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Battlefield Acoustic Sensing, Multimodal Sensing, and Networked Sensing for Intelligence, Surveillance, and Reconnaissance (ISR) Applications

by Latasha Solomon, Wesley Wang, and Miriam Häge

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14. ABSTRACT
In an ongoing effort to reduce the size, weight, and power of current acoustic localization systems, the Task Group (SET-189 RTG) on Battlefield Acoustic Sensing, Multimodal Sensing, and Networked Sensing for Intelligence, Surveillance, and Reconnaissance (ISR) Applications evaluated the feasibility of replacing the pressure sensor microphone with that of a particle velocity sensor. The particular sensor of interest in this research was that of the Acoustic Multi-Mission Sensor (AMMS) developed by Microflown AVISA. This work addresses sensor capabilities and limitations both in the open field and more complex operational environments as they relate to small-arms fire (SAF).

15. SUBJECT TERMS
Acoustic Vector Sensor, Acoustic Multi-Mission Sensor, particle velocity, target localization

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Contents

List of Figures

Executive Summary

The scope of the effort conducted by the Task Group (SET-189 RTG) on Battlefield Acoustic Sensing, Multimodal Sensing, and Networked Sensing for Intelligence, Surveillance, and Reconnaissance (ISR) Applications is to address the ever-changing problem space and needed technologies to support North Atlantic Treaty Organization (NATO) forces conducting ISR operations for missions such as camp and forward operating base (FOB) protection, main supply route (MSR) monitoring, border surveillance, and human activity detection.

This work addresses using an Acoustic Multi-Mission Sensor (AMMS) to localize small-arms fire (SAF). Many SET-189 member nations have investigated this sensing technology and these efforts are highlighted in this integrated report. While the results are applicable to SAF, these same sensors have verifiable application to transient target localization for rocket-propelled grenades (RPGs) and mortars, as well as targets with continuous waveforms. An array of microphones can be replaced by a single sensor; this technology will allow for fewer, lightweight, low-power deployed systems, saving in overall system cost, size, weight, and power usage. When deployed as an unattended sensor system, AMMS will greatly reduce hardware setup time and periodic maintenance. The sensor has the capability to measure both the (scalar) sound pressure and the (vector) acoustic particle velocity and can provide 2-dimensional (2-D) bearing estimates.

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1. Introduction

The notion of using vector sensors to localize and track a number of potential targets of importance (both continuous and transient sources) has gained renewed interest in the past few years and is applicable to several tactical scenarios. Many SET-189 member nations have investigated and applied this sensing technology, and these efforts have been integrated in this report. This report discusses the following items for the Acoustic Multi-Mission Sensor (AMMS) developed by Microflown AVISA.

Highlights of the research findings include but not limited to the following:

1) Scope of evaluation and applications
2) Sensor detection range given specific target(s) and environmental conditions
3) Specific/unique algorithm approaches attempted and results
4) Observations related to wind noise rejection and/or effects
5) Limitations of technology
6) Pros and cons of technology given expertise in the subject matter area
7) Availability of data for SET-189 members, and for other transitions, such as other Partnership for Peace (PfP)/Mediterranean Dialogue (MD)/North Atlantic Treaty Organization (NATO) nations not specifically involved with SET-189
8) Future research and development (R&D) efforts

2. Acoustic Multi-Mission Sensor

AMMS measures the velocity of air across 2 tiny, resistive strips of platinum that are heated to 220 °C. In acoustics, this movement of air is termed *particle velocity*. When air flows across the strips, the first strip cools down a little and due to heat transfer the air picks up some heat. Hence, the second strip is cooled down with the slightly heated air and cools down less than the first wire. A temperature difference occurs in the wires, which causes a difference in their electrical resistance. This causes a voltage difference that is proportional to the particle velocity and the effect is directional: when the direction of the airflow reverses, the temperature difference will also reverse. In the case of a sound wave, the airflow across the strips alternates in conjunction with the waveform and thus the alternating output voltage.[1]

The *Acoustic Vector Sensor (AVS)* contains a pressure microphone as well as 3 Microflown elements that are sensitive in perpendicular directions to air flow. The *sound intensity* vector is obtained by multiplying the scalar pressure by the particle velocity vector. This vector points away from the acoustic source, such that the direction of the source can be determined for every sample of incoming data with very little processing. The direction of arrival (DOA) can be determined using data with frequencies from 10 Hz to 10 kHz,[2] which is wider than many other systems.

3. US Army Research Laboratory's (ARL) Data Collection Efforts

For the past several years, the US Army Research Laboratory (ARL) has evaluated the feasibility of replacing the current pressure sensor microphone with that of the particle velocity sensor developed by Microflown AVISA. To that end, ARL has independently developed our own unique signal processing algorithms based on a modified single value decomposition technique. This algorithm, when used in conjunction with the 2-dimensional (2-D) or 3-dimensional (3-D) particle velocity sensor, provides a reasonably accurate measure of DOA of various transient events such as small-arms fire (SAF), mortars, and rocket-propelled grenades (RPGs).[3]

The research presented was collected during a field experiment at the Playas Test Facility, Playas, New Mexico. This venue allowed us to evaluate each system in a realistic operational environment reflective of a current mountainous village. The primary purpose of the shot detection event was to characterize ARL-developed algorithms at the backend of the AMMS positioned in a mock village receiving SAF from high angle firing positions in a mountainous terrain. It has also allowed us to pinpoint scenarios where the current algorithm may need to be revisited to improve upon current detection and localization results of SAF. This venue allowed ARL to evaluate the pros and cons associated with a small, low-profile sensor while operating in a complex environment.

Figure 1 illustrates the microelectromechanical system (MEMS) particle velocity sensor and the respective 2-D AMMS used in this data collection effort.

Fig. 1 MEMS particle velocity sensor and the respective 2-D AMMS

AMMS data were collected and processed with a sampling rate of 10 kHz and azimuth angle estimates were computed using a modified single value decomposition algorithm. DOA estimates presented in Figs. 2 and 3 correspond to SAF with round calibers of 5.56 mm and 0.308 inches, respectively, while shooters were positioned ~500 m away from the sensor.

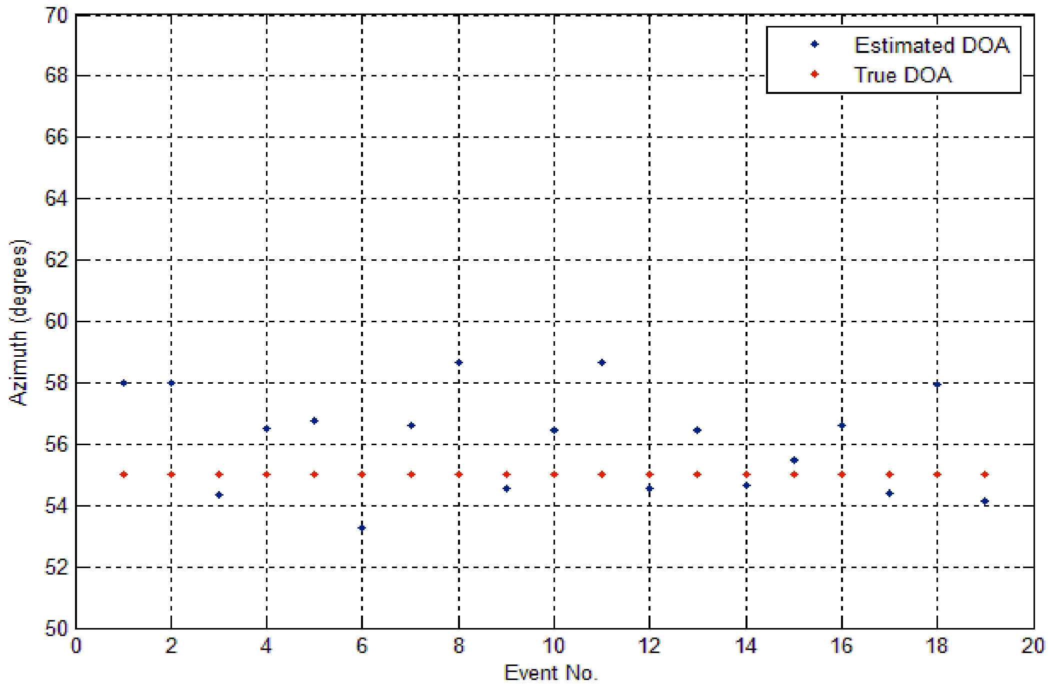

Fig. 2 DOA estimates of SAF with a round caliber of 5.56 mm

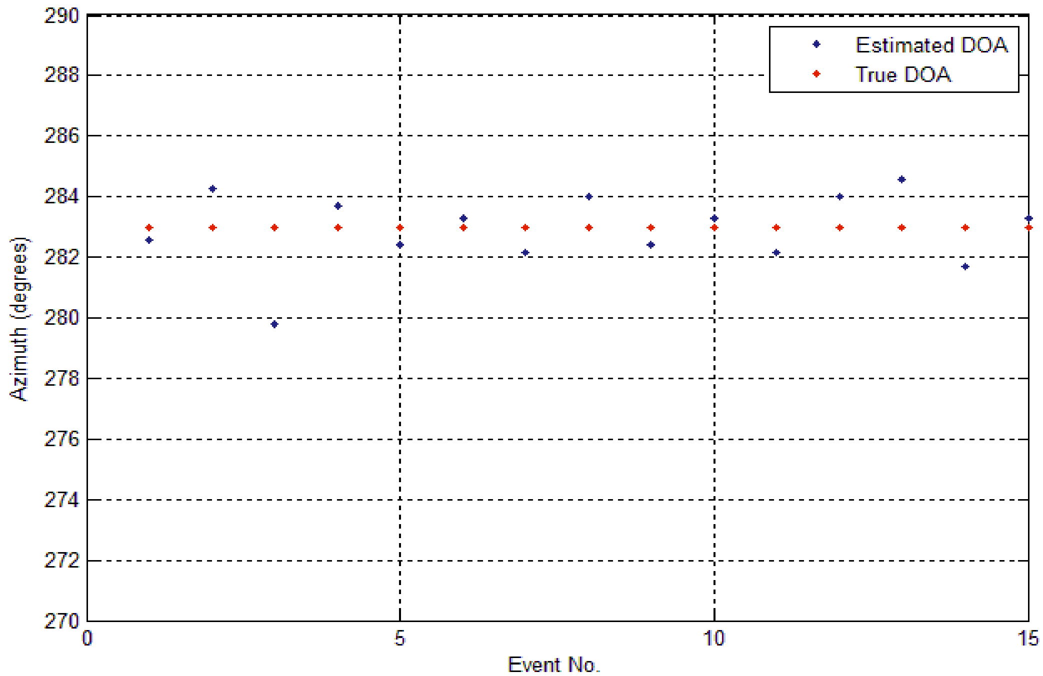

Fig. 3 DOA estimates of SAF with a round caliber of 0.308 inches

The AMMS detected 100% of the 5.56-mm and 0.308-inch rounds with no false alarms. The mean absolute azimuth error (MAE_θ) is calculated using

$$MAE_\theta = \frac{1}{n}\sum_{i=1}^{n}|e_i|, \tag{1}$$

where n is the total number of events, and e_i is the difference between the estimated azimuth and the true target location. The MAE_θ was estimated to be 1.6° and 0.94° for the 5.56-mm and 0.308-inch rounds, respectively.[4]

The results indicate that the sensor can be used for bearing estimation and target localization. This technology will allow for fewer, lightweight, low-power deployed systems. One limitation is that the sensor, on several occasions, failed to collect data and was later diagnosed as having corrupted drivers. The root cause of this failure remains unknown.

4. Fraunhofer FKIE's Data Collection Efforts

Using a 3-D Microflown AVS, as seen in Fig. 4, a shooter localization test was performed at a military training area in Germany in 2012. The experiment consisted of close-past shots, which passed to the left, above, and to the right of the sensor. The weapon used was a sniper rifle, which has a caliber of 7.62 x 67 mm and an initial muzzle velocity of v0 = 900 m/s. During the acoustic measurements a total of 30–50 shots were fired.[5]

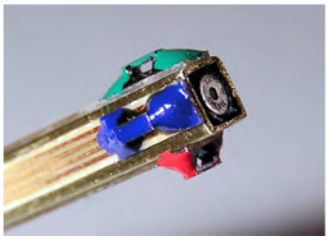

Fig. 4 3-D Microflown AVS

To test the sensors in the field experiment, 3 AVS were placed within a distance of 50 m to each other. Figure 5 shows the arrangement of the sensors (AVS) as well as the unknown shooter positions (SPs).

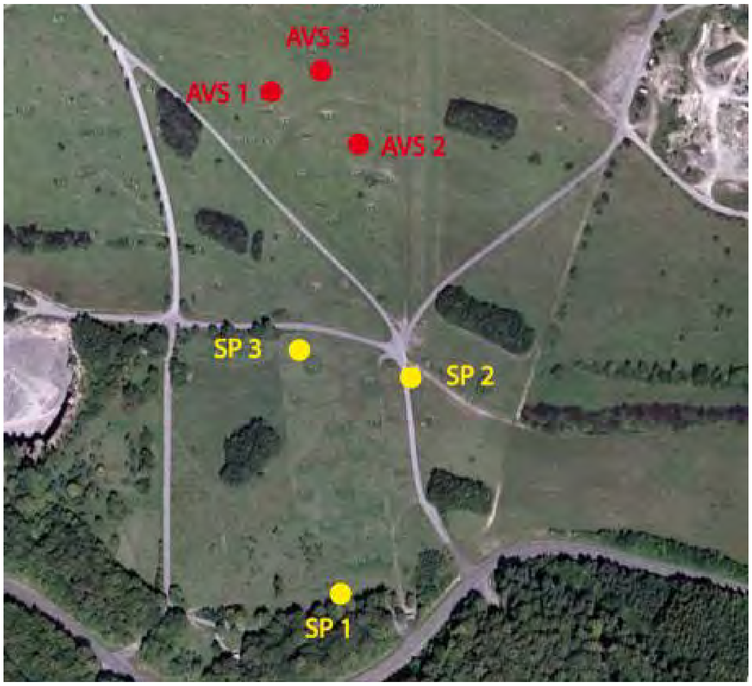

Fig. 5 Sensor positions (AVS 1, AVS 2, AVS 3) and shooter positions (SP 1, SP 2, SP 3) (© Google Earth)

The bearing of acoustic sound sources can be derived from measurements using a single AVS, making use of its inherent capability to determine the particle velocity vector of the incoming sound wave.[6] Supersonic munition is characterized by 2 consecutive acoustic impulses within a short period of time. First, the so-called shock wave is detected, which is radiated at any point of the trajectory if the bullet speed exceeds the local sound velocity. It is caused by an overpressure at the tip of the munition and negative pressure at its end, the shock wave propagates conical.

After a certain time, the muzzle blast is detected, which results from the exit of the munition at the muzzle.

Figure 6 shows an example of a single shot measured with the sound pressure channel of 1 AVS.

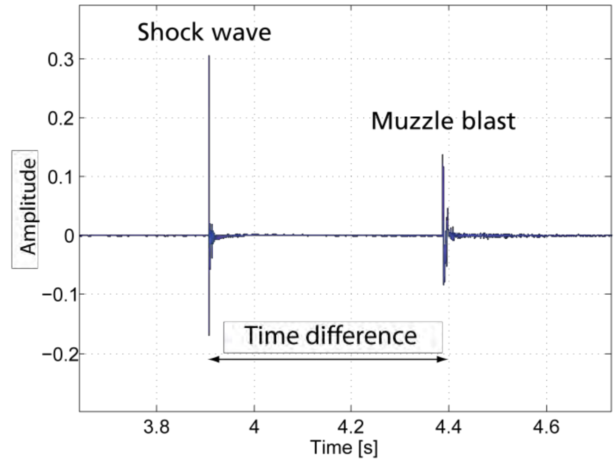

Fig. 6 Pressure channel of single SAF

The corresponding spectrogram of the signal shown in Fig. 6 is depicted in Fig. 7. It shows the power density spectrum within the frequency range of 0 to 2000 Hz.

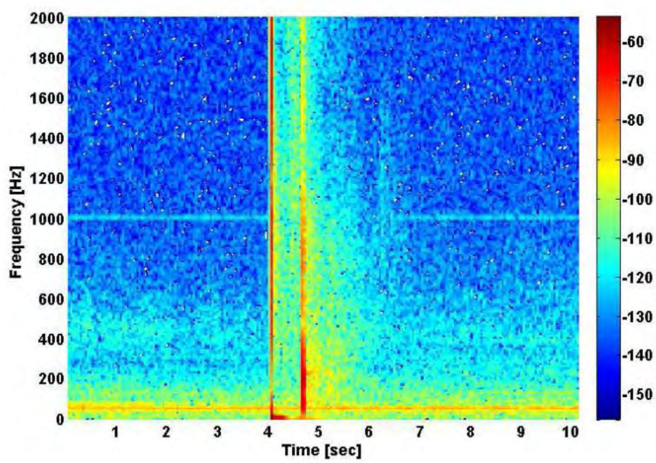

Fig. 7 Spectrogram of a single shot

Due to the propagation loss caused by vegetation and the atmosphere, the muzzle blast has its main energy content in a frequency range of 0 to 1200 Hz, whereas the shock wave contains higher energies from 10 kHz and beyond.

To determine the location of a sound source, both the DOA as well as the range to the source are needed, which can be calculated by the measured data of an AVS.

The azimuth angle can be derived from the velocity components $v_{MK,x}$ and $v_{MK,y}$ of the muzzle blast using

$$\alpha = arctan\frac{v_{MK,y}}{v_{MK,x}}. \tag{2}$$

Due to hardware reasons, the z-velocity component of the AVS could not be measured so that the determination of the elevation angle was not possible.

In order to calculate the range between sensor and shooter, a simplified approach is used, which assumes a known constant Mach number, Ma, derived from the muzzle velocity. Thus, the range is calculated using

$$R = \frac{(T-t)v_S}{1-\frac{1}{Ma}}, \tag{3}$$

where R is the range, T-t is the time difference between shock wave and muzzle blast, and v_s is the sound velocity.

With the measured data, shooter localization was performed. The results are shown in Fig. 8.

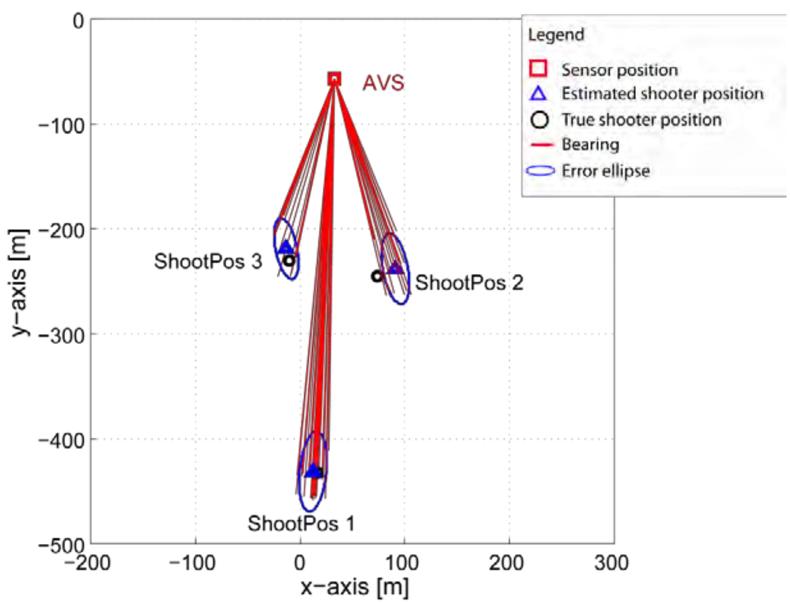

Fig. 8 Estimated shooter positions and error ellipses

Using the azimuth angles, derived from Eq. 2, the corresponding quadrant bearings are calculated. The lengths of the bearing lines represent the estimated ranges to the shooter. The mean deviation from the exact shooter position is approximately 4, 19, and 12 m for shooter positions 1, 2, and 3, respectively. These results indicate that it is possible to perform localizations with just a single AVS.

Despite the promising localization results, several sensor errors occurred during the field experiment, which led to incorrect measurements. These errors are listed below:

- No global positioning system (GPS) connection, which caused a missing timestamp in the measurement data.
- No time synchronization among the 3 sensors.
- Signal clipping in both x- and y-particle velocity channels, which caused an incorrect determination of the bearing angles using this sensor version.

5. US Army Armament Research, Development and Engineering Center's (ARDEC) Data Collection Efforts

The test comprised of open field-static and open field-dynamic scenarios that were conducted at Yuma Proving Grounds (YPG), Arizona, in June 2014. The static open field test consisted of scenarios in an open field environment where the system's performance was determined with shooter ranges from 100 to 600 m at a fixed 20-m shooter miss distance from the vehicle, which were conducted with the vehicle remaining stationary and scenarios repeated with the vehicle's engine off and on. The fixed-site system was situated at a 30-m offset on the opposite side of the firing line. The dynamic open field test involved scenarios in an open field environment where the system's performance was tested with shooter ranges from 100 to 300 m at a fixed 20-m miss distance from the vehicle, which were conducted with the vehicle traveling at a speed of 20 mph. AMMS-03 is the fixed-site system and systems AMMS-19 and AMMS-20 are the vehicle-mounted systems.

The vehicle-mounted systems, as seen in Fig. 9, were placed at the rear of the vehicle to minimize the noise and vibration from the engine and its intake and exhaust from the systems. An ad-hoc vehicle mount was fabricated specifically for this test to dampen the vibrations from the vehicle. The sensors were also located at the edges of the vehicle to minimize the vehicle's chassis from blocking the acoustic signatures of the gunshot event that could create shadow zones.

Fig. 9 Close-up view of the mounting of AMMS system 19 on the roof of the vehicle

Figure 10 shows the fixed-site system that was placed 30 m opposite of the firing line. This system gave a baseline on how the system would perform under benign circumstances.

Fig. 10 View of the fixed-site system on the ground

Figure 11 shows all of the localizations produced from the systems for the entire test. AMMS-03 is labelled as the blue diamond while AMMS-19 and AMMS-20 are included in the orange square icon representing the vehicle. AMMS-19 and AMMS-20 aren't represented as independent icons because they were separated by ~1–2 m and displaying separate icons wouldn't be discernible on that graph.

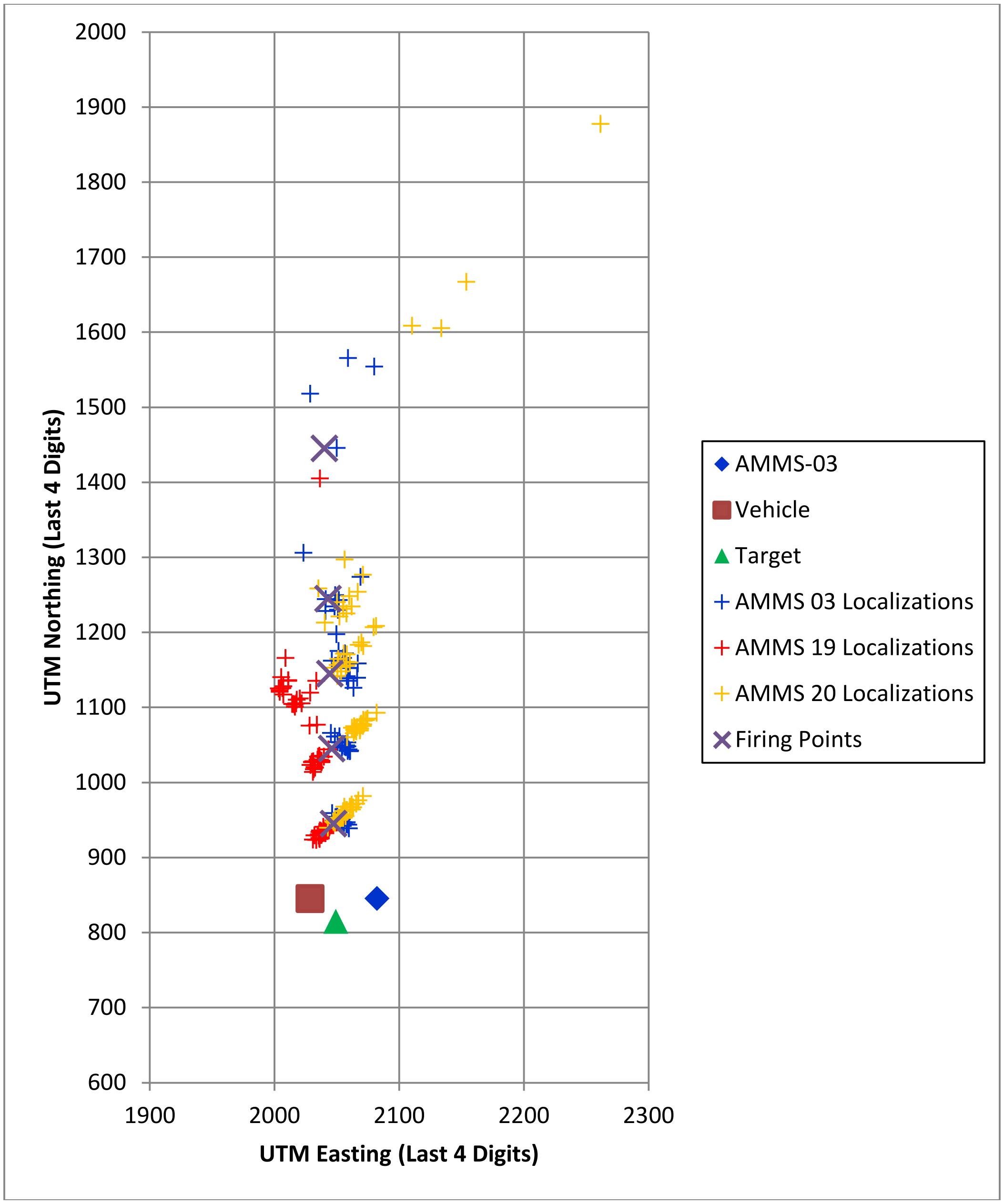

Fig. 11 Localizations reported from all systems during the entire test

For the stationary events with the engine off, all 3 systems had comparably correct localization percentages with the rate of correct localization dropping sharply beyond 300 m for all weapons. This could be due to the increase in wind speed and gusts during the 400- and 600-m scenarios. The average azimuth root mean square (RMS) errors for all systems were within 4 degrees for all systems, and the average standard deviation of the errors for all the systems was within 2 degrees. This may signify that the manually set orientation and position parameters for the systems were configured with inaccurate bearings, which resulted in biased angles to the shooter, but the azimuth error standard deviations show that the systems maintained good bearing precision. This bias is visible in Fig. 8 where the solutions for each system center on an offset bearing angle. For AMMS-19, the localization azimuths are biased on the left of the shooter, whereas AMMS-03 and AMMS-20 are clustered to the right of the shooter. For ranging, the systems had much poorer performance with AMMS-03 having the best performance at an average percent range error RMS of 12% with an average standard deviation of range error of less than 4%. Range solutions had the highest error with Weapon1 with an average percent RMS range error of 76% and average percent range error standard deviation of 11%, whereas the respective averages for both the Weapon2 and Weapon3 are 10% and 10%. Both AMMS-19 and AMMS-20 experienced overall poorer performance when compared to AMMS-03, which could be attributed to the shadow zones of the vehicle distorting both the “crack” and “bang” signatures and/or the dark metal surface where the systems were mounted, which may have heated the air significantly enough to impact the acoustic signatures compared to the fixed-site system.

For the stationary events with the engine on, the systems, especially the vehicle-mounted systems, experienced a significant decrease in performance compared to the engine off condition. The percentage of correct localizations produced by the vehicle-mounted systems dropped significantly from an average of 0.47 across all systems to an average of 0.27. Also, System 3 experienced a drop in localization accuracy with an average range error RMS of 30% and an average percent error standard deviation of 6% as compared to the 12% and 4%, respectively. The engine noise may have masked or distorted the acoustic signatures severely enough for the localization algorithm to result in this drop in performance.

The systems appeared to have severe issues localizing Weapon4, although it is the loudest of the weapons shot during the test. A closer look at the detection logs showed that the systems detected the impulsive events, but most of the detections were misclassified; much of the muzzle blasts were classified as shockwave detections. Additionally, there were problems with multi-path reflections, or echoes, where more than 2 impulsive events were detected during 1 shot, which may be due to sound reflections from the ground, targets, or the vehicle.

For the dynamic events, systems 19 and 20 failed to obtain the necessary acoustic signatures for localization. However, both systems managed to detect 1 of the 2 signatures for a small number of shots, but the systems never detected both signatures to produce a localization.

The results show that the system’s ability, at its current technology maturity, to localize a shooter is significantly degraded when background noise is applied. The system requires further improvements in the localization algorithm, noisecancelling algorithm, and hardware development to become more robust and reliable as a fixed-site system as well as a vehicle-mounted system. Also, it is recommended that the system incorporates a GPS location and orientation sensors to reduce or eliminate errors based on incorrect manually input sensor location and orientation parameters. There is still opportunity for continued improvements for this system.[7]

6. Summary and Conclusion

This report has summarized the efforts of Task Group SET-189 RTG on Battlefield Acoustic Sensing, Multimodal Sensing, and Networked Sensing for ISR Applications as it relates to the particle velocity sensor developed by Microflown AVISA. This research has concluded that the AMMS has performed well detecting and localizing SAF in realistic tactical scenarios. Analysis of the localization errors also suggests further attention should be given to improved GPS capabilities and signal processing techniques in low signal-to-noise environments.

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List of Symbols, Abbreviations, and Acronyms

2-D	2-dimensional
3-D	3-dimensional
AMMS	Acoustic Multi-Mission Sensor
ARDEC	US Army Armament Research, Development and Engineering Center
ARL	US Army Research Laboratory
AVS	Acoustic Vector Sensor
DOA	direction of arrival
FOB	forward operating base
GPS	global positioning system
ISR	intelligence, surveillance, and reconnaissance
MD	Mediterranean Dialogue
MEMS	microelectromechanical system
MSR	main supply route
NATO	North Atlantic Treaty Organization
PfP	Partnership for Peace
RMS	root mean square
RPGs	rocket-propelled grenades
SAF	small-arms fire
SP	shooter position
YPG	Yuma Proving Grounds

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