases from resolution cell to resolution cell. For example, if the sequence of phases 10°, 120°, 260°, 30°, 100°, 190°, 320°, 60°, 220° is seen along a string of neighboring cells, one infers that between 260° and 30°, and between 320° and 60°, the phase passes through 360° and \( \Delta d \) has increased by a wavelength. This scheme works as long as the height differences between adjoining cells are not so large that \( \Delta d \) changes by more than a wavelength. For this reason, skyscraper-studded urban canyons are not ideal venues for InSAR mapping.
SARs have difficulties in urban settings when buildings are high or if the streets are narrow. As noted in Chapter Four, imaging this geometry requires a steep depression angle to look down to street level. In this geometry, SARs suffer from the *nadir hole* problem. To understand the origin of the nadir hole, it is necessary to explain how SARs form an image. SARs obtain slant-range information (see Figure 4.3) in the same way some conventional radars do, using the time delay and amplitude of reflected pulses. Phase or frequency coding causes the SAR pulses to have large bandwidths. When the pulses are re-

In composing a SAR map, a simple transformation is performed to convert the slant-range data into ground range. If the SAR is viewing the scene at low depression angles, slant range and ground range directions are almost the same, and the resolution is not seriously degraded in transforming between them. At higher depression angles, the resolution along the ground is degraded in proportion to the secant of the depression angle; for example, a 1-m-resolution SAR has a ground-range resolution of 2 m at 60°, 2.9 m at 70°, and 5.8 m at 80° depression angle. At sufficiently high depression angles, the ground-range resolution is so poor that the imagery is not worth collecting—hence, the nadir hole.

Figure 6.4—Layover and Shadowing Effects in SAR Imagery

Azimuth information is obtained by Doppler-processing a sequence of these pulses as the sensor moves along its flight path or orbit.
Urban areas can also be troublesome to SARs because of shadowing and layover effects (see Figure 6.4). *Shadows* occur where the signal is obstructed, producing regions in which all information is lost. Shadowing can be mitigated by combining images from different angles. *Layovers* occur because SARs cannot distinguish between objects that are taller and objects that are merely closer—i.e., the tops of buildings appear to be lying on the ground in the foreground of the structure. Layover effects can be removed by InSAR processing, which restores the height information.

In their finest mode, typical military airborne SARs have resolution between 0.3 and 3 m. The SARs for both Predator and Global Hawk have 0.3-m resolution. As noted in a preceding paragraph, these values increase in the ground-range dimension at high depression angles.

SAR payloads for both aircraft and satellites have been used to generate InSAR maps. Although multipass InSAR imaging does not require additional hardware (each of the two platforms uses a single antenna), single-pass InSAR requires that additional apertures be offset along the cross-track direction. The primary requirement for handling InSAR data is that the coherent images (with the phase data intact) be datalinked to the processing center.

A good deal of work has been done in the last few years to automate the process of extracting height from InSAR maps (counting the phase cycles through 360° a process called *phase unwrapping*) and creating 3-D databases for computerized display. Recent improvements in the algorithms have reduced requirements for human intervention to a low level. However, the problems associated with building extremely precise maps in urban areas still require a great deal of human intervention.

Both civilian and military agencies have plans for spaceborne collection of worldwide topographic data using InSAR mapping. This strong interest is driven primarily by the prospect of providing high-resolution digital terrain elevation data (DTED). However, another particularly useful side benefit with InSAR maps is that they can detect change exquisitely, at the level of inches of vertical deflection. In cities, new construction shows up readily as a random mismatch of the phases between the “before” and “after” InSAR maps. Such
change detection could also be used to observe changes in roads that might indicate obstacles or other key features changing within a tactically relevant time-scale.

**Comparison of 3-D Imaging Technology**

Each of the three methods for obtaining 3-D urban data discussed has its pros and cons with respect to weather limitations, automated processing, resolution, and constraints on slope or depression angle.

Only the InSAR has all-weather capability. Clouds or fog can obscure the ground and deny useful imagery to laser radar and EO sensors, which operate in the optical bands. It is therefore advisable to use laser radar when possible, but have InSAR as a backup, when developing militarized payloads.

Each sensor technology offers other features that are useful and unique. Laser radar provides the most automated and rapid processing. EO provides the best horizontal resolution, and a great deal of qualitative information about structures. InSAR processing is reasonably well-automated, provides the best vertical resolution, and is all-weather, but it is somewhat constrained in imaging steep slopes and high depression angles.

It is likely that high-quality urban mapping will depend on combining data from all three techniques in the future. Today, a number of agencies routinely produce maps combining pairs of sensor types, most frequently EO and SAR, or EO in several bands. Although this combining is usually still performed by a human operating a workstation, the operator is using tools that are rapidly increasing in sophistication.

As to the likelihood that fusion and accurate geolocation of multi-sensor images will be fully automated before too long, we adduce three factors for optimism:

- No underlying physical barriers to broach or looming engineering paradigms to shift
- The presence of a large and active community, including universities, civilian agencies such as NASA, and the intelligence community, devoting significant resources to the problem
• Expansion of processing power at the rate predicted by Moore’s Law (doubling every 18 months) for at least another decade, as expected by computer engineers.

Platform Trade-Offs

The platforms used for data acquisition fall into two categories: air-breathing and spaceborne. The factors governing the choice of platform are the sensor type, area of coverage, level of threat, and political sensitivities.

The types of air-breathing platforms that can be used for imagery collection vary considerably, including small UAVs, small manned aircraft, business jets, fighter aircraft, high-altitude long-endurance UAVs, high-altitude manned aircraft, and larger transport-type aircraft.

Microwave and laser radars and electro-optical sensors have been deployed on both aircraft and spacecraft; in aircraft, they have been deployed over the full range of altitude. As noted in Chapter Four, the presence of manportable air defenses and light anti-aircraft artillery can preclude the use of UAVs like Predator at low altitude. Radar-guided tactical SAMs can be overflown with high-altitude aircraft such as U-2s and Global Hawks. Modern high-end SAMs such as SA-10s and SA-12s can engage these aircraft, thus potentially denying access to all but spaceborne collectors before a successful SEAD campaign.

Lasers and EO cannot penetrate cloud cover and dense fog and are degraded by atmospheric attenuation. Consequently, subject to threat considerations low-altitude operation has the advantage of extending the spectrum of weather conditions under which optical sensors can collect data. Low-altitude operation is also favored for optical sensors because their resolution improves with decreasing altitude. Optical sensors can operate at nadir; SARs cannot, because they depend for image formation on slant-range resolution, which degrades at nadir. The area sweep rate for EO depends primarily on the sensitivity, efficiency, and size of the detector elements, the size of the aperture and focal plane, and the speed of the aircraft. Since EO sensors are passive and not usually power-limited, they can gen-
erally be made to cover area more rapidly at high resolution than can SARs.

Microwave radar is nearly impervious to weather. However, heavy rainfall will blind it at frequencies above 10 GHz. The resolution of synthetic aperture radar does not depend on altitude as long as there is sufficient power to preserve a high signal-to-noise ratio. The demands for higher power and processing throughput usually decrease the area coverage rate with finer resolution.

Spacecraft offer the advantages of worldwide coverage, better covertness, and the ability to operate over areas denied by threats or political considerations. Disadvantages include higher initial procurement costs, greater complexity, long revisit time (depending on orbit), and unfavorable absentee ratio. Absentee ratio refers to the long time the spacecraft spends outside the viewing range of the area of interest due to its orbital motion. Many surveillance instruments use change detection, which requires a baseline image against which to compare the new image. Spaceborne systems have a unique ability to obtain baseline data without requiring permission of the host country for imaging.

Software Exploitation of 3-D Urban Maps

In the commercial sector, Digital Elevation Models (terrain plus features above the terrain) are extensively used to support a wide range of activities, from helping urban planners deal with land-use decisions and make water-drainage assessments, to predicting fires and exploiting telecommunications. Indeed, the wireless telecommunications industry’s use of DEMs for siting cell-phone towers represents one of the more prominent applications of this kind of technology, and there are many parallels with applications in the military sector.

DEM provide obstruction data, along with other parameters associated with signal propagation, which enable the optimal placement of transmitters. Analogous applications for the military include the placement of terrestrial communications relays, observation platforms, or anything that requires line-of-sight calculations, such as countersniper operations.
In the military context, software for exploiting the vast amount of data coming from capable sensors has received somewhat less attention than have sensors and surveillance and reconnaissance platforms. The problem of fusing and presenting data to decision-makers is, in many respects, a more technically challenging problem than collection. For instance, ambiguities in target identification, geolocation, and sensor measurements make associating multi-source information a major challenge, as do difficulties in constructing the underlying GIS. Thus far, the complexity involved in designing generalized fusion techniques has rendered the building of an effective, full-scale fusion system infeasible.

For achieving fusion, there are circumstances under which simpler approaches will yield substantial results. For example, simply combining essentially raw data from sensors with information stored in a GIS is often adequate to allow a skilled human operator to understand what is occurring.

The first step toward building a useful product is to combine imagery and DEMs to generate 3-D perspectives of target areas. These perspectives can be viewed using computer-based visualization, a technique employed for some time in mission-planning systems. The next step is to add in geospatial data and apply predictive algorithms. A common GIS can be used for the basic infrastructure, which avoids the cost of designing a system from scratch while providing the ability to capitalize on a wealth of commercially derived software. However, the most difficult parts of the problem remain: populating the database with current information and interfacing with a host of real-time intelligence and battle-management systems.

Once the database is formed, there are many pathways toward military utility. Some, like the countersniper example discussed in Appendix C, exemplify the use of very basic information to assist in an operation. More-sophisticated applications might allow the operator to formulate queries to understand the construction, use, or other aspects of structures in an area of interest.
COMMUNICATIONS AND NAVIGATION TECHNOLOGY FOR THE URBAN ENVIRONMENT

UAV Relays

Communication and the reception of navigation signals within the urban environment are bedeviled by multipath\(^{18}\) and obstruction, problems that are further compounded by co-channel interference and Doppler shifts when receiving data from a network of mini- or micro-UAVs. Jamming is also a potential problem, which could degrade control signals to the netted UAVs, or data uplinked to a satellite or relay UAV. Finally, signals from implanted sensors might be intercepted and geolocated, leading to the unit’s destruction or compromise.\(^{19}\)

Solving these problems calls for signaling techniques having inherent antijam and low-probability-of-intercept characteristics, such as spread spectrum or impulse radio. Both approaches allow many channels to coexist in the same band and can largely eliminate multipath effects through appropriate processing.

The weakening of signals by obstruction can be exacerbated by low power if the signal source is a MAV or propagation loss if the signal source is an in-building radio. MAVs, weighing a fraction of a pound in total, must restrict their communications payloads to a weight of several grams, with power consumption of perhaps 1 W. Obstruction from using cell phones for communications from inside buildings may reduce effective power to a fraction of a watt in passing through concrete block walls.

\(^{18}\)In topologically complex environments, such as urban areas, radio signals from a transmitter arrive at the receiver by diffracting and reflecting from the ground and from buildings. Since the signals arrive by way of a number of radio paths, the combined signal is called a \textit{multipath signal}. The relative delays between the component signals can cause them to mutually interfere. This interference can reduce the resultant signal power or can produce overlap between adjacent symbols in the data stream—in either instance, possibly leading to errors in the received signal.

The common view that commercial satellites are the panacea for these problems wavers under scrutiny. Recent problems in operating Iridium phones in the city and the very real possibility of uplink jamming should raise concern about the robustness of commercial satellites. Communications relays on high-altitude UAVs such as Global Hawk can offer line-of-sight, or near line-of-sight, links with reachback to fusion centers via additional UAVs, or links to commercial satellites that are over the horizon from ground-based jammers.

It is important to recognize that data links from MAVs and implants in the city are very challenging even when UAV relays are present. Even with image compression, a data rate on the order of 100 kilobytes per second (kB/sec) may be required to transmit imagery. To transmit within an extremely tight weight and power budget will require the development of specialized receivers-on-a-chip. The impulse radio techniques discussed in the next subsection may also contribute to the solution.

DARPA has an ongoing program to develop a UAV relay payload for Global Hawk, called Airborne Communication Node (ACN). The concept involves servicing a plethora of in-theater relay needs, including broadcast to forces on the move, theater paging, handheld radio, Joint Tactical Information Distribution System (JTIDS) support, position location (PLRS, EPRLRS), and acting as gateway among dissimilar radios, e.g., SINCGARS, HAVE QUICK. Electromagnetic self-interference and interoperability issues hamper meeting all these needs within a single payload. Software radios that can bridge different modulations and protocols are being developed to address some of these problems. Carefully tuning payloads to specific missions may be the key to success for this very important capability.

Through-the-Wall Communications

To potentially overcome many of the obstacles to communications in the urban environment, communications equipment using ultrawideband (UWB) impulse waveforms is being developed and tested.

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Promising features of this technology include low probability of intercept (LPI), non-interference with nearby users, relative immunity to multipath and jamming, and ability to penetrate structures.\textsuperscript{21}

Conventional communications is based on encoding data onto signals by modulating a carrier wave. Impulse radio is carrierless: Instead, millions of single-cycle nanosecond-duration impulses are transmitted per second, with randomized (but known to the receiver) interpulse intervals to make the waveform appear noiselike. The information content is encoded onto the pulse stream by pulse-position modulation (PPM): Binary 0 is delayed, and binary 1 is advanced a fraction of a nanosecond relative to the nominal pulse position. This scheme is referred to as time-modulated UWB.\textsuperscript{22}

Each data symbol consists of a stream of zeroes and ones, $10^2$ to $10^3$ bits long. The symbol is detected by coherently summing the energy from this set of bits. The individual bits can have such meager energy that they are below the level of ambient noise; yet, the processing gain achieved by coherent summation allows the receiver (with knowledge of the time code) to detect the symbols.

The ability to hide the time-modulated waveform in noise makes it difficult for hostile receivers to intercept. The receiver is resistant to jamming because it is receptive to signals only when they come within the short time interval during which a pulse is expected and because it is designed to sense the rapid increase in signal amplitude at the start of a pulse. The waveform is also resistant to multipath, the potentially destructive interference between signals arriving along slightly different paths, for example, a direct path through the air and one that bounces once off the ground or a building. The very short pulse width ensures that only propagation paths with lengths differing by as little as 0.3 m will mutually interfere—a situation that


applies to only a very small fraction of multipath bounces, even when communicating inside a building.\textsuperscript{23}

A single user’s transmitter is “on” only between 0.1 and 1 percent of the time. By employing different time codes, which are pseudorandom and have low cross-correlation, many users can operate on a non-interfering basis.\textsuperscript{24} The few pulses that randomly invade a neighbor’s time code will be overwhelmed by the coherent processing gain of the receiver using the correct code.

The typical center frequencies of impulse radio fall between 650 MHz and 5 GHz. Frequencies at the lower end can penetrate structures, such as concrete block walls, with minimal losses.

Impulse radios developed by Time Domain Corporation and Multispectral Solutions, Inc. (MSSI) are small and lightweight and have low power consumption.\textsuperscript{25} Tests of MSSI’s 1-W impulse packet radio, which weighs 1.9 kilograms (kg) and operates at a 9600-baud data rate, demonstrated the ability to operate a line-of-sight link successfully at a range of 20 mi. A handheld voice/data impulse radio developed by MSSI, weighing 1.1 kg, transmits data at a rate of 128 kB/sec, although, with its existing antenna, at rather short range. On the whole, this technology seems capable of supporting a variety of secure data links to high-altitude UAV relays from Special Forces inside buildings and from implanted sensors, mini-UAVs, and MAVs.

However, the future of UWB radios is threatened by concerns about interference with navigation systems.\textsuperscript{26} The Federal Aviation Administration (FAA) is petitioning the Federal Communications Commission (FCC) to ban UWB radios on the grounds of potential interference with avionics and navigation units. Although the wide bandwidth of UWB does impinge on sensitive frequencies, impulse


\textsuperscript{26}W. Scott, “UWB Industry Fate May Hinge on Review,” Aviation Week & Space Technology, December 14, 1998, pp. 63–64.
radio’s low power spectral density should allow room for some level of use. If UWB is shut down domestically, the loss of dual-use efficiencies will have cost ramifications for military-only systems.

**Pseudolites**

*Pseudolites* are ground-based or airborne transmitters that supplement or replace GPS for navigational purposes. The civilian world is interested in pseudolites primarily for improving accuracy. Civilian applications include precision approach and landing of aircraft and land surveying. Recent flight tests have been conducted to determine the value of integrating a pseudolite into the FAA’s ground-based Local Area Augmentation System (LAAS). The LAAS is intended to bolster GPS to permit all-weather landings at airports.\(^\text{27}\)

Military interest is centered on exploiting the pseudolite’s shorter range to the user and possibly higher power in order to strengthen the GPS signal against jammers. In the urban environment, the pseudolite would function to counter jamming, propagation loss in the urban canyons, and multipath. Overcoming severe propagation losses in the city calls for an airborne pseudolite, which generally has a more direct line of sight to users in an area than does a ground-based pseudolite. Preferably, the pseudolite would be mounted on a high-altitude, enduring platform such as Global Hawk.

Several technological challenges have been encountered in developing airborne pseudolites:\(^\text{28}\)

- Accurately determining the location of the pseudolite platform
- Transmitting ranging signals that can be received by GPS receivers
- Injecting pseudolite position data into a format compatible with existing GPS equipment

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Avoiding signal degradation from interference with satellite GPS signals.

None of these challenges appears overly daunting.

The feasibility of a pseudolite payload for Global Hawk is being investigated by DARPA/Sensor Technology Office (STO), and DoD is planning a UAV flight test in the near future. The concept is for a pseudolite with a sophisticated antenna to receive the GPS signal (for its own localization) by placing deep nulls on jammers. The pseudolite then broadcasts its own ranging signal, which can be picked up by slightly modified GPS receivers.29

IMAGING SENSOR TECHNOLOGY
FOR URBAN OPERATIONS

A revolution in imaging sensor technology is under way and will profoundly affect the design of surveillance payloads in the next decade.30 The advances are appearing in several domains, the most important being

- Large focal plane arrays (FPAs), in the megapixel class, in all the optical bands
- Large, uncooled FPAs operating in the IR bands
- Microsensors suitable for expendable implants and MAVs.

As digital cameras, large FPAs operating in the visible band have been highly commercialized, which has significantly reduced their cost. Large FPAs offer high resolution, large field-of-view, rapid read-out, good dynamic range, and frame rates adequate to surveil scenes that change quickly.

Large cooled FPAs operating in the IR will have improved sensitivity, enabling them to detect in multiple bands for improved discrimina-

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Uncooled IR FPAs have extensive commercial applications—for security, police work, medical sensing, traffic control, etc.—and the competitive dual-use market is already whittling down the cost of FPAs of modest size. The obviation of requirements for cooling and temperature stabilization will decrease the complexity and expense of these systems.

Microsensors employing large FPAs in both the visible and IR bands represent a completely new category of imaging sensors. They will be sufficiently small and light weight to serve as payloads for MAVs or as expendable implanted sensors.

Apart from the visible-band cameras, numerous technical challenges must be met before these new sensors are available for urban surveillance. The uncooled FPAs need improved sensitivity, and the large megapixel arrays, for which the commercial market may be thin, must undergo innovations to reduce their cost. The microsensors share these two challenges, as well as the need to miniaturize electronics, reduce power requirements, compensate for temperature deviations in lieu of stabilization, and find commercial markets. The challenges for cooled FPAs are to decrease non-uniformity, shrink pixel size to accommodate multiband detectors, and raise FPA operating temperature to minimize cooling loads.

In the domain of urban operations, all the imaging technologies mentioned above have worthwhile applications. As stated in Chapter Four, a major challenge for aerospace operations is the lack of high-resolution sensors that can identify adversaries who are potentially mingled with civilians or friendly troops. Confidently identifying people is not a strong suit of IR sensors, which lack adequate resolution except at very close range. Even then, IR sensors do not supply the characteristic cues that humans rely on to “check people out” in the visible band.

The most appealing solution is to employ a visible sensor having good low-light-level capability, supplemented by active laser illumination at night or when looking through windows into darkened
rooms. Researchers at Lincoln Laboratory are developing a silicon charge-coupled-device (CCD)-based microsensor with sensitivity into the near-IR that fills this niche. By selecting a laser wavelength just beyond the visible band, the laser can be operated covertly from a mini-UAV, MAV, or, in some cases, a high-altitude UAV.

An example of the weight trade-offs with range for a CCD sensor are shown in Figure 6.5, for daylight in clear weather. The CCD array has a dimension of $640 \times 480$ pixels, with detector spacing of $24 \mu$m. The f-number of the optics is 2.7. In the figure, the optics diameter is scaled up as the weight increases, resulting in extended range per-

![Figure 6.5–Imaging-Sensor Weight and Performance Trade-Offs](image)


formance. We see that, for a mini-UAV of size intermediate between a Sender and Swallow and having a payload capacity of 5 lb, NIIRS-9 quality can be achieved at a range of approximately 150 m. A MAV with a 15-g payload achieves this NIIRS level at approximately 25 m.

A mini-UAV is likely to be detected acoustically, then optically, at a range of 150 m by an alert human “target.” Therefore, it might be better utilized for surveillance tasks short of human identification. Although detectable at 25 m, the MAV can probably fly in under the cover of night and perch on buildings adjacent to the target building.

An added advantage of this approach is that the MAV need not exhaust its batteries and cease functioning in a mission of just 1 hr. The MAV also has an opportunity to recharge batteries, as discussed in Appendix B.

The resolution associated with NIIRS 9 depends on design details of the optics, focal plane, and processing, as well as on atmospheric and lighting conditions; however, for the clear-weather/daylight case represented in the figure, a typical NIIRS-9 resolution is in the range of 2.5 to 3.8 cm.\(^{33}\)

A more detailed performance evaluation shows that a sensor designed to “identify” in daylight is reduced to “recognition” capability at twilight and must resort to laser illumination to retain recognition capability if lighting degrades further. If the optics is stationary, either housed in an implant or a parked MAV, resolution degrades more gracefully with low lighting, because integration time can be increased and more photons collected without motion-related smearing of pixels.

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NON-IMAGING SENSOR TECHNOLOGY
FOR URBAN OPERATIONS

This section discusses some non-image options for overcoming the difficulties associated with imaging sensors, such as bandwidth problems and weather restrictions, and the challenge of interpreting massive amounts of imagery.

Seismic and Acoustic Sensors

Seismic and acoustic devices have been considered an integral part of unattended ground sensors (UGS) for decades, during which steady advances have been made in sensor technology, particularly in signal processing.34 Examples of already-developed UGS devices include the Remotely Monitored Hand-Emplaced Battlefield Sensor System (REMBASS), which adds infrared and magnetic sensing to acoustics; IREMBASS (the improved version of REMBASS); and Alliant Technology’s SECURES, a commercial acoustic countersniper network. Further development of these devices is underway by DARPA and the services. In this subsection, we focus on vehicle surveillance using acoustic and seismic devices. For a discussion of countersniper sensors, refer to Appendix C.

The battlefield sensing problem involves detecting, classifying, and geolocating wheeled and tracked vehicles. Detection ranges of hundreds of meters to kilometers are typical, and networked sensors are able to establish locations with modest accuracy by measuring time-difference-of-arrival (TDOA) to several sensors in the network. Geolocation is complicated by the need to correctly associate detections made by different UGS in the network.35 Ambiguities in association multiply as the density of vehicles increases, because the sensors have poor angular resolution, there are mismatches in the signals as a result of different Doppler shifts experienced at the nodes,

35Association refers to the matching up of detections or tracks of a target by the same sensor or different sensors, so that it is apparent that all the data refer to the same target. The likelihood of confusion increases if the sensors individually have poor resolution, which results in a group of targets being perceived as an undifferentiated blob.
and detection dropouts caused by the masking of distant sources by proximate sources leave too few independent detections to perform TDOA.

All the complexities of the battlefield are amplified in the city. Beyond short ranges, high levels of ambient traffic and anomalous propagation can make hopeless the resolution of ambiguities in associating targets. An appropriate role for seismic and acoustic sensing in the urban environment is to count and classify vehicles passing at close range over key roads or through key intersections.

Classification by seismic and acoustic sensors is based on recognizing the characteristic frequency content of a particular class of vehicles. Acoustic and seismic frequency spectra consist mostly of lines, which typically form a series that are integer multiples of a fundamental frequency. These series, consisting of a fundamental and its harmonics, can be traced to specific physical phenomena. The engine’s acoustic signature comes from the exhaust, and (in tracked vehicles) from the back cogwheel. The seismic signature (detected in the vibration of the ground) comes from the roller wheels moving over the track elements and, to some extent, from coupling into the ground of the acoustic sources.

There remain significant challenges in signal processing for classification. Data describing line series for a wide variety of vehicles have been collected by, for example, Sandia National Laboratories. Algorithms need to be perfected that can classify line series in the presence of line overlaps and that can deal with the overlap of whole spectra occurring when closely spaced vehicles pass by.

**Through-the-Wall Radar**

Two radar technologies have been developed in recent years that are referred to as “through-the-wall”: (1) motion detectors, developed by GTRI and Hughes Advanced Electromagnetic Technologies Center

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(HAETC),\textsuperscript{38} and (2) ultra-wideband radars,\textsuperscript{39} which have been developed by Time Domain Corporation, Lawrence Livermore Laboratory, Lockheed Sanders,\textsuperscript{40} and others. These devices are being promoted for police work, urban warfare, and medical monitoring. Applications for police and urban warriors include avoiding ambushes and sizing up hostage situations. Through-the-wall radar has promise under some conditions but may prove to be easily countered by simple measures, such as foil lining on walls or even water on walls.

GTRI’s motion detector, called a “radar flashlight,” is a low-power X-band (near 10 GHz) continuous-wave Doppler radar that fits in a handheld cylindrical package. As with other Doppler radars, it is able to extract a small signal from a moving object in the midst of much higher-amplitude reflections from surrounding clutter. X-band is not optimal for penetrating walls, but the flashlight is sensitive to the movements of human respiration. The shock wave of the beating heart as it propagates to the chest wall—the signal picked up by stethoscopes—can be detected through a 20-cm-thick concrete-block wall.

The current version of the flashlight is designed to be operated while stationary, a limitation that current development efforts are laboring to overcome. As with airborne Doppler radar, the messy problem is how to reject clutter that has relative motion of comparable magnitude to the target. If successful, packaging for a mini-UAV might be feasible.

A motion detector developed by HAETC is a briefcase-sized device operating around 900 MHz. At this low frequency it is able to penetrate through 3 ft of concrete-block wall. The radar does not use Doppler processing but, instead, detects small phase changes when the position of any objects in the room changes. When the received


signal is demodulated, the voltage changes fall into the acoustic frequency band. They are presented to the user as a tone, analogous to submarine sonar, which allows for some degree of target discrimination by an experienced operator.

Ultra-wideband (UWB) radars have been the subject of intense research for nearly a decade.\textsuperscript{41} UWB waveforms are either impulse, like the through-the-wall communications technology discussed earlier, or coherently modulated, like spread-spectrum communications. The UWB radars of the impulse variety employ very short pulses of approximately 1-nanosecond (nsec) duration. The coherent modulated waveforms have much longer duration; however, upon demodulation in the receiver, their phase or frequency coding allows them to be compressed to the short duration of the impulse waveforms. Both types of UWB pulses have very high percentage bandwidth, which means that the ratio of the frequency spread of the energy to the center frequency is greater than 25 percent. Conventional radars having a low-percentage bandwidth cannot support wideband waveforms at the lower radar frequencies.

UWB radars offer a means to enhance wall penetration and range resolution simultaneously. They can operate at the lower radar frequencies that penetrate earth, concrete, etc., with smaller losses than at higher frequencies, and they have the wide bandwidth that is required to obtain good resolution in range. The very fine resolution of UWB radars (typically \(\approx 15\) cm) also affords relative immunity to multipath, a feature that is held in common with UWB communications.

Both Time Domain Corporation and Sanders have operated UWB radars in the synthetic-aperture-radar mode, obtaining through-the-wall images of objects in a room. The Sanders device, developed under DARPA’s Smart Module Program, is called Hand Held Synthetic Aperture Radar (HHSAR). Its 2-GHz bandwidth translates into a resolution in range of 9 cm. Usually, a large enough aperture is synthesized to achieve the same resolution in cross-range as in range. For a room measuring 5 m in depth from the radar aperture, the radar has to be moved laterally a distance of 4 m to accomplish this resolution.

The relative location of the radar across this synthesized aperture must be known to within a few centimeters. Sanders is looking into coupling a miniaturized GPS/Inertial Navigation System (INS) module to the radar for this purpose. Final packaging will determine whether this kind of device is suitable for mounting on robotic vehicles or, perhaps, mini-UAVs. A small package implies that the low-frequency antenna will be inefficient; that inefficiency will be compensated for somewhat by reduced propagation loss through the wall and improved coupling into the target.

UWB SARs with very fine resolution are a technology worth pursuing for urban operations. They can detect and localize (though not identify) individuals inside buildings, which is more instructive than merely detecting the presence of lifeforms. In addition, impulse SARs have the potential for object recognition based on target impulse response.42

The idea underlying target impulse response is familiar from acoustics. When a hammer strikes a steel bar, it delivers an impulse, causing the bar to “ring” at its resonance frequencies, which are characteristic of its shape, structure, and composition. The ringing persists after the sound of the initial hammer strike is heard, then damps out. These “late-time” resonances are typically associated with specific scattering centers or modes, such as the propagation of the acoustic wave down the gun barrel and back again some integral number of times.

Irradiating an object, such as a rifle, with an electromagnetic pulse causes the radar echo to display similar tell-tale resonances, if the spectrum of the incident waveform contains significant energy at the resonant frequencies of the object. Typically, an object’s lowest frequency resonance occurs at a wavelength twice the length of the object. This amounts to about 2 m for a gun barrel, corresponding to a radar frequency of 300 MHz. For discriminating rifles using reso-

nances, we infer that we need to operate the UWB SAR in the VHF band, much lower than the Sanders device. The Army Research Laboratory (ARL) has attempted to detect buried mines using an impulse UWB SAR with its spectral peak in the VHF band—with discouraging results for a small mine buried in loose soil. Results looked promising for larger objects on the surface and closer to a meter in length.

Since SARs can produce an image of the objects in a room, the most effective use of target resonances would be as discriminants for testing objects that appear to be weapons. The imagery would allow the orientation (i.e., compass direction and angle up or down) of the possible weapon to be estimated. Orientation is a required input for estimating the resonant signature. A VHF impulse SAR, if packaged similarly to Sanders’ HHSAR, might be an effective ambush detector.

Remote Listening

Remote listening occupies a unique niche: It enables human intelligence to be collected covertly without agents on the ground. This capability could play a role in ambush detection and, in concert with other implanted sensors, in general surveillance.

Laser remote-listening devices were developed decades ago. The concept involves illuminating windows with a low-power continuous-wave laser and recovering conversations in the building from the reflected signal. Acoustic waves impinging on the window cause it to vibrate, much like a microphone diaphragm. This vibration modulates the phase of the laser beam. Of course, unlike the microphone, the window is far from an ideal, high-fidelity transducer.

With the advent of solid-state lasers and miniaturized processors, it is possible to package remote-listening lasers as payloads for mini-UAVs or as implanted sensors.\textsuperscript{43} Since the voice bandwidth is narrow, a data link for sending demodulated signals up to a high-altitude UAV need be no larger than a cell phone.

The latest entry into the remote-listening field is a research effort by Sandia Laboratories to develop a *microwave* remote-listening device.\textsuperscript{44} Experiment will determine whether microwaves are better able to capture voice modulations from the window than lasers are. One might hope to extend the range of a microwave device beyond the laser; however, if the microwave beam spreads out to cover several windows, overlapping conversations might degrade intelligibility.

Employing higher radio frequencies and millimeter waves instead of microwaves could help. With a typical window spacing of 3 m and a 1-m-diameter antenna operating at 95 GHz, the range could be increased to approximately 1.5 km before two windows are in the beam. To extend the listening range even further, operation could be bistatic, with the illuminator on a UAV and the receiver an implanted or parked device on a facing building. If the implant has a 6-in. antenna and is situated 50 m away, its receive beam would be only 1 m across, the width of a single window. Under remote control, it could interrogate any of the windows illuminated by the UAV’s beam and, being passive, would consume very little power, primarily for its data link.

**Chemical Sniffing**

Several rapidly developing technologies may lead to chemical-/biological-sniffing payloads for mini-UAVs in the near term. Applications to urban operations include detection of explosives (car bombs and weapons caches), mines, drugs, and releases of chemical or biological weapons. Because of this potential for military applications,\textsuperscript{45} DARPA is investing heavily in chemical/biological sensing. However, the underlying micro-instrumentation technology is primarily commercial, with applications to medical diagnostics, food processing, chemical industry, hazardous materials ("hazmat")-site profiling, environmental monitoring, cell sorting, protein separation, and DNA sequencing.

\textsuperscript{44}R. Martinez, Sandia National Laboratories, Albuquerque, N.M., Private Communication, February 13, 1998.

The most promising of these sensing technologies is microfluidic lab-on-a-chip devices. In general, these consist of an array of microcells or channels—arrays up to 90,000 cells have been developed for genetic research—microfabricated on planar substrates. For detection, each array element reacts with or binds to specific substances. This parallelism enables many reactions to be tested simultaneously, hence the capability for ultra-high throughput screening (UHTS).

Typically, the microchips involve input and output by pipette, inkjet, or electrospray. Chemical separation may be built onto the chip using liquid chromatography or electrophoresis. A variety of techniques have been employed in the final stage of chemical detection, including quadrupole or ion-trap mass spectrometry, matrix-assisted laser-desorption ionization time-of-flight spectrometry, cell-based assaying (using multicolor fluorescence analysis in living cells), fiber-optic fluorimetry (the fibers are coated with antibodies aimed at specific biological agents), and electrical resistance of absorptive polymers (the resistance of each polymer changes in a characteristic manner after absorbing the chemical vapor under test).

In 1996, the Naval Research Laboratory (NRL) successfully flew a biological-warfare-agent detection system on a Swallow mini-UAV. The biosensor was of the fiber-optic fluorimetric type. Although not in the form of a microchip, it fit within the 10-lb payload capacity of the aircraft. Further developments in this field are likely to provide even smaller payloads, increased sensitivity, and improved discrimination.

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SENSOR FUSION IN SUPPORT OF URBAN OPERATIONS

Sensor fusion is the process whereby information from different sensor types is integrated and presented on a single display. For example, visual, IR, and SAR images can be combined to give a richer picture than any single sensor could provide. Sensor fusion can also be used to reduce false alarms. For example, the sensor-fusion system might be programmed to ignore seismic detections, unless nearby acoustic sensors also detected the unique signature of a vehicle engine.

Effective sensor fusion has proven difficult when more than a few sensors are involved, phenomenologies differ, or the types of errors are significantly different. As well, daunting problems remain in processing, network design for ease of scaling, and algorithm development. As the number of nodes having overlapping coverage in the sensor network increases, the number of operations involved in fusing the information grows extremely rapidly. Achieving a common picture requires the ensemble of sensors viewing each event to be reconciled. This nonlinearity implies that achieving fusion through brute-force processing power is a dubious proposition. The problem is compounded by the tendency to increase the dimensionality of the data to more fully characterize the targets being observed.

Fortunately, short of full-scale data fusion, two steps can provide utility:

1. Assist the operator by collecting multiple sources of information at a single point and allowing the overlay of various data elements. In assisting with visualization, the various sources are largely accepted as ground truth and are usually correlated only within each data type. For instance, if acoustic sensors report three discrete targets and radar reports four targets in the same very small area, the actual count would be ambiguous. It would be difficult to know which, if either, source is reporting the correct number. Consequently, a visualization system might present one set of results, present both sets, or contrive a rough correlation without really addressing some of the ambiguities and resolving the issue fully. Perhaps the greatest value would be in highlighting discrepancies among sensor types.
2. Assist the operator by filtering the data from a large array of sensors so that unusual activities that might warrant a closer look by other sensor systems can be detected and brought to the operator’s attention. The system would aid in understanding what is happening by providing, for example, a screen, a monitor that flags unusual events, or a backstop to human observation of the data network. The technology for anomaly detection builds upon the GIS outlined earlier in this chapter. It includes a statistical analysis of both patterns of dynamic activity and unusual changes in objects that can be located again. A now relatively mature technology, anomaly detection can alert human operators of command and control (C2) systems to investigate activities that differ from the norm.

At work in both commercial and military domains, many of the basic technologies for simple fusion are based on neural nets that are “trained” to recognize normal and abnormal activities and to cue humans for intervention when critical thresholds are crossed. Extensive training is required for the neural networks to establish proper baselines of behavior and to establish acceptable false-positive and false-negative rates.

The critical weakness of all current approaches for anomaly detection is that they have a significant high false-positive rate under real-world conditions. Whereas systems that simply look for change can be set to flag changes, dynamic environments require the software to cull abnormal changes from a large array of normal changes that occur on a day-to-day basis. Consequently, these computer-based systems often perform more poorly than a skilled human examining the same data—but they can examine much more data than a human can, and will do so without becoming bored or tired.

Traffic monitoring in a peacekeeping situation is an illustrative application of such a system in an urban area. Here, a large number of sensors might be used to create an estimate of normal traffic patterns as a function of date, day of week, and time of day. By flagging areas of unusually low or high activity, such a system could be used to warn of trouble and could alert controllers to dispatch close-look sensor platforms or patrols appropriately. It could also be used by logistics support groups, operators, and others planning operations
in the urban area to better take into account the traffic in and around areas of interest.

AIR-LAUNCHED SENSOR PLATFORMS

As discussed in Chapter Five, air-launched sensors have the potential to greatly improve the ability of manned platforms to detect and identify adversary forces. In some cases, a mini-UAV or air-implanted ground sensor would accomplish this detection by putting an EO/IR sensor close enough to the target to collect high-resolution imagery. In other cases, small ground sensors could be implanted from the air in locations that friendly ground forces did not have access to.

These sensor platforms could be mini- or micro-UAVs, parafoils, other airborne platforms, or remote ground units. In all cases, they would have to be simple—and cheap enough to be disposable, which might limit the type and number of sensors they could carry. Depending on cost and weight, these platforms could exploit the full spectrum of sensor phenomenologies, including acoustic, seismic, EO/IR, magnetic, chemical, and radar.

A variety of mini-UAVs, both battery-powered and gas-powered, with wingspans as small as 4 ft and endurance up to 2 hr, are already flying with small sensor packages. Thus, the technical challenge is less in the design of the aircraft and more in its packaging and deployment. And, as was pointed out in Chapter Five, “Provide Rapid, High-Resolution Imagery for Target ID,” a means is needed to quickly get the offboard sensor from the medium altitudes at which manned platforms typically operate at down to its operating altitude of 1,000 ft or lower. A small, light UAV would simply take too long to fly down to its operating altitude.

To solve this problem, an aerodynamic container could be used for a UAV. It would be carried on a hard point on the aircraft exterior or could be deployed through the back right personnel door on the AC-130. It could be guided or ballistic. At the appropriate altitude, it would need to slow and be stabilized in order to deploy the UAV. This might be done with a drogue parachute. The UAV would need folding wings that deployed once it was released from the container. Some aerodynamic and control issues would have to be solved. Once
deployed, the UAV would fly autonomously or be remotely piloted to the surveillance area and would broadcast imagery back to the launch platform.

Alternatively, as discussed in Chapter Five, a lifting body/parafoil could carry the sensors, all in a container on the aircraft exterior or launched from the inside of larger aircraft. Some aerodynamic challenges are associated with designing a small lifting body that carries its own parafoil, but, again, the engineering details do not appear excessively demanding. Stabilization and control of the sensor optics could be challenging, since the parafoil may have oscillation problems not encountered on winged air vehicles. These difficulties might be overcome by avoiding dramatic changes in direction. Once the parafoil was established in a constant descending circle over the target area, it should be possible to get a reasonably stable field of view. Clearly, tests with prototype vehicles will be necessary to fully explore these issues. Given the simplicity and light weight of the vehicle, they should not be particularly difficult or expensive.

When more enduring surveillance of a particular building or other site is needed, it is difficult to meet both high-resolution and covertness requirements from airborne platforms. Also, some sensor phenomenologies have such limited range that airborne application is not feasible. Thus, we may want to implant ground sensors from the air for some missions. However, air-implanted ground sensors appear to be more technically challenging than the airborne sensors discussed above. Dating back at least to the Igloo White program of the Vietnam era, the two approaches—high-speed spikes that embed themselves in the ground and parachute packages designed to hang in trees—are designed for rural applications. Urban ground sensors will primarily need to be able to land on and adhere to rooftops, windows, or the sides of buildings. Urban foliage may offer some opportunities to hide sensors, but the sensors would have to be delivered with much greater precision and be much more covert than sensors dropped in vast woodlands or other isolated areas.

Several approaches are possible. In Chapter Five, we discussed implanting a shoebox-sized sensor package by VTOL UAV. The UAV might be able to place the sensor in the optimal surveillance location; however, to maintain covertness most of the time, the sensor would have to be dropped out of line of sight to the target. Even then,
there is the possibility that the UAV would be detected acoustically. Once in place, the sensor would need some limited mobility to get to its surveillance location. Although technically feasible, this approach has several weaknesses: requiring a fairly large UAV to hover within a few hundred feet of the target, leaving a detectable object on a rooftop where it might be discovered, and requiring sufficient mobility to get around and over rooftop obstructions.

Another approach would use a higher-flying manned aircraft, UAV, or munitions dispenser to drop a small, guided sensor. This sensor would fly directly to its surveillance spot, ideally a building wall facing the target, and implant itself, which would have the advantage of minimizing the acoustic signature but the disadvantage of likely discovery. Technical challenges include precision guidance to fly the sensor to within inches or feet of its desired locations to avoid flying through windows; wall-adherence techniques to keep it attached to the building; and resolution so that the sensor would be small enough to avoid casual detection but large enough to see across a street or perhaps farther.

Still another approach, remote ground sensors deployed by agents or friendly forces, has great potential to enhance air operations. Law-enforcement and covert organizations have used such devices to supplement manned surveillance locations for years and have perfected a host of camouflage techniques. Hand-deployed sensors can often be placed very close to the target. Combined with very powerful telephoto lenses and high-quality optics, these systems have the potential to provide imagery of such quality that individuals can be identified—a common requirement in covert and law-enforcement operations.

This successful quality suggests that, as a hedge against the possibility that air-implanted sensors will be infeasible, the USAF R&D community, in concert with other services and agencies, might do well to explore the development of quality remote ground sensors. As well, not only must remote sensors not compromise technologies and techniques essential to other intelligence-collection operations—a key consideration in their development—but means must be developed to limit the consequences of discovery and analysis by adversary technical experts, since any remote sensor has the potential of being discovered. Various self-destruct techniques might be
used to prevent the adversary from using or fully understanding key parts of the remote sensor. Since such techniques are never completely reliable, it is likely that the most-sensitive remote-sensor phenomenologies will have to be avoided and less-than-state-of-the-art technologies used in many cases.

LIMITED-EFFECTS MUNITIONS

As discussed in Chapter Four, USAF weapons are optimized for precision attack against medium to hard targets and are extremely valuable in more-conventional urban fights. However, in operations in which restrictive ROE require that damage be limited within buildings, perhaps even to single rooms, these weapons have too much explosive power and penetration potential. Anti-personnel weapons, such as the 40mm and 105mm guns on AC-130 gunships, are more appropriate under these more-constrained conditions, but they also have limitations, particularly against interior targets in urban canyons.

A growing requirement beyond these more-traditional weapons is for highly discriminating weapons whose effects can be tailored to meet the unique needs of each situation. As the precision of air-delivered ordnance has improved over the twentieth century, effects have shrunk from citywide to blocks to individual buildings. It is only natural that airmen would continue this evolution, taking the next step and developing weapons that have effects limited not just to buildings but to individual rooms within buildings: kinetic-energy weapons; laser-guided hand grenades; miniature glide bombs, cruise missiles, and killer UAVs; and nonlethal weapons.

Kinetic-Energy Weapons

As discussed in Chapters Four and Five, several approaches can be taken to make air-delivered ordnance more discriminating in urban settings. The first approach would simply reduce the explosive yield of existing weapons so that the effects would be more limited. Some experimentation would be necessary to understand the effects associated with various smaller warheads. In the extreme, the explosives can be taken out completely, as in the laser-guided training round or the 2,000-lb bombs filled with solid concrete used against Iraqi air
defense sites during Operation Northern Watch strikes in October 1999.\textsuperscript{50} With explosives removed, the amount of damage is a function of the speed, weight, and density of the weapon casing and fill, variables that can be adjusted for. Such weapons, if sufficiently accurate, can inflict substantial damage against equipment, vehicles, and smaller structures, but their effect on people in structures is harder to predict. In smaller rooms, kinetic-energy weapons are likely to kill or injure occupants. In larger rooms, however, the lethal/injury radius from shock or fragmentation may not cover the entire space. In general, a unitary kinetic-energy weapon is less effective against area targets than is a weapon relying on explosive effects. Additional testing of shock-wave, spalling, and other effects will be necessary to adequately assess the anti-personnel potential of kinetic-energy weapons. Finally, such weapons (at all but the slowest speed/weight combinations) still present a serious penetration danger when damage is to be limited to a single floor, although perhaps they could be designed to shatter on impact to avoid this problem.

“Laser-Guided Hand Grenades”

Alternatively, it may be worth exploring very small, laser-guided weapons, such as the Marines have done with 2.75-in. rockets. A precision weapon of this class, a “laser-guided hand grenade”\textsuperscript{51} if you will, could be delivered against targets in all but the steepest and narrowest urban canyons. It would require more-focused and more-precise laser designators than are currently deployed, so that this small weapon would, for example, go through a window rather than bounce harmlessly off the outside of a building.

Miniature Glide Bombs, Cruise Missiles, and Killer UAVs

An alternative to this “hand grenade” approach would use a small, slow-flying platform (such as a UAV or a small cruise missile like LOCAAS) to deliver a small munition (weighing from a few ounces to

\begin{itemize}
  \item \textsuperscript{51}A term coined by RAND colleague David Shlapak a few years ago on a related project.
\end{itemize}
a few pounds). The main challenges here are developing a platform that is so agile and accurate that it can maneuver down into the urban canyon and either fly by the target and fire a projectile sideways at the target or fly into the target. Lacking much penetration potential by design, both the laser-guided hand grenade and this concept would work best against targets in the open, in open rooms, or behind glass. They would also have to be exceptionally accurate, which is unlikely to be feasible without a navigation system integrating GPS pseudolites and 3-D maps, as discussed earlier in this chapter. This is probably the most technically challenging of the weapon options in this report.

**Nonlethal Weapons**

Finally, there is the option of using nonlethal weapons against urban targets. These weapons include a wide range of technologies designed to accomplish quite disparate tasks. Their primary attraction for urban operations is the hope of solving the target-discrimination problem by achieving an acceptable effect on adversaries without harming the civilians when combatants and noncombatants are intermingled or are very near by. For example, if a sniper were firing from an apartment building, a nonlethal weapon such as a sedative gas might be used to stop him from firing. If the gas canister missed and landed in someone's living room or if the gas drifted into other spaces, the worst that would happen, in theory, is that the civilians would fall asleep for some period of time. As discussed later in this subsection, there are a variety of reasons why this is very hard to do in practice, but that is the promise.

Most nonlethal weapons are designed for close-in use by infantry or police, but several technologies have promise as air-delivered weapons. Many nonlethal weapons are already being deployed or are in development. The following paragraphs discuss a few of these—acoustic devices, optical effects, nonlethal barriers, high-powered

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microwaves, chemical agents, and biological agents—as well as pro-
scriptions against anti-personnel nonlethal weapons.

**Acoustic Devices.** Acoustic devices, including beams, blast waves, 
curdlers, squawk boxes, and sonic bullets, are all possibilities for air-
borne weapons. Some can produce point effects; others produce ef-
cfects over larger areas. As these technologies evolve, it may be possi-
ble to achieve more-precise effects.

Acoustic beams use high-power, very-low-frequency beams to cause 
body cavities to resonate at particular frequencies. The effects can 
range from mild nausea all the way to permanent injury and death, 
depending on range, decibel level, and exposure time. Acoustic blast 
waves can be generated by pulsed lasers, producing a hot, high-
pressure plasma similar to chemical explosives. Acoustic curdling 
produces a shrieking noise that can be used to disperse rioters. 
Another crowd-control device that might have utility as a 
countersniper weapon is the “squawk box,” first used by the British 
Army in 1973 in Northern Ireland. It combines two ultrasonic 
frequencies that, when mixed in the human ear, produce “giddiness, 
nausea or fainting.” The beam is reportedly so small that it can be 
directed at specific individuals. Finally, high frequencies can produce 
an impact wave that hits the target similarly to a blunt object, 
producing effects ranging from discomfort to death.\(^5\)

The effects of urban structures on acoustic weapons are not com-
pletely understood. Some have expressed concern that structures 
could magnify the effects to potential lethal levels or that, under 
some combination of high power levels, building-construction mate-
rials, and weapon orientations, acoustic weapons could cause 
structural damage to buildings.\(^6\)

The directionality of weapons effects and range can limit the devel-
opment of airborne acoustic weapons. To the extent that direction-
ality can be controlled, concepts such as the acoustic beam may be


\(^{54}\)Greg Schneider, _Nonlethal Weapons: Considerations for Decision Makers, ACDIS 
feasible from airborne platforms. If, however, the beam is omni-directional, it should clearly not be put on a manned platform because it would harm the crew. A UAV might carry such a device, assuming that the acoustic energy would not interfere with or damage the UAV itself. Alternatively, an acoustic-beam-generating device might be dropped by parachute from a manned platform. Some acoustic weapons have ranges measuring a few hundred meters, well below altitudes where manned aircraft typically operate. Even longer range acoustic systems would require manned platforms to fly within the envelope of MANPADS and AAA. For these reasons, it might make sense to put acoustic weapons on low-flying UAVs.

**Optical Effects.** Optical effects can also be exploited to produce nonlethal effects. Bright lights, strobes, and flash/bang grenades can be used to stun, disorient, or even cause epileptic seizures. For example, high-intensity strobe lights flashing near human brain-wave frequency reportedly cause vertigo, nausea, and disorientation, and might cause epileptic seizures in some people. A less exotic application is found in the Mk-1 illuminating grenade, which was used during the Vietnam War as a counter-ambush weapon. It produced 55,000-candlepower illumination for 25 sec, temporarily blinding those caught nearby. Such devices might also be useful to counter urban ambushes or to prevent a MANPADS operator or sniper from sighting in on his target, allowing the friendly aircraft or personnel to move beyond line of sight. Lasers, such as the Army’s Stingray system, can be used to damage optics on sensors and weapons, as well as to temporarily or permanently blind adversary personnel. Airborne lasers might be useful as obscurants, to damage sensors and other optics or to prevent adversary forces from seeing through windows. For example, lasers “have the capability of heating and distorting or cracking the glass lenses of optical systems. This effect is called crazing and is caused when the heat buildup and subsequent cooling in the glass surface creates uneven stresses in the glass surface to crack it. The result is a frosted effect, making it impossible to see through the glass lenses or vision blocks (glass windows) in

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56For more on this system, see U.S Department of the Army, FM-90-10-1, 1995, p. I-8.
Alternatively, an argon laser can be used to temporarily prevent vision through the window of a vehicle or structure. Small abrasions in the glass scatter this frequency of light, causing the entire window to turn an opaque green as long as it is illuminated.

**Nonlethal Barriers.** Low-friction polymers (super-lubricants), high-friction polymers (sticky foams), aqueous foams, Caltrops (multisided steel barbs), and other devices can be used as nonlethal barriers. Low-friction polymers impede personnel or vehicle movement, producing an ice-slick surface impossible to stand or drive on. Sticky foams produce a gluelike barrier that cannot be penetrated; they were used during the withdrawal from Somalia. Aqueous foams are dense suds that are used in conjunction with barbed wire, Caltrops, and other antimobility devices. The foams make it difficult for adversaries to see and remove the antimobility devices. Caltrops, tetrahedrons, and similar devices are designed to puncture vehicle tires or limit foot traffic. The standard design has four points. No matter how it lands, the device always presents one barb upward. Tetrahedrons (a four-sided barb) were used to interdict North Korean road traffic during that conflict; Caltrops were used by U.S. Marines during the final hours of the withdrawal from Somalia.

Any of these devices might be delivered by air to produce a barrier in a small area, but polymers and sticky foams are best delivered in urban areas by ground vehicles or stationary equipment. In situations where a small area—such as a rooftop, alleyway, stairway—needed to be blocked, one could imagine a UAV, LGB, or glide bomb delivering foam or low-friction polymer. Caltrops, in contrast, could be easily delivered over a large area by aircraft.

**High-Powered Microwaves.** High-powered microwaves (HPM), which are transmitted by a radarlike antenna or generated through an explosive device, have potential as air-delivered nonlethal weapons for both anti-personnel and antimateriel applications.

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57Bunker, 1997, p. 16.
Some have advocated HPM weapons in the anti-personnel role because of their supposed potential to render personnel unconscious without permanent damage. Yet, given what is known about the effects of microwaves on humans, it seems unlikely that these weapons could be that benign.

HPM-induced changes in brain temperatures of a few degrees (in laboratory rats) caused convulsions, unconsciousness, and temporary blindness. Higher dosages on humans could cause effects ranging from heart and respiratory failure to permanent brain damage. The power density required to produce unconsciousness in humans is “10 to 50 milliwatts per square centimeter for continuous exposures at microwave frequencies up to 10 GHz . . . [while the] . . . single-pulse fluence that produces significant heating at these frequencies is about 100 joules per square centimeter.” This is much higher than what is required to damage electronics. For example, some microwave detector diodes will burn out at 1 microjoule. Thus, in theory, antimateriel weapons could be made to preclude the worst effects on humans. Whether this could be done in practice remains unclear, since the pulse degrades with range. To produce a pulse that would damage electronics in a target 1 km away might require power levels that would harm humans closer to the HPM source.

HPM weapons create an electromagnetic pulse that produces a surge of power through unprotected electrical equipment, potentially disabling vehicles, radios, computers, and radars. Depending on the power levels experienced by the target, the damage may be transitory (e.g., requiring computers to be rebooted) or permanent (e.g., by physically damaging integrated circuits). Designed without significant protection against low-power accidental interference, commercial systems (especially communications) are usually more vulnerable to these type of effects. Consequently, if the military mission required that an adversary’s systems be permanently damaged,
the higher power required to do so would increase the chances that nearby civilian systems would be damaged also. This might limit the use of HPM near essential civilian electronics (e.g., telecommunications, hospitals, electrical-power facilities) and might rule out its use where civilian and adversary systems were located in the same building. In most cases, however, it appears that HPM can be tailored so that permanent damage is limited to quite small areas.

**Chemical Agents.** A variety of reactant chemical agents have been developed as antimateriel weapons. These include combustion-altering agents, super-caustic agents, and liquid-metal embrittlement. Some of these agents would be quite lethal if humans were exposed; their nonlethality assumes that humans are not nearby when they are used.

Combustion-altering agents either contaminate or change the viscosity of fuel, causing engine failure. They can be delivered as a vapor through engine air intakes or introduced into the fuel supply. Super-caustic agents are mixes of acids that will dissolve most metals. They could be used against buildings, roads, and vehicles. Liquid-metal embrittlement changes the molecular structure of base metals, potentially causing structural failure of bridges, buildings, aircraft, and ground vehicles.\(^{65}\)

Most of these agents could be delivered by air. However, their greatest utility is for special operations rather than for routine use by general-purpose forces. The political consequences of causing civilian injuries with super acids or other volatile compounds could be devastating in more-constrained operations and will likely keep these compounds from becoming widely used in urban settings.

**Biological Agents.** Finally, a variety of biological and chemical nonlethal agents are available, such as tear gas, calmative agents, malodorous agents, and sickening agents. The practicality of these concepts varies, but as is discussed in the next subsection, we do not believe these weapons have much applicability in urban operations.

**Proscriptions Against Anti-Personnel Nonlethal Weapons.** Nonlethal weapons clearly have utility in some urban military situa-

\(^{65}\)Kokoski, 1994, p. 377.
tions, particularly those faced by special operations forces. However, several factors are likely to prevent anti-personnel nonlethal weapons from being widely used when civilians and adversary forces are intermingled.

First, nonlethals fail to meet mission requirements in many situations. Most of the time, U.S. forces want to permanently remove adversary forces from the fight by capturing or killing them or to undermine an adversary's morale by producing casualties. Consider an adversary sniper firing on friendly forces. Knocking him out with a nonlethal weapon would have the benefit of stopping him from harming any other friendlies at that time. Yet, unless friendly forces were able to find and capture the unconscious sniper, he would be fit to return to fighting soon thereafter. This also would have the undesirable effect of under-deterring violent actions. Also, not all nonlethal-weapon effects occur immediately. Timing the onset of effects and limiting their duration can be quite complex; one could not be certain that the adversary was incapacitated at the critical time, which suggests that, most of the time, lethal weapons would be the preferred option.

Second, there is the possibility that nonlethals would, in fact, kill or permanently harm civilians. Urban areas increase the probability that nonlethals could harm civilians because (1) the high population densities simply increase the number of people who might be exposed to an amount, or in a way, that would be harmful and (2) enclosed spaces, whether alleys, courtyards, or interior spaces in buildings, may interact with nonlethal weapons in unforeseen ways to concentrate dosages, intensify effects, or limit avenues of escape.

Nonlethals are attractive because they might solve the target-discrimination problem when adversary forces and noncombatants are intermingled. A riot-control agent or acoustic weapon might be used to drive an intermingled group away or to incapacitate them until friendly forces could sort them out on the scene. Technologies already exist to drive people off with fairly low risk. But rendering people unconscious is a much trickier business; it has the potential of killing the young, old, or sick, or of causing permanent harm. Each of these concepts will need to be explored in great depth to ensure that the effects are sufficiently benign to use against noncombatants. However, if the alternative is firing lethal weapons into a crowd, such
risks might appear small. The difficult question for policymakers is whether there are a sufficient number of such circumstances to justify developing and deploying these systems as backups.

Third, the U.S. is signatory to a number of agreements that may prohibit or limit the use of some nonlethal weapons. For example, states that signed the Biological Weapons Convention of 1972 agreed not to “develop, produce, stockpile or otherwise acquire or retain . . . microbial or other biological agents, or toxins whatever their origin or method of production, of types and in quantities that have no justification for prophylactic, protective or other peaceful purposes.”66 Many of the biotechnical concepts appear to run afoul of this agreement. The Chemical Weapons Convention of 1993 obligates (in Article I) signatory nations not to use chemical weapons, which it defines (in Article II) as “any chemical which through its chemical action on life processes can cause death, temporary incapacitation or permanent harm to humans or animals.” It specifically states that “each State Party undertakes not to use riot control agents as a method of warfare.” 67 Finally, both customary international law and treaty law restrict the use of weapons that cause superfluous injury or are entirely incapable of discrimination. To the extent that weapons such as lasers, high-power microwaves, or acoustic weapons produce long-term health problems, they might be arguably in violation of this principle. In sum, a strict reading of these agreements and customs could rule out the use of many of the nonlethal concepts being explored today.68

Even if the use of certain nonlethal weapons is not prohibited or limited under international law, the public reaction—in the local urban setting, the region, and globally—to their use could produce costs that greatly exceed any immediate tactical advantage. Even relatively benign weapons such as CS gas69 could produce lethal effects in enclosed spaces and against the young, elderly, and sick. It could also

66http://www.acda.gov/treaties/bwc1.htm
67http://www.acda.gov/treaties/cwcart.htm#I
68For more details on the potential implications of these treaties for nonlethal weapons technologies, see Barbara Hatch Rosenberg, “‘Non-lethal’ Weapons May Violate Treaties,” The Bulletin of the Atomic Scientists, September/October 1994, pp. 44–45.
69CS gas is the most widely used riot-control agent.
cause a crowd to panic and stampede or crush people to death in a rush to escape the gas. Adversary propaganda, local myths, and rumors could cause overreactions through misinformation about the agents (e.g., claiming that they were lethal, caused infertility, or carried other frightening effects).

Although, in many cases, the effects from nonlethals are less harmful or at least no more harmful than those of conventional weapons, the nature of the effects could produce disastrous political fallout. For example, imagine an operation that resulted in civilians being blinded or terribly burned with acids instead of being killed. The media and public reactions to the blinding and burning events would likely be much worse, at least in part because there would be survivors to photograph, interview, and write about. Therefore, they are likely to be a factor of great concern to U.S. leaders anytime the use of these weapons is contemplated.

In short, we recommend continued research and development of nonlethal weapons for appropriate situations but see them as having little applicability in most urban operations. For this reason, this study has emphasized more-conventional weapons.

**CONCLUSION**

This chapter has sought to show the breadth of technological developments relevant to urban aerospace operations. Many technical hurdles remain and some capabilities may be decades from being realized. However, many technologies are sufficiently mature to justify the development of prototypes and the initiation of operational testing. As noted at the beginning of this chapter, these systems have the potential to greatly enhance aerospace operations in urban environments, but they are unlikely to come to fruition without strong institutional support to take promising ideas out of the laboratory and into the field.

We now turn to Chapter Seven and offer some final observations about the role of aerospace forces in urban settings.