

## NETWORKED ACOUSTIC SENSOR ARRAY'S PERFORMANCE DURING 2004 HORIZONTAL FUSION – WARRIOR'S EDGE DEMONSTRATION

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### ABSTRACT

As the Army transforms to the Future Force, particular attention must be paid to operations in Complex and Urban Terrain. Because our adversaries realize that we don't have battlefield dominance in the urban environment, and because population growth and migration to urban environments is still on the increase, our adversaries will continue to draw us into operations in the urban environment. The Army Research Laboratory (ARL) is developing technology to equip our soldiers for the urban operations of the future. Sophisticated small robotic platforms with diverse sensor suites will be an integral part of the Future Force, and must be able to collaborate not only amongst themselves but also with their manned partners. ARL has developed a Reconnaissance, Surveillance, and Target Acquisition (RSTA) sensor payload for integration onto small robotic vehicles (Packbots), larger robotic scout vehicles (M-Gators), manned soldier transports (ATVs), and on a tethered aerial platform (aerostat). The RSTA sensor payload is equipped with an acoustic array that will detect and localize on an impulsive noise event, such as a sniper's weapon firing. Additionally, the robot sensor head is equipped with visible and thermal camera for operations both day and night. The Packbot can be deployed from the soldier's ATV to enhance their situational awareness in the urban environment, while keeping them out of harms way. The information from one Packbot can then be fused with other sensors as part of a sensor network. Sensor equipped mobile platforms provide an awesome capability to the future dismounted infantry soldier during warfighting and peacekeeping operations in complex and urban terrain by enhancing their situational awareness and improving their survivability.

ARL demonstrated networked acoustic detection and localization of mortar, sniper fire, gunfire, and vehicle tracking at the August 11, 2004 Horizontal Fusion – Warrior's Edge (WE) demonstration at the McKenna Village at Fort Benning, Georgia. Fifteen different acoustic sensor arrays in six different configurations were collaborating to provide unprecedented real-time acoustic situational awareness. The vehicle, unattended ground sensors (UGS), and

robot systems were directly wired into the vehicle's network that had wireless access to the entire demonstration's network. The five UGS used serial radios to transmit line-of-bearing (LOB) solutions back to one of the networked vehicles. All acoustic detection solutions and relevant intelligence from any of the acoustic sensor systems were made available to the collateral space via the network, and a fusion tracker located on a separate HMMWV used all the LOB and detection reports to create a cohesive picture using tracker software.

### 1. INTRODUCTION

Operation Enduring Freedom in Afghanistan, and Operation Iraqi Freedom have used small robots to enhance the situational awareness of the soldiers by remotely reconnoitering urban areas, caves and other potentially dangerous environments, while simultaneously keeping the soldiers out of harms way. "The Army does not currently dominate the complex terrain/urban battlespace." [2] It is operations like these, and programs such as the Future Force Warrior (FFW) and Future Combat Systems (FCS) that have motivated the work that is discussed in this report. The work discussed in this paper builds on previous work, and introduces the capability of soldier/robot teams working collaboratively to detect and localize on acoustic events<sup>2</sup>.

Unmanned RSTA payloads will greatly enhance the soldiers of the future force and are critical to keeping soldiers out of harms way. "The employment of UAV/UGV assets, to assist with deep reconnaissance...will be utilized to reconnoiter complex terrain, and map high-risk areas, such as subterranean complexes... and minefields. Manned surveillance elements will remain on the periphery of the urban area, and collect intelligence through the insertion of unmanned systems." [2] The use of acoustic sensors on robotic and manned platforms, as shown in this paper, will greatly aid the soldiers of the future force in performing numerous types of missions including Reconnaissance, Surveillance, and Target Acquisition (RSTA) by providing situational awareness, particularly to the dismounted soldier operating in the urban

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environment. The work conducted by the Army Research Laboratory, discussed in this paper will be transitioned to the FCS-Small Unattended Ground Vehicle (SUGV) program, the FFW program and subsequently, Land Warrior-Advanced Capability (LW-AC). The Army Research Laboratory is already working with these programs to ensure a feasible migration path.

This paper focuses on five areas relating to acoustic sensing on platforms for the urban environment: small (man-portable) robot detection of a sniper weapon firing, mule-sized robot- and manned-vehicle systems to detect mortar and other loud transients, unattended ground sensors (UGS) for the tracking of ground vehicles, data fusion across multiple platforms, and soldier/robot team interactions.

## 2. BACKGROUND

ARL has established expertise in the area of acoustic sensor development and signal processing related to detection, ID, and tracking of tactically significant acoustic events.[1] ARL efforts in transient detection have led to the development of an acoustic mortar detection system that uses dispersed arrays to triangulate on the launch's sound. ARL continues to conduct research and development on counter-sniper systems that use the detected acoustic shockwave and muzzle blast direction-of-arrival (DOA) information to locate the sniper. Similarly, ARL has developed hardware and software specific to RSTA on mobile platforms, and in particular, on small robots such as iRobot's ATRV-II and Packbot platforms. Figure 1 shows the WE-2003 demonstration's ATRV-II robot from the with associated acoustic, imaging, navigation, and communications hardware.



Figure 1: ATRV-II robot acoustically cues cameras mounted on a pan/tilt when sniper fires from roof.

Sophisticated robotic platforms with diverse sensor suites are quickly augmenting the eyes and ears of soldiers on the complex battlefield. ARL has developed a robot-based acoustic detection system that will detect impulsive and transient noise events, such as a sniper's weapon firing, mortar launch, explosion, or door slam, and alert the soldier operator while simultaneously activating a pan-tilt to orient a visible and infrared

camera toward the detected sound. The coordinates of all vehicles, and their respective solutions, were all fed to a central tracker to develop a global solution for the sniper detection. Figures 2 and 3 are from the 2003 Warrior's Edge demonstration, and show three ATRV-II robots acoustically detecting and localizing on sniper fire in the MOUT, and the UGS field tracking light ground vehicles. [3, 4, 5]

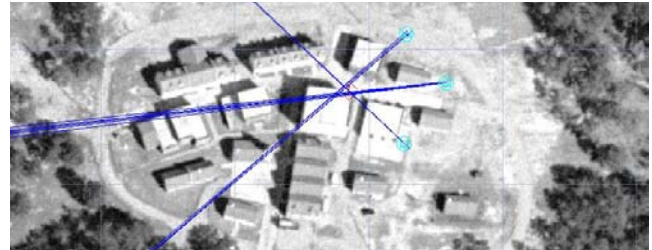


Figure 2: Three ATRV-II robotic arrays detect sniper and LOBs plotted at gateway tracker.

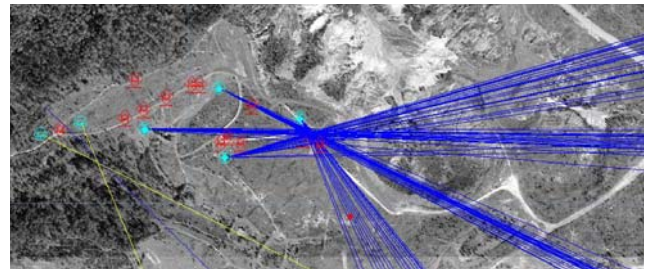


Figure 3: Acoustic UGS tracking convoy of vehicles.

Once the cameras are cued to the target, onboard image processing can then track the target and/or transmit the imagery to a remote operator for navigation, situational awareness, and target detection. Collaboration between multiple robots or other acoustic sensors (air/ground), all with known positions and orientations, can provide useful triangulation information for more precise localization of the acoustic events and tracking. These robots can be mobile sensor nodes in a larger, more expansive, sensor network that may include stationary ground sensors, UAVs, and other command and control assets.

In addition to providing many of the logistics tasks for the future force, such as food, water, ammunition, a robotic MULE can provide advanced signal processing capability, sensor fusion, memory capability, and perform smart battery charging, and communications relay. The robotic MULEs are outfitted with a suite of acoustic sensors as well as visible and thermal imagers for RSTA missions. The robotic MULE can also fuse information from other sensors (UGVs, UAVs, and UGS) to create an enhanced situational picture for the soldier. This "fused" picture is then sent to the squad members in a fashion that truly provides enhanced situational awareness and not just information overload.

### 3. EXPERIMENT DESCRIPTION

The WE 2004 demonstration scenarios included acoustic sniper/gunfight detection within the military operations in urban terrain (MOUT) facility with IR/visible camera cued by the small robot, ATV, and M-Gator arrays. Another scenario was the tracking of a vehicle North of the MOUT as it maneuvers to set up a mortar tube, detect the launch and ensuing detonation of a mortar round, and track the vehicle as it vacates the launch area through the UGS field. Figure 4 shows the sensor/vehicle locations positioned on a LADAR elevation map of the local terrain, and the locations of the mortar launch, detonation, checkpoint, and vehicle path leading into the MOUT.

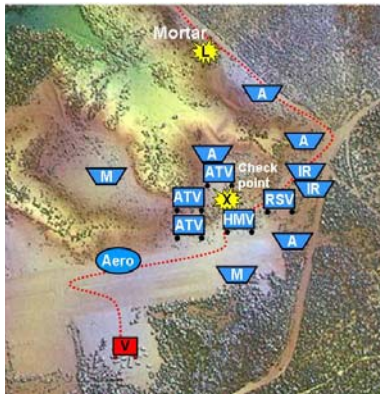


Figure 4: Convoy scenario going through sensor field.

In figure 4, “A” represents acoustic UGS for vehicle tracking, “M” represents ground-based mortar detection systems, “ATV” and “RSV” represent acoustic sensors on these platforms, “HMY” represents a HMMWV with fusion center (no acoustics), “AERO” is the location of the aerostat, with “L”, “X”, and “V” representing the launch, detonation, and vehicle locations respectively.

The vehicle tracking was done with the MAIS nodes, and the impulsive detections were done with the vehicle, aerostat, and tetrahedral arrays. Although the quality of the vehicle-system data was sufficient for vehicle tracking, the vehicle-mounted systems were only used for transient detection and localization at the demo.

### 4. GROUND SENSORS & VEHICLE TRACKING

Four UGS were used to track a convoy of light commercial vehicles (non-military). Figure 5 shows the MAIS hardware used in this experiment. The MAIS nodes utilize an acoustic MVDR beamforming algorithm embedded within its processor to conduct vehicle detection and bearing estimation in real time. Each MAIS sensor node had an array of eight microphones at a 1-m radius, and the array was oriented manually

toward North or some other visible landmark with precisely known bearing with respect to true North. LOB solution data were radioed at 1 second intervals from each MAIS node and were received and processed by the tracker to produce continuous tracks and place icons at periodic intervals, as can be seen in figure 3.

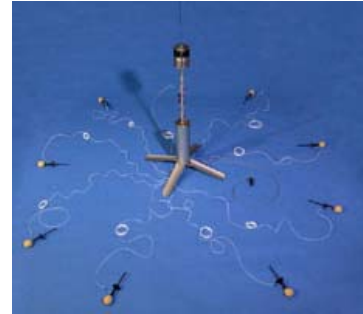


Figure 5: UGS sensor showing mics dispersed.



Figure 6: UGS mics/template for convoy tracking

Figure 7 shows the UGS field use in WE04 tracking a convoy of vehicles through the sensor field, as compared to the road truth data. It can be seen in figure 7 that there were several logging vehicles that were off the road, and that the vehicle we were tracking during this experiment (center of graphic) was tracked nicely to the road it was actually traveling on. Figure 8 also shows one vehicle being tracked for a long distance (yellow-cross track starting at top center and following road to the SE, then to the SW). The other two vehicle tracks in the center were engineers in their vehicles tending to the sensors along that road.

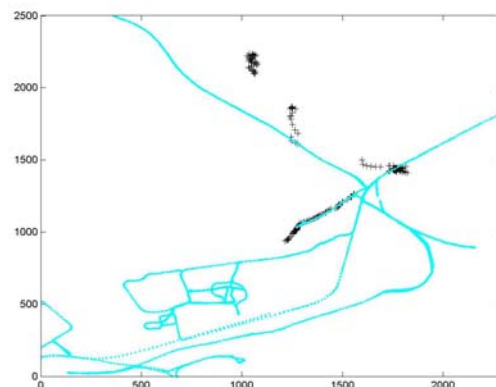


Figure 7: Plot of segment of vehicle tracks on road, and logging vehicles in woods. Blue represents roads.



Figure 8: Screen dump of UGS track icons superimposed on digital map.

Figure 9 is a predictive tool used at the fusion center to show location-probability of a vehicle based on the most recent detection, and is time-dependent based on the previously tracked velocity of the same vehicle.

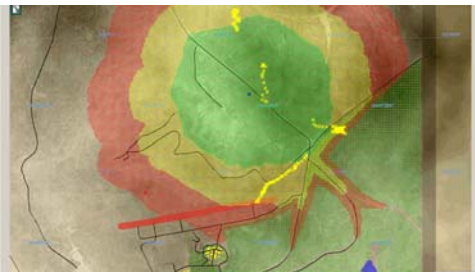


Figure 9: Predictive tool shows time varying probability of current location based on last detection.

## 5. PACKBOT ARRAY FOR SNIPER DETECTION

ARL outfitted an iRobot Packbot with an 8-channel acoustic array with associated signal processing and communications to demonstrate the performance of acoustic arrays on the small platform. Figure 10 shows the Packbot with the acoustic processor module and microphone spring-post mounts.



Figure 10: PackBot with 8-mic array, extensible imaging head, GPS and communications antennae.

Within the tan processor box is a PC-104 computer with a PCMCIA data acquisition card, preamplifier/filter board, and an ad-hoc networking board stack in another compartment of the enclosure. Small 1 inch diameter cylindrical windscreens are used,

but not shown. The microphone elevations are staggered to create a volumetric array that will enhance the elevation solution. Flexible microphone posts were chosen to enable the robot to bump into things or even flip over without damaging the mic mounts or having the mic mounts prevent the robot from re-righting itself. A revised design is already being considered to eliminate a clearance oversight between the forward mics and the lowering/parking of the robot's extensible head assembly.

Vehicle GPS and electronic compass heading help orient the vehicle-centric acoustic solution to the global frame of reference. Running on the single-board computer is a LabView executable virtual interface that interacts with the 16-bit data acquisition PCMCIA-card to sample the data for eight microphones at 20 kHz, and process the data for high-energy transient triggers. Once triggered the algorithm will develop an azimuth and elevation solution, and package this information in a standardized message format that the Packbot network can accept and disseminate. This current algorithm will develop a LOB solution for any transient that exceeds a preset threshold, and will thus form a beam to gunfire, explosions, door slams, yells, etc... It was felt that for this demo and the early stages of development, it would be more beneficial to localize on too many events, rather than miss a key event like a distant sniper shot. More detections makes the tracker's job difficult, but does provide acoustic awareness. Figure 11 shows the Packbot's icon and track history of movement (yellow crosses), along with a LOB detection report (solid yellow line). The acoustic stack within the Packbot worked well, but due to the internal ad-hoc communications node not working well, there is not a lot of data to document the performance of the Packbot system during the demonstration. This figure also shows that the RSV2 icon did not generate a detection report, further indicating the high sensitivity of the Packbot.

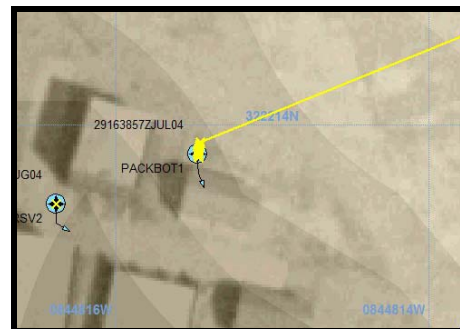


Figure 11: Screen dump from fusion center showing robotic PackBot-1 position near a building and an acoustic detection line-of-bearing to the NE.

## 6. GROUND-BASED MORTAR DETECTION

ARL has been working in the area of acoustic mortar detection and has developed and fielded prototype systems that triangulate on loud low-frequency transients [6]. One of the newer versions of the ARL mortar detection system is shown in figure 12, and was one of two systems used in the WE04 demo. The 1-meter radius tetrahedral arrays contains four microphones that are sampled at 1024-Hz with a 24-bit analog-to-digital converter, and a signal processor board and embedded algorithm accurately localize on mortar launches and detonations based on the times-of-arrivals at each of the microphones.



Figure 12: 1-m tetrahedral UGS acoustic array for transient detection, with battery, tripod and processor.

## 7. VEHICLE-MOUNTED MORTAR DETECTION

Variations of the ground-based design shown in figure 12 were mounted on the vehicle cargo boxes. Figure 13 shows two ATVs and one M-Gator platform with the acoustic sensors/windscreen balls extending upwards from the top of the system electronics processor module. Each vehicle has GPS, electronic compass, and roll/pitch inclinometers, in addition to cameras, video servers, numerous networks/hubs, generators, and power management circuitry.

It was observed during this demonstration that the electronic compasses were not zeroed properly, and that some of the reported vehicle orientations were off. This obviously adds error to the acoustic triangulation, since the acoustically derived LOBs are relative to the vehicle's front. Figure 18 shows the four vehicles and two ground-based mortar detection systems localizing on a firefight. Notice that one of the systems does not intersect with the other four LOB sets (the LOBs originating in upper-center, with detection fan pointing down to the right slightly should be rotated counter-clockwise for agreement with the other four systems). The accuracy of these vehicle positional sensors is an important consideration, especially when the vehicles could be in a MOUT situation where underground pipes,

building structures, vehicles, etc. could influence the compass bearing and ultimately the perceived system accuracy.



Figure 13: Acoustic sensors with windscreens shown on the RSV (right) and two ATV's (left).

Figure 17 also shows the vehicles with the soldiers in front. Several of the soldiers can be seen wearing the soldier system hardware that allows them to interface with the fusion center and gain access to the acoustic detection reports, digital maps with icons, imagery from vehicle/robot cameras, and actual control of the robotic assets. The overall performance of the soldier system performance during this demonstration will be documented by other authors in the future.

## 8. AEROSTAT DETECTION ARRAY

A similar variation was designed and built for the underside of an aerostat to detect impulsive sounds during the scenarios. By elevating the acoustic array to the point where all targets are essentially line-of-sight, propagation losses from ground impedance, vegetation, and terrain features can be removed. Figure 14 shows the acoustic sensor arms protruding from the electronics processor box and the IR/visible camera system mounted below, and the original balloon showing a surrogate payload below. Unfortunately, the aerostat was lost during an abrupt and violent thunderstorm, and was not available for the demonstration. A smaller balloon was used for the demo to carry a networked camera, but the payload was too small to include any additional sensors, such as the acoustic mortar detection array. A new balloon has been purchased and more experimentation will be conducted in the near future to demonstrate the elevated acoustic array with acoustics LOB reports controlling the camera's look direction.

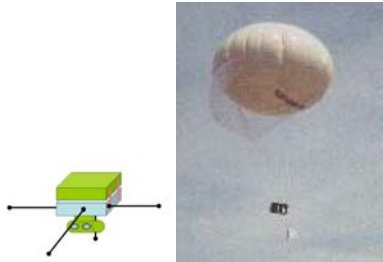


Figure 14: (a) Depiction of acoustic array and camera assemblies, (b) aerostat with hardware below.

The baseline acoustic algorithm produces azimuth and elevation solutions from the frame of reference of the array. GPS, magnetic compass, and inclinometers measure the exact orientation and location of the aerostat and ground vehicles at time of acoustic detection, and can relate the acoustic solution to global coordinates. Furthermore, infrared and visible cameras mounted on pan/tilt units can be directed to view the acoustically indicated region of interest.

## 9. TRACKING NUMEROUS EVENTS IN NOISE

Acoustic arrays are traditionally used for tracking aircraft and heavy military vehicles. Fort Benning was an active site and the sensor field continually detected such potential targets. Somewhat incongruously, the tracker was required to reject them, as our objective was to track the much quieter SUVs traveling on nearby roads. For tracking ground vehicles or determining a mortar launch location, the primary challenge was one of data association between sensors. If two sensors report an LOB to a single target, that target's location may be determined by simple triangulation to see where the LOBs intersect, as seen in figure 15.

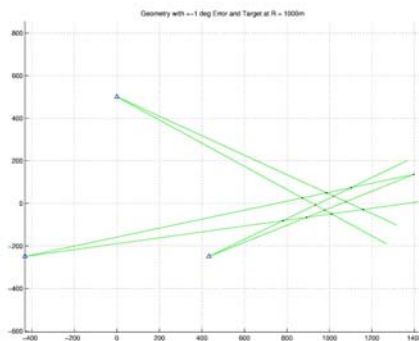


Figure 15: Simulated +/- 1 degree total localization error for target detected 1000 m from centroid of arrays.

But when the sensors in the field each report several simultaneous LOBs, there will be many more intersections than targets, as seen in figure 16. The tracking algorithm used a genetic algorithm to generate and test multiple hypotheses, searching for one that best explains the reports coming from the sensors over a time

window. We used a terrain database to bias the hypotheses to favor those placing targets on more navigable routes.



Figure 16: Screen dump of UGS LOBs and detections from other vehicle-mounted arrays demonstrating the complexity of the tracker's job. Blue represents roads.

## 10. GATEWAY TRACKER DEMO RESULTS

Artillery and hand grenade simulators were used as the impulsive noise associated with the launch and detonation of mortar rounds. The grenade simulators were initiated inside of a surrogate mortar tube to help recreate an appropriate launch signature. The artillery simulators were detonated on the ground. Small arms firing included 7.62 and 5.56 mm automatic assault weapons firing blanks. Flash-bang simulators were used in the MOUT during the room-clearing scenarios. It should be noted that the mortar detection system that is the basis for the vehicle and ground-based components in this demo have been fully characterized and has exceptional performance for real mortar launches and high-explosive detonations.

Figure 11 is a screen dump taken from the fusion-center display during the sniper/assault scenario, and shows a Packbot acoustic detection LOB report pointing outside of the MOUT. Figure 18 shows numerous LOB reports within the MOUT gunfight scenario from the three ATVs, one M-Gator platform, and two fixed-site mortar detection ground sensors. Due to the numerous LOB reports, soldier-system positions, and track log details, it is not clear that the Packbot reported these detections.

Figure 19 shows a screen dump from an engineering display showing an abundance of acoustically derived information for an enhanced situational awareness of the entire region. The graphic shows numerous ongoing tracks (yellow crosses), LOB reports from UGS arrays (green icon with solid yellow line), LOB reports from MAIS nodes on vehicle/other sounds (blue lines), icons from vehicle-mounted transient detections (orange diamonds), and blue-force tracking (green circles, with yellow lines showing that when the soldiers had GPS dropouts the tracker erroneously

positioned them outside of area of regard as a default location). An engineering display is one where high and low confidence LOB reports and other support data are presented so that the observers can derive some real-time measure of performance. This additional data is often confusing to the soldier and can be turned off to only show icons and minimize the duration of track histories. In figure 19 you will see consistent vehicle tracks along the roads. These are very high-confidence tracks, in that they must persist for more than 10 seconds before a track is drawn. When the tracker perceives the track has been lost, it will initiate a new track once it reappears, and will assign a new track number to this track. The transient event icons (orange diamonds) show a lot of loud ambient noise over the course of the day in and around the MOUT vicinity. These icons can either persist indefinitely or be automatically removed after a certain amount of time.

## 11. CONCLUSIONS

ARL successfully conducted a very large-scale WE04 demonstration of acoustic detection from manned vehicles, MULE-size robots, small man-portable robots, and stationary unattended ground sensors. Real-time intelligence from all of these systems was transmitted wirelessly to a fusion center, processed for fusion and tracking, and presented to the collateral space for viewing by any permitted subscriber. The sensor systems and soldiers on the edge of the battle were not only creating data for the collateral space, but were also able to benefit from the robot/soldier/sensor team's composite data, and control the robotic assets via the network infrastructure. The acoustic sensors in this demonstration located mortar and small-arms firing and tracked numerous vehicles to provide instantaneous situational awareness and actionable intelligence to enhance the survivability and lethality of the soldier.

Many of the lessons learned are being used to refine the systems and algorithms used during this experiment. Of particular interest to programs such as FCS and FFW were the robotic sensors, the UGS, and the ad-hoc communications nodes that were used to bring the data together in order for it to be fused into a soldier-usable product.

Clutter and multipath in the urban environment (both acoustically and RF) continue to be difficult challenges, but experiments like the one presented in this paper demonstrates ARL's commitment to address these challenges head-on, in order to increase the survivability of our soldiers.

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Figure 17: Soldiers lined up in front of M-Gator, three ATVs, HMMWV fusion center, with the aerostat in the background. Some of the soldiers are wearing the soldier system hardware and heads-up displays that presented the acoustic detection and tracking information.

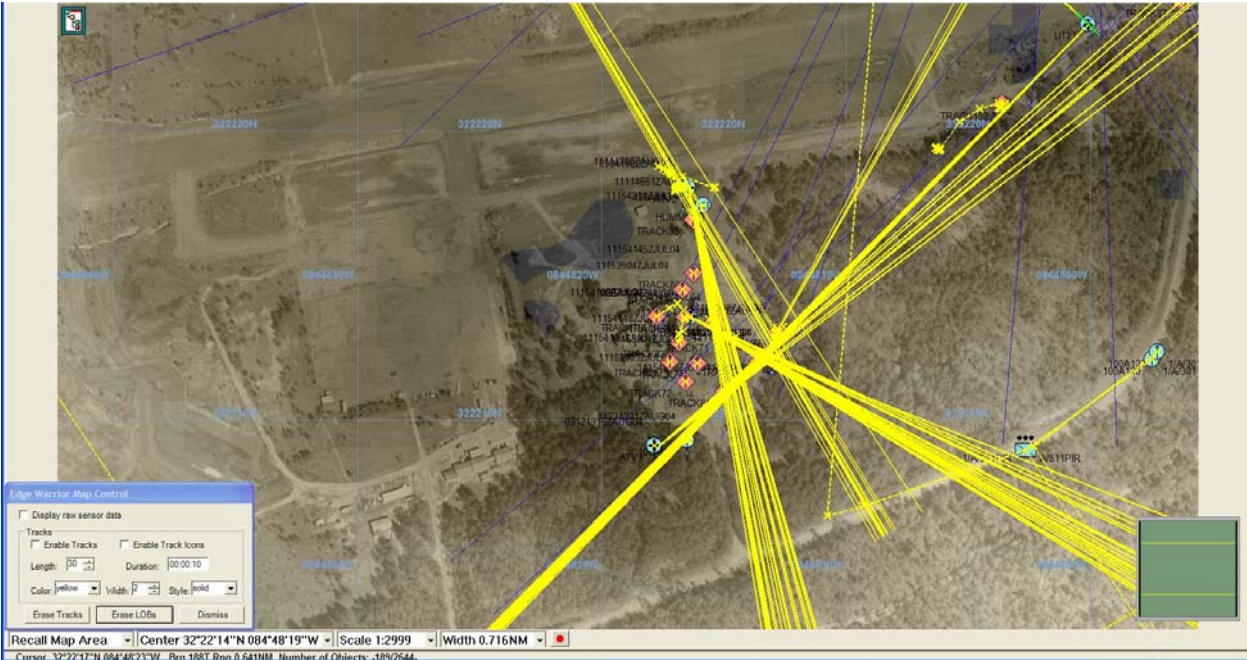


Figure 18: Screen dump of detections within MOUT from ATVs, M-Gator, and mortar detection UGS. These LOB fans are from machine gun firing from numerous members of the squad, and numerous LOBs from each vehicle demonstrate the rate, locations, and history of firing (from both blue and red forces).

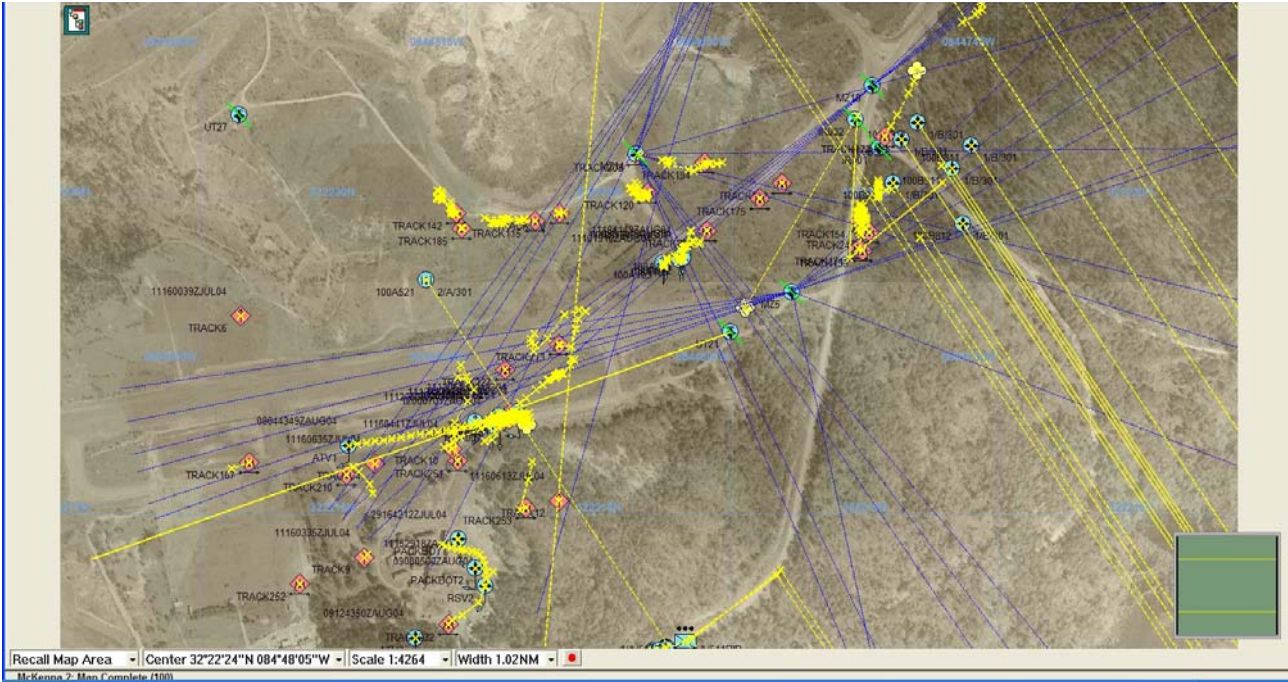


Figure 19: Screen dump of engineering display shows numerous ongoing tracks, LOB reports from UGS, LOB reports from MAIS nodes on vehicle/other sounds, icons from vehicle-mounted transient detections, and blue-force tracking.