Fixed and wearable acoustic counter-sniper systems for law enforcement

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ABSTRACT

BBN has developed flexible counter-sniper technology capable of shooter and bullet trajectory localization using fixed, vehicle mounted, and/or body-worn microphone sensors. The proof-of-principle (POP) systems developed are accurate, low-cost, lightweight, and easy to install and use. The use of both supersonic bullet shock waves, and/or the muzzle blast, allows detection and localization of shooters with intentional or accidental muzzle blast suppression, or with subsonic rounds. This makes the system capable of finding shooters firing from within buildings or vehicles. It also requires fewer sensor installations per unit area and increases system robustness to the noise and reverberation present in urban settings. In this paper we first summarize the current POP system hardware and software configurations and show the results of government testing in urban and rural environments for military applications. Following this, cost and performance issues for urban law enforcement applications are presented, and performance predictions for various system configurations in an urban street monitoring scenario are given.

Keywords: counter-sniper, sniper, gunfire, acoustic, shock wave, muzzle blast, bullet

1. INTRODUCTION

BBN has developed, tested, and fielded two pre-production versions of a versatile acoustics-based counter-sniper system. These systems were developed for the DARPA Tactical Technology Office to provide low cost and accurate sniper detection and localization. They use observations of the shock wave from supersonic bullets to estimate the bullet trajectory, Mach number, and caliber. If muzzle blast observations are also available from unsilenced weapons, the exact sniper location along the trajectory is also estimated. A newly developed and very accurate model of the bullet ballistics and acoustic radiation is used which includes bullet deceleration. This allows the use of very flexible acoustic sensor types and placements, since the system can model the bullet's flight, and hence the acoustic observations, over a wide area very accurately. System sensor configurations can be as simple as two small four-element tetrahedral microphone arrays on either side of the area to be protected, or six omnidirectional microphones spread over the area to be monitored. It has also been configured using microphone arrays flush mounted on standard army helmets, and can provide degraded localization with only one helmet, or full performance if two or more share data. Increased performance can be obtained by expanding the sensor field in size or density, and the system software is easily reconfigured to accommodate this at deployment time and dynamically as assets are available. For fixed systems, sensor nodes can communicate using wireless network telemetry or hardwired cables to the Command Node processing and display computer. For the wearable system, each helmet is supported by wireless communications, an orientation sensor, GPS, and a backpack mounted computer system that computes and displays the solutions. The systems have been field tested in five government sponsored tests in both rural and simulated urban environments at the Camp Pendleton MOUT (Military Operations, Urban Terrain) facility. Performance was characterized during these tests for various shot geometries and bullet speeds and calibers.

Two primary variants of the acoustic sniper detection and localization systems have been developed at BBN under DARPA funding:

- A “fixed” system, sometimes referred to as “Bullet Ears”, uses two fixed microphone arrays and RF or hardwired telemetry from the arrays to the processing and display computer.
- A “wearable” system allows an arbitrary number of arrays to be in motion, and to share data using a wireless RF network. In the version built and currently undergoing testing, the arrays are made of flush-mounted microphones on standard Army helmets, and each is supported by its own processing and display system.

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At the core of each system is a detailed parametric model of the shock wave and muzzle blast space-time waveforms. Using this, observations of the shock wave and/or muzzle blast on two or more small microphone arrays, or six or more distributed omnidirectional microphones, are inverted for the bullet trajectory, speed, and caliber. If the muzzle blast is available, the shooter 3-coordinate location is also estimated. Both amplitude and spectral characteristics as well as travel-time measurements are extracted from the acoustic data to globally estimate the unknown parameters using robust modeling techniques. A key feature of these systems is the use of low-frequency data (<10kHz). This allows both inexpensive and low power sensors and processing, and extends the area that each sensor can cover, since propagation loss is greater at high frequencies. Patents for key technologies described herein have been applied for.

1.1 Fixed counter-sniper system

A ruggedized fieldable prototype fixed system was developed and extensively tested in real-time with live-fire tests. Shown in Figure 1, this system uses a PC-based Command Node hosting the detailed detection, classification, and localization algorithms, as well as the graphical user interface. Acoustic data from the microphones are digitized either directly by the Command Node for a "hard-wired" system, or by environmentally protected PC-104 based Data Nodes communicating with the Command Node over an RF network for the wireless version. Small size, battery power, and GPS-based time synchronization of these Data Nodes allows the sensors to be arbitrarily distributed and optimized for acoustic accuracy and coverage. While the system will operate with as few as two directional acoustic nodes, barrier-type coverage and increased reliability and accuracy can be obtained with additional Data Nodes and microphones. Both the localization algorithms and software, and the RF network communications architecture allow reconfiguration for more acoustic sensors, either omni or directional. The algorithms can be made to automatically adapt to handle the total available sensor field, as well as the particular set of microphones which have detectable signals on any given shot. Results are displayed in both numerical form, and as an overlay on a digital map display.

In Section 2.3 we describe the results from government testing with hundreds of accurately known shots in both open and urban environments. Key to system performance is a supersonic projectile trajectory model derived from physical principles which is documented in reference [1].

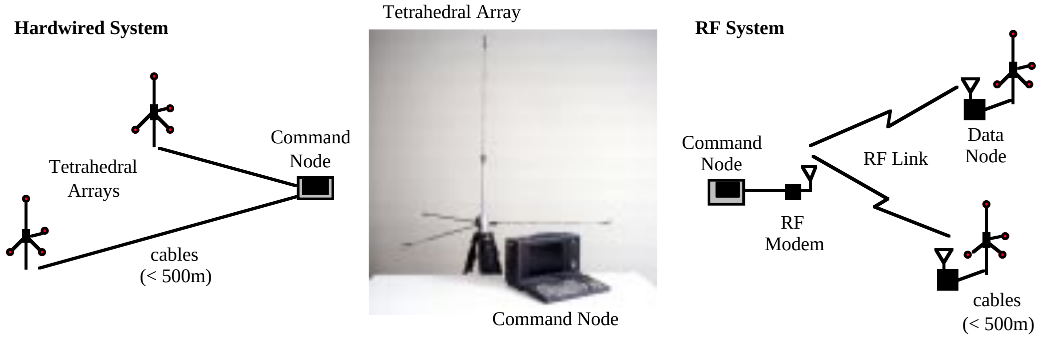
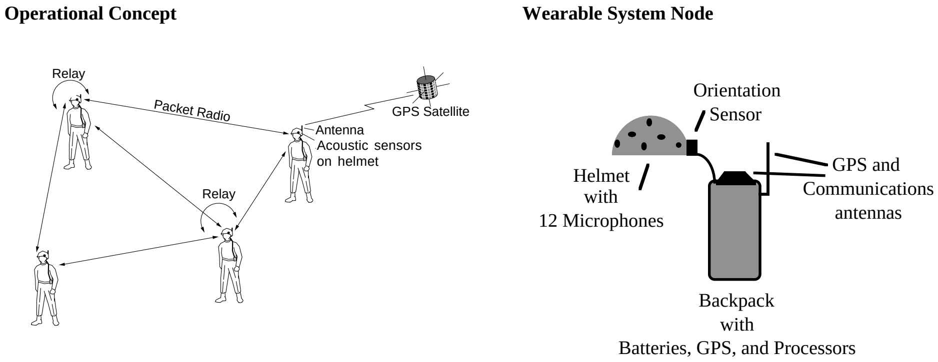


Figure 1. Fixed Acoustic Counter-sniper System Hardware configuration options.

1.2 Wearable counter-sniper system

Following the development and delivery of five fixed systems to the government, BBN developed a helmet-mounted sensor suite and a backpack mounted processing system to demonstrate the feasibility of a wearable acoustic counter-sniper capability. The operating concept includes both data-sharing among the wearable systems which detect the signal from the bullet to achieve an accurate “multi-node” solution, and a “single-helmet” solution for bullet trajectory and sniper location. This later solution is generally poorer quality, and requires the muzzle, as well as the shock wave, but provides a backup in the event of communications loss. The key elements of the wearable acoustic counter-sniper system are shown in Figure 2. They include twelve microphones flush mounted on the helmet, a helmet orientation sensor, a GPS for system location, and a processor and display system. In the limited testing to-date, its accuracy, when supported by the real-time COTS (Commercial, Off-The-Shelf) head orientation and GPS location sensors, is comparable to the fixed system. Testing under moving helmet conditions is still to be completed. The test results to date are summarized in Section 2.3.



Operational Concept

Wearable System Node

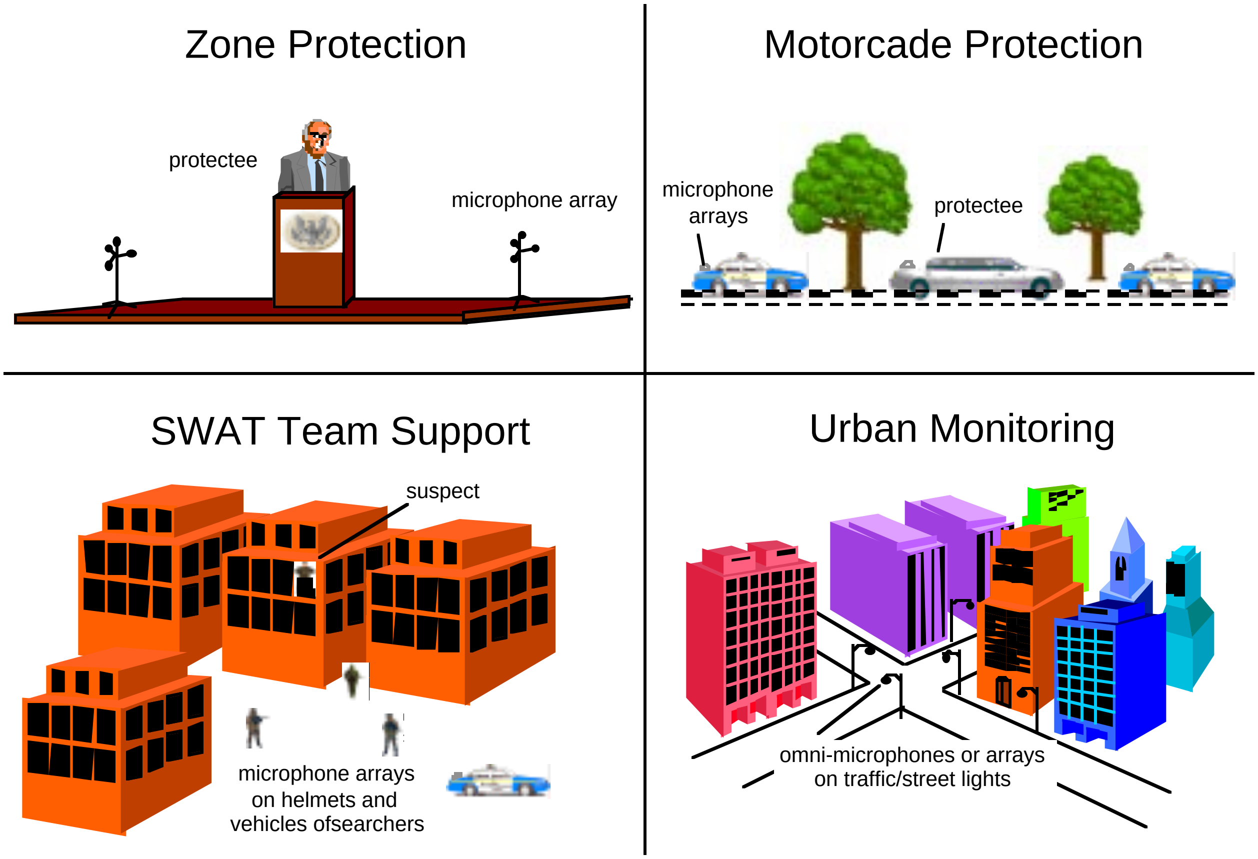
Figure 2. Wearable Acoustic Counter-Sniper System Hardware.

1.3 Application to law enforcement

The technologies developed for the DARPA counter-sniper systems will allow rapid and inexpensive insertion of accurate, reliable, and low-cost counter-sniper capability into the law enforcement community. The technology developed supports many law enforcement missions, including:

1) Zone Protection (e.g. a podium or observation platform)
2) Motorcade Protection
3) SWAT-Team support, including Area Monitoring and Search Teams
4) Short or long-term Urban Monitoring.

These are shown in Figure 3.



Zone Protection

Motorcade Protection

SWAT Team Support

Urban Monitoring

Figure 3. Potential law enforcement applications of counter-sniper technology.

In Zone and Motorcade protection, the ability to instantly pinpoint the bullet trajectory and shooter location allows protecting forces to immediately respond to suppress continued attacks, and to apprehend the shooter(s). The acoustic counter-sniper technology can support SWAT-Teams using rapidly setup fixed systems which will allow monitoring of the endangered area and immediate localization of the shooter and bullet trajectory for counter response. The system can be hastily and safely emplaced because the array orientation and location are provided by onboard real-time sensors, and communications are done by an RF network- no wiring is needed. Systems may be mounted on (armored) vehicles for location in the line of fire while under-fire. The ability of the sensor system to be worn on a helmet allows search teams to have enhanced shooter location capabilities for self protection and increased effectiveness. Finally, temporary or permanent installation in urban trouble spots can be used for faster and more accurate response vectoring, and for forensic data collection. It is expected that these factors will have the long-term effect of reducing the incidence of urban street shootings.

In all these cases the forensic evidence collected is extensive. For example, the bullet trajectory and shooter location can be used to reconstruct the crime scene. The recorded acoustic signatures of the shock wave and muzzle blast can be used to help determine the bullet and weapon type. With the cost of video cameras and digital recording equipment breaking the $100 per installation price point, the acoustic system could be used to cue a high resolution, small field of view, digital camera at the shooter location immediately after the shot. In this information age, collecting of video data is not the cost driver, but rather communication, storage, and efficient access to the relevant portions of that data. The acoustic counter-sniper capability allows an effective means of identification, tagging, and archiving of important segments for later analysis.

The primary features and benefits of the BBN counter-sniper technology relevant to law enforcement applications are shown in Table 1. Particularly unique to the BBN system is the ability to accurately model, and thus combine both shock and muzzle measurements taken over a large area. When coupled with our unique robust estimation algorithms which automatically sense missing or poor quality (noisy, shadowed, refracted, reflected,...) data and eliminate them, the combination allows both low-cost sparse deployments over large coverage areas and high accuracy.

Table 1. Features and Benefits of BBN Counter-Sniper based law enforcement system.

Features	**Benefits**
1. low acoustic bandwidth (< 10 kHz) 2. commodity microphone sensors 3. moderate processing requirements	1. low cost commodity hardware can be used 2. low power consumption for battery operation 3. small size and weight for portability 4. can be made wearable
4. small communications bandwidth required	5. low-power RF-networkable
5. accurate global ballistic/acoustic model 6. shock only / shock+muzzle / muzzle only modes 7. robust processing algorithm	6. high accuracy potential 7. flexible sensor configurations 8. distributable- can avoid single point of failure 9. robust to reverberation and ambient noise 10. supportable by practical sensor orientation and location subsystems 11. graceful degradation with sensor errors and dropouts 12. robust to subsonic projectiles and suppressed muzzle blast
8. uses and records raw waveforms, feature amplitudes, and travel time data	13. bullet type classification 14. data available for forensics

In Section 2 we present the DARPA system concepts, design, implementation, and measured performance. In Section 3 cost and performance issues for urban law enforcement applications are presented, and performance predictions for various system configurations in an urban street monitoring scenario are given. Section 4 summarizes our conclusions and recommended future work.

2. SYSTEM CONCEPT, IMPLEMENTATION AND PERFORMANCE

2.1 System concept summary

The acoustic counter-sniper system concept is summarized in Figure 4. It shows:

- Low-cost distributed acoustic sensors of various types: omni, tetrahedral arrays, and helmet mounted arrays. These sensors may be in motion as long as supporting location and orientation data are provided.
- Wireless network communications among Sensor Nodes and Command Nodes. The two may be combined at one site, such as in a wearable system. The network passes partially processed acoustic data and logistics support data, as well as solutions for the trajectory and sniper location. All of these are fundamentally low data rate.
- Use of the shock and optionally the muzzle blast to estimate the bullet trajectory and sniper location globally, using all available data integrated by an accurate ballistic and acoustic model.

One of the key features of the system concept is that it can still provide performance without the muzzle wave. We do not believe that a system which absolutely relies on detecting a high quality direct path muzzle blast, either alone, or in combination with the shock wave, is operationally sound. Intentional muzzle countermeasures, or blockage by topographic or urban features, is likely. However, the shock wave is generated much closer to the area under protection, and is much less likely to be blocked or distorted.

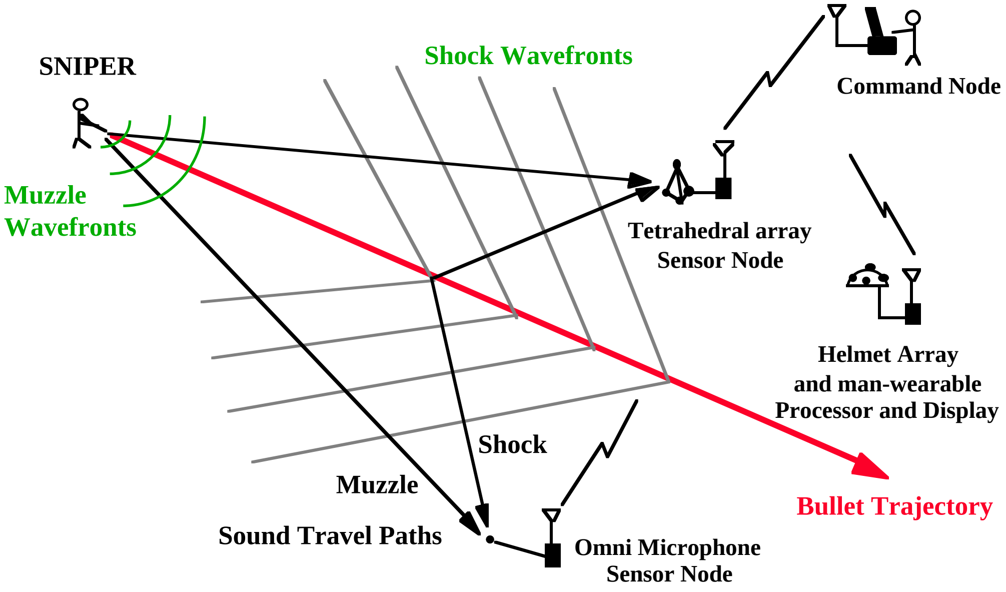


Figure 4. Distributed acoustic counter-sniper system concept.

The BBN counter-sniper system development was guided by three primary goals:

1. Robust and high-accuracy estimation of both bullet trajectory and shooter location.
2. Ease of reconfiguration to handle different threat and system deployment scenarios.
3. Implementation using robust and inexpensive sensors and processing.

Each of these and their system concept implications are discussed in the following subsections.

Goal 1: High-accuracy estimation of bullet trajectory and shooter location

High accuracy is required in a counter-sniper system because the threat must be localized for both self protection and response. Our goal was to obtain window-sized localization at several hundred meters range to the shooter. Because the muzzle blast and flash can be easily countermeasured, observables from the actual flight of the supersonic bullet must be used. A characteristic and unavoidable signature of such bullets is the acoustic shock wave emitted from all points along its trajectory, leading naturally to our choice of an acoustic sensing technique. If the bullet trajectory is estimated, it can then be followed back to the shooter. While observations of the shock alone do not uniquely locate the shooter along this trajectory, prior information on the muzzle speed of the bullet or the intersection of the trajectory with known topographic or man-made features provide relatively unambiguous shooter locations. Additionally, if the acoustic muzzle blast signature is also observed, a very accurate estimate of the shooter location can be obtained using the time of arrival difference between the shock and muzzle waves.

Modeling of the estimation performance of various sensor geometries, from dense compact arrays to widely distributed omni microphones, led us to the conclusion that a distributed sensor concept would provide the highest performance with practical sensor tolerances and costs. In particular, a system with microphones on either side of a trajectory greatly decreases the ambiguity between the Mach cone angle and the trajectory angles. A distributed system naturally provides this type of geometry. This vastly improves accuracy and reduces system tolerance requirements by not requiring wavefront curvature to be observed across a small aperture to resolve the ambiguity. However, because the Mach angle changes as the bullet slows, we have developed an accurate ballistics model which includes bullet deceleration to model and integrate the data over a distributed area for trajectory estimation.

Goal 2: Ease of reconfiguration to handle different threat and system deployment scenarios

A versatile counter-sniper system should be applicable to multiple scenarios, including:

- Area Protection: e.g. determination of the direction of incoming fire on a compound.
- Area Monitoring: e.g. determination of the exact source of fire from a building.
- Zone Protection: e.g. protection of a stage or podium area.
- Convoy protection: e.g. protection of a motorcade or convoy.
- Small unit operations: e.g. rapid determination of source of fire on a small moving group.
- Individual operation: e.g. a single soldier or law enforcement officer or vehicle.

The first two are best served by fixed distributed sensors in or around the area to be protected or monitored. In this type of deployment, either single microphone (omnidirectional) sensors or small arrays may be used. Single microphones are more easily concealed, but require occupation of more points, with increased infrastructural demands for either local power for RF links or for communications and power cables. Alternatively, a lower density of small arrays may be used if their size and visibility are not a limitation. With the wearable system, we have shown that sensors may be located on a solid curved surface, such as a helmet. This indicates that street lamps and other everyday objects can be used to support small unobtrusive arrays. For Zone protection, two arrays flanking the protected area are ideal. These may be permanent or temporary, and their locations can be determined by a survey at time of installation.

Moving convoy protection requires sensors to be mounted on the moving vehicles. This scenario requires that some wind noise abatement be applied to the sensors, but the high acoustic level and broadband characteristics of the bullet shock wave make this and engine noise a minimal problem. As long as two or more vehicles are available, the distributed array concept works well.

Finally, small unit and individual soldier operations require an acoustic sniper system because of the ruggedness, and the potential for low cost, small size, and low power requirements of the acoustic solution. If six or more soldiers operate in close proximity (e.g. within a 200 meter radius) individual omni microphones on their helmets with data shared among them by RF communications, and localized by differential GPS (or equivalent), would provide adequate performance. Helmet omni sensors are also attractive in that they do not require orientation sensors to determine the array's attitude. However, this operational scenario (six helmets with a clear view of the shock wave) seems overly restrictive. Alternatively, the helmet can be used as a platform for a flush mounted multi-microphone array. Our current wearable system has shown that this is adequate for both accurate distributed localization using shared data from two or more such helmets (supported by GPS and head orientation sensors), and for a lower quality single-helmet solution using shock and muzzle observations. This single-helmet solution is still adequate for indicating a small angular sector and range to the shooter, and provides a backup single-soldier capability if communications are lost.

Goal 3: Implementation using robust and inexpensive sensors and processing

Although the shock wave of a supersonic bullet is quite wide bandwidth near its origin on the trajectory, it gradually loses high frequency content due to acoustic propagation losses. Shock-only acoustic counter-sniper systems using solitary compact arrays must effectively use this high-frequency information to obtain the extremely accurate inter-sensor time delays needed over a small aperture for simultaneous estimation of trajectory and bullet speed. Not only does this potentially reduce the effective area of coverage per microphone of the systems, but this high precision also requires extremely accurately placed and calibrated microphones and broadband data acquisition channels. The high data rates from these can impose powerful processing requirements. All of these requirements serve to increase the cost of small-baseline shock-only acoustic systems.

For a spatially distributed system, the timing and sensor localization requirements for each microphone are dramatically reduced because of the long acoustic baselines and the better numerical conditioning of the inversion problem using observations on each side of a trajectory. Thus, the bandwidth, calibration, and signal to noise ratio requirements of each microphone are much reduced, and the area covered by each microphone is increased. This leads to fewer and cheaper sensors, electronics, and lower data rate signal processing. Low bandwidth also has the advantage of reduced power consumption at all levels. We have found that adequate muzzle and shock arrival time estimates are obtainable with less than 8 kHz bandwidth (20 kHz sampling). This bandwidth is also adequate to support accurate bullet caliber classification using the details of the shock's N-wave. This classification is used for estimation of the bullet ballistic coefficient, which is used in the detailed trajectory modeling supporting the distributed sensor concept. Finally, the use of low-frequency microphones for the shock wave also allows them to be used for the muzzle blast and in distributed mortar and artillery location systems as well. This maintains hardware simplicity, while adding additional capability.

In addition to the cost, power, and area coverage/microphone advantage of a distributed system, it is also fundamentally more robust than solitary array solutions. Additional sensors may be added to improve performance or coverage seamlessly, and some may fail without degrading the solutions significantly. Since inter-sensor data rates are small, and the signal processing burden is light, computation may easily be distributed to multiple sites, even to the individual user level, further enhancing the system's robustness and usefulness. Finally, the distributed array concept allows mechanically simple arrays, and low-precision sensor orientations and locations which can be obtained using inexpensive tape measures and construction levels. Automatic sensor survey using GPS and electronic orientation sensors, while adding to convenience, is not required if system cost reduction is paramount.

2.2. System architecture and implementation

Guided by the system concepts discussed above, a proof-of-principle (POP) fixed-array system was constructed for live-fire testing directed by the government. The POP system is small enough to be mobile and portable, but the sensors are fixed in location and orientation when in use. It was hardened and documented enough to allow five systems to be delivered to the government for further testing by operational personnel with minimal system training. This delivery was less than one year after the beginning of our initial POP development contract.

Following development of the fixed array system, we began development of a sensor and processing concept which could ultimately be “wearable.” The key technical issues for the wearable system were:

1) Development of an acoustic array small enough to be body-worn.
2) Integration of real-time array location and orientation sensors.
3) Development of robust algorithms for fusion of data from multiple wearable systems. By their nature the data quality can be poor (head in the mud or otherwise acoustically shadowed, or intermittent due to unreliable RF communications).
4) Development of a “degraded” operational mode using only the data from one wearable system. This gives some capability in the event of poor acoustical or communications conditions.

These issues were resolved in the early part of the program, and a “luggable,” if not “wearable,” proof-of-principle system was developed for testing. Initial testing to date, just before delivery of the six node system to the government, has shown that the system can deliver accuracies similar to the hand-surveyed fixed system with static sensors supported by the real-time GPS localization and magnetometer/level-based orientation sensors. The system has not yet been tested in motion.

2.2.1 Fixed System Hardware Architecture and Implementation

The POP fixed system was developed primarily with commercial off-the-shelf (COTS) components and was designed with reconfigurability, incremental development, and ease of use in mind. Two versions were developed, an “RF” and a “hardwired”. Pictured in Figure 5a, the RF system consists of Data Nodes which acquire time synchronized waveform data on up to 4 channels at 20 kHz each after detecting a shock wave, and a Command Node which receives the digitized data from two Data Nodes over a COTS FCC Pt. 15 wireless network using the Proxim RangeLAN II, which operates at 2.4 GHz. The Command Node archives and processes the data from both nodes, and displays the trajectory, caliber, and sniper location results. Figure 5b shows the hardwired configuration which eliminates the data nodes by installing an A/D board and additional data-node software in the command computer. Further details on this system, including hardware, software, and algorithms, are given in references [1] and [2].

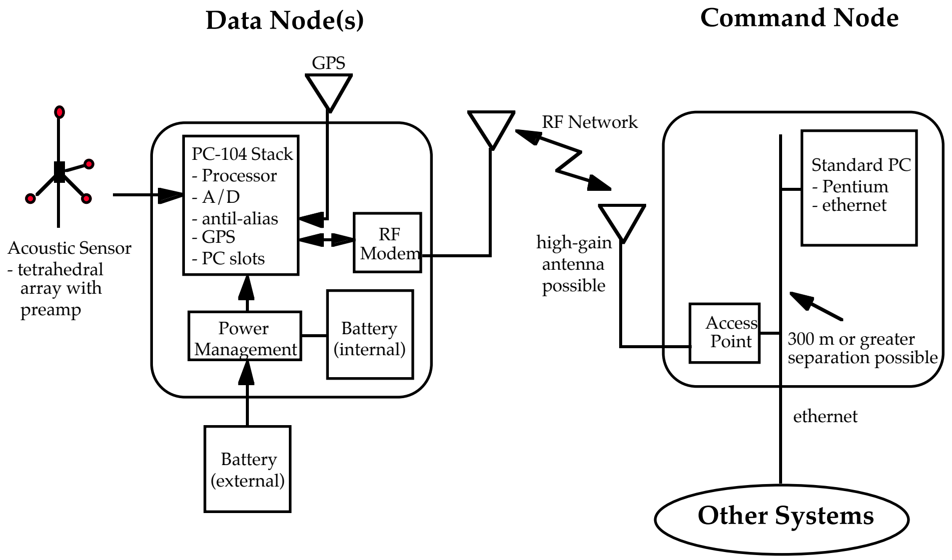


Figure 5a. <u>RF</u> Fixed Counter-sniper System hardware configuration.

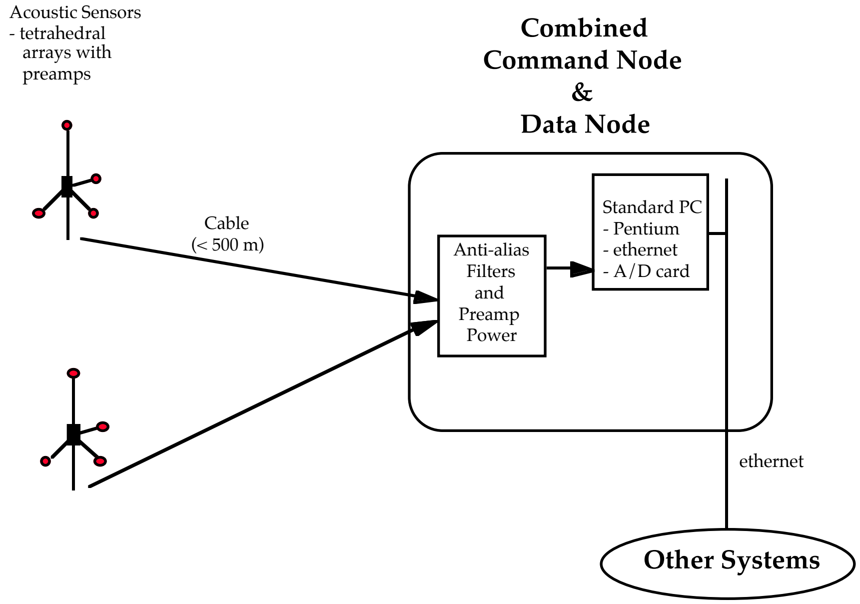


Figure 5b. <u>Hardwired</u> Fixed Counter-sniper System hardware configuration.

The Command Node software can be run on any capable PC running Windows 3.1 or Windows 95. We use a convenient lunchbox-style Pentium 160 MHz unit with PCI bus and color display, although a Laptop unit has been used successfully, and has the advantage of making the entire system battery powered.

The Hardwired Command Node shown in Figure 5b eliminated the RF modem, and required a PCI bus to support the 12 bit, 200 kHz aggregate A/D board used to implement the virtual data nodes in software. The anti-alias filter used switched capacitor filters to provide rolloff at 8 kHz. The sampling rate was 20 kHz.

For our Fixed System POP tests, we fielded two types of sensors in various configurations; distributed fields of 6 to 12 omni microphone sensors over 100 m aperture, and distributed fields of 2 or 3 four-element tetrahedral arrays with 1.5 meter intermicrophone spacing and 20-100 meter inter-tetrahedron spacing. Our six Data Nodes were capable of acquiring and transmitting data from all of these sensors simultaneously. The Command Node archived all raw waveform data and was variously configured to process all simultaneously, or just process subsets to determine the performance as a function of array configuration.

The tetrahedral arrays were of unique construction. A central weatherproof 0.05 cubic foot anodized aluminum hub housed the preamplifier and mounted to a tripod. The arms of the tetrahedron were mounted to the hub via rigid weatherproof connectors so the system could be easily broken down and shipped. They were constructed of thin aluminum tubing which also serves as an electrostatic shield, and had the microphones mounted at the ends. The small size and cross-section of the black and green hubs and arms also rendered them nearly invisible against both urban and natural backgrounds. They can be easily broken down and assembled without tools and are easily transportable. An integral level and site in the hub allows setup to the required accuracy without additional tools or instruments other than a tape measure. Intra-array tolerances on the element locations of approximately 1 inch are easily achievable mechanically and are verifiable with a tape measure in the field. Inter-array accuracies of 1% of the separation distance between the arrays gives approximately 1 degree trajectory estimate error. A cable of up to 0.5 km (typically 50 m) connected to the Data Node or Command Node carried signal and power. Although the arms of the currently tested system are approximately 1 m in length, reduction to a modest 1 foot size is possible, and will yield equivalent performance if the microphone location tolerance is maintained proportional to the array size (i.e. 1/3 inch instead of 1 inch).

2.2.2 Wearable system hardware architecture and implementation

Like the fixed system, the POP wearable system was developed using primarily COTS components. Shown in Figure 6, each of the six units delivered to the government consisted of a helmet-mounted, 12-microphone array, supported by an electronic compass and electrolyte level orientation sensor, and a processing system and GPS mounted in a backpack. The processing system consisted of a small, low power, Digital Signal Processing single board computer for data acquisition and detection processing, and a Pentium laptop for localization processing and display. Location of the system was supported by a differential GPS system. Communications among all systems, and a remote display node, use the same RF network hardware used in the fixed system.

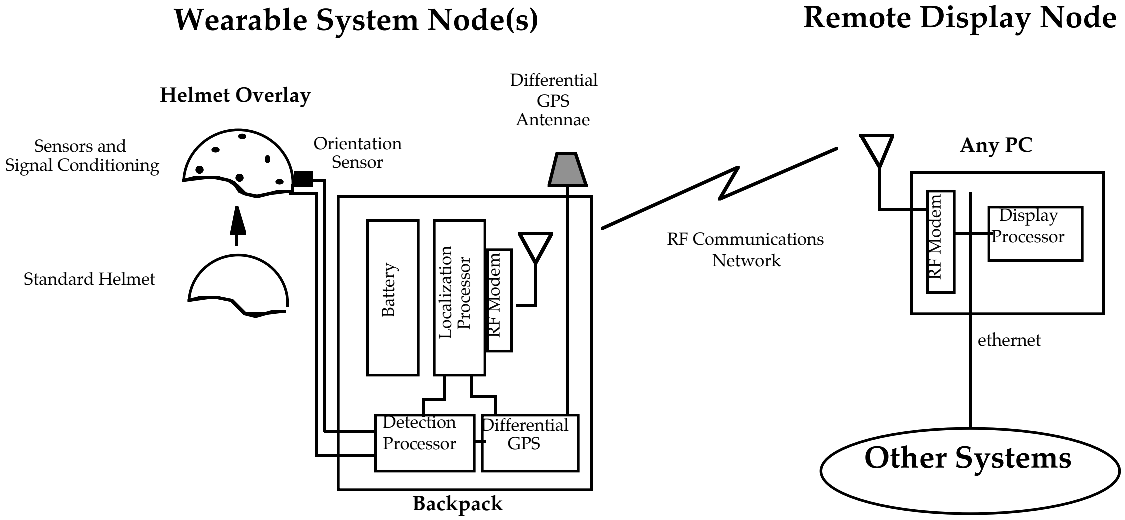


Figure 6. Wearable Counter-sniper System hardware configuration.

We arrived at the helmet as the most logical location for the microphone sensors for the following reasons:

- It is the most likely region of the body to be exposed to the sound from the shock and muzzle blast.
- It provides a reasonably sized and geometrically stable aperture to support the sensors.
- Its rigid structure and location away from most magnetic materials made it easier to measure orientation using three-axis magnetometers.

We felt that protrusions from the helmet would not be acceptable in a combat environment and would be subject to damage, so we considered only flush-mounted microphones. It was also felt that the integrity of the helmet was important, so we wanted to make no modifications to the structure of the helmet itself. For these reasons, we developed a lightweight but durable PVC plastic overlay which fit all size standard issue helmets. The 12 small microphone elements were attached to a flexible circuit board, along with the signal conditioning electronics (anti-alias filters and cable drivers) which glued conformally to the inner surface of the overlay, exposing the active microphone faces through holes in the overlay. The waterproof electret microphones were supplied by Gentex, and were a desensitized version of one of their standard parts costing approximately $5 each. The desensitization allowed linear transduction at up to 160 dB re 20μPa.

A small bulge (approximately 2 cm clearance to helmet) on the back of the overlay was included which contained adequate room to house a customized three-axis magnetometer and level sensor for helmet orientation. For the POP system described here, a COTS version of this sensor from Precision Navigation was mounted in a small waterproof box external to this bulge. A rugged multi-conductor cable carried the analog microphone signals and the RS-232 signals from the orientation sensor to the processing system in the backpack. The helmet overlay and all sensors and electronics weigh approximately 7 ounces in this POP prototype. Weight reduction is possible using thinner materials and housing the orientation sensor in the overlay itself.

Further details of the wearable system hardware, software, and processing algorithms are available in reference [2]. Note that the very small arrays (10 cm aperture) used for the wearable system show that small tetrahedral apertures can be used for the fixed systems. It also shows that covert mounting of arrays on solid objects in an urban environment is possible.

We focused most of our custom prototype efforts on the helmet sensor subsystem, which was the highest risk element that the POP wearable system needed to demonstrate. The next greatest risk was the development of reliable algorithms for processing the acoustic data from a helmet. Because the final algorithms and the number of channels required per individual wearable system were not defined until these higher-risk elements were resolved, it was determined that the cost and schedule risk of developing a custom low power, low cost, small size, and low weight GPS, processing, and display system was too high for this phase. Instead, COTS components were customized and integrated for the POP wearable system. In addition, it was expected that the core counter-sniper specific sensors and processing would eventually be combined with state-of-the-art orientation, GPS or other location technology, warfighter oriented display, wearable computation, and battlefield communications subsystems, either existing within the military, or under current development by other DARPA programs. Figure 7 shows the likely location of each component of an operational wearable counter-sniper system. The POP counterparts are in Figure 6.

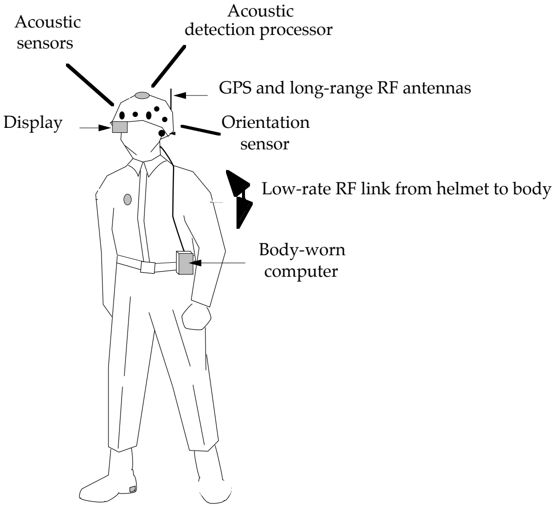


Figure 7. Potential hardware configuration of an operational wearable counter-sniper system.

The acoustic sensors, which may be shared with other acoustic detection/localization tasks, are still mounted on the helmet. The detection and initial data reduction processor is also located on the helmet to convert the large bandwidth, continuous sensor data to a small number of discrete detections and their parameters. This processor is dedicated to this task because it is continuously looking for shots in the 500 Kbytes/sec data stream. The counter-sniper system needs only 1 kbyte of data from each helmet for each detected shot, reduced from 500 kbytes of raw acoustical data for a typical 1 second shot snippet containing shock and muzzle arrivals. This includes sensor orientation, and GPS location, and amplitude and absolute and relative arrival times on each microphone for the shock and muzzle waves. This vastly reduces the bandwidth of communications off the helmet, and allows a micropower RF link to be used. These reduced data are sent to the body-worn computer shared by multiple tasks from other systems. For counter-sniper it makes sense to share this computer since it only needs computational resources when a shot is detected, and the own-helmet data is combined with that from others coming in over the RF network to form the sniper location and bullet trajectory and classification solution. This computer also forwards its own-helmet data to other wearable (and fixed) systems for their use, and drives the display to communicate the solution to the user.

Referring to Figure 6, the POP hardware placeholder for the helmet-mounted detection processor is an Innovative Integration SBC-31, TMS320C31 based single board computer with 16-channel A/D capability at 18,500 Hz/channel. It is a small 3U card which consumes less than 3 Watts at 5 and ±12 volts. It also has one serial port for communicating with the orientation sensor, and one for communicating with the laptop. One analog channel is also used for GPS time synchronization.

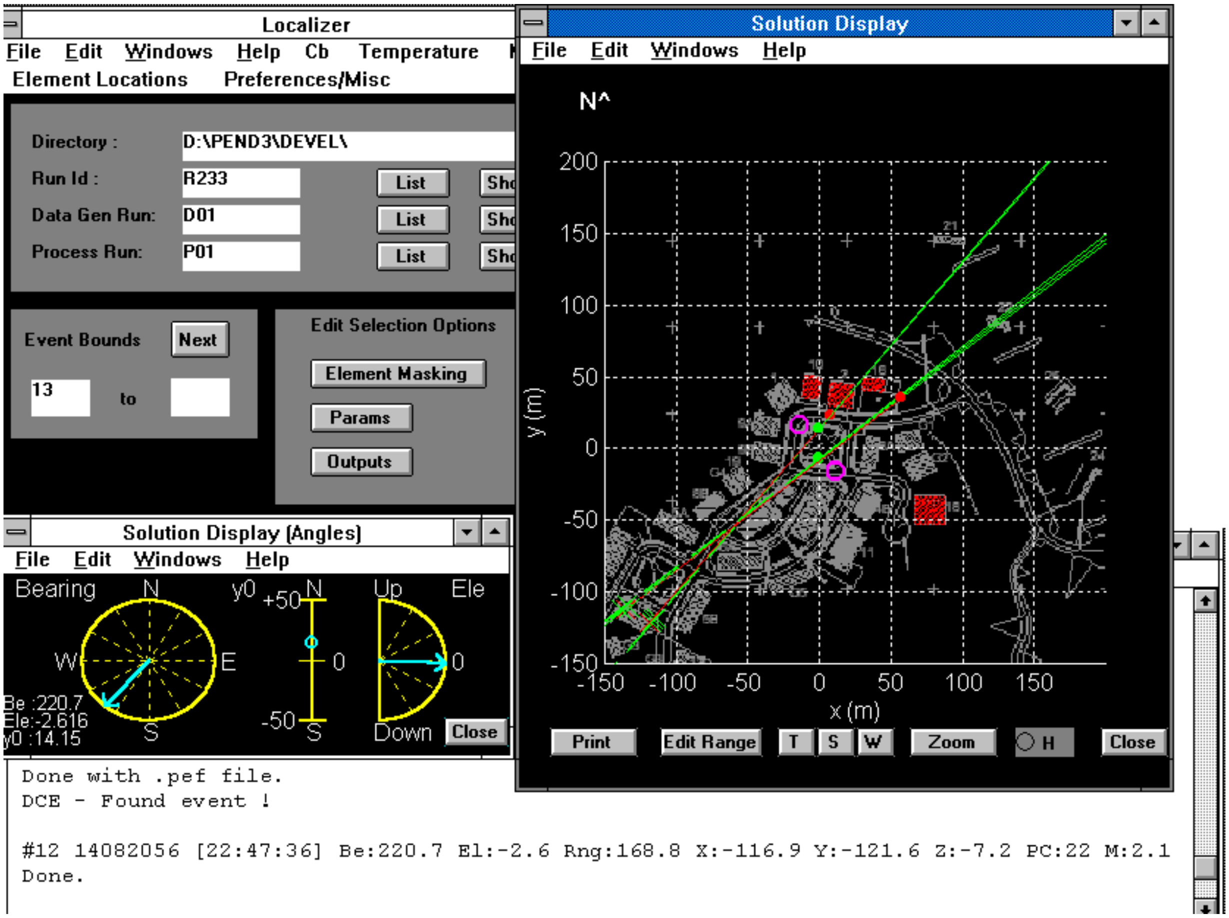
The POP implementation of the shared body-worn computer and long-range RF communications is a moderate to high-end Pentium laptop with two serial ports and an RF network PCMCIA card. One serial port communicates with the detection processor, the other with the differential GPS. The GPS was a Trimble DSM-Pro unit with integrated real-time differential capabilities using the U.S. Coast Guard differential correction broadcasts. Power was provided by one or two flat-panel Zinc-Air batteries, or by external lead-acid batteries. Total power consumption was approximately 25 Watts. Neither the GPS nor the laptop are particularly efficient for this task. Although this POP system was a COTS lash-up, it was environmentally robust, and the hardware performed flawlessly inside the backpack in direct sun at 95°F for the day-long tests. Because the POP systems were to be used in the line of fire, and would not be manned, no display other than the laptop screen was integrated with the system. However, a remote display (e.g. the helmet-mounted Private Eye) could be easily integrated using the VGA port on the laptop. For testing, any PC communicating using the RF network can be used to run the remote display software.

2.2.3 System setup and user interface

The user interface provides both text and graphical output displays of intermediate data products, including raw snippet data, and bullet trajectories and shooter locations overlaid and justified to digital maps and grid coordinates. This display also provides different perspectives to view elevations as well as plan views. A helpful feature in the GUI (Graphical User Interface) used for configuring the system and setting system parameters is an intelligent "guide" that highlights the next logical dialog box, button, or entry to be modified or verified. This guides the user through system setup, reducing setup time and decreasing operator errors. Another useful feature is an RF link status panel which alerts the operator to malfunctioning communication links. This is tested every 30 seconds by exercising the network. Because the raw data are all archived, they may be reprocessed by the system in a playback mode to test algorithm and parameter changes. This feature was essential for the POP systems, which are used for continuous algorithm development and improvement.

Figure 8 shows an example system display from the POP fixed counter-sniper system. This was taken from the competitive government-run tests described in reference 2. Running on a standard Windows 95 computer, this display shows a setup window for the localizer in the upper left corner. This window is used to set up and change processing parameters and archive locations. Once in operation, this screen is not used. For an operational system, this setup process could be totally automated. An instantaneous solution display is on the left, showing a compass with bearing to shooter indicated, a N-S bar showing how many meters away from the reference point ((0, 0, 0), in this case) the bullet passed, and an up/down indicator showing the elevation of the shooter on the bearing line. This display also contains a numerical readout of the Bearing, Elevation, and Miss Distance.

At the bottom of the screen is a simple text readout showing the time of shot, bearing, elevation, range to shooter, grid coordinates (X, Y, Z) of shooter, caliber of bullet (labeled “PC”), and Mach number (M) of bullet as it passed through the X=0 reference grid plane. Finally, the most intuitive display is on the right—a map plan view, with topographical/urban features as a background, and the bullet trajectory (lines) overlaid on it. Hard to see in this black and white rendering are "X" annotations showing the location of the estimated shooter location on the trajectory . In this case, a history of trajectories from two shooter locations is shown, showing the shot to shot scatter, which was about a meter at the shooter location. The map is of the Camp Pendleton MOUT (Military Operations, Urban Terrain) facility where the data shown were collected. The control buttons on the bottom of the map screen allow changing the view from (X, Y) “top” (T) view shown to “side” (S) view in (X, Z) coordinates, or “wall” (W) view in (Y, Z) coordinates. All views may be zoomed using a rubberband box, and the default display range can be set. The “Hold” button (H) keeps the screen from refreshing on each shot so that a history of shots can be viewed. Although a simple local grid in N-E meters is shown here (established by the government for these tests), for operational use the setup screen allows the display to use military grid coordinates.



Directory : D:\PEND3\DEVEL\
Run Id : R233
Data Gen Run: D01
Process Run: P01
Event Bounds 13 to

```
Be :220.7
Ele:-2.616
y0 :14.15
```

```
Done with .pef file.
DCE - Found event !

#12 14082056 [22:47:36] Be:220.7 El:-2.6 Rng:168.8 X:-116.9 Y:-121.6 Z:-7.2 PC:22 M:2.1
Done.
```

Figure 8. Example User Interface display for the Fixed Counter-sniper System. The Wearable System display is similar.

2.3. System demonstration and performance

The fixed-array version of the acoustic counter-sniper system was demonstrated in three government sponsored and directed tests at Camp Pendleton [3] in the spring of 1996. These included both distributed omni and tetrahedral array deployments in an open firing range area and a simulated urban environment called the Mobile Operations, Urban Terrain (MOUT) facility. Several hundred shots were fired during these tests from several shooter positions to several target locations. Different types of rifles with various muzzle speeds were used, and included 22, 30, and 50 caliber rounds. The trajectories were designed to exercise different potential performance problems. Although our system was designed for, and achieves, its best performance with a large distributed array of sensors, most testing was done on a two-tetrahedral array configuration with a 40 m separation. This configuration used only 8 microphones and two RF data nodes. This configuration was chosen because it was consistent with the sensor configurations of other systems being tested at the same time. For the Fixed System, we report only the results of that final test here. Comparisons with the other systems tested at that time are documented in reference [3].

For the wearable version of the system, only integration-level testing with non-moving systems has been conducted to date. When compared to the fixed system, in addition to integration of the real-time array support sensors (orientation and GPS location), numerous algorithmic improvements were made to support the smaller intra-array baseline and more difficult acoustics of the helmet platform. The results compare favorably with the Fixed System.

2.3.1 Fixed Acoustic Counter-Sniper System performance

The two-tetrahedral system was set up in the town-square area of the MOUT facility. The arrays were deployed 1.5 meters above the sidewalk pavement, and within 10 to 20 meters of substantial 2 to 5 story concrete block buildings. Other acoustic obstructions and scatterers, such as burned out vehicles were also near the arrays. The array location points on the sidewalk were provided by the government from a commercial GPS survey. We set up the tetrahedra and leveled them using their built-in bubble levels to approximately 0.2 degrees resolution. The arrays were oriented using their built-in sites to aim a particular arm on each at the other array. This procedure is documented in a complete user's manual, which walks the user through setup and entry of the setup data into the appropriate tables in the GUI. The entire setup procedure takes about 30 minutes. It should also be noted that if justification to a map grid is not needed, all surveying of the relative array locations could have been done with a tape measure (on level ground). A transit level, or a simple digital level with diode laser (available at hardware stores) can be used if there is significant topography. From these data, one can define their own local coordinate system.

The data were transmitted from the Data Nodes in the town square to the Command Node antenna on a building approximately 100 m away. Direct line of site to one of the nodes was obscured by a group of buildings with concrete block walls and steel-reinforced concrete floors, but the RF link still functioned well.

The data taken during the last test using only two tetrahedral arrays were processed using the software delivered to the government with the five systems to be tested. The results from this processing on the 167 shots from day two of the test are shown in column 1 of Table 2.

Table 2. Performance Comparison of the Fixed and Wearable Systems.

	Fixed System	**Helmet System, multi-node processing**	**Helmet System, single-node processing**
Total number of Shots	167	20	90
% shots detected	90%	100%	92%
Azimuth Performance < 1 degree	72%	N/A	N/A
< 5 degrees	93%	90%	33%
< 20 degrees	96%	100%	73%
Elevation Performance < 1 degree	38%	N/A	N/A
< 5 degrees	91%	100%	33%
< 20 degrees	N/A	100%	78%
Range Performance < 1%	28%	N/A	N/A
< 5%	60%	50%	13%
< 20%	70%	100%	38%
Caliber % correct	90%	100%	83%

Grouped together, these statistics correspond to 1.2 degrees rms for the azimuth and 3.0 degrees rms for the elevation errors. This performance was obtained with the weakest sensor configuration (poorest geometrical layout) that the current POP system can handle, two tetrahedra spaced a distance apart. An additional tetrahedron, or even one or more omni sensors would significantly increase the performance of the system. We also believe that a large component of these errors was due to sensor orientation and position errors, with a smaller contribution from unmodeled propagation phenomena, such as wind and temperature variation.

2.3.2 Wearable Acoustic Counter-Sniper System performance

In December, 1997, an integration test of the POP Wearable Acoustic Counter-sniper System was conducted on Range 216 at Camp Pendleton, CA. The six-node system was tested in a non-moving open-field scenario. The operation included static testing and initial integration of the BBN-supplied counter-sniper system nodes with government supplied motion systems. The six nodes were deployed 200 m from the shooter location, and were spread over an area approximately 100 m by 100 m. The topography was varied, with node height varying approximately 20 meters from nodes on a hillside, to nodes near a dry stream bed in the rugged terrain.

A very limited number of shots were fired at this test because of extremely heavy rainfall which made it impossible to shoot. In addition, there was concern about the untested waterproofing of the backpack mounted processing system in this proof-of-principal configuration. Following breakdown of the test setup in the rain, the six-node system was immediately delivered to the government for continued testing. Further test results have not yet been reported. Most of the shots reported here were intended to be used as diagnostic/setup test shots. As a result, all of the real-time parameters, such as magnetic declination offsets and *in situ* head orientation sensor calibrations, were not yet installed in the system and set to produce accurate real-time solutions. Because of this, the results described herein were produced using partial post-processing with these parameters set as well as could be reconstructed. No special processing unavailable in the real-time system has been applied.

Multi-helmet performance

Detection performance of the system is improved over the fixed system to 100% of the available shots, although the statistical base of 20 shots is small, and only two different shot trajectories were used. Table 2 shows that the multi-helmet processing located 90% of the shooters to within five degrees in azimuth, and all were within 20 degrees. Ground truth accuracy was not sufficient to allow determination of whether the shots were within 1 degree. The estimates of the elevation were within five degrees for all the shots. All of the bullet calibers were correctly determined. 50% of the range estimates were within 5% of the actual range. All were within 20% of the actual range. Poor muzzle detection performance is the main cause of these larger errors in the range estimates. It is our belief that we will be able to improve on these results with minor modifications to the algorithms or parameter values used in the existing algorithms. However, the results indicated that even in an open environment, quality detection of muzzle arrival time is much more difficult than for the shock wave. This point should be borne in mind when evaluating the performance predictions in Section 3. For all shots the caliber was estimated correctly.

Single Helmet performance

Table 2 shows the performance results achieved in this test. Ninety single helmet detection opportunities were available since not all six nodes were deployed in the field for all 20 shots. Of these, 92% of single helmet detection opportunities were successful. As expected, the single helmet performance is degraded as compared to the multi-helmet results. At best, one helmet produced estimates with azimuth errors of less than five degrees on 44% of its detected shots. Unlike the multi-helmet solution, which is very forgiving of the muzzle data, accurate detection times for both shock and muzzle are required for the single-helmet solution to be reliable. Since the shock detection algorithm always performed well, any improvement to the muzzle detection performance will lead to much better single helmet solutions. Further analysis is required in the area of muzzle detection to improve the parameters and suggest refined processing algorithms. In the short test time, we did not have an opportunity to adjust detection thresholds and classification parameters for the multipath environment of Range 216, which was different from the BBN test range for which the system was tuned. We expect a universal parameter set to be applicable eventually, but much more data collection to fully characterize the shock multipath characteristics, which are a noise source during muzzle processing, is needed to arrive at that result. The reprocessing discussed above to include the orientation calibrations did not include the initial “detection processing” stage- the field-produced real-time results were used, and only the “Localization Processing” which uses the orientation and location of the nodes was re-run.

Another factor in the variability of the single helmet results is the relative proximity of the helmet to the bullet trajectory. The theoretical accuracy has a strong geometric dependence on the angle between the muzzle and shock arrivals, and the effect of this on these specific results needs to be analyzed further. Additionally, we did not have an opportunity to review the final orientations and calibrations of some of the head orientation sensors. It is possible that orientation system calibration errors occurred due to the simultaneous integration work with the government provided motion systems. The calibrations were done just before the heavy rain, and subsequent rapid equipment backhaul, and could not be checked. The multi-helmet solution is extremely robust to helmet orientation errors, so could perform well with the 5 to 20 degree helmet pointing errors this might have caused. The single-helmet solution is not robust to this type of error.

We base these single helmet conclusions on our experience in testing at the BBN firing range. In those tests, the single helmet solutions were generally better than achieved here. Helmet orientation errors were sometimes purposely induced in those tests. The multi-helmet solutions were virtually unaffected by 90 degree errors, while single helmet solutions were off by the head orientation error. The multi-helmet solution achieves its robustness because the large-baseline inter-helmet data are "trusted" by the algorithm more than the small-baseline intra-helmet data. The large baseline data derive their angular accuracy primarily from the GPS locations of the distributed nodes, not the head orientation of the individual nodes.

GPS node localization and Helmet Orientation Sensor performance

The GPS (Global Positioning System) data collected during the experiment produced stable helmet locations. Only sub-meter jumps in relative helmet locations occurred between shots. The helmet orientation sensors produced stable and repeatable data to within a quarter to half degree (precision). However, the true angular accuracy in the map coordinate system is dependent on local magnetic disturbances and limitations in the setup procedure, which were rushed as noted above. Since no shots occurred while the helmets were moving, the impact of motion on both the GPS and orientation measurement devices was not explored during this experiment. These tests are now being conducted by the government with the delivered systems.

It is expected that the impact of this motion on the GPS will be minimal, but some tuning of the tracking filters may be required. These filters are used to remove outlier data from the GPS positions, and must be tuned to distinguish GPS outlier errors from true motion. The tuning is platform dependent (i.e. tuning for stationary use is different from carried, which is different from vehicle mounted). The performance of the orientation sensor does need to be verified by future tests. Since the current orientation sensor uses a fluid level measurement, and does not include a gyro, it does not handle head accelerations perfectly. In steady (non-accelerating) motion, they are expected to work well, and because the multi-helmet solution is so robust to helmet orientation errors, it should be adequately supported by this technology. However, acceleration may be problematic to the single helmet solutions, and a gyro-based orientation system may be required.

3. LAW ENFORCEMENT ISSUES AND PERFORMANCE

3.1 System issues for law enforcement

Most of the system concepts, goals, and issues addressed in Section 2.1 for the military oriented systems are equally applicable to the law enforcement applications summarized in Section 1.3 and illustrated in Figure 3. The critical areas which warrant further attention and enhancement to tailor the DARPA systems for law enforcement are:

- enhanced muzzle-blast capabilities
- robustness testing
- deployment aids.

The first involves inclusion of a “muzzle-only” localization mode which can be applicable to very short range, and potentially subsonic shots, and enhancement of muzzle detection and discrimination from environmental noise and shock reverberation.

The second area, robustness testing, is important because many law enforcement scenarios involve highly complex and reverberant environments. The robust inversion techniques used in the BBN systems which automatically discriminate direct path from scattered (multipath) arrivals are important. The performance of these algorithms in realistic urban environments needs much more extensive evaluation, both through models, and short and long term live-fire testing in real environments.

Finally, the most cost-effective microphone sensor deployment strategy needs to be determined. Since the indoor / outdoor / urban / suburban / rural environments are highly variable, an easy-to-use tool is needed to:

- Evaluate the shooter location performance of notional sensor layouts in the context of the reverberation and shadowing environment
- Suggest optimal sensor layouts given the urban layout and topography, desired zone to be protected, and likely threat locations and characteristics (e.g., caliber, muzzle speed, muzzle countermeasures, …).

Some examples of the former type of performance evaluation are shown in the next section.

The critical issues in the design of an urban monitoring system are cost, performance (localization error and false alarm susceptibility for a given probability of detection), and robustness of performance to environmental, weapon/round type, and shot trajectory variability. The primary components of system life cycle cost, in decreasing order of importance, are:

- Installation cost
- Communications cost
- Maintenance cost
- Equipment cost.

The primary factors in performance, robustness and flexibility of the systems are, in decreasing order of importance:

- Microphone count and distribution
- Use of shock and/or muzzle or muzzle alone
- Sophistication of the signal and information processing used in the system.

Thus the major tradeoff in design of an urban monitoring system is between the combined installation / communication / maintenance (ICM) cost and performance, since microphone count and spatial distribution will dominate these costs. A critical question is whether a small increase in (fixed) equipment cost (which is a minor term in life cycle cost) will allow systems with significantly lower (predominantly recurring) ICM cost while maintaining an adequate level of performance under all conditions. This higher equipment cost will support the latter two factors- use of shock and muzzle, and more sophisticated processing.

3.2 Urban Monitoring performance predictions

This section documents the predicted performance of some notional sensor configurations deployed in an urban area. It will show the performance achievable for systems which use muzzle blast alone, and for those, like BBN's, that also use the shock wave when available. To highlight these issues, we consider two microphone sensor deployment scenarios, each of which covers an intersection and half of each of the four blocks leading into it. Scenario 1 uses 12 microphones in three compact (0.5 m) tetrahedral arrays six meters above the street on traffic lights in the intersection. Scenario 2 has four omnidirectional microphones in the intersection, and two a third of the way down each block, also at six meters height on street lamps. These notional scenarios are illustrated in Figure 9.

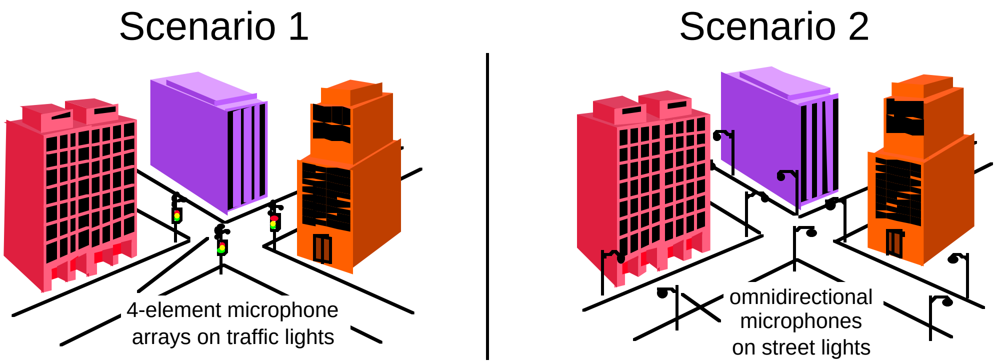


Figure 9. Two Urban Monitoring sensor deployment scenarios.

We feel that Scenario 1 may have significant ICM cost advantages over Scenario 2 because of:

- Fewer installation sites (one quarter of Scenario 2)
- Readily available space, power, and communications (e.g. traffic light controller with network drop or telephone line)
- Ability to wire all 12 microphones into one processor (e.g., short-range transmission using modulation over traffic light power/control cable)
- Reduced long-haul communications cost (one low bandwidth link for all 12 microphones)
- No battery maintenance required.

In evaluating the performance and robustness the primary unknowns are the quality and characteristics of the shock and muzzle data available in a dense, populated, urban environment. For this reason, we consider three data quality cases for Scenario 1 (three compact arrays) and two of these cases for Scenario 2 (distributed omni). These data quality cases are summarized in Table 3.

In general, Case A has good quality shock and muzzle data of accuracy similar to that achieved with the helmet system in an open-field environment. Case B is more typical of data received in our MOUT testing of the fixed tetrahedral array system. The muzzle was weak and spread because of shadowing and multipath for shots originating from distant buildings. Case C is our estimate of the effects of high shock-wave reverberation making the directionality of the muzzle wave difficult to estimate. Note that the quality of the shock arrival is generally high. This has been our experience throughout the DARPA

Counter-sniper Program because the shock is always the first to arrive, has consistently high amplitude, and only the first 0.3 msec of the wave are needed; thus it is always free of multipath. We have found that muzzle data are always weaker and much more variable. We believe that a muzzle-only mode has a role to play for shots that are subsonic or offer a poor shock-wave geometry, but should not be the only observable if shock is available.

Table 3. Data quality case descriptions.

	Case A	**Case B**	**Case C**
	• Inter-array accuracy dominated by array placement to 1 ft error; • Intra-array accuracy controlled by signal bandwidth	• Shock accuracy as in Case A; • Muzzle accuracy severely degraded by decreased bandwidth and noise	• Shock accuracy as in Case A; • Muzzle directional accuracy severely degraded by reverberation
Shock timing accuracy between arrays (inter-array)	1 msec	1 msec	1 msec
Shock timing accuracy within compact arrays (intra-array)	20 µsec	20 µsec	20 µsec
Muzzle timing accuracy between arrays (inter-array)	1 msec	3 msec	1 msec
Muzzle timing accuracy within compact arrays (intra-array)	50 µsec	100 µsec	1000 µsec

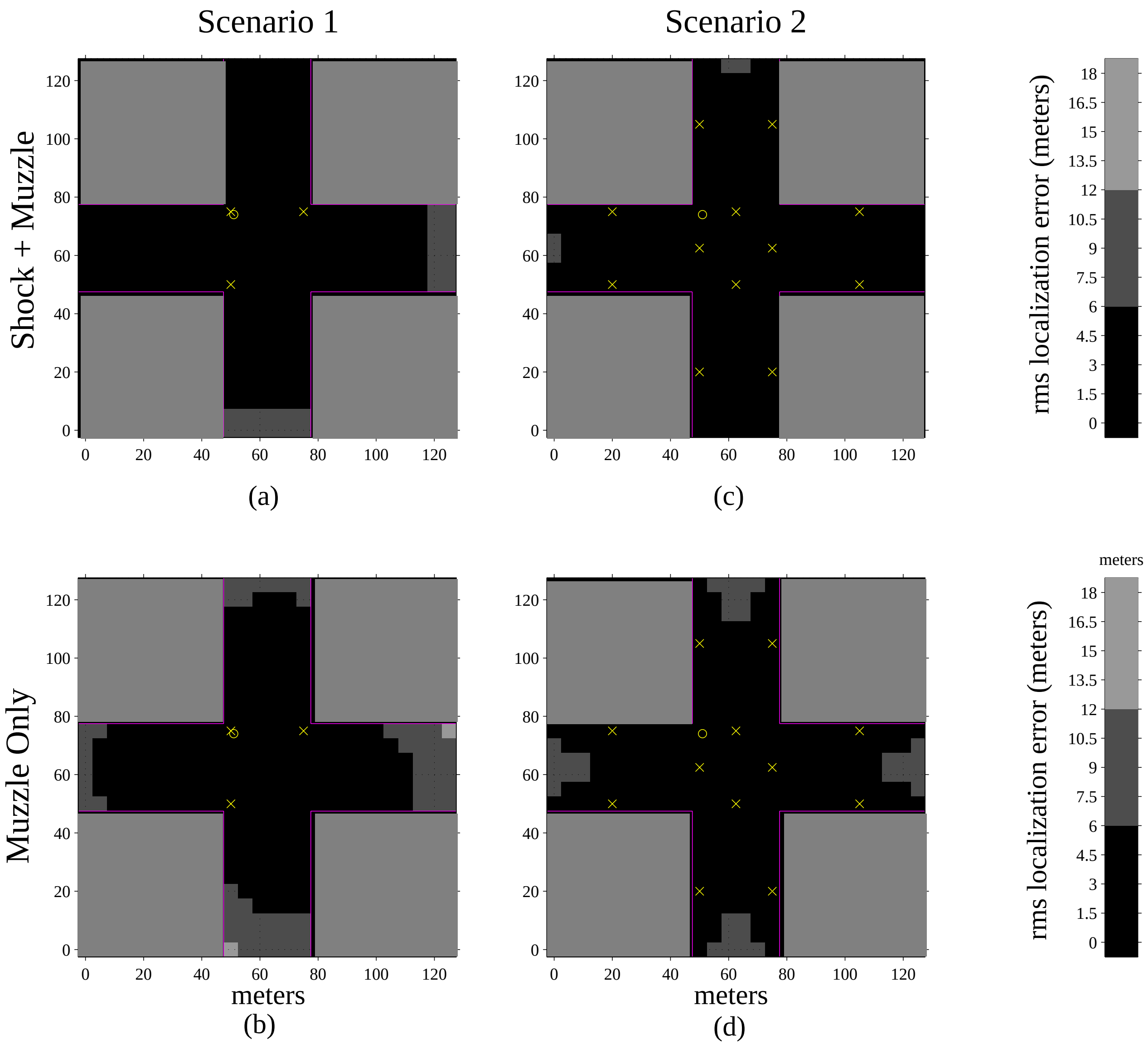
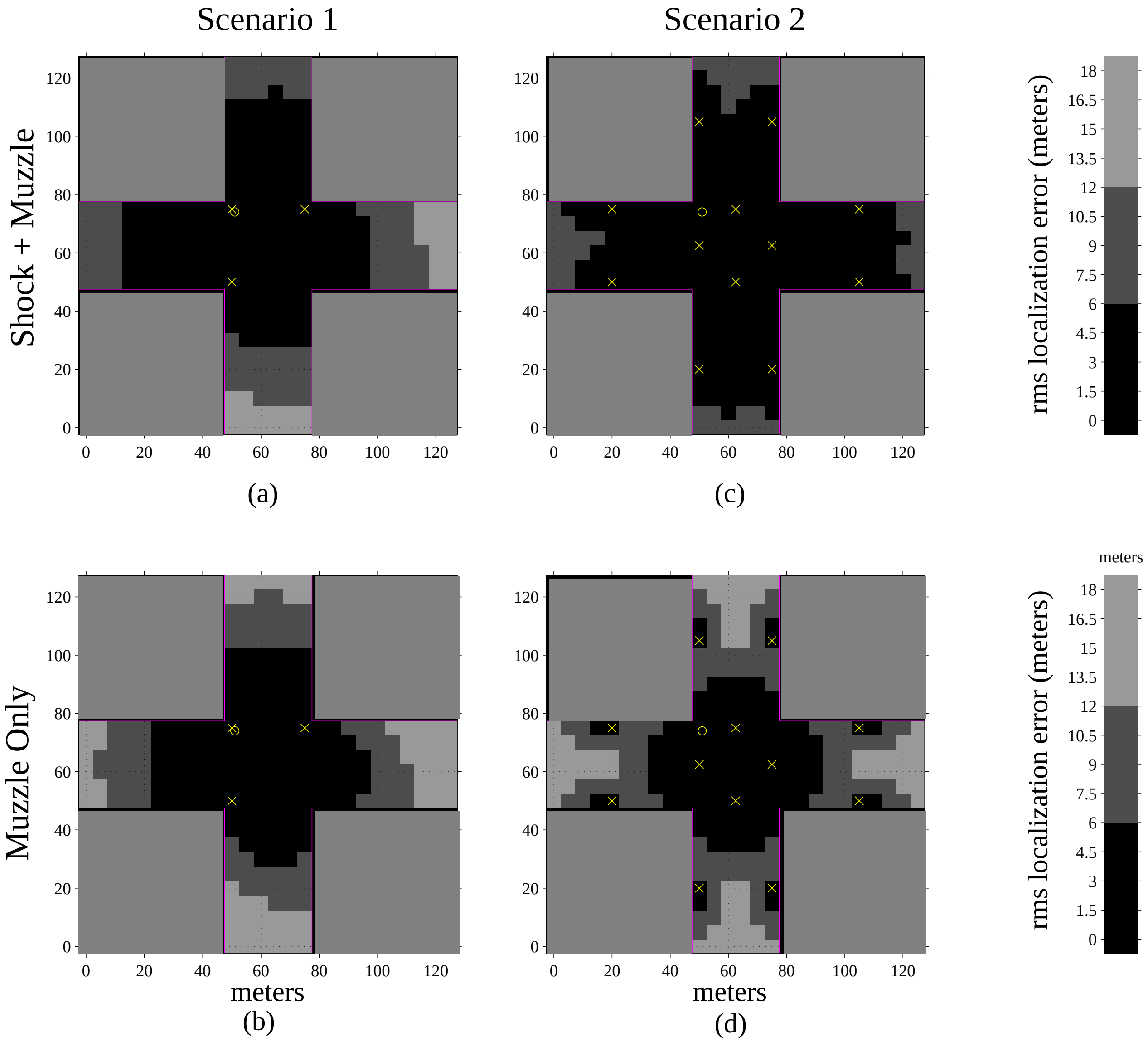


Figure 10. Good quality data (Case A)
(a) Scenario 1, shock and muzzle available. (b) Scenario 1, muzzle only.
(c) Scenario 2, shock and muzzle available. (d) Scenario 2, muzzle only.

Figure 10 shows the comparison between shock and muzzle and muzzle-only for Scenarios 1 and 2 under data quality Case A. The plots show the 3-D RMS error in meters predicted by a Cramer-Rao error bound calculation for a shooter at each street location shooting at a target on one corner (indicated by the circle). The bullet speed is Mach 2. The X's show the four-microphone compact array locations (Scenario 1) and omni microphone locations (Scenario 2). For simplicity and reproducibility, black shows errors less than 6 meters, dark gray 6-12 meters, and light gray more than 12 meters. The shooter is never in the interior of a building (diagonal lines). This performance prediction shows a slight performance advantage for the distributed array. The shock-and-muzzle is slightly better than muzzle-only under the Case A assumption of very good quality muzzle data.



(a) (c) (b) (d)

Figure 11. Degraded Muzzle data (Case B)
(a) Scenario 1, shock and muzzle available. (b) Scenario 1, muzzle only.
(c) Scenario 2, shock and muzzle available. (d) Scenario 2, muzzle only.

Figure 11 shows the same comparison for data quality Case B. The muzzle plus shock-wave performance is somewhat better than the muzzle-only for Scenario 1 and significantly better for Scenario 2. For this case, in which the muzzle is weak, the distributed array in Scenario 2 has advantages when coupled with the shock wave data as shown in Figure 11 (c).

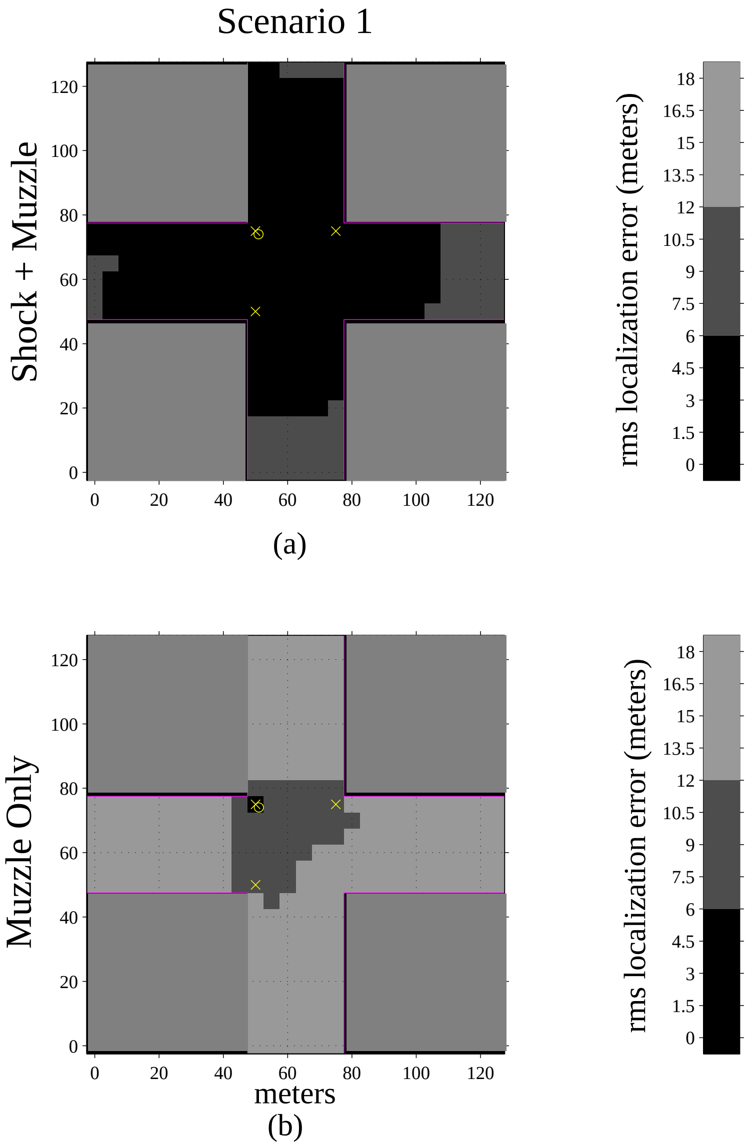


Figure 12. Degraded Muzzle Directivity data (Case C)
(a) Scenario 1, shock and muzzle available. (b) Scenario 1, muzzle only.

Finally, Figure 12 shows a comparison of shock plus muzzle to muzzle-only when reverberation corrupts the muzzle directionality for Scenario 1. (Since directionality on small arrays is not used in Scenario 2, it is not shown). In this case, the shock adds very significantly to the performance. This type of data quality may exist in many urban settings. It should be noted that when the low frequency muzzle blast is very poor or unavailable due to silencers or shooting from within a building, the shock solution still gives a bullet trajectory- the line connecting the shooter and the target. This alone can be a great use in an investigation.

In summary, we believe that this very cursory performance comparison indicates that shock is a useful observable and contributes significantly to the performance and robustness of a notional urban monitoring system. It also suggests that it may allow the use of less costly equipment (life cycle) in the form of small multi-microphone arrays at a few sites, although performance may drop for some bullet trajectories if the muzzle blast quality is extremely poor. It should also be noted that systems that use shock waves are significantly less prone to false alarms than muzzle-only systems. This is because the loud, high bandwidth shock is very easy to distinguish from typical urban noise. In less demanding testing, the BBN system experienced no false alarms, except under conditions of very heavy rainfall. This performance can be improved with minor algorithm enhancements.

4. CONCLUSIONS AND RECOMMENDED FUTURE WORK

It is clear from the wide variation in predicted performance for the different data quality cases that testing in an urban environment is required. Extended deployment in a populated urban environment would obtain false alarm data, ambient noise statistics, and ambient noise waveforms for further analysis. However, any actual shots obtained would not have particularly good ground truth. An extensive live-fire test in a MOUT facility should be done to obtain *in situ* performance data, and to provide a truthed dataset for further algorithm development and tuning. Combined with ambient noise data from the populated environment, the detection-time statistics needed to run future performance modeling, such as that shown here, could be made available. This testing should exercise a significant number of shooter-target geometries. Because the dominant error mechanism will be reverberation, not environmental variability, only a few shots for each geometry would be needed. We estimate that a database of a few hundred shots collected on the sensor geometry of Scenarios 1 and 2 would allow the necessary statistical data collection and algorithm tuning. Once these fundamental performance data are available, the hardware cost and the most effective deployment scenario can be optimized as the next logical step.

5. ACKNOWLEDGMENTS

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