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Performance Metrics for Acoustic Small Arms Localization Systems

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ABSTRACT

In the past ten years, in-air acoustic sensor systems have been developed for the localization of small arms fire. A number of countries have systems at different stages of advancement that they have deployed on operations. These systems are being mounted on vehicles to provide crews with better situational awareness, thereby enhancing crew safety and force protection. The acoustic system is starting to be incorporated into vehicle equipment as a standard item, especially in new vehicles. The introduction of this new technology requires a pragmatic approach to specifying the performance of these systems. For a number of years, Defence R&D Canada – Valcartier has worked on the development of the Ferret small arms detection and localization system. Our involvement in the design and fielding of the Ferret has provided us with an inside view on how these systems should be specified. In this paper, we propose a basis for the specification of such a system.

1.0 INTRODUCTION

As major buyers of military technology, governments are playing a lead role in establishing performance criteria and benchmarks for evaluation and qualification purposes. Defence R&D Canada, with its long-term expertise in atmospheric acoustics, is proposing performance metrics for the qualification of acoustic small arms localization systems. This consistent framework is a consolidation of criteria that have been developed for the procurement of the Ferret system by the Canadian Army. Consistent performance metrics will contribute to an improved understanding of in-air acoustic technology by both the public and private sectors, especially for those agencies with little knowledge in the field. In the long run, this will manage expectations at all levels of the procurement process and promote the strengths of the technology and awareness of its limitations in the best interests of the troops in the field.

An acoustic small arms localization system[1-7] provides the location of the shooter in range and angle, the bullet miss distance and the bullet calibre[1]. The performance metrics indicate the probability that the shot will be detected and identified, the accuracy of the solution provided and the level of confidence in that accuracy. There is a dramatic difference between a system detecting 90% of the shots fired and providing good shooter information on only 10% of the shots, and a system detecting only 10% of the shots fired but providing good shooter information on 90% of them. Providing the probability of detection alone is incomplete; an operator needs to know what level of confidence he or she can have in the information provided.

The specific characteristic of in-air acoustics is the non-stationary nature of the atmosphere. Wind, turbulence and changes in the speed of sound with height affect the propagation of a sound. The atmosphere can enhance or impede the detection of a sound for a few seconds or a few hours. Terrain and

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[1] See also the Pilar system from Metravib, France on the Internet.

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Available from: http://www.rto.nato.int/abstracts.asp.

obstructions in the area also affect the detection and recognition of an acoustic event. In principle, the probabilities provided in performance metrics should be obtained from long-term averages taken in a variety of environments. For obvious reasons, it is not feasible to test small arms fire in many environments. Even if this were possible, it is not desirable to select performance metrics that could not be used with reasonable effort.

The performance metrics that are proposed in this document were derived for open terrain, an environment typical of most trial sites around the world. The metrics are intended for single array systems as opposed to distributed sensor networks that use triangulation and/or fusion with other sensors for detection and recognition. To understand the compromises that were made in selecting the performance parameters, Section 2 describes the acoustic phenomenology of small arms fire. It describes the sounds that are created by small arms fire and the effect of the atmosphere on them. In Section 3, we present the proposed metrics along with the reasoning that substantiate the choice of each parameter. Section 4 summarizes the approach.

2.0 ACOUSTIC PHENOMENOLOGY

2.1 Propagation geometry

Most small arms fire generates two distinct impulse sounds: the muzzle blast and the shockwave (see Figure 1). The muzzle blast is created at the weapon by the rapid discharge of the propellant and the fast combustion that occurs when the unburned part of the propellant mixes with air outside the muzzle. The shockwave is created by the supersonic bullet travelling through the air, similar to the sonic boom of a supersonic aircraft.

For a sensor exposed to small arms fire, the muzzle blast wave originates from a point source (the muzzle), and propagates spherically from the muzzle at the speed of sound. Hence, it can be detected from anywhere around the firing position (shown in blue below). From the sensor perspective, the muzzle blast wave propagates from the weapon directly towards the sensor, given that there are no obstructions in the propagation path.

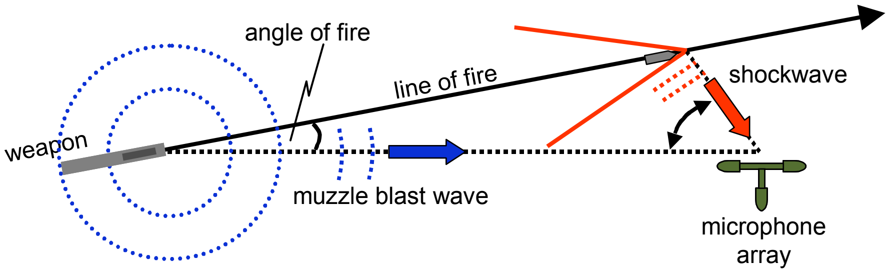

Figure 1: Muzzle blast and shockwave propagation at low angle of fire (U)

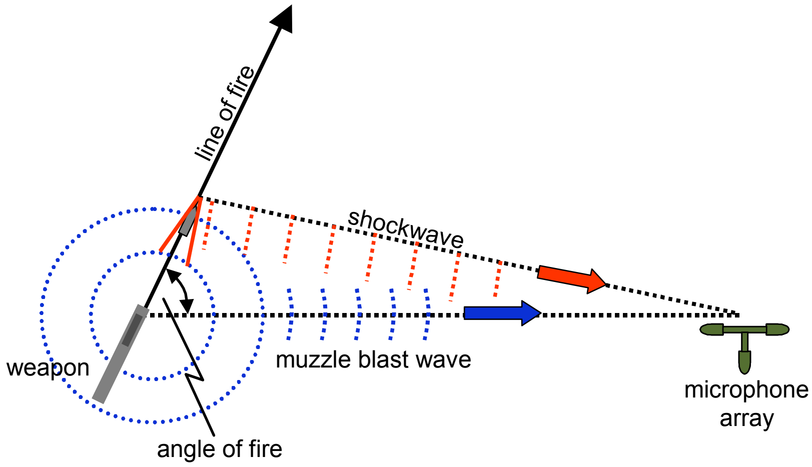

Figure 2: Muzzle blast and shockwave propagation at high angle of fire (U)

The shockwave cone produced by the bullet is similar to the triangular wake created by a boat on the surface of the water. The tip of the cone moves along the line of fire at the speed of the bullet, but the acoustic wave front that is produced propagates perpendicular to the shockwave front (in red) at the speed of sound.

From a sensor perspective, the bullet travels from the muzzle of the weapon to the point where the shockwave detaches from the bullet and propagates to the sensor. The time for the shockwave to reach the sensor after the shot is calculated by adding the bullet's time of travel to the point of detachment and the propagation time of the shockwave from the point of detachment to the sensor. As shown in Figure 2, at a high angle of fire, the point of detachment of the shockwave is close to the weapon, and the shockwave and muzzle blast appear to originate from the same area. From a sensor perspective, their times of arrival are almost the same and their directions of arrival are almost the same.

As the angle of fire and the distance between the weapon and sensor vary, the difference between the times of arrival of the two pulses and the difference between the directions of arrival of the pulses change in a predictable manner. This predictability allows the system to map out the entire geometry of the fire event by collecting and analyzing the sounds produced by the two pulses. These pulses are the only sources of information available to an acoustic system.

2.2 Acoustic signal

Figure 3 illustrates the idealized shockwave and muzzle blast waves that would be received by a microphone exposed to small arms fire. This idealized illustration does not allow for the effects of reflections from obstructions and terrain features, reverberation, atmospheric refraction bending the propagation path and filtering out the high frequencies, and diminished sound clarity caused by turbulence.

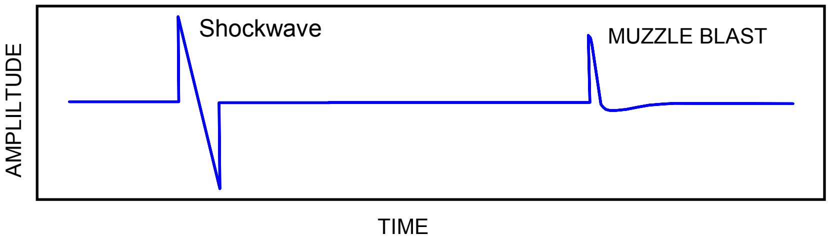

Figure 3: Idealized sound received at a microphone exposed to small arms fire (U)

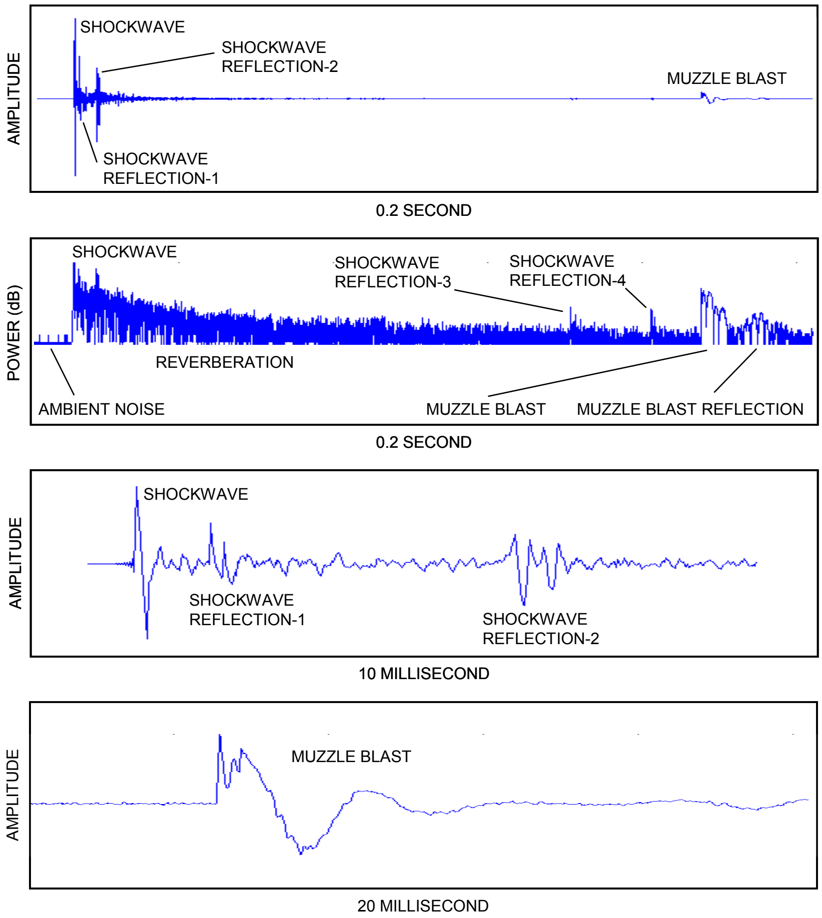

Figure 4: Sound generated by small arms fire (from top to bottom): the amplitude of the entire signal, the instant power of the entire signal, the zoomed shockwave region and the zoomed muzzle blast region

Figure 4 is an example of the sound measured by a microphone in an actual small arms fire event. The top trace shows the entire sound pressure over a period of 0.2 second, including the shockwave and muzzle blast. The second trace is the instant power obtained by squaring the pressure, limiting its minimum value for visual purposes and taking the logarithm. The other two traces are segments of the pressure zoomed around the shockwave and muzzle blast. This particular case shows four reflections of the shockwave and one reflection of the muzzle blast. It is interesting to note the level of noise created by the shockwave reverberation observed after the arrival of the shockwave. That noise can remain for a few seconds after the arrival of the shockwave. In this particular example, the shot was fired into an open corridor bordered on each side by trees. The reflections observed are reflections from the ground and trees, which act like walls.

The function of the acoustic system is to recognize the primary shockwave and its associated muzzle blast pulses among the variety of sound pulses generated by a shot. The system must disregard reflections and reverberations, as well as the sound of the bullet impacting the target, if detected. In addition to these unwanted sounds, the environment generates its own sounds which must also be disregarded: lightning, doors slamming, people talking, motors starting, etc.

3.0 PERFORMANCE METRICS

3.1 General

The following nine (9) parameters are proposed as the performance metrics for the evaluation and/or qualification of acoustic small arms localization systems.

1. Probability of detection as a function of miss distance
2. Probability of full localization
3. Probability of good solution
4. Probability of false alarm
5. Azimuth angle accuracy
6. Elevation angle accuracy
7. Range accuracy
8. Miss distance accuracy
9. Calibre accuracy

The performance metrics are intended for single array systems exposed to single shots. Multiple shots fired from different shooters or by the same shooter can be considered as a sequence of single shots if the time between the arrivals of the shockwaves is more than two seconds. This ensures that the muzzle blast of a shot arrives before the shockwave from the next shot. This avoids the confusion in processing which can cause errors in the range estimate.

In addition to creating confusion, multiple shots raise the level of noise in the environment. When a single shot is fired, the reverberation noise (similar to the echo) can be heard for as much as 10 seconds. If another shot is fired during that time, the chances of detecting that shot are lowered by the increased background noise level. This does not mean that the acoustic system will stop working; it simply means that its performance might be affected for a few seconds. When one measures systems specifications using the proposed metrics, sufficient time should be allowed for the reverberation to fade away.

3.2 Probability of detection

Probability of detection refers to the probability that a shot will be detected and recognized. As we indicated in the previous section, a small arms fire event is characterized by the presence of the shockwave and muzzle blast pulses. Muzzle blast is basically an explosion. Several sources of sound can produce a similar pulse: blank ammunition, artillery simulators, firecrackers, etc. In addition, as the distance increases between the shooter and the sensor, the effects of turbulence and refraction gradually modify the time-domain features of the pulse and thus its ability to be recognized.

On the other hand, the shockwave pulse is a sound that is not common in nature and is difficult to reproduce. For that reason, the probability of detection is linked directly to the probability of detecting the presence of the shockwave. The shockwave presence is not the only means of recognizing that a shot has been fired, but it is the primary signal used for recognition. Because of the effects of atmospheric propagation, shockwave recognition depends largely on the bullet miss distance. On average, as the miss distance increases, the probability of detection decreases. That does not preclude the fact that a shockwave would be recognized from 200 metres on one day and not recognized from 50 metres on another day.

Because of the relation between bullet miss distance and probability of detection, we propose that probability of detection be specified at a number of given miss distances, such as 2, 20 and 200 metres. The probability at intermediate miss distances may be obtained using a simple linear (or possibly log-linear) interpolation.

3.3 Probability of full localization

Probability of full localization refers to the probability that a complete solution will be determined, given that the shot has been detected. A complete solution includes range, azimuth and elevation angles, miss distance and calibre. The probability that a system will provide a full localization is linked to the probability of recognizing the muzzle blast amongst the reverberation, reflections and ambient sounds. In principle, the strength and fidelity of the muzzle blast depends on the distance between the shooter and the sensor. However, our experience showed that atmospheric refraction and turbulence play a more important role than range for distances greater than approximately 200 metres. Because of the randomness nature of these two effects (range and turbulence), the range dependency is not generally significant. For that reason, a single value could be used for the probability of full localization, independent of range.

3.4 Probability of good solution or confidence interval

Probability of good solution refers to the probability that a solution provided by the system will fall within the accuracy bounds specified by the azimuth angle accuracy, elevation angle accuracy, range accuracy, miss distance accuracy and calibre accuracy. For example, a probability of good solution of 90% with an azimuth angle accuracy of 5 degrees, an elevation angle accuracy of 10 degrees, a range accuracy of 10%, a miss distance accuracy of 30% and a calibre accuracy of 40%, indicates that the solution provided has a 90% chance that the azimuth angle error be less than 5 degrees, the elevation angle error be less than 10 degrees, the range error be less than 10%, the miss distance error be less than 30% and the calibre error be less than 40%.

The probability of good solution can be estimated from a number of live fire shots by dividing the number of shots that fell within the accuracy bounds for azimuth angle, elevation angle, range, miss distance and calibre by the total number of shots fired.

The accuracies specified for azimuth angle, elevation angle, range, miss distance and calibre define the good solution.

3.5 Probability of false alarm

The probability of false alarm is one piece of information often requested by operators. It tells them the chances of being wrongly alerted to small arms fire. False alarms are caused by a specific source of sound that mimics the shockwave sound. The question then reverts to what are the chances of being in the presence of that source. For example, if the system triggered to the sound of thunder, and there were five occurrences of that sound in one year and no small arms fire, the proportion of false alarms in that year would be 100%. On the other hand, if the system was exposed to 100 small arms shots, the proportion of false alarms would be 5%.

One common source of false alarms occurs when a shot is fired away from the acoustic sensor. In other words, the acoustic system is located behind the shooter. At that location, only the muzzle blast is detected. There is no shockwave propagation behind the shooter. Because the muzzle blast is loud and short in duration, some systems wrongly recognize that muzzle blast as a shockwave. Some might argue that this is not a false alarm because a shot was actually fired. We believe that these systems should exclude friendly fire. This also includes all firing in the close vicinity of the sensor. Even if there were a shockwave detected at the sensor, if the shooter is within a certain range threshold, say 5 or 10 metres, the event should not trigger the acoustic system.

The recognition of a small arms fire event is carried out through a complex set of thresholds, criteria and rules. For some detection systems, a simple threshold can be applied to the random input noise to meet a given false alarm rate. That is not the case for the recognition of small arms fire.

In our opinion, if certain sources of noise create false alarms, the operators should know about them. If a probability of false alarm is specified, a method must also be provided to verify that number; otherwise the specification is meaningless and should not be used within performance metrics.

3.6 Azimuth angle accuracy

Azimuth angle accuracy is a bound that defines the range of azimuth angles for a good solution. It is used in conjunction with the probability of good solution. For example, an azimuth angle accuracy of 5 degrees and a probability of good solution of 90% indicate that if the system provides a solution, the azimuth angle error will be less than 5 degrees 90% of the time.

Azimuth angle accuracy depends mostly on the level of turbulence at the time of the shot. The azimuth angle is obtained from the direction of arrival of the acoustic muzzle blast pulse. A turbulent atmosphere often gives rise to multi-path propagation, which creates several acoustic rays that recombine at the sensor. This not only alters the direction of propagation but also decreases the coherence of the pulse between the microphones within the acoustic array. A side effect of turbulence is to decrease the similarity between the sounds measured at each microphone. This decreased similarity introduces errors in the estimation of the difference in the times of arrival, which in turn translates into errors in the estimation of the azimuth.

3.7 Elevation angle accuracy

Elevation angle accuracy is a bound that defines the range of elevation angles for a good solution. It is used in conjunction with the probability of good solution. For example, an elevation angle accuracy of 10 degrees and a probability of good solution of 90% indicate that if the system provides a solution, the elevation angle error will be less than 10 degrees 90% of the time.

The elevation angle of the shooter is obtained from the direction of propagation of the muzzle blast. Propagation of the muzzle blast wave is strongly affected by the atmosphere. The changes in the speed of sound with height caused by wind and the changing ground temperature during the day cause refraction, which bends the acoustic propagation path downward or upward. In other words, sounds do not propagate in a straight line. They either propagate up and then down like a ball, or down and then up. Note that the azimuth angle is not affected by atmospheric refraction, only the elevation angle.

The atmosphere bends the acoustic ray to some extent, but elevation angle estimates are still valid at short ranges.

3.8 Range accuracy

Range accuracy is a bound that defines the range of shooter distances (range) for a good solution. It is used in conjunction with the probability of good solution. For example, a range accuracy of 10% and a probability of good solution of 90% indicate that if the system provides a solution, then 90% of the time the range error will be less than 10%. Range accuracy is relative to the range estimate and thus is expressed as a percentage. Unlike azimuth error, range error increases almost linearly with range. This is due mainly to errors in the assumed ballistics of the bullet.

Range accuracy depends on the geometry of the shooting, the accuracy in the measurement of the direction and time of arrival of the shockwave and muzzle blast, the time feature of shockwave pulse, and advance knowledge of the ballistics of the bullet. The estimation of range requires the reconstruction of the entire geometry of shooting. When the distance between the shooter and the shockwave detach point is small, the most important parameters in range estimation are the difference in the angles of arrival of the muzzle blast and shockwave and the time features of the shockwave: duration and amplitude. At the other extreme, when the distance between the shooter and the shockwave detach point is large compared to the miss distance, the most important parameter in range estimation is advance knowledge of the bullet drag.

3.9 Miss distance accuracy

Miss distance accuracy is a bound that defines the range of miss distances for a good solution. It is used in conjunction with the probability of good solution. For example, a miss distance accuracy of 30% and a probability of good solution of 90% indicate that if the system provides a solution, then 90% of the time the miss distance error will be less than 30%. Miss distance accuracy is relative to the miss distance estimate and thus is expressed as a percentage.

Miss distance accuracy is linked directly to the time feature of the shockwave. The shooter range and the ballistics of the bullet have a weak effect on those parameters by changing the speed of the bullet at the detach point, which in turn changes the duration and amplitude of the shockwave. In order to simplify the performance metrics, miss distance accuracy is not expressed in terms of range or bullet calibre. The value provided for accuracy should take these effects into account.

3.10 Calibre accuracy

Calibre accuracy is a bound that defines the range of calibres for a good solution. It is used in conjunction with the probability of good solution. For example, a calibre accuracy of 30% and a probability of good solution of 90 % indicate that if the system provides a solution, then 90% of the time the calibre error will be less than 30%. Calibre accuracy is relative to the calibre estimate and thus is expressed as a percentage.

Calibre accuracy is linked directly to the time feature of the shockwave. The shooter range and the ballistics of the bullet have a weak effect on those parameters by changing the speed of the bullet at the detach point, which in turn changes the duration and amplitude of the shockwave. In order to simplify the performance metrics, miss distance accuracy is not expressed in terms of range or bullet calibre. The value provided for accuracy should take these effects into account.

7.0 SUMMARY

In this paper, we have presented metrics for evaluating the performance of single array acoustic systems used for the localization of small arms fire. A good metrics framework does not necessarily provide a true account of the performance of a system in actual operational conditions. Rather, it provides a means of quantifying performance that can be reproduced through a reasonable effort.

Small arms fire produces a shockwave and a muzzle blast, along with reflections and reverberation. Recognizing that a shot has been fired is accomplished by recognizing the shockwave. Because the time features of the shockwave fade away with range, the probability of detection depends on average upon the miss distance. Recognizing the presence of a clear muzzle blast can help in recognizing that a shot was fired, but that is a rare event. Shooters are often far from the sensor and may be firing from among or within buildings.

The performance metrics are based on defining error bounds for each parameter of the solution: range, azimuth angle, elevation angle, miss distance and calibre. A solution is declared to be good if the error on each of those parameters is within the predefined bounds. The probability of good solution is the probability that a solution reported to the operator will be within the specified bounds for all the parameters.

The probability of false alarm has little meaning in the context of small arms fire localization. If the background noise was truly random, one could probably set the algorithms to meet a certain probability of false alarm. For an acoustic system operating outdoors, ambient sounds are not random but a sum of recognizable noises: people talking, door slamming, engine starting, traffic noise, etc. One of those noises may cause false alarms. If this is known to the manufacturer, operators should be informed. For example, if false alarms occur when people talk within one metre of the sensor, the operator should be told how to avoid causing false alarms.

1. REFERENCES

[1] Bédard, J., Operating Ferret on a Patrol Boat, Proc. SPIE Vol. 6231, 62310Z, May 2006.

[2] Donzier, A., Cadavid, S., Small arm fire acoustic detection and localization systems: gunfire detection system, Proc. SPIE Vol. 5778, p. 245–253, Jun 2005.

[3] Mazurek, J.A., Barger, J.E., Brinn, M., Mullen, R.J., Price, D., Ritter, S.E., Schmitt, D., Boomerang mobile counter shooter detection system, Proc. SPIE Vol. 5778, p. 264–282, Jun 2005

[4] Bédard, J. Paré, S., Ferret, A small arms fire detection system: Localization concepts, Proc. SPIE Vol. 5071, p. 497–509, Sep 2003.

[5] Bédard, J. Paré, S., Martin, B., Guardian: An Acoustic Sniper Detection System, *Proceedings of the 3rd NATO-IRIS Joint Symposium*, Québec, Canada, Oct 1998.

[6] Carapezza, E.M., Law, D.B., Csanadi, C.J., DARPA counter-sniper program: Phase 1 Acoustic Systems Demonstration Results, Proc. SPIE Vol. 2938, p. 299–310, Feb 1997.

[7] Duckworth, G.L., Gilbert, D.C., Barger, J.E., Acoustic counter-sniper system, Proc. SPIE Vol. 2938, Nov 1996.